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LAUNDERING SHRINKAGE OF WOVEN LYOCELL AND LYOCELL BLENDED FABRICS

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In Partial Fulfilment of

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MASTER OF SCIENCE

Department of Clothing and Textiles

University of Manitoba

by

George Guoan Tang

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ABSTRACT

Recent developments in finding new solvents for cellulose and the production of a new generation of man-made cellulosic fibres under the generic name lyocell, are believed to overcome the shrinkage problem associated with viscose rayon fabrics. The purpose of this study was to investigate whether lyocell and lyocell blended fabrics can be laundered without excessive shrinkage rather than be dry-cleaned, and if so, what laundering conditions would control the level of shrinkage within acceptable limits. A second objective was to determine whether enzyme finishing changes the level of shrinkage observed during subsequent laundering.

Three woven chambray fabrics with similar fabric constructions were selected for this study. Their fibre contents were 100% Tencel, 60/40 cotton warp/Tencel weft union blend and 100% cotton. The effect of the following four laundering treatments were assessed: hand or machine washing, 20 or 40 ^{0}C washing temperature, tumble drying or drying flat, and 1 or 5 laundering cycles. A fifth independent variable was added by submitting the two lyocell containing fabrics to enzyme finishing prior to laundering. The effect of the four laundering conditions and enzyme finishing on the warp and weft shrinkage levels was determined by full factorial statistical analysis. In addition, certain geometric dimensions, such as inter-yarn distance and crimp height, were measured microscopically on fabric cross-sections before and after the most severe laundering conditions.

The level of observed shrinkage varied from 0 to 5% depending on the type of fabric, the fabric direction, the laundering condition and the enzyme treatment. In the warp direction, the 100% cotton fabric had more shrinkage than the blend, which had more shrinkage than the 100% Tencel fabric, whereas in the weft direction, the reverse was found. The

results also indicated that machine rather than hand washing, and 5 rather than 1 laundering cycle contributed to significantly more shrinkage, whereas the drying method and washing temperature had less effect. Enzyme finishing was found to improve the dimensional stability of the two lyocell fabrics during laundering. The observed changes in inter-yarn distance correlated with the measured fabric shrinkage results, and usually, the changes in warp and weft crimp height could be explained by the established theory of relaxation shrinkage. However, crimp heights for the 100% Tencel fabric increased during laundering pointing to possible changes in yarn diameter and yarn structure and fibre migration.

In conclusion, lyocell and lyocell blended fabrics have the potential to provide dimensionally stable light weight fabrics with less laundering shrinkage than equivalent cotton fabrics. However, appropriate finishing conditions and a post-finishing enzyme treatment may be needed to ensure that laundering shrinkages remain within acceptable levels.

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CHAPTER 1

INTRODUCTION

Rayon, the first man-made fibre was produced as early as 1832 (Tortora, 1987). It initially came into the market as an inexpensive substitute for silk, for rayon first appeared as a silk-like lustrous filament. Rayon is made from cotton linters and wood pulp (cellulose), and has many characteristics of cotton and linen. The manufacture of "Artificial Silk" by Chardonnet in 1891 marked the beginning of commercial production. By 1905, the Samuel Courtauld Company (UK) was in serious production of viscose yarn by a process fundamentally similar to that still used today. Events in the further development of the viscose process were colour pigmentation (1926), cut staple fibre (1934), tyre reinforcement yarn (1935), improved tyre yarn (1956), crimped yarn (1957), high-wet-modulus fibre (1965) and hollow fibre (1976) (Ford, 1991b). Viscose fibres not only have some unique properties particularly for clothing but also for hygiene and non-woven products. Production of viscose fibres is limited mainly by the heavy investment required to meet the needs of environmental protection (Nousiainen, 1993).

The world production of rayon fibres continued to grow until 1973, when various competing synthetic fibres caused pressure on many of its market outlets. For decades, rayon was misunderstood as a "cheap" substitute for cotton (Greenfield, 1988). The rayon price is 15%-45% lower than that of cotton. In mid-1980's, the European fashion world took a second look at rayon (Textile World, 1989), and this time, rayon's rose to popularity quickly as apparel designers discovered its inherent characteristics, namely its "natural" hand, soft drape, vivid colours and comfort to wear, which are perfectly suited to today's fashion.

1.1 Problem Statement

While rayon has some unique aesthetic and comfort properties, which are preferred by consumers, rayon also has some disadvantages (Lyle, 1982; "Rayon", 1977). The biggest problem is shrinkage. Because the wet modulus and strength of rayon fibre are low, rayon fibres or yarns are easily stretched when wet (Bonnet, 1946) and if dried under tension remain in an extended condition until wet again. This obviously is a potential cause of fabric shrinkage, which can easily occur during laundering. Some rayon crepe fabrics have been known to shrink as much as 25% after laundry. A degree of shrinkage of over 2% ("shrinkage", 1984) will alter the fit of most garments and will be readily noticed by consumers wearing tight and form-fitting garments. The shrinkage tolerance of most garments made of woven fabric is 2.5% (Powderly, 1978). Excessive dimensional change can make a garment physically unwearable and shrinkage in fabrics can cause a variety of problems for the finisher, garment maker and wearer such as :

- Seam puckering that cannot be pressed out;
- Garment distortion and discrepancy from intended size;
- Bubbling of pleated panels;
- Delamination of fusible interlinings;
- Deteriorating appearance in wear and laundering.

Consequently consumers consider shrinkage to be a critical performance criterion. The cost of shrinkage to the apparel manufacturer can be high in terms of lost repeat sales (Bannasch, 1987). Woven rayon and rayon blend fabrics in light (below 150 g/m^2) and medium weights (150-200g/m^2) are popular for manufacturing linings and women's blouses, dresses and skirts. Traditionally, due to problems of high laundering shrinkage, which is over 2.0% (CAN/CGSB-86.1-M91), apparel manufacturers have attempted to minimize complaints and the number of returned goods by labelling such garments "DRY CLEAN ONLY". Dry cleaning is essentially a non-aqueous process, which causes less shrinkage than wet cleaning does (Rhodes, 1970a). But this practice is not desirable or convenient for the ultimate consumer, particularly when certain blend levels with more dimensionally stable fibres, and new types of solvent-spun cellulosic fibres, such as lyocell, can be washed without unacceptable shrinkage levels. Also some consumers prefer the economy of buying washable garments ("Writing a", 1984).

In order to control shrinkage and manufacture satisfactory garments, first of all the mechanism of fabric shrinkage had to be better understood. The basic mechanisms that control the change in fabric dimensions are relaxation shrinkage, swelling shrinkage and progressive shrinkage. As early as the 1930's, researchers (Collins, 1939; Peirce, 1937) had studied the principles of shrinkage and proposed methods to control it. Traditionally, two basic methods can be applied in controlling the shrinkage of rayon fabrics (Powers, 1949). They are chemical treatments (resins) and mechanical treatments. Both resins and mechanical treatments can produce a washable fabric (Pfeffer, 1948), but they both have disadvantages. Using a resin finish, the desirable aesthetic, handling properties, and tear strength are often sacrificed, while the mechanical treatments often cause excessive yardage loss.

Naturally, one of the main objectives of developing a new kind of rayon is to reduce the level of fabric shrinkage. There have been a number of attempts over the years to spin a better rayon fibre with improved dimensional stability, particularly under wet conditions. More recently, research into finding more desirable solvents for cellulose (Turbak, 1977) has generated the development of a new type of solvent spun cellulosic fibre (Loubinoux, 1987) with attractive properties compared with viscose, modal, high wet modulus rayon, and cotton fibres (Cole & Jones, 1990).

The new process of solvent-spun cellulosic fibre is different from conventional viscose rayon processing. In this new process, no chemical reactions are involved, and virtually all of the dissolving agent is recovered with minimal, nonhazardous effluent (Rudie, 1993). The lyocell process is simpler and more environmentally friendly (Marini, 1993), and the resultant fibre has the natural absorbency and comfort of cotton and the strength and ease of care of a synthetic fibre. Fabrics manufactured from lyocell fibres have very low shrinkage, i.e. only about 2% in the warp and weft directions (Clark, 1992).

To assist apparel manufacturers in determining the appropriate care labels to be attached to apparel items made from these fabrics there is a need for guidance about what possible cleaning conditions (washing/drying/pressing or dry cleaning) might be satisfactorily achieved with certain fibre types, blend levels, fabric weights and types of woven construction.

Given that fabrics woven from new 100% solvent spun cellulosic fibres and from blends of lyocell with cotton are less susceptible to progressive shrinkage during repeated washing and drying cycles, there is a need to understand the mechanism responsible for this improved performance, particularly in terms of the level of fibre swelling (hygral expansion), the changes in fabric geometry over repeated cycles, as well as defining the characteristics of the "stabilized" structure when the fabric has reached its shrinkage limit.

1.2 Objectives of the Study

In order to assist the garment manufacturer in determining the appropriate care labels and help consumers take better care of their garments made from lyocell fabrics, it is necessary to identify and priorize those variables that influence the level of fabric shrinkage, particularly those conditions that cause an unacceptable level of 2% or greater according to the Canadian Labelling Standard (CAN/CGSB-86.1-M91).

To meet this objective the following independent variables, which are considered the most likely parameters to cause shrinkage, will be tested:

- Washing method;
- Washing temperature;
- Drying method;
- Number of laundering cycles.

In this study, three fabrics made from 100% Tencel, cotton/Tencel blend, and 100% cotton will be selected and laundered using 16 different conditions. The mean shrinkage values for these 16 laundering treatments will be calculated, and compared to the acceptable shrinkage criteria of 2%

(CAN/CGSB-86.1-M91). In addition, a full factorial statistical analysis will be used to determine which independent variables influence the level of fabric shrinkage. The independent variables and the interactions which possess a significant effect on the laundering shrinkage will be analyzed in detail. By including the type of fabric as another independent variable, the effect of weaving different fibres in the warp and weft directions on shrinkage will also be analyzed by using a full factorial analysis.

To obtain lyocell's soft and luxurious hand (Clark, 1992) together with its excellent drape characteristics, an enzyme treatment is often recommended for lyocell fabrics. In this study, the 100% Tencel, and cotton/Tencel blend fabrics will be enzyme treated and then laundered. The resultant shrinkages will be compared with those which have not endured enzyme treatment although laundered under the same conditions.

In order to understand the shrinkage mechanism in more detail, the cross-sectional dimensions of those fabrics which have the highest laundering shrinkage will be determined by encapsulating the fabric in resin and cutting thin sections with a microtome. Two parameters, inter-yarn distance and crimp height, will be measured using a microscope fitted with an eye-piece micrometer, so that the geometric structural changes during laundering and enzyme treatment can be identified. It is hoped that the results of this study will help manufacturers control shrinkage, minimize returns, and help consumers take proper care of garments produced from lyocell and lyocell blended fabrics.

1.3 Hypotheses

Ho_1: The shrinkages of 100% lyocell, lyocell/cotton blend and 100% cotton fabric after laundering will not exceed 2% in either direction.

Ho_2: There is no significant difference in the shrinkage of 100% lyocell, lyocell/cotton blended and 100% cotton fabrics when using different:

A. Washing methods;

B. Washing temperatures;

C. Drying methods;

D. Number of laundering cycles.

Ho_3: The fibre content in one yarn direction does not affect the shrinkage in the other yarn direction.

Ho_4: The enzyme treatment has no significant effect on the shrinkage of lyocell and lyocell blended fabrics.

Ho_5: There is no significant difference in geometric structural changes:

A. Before and after laundering;

B. Before and after enzyme treatment;

C. Before and after laundering of the fabric after enzyme treatment.

Ho_6: There is no significant linear dependent relationship of the shrinkage measured from fabric specimen on the shrinkage calculated from the changes of inter-yarn distance.

The hypotheses will be tested using the data obtained by testing the lyocell, lyocell blended and cotton fabric samples in the Textile Laboratories at the University of Manitoba.

1.4 Outline of Thesis

The current chapter contains the introduction of the thesis, the problem statement, the objective, justification, and hypotheses, as well as a list of relevant terminology. The next chapter contains a literature review which describes previous research on shrinkage, methods for controlling and measuring shrinkage, and the development of the new solvent-spun cellulosic fibre, called lyocell. As well as including the history, manufacturing process and properties of lyocell fibres, the chapter introduces the performance, application and market of lyocell derived fabrics. The description of the fabrics received, details of the experimental design of the laundering and enzyme treatment studies, as well as descriptions of the methods used to measure the fabric properties, to perform the laundering and enzyme treatments, and to undertake the statistical analysis, are all included in Chapter 3. Chapter 4 reports on the results of the experiments and the discussion of results as well as the rejection or acceptance of hypotheses. The final chapter contains the conclusion and recommendations of the study.

1.5 Terminology

1. Rayon is A manufactured fibre composed of regenerated cellulose, as well as manufactured fibres composed of regenerated cellulose in which substitutes have replaced not more than 15 percent of the hydrogens of the hydroxyl groups (Grover & Wiggins, 1964).
2. Lyocell is the generic name for a new cellulosic fibre according to The International Bureau for the Standardisation of Man-made Fibres (BISFA) which is obtained by an organic solvent-spinning process, using a mixture of organic chemicals and water and without the formation of a cellulose derivative (Marini, 1993).
3. Tencel is Courtaulds' registered trade mark for lyocell fibres.
4. Laundering is a process intended to remove soils and/or stains by agitating a textile material in an aqueous detergent solution, and normally including rinsing, extraction and drying (AATCC Test Method 135-1987).
5. Laundering shrinkage represents a decrease in the length or

width of a fabric specimen subjected to specified washing and drying conditions. Laundering shrinkage of cellulosic fabrics can be explained by three concepts i.e. relaxation shrinkage, progressive shrinkage, and swelling shrinkage.

6. Relaxation shrinkage (Lyle, 1977) is the tendency of the fibres and yarns to revert to their normal unstretched dimension.

7. Progressive shrinkage (Lyle, 1977) is the accumulation of shrinkage through successive laundering cycles until the fabric reaches its shrinkage limit.

8. Fabric Swelling shrinkage means that fabrics containing hydrophilic fibres shrink and stretch reversibly depending on their moisture content, the level of fibre hygral expansion and the level of yarn shrinkage. Figure 1A represents a warp yarn in the cross-section of a dry cloth interlacing with three weft yarns. If the weft yarns increase in diameter when the fabric becomes wet (Figure 1B), there is a tendency for the weft threads to move together, resulting in fabric shrinkage and a reduced inter-yarn distance (Collins, 1939).

9. Yarn shrinkage means that when the fibre diameter increases due to hygral expansion, most yarns will also increase in diameter (Collins, 1939). Because fibres in a staple spun yarn lie both in the longitudinal and the circumferential directions of the yarn bundle, any increase in spun yarn diameter will increase the distance that an individual fibre must travel in the circumferential direction without

stretching. Since viscose rayon fibres experience only marginal increases in length, there is a net reduction in the longitudinal distance travelled by each fibre. This reduction in longitudinal distance results in a shortening of the yarn length, an increase in yarn twist angle, and overall fabric shrinkage. The only exception is for very soft and open yarns where each fibre can swell without touching its neighbours. In this situation, the yarn will not increase in diameter when wet.

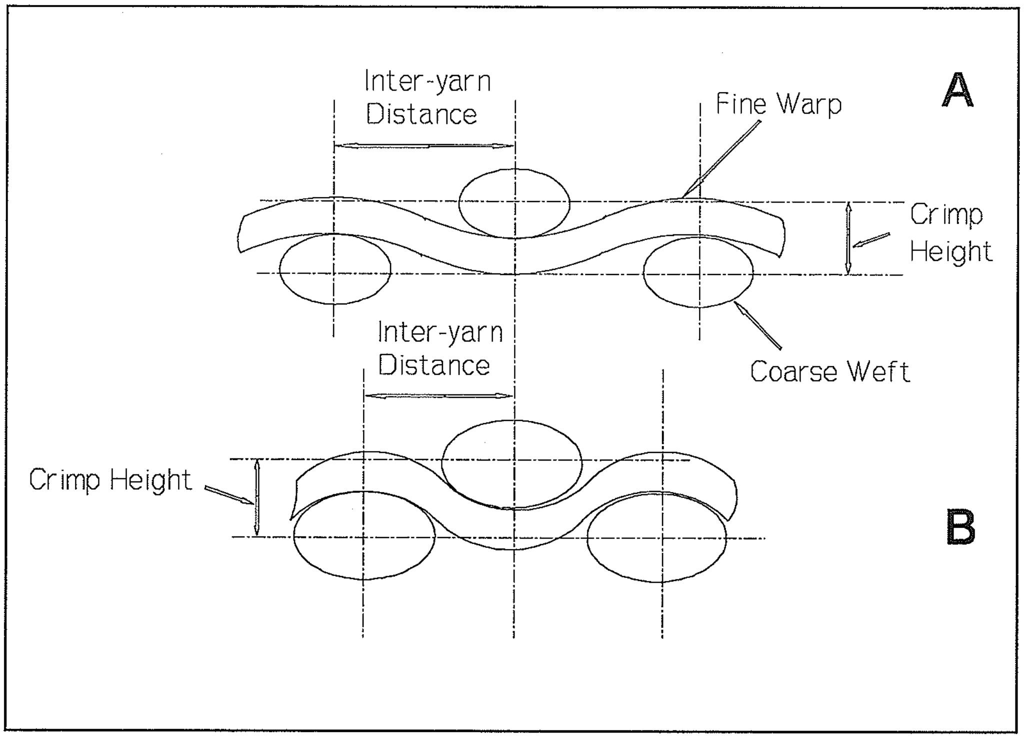


Figure 1. A geometric explanation of fabric swelling shrinkage.

10. Hygral expansion is the swelling of hydrophilic fibres during fabric steaming or wetting (Ly, Denby, and Hoschke, 1988).

11. Shrinkage limit is the point at which no further decrease in the length or width of a fabric occurs as a result of an additional laundering cycles.

12. Fibrillation means the peeling off of fibrils along the fibre surface of individual fibres swollen with water induced by mechanical stress (Marini, 1993).

1.6 Assumptions

1. The respective fibre properties of Tencel and cotton are the same in the three fabric samples.
2. The three fabrics are woven from the same type of Tencel and cotton yarns with the same respective yarn properties.
3. The Tencel and cotton yarns are spun on the same spinning system.

1.7 Limitation of the Study

This study is limited to plain weave lyocell, lyocell/cotton union blend, and cotton fabrics. Since the fabric samples are finished goods supplied by the manufacturer, some independent variables, such as fibre properties, yarn type, yarn twist, fabric cover factor, and the finishing processes, cannot be controlled. Because the fabric specimens without and after enzyme treatment are laundered at two distinct times, the specimens are not totally randomized.

CHAPTER 2

LITERATURE REVIEW

2.1 Mechanisms of Fabric Shrinkage

Garments made of rayon fibres, while quite desirable in many respects, suffer the disadvantage of a high degree of shrinkage during washing unless the fabric is finished and laundered properly (Scott, 1959). Fabric shrinkage has been studied by many researchers over the years, and has been found to be influenced by fibre properties, yarn structure, fabric construction, finishing processes, washing conditions, and laundry load (Lund & Waters, 1959; Marsh, 1966; Morton & Hearle, 1975; Peirce, 1937; Ukponmwan, 1990).

Peirce (1937) was the first to use pure geometry to describe the relationship between yarn crimp and cloth construction, and to show theoretically how shrinkage occurs when yarns are woven into a fabric. Peirce pointed out that crimp height which determined the shrinkage was dependent on yarn number, fabric density and fabric weave. Collins (1939) studied the fundamental principles of the shrinkage of cotton fabrics caused by washing, and explained the swelling shrinkage of fibre, yarn and fabric. He pointed out how fabric shrinkage was associated with the swelling of fibres and the increase in yarn diameter when a fabric becomes wet. If the warp and filling threads were to retain their original spacings, they would have to increase in length or to be stretched. In the absence of the force required to stretch them, they follow the path of least resistance and the threads move together, resulting in fabric shrinkage.

Bonnet (1946) reported that rayon fibres or yarns were easily stretched in the swollen state, and, if dried under tension, remained in an extended condition until wet again. This obviously was a potential cause of fabric shrinkage, which could easily occur when wetting and drying fabrics under different tensions.

Lund and Waters (1959) investigated the laundry shrinkage of rayon fabrics, and reported that shrinkage was due to three different mechanisms which were referred to as: swelling, relaxation, and progressive shrinkage. Fibres which undergo 5% extension when stressed at 0.3-0.4 g/den or less are likely to suffer progressive shrinkage when washed vigorously. Yarn twist, twist direction, denier, staple length, fabric construction, and type of weave will all affect the amount of progressive shrinkage. Lund and Waters also pointed out that the laundry load had a great influence on the level of shrinkage. Shrinkage with an 8 pound (3.6 kg) load was considered to represent an approximate measure of swelling shrinkage, and that the additional shrinkage experienced due to the greater movement and agitation of the fabric using a 1 pound (450 g) load was believed to measure the level of progressive shrinkage. These findings were supported by Scott (1959) who studied the washing shrinkage of 6 different fibres including rayon. He reported that the dimensional stability of a fabric after repeated washing was not solely dependent on fibre swelling. The resistance of the fibre to stretching when wet had a large influence on the control of fabric shrinkage. For example fabrics made from fibres which require a load of 0.5 grams/denier or higher to produce an extension of 5% while wet exhibit no appreciable progressive shrinkage. On reviewing the literature, Ukponmwan (1990) stated that the mechanism of fabric shrinkage was influenced by five different fibre properties, namely:

- Transverse swelling in water;
- Extension and modulus (dry and wet);
- Whether it is in staple for or continuous filaments;
- Setting properties;
- Flexural rigidity (crimp inter-change).

2.2 Controlling Shrinkage

Rayon fabric has a reputation for high shrinkage. Because of their extremely low wet strength and high wet elongation, rayon fibres or yarns are easily stretched during finishing. When dried under tension, they will remain in an extended condition until wet again. Rayon also exhibits a large amount of cross-sectional swelling. The cross-section of rayon fibre can increase by 44-86% when wet (Morehead, 1947). This aids the potential relaxation shrinkage of rayon fabric. In order to promote the selling of rayon fibre in apparel end-uses, the shrinkage of rayon fabric has to be controlled. Powers (1946) reported that resin and mechanical treatments combine to produce a serviceable and washable fabric. The resin stabilizes the fabric and sets it so that it can respond to the mechanical shrinkage. The mechanical shrinkage alone may cause excessive loss of yardage, so the combined use of resin and mechanical finishing saves yardage, sets the fabric to the desired dimensions and controls subsequent shrinkage. To achieve this, however, desirable aesthetic and handling properties and tear strength are often sacrificed.

Shapiro and Henschel (1947) introduced a series of equipment and setting conditions to stabilize the fabric shrinkage. They pointed out that it is essential to conduct a laundering test in order to determine the proper width at which the fabric must be finished for controlled shrinkage, and also to check whether the warp has been adequately stabilized. Pfeffer (1948) stated that the various manufacturing and wet finishing operations cause severe stretching of rayon fabrics, and the excessive radial swelling of the rayon fibre when wet. These two factors together result in relaxing during laundering, resulting in high amounts of shrinkage. Pfeffer also pointed out that the most valuable means of controlling the shrinkage of rayon fabrics is to reduce fibre swelling by treating the fabric with chemicals such as glyoxal and cross-linked resins. Both resins and mechanical treatments can produce a stabilized washable fabric.

Woodruff (1950) stated that when controlling fabric shrinkage, nine factors have to be considered. These include the maximum amount of shrinkage control possible, whether or not crease resistance is required, the cost of treatment and possible variations of hand. A number of different techniques used to control shrinkage are listed in Table 1 (Woodruff, 1950).

Table 1

Shrinkage Control Technique

Classification	Examples
Reactants	Formaldehyde
Bonding	Hydroxyl ethyl cellulose
Chemical modifier	Alkalis
Thermosetting resin	Urea formaldehyde
Compressive shrinkage	Sanforizer

Also, these techniques can be combined to get the best shrinkage control. Hamburger and Fox (1956) explained the shrinkage mechanism of swelling and drying cycles, and stated that shrinkage can be controlled by one of two basic procedures: either by inhibiting fibre swelling, or by inducing shrinkage as part of the finishing procedure so that no further shrinkage will occur on subsequent washing. This second approach introduced the principle of compacting or preshrinking fabric during finishing.

Marsh (1966) has stated that no textile material demands more care during finishing than rayon. The golden rule of finishing rayon fabrics is to maintain tensions at a minimum and to allow adequate shrinkage during the last drying process; otherwise, a thin papery handle instead of a full body is obtained. If tensions are not controlled during the various manufacturing and wet finishing operations, stretching of rayon fabrics is inevitable, and the excessive radial swelling of the fibres when wet contributes a high level of fabric relaxation shrinkage during laundering. Bannach (1987) recommended a compressive shrinking machine to stabilize the fabric's dimensions. The machine is known in the textile industry as the SANFOR range. SANFOR process has enjoyed a dominant position in the world since it was invented 50 years ago.

An alternative way to reduce the shrinkage of rayon fabric is to blend rayon fibre with a low shrinkage fibre, such as polyester. The earliest theoretical work published concerning blended yarns was by Hamburger (1949). Since then, many researchers have investigated the mechanical, dyeing resistant (Tumer, 1991; Herlant, 1985) and flame resistant (Bajaj, Chakrapani, Jha, & Jain, 1984; Nousiainen & Mattila-Narmi, 1986) properties of rayon fibres blended with polyester. However very little work has focused on the shrinkage of cotton/rayon blended fabrics.

2.3 Measuring Shrinkage

Williams (1946) tested the rayon fabric shrinkage and found out that about 48 percent of the materials had the shrinkage of over 2% in length, and 15 percent of materials had a shrinkage in length of over 5%. He suggested that there is a pronounced difference between exposure to high humidity and actual wetting, the first producing extension and the latter contraction. The first person to photograph cross-sections of different textile fibres so as to measure and compare their area swelling was Morehead (1947). Later, Welo, Ziifle, and Loeb (1952) used a desiccation rate method to determine the relative swelling capacities of cotton and other fibres. They pointed out that existing techniques for measuring swelling capacities were tedious and time consuming.

Clark and Preston (1956) used a centrifuge method to measure the effect of temperature on the swelling of viscose rayon and cotton fibres. They reported that the temperature/swelling curve for both fibres passed through a minimum in the region of 50-60 ^{0}C. Cednas (1961) investigated the dimensional stability of wool fabrics. He stated that the amount of shrinkage which occurs during making up should be predictable and capable of being controlled. The dimensional stability of wool cloth, besides being affected by the cloth construction, depends on the finishing treatments, of which the setting operations are particularly important. This fundamental issue is not confined to wool only. Other fabrics are equally influenced in the same way by the setting condition, particularly if the fibre material can be set in its wet swollen state.

More recently, Powderly (1978) measured laundering shrinkage of both fabrics and garments and found that different results can be obtained even if the same methods are used. Garment manufacturers should measure more than the initial laundering shrinkage of a fabric during the laundering test. In addition standardized laundering methods should be followed so as to ensure good precision and reliability. The AATCC Test Method 135 (1989) and the Canadian method (CAN2-4.2-M90, Method 25.1 & 58) are considered to be satisfactory.

Ly, Denby and Hoschke (1988) stated that the conventional wet-dry method to measure both hygral expansion and relaxation shrinkage is relatively simple, requiring a minimum of equipment and expertise. But the required conditioning time is long, so results cannot be obtained within one working day. They used a domestic microwave to reduce conventional drying times. Thus it is possible to obtain data on relaxation shrinkage and hygral expansion of a sample in less than one hour. The results obtained with the microwave method agree well with those determined by the conventional wet-dry method.

Recently Baird, Laird and Weedall (1994) built an instrument to measure hygral expansion which consists of a test chamber mounted in a fan assisted oven. The sample is suspended inside the test chamber from a balance above the oven. By linking the balance through a serial communications link to a computer, continuous monitoring of the sample weight during test is achieved. Subsequently, the relationship between hygral expansion and moisture regain could be plotted. The relationship between hygral expansion and yarn twist and weave construction have also been investigated (Baird, Laird, and Weedall, 1994).

2.4 Development of Lyocell

In addition to controlling rayon fabric shrinkage by mechanical treatments, chemical methods using resins (Bannasch, 1987), and blending with low shrinkage fibres, there have been a number of attempts over the years to spin a better rayon fibre with improved dimensional stability, particularly under wet conditions. In the 1960's, modal, high wet modulus and polynosic rayon fibres were developed with the objective of reducing wet shrinkage. More recently, research into finding more desirable solvents for cellulose (Turbak, 1977) has generated the development of a new type of solvent spun cellulosic fibre (Loubinoux, 1987). This fibre has attractive properties when compared with modal, high wet modulus and polynosic rayon fibres (Mach, 1982; "Washable silk", 1989).

In 1978 (Clark, 1992), a British research team led by Pat White of Courtaulds Fibres Ltd. started a project called "Project Genesis". In essence the Genesis team developed a method of producing a man-made cellulose fibre utilising a solvent spinning technique. The developed fibres exhibited properties of a potentially successful commercial textile fibre. In partnership with Courtaulds Engineering Division, the team scaled up the original development work in the Coventry laboratory by establishing a major pilot plant in Grimsby, U.K. which started the first commercial production.

The relative complexity and environmental hazards associated with traditional viscose rayon manufacturing methods has stimulated scientists to pursue alternative and chemically simpler processing routes for the manufacture of man-made cellulosic fibres. It is important that such a process uses materials which do not create any adverse environmental effects, and that the properties and performance characteristics of any resulting products would be at least competitive with and ultimately superior to the very best existing products available in the marketplace. Obviously any such process should ultimately be developed into a commercially viable entity, which would yield a profitable return for both Courtaulds and its customers (Cole & Jones, 1990).

Since 1982, Lenzing AG (Firgo, 1993) has been working on various alternative methods to produce cellulosic fibres. From 1986 this research has concentrated exclusively on the solvent system N-methylmorpholine-oxide/water/cellulose. Because early experimental results were encouraging, a continuously working pilot plant producing 500 kg per day was established in 1989/90.

Courtaulds believes that man-made cellulosic fibres have a very good long-term future (Cole & Jones, 1990). They are based on renewable natural resources which are cultivated on land which is largely unsuitable for food production. The fibres are generally versatile and particularly good where moisture absorption is important for comfort and technical performance.

Courtaulds later gave the developed product the name "tencel", and this was intended to be a generic name for all such solvent-spun cellulosic fibres (Davies, 1989). But The International Bureau For The Standardisation of Man-made Fibres (BISFA) gave this fibre the generic name "lyocell". Courtaulds now uses Tencel as its own registered trademark. Tencel is described as one of the most significant innovations in man-made fibres in the last 30 years (Clark, 1992).

2.5 Lyocell Spinning Process

In summary, the process involves mixing dissolved wood pulp with a chemical solvent. The solvent used by Courtaulds is amine oxide. This chemical, when hot, dissolves wood pulp to produce a very clear but very viscous solution, which is filtered and then spun into a coagulating bath containing a dilute aqueous solution of amine oxide. The bath removes the amine oxide from the fibres, which are washed and dried. The dilute amine oxide from the spinning, coagulation and washing stages is concentrated by removing water, purified and then re-cycled into the process again. Because virtually all of the solvent is recovered with minimal, nonhazardous effluent (Rudie, 1993), there are therefore no environmental problems with this process. Figure 1 (Woodings, 1992) shows an outline of the solvent process.

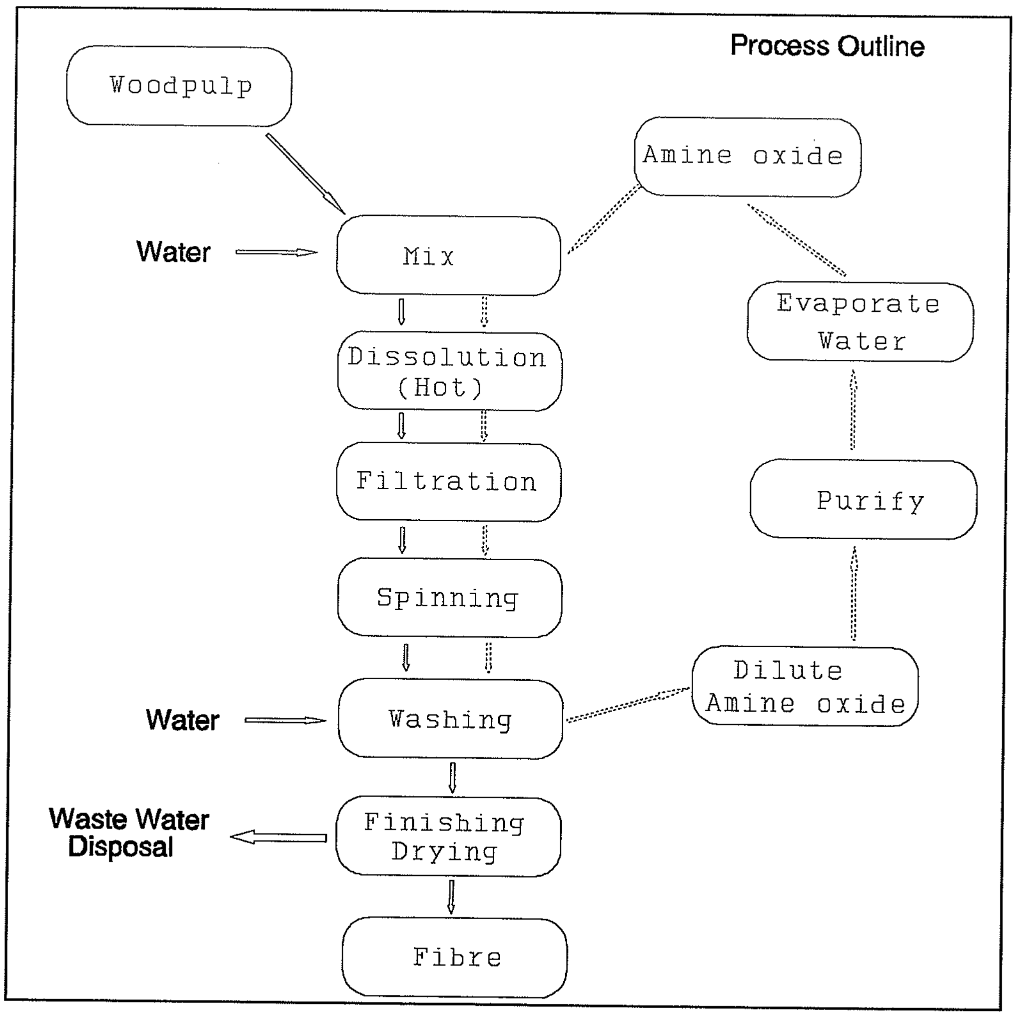


Figure 2. Process of solvent-spun fibre.

The fundamental difference between this process and other established and conventional methods of cellulose fibre manufacturing lies in the absence of any chemical reaction with the cellulose structure. No intermediate compound, such as cellulose xanthate, is formed in the process.

2.6 Lyocell Fibre Properties

Because the translation of cellulose molecules from wood pulp into textile filaments relies on a physical rather than a chemical process, there are significant differences in fibre properties between Tencel and other man-made cellulosic fibres, such as viscose rayon. The solvent spun process creates fibres which have a round cross-section. This, coupled with the smooth surface structure, affects the cohesive properties and hence the processing performance of the fibres.

The lack of chemical disturbance to the cellulose molecules ensures that the resultant fibre retains a significantly higher degree of polymerisation compared to all other types of rayon. Yamashiki and Matsui (1992) examined the crystallinity of these new solvent spun cellulosic fibres using x-ray diffraction analysis, and confirmed that they have a more highly crystalline structure than traditional regenerated cellulosic fibres. This in turn leads to significant increases in fibre tenacity in the dry state. These differences, however, become especially pronounced in the wet state where for the first time man-made cellulose staple wet tenacity exceeds even that of cotton (Cole & Jones, 1990; Davidson, 1993; Davies, 1989; Raven, 1990). Marini (1993) has also pointed out that the lyocell process is simpler and more environmentally friendly, and the lyocell fibres have new and improved properties.

In particular the new solvent-spun cellulosic fibre, lyocell ("A new", 1991) has low shrinkage. Clark (1992) stated that overall, Tencel fibre-derived fabrics have very low shrinkage, i.e. only 2% in the warp and weft directions. Cole (1992) tested the area shrinkage of different blend level of Tencel/cotton and Tencel/viscose fabrics. The area shrinkage is 2.0-2.4% for Tencel/cotton blends, and 2.8-4.0% for Tencel/viscose blends. The typical fibre properties of lyocell are shown in Table 2 (Cole & Jones, 1990).

Table 2

Comparative Fibre Properties

	Tencel	Viscose	Modal	Cotton Middling	Cotton Egyptian	Polyester
Linear Density (dtex)	1.7	1.7	1.7			1.7
Tenacity (cN/tex)	40-42	22-26	34-36	20-24	24-26	55-60
Elongation (%)	13-15	20-25	13-15	7-9	7-9	25-30
Wet Tenacity (cN/tex)	34-38	10-15	19-21	26-28	30-34	54-58
Wet Elongation (%)	16-18	25-30	13-15	12-14	12-14	25-30
Wet Modulus (@ 5% extension)	270	50	110	100	110	210
Moisture Regain (%)	11.5	13	12.5	8	8	0.5
Water imbibition	65	90	75	50	50	3

2.7 Lyocell Textile Performance and Applications

Tencel fabric is essentially aimed at the high, designer end of the apparel market. It has the natural absorbency and comfort of cotton and the strength and ease of care of a synthetic fibre, yet it is neither cotton nor a synthetic. Tencel also resists wrinkling and can be safely laundered at home. Its main advantages are listed below (Courtaulds, 1993):

- Stronger than all other cellulosic fibres;
- Exceptional wet strength;
- Blends easily with all other fibres;

- Can be spun from coarse to fine counts;
- Excellent thermal stability;
- Processes easily from fibre to fabric;
- Wash stability results in extremely low shrinkage;
- Dyes to deep vibrant colours;
- A wide variety of hand effects possible;
- Luxurious drape;
- Desirable subtle lustre;
- Comfortable, natural absorbent;
- Environmentally responsible and favourable.

Commercial Tencel fabric was first introduced in Japan in December 1990. Market reaction was excellent, and stimulated more development work and a considerable expansion in the variety of fabric types. In May 1992, Courtaulds Fibre Inc.'s new Tencel producing facility in Axis, Alabama, U.S.A. came on stream. The new plant is 1000 times larger than the pilot operation in Coventry (Rudie, 1993). While the Coventry facility produced 25 metric tons of fibre a year, the new plant is expected to produce 20000 metric tons a year. Now Tencel fabrics are available from very light weight chambray shirting to heavy weight denims in both Europe and North America. Tencel fibre is also reported (Woodings, 1992) to be an excellent fibre for non-wovens, especially for high strength absorbent non-wovens.

Although lyocell fibres possess some excellent properties, unfortunately, lyocell fibres have a strong leaning towards surface fibrillation which detracts from the aesthetic properties of the finished fabric. The effect of fibrillation often causes a harsher hand. The recommended procedure for resolving this problem is to apply an enzyme treatment together with other physical and chemical finishing techniques, which can be used to obtain a broad variety of unique aesthetic effects (Clark, 1992), such as peach skin effect, sand washed, microveluttino, soft touch, emerized or simply the used-look. Furthermore, after enzyme treatment in combination with mechanical treatments, the extent of fibrillation is reduced and therefore it is more desirable (Marini, 1993). Enzymatic treatments have been used for years in textile processing and more recently after garment dyeing to obtain improved fabric softness, better surface appearance and fashionable looks. In addition, it has the potential to simplify and cheapen the manufacturing process (Diller, Zeronian, Pan and Yoon, 1994), especially in denim garment washing processes, where it can be used as an alternative to stone washing (Koo, Ueda and Wakida, 1994).

CHAPTER 3

MATERIALS, METHODOLOGY AND EXPERIMENTAL DESIGN

3.1 Materials

Three fabric samples were received from Greenwood Mills, Inc., New York, U.S.A. The following table gives the information provided by the company.

Table 3

Fabric Specifications Provided by Greenwood Mills

	Fabric 1	Fabric 2	Fabric 3
Style	05 0540	35 0531	35 0091
Fibre content	100% Tencel	60/40 Cotton/Tencel	100% Cotton
Finish	L316	L316	L316
Length (Yards)	20	20	20
Width (Inches)	64.00"	63.00"	60.00"

For easy identification of these three fabrics, each specimen was marked with the following code in the laboratory:

Fabric 1: T;

Fabric 2: C/T;

Fabric 3: C.

3.2 Fabric Specification

In order to confirm the fabric specification provided by the mill, the following seven test procedures and standards were used.

3.2.1 Fibre Content

In order to identify the fibres presented in each fabric, burning tests, microscopic examination, and solubility tests, were carried out according to standard method AATCC20-1990. Since the lyocell fibre is a new fibre, The additional reagent and different dissolving times are used, the following three reagents; 60% sulfuric acid, concentrated hydrochloric acid, and zinc chloride/formic acid, were used at different temperatures and dissolving times to assess the comparative solubility of the fibres in the 3 fabrics together with standard 100% cotton and 100% viscose rayon test fabrics.

A small sample of the fibres was placed in a test tube, containing about 1 ml of solvent per 10 mg of fibre. The temperature was controlled by preheating the reagent to the desired temperature in a constant temperature water bath.

Since Fabric 2 was a union blend of cotton and Tencel, the mechanical separation method described in standard test method AATCC 20A - 1989 was used to calculate the blend level using the masses of the warp and weft yarns. Five specimens were cut by a rectangular cutting die. The warp yarns and weft yarns were carefully separated by hand, and weighed separately on a scientific balance (Sartorius-Werke GMBH Gottingen, Germany) to the nearest milligram. The percentage of the warp and weft yarns was calculated as a percentage of the combine mass. In order to confirm the above test result, and in case of the need to analyze intimate blended fabrics in the future, a zinc chloride/formic acid method (CAN2-4.2-M88, Method 14.4) for separating cotton and lyocell fibre chemically was developed and is listed in Appendix 1.

3.2.2 Yarn Crimp

The yarn crimp was measured according to ASTM D3883-90, Option B. Ten yarns in the warp and weft directions of each fabric were marked off indicating a distance of 250 mm, prior to removal from the fabric and extension in a Crimp Tester (Shirley Crimp Tester, Shirley Developments Limited, England). The applied force in grams to remove the crimp was calculated by multiplying the yarn tex by approximately 0.5. The average yarn crimp for each set of 10 specimens was calculated and expressed as a percentage of the original 250 mm.

3.2.3 Yarn Linear Density (Tex)

The yarn number (based on short-length specimen) was tested according to ASTM D1059 - 87 using the same 10 yarn specimens as for the yarn crimp test. The yarn number was calculated after weighing the total yarn length of all ten specimens on a scientific balance (Sartorius-werke GMBH

Gottingen, Germany) to the nearest 0.1 mg.

3.2.4 Fabric Length (Yard)

The length of the fabrics was measured by using a fabric inspection machine at Siltex Ltd, Winnipeg, Canada.

3.2.5 Fabric Width (Inch)

The width was measured according to ASTM D3774 - 89. Five measurements were made at random along the length of each fabric sample.

3.2.6 Fabric Count (Thread per centimetre)

Fabric count was tested according to ASTM D3775 - 85. Five measurements were made for each fabric in both directions and averaged to the nearest whole number.

3.2.7 Fabric Weight (Gram/meter^2 and ounce/yard^2)

Fabric weight was measured according to ASTM D3776 - 85, Option C. Five specimens were cut (Punch Presser, Instrument Company, Inc., Switzerland) at different places from each fabric sample. The diameter of the cutting die was 8.67 cm, giving an area of 59.0 cm^2 for each circular specimens. After five specimens were weighed together on a scientific balance (Sartorius-werke GMBH Gottingen, Germany) to the nearest milligram, the fabric weight was calculated in g/m^2 and converted to oz/yd^2. So that actual mass could be compared to the mill specification.

3.3 Experimental Design

In order to analyze the laundering shrinkage, it was necessary to identify and priorize those independent variables that influence the level of fabric shrinkage, particularly those conditions that cause an unacceptable level of 2% or greater. Four independent variables, which were considered the most likely parameters in the laundering cycle, were selected:

A. Washing method (2 levels: hand wash/machine wash);

B. Washing temperature (2 levels: 20 ^{0}C/40 ^{0}C);

C. Drying method: (2 levels: flat dry/tumble dry);

D. Number of laundering cycles (2 levels: 1 and 5 cycles).

To perform a full factorial analysis, the combinations of these 4 independent variables each with 2 levels, comprised 16 different laundering cycles or treatments. The 16 different treatment combinations are listed in Table 4. The dependent variables to be measured were fabric shrinkage in both warp and weft directions.

The mean warp and weft shrinkage values of these 16 different treatments were calculated to determine whether different laundering conditions provided acceptable or unacceptable shrinkage of the different fabrics being tested.

Table 4

Sixteen Different Laundering Treatments

Treatment	Washing Method	Washing Temperature	Drying Method	Number of Cycles
1	Hand	20 °C	Flat	1
2	Hand	20 °C	Flat	5
3	Hand	20 °C	Tumble	1
4	Hand	20 °C	Tumble	5
5	Hand	40 °C	Flat	1
6	Hand	40 °C	Flat	5
7	Hand	40 °C	Tumble	1
8	Hand	40 °C	Tumble	5
9	Machine	20 °C	Flat	1
10	Machine	20 °C	Flat	5
11	Machine	20 °C	Tumble	1
12	Machine	20 °C	Tumble	5
13	Machine	40 °C	Flat	1
14	Machine	40 °C	Flat	5
15	Machine	40 °C	Tumble	1
16	Machine	40 °C	Tumble	5

A full factorial analysis was performed to determine which independent variables have a significant influence, and the effects of interaction between independent variables on the fabric shrinkage.

Those fabrics with the same fibre in the same direction were combined to determine how the fibre content in one direction affects the shrinkage in the other direction. By adding fabric as an additional independent variable, a full factorial analysis with 5 independent variables was used for this purpose. Therefore the results from Fabrics 1 and 2 were combined to determine whether the shrinkage in the weft direction was influenced by the different fibre content in the warp. Likewise, the results from Fabrics 2 and 3 were combined to determine whether the shrinkage in the warp direction was influenced by the different fibre content in the weft direction.

In order to obtain a soft and luxurious hand, together with good drape characteristics, it is recommended by Courtaulds that Tencel and Tencel blended fabrics by finishing with an enzyme treatment (Clark, 1992; Courtaulds, 1994). In this study, the effect of such an enzyme finish on fabric shrinkage was investigated. Fabrics 1 and 2 were treated with a standard enzyme treatment at Western Glove Works Ltd, Winnipeg, and then were laundered in triplicate using 8 machine wash and drying conditions. These 8 conditions, which were predicted from pre-testing as being the more severe treatments, are listed in Table 5. In view of the limited amount of fabric available, the same specimens were used for

1 and 5 cycles. Otherwise, the same conditions were followed as described previously in Table 4 (Treatments 9-16). A full factorial analysis with 5 independent variables was performed to determine which independent variables had a significant influence on fabric shrinkage. These 5 independent variables included 3 independent variables from Table 5 (i.e. washing temperature, drying method, and number of cycles) each with two levels, and 2 additional independent variables, namely enzyme finishing and the type of fabric, each with two levels. Because the fabric specimens before and after enzyme finishing were laundered at two distinct times, the specimens were not totally randomized.

Table 5

Eight Laundering Treatments for Specimens after Enzyme Finishing

Treatment	Washing Method	Washing Temperature	Drying Method	Number of Cycles
9	Machine	20 ^{0}C	Flat	1
10	Machine	20 ^{0}C	Flat	5
11	Machine	20 ^{0}C	Tumble	1
12	Machine	20 ^{0}C	Tumble	5
13	Machine	40 ^{0}C	Flat	1
14	Machine	40 ^{0}C	Flat	5
15	Machine	40 ^{0}C	Tumble	1
16	Machine	40 ^{0}C	Tumble	5

Finally, changes in the geometric structure of those specimens which demonstrate the most fabric shrinkage in any one direction was analyzed by means of microscopic measurements of fabric cross-sections taken before and after laundering. The cross-sectional dimensions of fabrics after enzyme finishing and laundering cycles were also taken to follow changes in geometric structure due to laundering. From each cross-section, the following dependent variables were measured in both warp and weft directions:

a. Inter-yarn distance (cloth length);

b. Yarn crimp height.

The geometric parameters before and after laundering and before and after enzyme finishing were compared statistically by means of a t-test. In addition, the shrinkages calculated from inter-yarn distance measurements were compare with those measured on fabric specimens by using a regression analysis.

3.4 Preparation of Specimens for Laundering

Each fabric type was laundered using 16 different treatments, with three replicates of each. Therefore, 48 specimens will be required for each fabric sample to complete the treatments in the full factorial design.

To minimize sampling bias, selection of specimens was restricted so that the same warp and weft yarns were not present in the replicate specimens for the same treatment. Since the width of all three fabric sample was over 152 cm, 4 specimens could be cut across the full fabric width. Consequently the fabric specimens were cut according to Figure

3. Code numbers from 1 to 16 were assigned to each specimen to represent the 16 treatment combinations; D1 to D16 represented the duplicate specimens; and T1 to T16 represented the triplicate specimens. Fabric codes were also used to identify each fabric (See Section 3.1).

1	5	9	13	D16	D4	D8	D12	T15	T3	T7	T11
2	6	10	14	D1	D5	D9	D13	T16	T4	T8	T12
3	7	11	15	D2	D6	D10	D14	T1	T5	T9	T13
4	8	12	16	D3	D7	D11	D15	T2	T6	T10	T14

< ---- Fabric Length ---- >

Figure 3. Cutting plan for fabric specimens.

After cutting the fabric specimens, the 38 cm x 38 cm specimens were conditioned for a minimum of 4 hours in a standard atmosphere of 20 ± 1 ^{0}C and 65 ± 2% R.H., and then each specimen was marked with three 25.4 cm pairs of bench marks parallel to the length of the fabric and three 25.4 cm pairs of bench marks parallel to the width of the fabric. Each bench mark was placed at least 5 cm from the cut edges of the test specimen. Pairs of bench marks in the same direction were approximately 12 cm apart (AATCC Test Method 135 - 1992). All the marks were made by an indelible ink mark pen. After marking, all edges of the specimen were serged to prevent fraying of the cut edges during laundering.

3.5 Laundering Procedures

The Canadian standard methods CAN2-4.2-M90, Method 25.1 and CAN2-4.2-M90, Method 58 were used as the guide-lines for performing the hand wash and machine wash procedures respectively. Method 58 involves the use of a standard detergent, whereas Method 25.1 does not. The laundering order was randomized to eliminate any effect that time might have had on the dependent variable. For the 16 treatments with 3 replicates, the total number of laundering procedures was 48. Random numbers (Montgomery, 1984) from Table 6 were used to determine the sequence of laundering procedures where number 17-32 refer to specimens D1-D16, and number 33-48 refer to specimens T1-T16.

Table 6

Random Order for Laundering Procedures

33	3	9	14	24	7	26	12	30	6	27	18
17	48	31	23	42	47	13	19	46	44	4	20
2	39	16	41	25	38	40	35	36	45	32	28
29	5	22	8	1	10	34	21	11	37	15	43

The washing load was held constant at 1.5 kg (CAN2-4.2-

M77, Method 24.2) using a dummy load of polyester/cotton fabrics as necessary. Specimens with different drying method but with the same washing method and temperature, were washed together. Each replicate sample was washed separately.

After drying the specimens, if the wrinkle recovery of the fabrics were rated 1 or 2 when tested by the standard method (AATCC128-1989), then a cool iron was used to remove the worst wrinkles. The fabrics were wetted by spraying with distilled water, and the iron was moved only vertically up and down to minimize any fabric stretching.

After conditioning the laundered specimens for at least 8 hours in a standard atmosphere, the dependent variable, fabric shrinkage, was measured in both directions.

3.6 Enzyme Finishing

Five yards of Fabrics 1 and 2 were sent to Western Glove Works Ltd. for enzyme finishing. Before sending them, 5 pairs of 60 cm bench marks were made parallel to both the warp and weft directions on both fabrics. Sewing thread was used for marking. The amount of shrinkage that occurred during the enzyme finishing was then determined by measuring the distance between those marks after the enzyme finishing and calculating the difference. The whole enzyme finishing process can be divided into three steps:

1. Desizing:

   60 ^{0}C water (Water:Fabric weight = 10:1)

1 % Blue J 7-11 (Amylase stripped)

0.3 % Blue J Scour (Anti-redeposition detergent)

Duration: 10 minutes (pH: Neutral)

2. Enzyme Treatment:

60 °C water (Water:Fabric weight = 10:1)

1 % Blue J Stone Free I (Neutral Cellulase)

0.67 % Blue J Scour

0.3 % Blue J Stone Free II (6.0 pH buffer)

Duration: 30 minutes

3. Warm Rinse

35 °C water (Water:Fabric weight = 10:1)

Duration: 5 minutes

3.7 Measurement of Geometric Structure

3.7.1 Selection of Specimens for Cross-Sectional Analysis

To investigate the changes in the geometric structure of the fabric after laundering, specimens with the highest average shrinkage were selected. In addition, to determine how enzyme finishing affected the geometric structure, those specimens which yielded the highest shrinkage after the enzyme finishing and after the enzyme finishing and laundering were also selected. The specimen selection plan for cross-sectioning is listed in Table 7.

Table 7

Selection Plan of Specimens for Cross-Sectioning

Treatment	Fabric Specimens		
Before Laundering	1	2	3
After Finishing X	1	2	3
After Enzyme Finishing	1	2	
After Enzyme Finishing & Treatment X	1	2	

Note. Each fabric specimen includes warp and weft, Treatment X is the laundering condition, which yields the highest average shrinkage out of 16 treatment combinations.

3.7.2 Embedding and Sectioning

A JB-4 Embedding Kit (Analychem Corporation, Markham, Ontario) was used in this study. Fabric specimens were cut in a rectangular shape measuring 11 mm x 6 mm with the longer direction corresponding to the direction of the fabric to be analyzed. To prepare the embedding resin, 25 ml of JB-4 Solution A were added to 0.22 grams of dry catalyst C, and mixed until dissolved. Exactly 1 ml of JB-4 Solution B was added to 25 ml of freshly catalyzed Solution A, stirred well, and placed in an ice bath to retard premature polymerization. To obtain a good cross-section, it was important to place the fabric specimen perpendicular to the bottom of the cup in the molding tray (Analychem Corp). Each cup was then covered with a plastic GMA block holder, so that the resin could attach itself to the block during polymerization overnight at room temperature.

Sectioning was performed with a microtome (JB-4 Microtome, Ivan Sorvall Inc., Newtown, Connecticut, USA). Sections measuring 1μm-4μm in thickness were cut with a dry glass knife, collected with forceps and transferred to a room temperature water bath, releasing them before they touched the water. A few drops of concentrated NH_4OH were added to the water bath to aid in flattening the sections which were collected on glass slides and air dried before staining with Toluidine Blue.

3.7.3 Measurement of Cross-Section

A transmitted light microscope (Leitz HM-Lux 3, Leitz, Germany) with an objective and eye piece to achieve a magnification of X40 was used. The eye piece contained a micrometer scale that was able to measure distances to the nearest 1μm. The focal distance was adjusted by placing a clean glass slide under the specimen slide. The micrometer scale was calibrated by a standard slide containing line 1 mm long, divided into 100 divisions.

When measuring inter-yarn distance and crimp height, a cursor line was used instead of a central cross in the eye piece micrometer. The advantage of using the cursor line was that it was easier to define the start and end point in the cross-section measurement. Figure 4 demonstrates how warp crimp height was measured. The cursor line was placed at L1 and the position measured. Then the cursor line was moved to position L2 and the new position recorded. The measured distance between L1 and L2 is the warp crimp height. To measure the inter-yarn distance, the distance AC was measured instead of AB. Because there would have been potentially large errors in the measurement of AB and BC, it was felt that the distance AC would give a more precise determination of the inter-yarn distance.

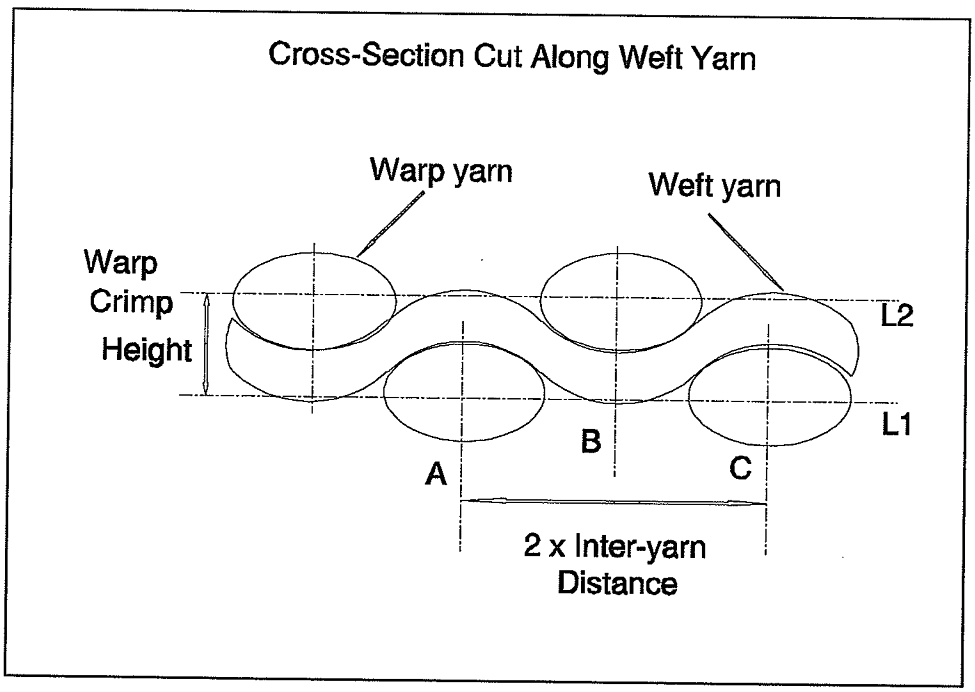


Figure 4. Measurement of geometric parameters.

As indicated in Figure 4, it is important to distinguish between the warp and weft directions during measurement of cross-sections. When determining the cross-sectional dimensions along a weft yarn, then the warp crimp height and warp inter-yarn distance are measured. One needs to cut the fabric in the warp direction in order to measure the weft crimp height and weft inter-yarn distance.

At least eighteen cross sections were cut for each chosen specimen. Out of those 18, the 12 most uniform sections were selected and 2 measurements were taken from each, making a total of 24 data points for each geometric parameter. In order to reduce the effect of extreme or unusual measurements, the 2 highest and 2 lowest values were discarded in prior to statistical analysis.

3.8 Methods of Statistical Analysis

3.8.1 Calculation of Mean and Standard Error of Shrinkage

The SAS program (SAS, 1985) was used to calculate the mean and standard error of shrinkage in each direction of each fabric after the 16 laundering treatments. The resulting mean shrinkage values were then compared to the fabric shrinkage criterion of 2% (CAN/CGSB-86.1-M91) in order to determine which laundering condition gave an acceptable level of shrinkage and which did not. This Canadian Care Labelling Standard requires that woven fabrics do not shrink more than 2% in either direction after three standard laundering procedures. The following abbreviations were used in the SAS programs (Appendices 2, 3 and 4).

WPSHRK: Dependent variable, washing shrinkage in warp direction.

WFSHRK: Dependent variable, washing shrinkage in weft direction.

Std Dev (SD): Standard deviation.

Std Error: Standard error.

3.8.2 Full Factorial Analysis

A full factorial analysis model was designed using the SAS program (Appendix 2) to determine which independent variables and interactions of independent variables have the most influence on fabric shrinkage. General linear models were applied in the SAS program for testing the hypotheses in a full factorial analysis of variance. Table 10 lists the symbols of the independent variables as entered into the model.

Where possible p values are provided in the reporting of the analysis, and for purposes of determining statistical significance, a significance level of 0.05 is used in this study which is in keeping with common practice in the field. From full factorial analysis of variance, those variables and interaction of variables which had a significant influence on the shrinkage were determined. The mean values are calculated and tabulated for further discussion.

Table 8

Symbol of Independent Variables

Symbol	Independent variable	Levels	
W	Washing method	H:	Hand wash
		M:	Machine wash
T	Washing temperature	20:	20 °C
		40:	40 °C
D	Drying method	F:	Flat dry
		T:	Tumble dry
N	Number of cycles	1:	1 Cycle
		5:	5 Cycles
F	Fabric	1:	100% Tencel
		2:	60/40 Cotton/Tencel
		3:	100% Cotton
n	Number of measurements		
Z	Enzyme finishing	E:	With enzyme finishing
		O:	No enzyme finishing

3.8.3 Student t-Test

The mean values and standard deviations of fabric shrinkage during laundering were compared with and without the enzyme finishing for each of the 8 laundering conditions (Table 5) using a Student t-Test (Brockett, 1984) to determine whether there were any significant differences. The following formula was used for those two sample comparisons:

$$|t| = \frac{|\overline{X_1} - \overline{X_2}|}{\sqrt{\frac{S_1^2 + S_2^2}{n}}}$$

$\overline{X}_1$ and $\overline{X}_2$ are the mean shrinkage values of the sample 1 and sample 2 respectively; S_1 and S_2 are standard deviations of laundering shrinkage of sample 1 and sample 2 respectively; n is the number of measurements. The degrees of freedom = 2n - 2.

3.8.4 Comparison of Shrinkage Measurement from Fabric Specimens with Those from Inter-yarn Distance

By measuring the inter-yarn distance of the sectioned fabrics before and after laundering and enzyme finishing, it was possible to calculate fabric shrinkage on a microscopic scale. Laundering shrinkage values were also obtained by measuring the fabric dimensions in Section 3.5; therefore, a linear regression model was developed from the SAS program to determine the relationship between those two sets of shrinkage data and to assess whether or not the same shrinkage results are obtained regardless of the method used.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of Fabric Specification Testing

Since Tencel is a new fibre, the reagents used in identifying it and other lyocell fibres by solubility testing are not included in current standards, such as AATCC 20 - 1989. The results of the solubility tests undertaken are shown in Table 9.

Table 9

Solubility Test Results for Experimental Fabrics

Reagent	Cotton (Control)	Fabric 1 Warp Tencel	Fabric 1 Weft Tencel	Fabric 2 Warp Cotton	Fabric 2 Weft Tencel	Fabric 3 Warp Cotton	Fabric 3 Weft Cotton	Viscose Rayon (Control)
Sulfuric Acid 60% 40 ^{0}C, 30 mins	I	PD	PD	I	PD	I	I	PD
Sulfuric Acid 60% 40 ^{0}C, 2 hrs	PD	PD	PD	PD	PD	PD	PD	PD
Concentrated Hydrochloric Acid 23 ^{0}C, 30 mins	I	PD	PD	I	PD	I	I	D
Zinc chloride/ Formic Acid 40 ^{0}C, 2 hrs	I	D	D	I	D	I	I	D

Note. I: Insoluble, PD: Partly dissolved, D: Dissolved.

Two noticeable phenomena and probably useful pieces of information are that viscose rayon dissolved faster than

Tencel fibres during the solubility tests, and that concentrated hydrochloric acid dissolved viscose rayon fibres, but only partly dissolved Tencel fibres. These results support the fact that Tencel fibres have a higher degree of polymerisation and a more highly crystalline structure (Yamashiki & Matsui, 1992) than viscose rayon fibres.

The results of the tests to confirm the fabric specifications are summarized in Tables 10 and 11.

Table 10
Confirmation of Greenwood Mills Fabric Specification

	Fabric 1	Fabric 2	Fabric 3
Fabric Weave	Plain	Plain	Plain
Fibre Content	100% Tencel	60.5% Cotton/ 39.5% Tencel	100% Cotton
Yarn Type	Z-twist Staple	Z-twist Staple	Z-twist Staple
Length (Yard)	20.5	20.5	20.5
(meter)	18.7	18.7	18.7
Width (Inch)	64.00	63.75	61.75
(cm)	162.56	161.93	156.85
Fabric Weight (g/m^2)	153.56	144.62	147.86
(oz/yd^2)	4.53	4.27	4.36

Table 11
Measurements of Yarn and Fabric Structural Parameters

	Fabric 1		Fabric 2		Fabric 3	
	Warp	Weft	Warp	Weft	Warp	Weft
Yarn Tex	31.5	26.9	29.5	26.9	29.5	25.5
Yarn Crimp (%)	11.7	5.38	11.8	4.29	11.4	8.77
Fabric Count (n/cm)	26.0	20.9	26.0	19.8	26.9	20.0
(n/inch)	66.0	53.0	66.0	50.2	68.4	50.9

Fabric 2 is not an intimate blend fabric; it is a union blend fabric composed of 100% cotton in the warp and 100% Tencel in the weft. The overall fibre content obtained by mechanical separation method is very close to the figure provided by mill. The weft crimp value for Fabric 3 is almost twice as large as the weft crimp of Fabrics 1 and 2. All other yarn and fabric structural parameters of the 3 fabrics listed in Table 11 are considered to be similar. In fact the Tencel weft yarns in Fabrics 1 and 2 appear to have a similar yarn structure, as do the cotton warp yarns in Fabrics 2 and 3.

4.2 Fabric Shrinkage after Laundering Treatments

The SAS program (SAS, 1985) was used to calculate the mean value and standard error of laundering shrinkage of Fabrics 1, 2, and 3 in both warp and weft directions. The results of these calculations are listed in Tables 12 and 13 for the warp and weft directions respectively. The maximum acceptable woven fabric shrinkage criterion after 3 laundering cycles is 2% according to the Canadian care labelling standard (CAN/CGSB-86.1-M91). Table 12 lists the warp shrinkages of fabrics after one and five cycles. The warp shrinkages of Fabric 1 after hand washing or 1 cycle of machine washing were all below this 2 % criterion, whereas the shrinkages after 5 cycles of machine washing all exceeded this limit. Therefore, Ho_1 was rejected for Fabric 1 after 5 cycles of machine wash. The warp shrinkages of Fabric 2 after 1 cycle of hand washing or 5 cycles of hand washing and drying flat were less than 2%. Whereas the shrinkages after 5 cycles of hand washing and tumble drying, machine washing and drying flat on both 1 and 5 cycles and tumble drying after 5 cycles exceeded 2%, therefore, Ho_1 was rejected for the above laundering conditions. The laundering shrinkage of Fabric 3 after 5 cycles hand or machine washing and machine wash drying flat after 1 cycle exceeded 2%. Therefore, Ho_1 was rejected for these laundering treatments.

Table 13 lists the fabric laundering shrinkage results in the weft direction. The shrinkages of Fabric 1 after 5 cycles of machine washing and after 1 cycle of machine wash and drying flat exceeded 2%. Therefore, Ho_1 was rejected for these laundering conditions. When the 100% Tencel fabric was machine washed, the weft shrinkage was not only invariably above 2% but it was also always greater than warp shrinkage. this was an unexpected result since most fabrics, including Fabrics 2 and 3, tend to shrink more in the warp than the weft direction. In comparison, the weft shrinkages for Fabrics 2 and 3 were low, with most treatments giving values of less than 1%, and the highest shrinkage being only 1.4%.

By comparing the overall shrinkage of the Tencel warp yarns in Fabric 1 with the cotton warp yarns in Fabrics 2 and 3 it is clear that the Tencel invariably shrinks less than cotton (Table 12). However, on comparing the overall shrinkage of the Tencel weft yarns in Fabrics 1 and 2 with the cotton

Table 12

Mean Warp Shrinkage of Fabric after Laundering Treatments

		Fabric 1				Fabric 2				Fabric 3			
		Hand		Machine		Hand		Machine		Hand		Machine	
		1	5	1	5	1	5	1	5	1	5	1	5
Flat	20°C	0.40	1.06	1.93	3.56	0.84	1.42	2.13	4.66	1.63	2.52	2.96	4.83
		(0.11)	(0.19)	(0.11)	(0.20)	(0.15)	(0.04)	(0.07)	(0.10)	(0.15)	(0.21)	(0.19)	(0.44)
	40°C	0.53	0.70	1.58	2.92	0.58	1.90	2.22	4.39	1.16	2.62	2.96	4.92
		(0.13)	(0.22)	(0.17)	(0.16)	(0.11)	(0.12)	(0.05)	(0.12)	(0.19)	(0.10)	(0.14)	(0.21)
Tumble	20°C	0.49	0.74	0.92	3.13	1.00	2.87	1.56	3.89	2.01	4.03	2.21	5.09
		(0.18)	(0.12)	(0.18)	(0.27)	(0.11)	(0.14)	(0.10)	(0.06)	(0.14)	(0.17)	(0.39)	(0.20)
	40°C	0.72	1.33	1.21	2.66	0.91	2.86	2.01	4.03	2.27	4.13	2.20	5.09
		(0.18)	(0.23)	(0.15)	(0.19)	(0.14)	(0.14)	(0.07)	(0.11)	(0.17)	(0.25)	(0.16)	(0.14)

Note. The value in ( ) is the standard error of mean.

Table 13

Mean Weft Shrinkage of Fabric after Laundering Treatments

		Fabric 1				Fabric 2				Fabric 3			
		Hand		Machine		Hand		Machine		Hand		Machine	
		1	5	1	5	1	5	1	5	1	5	1	5
Flat	20°C	1.58	1.57	2.53	4.16	0.20	0.41	0.49	1.08	0.03	0.00	0.32	1.36
		(0.15)	(0.22)	(0.14)	(0.14)	(0.10)	(0.12)	(0.08)	(0.14)	(0.02)	(0.00)	(0.10)	(0.20)
	40°C	1.12	1.22	2.43	4.09	0.07	0.23	0.33	1.13	0.00	0.09	0.30	1.28
		(0.10)	(0.30)	(0.18)	(0.18)	(0.04)	(0.09)	(0.10)	(0.12)	(0.00)	(0.05)	(0.07)	(0.19)
Tumble	20°C	1.47	1.99	2.04	4.30	0.11	0.28	0.12	1.23	0.04	0.13	0.01	1.36
		(0.26)	(0.14)	(0.12)	(0.24)	(0.06)	(0.14)	(0.06)	(0.20)	(0.03)	(0.07)	(0.01)	(0.30)
	40°C	1.31	2.27	2.12	3.11	0.13	0.12	0.23	0.72	0.00	0.07	0.07	1.18
		(0.16)	(0.15)	(0.14)	(0.14)	(0.07)	(0.06)	(0.12)	(0.20)	(0.00)	(0.04)	(0.05)	(0.16)

Note. The value in ( ) is the standard error of mean.

weft yarns in Fabric 3, the reverse is true (Table 13).

From above results, the rejection of Ho_1 depends on the fabric type, fabric direction and the conditions of laundering.

The level of yarn crimp of the Tencel yarns in the weft direction of Fabrics 1 and 2 were similar but the weft shrinkage of Fabric 1 was much higher than that of Fabric 2. Similarly, the level of yarn crimp of the cotton yarns in the warp direction of Fabrics 2 and 3 were similar, but the warp shrinkage of Fabric 3 was invariably higher than that of Fabric 2. These results imply that the fabric shrinkage results were not influenced primarily by fibre content or the yarn crimp.

4.3 Full Factorial Analysis

A full factorial analysis method was used to determine the effect of the four independent variables (i.e. washing method (W), washing temperature (T), drying method (D) and number of laundering cycles (N)) each with 2 levels on the laundering shrinkage of Fabrics 1, 2, and 3. The analysis was performed separately in each direction. The experiment was designed in triplicate, so that each treatment was applied to 3 independent specimens. Three measurements were taken on each specimen, which are considered as sub-samples. In this study, the significance level for rejecting the hypotheses was 0.05.

4.3.1 Analysis of Warp Shrinkage in the 100% Tencel Fabric (Fabric 1)

The results of the full factorial analysis of variance generated by a SAS program (SAS, 1985)(Appendix 2) on the warp shrinkages in the 100% Tencel fabric were listed in Table 14. The effect denoted by the parameter, I, measures the variability of the 3 replicate specimens in the same treatment combination. The high significance of this variable (p = 0.0001) means that the variability of the measurements between specimens is greater than that within specimen variability.

From Table 14, it can be seen that W, W*D, N, and W*N significantly influenced the dependent variable warp shrinkage. To explain how those independent variables affected the dependent variable, their mean values were calculated, and listed in Table 15.

To facilitate understanding, Figures 5-8 have been drawn to illustrate the data in Table 15. Figure 5 illustrates how the washing method affected the warp shrinkage, and it can be easily seen that on average machine washing gave a higher shrinkage level (over 2.2%) than hand washing (less than 0.8%). It is proposed that this difference in shrinkage is caused by the greater agitation under the machine washing conditions (Lund and Water, 1959; Scott, 1959).

Figure 6 illustrates how the number of laundering cycles affected the warp shrinkage. As expected, the specimens shrank more after 5 laundering cycles than after 1 cycle. This can be

Table 14
Full Factorial Analysis of Variances
Warp Shrinkage of 100% Tencel Fabric

Source	Type III MS	Denominator MS	F Value	p Value
W	80.1025	0.7386	108.450	0.0001
T	0.1878	0.7386	0.254	0.6176
W*T	1.7778	0.7386	2.407	0.1306
D	1.2100	0.7386	1.638	0.2098
W*D	4.0000	0.7386	5.416	0.0264
T*D	1.9136	0.7386	2.591	0.1173
W*T*D	0.0336	0.7386	0.046	0.8324
N	38.8544	0.7386	52.605	0.0001
W*N	13.6900	0.7386	18.535	0.0001
T*N	0.7803	0.7386	1.056	0.3117
W*T*N	0.4669	0.7386	0.632	0.4324
D*N	0.3025	0.7386	0.410	0.5268
W*D*N	0.2336	0.7386	0.316	0.5778
T*D*N	0.0711	0.7386	0.096	0.7584
W*T*D*N	1.0000	0.7386	1.354	0.2532
I	0.7386	0.1462	5.053	0.0001

Note. MS is Mean square.

Table 15
Effects and Interactions of Independent Variables
Warp Shrinkage of 100% Tencel Fabric

Level of variables		Number of Measurements	Mean Value of Shrinkage (%)
	W		
	H	72	0.75
	M	72	2.24
	N		
	1	72	0.97
	5	72	2.01
W	D		
H	F	36	0.67
H	T	36	0.82
M	F	36	2.50
M	T	36	1.98
W	N		
H	1	36	0.54
H	5	36	0.96
M	1	36	1.41
M	5	36	3.07

explained by the fact that the shrinkage after 1 cycle was the combination of relaxation and swelling shrinkage (Lyle, 1977), while shrinkage after 5 cycles was the combination of relaxation, swelling and progressive shrinkage (Lund and Water, 1959; Scott, 1959). In other words, the difference in shrinkage between 1 and 5 cycles was due solely to progressive shrinkage (Lyle, 1977).

Figure 7 presents the two way interaction of washing and drying methods on the warp shrinkage. In general, machine washing had greater shrinkage than hand washing. When machine washed, drying flat produced higher shrinkage than tumble drying; whereas, when hand washing, tumble drying produces higher shrinkage than flat drying. These results were not anticipated, and an explanation for such abnormal results is that most of the specimens wrinkled badly after tumble drying. Their wrinkle recovery ratings were only 1 or 2 (AATCC 66 - 1990). In order to obtain valid measurements, the wrinkles were removed by wetting the specimens and ironing with a cool iron. The ironing process may have distorted the fabrics and reduced the shrinkage level. Because the specimens after flat drying did not need ironing, this may explain why the tumble dried specimens had lower shrinkage than the flat dried specimens.

Figure 8 illustrates the two way interaction of the washing method and the number of laundering cycles on the warp shrinkage. The effect of the number of laundering cycles

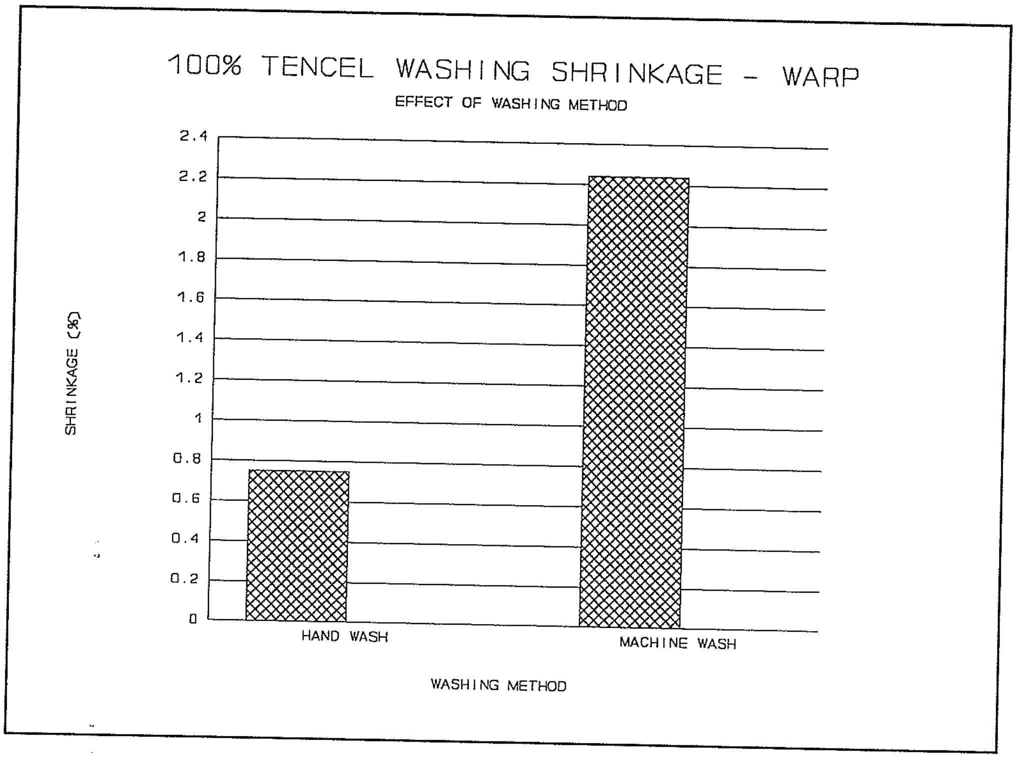


Figure 5. Effect of washing method.

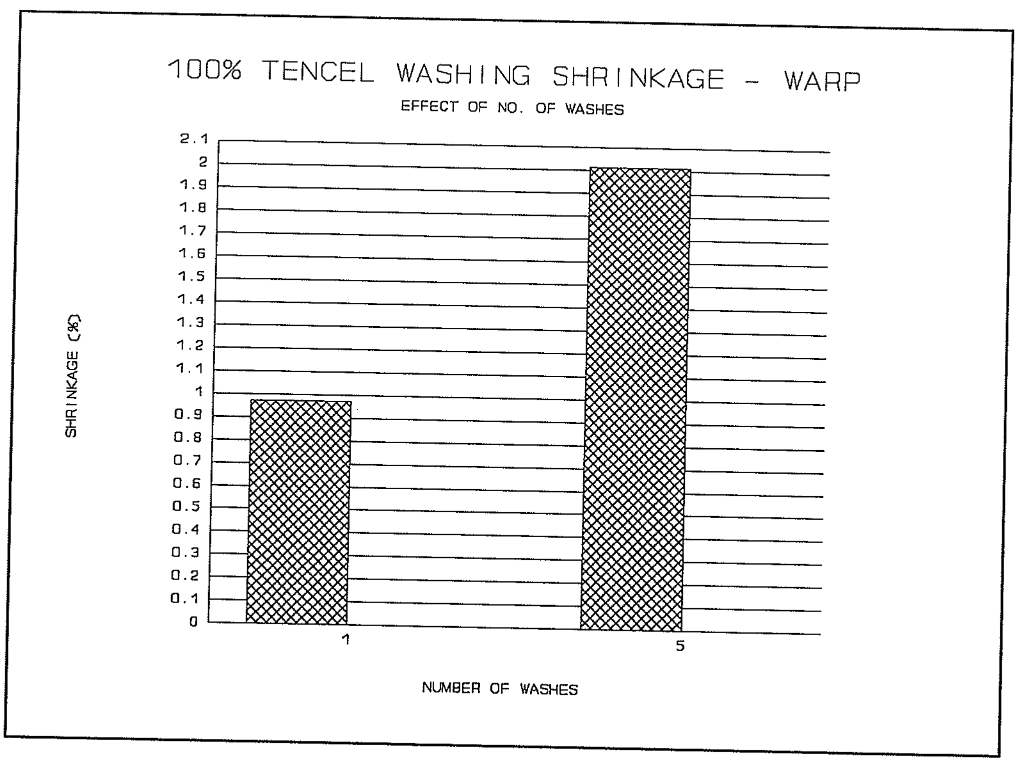


Figure 6. Effect of number of washing cycles.

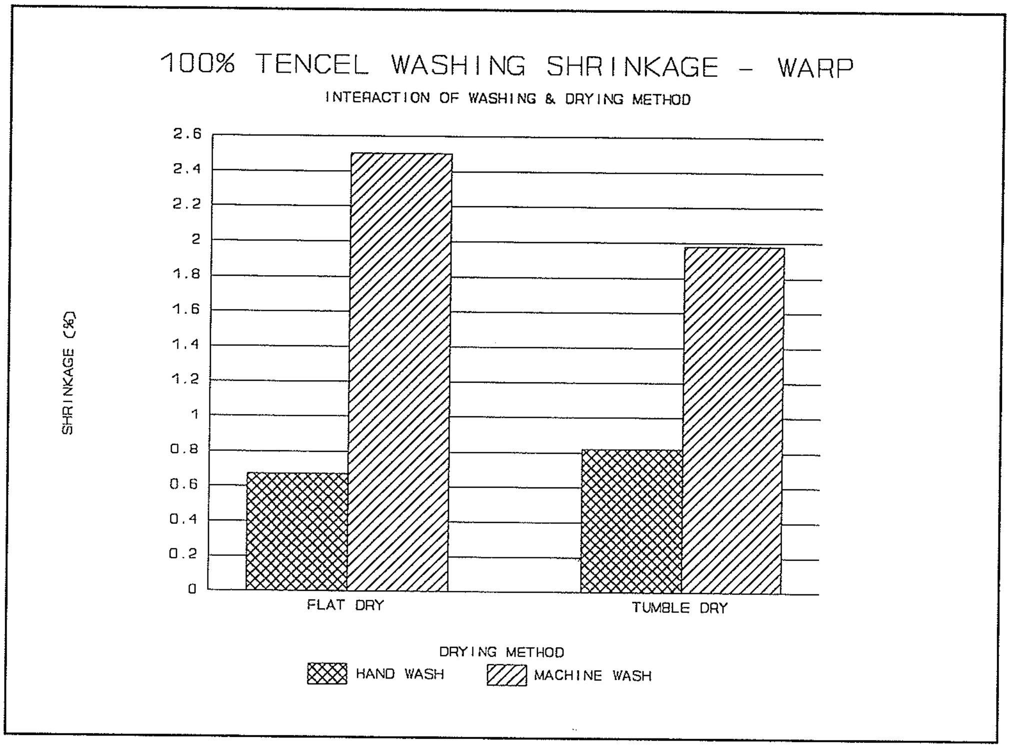


Figure 7. Interaction of washing and drying method.

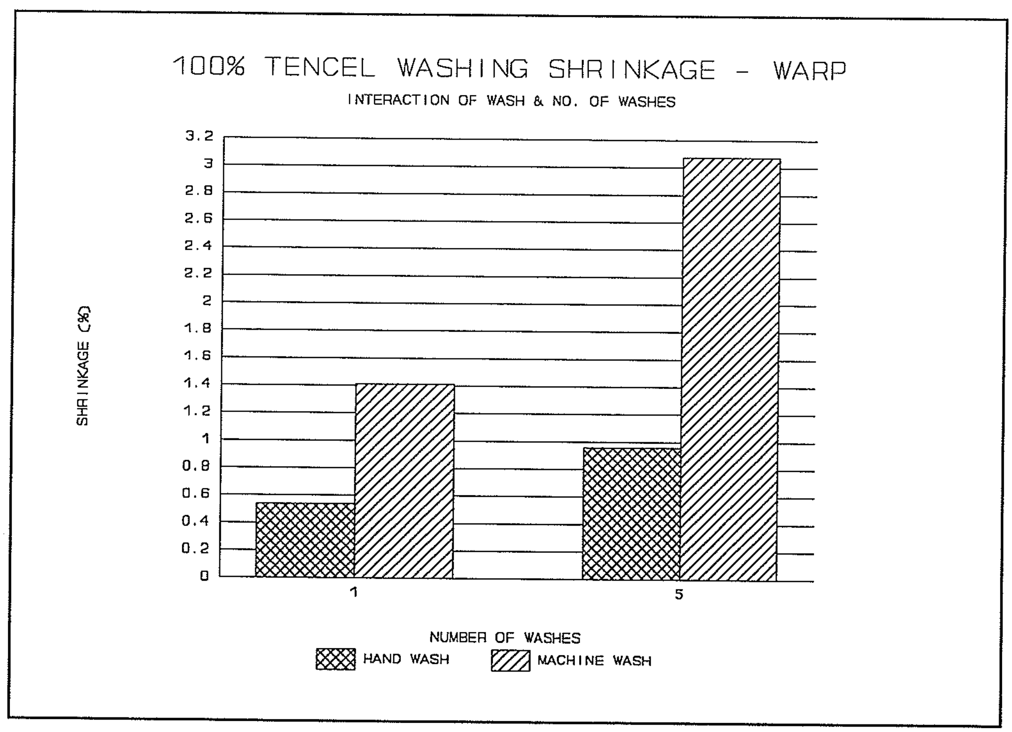


Figure 8. Interaction of washing method and number of washes.

depended on the washing method with machine washing yielding as expected higher shrinkages than hand washing.

4.3.2 Analysis of Weft Shrinkage in the 100% Tencel Fabric (Fabric 1)

The results of the full factorial analysis for the 100% Tencel fabric in the weft direction are shown in Table 16. From Table 16, it can be seen that W, W*D, N, and W*N had a significant influence on the weft shrinkage. To explain how those independent variables affected the dependent variable, their mean values were calculated and the results are listed in Table 17.

To facilitate understanding, Figures 9-12 have been drawn to illustrate the data in Table 17. From Figure 9, it can be seen that machine washing caused more weft shrinkage than hand washing. Figure 10 illustrates the effect of the number of cycles on weft shrinkage. Specimens after 5 laundering cycles had a higher shrinkage level than after 1 cycle. Figure 11 shows the two way interaction of washing and drying methods on weft shrinkage. In general, machine washing caused greater shrinkage than hand washing. When hand washed, tumble drying produced higher shrinkage than flat drying. But surprisingly when machine washed, flat drying produced higher shrinkage than tumble drying. An explanation for this unexpected result is the same as that given earlier for the interaction of the washing and drying methods in the warp direction (see Section

4.3.1). Figure 12 illustrates the two way interaction of washing method and the number of laundering cycles on the weft shrinkage. The effect of the number of laundering cycles depended on the washing method. Machine washing yielded higher shrinkage results than hand washing.

Table 16

Full Factorial Analysis of Variance

Weft Shrinkage of 100% Tencel Fabric

Source	Type III MS	Denominator MS	F Value	p Value
W	84.6400	1.0102	83.779	0.0001
T	2.1511	1.0102	2.129	0.1543
W*T	0.2025	1.0102	0.200	0.6574
D	0.0044	1.0102	0.004	0.9475
W*D	5.6803	1.0102	5.622	0.0239
T*D	0.0003	1.0102	0.000	0.9869
W*T*D	1.9600	1.0102	1.940	0.1733
N	36.8044	1.0102	36.430	0.0001
W*N	13.8136	1.0102	13.673	0.0008
T*N	0.2669	1.0102	0.264	0.6108
W*T*N	1.7778	1.0102	1.760	0.1941
D*N	1.0336	1.0102	1.023	0.3194
W*D*N	1.1378	1.0102	1.126	0.2965
T*D*N	0.5378	1.0102	0.532	0.4709
W*T*D*N	1.4803	1.0102	1.465	0.2350
I	1.0102	0.0531	19.042	0.0001

Note. MS = Mean square.

Table 17

Effects and Interactions of Independent Variables Weft Shrinkage of 100% Tencel Fabric

Level of Variables		Number of Measurements	Mean Value of Shrinkage (%)
W			
H		72	1.57
M		72	3.10
N			
1		72	1.83
5		72	2.84
W	D		
H	F	36	1.37
H	T	36	1.76
M	F	36	3.30
M	T	36	2.89
W	N		
H	1	36	1.37
H	5	36	1.76
M	1	36	2.28
M	5	36	3.91

In summary, the shrinkage of the 100% Tencel fabric (Fabric 1) was influenced by the same independent variables in the warp as in the weft direction. But the amount of laundering shrinkage was invariably higher in the weft direction than in the warp direction. An explanation for this unexpected finding (Williams, 1946) may be found in the interaction of the Tencel yarn and fabric construction with the fabric finishing conditions.

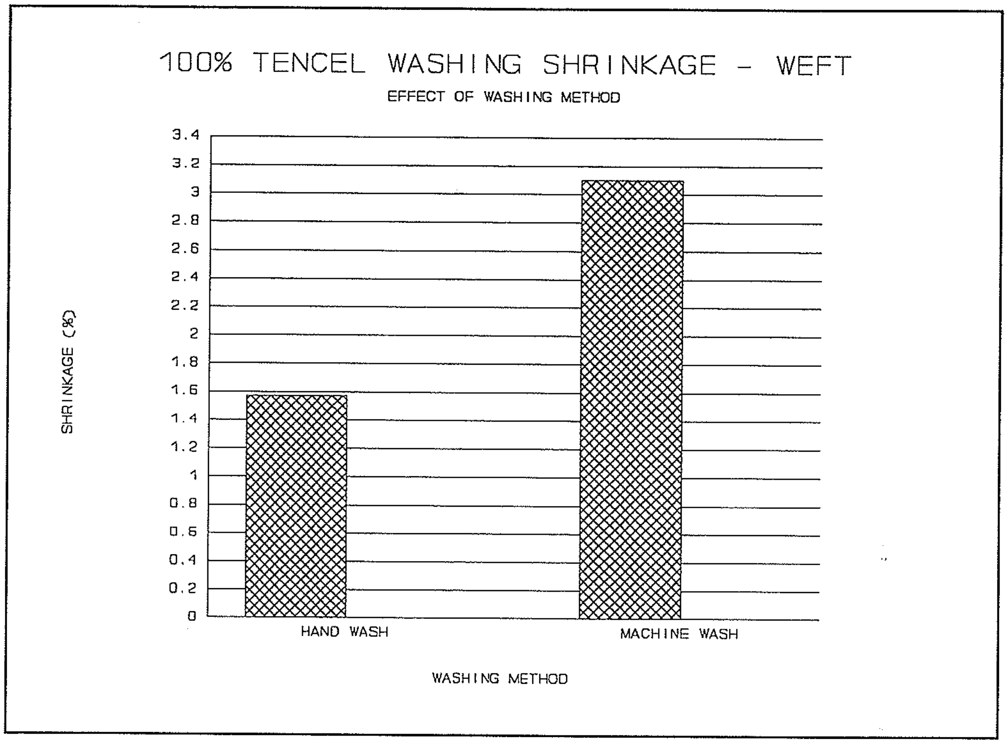


Figure 9. Effect of washing method.

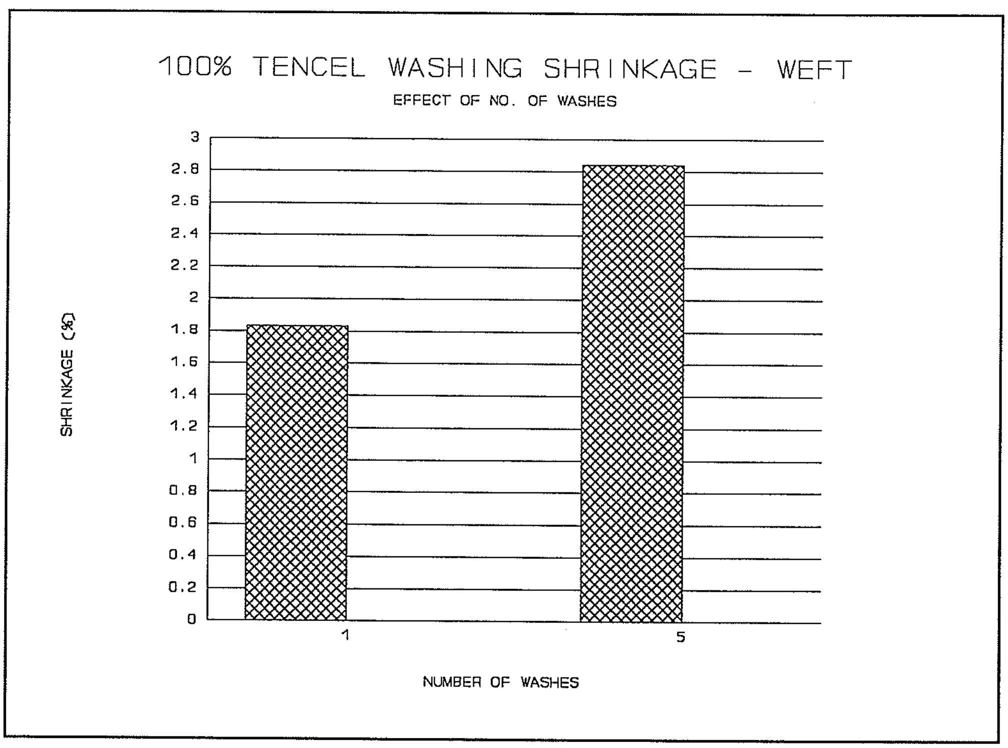


Figure 10. Effect of number of washing cycles.

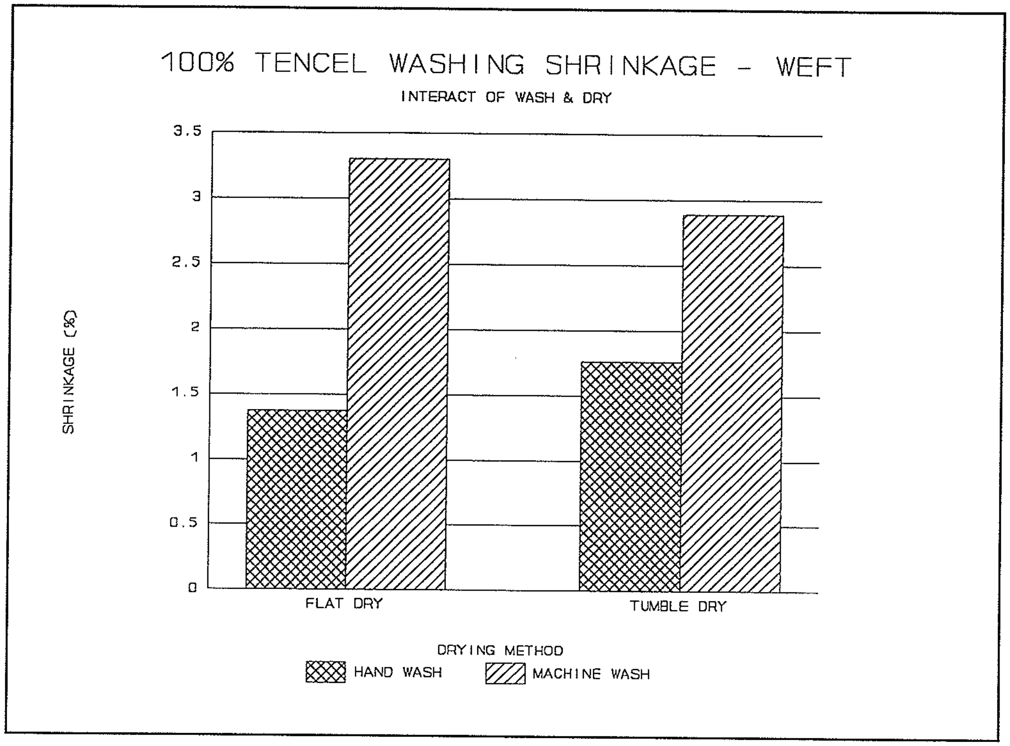


Figure 11. Interaction of washing and drying methods.

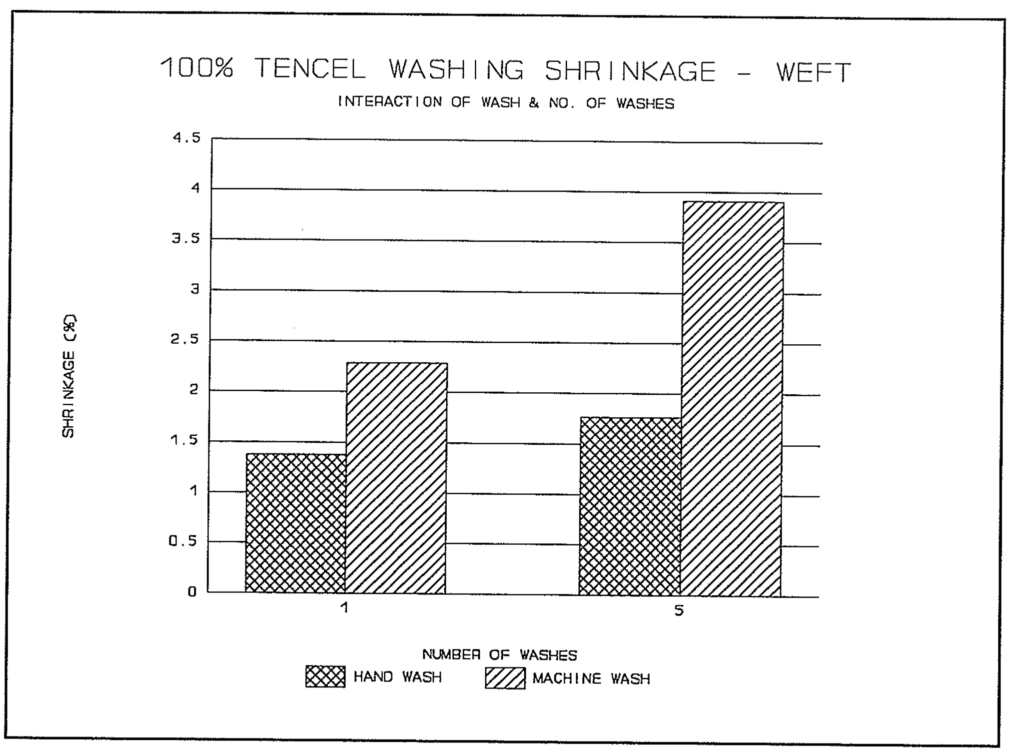


Figure 12. Interaction of washing method and No. of washes.

4.3.3 Analysis of Warp Shrinkage in the Cotton/Tencel Fabric (Fabric 2)

The results of the full factorial analysis for warp shrinkage of the 60/40 cotton/Tencel fabric are listed in Table 18. It can be seen that W, W*D, N, W*N, W*T*N, D*N, and W*D*N had a significant effect on the dependent variable warp shrinkage. To explain how these independent variables affected the dependent variable, their mean values were calculated, and the results listed in Table 19. As before, bar diagrams Figures 13 - 21 have been drawn to illustrate the data in Table 19.

However, Table 19 includes some three way interactions, W*D*N and W*T*N. To analyze a three way interaction, one independent variable has to be fixed, and then the two way interactions can be examined. So to analyze the 3 way interaction of W*D*N, 2 diagrams, Figure 18 and Figure 19, were required. In Figure 18, the hand washing method was considered alone, while the interaction of D and N was analyzed. In Figure 19, the machine washing method was held constant, and the interaction of D and N were analyzed. In the same way, Figures 20 and 21 were prepared so as to analyze the 3 way interaction: W*T*N.

Figure 13 illustrates how the washing method affected the warp shrinkage. It can be seen that machine washing caused more shrinkage than hand washing. Figure 14 illustrates how the number of laundering cycles affected the warp shrinkage.

As expected, specimens after 5 laundering cycles have greater shrinkage than after 1 cycle.

Figure 15 illustrates the two way interaction of washing method and number of laundering cycles on the warp shrinkage. The effect of the number of laundering cycles depended on the washing method with machine washing yielding higher shrinkage values than hand washing.

Table 18

Full Factorial Analysis of Variance

Warp Shrinkage of 60/40 Cotton/Tencel Fabric

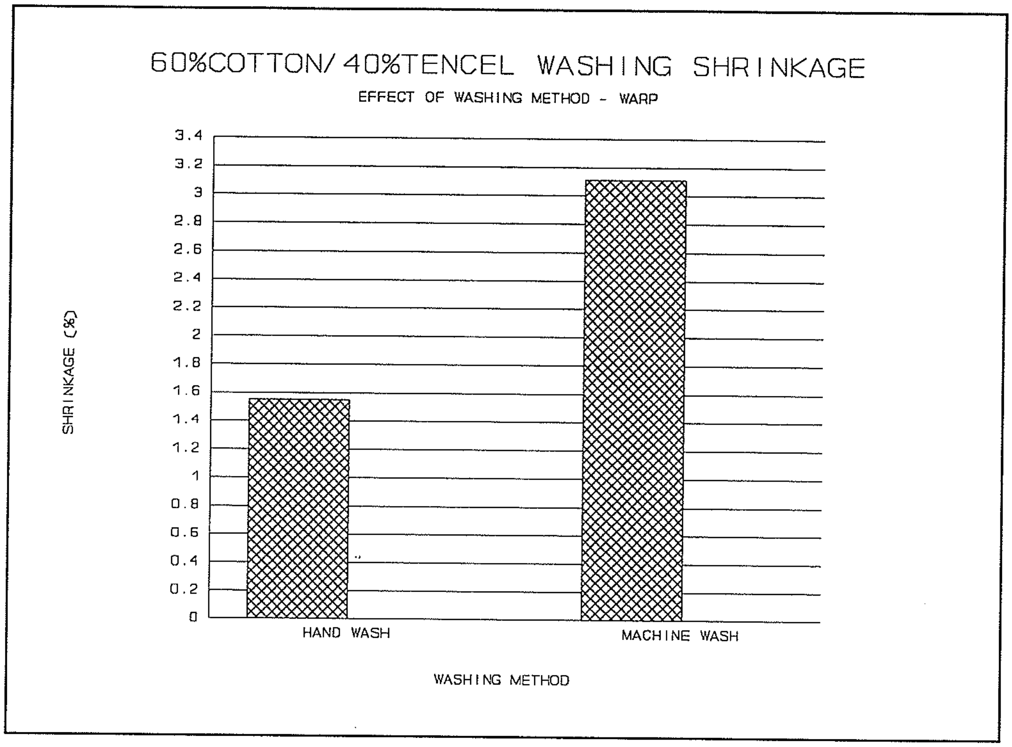
Source	Type III MS	Denominator MS	F Value	p Value
W	88.0469	0.2228	395.100	0.0001
T	0.1600	0.2228	0.718	0.4031
W*T	0.0544	0.2228	0.244	0.6245
D	0.5378	0.2228	2.413	0.1302
W*D	12.9600	0.2228	58.156	0.0001
T*D	0.1225	0.2228	0.550	0.4638
W*T*D	0.6669	0.2228	2.993	0.0933
N	122.4711	0.2228	549.574	0.0001
W*N	6.2500	0.2228	28.046	0.0001
T*N	0.0136	0.2228	0.061	0.8064
W*T*N	1.2469	0.2228	5.596	0.0242
D*N	1.4003	0.2228	6.284	0.0175
W*D*N	2.8336	0.2228	12.715	0.0001
T*D*N	0.2178	0.2228	0.977	0.3303
W*T*D*N	0.2844	0.2228	1.276	0.2670
I	0.2228	0.0627	3.554	0.0001

Note. MS is mean square.

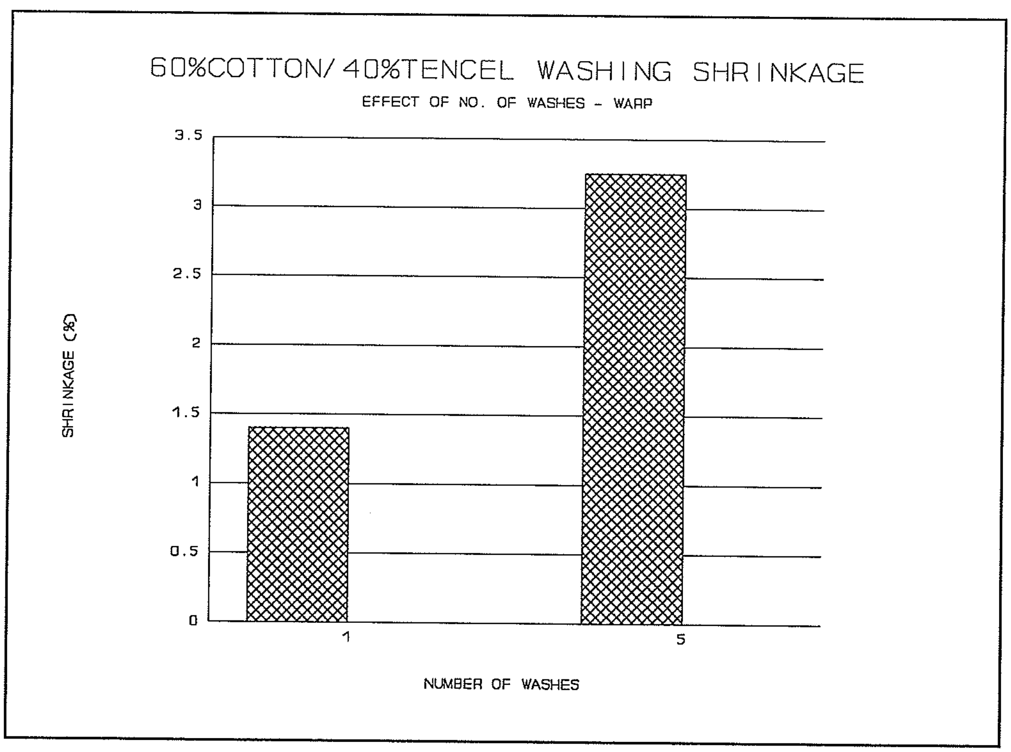
Table 19

Effects and Interactions of Independent Variables
Warp Shrinkage of 60% Cotton/40% Tencel Fabric

Level of Variables			Number of Measurements	Mean Value of Shrinkage (%)
W				
H			72	1.55
M			72	3.11
N				
1			72	1.41
5			72	3.25
W	D			
H	F		36	1.19
H	T		36	1.91
M	F		36	3.35
M	T		36	2.87
W	N			
H	1		36	0.83
H	5		36	2.26
M	1		36	1.98
M	5		36	4.24
D	N			
F	1		36	1.44
F	5		36	3.09
T	1		36	1.37
T	5		36	3.41
W	D	N		
H	F	1	18	0.71
H	F	5	18	1.66
H	T	1	18	0.96
H	T	5	18	2.86
M	F	1	18	2.18
M	F	5	18	4.52
M	T	1	18	1.78
M	T	5	18	3.96
W	T	N		
H	20	1	18	0.92
H	20	5	18	2.14
H	40	1	18	0.74
H	40	5	18	2.38
M	20	1	18	1.84
M	20	5	18	4.27
M	40	1	18	2.12
M	40	5	18	4.21



<u>Figure 13.</u> Effect of washing method.



<u>Figure 14.</u> Effect of number of washing cycles.

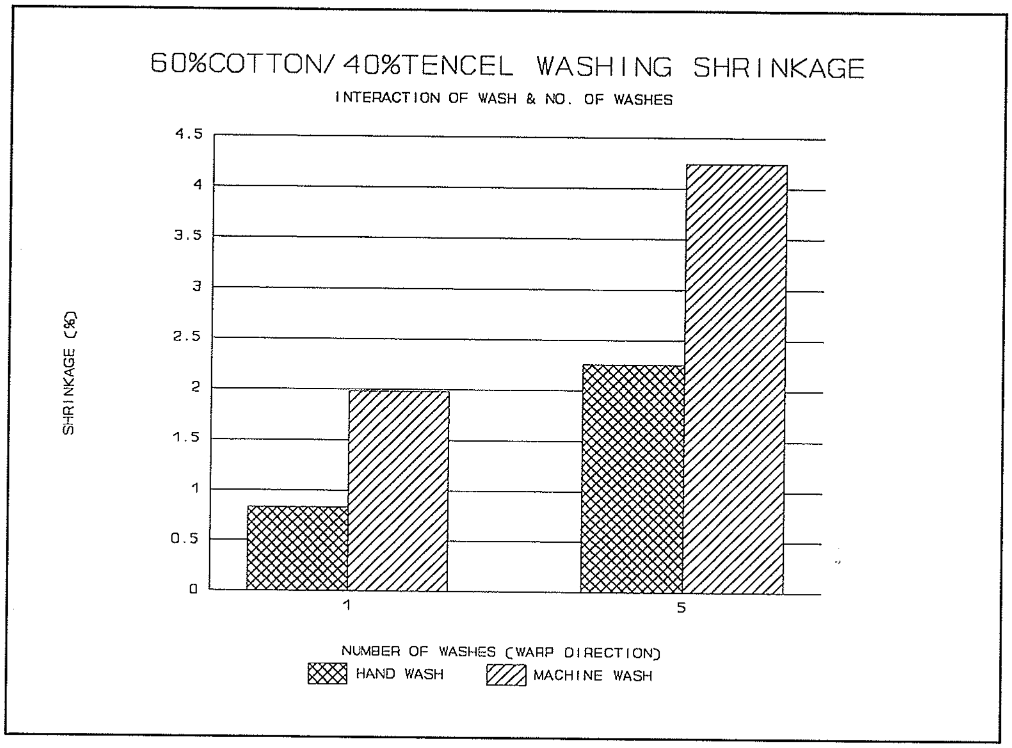


Figure 15. Interaction of washing method and number of washes.

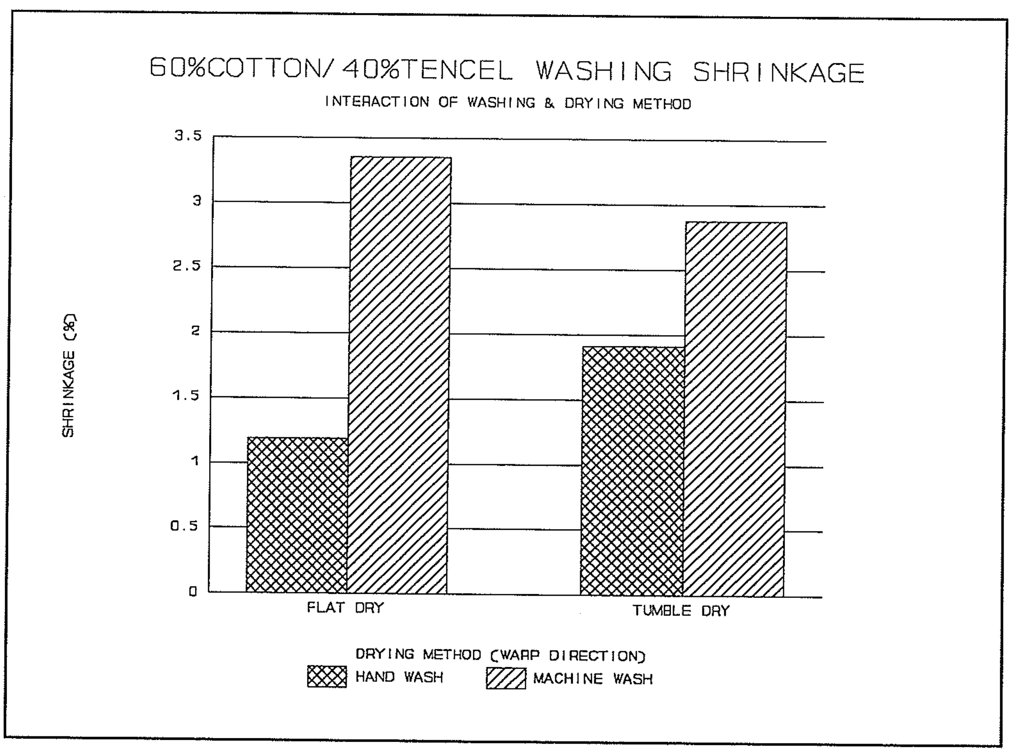


Figure 16. Interaction of washing and drying methods.

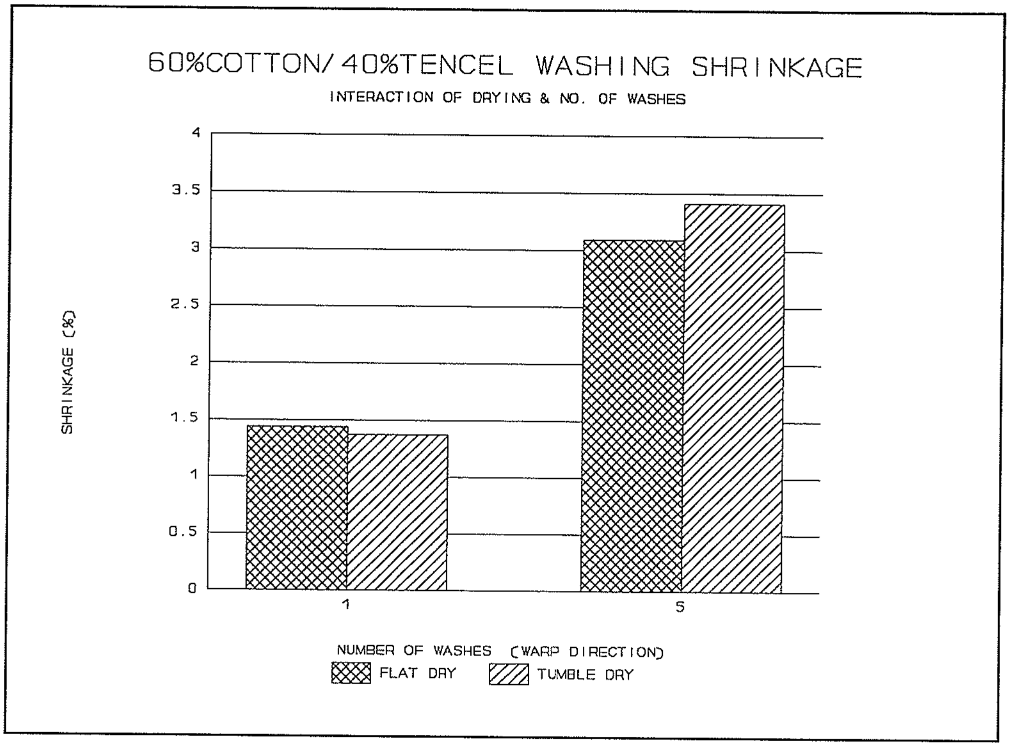


Figure 17. Interaction of drying method and number of washes.

Figure 16 illustrates the two way interaction of washing and drying methods on the warp shrinkage. In general, machine washing gave greater shrinkage than hand washing, but tumble drying did not always produce higher shrinkage levels than drying flat as expected. For example, machine washing and drying flat produced more shrinkage than machine washing and tumble drying. An explanation for this is believed to be the same as that provided in the discussion of Figure 7.

Figure 17 illustrates the two way interaction of the drying method and the number of laundering cycles on the warp shrinkage. After one laundering cycle, drying flat and tumble drying yielded similar shrinkage levels, while after 5 cycles, the tumble drying yielded higher shrinkage than drying flat.

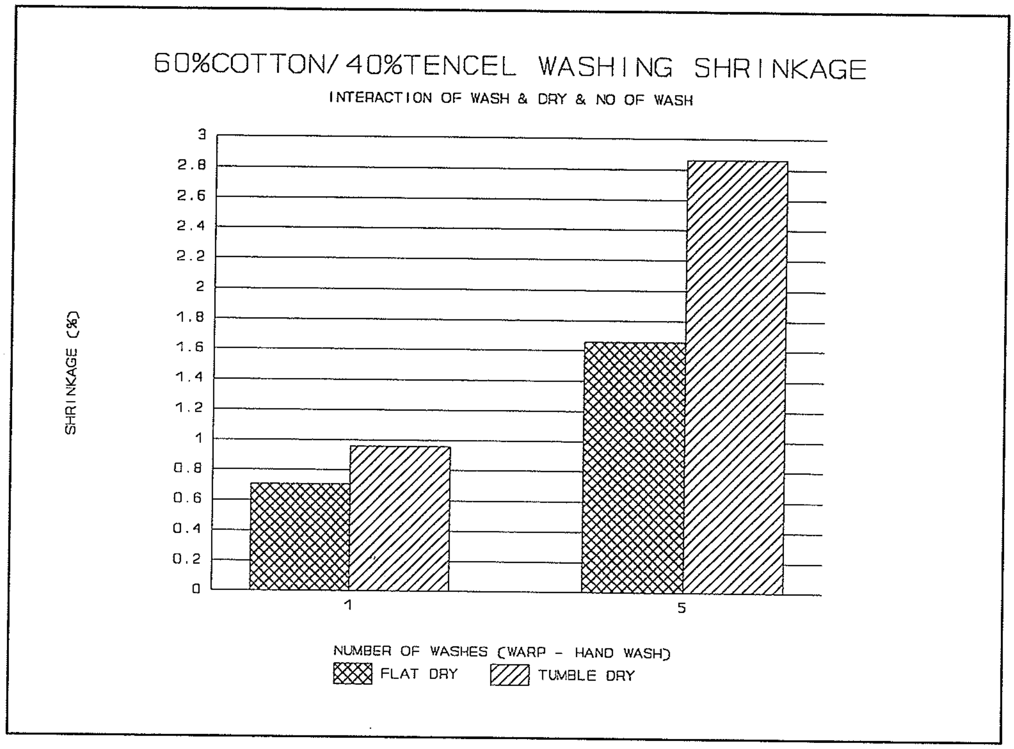


Figure 18. Interaction of wash, dry, and number of washes.

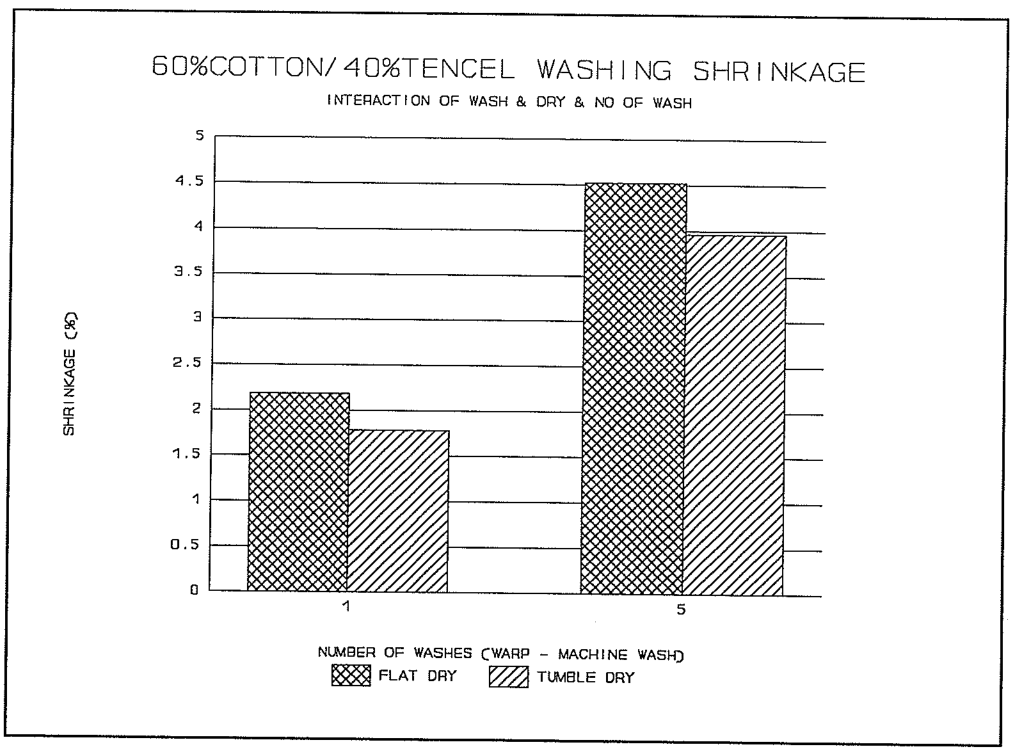


Figure 19. Interaction of wash, dry, and number of washes.

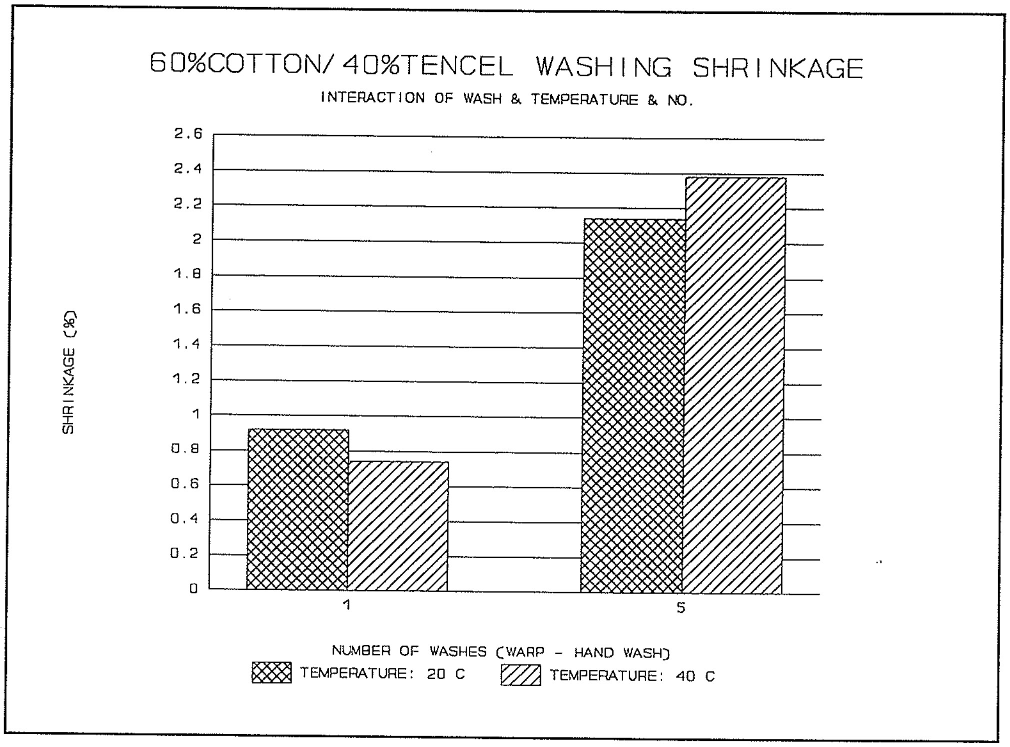


Figure 20. Interaction of wash, temperature & No. of washes.

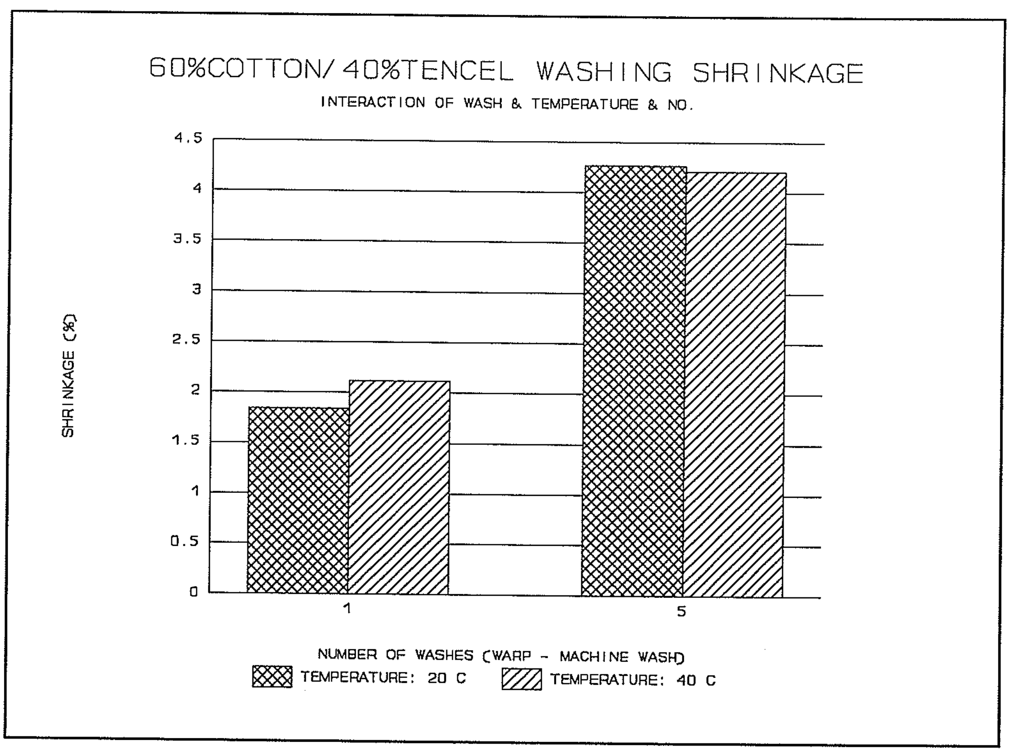


Figure 21. Interaction of wash, temperature & No. of washes.

Figures 18 and 19 illustrate the 3 way interaction: W*D*N. Figure 18 shows the interaction of D and N, for the hand washing method. Under such conditions, tumble drying yielded higher shrinkage than drying flat after both one and 5 cycles. In Figure 19, the interaction between D and N is illustrated for the machine washing conditions. Surprisingly drying flat gave greater shrinkage than tumble drying under such conditions. A possible explanation for this contradictory shrinkage behaviour is that hand washing yielded much less shrinkage; i.e. less than 1% after one cycle, so that the drying method had a greater impact on the overall shrinkage. By contrast, machine washing was more severe, and hence the drying methods did not add much additional shrinkage. In addition, as explained previously, the wrinkles may have had an unforeseen influence on the shrinkage measurement.

Figures 20 and 21 illustrate the 3 way interaction: W*T*N. In Figure 20, the washing method is set to hand washing, and it is obvious that the number of cycles had a great effect on the level of warp shrinkage. The increase in the amount of shrinkage from 1 to 5 cycles was 1.2% when using cold water compared to 1.7% for warm water. Clearly the washing temperature had less of an effect on shrinkage than the number of cycles, since the difference in shrinkage between cold and warm water is less than 0.3% after both 1 and 5 cycles. Figure 21 is the interaction of washing temperature and number of cycles on the warp shrinkage under machine washing conditions. The effect is quite similar to that observed in Figure 20, although the shrinkage level is higher because of the machine washing conditions.

4.3.4 Analysis of Weft Shrinkage in the 60/40 Cotton/Tencel Fabric (Fabric 2)

The results of the full factorial analysis for the 60/40 cotton/Tencel fabric in the weft direction are listed in Table 20. From Table 20, it can be seen that W, N, and W*N had a significant influence on dependent variable weft shrinkage. To explain how these independent variables affected the dependent variable, their mean values were calculated and listed in Table 21. Nearly all the shrinkage values in Table 21, however, are very low, i.e. less than 1%. Only after 5 cycles of machine washing did the weft shrinkage exceed 1%.

In summary, unlike Fabric 1, the independent variables that influenced the shrinkage of Fabric 2 were different in the warp and weft directions. Also, as expected, the observed shrinkage levels of the cotton warp yarns were invariably much higher than those in the Tencel weft direction.

Table 20

Full Factorial Analysis of Variance

Weft Shrinkage of 60% Cotton/40% Tencel Fabric

Source	Type III MS	Denominator MS	F Value	p Value
W	8.0751	0.4291	18.819	0.0001
T	0.5017	0.4291	1.169	0.2876
W*T	0.0018	0.4291	0.004	0.9497
D	0.5501	0.4291	1.282	0.2660
W*D	0.1167	0.4291	0.272	0.6056
T*D	0.0084	0.4291	0.020	0.8896
W*T*D	0.1284	0.4291	0.299	0.5882
N	6.9784	0.4291	16.263	0.0003
W*N	3.3917	0.4291	7.904	0.0084
T*N	0.2256	0.4291	0.526	0.4736
W*T*N	0.0201	0.4291	0.047	0.8302
D*N	0.0001	0.4291	0.000	0.9899
W*D*N	0.1056	0.4291	0.246	0.6232
T*D*N	0.5256	0.4291	1.225	0.2766
W*T*D*N	0.2756	0.4291	0.642	0.4288
I	0.4291	0.0141	30.438	0.0001

Table 21

Effects and Interactions of Independent Variables

Weft Shrinkage of 60/40 Cotton/Tencel Fabric

Level of Variables		Number of Measurements	Mean Value of Shrinkage (%)
W			
H		72	0.21
M		72	0.65
N			
1		72	0.19
5		72	0.67
W	N		
H	1	36	0.13
H	5	36	0.26
M	1	36	0.29
M	5	36	1.04

4.3.5 Analysis of Warp Shrinkage in the 100% Cotton Fabric (Fabric 3)

The results of the full factorial analysis for the 100% cotton fabric in the warp direction are listed in Table 22, where it can be seen that W, D, W*D, N, W*N, and D*N had a significant influence on the dependent variable, warp shrinkage. To explain how these independent variables affected the dependent variable, their mean values were calculated, and the results are listed in Table 23.

Again bar diagrams, Figures 22 - 27, have been drawn to illustrate the data in Table 23. Figure 22 shows how the washing method affected the warp shrinkage, and as anticipated it can be seen that machine washing caused more shrinkage than hand washing. Figure 23 illustrates the main effect of the drying method on the shrinkage, and shows that tumble drying yielded higher shrinkage than flat drying. This independent variable did not influence the shrinkage of Fabrics 1 and 2. Figure 24 shows how the number of laundering cycles affected the warp washing shrinkage, and as expected, specimens after 5 laundering cycles hade greater shrinkage than after one.

Figure 25 shows the two way interaction of the washing and drying methods. With hand washing, tumble drying produced higher warp shrinkage than drying flat, whereas after machine washing, the reverse was observed. Figure 26 illustrates the two way interaction of washing method and the number of cycles on the warp shrinkage. Both the choice of machine washing, and the use of 5 rather than 1 cycle had the effect of increasing the shrinkage level which rose on average by 2.4% from 1 cycle to 5 cycles. Figure 27 illustrates the two way interaction of drying method and number of cycles on warp shrinkage. Tumble drying generated higher shrinkages than drying flat after 5 cycles, but after only one cycle, no such difference were observed.

Table 22

Full Factorial Analysis of Variance

Warp Shrinkage of 100% Cotton Fabric

Source	Type III MS	Denominator MS	F Value	p Value
W	54.8834	1.5197	36.116	0.0001
T	0.0017	1.5197	0.001	0.9732
W*T	0.0056	1.5197	0.004	0.9519
D	6.6306	1.5197	4.363	0.0448
W*D	17.5701	1.5197	11.562	0.0018
T*D	0.2256	1.5197	0.148	0.7025
W*T*D	0.3906	1.5197	0.257	0.6156
N	141.4117	1.5197	93.055	0.0001
W*N	6.3756	1.5197	4.195	0.0488
T*N	0.1534	1.5197	0.101	0.7528
W*T*N	0.0584	1.5197	0.038	0.8458
D*N	6.7167	1.5197	4.420	0.0435
W*D*N	0.0851	1.5197	0.056	0.8145
T*D*N	0.3701	1.5197	0.244	0.6250
W*T*D*N	0.2417	1.5197	0.159	0.6927
I	1.5197	0.0717	21.204	0.0001

Note. MS is mean square.

Table 23

Effects and Interactions of Independent Variables

Warp Shrinkage of 100% Cotton Fabric

Level of Variables		Number of Measurements	Mean Value of Shrinkage (%)
W			
H		72	2.55
M		72	3.78
D			
F		72	2.95
T		72	3.38
N			
1		72	2.17
5		72	4.16
W	D		
H	F	36	1.98
H	T	36	3.11
M	F	36	3.92
M	T	36	3.65
W	N		
H	1	36	1.77
H	5	36	3.33
M	1	36	2.58
M	5	36	4.98
D	N		
F	1	36	2.18
T	5	36	3.73
F	1	36	2.17
T	5	36	4.59

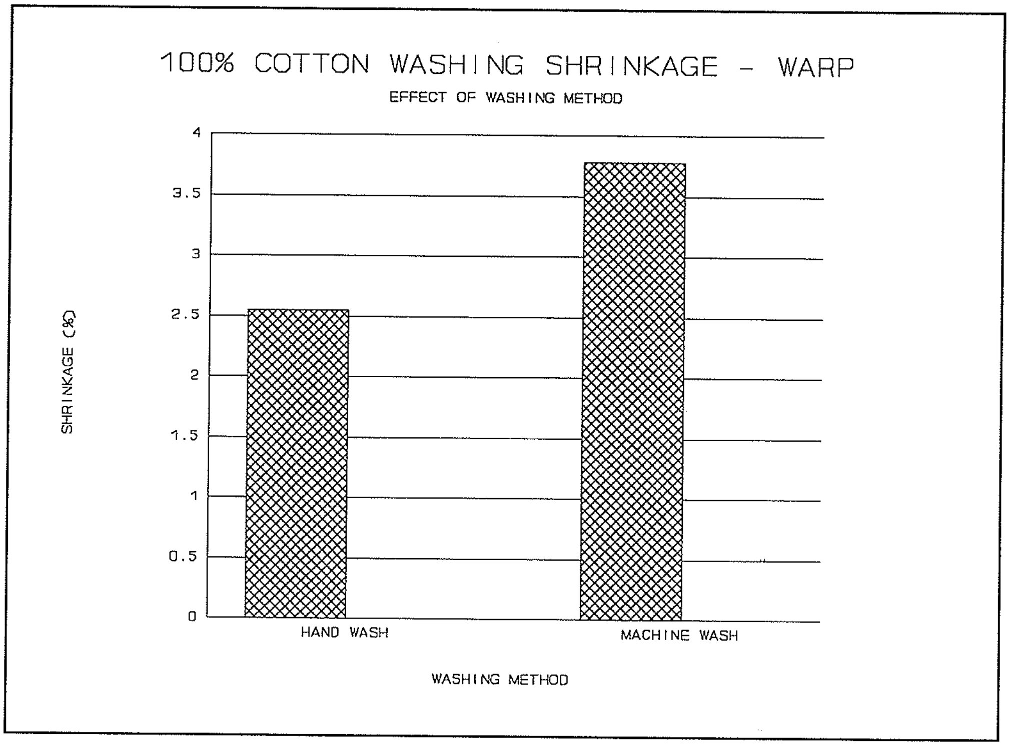


Figure 22. Effect of washing method.

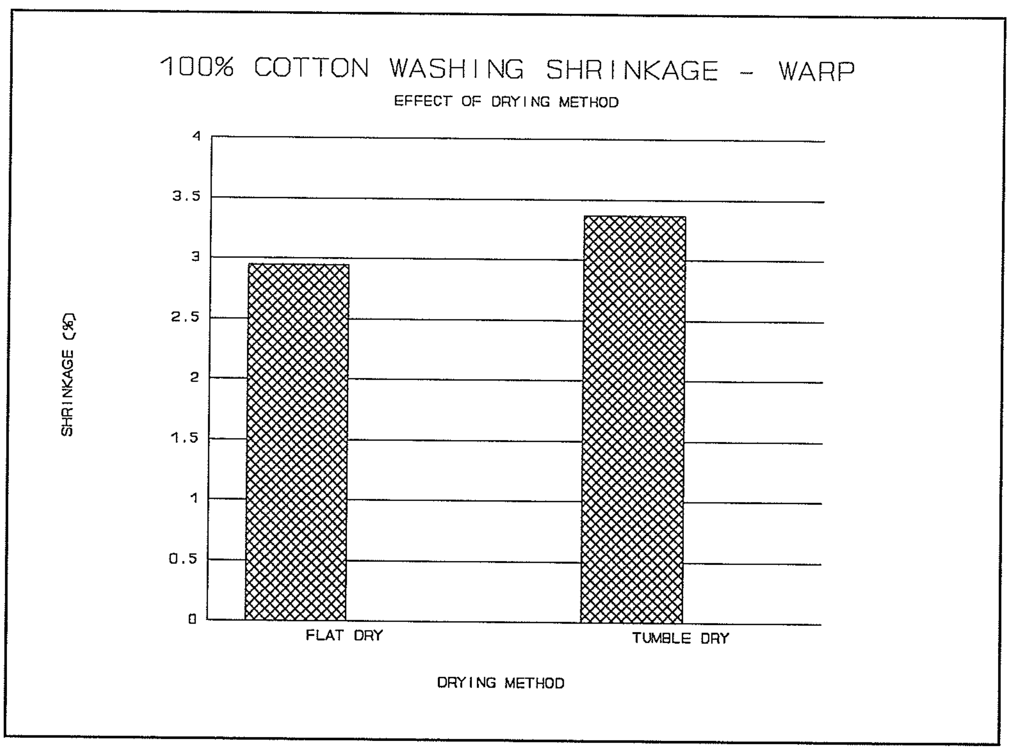


Figure 23. Effect of drying method.

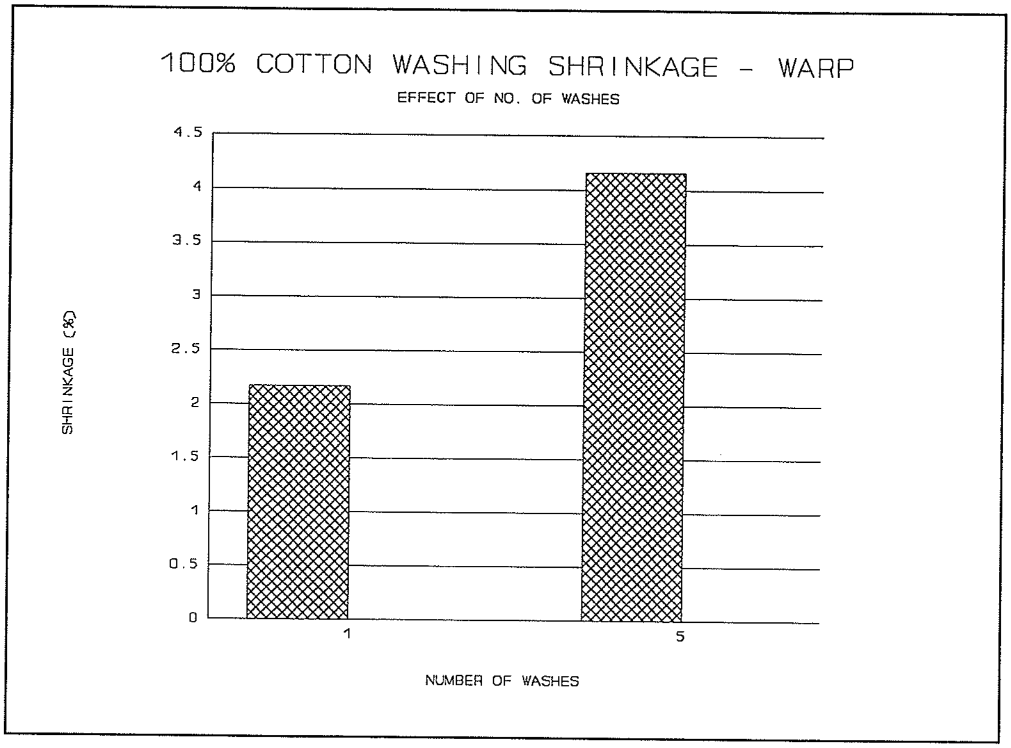


Figure 24. Effect of number of laundering cycles.

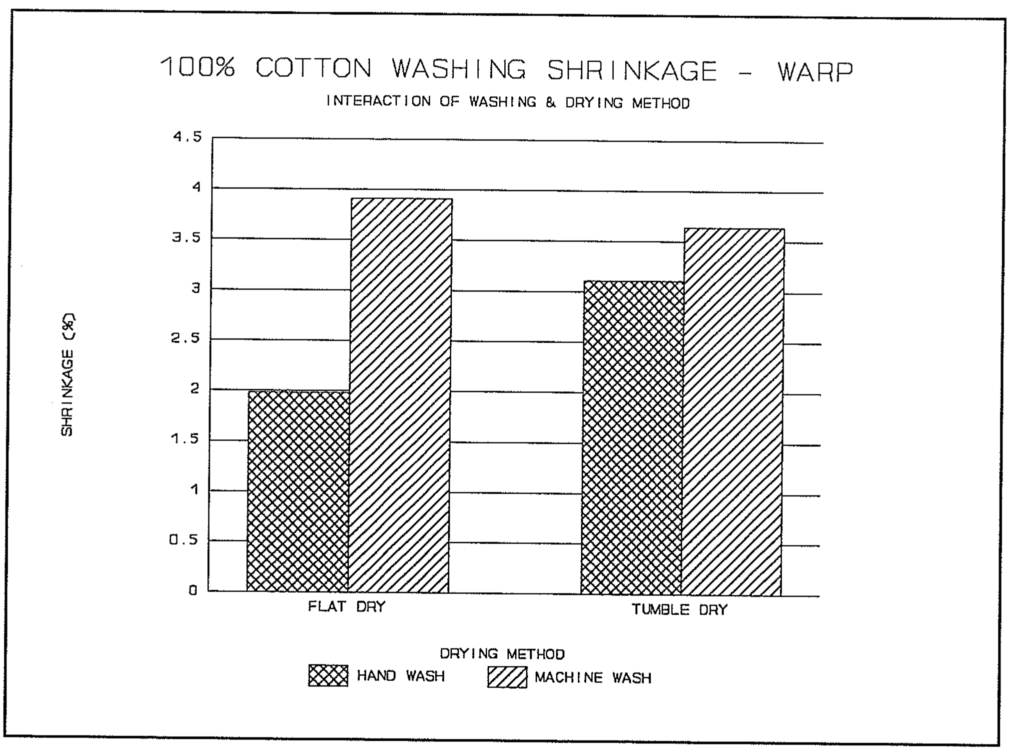


Figure 25. Interaction of washing and drying method.

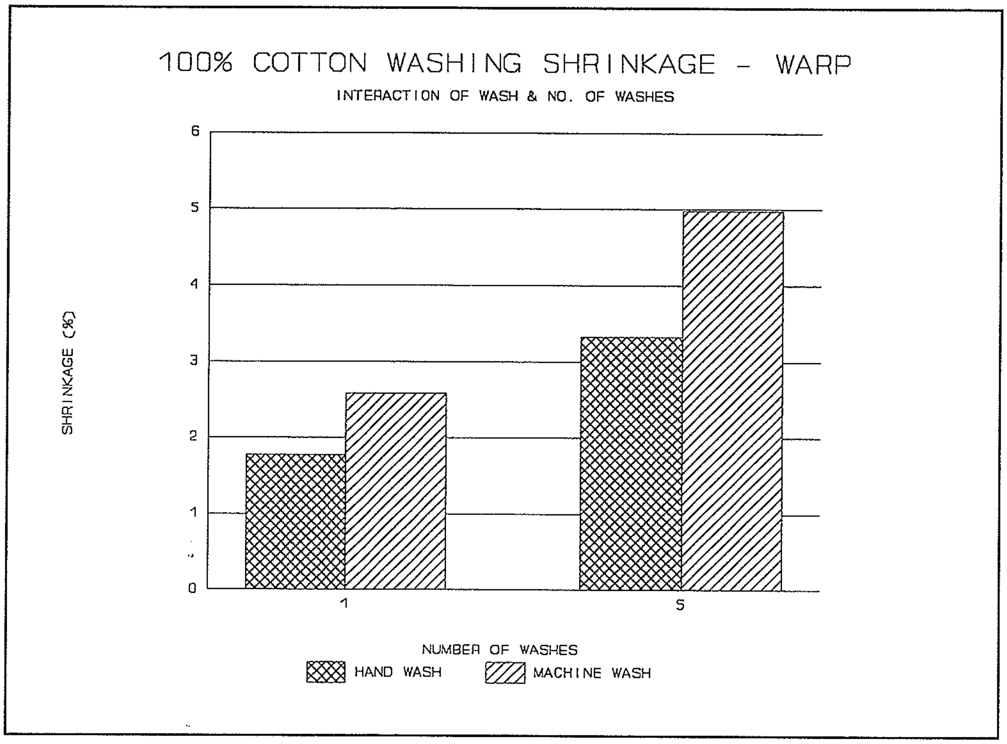


Figure 26. Interaction of washing method & No. of washes.

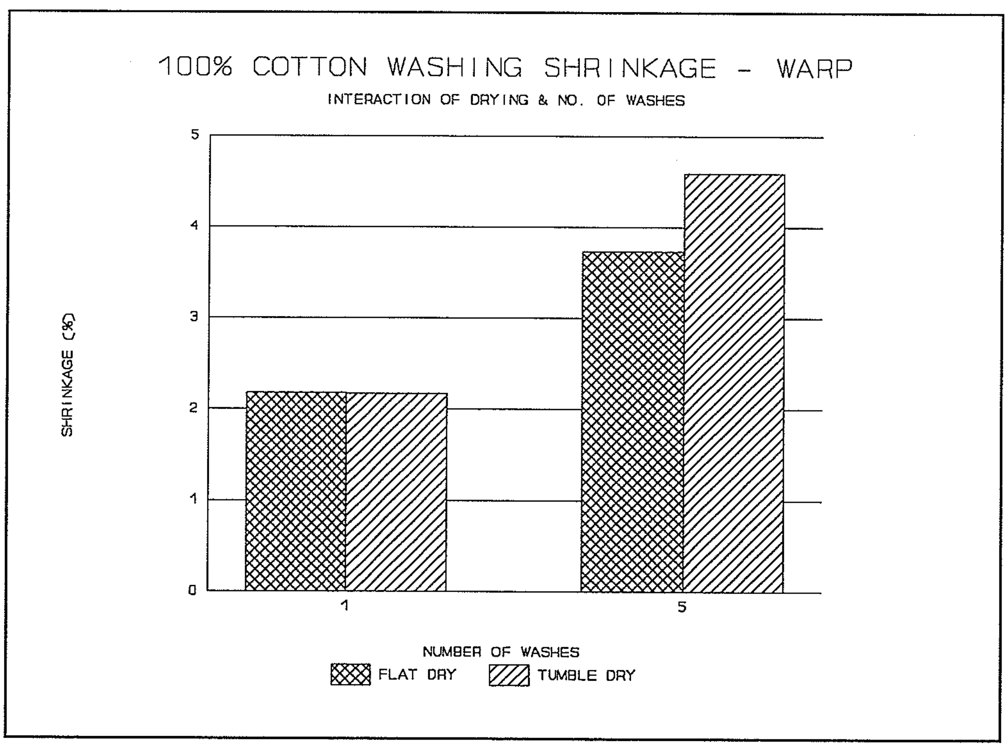


Figure 27. Interaction of drying method & No. of washes.

4.3.6 Analysis of Weft Shrinkage in the 100% Cotton Fabric (Fabric 3)

The results of the full factorial analysis for the 100% cotton fabric in the weft direction are listed in Table 24. From this table, it can be seen that W, N, and W*N had significant influences on the dependent variable, weft shrinkage. To explain how those independent variables affected the dependent variable, their mean values were calculated and the results are listed in Table 25. It can be seen from Table 25 that nearly all the shrinkage values in the weft direction are very low, i.e. less than 1%. Only one laundering condition resulted in a weft shrinkage of greater than 1%, and that involved 5 cycles of machine washing.

Table 24
Full Factorial Analysis of Variance
Weft Shrinkage of 100% Cotton Fabric

Source	Type III MS	Denominator MS	F Value	p Value
W	17.0156	0.4378	38.862	0.0001
T	0.0434	0.4378	0.099	0.7549
W*T	0.0156	0.4378	0.036	0.8514
D	0.1534	0.4378	0.350	0.5581
W*D	0.3306	0.4378	0.755	0.3913
T*D	0.0201	0.4378	0.046	0.8318
W*T*D	0.0117	0.4378	0.027	0.8710
N	12.3084	0.4378	28.111	0.0001
W*N	10.1867	0.4378	23.266	0.0001
T*N	0.0201	0.4378	0.046	0.8318
W*T*N	0.0851	0.4378	0.194	0.6623
D*N	0.1667	0.4378	0.381	0.5415
W*D*N	0.0667	0.4378	0.152	0.6988
T*D*N	0.0584	0.4378	0.133	0.7173
W*T*D*N	0.0006	0.4378	0.001	0.9701
I	0.4378	0.0183	23.883	0.0001

Note. MS is mean square.

Table 25

Effects and Interactions of Independent Variables
Weft Shrinkage of 100% Cotton Fabric

Level of Variables		Number of Measurements	Mean Value of Shrinkage
W			
H		72	0.05
M		72	0.73
N			
1		72	0.10
5		72	0.68
W	N		
H	1	36	0.02
H	5	36	0.07
5	1	36	0.18
5	5	36	1.29

In summary, the independent variables that influenced the shrinkage of all cotton Fabric 3 were different in the warp and weft directions. As anticipated, the observed shrinkage level were always much higher in the warp than the weft direction.

From the above results, the data provide sufficient evidence that Ho_2A, Ho_2C and Ho_2D can be rejected, however, Ho_2B cannot be rejected. Note that the difference between the hand washing and machine washing methods used involved not only a different level of mechanical agitation, but also the absence and presence of detergent and cool ironing. Therefore the rejection of HO_2A may be due in part to the detergent and cool ironing, as well as the amount of agitation.

4.4 Full Factorial Analysis of Two Fabrics

After having analyzed individual fabric shrinkages in both warp and weft directions separately by using a full factorial analysis method, the fibre blend level in the fabrics was considered as another independent variable. This means that the fabric was included as an additional variable in the factorial analysis with two levels. Since the 60/40 cotton/Tencel fabric was a union blend fabric composed of 100% cotton warp yarns and 100% Tencel weft yarns, it was only possible to compare cotton yarns between fabrics in the warp direction and Tencel yarns in the weft direction. To do this the warp shrinkage in Fabrics 2 and 3 were compared, since they have the same cotton warp yarn, but different weft yarns. Likewise, the weft shrinkage of Fabrics 1 and 2 were compared, since they have the same Tencel weft yarn, but different warp yarns.

4.4.1 Factorial Analysis of Warp Shrinkage in Fabrics 2 and 3

A full factorial analysis method was used to analyze the warp shrinkage of Fabrics 2 and 3. By applying a full factorial analysis of variance by means of a SAS program (in Appendix 3), the results are listed in Table 26. From this table, it can be seen that F, W, D, W*D, N, W*N, and D*N had significant influences on the dependent variable, warp shrinkage. To explain how those independent variables affect the dependent variable, their mean values were calculated and the results are listed in Table 27.

As mentioned previously, a number of bar diagrams have be drawn to illustrate the main effects and the observed interactions. Figure 28 illustrates how the washing method affected the warp shrinkage, and it readily shows that machine washing caused more shrinkage than hand washing. Figure 29 illustrates how the number of laundering cycles affected the warp shrinkage. As expected specimens after 5 cycles had greater shrinkage than those after 1 cycle. Figure 30 illustrates the effect of the fabric type on the level of warp shrinkage. The 100% cotton fabric had higher shrinkage than the 60/40 cotton/Tencel blend fabric. Figure 31 illustrates the effect of the drying method on the warp shrinkage, and shows that tumble drying gave slightly more shrinkage than drying flat.

Figure 32 illustrates the two way interaction of drying method and number of laundering cycles. After one cycle, drying flat and tumble drying produced similar shrinkage results, while after 5 cycles, tumble drying was responsible for significantly higher shrinkage values. Figure 33 illustrates the two way interaction of washing method and number of cycles on the warp shrinkage. The choice of both machine washing and 5 cycles increased the amount of shrinkage

Table 26

Full Factorial Analysis of Variance

Warp Shrinkage of Fabrics 2 and 3

Source	Type III MS	Denominator MS	F Value	p Value
F	50.2503	0.8713	57.676	0.0001
W	140.9800	0.8713	161.814	0.0001
W*F	1.9503	0.8713	2.239	0.1395
T	0.0975	0.8713	0.112	0.7390
T*F	0.0642	0.8713	0.074	0.7869
W*T	0.0475	0.8713	0.055	0.8161
W*T*F	0.0125	0.8713	0.014	0.9049
D	5.4725	0.8713	6.281	0.0148
D*F	1.6959	0.8713	1.946	0.1678
W*D	30.3505	0.8713	34.841	0.0001
W*D*F	0.1750	0.8713	0.201	0.6555
T*D	0.3403	0.8713	0.391	0.5342
T*D*F	0.0078	0.8713	0.009	0.9249
W*T*D	0.0184	0.8713	0.021	0.8850
W*T*D*F	1.0392	0.8713	1.193	0.2789
N	263.5425	0.8713	302.488	0.0001
N*F	0.3403	0.8713	0.391	0.5342
W*N	12.6253	0.8713	14.491	0.0003
W*N*F	0.0003	0.8713	0.000	0.9849
T*N	0.12928	0.8713	0.148	0.7014
T*N*F	0.0378	0.8713	0.043	0.8356
W*T*N	0.9225	0.8713	1.059	0.3073
W*T*N*F	0.3828	0.8713	0.434	0.5098
D*N	7.1253	0.8713	8.178	0.0057
D*N*F	0.9917	0.8713	1.138	0.2900
W*D*N	0.9684	0.8713	1.111	0.2957
W*D*N*F	1.9503	0.8713	2.239	0.1395
T*D*N	0.5778	0.8713	0.663	0.4185
T*D*N*F	0.0100	0.8713	0.012	0.9149
W*T*D*N	0.5253	0.8713	0.603	0.4403
W*T*D*N*F	0.0009	0.8713	0.001	0.9749
I	0.8713	0.0672	12.967	0.0001

Note. MS is mean square.

Table 27

Effects and Interactions of Independent Variables

Warp Shrinkage of Fabrics 2 and 3

Level of Variables		Number of Measurements	Mean Value of Shrinkage (%)
	F		
	2	144	2.33
	3	144	3.16
	W		
	H	144	2.05
	M	144	3.45
	N		
	1	144	1.79
	5	144	3.70
	D		
	F	144	2.61
	T	144	2.88
W	D		
H	F	72	1.58
H	T	72	2.51
M	F	72	3.63
M	T	72	3.26
W	N		
H	1	72	1.30
H	5	72	2.79
M	1	72	2.28
M	5	72	4.61
D	N		
F	1	72	1.81
F	5	72	3.41
T	1	72	1.77
T	5	72	4.00

observed. Figure 34 shows the two way interaction of the washing and drying methods. In general, as expected, machine washing caused greater shrinkage than hand washing. When hand washing was combined with tumble drying, they produced higher shrinkage than drying flat. However after machine washing,drying flat produces the higher shrinkage. A possible explanation for this unexpected phenomenon was given previously in the discussion of Figure 7.

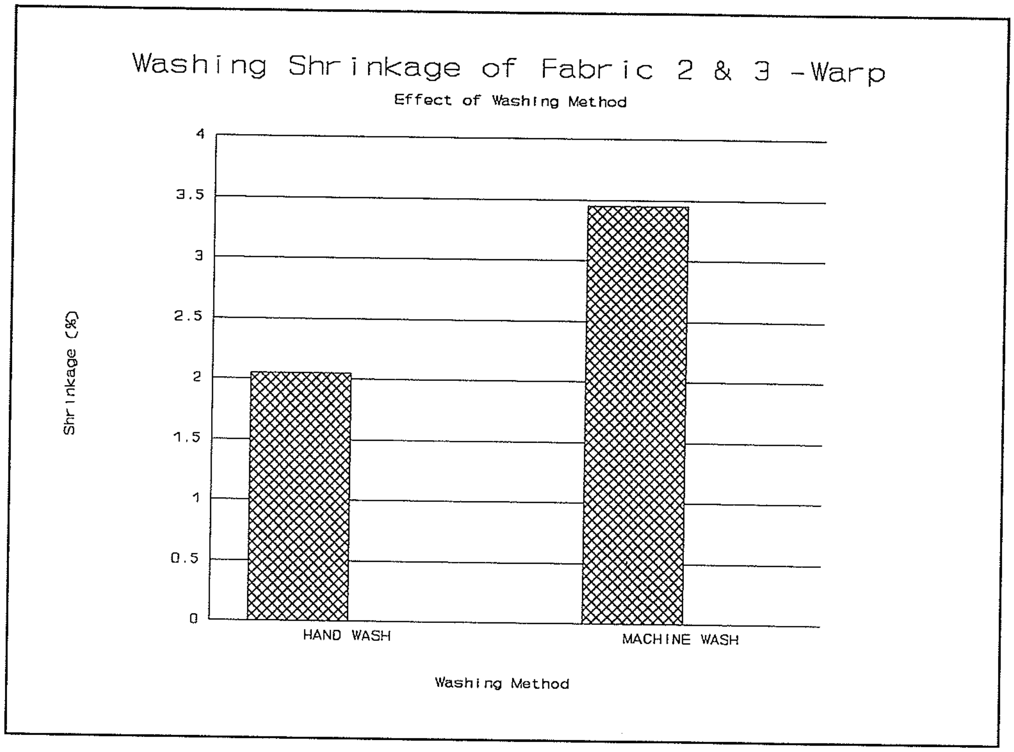


Figure 28. Effect of washing method.

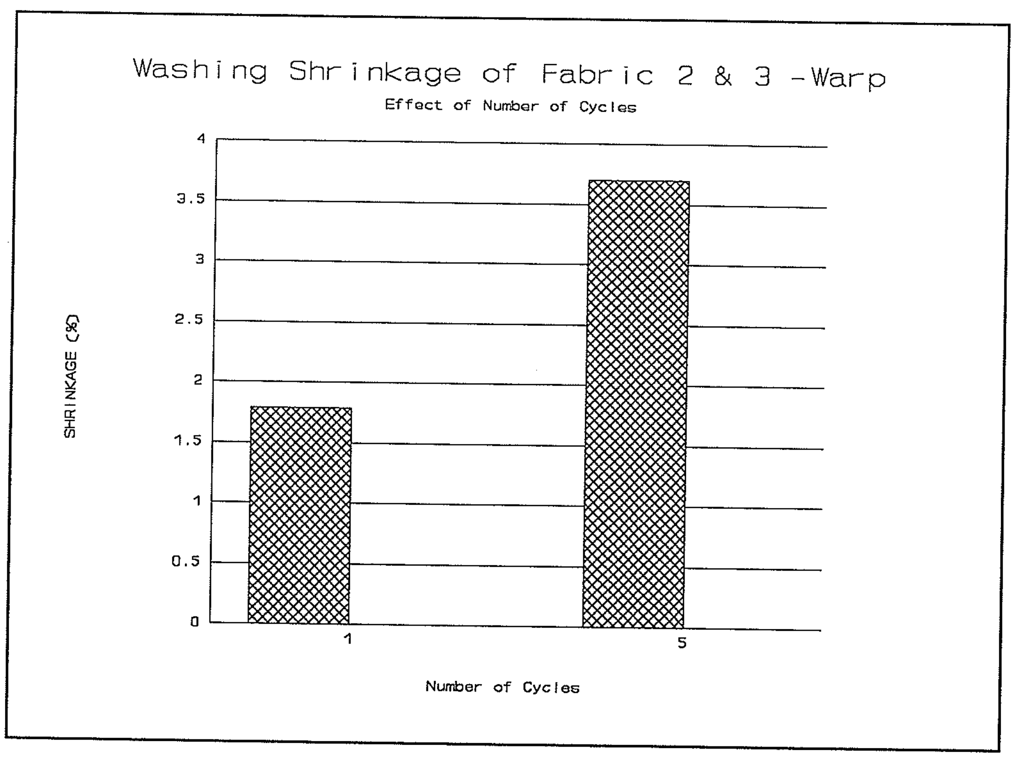


Figure 29. Effect of number of laundering cycles.

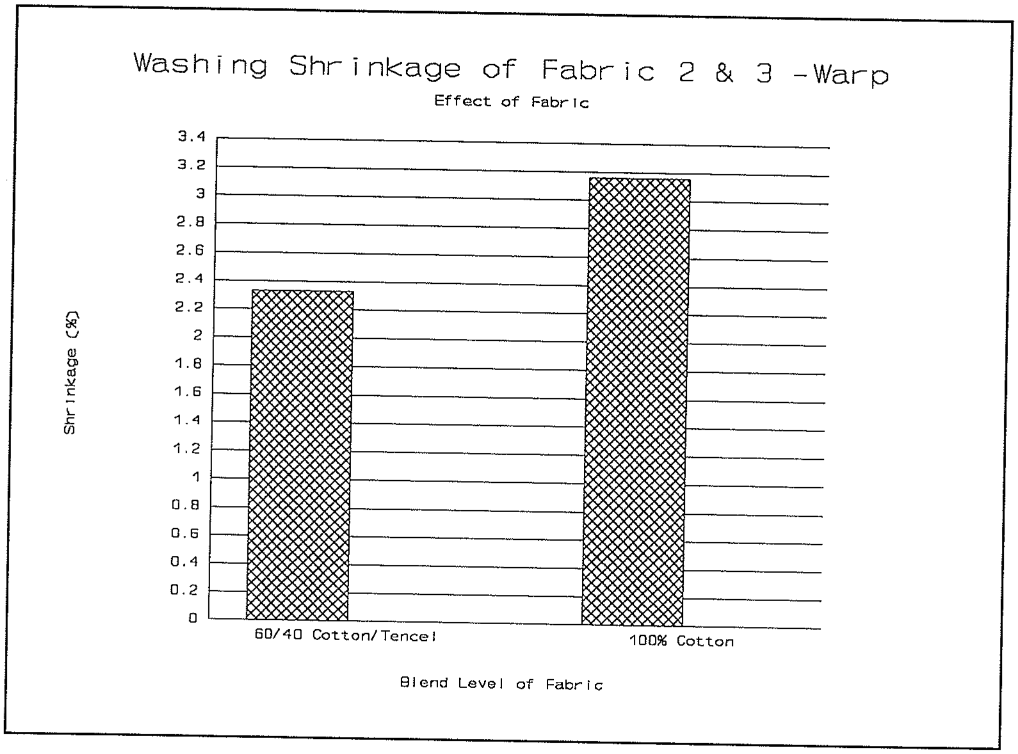


Figure 30. Effect of fabrics.

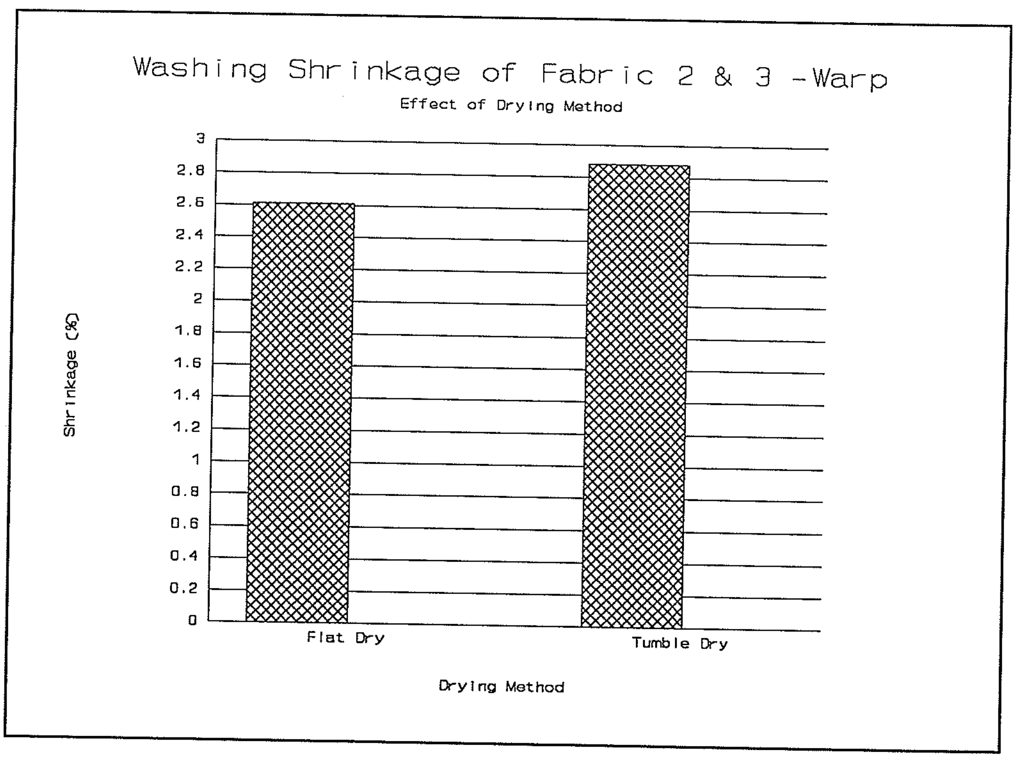


Figure 31. Effect of drying method.

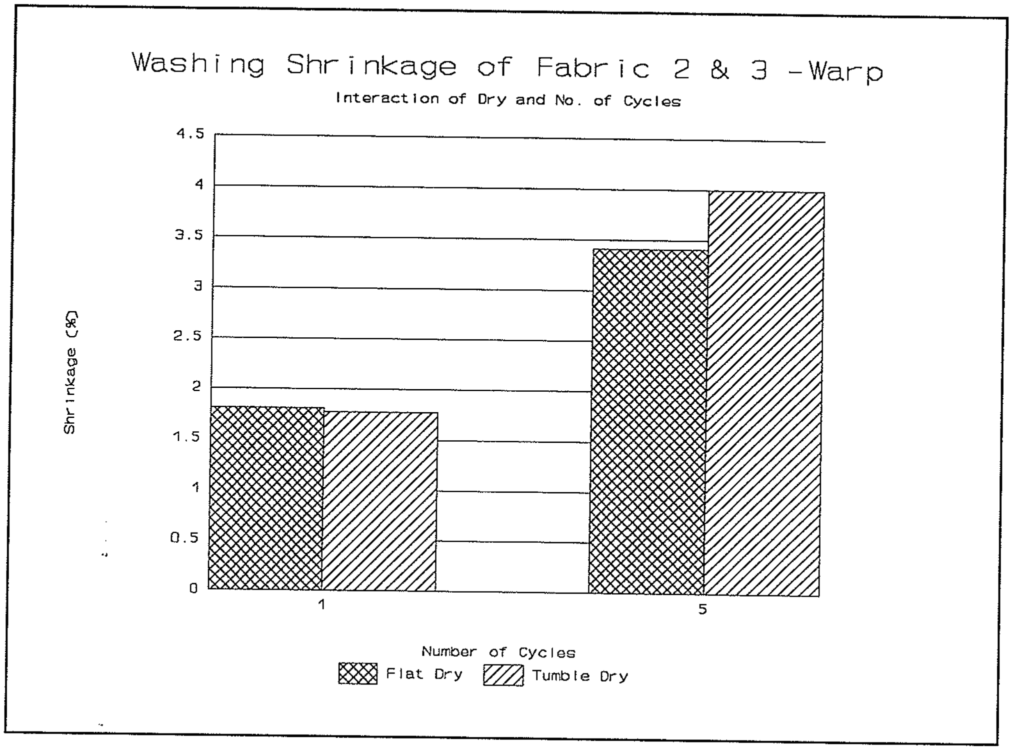


Figure 32. Interaction of drying method & number of washes.

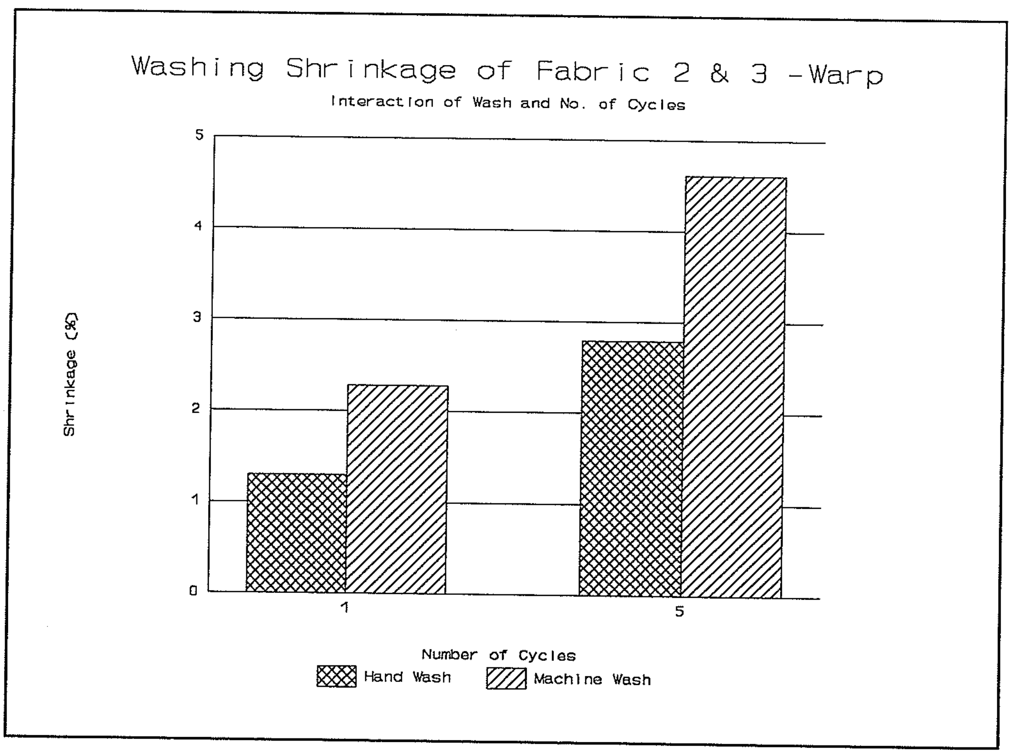


Figure 33. Interaction of washing method & number of washes.

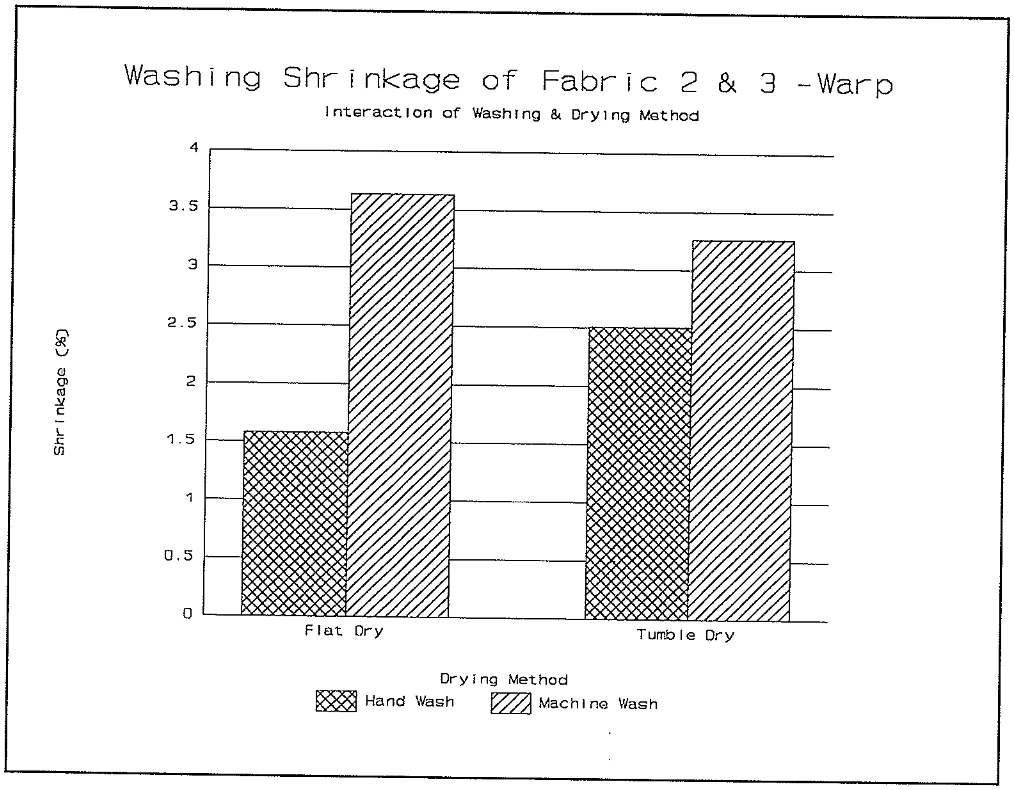


Figure 34. Interaction of washing and drying methods.

4.4.2 Factorial Analysis of Weft Shrinkage in Fabrics 1 and 2

The results of the full factorial analysis for the 100% Tencel, and the 60/40 cotton/Tencel fabrics in the weft direction are listed in Table 28. From this table, it can seen that F, W, W*F, W*D, N, N*F, and W*N had significant influences on the dependent variable, weft shrinkage. To explain how those independent variables affected the dependent variable, their mean values were calculated and are listed in Table 29. The bar diagrams in the Figures 35 - 41 that follow have been drawn so as to illustrate the data in Table 29.

Table 28

Full Factorial Analysis of Variance

Weft Shrinkage of Fabrics 1 and 2

Source	Type III MS	Denominator MS	F Value	p Value
F	260.1100	0.7197	361.421	0.0001
W	72.5009	0.7197	100.739	0.0001
W*F	20.2142	0.7197	28.087	0.0001
T	2.3653	0.7197	3.287	0.0745
T*F	0.2875	0.7197	0.400	0.5296
W*T	0.1208	0.7197	0.168	0.6833
W*T*F	0.0834	0.7197	0.116	0.7347
D	0.3267	0.7197	0.454	0.5029
D*F	0.2278	0.7197	0.317	0.5757
W*D	3.7128	0.7197	5.159	0.0265
W*D*F	2.0842	0.7197	2.896	0.0937
T*D	0.0059	0.7197	0.008	0.9283
T*D*F	0.0028	0.7174	0.004	0.9503
W*T*D	1.5459	0.7197	2.148	0.1477
W*T*D*F	0.5425	0.7197	0.754	0.3885
N	37.9175	0.7197	52.686	0.0001
N*F	5.8653	0.7197	8.150	0.0058
W*N	15.4475	0.7197	21.464	0.0001
W*N*F	1.7578	0.7197	2.442	0.1230
T*N	0.4917	0.7197	0.683	0.4116
T*N*F	0.0009	0.7197	0.001	0.9724
W*T*N	1.0878	0.7197	1.512	0.2234
W*T*N*F	0.7100	0.7197	0.987	0.3243
D*N	0.5084	0.7197	0.706	0.4038
D*N*F	0.5253	0.7197	0.730	0.3961
W*D*N	0.2750	0.7197	0.382	0.5386
W*D*N*F	0.9684	0.7197	1.346	0.2504
T*D*N	1.0633	0.7197	1.478	0.2286
T*D*N*F	0.0000	0.7197	0.000	0.9945
W*T*D*N	1.5107	0.7197	2.107	0.1515
W*T*D*N*F	0.2392	0.7197	0.332	0.5663
I	0.7197	0.0336	21.434	0.0001

Note. MS is mean square.

Table 29

Effects and Interactions of Independent Variables

Weft Shrinkage of Fabrics 1 & 2

Level of Variables		Number of Measurements	Mean Value of Shrinkage (%)
F			
1		144	2.33
2		144	0.43
W			
H		144	0.88
M		144	1.88
N			
1		144	1.02
5		144	1.74
W	F		
H	1	72	1.57
H	2	72	0.19
M	1	72	3.10
M	2	72	0.67
W	D		
H	F	72	0.80
H	T	72	0.96
M	F	72	2.03
M	T	72	1.74
N	F		
1	1	72	1.83
1	2	72	0.21
5	1	72	2.84
5	2	72	0.65
W	N		
H	1	72	0.75
H	5	72	1.01
M	1	72	1.29
M	5	72	2.48

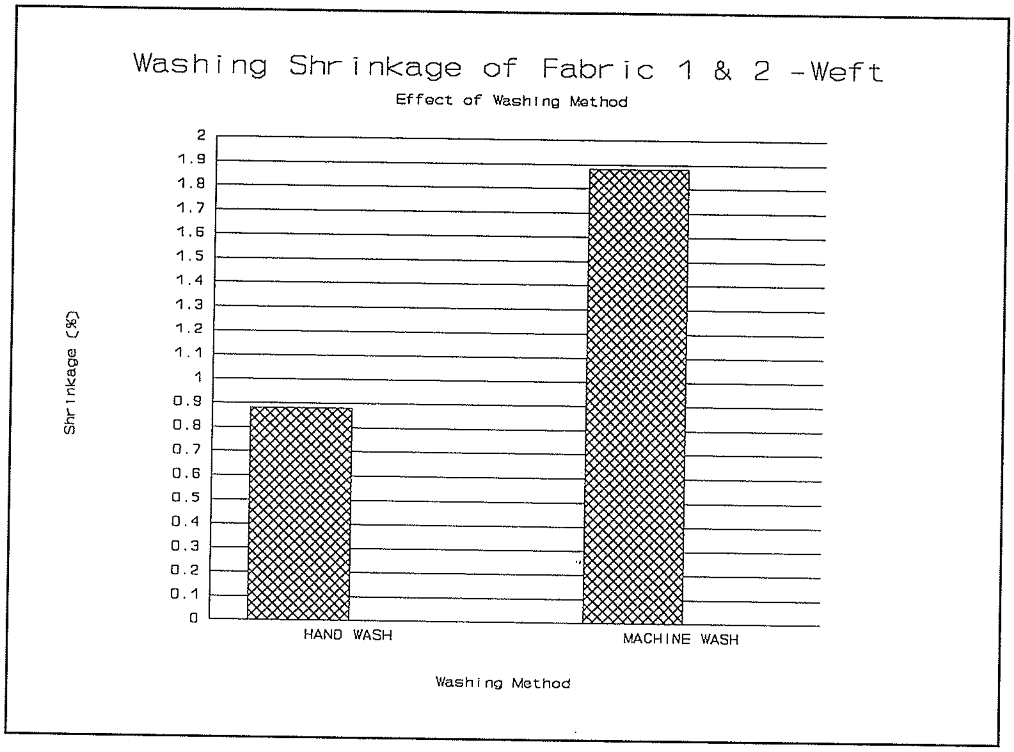


Figure 35. Effect of washing method.

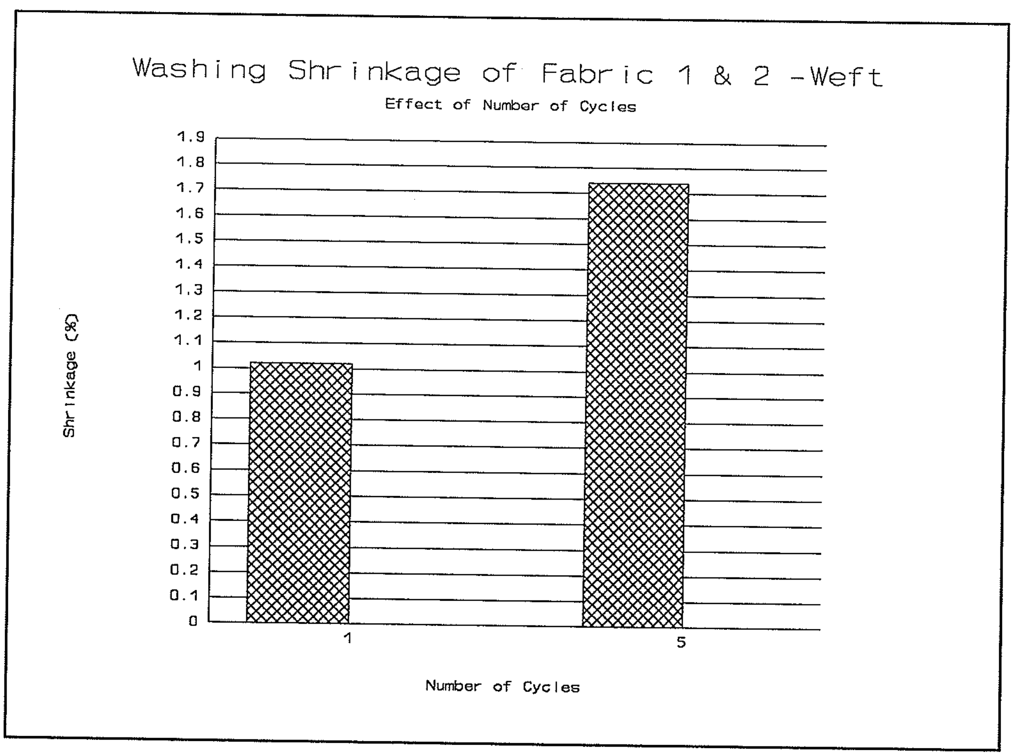


Figure 36. Effect of number of laundering cycles.

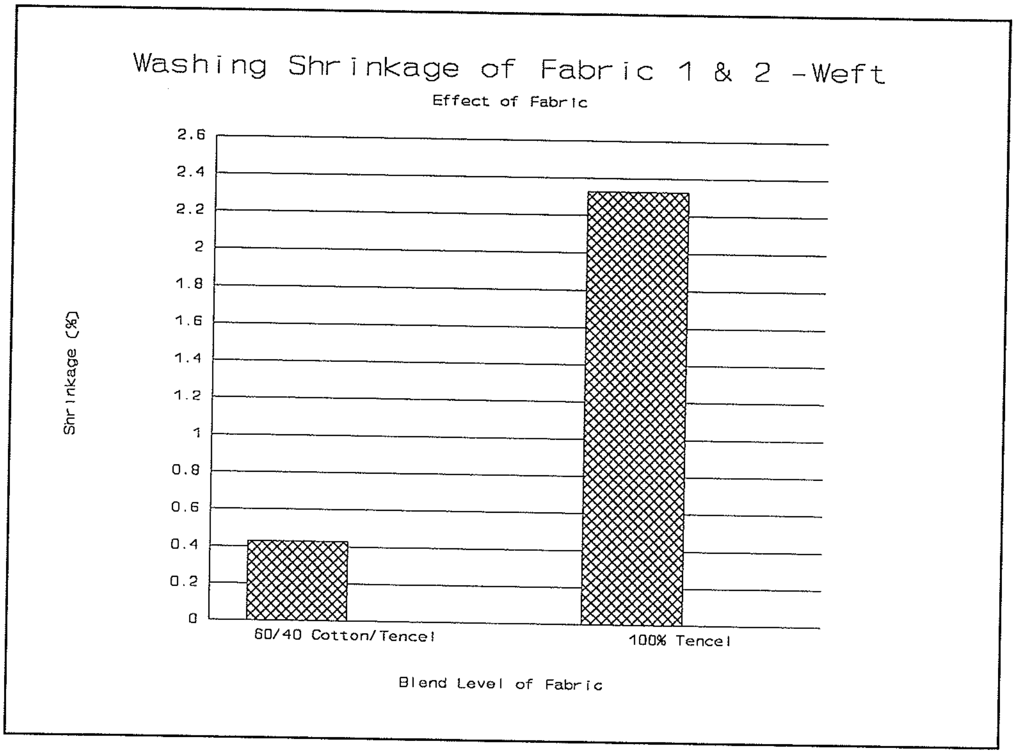


Figure 37. Effect of fabrics.

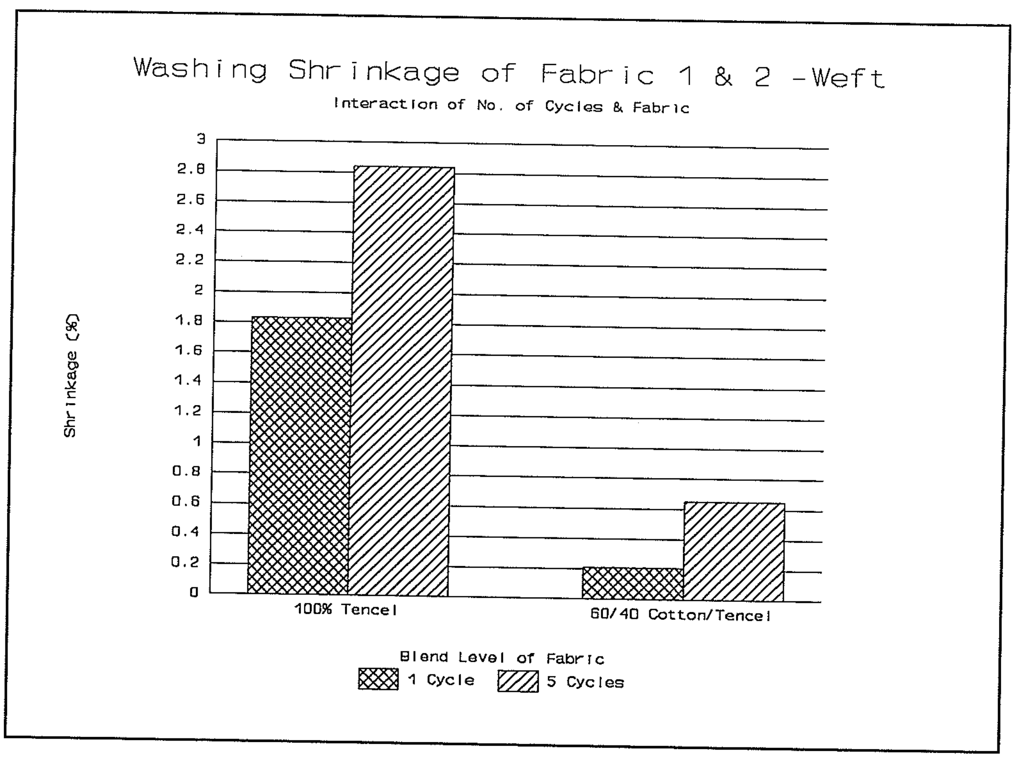


Figure 38. Interaction of number of washes & fabrics.

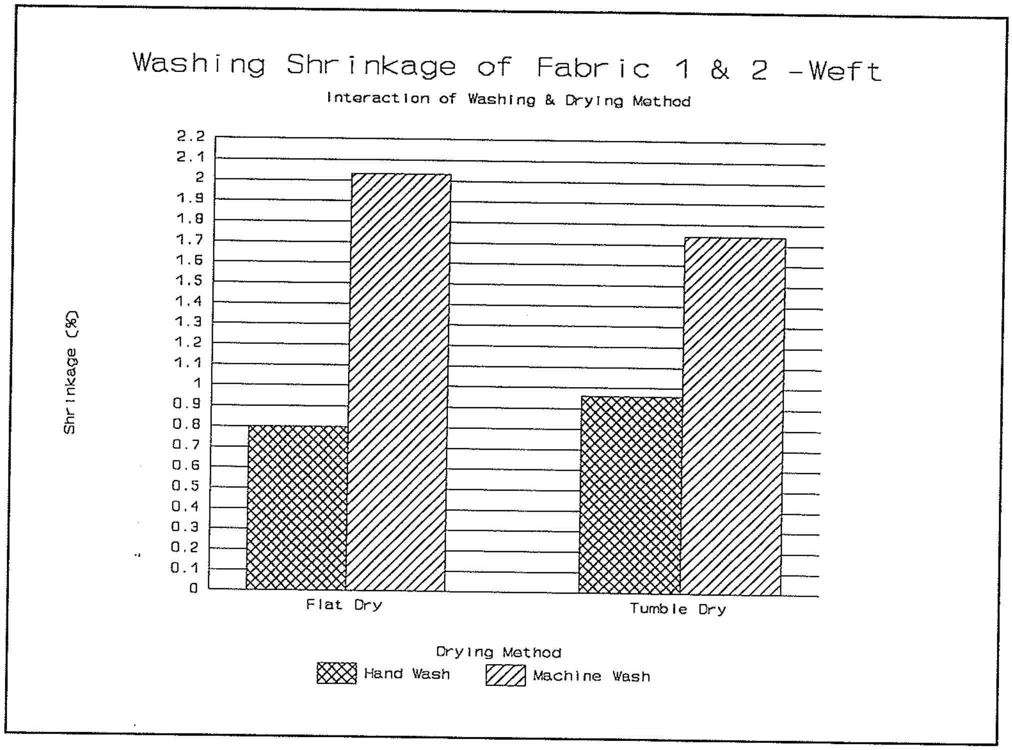


Figure 39. Interaction of washing and drying methods.

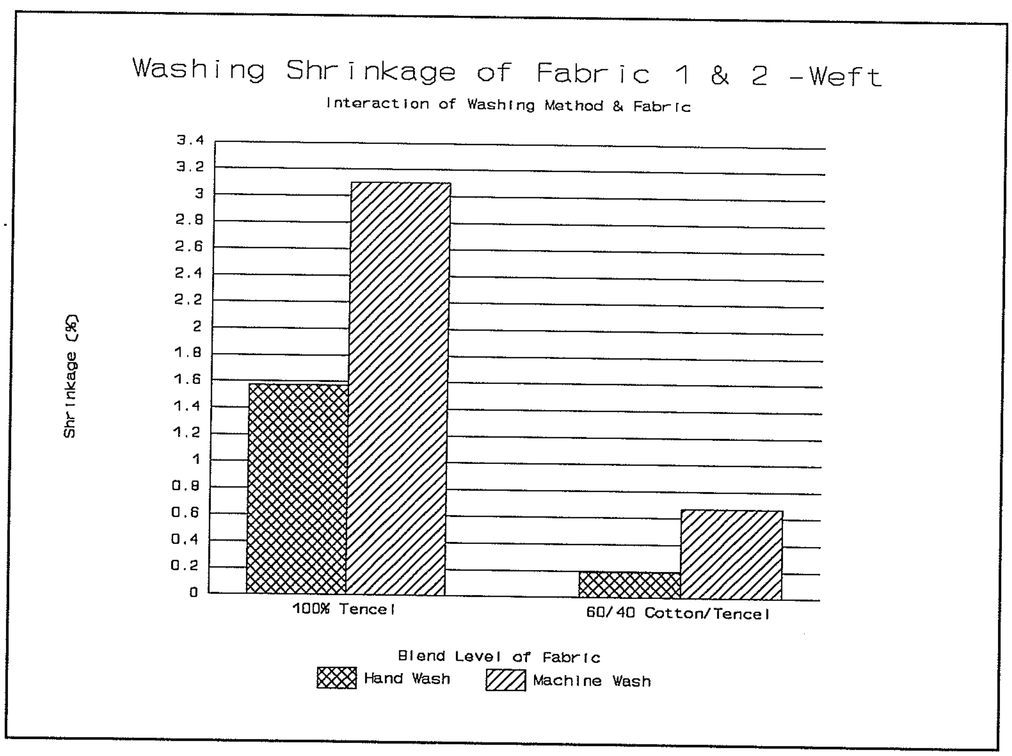


Figure 40. Interaction of washing method and fabrics.

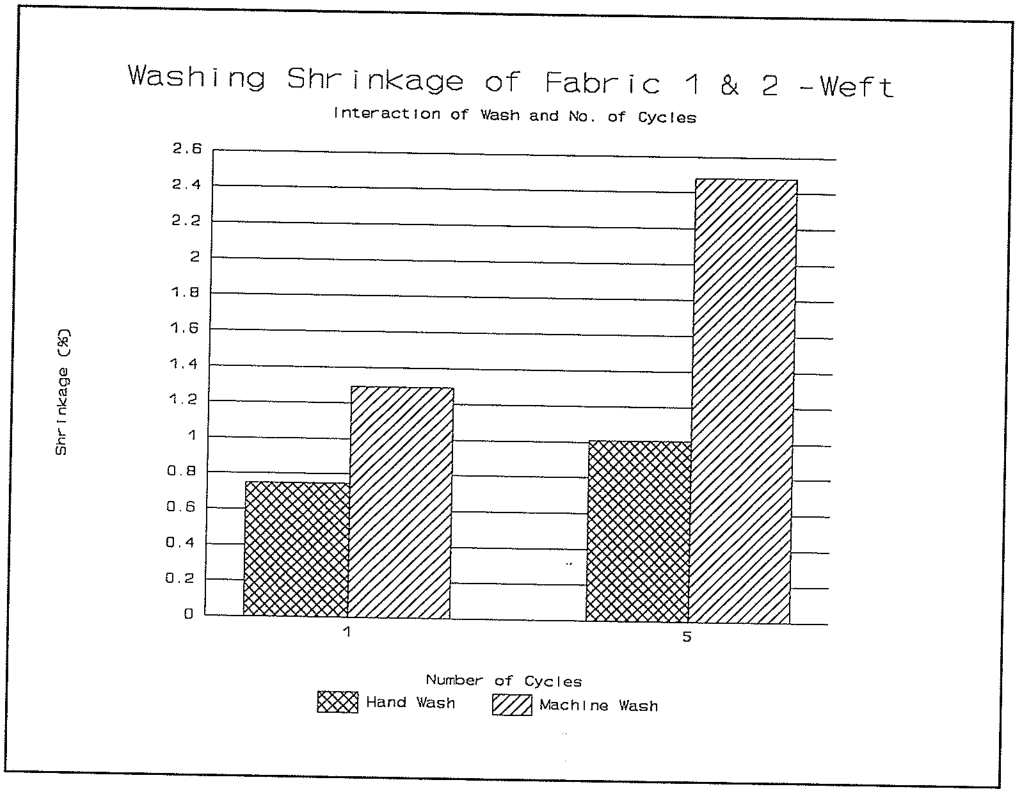


Figure 41. Interaction of washing method & No. of washes.

Figure 35 presents how the washing method affected the weft shrinkage, and it can be easily seen that machine washing resulted in greater shrinkage than hand washing. Figure 36 illustrates how the number of laundering cycles affected the weft shrinkage, and shows that after 5 cycles the fabric specimens had greater shrinkage than after 1 cycle. Figure 37 shows the considerable effect of the fabric type on the weft shrinkage. The shrinkage in the 60/40 cotton/Tencel fabric was very low, while that in the 100% Tencel fabric was high, reaching levels in excess of 2%.

Figure 38 illustrates the interaction of the number of laundering cycles and the type of fabric on the weft shrinkage. while the choice of the 100% Tencel fabric and 5 rather than 1 cycle contributed consistently to higher shrinkage levels, the shrinkage the of 60/40 cotton/Tencel fabric was always low (i.e., less than 1% even after 5 cycles). The two way interaction of washing and drying methods is presented in Figure 39. The shrinkage behaviour was similar to that found in Figure 7. Figure 40 illustrates the two way interaction of washing method and the type of fabric. The weft shrinkage of the 60/40 cotton/Tencel fabric was low after either machine or hand washing, whereas the 100% Tencel fabric exhibited high shrinkage levels, especially after machine washing when they reached 3.1%. Figure 41 shows the two way interaction of washing method and number of laundering cycles both of which have a significant effect on the weft shrinkage. After 1 cycle, the shrinkage was low regardless of the washing method, while after 5 cycles, the hand washing shrinkage was still low (about 1%), while machine washing had resulted in a high shrinkage of about 2.5%.

From observed results, the fibre content in one direction has a significant effect on the shrinkage in other direction. This supports Ukponwan's (1990) previous study. Therefore, Ho_3 is rejected.

4.5 Discussion of the Significant Effects on Shrinkage

From the previous full factorial analyses of individual fabrics, and the 2 fabric comparisons, the independent variables which have had significant effects on the shrinkage in the warp and weft directions are summarized and listed in Tables 30 and 31 respectively.

Table 30
Significant Effects on Warp Shrinkage

Tencel	Cotton/Tencel	Cotton	Cotton/Tencel vs Cotton
			F
W	W	W	W
		D	D
W*D	W*D	W*D	W*D
N	N	N	N
W*N	W*N	W*N	W*N
	D*N	D*N	D*N
	W*D*N		
	W*T*N		

Table 31
Significant Effects on Weft Shrinkage

Tencel	Cotton/Tencel	Cotton	Cotton/Tencel vs Tencel
			F
W	W	W	W
			W*F
W*D			W*D
N	N	N	N
			N*F
W*N	W*N	W*N	W*N

From Tables 30 and 31, it can be seen that the washing method and the number of laundering cycles had main effects and caused interactions on the shrinkage of each fabric in both warp and weft directions, as well as on the shrinkage of two fabrics compared together. This indicates that the washing method and the number of laundering cycles are the two most important independent variables in controlling the shrinkage level during laundering and means that when selecting care labels, the washing method has to be considered very carefully. The significance of the number of laundering cycles indicates that progressive shrinkage plays a dominant role on the behaviour of these three fabrics.

In addition, in the warp direction, the drying method had a marginal ($p = 0.0448$) main effect on the shrinkage of the 100% cotton fabric, but not on the 100% Tencel or the cotton/Tencel blend fabrics. When the cotton/Tencel blend and 100% cotton fabrics were analyzed together, this main effect also occurred. Further more, the drying method interacted with the washing method for all three fabrics, and with the number of cycles for the cotton/Tencel blend and the 100% cotton fabric, but not the 100% Tencel fabric. When the warp direction of the cotton/Tencel blend and 100% cotton fabric were compared, this interaction was unexpectedly observed again.

In addition, the washing method and the number of cycles were involved together in two 3 way interaction in the warp shrinkage of only the cotton/Tencel blend fabric. One of these 3 way interactions with the drying method was quite significant ($p = 0.0001$), whereas the one with temperature, which was not involved in any main effects was quite marginal ($p = 0.0242$).

The type of fabric had a main effect on the warp shrinkage when Fabrics 2 and 3 were compared, but it did not interact with any other independent variable. A possible explanation for this is that the warp shrinkage of these two fabrics are quite similar.

In addition, in the weft direction, the drying method had an interaction with the washing method for the 100% Tencel fabric and when the 100% Tencel and cotton/Tencel blend fabrics were compared. On account of the much higher weft shrinkage observed for the 100% Tencel fabric than with the cotton/Tencel blend fabric, it is to be expected that when they were compared, the type of fabric would appear as a main effect. In addition, it was found that this two fabric comparison identified 2 way interactions between the type of fabric and the washing method and the number of cycles.

4.6 Shrinkage after Enzyme Finishing

Before enzyme finishing (Clark, 1992), 5 pairs of marks 60 cm apart were made on the two fabrics with Tencel content, i.e. Fabrics 1 and 2 in both directions. The marks were measured again after enzyme finishing. The shrinkage that occurred during enzyme finishing was then calculated for each fabric in each direction, and the results are listed in Table 32.

Table 32
Shrinkage during Enzyme Finishing

Shrinkage	Fabric 1		Fabric 2	
	Warp	Weft	Warp	Weft
Mean (%)	0.93	2.42	2.78	1.14
Standard Deviation	0.57	0.43	0.33	0.19

After enzyme finishing, Fabrics 1 and 2 were laundered using the 8 machine washing conditions which had yielded the highest laundering shrinkages during the previous experiments, i.e. Treatments 9 - 16. The mean values and standard deviations of laundering shrinkage were calculated by the SAS program (SAS, 1985). The results are listed in Table 33. For comparison purposes, the laundering shrinkages of Fabrics 1 and 2 without enzyme finishing are also listed in Table 33.

Table 33

Laundering Shrinkage Comparison before and after Enzyme Finishing (%)

Treatment		Shrinkage before Enzyme Finishing				Shrinkage after Enzyme Finishing			
		Fabric 1		Fabric 2		Fabric 1		Fabric 2	
		Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
9	Mean (%)	1.93	2.53	2.13	0.49	1.44	1.22	1.53	0.36
	Std Dev	0.33	0.43	0.21	0.25	0.57	0.40	0.23	0.32
10	Mean (%)	3.56	4.16	4.66	1.08	1.72	1.53	2.34	0.20
	Std Dev	0.61	0.42	0.30	0.41	0.65	0.45	0.21	0.12
11	Mean (%)	0.92	2.04	1.56	0.12	1.28	1.16	1.78	0.77
	Std Dev	0.54	0.35	0.29	0.19	0.20	0.30	0.30	0.28
12	Mean (%)	3.13	4.30	3.89	1.23	2.23	1.71	2.94	0.90
	Std Dev	0.81	0.71	0.19	0.60	0.50	0.23	0.55	0.27
13	Mean (%)	1.58	2.43	2.22	0.33	1.33	1.39	1.84	0.67
	Std Dev	0.50	0.55	0.16	0.29	0.44	0.42	0.49	0.32
14	Mean (%)	2.92	4.09	4.39	1.13	1.43	1.64	2.29	0.60
	Std Dev	0.49	0.55	0.37	0.35	0.69	0.45	0.53	0.26
15	Mean (%)	1.21	2.12	2.01	0.23	1.32	0.96	1.37	0.34
	Std Dev	0.45	0.42	0.20	0.35	0.38	0.27	0.45	0.12
16	Mean (%)	2.66	3.11	4.03	0.72	2.10	1.38	2.92	0.54
	Std Dev	0.58	0.42	0.32	0.59	0.60	0.35	0.52	0.26

From Table 33, it is evident that the level of warp and weft shrinkage was usually smaller after enzyme finishing than before. Student t-tests were performed to determine if the observed difference in laundering shrinkage before and after enzyme finishing were significant or not. Each pair of shrinkage data was tested according to the following formula:

$$|t| = \frac{|\overline{X_1} - \overline{X_2}|}{\sqrt{\frac{S_1^2 + S_2^2}{n}}} \qquad \text{Degrees of freedom} = 2n - 2$$

Where $\overline{X}$ = the mean shrinkage value.

S = standard deviation of shrinkage.

n = the number of measurements.

The t-test results were converted to p values and listed in Table 34.

Table 34
<u>Test of Significance in Shrinkage Change</u>

Treatment and (Condition)	p Value of Fabric 1 Warp	p Value of Fabric 1 Weft	p Value of Fabric 2 Warp	p Value of Fabric 2 Weft
9(20, F, 1)	0.0401	< 0.0001	< 0.0001	0.3450
10(20, F, 5)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
11(20, T, 1)	0.0845[I]	< 0.0001	0.1278[I]	< 0.0001[I]
12(20, T, 5)	0.0121	< 0.0001	0.0002	0.1457
13(40, F, 1)	0.2914	0.0003	0.0435	0.0335[I]
14(40, F, 5)	0.0001	< 0.0001	< 0.0001	0.0021
15(40, T, 1)	0.5773[I]	< 0.0001	0.0012	0.3826[I]
16(40, T, 5)	0.0629	< 0.0001	0.0001	0.4211

Note. The significance level is 0.05. [I] means that the mean fabric shrinkage was higher after enzyme finishing rather than before.

From Table 34, it can be seen that for the 100% Tencel fabric, Fabric 1, all the weft shrinkages are significantly difference and lower after enzyme finishing compared with before. In the warp direction, shrinkages after enzyme finishing, however, significantly lower occurred usually only after 5 cycles of machine washing and not after 1 cycle. the one exception was found with Treatment 16 where the p value was marginal at 0.0629.

From the previous results with no enzyme finishing, the weft shrinkage of the 100% Tencel fabric was surprisingly greater than the warp shrinkage. It appears that after enzyme finishing this fabrics became much more stabilized, because the level of weft shrinkage was significantly reduced. In fact the weft shrinkage fell to such a low level, that in all but 2 cases (Treatments 13 and 14), it was now lower than the amount observed in the warp direction (Table 33).

A similar stabilizing effect was observed in the warp direction of the cotton/Tencel blend fabric, Fabric 2. In all cases except Treatment 11, the warp shrinkage was significantly as a result of enzyme finishing. This means that the relatively high level of shrinkage of the cotton warp yarns in Fabric 2 which were on average 1.98% and 4.24% for 1 and 5 cycles respectively, were reduced to more acceptable levels (1.63% and 2.62% respectively) as a result of including an enzyme finishing step.

The weft shrinkage of Fabric 2 was found to be low both before and after enzyme finishing. With the average shrinkage value falling from 0.67% before enzyme finishing to 0.55% after, it is believed that these values are too small for enzyme finishing to have any significant effect. It should to remembered that the estimated experimental error associated with making any one shrinkage measurement was ± 0.5%.

If the observed level of shrinkage that occurred during enzyme finishing is added to the observed laundering shrinkage after enzyme finishing (Tables 32 and 34), then the total calculated shrinkage has been found to be invariably higher than the laundering shrinkage without enzyme finishing. This could be interpreted to mean that the shrinkage level reached after 5 cycles of laundering treatment was not the shrinkage limit, but this is not necessarily the case, since the temperature and agitation conditions during enzyme finishing were more severe than any of the 16 experimental laundering conditions used in this study.

4.7 Full Factorial Analysis after Enzyme Finishing

The laundering conditions of fabric specimens exposed to enzyme finishing are listed in Table 5 (Chapter 3). With these 8 treatments, there were 3 independent variables: washing temperature (T), drying method (D), and number of laundering cycles (N), each with two levels. In addition 2 other independent variables were also included: enzyme finishing (Z) and the type of fabric (F), each again with 2 levels.

Therefore a full factorial analysis was performed using these 5 independent variables in a SAS program (SAS, 1985)(Appendix 4) in order to determine which variables had significant influences on the dependent variable: warp or weft shrinkage. The significance level was again maintained at $p \leq 0.05$.

4.7.1 Full Factorial Analysis of Warp Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

A full factorial analysis method was undertaken to investigate the effect of enzyme finishing on the laundering shrinkage of Fabrics 1 and 2 in the warp direction. The results are listed in Table 35. From Table 35, it can be seen that the variables F, Z, Z*F, D*Z, N, N*F, N*Z, and D*N had a significant influence on the level of shrinkage. Since the effect of laundering conditions, such as drying and number of cycles, and the type of fabric have already been discussed in a previous section of this chapter, they will not be discussed again here. Only the enzyme finishing (Z) and the independent variables which interacted with the enzyme finishing will be discussed. Their mean values were calculated using the SAS program, and the results are shown in Table 36.

Table 35

Full Factorial Analysis of Variance

Warp Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

Source	Type III MS	Denominator MS	F Value	p Value
F	34.1689	0.5317	64.268	0.0001
Z	47.6939	0.5317	89.706	0.0001
Z*F	2.4200	0.5317	4.552	0.0367
T	0.4835	0.5317	0.909	0.3439
T*F	1.1501	0.5317	2.163	0.1462
T*Z	0.0113	0.5317	0.021	0.8848
T*Z*F	0.3901	0.5317	0.734	0.3948
D	0.9800	0.5317	1.843	0.1793
D*F	0.0200	0.5317	0.038	0.8468
D*Z	10.4272	0.5317	19.612	0.0001
D*Z*F	0.0006	0.5317	0.001	0.9743
T*D	0.3335	0.5317	0.627	0.4313
T*D*F	0.3613	0.5317	0.679	0.4128
T*D*Z	1.2013	0.5317	2.259	0.1377
T*D*Z*F	0.3335	0.5317	0.627	0.4313
N	131.7606	0.5317	247.825	0.0001
N*F	4.9089	0.5317	9.233	0.0034
N*Z	26.4022	0.5317	49.659	0.0001
N*Z*F	0.1250	0.5317	0.235	0.6294
T*N	1.0513	0.5317	1.977	0.1645
T*N*F	0.2112	0.5317	0.397	0.5307
T*N*Z	0.6235	0.5317	1.173	0.2829
T*N*Z*F	0.0035	0.5317	0.007	0.9358
D*N	3.0422	0.5317	5.722	0.0197
D*N*F	0.1800	0.5317	0.339	0.5627
D*N*Z	1.8689	0.5317	3.515	0.0654
D*N*Z*F	0.4356	0.5317	0.819	0.3688
T*D*N	0.0113	0.5317	0.021	0.8848
T*D*N*F	0.3901	0.5317	0.734	0.3948
T*D*N*Z	0.3335	0.5317	0.627	0.4313
T*D*N*Z*F	0.0035	0.5317	0.007	0.9358
I	0.5317	0.1047	5.080	0.0001

Table 36

Effects and Interactions of Independent Variables
Warp Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

Level of Variables		Number of measurements	Mean Value of Shrinkage (%)
	Z		
	E	144	1.86
	O	144	2.68
Z	F		
E	1	72	1.61
E	2	72	2.11
O	1	72	2.24
O	2	72	3.11
D	Z		
F	E	72	1.73
F	O	72	2.92
T	E	72	1.99
T	O	72	2.43
N	Z		
1	E	72	1.49
1	O	72	1.70
5	E	72	2.23
5	O	72	3.65

Note. E: After enzyme finishing, O: No enzyme finishing.

In order to clarify these effects, bar diagrams have been drawn in Figures 42 - 45 to illustrate the data in Table 36. Figure 42 shows the main effect of enzyme finishing. On average the warp shrinkage of Fabrics 1 and 2 fell from a level of about 2.7% without enzyme finishing to less than 2% after enzyme finishing. Figure 43 illustrates the interaction of enzyme finishing with the type of fabric. In general, Fabric 2 had a higher warp shrinkage than Fabric 1, and after enzyme finishing, not only did the shrinkage level of both fabrics decrease, but the cotton warp in Fabric 2 shrank more than the Tencel warp in Fabric 1.

Figure 44 shows the interaction of enzyme finishing with the drying method. After enzyme finishing, tumble drying had slightly higher warp shrinkage than drying flat. Whereas without enzyme finishing, the opposite was observed. An explanation for this unexpected shrinkage behaviour was given previously when discussing the meaning of Figure 7. Figure 45 illustrates the interaction of enzyme finishing and the number of laundering cycles. Regardless of the enzyme finishing, the warp shrinkage was always greater after cycles than 1 cycle. However this difference of about 2% without enzyme finishing was reduced to only about 0.7% after enzyme finishing.

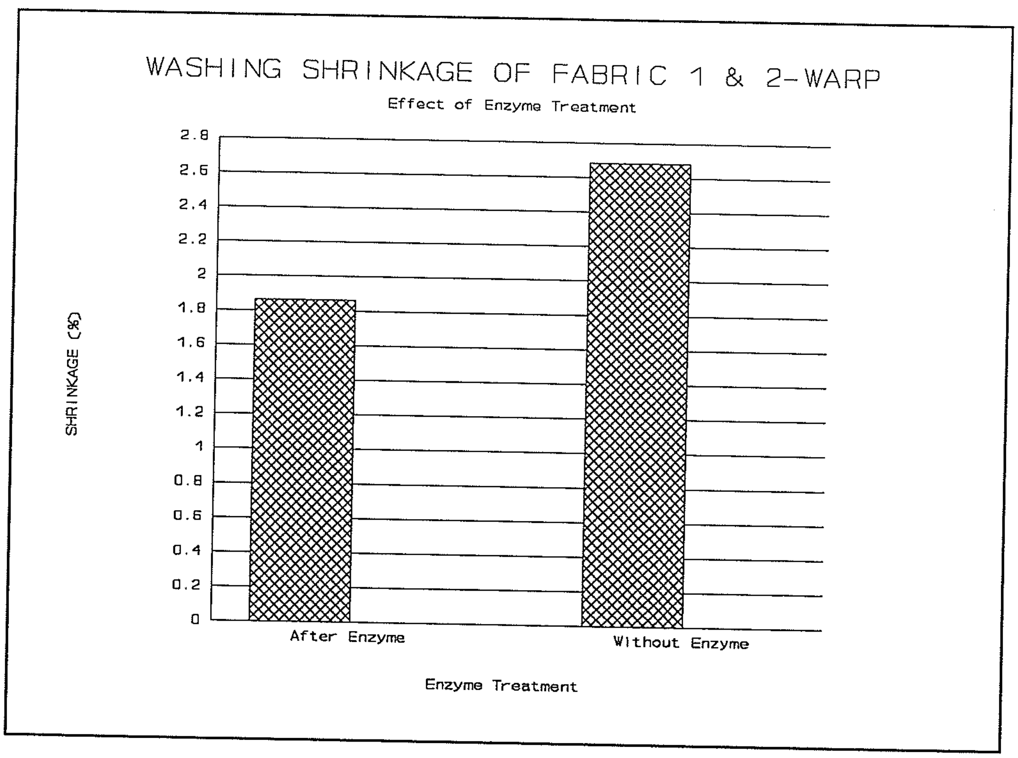
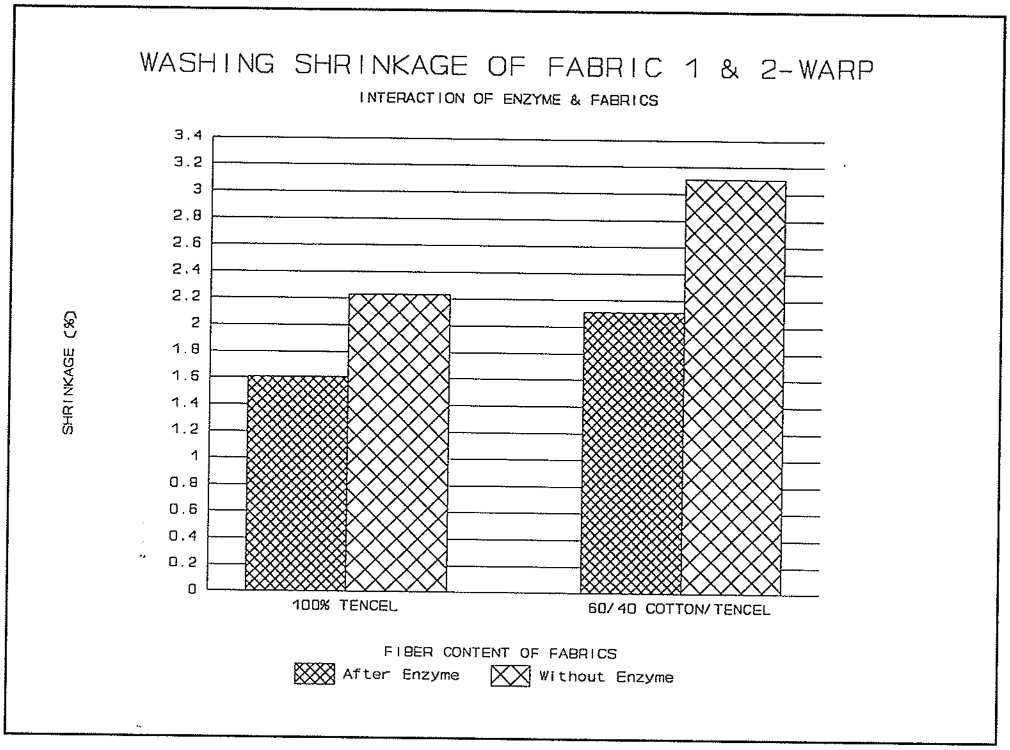
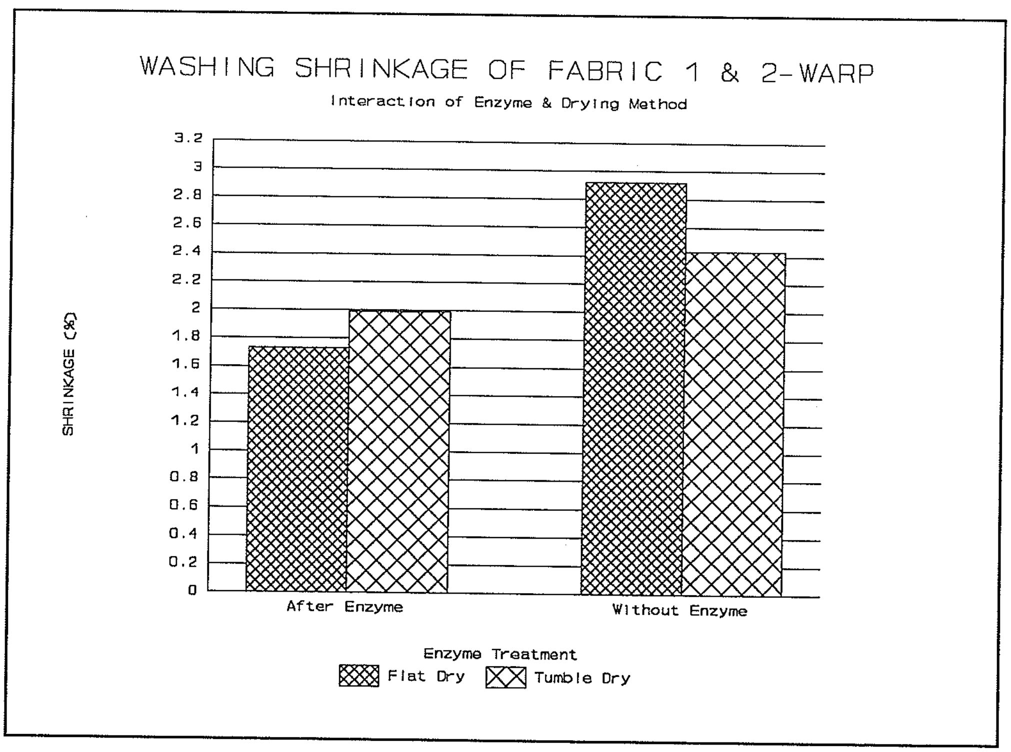


Figure 42. Effect of enzyme finishing.



<u>Figure 43.</u> Interaction of enzyme finishing and type of fabric.



<u>Figure 44.</u> Interaction of drying method and enzyme finishing.

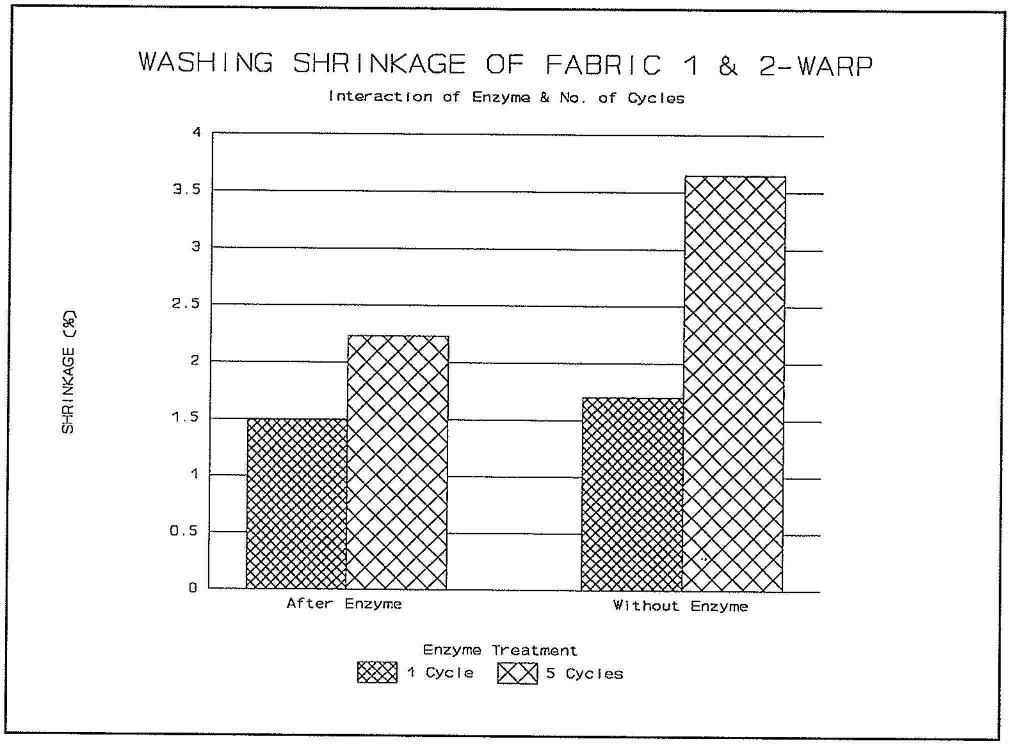


Figure 45. Interaction of No. of cycles and enzyme finishing.

4.7.2 Full Factorial Analysis of Weft Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

The same statistical method was used to investigate the effect of enzyme finishing on the weft shrinkage of Fabrics 1 and 2 as was described previously for the warp direction. The statistical results are listed in Table 37, where it can be seen that the variables F, Z, Z*F, T*D, N, N*F, and N*Z had a significant influence on the level of weft shrinkage. Since the effects of the laundering conditions and the type of fabric have already been discussed in a previous section of this chapter, they will not be discussed again here. Only the effect of the enzyme finishing (Z) and the independent variables which interacted with the enzyme finishing i.e. Z, Z*F, and N*Z will be discussed. Their mean shrinkage values were calculated by the SAS program, and the results are shown in Table 38.

Table 37
Full Factorial Analysis of Variance
Weft Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

Source	Type III MS	Denominator MS	F Value	p Value
F	190.9384	0.4798	397.932	0.0001
Z	61.3278	0.4798	127.813	0.0001
Z*F	46.3203	0.4798	96.536	0.0001
T	1.2403	0.4798	2.585	0.1128
T*F	0.2628	0.4798	0.548	0.4620
T*Z	0.5959	0.4798	1.242	0.2693
T*Z*F	0.0975	0.4798	0.203	0.6536
D	1.3750	0.4798	2.866	0.0953
D*F	1.4028	0.4798	2.924	0.0921
D*Z	1.7578	0.4798	3.663	0.0601
D*Z*F	0.0475	0.4798	0.099	0.7540
T*D	3.5334	0.4798	7.364	0.0085
T*D*F	0.0003	0.4798	0.001	0.9797
T*D*Z	0.3134	0.4798	0.653	0.4220
T*D*Z*F	0.4917	0.4798	1.025	0.3152
N	35.0703	0.4798	73.090	0.0001
N*F	6.9378	0.4798	14.459	0.0003
N*Z	17.3559	0.4798	36.171	0.0001
N*Z*F	1.2403	0.4798	2.585	0.1128
T*N	0.7917	0.4798	1.650	0.2036
T*N*F	0.3828	0.4798	0.798	0.3751
T*N*Z	0.7300	0.4798	1.521	0.2219
T*N*Z*F	0.0642	0.4798	0.134	0.7157
D*N	0.3684	0.4798	0.768	0.3842
D*N*F	0.0425	0.4798	0.089	0.7669
D*N*Z	0.1750	0.4798	0.365	0.5480
D*N*Z*F	0.0028	0.4798	0.006	0.9392
T*D*N	1.4028	0.4798	2.924	0.0921
T*D*N*F	0.0767	0.4798	0.160	0.6906
T*D*N*Z	1.1628	0.4798	2.423	0.1245
T*D*N*Z*F	0.0475	0.4798	0.099	0.7540
I	0.4798	0.0417	11.506	0.0001

Table 38
Effects and Interactions of Independent Variables
Weft Shrinkage of Fabrics 1 and 2 after Enzyme Finishing

Level of Variables			Number of Measurements	Mean Value of Shrinkage (%)
	Z			
	E		144	0.96
	O		144	1.88
Z		F		
E		1	72	1.37
E		2	72	0.55
O		1	72	3.10
O		2	72	0.67
N		Z		
1		E	72	0.86
1		O	72	1.29
5		E	72	1.06
5		O	72	2.48

The bar diagrams in Figures 46 - 48 have been drawn to illustrate the data in Table 38. Figure 46 shows the main effect of enzyme finishing. Similar to the findings in the warp direction, the level of weft shrinkage was reduced significantly to a level of below 1% as a result of enzyme finishing. Figure 47 illustrates the interaction of the enzyme finishing with the type of fabric. Unlike the results observed in the warp direction, the Tencel weft in Fabric 1 was invariably associated with much higher shrinkage level than that in Fabric 2. However, as observed previously, the effect of enzyme finishing was to reduce the level of weft shrinkage of both fabrics, and this reduction was felt to a much greater effect by Fabric 1 than by Fabric 2. Figure 48 illustrates the interaction of enzyme finishing and the number of laundering cycles. With or without enzyme finishing, the weft shrinkage was always higher after 5 cycles, while after enzyme finishing, the level of shrinkage fell for both 1 and 5. The much lower weft shrinkage after 5 cycles suggested that enzyme finishing does provided significant stabilization to both types of fabrics.

From observed results, the data provide sufficient evidence that enzyme finishing has significantly reduced the fabric shrinkage and stabilized the fabric dimension. Therefore, Ho_4 is rejected. It is worth noting that since the enzyme treated samples were washed at a different time from the non-enzyme treated samples, there remains a possibility that the rejection of this hypothesis is due to the non-totally randomized design.

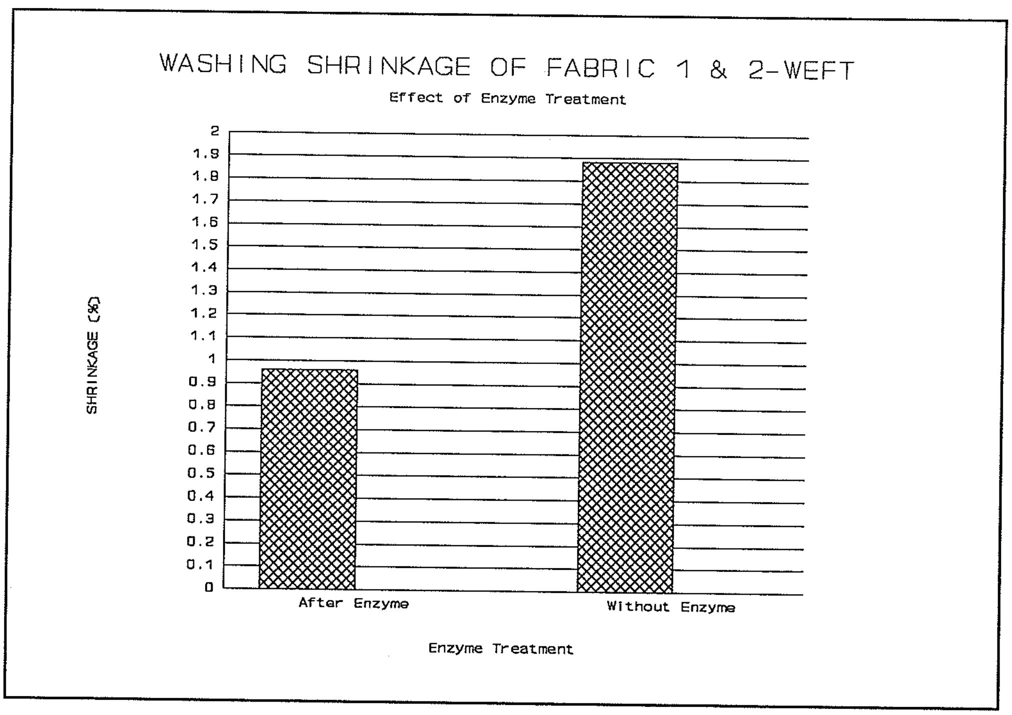


Figure 46. Effect of enzyme finishing.

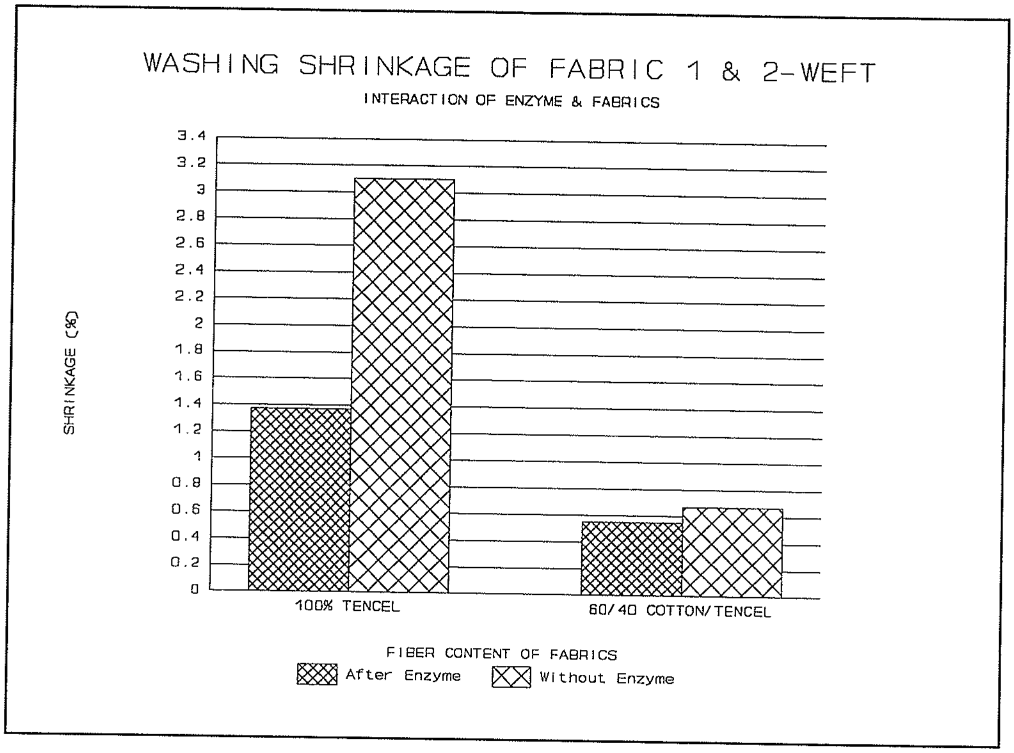


Figure 47. Interaction of enzyme finishing and type of fabric.

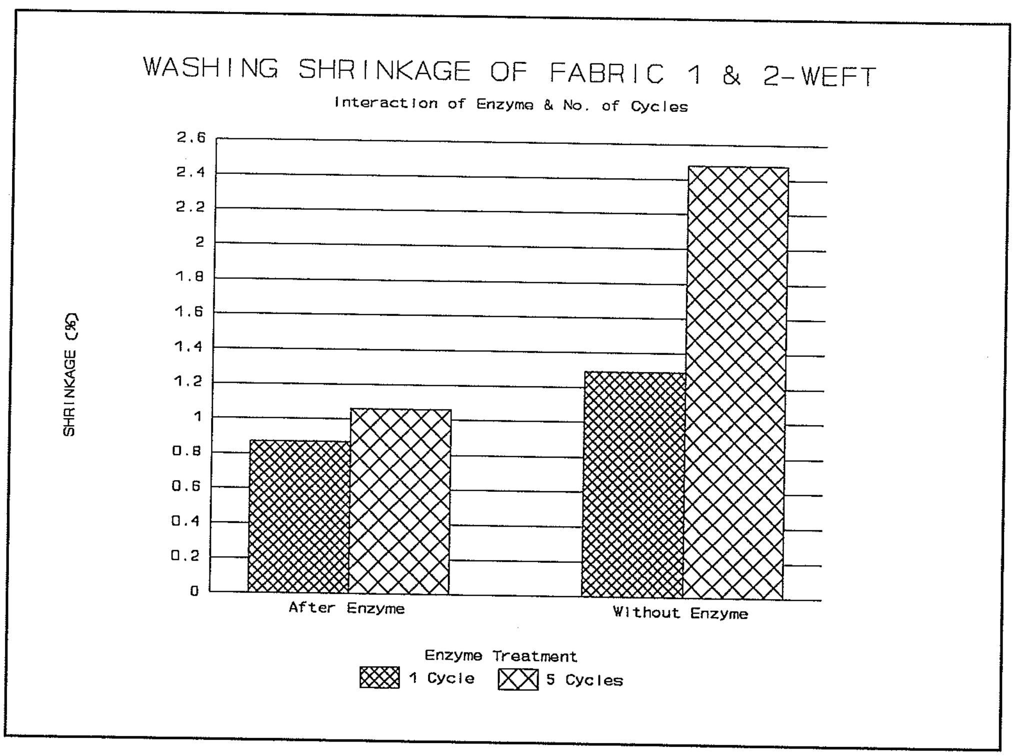


Figure 48. Interaction of No. of cycles and enzyme finishing.

4.8 Results of Changes in Geometric Structure

4.8.1 Change in Geometric Structure due to Laundering and Enzyme Finishing

With a view to investigating the changes in geometric structure of the fabrics due to laundering, those specimens from each of the 3 fabric types which possessed the highest average shrinkage after laundering were selected for cross-sectioning and geometric analysis. From the previous results in the study Treatment 12 was found to have the highest average shrinkage. Also, to determine the effect of enzyme finishing on the geometric structure, additional fabric specimens were selected after enzyme finishing and after both enzyme finishing and Treatment 12. The plan for selecting these specimens for cross-sectioning is presented in Table 7 except that Treatment X was replaced by Treatment 12.

The inter-yarn distance and crimp height of the cross sections were measured, and their mean values and standard deviations were calculated. The results are listed in Table 39. To compare the geometric parameters before and after laundering or enzyme finishing or both, student t tests were used, and the results after converting to p values are listed in Table 40.

From Table 40, it can be seen that all of the mean inter-yarn distances in both directions decreased as a result of the laundering treatment, enzyme finishing, or both. This result was expected because fabric shrinkage results in a more

Table 39
Measurements of Geometric Structure (mm)

Treatment	Fabric Type	Direction	Inter-yarn Distance Mean	Inter-yarn Distance SD	Crimp Height Mean	Crimp Height SD
Before Laundering	Fabric 1	Warp	1.041	0.018	0.252	0.030
		Weft	0.851	0.033	0.297	0.026
	Fabric 2	Warp	1.127	0.041	0.308	0.016
		Weft	0.871	0.023	0.300	0.014
	Fabric 3	Warp	1.124	0.054	0.267	0.025
		Weft	0.817	0.038	0.318	0.030
After Treatment 12	Fabric 1	Warp	1.001	0.028	0.274	0.037
		Weft	0.825	0.033	0.320	0.032
	Fabric 2	Warp	1.090	0.045	0.205	0.025
		Weft	0.858	0.046	0.288	0.028
	Fabric 3	Warp	1.078	0.048	0.253	0.016
		Weft	0.801	0.030	0.357	0.021
After Enzyme Finishing	Fabric 1	Warp	1.017	0.022	0.242	0.018
		Weft	0.822	0.027	0.306	0.022
	Fabric 2	Warp	1.097	0.014	0.265	0.021
		Weft	0.864	0.033	0.295	0.022
After Enzyme Finishing and Treatment 12	Fabric 1	Warp	0.996	0.026	0.250	0.026
		Weft	0.803	0.010	0.303	0.024
	Fabric 2	Warp	1.071	0.037	0.231	0.031
		Weft	0.851	0.029	0.290	0.025

Note. SD: Standard Deviation.

compact fabric with closer yarn distance. However, some of the measured mean crimp heights increased while others decreased. This phenomenon can be explained when the warp and weft crimp heights of the same fabric change in opposite directions, because the sum of the two is a constant if the diameter of the 2 yarns remains constant (Peirce, 1937).

Table 40

Test of Significance of Geometric Parameters (p Value)

Comparison		Fabric 1 Warp	Fabric 1 Weft	Fabric 2 Warp	Fabric 2 Weft	Fabric 3 Warp	Fabric 3 Weft
Before & After Treatment 12	ID	< 0.0001	0.0168	0.0105	0.2795	0.0066	0.1327
	CH	0.0384[I]	0.0148[I]	< 0.0001	0.1120	0.0471	0.0002[I]
Before & After Enzyme Finishing	ID	0.0005	0.0039	0.0027	0.4457		
	CH	0.2359	0.2558[I]	0.0000	0.3996		
After Enzyme Finishing & Enzyme Plus Treatment 12	ID	0.0099	0.0059	0.0053	0.1769		
	CH	0.2610[I]	0.6900	0.0002	0.5643		

Note. The significance level is 0.05. All p value refer to decrease in geometric distances after treatments unless indicated with an [I] which indicates an increase. ID is inter-yarn distance, and CH is crimp height.

All of the warp and weft inter-yarn distances of the 100% Tencel fabric, Fabric 1 became significantly smaller as a result of the laundering treatment, enzyme finishing, or both treatments. The only significant change in crimp height occurred due to the laundering treatment, when both warp and weft crimp heights were observed to increase. This was not anticipated, and may have been due to changes in yarn structure, fibre migration and possibly changes in yarn diameter during the laundering treatment.

The only significant changes in inter-yarn distance and crimp height for the cotton/Tencel blend fabric, Fabric 2 were observed in the warp direction. Significant decreases in both geometric parameters were recorded after all 3 treatments, which confirm that there was significant shrinkage of the cotton warp yarns, but not by the Tencel yarns in the weft direction.

A similar finding was made in the geometric structure of the all cotton fabric, Fabric 3, as a result of laundering by Treatment 12. Significant decreases in warp inter-yarn distance and crimp height were observed which accompanied by a increase in weft crimp height. Theoretically, the sum of the warp and weft crimp heights should be a constant, so that an increase in crimp height in one direction will result in a decrease in the other direction (Pierce, 1937). From the observations in Table 40, the behaviour of Fabric 3 agrees well with this theory.

If either the inter-yarn distances or the crimp heights in Table 40 have a p value smaller than 0.05, then the hypotheses will be rejected. Therefore, Ho_5A, Ho_5B and Ho_5C are rejected except for Fabric 2 in the weft direction.

4.8.2 Comparison of Shrinkage Measurements with Changes in Inter-yarn Distance

By comparing the observed inter-yarn distances before and after the different treatments from Table 39, it can be seen that this geometric parameter decreases in both directions after Treatment 12. This means that the distance between the individual yarns became smaller by the difference between L_0 and L_1 (See Figure 49).

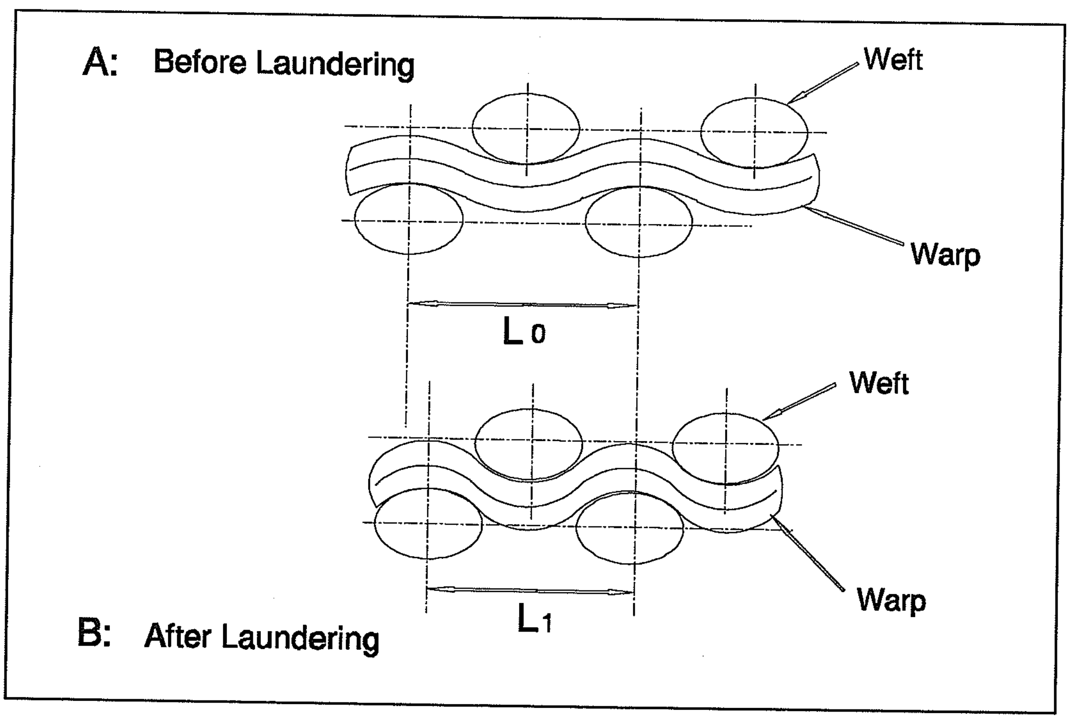


Figure 49. Analysis of geometric structure.

Fabric shrinkage can also be calculated from the changes in inter-yarn distance according to following formula:

$$\text{Shrinkage} = (L_0 - L_1)/L_0 \times 100\%$$

In other words, a value for warp and weft shrinkage can also be obtained from the changes in inter-yarn distance. Such calculated values for shrinkage were calculated after enzyme finishing and both laundering and enzyme finishing in the same way. The results are listed in Table 41. For comparison purposes, the mean warp and weft shrinkage results measured directly on the fabric specimens are also listed in Table 41.

Table 41

Shrinkage Values Calculated from Inter-yarn Distances and From Fabric Specimen Measurements

Treatment	Specimen		Calculated by ID	Measured on FS
After Treatment 12	Fabric 1	Warp	3.84	3.13
		Weft	3.03	4.30
	Fabric 2	Warp	3.27	3.89
		Weft	1.46	1.23
	Fabric 3	Warp	4.13	5.09
		Weft	2.02	1.36
After Enzyme Finishing and Treatment 12	Fabric 1	Warp	2.05	2.23
		Weft	2.30	1.71
	Fabric 2	Warp	2.39	2.94
		Weft	1.56	0.90

Note. ID: Inter-yarn Distance, FS: Fabric Specimen.

From Table 41, it can be seen that the shrinkage values calculated from inter-yarn distance are close to those measured directly on the fabric specimens. To test this relationship, a regression model was used by means of a SAS program (SAS, 1985). It was assumed that the shrinkage calculated from inter-yarn distance measurements was the independent variable, X, and the shrinkage measured directly from the fabric specimens was the dependent variable, Y. The results of the analysis of variance are presented in Table 42, and Figure 50.

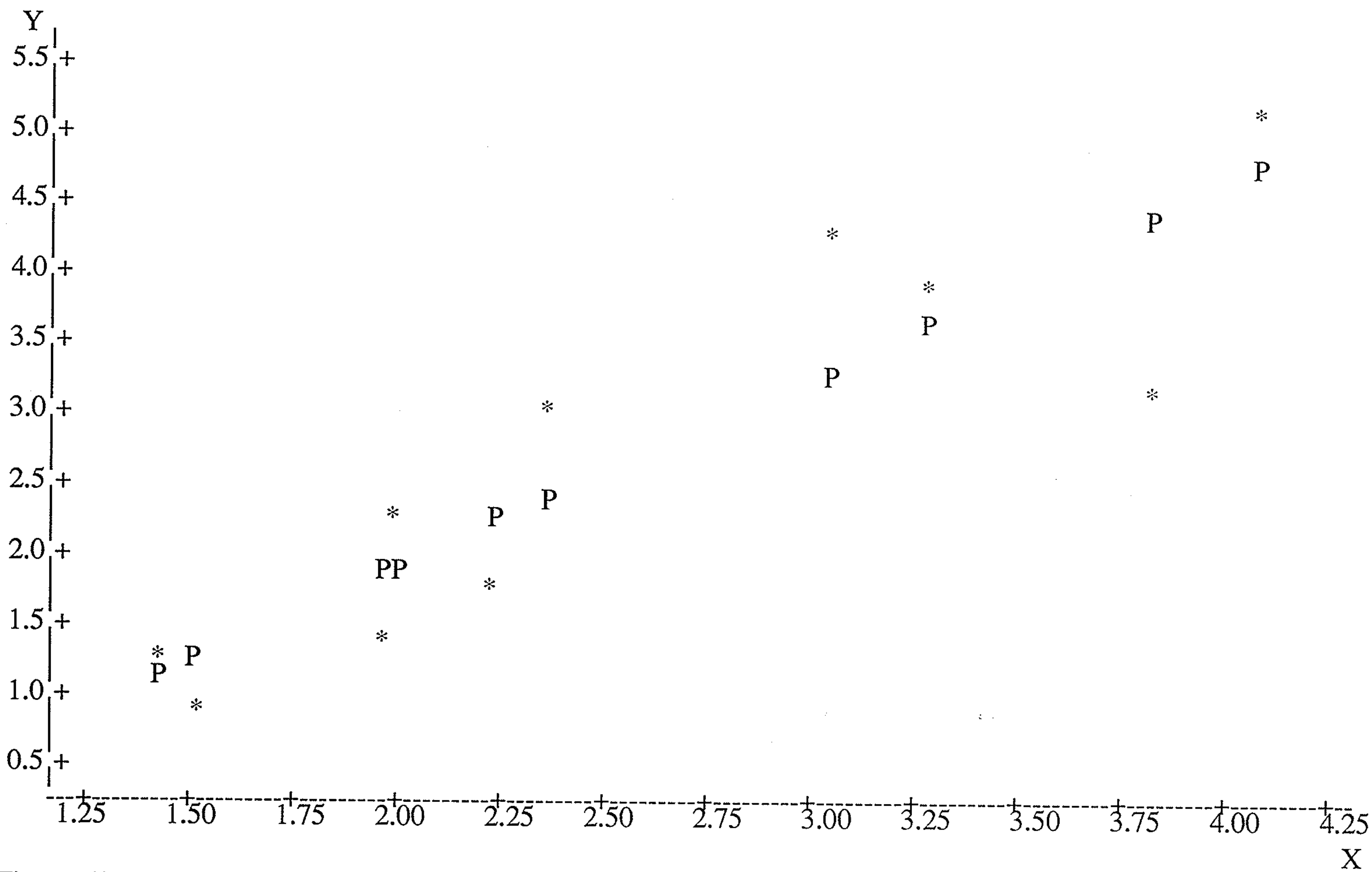
Table 42
Regression Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	p Value
Model	1	14.4198	14.4198	29.592	0.0006
Error	8	3.8983	0.4872		
R-square		0.7872			

Note. DF = Degrees of Freedom.

The results in Table 42 shows that the relationship between the two sets of data is strong, with 79% of the variability in Y explained by the linear regression of Y on X. Such a finding supports the conclusion that both experimental methods have validity in measuring the shrinkage characteristics of woven fabrics.

The p value for linear regression is 0.006. Therefore, there is sufficient evidence to reject Ho_6.



<u>Figure 50.</u> Shrinkage relationship between geometric parameter and fabric specimen after laundering.
<u>Note.</u> Y: Shrinkage measured from fabric specimens.
X: Shrinkage calculated from the change of inter-yarn distance.
"P" is the predicted shrinkage value.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions and Implications of Laundering Conditions

From the results of this study, the following conclusions are made. The level of observed shrinkage varied from 0 to 5% depending on the type of fabric, the fabric direction, and the laundering condition. Therefore, the rejection of Hypothesis 1 depends on the type of fabric, the fabric direction and the laundering condition. In this study, Ho_1 is rejected on the following types of fabric, fabric directions and laundering conditions:

Fabric 1: after 5 cycles of machine washing in both directions, after 1 cycle of machine washing and drying flat in the weft direction;

Fabric 2: after 5 cycles of hand washing and tumble drying, one cycle of machine washing and drying flat, 5 cycles of machine washing in the warp direction only;

Fabric 3: after 1 cycle of machine washing and drying flat, after 5 cycles of hand washing or machine washing in the warp direction only.

In the warp direction, the 100% cotton fabric had more shrinkage than the blend, which had more shrinkage than the 100% Tencel fabric, which agrees with Clark's (1992) finding that Tencel fabrics have low shrinkage. The shrinkage result of this study in the warp direction may apply to other Tencel and Tencel blended fabrics. For confirmation, more Tencel and Tencel intimated blend fabrics need to be tested. Whereas in the weft direction, the reverse was found, with the 100% Tencel fabric shrinking much more than the other two fabrics. It is believed that this unexpected finding is due to rearrangements in the yarn and fabric structure during laundering.

The washing method and the number of laundering cycles have a significant effect on the shrinkage of all fabrics in each direction (Tables 30 and 31). Machine washing causes a significantly higher shrinkage than hand washing, which implies that the agitation and/or detergent and/or cool pressing involved during machine washing has a major effect on increasing the level of observed shrinkage. Therefore, when selecting appropriate care labels, the washing method has to be carefully chosen, because a different washing method will result in significantly different shrinkages.

The shrinkages after 5 cycles of laundering are significantly higher than after 1 cycle. This difference in shrinkage between 1 cycle and 5 cycles is caused by progressive shrinkage. This type of shrinkage has a significant effect on the amount of shrinkage experienced by all three fabrics both in the warp and weft directions (Tables 30 and 31).

The drying method has only a marginal main effect on the warp shrinkage of the 100% cotton fabric and no effect on the other two fabrics. Nevertheless, it does have some interaction with the washing method on the shrinkage of all three fabrics in the warp direction, and with the 100% Tencel fabric in the weft direction. This implies that when the washing method is being selected for a care label, the drying method must also be specified, because the different drying methods result in significantly different shrinkage levels when different washing methods are used.

The washing temperature does not have a significant effect on the level of shrinkage of any of the three fabrics. So when care labels are selected, the specified temperature can be either 20 ^{0}C or 40 ^{0}C.

It is therefore concluded that while Ho_2A, Ho_2C and Ho_2D are rejected, Ho_2B cannot be rejected.

With respect to Hypothesis 3, it was observed that the fibre content in one direction has a significant effect on the amount of shrinkage in the other direction. This supports Ukponmwan's previous study (Ukponmwan, 1990). Therefore, Ho_3 is rejected.

At the same time, the amount of yarn crimp does not appear to have a direct effect on the level of observed shrinkage.

5.2 Conclusions on the Effect of Enzyme Finishing

Enzyme finishing has a significant effect on the level of shrinkage of the lyocell and lyocell blended fabrics. Both fabrics have a significantly lower amount of shrinkage after enzyme finishing than before. For example, before enzyme finishing the average warp shrinkages of Fabrics 1 and 2 increases by about 2% between 1 and 5 cycles of laundering, whereas after enzyme finishing, the increases are reduced to only about 0.8% (Table 36). Similarly in the weft direction, the average increase in shrinkage for Fabrics 1 and 2 is about 1.2% between the first and fifth cycles without enzyme finishing, whereas this figure is reduced to only 0.2% after including an enzyme finishing treatment (Table 38). This means that the enzyme finishing process significantly improves the dimensional stability of lyocell and lyocell blended fabrics. Therefore it is concluded that Ho_4 is rejected.

5.3 Conclusions on Change in Geometric Structure

When the level of fabric shrinkage is high after laundering, there is also a significant reduction in the observed inter-yarn distance. And when the amount of shrinkage is low, no significant changes in inter-yarn distance are observed. In fact the theoretical shrinkage calculated from changes in inter-yarn distance has been shown to be closely related to the shrinkage measured directly on the fabric specimens (Figure 50, Table 42).

Most of the changes in crimp height measured on the fabrics in this study followed a similar pattern to the changes in inter-yarn distance. And in most cases the warp and weft crimp heights were found to be dependent on each other. However when laundering the 100% Tencel fabric under the most severe conditions the warp and weft crimp height were observed to be independent of each other, suggesting that changes in yarn diameter were having a confounding effect. To thoroughly understand such changes in crimp height, more experiments need to be done so that the contribution caused by fibre migration and changes in yarn diameter during the laundering treatments can be measured. The rejection of Hypothesis 5 depends on the type of fabric, fabric direction and laundering conditions under consideration. In this study, Ho_5A, Ho_5B and Ho_5C are rejected except for Fabric 2 in the weft direction.

5.4 Conclusion of Comparison of Shrinkage Measurements with Changes in Inter-yarn Distance

The observed changes in inter-yarn distance were closely correlated with the measured fabric shrinkage results, with 79% of the variability in measured fabric shrinkage explained by the linear regression of the measured fabric shrinkage on changes in inter-yarn distance. Therefore, there is sufficient evidence to demonstrate a linear dependence relationship between the shrinkage measured from fabric specimens and the shrinkage calculated from the changes in inter-yarn distance. Ho_6 is rejected. Such a finding supports the fact that both experimental methods have validity in measuring the shrinkage characteristics of woven fabrics.

5.5 Recommendations

5.5.1 Recommendations for Care Labels

From the results of this study which measured the mean shrinkage values of 16 different laundering treatments, the following care labels can be recommended for the three fabric samples:

Hand washing is recommended for the 100% Tencel fabric. The choice of washing temperature between 20 ^{0}C and 40 ^{0}C and the choice of drying method between tumble drying and drying flat are optional for this care label.

Since hand washing and tumble drying resulted in an unacceptable level of shrinkage for the 60/40 cotton/Tencel fabric (2.9% after 5 cycles)(Table 12), hand washing with drying flat are the recommended care instruction. Again the washing temperature can be specified at either 20 ^{0}C or 40 ^{0}C.

The laundering shrinkage of the 100% cotton fabric is not acceptable when either machine washing and/or tumble drying are involved (Table 12). Therefore, preshrinkage treatments may be required for this particular fabric.

5.5.2 Recommendation for Future Study

In the event that this study is repeated, it is recommended that the fabric specimens before and after enzyme finishing all be laundered at the same time, so that the effect of time can be eliminated. Also, the ironing procedure of fabric specimens after laundering should be more strictly controlled. It is suggested that every fabric specimen should be ironed in the same way; otherwise, the ironing procedure should be considered as an independent variable.

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APPENDICES

Appendix 1

Quantitative Analysis of Cotton/Lyocell Blend Fabric

Zinc Chloride/Formic Acid Method (CAN/CGSB-4.2-M88, Method 14.4)

Three specimens were tested. The finish (starch) on the fabric was not removed. After dissolving Tencel by Zinc Chloride/Formic Acid. The cotton is left. The percentage of residue weight of cotton is:

Percentage	1	2	3	Average
Cotton (%)	52.18	51.65	51.90	51.91

Note. The correction factor is not added.

The starch weight in the fabric will certainly affect the percentage of cotton, so it is necessary to remove starch (AATCC 20A - 1989).

The procedure of removing starch is : Immerse the dried specimen in 100 times its weight of 0.1 N HCl at 80 ^{0}C for 25 minutes, stirring occasionally. Rinse thoroughly with hot water and dry at 105 ^{0}C to constant weight. Two specimens were tested. The results are listed below:

Specimen	Before Treatment	After Treatment	Starch Weight	Starch (%)
1	4.3499 (g)	4.0075 (g)	0.3424 (g)	7.87
2	1.7496 (g)	1.6152 (g)	0.1344 (g)	7.68
Average				7.775

Note. All weight is dry weight.

Considering the starch weight, the above tested percentage of cotton must be adjusted:

Adjusted cotton (%) is: Cotton (%) x 1/(1-starch(%))

= 51.91 x 1/(1-0.07775) = 56.29 (%).

After removing the finish, three specimens were again tested to determine the percentage of cotton. The procedure is the same with the specimens without removing the finish. The results is:

Cotton Weight (%)	1	2	3	Average
Residue Cotton (%)	56.74	55.04	55.64	55.807

Note. The correction factor is not added.

Further Research on Correction Factor of Cotton/Tencel Blended

Fabric

The correction factor for cotton/Tencel blended fabric is unknown. To determine this correction factor, more quantitative analysis are required. The outline of test can be designed like this: First prepare the pre-determined different blend level of cotton/Tencel fabrics, such as 30% cotton/70% Tencel, 40% cotton/60% Tencel, etc. then use zinc chloride / formic acid to perform the quantitative analysis. The difference between pre-determine percentage and tested percentage of cotton fibre will be the correction factor.

Appendix 2
SAS PROGRAM 1

Full Factorial Analysis for
100% Tencel Fabric - Warp

```
comment
          Washing Shrinkage - Warp
          100% Tencel Fabric
;
DATA WARPSHRK;
  INPUT W T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARP @;
    OUTPUT;
    END;
  END;
CARDS;
-1 -1 -1 -1 3.2 2.9 1.9 2.3 2.8 3.4 2.7 3.0 1.7
-1 -1 -1 1  1.2 1.2 0.5 0.8 1.2 1.3 1.0 1.7 2.0
-1 -1 1  -1 2.6 3.0 2.7 3.2 3.7 3.6 2.3 2.7 2.5
-1 -1 1  1  1.5 1.5 0.8 0.8 1.5 2.0 2.0 2.1 2.0
-1 1  -1 -1 1.8 2.2 2.5 3.5 4.0 2.9 3.5 3.9 3.9
-1 1  -1 1  0.5 1.0 1.0 1.5 1.5 0.3 0.0 1.1 1.4
-1 1  1  -1 4.2 4.4 4.2 3.6 3.7 2.9 3.0 3.2 2.8
-1 1  1  1  2.0 2.0 1.6 2.1 2.5 2.2 1.4 1.9 1.7
1  -1 -1 -1 1.0 1.0 0.4 1.3 2.2 2.6 0.8 1.5 1.2
1  -1 -1 1  1.0 1.0 1.4 0.5 0.0 0.0 0.2 1.1 1.3
1  -1 1  -1 1.4 1.7 1.4 0.5 0.7 0.6 0.0 0.0 0.0
1  -1 1  1  0.0 0.6 1.3 0.3 0.7 0.8 0.2 0.6 0.3
1  1  -1 -1 0.8 0.9 0.2 0.1 0.7 1.2 0.8 1.0 1.0
1  1  -1 1  1.3 1.3 1.0 0.0 0.1 0.2 0.3 0.2 0.0
1  1  1  -1 1.5 1.5 1.7 1.0 1.5 1.2 0.6 0.5 0.0
1  1  1  1  0.3 0.4 1.0 0.5 0.7 0.5 0.2 0.0 0.0
;
PROC PRINT DATA=WARPSHRK;
  TITLE1'100% Tencel Washing Shrinkage - Warp';
  TITLE2'-----------------------------------';
  TITLE3' ';
PROC SORT;
BY W T D N;
PROC MEANS MEAN STD STDERR;
BY W T D N;
VAR WARP;
PROC GLM;
   CLASS W T D N I;
   MODEL WARP=W|T|D|N I(W*T*D*N);
   RANDOM I(W*T*D*N)/TEST;
MEANS W*N W N;
```

Appendix 3

SAS PROGRAM 2

Full Factorial Analysis for Fabric 2 and 3 - Warp

```
comment
          Washing Shrinkage - Warp

          Fabric 2 and 3
;
DATA WARP2;
FABRIC=2;
  INPUT W T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
-1 -1 -1 -1 4.2 4.0 3.8 3.9 4.2 3.7 3.7 4.7 4.1
-1 -1 -1 1  2.2 2.2 2.0 1.7 2.1 1.8 2.1 2.2 1.8
-1 -1 1  -1 4.2 4.1 4.0 4.5 4.4 4.0 4.4 5.1 4.8
-1 -1 1  1  2.2 2.5 2.3 2.2 2.0 2.3 2.2 2.0 2.3
-1 1  -1 -1 3.9 4.3 3.7 4.0 3.7 3.8 3.8 4.0 3.8
-1 1  -1 1  1.5 1.3 1.1 1.5 1.7 1.5 1.5 1.8 2.1
-1 1  1  -1 4.5 4.8 4.5 4.5 5.2 5.0 4.4 4.7 4.3
-1 1  1  1  2.3 2.0 2.3 2.0 2.1 1.7 2.3 2.3 2.2
1  -1 -1 -1 3.0 3.1 3.1 2.1 2.8 2.5 2.7 3.6 2.8
1  -1 -1 1  0.7 0.7 0.6 1.4 1.6 1.3 0.5 0.6 0.8
1  -1 1  -1 2.0 2.2 1.8 1.5 1.5 1.5 2.0 2.5 2.1
1  -1 1  1  0.0 0.5 0.3 0.3 0.7 0.7 1.1 0.8 0.8
1  1  -1 -1 2.5 3.0 2.7 2.3 3.0 2.5 3.4 3.6 2.8
1  1  -1 1  0.5 1.5 1.0 0.6 1.0 1.2 0.7 1.3 1.2
1  1  1  -1 1.2 1.5 1.3 1.5 1.5 1.3 1.5 1.5 1.5
1  1  1  1  0.3 0.8 0.3 0.7 0.9 0.6 1.6 1.0 1.4
;
DATA WARP3;
```

```
FABRIC=3;
  INPUT W T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
-1 -1 -1 -1 5.2 5.5 5.1 5.3 5.3 5.6 4.4 4.9 4.5
-1 -1 -1 1  2.6 2.9 2.7 1.7 2.2 2.3 1.8 2.1 1.5
-1 -1 1  -1 4.8 5.0 5.0 4.3 4.2 4.1 5.7 5.6 5.6
-1 -1 1  1  3.0 2.5 2.5 2.7 2.6 3.0 3.5 3.6 3.2
-1 1  -1 -1 4.7 5.4 4.7 4.3 4.6 4.8 5.7 6.0 5.6
-1 1  -1 1  0.4 1.0 0.8 2.6 3.6 2.7 2.8 3.2 2.8
-1 1  1  -1 3.3 3.1 3.0 5.3 5.9 5.4 5.7 6.3 5.5
-1 1  1  1  3.0 3.0 3.0 2.2 2.3 2.3 3.6 3.6 3.6
1  -1 -1 -1 3.3 3.9 2.8 4.0 4.6 4.2 4.7 5.2 4.5
1  -1 -1 1  2.0 1.6 1.7 2.0 2.6 2.1 2.8 3.1 2.5
1  -1 1  -1 2.7 2.9 3.0 2.4 2.5 2.1 2.5 3.0 2.5
1  -1 1  1  0.8 0.4 0.3 1.2 1.4 1.3 1.8 1.9 1.3
1  1  -1 -1 3.2 4.1 3.2 4.2 4.6 4.3 4.2 4.5 4.0
1  1  -1 1  2.3 2.3 2.5 1.7 2.3 2.3 1.8 1.3 1.6
1  1  1  -1 2.3 2.5 2.5 3.3 3.3 3.2 1.7 2.0 1.9
1  1  1  1  0.7 1.3 1.3 2.0 2.0 2.0 1.7 2.0 1.7
;
  TITLE1'Washing Shrinkage of Fabric 2 and 3 - Warp';
  TITLE2'---------------------------------------';
  TITLE3' ';
DATA ALL;
SET WARP2 WARP3;
PROC GLM;
   CLASS W T D N I FABRIC;
   MODEL WARPSHRK=FABRIC|W|T|D|N I(FABRIC*W*T*D*N);
   RANDOM I(FABRIC*W*T*D*N)/TEST;
MEANS FABRIC W N D W*D W*N D*N;
```

Appendix 4

SAS PROGRAM 3

Full Factorial Analysis for Fabric 1 and 2 - Warp
Effect of Enzyme Treatment on Shrinkage

```
comment
        Washing Shrinkage of Fabric 1 and 2 - Warp
        Before and after Enzyme Treatment
;
DATA WARP1;
FABRIC=1;
  INPUT Z T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
-1 -1 -1 -1 3.2 2.9 1.9 2.3 2.8 3.4 2.7 3.0 1.7
-1 -1 -1 1  1.2 1.2 0.5 0.8 1.2 1.3 1.0 1.7 2.0
-1 -1 1  -1 2.6 3.0 2.7 3.2 3.7 3.6 2.3 2.7 2.5
-1 -1 1  1  1.5 1.5 0.8 0.8 1.5 2.0 2.0 2.1 2.0
-1 1  -1 -1 1.8 2.2 2.5 3.5 4.0 2.9 3.5 3.9 3.9
-1 1  -1 1  0.5 1.0 1.0 1.5 1.5 0.3 0.0 1.1 1.4
-1 1  1  -1 4.2 4.4 4.2 3.6 3.7 2.9 3.0 3.2 2.8
-1 1  1  1  2.0 2.0 1.6 2.1 2.5 2.2 1.4 1.9 1.7
;
DATA WARP2;
FABRIC=2;
  INPUT Z T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
-1 -1 -1 -1 4.2 4.0 3.8 3.9 4.2 3.7 3.7 4.7 4.1
-1 -1 -1 1  2.2 2.2 2.0 1.7 2.1 1.8 2.1 2.2 1.8
-1 -1 1  -1 4.2 4.1 4.0 4.5 4.4 4.0 4.4 5.1 4.8
-1 -1 1  1  2.2 2.5 2.3 2.2 2.0 2.3 2.2 2.0 2.3
-1 1  -1 -1 3.9 4.3 3.7 4.0 3.7 3.8 3.8 4.0 3.8
-1 1  -1 1  1.5 1.3 1.1 1.5 1.7 1.5 1.5 1.8 2.1
-1 1  1  -1 4.5 4.8 4.5 4.5 5.2 5.0 4.4 4.7 4.3
-1 1  1  1  2.3 2.0 2.3 2.0 2.1 1.7 2.3 2.3 2.2
;
```

```
DATA WARP3;
FABRIC=1;
  INPUT Z T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
1 1 1 1   1.2 0.8 0.8 2.0 2.2 2.2 1.3 1.5 1.0
1 1 1 -1  1.2 1.0 1.0 2.5 2.7 2.1 1.2 2.0 1.8
1 1 -1 1  1.0 1.2 1.0 1.5 1.6 1.3 1.2 1.3 1.4
1 1 -1 -1 1.6 1.8 1.5 2.5 3.0 2.5 2.3 2.3 2.6
1 -1 1 1  1.2 1.2 0.8 1.0 1.0 1.1 1.9 1.8 2.0
1 -1 1 -1 1.1 1.1 0.5 1.2 0.8 1.3 2.2 2.3 2.4
1 -1 -1 1 1.0 1.6 1.1 1.2 1.0 1.0 1.2 1.8 2.0
1 -1 -1 -1 1.5 2.6 1.5 1.5 2.0 1.7 3.1 2.7 2.3
;
DATA WARP4;
FABRIC=2;
  INPUT Z T D N @;
  DO I=1 TO 3;
    DO J=1 TO 3;
    INPUT WARPSHRK @;
    OUTPUT;
    END;
  END;
CARDS;
1 1 1 1   1.8 1.3 1.6 1.2 1.5 1.5 1.8 1.8 1.3
1 1 1 -1  2.2 2.4 2.0 2.5 2.2 1.6 2.2 2.6 2.4
1 1 -1 1  1.3 1.7 1.6 1.9 2.0 1.6 2.0 2.3 1.6
1 1 -1 -1 3.2 3.7 2.9 2.8 2.1 2.2 2.9 3.6 3.1
1 -1 1 1  1.2 1.5 1.4 1.8 1.9 1.5 2.6 2.4 2.3
1 -1 1 -1 1.8 1.9 1.7 2.0 2.3 2.2 2.5 3.2 3.0
1 -1 -1 1 1.0 1.4 1.1 1.8 1.7 0.6 2.0 1.6 1.1
1 -1 -1 -1 2.0 2.8 2.5 3.2 3.3 2.7 3.4 3.7 2.7
;
  TITLE1'Washing Shrinkage of Fabric 1 and 2 - Warp';
  TITLE2' Before and after Enzyme Treatment  ';
  TITLE3' ---------------------------------';
DATA ALL;
SET WARP1 WARP2 WARP3 WARP4;
PROC GLM;
   CLASS T D N I Z FABRIC;
   MODEL WARPSHRK=FABRIC|Z|T|D|N I(FABRIC*Z*T*D*N);
   RANDOM I(FABRIC*Z*T*D*N)/TEST;
 MEANS FABRIC Z N Z*FABRIC D*Z N*FABRIC N*Z D*N;
```

Appendix 5

Shrinkage Data of 3 Fabrics after Laundering Treatments

Shrinkage Data of 100% Tencel Fabric after 16 Treatments

Treatment		Single			Duplicate			Triplicate		
1	Warp	0.3	0.4	1.0	0.5	0.7	0.5	0.2	0	0
	Weft	1.2	1.1	1.2	1.4	1.5	1.5	1.8	2.2	2.3
2	Warp	1.5	1.5	1.7	1.0	1.5	1.2	0.6	0.5	0
	Weft	2.3	2.2	2.1	1.7	1.8	1.8	0.7	0.8	0.7
3	Warp	1.3	1.3	1.0	0	0.1	0.2	0.3	0.2	0
	Weft	2.2	2.5	2.5	0.9	1.1	0.8	0.4	1.6	1.2
4	Warp	0.8	0.9	0.2	0.1	0.7	1.2	0.8	1.0	1.0
	Weft	1.5	1.8	1.4	1.8	2.0	1.9	2.4	2.6	2.5
5	Warp	0	0.6	1.3	0.3	0.7	0.8	0.2	0.6	0.3
	Weft	0.8	0.6	0.8	1.2	1.5	1.3	1.3	1.3	1.3
6	Warp	1.4	1.7	1.4	0.5	0.7	0.6	0	0	0
	Weft	2.6	2.5	2.0	0.7	1.0	0.9	0.6	0.4	0.3
7	Warp	1.0	1.0	1.4	0.5	0	0	0.2	1.1	1.3
	Weft	1.8	1.9	2.0	0.8	1.0	0.8	1.0	1.5	1.0
8	Warp	1.0	1.0	0.4	1.3	2.2	2.6	0.8	1.5	1.2
	Weft	1.7	2.0	1.5	2.5	2.4	2.3	2.6	2.7	2.7
9	Warp	2.0	2.0	1.6	2.1	2.5	2.2	1.4	1.9	1.7
	Weft	2.0	2.2	2.4	3.2	3.0	3.0	2.5	2.2	2.3
10	Warp	4.2	4.4	4.2	3.6	3.7	2.9	3.0	3.2	2.8
	Weft	4.5	4.7	4.6	3.7	4.0	3.6	3.8	4.5	4.0
11	Warp	0.5	1.0	1.0	1.5	1.5	0.3	0	1.1	1.4
	Weft	2.4	2.7	2.2	1.9	2.0	1.6	2.0	2.0	1.6
12	Warp	1.8	2.2	2.5	3.5	4.0	2.9	3.5	3.9	3.9
	Weft	3.2	3.7	3.4	4.7	5.0	4.4	4.5	5.2	4.6
13	Warp	1.5	1.5	0.8	0.8	1.5	2.0	2.0	2.1	2.0
	Weft	2.2	2.2	2.2	1.8	2.2	1.9	3.3	3.1	3.0
14	Warp	2.6	3.0	2.7	3.2	3.7	3.6	2.3	2.7	2.5
	Weft	4.6	5.0	4.8	3.7	3.9	3.8	3.7	3.7	3.6
15	Warp	1.2	1.2	0.5	0.8	1.2	1.3	1.0	1.7	2.0
	Weft	2.5	2.5	2.4	2.5	1.5	2.4	1.8	1.9	1.6
16	Warp	3.2	2.9	1.9	2.3	2.8	3.4	2.7	3.0	1.7
	Weft	3.0	4.0	3.4	2.8	3.2	2.9	3.0	3.2	2.5

Shrinkage Data of 60/40 Cotton/Tencel Fabric after 16 Treatments

Treatment		Single			Duplicate			Triplicate		
1	Warp	0.3	0.8	0.3	0.7	0.9	0.6	1.6	1.0	1.4
	Weft	0	0	0	0	0	0	0.8	0.5	0.5
2	Warp	1.2	1.5	1.3	1.5	1.5	1.3	1.5	1.5	1.5
	Weft	0.8	0.8	0.8	0.5	0.4	0.4	0	0	0
3	Warp	0.5	1.5	1.0	0.6	1.0	1.2	0.7	1.3	1.2
	Weft	0.3	0.2	0.5	0	0	0	0	0	0
4	Warp	2.5	3.0	2.7	2.3	3.0	2.5	3.4	3.6	2.8
	Weft	0	0	0	0	0	0	0.9	0.8	0.8
5	Warp	0	0.5	0.3	0.3	0.7	0.7	1.1	0.8	0.8
	Weft	0	0	0	0.1	0	0	0.1	0	0.4
6	Warp	2.0	2.2	1.8	1.5	1.5	1.5	2.0	2.5	2.1
	Weft	0.7	0.4	0.5	0.3	0.2	0	0	0	0
7	Warp	0.7	0.7	0.6	1.4	1.6	1.3	0.5	0.6	0.8
	Weft	0.4	0.5	0.3	0	0	0	0	0	0
8	Warp	3.0	3.1	3.1	2.1	2.8	2.5	2.7	3.6	2.8
	Weft	0	0	0	0	0	0	0.3	0.5	0.3
9	Warp	2.3	2.0	2.3	2.0	2.1	1.7	2.3	2.3	2.2
	Weft	0.2	0.3	0.6	0.7	0.7	0.9	0.5	0.2	0.3
10	Warp	4.5	4.8	4.5	4.5	5.2	5.0	4.4	4.7	4.3
	Weft	1.2	1.2	1.0	0.7	0.6	0.5	1.3	1.6	1.6
11	Warp	1.5	1.3	1.1	1.5	1.7	1.5	1.5	1.8	2.1
	Weft	0.3	0.5	0.3	0	0	0	0	0	0
12	Warp	3.9	4.3	3.7	4.0	3.7	3.8	3.8	4.0	3.8
	Weft	1.5	1.7	1.7	0.6	0.6	0.2	1.5	1.8	1.5
13	Warp	2.2	2.5	2.3	2.2	2.0	2.3	2.2	2.0	2.3
	Weft	0	0	0	0.6	0.6	0.7	0.4	0.2	0.5
14	Warp	4.2	4.1	4.0	4.5	4.4	4.0	4.4	5.1	4.8
	Weft	1.4	1.3	1.5	1.2	1.2	1.5	0.8	0.7	0.6
15	Warp	2.0	2.2	2.2	1.7	2.1	1.8	2.1	2.2	1.8
	Weft	0.7	0.7	0.7	0	0	0	0	0	0
16	Warp	4.2	4.0	3.8	3.9	4.2	3.7	3.7	4.7	4.1
	Weft	0.9	0.8	0.6	0	0.2	0	1.5	1.6	0.9

Shrinkage Data of 100% Cotton Fabric after 16 Treatment

Treatment		Single			Duplicate			Triplicate		
1	Warp	0.7	1.3	1.3	2.0	2.0	2.0	1.7	2.0	1.7
	Weft	0	0	0	0	0	0	0.2	0.1	0
2	Warp	2.3	2.5	2.5	3.3	3.3	3.2	1.7	2.0	1.9
	Weft	0	0	0	0	0	0	0	0	0
3	Warp	2.3	2.3	2.5	1.7	2.3	2.3	1.8	1.3	1.6
	Weft	0	0.3	0.1	0	0	0	0	0	0
4	Warp	3.2	4.1	3.2	4.2	4.6	4.3	4.2	4.5	4.0
	Weft	0	0.2	0	0	0	0	0.2	0.6	0.2
5	Warp	0.8	0.4	0.3	1.2	1.4	1.3	1.8	1.9	1.3
	Weft	0	0	0	0	0	0	0	0	0
6	Warp	2.7	2.9	3.0	2.4	2.5	2.1	2.5	3.0	2.5
	Weft	0.2	0.3	0.3	0	0	0	0	0	0
7	Warp	2.0	1.6	1.7	2.0	2.6	2.1	2.8	3.1	2.5
	Weft	0	0	0	0	0	0	0	0	0
8	Warp	3.3	3.9	2.8	4.0	4.6	4.2	4.7	5.2	4.5
	Weft	0	0	0	0	0	0	0	0.3	0.3
9	Warp	3.0	3.0	3.0	2.2	2.3	2.3	3.6	3.6	3.6
	Weft	0.6	0.7	0.7	0	0.4	0	0	0.3	0.2
10	Warp	3.3	3.1	3.0	5.3	5.9	5.4	5.7	6.3	5.5
	Weft	2.0	2.2	2.2	1.0	1.2	0.9	0.9	1.0	0.8
11	Warp	0.4	1.0	0.8	2.6	3.6	2.7	2.8	3.2	2.8
	Weft	0	0.1	0	0	0	0	0	0	0
12	Warp	4.7	5.4	4.7	4.3	4.6	4.8	5.7	6.0	5.6
	Weft	0.8	1.2	1.0	0.5	0.8	0.4	2.2	2.7	2.6
13	Warp	3.0	2.5	2.5	2.7	2.6	3.0	3.5	3.6	3.2
	Weft	0	0.2	0	0.5	0.4	0.3	0.5	0.3	0.5
14	Warp	4.8	5.0	5.0	4.3	4.2	4.1	5.7	5.6	5.6
	Weft	2.0	2.2	1.7	0.9	1.2	0.6	0.7	1.0	1.2
15	Warp	2.6	2.9	2.7	1.7	2.2	2.3	1.8	2.1	1.5
	Weft	0	0.4	0.2	0	0	0	0	0	0
16	Warp	5.2	5.5	5.1	5.3	5.3	5.6	4.4	4.9	4.5
	Weft	0.5	0.7	0.7	1.0	1.5	1.2	2.0	1.6	1.4

Shrinkage Data of 100% Tencel Fabric after Enzyme Finishing and after 8 Machine Wash Treatments

Treatment		Single			Duplicate			Triplicate		
9	Warp	1.2	0.8	0.8	2.0	2.2	2.2	1.3	1.5	1.0
	Weft	1.5	1.0	1.0	1.7	1.7	1.6	1.0	0.8	0.7
10	Warp	1.2	1.0	1.0	2.5	2.7	2.1	1.2	2.0	1.8
	Weft	1.5	1.0	0.9	2.2	1.7	2.1	1.7	1.5	1.2
11	Warp	1.0	1.2	1.0	1.5	1.6	1.3	1.2	1.3	1.4
	Weft	1.7	1.3	1.2	1.2	1.3	1.2	0.8	0.7	1.0
12	Warp	1.6	1.8	1.5	2.5	3.0	2.5	2.3	2.3	2.6
	Weft	2.0	1.5	1.6	1.6	2.1	1.8	1.5	1.8	1.5
13	Warp	1.2	1.2	0.8	1.0	1.0	1.1	1.9	1.8	2.0
	Weft	1.2	1.2	1.2	1.2	0.7	1.5	2.1	1.9	1.5
14	Warp	1.1	1.1	0.5	1.2	0.8	1.3	2.2	2.3	2.4
	Weft	1.3	1.2	1.3	1.7	1.2	1.5	2.3	2.2	2.1
15	Warp	1.0	1.6	1.1	1.2	1.0	1.0	1.2	1.8	2.0
	Weft	1.2	1.0	0.7	0.6	0.6	0.9	1.1	1.2	1.3
16	Warp	1.5	2.6	1.5	1.5	2.0	1.7	3.1	2.7	2.3
	Weft	1.2	1.2	1.2	1.1	0.9	1.5	1.5	1.8	2.0

Shrinkage Data of 60/40 Cotton/Tencel Fabric after Enzyme Finishing and after 8 Machine Wash Treatments

Treatment		Single			Duplicate			Triplicate		
9	Warp	1.8	1.3	1.6	1.2	1.5	1.5	1.8	1.8	1.3
	Weft	0.2	0.3	0.2	0.8	0.8	0.7	0.2	0	0
10	Warp	2.2	2.4	2.0	2.5	2.2	1.6	2.2	2.6	2.4
	Weft	0.2	0.3	0.2	0.1	0.3	0.4	0.2	0.1	0
11	Warp	1.3	1.7	1.6	1.9	2.0	1.6	2.0	2.3	1.6
	Weft	0.5	0.8	0.5	1.0	1.2	1.1	0.5	0.8	0.5
12	Warp	3.2	3.7	2.9	2.8	2.1	2.2	2.9	3.6	3.1
	Weft	0.7	1.0	1.0	0.8	1.0	0.8	0.6	1.5	0.7
13	Warp	1.2	1.5	1.4	1.8	1.9	1.5	2.6	2.4	2.3
	Weft	0.3	0.3	0.3	0.7	0.7	0.7	0.8	1.2	1.0
14	Warp	1.8	1.9	1.7	2.0	2.3	2.2	2.5	3.2	3.0
	Weft	0.2	0.5	0.2	0.9	0.8	0.8	0.5	0.8	0.7
15	Warp	1.0	1.4	1.1	1.8	1.7	0.6	2.0	1.6	1.1
	Weft	0.2	0.4	0.3	0.2	0.4	0.5	0.2	0.4	0.5
16	Warp	2.0	2.8	2.5	3.2	3.3	2.7	3.4	3.7	2.7
	Weft	0.2	0.5	0.2	0.4	0.5	1.0	0.7	0.8	0.6

Appendix 6

Data Collected from Measuring the Geometric Parameters

100% Tencel Fabric before Laundering

ID	(Warp)	610	638	611	620	603	625	623	632	599	608	615	604
		616	620	602	619	625	597	596	642	623	599	607	639
	(Weft)	513	486	487	495	532	490	468	531	531	499	531	514
		483	508	527	481	470	485	468	502	502	546	485	543
CH	(Warp)	158	143	186	151	187	142	143	165	120	127	139	131
		132	168	202	180	149	130	132	168	163	123	134	130
	(Weft)	201	194	193	180	204	177	158	156	183	182	143	144
		198	197	170	189	152	163	182	158	153	167	162	192

60/40 Cotton/Tencel Fabric before Laundering

ID	(Warp)	622	641	670	710	621	660	642	670	631	704	628	710
		654	648	717	752	678	665	648	670	704	666	647	667
	(Weft)	523	525	524	502	541	465	496	509	499	517	524	528
		502	501	507	551	511	492	490	503	527	530	540	529
CH	(Warp)	198	196	204	218	180	178	167	187	153	179	180	158
		182	176	198	157	182	189	179	183	185	178	181	183
	(Weft)	200	192	184	169	174	187	183	165	182	172	163	162
		171	185	156	172	164	174	180	187	179	185	190	174

100 Cotton Fabric before Laundering

ID	(Warp)	675	618	651	653	663	608	644	640	579	726	736	728
		729	688	685	667	653	647	605	704	697	622	653	667
	(Weft)	471	405	434	498	485	499	460	499	522	436	523	487
		473	509	462	496	502	463	505	478	512	513	460	446
CH	(Warp)	126	118	131	127	152	133	159	164	168	143	180	206
		151	171	187	170	181	166	153	165	162	158	157	160
	(Weft)	205	227	228	230	157	159	170	183	194	209	161	213
		197	189	175	196	165	177	200	192	177	150	178	190

100% Tencel Fabric after Treatment 12

ID	(Warp)	629	630	570	614	583	602	568	612	598	574	605	586
		589	612	574	628	594	585	588	589	591	565	525	551
	(Weft)	472	477	500	522	486	478	491	475	475	442	491	473
		522	476	493	500	543	466	445	506	518	522	481	445
CH	(Warp)	143	173	182	140	176	198	122	128	120	138	142	143
		150	177	170	151	185	175	208	207	187	168	127	187
	(Weft)	209	190	155	237	175	170	210	230	193	229	182	192
		189	203	191	161	197	192	158	213	168	157	160	202

60/40 Cotton/Tencel Fabric after Treatment 12

ID	(Warp)	658	706	626	627	645	718	625	640	625	615	668	707
		620	619	611	648	639	670	723	622	618	642	658	611
	(Weft)	491	492	497	534	517	521	478	500	550	441	554	445
		507	500	536	437	538	505	458	557	518	576	490	509
CH	(Warp)	129	155	90	116	147	130	130	139	127	95	103	107
		145	93	100	116	129	153	101	118	132	133	106	120
	(Weft)	185	174	149	125	133	179	183	157	180	146	170	185
		180	176	165	140	202	187	150	178	214	174	145	215

100 Cotton after Treatment 12

ID	(Warp)	628	655	683	695	659	649	679	650	587	610	595	616
		588	658	600	612	678	630	621	666	643	603	600	700
	(Weft)	487	508	497	476	465	446	481	473	442	456	424	490
		504	450	443	500	493	524	455	469	470	466	471	467
CH	(Warp)	162	140	188	157	148	150	143	116	142	133	120	142
		145	156	157	143	144	160	193	169	158	161	140	145
	(Weft)	173	191	223	222	222	215	234	228	222	200	185	202
		221	211	222	207	173	184	225	211	220	217	209	210

100% Tencel after Enzyme Treatment

ID	(Warp)	635	620	593	624	562	608	607	644	599	600	612	605
		613	599	595	625	587	601	590	583	643	600	608	584
	(Weft)	480	502	458	449	510	510	477	467	522	484	471	475
		481	473	507	491	463	515	500	468	503	506	468	471
CH	(Warp)	154	171	145	166	133	157	123	156	146	151	148	134
		150	123	170	135	104	100	140	135	142	142	135	145
	(Weft)	146	198	170	173	215	222	179	152	205	192	164	160
		162	167	166	195	179	165	195	183	171	180	189	197

60/40 Cotton/Tencel after Enzyme Treatment

ID	(Warp)	659	635	650	662	663	637	660	600	645	625	647	647
		680	654	633	646	648	638	667	647	646	650	651	645
	(Weft)	497	491	531	514	518	508	491	508	545	470	517	552
		473	502	508	490	470	533	481	574	532	532	528	513
CH	(Warp)	180	147	137	114	192	152	147	171	161	140	180	147
		205	122	156	148	166	157	147	158	153	168	171	148
	(Weft)	185	170	159	184	176	167	180	185	190	191	169	151
		183	146	172	202	187	162	158	155	204	195	162	152

100% Tencel after Enzyme Finishing and Treatment 12

ID	(Warp)	615	559	567	554	579	554	580	608	560	583	598	610
		600	598	613	595	630	582	588	578	604	579	600	584
	(Weft)	467	477	488	470	477	466	471	468	471	476	472	464
		440	480	477	501	469	480	500	465	476	477	475	482
CH	(Warp)	201	160	146	127	139	127	151	148	135	148	167	143
		138	127	161	132	179	181	130	135	163	150	121	177
	(Weft)	162	203	188	194	168	160	210	185	167	174	175	166
		185	160	156	159	147	188	173	195	212	195	205	173

60/40 Cotton/Tencel after Enzyme Finishing and Treatment 12

ID	(Warp)	646	665	625	587	640	645	600	583	626	646	585	645
		638	648	645	605	673	670	632	585	661	643	624	645
	(Weft)	482	492	488	511	495	508	492	497	565	490	499	483
		490	546	555	494	515	550	505	508	502	490	492	491
CH	(Warp)	158	148	201	160	192	133	136	104	95	133	104	138
		105	140	120	167	173	150	114	120	135	129	130	138
	(Weft)	182	132	144	140	195	174	134	177	202	171	180	185
		160	150	156	175	170	177	181	163	173	198	188	190

Note. ID is inter-yarn distance; CH is crimp height.

Appendix 7

<u>Mill and Converter Source List for Tencel Fabric</u>

BPC TEXTILE LTD.
145 W. 22nd St.
Los Angeles, CA 90007
213-748-6806
Contact: Raphael Javaheri
End Use: Sportswear, two-piece dresses

BURLINGTON DENIM
1345 Avenue of the Americas
New York, NY 10105
212-621-4037
Contact: Robert J. Thomson
End Use: Denim

BURLINGTON KNITTED FABRICS
1345 Avenue of the Americas
New York, NY 10105
212-621-3996
Contact: Rod Kosann
End Use: tops and sportswear for men's, women's and children's wear

CENTENNIAL FABRICS
1384 Broadway
New York, NY 10018
212-221-3425
Contact: Mel Bernstein
End Use: two-piece dresses and sportswear

FISHER & GENTILE
1412 Broadway
New York, NY 10018
212-221-1800
Contact: Artie Schreiber
End Use: two-piece dresses and sportswear

FOLIO IMPRESSIONS INC.
25 W. 39th St.
New York, NY 10018
212-764-1585
Contact: Ron Jebran
End Use: two-piece dresses and sportswear

MILLIKEN & CO.
P.O.Box 1926
Spartanburg, SC 29304
803-573-2815
Contact: Brenda Burris Drake
End Use: knits for tops, dresses and soft sportswear

RELTEX
1359 Broadway
New York, NY 10018
212-643-8820
Contact: Marti Newland
End Use: syits, sportswear

TANDLER TEXTILE INC.
104 W. 40th St.
New York, NY 10018
212-869-9800
Contact: Denise Rosano
End Use: two-piece dresses and sportswear

WEAVE ONE KNIT TWO
108 W. 39th St.
New York, NY 10018
212-719-4390
Contact: Jack Biderman
End Use: two-piece dresses and sportswear