The FAST Fabric Objective Measurement Properties of Commercial Worsted Apparel Fabrics Available in South Africa

by

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In accordance with Rule G5.6.3, I hereby declare that the above-mentioned treatise/ dissertation/ thesis is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

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ABSTRACT

In the last few decades, there has been a shift globally towards the objective measurement of these textile fibre, yarn and fabric properties which determine processing performance and product quality. This shift is also very apparent in the objective measurement of fabric properties, particularly those relating to handle and making-up into a garment.

This study was motivated by the fact that the adoption of fabric objective measurement (FOM), specifically the FAST system, will benefit the South African worsted apparel sector, as it has done in various other countries which produce high quality worsted apparel fabrics and garments. FAST is robust and portable, yet inexpensive. The main objective of the study was to develop a FAST referencing system which can be used for benchmarking by the local apparel industry and, as a basis for encouraging and persuading the industry to adopt this system of fabric quality measurement and assurance and thereby improve their product quality and international competitiveness. To achieve the main objective, involved sourcing and FAST testing a representative cross-section of commercial worsted apparel fabrics with the emphasis on wool and wool blends from the local fabric and clothing manufacturing industry, and determining how the various FAST properties were affected by factors such as fabric weave, fibre blend and weight, since this could impact on the specific nature and validity of the referencing system.

A total of some 394 worsted type commercial fabrics, mainly in wool and wool blends, were sourced from, and with the inputs of, local apparel fabric and clothing manufacturers so as to ensure the local fabric and garment representative of the sample population and after which the fabrics were tested on the FAST system. ANOVA (regression analysis) was carried out on each of the FAST parameters in order to determine whether fabric weight, weave, thickness and fibre

composition (pure wool and wool blends) had a statistically significant effect on them, since this is an important aspect which needs to be clarified prior to the development of a envisaged meaningful FAST system.

KEYWORDS

Fabric Objective Measurement, FAST, Fingerprint charts, Worsted apparel fabrics

Contents

1. Introduction

1.1 Background information

The South African clothing and textiles industry is a highly diverse and labour intensive industry, with an important role to play as an employer in the country. South Africa is one of the largest producers of fine apparel wool and the largest producer of mohair in the world, both of which are of outstanding quality and are used in high quality worsted apparel fabrics destined for men's and women's suitings and other formal wear, hence the focus of this study on wool and mohair based worsted apparel fabrics. Within this context, it is also very important to mention that almost 95% South African wool and mohair are exported in the unprocessed or semi-processed form, and there is therefore the tremendous scope for their local beneficiation, with the associated benefits of job creation and foreign exchange earnings.

Apparel fabrics, particularly at the high quality and higher end ones, are constantly being assessed and judged, mainly in terms of handle and appearance, by the finisher, garment manufacturer and consumer. The fabric aesthetic properties, such as colour, texture and drape, are important, and so are those mechanical properties, usually assessed by handling the fabric, which play a key role in determining the fabric suitability for an intended use. Fabric quality, particularly of fabrics destined for formal apparel, has been traditionally, and often still is, subjectively evaluated by experts belonging to the textile and clothing industries as well as by people from other backgrounds, including consumers. By handling a fabric, an expert can usually get a good indication of the ease with which it can be made up into the required garment as well as of the garment performance during wear.

Fabric properties, which play a role in satisfying the requirements of the clothing manufacturer as well as of the consumer, are listed in Table 1.1. Basically, the clothing manufacturer requires that the fabric is easy to tailor, passes through the making-up process easily and without undue problems and that the finished garment has a good appearance and performance during wear.

Table 1.1: Assessment of apparel fabric performance

For Consumer	
Aesthetic impression	Visual colour and pattern Drape
Cover	Light transmission Body Shape
Comfort Strength and durability	Permeability, heat, moisture Skin contact Breakage and loss of fibre Damage-prone sharp folds
Appearance retention	Wrinkling and creasing Change of aesthetics (i.e. pilling) Ease of care
For Clothing Manufacturer Handling characteristics	Laying down, cutting, transporting, sewing manipulation, needle and stitch action Forming and pressing
All involve complex buckling of fabrics related to fabric handle	

(Source: Hearle, 1993)

Various international surveys and studies, mostly on worsted type of apparel fabrics (De Jong et al., 1980; Kawabata et al., 1981; Mahar and Postle, 1985; Stearn et al., 1985, 1987, 1988; House, 1986; Postle, 1989; Mahar and Postle, 1989; Mahar et al., 1990; Tomasino, 2005; Sun and Stylios, 2007; Tokmak et al., 2010; Bajzik, 2012; Bajzik, 2016), showed that there was not a very good agreement between the handle assessments of different people, even between expert judges from different countries. There were many reasons for the lack of agreement, including differences in cultural background and/or climatic differences between the countries. Furthermore, there has been an increase in the added value and diversity of products, in both the textile and clothing industries, increasing the difficulty of dealing on a subjective basis, with the many and diverse new types of fabrics being processed (Mahar and Postle, 1982;

Postle et al., 1985; Postle, 1989; Chen and Leaf, 2000; Behera and Mishra, 2007; Alamdar-Yazdi, 2008; Das et al., 2015). There is also the need for fabrics to be "right first time", to enable fast-response and "just-in-time" manufacture (Harlock, 1989) and thereby, satisfy increasingly demanding customers, who expect fashionable and good product quality and appearance with superior performance. This, together with constant demands for new styles and patterns and large scale production, increased the need for a systematic, objective, accurate, efficient and reliable quick response system of fabric quality assessment, hence the development of "fabric objective measurement". Research has shown that the fabric mechanical properties largely determine the fabric and garment quality and performance, including handle (Postle et al., 1982; Behery, 2005; Chattopadhyay, 2008; Das, 2011; Das and Hunter, 2015; Bajzik, 2016), handle being defined as 'the subjective assessment of a textile material obtained from a sense of touch' (Denton and Daniels, 2002).

According to Postle (1989), the basic concept of fabric objective measurement (FOM) technology is "that a necessary and sufficient set of instrumental measurements be made on apparel fabrics in order to specify and control the quality, tailorability and ultimate performance, in garment form, of the fabric". Fabric Assistance by Simple Testing (FAST) is one of the FOM methods of testing the quality characteristics of a fabric, particularly a worsted type apparel fabric, in terms of its garment manufacturing and wear performance. It, together with the pioneering Kawabata FOM system, is widely used in countries specialising in, or producing, significant quantities of good quality worsted type of fabrics, to monitor and improve their quality. Nevertheless, inspite of the advantages and benefits of FOM systems, such as FAST, in quality improvement and assurance, they have not been adopted to any significant extent in South Africa.

The reason for the lack of the adoption of FAST systems in South Africa (SA) was investigated by means of a survey of local apparel fabric and clothing manufacturers and retailers (Das,

2011; Das and Hunter, 2015; Das et al., 2015; Das et al., 2017). It was found that only one FAST system was in use in the SA local industry at the time, with most apparel fabric and garment manufacturers and retailers apparently carrying little knowledge of the FAST system and its potential benefits. This made it clear that a concerted effort was required to create an awareness of, and promote and implement FAST in SA, which could be of great benefit, SA being a leading producer of good quality apparel wool and mohair. As a step in that direction it was decided to create a FAST referencing and fingerprint system for locally produced wool and wool blend worsted apparel fabrics for use by local fabric and garment manufacturers and retailers. To achieve this, it was considered necessary to source and test (on the FAST system) a large, and representative number of commercial worsted apparel fabrics produced and used in the local apparel manufacturing sector. Hence a representative sample, of some 394 worsted wool and wool blend fabrics were sourced from the local apparel manufacturing sector.

1.2 Aim of the study

To be competitive in the current global market, SA needs to produce fabrics and garments of excellent quality and value for money. One means of achieving this is by implementing the highly advanced and integrated FOM systems, such as FAST, with a "benchmark or reference data system", as planned in this study.

The main objective of this study was to develop a FAST based fabric data system (Microsoft Excel data sheet) and "fingerprints", which can be used, as a benchmark and a means, to assess and improve the quality of locally produced worsted apparel fabrics, and thereby the global competitiveness and sustainability of the local worsted fabric and clothing sectors. The ultimate aim is that this will facilitate and encourage in creating local beneficiation of South African wool and mohair, with the associated benefits in terms of much needed job creation and export earnings.

1.3 Outline of the thesis

As already mentioned, to achieve the aims and objectives of the study, a wide and representative range of some 394 commercial worsted apparel fabrics have been sourced from local apparel fabric and clothing manufacturers and tested on the FAST system. The results so obtained have been tabulated, analysed (ANOVA) and graphically plotted to determine the influence of various fabric parameters on the FAST results, and to illustrate the main trends and findings. The thesis has been divided into five chapters. Chapter 1 gives the Introduction, also covering the background and motivation for the study. Chapter 2 contains the Literature Review, Chapter 3 covers the Experimental part of the study. Chapter 4 covers the Results and Discussion and Chapter 5 the Conclusions and Chapter 6 covers the Recommendations for Future Research.

2. Literature Review

2.1 General background and introduction

In garment manufacturing and tailoring, a flat two dimensional fabric sheet is converted into an assembled three dimensional shell structured garment to accommodate the shape of the human body and requirements of the human being. To be able to do so, the fabric must have shear and bending flexibility so that it can be deformed or moulded into the desired three dimensional shape, which brings into play the corresponding fabric mechanical properties. Traditionally, fabric quality related aspects, such as handle, tailorability, colour, lustre and performance, have been evaluated subjectively, not only by experienced judges or experts in the textile and clothing industries, but in many respects, also by the consumer. Handle, on the shop floor in particular, has been accepted, and used, as a factor to determine the acceptability of a fabric, also in terms of making up performance. The subjectiveness of such an assessment, together with the need to cope with the ever growing changes in the textile and clothing sector in terms of design, appeal and "right first time", lead to the development of a new technology of characterising fabric quality, which was accurate, consistent and objective, FOM. FOM is a term used to describe a series of measurements made on various test instruments which are designed to quantitatively characterise a fabric and ensure that, before it is cut and used to make a garment, it is suitable for its intended end-use. Other than predicting the performance of a fabric in garment making, FOM can also provide considerable information on many other characteristics of the fabric which contribute to fabric quality, such as aesthetics and durability during wear. According to Niwa (2001, 2002), there are three criteria for the objective evaluation of good fabric quality, namely good handle, good garment appearance and good comfort. Although originally developed for men's worsted suiting fabrics, FOM has also been extended to nonwoven fabrics (Barker and Scheininger, 1982; Kawabata et al., 1994; Yokura and Niwa, 1997), men's shirts (Yick et al., 1995; Jyothi et al., 2007) and diapers (Yokura and Niwa, 2003).

The research and scientific approach, which forms the foundation of FOM, dates back to the pioneering papers published by Peirce (1930) in the 1930s, with the initial focus being on fabric handle. The ground breaking work of Peirce (1930) on the objective measurement of fabric mechanical properties, was followed by work which related the fabric low stress mechanical properties to tailorability and which was carried out at TEFO, a Swedish institute for textile research in the 1950s and 1960s (Eeg – Olofsson, 1959; Lindberg et al., 1960; Lindberg et al., 1961; Shishoo, 1995). In the 1950s Cassie et al., (1955), at WIRA, Bradford (UK), published a series of papers which dealt with fabric thermal properties, comfort and the warmth/coolness of clothing. Through their work, fabric properties, such as thickness, density and compression, were identified as of critical importance in determining the fabric's thermal or comfort related characteristics.

In the early 1960s, Lindberg headed a research team at TEFO in Sweden, where, for the first time, fabric tailorability and garment appearance became the focus of serious research (Lindberg et al., 1960). Also in the 1960s, Grosberg and others (1969) at Leeds University, England, pioneered the theoretical analysis of fabric mechanical properties, such as tensile strength, bending, buckling, shear and compression. In 1967, Baird et al., (1995) undertook research on the instrumental assessment of handle. After 1970, certain researchers proposed a more comprehensive approach, based upon the assumptions that fabric handle (AATCC Technical Manual, 2004) is basically determined by the fabric mechanical properties, such as tensile, shearing and bending tested at low stress level, as well as by the fabric surface characteristics, weight and thickness. Many technological advances and changes were taking place in the textile and clothing industries during the second half of the previous century. Whereas some of these changes were introduced to accommodate new technologies that have improved the cost effectiveness of production, others have been made in response to the changing needs in the marketplace. This turned out to be the first step, lead being taken by

Kawabata and Niwa (1972) towards the highly advanced and sophisticated FOM technology. The most important work on FOM occurred in the 1970s, when they organised a committee in Japan, called Hand Evaluation and Standardisation Committee, which developed the objective method of fabric handle evaluation and ultimately, the very important Kawabata Evaluation System for Fabrics (KES-F). The development of the Kawabata KES-F system represented a giant step ("quantum leap") in terms of FOM technology and its practical application. Kawabata and his team in Japan, for the first time, provided a feasible instrument based technology and system to evaluate hand quality or handle, which related the basic mechanical properties to the quality and performance characteristics of the fabric, particularly handle and making-up. Years later, the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Division of Wool Technology, Australia, developed the FAST system for measuring those fabric properties affecting garment making-up (tailorability) and which was a much simpler, user friendly and inexpensive system, compared to the Kawabata KES-F system. Nevertheless, in many parts of the world, and even today the active application of FOM still remains largely in the research and academic domain, except for a few selected countries (Das and Hunter, 2015; Das et al., 2017). Therefore, it can be concluded that, during the past 20th century, researchers from all over the world have contributed towards developing and implementing FOM to not only for laboratory testing and research purposes, but even more importantly, for industrial usage.

During the last few decades of the 20th century, FOM represented one of the most active areas of research (Postle, 1989; Harlock, 1989; Curiskis, 1989), largely due to the ground breaking work of Kawabata and his co-workers in Japan, and their subsequent collaboration with Postle and others (Postle and Mahar, 1982; Postle, 1983, 1986, 1989 and 1990; Postle et al., 1985) in Australia.

According to Bishop (1996), FOM refers to "the evaluation of fabric handle, quality, and related fabric-performance attributes, in terms of objectively measureable properties". A definition of the FOM concept, proposed by Postle (1989) is, 'that a necessary and sufficient set of instrumental measurements be made on fabrics in order to specify and control the quality, tailorability and ultimate performance of apparel fabric'.

The great interest in FOM technology led to a series of symposia and conferences dedicated to this field, and also resulted in a large number of publications on the subject (e.g. Kawabata et al., 1982; Mahar and Postle, 1982; Hunter et al., 1982; Postle, 1983; Postle et al., 1983; Kawabata et al., 1984; Mathews, 1985; Niwa and Kawabata, 1985; Kawabata et al., 1986; Das, 2011; Das and Hunter, 2015; Das et al., 2015; Das et al., 2017).

Postle (1989) identified the following six main areas in which FOM technology was being applied in different countries and by different companies, as covered by the three Japan-Australia Science and Technology Symposia (Kawabata et al., 1982, 1984, 1986):

i.   Objective measurement of fabric quality and handle, and their primary components for various textile products;

ii. Design and production of a diverse range of high quality yarns and fabrics by using objective mechanical and surface-property data;

iii. Objective evaluation and control of textile processing and finishing sequences for the production of high-quality yarns and fabrics;

iv. Objective evaluation of fabric tailorability and finished-garment quality and appearance;

v.   Objective specifications, by tailoring companies, for fabric selection, production planning, process control, and quality assurance by using fabric mechanical- and dimensional- property data; and

vi. Measurement and control of the comfort, performance, and stability of fabrics and clothing during use.

2.2 Handle and its importance

2.2.1 Definition, concept and background

"Hand" or "Handle" is an important factor influencing the choice of fabrics for apparel end-uses (Kawabata and Niwa, 1994; IWS F.A.C.T., 1981). It is difficult to overestimate the importance of the fabric handle as the traditional subjective measure of finished fabric quality. As per Postle (1983), subjective expressions of fabric handle have invariably been used as the basis of communication for product development, production, quality control, specification and marketing of textile materials and garments. The handle of fabrics certainly represented and still today represents the traditional measure by which the quality of wool fabrics is subjectively assessed within the textile industry.

Many papers have offered alternative definitions of the concept of handle, including the following:

- It has been defined as the quality of a fabric or yarn assessed by the reaction obtained from the sense of touch (Owen, 1970/71; Kawabata and Niwa, 1994; Denton and Daniels, 2002).

- 'A person's estimation, when feeling fabrics between fingers and thumb' (Thorndike and Varley, 1961).

- 'The summation of the weighted contributions of stimuli evoked by fabric on the major sensory centres' (Lundgren, 1969).

- 'What man sensorily assesses from the mechanical properties of a fabric' (Matsuo et al., 1971).

- 'The sum total of the sensations expressed when a textile fabric is handled by touching, flexing of the fingers, smoothing and so on' (Dawes and Owen, 1971).

2.2.2 Subjective assessment of fabric handle

The measurement of fabric handle involves carrying out subjective tests on a series of fabrics using a panel of judges. One method is to place the fabrics in order of preference, without assessing the magnitude of differences. Howarth and Olivier (1957) found, however, that when the number of samples exceeds six, it was preferable to compare them in pairs, this being a well-known technique used in subjective assessments (Kendall and Gibbons, 1990; Chattopadhyay, 2008; Das, 2011; Das and Hunter, 2015; Bajzik, 2016). In this approach, from a set of fabrics, all possible pairs are randomly presented to the judges, who then rate each pair in order of preference for a particular property. In this way, it is possible to detect inconsistencies in ranking.

The problems associated with the subjective assessment of handle, particularly when persons, even experts from different cultures, countries and background were involved, lead to research aimed at the objective measurement of fabric handle.

2.2.3 Objective measurement of fabric handle

The objective approach to assessing fabric handle is based on the assumption that certain physical properties of a fabric contribute to differences in handle. It is, therefore, necessary to define and measure these properties using suitable instruments. Various studies (Matsus et al., 1971; Vaughn and Kim, 1973) refer to surface and compressional properties, weight, thickness, surface contour and thermal characteristics, as being the important fabric properties relating to fabric handle. Developments in the assessment of handle have been reviewed by Vaughn and Kim (1975), Ellis and Garnsworthy (1980), Slater (1993), Behery (2005), Strazdiene and

Gutauskas (2005), Mahar and Wang (2010), Wang et al., (2012), Bajzík (2012, 2016), Mahar et al., (2013), McGregor (2015) and Sun et al., (2017).

2.2.4 Other approaches to fabric handle characterisation

Although the KES – F systems approach to the objective measurement of fabric handle has been the most comprehensive and widely accepted one, there have also been several different attempts to obtain an objective measure of the handle of fabrics using fewer parameters than those used by KES-F, with a view to simplifying the calculations of the hand value (Colourage, 1995). Many instruments and systems, which are simpler and cheaper than either KES-F or FAST, have been proposed and developed (Hearle and Amirbayat, 1987; Sultan et al., 1993; Tokmak et al., 2010), although few, if any, have been adopted to any significant extent. Chen and Leaf (2000) developed a software program (MECH FAB) to optimise woven fabric structural parameters, based on the specifications of the eight most commonly used physical and mechanical properties, including tensile, bending and shear moduli. Discriminant (Chang and Shyr, 1996), fuzzy logic (Park et al., 2000) and neural network (Lai et al., 2002), analyses utilising KES-F and FAST fabric measurements, have been used to develop models to classify and predict the handle of cotton, linen, wool and silk fabrics. Park et al., (2000) found that fuzzy logic and neural network analyses transformed overall hand values, based upon the KES-FB measured mechanical properties, such as bending rigidity, shear hysteresis, surface roughness and weight. Wong et al., (2004) concluded that hybrid models, incorporating traditional statistics and neural networks and fuzzy logic, best predicted overall clothing comfort, including tactile comfort. Lai and Lin (2007) used ten FAST based physical properties to characterise the generic handle of cotton, linen, wool and silk woven fabrics by means of discriminant analysis and neural networks.

2.3 Tailorability and the factors influencing it

2.3.1 Defining the concept of tailorability

Tailorability can be defined as the "ease with which two-dimensional fabrics can be converted into three-dimensional ready-made garments with a pleasing appearance" (Kim and Vaughn, 1975; Mahar et al., 1982, 1983; Finnimore, 1985; Postle et al., 1988; Shishoo, 1989; Roczniok et al., 1990; Sule and Bardhan, 1999, 2000; Yokura and Niwa, 2003; Ozcelik et al., 2008). Tailorability, as an area of interest, initially arose in the area of worsted suiting production (Postle et al., 1988). Good garment appearance and fit are closely dependent upon the fabric tailorability, and have a considerable influence on the price of a garment that the consumer is prepared to pay. Since worsted suiting type garments are very costly, it was advantageous for the garment manufacturing industries to adopt an objective method in the manufacture of its products, thereby improving tailorability and overall quality (Postle et al., 1988; Sule and Bardhan, 2000; Wong et al., 2003; Behera and Mishra, 2007).

The overall appearance of a finished garment is mainly determined by the properties of the fabric, the sewing thread used in making-up of the garment, interlining if any, environmental conditions and the manufacturing skills of the operator in the garment industry (Postle, 1983). This is illustrated schematically in Figure 2.1 (Postle, 1983). The resulting shape and appearance of the garment must be retained by pressing and setting operations.
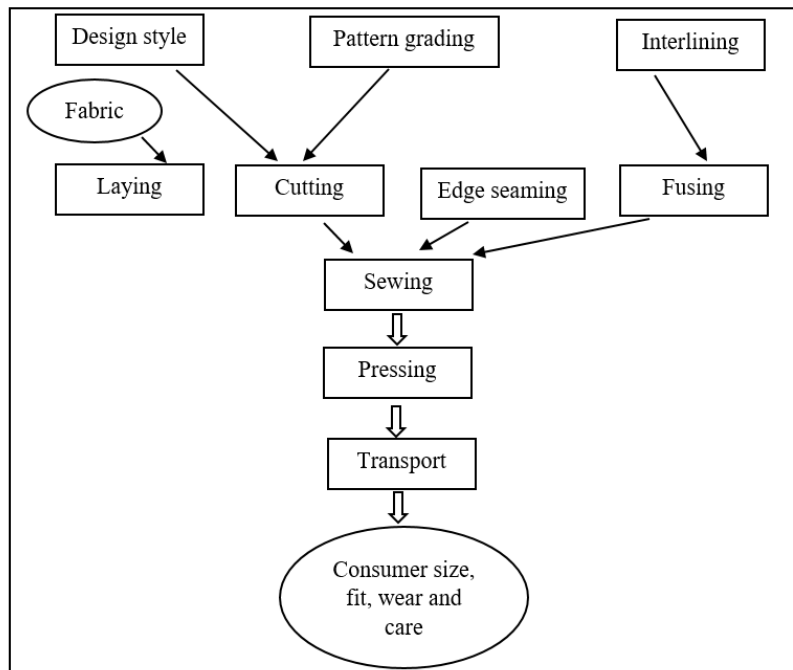
Figure 2.1: Schematic representation of the various factors influencing the overall appearance of garments (Source: Postle, 1983)

As Postle (1983, 1986) so rightly points out, while the textile material is the finished product of the textile industry, it is the start or the 'raw' material for the garment manufacturing or tailoring industry. Garment manufacturers require a reliable objective method for the selection and buying control of suitable fabrics for tailoring into particular end-products.

2.3.2 Factors affecting tailorability

Furthermore, Postle (1983, 1986) emphasized the fact that the tailoring industry requires an objective method for production and process control, based on the quantitative specification of fabric mechanical properties required for each particular operation in the tailoring or cutting and sewing sequence. According to Postle (1983, 1990), textile research has shown that the mechanical, surface and dimensional properties of fabrics are the most important characteristics which ultimately determine their performance during tailoring, as well as the quality of the final garment. Further research into objective measurement and fabric low-stress

mechanical properties, such as, tensile, bending and shear and their relationship to tailorability, were undertaken at the University of New South Wales, Sydney (Carnaby and Postle, 1974; Hamilton, 1975; Hamilton and Postle, 1973, 1974, 1976; Dhingra and Postle, 1980; Bassett, 1981; Mahar et al, 1990) and at other places (Yokura and Niwa, 1997; Yokura and Niwa, 2003; Sanad and Cassidy, 2016). According to Postle (1983), fabric compression is another mechanical property, like shear, which is important in determining tailorability.

2.4 Historical development of FOM

2.4.1 Development of FOM

Within the context of FOM, fabric evaluation carried out by people is usually called subjective evaluation, whereas evaluation made by using instruments is called objective measurement. Fritz (1990) stated that 'people are capable of making objective, quantitative, and repeatable assessments of their sensations', therefore, for the FOM concept to be successful, in terms of handle, the subjective evaluation of fabrics should be based on psychophysical measurements of fabric attributes that give reasonably consistent results from one individual to another, regardless of their background and experience.

The work of Kawabata and Niwa (1989), which was initially on fabric handle, as part of their basic research on fabric mechanical properties was aimed at the following;

- To explain what leads to better quality (handle) in clothing fabrics. Therefore, the target of their work was focussed on the analysis of the judgement of handle as carried out by experts in textile mills.

- To develop an objective evaluation system of fabric handle, based on the analysis of the experts judgement of handle.

- To predict fabric performance in clothing manufacture, when it was realised that the data collected correlated with fabric behaviour in clothing manufacture and making-up.

The outcome of the work by Kawabata and his team, was the development of the KES-F in 1980, involving a set of four instruments designed to measure 16 (sixteen) basic fabric properties considered applicable to apparel fabrics. Despite its widespread use in the Japanese clothing industry, as well as in research laboratories worldwide since 1972, only being commercialized in 1980, the KES-F system hasn't met with general individual acceptance, due to certain drawbacks, associated with its high cost, complexity, time taken to carry out the tests, and inconsistency when interpreting the results (Ly et al., 1988).

Following on the work of Kawabata and his team, the CSIRO in Australia developed the alternative FAST, FOM system (Ly et al., 1988). This system, aimed primarily at predicting fabric tailorability as opposed to handle, was claimed to be faster, cheaper and simpler than KES-F, but was not initially widely accepted by the industry.

2.4.2 Aims of fabric objective measurement

The application of objective measurement should have five broad aims (Postle, 1982, 83, 85, 86, 89) namely:

1. To maintain and upgrade the quality of all existing textile products

2. To optimize the use of different qualities and varieties of natural and man-made fibres

3. To provide a scientific basis for the control of fabric quality and performance as a result of new process and product development

4. To quantitatively specify and control the performance characteristics of fabrics and clothing

5. To establish an objective basis for communication between researchers, industry sectors and traders in fibres and products.

2.5 Historical development of the Kawabata evaluation system for fabrics (KES-F)

2.5.1 Development of KES-F System

KES-F was used in evaluating the mechanical properties of fabrics (Behery, 2005). Later models, called the KES-FB series, were released in 1978 and were designed to reduce the time required for specimen preparation and testing (Behera and Hari, 1994). Development of more automated versions of the KES-F system (called the KESFB-AUTO-A system), which included automated sample loading procedures and thereby further reduced operator working time, was completed in 1997 (Behery, 2005; Kato Tech, 2017).

Kawabata's major research was on fabric handle or hand, which led to the following (Fortress et al., 1985):

a) The formation, in 1972, of a Hand Evaluation and Standardisation Committee (HESC), under the Textile Machinery Society of Japan, made up of experts in the field of fabric handle.

b) The definitions of expressions commonly used in evaluating handle, eg. smoothness, crispness, fullness and stiffness, designated as Primary Handle Values or PHVs, and another concept of a Total Hand Value (THV), made up of the PHVs, to specify overall fabric handle.

c) The development of the KES-F measuring instruments, to objectively measure the basic mechanical properties associated with handle, tailorability and other subjective fabric and garment quality and performance attributes.

Hence, it can be said that, Kawabata's contribution in terms of developments in the form of measuring instruments to understand the various properties of fabrics and garments brought a big revolution in itself to the clothing industry.

2.5.2 Description of KES-F

Kawabata designed the KES-F system in 1972 (Kawabata, 1973, 1982). He identified a need for instrumentation that would enable the fabric parameters to be measured 'as quickly as possible with high accuracy and good reproducibility'. He noted at the time, that 'the design of low-cost instruments was also required for future development of FOM' (Kawabata, 1972). The KES-F system is a systematic method of measuring certain mechanical and surface properties of the fabrics, using testing devices developed by Kawabata and his team, the aim of which initially was to obtain an objective assessment of fabric handle.

Kawabata stressed that the fabric mechanical properties should be measured under conditions similar to the actual fabric deformation used for the judgement of hand (Kawabata, 1973, 1980; Kawabata and Niwa, 1991), and that the hysteresis behaviour, in tensile, shear, bending and compression deformation, must be measured to determine fabric resilience or springiness (Kawabata and Niwa, 1991). The various low stress mechanical properties, which are evaluated by the KES-F system, are tensile, bending shear, compression, surface friction, surface roughness, thickness and weight.

As already mentioned, extensive research, on the objective measurement of fabric properties, and their effects on fabric handle and garment tailorability and appearance, was initiated by Kawabata, who, with Niwa, summarised their work in this respect (Kawabata and Niwa, 1989). Around 1989, it was found that some of the data, obtained by Kawabata and Niwa, correlated well with fabric processability in clothing manufacture and with the making-up of suits in tailoring i.e. with tailorability (Kawabata and Niwa, 1989). The KES-F generated parameters, therefore, also allowing fabric performance, in terms of making-up i.e. tailorability, to be predicted.

The KES-F system has been described in detail in various publications (Kawabata, 1973, 1982; Ly and Denby, 1988; Harlock, 1989; Kawabata and Niwa, 1989; Kawabata and Niwa, 1991; Smuts et al., 1991; Slater, 1993; Kawabata and Niwa, 1994; Tokmak, 2010; Kato Tech, 2017). As summarised by Kim and Vaughn, the KES-F comprises four separate instruments, and corresponding parameters, for measuring the relevant fabric mechanical and surface properties (see Table 2.1).

Table 2.1: Measuring Instruments of the KES - F system

Instrument	Properties tested	Characteristic parameters
KES – F1 (Tensile and Shear Tester)	Tensile and shear elastic properties	WT, RT, LT, G, 2HG, 2HG5
KES – F2 (Bending Tester)	Flexural properties	B, 2HB
KES – F3 (Compression Tester)	Compression properties	WC, RC, LC, T
KES – F4 (Surface Friction and Geometrical Roughness Tester)	Surface properties	MIU, MMD, SMD

(Source: Kim and Vaughn, 1975)

With the exception of KES-F4, which measures friction and roughness parameters in different ways from previous instruments, the KES-F instruments measure conventional fabric mechanical parameters like, tensile, compression, bending and shear. The KES-F system has the advantage, that it is designed so that the same test specimens can be used on all four instruments, provided that the tests are run in the appropriate order. Kawabata (Kawabata, 1980), stated that the KES-F instruments generate both digital and graphical output that is used to characterize the deformation and recovery properties of the fabrics, the measurement of low

stress mechanical properties demanding very high levels of attention to detail, precision and accuracy. Hence, it is clear that the KES-F instruments require great care in fabric handling, both prior to, and during, the actual tests, making the testing procedures cumbersome and time consuming, the acceptance of the KES-F system generally being hampered by the cost of the equipment, complexity of the test results and difficulty in their interpretation.

In 1991, an automated version of the tensile and shear tester, KES-FB – Auto – A (Figure 2.2), was introduced "for rapid use in the industry" (Kawabata et al., 1991; Bishop, 1996; Kato Tech, 2017). The automated version makes it easy for industrial and rapid use saving time, with better precision and efficiency. Later, a new ultra-sensitive compression tester, KGS – G5, was also offered as an improvement on the conventional KES – FB3 compression tester (Bishop, 1996). The automated system shown in Figure 2.2, measures various fabric properties, such as tensile energy, strain, resilience, bending property, compressional property and surface properties, with ease (Kato Tech, 2017).

Figure 2.2: KES FB - Auto – A System (Source: Kato Tech, 2017)

2.5.3 Disadvantages attributed to the KES-F system

Despite having been in use for a long time, the KES-F system has not found widespread use, except in Japan (Kawabata et al., 1983), mainly because of the following reasons.

1. Amongst the more negative comments, made about the KES-F system, is that the equipment is intricate and complex to use. The latter probably refers to the large number of properties involved.

2. The usage and maintenance of the KES-F instruments require a trained specialist technician/skilled operator who can competently manage the difficult and complex calibration procedures (Mazzuchetti and Demichellis, 1990).

3. The KES-F system is relatively expensive (Mazzuchetti and Demichellis, 1990).

4. The results of inter-laboratory trials, conducted at the CSIRO and the University of South Wales, to test repeatability, reproduceability and accuracy of the KES system indicated (Ly and Denby,1988) the following:

- Unacceptable repeatability of certain parameters

- A lack of standard procedures

- Inadequate guidelines with respect to sampling, sample preparation and test procedure

5. The tests are time-consuming, requiring several hours per sample (Mazzuchetti and Demichellis, 1990) and a dedicated operator, until the automated systems came into use.

6. Tests must be carried out under controlled temperature and humidity conditions.

7. It was mentioned that even using controlled conditions and skilled operators there can be a certain degree of operator bias.

As the KES-F instrument is difficult to use, time consuming and complex in operation, few manufacturers use it on a daily basis.

2.6 The FAST (SiroFAST) system

The CSIRO SiroFAST system (hereafter referred to as the FAST system), developed by the CSIRO, aims to predict some aspects of fabric quality, and can be used as an alternative to the KES-F system in many applications, such as fabric development, optimisation of finishing routes, evaluation of new technologies and buying control for garment makers, as well as in quality control in various stages of fabric and garment production and use (De Boos and Tester, 1994). Only nine fabric parameters are utilised in the FAST system, compared to the 16 used in the KES-F system, with only six being common to both systems, namely weight, thickness, surface thickness, extensibility, bending rigidity and shear rigidity (Rouette and Kittan, 1991). Many articles have dealt with FAST and its usage as a device to measure the quality of fabrics and garments (Kim and Vaughn, 1975; Ly et al., 1988; Mazzuchetti and Demichelis, 1990; Allen et al., 1989, 1990; Sule and Bardhan, 2000; Barndt et al., 1990; Rouette and Kittan, 1991; Hearle, 1993; Minazio, 1995; Kadole, 1995; Lai et al., 2002; Lai and Lin, 2007; Jyothi et al., 2007; Tokmak, 2010; Das et al., 2015; Das et al., 2017).

The FAST system comprises the following three instruments (Figure 2.3, SIROFAST) and a test method (Tester and De Boos, 1990, b; SiroFAST, 2017):

FAST – 1: Compression meter (SiroFAST-1)

FAST – 2: Bending meter (SiroFAST-2), and

FAST – 3: Extensibility meter (SiroFAST-3),

FAST – 4: Test method for measuring relaxation shrinkage and hygral expansion
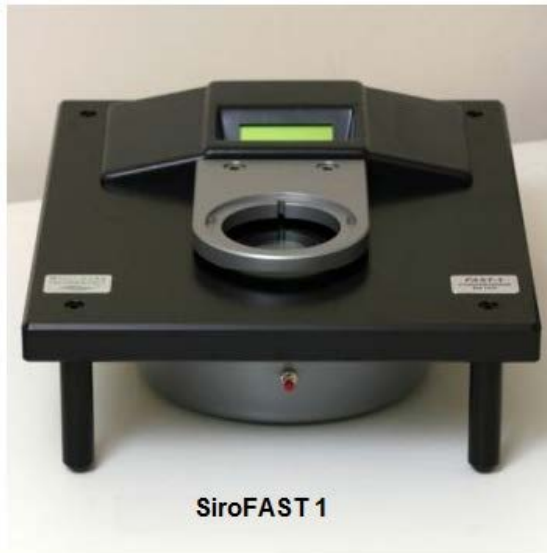
Figure 2.3: The set of FAST instruments: FAST – 1 Compression Meter, FAST – 2 Bending Meter, FAST – 3 Extension Meter (Source: SiroFAST System (2017)

Each of the FAST instruments performs or measures certain fabric properties, as explained below.

Fast -1 Compression meter;

The compression meter assists in measuring the following properties:

- Fabric thickness (T)

- Fabric surface thickness ($ST = T_2 - T_{100}$)

- Released/relaxed surface thickness

The Compression meter (Tester and De Boos, 1990, b) measures the thickness of fabrics at two loads, namely 2 gf/cm^2 and 100 gf/cm^2, from which the surface layer thickness can be derived, which is defined as the difference in the fabric thickness at the two predetermined loads, in other words, the compressible part of the fabric. A further measurement of the fabric surface thickness, after release in steam/water, provides a measure of the stability of the finish of the fabric; the larger the difference, the less stable the finish. This measurement is important in determining the extent of subsequent changes in the appearance and handle of the fabric after garment pressing and can indicate the potential re-emergence of aspects, such as running marks.

Fast - 2 Bending meter;

The bending meter measures the following properties:

- Bending length (BL in mm – measured at an angle of 41.5^0)
- Bending rigidity (BR in µN. m) $= 9.8 \times 10^{-6}$ W $(BL)^3$

  where W = fabric weight, g/m^2.

The Bending meter measures the fabric bending length, using the cantilever principle. A sample of fabric is pushed over an edge and allowed to bend under its own weight until it cuts a plane inclined at an angle of 41.5^0. The length of fabric which extends over the edge is twice than that which is called fabric bending length. The bending rigidity of the fabric can be calculated from its mass per unit area and its bending length. This is important in terms of the handle of the fabric, and also influences the cutting and sewing performance and the ease with which the fabric can be processed by automated handling equipment (Tester and De Boos, 1990, b). Too

stiff a fabric can lead to problems in moulding the fabric, whereas too limp a fabric can be difficult to cut, as it will easily distort, and can also lead to seam pucker.

Fast - 3 Extension meter;

The extension meter measures the following properties:

- Warp extensibility

- Weft extensibility

- Bias (45^0) extensibility

- Shear rigidity (N/m) = 123/ EB5 (% bias extension)

The Extension meter (Tester and De Boos, 1990, b) measures the extensibility of the fabric at three different loads, namely 5gf/cm (4.9 N/m), 20 gf/cm (19.6N/m) and 100 gf/cm (98.1 N/m), in both warp and weft directions, to indicate potential problems in the laying up of the fabric and seams that require overfeed. This information is further combined with bending rigidity to determine the fabric 'formability' as explained by Tester and De Boos (1990, a), which is a measure of the fabric's propensity to pucker when it is compressed along the seams. The extensibility is also measured on samples that are cut on the bias, to determine fabric shear rigidity. This measurement indicates potential problems in laying up and also issues relating to formation of smooth three-dimensional shapes, such as those needed around the sleeve head and shoulder region in a structured jacket.

It can be said that, a low shear rigidity indicates that the fabric will be easily distorted in laying-up, marking and cutting, whereas a high value indicates that the fabric will be difficult to form into smooth three-dimensional shapes, causing problems in moulding and sleeve insertion. Whereas, too low a value may result in difficulty in laying up, and may require pinning, too high a value could indicate problems with moulding the fabric and inserting sleeves.

Fast - 4 Dimensional stability test method;

The dimensional stability test method aims at measuring the following:

- Relaxation shrinkage (RS) = $L_0 - L_D / L_0$

- Hygral expansion (HE) = $L_W - L_D / L_D$

(where L_0 = the original length, L_D = the dried length and L_W = the relaxed length in water)

The dimensional stability of a fabric is its ability to retain its dimensions, within reasonable limits, during garment making – up and subsequently during wear. The test method is used for measuring relaxation shrinkage and hygral expansion.

The dimensional stability test enables both the relaxation shrinkage and the hygral expansion of the fabric to be determined (Tester and De Boos, 1990, b). Relaxation shrinkage is the "once only" change in fabric dimensions, associated with the release of strains set up in the fabric as a result of spinning, weaving and finishing. It is irreversible and occurs when a fabric is relaxed in water or steam, and recovers from the cohesively-set strains imposed during finishing.

Hygral expansion is the reversible change in fabric dimensions associated with the absorption and desorption of moisture by hygroscopic fibres, such as wool. The garment appearance can deteriorate i.e. seam puckering and bubbling, when exposed to high humidity, if hygral expansion is high, especially those garments that were made up under conditions of low relative humidity (Tester and De Boos, 1990, b). Steam and chemical setting of wool fabrics increase hygral expansion, the latter being related to the degree of fibre swelling during setting (Shishoo, 1990).

Table 2.2 lists the various FAST instruments and the related properties they measure, along with the units and symbols that they represent (Smuts et al., 1991).

Table 2.2: List of fabric properties which can be measured or derived, using the FAST system

Instrument	Measured or derived (**) fabric properties	Symbol	Unit
FAST-1-Compression meter	Fabric thickness at 2 gf/cm^2	T2	mm
	Fabric thickness at 100 gf/cm^2	T100	mm
	Surface thickness (**)	ST	mm
	Relaxed surface thickness (**)	STR	mm
FAST-2-Bending meter	Bending length	C	mm
	Bending rigidity (**)	B	μN m
FAST-3-Extension meter	Warp and weft extensibility at 5 gf/cm	E5	%
	Warp and weft extensibility at 20 gf/cm	E20	%
	Warp and weft extensibility at 100 gf/cm	E100	%
	Bias extensibility	EB5	%
	Shear rigidity (**)	G	N/m
	Formability		
FAST-4-Dimensional stability	Relaxation shrinkage	RS	%
	Hygral expansion	HE	%

(Source: Smuts et al., 1991)

The derived properties (the ones marked by **) are calculated from the following properties:

Derived properties (**)	Calculated from:
Bending rigidity	Bending length and fabric weight
Shear rigidity	Bias extensibility
Formability	Bending rigidity and warp and weft extensibility
Finish stability	Fabric surface thickness and relaxed surface thickness

It is clear that the derived properties like bending rigidity are not obtained directly but are calculated from other properties, for example bending length and fabric weight.

2.6.1 Fabric control chart and its tolerance limits

To simplify the presentation and interpretation of results, fabric control charts ("snake charts or fingerprints") are used. Nevertheless, according to Rouette and Kittan (1991), interpretation by the wool fabric finisher or by the tailor, of fabric data using a snake chart, wasn't always accurate. The CSIRO extended such a chart by setting tolerance limits for each parameter and indicating the various problems which might be encountered if the tolerance limits are exceeded (Ly and De Boos, 1990; Rouette and Kittan, 1991). An example of such FAST

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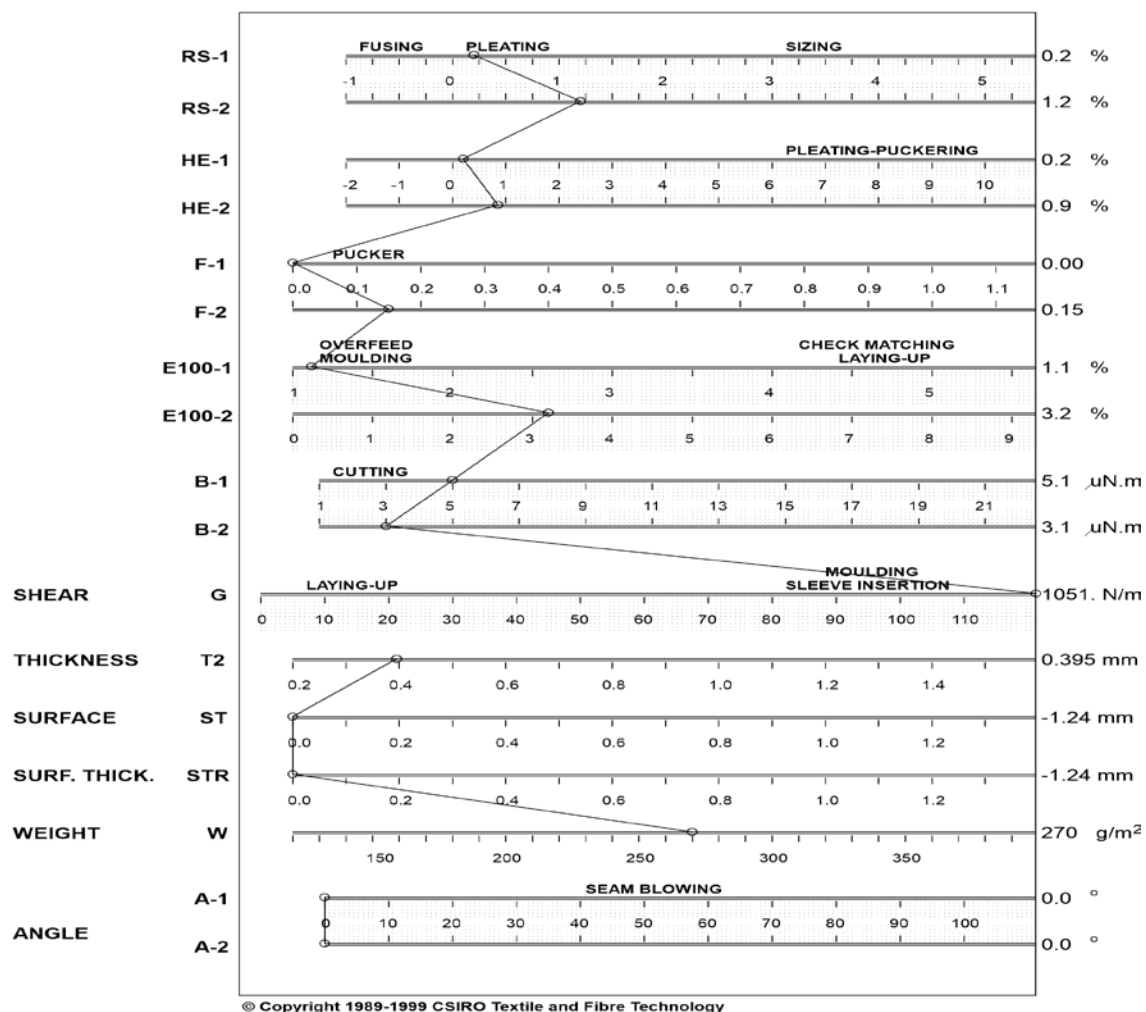
control chart is given in Figure 2.4 (CSIRO, 1999).

Figure 2.4 SiroFAST control chart for tailorability (Source: CSIRO, 1999)

As stated by Ly and De Boos (1970), "while the measurement of fabric properties with FAST is a relatively simple procedure, the interpretation of the data requires an understanding of how each fabric property influences the tailoring performance". This task is simplified with the help of the FAST Control Chart. In this chart, the measured properties are plotted (plotting can be done automatically when using a PC and the FAST Data Program) and the points joined to give a "fabric fingerprint" which helps to interpret the data, i.e. whether the fabric tested is suitable for an intended end use (Postle, 1983). FAST can be linked directly to any PC via the FAST data acquisition program, enabling automatic acquisition and processing of data (De Boos and Tester, 1991). FAST – 4 results, however, are recorded manually and input to the computer via the keyboard (SiroFAST, 2017).

From Figure 2.4, the FAST "fingerprint", also called the "control chart", can be used by the finisher to compare the data from the latest batch of fabrics with the fingerprint of the agreed standard, or to check the data from two batches of the same fabric to ensure consistent quality. Ly and De Boos (1970) state that the FAST "fingerprint" thus provides a simple means for quality control and quality assurance as an example, if the fingerprint falls outside the limits it indicates more work needs to be done on this particular fabric. Therefore, it can be concluded that FAST fingerprint chart assists in identifying problems in areas that could possibly occur and corrective measures required to ward of such errors.

Table 2.3 lists the various FAST instruments and the various properties they measure, as well as potential problems associated with them.

Table 2.3: CSIRO's FAST system

Instrument	Measurement	Predicts problems in:
FAST – 1	Compression Thickness	Pressing Finish stability
FAST – 2	Bending	Cutting, automated handling
FAST – 2 and 3	Formability	Seam pucker
FAST – 3	Extensibility	Laying up, pattern matching, overfed seams, moulding
FAST – 4	Relaxation shrinkage Hygral expansion	Size, seam pucker and pleating Looks, pleating

(Source: Sule and Bardhan, 1999)

Table 2.3, illustrates that problems associated with the compression or thickness of the fabric, might lead to difficulties in pressing and finish fabric stability. Similarly, "out of tolerance" bending length results might lead to difficulties with cutting of the fabric. Seam puckering, irregularity in laying-up and pattern matching are a few of the potential problems associated with "out of tolerance" formability and extensibility levels.

2.6.2 Reproducibility of FAST

De Boos and Tester (1991) pointed out that effective communication, about fabric properties, is necessary between the garment manufacturers and suppliers, to ensure that the required quality standards are met within the FAST system, and this is achieved by:

- ensuring that the instruments are accurate and simple

-   using difference measurements at low strains, which can compensate for any small changes in the fabric sample

Mazzuchetti and Demichelis (1990) claim that, on the basis of limited data available and where a comparison is possible, the FAST system apparently gave more precise measurements than the KES-F system.

2.6.3 Advantages attributed to the FAST system

- Instruments and test procedures are relatively simple (Ly et al., 1988; Mazzuchetti and Demichellis, 1990)

- It is relatively quick, a full evaluation taking less than two hours (Mazzuchetti and Demichellis, 1990).

- Technicians can be trained to operate the instruments in a relatively short time (Mazzuchetti and Demichellis, 1990)

- Cost of the system is relatively low (Ly et al., 1988; Mazzuchetti and Demichellis, 1990)

- The system is user friendly, and suitable for a textile company environment (Mazzuchetti and Demichellis, 1990).

- Relatively little fabric is required to carry out the whole range of tests.

- It is a reliable system (Ly et al., 1988).

- It is robust and portable (Ly et al., 1988).

All the above make FAST ideally suited to an industrial environment (Allen et al., 1990).

2.6.4 Application of FAST

According to Smuts et al., (1991), Lin (2002), Jyothi et al., (2007), Lai and Lin (2007) and SiroFAST (2017), the FAST system can be used for the following:

- Comparison of the effects of yarn properties on the resultant fabric properties

- Fabric development, directed specifically towards good garment manufacture

- Comparison of new with existing or competitive products

- Optimisation of fabric finishing routines

- Evaluation of new or alternative finishing machinery

- Engineering special finishes

- Fabric buying control by garment makers

- Routine quality control by all sectors of the industry

It can, therefore, be concluded that the FAST system can assist in developing a quality fabric, evaluating new and special finishes and in ensuring good garment manufacture.

2.6.5 Disadvantages of FAST

From my own experience, the following possible disadvantages of FAST exist:

- There are chances of human error during the handling of the instruments, i.e. the fabric might be slack or have folds which could introduce errors in the compression measurements.

- Manual error might occur while handling the fabrics between instruments, this can happen while moving the fabric panels from one instrument to another, for example, damp or wet hands can affect the measurements.

- Compression results might be inaccurate, if the fabric isn't placed correctly on the plane glass surface, or if there are creases or folds in the fabric.

- Bending length may vary, if the fabric isn't clamped correctly at both ends, causing the fabric to become loose, thereby preventing accurate measurements.

2.7 Effect of dyeing and finishing treatments on fabric properties

The effects of dyeing and finishing on FOM measured properties and handle have been reviewed by Tomasino (2005) under the following headings:

a. Chemical treatments

b. Mechanical finishing

c. Garment refurbishing

2.7.1 Chemical treatments

- According to Tomasino (2005), any fabric or garment dyeing and finishing procedure, which reduces fibre-to-fibre and yarn-to-yarn friction (i.e. which increases fibre and yarn mobility within the fabric), induces relaxation, bends and flexes the fabric and increases fabric surface hairiness, is likely to result in an increase in fabric softness.

- Tomasino also stressed that, due to the important effect of chemical treatments on fabric relaxation and fibre and yarn mobility, fabric dyeing and finishing, notably the latter, have a major effect on fabric handle and making-up performance, the effect being most apparent in fabric shear rigidity and hysteresis. Fabric dyeing and finishing generally effect large reductions in fabric bending and shear rigidity and hysteresis, essentially through their effects on fabric relaxation (i.e. moving the fabrics towards a minimum energy state) and consequently on fibre and yarn mobility.

It can be concluded that any reduction in friction, be it yarn-to-yarn or fibre-to-fibre, leads to an increase in fabric softness and handle.

2.7.2 Mechanical finishing

Where chemical finishing generally involves subjecting the fabric to a chemical reaction or treatment in a solution, mechanical finishing mainly involves subjecting the fabric to a mechanical or physical action, such as surface finishing, calendaring, setting and pressing. Such actions generally produce a softer fabric handle due to their beneficial effect on fabric relaxation and surface related properties (Tomasino, 2005).

2.7.3 Effect of garment refurbishing

Garment refurbishing generally refers to the care and maintenance treatments applied to the garment during its use or wear. It includes laundering, dry-cleaning, pressing and ironing (De Boos, 2005). Dry-cleaning changes various fabric mechanical properties, which are related to fabric handle, largely as a result of its changing fabric structure, mainly in terms of fabric and yarn mobility (Okamoto, 1985). As stated by De Boos (2005), dry-cleaning improves the handle of wool fabrics, the fabric becoming more supple, fuller and smoother, whereas, laundering of cotton fabrics increases fabric shear, bending stiffness and hysteresis and decreases fabric extensibility, thereby causing a deterioration in fabric handle. Overall, chemical or dyeing or refurbishing treatments mostly enhance the handle of the fabric as well as other properties, like bending and shear.

2.8 Interrelationship between FAST measured fabric properties and fabric and garment construction (Tailorability)

2.8.1 Introduction

Tailorability is mainly dependent upon fabric formability (bending rigidity $\times$ low stress extensibility), which, in turn, is derived from other FAST properties (Behera and Mishra, 2007).

Table 2.4 summarises FAST fabric properties associated with problems in garment construction (Anon, 1981).

Table 2.4: FAST fabric properties associated with potential problems in garment making

Property	Potential problem
Low relaxation shrinkage	Bubbling of fused panels Delamination of fused panels Bubbling in pleating Difficulty shrinking out fullness
High relaxation shrinkage	Excessive fusing press shrinkage Excessive steam press shrinkage Variation in size of cut panels
Excessive hygral expansion	Excessive shrinkage during manufacture Bubbling of fused panels Bubbling of pleated panels
Low formability	Difficulty in sleeve setting
Low extensibility	Difficulty with sewing overfed seam Difficulty in pressing Difficulty shrinking out fullness
High extensibility	Difficulty matching checks Difficulty sewing unsupported seams Easy to stretch in laying up leading to shrinkage problems
Low bending rigidity	Difficulty to cut and sew Automated handling problems
High bending rigidity	Difficulty to mould and press

Low shear rigidity	Easy to distort in laying up, marking and cutting
	Difficulty in garment moulding
High shear rigidity	Difficulty to form smooth 3D shapes

(Source: Anon, 1981)

For a garment manufacturer, problems associated with the properties of a fabric can be either those that cause difficulties during the garment making operations or those faults that appear only in the final garment. For example, if the relaxation shrinkage happens to be low it can result in bubbling and delamination of fused panels, whereas high relaxation shrinkage can lead to variation in size of cut panels. Similarly, low extensibility of the fabric can result in difficulty in sewing and pressing of garments, whereas on the other hand, high extensibility can create difficulty in matching checks while laying or cutting of the fabric.

Problems arising in garment making do not necessarily make a fabric unusable. Behera and Shakyawar (2000) state that a fabric may be difficult to manufacture because of style, drape or handle, but a garment maker may choose to persevere with it, knowing that the additional costs, in terms of time and extra processing, can be recovered in the final price of the garment.

Dhingra and Postle (1980) agree that, faults that appear only in the final garment, are of much greater concern to the fabric manufacturer because, by the time they are evident, the full costs of garment manufacture have been incurred. It is, therefore, evident that the earlier a potential problem can be identified and rectified, the greater will be the cost saving for all concerned. Curiskis (1989), on the other hand, state that the philosophy behind FOM is to predict the performance of fabrics and correct any problems at the earliest possible stage of production and that FOM is a powerful tool, a tool that industries can use to save money, improve quality and make their product right first time. A cost-effective system, for making the required

measurements, requires simple, easy-to-use instrumentation, and an equally simple method of collecting and presenting this information in a form which is easily understood and interpreted.

2.8.2 Effect of fibre, yarn and fabric properties on FOM measured properties

Very little research has been published on the effect of fibre, yarn and fabric properties on FOM properties, some of which are summarised below:

- Mori (1983) found the effect of weft yarn twist, on KES-F and FAST properties, to be small in practice, with finer yarns tending to produce smoother and softer fabrics, provided twist factor was constant.

- Behera and Mishra (2007) found that singles wool and wool blend yarns had produced fabrics with a higher THV than the corresponding two-ply yarns, for both winter and summer applications, due to lower (easier) compressibility and bending rigidity giving greater softness and fullness.

- Hunter et al., (1982) found mean fibre diameter to have the main influence on the Primary Handle Values (PHV), as measured by KES-F, the latter generally increasing with increasing mean fibre diameter. An increase in fibre crimp was found to increase shear stiffness and hysteresis as measured by the means of KES-F.

Some of the fabric properties that affect the fabric and hence the garment on completion of the final product are mentioned below.

2.8.2.1 Fabric weight

The weight of a fabric *is* particularly important when having to choose between two similar fabrics which are of different weights (Stauffer, 2004; Angelova, 2015). Fabric weight is considered as one of the important factors for evaluation or measurement of FOM parameters. For instance, according to Collier (1991), fabric weight and bending rigidity have an influence while predicting fabric drape. Also medium weight fabrics, when observed microscopically,

appeared to have higher crimp than thicker fabrics with larger yarns and more compact construction, which affected the shear properties of a fabric.

2.8.2.2 Fabric thickness

Fabric thickness is defined as perpendicular distance through the fabric, which determines the dimension between the upper and lower side of the fabric and is dependent on the fabric weave as well as the thread's position in the binding repeat (Kremenakova et al., 2004, 2008; Angelova, 2015). Yarns with identical parameters have a long float, hence have greater thickness than plain weave with a small float (Sirkova, 2012). Twill fabric are generally thicker and very opaque than plain fabrics (Angelove, 2015).

According to Collier (1991) fabric thickness has an effect on shearing properties. Fabrics of medium thickness had higher drape values and lower shear hysteresis values, while thinner and thicker fabrics exhibited a wider range of drape and shear values.

2.8.2.3 Fabric weave structure

Fabric weave has a significant effect on the handle properties of the fabrics, particularly bending rigidity, due to the different floats of the yarns (Ozguney, 2009). In plain weave, floats are comparatively small, interlacing points are high and free spaces between the yarns are zero, making the fabric to be relatively firm. On the contrary, this is just the opposite case in twill weave fabrics, which causes decreasing bending rigidity. According to Das et al., (2017), fabric weave structure also influence formability of the fabric. Among various properties tensile strength, tearing strength, abrasion resistance, pilling resistance and stiffness are the ones that make an impact on the weave and structure of yarn (Realff et al., 1991; Chattopadhyay, 2008). Strength wise, the tensile strength of plain weave fabric is higher than that of twill weave fabric (Booth, 1961; Grosberg, 1966; Witkowska and Frydrych, 2008; Triki et al., 2011).

2.8.2.4 Dimensional stability

The dimensional stability of wool fabrics has two components, both of which contribute to the shrinkage or expansion of garment panels in garment making (International Wool Secretariat, 1991). These components are relaxation shrinkage and hygral expansion.

2.8.2.4.1 Relaxation shrinkage

As per the International Wool Secretariat (1991), relaxation shrinkage is the irreversible change in dimensions that occur when a fabric is wet out or relaxed in steam. It is the result of deformations imposed on the fabric during finishing, which are held only by temporary or cohesive set. Unless these deformations are removed or controlled, they will be released during garment making.

2.8.2.4.2 Hygral expansion

Hygral expansion is the reversible change in fabric dimensions that occurs when the moisture content of the hygroscopic fibres, such as wool, is altered. It can be defined as a reversible dimensional change which occurs when the moisture regain of a fabric is altered at a constant temperature (Baird, 1963; Lindberg, 1965; Wemyss and White, 1985). When worn in a humid environment, deterioration in the appearance of a fabric occurs if the garment is manufactured from a fabric with high hygral expansion. Hygral expansion, and its important effect on tailorability and wear performance, has been extensively studied since the 1960s (Shaw, 1978, 1986; Frydrych, 2003; Li et al., 2007). The reversible change in fabric dimensions, particularly wool and wool-rich blends, which occurs when the moisture regain of the fabric changes, is largely due to the fibre undergoing reversible swelling (De Jong et al., 1980). The regain of the wool, when increased, leads to radial swelling of the fibres, which causes a decrease in weave crimp, leading to an increase in both the length and width of the fabric (Frydrych, 2003; Li et al., 2007). The changes are reversible, and, on decreasing the regain, the fabric returns to its

original dimensions. De Jong and his co-authors agree that excessive levels of hygral expansion (e.g. 5 to 6%) can cause a number of problems in the appearance of wool and wool blend garments, including bubbling, seam puckering and delamination of the shell fabric (De Jong et al., 1980). With the ever-changing trends towards light weight fabrics, hygral expansion has become a more serious problem in tailored garments (Cookson et al., 1991). Factors which influence hygral expansion include weave crimp, fabric setting and fabric structure.

2.8.2.5 Fabric extensibility

Extensibility is a measure of the degree to which a fabric will stretch when it is subjected to a tensile load (De Boos and Roczniok, 1996). In the tests used for FOM, the loads used are relatively low, reaching a maximum of 500 gf/cm sample width.

In addition to measurements on the KES-F and FAST systems, the extensibility of the fabric was defined as (Boos and Slota, 1998):

$$\text{Extensibility (as \%)} = \frac{\text{Ext (100)} - \text{Ext (5)}}{0.95}$$

Where Ext (100) and Ext (5) are the percentage extensions of the sample at loads of 100 N/m and 5 N/m, respectively. This measure of extensibility correlated well with that measured with the FAST and KES-F systems.

Different weaves have different degrees of extensibility (Anderson, 2007). The amount of crimp within the fabric construction determines the extensibility of a fabric and higher the number of interlacings, the greater the crimp (Anderson, 2007). A plain weave has the greatest number of interlacings in a given area, and therefore the highest degree of crimp (Behera and Hari, 2010; Miao and Xin, 2017). A plain weave fabric will extend more than a twill weave fabric, which means the longer the floats within the construction the less extensible the fabric will be.

Problems caused by high and low extensibility

A high value of extensibility can give rise to difficulties in laying-up operations and also in seam production and it's also seen that the warp value is generally more important than the weft, due to the fact that tensions in laying-up are mainly imposed on the warp, and as well as the fact that in most garments, there are more warp direction seams, which are generally also greater in length (De Boos and Roczniok, 1996; Anderson, 2007; Qing Li et al., 2007; Erdumlu, 2015).

Low values of extensibility have been found to cause difficulties with overfeeding and moulding operations, and can also limit the comfort of the garments in wear (De Boos and Roczniok, 1996; Erdumlu, 2015).

2.8.2.6 Fabric bending properties

Generally, one of the first things done when picking up a fabric is to bend it. The force required to do this is known as bending rigidity (Lindberg et al., 1961; Cusick, 1965; Grosberg, 1966; Grosberg and Park, 1966; Grosberg et al., 1968; Erdumlu, 2015). The importance of bending rigidity in handle is obvious, but this property is also critical in making-up and garment appearance.

There are two approaches to the measurement of bending rigidity, the simplest is the cantilever test (Cusick, 1965; Grosberg, 1966). This simple test measures the bending length, which is the length of fabric required to cantilever to an angle of 41.5^0, this value then being combined with the fabric weight in calculating the fabric bending rigidity (Cusick, 1965; Grosberg, 1966; Ajeli, 2009; Sule, 2012).

A great deal of work has been undertaken on the bending of woven fabrics (Peirce, 1930; Lindberg et al., 1961; Cusick, 1965; Grosberg et al., 1968; Ajeli et al., 2009), far less having been done on weft knitted fabrics (Carnaby and Postle, 1974; Postle and Suurmeyer, 1974;

Hamilton and Postle, 1974, 1976; Hamilton, 1975) and on warp knitted fabrics (Davies and Owen, 1971). Bending properties of fabric are closely related to the fabric drape and handle (Lindberg et al., 1961; Sule, 2012; Erdumlu, 2015) as well as to the ease of tailoring fabrics into garments.

Ajeli et al., (2009) investigated and concluded that, bending rigidity increases for the fabrics with a higher density and underlap length of the front and back guide bars. According to Sule (2012) and Akter (2017), statistical analysis shows that the stiffness of woven fabrics has been affected significantly at 95% confidence interval both by the weave structure and weft count. As the weft count increases, the fabric stiffness is decreased, stiffness being one of the widely used parameter in bending rigidity. This is because, the increase in weft count decreases the fabric tightness and hence the stiffness is decreased. It is also found that the stiffness of plain weave fabrics is higher than the other forms of structures. The higher stiffness of the plain weave fabrics can be assigned to the higher tightness of fabrics.

Problems caused by high and low bending rigidity

A high bending rigidity indicates that the fabric is stiff and difficult to bend, this may detract from the drape characteristics of the fabric and can also cause difficulties during sewing operations (Grosberg et al., 1968; Lindberg et al., 1961).

Although a low bending rigidity can also cause difficulties during sewing operations, it is more likely to cause problems earlier in production, for example during automated handling and cutting operations (Lindberg et al., 1961; Grosberg et al., 1968; Gibson et al., 1979; Ajeli et al., 2009; Ozguney, 2009).

Bending rigidity is an important fabric property in terms of FOM.

2.8.2.7 Fabric shear rigidity

A fabric is sheared when it is distorted sideways or in the bias direction i.e. not along the warp or weft yarn directions (Bassett, 1981). Initially, fabric shear rigidity was measured by means of a special attachment to a tensile tester, the distortion of the fabric being measured under a given shear load (Behre, 1961; Behera and Shakyawar, 2000). Later, a much simpler approach was adopted in Australia, in that shear rigidity was calculated as a function of the bias extensibility of the fabric (Bassett, 1981). The shear behaviour of fabrics is an important component of various fabric properties, such as drape, handle, tailorability, shape retention and creasing (Hamilton and Postle, 1976; Dhingra and Postle, 1979). Various testing methods, for measuring the shearing properties of woven fabrics, have been developed (Morner and Eeg-Olofsson, 1957; Behre, 1961; Treloar, 1965; Bishop, 1996). Extensive research on the woven fabric shear has been undertaken (Cusick, 1961; Lindberg et al., 1961; Grosberg and Park, 1966; Grosberg et al., 1968; Hamilton, 1975; Hamilton and Postle, 1976; Jyothi et al., 2007; Hasani, 2010; Jahan, 2017) as well as some work on weft-knitted and warp-knitted fabrics (Gibson et. al. 1979).

Problems caused by high and low shear rigidity

Too high a value of shear rigidity can indicate problems relating to moulding operations, as it becomes difficult to form a smooth three-dimensional shape with fabrics that have high shear rigidity. Too low values of shear rigidity, on the other hand, are primarily associated with difficulties during laying-up operations, as the fabric will readily skew or bow on the table (Carnaby and Postle, 1974; Bassett, 1981; Jyothi et al., 2007; Hasani, 2010; Jahan, 2017).

Due to difficulties in forming a three dimensional shape, as a result of high shear rigidity, the garment doesn't fall (drape) well on the body, reflecting irregularities. Similarly, too low a

shear rigidity, may result in difficulties during laying-up, creating errors during cutting which might result in the fabric showing bow or skew.

2.8.2.8 Fabric formability

Technically, formability is a measure of the degree to which a fabric can be compressed in to its own plane before buckling occurs, and is derived from the fabric bending rigidity and extensibility (De Boos and Roczniok, 1996). According to Shishoo (1989), factors, such as formability and sewability can have a major influence on tailorability. De Boos and Roczniok (1996) stated that the concept of fabric formability was derived from fabric bending and longitudinal compressional properties, or from bending and tensile properties, which have been shown to predict tailoring performance to some extent (Lindberg et al., 1960; Mahar et al., 1983; De Boos and Roczniok, 1996; Mousazadegan, 2013; Das et al., 2017). As defined by Lindberg et al., (1960), fabric formability relates to the deformation that the fabric can bear before buckling, it providing a measure of how easily the two-dimensional flat surface of the fabric can be transformed into a three-dimensional shape, for example, at the shoulder of a jacket. Fabric formability can be used to predict the limit of overfeed before buckling and it is very important in determining the sewing performance of fabrics (De Boos and Roczniok, 1996). It is also the biggest single contributor to the occurrence of seam pucker in garments (De Boos and Roczniok, 1996).

Formability is not measured directly, but is derived from other fabric properties as follows:

Formability = bending length * extensibility

The formula for formability, on the basis of FAST variables, is as follows (Tester and De Boos, 1990):

$F = (E20 - E5) \times B/14.7$

Where F = formability of the fabric

E20 = extensibility of the fabric at 20 gf/cm

E5 = extensibility of the fabric at 5 gf/cm

B = bending rigidity of the fabric

Formability is important in overfeeding during sewing (Lindberg et al., 1960; Postle et al., 1983; Kawabata et al., 1986; Amirbayat and Hearle, 1989; Kawabata and Niwa, 1989; Erdumlu, 2015; Frydrych and Matusiak, 2015). Good sewability means the ease of formation of shell structures and styles, and absence of fabric distortion and seam damage. The most acceptable way of increasing formability is by increasing the extensibility of the fabric.

Formability measurements allow prediction of fabric performance in sewing operations, more specifically, prediction of seam pucker (Amirbayat and Hearle, 1989; De Boos and Roczniok, 1996). During seaming, the sewing thread, passing through the fabric, occupies space and hence the fabric tends to expand along the line of the seam (De Boos and Roczniok, 1996). If this tendency cannot be accommodated by in-plane compression of the fabric, buckling will occur, producing seam pucker (De Boos and Roczniok, 1996).

Wang et al., (2003) attempted to modify lightweight wool and wool-blend fabrics tailorability by increasing its bending rigidity and formability. Zhang et al., (2006) studied fabric softness and the results show that pulling force is significantly correlated to fabric's properties such as its bending rigidity, thickness, formability and extensibility. Doustar et al., (2010) examined the influence of weave design and fabric weft density on bagging of cotton woven fabrics. They concluded that fabric's formability increased significantly by increment in weft density. Alamdar-Yazdi and Bidoki (2010) and Frydrych and Matusiak (2015) agreed that the effect of the yarn twist on the formability of a woven fabric and their outcomes present that utilizing warp and weft yarns with unidirectional twist lead to higher fabric formability. In addition, in

this condition, if the total helix angle of warp and weft yarns is close to 90^0, highest fabric formability is expected. Kim and Kim (2011) investigated influence of fabric properties and sewing parameters on seam puckering formation and their results show that fabric properties affect sewn fabric appearance considerably compared to sewing parameters and among various fabric's properties, fabric bending rigidity and formability are the determinant factors. It can be concluded that formability affects fabric performance, such as buckling, seam pucker, which can result in seam damage.

Problems caused by high and low formability

If the fabric formability is too low, seam pucker is likely to result, whereas if it is too high, the fabric is able to accept compression, without buckling and resulting in a good seam (De Boos and Roczniok, 1996). The lower the formability, the more likely it is for seam pucker to occur, since the fabric is unable to accommodate the small compressions placed on the fabric by the sewing thread (Amirbayat and Hearle, 1989; De Boos and Tester, 1994). Puckering and sleeve settings represent common problems experienced with low fabric formability. Factors which can influence formability, include, weave structure and fabric density (compactness or tightness) (De Boos and Roczniok, 1996).

2.9 Objective measurement of other fabric sensory properties relevant to fabric handle and overall quality

2.9.1 Thermal and water vapour transmission

Fabric thermal and water vapour transmission properties are important in terms of fabric and garment comfort and are therefore often measured. In a series of papers, Yoneda and Kawabata (1983) have discussed heat conduction and transmission and their relation to the thermal

properties of fabrics (Hollies and Goldman 1977; Yoneda and Kawabata, 1983, 1985, 1988; Angelova, 2015). They have identified the parameters that influence the perception of the warm/cool feeling of fabrics and have developed instruments for their measurement. Hes and Dolezal (1989) have also described new methods for measuring thermal properties of textiles, and these have led to the development of commercially available instruments for measuring thermal conductivity, thermal diffusivity, thermal absorptivity and thermal resistance, as well as instrument for measuring water and water vapour permeability of textiles. The thermal resistance of a fabric, and even of a garment, is generally determined by the volume of the air entrapped in the fabric or garment. Water vapour transmission mainly depends upon the pores within fabric and their distribution, and can be changed by changing thread density, yarn count and yarn surface characteristics (Chattopadhyay, 2008; Angelova, 2015). Woven fabrics have well defined pores, in knitted fabrics the pores are generally at an angle with respect to the fabric plane, whereas nonwovens have a wide range of pores, the upper and lower limits of which depend upon the method of production. Thermal manikins have been developed which allow the comfort related properties, such as heat and water vapour resistance, to be measured under conditions which simulate actual wear (Gavin, 2003; Konarska, 2006; Wang, 2010).

2.9.2 Drape

It is likely that, when fabrics are handled unseen, all the mechanical properties that determine drape are sensed by hand. Similarly, objective measurement, of appropriate fabric mechanical properties, may permit accurate prediction of drape coefficient (Hearle and Amirbayat, 1986; Amirbayat and Hearle, 1989; Collier et al., 1991; Vangheluwe and Kiekens 1993; Postle, 1993). Since the drape coefficient is easily measured, there is also a case for its inclusion in the objective parameters to be used for the prediction of fabric handle and quality. Nevertheless, drape is largely a function of the fabric shear and bending rigidity (Cusick, 1965; Vangheluwe and Kiekens, 1993; Tokmak 2010; Sule, 2012; Erdumlu, 2015).

2.9.3 Surface appearance, lustre and hairiness

The appearance of fabric can influence the subjective assessment of handle, the nature of fabric surfaces being considered to make an important contribution to fabric handle, as perceived by the Japanese expert panel used by Kawabata (Kawabata, 1975). Fabric properties, such as hairiness and lustre, contribute in different ways to the perception of fabric quality for different end-uses. The smoothness or hairiness of a fabric has an important effect on the "contact comfort" experienced by the wearer when in contact with the fabric. It is therefore surprising, that current FOM systems, even when designed to correlate with visual assessments of fabric hand, do not measure these properties. It is apparent that instruments designed to measure fabric roughness, by optical methods, can also give accurate information on the height and distribution of fuzz fibres and/or pills (Ramgulam et al., 1993).

2.9.4 Fabric prickle

Prickle is a rather negative attribute, associated particularly with fabrics containing a proportion of relatively coarse wool or other fibres, for example about 30 µm or coarser in diameter (Garnsworthy et al., 1988; Matsudaira, 1990; Naylor et al., 1992). These fibres are sufficiently stiff to stimulate particular nerve endings, on or just below, the surface of the skin, causing a pain or prickle sensation when fabrics, containing them, are worn next to the skin.

Since very many applications of FOM technology have been, and continue to be, concerned with the handle and quality of wool and wool-containing fabrics, it would seem appropriate to include prickle in the criteria against which they are evaluated (McGregor et al., 2015). Naylor et al., (1992) have shown that an instrument, based on a modified audio pick-up, can be used to give a signal related to the stiffness of fibre ends protruding from the fabric. Good correlation was obtained between its objective measurement of prickle and subjective assessment of

prickle, and the technique has been successfully applied to the evaluation of finishing processes for selected fabrics (Matsudaira, 1990; Ramsay et al., 2012).

To understand the sensation of fabric-evoked prickle and to avoid cost and time involved with conducting wearer trials, the Wool ComfortMeter (WCM) has been developed to provide a rapid instrumental approach to replace subjective, lengthy and expensive wear trials (Ramsay, 2010; Tester, 2010; Ramsay et al., 2012; Naebe and McGregor, 2013; McGregor and Naebe, 2013; Naebe et al., 2013; Stanton et al., 2014; Sun et al., 2017). The Wool HandleMeter is a recently developed device to measure the handle parameters of knitted single jersey fabric (Mahar and Wang, 2010; Wang et al., 2013; Wang et al., 2014). According to McGregor et al., (2015), the handle and comfort properties of lightweight, wool jersey fabrics can be quantified accurately using the Wool HandleMeter and Wool ComfortMeter.

2.9.5 Seam puckering

Seam pucker is a distortion of the surface of a sewn fabric and appears as a "swollen" or "corrugated" effect along the line of the seam (Rosenblad-Wallin and Cednas 1973). Seam pucker is influenced by the sewing thread tension, sewing machine variables and certain fabric properties, such as formability (Rosenblad-Wallin and Cednas, 1973; De Boos and Tester, 1991). Kawabata et al., (1991) showed a clear correlation between seam pucker and the fabric mechanical properties. Seam pucker, related to the fabric mechanical properties, appeared most apparent in a seam line when overfeed was applied (De Boos and Tester, 1991).

2.10 Other FOM methods

Although the Kawabata and FAST systems dominate fabric objective measurement, various other alternative methods have been developed (Kawabata and Niwa, 1998; Fan et al., 2002), such as, universal tensile tester based (Lord et al., 1988; Pan et al., 1993; Bereck et al., 1997; Sule and Gurudutt, 2000; Ramkumar, 2000; Chen et al., 2001; Alamdar-Yazdi, 2004), a

polymeric human finger sensor (Ramkumar, 2000; Ramkumar et al., 2003), pressure sensitive glove (Lee et al., 2007), measuring the force required to pull a fabric through a ring or nozzle (Alley and Mchattan, 1978; Behery, 1986; Pan and Yen, 1992; Grover et al., 1993; Kim and Slaten, 1999; Siedel, 2001; Strazdiene et al., 2002; Daukantiene, 2005) or through pins (Zhang et al., 2006), as well as a system of online measurement of fabric compressional behavior (Huang and Ghosh, 2002). Breugnot et al., (2006) used differences in the mechanoreceptors of the skin, to tactile stimuli, to modify mechanical measurement of fabric touch or handle.

Inspite of all the above developments and very many new and advanced techniques and testing instruments, it is safe to say that the Kawabata and FAST systems are presently still the only two which have been accepted internationally for research and industrial purposes.

2.11 Use of regression analysis in FOM

For any kind of assessment or evaluation in FOM, whether in the industry or for research purposes, regression analysis has been carried out many a times and the results have been positive. Most of the research work done (Mu et al, 1994; Ozcelik et al., 2008; Sular and Okur, 2008; Krasteva and Kandzhikova, 2015; Sanad and Cassidy, 2016) relating to FOM and using regression analysis for a further clarification to obtain accuracy in the outcomes in the form of statistical analysis supports the fact. Mu et al., (1994), tried to obtain the clarity on micro differences on same kinds of fabric on fabric lustre, therefore preferred to adopt regression analysis in obtaining the same. Ozcelik et al., (2008), has tried to evaluate the fabric handle of 20 different shirt fabrics objectively, for which they preferred to carry out multiple regression analysis from where both subjective and objective measurement results were obtained. Similarly, Sular and Okur (2008) prepared a database of 71 worsted men's suitings and used linear regression analysis using 43 parameters to predict fabric handle. Krasteva and Kandzhikova, (2015), also used the regression analysis method for their research work to carry

on an integrated assessment for the objective evaluation of terry fabric handle. Sanad and Cassidy (2016), have worked on the drape aspect of FOM by using regression analysis to obtain accuracy. Hence all the above researchers have used and were benefitted in terms of the clarity of the outcomes post using the regression analysis method. This acted as a stepping stone in motivating the current research work to use regression analysis, ANOVA in particular in this case, to obtain validity and accuracy in the results obatined.

2.12 South African apparel industry

The recent turbulence in global markets has left the South African clothing and textiles industries particularly vulnerable to cheap imports from China and other Asian countries. A substantial increase in textile and apparel import and weakened rand have put strain on the industries trade balance, causing unemployment levels to suffer correspondingly. Furthermore, import taxes on certain fabrics, which is the biggest input cost for the clothing industry (Mail and Guardian, 2014). Given the sectors intensive employment of low-skilled labour as a factor of production and thus its importance to the South African economy, the present crisis that has been the same for the past few years is all the more pressing (CCTC, 2014). The use of locally manufactured products enables quicker delivery times, adds value to local economic development and therefore Gross Domestic Product (GDP), and allows retailers to capitalize on fashion trends more quickly.

The South African wool Industry provides a high-quality, environmentally-sound product which meets the needs of the textile industry. On-farm classing and clip preparation for greasy wool is of a high standard and is considered one of the many tangible assets of the industry (Cape Wools SA, 2016). South African wool has, over the years, earned a reputation for uniformity, softness to the touch and other quality features. According to Cape Wools SA, 2016, the statistical overview says that the South African wool fetched an average price of

R77.40 per kg, which is a 29.13% increase from last season's average price with a slight drop of 0.16% in production. Similarly, according to Cape Wools SA (2016), the annual sales statistics for 2016/2017 shows that there has been a sales of over R4.21 billion in the all wool category as against R3.75 billion for the year 2015/2016. Wool and woolen fabrics, specifically mohair, form part of the niche apparel market, and therefore needs to undergo special tests, such as on the FAST instrument, to check the quality parameters making it more and more available for people to use locally to generate products out of it and also internationally making it available to all. Looking at the incomparable quality of South African wool, its sales figures which speaks volumes and a continuous demand in the local as well as the international market led to doing a research work on the wool and wool blend fabrics manufactured and used by the clothing and textiles companies in South Africa. Also doing a background research on creating a database on FOM parameters (Gider, 2004; Fan et al., 2004; Fairhurst 2008; Sular 2008; Sular and Okur, 2008; Sanad et al., 2012), brings to the knowledge that, people have worked on creating database or a referencing system using one or a few FOM parameters and have used a small amount of fabric to obtain an outcome out of it. But no one in particular from South Africa, where FAST isn't used as much (Das et al., 2015; Das et al., 2017), had tried to create a similar analysis and come out with an overall outcome, which can be used as a reference or benchmarking system by clothing and textile manufacturers. Working on this research was only possible by collecting and analyzing a larger number and variety of fabrics of different fabric structure and blend composition before coming down to a conclusion.

2.13 Motive behind doing the research

There can be no doubt that the adoption of FOM has beneficially affected the quality of worsted (wool and wool blend) and other types of apparel fabrics in many countries producing fabrics and garments of high quality, and which compete with South Africa in this respect. Nevertheless, a previous survey and study of the local apparel manufacturing and retailing

sector (Das, 2011; Das and Hunter, 2015; Das et al., 2015; Das et al., 2017) showed that FOM has not been adopted to any significant extent in South Africa and that, in fact it was hardly known here. It was therefore considered necessary to undertake a study on the FOM (in this case FAST) properties of commercial worsted type apparel fabrics produced in South Africa and to use the information so generated to produce a list of FOM properties which can be used by local manufacturers. In doing so it was important to identify those fabric parameters (e.g. weave, weight and composition) which influence the FAST measured properties in order to produce FAST "fingerprints" which can be used as a basis of reference or benchmark by the local worsted fabric manufacturers.

3. Experimental

3.1 Introduction

The research was initiated by sample collection, with the collection of some 394 different worsted apparel fabrics. Most of the fabrics were collected from and with the assistance of the leading worsted fabric and clothing manufacturers as well as a few retailers, mostly in the Western Cape province, as this province has the most and leading formal clothing manufacturers. The companies assisted in ensuring that the fabrics were representative of the worsted type fabrics and or clothing. At least $1m^2$ fabric sample was taken in each case. The fabric testing was carried out at the CSIR, Port Elizabeth, laboratory, where a FAST instrument is located. FAST testing, and analysis results are detailed in what follows.

3.2 Materials

The 394 fabrics sourced were commercial worsted type suiting fabrics, typical of men's and ladies suitings and related formal wear, manufactured in South Africa and ranged in weight from about 100 to 300 g/m^2. The fabrics were grouped into three groups, namely: plain, twill and other and also into various broad blends groups namely: 100% wool (100W), Wool/Mohair (W/M), Wool/Polyester (W/PES), Acrylic/Wool (Ac/W) and Polyester/Viscose (PES/V). Table 3.1 provides details of the fabrics. As can be seen from Table 3.1, the fabrics mainly comprised pure wool and some wool blends (here it covers, W/M, W/PES, Ac/W and PES/V), and plain and twill weave structures, which again, are known to be typical of formal men's and ladies wear fabrics and garments produced in South Africa, and was confirmed by the respective local manufacturing and local sectors.

Table 3.1: Details of fabrics

Number of fabrics

Fabric composition	Twill weave	Plain weave	Other structures (venetian,gabardine, barathea, hopsack, herringbone)	Total
100W	109	67	27	203
Wool blends	25	61	13	99
Other blends	22	58	12	92
Total	156	186	52	394

Tables 3.2 and Table 3.3 shows the average fabric weight and thickness according to structure and blend. It is apparent from the two tables that, as would be expected, the twill weave fabrics were on average, heavier and thicker than the plain weave fabrics, the 'other' fabric structure were the thickest and heaviest, on average, which is again as to be expected on the basis of their structures.

Table 3.2: Average weight (mass) of the different fabric structures and blends

	Average fabric weight (g/m^2)		
Fabric Blend	**Twill weave**	**Plain weave**	**Other structures** (venetian,gabardine, barathea, hopsack, herringbone)
100W	251	189	274
Wool blends	239	198	210

Table 3.3: Average thickness of the different fabric structures and blends

Fabric blend	Fabric thickness (mm)		
	Twill weave	Plain weave	Other structures (venetian,gabardine, barathea, hopsack, herringbone)
100W	0.66	0.45	0.71
Wool blends	0.62	0.46	0.61

3.3 Fabric tests

The worsted fabrics were tested on the range of FAST instruments, according to the prescribed test method in the FAST Manual, and will be described later. Samples were conditioned under standard atmospheric conditions (60±5% Relative Humidity (RH) and 20±3^{0}C), in an "open" state, for atleast 24 hours prior to testing. In brief, the FAST tests were carried out on the various FAST instruments as follows:

FAST 1 – Compression meter

The FAST-1 test involved measuring the thickness of the fabric at two loads, namely 2gf/cm^2 and 100 gf/cm^2. From each fabric sample, five specimen, each measuring 300 mm x 300 mm, were cut for testing. For each sample, 250 mm x 250 mm was marked at its corners and mid-points thereby ensuring a 25 mm margin between the edges of the fabric and that to be tested (Barndt, 1990). The fabric sample was placed on the Compression meter, and subjected to a load of 2 gf/cm^2 and then to one of 100 gf/cm^2, in sequence, and the two corresponding measurements recorded. The difference in the two thickness readings is termed, and provides a measure of, the thickness of the surface layer of the fabric (Kremenakova et al., 2008; Sirkova, 2012; Angelova, 2015). The fabric thickness measurements were repeated after the

fabrics had been steamed on a Hoffman press for 30 sec (Patricia, 2012), in order to determine the stability of the surface layer. The value obtained after the fabric had been steamed, is known as the "released surface thickness" (Smuts et al., 1991). This measurement can indicate the potential re-emergence of certain aspects, such as running marks.

FAST- 2 – Bending meter

The FAST – 2 Bending meter measures the fabric bending length, a measure of fabric stiffness, which is a critical property in making-up and tailorability, using the cantilever principle. The bending length obtained is used to derive bending rigidity. For each fabric sample, five specimens, each measuring 300 mm x 300 mm, were cut for testing. Each sample 250 mm x 250 mm, was marked at its corners and mid-points, ensuring a 25 mm margin between the edges of the fabric and the measurement region. This procedure permits five warp and five weft measurements to be made for each fabric. The fabric specimen was placed on the Bending meter, projected until it reached the specified angle of 41.5^{0}, at the vertical edge of the instrument. The value recorded at this point taken were made in each of the warp and weft directions, and averaged for each direction, is the bending length of the fabric in all five measurements. The bending rigidity, which is related to perceived stiffness, is calculated from the bending length and fabric mass/unit area.

FAST -3 – Extension meter

The FAST – 3 Extension meter measures the extensibility of the fabric (De Boos and Roczniok, 1996; Anderson, 2007; Qing Li et al., 2007; Erdumlu, 2015) at three different loads 5, 20 and 100 gf/cm, in the warp and weft directions and, at the lowest load (5gf/cm) also in the bias direction of 45^{0}. The fabric is held tightly at both ends via a fabric clamping device (jaw), which is tightened by a knob present in the centre (Boos and Tester, 1994). From each fabric, five specimen each measuring 300 mm x 300 mm, were cut for testing. Each sample 250 mm

x 250 mm was marked at its corners and mid-points, ensuring a 25 mm margin between the edges of the fabric and the measurement region. Each of the fabric specimen was placed on the Extension meter, and subjected to stretch (extension) at various loads. Three weights were loaded one after the other, to obtain the extensibility of the fabric under the three different loads, namely i.e. 5, 20 and 100 gf/cm. five warp and five weft measurements were made for each fabric sample, and their results averaged. The bias extension was converted to shear rigidity, which is directly related to the ease with which the fabric can be distorted or extended along its plane. Extensibility is used, in conjunction with bending rigidity, to calculate formability of the fabric (Boos and Roczniok, 1996; Anderson, 2007; Qing Li et al., 2007; Erdumlu, 2015).

FAST - 4 - Dimensional stability test

The FAST – 4 dimensional stability test measures the dimensional stability of the fabric, where the fabric is subjected to a cycle of drying, wetting and then drying again, in an oven (Boos and Roczniok, 1996; Qing Li et al, 2007). After each stage, the fabric dimensions, in both warp and weft directions, are measured. From each fabric, three specimen, each measuring 300 mm x 300 mm, were cut for testing. For each specimen 250 mm x 250 mm was marked at its corners and mid-points, ensuring a 25 mm margin between the edges of the fabric and the measurement region. Three warp and three weft measurements are made for each fabric and their results averaged. The samples were relaxed in water containing a wetting agent, in a tray, for an hour at 35^0C, and their wet dimensions measured, with the fabric still immersed in the water. After removal of excess water, by gently patting with a towel, the fabrics were dried in a convection oven for an hour at 106^0C. Measurements of the dry dimensions were made within 30 seconds after the sample was removed from the oven. Hygral expansion and relaxation shrinkage values were derived from the results obtained (Wemyss and White, 1985; Frydrych, 2003). The detailed FAST test results of the 394 fabrics are given in appendices.

Abbreviations used for FAST parameters

The various abbreviations used for the FAST parameters are as follows:

RS – 1%: Relaxation shrinkage along the warp-wise direction

RS – 2%: Relaxation shrinkage along the weft-wise direction

HE – 1%: Hygral expansion along the warp-wise direction

HE – 2%: Hygral expansion along the weft-wise direction

F – 1 mm^2: Formability along the warp-wise direction

F – 2 mm^2: Formability along the weft-wise direction

E5 - 1%: Extensibility at 5gf/cm in the warp-wise direction

E5 – 2%: Extensibility at 5gf/cm in the weft-wise direction

E20 - 1%: Extensibility at 20gf/cm in the warp-wise direction

E20 – 2%: Extensibility at 20gf/cm in the weft-wise direction

E100 – 1%: Extensibility at 100gf/cm in the warp-wise direction

E100 – 2%: Extensibility at 100gf/cm in the weft-wise direction

EB5%: Bias extension

C – 1 (mm): Bending length along the warp-wise direction

C – 2 (mm): Bending length along the weft-wise direction

B – 1 (µN.m): Bending rigidity along the warp-wise direction

B – 2 (µN.m): Bending rigidity along the weft-wise direction

G (N/m): Shear rigidity

T2 (mm): Average thickness at 2gf/cm^2

T100 (mm): Average thickness at 100gf/cm^2

ST (mm): Surface thickness

T2R (mm): Average released thickness at 2gf/cm^2

T100R (mm): Average released thickness at 100gf/cm^2

STR (mm): Released surface thickness

3.4 Regression (ANOVA) analysis

For the ease of understanding and interpreting the ANOVA regression analysis tables, dummy variables have been assigned and allocated on the basis of fabric weave structure (F1 and F2) and blend (B1, B2, B3, B4), as also proposed by Mendenhall and Sincich (1996). In Table 3.4, the fabric weave structure dummy variables has been assigned with the twill structure as the reference (hence '0' for F1 and F2) and analysed against the plain and 'other' structures, which means, that the plain weave and 'other' structures are compared to the reference i.e. twill, with '1' indicating which one is being compared to the reference fabric. If F1 is significant, it means that 'other' structures differ statistically significantly from the reference (twill) and if F2 is significant, it means, the plain weave fabrics differ statistically significantly from the reference (twill) fabrics.

Table 3.4: Allocation of dummy variables on the basis of fabric weave structure

Weave structure	F1	F2
Twill	0	0
Plain	0	1
Other	1	0

In Table 3.5, fabric blends, dummy variables have been assigned with the 100W fabrics as reference, as shown in Table 3.5, the '1' indicating which blend is compared to the reference. Therefore, if B1 is significant, it means the W/PES blend fabrics is differing statistically significantly from the reference blend i.e. the 100W fabrics, and so on for B2, B3 and B4.

Table 3.5: Allocation of dummy variables on the basis of blends

Blend		B1	B2	B3	B4
Composition	**Code**				
100% Wool	100W	0	0	0	0
Wool/Polyester	W/PES	1	0	0	0
Acrylic/Wool	Ac/W	0	1	0	0
Wool/Mohair	W/M	0	0	1	0
Polyester/Viscose	PES/V	0	0	0	1

ANOVA (Analysis of variance), the mode of regression analysis was carried out on the FAST test results to determine the effects of certain independent fabric parameters, such as mass, thickness, weave structure and blend, on the various FAST properties. The FAST parameters have been discussed and are named as in brackets: Relaxation shrinkage (RS –1% and RS-2%), Hygral expansion (HE –1% and HE-2%), Formability (F–1 and F-2), Bending rigidity (B-1 μN.m and B-2 μN.m), Extensibility at 100 gm/cm^2 and along the bias direction (E100-1% and E100-2%), Shear rigidity (G N/m), Thickness (T2 mm), Surface thickness (ST) and Surface thickness released (STR).

ANOVA regression analysis, can provide new statistically sound insights that can help in decision making and lend quantitative support towards any discussion (Bagozzi et al., 1991; Lozano, 2008; Lieberman, 2008; Brinkman et al., 2009). The ANOVA provides a statistically sound test of whether or not the means of several groups are equal, and therefore generalizes the *t*-test to more than two groups at a time.

ANOVA is a particular form of statistical hypothesis testing which is frequently used in the analysis of experimental data (Lozano, 2008). According to Lieberman (2008) a test result (calculated from the null hypothesis and the sample) is called statistically significant if it is deemed unlikely to have occurred by chance, assuming the truth of the null hypothesis. A statistically significant result, when a probability (p-value) is less than a threshold (significance level), justifies the rejection of the null hypothesis, but only if the prior probability of the null hypothesis is not high (Lieberman, 2008). Brinkman et al., (2009) agree to the fact that in the typical application of ANOVA, the null hypothesis is that all groups are simply random samples of the same population. For example, when studying the effect of different treatments on similar samples of patients, the null hypothesis would be that all treatments have the same effect (perhaps none). Rejecting the null hypothesis would imply that different treatments result in altered effects. In short, ANOVA is a statistical tool used in several ways to develop and confirm an explanation for the observed data.

The F-test

The F-test is used for comparing the factors of the total deviation (Box and Cox, 1964; Kutner et al., 2004).

If the test statistic is much larger than the critical value, the null hypothesis of equal population means is rejected and it can be concluded that there is a (statistically) significant difference between the population means (Kutner et al., 2004). The value of F is 1 for no treatment effect.

As the value of F increases above 1, the evidence becomes increasingly inconsistent with the null hypothesis.

The following steps are used to implement a regression model and analyze the results (Anderson, 2013), which more or less resembles the mode of regression analysis carried out i.e. ANOVA and interpreted in the research work on worsted type apparel fabrics, as discussed in Chapter 4:

- Specify the dependent and independent variables

- Check for linearity

- Check alternate approaches if variables are not linear

- Estimate the model

- Test the fit of the model using the coefficient of variation (R^2)

- Perform a joint hypothesis test on coefficients (if a multiple regression model)

- Perform hypothesis test on the individual regression coefficients

- Check for violations of the assumptions of regression analysis

- Interpret the results

- Forecast the future values

Hence the regression analysis assists in determining the validity of relationships between independent and dependent variables.

3.5 Average FAST properties and finger print charts

There has been a great deal of research on a large number of the worsted woolen fabrics (Gider, 2004; Fan et al., 2004; Fairhurst, 2008; Sular, 2008; Sular and Okur, 2008; Sanad et al., 2012), aimed at creating databases, using one or more FOM parameters. But no such databease have been created or developed, here in South Africa. Mean and standard deviation values were obtained for each FAST property and each group of fabrics (see in Table 3.6). Similar tables are created for mean and standard deviation values of fabrics specifically on the basis of fabric structure and blends.

Table 3.6: Mean and standard deviation values of FAST properties according to fabric structure and blend

Fabric structure and blends FASTproperties	Twill weave 100W	Twill weave wool blends	Plain weave 100Wool	Plain weave wool blends	Other 100W	Other wool blends
RS-1 %	1.83	1.04	2.19	0.99	1.81	0.72
RS-2%	0.73	1.03	0.55	0.66	0.85	0.67
HE-1%	3.59	1.42	3.27	1.60	3.65	0.52
HE-2%	4.10	1.61	3.37	1.63	4.00	0.79
F-1mm^2	0.74	0.63	0.39	0.37	0.73	0.38
F-2mm^2	0.78	0.42	0.44	0.33	0.76	0.41
E5-1 %	0.35	0.29	0.31	0.28	0.36	0.36
E5-2 %	0.50	0.32	0.43	0.25	0.44	0.35
E20-1 %	1.07	0.87	0.96	0.80	1.00	0.96

E20 -2%	1.65	0.96	1.31	0.71	1.31	1.02
E100-1 %	2.96	2.54	2.75	2.45	2.67	2.54
E100-2 %	4.68	2.70	3.99	2.56	3.76	2.93
EB5	3.65	3.18	3.41	2.55	3.83	3.07
C-1 mm	17.94	18.12	16.89	16.52	18.82	16.84
C-2 mm	16.36	16.96	17.14	19.19	16.86	18.94
B-1 (µN.m)	14.76	15.80	9.36	9.45	16.12	10.57
B-2 (µN.m)	11.27	12.77	10.59	11.08	13.15	9.39
G (N/m)	40.69	56.21	42.37	57.80	39.83	45.00
T2 mm	0.67	0.62	0.46	0.47	0.71	0.61
T100 mm	0.55	0.057	0.39	0.53	0.64	0.49
ST mm	0.10	0.05	0.06	-0.06	0.07	0.11
T2R mm	0.75	0.66	0.48	0.50	0.70	0.61
T100R	0.57	0.59	0.40	0.54	0.66	0.50
STR	0.17	0.10	0.08	0.03	0.10	0.15

The mean and standard deviation values obtained for each of the FAST properties were used to formulate the FAST referencing system and the corresponding control charts (fingerprints) for the different fabric weave structures and blends.

The ultimate aim was to develop FAST fingerprints for each of the above mentioned fabric groups where they are if different, and which are typical and representative of each particular group of worsted apparel fabrics used in South Africa.

4. RESULTS AND DISCUSSION

4.1 Effect of fabric structure and fibre blend on FAST properties

4.1.1 Introduction

Before developing a meaningful FAST data system and fingerprint, which can be of practical value for the South African worsted apparel fabric and clothing industry, it is first of all necessary to determine what influence, if any, fabric structure (weave), weight and blend have on the various FAST parameters, since this will impact on the way the 'fingerprints' are prepared and presented and used for reference and benchmarking purposes. First of all, the mean (average) and standard deviation (SD) of each FAST parameter have been calculated for each of the above groups, in order to determine whether or not they differ statistically significantly. Furthermore, ANOVA has also been carried out in the following sections, the results of these analysis are presented in tabular and/or graphical forms, as appropriately on each of the FAST parameters to determine which of the aforementioned fabric parameters play a statistically significant role in describing each of the FAST parameters and discussed for each FAST parameter in turn.

4.2 Relaxation shrinkage in the warp direction (RS – 1%)

4.2.1 Mean and standard deviation values of RS – 1%

The first FAST property (parameter) considered, is that of percentage relaxation shrinkage (RS – 1%) in the warp direction. Figure 4.1 (a) presents the Mean and standard deviation values for RS – 1%, according to fabric structure, the corresponding 95% confidence limits being shown on the bar charts. From the figure, it is clear that, although the differences are relatively small, the twill and plain weave fabrics have on average, a slightly, though significantly, higher relaxation shrinkage (RS – 1%) than the 'other fabric' group, with the values of the plain and twill weave fabrics not differing statistically significantly. The standard deviation values indicate that the results for individual fabrics, within a weave structure group, varied greatly,

which is not entirely unexpected, considering the fact that these are commercial fabrics, sourced from different fabric and garment manufacturers and of different weights and blends.

Mean and SD values of RS - 1%

	Other	Twill	Plain
■ Mean	1.32	1.61	1.58
□ SD	0.95	1.27	1.5
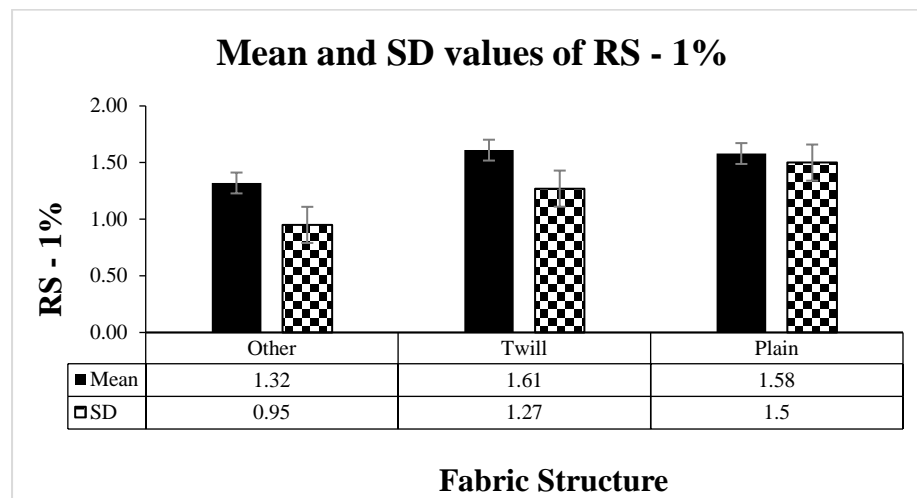
Fabric Structure

Figure 4.1 (a): Mean and SD RS -1% values for the different fabric weave structures
(*The error bars in the graph represents the 95% confidence limits)

The mean and standard deviation values of RS – 1% for the different blends are presented graphically in Figure 4.1(b), from which it can be seen that, on average, the PES/V blend fabrics had the highest relaxation shrinkage, followed by the W/M and W/PES fabrics. Nevertheless, the differences between the averages of the different blends are generally quite small, and probably of little practical consequence. Hence fabric blend need not be considered when deriving "benchmark" values for RS – 1% for worsted type apparel fabrics. As in the case of the weave structure groups, the standard deviation values, indicate, once again that the results of the individual fabrics within a group, in this case of blend group, vary widely and overlap considerably, as also previously reported and illustrated in a research paper already published from this research (Das et al., 2017).
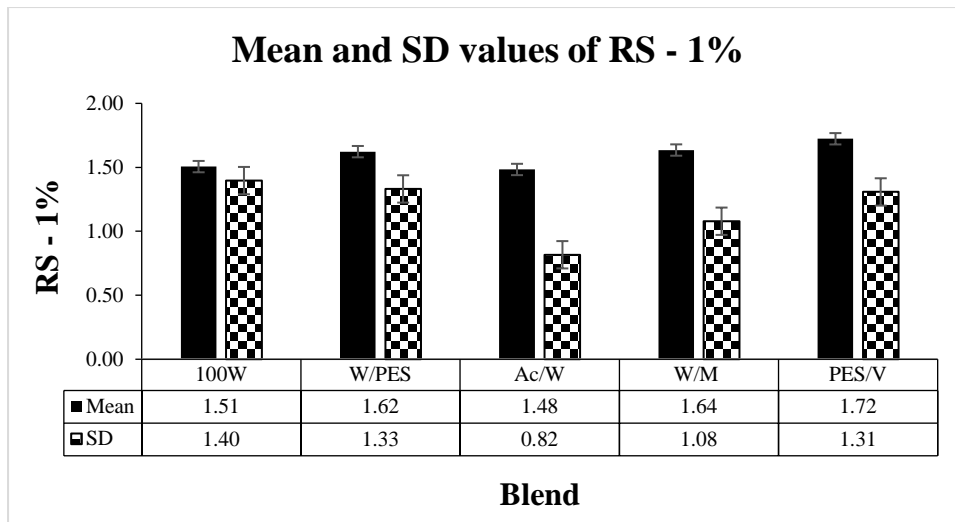
Figure 4.1 (b): Mean and SD RS -1% values for the different blends

(*The error bars in the graph represent the 95% confidence limits)

4.2.2 Analysis of Variance (ANOVA) for RS – 1%

ANOVA was carried out with RS – 1% as dependent variable and fabric structure (F1 and F2), blend (B1, B2, B3, B4), mass (g/m^2) and thickness (mm) as independent variables. The P-values that are statistically significant are highlighted in bold and italics for clarity and for ease of differentiation.

Table 4.1: Results of ANOVA for RS-1%

ANOVA for RS – 1 %	
Multiple R	0.419549143
R Square	0.176021483
Adjusted R Square	0.158396274
Standard Error	1.231501927
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	121.1690159	15.14612699	9.986916119	1.2503E-12
Residual	374	567.2072765	1.516596996		
Total	382	688.3762924			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.773505913	0.369141461	2.09541868	*__0.036805716__*	0.04765302	1.499358802
F1	-0.166386186	0.199433455	-0.834294255	0.404647748	-0.55853761	0.225765239
F2	0.529616943	0.167257535	3.166475843	*__0.001669639__*	0.20073391	0.85849998
B1	-1.149678452	0.154456186	-7.443395343	*__6.81406E-13__*	-1.45338985	-0.845967056
B2	-0.780392854	0.355844021	-2.193075638	*__0.028917128__*	-1.48009863	-0.080687082
B3	-0.974543776	0.33273144	-2.928920017	*__0.003609807__*	-1.62880265	-0.3202849
B4	-0.655396438	0.247042277	-2.652972787	*__0.008318652__*	-1.14116238	-0.169630494
Mass (g/m^2)	0.001433495	0.001548636	0.925649858	0.355224864	-0.00161163	0.00447862
Thickness (mm)	1.146760519	0.592797191	1.934490475	0.053806759	-0.01887271	2.312393749

The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes the exponential value.

According to Table 4.1, F2, which represents the plain weave, differs significantly from the twill weave. It is also evident, that fabric blend, but not thickness and mass, had a statistically significant effect on the fabric relaxation shrinkage in the warp direction (RS-1%), which is in agreement with the Mean and standard deviation values, as illustrated in Figure 4.1 (a) and (b). This agree with the results obtained in previous studies, where it was found that fabric blend

and structure, and not fabric thickness and mass, tended to influence fabric relaxation shrinkage (Goktepe, 2002; Doustaneh et al., 2013).

4.3 Relaxation shrinkage in the weft direction (RS – 2%)

4.3.1 Mean and standard deviation values of RS – 2%

Figure 4.2 (a) presents the average and standard deviation values for relaxation shrinkage in the weft direction (RS – 2%) for the different fabric weave structures. From Figure 4.2 (a) it is apparent that, as in the case of the warp relaxation shrinkage (RS – 1%), the "other" fabric structures had the lowest relaxation shrinkage in the weft direction, with that of the twill and plain weaves not differing statistically significantly this once again being in line with the results of Goktepe (2002) and Doustaneh et al., (2013), they agreed that fabric structure, tends to influence fabric relaxation shrinkage. What is also very clear from the relatively large standard deviation values, is that the individual fabric values within a weave group generally vary widely and overlap greatly with those form the other weave groups as reported previously (Das et al., 2017).

Mean and SD values of RS - 2%

	Other	Twill	Plain
■ Mean	0.58	0.76	0.74
■ SD	1.25	1.04	1.12
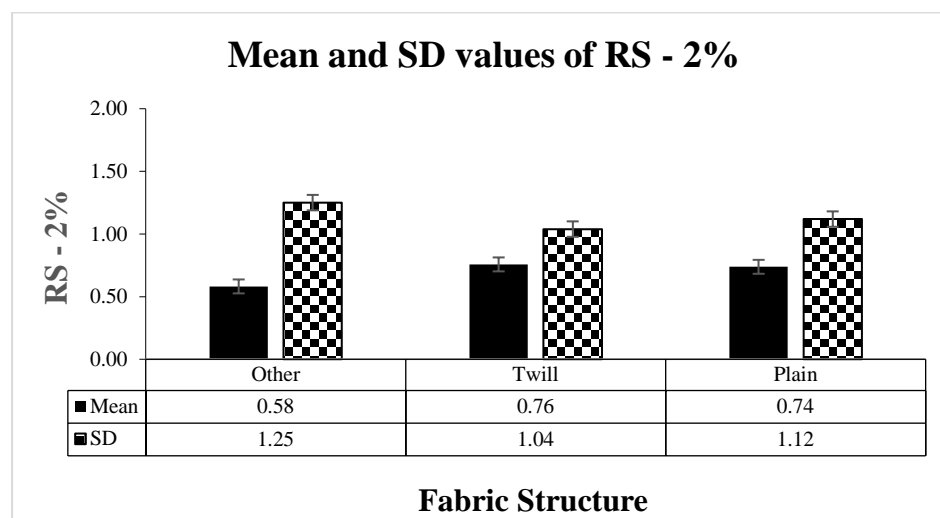
Fabric Structure

Figure 4.2 (a): Mean and SD RS - 2 % values the different fabric weave structures

(*The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of the relaxation shrinkage values in the weft direction (RS – 2%) for the various blends are presented in Figure 4.2 (b), from which it is apparent, that as in the case of RS – 1%, the PES/V fabrics had, on average, the highest relaxation shrinkage in the weft direction, followed by the W/M fabrics, with that of the Ac/W blend being the lowest, although the individual values within a blend varied considerably, as reflected in the standard deviation values (CV% ≥ 100%). According to the research by Liao and Brady (2010), weave structure and thickness can play a role in relaxation shrinkage, but factors like dyeing and finishing also have an effect and need to be considered. This is particularly important when dealing with commercial fabrics as is the case here. Nevertheless, the differences in the average weft relaxation shrinkage values were relatively small (extreme range is less than 0.55% absolute) and probably of little practical significance.

Mean and SD of RS - 2%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.70	0.61	0.63	0.94	1.16
□ SD	1.16	1.00	0.60	1.46	0.86
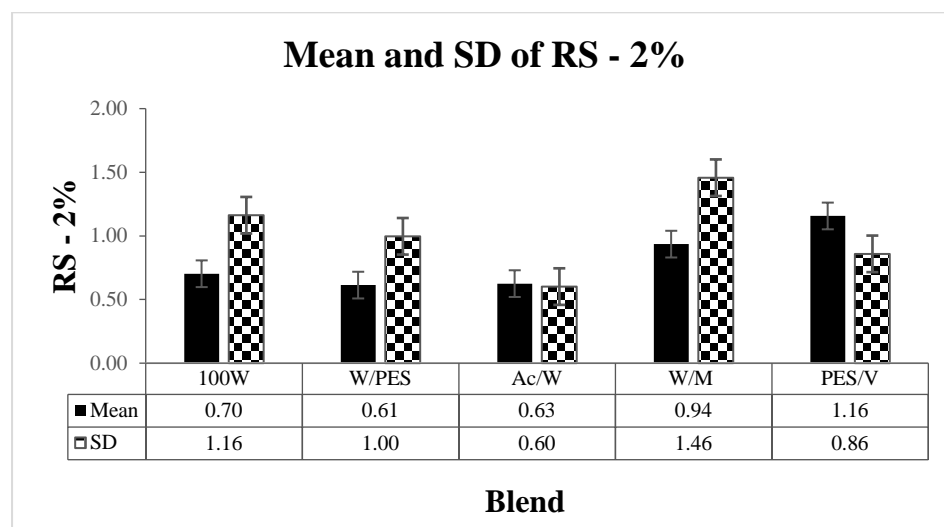
Blend

Figure 4.2 (b): Mean and SD RS -2% values for the different blends

(*The error bars in the graph represent the 95% confidence limits)

4.3.2 ANOVA for RS – 2%

ANOVA was carried out on the RS – 2% data, as was done on the RS – 1% data, the results being given in Table 4.2.

Table 4.2 Results of ANOVA for RS-2%

ANOVA for RS –2%

Multiple R	0.216629565
R Square	0.046928368
Adjusted R Square	0.02654181
Standard Error	1.092031802
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	21.96099875	2.745125	2.301927	0.020346841
Residual	374	446.007513	1.192533		
Total	382	467.9685117			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.166916733	0.327335432	0.509926	0.610404	-0.476731824	0.810565291
F1	-0.085366076	0.176847207	-0.48271	0.629583	-0.433105546	0.262373393
F2	-0.095794521	0.148315275	-0.64588	0.51875	-0.387430878	0.195841836
B1	-0.073729875	0.136963705	-0.53832	0.590679	-0.343045332	0.195585581
B2	0.834142425	0.315543954	2.643506	***0.00855***	0.213679771	1.45460508
B3	0.254920896	0.295048921	0.863995	0.388144	-0.325241818	0.835083609
B4	0.382870494	0.219064231	1.747754	0.081327	-0.047881459	0.813622447
Mass (g/m^2)	0.002615111	0.00137325	1.904323	0.057635	-8.51475E-05	0.005315369
Thickness (mm)	-0.031384876	0.52566169	-0.05971	0.952422	-1.065007747	1.002237995

The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

From the results of the ANOVA, given in Table 4.2, it is apparent that, in contrast to RS – 1%, the relaxation shrinkage in the weft direction was not significantly dependent on any of the parameters considered, exactly for the Ac/W blend (B2), which differed statistically significantly from the 100W fabrics. This appears to be at variance with the mean value results in the previous section, which could be due to comforting factors, such as fabric weight, weave and thickness.

4.4 Hygral expansion in the warp direction (HE – 1%)

4.4.1 Mean and standard deviation values of HE – 1%

The mean and standard deviation values for the hygral expansion values in the warp direction (HE – 1%), for the various fabric structures, are presented in Figure 4.3 (a), from which it is apparent that the twill fabric had, on average, the lowest hygral expansion in the warp direction, with those of the plain and 'other' fabric structures significantly higher and similar. Hygral expansion generally occurs when the moisture regain of the fabric changes, this, in turn, causing the fibre to undergo reversible swelling (De Jong et al., 1980, Cookson et al., 1991 and Das et al., 2017), with weave structure, weave crimp in particular, also playing a significant role in this respect.
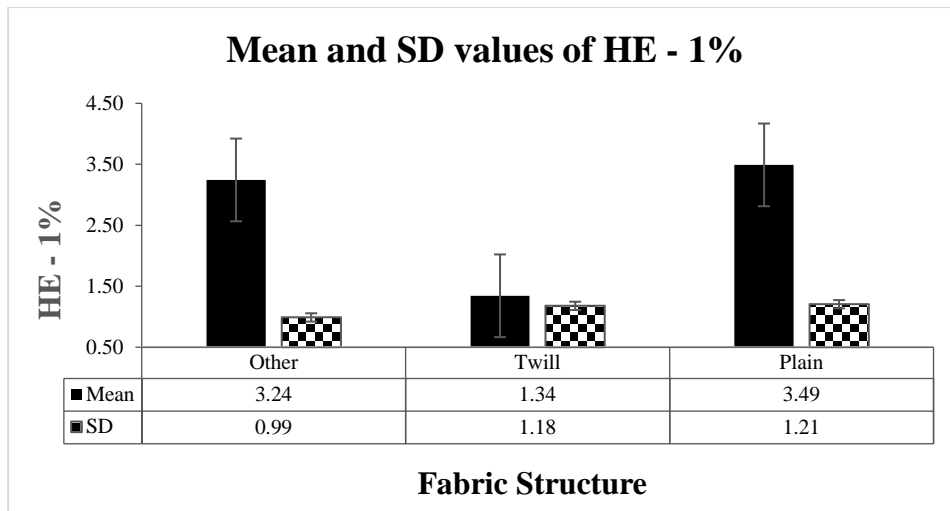
Figure 4.3 (a): Mean and SD HE – 1% values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

As can be seen, from Figure 4.3 (b), the average and standard deviation values for hygral expansion, in the warp direction, is the highest for the 100W fabric and the lowest for the PES/V fabrics, which is not surprising, in view of the higher water absorption and swelling of wool fibres versus those of polyester and viscose fibres, this being the main source of hygral expansion (Shaw, 1986). Excessive levels of hygral expression (e.g. 5 to 6%) can cause a number of problems in the appearance of wool and wool blend garments, including bubbling, seam puckering and delamination of the shell fabric (Wemyss and White, 1985; Das et al., 2017). It is perhaps also important to note that, with the ever-changing trend towards lighter weight fabrics, hygral expansion has become a more serious problem in tailored garments (Cookson et al., 1991). It therefore follows that a reference, typical benchmark or fingerprint value for hygral expansion, must allow for fabric blend differences reflecting, for example, higher values for higher levels of wool i.e. a 'fit all' or generic typical or benchmark value cannot be given for HE – 1%, in terms of fibre blend type and level.
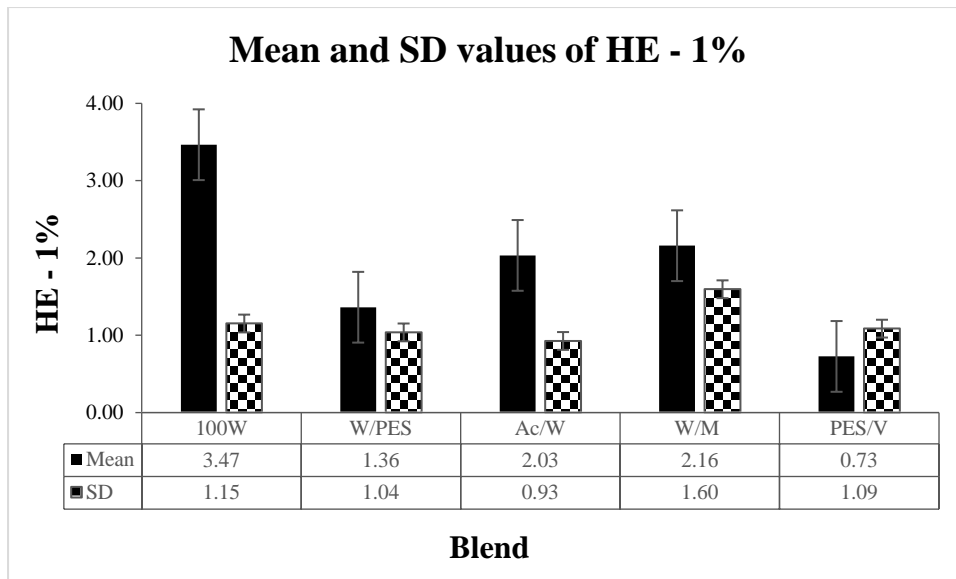
Figure 4.3 (b): Mean and SD HE – 1% values for the different blends

(*The error bars in the graph represent the 95% confidence limits)

It is very important to note once again, however, that as can be seen from the relatively high standard deviation values, and correspondingly very large CVs, the values of the individual fabrics vary widely within a weave structure and blend fabric group, and overlap greatly between fabric groups, as reported previously in a referred paper published on this research (Das et al., 2017), and attached as appendix in this thesis.

4.4.2 ANOVA on HE – 1%

The results of the ANOVA are given in Table 4.3.

Table 4.3 Results of ANOVA on HE-1%

ANOVA for HE –1%

Multiple R	0.716037
R Square	0.512709
Adjusted R Square	0.502285
Standard Error	1.094023
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	470.9839	58.87299	49.18847991	6.36706E-54
Residual	374	447.6352	1.196886		
Total	382	918.6191			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	3.040378	0.327932	9.271361	***1.49008E-18***	2.395555752	3.6852
F1	-0.25912	0.17717	-1.46257	0.44425973	-0.607495693	0.089251
F2	-0.12612	0.148586	-0.84878	0.396544362	-0.418285196	0.166051
B1	-2.13352	0.137213	-15.5489	***2.10117E-42***	-2.403322027	-1.86371
B2	-1.33529	0.316119	-4.224	***3.01802E-05***	-1.956880672	-0.71369
B3	-0.42141	0.295587	-1.42568	0.15479532	-1.002632108	0.159809
B4	-2.77545	0.219464	-12.6465	***9.14471E-31***	-3.206982368	-2.34391
Mass (g/m^2)	0.000861	0.001376	0.626074	0.531648443	-0.001843858	0.003567
Thickness (mm)	0.528056	0.52662	1.002727	0.316640974	-0.507451226	1.563563

The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes the exponential value.

From the ANOVA results, given in Table 4.3, it can be seen that the hygral expansion, in the warp direction (HE-1%) was statistically significantly dependent upon the blend, but not on fabric structure, weight or thickness.

4.5 Hygral expansion in the weft direction (HE-2%)

4.5.1 Mean and standard deviation values of HE – 2%

The mean and standard deviation values for the hygral expansion in the weft direction (HE – 2%), are presented in Figure 4.4 (a), for the various fabric structures from which it is apparent, that as in the case of HE – 1%, the plain and 'other' fabric structures had, on average, a much higher hygral expansion in the weft direction, than the twill fabrics. According to Shaw (1978, 1986), Frydrych (2003) and Qing Li et al., (2007) the fabric structure tends to impart restrictions on hygral expansion, with weave crimp the fabric structural feature having the most important influence on hygral expansion, the greater the yarn (i.e. weave) crimp, the greater the hygral expansion. Therefore, the effect of weave structure on hygral expansion is most likely due to the weave crimp (not measured here) being different, on average, for the different structures, and probably lowest for the twill weave fabrics.

Mean and SD values of HE - 2%

	Other	Twill	Plain
■ Mean	4.10	1.43	3.68
■ SD	1.49	1.25	1.80
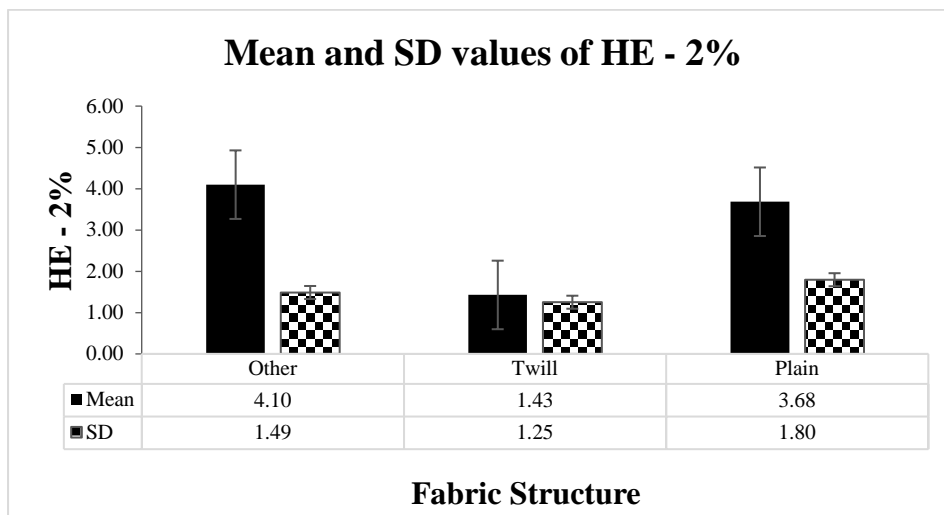
Fabric Structure

Figure 4.4 (a): Mean and SD HE – 2% values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

Figure 4.4 (b) gives the mean and standard deviation values for the hygral expansion (HE – 2%) in the weft direction (HE – 2%), for the different blends. From Figure 4.4 (b), it is apparent that, as in the case of HE – 1%, the 100W fabrics had, on average, the highest hygral expansion in the weft direction, and the PES/V fabrics the lowest, the reasons for this being as discussed before. Once again, the relatively large standard deviation values for HE-2%, as for HE-1%, with a considerable variability in the values of the individual fabrics within a group, and a great overlap of their values between groups, as was reported previously (Das et al., 2017).

Mean and SD values of HE - 2%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	3.79	1.38	2.41	1.99	1.25
□ SD	1.73	1.24	1.05	1.62	1.40
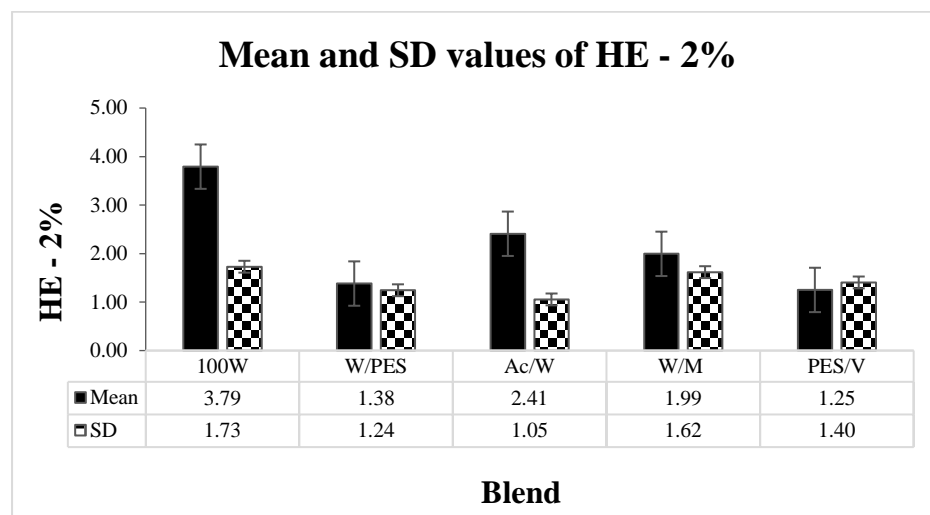
Blend

Figure 4.4 (b): Mean and SD HE – 2% values for the different fabric blends

(The error bars in the graph represent the 95% confidence limits)

4.5.2 ANOVA for HE – 2%

ANOVA was carried out on the HE - 2% data, as was done on the HE – 1% data, the results being given in Table 4.4.

Table 4.4 – Results of ANOVA for HE-2%

ANOVA for HE – 2%

Multiple R	0.65559702
R Square	0.42980745
Adjusted R Square	0.41761082
Standard Error	1.4802173
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	617.696243	77.21203	35.23984748	2.16918E-41
Residual	374	819.45018	2.191043		
Total	382	1437.146423			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	4.22047388	0.443693644	9.512135	*2.34316E-19*	3.348027012	5.092920758
F1	-0.3253894	0.239711238	-1.35742	0.175465544	-0.796740137	0.145961309
F2	-0.5053808	0.201037036	-2.51387	*0.012360712*	-0.900685418	-0.11007624
B1	-2.3026272	0.185650313	-12.403	*7.94257E-30*	-2.667676411	-1.9375779
B2	-1.0406455	0.42771064	-2.43306	*0.015439759*	-1.881664566	-0.19962645
B3	-0.6549362	0.399930219	-1.63763	0.10234075	-1.441329839	0.131457482
B4	-3.1158275	0.296935185	-10.4933	*9.45204E-23*	-3.699699264	-2.53195581
Mass (g/m^2)	-0.0067823	0.0018614	-3.64363	*0.000306788*	-0.010442382	-0.00312214
Thickness (mm)	2.31972783	0.712519111	3.255671	*0.001234459*	0.91868213	3.720773524

*The values in bold italics are statistically significant at the 95% significant limits. 'E' denotes the exponential value.

From Table 4.4, it is apparent that fabric weight, thickness, structure (to some extent) and blend all had a statistically significant effect on HE-2%. This is somewhat different to that observed for HE-1%, where only fabric blend had a statistically significant effect, but could be due to an effect of fabric weight and thickness on the weave crimp in the weft direction.

4.6 Formability in the warp direction (F – 1 mm^2)

4.6.1 Mean and standard deviation values of F – 1 mm^2

Figure 4.5 (a) gives the mean and standard deviation values for the formability in the warp direction (F – 1 mm^2) of the different fabric structures, which shows that the plain group of fabrics had a higher (better) formability than the other two groups. Formability, being an intrinsic fabric property, depends on certain fabric structural parameters, such as warp and weft-interlacing pattern (weave structure) and the number of yarn intersection density and fabric density, the former generally being higher for plain weave fabrics (Mousazadegan, 2013). This probably explains the slightly better formability of the plain weave fabrics. The relatively high standard deviations (Figure 4.5 (a)) once again show that the individual fabric values vary greatly within a weave structure, and thus also overlap greatly for the different structures, as reported previously (Das et al., 2017).

Mean and SD values of F - 1 mm^2

	Other	Twill	Plain
■ Mean	0.50	0.45	0.63
▦ SD	0.26	0.53	0.50
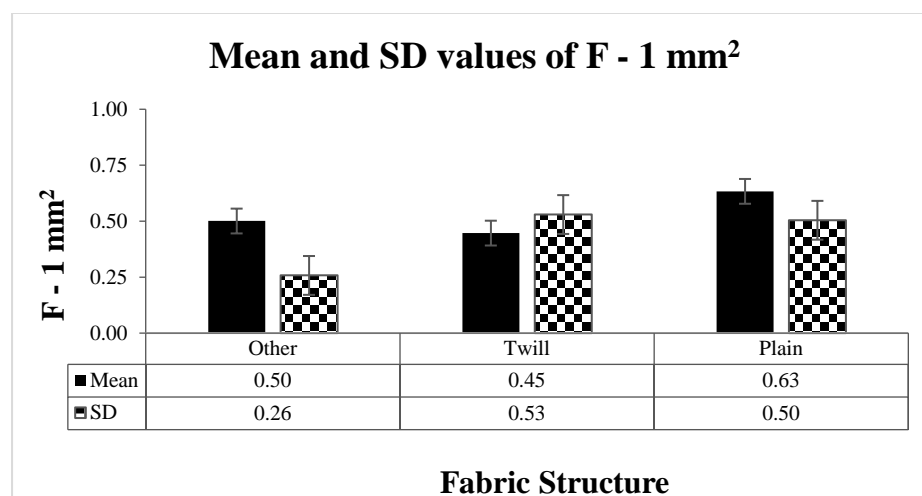
Fabric Structure

Figure 4.5 (a): Mean and SD F – 1 mm^2 values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values for the different blends are given in Figure 4.5 (b). From Figure 4.5 (b), it is apparent that the 100W fabrics had, on average, the highest (best) formability in the warp direction and the W/PES and Ac/W fabrics the lowest.

Mean and SD values of F - 1 mm^2

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.61	0.41	0.41	0.48	0.56
▣ SD	1.73	0.52	0.22	0.67	0.50
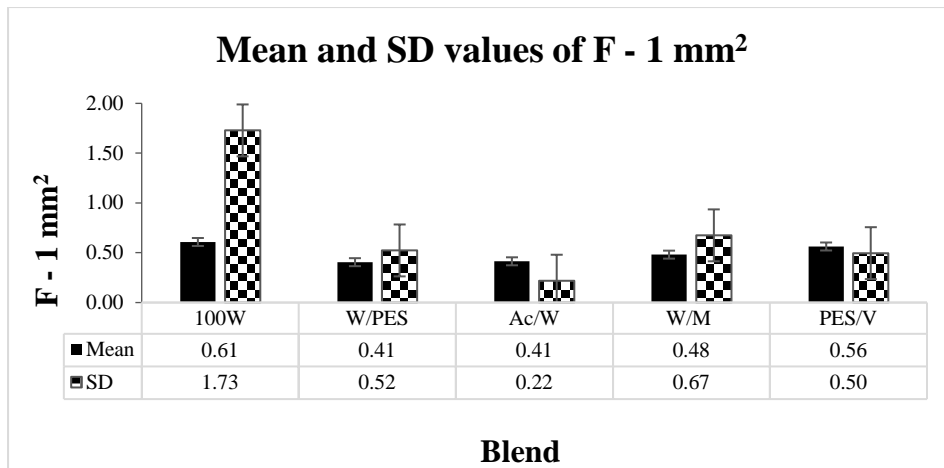
Blend

Figure 4.5 (b): Mean and SD F – 1 mm^2 values for the different fabric blends

(The error bars in the graph represent the 95% confidence limits)

4.6.2 ANOVA for F – 1 mm^2

The results of the ANOVA for the formability in the warp direction is given in Table 4.5.

Table 4.5 – Results of ANOVA for F-1 mm^2

ANOVA for F- 1 mm^2

Multiple R	0.628531291
R Square	0.395051584
Adjusted R Square	0.382111511
Standard Error	0.388886867
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	36.93631971	4.617039963	30.52931634	1.07936E-36
Residual	374	56.56114034	0.151232996		
Total	382	93.49746005			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.65881619	0.116568446	-5.651754058	*3.15365E-08*	-0.88802789	-0.429604485
F1	-0.14959915	0.062977613	-2.375433752	*0.018031675*	-0.27343374	-0.025764555
F2	0.068226852	0.052817017	1.291758904	0.197238339	-0.03562868	0.17208239
B1	-0.03218915	0.048774574	-0.659957546	0.509687285	-0.12809592	0.063717623
B2	-0.15217563	0.112369346	-1.354245056	0.176475854	-0.37313053	0.068779269
B3	0.018440628	0.105070796	0.175506694	0.860776493	-0.18816293	0.22504419
B4	-0.08836249	0.07801165	-1.132683236	0.258072928	-0.24175892	0.06503394
Mass (g/m^2)	0.000688451	0.000489032	1.407781868	0.160026285	-0.00027315	0.001650048
Thickness (mm)	1.860002411	0.187195032	9.936174014	*8.42902E-21*	1.491915731	2.22808909

The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes exponential value.

From the results of the ANOVA, given in Table 4.5 it is apparent that fabric thickness had a statistically significant effect on the formability, which was also significantly different for the twill fabric. The lower the formability, as in the case of the twill weave fabrics, the more likely

seam pucker will occur, since the fabric is less likely to accommodate the small compression placed on it by the sewing thread (De Boos and Tester, 1994), puckering and sleeve settings representing common problems experienced with low fabric formability (Kim and Kim, 2011; Alamdar-Yazdi and Bidoki, 2010; Frydrych and Matusiak, 2015).

4.7 Formability in the weft direction (F – 2 mm^2)

4.7.1 Mean and standard deviation values of F – 2 mm^2

The mean and standard deviation values for the formability in the weft direction (F-2mm^2) are shown as "bar charts" in Figure 4.6 (a), from which it can be seen that, on average, the plain weave fabrics had the highest formability and the twill fabrics the lowest, which was also the case for the formability in the warp direction (F-1mm^2). The relatively high standard deviation once again illustrating that the results of the individual fabrics within a group, varied very widely and overlap greatly between structures.

Mean and SD values of F - 2mm2

	Other	Twill	Plain
■ Mean	0.63	0.36	0.65
▣ SD	0.33	0.25	0.48
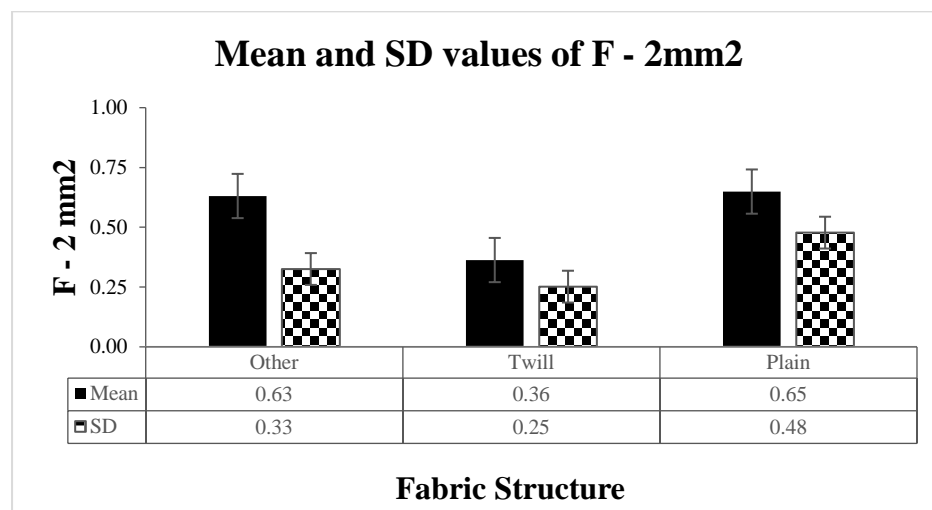
Fabric Structure

Figure 4.6 (a): Mean and SD F–2mm^2 values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

The F-2mm^2 mean and standard deviation values for the different blends are shown as "bar charts" in Figure 4.6 (b), from which it can be seen that, as in the case of F – 1 mm^2, the 100W fabrics had, on average, the highest formability, and the wool/polyester the lowest. This is in line with practical experience and results obtained by other researchers, namely that wool fabrics are generally more easily formed into three dimensional shapes than synthetic fabrics (Roczniok, 1990; Zhang et al., 2006; Doustar et al., 2010).
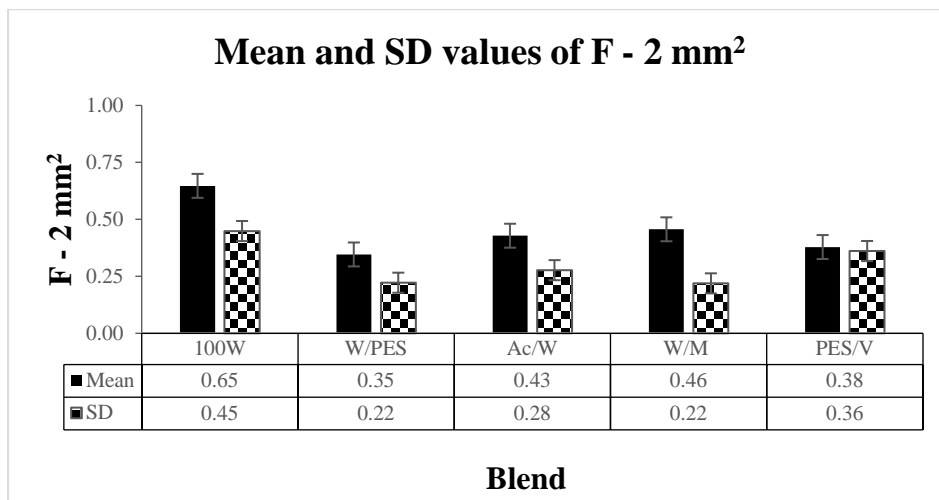
Figure 4.6 (b): Mean and SD F–2mm^2 values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.7.2 ANOVA for F – 2 mm^2

ANOVA was carried out on the F-2 mm^2 data, as was done on the F – 1 mm^2 data, the results being given in Table 4.6.

Table 4.6 Results of ANOVA for F-2mm^2

ANOVA for F – 2 mm^2	
Multiple R	0.731564408
R Square	0.535186482
Adjusted R Square	0.525243947
Standard Error	0.279676643
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	33.68297044	4.210371	53.82797	1.05656E-57
Residual	374	29.2539152	0.078219		
Total	382	62.93688564			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.156346295	0.083832792	1.864978	0.0629675	-0.008496402	0.321188992
F1	-0.04264721	0.045291752	-0.94161	0.3469997	-0.131705609	0.046411195
F2	-0.05515406	0.037984533	-1.45201	0.1473362	-0.129844083	0.019535957
B1	-0.16427419	0.03507732	-4.6832	*3.958E-06*	-0.233247674	-0.095300697
B2	-0.1129069	0.080812916	-1.39714	0.1632	-0.271811537	0.045997728
B3	0.019971119	0.075564001	0.264294	0.7916989	-0.128612429	0.168554667
B4	-0.46109293	0.056103814	-8.21857	*3.415E-15*	-0.571411381	-0.350774473
Mass (g/m2)	-0.00329855	0.000351698	-9.37891	*6.544E-19*	-0.003990103	-0.002606994
Thickness (mm)	2.154661889	0.134625472	16.00486	*2.75E-44*	1.889944164	2.419379615

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes exponential values.

According to the results of the ANOVA (Table 4.6) only the W/PES blend (B1) differed statistically significantly, the formability for this blend being lower than that of the other blends, the reasoning being as before.

4.8 Extensibility at 5% in the warp direction (E5-1%)

4.8.1 Mean and standard deviation values for E5 – 1%

Figure 4.7 (a) shows the mean and standard deviation values for E5-1%, according to fabric structure, presented in bar chart form. From the figure, it is clear that, the plain fabrics had, on average, a slightly higher extensibility in the warp direction, than the twill and 'other' fabrics, the relatively large standard deviations once again indicating, large variability of the individual fabrics within a weave group. Different weaves have different degrees of extensibility (Anderson, 2007; Doustar et al., 2010), with the amount of crimp within the fabric construction largely determining the extensibility of a fabric, also the higher the number of interlacings, the greater the crimp generally (Wang et al., 2003; Anderson, 2007). Plain weave generally have a greater number of interlacings, and therefore greater degree of crimp, which could explain the higher extensibility of the plain weave fabrics on average.

Mean and SD values of E5 - 1%

	Other	Twill	Plain
Mean	0.32	0.30	0.35
SD	0.17	0.20	0.18
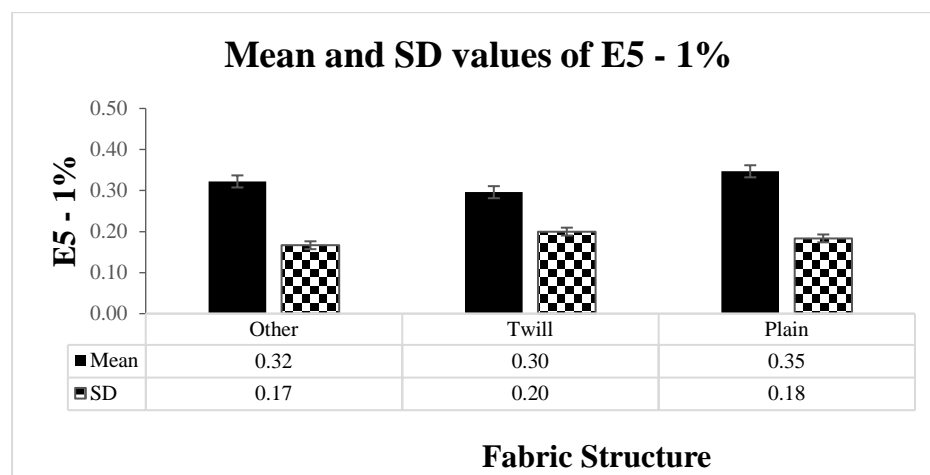
Fabric Structure

Figure 4.7 (a): Mean and SD E5-1 % values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of E5-1% for the different fibre blends are presented graphically in Figure 4.7 (b), from which it can be seen that, on average, the W/M fabrics had the highest extensibility in the warp direction, followed by the 100W fabrics, confirming the better extensibility of wool generally. Nevertheless, the differences between the different blends are generally quite small, and probably of little practical consequence, with the individual fabric values within a blend, varying widely as illustrated by the relatively high standard deviations. Furthermore, the individual fabric results for the different blends also overlapped to a great extent.

Mean and SD values of E5 - 1%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.34	0.28	0.26	0.41	0.31
▣ SD	0.18	0.20	0.12	0.27	0.16
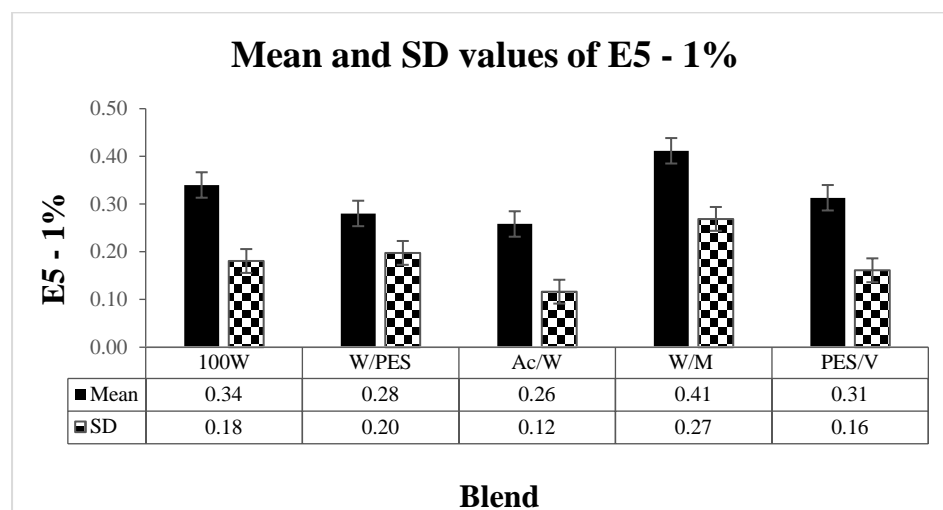
Blend

Figure 4.7 (b): Mean and SD E5-1 % values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.8.2 ANOVA for E5 – 1%

ANOVA was carried out on the E5-1% data, the results being given in Table 4.7.

Table 4.7 Results of ANOVA for E5-1%

ANOVA for E5 – 1%

Multiple R	0.33837525
R Square	0.11449781
Adjusted R Square	0.09555659
Standard Error	0.17963181
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	1.560434727	0.195054	6.044900389	2.5507E-07
Residual	374	12.06807702	0.032268		
Total	382	13.62851175			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.2356887	0.053844453	4.377214	*1.56184E-05*	0.12981289	0.341564514
F1	0.01989681	0.029090163	0.68397	0.494417405	-0.037304	0.077097589
F2	0.01948193	0.024396854	0.798543	0.425062507	-0.0284903	0.067454123
B1	-0.0444803	0.022529598	-1.9743	*0.049082487*	-0.0887808	-0.000179724
B2	-0.0196272	0.051904835	-0.37814	0.705542656	-0.1216891	0.0824347
B3	-0.0069642	0.048533541	-0.14349	0.885978374	-0.102397	0.088468613
B4	-0.0026467	0.036034576	-0.07345	0.941488734	-0.0735024	0.068209093
Mass (g/m^2)	-0.0008606	0.00022589	-3.8097	*0.000162608*	-0.0013047	-0.000416399
Thickness (mm)	0.49224504	0.086467774	5.692815	*2.529E-08*	0.32222111	0.662268973

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes the exponential value.

From the results given in Table 4.7, it is apparent that the extensibility in the warp direction is statistically significantly affected by fabric mass and thickness with increasing fabric mass and thickness with increasing the fabric extensibility. The extensibility is also on average,

statistically significantly higher for the 100W fabrics. It should be noted that, too high an extensibility can give rise to difficulties in laying-up operations and also in seam production. The warp extensibility is generally more important than that of the weft, due to the fact that tensions in laying-up are mainly imposed on the warp, and in most garments, there are more warp direction seams and they are also greater in length (International Wool Secretariat, 1991; Behera and Hari, 2010; Miao and Xin, 2017).

4.9 Extensibility in the weft direction (E5-2%)

4.9.1 Mean and standard deviation values of E5 – 2%

The mean and standard deviation values for the fabric extensibility in the weft directions are given in the form of bar charts in Figure 4.8 (a). From Figure 4.8 (a), it is apparent that, as in the case of E5-1, the plain weave fabric group had, on average, the highest extensibility in the weft direction, the differences between the weave structures being much more pronounced than that was the case in the warp direction. The higher extension of the plain weave fabrics has already been discussed for the extension in the warp direction, being attributed to the greater number of interlacings of the plain weave. The relatively large standard deviations, once again illustrating the variability and the individual fabric results.

Mean and SD values of E5 - 2%

	Other	Twill	Plain
■ Mean	0.45	0.27	0.48
▣ S	0.25	0.20	0.37
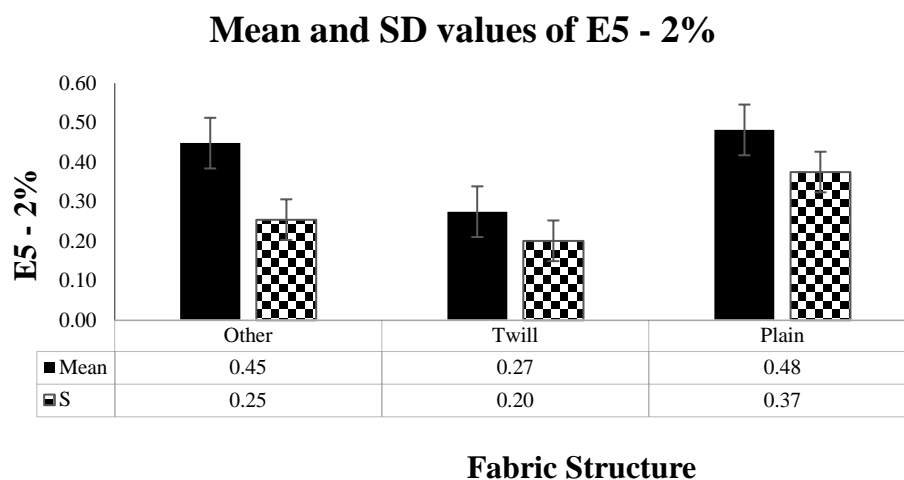
Fabric Structure

Figure 4.8 (a): Mean and SD E5-2% values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

The mean extensibility and standard deviation values in the weft direction (E5-2%), for the various blends, are presented in Figure 4.8 (b), from which it is apparent, that, similarly to E5-1%, the 100W and W/M fabrics had, on average, the highest extensibility in the weft direction, with that of Ac/W being the lowest.

Mean and SD values for E5 - 2%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.47	0.29	0.24	0.36	0.26
□ SD	0.35	0.24	0.12	0.21	0.20
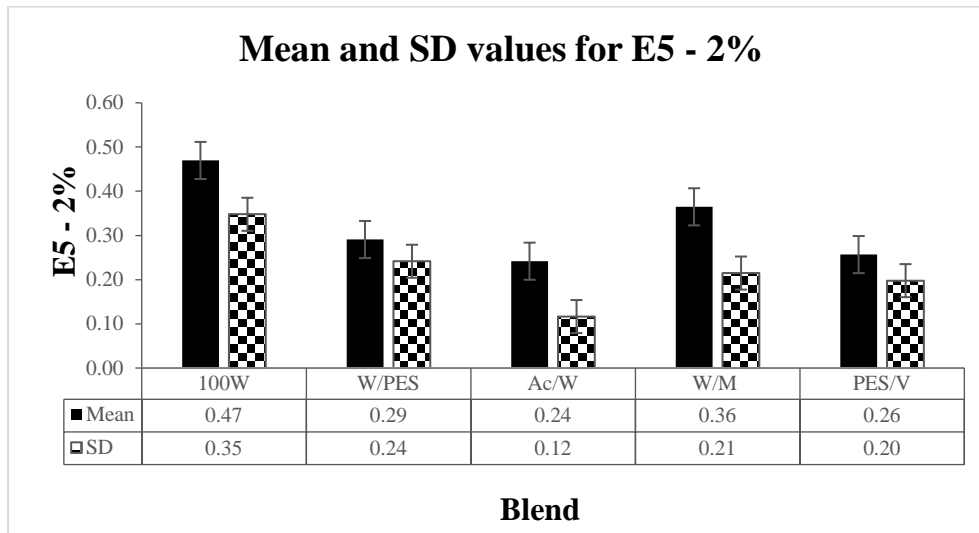
Blend

Figure 4.8 (b): Mean and SD E5-2 % values for the different blends

(The error bars in the graph represent at the 95% confidence limits)

4.9.2 ANOVA for E5 – 2%

ANOVA was carried out on the E5-2% data, as was done on the E5-1% data, the results given in Table 4.8.

4.8 Results of ANOVA for E5-2%

ANOVA for E5 – 2%

Multiple R	0.56468237
R Square	0.31886618
Adjusted R Square	0.30429647
Standard Error	0.2636007
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	12.16580197	1.520725	21.88556	2.46263E-27
Residual	374	25.98751396	0.069485		
Total	382	38.15331593			

|	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.64836352	0.079014045	8.205674	*3.74E-15*	0.492996053	0.803730984
F1	-0.02564987	0.042688361	-0.60086	0.548295	-0.109589156	0.058289415
F2	-0.05842626	0.035801165	-1.63197	0.103528	-0.128823064	0.011970545
B1	-0.14947942	0.03306106	-4.52131	*8.26E-06*	-0.214488286	-0.084470563
B2	-0.0214092	0.076167753	-0.28108	0.778805	-0.17117992	0.128361527
B3	-0.22684469	0.071220548	-3.1851	*0.001568*	-0.366887591	-0.086801792
B4	-0.2698132	0.052878941	-5.10247	*5.34E-07*	-0.373790504	-0.165835904
Mass (g/m^2)	-0.00337143	0.000331483	-10.1708	*1.29E-21*	-0.004023238	-0.002719631
Thickness (mm)	1.05056755	0.12688714	8.279543	*2.22E-15*	0.801065916	1.30006918

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential values.

According to the results given in Table 4.8, the extensibility in the weft direction was statistically significantly affected by the fabric blend, mass and thickness but, in this case not by fabric structure. This indicates that the differences present in the fabric values for the

different weave structures may be due to associated differences in the fabric mass and thickness.

4.10 Extensibility at 20% in the warp direction (E20 – 1%)

4.10.1 Mean and standard deviation values of E20 – 1%

Figure 4.9 (a) presents the mean and standard deviation values for the extensibility in the warp direction (E20-1%) of the different fabric structures, from what it is apparent that, as in the case of the (E5 – 1%) warp extensibility, the plain fabric structure had, on average, the highest extensibility (E20-1%), in the warp direction, with that of the twill fabrics the lowest. Although the differences are not very large, the relatively high standard deviations once again indicate the great variability of the individual fabric results, within a fabric weave group, and the overlap between the different weave groups for the individual values.

Mean and SD values of E20 - 1%

	Other	Twill	Plain
■ Mean	0.96	0.84	1.04
▣ SD	0.51	0.63	0.49
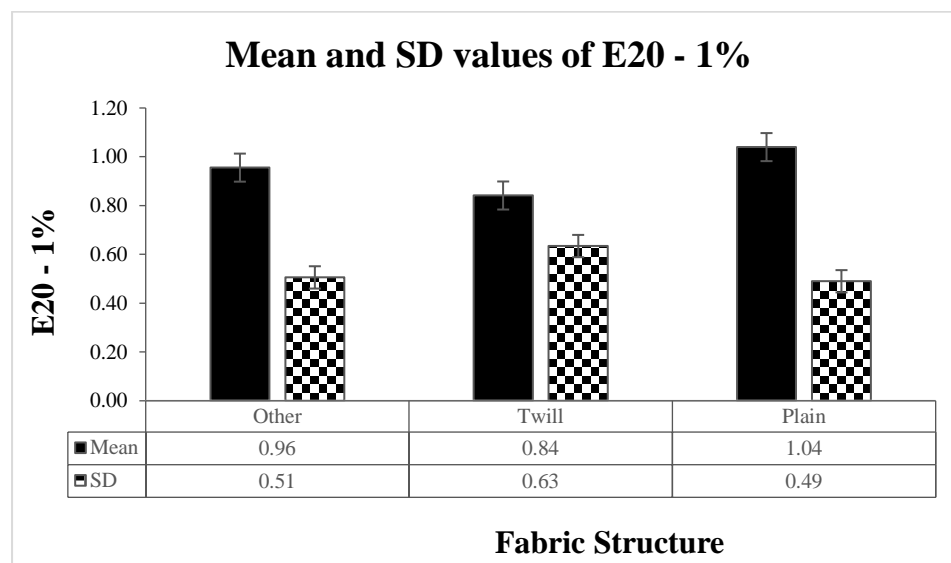
Fabric Structure

Figure 4.9 (a): Mean and SD E20-1% values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values in the warp direction (E20-1%) are presented in Figure 4.9 (b) for the various blends. From this figure it is apparent that, as in the case of E5-1%, the wool/mohair (W/M) and 100W fabrics had, on average, the highest extensibility in the warp direction, similar reasoning applying as for E5-1%. The relatively large standard deviation

values once again indicating large variability and overlap, within and between blends, of the

individual fabric values.
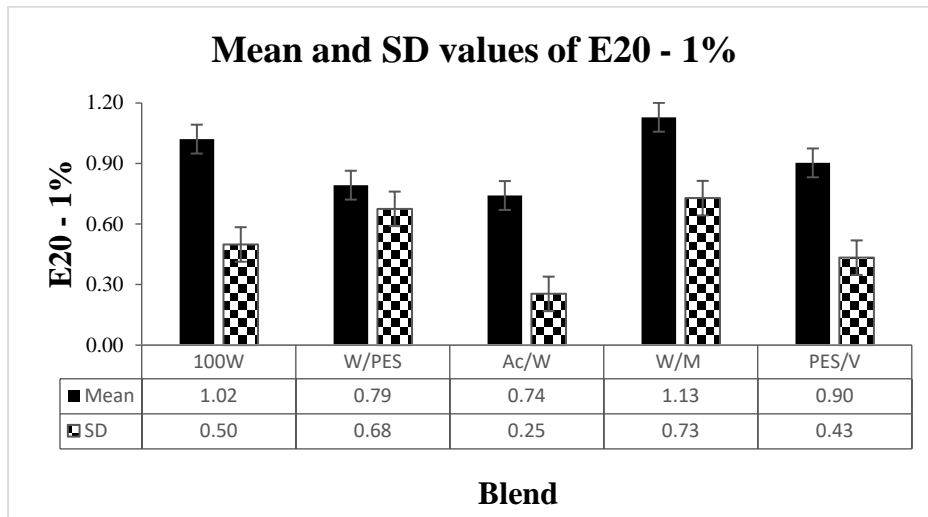
Figure 4.9 (b): Mean and SD E20-1% values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.10.2 ANOVA for E 20 – 1 %

ANOVA was carried out on the E20-1%, the results given in Table 4.9.

Table 4.9 Results of ANOVA for E20-1%

ANOVA for E20 -1%	
Multiple R	0.369944112
R Square	0.136858646
Adjusted R Square	0.11839573
Standard Error	0.524931659
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	16.34057932	2.042572	7.4126233	3.56233E-09
Residual	374	103.0569142	0.275553		
Total	382	119.3974935			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.622059173	0.157347735	3.953404	***9.21416E-05***	0.312662044	0.931456303
F1	-0.052819701	0.085009152	-0.62134	0.534753572	-0.219975507	0.114336105
F2	0.06583723	0.071294062	0.92346	0.35636281	-0.074350223	0.206024683
B1	-0.154604301	0.065837446	-2.34827	***0.019380814***	-0.284062261	-0.02514634
B2	-0.238520924	0.151679659	-1.57253	0.116673074	-0.53677276	0.059730913
B3	-0.058147297	0.141827847	-0.40999	0.682051655	-0.337027248	0.220732654
B4	-0.062964886	0.105302565	-0.59794	0.550240152	-0.270024183	0.144094411
Mass (g/m^2)	-0.002550918	0.000660111	-3.86438	***0.000131269***	-0.003848912	-0.00125292
Thickness (mm)	1.63089207	0.25268171	6.454334	***3.37414E-10***	1.134037156	2.127746985

*The values in bold italics that are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

According to Table 4.9, the trends for E20-1% were similar to those for E5-1%, i.e. the effects of fabric mass and thickness being statistically significant and with the 100W fabric also being significantly different. The effects could be due to associated differences in the number of

interlacings and weave crimp (Anderson, 2007; Behera and Hari, 2010; Miao and Xin, 2017), hence higher extensibility of the fabric.

4.11 Extensibility at 20% in the weft direction (E20-2%)

4.11.1 Mean and standard deviation values of E20 – 2%

The mean and standard deviation values for E20-2% are shown graphically in Figure 4.10 (a), for extensibility in the weft direction. According to fabric weave structures, from the Figure it is apparent that, the 'other' fabric structures had the highest extensibility in the weft direction, with that of the twill weave fabric much lower. As reported by Anderson (2007), the longer the floats within the construction the less extensible the fabric will be, such is the scenario along the weft direction for the extensibility of the fabric.

	Other	Twill	Plain
■ Mean	1.53	0.79	1.47
□ SD	0.90	0.57	1.10
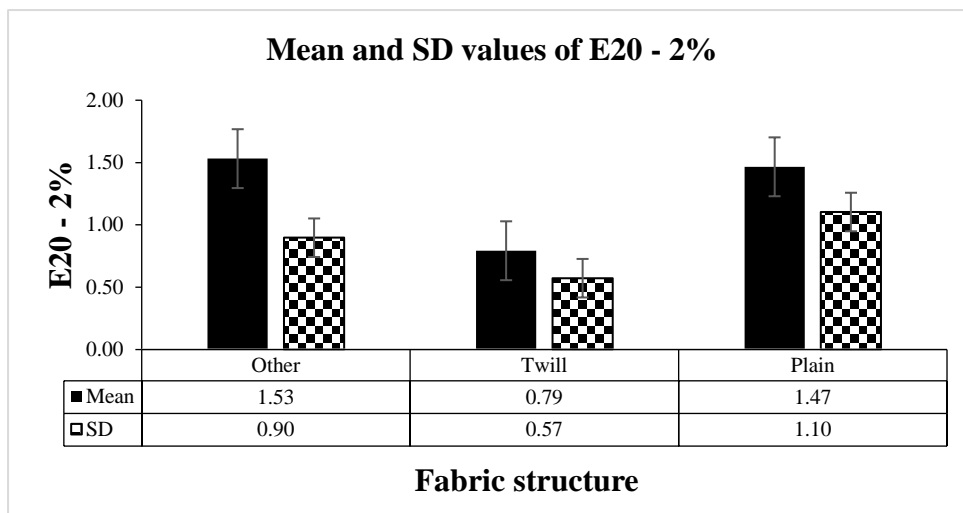
Fabric structure

Figure 4.10 (a): Mean and SD E20-2% values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of the extensibility in the weft direction (E20-2%) for the various blends are presented in Figure 4.10 (b), from what it is apparent that, as in the case of E20-1%, the 100W fabrics had, on average, the highest extensibility in the weft direction, followed by the W/M fabrics, with that of the PES/V blends being the lowest. The relatively

high standard deviations once again indicate the great variability for the values of the individual fabrics within a blend, as well as the overlap of such fabrics, between blends.

Mean and SD values of E20 - 2%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	1.47	0.81	0.83	1.11	0.73
▣ SD	1.05	0.68	0.31	0.63	0.61

Blend

Figure 4.10 (b): Mean and SD E20-2% values for the different fabric blends

(The error bars in the graph represent the 95% confidence limits)

4.1.11.2 ANOVA for E 20 – 2 %

ANOVA was carried out on the E20-2% data, the results being given in Table 4.10.

Table 4.10 Results of the ANOVA for E20-2%

ANOVA for E20 – 2%

Multiple R	0.613606119
R Square	0.376512469
Adjusted R Square	0.363175838
Standard Error	0.765611336
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	132.385343	16.54817	28.23145145	2.64776E-34
Residual	374	219.2241087	0.586161		
Total	382	351.6094517			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	2.16398654	0.229491226	9.429496	*4.4354E-19*	1.712731704	2.61524138
F1	-0.177835572	0.123985607	-1.43432	0.15231532	-0.421631842	0.0659607
F2	-0.295119005	0.103982188	-2.83817	*0.004784744*	-0.499582007	-0.090656
B1	-0.530014435	0.096023728	-5.51962	*6.36178E-08*	-0.718828502	-0.34120037
B2	-0.140071924	0.221224353	-0.63317	0.527011665	-0.575071383	0.29492753
B3	-0.680220983	0.206855513	-3.28839	*0.001103149*	-1.086966601	-0.27347536
B4	-0.946330513	0.153583493	-6.16167	*1.86256E-09*	-1.248325911	-0.64433512
Mass (g/m^2)	-0.010719634	0.00096277	-11.1342	*4.61128E-25*	-0.012612755	-0.00882651
Thickness (mm)	3.228792764	0.368535558	8.761143	*6.82025E-17*	2.504131279	3.95345425

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

The results of the ANOVA in Tables 4.10, show that, virtually all the "independent variables" had a statistically significant effect on the extensibility in the weft direction.

4.12 Extensibility at 100% in the warp direction (E100-1%)

4.12.1 Mean and standard deviation values of E100 – 1%

The mean and standard deviation values for the weft extensibility at 100% (E100 1%) are displayed graphically in Figure 4.11 (a). From the figure, it can be seen that, on average, the plain and 'other' fabrics had slightly higher extensibility than the twill weave fabrics. As stated by Anderson (2007) the weaves have different degrees of extensibility. The amount of crimp within the fabric construction determines the extensibility of a fabric and higher the number of interlacings, the greater the crimp tends to be (Anderson, 2007). A plain weave generally has the greatest number of interlacings in a given area, and therefore more likely also the highest degree of crimp (Behera and Hari, 2010; Miao and Xin, 2017). The plain weave fabrics tends to be more extensible than the twill weave fabrics, due to its looser structure allowing the yarns and fibres to adjust and realign when deformation forces are applied, which results in its higher extensibility (Hu, 2004; Raj and Sreenivasan, 2009).

Mean and SD values of E100 - 1%

|	Other	Twill	Plain
■ Mean	2.71	2.50	2.86
▣ SD	1.19	1.65	1.07
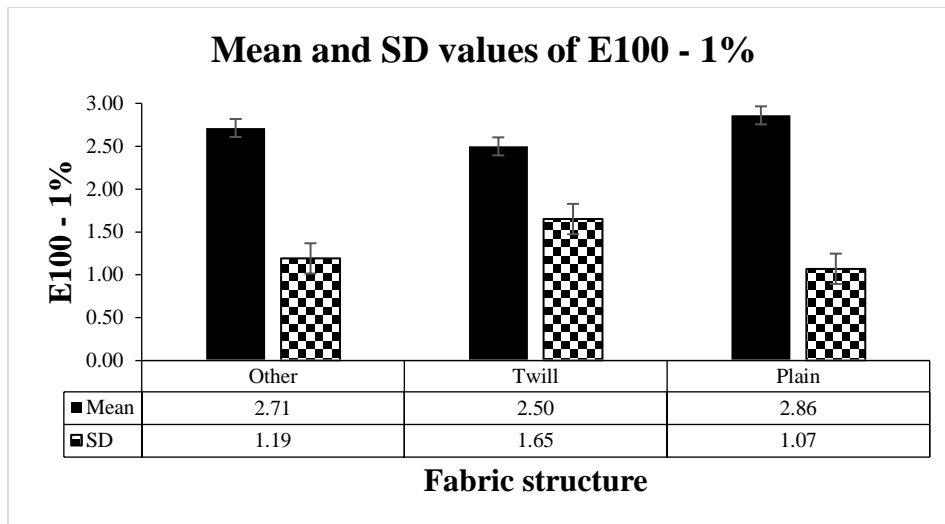
Fabric structure

Figure 4.11 (a): Mean and SD E100-1% values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values for the warp extensibility (E100-1%), according to fabric blend, presented graphically in Figure 4.11 (b), from which it can be seen that, on average, the 100W and W/M blend fabrics had the highest extensibility followed by the PES/V fabrics. The relatively high standard deviation values once again indicating and considerable individual fabric results, both within and between fabric blends.

Mean and SD values of E100 - 1%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	2.84	2.33	2.29	3.02	2.77
▣ SD	1.10	1.79	0.50	1.54	1.30
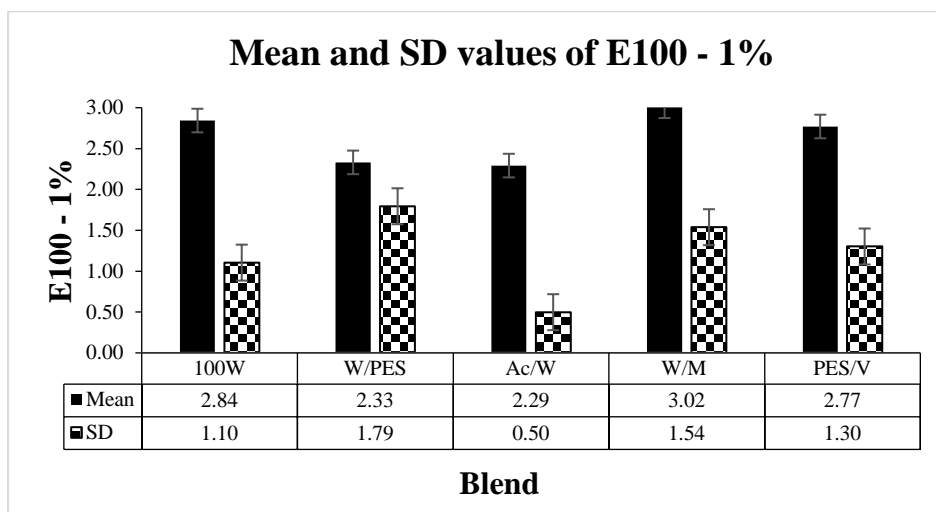
Blend

Figure 4.11 (b): Mean and SD E100-1% values for the different fabric blends
(The error bars in the graph represent the 95% confidence limits)

4.12.2 ANOVA for E 100 – 1%

ANOVA was carried out on the E100-1% data, and the results are given in Table 4.11.

Table 4.11 – Results of ANOVA for E100-1%

ANOVA for E100 – 1%	
Multiple R	0.320062513
R Square	0.102440012
Adjusted R Square	0.083240868
Standard Error	1.292409195
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	71.2980775	8.91226	5.33565516	2.33063E-06
Residual	374	624.7002515	1.670322		
Total	382	695.998329			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1.591208265	0.387398353	4.107421	***4.9179E-05***	0.829456352	2.352960177
F1	-0.315997586	0.209296978	-1.5098	0.13193759	-0.72754392	0.095548751
F2	0.26559217	0.17552971	1.51309	0.13110147	-0.07955667	0.610741009
B1	-0.325875809	0.162095235	-2.0104	***0.04510663***	-0.64460808	-0.00714354
B2	-0.891980198	0.373443253	-2.38853	***0.01741121***	-1.62629182	-0.15766858
B3	-0.111657738	0.349187576	-0.31976	0.74932552	-0.79827476	0.574959286
B4	0.140835773	0.259260423	0.543221	0.58730108	-0.36895504	0.650626591
Mass (g/m^2)	-0.002678596	0.001625228	-1.64814	0.10016465	-0.00587433	0.000517134
Thickness (mm)	3.044350319	0.622115584	4.893545	***1.4748E-06***	1.821067536	4.267633102

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes the exponential value.

From the Table 4.11, it is evident that fabric blend (particularly, B3 and B4, i.e. W/M and PES/V) and thickness but not fabric mass and structure had a statistically significant effect on fabric extensibility in the warp direction.

4.13 Extensibility at 100% in the weft direction (E100-2%)
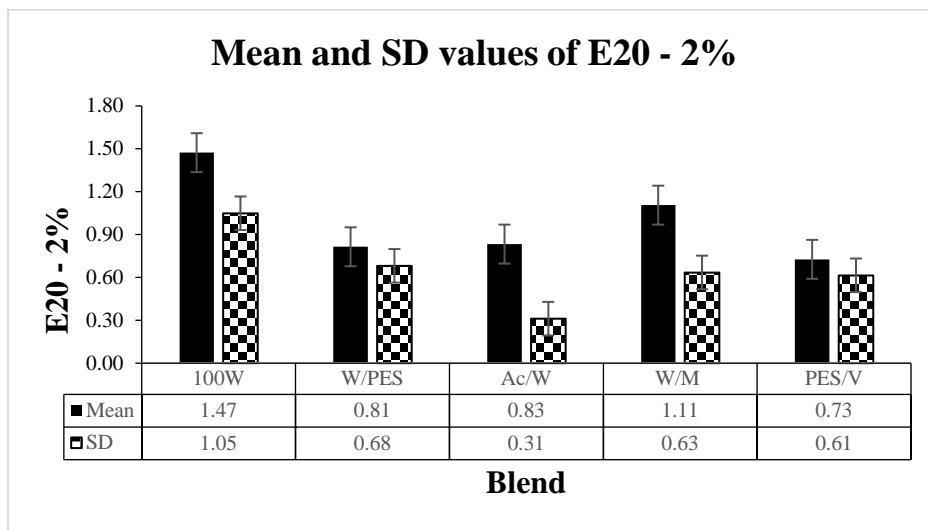
4.13.1 Mean and standard deviation values of E100 – 2%

Figure 4.12 (a) presents the mean and standard deviation values for extensibility in the weft direction (E100-2%) according to the different fabric structures, from which it is apparent that, as in the case of the extensibility (E100-2%) in the warp direction, the twill weave fabrics also, had on average, the lowest extensibility in the weft direction, with that of the 'other' and plain weave differing statistically significantly. Within this context, it has been found that the type of weft yarn and the weave structure significantly make an impact on the extensibility of the fabric (Erdumlu, 2015). The relatively high standard deviation values again illustrates the large scatter of individual fabric results within a fabric structure, and overlap between fabric structures.

Mean and SD values of E100 - 2%

	Other	Twill	Plain
■ Mean	4.52	2.60	4.21
□ SD	2.18	1.29	2.54
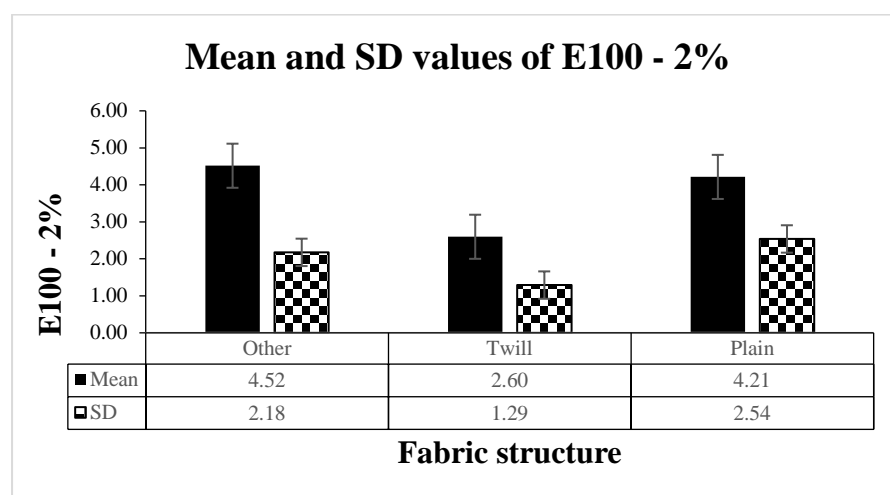
Fabric structure

Figure 4.12 (a): Mean and SD E100-2% values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

Figure 4.12 (b), presents the mean and standard deviation values for the extensibility in the weft direction (E100-2%). According to blend, from Figure 4.12, it is apparent that, as in the case of the warp extensibility (E100-2%), the 100 W and W/M fabrics, had the highest average values. The relatively large standard deviation values once again illustrates the large scatter of individual fabrics results within a fabric structure, and overlap between fabric structures.

Mean and SD values of E100 -2%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	4.28	2.64	2.62	3.41	2.34
□ SD	2.45	1.41	0.72	1.18	1.62

Blend

Figure 4.12 (b): Mean and SD E100-2% values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.13.2 ANOVA for E100 – 2%

ANOVA was carried out on the E100-2% data, as was done on the E100-1% data, the results being given in Table 4.12.

Table 4.12 Results of ANOVA for E100-2 %

ANOVA for E100 – 2%

Multiple R	0.550043208
R Square	0.30254753
Adjusted R Square	0.287628761
Standard Error	1.886630111
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	577.4629447	72.18287	20.27965728	1.76565E-25
Residual	374	1331.205567	3.559373		
Total	382	1908.668512			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	5.923350008	0.565515473	10.47425	*1.10441E-22*	4.81136156	7.035338456
F1	-0.46912652	0.305527059	-1.53547	0.125514824	-1.069892681	0.131639641
F2	-0.581590559	0.256234354	-2.26976	*0.023790743*	-1.085431135	-0.07774998
B1	-1.430696982	0.236623008	-6.04631	*3.59149E-09*	-1.895975235	-0.96541873
B2	-0.839076728	0.545144129	-1.53918	0.124605159	-1.911008447	0.232854991
B3	-1.498292442	0.509736234	-2.93935	*0.003493211*	-2.500600655	-0.49598423
B4	-2.275516105	0.378462582	-6.01253	*4.34522E-09*	-3.019697367	-1.53133484
Mass (g/m^2)	-0.020779937	0.002372471	-8.75877	*6.94032E-17*	-0.025444992	-0.01611488
Thickness (mm)	5.786987014	0.90815045	6.372278	*5.48062E-10*	4.001266097	7.57270793

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes the exponential value.

From Table 4.12 it is apparent that, fabric structure (in terms of F2 i.e. 'other' fabrics), fabric blend (W/PES, W/M and PES/V in particular), mass and thickness, all had a statistically significant effect on extensibility in the weft direction (E100-2%). In the case of the extensibility in the warp direction (E100-2%), neither fabric structures nor fabric mass were

statistically significant. According to De Boos and Roczniok, (1996), a high extensibility in a certain direction can lead to the fabric being stretched during laying-up, causing the fabric panels to shrink when removed from the cutting table, whereas a low extensibility can lead to difficulties in producing overfeed seams, problems in moulding and seam pucker.

4.14 Extensibility in the bias direction (EB-5%)

4.14.1 Mean and standard deviation values of EB – 5%

Figure 4.13 (a) shows the mean and standard deviation values for extensibility in the bias direction (EB-5%) in the bar chart form. From the figure it can be seen that, on average, the twill weave fabrics had a significantly lower extensibility than plain weave and 'other' fabrics, which had similar values. The bias extensibility provides a measure of fabric shear, which is important in laying up and also issues in the formation of smooth three-dimensional shapes, such as are needed around the sleeve head and shoulder region in a structured jacket. The relatively large standard deviations once again show the great variability in the individual fabric results, within a weave structure, and also indicates significant overlap in the values between weave structures.

Mean and SD values of EB - 5%

	Other	Twill	Plain
■ Mean	3.56	2.74	3.61
■ SD	1.26	1.46	1.69
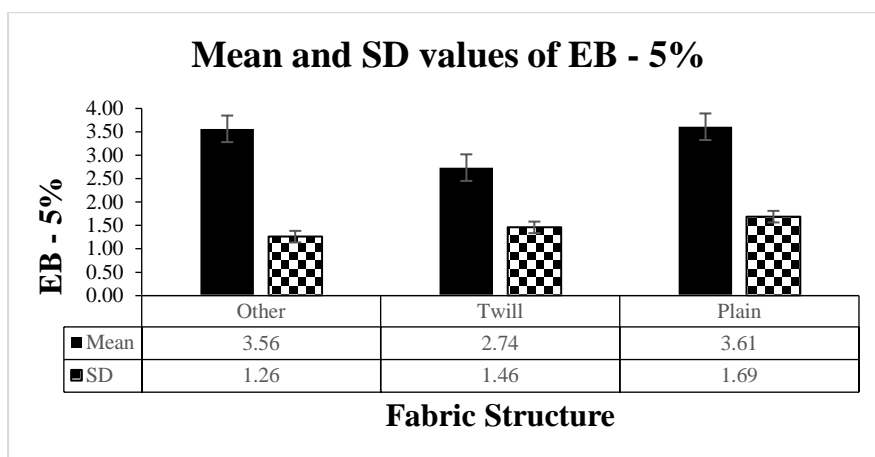
Fabric Structure

Figure 4.13 (a): Mean and SD EB-5% values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of EB-5% for the different fabric blends are presented graphically in Figure 4.13 (b) from which it can be seen that, on average, the 100W and W/M blend fabrics had the highest bias extensibility, with that of the other similar fabric blends. The relatively large standard deviations once again illustrate the large variations in the values of the individual fabrics within a blend and their overlap between blends, which are also considered as their respective mean values.

Mean and SD values of EB - 5%

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	3.58	2.63	2.83	3.69	2.84
■ SD	1.57	1.56	1.75	1.48	1.24
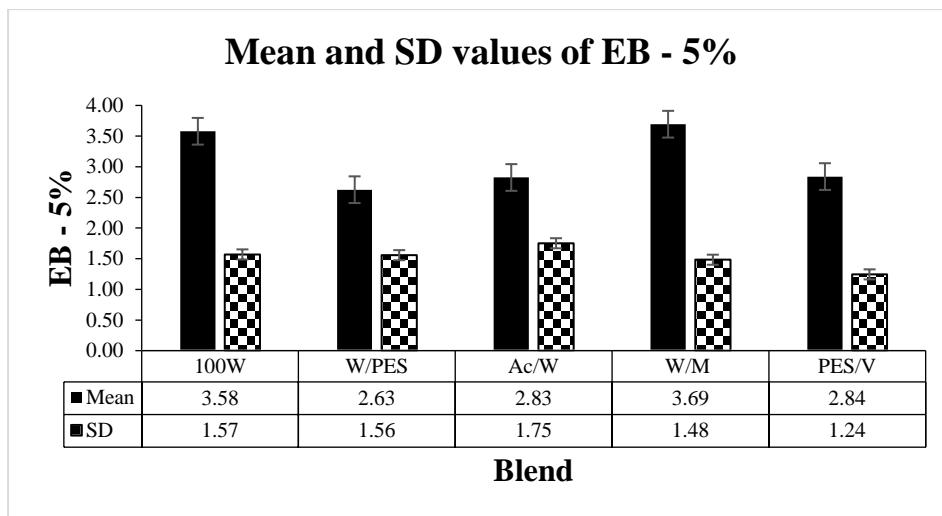
Blend

Figure 4.13 (b): Mean and SD EB-5% values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.1.14.2 ANOVA of EB – 5%

ANOVA was carried out on the EB-5% data, with the results given in Table 4.13.

Table 4.13 – Results of ANOVA for EB-5%

ANOVA for EB-5 (%)

Multiple R	0.72133441
R Square	0.52032333
Adjusted R Square	0.51006286
Standard Error	1.11923528
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	508.2051732	63.52565	50.71148316	3.49811E-55
Residual	374	468.5051662	1.252688		
Total	382	976.7103394			

|	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	5.98537917	0.335489646	17.84073	*5.96405E-52*	5.325696756	6.64506158
F1	0.09933777	0.181252627	0.548063	0.583975939	-0.257064197	0.45573974
F2	-0.62951794	0.15200994	-4.14129	*4.27233E-05*	-0.928419217	-0.3306167
B1	-0.74446245	0.140375592	-5.30336	*1.94978E-07*	-1.020486796	-0.4684381
B2	-0.003648	0.323404433	-0.01128	0.991006067	-0.63956693	0.63227093
B3	-0.35366253	0.30239885	-1.16952	0.24293762	-0.948277606	0.24095255
B4	-1.37886152	0.224521315	-6.14134	*2.09E-09*	-1.820343883	-0.9373792
Mass (g/m^2)	-0.0248739	0.001407459	-17.6729	*3.0192E-51*	-0.027641421	-0.0221064
Thickness (mm)	5.9755369	0.538756387	11.09135	*6.61241E-25*	4.916165566	7.03490823

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes exponential value.

From the ANOVA results (Table 4.13), it is evident that, certain of the fabric blends i.e. Ac/W, W/M, differed statistically significantly, and that, fabric structure, mass and thickness also had a statistically significant effect on fabric extensibility along the bias direction.
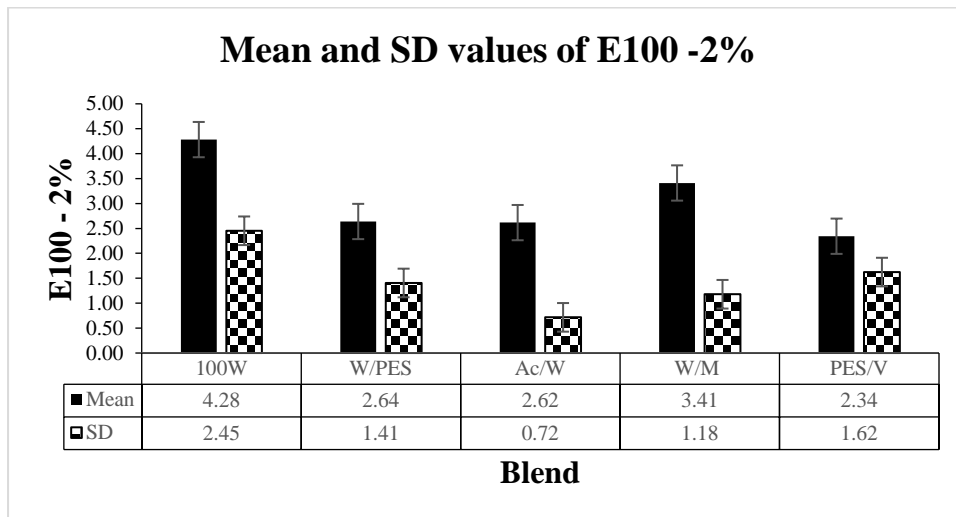
4.15 Bending length in the warp direction (C-1 mm)

4.15.1 Mean and standard deviation values

Figure 4.14 (a) present the mean and standard deviation values for bending length in the warp direction (C-1 mm), according to fabric weave structures. From the figure it is apparent that, as in the case of the different fabric weave structures had very similar bending lengths in the warp direction with the relatively small standard deviations indicating that the C-1 mm values for the individual fabrics did not change as much, relatively speaking, as the other parameters discussed so far.

Mean and SD values of C - 1 (mm)

	Other	Twill	Plain
■Mean	17.41	16.97	17.56
▣SD	1.87	3.84	2.21
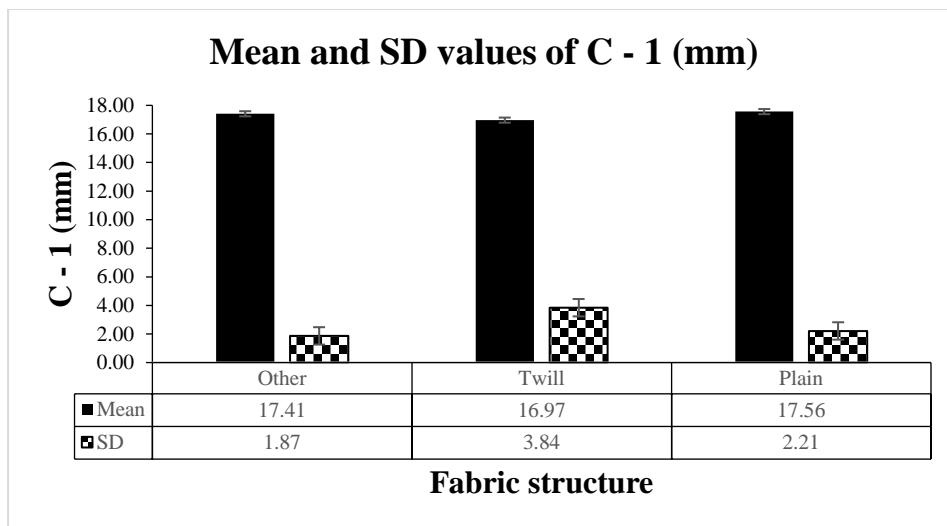
Fabric structure

Figure 4.14 (a): Mean and SD C-1 (mm) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

Figure 4.14 (b) present the mean and standard deviation values for bending length C-1 (mm) in the warp direction, according to fabric blends. It is apparent from the figure that, on average, different fabric blends have rather similar bending lengths with the differences of little practical consequence.
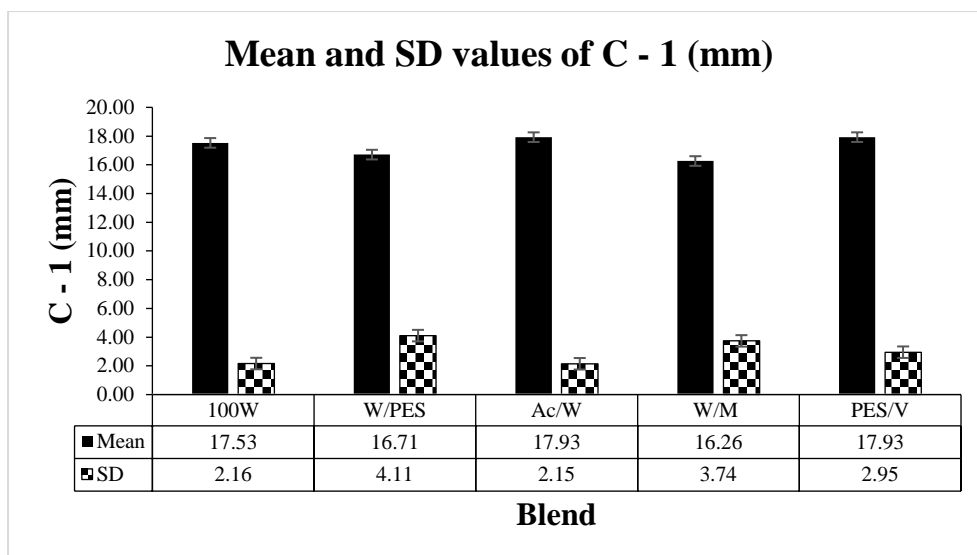
Figure 4.14 (b): Mean and SD C-1 (mm) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.15.2 ANOVA for C – 1 (mm)

ANOVA was carried out on the C-1 mm data, and the results are given in Table 4.14.

Table 4.14 Results of ANOVA for C-1 (mm)

ANOVA for C-1 (mm)

Multiple R	0.61134776
R Square	0.37374608
Adjusted R Square	0.36035027
Standard Error	2.344746
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	1227.126667	153.3908	27.90023115	5.9286E-34
Residual	374	2056.189835	5.497834		
Total	382	3283.316501			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	16.8527104	0.702835248	23.97818	*1.27494E-77*	15.4707063	18.2347144
F1	-0.7462492	0.379715846	-1.96528	*0.050121118*	-1.4928948	0.00039636
F2	-0.3129591	0.318453773	-0.98275	0.326367873	-0.9391434	0.31322521
B1	0.0556676	0.294080354	0.189294	0.849965197	-0.5225906	0.6339258
B2	-0.3858081	0.677517286	-0.56944	0.56939677	-1.7180288	0.94641256
B3	-0.3143344	0.633511564	-0.49618	0.620060445	-1.5600254	0.93135664
B4	-0.9406728	0.470361741	-1.99989	*0.046234669*	-1.8655579	-0.0157877
Mass (g/m^2)	-0.0341442	0.00294856	-11.58	*1.03876E-26*	-0.0399421	-0.0283464
Thickness (mm)	14.7538461	1.128669642	13.07189	*2.01421E-32*	12.5345123	16.9731799

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

From the results of the ANOVA (Tables 4.14), it is apparent that, fabric structure (F1), one blend (PES/V), and fabric mass and thickness emerged as statistically significant. Nevertheless, the average differences were rather small, and of little practical significance.

4.16 Bending length in the weft direction (C-2 mm)

4.16.1 Mean and standard deviation values

Figure 4.15 (a) shows the mean and standard deviation values for bending length (C-2 mm) in bar chart form. From this Figure 4.15 (a) it is apparent that, on average, the differences in the bending length (C-2 mm) of the different fabric structures were rather small, and of little practical consequence, in here with the warp results.

Mean and SD values of C - 2 (mm)

	Other	Twill	Plain
■ Mean	16.07	17.39	16.97
□ SD	2.51	5.92	2.86
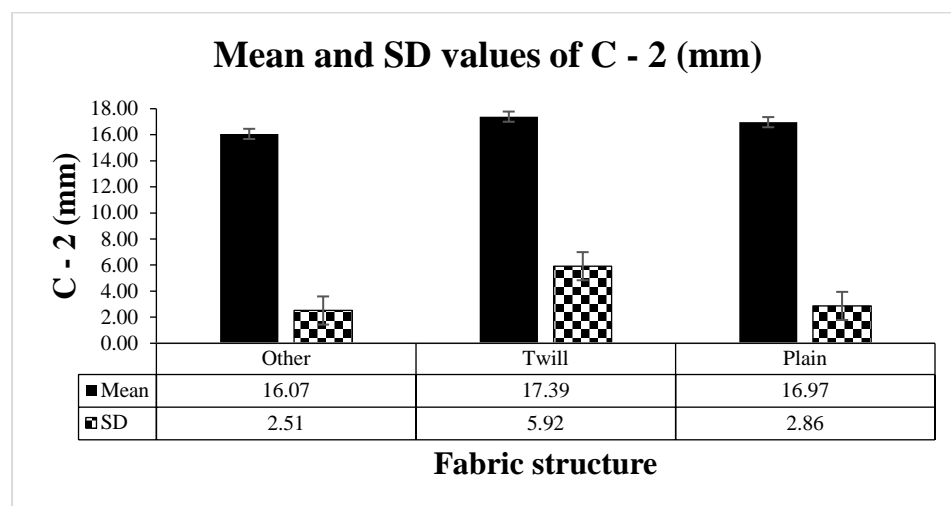
Fabric structure

Figure 4.15 (a): Mean and SD C-2 (mm) values for the different fabric weave structure
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of C-2 mm, according to fabric blend are presented graphically in Figure 4.15 (b), from which it can be seen that, on average, with the different fabric blends very similar bending lengths, with the differences between the different blends generally small, and of little practical consequence. Fabric bending length provides a measure of the fabric stiffness and is a function of making-up factors, such as fibre diameter, weave

crimp, the yarn count (tex), fabric tightness, structure and weight (Gibson and Postle 1978; Ajeli, 2009; Gulcan, 2012).

Mean and SD values of C - 2 (mm)

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	16.76	17.15	17.60	17.56	17.83
▣ SD	2.83	7.01	2.54	3.12	3.06
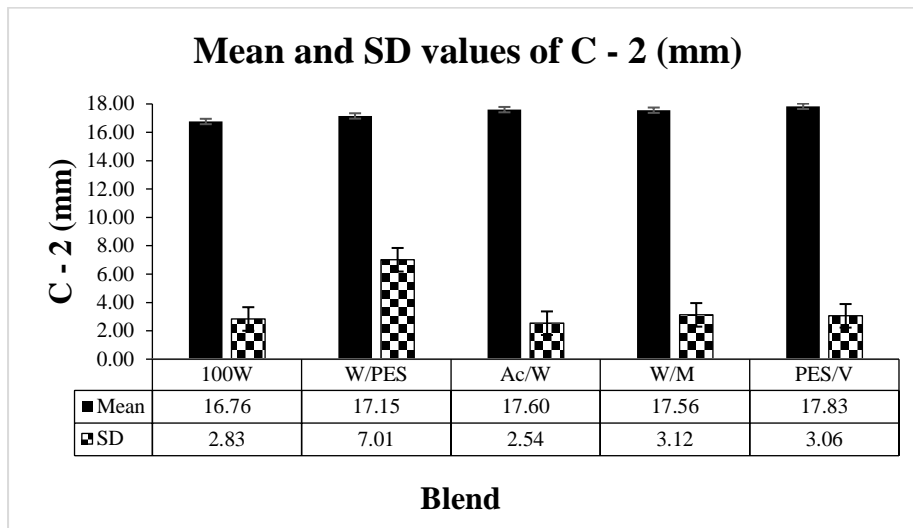
Blend

Figure 4.15 (b): Mean and SD C-2 (mm) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.16.2 ANOVA

ANOVA was carried out on the C-2 (mm) data, with fabric weave structure, blend, mass and thickness as independent variables (Table 4.15).

Table 4.15 – Results of ANOVA for C-2 mm

ANOVA for C-2(mm)	
Multiple R	0.32692655
R Square	0.10688097
Adjusted R Square	0.08777682
Standard Error	4.11164644
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	756.6484622	94.58106	5.59464637	1.03998E-06
Residual	374	6322.708039	16.90564		
Total	382	7079.356501			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	13.2460541	1.232461875	10.74764	*1.1652E-23*	10.82263081	15.6694774
F1	1.09308204	0.665853491	1.641625	0.10150823	-0.216203777	2.40236786
F2	1.39359872	0.558426936	2.495579	*0.01300529*	0.295548657	2.49164878
B1	0.62105253	0.51568675	1.204321	0.22922702	-0.392956349	1.6350614
B2	-0.0610353	1.188065379	-0.05137	0.9590552	-2.397160519	2.27508998
B3	3.98406839	1.110898825	3.586347	*0.00037985*	1.799677833	6.16845895
B4	-0.3622581	0.824806261	-0.4392	0.66076743	-1.984097114	1.25958083
Mass (g/m^2)	-0.0157538	0.00517047	-3.04687	*0.00247651*	-0.025920605	-0.0055869
Thickness (mm)	10.8534566	1.979186883	5.483796	*7.6775E-08*	6.9617276	14.7451855

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes the exponential value.

From the results, given in Tables 4.15, it is apparent that the one weave structure (F2), blend, Ac/W (B2), mass and thickness, being significant. Nevertheless, the differences, even though statistically significant, are relatively small and of little practical consequence.

4.17 Bending rigidity in the warp direction (B-1 μN.m)

4.17.1 Mean and standard deviation values of B-1 (μN.m)

The mean and standard deviation results for the bending rigidity (B-1) in the warp direction of the fabrics, derived from fabric bending length, together with the corresponding standard deviations are shown in Figure 4.16 (a) in the bar chart form. From the figure it is clear that, on average, the plain weave fabrics have a higher bending rigidity than the twill weave and 'other' fabrics.

Mean and SD values of B-1 (μN.m)

	Other	Twill	Plain
■ Mean	11.86	11.36	13.05
□ SD	4.27	7.74	6.84
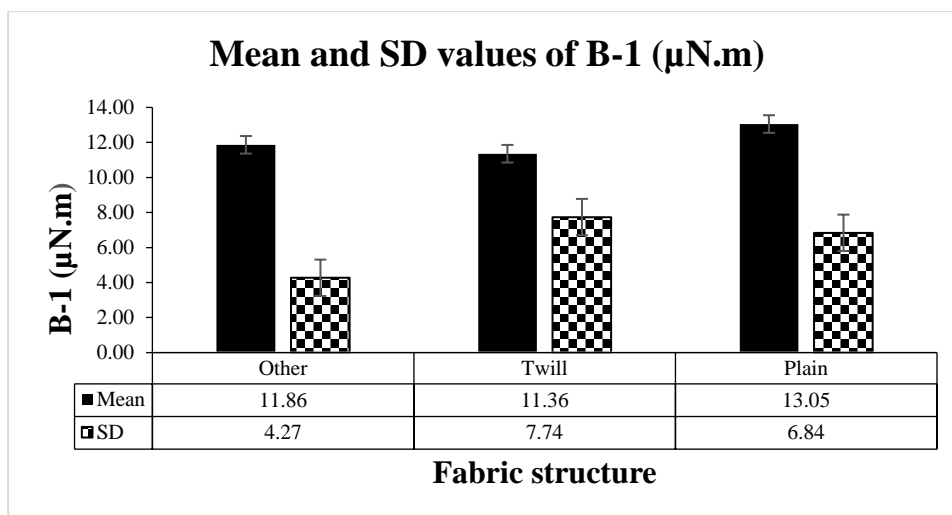
Fabric structure

Figure 4.16 (a): Mean and SD B-1 (μN.m) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of B-1 (μN.m) according to, fabric blend are presented graphically in Figure 4.16 (b), from which it can be seen that, on average, the PES/V fabric blends had the highest bending rigidity (i.e. were the stiffest), with the W/M having the lowest bending rigidity. On average, unacceptably high fabric bending rigidity (stiffness) will result in a poor fabric handle and drape and could also affect fabric making-up (Lindberg et al., 1961; Cusick 1965 and Akter 2017). Too low a bending rigidity can cause difficulties during sewing operations, but is more likely to cause problems earlier in production.
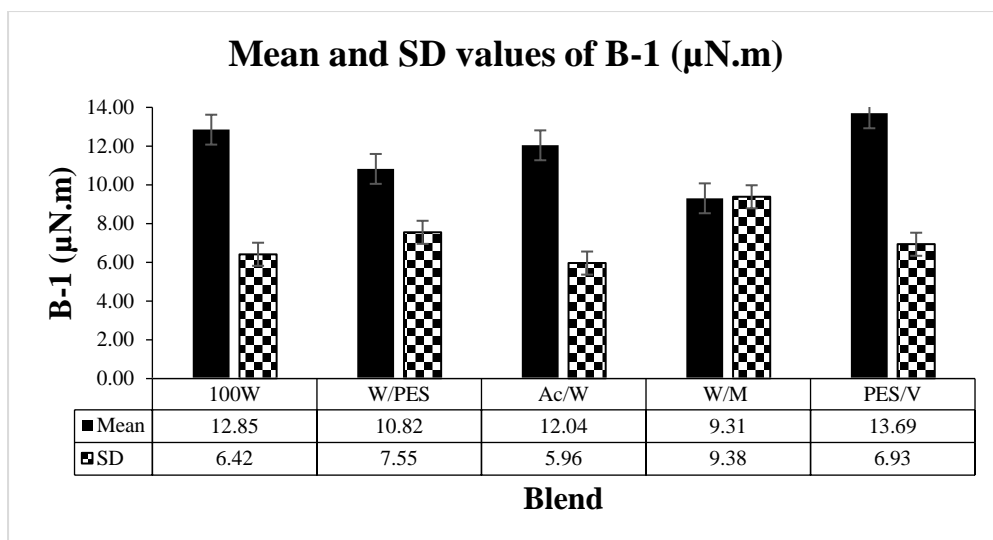
Figure 4.16 (b): Mean and SD B-1 (µN.m) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.1.17.2 ANOVA on B-1 (µN.m)

ANOVA was carried out on the B-1 (µN.m) data, with the results being given in Table 4.16.

Table 4.16 – Results of ANOVA for B-1(µN.m)

ANOVA for B-1 (µN.m)	
Multiple R	0.6798661
R Square	0.4622179
Adjusted R Square	0.4507145
Standard Error	5.1527036
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	8534.582711	1066.823	40.1811151	4.75598E-46
Residual	374	9929.832485	26.55035		
Total	382	18464.4152			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-3.1932287	1.544517704	-2.06746	*0.03937819*	-6.230255865	-0.1562016
F1	-1.7823935	0.834445694	-2.13602	*0.03332651*	-3.423186742	-0.1416002
F2	-0.3877593	0.699819042	-0.55409	0.57985178	-1.763832476	0.98831393
B1	1.0102756	0.646257163	1.563272	0.11883441	-0.260477462	2.28102859
B2	-1.3251653	1.488880142	-0.89004	0.3740157	-4.252790786	1.60246021
B3	0.0756512	1.392175236	0.05434	0.95669308	-2.661820834	2.81312319
B4	-1.2479032	1.033644852	-1.20728	0.22808563	-3.280387198	0.78458074
Mass (g/m^2)	-0.0092491	0.006479618	-1.42742	0.1542932	-0.021990186	0.00349191
Thickness (mm)	31.320861	2.480311352	12.62779	*1.0803E-30*	26.44375771	36.197965

***The values in bold italics are statistically significant at the 94% confidence level. 'E' denotes exponential value.**

From the Table 4.16, it is apparent that only fabric structure (F1) and thickness emerged as statistically significant.

4.18 Bending rigidity in the weft direction B-2 (µN.m)

4.18.1 Mean and standard deviation values

Figure 4.17 (a) shows the mean and standard deviation values for bending rigidity in the weft direction (B-2 µN.m), from which it is apparent that, as in the case of the warp bending rigidity (B-2 µN.m), the plain weave fabric had the slightly higher bending rigidity, in the weft direction. Nevertheless, for the bending rigidity in the weft direction, the 'other' weave structures had the lowest values, which was not the case for that in the warp direction.

Mean and SD values of B-2 (µN.m)

Fabric structure	Other	Twill	Plain
Mean	9.78	11.29	11.70
SD	5.18	7.55	6.29
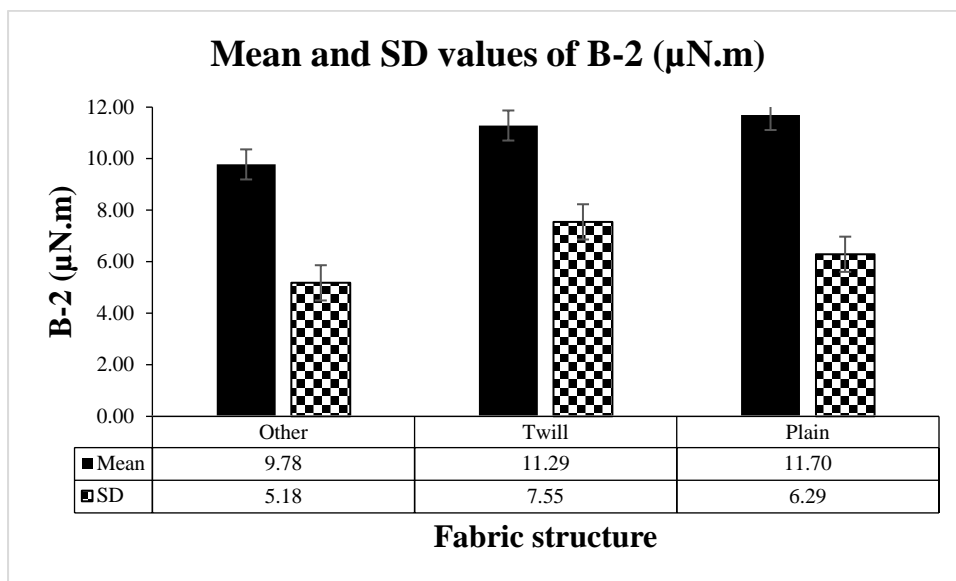
Figure 4.17 (a): Mean and SD B-2 (µN.m) values for the different fabric weave structures (The error bars in the graph represent the 95% confidence limits)

Figure 4.17 (b) present the mean and standard deviation values for bending rigidity in the weft direction (B-2 µN.m) according to fabric blend. From the figure it is apparent that, as in the case of the warp bending rigidity (B-2 µN.m), the W/M fabric blends, on average, had the lowest bending rigidity in the weft direction and with that of the PES/V the highest.
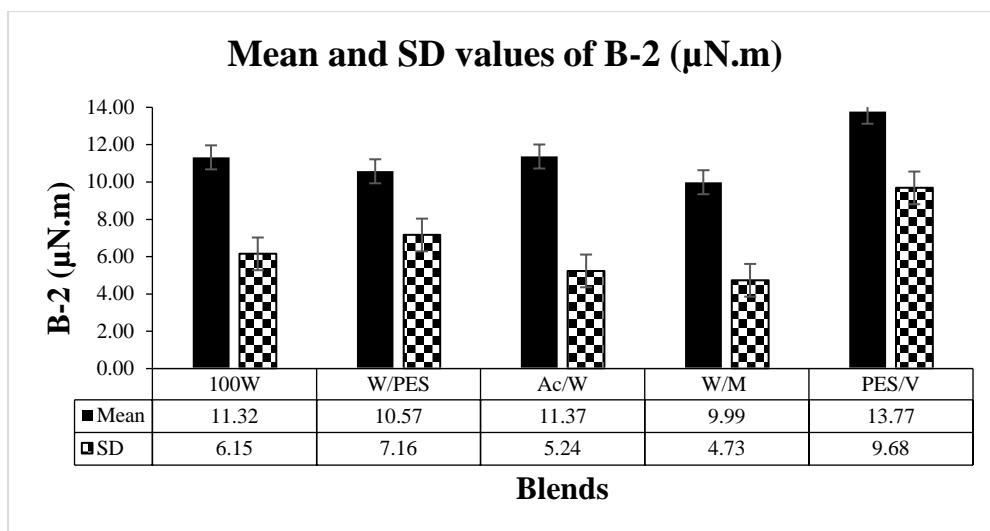
Figure 4.17 (b): Mean and SD B-2 (µN.m) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.18.2 ANOVA for B-2 (µN.m)

Analysis of variance was carried out on the B-2 (µN.m) data, as was done on the B-1 (µN.m), the results being given in Table 4.17.

Table 4.17 – Results of the ANOVA for B-2 (µN.m)

ANOVA for B-2 (µN.m)

Multiple R	0.48443673
R Square	0.23467895
Adjusted R Square	0.21830844
Standard Error	5.91705721
Observations	383

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	4015.259375	501.9074	14.33547479	2.91202E-18
Residual	374	13094.32569	35.01157		
Total	382	17109.58507			

|	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-2.682857	1.773631932	-1.51263	0.131217029	-6.170397685	0.80468368
F1	-0.7821261	0.958227623	-0.81622	0.41489296	-2.666315109	1.10206294
F2	2.99702637	0.803630412	3.729359	***0.000221705***	1.41682605	4.5772267
B1	0.49064621	0.742123148	0.661139	0.50893054	-0.96861071	1.94990313
B2	-1.9124259	1.709741077	-1.11855	0.264051326	-5.274336257	1.44948446
B3	5.3070008	1.598690936	3.319591	***0.0009901***	2.16345136	8.45055025
B4	0.65175281	1.186976045	0.549087	0.583273593	-1.682230456	2.98573607
Mass (g/m^2)	-0.0102991	0.007440806	-1.38413	0.167143191	-0.024930123	0.004332
Thickness (mm)	25.7371601	2.848241496	9.036158	***8.82972E-18***	20.13658539	31.3377347

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes exponential value.

From the results in Table 4.17 it is apparent that one fabric structure, F2 (plain weave), one blend (B3) and fabric thickness emerged as statistically significant.

4.19 Shear rigidity in the warp direction G (N/m)

4.19.1 Mean and standard deviation values for G (N/m)

The mean and standard deviation values for the shear rigidity (G N/m) within the warp direction according to the fabric structure are shown in Figure 4.18 (a) in the bar chart form. From the figure it is seen that, on average, the twill weave fabrics had a significantly higher shear rigidity than the 'other' and plain weave fabrics, the values of which were similar. Fabric shear properties are largely determined by the fabric construction, including weave structure and tightness (Gibson and Postle, 1978; Singh and Verma, 2016).

Mean and SD values of Shear G (N/m)

	Other	Twill	Plain
■ Mean	39.15	56.25	41.72
▨ SD	17.70	35.37	21.89
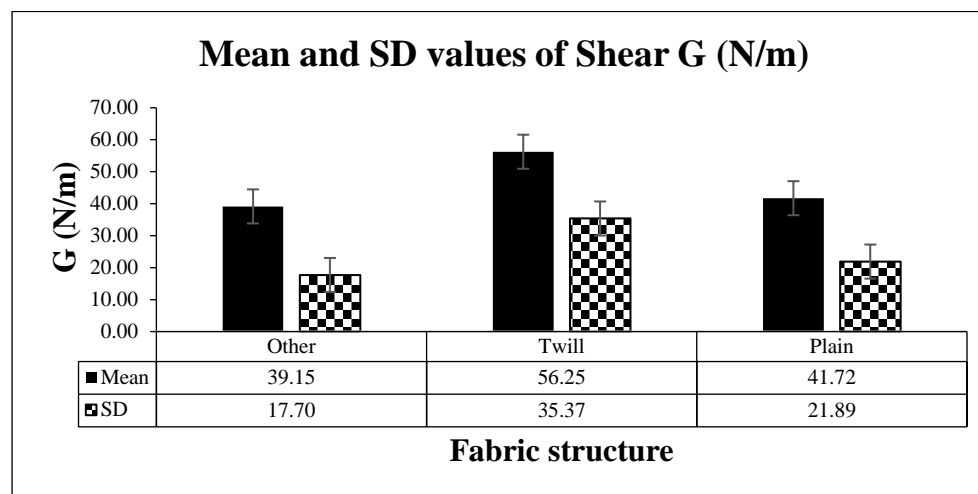
Fabric structure

Figure 4.18 (a): Mean and SD shear rigidity G (N/m) values for the different fabric weave structures

(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of G (N/m) are presented graphically in Figure 4.18 (b) from which according to the blend it can be seen that, on average the W/PES blend fabrics had the highest and the W/M fabrics the lowest shear rigidity in the warp direction. Nevertheless, relatively high standard deviations once again indicate the great variability in the in individual fabric results, within blend and also on overlap between blends. Shear rigidity is a function of bias shear extensibility, with too high a value of shear rigidity can indicate

problems relating to moulding operations, as it becomes difficult to form a smooth three-dimensional shape (Wang et al., 2003; Li et al., 2007).
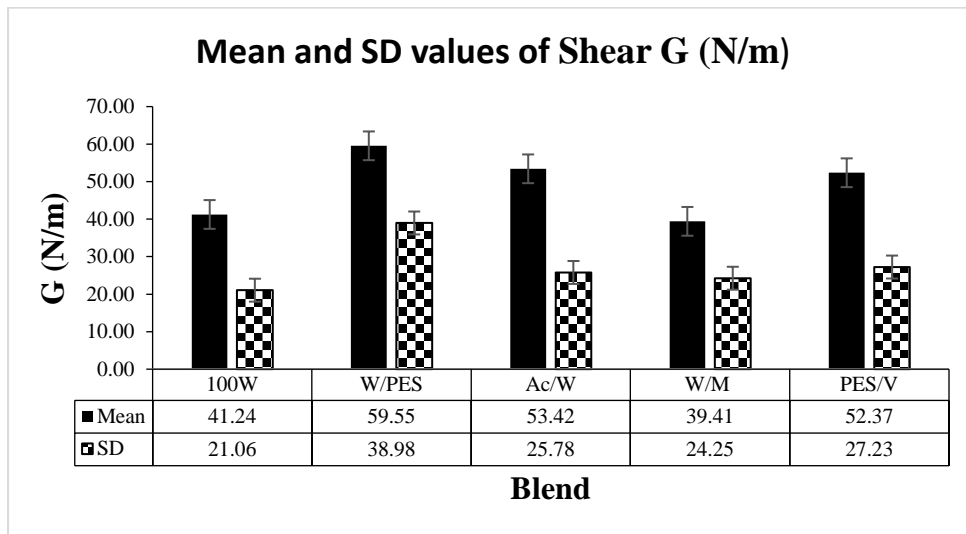
Figure 4.18 (b): Mean and SD shear rigidity G (N/m) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.19.2 ANOVA for G (N/m)

ANOVA was carried out on the G (N/m) data, and the results are given in Table 4.18.

Table 4.18 – Results of ANOVA for G (N/m)

ANOVA for Shear G (N/m)

Multiple R	0.70097834
R Square	0.49137063
Adjusted R Square	0.48049086
Standard Error	20.5129404
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	152032.0669	19004.01	45.16368575	1.69711E-50
Residual	374	157371.9905	420.7807		
Total	382	309404.0574			

|	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-6.16033433	6.148733198	-1.00189	0.317046058	-18.25075556	5.930086902
F1	-4.44315345	3.321932749	-1.33752	0.181865569	-10.97516011	2.088853217
F2	8.57566683	2.785983328	3.078147	*0.002236576*	3.097512082	14.05382158
B1	15.1162434	2.572753203	5.875512	*9.32875E-09*	10.05736881	20.17511792
B2	14.7699383	5.927239767	2.491875	*0.013139433*	3.115045644	26.424831
B3	2.57174598	5.542257021	0.464025	0.642899779	-8.326144658	13.46963662
B4	22.0129348	4.114945654	5.349508	*1.5399E-07*	13.92160535	30.10426435
Mass (g/m^2)	0.43765747	0.025795393	16.9665	*2.74152E-48*	0.386935289	0.488379656
Thickness (mm)	-94.3204223	9.874132689	-9.55227	*1.71665E-19*	-113.7361978	-74.9046467

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential values.

From the results given in Table 4.18 it is apparent that, fabric structure (except for the plain weave), fabric blend (except for W/M blend), fabric mass and thickness all play a significant

role. Fabric weight and thickness, are known to affect the shear rigidity (Dhingra and Postle, 1979, (Kothari and. Tandon, 1989 and Singh and Verma, 2016).

4.20 Thickness at 2gf/cm^2 (T2 mm)

4.20.1 Mean and standard deviation values

Figure 4.19 (a) shows the mean and standard deviation values for thickness (T2 mm) according to fabric structure in bar chart form. From the figure it is clear that on average, the different weave structures have very similar thickness.

Mean and standard deviation values and SD of T2 (mm)

	Other	Twill	Plain
■Mean	0.57	0.54	0.60
□SD	0.11	0.15	0.19
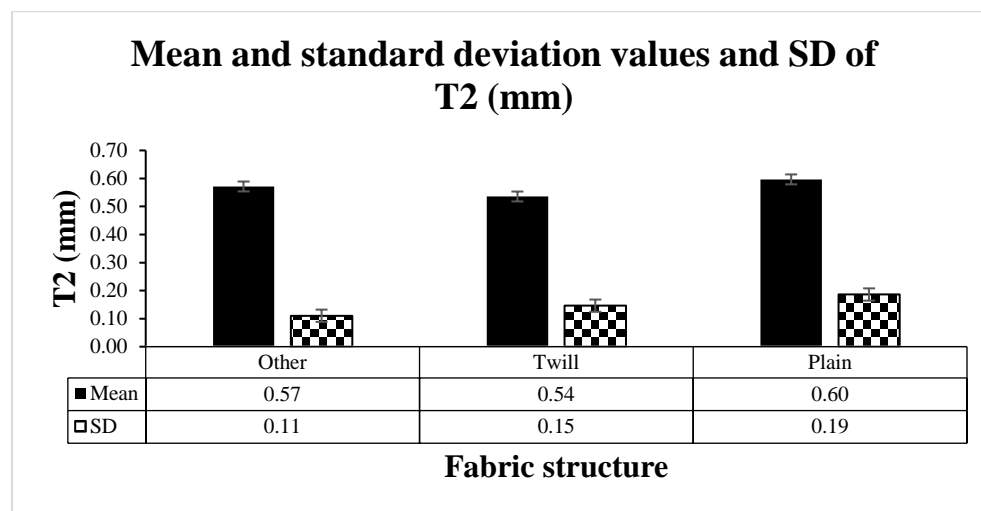
Fabric structure

Figure 4.19 (a): Mean and SD T2 (mm) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean thickness and corresponding standard deviation values of the various blends are presented in Figure 4.19 (b), from which it is apparent that, the PES/V and 100W fabrics had, on average, the highest thicknesses with the other three blends being very similar. The relatively high standard deviation values once again indicate large variability in the results of the individual fabrics within a blend, which together with the corresponding mean implying considerable overlap between blends.
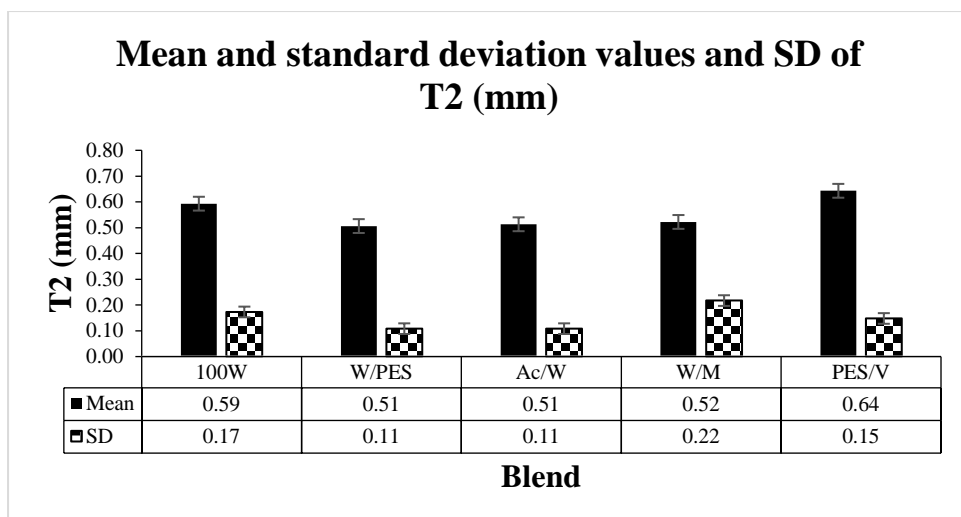
Figure 4.19 (b): Mean and SD T2 (mm) values for the different blends

(The error bars in the graph represent 95% confidence limits)

4.1.20.2 ANOVA for T2 (mm)

ANOVA was carried out on the T2 mm data, the results being given in Table 4.19.

Table 4.19 – Results of the ANOVA for T2 (mm)

ANOVA for T2 (mm)

Multiple R	0.99617639
R Square	0.99236739
Adjusted R Square	0.99220413
Standard Error	0.01450191
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	10.22637363	1.278297	6078.287059	0
Residual	374	0.078654227	0.00021		
Total	382	10.30502785			

|	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.004863	0.004346933	-1.11871	0.263981102	-0.013410458	0.00368453
F1	0.0008387	0.002348487	0.357125	0.721199996	-0.003779191	0.0054566
F2	0.00117888	0.00196959	0.598539	0.549842586	-0.002693982	0.00505173
B1	0.00301922	0.001818844	1.659967	0.097759165	-0.00055722	0.00659566
B2	0.00289682	0.004190345	0.691308	0.489800929	-0.005342771	0.01113641
B3	-0.000453	0.003918176	-0.1156	0.908028565	-0.008157373	0.00725146
B4	0.00445891	0.002909119	1.532735	0.126186679	-0.001261372	0.01017919
Mass (g/m^2)	0.00010434	1.82364E-05	5.721673	***2.16E-08***	6.8484E-05	0.0001402
Thickness (mm)	0.96713374	0.006980657	138.5448	***0***	0.953407485	0.98085999

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

From the above results of the ANOVA given in Table 4.19, it is apparent that, only change in the fabric mass had a statistically significant effect on T2 (mm). This is not unexpected, since

fabric thickness measured under two different loads should be correlated, and also correlated with fabric mass.

4.21 Thickness at 100 gf/cm^2 (T100 mm)

4.21.1 Mean and standard deviation values

Figure 4.20 (a) present the mean and standard deviation values of thickness according to fabric structures. From the figure, it is apparent that, on average, the different fabric structures did differ much for the different twill weave fabric structures, all being, on average, approximately 0.5 mm thick. The relatively high standard deviation values are low indicating that the values for individual fabrics within the blend groups vary quite widely.

Mean and SD values of T100 (mm)

	Other	Twill	Plain
■ Mean	0.47	0.54	0.52
■ SD	0.20	0.41	0.28
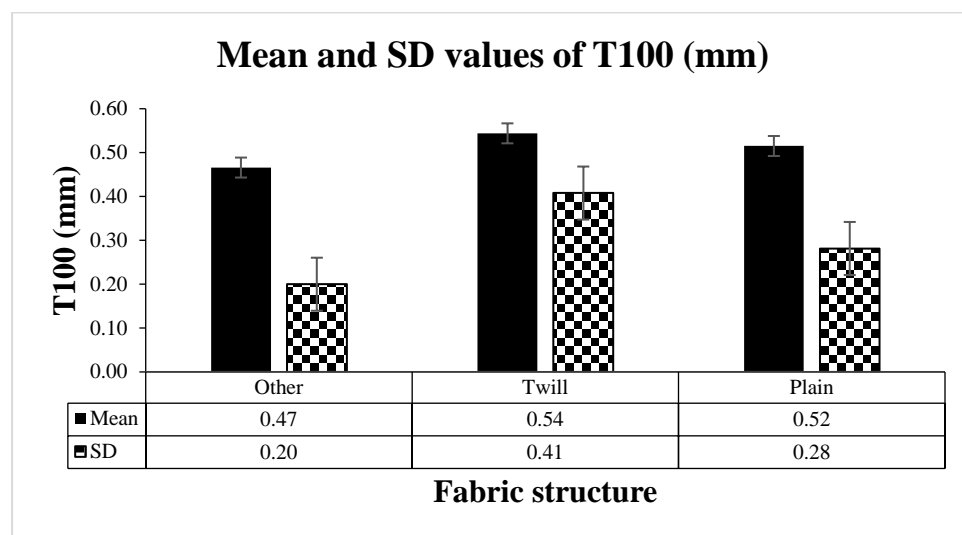
Fabric structure

Figure 4.20 (a): Mean and SD T100 (mm) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values of T100 mm for the different fabric blends are presented graphically in Figure 4.20 (b) from which it can be seen that, on average, the W/PES blend fabric had the highest thickness at 100gf/cm^2, followed by the 100W, Ac/W and PES/V fabrics. Nevertheless, the average differences between the different blends are generally quite

small, and probably of little practical consequence. Surprisingly, the W/M blends had the lowest average thickness.
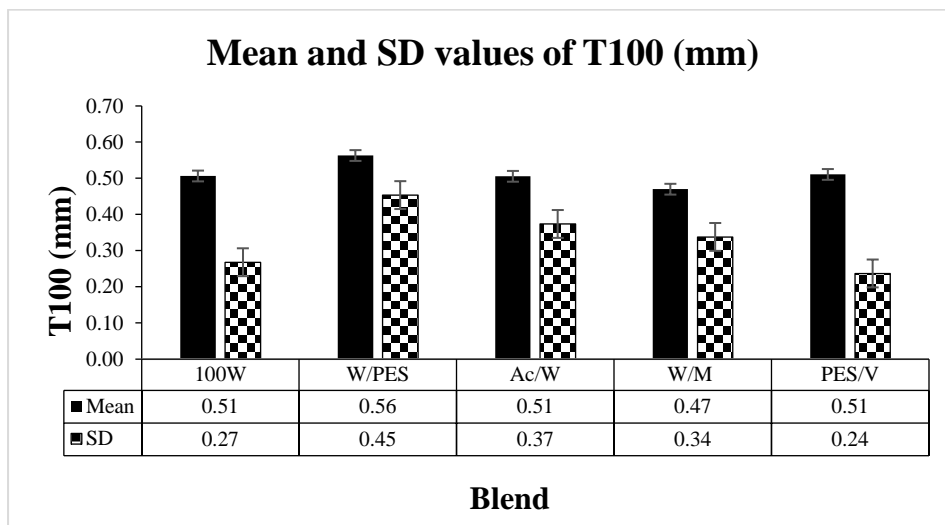
Figure 4.20 (b): Mean and SD T100 (mm) values for the different blends

(The error bars in the graph represent 95% confidence limits)

4.21.2 ANOVA for T100 (mm)

ANOVA was carried out on the thickness (T100 mm) data, and the results are given in the Table 4.20.

Table 4.20 – Results of ANOVA for T100 (mm)

ANOVA for T100 (mm)

Multiple R	0.76681782
R Square	0.58800957
Adjusted R Square	0.57919695
Standard Error	0.21315193
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	24.25199167	3.031499	66.7235109	2.22911E-67
Residual	374	16.99222051	0.045434		
Total	382	41.24421218			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.32178563	0.063892076	-5.03639	*7.3944E-07*	-0.447418357	-0.19615291
F1	0.02371792	0.034518521	0.687107	0.4924411	-0.044156788	0.09159263
F2	0.03655949	0.02894942	1.262875	0.207421	-0.020364541	0.09348352
B1	0.08352077	0.026733725	3.124173	*0.00192216*	0.030953521	0.13608802
B2	0.14755306	0.061590516	2.395711	*0.01707901*	0.026445957	0.26866017
B3	-0.00819496	0.057590124	-0.1423	0.88692129	-0.121435982	0.10504607
B4	0.09558042	0.042758794	2.235339	*0.02598475*	0.011502638	0.1796582
Mass (g/m^2)	0.00568361	0.000268042	21.20413	*4.2879E-66*	0.005156546	0.00621066
Thickness (mm)	-0.83671247	0.102603059	-8.15485	*5.3495E-15*	-1.038463657	-0.63496129

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential values.

From the Table 4.20, it is evident that fabric blend, mass and thickness, but not fabric structure, had a statistically significant effect on fabric thickness at 100 gf/cm2. Fabric thickness is known

to effect the handle of the fabric, garment making and laying-up operations and if the fabric is too thick or too thin it might create problems in handling and laying-up of the fabric giving rise to cutting problems (Elder et al., 1984; Kremenakova, 2004, 2008; Angelova, 2015).

4.22 Surface thickness (ST mm)

4.22.1 Mean and standard deviation values of ST (mm)

Figure 4.21 (a), presents the mean and standard deviation values for surface thickness for the different fabric structures. From the figure it is apparent that, on average, the twill weave fabrics had the lowest surface thickness, with that of the plain and twill weave fabrics not being similar. Nevertheless, the relatively large standard deviation indicate a wide scatter, and overlap, in the individual fabric values.

Mean and SD values of ST (mm)

	Other	Twill	Plain
■Mean	0.11	-0.01	0.08
□SD	0.19	0.42	0.25
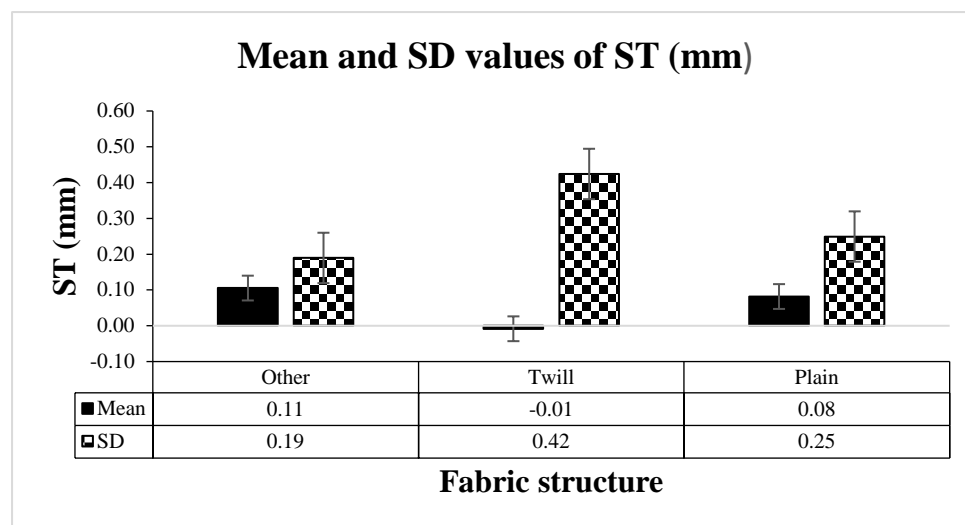
Fabric structure

Figure 4.21 (a): Mean and SD ST (mm) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values for surface thickness (ST mm) for the various blends are presented in Figure 4.21 (b), according to blends from which it is apparent that, the PES/V fabrics had, on average, the highest and the W/PES and Ac/W, the lowest surface thickness. It

is clear, from the relatively high standard deviations that there is a wide scatter of the individual fabric results within a fabric blend, and also an overlap between blends.

Mean and SD values of ST (mm)

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.09	-0.06	0.01	0.05	0.13
▣ SD	0.24	0.46	0.39	0.36	0.27
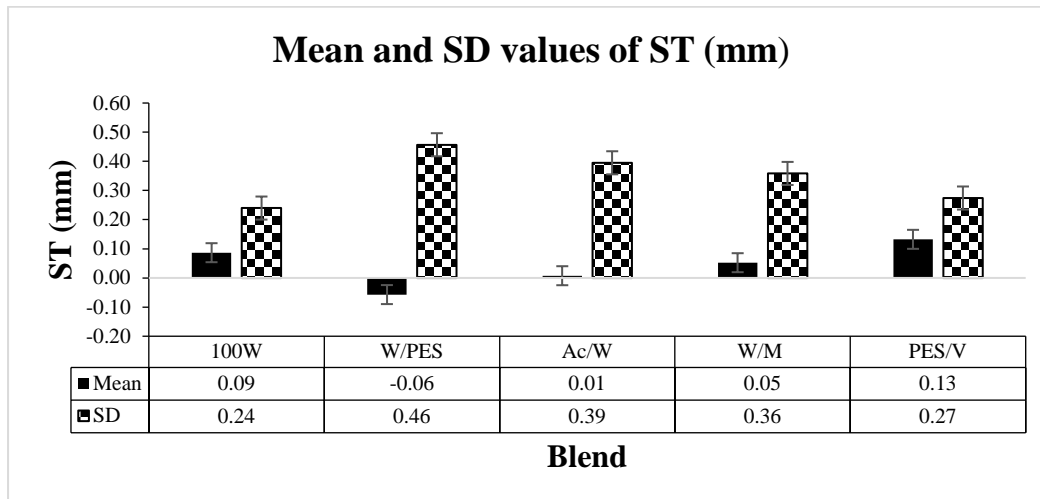
Blend

Figure 4.21 (b): Mean and SD ST (mm) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.22.2 ANOVA

ANOVA was carried out on ST (mm) data, and the analysis given in Table 4.21

Table 4.21 – Results of the ANOVA for ST (mm)

ANOVA for ST (mm)

Multiple R	0.77276977
R Square	0.59717312
Adjusted R Square	0.58855651
Standard Error	0.20915241
Observations	383

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	24.25376446	3.031721	69.30481836	3.47819E-69
Residual	374	16.36052897	0.043745		
Total	382	40.61429344			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.31616067	0.062693223	5.04298	*7.15995E-07*	0.192885284	0.439436063
F1	-0.02350053	0.033870826	-0.69383	0.48822079	-0.090101653	0.043100599
F2	-0.03503739	0.028406221	-1.23344	0.218185953	-0.090893319	0.020818531
B1	-0.08084573	0.026232101	-3.08194	*0.002208987*	-0.132426627	-0.029264839
B2	-0.14470984	0.06043485	-2.39448	*0.017135694*	-0.263544528	-0.025875152
B3	0.00765554	0.056509519	0.135473	0.892310474	-0.103460667	0.118771741
B4	-0.09079809	0.041956481	-2.1641	*0.031088956*	-0.173298259	-0.008297921
Mass (g/m^2)	-0.00557746	0.000263013	-21.206	*4.21068E-66*	-0.006094625	-0.005060286
Thickness (mm)	1.80423233	0.100677845	17.92085	*2.74836E-52*	1.60626675	2.002197916

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential values.

From the results given in Table 4.21, it is apparent that the surface thickness is not significantly dependent on fabric structure, but is statistically significantly dependent upon the fabric blend, mass and thickness of the fabric surface thickness providing a measure of the stability of the

finish of the fabric, the larger the value, the less stable the finish. According to De Boos and Tester (1994), this measurement is important in determining the extent of subsequent changes in the appearance and handle of the fabric after garment pressing and can indicate the potential re-emergence of aspects, such as running marks.

4.23 Released thickness at 2gf/cm^2 (T2R mm)

4.23.1 Mean and standard deviation values of released thickness at 2 gf/cm^2

Figure 4.22 (a) present the mean and standard deviation values for the released thickness at 2gf/cm^2 for the different fabric structures. From Figure 4.22 (a), it is apparent that the twill weave fabrics had the lowest and the plain weave fabrics had the highest released thickness, with the differences relatively of little practical consequence.

Mean and SD values of T2R (mm)

	Other	Twill	Plain
■ Mean	0.60	0.56	0.65
■ SD	0.15	0.16	0.23
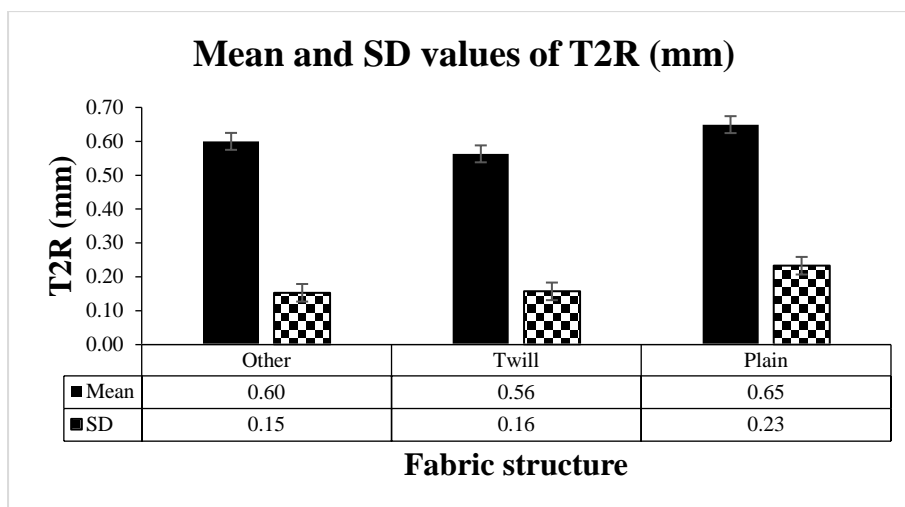
Fabric structure

Figure 4.22 (a): Mean and SD T2R (mm) values for the different fabric weave structures
(The error bars in the graph represent the 95% confidence limits)

The mean and standard deviation values are presented graphically in Figure 4.22 (b) according to the fabric blend can be seen that, on average, the PES/V blend fabrics had the highest released thickness and the W/M and W/PES fabrics the lowest. Nevertheless, the average

differences between the different blends are generally quite small, and probably of little practical significance.
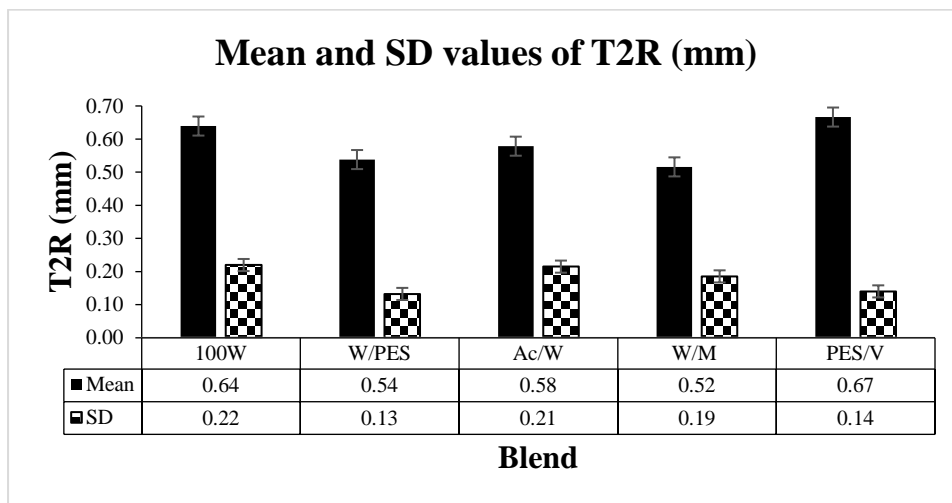
Figure 4.22 (b): Mean and SD T2R (mm) values for the different blends

(The error bars in the graph represent the 95% confidence limits)

4.23.2 ANOVA

ANOVA was carried out on the T2R mm data, and the results are given in Table 4.22.

Table 4.22 – Results of ANOVA for T2R (mm)

ANOVA for T2R (mm)

Multiple R	0.870923217
R Square	0.758507249
Adjusted R Square	0.753341629
Standard Error	0.099020751
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	11.5180689	1.439759	146.8375916	1.9787E-110
Residual	374	3.66711082	0.009805		
Total	382	15.18517972			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.073248861	0.02968137	2.46784	***0.014039919***	0.014885575	0.131612146
F1	-0.066726498	0.016035745	-4.16111	***3.93299E-05***	-0.098258019	-0.035194977
F2	-0.030558641	0.013448592	-2.27226	***0.02363814***	-0.057002973	-0.004114309
B1	-0.022659144	0.01241928	-1.82451	0.068872155	-0.047079512	0.001761224
B2	0.089980318	0.02861217	3.144827	***0.001794769***	0.033719431	0.146241205
B3	-0.019956443	0.026753768	-0.74593	0.456178165	-0.072563105	0.032650219
B4	0.007259174	0.019863803	0.365447	0.714984092	-0.031799562	0.04631791
Mass (g/m^2)	-5.53585E-05	0.00012452	-0.44457	0.656884774	-0.000300206	0.000189489
Thickness (mm)	1.011222668	0.047664743	21.21532	***3.84908E-66***	0.917498188	1.104947149

*The values in bold italics are statistically significant at the 95% confidence level. 'E' denotes exponential values.

From the Table 4.22, it is evident that, the effects on T2R of fabric structure, blend (W/PES) and thickness were statistically significant. This is in line with previous studies in which fabric

structure and thickness, but not mass influenced the released thickness of the fabric (Elder et al., 1984).

4.24 Released fabric thickness at 100gf/cm^2 (T100R mm)

4.24.1 Mean and standard deviation values for T100R

Figure 4.23 (a) presents the average and standard deviation values for the released thickness (T100R mm) of the different fabric structures. From this figure, it is apparent that, the released thickness of the 'other' fabric structures was on average, slightly lower than that of the twill and plain weave fabrics, this being almost the reverse to that found for the released thickness at 2gf/cm^2 (T2R).

Mean and SD values of T100R (mm)

Fabric structure	Other	Twill	Plain
■ Mean	0.47	0.55	0.53
□ SD	0.20	0.41	0.28
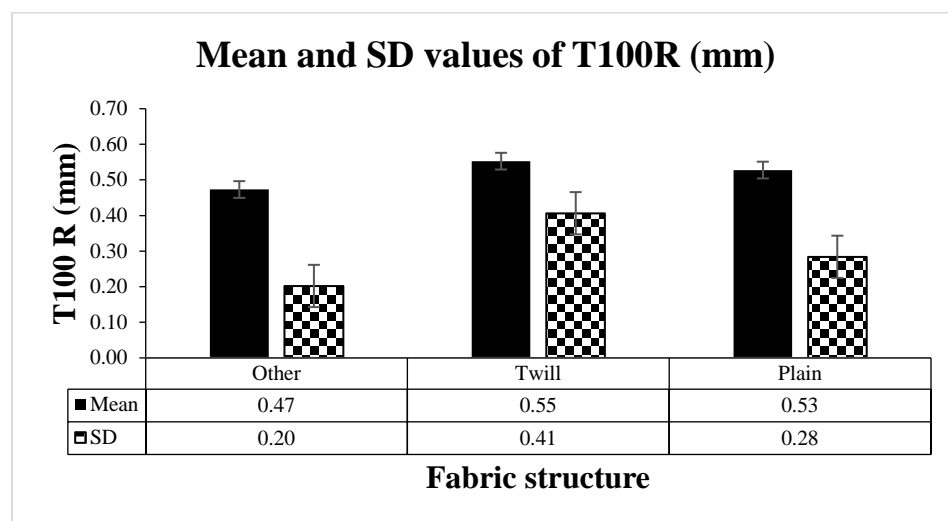
Figure 4.23 (a): Mean T100R (mm) values for fabric weave structures

(The error bars in the graph represent 95% confidence limits)

The mean and standard deviation released thickness (T100R) values for the various blends are presented in Figure 4.23 (b), from which it is apparent that, the W/PES fabrics had, on average, the highest and the W/M the lowest released thickness. This was also the case for the T2R values. Nevertheless, the average differences are quite small and of little practical importance.

Mean and SD values of T100 R (mm)

	100W	W/PES	Ac/W	W/M	PES/V
■ Mean	0.52	0.57	0.52	0.48	0.52
▪ SD	0.27	0.45	0.37	0.34	0.24
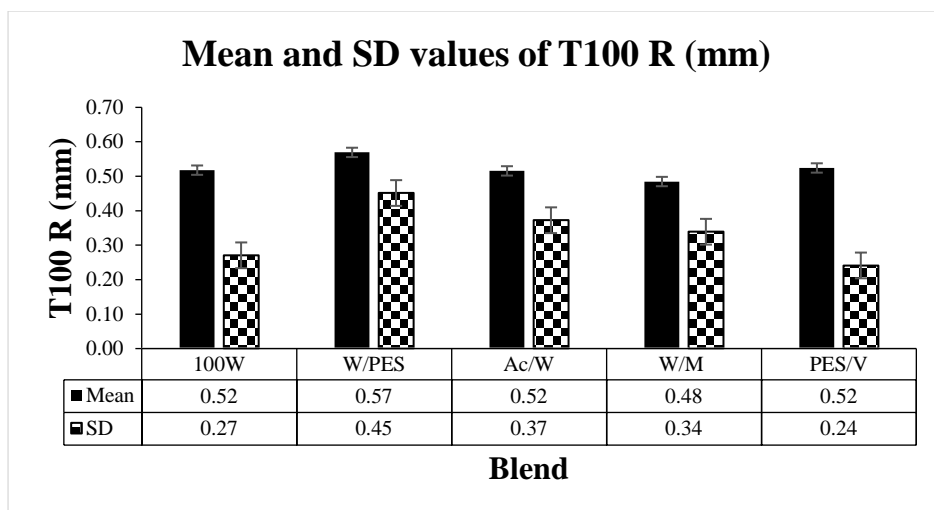
Blend

Figure 4.23 (b): Mean and SD T100R (mm) values for the different fabric blends

(The error bars in the graph represent 95% confidence limits)

4.24.2 ANOVA

ANOVA was carried out on the T100R (mm) data, the results being given in Table 4.23.

Table 4.23 – Results of ANOVA for T100R (mm)

ANOVA for T100R (mm)

Multiple R	0.764391329
R Square	0.584294104
Adjusted R Square	0.575401999
Standard Error	0.214516916
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	24.19023084	3.0237789	65.7093142	1.17239E-66
Residual	374	17.21054778	0.0460175		
Total	382	41.40077863			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.335107014	0.064301229	-5.211518	**3.10351E-07**	-0.46154427	-0.20866976
F1	0.023655624	0.034739572	0.6809417	0.496329738	-0.04465374	0.09196499
F2	0.036808947	0.029134807	1.2634011	0.207232061	-0.02047962	0.09409751
B1	0.082712141	0.026904923	3.0742381	**0.002265351**	0.029808259	0.13561602
B2	0.159522781	0.061984931	2.5735736	**0.010449825**	0.037640126	0.28140544
B3	0.003409438	0.057958921	0.0588251	0.953122851	-0.11055676	0.11737564
B4	0.088317989	0.043032614	2.0523501	**0.040831189**	0.00370179	0.17293419
Mass (g/m^2)	0.00562374	0.000269759	20.847284	**1.34555E-64**	0.005093306	0.00615417
Thickness (mm)	-0.771925474	0.103260111	-7.475544	**5.51034E-13**	-0.97496864	-0.56888231

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

From the results given in Table 4.23 it is apparent that, with the exception of the fabric weave structure and blend (B3), all the other variables played a statistically significant role in determining the released thickness.

4.25 Released surface thickness (STR)

4.25.1 Mean and standard deviation values

Figure 4.24 (a) presents the mean and standard deviation values for the released surface thickness (the difference in thickness between $2gf/cm^2$ and $100gf/cm^2$ loads) according to fabric structures. From the figure it is apparent that, the twill weave fabrics had the lowest released surface thickness, with that of the 'other' and plain weave fabric structures not differing statistically significantly. Nevertheless, the relatively high standard deviation values indicate that the individual fabric results vary widely, which needs to be taken into consideration in practice.

Mean and SD values of STR (mm)

	Other	Twill	Plain
■ Mean	0.15	0.02	0.13
□ SD	0.20	0.44	0.27
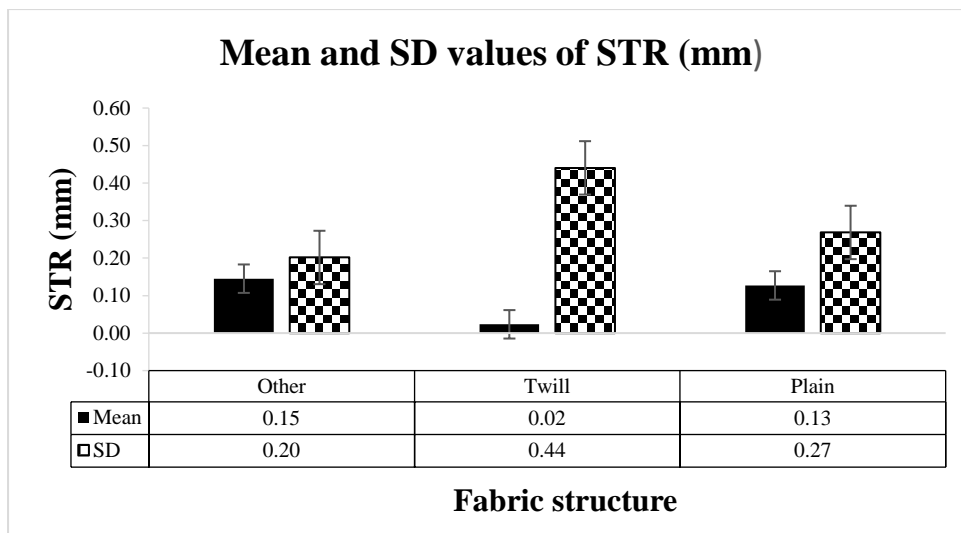
Fabric structure

Figure 4.24 (a): Mean and SD STR (mm) values for the different fabric weave structures (The error bars in the graph represent 95% confidence limits)

The mean and standard deviation values for the various fabric blends are presented in Figure 4.24 (b) from what it is apparent that, the PES/V fabrics had, on average, the highest released surface thickness, followed by 100W and the W/M fabrics, with that of W/PES blend fabrics being the lowest. Nevertheless, the very high, relatively speaking, standard deviations indicate great variability of the individual fabric results within a blend.
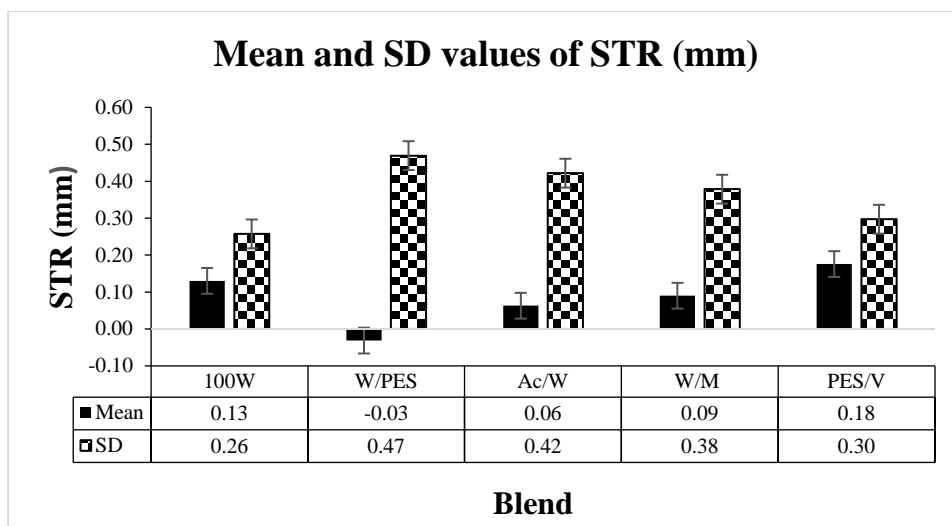
Figure 4.24 (b): Mean and SD STR (mm) values for the different fabric blends

(The error bars in the graph represent the 95% confidence limits)

4.25.2 ANOVA for STR (mm)

ANOVA was carried out on the STR (mm), the results of which are given in the Table 4.24.

Table 4.24 – Results of ANOVA for STR (mm)

ANOVA for STR (mm)

Multiple R	0.808074287
R Square	0.652984053
Adjusted R Square	0.645561252
Standard Error	0.204239156
Observations	383

ANOVA

	df	SS	MS	F	Significance F
Regression	8	29.35639729	3.66954966	87.9700335	3.5072E-81
Residual	374	15.60089862	0.04171363		
Total	382	44.95729591			

|	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.292851891	0.061220481	4.78356077	**2.4822E-06**	0.1724724	0.413231387
F1	-0.04322023	0.033075158	-1.3067279	0.19210805	-0.1082568	0.021816349
F2	-0.0416912	0.027738923	-1.5029856	0.13368665	-0.096235	0.012852597
B1	-0.08136096	0.025615876	-3.1761927	**0.00161614**	-0.1317302	-0.03099176
B2	-0.07637425	0.059015159	-1.2941463	0.19641342	-0.1924174	0.03966886
B3	-0.00158715	0.05518204	-0.0287621	0.97706968	-0.1100931	0.106918794
B4	-0.11547554	0.040970871	-2.8184791	**0.00508164**	-0.1960377	-0.0349134
Mass (g/m^2)	-0.00593361	0.000256834	-23.102843	**5.2215E-74**	-0.0064386	-0.00542858
Thickness (mm)	2.064316765	0.098312796	20.9974373	**3.154E-65**	1.87100164	2.257631888

*The values in bold italics are statistically significant at the 95% confidence limits. 'E' denotes exponential value.

From the Figure 4.24 (a), it appears that fabric blend (B1 and B4), mass and thickness but not structure, are statistically significant.

4.26 FAST benchmark tables and fingerprints control chart for tailorability

4.26.1 Summarized tables

Taking the mean values of various FAST properties obtained earlier and formulating Table 4.26.1 which summarizes the influence of fabric structure and blend on the various FAST properties, based upon the ANOVA that was carried out. A '0' (zero) indicates a statistically significant, whereas an 'X' indicates that the effect was not statistically significant.

Table 4.26.1 – Summary of the effect of fabric structure and blend on the various FAST properties

FAST Parameters	Fabric Structure(Twill/Plain/Other)			Fabric Blends (100W, W/PES, W/M, Ac/W, PES/V)				
	Twill	Plain	Other	100W	W/PES	W/M	Ac/W	PES/V
RS-1 %	X	0	X	X	X	X	X	X
RS-2%	X	X	X	X	0	X	X	X
HE-1%	X	X	X	0	0	0	0	0
HE-2%	X	0	X	0	0	0	X	0
F-1mm^2	0	X	X	X	X	X	X	X
F-2mm^2	X	X	X	0	X	0	X	X
E5-1 %	X	X	X	0	X	X	X	X
E5-2 %	X	X	X	0	X	0	0	X
E20-1 %	X	X	X	0	X	X	X	X
E20 -2%	X	0	0	X	0	X	X	X
E100-1 %	X	X	X	0	0	X	X	x
E100-2 %	X	0	0	X	0	X	X	X

EB5	0	X	X	0	X	X	X	x
C-1 mm	0	X	X	0	X	0	X	X
C-2 mm	0	X	X	X	X	0	X	X
B-1 (µN.m)	0	X	X	X	X	X	X	X
B-2 (µN.m)	X	0	X	X	X	0	X	X
G (N/m)	X	0	X	0	0	0	X	0
T2 mm	X	X	X	0	0	0	X	X
T100 mm	X	X	X	0	0	0	X	0
ST mm	X	X	X	0	0	0	X	0
T2R mm	0	0	0	X	X	X	X	X
T100R	X	X	X	0	0	X	0	0
STR	X	X	X	0	X	X	X	0

The table 4.26.2 below gives a list of mean values for all the FAST parameters which acts as a reference or benchmarking system and assists in formulating fingerprint charts, results of the fabrics covered in this research, and can be taken as representative of the worsted type of apparel fabrics produced and used in South Africa. The table mainly deals with the major weaves (twill and plain) and wool and W/PES blends that are more in number out of the 394 commercial fabrics collected and are more often commonly used in the manufacturing processes.

Table 4.26.2 – Average values of the various FAST properties for the different fabric weaves and blends

FAST Property	Twill Weave	Plain Weave	100W	(W/PES)
RS-1 %	1.61	1.58	1.50	1.62
RS-2%	0.85	0.60	0.70	0.61
HE-1%	3	2.41	3.46	1.36
HE-2%	3.43	2.49	3.79	1.38
F-1mm^2	0.71	0.39	0.61	0.40
F-2mm^2	0.69	0.39	0.65	0.35
E5-1 %	0.34	0.30	0.34	0.28
E5-2 %	0.46	0.34	0.47	0.29
E20-1 %	1.02	0.88	1.02	0.79
E20 -2%	1.47	1.01	1.47	0.81
E100-1 %	2.84	2.60	2.84	2.33
E100-2 %	4.14	3.26	4.28	2.64
EB5	3.54	2.97	3.58	2.62
C-1 mm	18.00	16.70	17.53	16.71
C-2 mm	16.55	17.17	16.76	17.153
B-1 (µN.m)	15.09	9.41	12.85	10.82
B-2 (µN.m)	11.73	10.84	11.32	10.57
G (N/m)	44.70	50.22	41.24	59.55
T2 mm	0.66	0.47	0.59	0.50
T100 mm	0.56	0.46	0.50	0.56
ST mm	0.09	0.001	0.08	-0.06

T2R mm	0.72	0.49	0.64	0.54
T100R	0.575	0.471	0.517	0.569
STR	0.153	0.023	0.130	-0.031

4.26.2 Tables and control charts (fingerprints) representative of the twill and plain weave fabrics

Using Table 4.26.2 as a basis, FAST control charts (fingerprints) and data sheets have been prepared and are given in the following pages, part of all for the plain weave (Table 4.26.3 and Figure 4.26.1) and twill weave (Table 4.26.4 and Figure 4.26.2) fabrics separately, and then for them averaged (Figure 4.26.3) and together (Figure 4.26.4).

Table 4.26.3: FAST data sheet representing plain weave fabrics

```
                        SiroFAST DATA SHEET

        FABRIC ID: plain weave
          END USE:
           SOURCE:
             DATE: 22/07/2016
           REMARK:

                   MEAN      1      2      3      4      5      6
DIMENSIONAL STABILITY
  RS-1  (%)        1.6
  RS-2  (%)        0.6
  HE-1  (%)        2.4
  HE-2  (%)        2.5

FORMABILITY
  F-1              0.34
  F-2              0.43

EXTENSION
  E5-1  (%)        0.3    0.3    0.0    0.0
  E5-2  (%)        0.3    0.3    0.0    0.0
  E20-1 (%)        0.9    0.9    0.0    0.0
  E20-2 (%)        1.0    1.0    0.0    0.0
  E100-1(%)        2.6    2.6    0.0    0.0
  E100-2(%)        3.3    3.3    0.0    0.0
  EB5   (%)        3.0    3.0    3.0    3.0    0.0    0  ⬭ _ ◻

BENDING
  C-1   (mm)       16.7   16.7   16.7   16.7   16.7   16.7   16.7
                          0.0    0.0    0.0    0.0    0.0    0.0
  C-2   (mm)       17.2   17.2   17.2   17.2   17.2   17.2   17.2
                          0.0    0.0    0.0    0.0    0.0    0.0
  B-1 (µN.m)       8.7
  B-2 (µN.m)       9.4

SHEAR
  G    (N/m)       41.4

COMPRESSION
  T2    (mm)       0.466  0.466  0.000  0.000  0.000  0.000
  T100  (mm)       0.465  0.465  0.000  0.000  0.000  0.000
  ST    (mm)       0.001
  T2R   (mm)       0.495  0.495  0.000  0.000  0.000  0.000
  T100R (mm)       0.471  0.471  0.000  0.000  0.000  0.000
  STR   (mm)       0.024

WEIGHT
  W   (g/m²)       190

PRESS TEST ANGLE
  A-1   (°)        0.0
  A-2   (°)        0.0
```
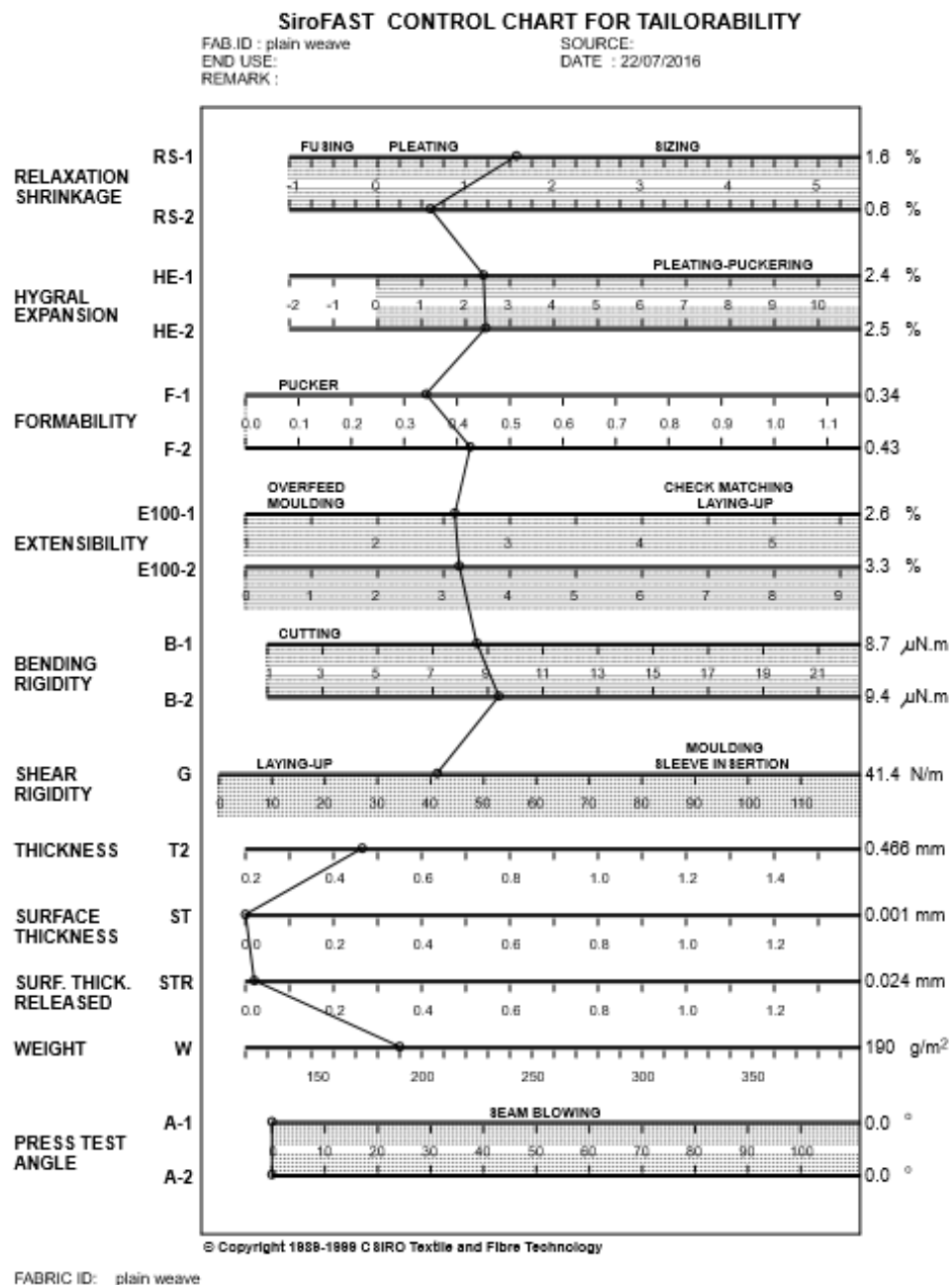
Figure 4.26.1: FAST control chart for plain weave fabrics representation of commercial worsted apparel fabrics

Table 4.26.4: FAST data sheet representing twill weave fabrics

```
                    SiroFAST DATA SHEET


        FABRIC ID: twill weave
          END USE:
           SOURCE:
             DATE: 22/07/2016
           REMARK:

                     MEAN     1      2      3      4      5      6

DIMENSIONAL STABILITY
   RS-1  (%)      1.6
   RS-2  (%)      0.8
   HE-1  (%)      3.0
   HE-2  (%)      3.4

FORMABILITY
    F-1           0.69
    F-2           0.79

EXTENSION
   E5-1   (%)     0.3     0.3    0.0    0.0
   E5-2   (%)     0.5     0.5    0.0    0.0
   E20-1  (%)     1.0     1.0    0.0    0.0
   E20-2  (%)     1.5     1.5    0.0    0.0
   E100-1 (%)     2.8     2.8    0.0    0.0
   E100-2 (%)     4.1     4.1    0.0    0.0
   EB5    (%)     3.5     3.5    3.5    3.5    3.5    3.5    3.5

BENDING
    C-1   (mm)    18.0    18.0   18.0   18.0   18.0   18.0   18.0
                          0.0    0.0    0.0    0.0    0.0    0.0
    C-2   (mm)    16.5    16.5   16.5   16.5   16.5   16.5   16.5
                          0.0    0.0    0.0    0.0    0.0    0.0
    B-1 (µN.m)    14.9
    B-2 (µN.m)    11.5

SHEAR
    G    (N/m)    34.7

COMPRESSION
    T2    (mm)    0.656   0.656  0.000  0.000  0.000  0.000
    T100  (mm)    0.561   0.561  0.000  0.000  0.000  0.000
    ST    (mm)    0.095
    T2R   (mm)    0.722   0.722  0.000  0.000  0.000  0.000
    T100R (mm)    0.575   0.575  0.000  0.000  0.000  0.000
    STR   (mm)    0.147

WEIGHT
    W   (g/m²)     260

PRESS TEST ANGLE
    A-1    (°)     0.0
    A-2    (°)     0.0
```

Figure 4.26.2: FAST control chart (fingerprint) for twill weave fabrics representation of commercial worsted apparel fabrics

Figure 4.26.3: FAST control charts (fingerprint) averaged values respectively, for plain and twill weave fabrics representation of commercial worsted apparel fabrics

From the FAST control charts representing the plain (Figure 4.26.1) and twill (Figure 4.26.2) weave fabrics, and superimposed (Figure 4.26.3), it is apparent that the fingerprints be within the control chart tolerance limits, without any major fabric quality defects. It is therefore apparent that, based upon the overall average values, the commercial worsted apparel fabrics used in South Africa, easily meet international quality requirements.

On summarizing together, it can be said that the twill fabrics was on average heavier and thicker than the plain weave fabrics, and exhibited, again on average, higher relaxation shrinkage and hygral expansion but lower formability, extensibility and shear stiffness than the plain weave fabrics. Nevertheless, the results of the individual fabrics varied and overlapped greatly.

4.26.3 Tables and control charts (fingerprint) representative of the 100W and W/PES fabrics

4.26.3.1 100W fabrics

Table 4.26.3.1: FAST data sheet representing the 100W fabrics

```
                        SiroFAST DATA SHEET

        FABRIC ID: 100 % Wool
          END USE:
           SOURCE:
             DATE: 22/07/2016
           REMARK:

                     MEAN     1      2      3      4      5      6

    DIMENSIONAL STABILITY
      RS-1  (%)      1.5
      RS-2  (%)      0.7
      HE-1  (%)      3.5
      HE-2  (%)      3.8

    FORMABILITY
      F-1            0.60
      F-2            0.77

    EXTENSION
      E5-1   (%)     0.3     0.3    0.0    0.0
      E5-2   (%)     0.5     0.5    0.0    0.0
      E20-1  (%)     1.0     1.0    0.0    0.0
      E20-2  (%)     1.5     1.5    0.0    0.0
      E100-1 (%)     2.8     2.8    0.0    0.0
      E100-2 (%)     4.3     4.3    0.0    0.0
      EB5    (%)     3.6     3.6    0.0    0.0    0.0    0.0    0.0

    BENDING
      C-1   (mm)    17.5    17.5   17.5   17.5   17.5   17.5   17.5
                            0.0    0.0    0.0    0.0    0.0    0.0
      C-2   (mm)    16.8    16.8   16.8   16.8   16.8   16.8   16.8
                            0.0    0.0    0.0    0.0    0.0    0.0
      B-1 (µN.m)    12.9
      B-2 (µN.m)    11.3

    SHEAR
      G    (N/m)    34.4

    COMPRESSION
      T2    (mm)    0.593  0.593  0.000  0.000  0.000  0.000
      T100  (mm)    0.506  0.506  0.000  0.000  0.000  0.000
      ST    (mm)    0.087
      T2R   (mm)    0.639  0.639  0.000  0.000  0.000  0.000
      T100R (mm)    0.517  0.517  0.000  0.000  0.000  0.000
      STR   (mm)    0.122

    WEIGHT
      W   (g/m²)     245

    PRESS TEST ANGLE
      A-1    (°)     0.0
      A-2    (°)     0.0
```
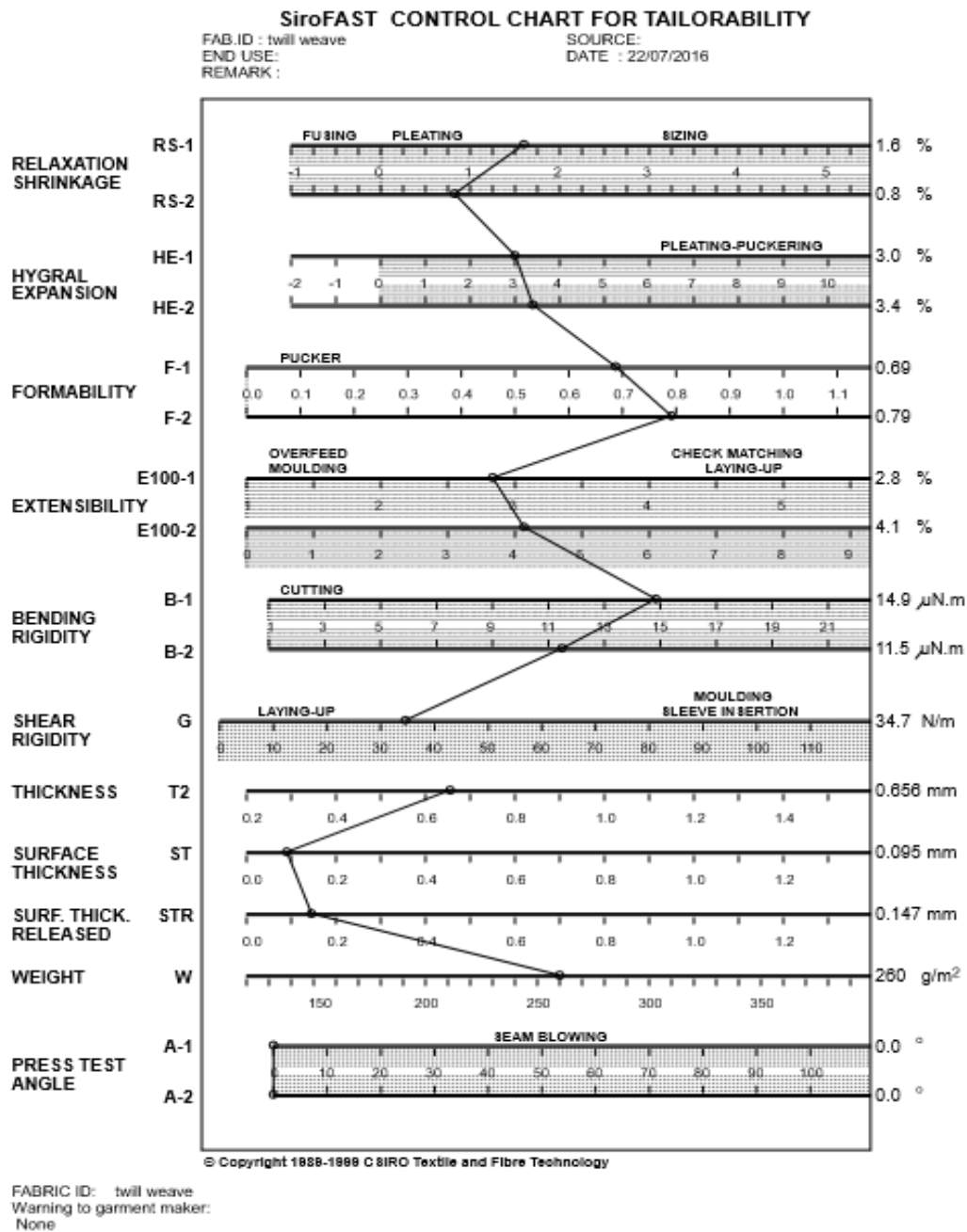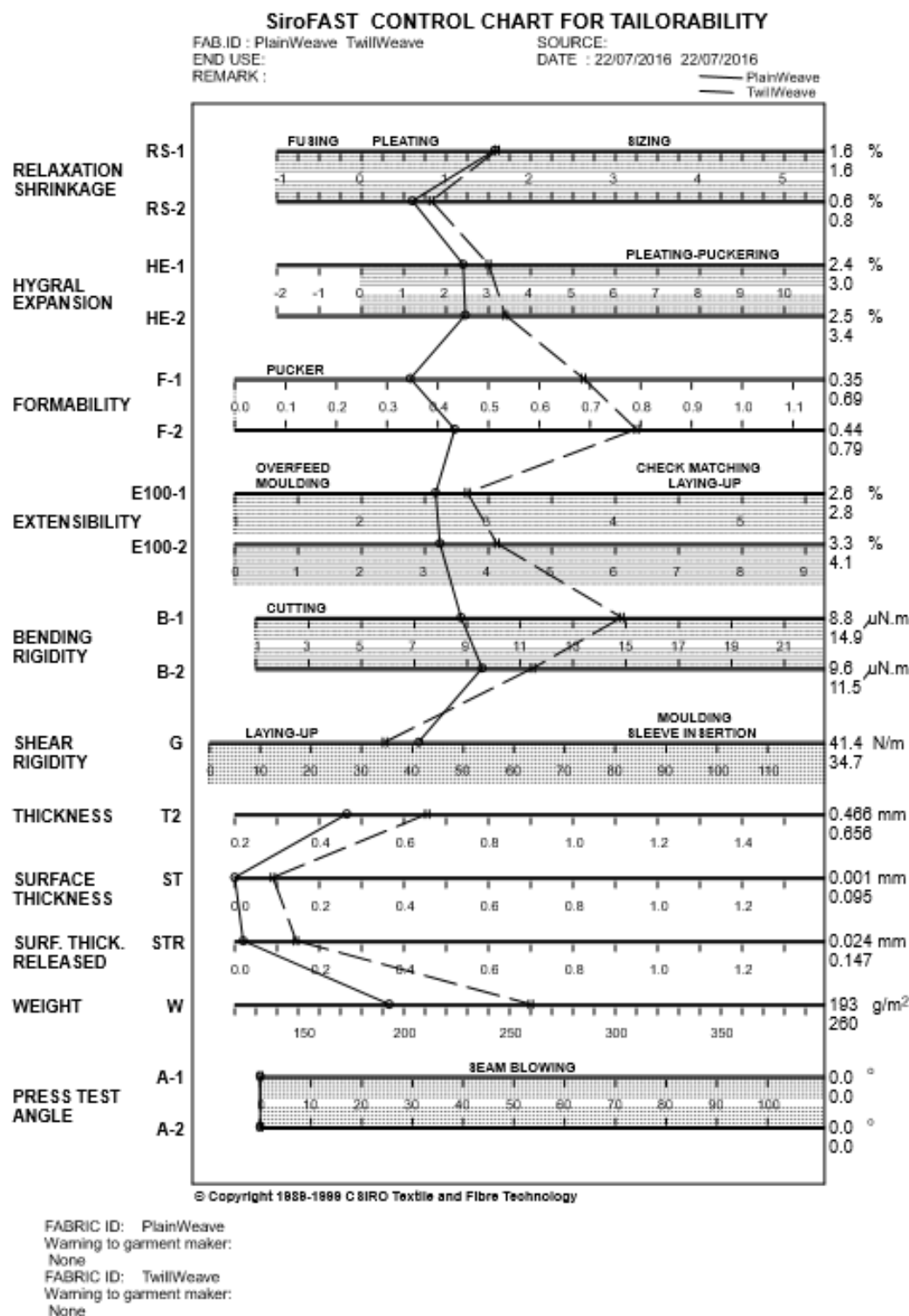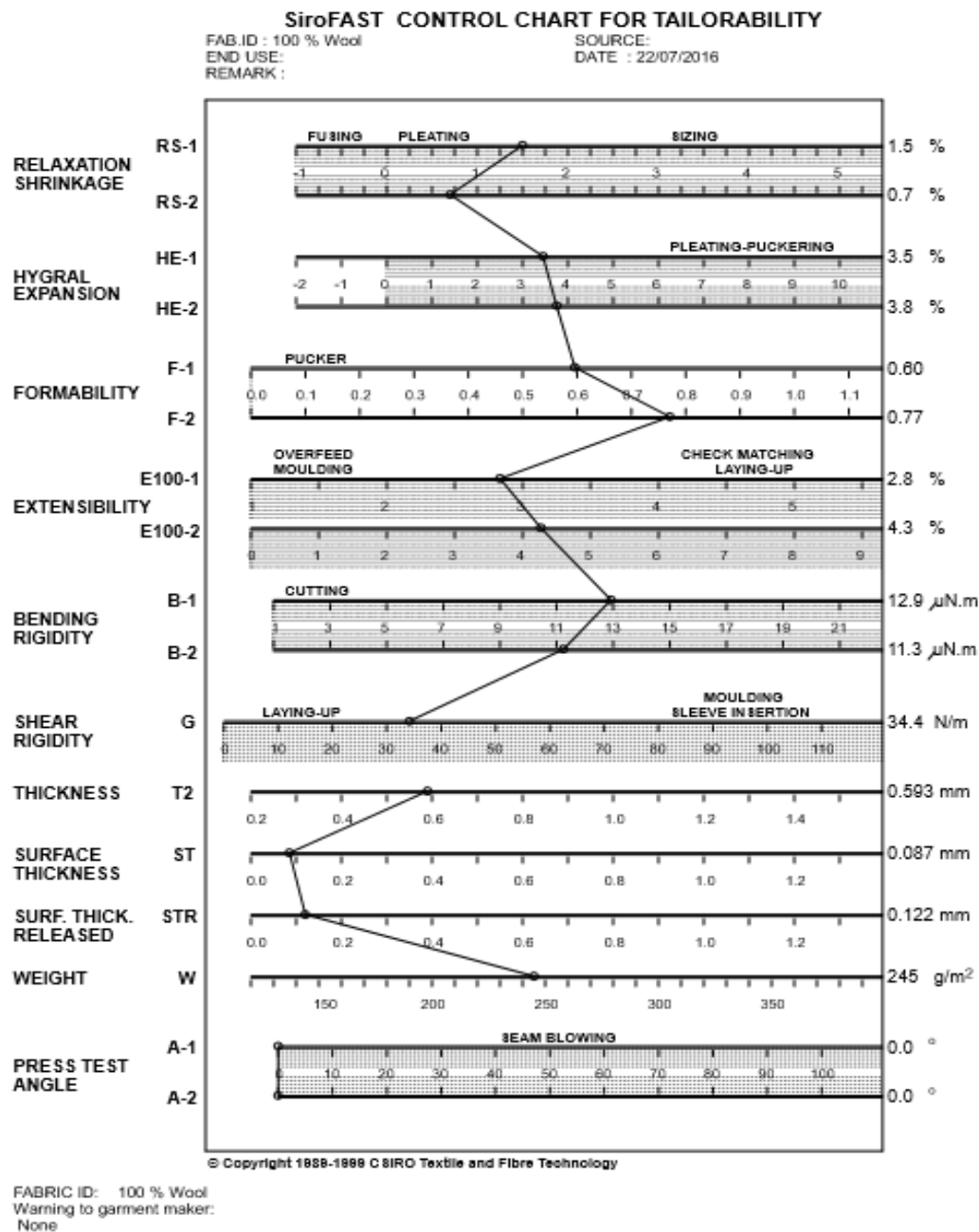
Figure 4.26.4: FAST control chart (fingerprint) averaged values, for the 100W fabrics representation of commercial worsted apparel fabrics

4.26.3.2 W/PES fabrics

Similarly like the twill and plain weave fabrics, Table 4.26.3.2 and Figure 4.26.5 are representative of the W/PES fabrics.

Table 4.26.3.2: SiroFAST data sheet for W/PES fabrics

```
                    SiroFAST DATA SHEET

    FABRIC ID: Wool PES
      END USE:
       SOURCE:
         DATE: 22/07/2016
       REMARK:

                    MEAN    1      2      3      4      5      6

  DIMENSIONAL STABILITY
    RS-1  (%)     1.6
    RS-2  (%)     0.6
    HE-1  (%)     1.4
    HE-2  (%)     1.4

  FORMABILITY
    F-1           0.37
    F-2           0.41

  EXTENSION
    E5-1  (%)     0.3    0.3    0.0    0.0
    E5-2  (%)     0.3    0.3    0.0    0.0
    E20-1 (%)     0.8    0.8    0.0    0.0
    E20-2 (%)     0.8    0.8    0.0    0.0
    E100-1(%)     2.3    2.3    0.0    0.0
    E100-2(%)     2.6    2.6    0.0    0.0
    EB5   (%)     2.6    2.6    0.0    0.0    0.0    0.0    0.0

  BENDING
    C-1   (mm)    16.7   16.7   16.7   16.7   16.7   16.7   16.7
                         0.0    0.0    0.0    0.0    0.0    0.0
    C-2   (mm)    17.2   17.2   17.2   17.2   17.2   17.2   17.2
                         0.0    0.0    0.0    0.0    0.0    0.0
    B-1 (µN.m)    10.7
    B-2 (µN.m)    11.6

  SHEAR
    G     (N/m)   46.9

  COMPRESSION
    T2    (mm)    0.506  0.506  0.000  0.000  0.000  0.000
    T100  (mm)    0.563  0.563  0.000  0.000  0.000  0.000
    ST    (mm)   -0.057
    T2R   (mm)    0.538  0.538  0.000  0.000  0.000  0.000
    T100R (mm)    0.569  0.569  0.000  0.000  0.000  0.000
    STR   (mm)   -0.031

  WEIGHT
    W   (g/m²)     235

  PRESS TEST ANGLE
    A-1   (°)     0.0
    A-2   (°)     0.0
```

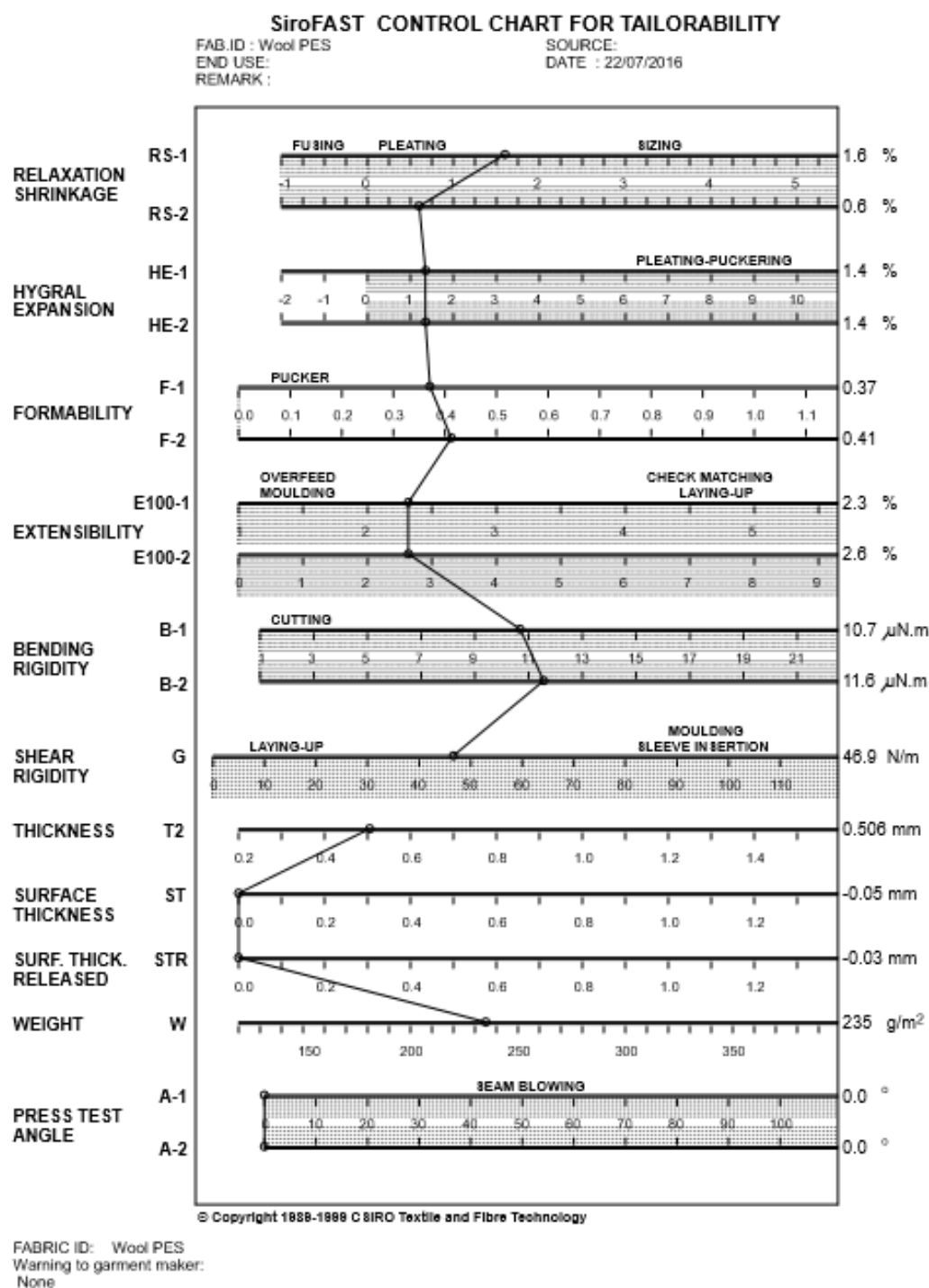**Figure 4.26.5: FAST control charts (fingerprints) averaged values, for the W/PES fabrics representation of commercial worsted apparel fabrics**

4.26.3.3 100W and W/PES fabrics

Figure 4.2.6 shows the fingerprints of the 100W and W/PES fabrics superimposed.
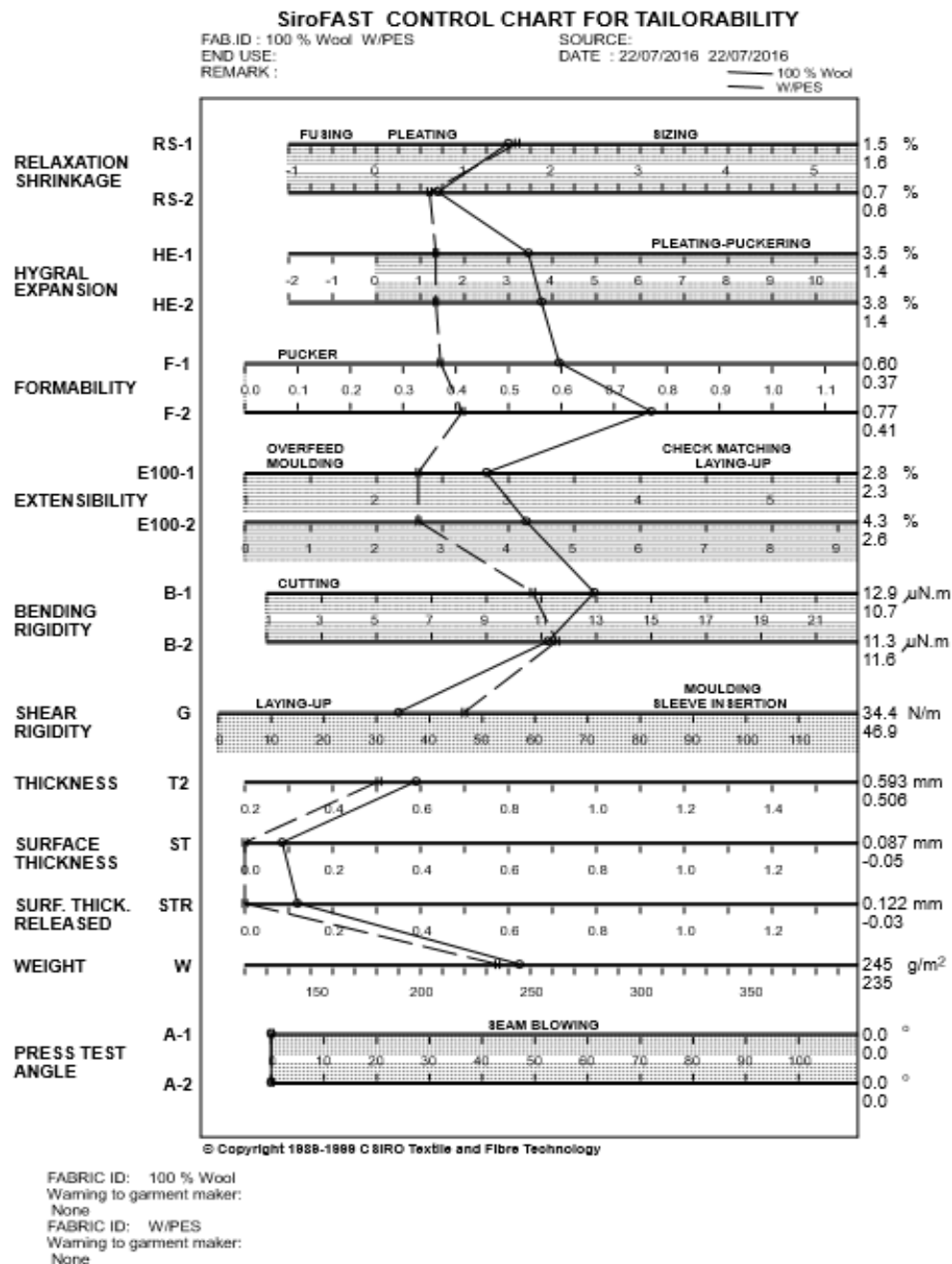
Figure 4.26.6: FAST control chart averaged values respectively, for 100W and W/PES fabrics representation of commercial worsted apparel fabrics

Overall, it can be said that the 100W fabrics were, on average, heavier and thicker than the W/PES fabrics and exhibited higher relaxation shrinkage, hygral expansion, formability and extensibility but lower bending and shear rigidity than the W/PES fabrics. Nevertheless, it is once again important that the above refer to the average values, and that the results of the individual fabrics varied widely and overlapped for the two blends.

As discussed in the previous chapter, there wasn't much work done on the FAST parameters referencing system in SA. The system created can be further sent to the companies where it can be used as a standard by manufacturers to create a quality garment by following the sequence of tests. The conclusions derived from both the fingerprint chart of fabric structure and blends will hence assist the manufacturers and retailers in doing so thereby motivating them to go local and not import fabrics and ready-made garments. This will lead to SA being a globally competitive niche market manufacturing as well as exporting excellent quality garments in the worsted apparel segment.

5. Summary and Conclusions

5.1 Summary

This study was motivated by the fact that the adoption of fabric objective measurement (FOM), specifically the FAST system, will benefit the South African worsted apparel sector, as it has done in various other countries which produce high quality worsted apparel fabrics and garments. FAST is robust and portable, yet inexpensive. These factors, plus the fact that the testing and calibration procedures are simple and straightforward, make FAST an attractive package for quality control and product development by fabric and garment manufacturers and finishers.

Many countries have implemented FAST to the benefit of their apparel fabric and clothing manufacturing sectors, particularly those involved in the high quality worsted woven suiting's end of the market. A survey (Das, 2011) done on South African apparel merchandising, has shown that South Africa seriously lags behind its global competitors in this respect, which adversely affects its global competitiveness, particularly when it comes to the high quality and value added sector of the market. The main objective of the study was to develop a FAST referencing system which can be used for benchmarking by the local apparel industry and, as a basis for encouraging and persuading the industry to adopt this system of fabric quality measurement and assurance and thereby improve their product quality and international competitiveness. To achieve the main objective, involved sourcing and FAST testing a representative cross-section of commercial worsted apparel fabrics with the emphasis on wool and wool blends from the local fabric and clothing manufacturing industry, and determining how the various FAST properties were affected by factors such as fabric weave, fibre blend and weight, since this could impact on the specific nature and validity of the referencing system.

A total of some 394 worsted type commercial fabrics, mainly in wool and wool blends, were sourced from, and with the inputs of, local apparel fabric and clothing manufacturers so as to ensure the local fabric and garment representative of the sample population and after which the fabrics were tested on the FAST system. ANOVA (regression analysis) was carried out on each of the FAST parameters in order to determine whether fabric weight, weave, thickness and fibre composition (pure wool and wool blends) had a statistically significant effect on them, since this is an important aspect which needs to be clarified prior to the development of a envisaged meaningful FAST system.

5.2 Conclusions

On the basis of the statistical analysis, a table of FAST measured values and fingerprints were drawn up which were considered typical of the various groups and types of fabrics, and can be used within the envisaged context for quality control benchmarking and referencing purposes not only by the local worsted fabric and apparel sector, but also by researchers and academicians. Briefly stated, the analysis showed that, on average, the 100W fabrics had on average, a higher relaxation shrinkage, hygral expansion, formability and extensibility, but a lower bending and shear stiffness than the W/PES blends, while the twill fabrics had, on average higher relaxation shrinkage and hygral expansion, but a lower formability, extensibility, bending and shear, than the plain weave. Nevertheless, it is important to note that, in all cases, the results of the individual fabrics varied greatly within a specific group or category and also overlapped considerable between such groups and categories. Hence, the average values and observed differences between groups, must be considered and interpreted, always with this in mind. It is also important to emphasize that, although there were statistically significant differences between the average values of certain of the groups and categories, the differences were generally small and mostly of little or no practical consequence, considering the large variations in the values of the individual fabrics within a specific group. It is believed

that this study is an important first step in the acceptance and implementation of the FAST based FOM system, by the South African worsted fabric and garment manufacturing and even the retailing sector.

5.3 Implications of the research work

The implications of the research are as follows:

- It not only provides a FAST referencing system and fingerprints which can be used by the local worsted apparel manufacturing industry, for benchmarking and referencing purposes, and to improve their quality, but to also encourage the industry to adopt the FAST system and to develop new and/or improved type quality of fabrics.
- It can also form the foundation for further research aimed at the relating FAST properties to making-up and wear performance, and engineering fabrics and garments accordingly.
- Fabric development, directed specifically towards good garment making-up and wear performance
- Evaluating any new or competitive products
- Engineering special fabric finishing
- Fabric buying control by garment makers
- Routine quality control by all sectors of the industry

6. Future Work

6.1 Future work

In depth studies, in collaboration with industry, should be undertaken to relate the FAST results and fingerprints to the actual performance of the fabrics during making-up and wear. This should cover wool and wool blend fabrics typically used for formal wear in the high quality end of the market, since this is a critical sector considering the beneficiation of the South Africa's excellent quality wool and mohair. The influence of fibre, yarn and fabric physical and structural properties, as well as different fabric finishing conditions, on FAST properties and fingerprints, should also be investigated and quantified.

A wider range of manufacturing fabrics of novel construction including different commercial fabrics, of known history and construction should be tested on the FAST to determine their potential for garment application.

6.2 Limitations of the research work

The main limitation associated with this work is that the FAST measured properties and fingerprints could not be directly related to garment making-up and wear performance. Furthermore, since the fabrics were commercially produced and used, their previous manufacturing history were not available.

7. References

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Appendix

THE DEVELOPMENT AND APPLICATION OF A FABRIC OBJECTIVE MEASUREMENT DATA SYSTEM IN THE SOUTH AFRICAN APPAREL INDUSTRY: HYGRAL EXPANSION AND FORMABILITY

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ABSTRACT

A programme has been initiated with the objective to develop an advanced Fabric Objective Measurement (FOM) based technology, knowledge and data system which is relevant to, and can be implemented in, the South African apparel industry to benchmark and improve the quality of locally produced woven apparel fabrics and garments. To this end, various FOM and other quality related parameters have been measured and analysed for a wide range of commercial worsted type fabrics used in the South African apparel manufacturing industry. This paper deals with one aspect of this data system, namely fabric hygral expansion and formability, two key properties when it comes to the making up
(tailorability) of fabrics. Further papers will deal with the other lesser important properties, and ultimately, with the system in its totality.

Some 394 commercial worsted woven type fabrics, of different structure (plain, twill, venetian, gabardine, barathea, hopsack and herringbone) and blend (mainly wool and wool blends), the majority varying in weight between 150 and 300 g/m2 have been sourced from fabric and garment manufacturers and tested on the Fabric Assurance by Simple Testing (FAST) FOM system. The effect of fabric weight, thickness, structure and composition on hygral expansion and formability has been investigated, using ANOVA, the results being presented in tabular and graphical form. It was found that the hygral expansion of the wool fabrics was, on average, higher than that of the wool blend fabrics, while the heavier and thicker fabrics had higher (better) formability in both warp and weft directions. These factors need to be taken into consideration in preparing the envisaged FOM based system.

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INTRODUCTION

The South African apparel industry is facing increasing competition within the global market, especially from the Asian countries, where quality and cost, or more specifically value for money, are often the main order qualifier, apart from other factors, such as quick response, on time delivery, fashion, etc. This is creating a huge question mark over the competitiveness and sustainability of the local labour intensive apparel manufacturing sector, with serious economic and social implications, particularly in terms of job losses. There are many reasons for the lack of competitiveness, including deficiencies in terms of appropriate knowledge, technological know-how and skills and technology systems and capacity. For South Africa (SA) to be globally competitive, it needs to produce, on time and on brief, fabrics and garments, which are of excellent quality, fashionable and represent 'value for money', notably in wool and wool blends for the higher value "niche" end of the local and international markets. To achieve this, the highly advanced and integrated Fabric Objective Measurement (FOM) systems, such as Fabric Assurance by Simple Testing (FAST) and Kawabata, widely used in competing countries to improve and ensure the quality of the fabrics and garments, could play a significant role and should be implemented in SA. To produce top quality fashionable garments, particularly from woven worsted fabrics, requires effective utilization of an FOM system, this already being widely used globally to improve and ensure fabric and garment quality.

The reason for the lack of the adoption of FOM systems in SA was investigated by means of a survey of local apparel fabric and clothing manufacturers and retailers (Das, 2011; Das and Hunter, 2015). It was found that only one FAST system was in use in SA, with most apparel fabric and garment manufacturers and retailers apparently carrying little knowledge of FOM systems and their potential benefits. This made it clear that a concerted effort was required to promote and implement FOM in SA, this being considered essential in improving the global competitiveness of the local apparel manufacturing industry dealing with worsted type of fabrics.

Various international studies (Kawabata, 1982; Mahar et al, 1983; Postle et al, 1983; Kawabata et al, 1984, 1986; Ly and De Boos, 1990) publications and conferences have demonstrated the need for upgrading from the mere traditional subjective assessment of fabric quality and tailorability to a more technologically advanced objective measurement system, such as FOM, which is far more accurate and reliable. Furthermore, it has been shown that the adoption of FOM leads to an increase in the added value of products, both in the textile and clothing industries, also facilitating dealing with the many new types of fabrics being developed and coming on to the market (Mahar et al, 1983; Postle, 1989).

Peirce (1930:377) was one of the first researchers to investigate the relationship between subjectively assessed fabric handle and the objectively measured fabric mechanical properties, and can be called "the father of FOM". After him, many other researchers, notably Postle (1989:72), Kawabata (1982) and Kawabata et al, (1984, 1986), made major contributions towards the technology of the objective measurement of fabric and garment quality related properties, such as handle, making-up and wear performance. This eventually resulted in the culmination of the KES-F system of FOM, popularly known as the Kawabata system (KES systems, 2016), developed by Prof. Kawabata and his team in Japan (Kawabata et al, 1984; 1986). Nevertheless, the system, though ideal for research laboratories and large and advanced fabric and clothing manufacturers, was considered too sophisticated and expensive for wider use. This lead to the development of the FAST system which was more user friendly and less expensive than the Kawabata system (CSIRO, 1989; De Boos and Tester, 1994; FAST systems, 2016). It was developed to provide the industry with a single, robust and relatively inexpensive system for the objective measurement of fabric properties important in tailoring. As rightly stated by Ly and De Boos (1990:370), "while the measurement of fabric properties with FAST is a relatively simple procedure, the interpretation of the data requires an understanding of how each fabric property influences the tailoring performance". This task is simplified with the help of a FAST Control Chart.

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In this chart, the measured properties are plotted (plotting can be done automatically when using a PC and the FAST Data Program) and the points joined to give a "fabric fingerprint", with control limits, which helps in the interpretation of the data, for example whether the fabric tested is suitable for an intended enduse (Postle, 1983; FAST systems, 2016). Prediction of tailoring performance is based on the suggested maximum and minimum limits for each property, as shown in the FAST control chart. If the fingerprint falls outside the limits, it indicates that more work, for example refinishing, needs to be done on that particular fabric. The FAST control chart indicates all the fabric properties that are tested, including, relaxation shrinkage, hygral expansion, formability, bending rigidity, extensibility, shear rigidity, thickness and weight. Of these, hygral expansion and formability are key for worsted type fabrics from wool and wool blends, and the most likely to be the source of making-up related problems to the South African apparel industry, and have therefore been selected as the focus of this paper.

Hygral expansion

Hygral expansions, and its important effect on tailorability and wear performance, have been extensively studied since the 1960s (Shaw, 1978; 1986). Hygral expansion can be defined as a reversible fabric dimensional change which occurs when the moisture regain of the fabric is altered at a constant temperature (Baird, 1963; Lindberg, 1965). A reversible change in fabric dimensions, particularly wool and wool-rich blends, occurs when the moisture regain of the fabric changes, this being largely due to the wool fibre undergoing reversible swelling. Increasing the regain of wool, leads to radial swelling of the fibres, which causes the fibres and yarns to straighten out and consequently to a decrease in weave crimp, resulting in an increase in both the length and width of the fabric. These changes are reversible, and, on decreasing the regain to its original level, the fabric returns to its former dimensions. Excessive levels of hygral

expression (e.g. 5 to 6%) can cause a number of commonly known problems in the appearance of wool and wool blend garments, including bubbling, seam puckering and delamination of the shell fabric. With the ever-changing trends towards light weight fabrics, hygral expansion has become a more serious problem in tailored garments, generally due to such fabric structures allowing easier movement of the yarns (Cookson et al, **TABLE 1: DETAILS OF FABRICS** 1991:135). As already discussed, fabric-related factors which influence hygral expansion include weave crimp, fabric setting and fabric structure

Formability

Fabric formability, derived from fabric bending and longitudinal compressional properties, or from bending and tensile properties, has been shown to be related to tailoring performance (Lindberg et al, 1960; Mahar et al, 1983). As defined by Lindberg et al, (1960), fabric formability relates to the deformation that the fabric can bear before buckling. It provides a measure of how easily the flat, two dimensional, surface of the fabric, can be transformed into a three-dimensional shape, for example, at the shoulder of a jacket. Fabric formability can be used to predict the limit of overfeed before buckling. The lower the formability, the more likely it is also for seam pucker to occur, because the fabric is unable to accommodate the small compression placed on it by the sewing thread (De Boos and Tester, 1994), puckering and sleeve settings representing common problems experienced with low fabric formability. Factors which can influence formability, include weave structure and fabric density (or tightness).

EXPERIMENTAL

Fabrics

Some 394 worsted type woven fabrics, of varying weight (mostly between 150 g/m^2 and 300 g/m^2), weave and blend, were sourced from various local fabric and garment manufacturers (Table 1).

Number of fabrics			
Fabric blend	**Twill weave**	**Plain weave**	**Total**
Wool 100%	109	67	203
Wool blends	25	61	99
Others blends	22	58	92
Total	156	186	394

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The fabrics mainly consisted of wool and wool blends in twill and plain weaves, which is typical of worsted-type suiting fabrics used for men's and ladies suiting's and related formal wear.

FAST tests

The various fabrics were measured on the FAST system in a standard atmosphere (20 ± 3^0C & the fabric immersed. After removal of excess water, by gently patting with a towel, the fabrics were dried in a convection oven for an hour at 105^0C. Measurements of the dried fabric dimensions were made within 30 seconds of removal from the oven. Hygral expansion (HE %) was calculated, for both warp (HE-1 %) and weft (HE -2 %) directions, as follows:

TABLE 2: AVERAGE AND CO-EFFICIENT OF VARIATION VALUES FOR HYGRAL EXPANSION AND FORMABILITY FOR THE VARIOUS FABRIC GROUPS

Fabric structure and blend (Code)	Weight (g/m^2)	Thickness (mm)	HE-1 (%)	HE-2 (%)	F-1 (mm^2)	F-2 (mm^2)
Plain/100% Wool (Pl/100W)	172	0.43	2.24 (19%)*	2.8 (35%)	0.30 (22%)	1.78 (26%)
Plain/blends (Pl/Bl)	169	0.44	0.73 (42%)	0.64 (30%)	0.27 (12%)	0.30 (19%)
Twill/100%Wool (Tw/100W)	179	0.47	2.9 (24%)	3.9 (16%)	0.28 (32%)	0.47 (43%)
Twill/blends (Tw/Bl)	205	0.52	0.9 (33%)	0.9 (17%)	0.42 (28%)	0.33 (19%)

$60\pm5\%$ RH) according to the test method as *Values in the parenthesis indicate the CV%.

$$HE\ \% = \frac{Wet\ length\ -\ Dry\ length}{Dry\ length} \times 100$$

discussed in the FAST System Instruction Manual (CSIRO, 1989). The FAST system involves three instruments, namely FAST-1, FAST-2 and FAST-3 and a test method FAST-4, as follows:
• FAST-1 measures the fabric thickness,
• FAST-2 measures the fabric bending length and rigidity,
• FAST-3 measures the fabric extensibility and shear rigidity and
• FAST-4 measures the dimensional stability of the fabric, i.e. hygral expansion and relaxation shrinkage, as described below.

Hygral expansion tests

From each of the fabrics, three square samples (300 mm x 300 mm) were cut out for hygral expansion testing. Each sample was marked at the corners and mid-points to represent a square, measuring 250 mm x 250 mm, thus ensuring a 25 mm margin between the edges of the fabric and the measurement region, enabling three warp and three weft measurements to be made for each sample. Samples were conditioned at $65\pm5\%$ Relative Humidity (RH) and 20 ± 2^0C for 24 hours prior to testing. Fabric samples were relaxed, for an hour in a tray containing water and a wetting agent at 35^0C, and the wet lengths measured with

Formability (F) is not measured directly, but is derived from other FAST parameters as:
Formability = bending length * extensibility (Tester, 1988). More specifically this can be expressed as F = (E20 – E5) x B/14.7 (where F = formability of the fabric; E20 = extensibility of the fabric at 20 gf/cm; E5 = extensibility of the fabric at 5gf/cm; B = bending rigidity of the fabric).

Statistical analysis

Statistical analyses (ANOVA) were carried out on the formability and hygral expansion results, with a view to compare the different fabrics in terms of their hygral expansion and formability, and also to find out if fabric weight, thickness, weave structure (plain and twill) and blend (100% wool and wool blend) had a significant effect on hygral expansion and formability since this is important when preparing a meaningful and useful database from a practical point of view. The results of the tests and statistical analyses are presented in tabular or graphical form, as appropriate, and are discussed below.

RESULTS AND DISCUSSIONS

The development and application of a fabric objective measurement data system in the

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The average and co-efficient of variation (CV %) values for the relevant FAST properties are given in Table 2 for the various wool and wool blend fabrics groups.

Hygral expansion

The ANOVA analysis on hygral expansion, in the warp direction (HE -1%) showed that fabric weave structure and blend had a statistically significant effect (Table 3), whereas fabric weight and thickness did not. According to Baird (1963; 1989) fabric structure restricts hygral expansion, and according to Shaw (1978; 1986) the weave crimp is the fabric structural feature having the most important influence on hygral expansion, the greater the yarn (i.e. weave) crimp, the greater the hygral expansion. The effect of fabric weave is most likely due to the
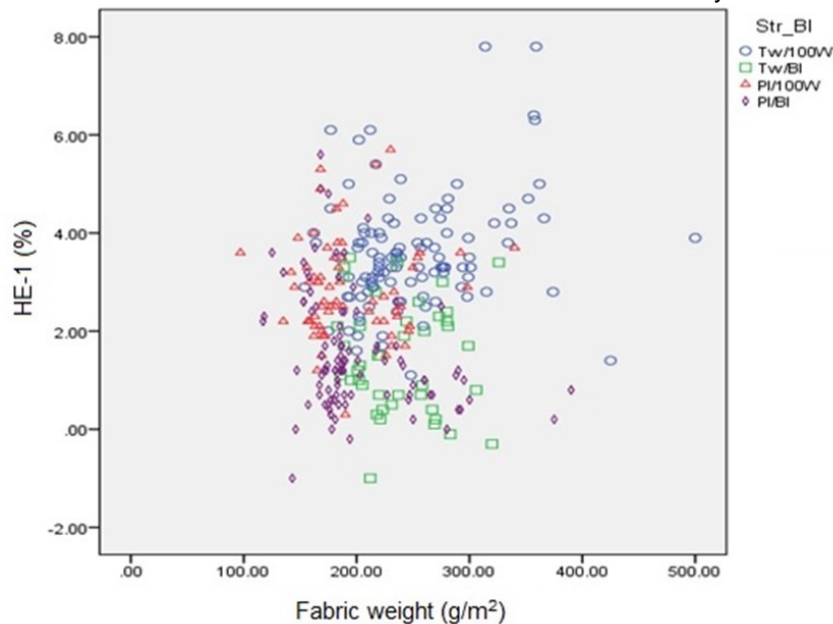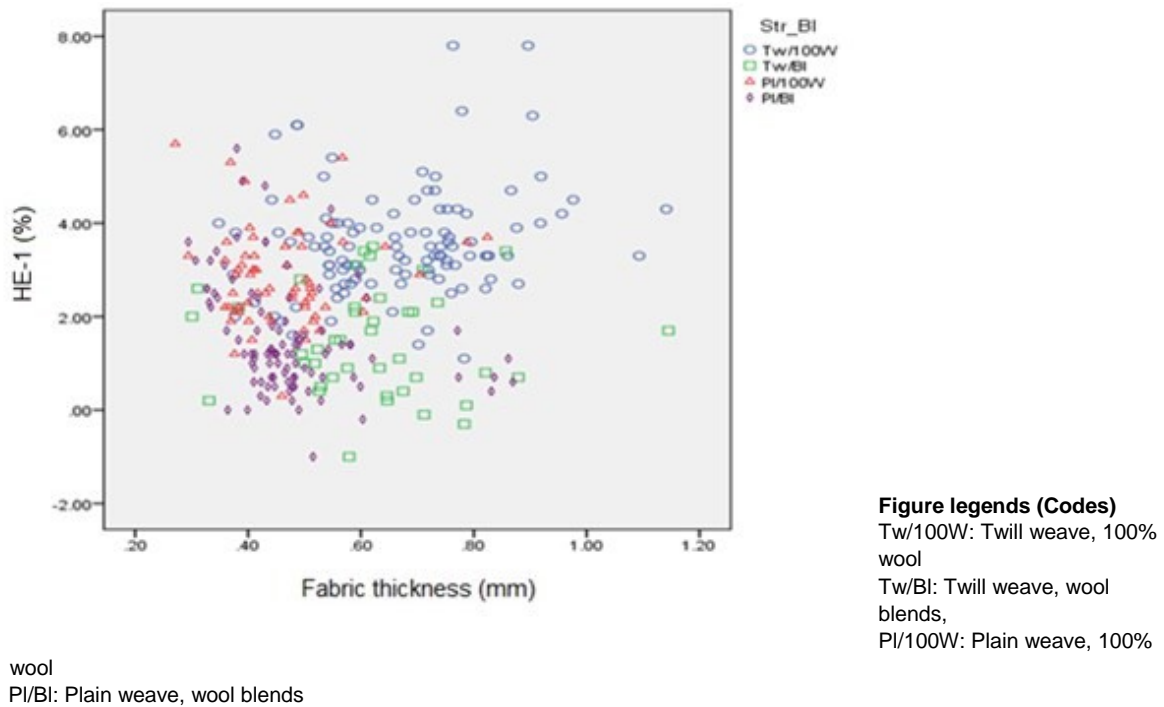
TABLE 3: ANOVA ANALYSIS ON HE-1(%) RESULTS

	SS	Degr. Of Freedom	MS	F	p				
Intercept	72.58237	1	72.58237	54.65999	0.0000				
Weight (g/m²)	0.055513	1	0.055513	0.041806	0.8381				
Thickness (mm)	0.038001	1	0.038001	0.028618	0.8658				
Fab. Structure	8.166845	1	8.166845	6.150249	0.0137		**Multiple R**	**Multiple R-sq**	**Adj. R-sq**
Blend	194.4533	1	194.4533	146.438	0.0000				
Error	414.3012	312	1.327888				0.6238	0.3891	0.3813

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 1(a): HE-1% VS FABRIC WEIGHT, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 1(b): HE-1% VS FABRIC THICKNESS, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

TABLE 4:   ANOVA ANALYSIS ON HE-2(%) RESULTS

	SS	Degr. Of Freedom	MS	F	p			
Intercept	196.0854	1	196.0854	100.6905	0.0000			
Weight (g/m²)	51.5138	1	51.5138	26.45252	0.0000			
Thickness (mm)	13.54386	1	13.54386	6.954822	0.0088			
Fab. Structure	5.172992	1	5.172992	2.65635	0.1041	**Multiple R**	**Multiple R-sq**	**Adj. R-sq**
Blend	377.4092	1	377.4092	193.801	0.0000			
Error	607.5907	312	1.947406			0.6713	0.4507	0.4436

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
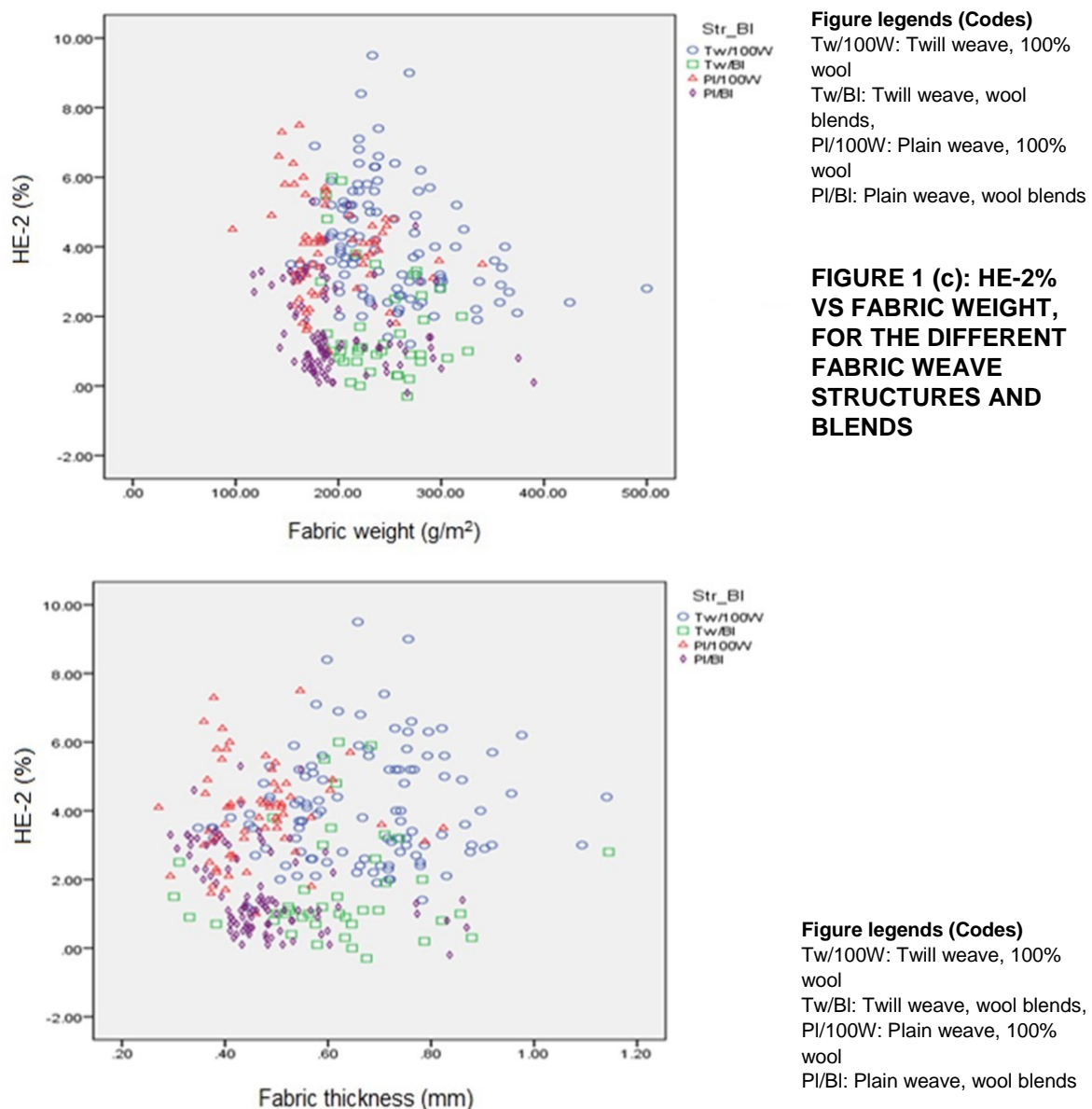Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 1 (c): HE-2% VS FABRIC WEIGHT, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 1 (d): HE-2% VS FABRIC THICKNESS, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

weave crimp generally being higher in twill than in plain weave fabrics, together with the twill weave producing less restriction on the yarn movement than the plain weave. The greater hygral expansion of the pure wool fabrics is easily explained in terms of the greater swelling properties of wool vis-à-vis that of the synthetic fibre component (mainly polyester) present in the wool blends. As already explained, such fibre swelling results in a decrease in weave crimp, and therefore greater hygral expansion. To illustrate the differences in HE-1% due to blend and weave structure, HE-1% has been plotted against fabric weight in Figure 1(a) and against fabric thickness in Figure 1(b), different symbols

and colours being used to represent the different fabric groups. What is clear from Figures 1 (a) and 1 (b), is that the individual hygral expansion values of the different weave structures and blends overlap considerably, and are only an average different. Similar statistical (ANOVA) analyses was carried out on the hygral expansion in the weft direction (HE-2%) as was done on HE-1%, the results being given in Table 4. From Table 4 it is apparent that fabric weight, thickness and blend all had a statistically significant effect on HE-2%, whereas fabric weave structure did not. This differs somewhat from that observed for HE-1%, where only fabric weave structure and blend had a statistically significant effect. Once

again, the pure wool fabrics, both plain and twill weaves, had a higher hygral expansion than the wool blend fabrics, the explanation being as for HE-1%. Although statistically not significant, the tendency was once again, as in the case of HE-1%, for the twill weave fabrics to have a higher hygral expansion than the plain weave fabrics (see Table 2). To illustrate some of the above effects, HE-2% has been plotted against fabric weight and thickness in Figures 1 (c) and (d), respectively.

On average, the heavier and thicker fabrics tended to have higher HE-2 % values than the lighter and thinner fabrics, which is different to what was found for HE-1% and contrary to the work of Cookson et al, (1991). This could be due to associated differences in the weave crimp and yarn linear density in the weft direction. Neverthless, it is apparent from Figure 1 (b), that, as in the case of HE-1, there is a considerable overlap in the individual fabric results for the different blends and structure. To compare the HE-2 values of the different fabric structures and blends, HE-2 % has been plotted against fabric weight and thickness in Figures 1 (c) and 1 (d), respectively.

From the above figures and tables, particularly Table 2, it is apparent that, in both warp and weft directions, the hygral expansion of the wool fabrics was, on average, higher than that of the wool blend fabrics. This is not difficult to understand, since the blends mainly contained polyester which has a very low regain and therefore swelling, resulting in a lower hygral expansion. Therefore, when preparing a FAST database, and average or benchmark values, for use by local fabric and garment manufacturing, appropriate allowance must be made for the effects observed and discussed above.

Formability

The ANOVA tests on formability showed (Tables 5 and 6) that only fabric thickness had a statistically significant effect on the formability in the warp direction (F-1 mm^2) whereas fabric weight, thickness and blend all had a statistically significant effect on the formability in the weft direction (F-2 mm^2).

The twill blend fabrics had, on average, the highest formability in the warp direction (F-1 mm^2), while the plain 100% wool fabrics had the highest formability, by far, in the weft direction (F -2 mm^2). To illustrate the differences in weft formability (F-1 mm^2) due to fabric structure and blend, F-1 has been plotted against fabric weight and thickness in Figures 2 (a) and 2 (b) respectively, F-1 tending to increase with an increase in fabric weight and thickness.

A similar analysis to that carried out on F-1, was carried out on F-2, the results of the analysis being given in Table 6.

According to the ANOVA results given in Table 6, the fabric weight, thickness and blend all had a statistically significant effect on the formability in the weft direction (F-2 mm^2), only fabric weave structure not having a statistically significant effect. The plain weave all wool fabrics (Pl/100W) had, on average, the highest formability, followed by the twill weave all wool fabrics (Tw/100W), indicating that, in the weft direction at least, the all wool fabrics had superior formability compared to the wool blend fabrics. To illustrate differences in formability in the weft direction (F-2) associated with the different fabric weave structure and blend, F-2 has been plotted against fabric weight and thickness in Figures 2 (c) and (d), respectively.

TABLE 5:   ANOVA ANALYSIS ON F-1 (mm^2) RESULTS

	SS	Degr. Of Freedom	MS	F	p				
Intercept	7.14227	1	7.14227	42.40991	0.0000				
Weight (g/m2)	0.645838	1	0.645838	3.834905	0.0511				
Thickness (mm)	13.3854	1	13.3854	79.48082	0.0000				
Fab. Structure	0.388953	1	0.388953	2.309556	0.1296		**Multiple R**	**Multiple R-sq**	**Adj. R-sq**
Blend	0.097725	1	0.097725	0.580279	0.4468				

*The development and application of a fabric objective measurement data system in the*

South African apparel industry: Hygral expansion and formability
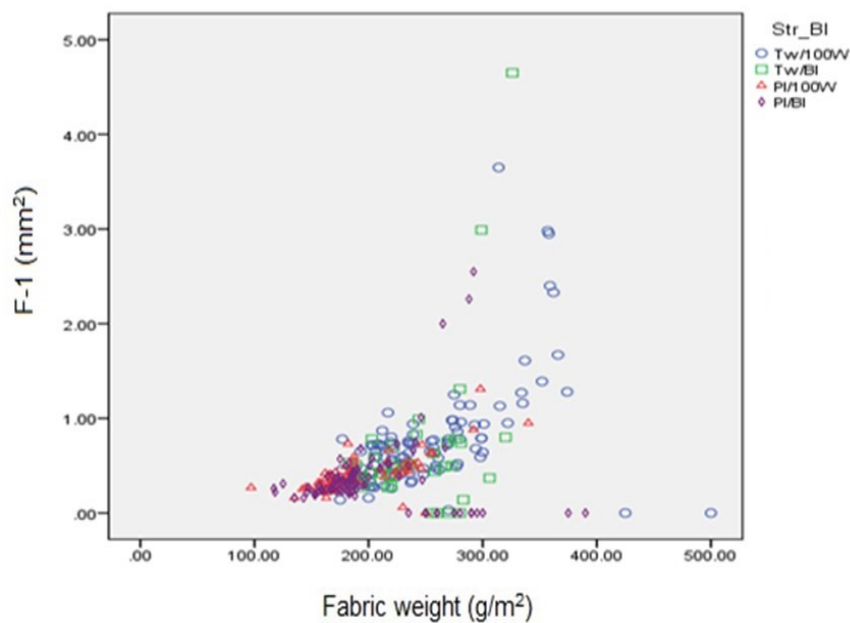
Error	52.54404	312	0.16841				0.628075	0.394478	0.386715

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

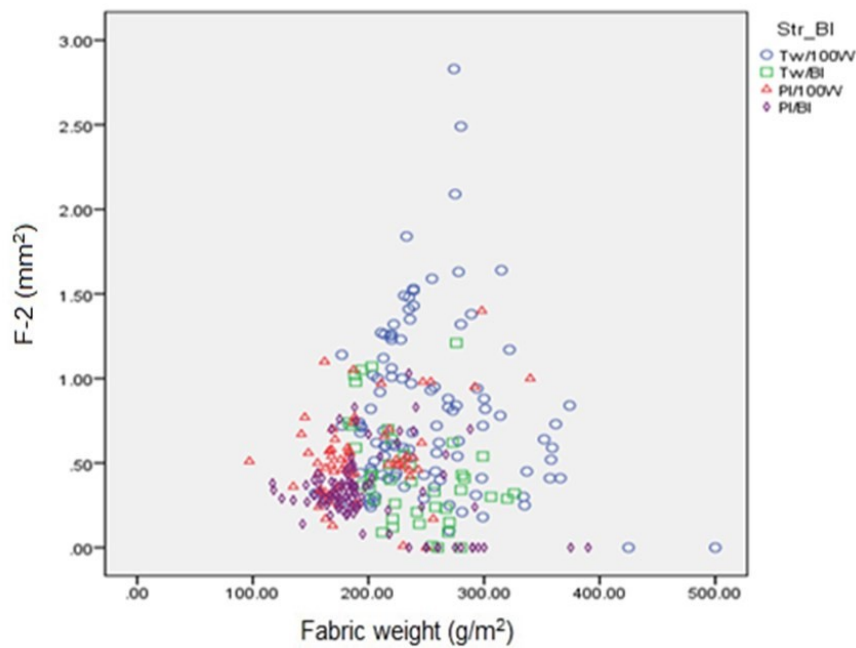**FIGURE 2 (a): F-1 VS FABRIC WEIGHT, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS**
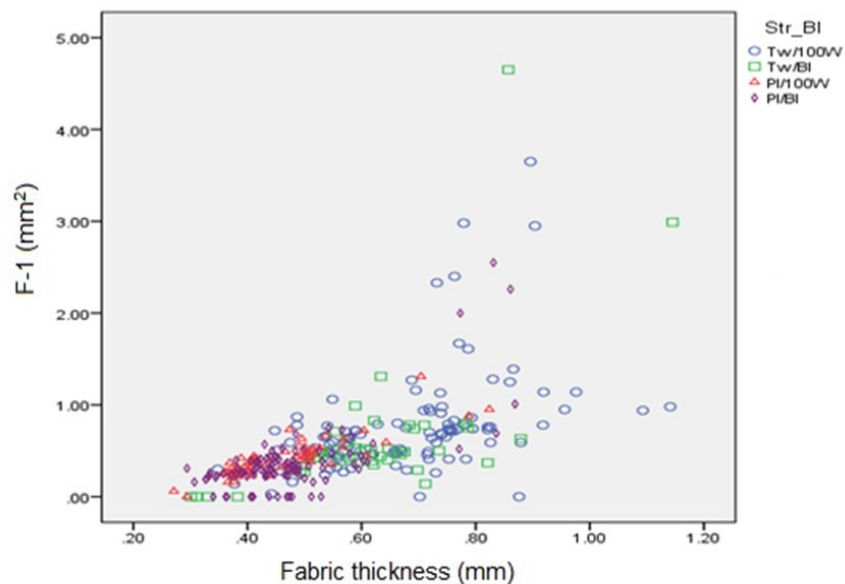
Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

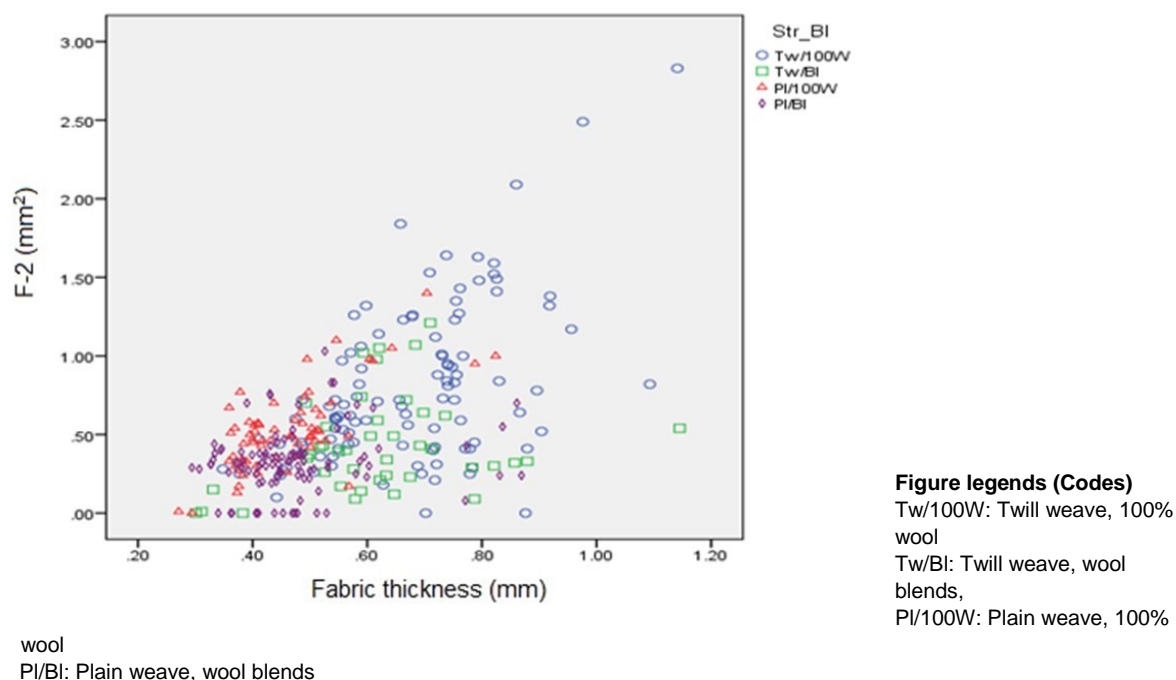**FIGURE 2 (b): F-1 VS FABRIC THICKNESS, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS**

TABLE 6: ANOVA ANALYSIS ON F-1 (mm²) RESULTS

	SS	Degr. Of Freedom	MS	F	p			
Intercept	0.458069	1	0.458069	5.524282	0.0194			
Weight (g/m²)	6.011595	1	6.011595	72.49949	0.0000			
Thickness (mm)	14.122	1	14.122	170.3106	0.0000			
Fab. Structure	0.009566	1	0.009566	0.115366	0.7343	**Multiple R**	**Multiple R-sq**	**Adj. R-sq**
Blend	4.173122	1	4.173122	50.32761	0.0000			
Error	25.87077	312	0.082919			0.7034	0.4948	0.4883

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 2 (c): F-2 VS FABRIC WEIGHT, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

Figure legends (Codes)
Tw/100W: Twill weave, 100% wool
Tw/Bl: Twill weave, wool blends,
Pl/100W: Plain weave, 100% wool
Pl/Bl: Plain weave, wool blends

FIGURE 2 (d): F-2 VS FABRIC THICKNESS, FOR THE DIFFERENT FABRIC WEAVE STRUCTURES AND BLENDS

Figures 2 (a) to (d) illustrate that fabric formability in both the warp and weft directions tend to increase with an increase in fabric thickness and weight, with the formability of the wool fabrics tending to be higher than that of the wool blend fabrics. This shows that the heavier and thicker wool fabrics should be easier to form into three-dimensional shapes during makingup, and therefore perform better than lighter and thinner wool blend fabrics. This also needs to be taken into consideration when preparing the corresponding FAST database and benchmark values. It is once again important to note that the individual fabric results overlap greatly.

CONCLUSION

Many countries have implemented fabric objective measurement (FOM) to the benefit of their apparel fabric and clothing manufacturing sectors, particularly those involved in the high quality worsted woven suiting's end of the market. A survey has shown that South Africa seriously lags behind its global competition in this respect, which adversely affects its global competitiveness. To address this, a comprehensive programme has been initiated, with the ultimate objective of developing an FOM

data based knowledge system and technology which can be applied in the South African apparel fabric and garment manufacturing industries for benchmarking and quality control and improvement purposes, thereby assisting them in their quest to become more globally competitive.

To achieve the above objective, almost 400 worsted type commercial fabrics, mainly in wool and wool blends, were sourced from local apparel fabric and clothing manufacturers and tested on the FAST FOM system. This paper, the first in a series, deals with two of the most important FAST derived fabric properties, namely hygral expansion and formability, both of which have a major effect on fabric making-up (tailorability) and garment wear performance. The focus of the paper has been on determining, initially by ANOVA, the influence of fabric weight, weave structure (plain and twill weaves), thickness and fibre composition (pure wool and wool blend) on fabric hygral expansion and formability, since these are important aspects which need to be clarified prior to the development of the intended FOM knowledge based system and benchmarks which are meaningful and useful in practice. Briefly stated, the ANOVA showed that the hygral expansion of

the 100% wool fabrics was, on average, higher than that of the wool blend fabrics, which is easily explained in terms of the greater swelling of wool fibres compared to synthetic fibres, such as polyester, when regain is increased. Furthermore, the hygral expansion of the twill weave fabrics was on average, higher than that of the plain weave fabrics, probably due to associated differences in yarn weave crimp and freedom of movement within the respective weave structures. The formability of the plain weave all wool fabrics was highest on average, followed by the twill weave 100% wool fabrics, and then the twill weave wool blend fabrics. Nevertheless, it is important to note that, in all cases, the results of the individual fabrics overlapped greatly.

It is intended that further publications, based on this research work, will cover the various other FAST properties and, eventually, the knowledge based FAST FOM system.

ACKNOWLEDGEMENT

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TheRole of Various Fabric Parameters on the FAST Results of Wool and Wool Blend Worsted Fabrics

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Abstract. The objective of this study was to develop a better understanding of the fabric parameters which affect the quality related properties of wool and wool blend worsted type fabrics. The main focus was on Fabric Objective Measurement (FOM), a highly developed technology which provides a more complete picture of fabric quality, tailorability and clothing performance. A range of mostly locally sourced commercial and pilot plant wool and wool blend fabrics were measured on the FAST (Fabric Assurance by Simple Testing) system for this purpose. The range of fabrics covered different weave structures and blends (100% wool, wool and polyester and wool and mohair. Composite FAST fingerprint charts were generated and results statistically analysed, tabulated and plotted so as to illustrate the main trends and effects.

Keywords: FOM, fabric quality, FAST

1. Introduction

Fabric quality, especially handle, colour and lustre, has been traditionally, and often still is, subjectively evaluated by individuals belonging to the textile and clothing industries as well as people from other backgrounds, including consumers. Handle, in particular, has been considered and used as a subjective measure of quality, and has been the basis of fabric selection. By handling a fabric an expert can form a considered opinion of the quality of the fabric and the ease with which it can be made up into the required garment. Nevertheless, there are inconsistencies in the results, even of such experts, the subjective assessments often varying due to various factors, such as culture and religion.

As mentioned by Kawabata et al. [1], it has been found that the fabric mechanical properties are of the utmost importance in determining fabric and garment quality and performance, including handle. This, together with limitations in subjective evaluations, have resulted in a considerable amount of research on the objective measurement of fabrics; firstly as a scientific means to quantify certain fabric quality and performance characteristics and secondly, as a basis for fabric specification, product and process development, process control and quality assurance. With increasing demands for new styles and patterns and large scale production, the need for a systematic, accurate, efficient and reliable system of fabric quality assessment became imperative.

It is probably true to say that Peirce [2] was one of the first researchers to investigate the relationship between fabric handle and the fabric mechanical properties, and can be called "the father of Fabric Objective Measurement". After him, many other researchers, notably Postle, Kawabata and Niwa [3-5] made major contributions towards the science and technology of the objective measurement and characterization of fabric quality related properties, such as handle, making up and wear performance. This eventually culminated in the revolutionary KES-F technology and communication system of fabric objective measurement (FOM), popularly known as the Kawabata system, developed by Prof. Kawabata and his team in Japan. This system certainly represented a quantum leap as far as fabric objective measurement is concerned. Nevertheless, the system, though ideal for research laboratories and large and advanced fabric and clothing manufacturers, was considered too sophisticated and expensive for wider use. This lead to the development of the Fabric Assurance by Simple Testing (FAST) system, which was more user friendly and less expensive than the Kawabata system. It was developed to provide the industry with a single, robust and relatively inexpensive system for the objective measurement of fabric properties important in tailoring.

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Although both the Kawabata and FAST system were initially developed for, and applied to, worsted type fabrics, mainly wool and wool blends, and for providing a measure of fabric handle and tailorability, both systems have found many other applications. A considerable amount of research, focused on specific aspects of FOM, has been carried out and published, much of which has been captured in review or book form. Except for the initial development of the KES-F and FAST database, charts (fingerprints) and control limits, little further work appears to have been carried out, or published at least, on creating more recent databases and also ones specific to a particular country or region. Furthermore, there can be no doubt that, in this highly competitive and technology driven global environment, no manufacturer of high quality fabric or clothing will continue to be globally competitive without resorting to FOM.

In the light of the above, and the fact that FOM is still in its infancy in South Africa, and attracts little interest from fabric and clothing manufacturers, it was decided to build a FAST database of worsted type fabrics either produced in South Africa or imported and converted locally into garments. This could be used by local fabric and clothing manufacturers as a basis of reference, or benchmark, in future, and could stimulate the interest of local fabric and clothing manufacturers in applying FOM (FAST in this case) on a routine basis for fabric and garment quality control and assurance, product development, etc. To this end, a wide selection of worsted type fabrics was sourced from different local fabric and clothing manufacturers and tested on the FAST system.

2. Research Methodology

2.1 FAST tests

The various FAST related properties were studied using different wool and wool blend fabrics of various weights ranging from 200-250 g/m^2. Three different fabrics of different weave types (plain and twill) and different blends (wool/mohair, wool/polyester and 100% wool) were sourced in South Africa. The data obtained by carrying out the FAST tests were analyzed, interpreted, and appropriate conclusions and recommendations made. Wherever relevant, individual FAST properties of various fabrics were combined and subjected to statistical analysis, using ANOVA, for assessing the statistical significance of the properties and any differences in this respect.

2.2 FOM application and distribution

The global manufacturers and suppliers of FAST and Kawabata FOM systems [6-8], with headquarters in Australia and Japan, respectively, were contacted for information on the global application, sales and distribution of their respective systems in order to assess the extent to which these systems have found application, as well as in which institutions and countries, thereby providing background and motivation for local companies to adopt FOM system for improved quality control and assurance.

3. Results and Discussions

On the basis of the testing carried out on the FAST set of instruments, control charts have been prepared(few of which are shown) and compared with other similar weight fabrics within a particular group categorized on the basis of area weight (g/m^2). In addition to this, a statistical analysis of the selected FAST properties was carried out by grouping similar weight fabrics. A particular group of fabrics, ranging in weight from 200 to 250 gm/m^2 have been selected for analyzing the FAST properties. The results were captured, tabulated and analyzed, where they collectively reflect on related aspects.

The ANOVA method was used to compare a group of fabrics in terms of certain fabric properties such as bending length and extensibility.

3.1 Data analysis: bending length

In the statistical analysis on warp bending length, as measured on the FAST, three different types of fabrics, varying in weave structure (plain and twill weave) and with weight within the range of 200 to 250 g/m^2, have been compared.

Table 1: Bending length (mm) of fabrics

Wool/Mohair (200 g/m^2)	Wool/Polyester (255 g/m^2)	100% Wool (250 g/m^2)
16.5	6.3	5

16	6	4
17	7	5
17	7.5	8
16.5	6.5	2
16	5	5
16.5	5.5	4.8

Table 2: Statistical analysis of warp bending length

ANOVA: Single factor   α   0.05

SUMMARY

Groups	Count	Sum	Average	Variance
Wool/Mohair	7	115.5	16.5	0.17
Wool/Polyester	7	43.8	6.3	0.73
Wool	7	33.8	4.8	3.14

ANOVA

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	567.4181	2	283.709	211	0.000	3.554557
Within Groups	24.21143	18	1.345079			
Total	591.6295	20				

Reject null hypothesis because p < 0.05 (Means are Different)

Table 1 shows the bending length results obtained on the FAST, the bending length varying significantly for the different fabric types and blends. As can be seen from Table 1, the wool/mohair fabrics generally had the highest bending length, which generally makes it easier to carry out the cutting operation, whereas the wool/polyester and 100% wool fabrics could cause problems during cutting. According to Table 2, since F< F $_{crit}$ i.e. 211 < 3.554557, it can be concluded that the null hypothesis is rejected, i.e. the differences are statistically highly significant, the wool/mohair fabrics being significantly stiffer.

3.2 Extensibility of different fabrics

Table 3: Warp extensibility (E100-1) of fabrics

Wool/Mohair	Wool/Polyester	100% Wool
1.6	2.2	2.1
1.5	1.6	1.9
1.7	2.8	2.3
1.5	2.2	2.1

Table 3 shows, the fabric extensibility, in the warp direction as measured on the FAST, the extensibility varying for the different fabric types and blends. The wool and wool/polyester fabrics had significantly higher extensibility (Table 4), which would make it easier to carry out the laying up operation before cutting, while the wool/mohair fabrics had a lower extensibility, which might cause overfeed and moulding issues.

Table 4: Statistical analysis of extensibility of fabrics

ANOVA: Single factor   α   0.05

SUMMARY

Groups	Count	Sum	Average	Variance
Wool/Mohair	4	6.3	1.575	0.009167
Wool/Polyester	4	8.8	2.2	0.24
Wool	4	8.4	2.1	0.026667

ANOVA

Source of Variation	SS	df	MS	F	P-Value	F crit

Between Groups	0.901667	2	0.450833	4.903323	0.036	4.256495
Within Groups	0.8275	9	0.091944			
Total	1.729167	11				

Reject Null Hypothesis because p < 0.05 (Means are Different)

3.3 Control Charts

On completion of the FAST tests, the data collected was formulated into control charts. Three control charts were created on the basis of the data obtained from the respective fabric types.

From the FAST data and control charts certain conclusions could be drawn. For example, the relaxation shrinkage of the 100% wool fabric was greater than that of the wool/polyester fabric, which could result in sizing issues, possibly causing difficulty in pleating and fusing of panels. Also, the hygral expansion of the 100% wool fabrics was greater than that of the wool/polyester fabric which could lead to problems with puckering. Formability is basically the difference between extensions at E20 and E5, which was very similar for the different types of fabric. The extensibility and bending properties of the fabrics have already been discussed. It was apparent that, although the fabric weights fell within the same range, of $200 - 250$ g/m^2, their FAST properties differed in many respects due to different weave types and blends.

3. FOM installations worldwide

According to the Kawabata manufacturers and suppliers around 2012 there were, 78 Kawabata systems being in place in 16 countries, with most systems being in Asia (45), followed by Europe (20), most systems being in place in research and educational institutions, as opposed to commercial firms. According to the FAST manufacturers and suppliers, around 2012 there were some 121 FAST systems in place in 31 countries, most (47) being in Europe, followed by Asia (43). Most of the systems, 70 in all, were used in companies, which contrasts with the Kawabata system.

Only two companies in South Africa own FAST instruments, one of which is no longer using their system, as they have changed their area of operation from manufacturing to retailing, the other firm using the FAST system for quality control purposes. There is therefore clearly a need and huge opportunity for local companies to adopt FOM in order to improve their apparel fabric as well as garment quality, particularly when they are involved in formal type of wear, such as worsted type jackets and suitings.

4. Conclusions

South Africa, as a country, lags behind most other countries in terms of the use of FOM. This indicates that there is considerable scope for introducing this highly advanced technology into the textile and clothing manufacturing and retail pipeline in South Africa, with the associated benefits of improved quality control and assurance, particularly in the field of formal wear. It was demonstrated that even if fabric weight fell within a similar range, fabrics could perform quite differently, with the wool/mohair fabric being best in terms of bending stiffness and wool and wool/polyester in terms of extensibility.

5. References

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