LOW STRESS MECHANICAL PROPERTIES OF HYDROENTANGLED FABRICS

BY

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Abstract

Nonwoven fabrics are used in many different applications including wipes, incontinence products, interlinings, blinds, bed linen, protective clothing and others. However, the potential uses of nonwovens in traditional clothing outerwear (e.g. shirtings) are still limited.

The low stress mechanical properties of fabrics (e.g. bending, extension, shear and recovery from extension) can be used as a measure of the suitability of fabrics to be used in clothing. In respect of the low stress mechanical properties of nonwoven fabrics, hydroentangled fabrics have values that are most similar to woven fabrics used for apparel applications.

Experimental hydroentangled fabrics produced using different conditions were studied and characterised in terms of their low stress mechanical properties. It was established that if the specific energy applied remains constant, the jet profile used to apply the energy influences low stress mechanical properties. In general, alternating injectors (face and back) gave the most acceptable combination of low stress mechanical properties for clothing applications. Fabric area density, thickness and density were also found to affect the low stress dimensional and mechanical properties. An investigation of hydroentangled fabric geometry and its relation to the low stress mechanical properties of fabrics was carried out. Hydroentanglement of webs in both the MD and CD (in succession) produced fabrics having a lower shear rigidity compared to fabrics hydroentangled in the MD or CD only (which is the normal convention).

Empirical models were produced to enable the prediction of the low stress mechanical properties of hydroentangled fabrics, based on the weight per unit area and the total applied specific energy.

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Recent years have been marked by a rapid development of unconventional technologies in textile production. A common feature of some of these technologies has been a partial or complete elimination of conventional textile operations such as weaving, knitting, and spinning operations. One of the distinguishing features of the new products, which differentiate them from conventional textiles, is the blend of physical properties and the extended range of end uses.

There are various definitions of a nonwoven fabric. For example, according to Textile Terms and Definitions[1], nonwoven fabrics can be defined as textile structures made directly from fibre rather than yarn. These fabrics are made from continuous filaments or from fibre webs or batts strengthened by bonding using various techniques. These include adhesive bonding, mechanical interlocking by needling or fluid jet entanglement, thermal bonding and stitch bonding[1].

Although nonwovens were known well before the 1940's, the commercial production of textiles made from adhesive bonded fibre webs dates back to about 1942 when the first few thousand metres were produced in the United States. It was at that time that the term "Nonwoven Fabrics" was born. The term has been translated literally in other languages. Thus, the name of these new products and new production techniques was created[2].

Within an historically very short period, production techniques have been developed based on the bonding of fibre webs with adhesive dispersions, spraying of fine webs, paper making (wet) processes, bonding with thermoplastic fibres, bonding with polymers in the form of powders, threads, foils and bonding with adhesives which coagulate at room temperature[2].

In the field of mechanically bonded nonwovens, in addition to the needlepunching process which dates back to around 1870, several other production techniques have been developed based on stitch bonding of fibre webs or thread systems with binding threads, and stitch bonding without the use of binding threads. Polymer to fabric techniques in which fabrics are produced directly from the spinneret or by splitting highly oriented films are also well established. These techniques are supplemented by lamination methods in which composites are produced from different fabrics. Thus, confusion and discussion has arisen over the use of nonwoven terminology and the need to consolidate and unify classifications has become more and more urgent[2].

1.2 Fibres for Nonwovens

Virtually all types of fibrous material can be used to make nonwoven bonded fabrics[3], the choice being dependent on:

(a) The required properties of the fabric;
(b) The cost/use ratio (cost effectiveness);
(c) The demands of further processing.

Chemical fibres of both cellulosic and synthetic origin are consequently preferred, but natural fibres, occasionally even inorganic ones, are also used. Since nonwoven bonded fabrics are always developed to meet specific requirements, the correct choice of fibre is of supreme importance. It is not only a question of finding the best kind of fibre, but of taking the special properties of the fibre concerned into consideration[3].

1.3 Nonwoven Interlinings

The ancient Egyptians from very early times (3400-2100 B.C.) practiced the art of stiffening and pleating linen garments. Early Cretan costume was based on fitted garments using leather incorporating a weave, which provided the stiffness. A following garment such as the Roman Toga created its own style by relying on the natural drape of the cloth itself[4].

The clothing institute in 1974 proposed the following simplified definition:
"..........an interlining which has been coated so that it adheres to other fabrics by the application of heat and pressure"[5].

With regard to the fusing of nonwoven interlinings to woven fabric and the bonding method can be compared to the formation of plywood, which results in a stiffening of

the laminate, i.e. the stiffness of the laminate is greater than the stiffness of the three constituent components (these being the top cloth, the backing material of the interlining, and the melt adhesive).
The more balanced the strength of the top cloth and the interlining, the stiffer the resultant laminate. Stiffness increases further if there are little differences in the way the top cloth and interlining handle along and across the grain. This explains why very short multi -directional randomly laid fibre webs can have a stiffening effect when used as the basic material for flexible interlinings[4].

There are many different types of nonwoven fabric used as interlinings.

1.3.1 Diagonally Stable Random Laid Nonwovens

These are used to prevent diagonal-extension as much as possible; such multi-directional fabrics can be extended in any direction to match the diagonal pull of the top cloth. These fabrics are used wherever a soft feel and elasticity are required, mainly for large areas such as full front interlinings or pockets.

1.3.2 Longitudinally Oriented Nonwovens

These are used in addition to the random oriented type. These fabrics are composed of fibres lying predominantly in a longitudinal direction, and exhibit anisotropic tensile properties[4].

1.3.3 Slit Nonwovens

These are used for interlinings that are slit longitudinally at regular intervals to give the fabric exceptional horizontal elasticity. A high percentage of fusible adhesive nonwoven interlining material is made in strip form. They are backed using transfer paper, which can only be removed when the fabric is hot, or easily peeled off without any need for heat application. As one would expect, those properties, which depend on the direction of the web, reflect the direction of the orientation of fibres in the web[4].

The development of interlinings through the years, has reviewed by Harold[5]. At first, interlinings were sewn, as sub-assemblies of fabrics inserted between the outer face and the lining of a garment. This served to stiffen, and reinforce a given area. Nowadays, the term “fusible interlining” is defined as a base fabric having a deposit of a thermoplastic adhesive resin, usually on one surface only, which is capable of being bonded to another fabric, such as the face cloth, by means of heat and pressure[5].

Interlinings[4] are designed to improve the shape of garments, ensure that they retain their shape, and to strengthen the top cloth. They are used either as full interlinings or in small pieces, and are made almost exclusively composed of synthetic fibres, chiefly polyester, polyamide and viscose rayon. The basic prerequisite is that they must be resistant to wear, laundering and dry-cleaning. In the manufacture of men's wear, the main areas of use are in coats, suit jackets, trousers, waistcoats, casual jackets, ties, caps and hats.

The picture for ladies wear is similar but far more dependent on fashion trends, and nonwoven bonded fabrics have to be adapted accordingly. They are used for trousers, jackets, blouses, hats and caps, as well as coats, suits, skirts and dresses. Other fields in which nonwoven interlinings are used are in men's and children's shirts, nightwear and corsetry, as well as for children's clothes, sports wear, beachwear, and leather and fur garments. There are many types of interlining[4].

1.3.4 Fusible Interlinings

Fusible interlinings, which are stuck down on to the top or bonded to the top cloth (or other lining materials), are now common. The bonding can be over small or large areas. The nonwoven bonded fabric itself and the melt adhesive employed vary depending on whether they are to be used on large or small areas. They are more timesaving than interlinings that have to be stitched, and the quantity used in clothing manufacturing has increased steadily over the years until they now account for 80-85% of all interlinings.

1.3.4.1 Adhesive Interlinings

Adhesive interlinings consist of spun laid or melt blown adhesives and bond textile fabrics when they are subjected to heat, pressure and occasionally steam using a fixing press or iron. These adhesive fabrics are manufactured both with and without a backing, which is normally paper.

1.3.4.2 Weldable Nonwovens

Weldable nonwovens are welded to the top fabric or lining by heat contact using either ultrasonic or high frequency methods. The welding can also be achieved in steam.

1.3.4.3 Mouldable Nonwovens

Mouldable nonwovens can be thermally moulded in presses. Whether the nonwoven interlining is to be sewn or fused is not important. Since moulding effects are normally only needed for small areas, nonwoven interlinings are primarily used for small areas such as collars, belts, cuffs, pocket edges and lapels[4].

An alternative method of compacting webs for clothing interlinings[6] is the use of the thermoplastic properties of certain fibres within the web. The development of core/sheath bicomponent fibres (BICO's) was pioneered by ICI Fibres in the early 1970s. When the web containing such fibres is heated to a temperature near to the melting point of the outer layer but below that of the inner core, the points where the fibres cross each other are fused together, or spot welded, and when cooled remain in a combined state. The heating is sometimes applied by heated engraved rollers, radiant heat or hot air, often with the addition of steam. Fabrics made this way, for example, Heterofil polyester bi-component fibres are used for sew-in interlinings and resemble a light and lofty felt, providing extra warmth for a garment. The main advantage is the excellent washability, which is achieved without risk of disintegration. Shoe linings are also made with Heterofil fibres, which are thermally bonded and sold under the Cambrelle trademark[6].

1.4 Nonwovens As Outer Wear

Nonwoven fabrics find a variety of uses in outer clothing. Many different techniques are employed in the manufacture of nonwoven bonded fabrics to be used in making garments. Spun-bonded fabrics are made into protective clothing for surgery, into caps for operating theatre staff, overalls, disposable garments for short-term use in laboratories, research departments, in the electronics and optical industries, in the food and pharmaceutical industries, in power stations and nuclear research establishments. They are also made into aprons, coats and suits with attached hoods and over shoes.

The proper fit of apparel[7] depends on the relationship of the size of the garment compared with the size of the wearer. Also the garment ease is important, which is defined, as the difference between the size of the garment and the size of the wearer. For example, protective clothing should provide maximum protection and comfort. It is important that the protective clothing fits properly so that wearer movement is not inhibited. Research has shown that a significant problem area for fit in protective clothing is in the crotch area. For example, in a study undertaken on overalls worn for asbestos abatement work, 80% of the subjects indicated the crotch area was prone to ripping. Addition of a suitable fabric to provide garment ease in the crotch area could possibly help eliminate the ripping of the garment, but too much ease may restrict certain leg movements (e.g. extension)[7].

US Patent 5 592 690 (1994), described garments such as a shirts, pants, skirts, dresses, under garments or socks, including an elastic laminated sheet next to a joint of the wearer. The product comprised an elastomeric film with a nonwoven fibrous web laminated to it, and has fibres extending from the laminated surface. The laminated sheet was stretchable and recoverable in response to movements of the joints of the wearer to provide a more comfortable and durable article of clothing[8].

Todd[9] explained how the use of protective fabrics and clothing has expanded as the industry progressed and the overall awareness increased in response to the deleterious effects of worker exposure to chemical, thermal, and environmental hazards present in the workplace. By the mid-1990s, natural rubber, which was being applied to various substrates in the latex process, had become the protective fabric of choice. Military needs for protective fabrics gave the first major technological stimuli to the protective clothing market, which resulted in the development of new materials, many of which comprised nonwovens.

The next significant expansion of the protective clothing industry came in the form of lightweight, highly chemically resistant, film based fabrics introduced in the late 1970s and early 1980s. Polyethylene, polypropylene, Saranex ™ (Dow), and others soon took place in the industry and created disposable and limited-use markets[9].

Four requirements for the performance of a protective clothing garment can be listed as follows:

a. Broad chemical resistance;

b. Good physical properties;

c. Flame resistance;

d. Anti-static properties.

The two basic considerations that must be taken into account in the design of an ideal protective fabric are, firstly the performance of the fabric which must satisfy the specified need, and secondly the fabric must be easily converted into protective items whose configuration will be determined by the expected end-use[9].

The protective clothing can be classified into three categories[9]:

a. Disposable;

b. Limited-use;

c. Durable.

Disposable nonwoven bonded fabrics have proved themselves eminently suitable for use in operating theatres by helping to prevent cross-infection and thus acting against prolonged hospitalization[4].

A wide range of nonwoven products is available as head coverings for male and female staff. The nonwoven usually preferred for this application is of the parallel-laid type, based on cellulose fibre, patterned and sometimes printed, although spunbonded fabrics are also used. The caps must be comfortable to wear, i.e. the material must be soft, pliable, air-permeable, absorbent, virtually lint-free and also sterilizable, even though headgear is not normally sterilized[4].

Gowns make rather different demands, basically they should breathe, i.e. are permeable to air, act as a barrier to liquids and bacteria, and are tear-proof, lint-free and soft. They must also withstand sterilization by all known methods, i.e. by steam, radiation or gas. Since it is difficult to produce a single material, which meets all these requirements, theatre gowns are often made of two different materials. The front, for example, is made of a composite comprising nonwoven and polyethylene film, whereas the back is made from nonwoven fabric alone[4].

The characteristics required of operating masks still need defining more clearly. The wearer expects comfort, i.e. a good fit, a high level of air-permeability, softness, lightness in weight and skin-compatibility, whilst providing the highest possible filter capacity[4].

1.5 Laminates and Composites

Miller[6] made a review of the historical development of the laminates when it became possible to make plastic foam, i.e., synthetic plastic material with small air cells created by gas bubbles. The idea of combining a fabric with a sheet of this foam was tried. It was found that the foam increased the thickness and warmth of the fabric but did not increase the weight to any great extent. It was also found that a thin layer of foam could be used to bond two fabrics together, by the use of heat, forming a triple laminate with the foam inside or, by using a very thin sheet of foam which virtually disappeared, being used entirely as an adhesive to fix the fabrics together.

Fabric laminates are not in themselves new - Mackintosh produced his now famous rubber and fabric laminate in 1823 - but until fairly recently they were only of limited clothing use because the method of lamination detracted from the handle and drape of the fabrics concerned. Special adhesives have now been developed which enable fabrics to be durably bonded without any noticeable effect on handle and drape, and these are used perhaps more than the foam method mentioned above. Furthermore, now that wide webs of adhesive filaments are being produced, the manufacturers of nonwoven fabrics, originally intended for fusing facings and hems of garments without the need for an interlining 'base cloth', this gossamer sheet of adhesive fibres is laid between the two layers of fabric, all three fed from rollers, pressed together and passed through heated ovens to cure the cross-linking agents in the adhesive, so making a very soft and supple composite fabric, which can be washed or dry cleaned according to the properties of the individual fabrics which have been laminated. As to whether the mini-layer of foam, an acrylic adhesive or the adhesive web is used depends on the end-use and the weights of the fabrics being bonded[6].

The process for the lamination of woven and knitted fabrics has been used for a long time now, particularly in the shoe making industry. Woven and knitted fabric laminates, while being cheap to produce are a little difficult to handle mainly due to excessive elongation of the knitted fabric themselves. They find a number of different end uses such as in ladies' and men's overcoats, ladies' dresses, children's coats, sportswear, decorative fabrics, dressing gowns and frocks of lace or Raschel knit fabrics. The end use of fabric/foam laminates (woven or knitted fabrics laminated preferably with polyurethane foam) is in outerwear fabrics, i.e. sportswear, overcoats, coats[2].

The lamination or joining of two planar systems may result in important changes in the original properties, which, in fact, determine the potential end uses of the laminated fabric. The properties that are liable to change are above all:

a. The strength and particularly the elongation;
b. The rigidity, drape and crease behaviour;
c. The dimensional stability and shape retention;
d. The permeability to air vapours and water[2].

To ensure the physiological function of nonwoven products, a quality criterion is needed. Umbach[10] introduced such a quality criterion by means of a minimum water vapour permeability index, which must be reached by a nonwoven/membrane-laminate. This index is determined out of the laminate's thermal and water vapour resistance. However, the special characteristics of the water vapour transport mechanisms in the membranes currently available demand that particularly the laminates' water vapour resistance is measured by a clearly defined test method in which, furthermore, the test conditions are simulating the actual wear conditions as nearly as possible.

This demand is best fulfilled by the thermoregulatory model of the human skin (skin model), a test device already standardized for the physiological testing of textiles. With the guideline of the controllable physiological quality criterion introduced with nonwoven/membrane-laminates, wet-weather protective garments can be made which in cold climates and in the presence of high wind speeds keep the wearer sufficiently warm. But on the other hand, due to their good breathability also with heavier physical activity, provide a dry microclimate next to the body and, thus, good wear comfort[10].

EP 0 755 325 (1995), described a nonwoven fabric laminate for barrier applications which has improved ratios of barrier and strength to weight, of softness to strength and of vapor transmission to barrier. The laminate comprised a melt-blown layer sandwiched between spunbonded layers. The melt-blown and spunbonded layers may have between 0.1 and 2.0% by weight of fluorocarbon and the melt-blown layer between 5.0 and 20% by weight polybutylene. The laminate may also be pigmented. These laminates are used for protective garments[11].

USP 5 593 765 (1997), details a flexible laminate comprising a layer of metal foil bearing a holographic image, a layer of flexible fabric, and an adhesive layer, including at least one plastic material, between the fabric and the foil. The laminate behaves as a flexible fabric and can be used to make clothing[12].

EP 0 757 624 (1997), describes an elastic fibrous nonwoven web laminate which exhibits elastic properties in at least one direction and, if desired, two or more directions due to the use of at least one fibrous nonwoven web facing layer which contains several slits. Laminating processes are also claimed. Uses include: surgical drapes, diapers, training pants, incontinence garments, sanitary napkins, bandages and similar products[13].

Harxmeier[14] discussed the thermal insulation property of still air. The higher the thermal insulation requirements a nonwoven has to meet, the better its capability must be for trapping air. The writer used combinations of nonwovens with water-vapour-permeable membranes to form laminates, to impart water proofness and windproofness.

Mate[15] described a composite fabric, composed of polyolefin polymers, i.e. polyethylene and polypropylene. This gives an advantage in the manufacture of composite and perhaps in converting to a finished product. Polyolefin's provide resistance to many harmful media including organic solvents and spray components. Their natural hydrophobic properties provide repellency to many high surface tension materials like water and inorganic solutions without any treatment. Coating, or chemical finishing, can further enhance the barrier properties.

In 1991, Duflot Industrie[16] featured a range of fire - proof nonwovens and nonwoven composites by combining textile films and multiplanar products with basic nonwovens. They created a range of composite products with different properties, each of which has been developed to perform specific functions. The material is claimed to have a wide range of applications. Because they emit only negligible amounts of toxic fumes they can be used to protect seating and upholstery. They are used in public environments and in public transport, as well as to improve the safety of furniture and bedding in homes. They are recommended for use in protective clothing required by certain industries, sportsmen, military personnel and fire fighters.

In 1990, the Minnesota mining and manufacturing Co. (3M)[17], was assigned a patent for a method of producing stretchable fabrics with enhanced thermal insulation properties. Such stretchable fabrics have particular use as insulation lining in thin, close fitting outwear such as ski and work clothing. The fabrics can be repeatedly stretched without losing their thermal insulative properties. The fabric is based on the use of an elastically stretchable carrier web such as a nonwoven web prepared from bi-component fibres that are fusion bonded. Using such an elastic carrier web, the enhanced insulating properties are conveyed by coating the carrier fabric with a micro fibre based coated layer, preferably derived from a melt blowing process.

Other specific applications of nonwoven technology in clothing include the following areas:

1. Synthetic Leather Manufacture (Footwear) [4,18]

In Europe, in 1940, especially in Germany, an effort was made to supplement or replace the genuine leather used by the shoe and leather goods industry with needled fabrics. These products had a fraying tendency, and with the use of matrix fibres, effective leather substitutes were produced from polyurethane bonded needle punched fabrics. These fibres are embedded in matrix bicomponent fibres. Dissolving this matrix in a solvent enabled production of micro-fibres that have high degree of porosity and a high resistance in fabric form. After opening, blending, carding and converting the micro-fibres in to the form of a web, the fibres are reoriented during preneedling and are then needled with suitable barbed needles to produce a high density synthetic leather structure. Splittable bicomponent fibres are also used. Mechanical splitting can be achieved during hydroentanglement to produce microfibres or chemical dissolution techniques are also practiced. Then, the synthetic leather goes through coating and impregnation processes and also pressing and slitting operations[18]. Nonwovens also serve as carrier materials for synthetic leather in the production of protective clothing and rainwear[4].

2. Hydroentangled (APEX fabrics) [19,20]

Polymer Group Incorporated (PGI company) has launched APEX technology. These fabrics are hydroentangled and have a visual appearance similar to woven and knitted fabrics depending on the design of the forming surface. The resulting Miratec fabrics are claimed to be suitable for a wide range of applications, including home furnishings, apparel, automotive, industrial, and medical applications.

3. Evolon (Freudenberg) [21]

Evolon fabrics have their origin in a proprietary process that combines the spinning of the bicomponent filaments, web-formation and web bonding using hydroentanglement. The split fibres can be as fine as 0,05 dtex up to 2,5 dtex, as well as smooth or crimped. The Evolon technique involves production of filaments of around 2 dtex, which are spun, drawn and laid down on a collecting surface. Using hydroentanglement, the filaments are split and entangled in one process to obtain a fabric containing microfilaments that have an attractive textile drape, high tensile strength and very good tear-resistance. These fabrics can be used in different applications such as interlinings, sports wear and protection wear.

4. Hydroentangled Liners (Outdoor Garments-Sportwool Tm) [22]

The University of Leeds together with industrial collaborators have successfully used hydroentanglement to create lightweight wool lining fabrics. In its first application, this fabric was bonded with a breathable membrane to line weatherproof coats. The forthcoming development is to produce fabrics for other outerwear apparel applications such as trousers and jackets.

5. Needlepunched Melton Type Cloths (WIRA + University of Leeds) [23,24]

Larsen et al.[23] carried out trials to study the production of nonwoven blazer cloths by the needle felting processes. The aim was to determine how the properties of finished cloths varied according to the production techniques used. It was found that needled fabrics could be made with properties in many ways similar to that of woven fabrics used for apparel applications. The results indicated that more intense raising treatments should bring the bending properties within the same range as similar woven fabrics[23]. Smith et al.[24] also found that by raising a needle felted wool fabric under suitable conditions, it was possible to obtain drape properties comparable to conventional woven fabrics used for apparel applications. Generally, raising reduced the strength and abrasion resistance of the nonwoven fabrics produced, but even so other fabric properties still compared well with woven fabrics.

6. Stitch Bonded (dresswear) [25]

Different apparel applications have been attempted using stitch-bonded fabrics. For example, polyester/wool dresses were developed, but tended to be too stiff and had good abrasion and wear performance. The problem with these garments was the durability due to the ease of fibre movement.

Although many nonwoven fabrics have appeared on the market, with recent developments in the field of nonwoven manufacture in the last few years, comparatively few detailed studies of the low stress mechanical properties of such fabrics has been reported to investigate the appropriateness of nonwovens for apparel applications.

A review of previous work concerned with the mechanical properties of fabrics to be used in clothing, including nonwovens, now follows.

1.6 Literature Review: Fabric Properties Related to Clothing Applications

1.6.1 Introduction

In the early 1950's and 1960's, major studies were undertaken in the field of nonwoven fabrics; it is of particular interest[26] that the science of the structural mechanics of the materials effectively ran parallel with the industrial innovation during this period of time. The most noteworthy was the research by Petterson[27] in 1958 of M.I.T. and later Petterson and Backer[28] in the 1960's, which described some early studies on nonwoven fabrics.

Early investigations[27,28,29,30] of the structural mechanics of nonwoven fabrics indicated that nonwoven fabrics were unsuitable for apparel applications because of deficiencies such as low drape, high shear modulus and poor fabric recovery from extension, which affected the dimensional stability of garments produced[31].

1.7 Basic Requirements of a Garment in Use

As engineered products, nonwovens are designed towards end-use requirements; therefore, the ability of the nonwoven manufacturers to continue to engineer their products for specific end-use applications has been an important factor in the success of this new industry[2].

In order to investigate the appropriateness of using these fabrics for apparel applications, it is important to study the requirements of fabrics to be used in garments.

In a study made by Shishoo[32], on consumer demands it was stated that there are a number of performance requirements that have to be fulfilled by clothing, the most important ones being:

1. appearance (garment shape, drape wrinkles);
2. fit (mechanical comfort, freedom of movement);
3. durability (tear and tensile strength, abrasion resistance);
4. tactility (softness, smoothness);
5. hand (compressibility, elongation);
6. transmission (heat, moisture, air).

A critical feature that has to be fulfilled in the garment to achieve consumer satisfaction is the fabric handle. The handle of fabrics has been defined as the quality of a fabric or yarn assessed by the reaction obtained from the sense of touch. It is concerned with the judgment of roughness, smoothness, harshness, pliability, and thickness[1].
To characterize the handle, two main systems are used:

1. subjective measurement system;
2. objective measurement system.

Subjective measurement is the assessment of the fabric handle by individual subjects, whereas objective measurement is concerned with the evaluation of fabric handle by means of instrumental measurement. In this thesis, only the objective measurement system will be focused on.

1.8 Objective Measurements of Fabric Properties

1.8.1 The Need for Fabric Objective Measurement

Although the subjective assessment of fabric quality and performance such as handle, comfort and appearance has been used in the textile and clothing industries for many years, this kind of assessment is becoming increasingly inadequate[33,34]. The reasons include:

1. numerous new fabrics, which need to be, assessed accurately where workers have no previous relevant experience;
2. increasing automation in the field of the textile and clothing industry, which require quantitative data of fabrics for simple and successful implementation of automatic manufacturing;
3. maintain the competitive ability of a company in the market, which requires quick response in solving the critical problems;
4. the need for a more global language of fabric properties for specifications and quality assurance.

1.8.2 The Concept of Fabric Objective Measurement

As defined by Postle[35], the concept of fabric objective measurement relies on the instrumental measurement of a set of parameters, which are required to specify fabric quality, tailorability and clothing performance. Based on this, fabric objective measurements can be used for:

1. engineering fabric properties for desirable performance and quality;
2. development of new finishes and finishing machinery and control of fabric finishing and refinishing to meet specific mechanical properties;
3. total fabric development from raw material to tailored garments.

1.8.3 Background of Fabric Objective Measurement

A review made by Stylios[36] summarizes the milestones in the development of fabric objective measurement. The objective measurement of fabric handle was pioneered in 1940 by Pierce[37] who tried to quantify fabric handle. Subsequently, important work was done by Lindberg and his co-workers at the Swedish Institute for Textile Research (TEFO).

The Kawabata KES-FB instrument was introduced in 1972 by Professor Kawabata to accurately measure fabric mechanical properties under low stress. These instruments included a tensile and a shear tester, a pure bending tester, a compression tester and a surface roughness tester.

In 1989, Professor Postle and his team in Australia[38] made important breakthroughs in using objective measurement in a number of areas including the tailorability of suiting fabrics.

More recently, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia developed their own version of objective measurement tools named FAST (Fabric Assurance by Simple Testing) which consisted of a compression meter, a bending meter, an extension meter and dimensional stability measurements[36].

1.9 Application of Fabric Objective Measurement System in Clothing

1.9.1 The Prediction of Garment Appearance from Measured Fabric Properties

As stated by Biglia et al.[39], garment appearance is the major selling factor and preservation of that appearance produces satisfied customers. However, good garment appearance is considered to be the end product of a number of operations including garment design, choice of fabric, tailoring skill and successful pressing. In addition, a highly skilled tailor, given sufficient time, can produce a garment of satisfactory appearance from almost any fabric.

However, today a garment manufacturer is required to produce a garment in a minimum time for minimum cost. For that reason, the selection of the right fabric is important to ensure that the tailoring operation, during both sewing and pressing produces garments of acceptable quality. Furthermore, the prediction of a fabric's performance at each stage of manufacture will simplify production and assist in accurately costing the making up of that fabric[40].

The quality, tailorability and performance characteristics of fabrics are related to their low stress mechanical, surface and dimensional properties namely tensile, shear, bending, compression, surface friction, hygral expansion and relaxation[35]. The experimental errors involved in the measurement of most of these properties are known to range from 5-12% and are therefore much less significant than the errors involved in subjective assessment made by individual judges[41]. This is another justification for preferring objective measurement techniques for evaluating fabric properties over subjective methods. Furthermore, these fabric mechanical and surface parameters are not difficult to measure. They can be readily stored in a computer database and they are much more precise than subjective opinions about fabrics, and, in addition, they are easy to communicate between industry sectors. They can also be used as the basis for product innovation, fabric specification, and quality assurance and process control in both textile and clothing manufacture[41].

1.9.2 Garment Manufacturing and Appearance Difficulties Associated with Fabric Mechanical Properties

1.9.2.1 Garment Manufacture

Bishop[40] has claimed that, for the manufacture of structured garments such as jackets and suits, the values for fabric mechanical properties should be appropriate to ensure smooth, quick and successful conversion of fabric into finished garments. Ideally, these mechanical property values should be within a specific range, if they are not, then a range of options are available to the fabric or garment manufacture. For example, the garment manufacturer can give precautions to the machine operatives or modify the operation to overcome the difficulties. In addition, the fabric manufacturer can change the properties of the fabric by modification of finishing processes or refinishing[40].

Kawabata presented a chart of the process control of men's suit production lines. This chart identified the tensile and shear fabric properties relevant to the difficulties in processing. Where the properties of the fabrics fall into a "non control" zone, no action is required. Alternatively, if some of the properties are outside the zone, some actions are required as defined in the guide manual [42,43].

In 1989, Harlock[44] reported a literature survey of the use of objective measurement systems in production control in apparel manufacture. He cited examples of its potential to predict a fabric's tailorability and the subsequent appearance of a garment produced from it.

1.9.2.2 Garment Appearance

For the garment appearance, Lindberg et al.[45] advocated that the design of the garment should retain a stable form, which follows approximately that of the human body. Some deviation from this form is necessary in order to cover anatomical shortcomings or to aid the production of certain aesthetic effects. An example of one of these basic requirements is the distribution of bending stiffness over the garment.

Lindberg[45] mentioned that a garment must provide freedom of movement in order to be comfortable. Bending an arm involves bending a cylinder of cloth, the sleeve, which leads to a large compression on the inside by buckling the cloth. Other examples from other parts of garments show a similar behaviour. The resistance to buckling under these conditions must be sufficiently low to make the garment comfortable. The buckling force is partly dependent on the bending stiffness of a plane fabric. Therefore, an upper limit of bending stiffness must not be exceeded.

He also[45] mentioned that cutting a sleeve "on the bias" generally makes the sleeve too extensible. The cloth in the garment must therefore be able to bear reasonable loads in certain directions without substantial extension. Limited extensibility in certain directions is therefore essential.

Lindberg[45] also indicated that when stitching layers of different fabrics together, any differences in dimensional stability under conditions met in use may lead to puckering or buckling of one or other of the layers, which impairs the appearance of the garment. Therefore, a certain balance in dimensional stability between different fabrics or portions of this fabric is also a basic requirement.

1.9.2.3 Limits of Fabric Properties

For the FAST system, limits are defined for the fabric properties or "control zones" which define the boundaries of properties for fabrics that offer problem free tailoring or indicate when problems can be expected. These limits depend on the end use for the fabric, garment design, the equipment available, etc. Accordingly, garment makers will be required to develop individual control zones for each fabric type according to the end use required[46].

1.9.2.4 The Relationship Between Handle and the Mechanical Properties

Taylor[47] defined the term 'handle' applied to a textile fabric as the sum total of the sensation experienced when it is handled; by touching, flexing in the fingers, smoothing, and so on. The more important of these requirements are those of thickness, softness (or hardness), stiffness (or pliability), and roughness (or smoothness).

For nonwoven fabrics, Smith et al.[48] warned that the resins used for bonding certain types of nonwoven fabric, are likely to affect the hand, drape, and strength of a fabric. In general, strong adhesives are also rigid. This means that higher fabric strength will tend to be accompanied by a coarser hand and stiffer drape. On the other hand, adhesives that are more elastic and yield a better drape yield weaker fabrics. Thus, for nonwoven fabrics, a stiff hand is associated with high strength, while a soft hand and good drape implies a weak cloth.

1.9.2.5 Relating Properties to the Structure of the Fabric

The mechanical and physical properties of a fabric are determined by the materials used to manufacture the fabric and the geometry of the construction (e.g. fibre type and fineness, yarn count and twist and fabric weave and cover factor) and also by any finishing procedures used[46].

Consequently, it can be concluded that many of the fabric properties are inter dependent because they are determined by structural parameters. For example, formability is a derived property of a fabric that can be calculated from the bending rigidity and extensibility, and thus depends on a large number of structural parameters. As a result, modifying some fabric properties during finishing will affect others at the same time[46].

1.9.2.6 Application of Objective Measurement to Nonwoven Fabrics

In a study made by Kawabata[41], fabric characteristics and surface properties of some nonwoven samples made of PET and fibre melt bonding using KES-F instruments were measured. These results showed that most of the concepts of the primary hand, which have been standardized for woven fabrics, might be applied to nonwovens.

Despite differences in the structure of woven and nonwoven fabrics, there may be a common base in the feeling of good or poor touch by the human hand as far as these fabrics are used as "human materials". Accordingly, the mechanical parameters of nonwovens will have a different range of values from the range exhibited by woven suiting fabrics[41].

In another study by Shishoo[32], the mechanical properties of eight different commercially produced nonwoven and nonwoven-based materials were measured. He observed that the mechanical properties for these fabrics varied quite significantly. Consequently, these differences have to be taken into account when drafting clothing patterns and suitable manipulations must be made for avoiding problems with garment fit and appearance. On the other hand, Shishoo[32] also indicated that these properties would influence the fabric conformation and distortions produced in the garments during use.

He also investigated the ease of making garments out of different fabrics, and he found that it varied quite significantly. For example, increasing the print-bonded area in spunbonded polypropylene (PP) from 8% to 27% decreased the formability of the garment, which was further decreased if the material was calendered[32].

Jain et al. carried out some testing of commercial disposable nonwoven fabrics using the FAST instrument[49,50]. They set some recommendations for changes in the FAST control chart for testing disposable nonwoven fabrics, such as changing the limits of the weight axis for lighter weight nonwoven fabrics, changing the limit of the BR (Bending Rigidity) and G (shear rigidity), as many nonwoven fabrics have always high values of BR and G, because nonwoven fabrics do not have the general characteristics of wool fabrics.

Barker et al.[51] tested six commercial nonwoven fabrics; three spunbonded and three spunlace fabrics of different weight, fibre content and construction. Laboratory tests were conducted and subjective evaluation made to compare the hand of these nonwovens with the hand of some woven fabrics sold into apparel applications. They found that the handle of spunlaced fabrics, especially the unfinished sample with an apertured pattern favourably compared with some of the softest woven fabrics.

Kawabata et al.[52] also investigated the objective evaluation of commercial nonwoven fabrics. He found that the equation developed previously for predicting the hand of men's suiting fabrics was applicable to predicting the hand of nonwoven fabrics with some slight differences. He then developed a new equation for predicting the quality of nonwoven fabrics.

1.10 Fabric Low Stress Mechanical Properties

It is evident from the review that the mechanical properties of nonwoven fabrics under low stress are of primary importance to garment production and appearance. This is because fabrics are unlikely to be subjected to heavy loads, or to vigorous bending or shear moments, or to be compressed under high loads during manufacture and during wear[36].

1.10.1 Typical Deformation-Recovery Behaviour for Textile Materials

Typical deformation-recovery curves[53] for a fabric subjected to either extension (or lateral compression) or bending or shear, display three main features, which are typical of textile materials:

1. the curves are non linear;
2. during fabric testing, selecting the maximum tension/ bending/ shear value for the recovery part of the cycle is important in reflecting the values experienced in garment performance;
3. during the deformation cycle some of the energy is lost, which is called hysteresis. As a result, some permanent distortion may be exhibited after the deformation cycle[53].

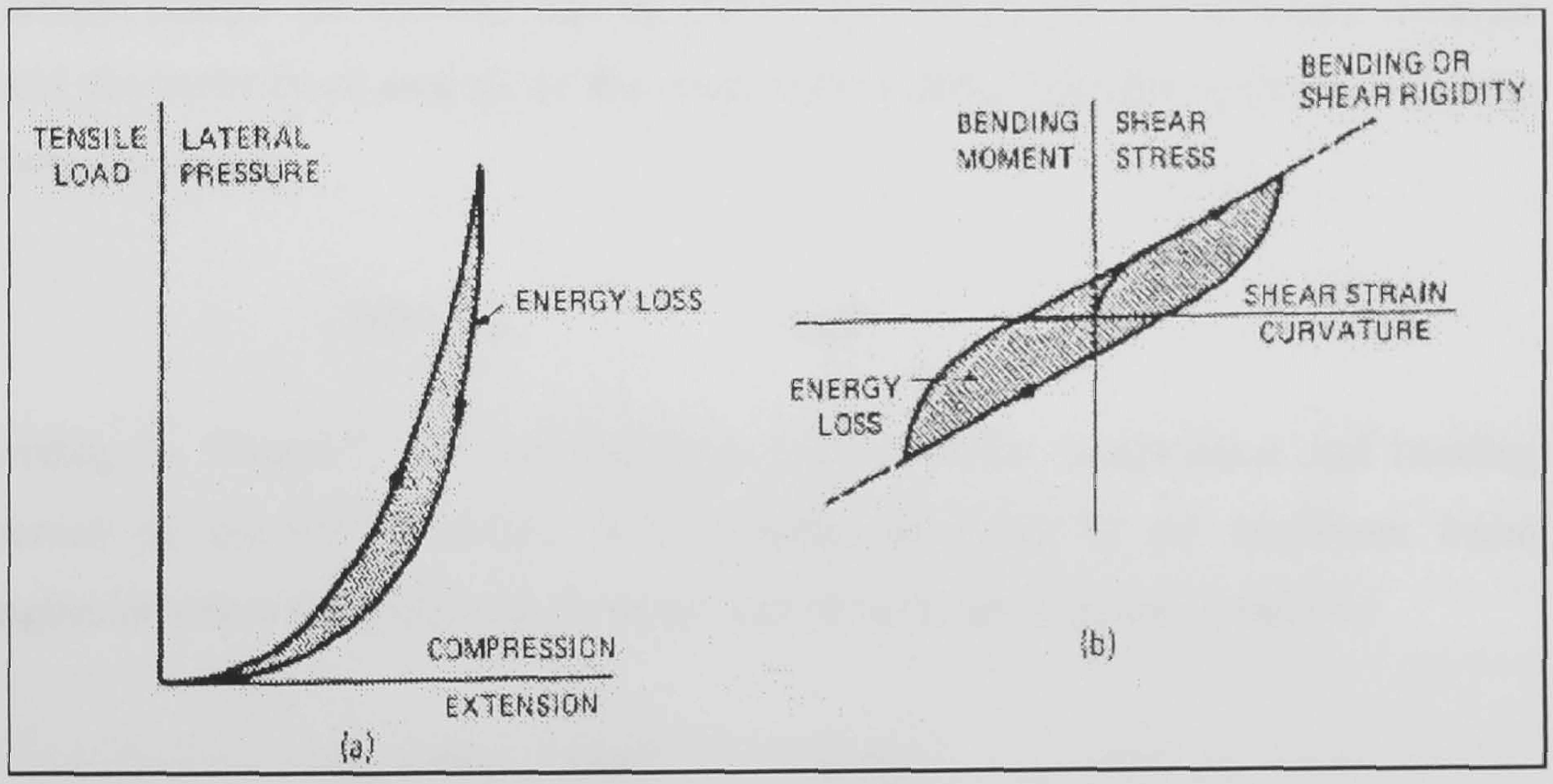


Figure 1.1 Typical Deformation-Recovery Curves for (a) Fabric Extension or Lateral Compression, and (b) Fabric Bending or Shear, Showing the Energy Loss During a Complete Cycle as the Shaded Area[53]

In figure 1.1, the hysteresis is shown as the shaded area to represent the energy lost during one complete deformation-recovery cycle[53].

1.10.2 Bending Properties

The bending length, as defined by Textile Terms and Definitions[1], is the length of a rectangular strip of material that will bend under its own weight to a specified angle. The flexural rigidity or the bending rigidity is defined as the measure of the resistance of materials to bending by external forces. It is related to stiffness and is one of the factors sensed when a fabric is handled[1].

Swani and Abbott[54,55] defined the bending stiffness of an elastic body by its flexural rigidity B, which is defined as the couple required to bend it to produce unit curvature. If M is the bending moment applied and p is the resulting radius of curvature, then:

$$\mathbf{M = B. \frac{1}{p}} \qquad \textbf{(1.1)}$$

In the case of a cloth, equation (1.1) can be applied to define its resistance to bending if it is assumed that the curvature is not very large and the strains produced in the fibres are small enough to bear a linear relationship with the applied stresses.
For simple bodies, the bending rigidity (BR) is directly related to the tensile modulus (E) and the moment of area (I) of the cross section about the neutral plane[54,55] by the following equation:

$$\mathbf{BR = EI} \qquad \textbf{(1.2)}$$

According to Wagner[56] who carried out a review of the compressive and bending properties of nonwoven fabrics, it is possible to resort to the cantilever beam arrangement where the deflection D_b at the end of the beam is given as follows:

$$\mathbf{D_b = W_1 L_o^3 / 8EI} \qquad \textbf{(1.3)}$$

Where W_1 is the weight of the sample in pounds per inch and the length, L_o is the length of the overhang in inches and I (the moment of area) is given as follows:

$$\mathbf{I = bh^3 / 12} \qquad \textbf{(1.4)}$$

Where b and h are the width and height (thickness) of the beam in inches respectively. As a result of these equations, the stiffness of a homogenous rectangular member varies with the cube of its thickness. So that the stiffness of different fabrics including nonwovens, is affected by the thickness and to a lesser degree due to fibre slippage. Therefore, thickness is still an important factor to consider when determining the stiffness of nonwoven[56].

Early investigations of the bending length in nonwoven fabrics showed that their bending length is generally higher than that of woven fabrics[57]. For example, Cusick et al.[30] tested the bending length of some commercial nonwoven fabrics and compared them with woven fabrics. He found that the bending length of nonwoven fabrics lies in the range 4 to 10 cm (40 – 100 mm). Whereas, for woven fabrics, the range was 1 to 4 cm (10 – 40 mm)[30].

Freeston et al.[58] pointed out that the binder used in nonwoven fabrics contributes to the fabric tensile strength but then prevents the relative fibre motion during bending which is necessary for good flexibility. He also claimed that, if the fibres were capable of drafting back and forth between the two surfaces of a nonwoven fabric and were bonded only at the midplane, in this case, the fabric might have sufficient tensile strength with markedly increased flexibility. It is the fibres that lay away from the midplane and near the fabric surface where increased freedom of relative fibre motion is needed to improve the total nonwoven fabric rigidity. Furthermore, the presence of excess fibre length between bond points allows additional deformability and hence decreased fabric rigidity.

Hearle et al.[59] investigated the relationships between adhesive bonded nonwoven fabric properties, especially those related to fabric drape, with the properties of the component fibre and binder. It is evident that increasing the fibre flexibility results in decreasing the drape coefficient of nonwoven fabrics. They also investigated the correlation between the drape coefficients with mean bending length. They found that increasing the drape coefficient will result in increasing the bending length of these fabrics. They also found that fabric stiffness is less sensitive to binder stiffness than to fibre stiffness. The drape coefficient also varies markedly with fibre modulus and to a smaller extent with the binder modulus. In addition, there is a large influence of fabric weight on drape. In addition, fabrics made from fibres that have a high resistance to extension, such as flax, tend to be stiffer than fabrics made from fibres such as wool, which are easily extended[59].

In a comparison between the bending of woven and nonwoven fabrics made by Backer and Petterson[28], the bending of a woven fabric depends on different mechanisms of deformation in varying degrees depending on yarn and fabric structures. These mechanisms are the local crimp interchange, yarn buckling at the bend, yarn flattening and compaction, fibre slippage, rotation, extension and bending.

On the other hand, in a nonwoven fabric, the mechanisms of deformation at a bend can be seen as fibre rotation, straightening in the fabric plane, buckling at the bend and bending out of the fabric plane, and bond rotation and bending.
Consequently, five distortion mechanisms are present in the woven fabric behavior, which require little or no elastic strain energy and afford a low order of resistance to the bending forces[29].

1.10.3 Stiffness Properties

The stiffness of a fabric is defined as the resistance offered by a material to a force tending to bend it[1].

Taylor[47] defined the stiffness of a fabric as its resistance to bending. She also defined the constructional features affecting the stiffness of a woven cloth, as mainly its weight, the nature of the fibres, and the compactness or density of the weave. For example, weaves such as twills and satins, in which the yarns are only loosely bound, provide limper fabrics than more tightly bound plain weave. Similarly, knitted fabrics are much less stiff than woven fabrics. Taylor[47] also stated that the stiffness of a fabric is also dependent to a high degree on the finishing treatment it has received. Finishes that tend to compact the cloth or make the fibres adhere promote an increase in stiffness. On the other hand, it is possible to reduce the coherence of the fibres and the friction between them by the use of suitable softeners, which act as lubricants, and also by suitable mechanical treatment of the cloth. In fact, the finisher has a variety of means at his disposal for changing the stiffness of a fabric and indeed for improving its' handle' in other respects also.

Smith et al.[48], stated that the properties of nonwoven materials are determined by the fibres used, the bonding agents, and the bond density. He also defined the bond density as the number of fibre to fibre bonds per unit area. A high number of bonds prevent the fibres from moving as the material is flexed, causing it to be stiff with high strength and low extensibility. On the other hand, a low bond density yields a more supple fabric with a lower strength.

As nonwoven fabrics are not isotropic[56] testing the stiffness of fabrics in one direction at a time in a simple fashion is desirable but is not practical. Also, because the fibres may be bonded in nonwovens, it was thought that the error in measurement of stiffness caused by frictional restraint would be of a smaller order than experienced by other researchers who tested woven fabrics. In addition, environmental conditions must also be considered because any change in the temperature or moisture affects the properties of textile fibres and will considerably, affect the bending properties of nonwoven fabrics[56].

1.10.4 Drape

According to the textile terms and definitions[1], the drape of a fabric is defined as its ability to hang in graceful folds, Cusick[30] defined the drape of a fabric as a description of the deformation of a fabric produced by gravity when only part of it is directly supported. This definition excludes the effect that lustre or other surface properties may have on the appearance of the fabric.

The drape coefficient is defined as[1] the percentage of the area of an annular ring covered by a vertical projection of the draped fabric. A high drape coefficient therefore indicates little deformation. The drape coefficient provides an objective description of the deformation, although this is not a complete description.

Swani[54] mentioned in his review of bending of woven fabrics that the way in which the fabric drapes depends basically on its stiffness and weight. The cube root of the ratio of these two quantities is considered as a quantitative measure of drape. It is termed as the "bending length" (BL). If W is the weight per unit area and BR is the bending rigidity of a fabric, then:

$$\mathbf{BL = (BR/W)^{1/3}} \qquad \mathbf{(1.5)}$$

A review made by Blakey[57], found that in woven fabrics, the drape coefficient increased as the bending length and shear modulus increased. Therefore, it is predictable that the drape coefficients obtained for nonwoven fabrics will be high, since both flexural rigidity and shear modulus are universally higher than for woven fabrics.

Cusick[30] found that the bending length usually gave the most significant correlation with the drape coefficient.

Taylor[47] stated that while the weight of the fabric provides the force causing it to drape, the stiffness provides the resistance. Thus, a stiff but heavy fabric may drape similarly to a limp but light fabric. In addition, it also has been shown that the manner in which a woven fabric drapes depends not only on the stiffness of the cloth but also on the resistance of the cloth to distortion by a change of the angle between the yarns, and the ease with which the cloth may be extended. For these reasons, compact woven fabrics such as taffeta, which has a high resistance to distortion, have a quality of drape that might be described as papery in appearance, compared with the drape of a fabric such as a woven voile, which has a low resistance to distortion[47].

Goodal[60] qualitatively assessed the drape characteristics of a cloth. For woven fabrics, stiffness was affected by many factors such as the yarn count and yarn characteristics such as the twist and the fibres used as well as, cloth set, cloth thickness, and the warp tension during weaving.

In another study made by Taylor[47], she cited many examples of different fabrics that may drape limply like some jersey fabrics, stiffly like taffeta, organza and canvas, in soft graceful folds such as chiffon, or with a richer effect like brocade. It may be stated that two factors, stiffness and weight, are of primary importance. In a comparison between fabrics, Taylor[47] also stated that fabrics differ considerably in their recovery from bending depending on fibre composition, silk being obviously more elastic than cotton. In general, it may be said that the more elastic fabrics tend to drape more elegantly than less elastic fabrics.

Stevenson[29] has stated that nonwoven fabrics made by the application of an adhesive binder to a fibrous web tend to be stiff and lacking in qualities of softness, drape and handle. Thus, if sufficient binder is incorporated to bring the strength to an acceptable level, the fabric becomes a wholly bonded network with high resistance to any significant deformation such as fabric bending, shearing and extension since the bonded network has no crimp effect or bias effect comparable with that in a woven structure. As a result, any deformation is contradicted directly by the fibres situated in the direction of stress and indirectly by the fibres at an angle to this direction based on the cantilever principle. Although the relation between drape and fabric structure is complex, there should be low resistance to small specific deformations to achieve an acceptable amount of drapeability. To improve the freedom of individual fibres in the nonwoven structure, Stevenson[29] carried out a systematic study of the effect of stretching and the accompanied selective bond breakage on the physical properties of commercial nonwoven fabrics.

1.10.5 Thickness and Compression Properties

Taylor[47] explained that the thickness of a woven fabric is dependent on its mass per unit area, the type of yarns used, the weave structure, and the finish. As a result, hard twisted yarns and plain weave give relatively thin cloths, whereas soft twisted yarns, bulked yarns and looser weaves give thicker cloths. Taylor[47] stated that the measurement of fabric thickness must be done at known pressures if it is to have any significance, since most textiles are readily compressible. He also stated that finishing treatments that apply pressure to the cloth, such as calendering, decrease fabric thickness. On the other hand, raising and bulking will increase the thickness. For nonwoven fabrics[61], thickness is measured as the distance between the face and backsides of the cloth or felt. In other words, two parallel smooth measuring surfaces of a certain size are used, between which the tested sample is clamped under constant pressure[61].

Apart from its relation to cloth handle, thickness is a factor of prime importance with regard to the protection a fabric will afford against cold conditions; that is, its 'warmth'[47]. Fourt et al.[62] defined the significance of thickness as a prime factor in determining the level of effectiveness for such comfort factors as insulation, water vapor transmission, and water holding capacity. This is true also in examining these properties as a function of clothing pressure and multiple layers.

The compressibility of a fabric is related to the subjective feeling of smoothness and fullness. A heavyweight thick fabric is able to tolerate greater variation in surface thickness, with no detectable change in handle or appearance. On the other hand, in lightweight, thin fabrics, it is easier to feel or observe any variation in surface thickness[33].

Cusick et al.[30] has examined some commercial nonwoven fabrics. The densities for these fabrics ranged between 0.05 and 0.2 g/cm^3. The higher end of the range, which was used for interlinings, was about half the density of the woven fabrics. The coefficients of variation of thickness (CV%), which are considered to be a measure of fabric uniformity, ranged between 1% and 18%.

1.10.6 Tensile Properties

The resistance of a material to stretching in one direction is measured during the tensile test[1]. A review made by Taylor[47], explains how the tensile strength of a woven fabric strip is mainly determined by the strength of the individual threads and the number of threads/cm. Other effects also are important, such as the support of weak places in yarns by the neighboring threads. As a result, fabrics made from spun yarns are stronger than might be expected from a consideration of the individual yarn strength. The tensile strength of a fabric is affected in some degree by almost every feature of construction and finish[47]. In general, the strength of a woven fabric is also higher than any nonwoven fabric except that of a parallel-laid nonwoven fabric[30].

Backer and Petterson[28] and Stevenson[29], compared the mechanism of woven fabric deformation with that of nonwoven fabrics. In a woven structure under the action of uniaxial tension at a slight angle to warp or filling, crimp interchange, thread shear, yarn flattening and compaction, and fibre rotation and extension accompany extension of the fabric. All of these mechanisms mentioned except the last, require little strain energy, therefore the structure offers a low order of resistance initially, to stretching. As a result, the forces necessary to bend a woven fabric are low. On the other hand, in the case of a nonwoven fabric, it has been found that fibre rotation and straightening, bond rotation and extension, and fibre extension are the main factors that affect the fabric deformation with the absence of almost all of the low energy mechanisms mentioned for the woven fabrics. As a result, a high resistance is offered to dimensional changes[28]. Backer and Petterson[28] suggest that there may be an improvement in the properties of nonwoven fabrics if the fibres were to be arranged in bunches in their structure in a way that simulates the yarn components of a woven fabric[28,29]

1.10.6.1 Reaction of Woven and Nonwoven Fabrics to Stress Concentration

According to Backer and Petterson[28], the reaction of a woven fabric to stress concentration along a single yarn involves:

1. extension of the longitudinal yarn in contact with the outside stress;
2. local displacement and rotation of adjacent cross yarns;
3. stress transfer from rotated cross yarns to adjacent longitudinal yarns.

However, the reaction of a woven fabric to the same stress but across a single yarn involves:

1. bending and extension of the side yarn in contact with the exterior stress;
2. slippage of the side yarn and jamming against other side yarns;
3. transfer of stress to other longitudinal yarns at the points of jamming.

Alternatively, the reaction of a nonwoven fabric to stress concentration such as in a puncture or pull involves:

1. rotating, bending and extension of the contact fibre;
2. collection of other fibres in the path of movement of the stress point[28].

As noticed, the major difference between woven and nonwoven fabrics is that in woven fabrics the initial stress application to the structural unit, which is the yarn, is followed by a high degree of slippage and dislocation. Whereas, in nonwoven fabrics where the structural unit is the fibre, the collective involvement of neighboring fibres depends completely on the extensibility of fibre and the bond structure and therefore it is limited[28].

Backer and Petterson also[28] discussed nonwoven properties as a function of fibre orientation. They proposed that a web may be considered to comprise of two perpendicular sets of fibres, each of which has essentially a parallel orientation in itself, and the bundles of fibres to comprise of *C* and *D* fibres (which are intimately mixed with each other). As a result of comparing various *C D* ratios, one can observe different directional moduli among postulated behaviour. The properties calculated for $C.D = 1$ come closest to matching the behaviour of a woven fabric[28].

Hearle et al.[63] studied the anisotropy of different types of nonwoven fabrics in terms of modulus, strength, breaking extension and fibre orientation. An additional important factor is the degree of fibre curl, and the results are compared for different types of fabrics in different directions. The fabrics studied fell into four groups: parallel-laid, cross-laid, random-laid and composite. From the results of testing, it was apparent that there was no single pattern of anisotropy in any fabric. It is evident that these patterns can be explained by the orientation of the fibres in the web and by the extent to which they follow a curved path. Different properties vary with direction in different ways. For example, in random laid fabrics, there is a general tendency for modulus and strength to decrease from the machine (MD) to the cross direction (CD). The breaking extension shows an opposite trend, with its reciprocal following the same trend as observed in the modulus and strength values.

In cross-laid fabrics, the modulus and the breaking extension show similar trends, as their values are lower in the machine direction as compared with that in the cross direction. Parallel-laid fabrics, show a high modulus and a high strength in the machine direction compared with the cross direction. Finally, composite fabrics (made up of parallel-laid and cross-laid webs) show trends that are similar to that of parallel-laid fabrics but not as anisotropic exactly as great in range as the parallel-laid fabrics[63].

Hearle et al.[64] also discussed the fibre curl distribution as an important factor in determining nonwoven fabric stress-strain properties and other fabric properties especially if the fabric is not highly orientated. They also discussed how the curl distribution can determine the number of fibres and bonded points bearing stress at any specific point on the stress-strain curve. As a result, the initial modulus depends mainly on the relative number of straight fibres lying in the direction of the applied stress. On the other hand, the maximum stress includes a combination of fibres at various angles. The number of these fibres can be determined by the curl distribution[64].

For nonwoven fabrics, determination of tensile strength and extension could be done using the same testing methods as used for woven fabrics[61].

1.10.6.2 Stress- Strain Curves

Grosberg et al.[65] stated that a consideration of the tensile properties of woven fabrics involves a fair number of different facets, basically because the cloth is both anisotropic and has a modulus, which varies considerably with strain (figure 1.2). For example, the variation of the initial moduli with direction in the cloth is very large; thus the modulus in the warp and weft directions differs because the cloth is not symmetrical as a rule.

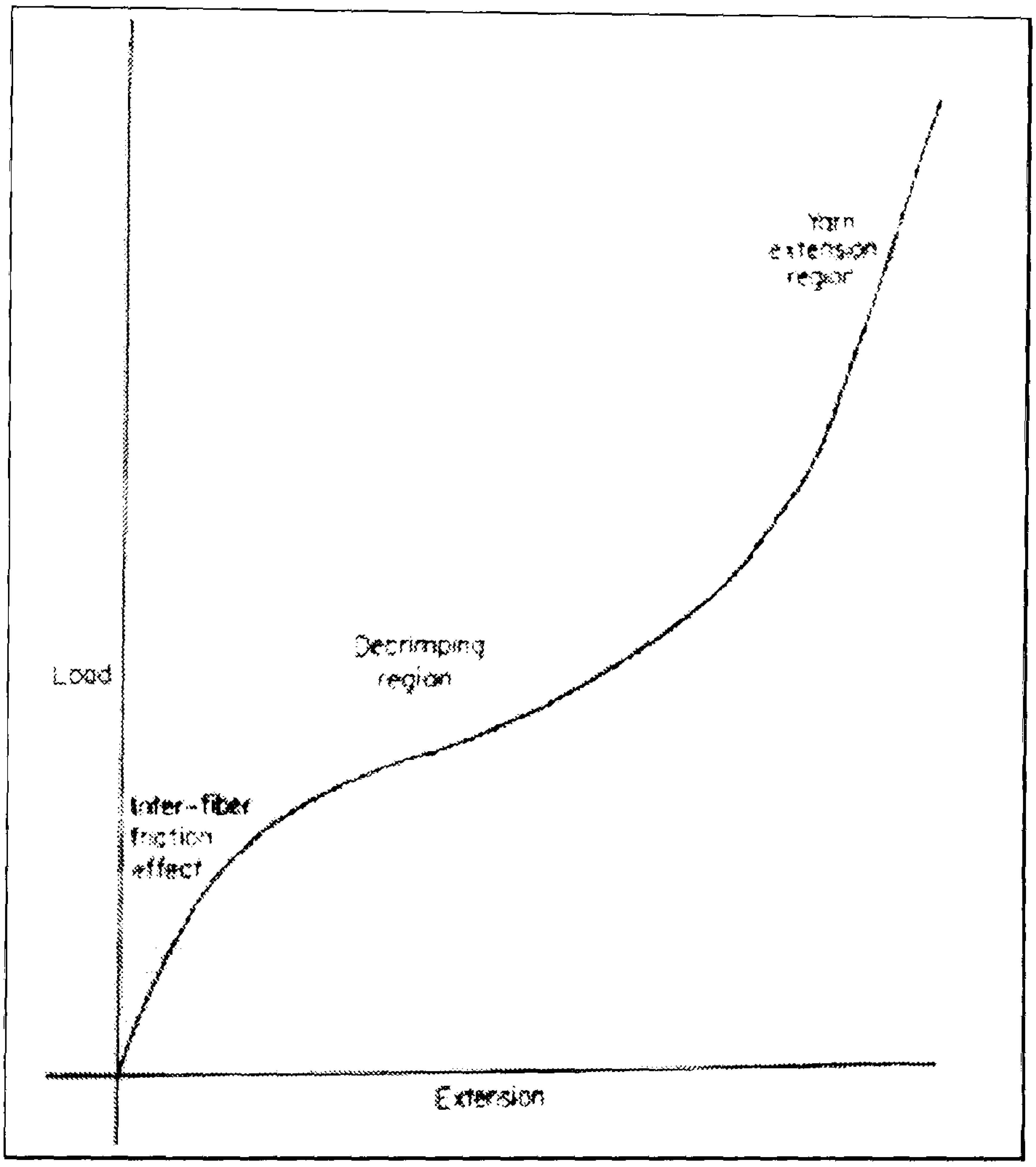


Figure 1.2 Generalized Load-Extension Curve[65]

Grosberg et al.[65] also demonstrates that the actual load-extension curve universally shows three sections as shown in figure 1.2. In general, the warp and weft extension behaviour dictates the first part of the curve (figure 1.2), further extension is due mainly to crimp redistribution while the latter part of the extension is due to fibre extension and, to a certain extent, to thread compression[65]. But, additionally, any extension, which takes place at an angle to the warp or weft direction, is very important, and involves a different mechanism of deformation.

Hearle and his co-workers[65] produced load-extension curves on an Instron testing machine, using specimens of both woven and nonwoven fabrics. Quantities such as the initial modulus, yield stress and extension, and rupture stress and extension, were calculated from the curves produced. The load-extension behaviour of nonwoven fabrics was found to be markedly different from that of woven fabrics. The latter showed an initial region in which extension was very easy as yarn crimp was interchanged between weft and warp; this was followed by a region in which it was much more difficult to extend the woven fabric than to extend most nonwoven fabrics. The strength of the woven fabrics was also higher than any of the parallel laid nonwoven fabrics studied. The ratio of rupture strength to initial modulus was much higher for woven fabrics than for nonwoven fabrics. The author suggested that this was likely to be a significant distinction between the two types of fabrics[65].

Cusick et al.[30] carried out experiments on some samples of non-woven fabrics, he produced some stress-strain curves for the fabrics. In the broadest terms, the mechanical behaviour of a nonwoven fabric must be determined by the fibre properties, the binder properties (if present), the web structure and the nature of the association between the fibre and binder. Cusick[30] also confirmed what Hearle et al.[65] suggested earlier that the behaviour of nonwoven fabrics is obviously different from that of woven fabrics. Woven fabrics have an initial region where extension is very easy because yarn crimp is interchanged between weft and warp. Subsequently, there will be a region where it is much more difficult to extend woven fabrics as compared to most nonwoven fabrics.

Hearle et al.[65] discussed the difficulties with nonwoven fabrics, which centre on the problem of securing a combination of strength with flexibility. In a woven fabric the flexibility at small strain is achieved by yarn crimp and by the freedom of lattice movements: at high strains, the threads tighten and take the load together, giving high strength. In contrast, a simple bonded fibre web loses these advantages where the cross-members stiffen the structure and the individual elements share the load unevenly to break easily. However, if the bonding is reduced, then fibre slippage becomes very easy, and strength decreases more. Nevertheless, there are now indications of ways in which these difficulties can be overcome[65].

Cusick et al.[30] indicated that comparing the initial modulus of nonwoven fabrics with different constructions is very difficult because these fabrics vary considerably in anisotropy. For instance, the longitudinal modulus of a random fabric cannot be compared with the longitudinal modulus of a cross-laid fabric. To minimize this difficulty, the mean value of the modulus in the long, cross and bias directions was calculated and represented as the mean initial modulus. They plotted the mean initial modulus against the percentage fibre content. This plot proposed a dependence of fabric modulus on the nature of the fibre. Cusick[30] also plotted the bending modulus against initial modulus on a log-log basis for both woven and nonwoven fabrics. All the points were reasonably represented by a single line drawn through them. But the correlation for a certain fabric construction is better than the general correlation. These results were anticipated since the process of bending causes similar structural changes to those involved in extension[30].

Cusick also found that the modulus of anisotropy is a more sensitive measure of orientation in the web than the strength anisotropy. This may be due to the fact that the fabric has undergone a substantial amount of deformation at the rupture point, which will mask to some extent, the influence of the fabric structure[30].

1.10.7 Shearing

Hearle et al.[65,66], defined the pure shear strain as the deformation of a body by uniform extension in one direction and contraction in a perpendicular direction, so that its area remains constant and the shear modulus is defined as the ratio of shear stress to shear strain. Cusick et al.[30] found that the shear moduli are generally higher for nonwoven fabrics than woven fabrics, although one sample, a fabric composed of acetate approached the value obtained for the woven cotton fabric. Cusick's results for the shear modulus of the nonwoven samples he tested ranged from 3.8 to 21.8 whereas they ranged from 0.06 to 4.0 for the woven samples.

1.10.8 Elastic Recovery and Creasing

Elastic recovery concerns the recovery from extension. Figure 1.3 shows a typical stress strain curve extensibility hysteresis where the elastic recovery deformation is non-linear[66].

Cusick et al.[30] investigated the elastic recovery of nylon, viscose, acetate fibres and nonwoven fabrics. He found that the elastic recovery of a nonwoven fabric is partially dependent on the recovery of the constituent fibres.

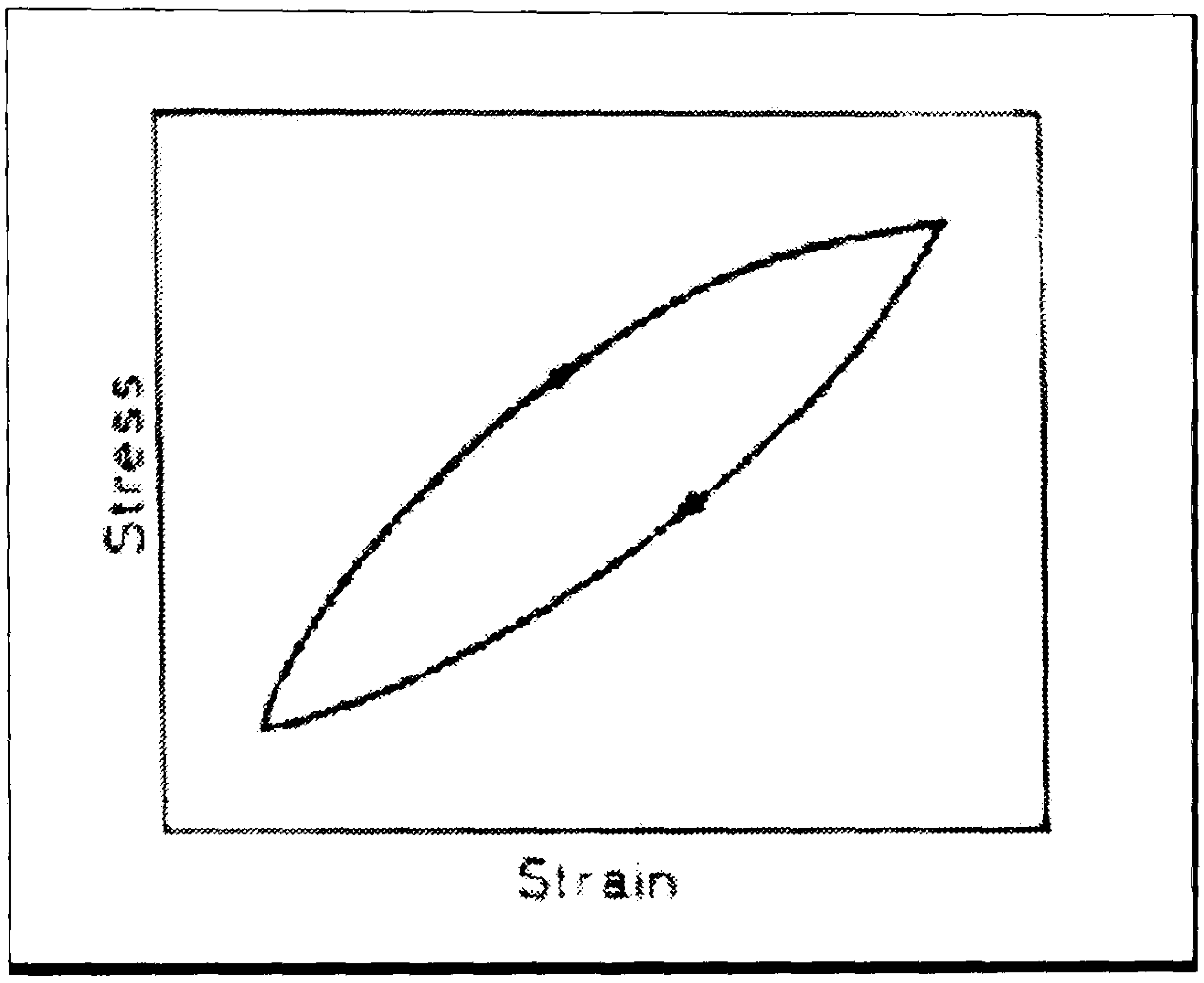


Figure 1.3 Hysteresis Loop[66]

The hysteresis losses are due to interfibre friction and the viscoelastic behaviour of the fibres.

1.10.9 Buckling Properties

Grosberg et al.[65] stated that buckling is a very common phenomenon during the use of fabrics in garments. For instance, the bending of a sleeve, the bending of a trouser leg and even the natural folding of a garment, often involves buckling.

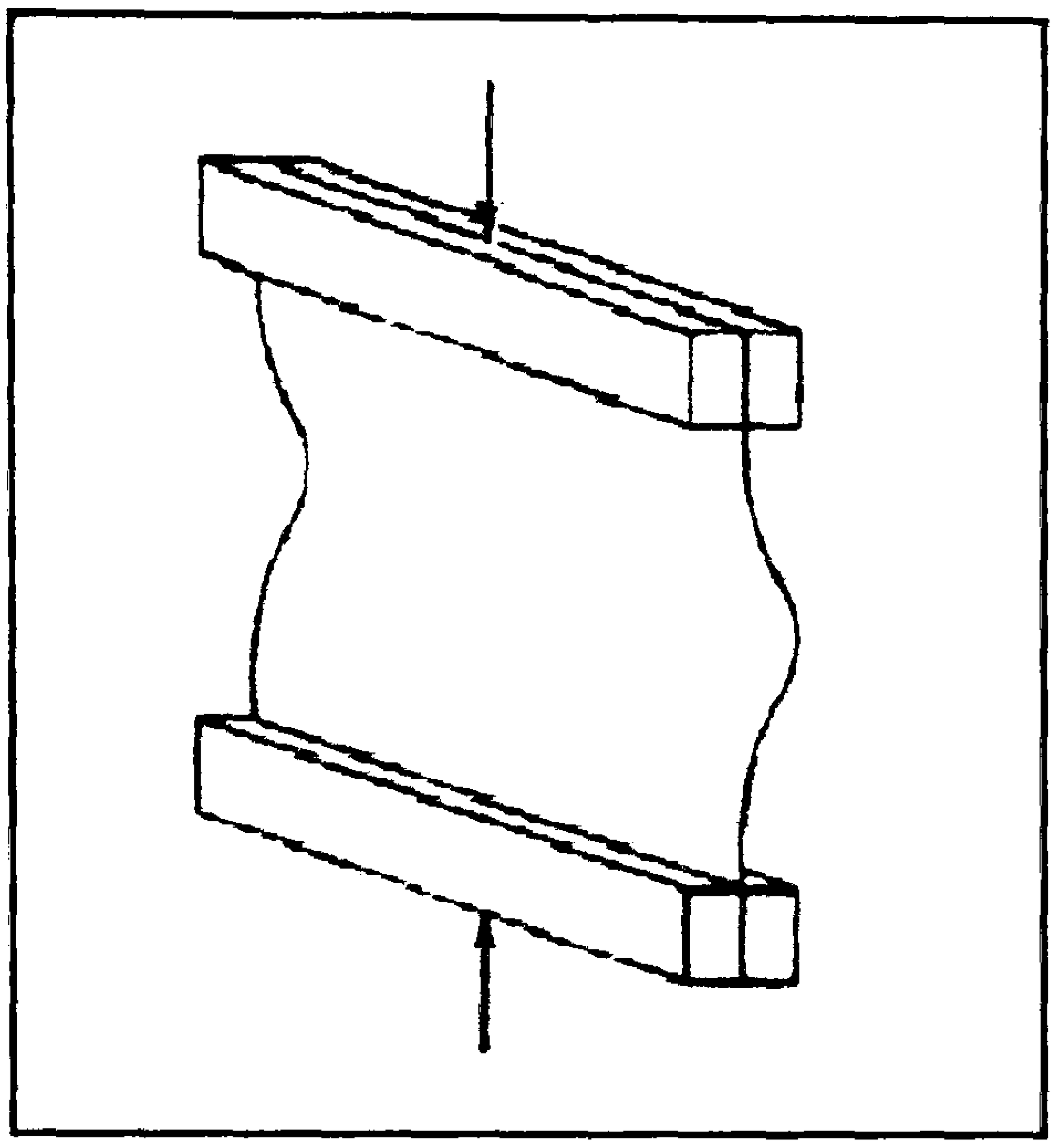


Figure 1.4 Diagrammatic Representation of Plate Buckling[67]

According to Dahlberg[67], the fabric may be regarded as a thin plate and such a plate could be deformed only in four main ways: compression, bending, longitudinal extension-compression and shearing. In the case where the longitudinal compression load exceeds a certain value, the plate will buckle and the load at which this happens is called the buckling load – see figure 1.4. However, before buckling occurs, the plate or the fabric is compressed a certain distance. Therefore, the total compression at the buckling load is called buckling compression and is shown to be of special importance in determining the formability of a fabric. Grosberg[65] claimed that the buckling of fabrics when used in garments is often of a more complex nature. For example, the bending of a sleeve involves buckling not only along the length of the sleeve but also produces a form of wave at right angles to the direction of bend.

In the early 1960s, Lindberg and his co-workers[45] showed that the tailoring performance of men's suiting materials depends on a function termed "formability" which was derived as the product of the fabric bending rigidity and the longitudinal compressibility of the fabric in its own plane prior to buckling. During tailoring, fabrics are overfed during the sewing operations in such a way that compression is allowed in the fabric plane to produce the three-dimensional shape of the garment, but fabric buckling or puckering should not occur. If it does, it should be removed during subsequent pressing operations. Thus, the limit of the fabric compressibility in its own plane (before the onset of buckling) is an important consideration from the viewpoint of fabric tailorability[45].

1.11 Lightweight Flexible Nonwoven Fabrics

It has been found from previous research that has been conducted by different workers that, some significant advances have been made to improve the properties of nonwoven fabrics. The most significant advances have been in discontinuing bonding, aperturing, and fibre entanglement. In recent years, hydroentanglement has become an important technology, which is known to provide fabrics with textile-like properties[68,89]. Purdy[68] stated that one of the primary goals of the nonwoven industry has been to achieve greater drape, softness, bulk, and visual complexity combined with strength and durability without manipulating yarns into fabrics.

1.11.1 Hydroentangled Fabrics

1.11.1.1 Definition and Background

Hydroentangled, spunlaced fabrics or hydraulically needled fabrics, are fabrics that made from webs in which fibre bundles are entangled using high-pressure water jets in a predetermined repeating pattern to form a strong structure in which the fibres or the fibre bundles are free to move relative to each other[70,71]. The entanglement, or mechanical interlocking of the fibres, is a result of the hydraulic drag force created by columnated water jets, causing the fibres or the fibre bundles to bend, twist, and rotate in the web structure to form loops around themselves or other fibres[70,72]. The fabric strength is therefore derived from inter-fibre friction and is a function of fibre entanglement[68,69,73]. As a result, some desirable properties are produced such as a soft handle and improved drape as compared with fabrics produced from fully bonded nonwoven fabrics such as chemical or thermal bonded fabrics. On the other hand, a major disadvantage of these fabrics is the poor recovery from deformation. There is also a difference in the physical properties of such fabrics in the machine and cross-directions[68,69,70].

The main end-uses for apertured hydroentangled polyester fabrics include home furnishings, bedding, industrial fabrics, and garments and depend on whether the structure is designated diagonal- or square-aperture, non-aperture, or lace[68,69].

In terms of shear modulus, hydroentangled fabrics appear to be more related to conventional woven and knitted textiles than other nonwoven structures[68,69,70].
Also, spunlaced fabrics have a 3-dimensional structure because the fibres are pushed from the surface down in to the interior of the fabric and are entangled or locked into position[70].

To enhance the desirable properties of spunlaced structures, finishing treatments have been developed, such as heat setting, which has been found to increase the breaking strength and reduces elongation, thus improving dimensional stability. Resin treatment also improves pilling-resistance, dimensional stability, and durability to washing. Such improvements are gained at the expense of fabric softness[68].

1.11.1.2 The Hydroentanglement Process

As well as imparting strength to fibres in a loose web structure, hydroentanglement can also be used to combine webs with substrates to create composite structures. By carefully selecting the fibres, the energy treatment level and the supporting member, it is possible to produce a large variety of fabrics that have a textile-like hand and feel[71,73].

It was suggested by Bertram[74] that the interaction between two different mechanisms can gives rise to the hydroentangled fabric structure as follows:

1. water jet / fibre interaction and;
2. water jet / belt interaction.

The first mechanism (water jet/fibre interaction) occurs as the water jet passes through the web; fibres will be encountered and will be forced out of the way. As the jets penetrate deeper, turbulent effects increase, and fibre entanglement is created. Fig.1.5 illustrates this concept.

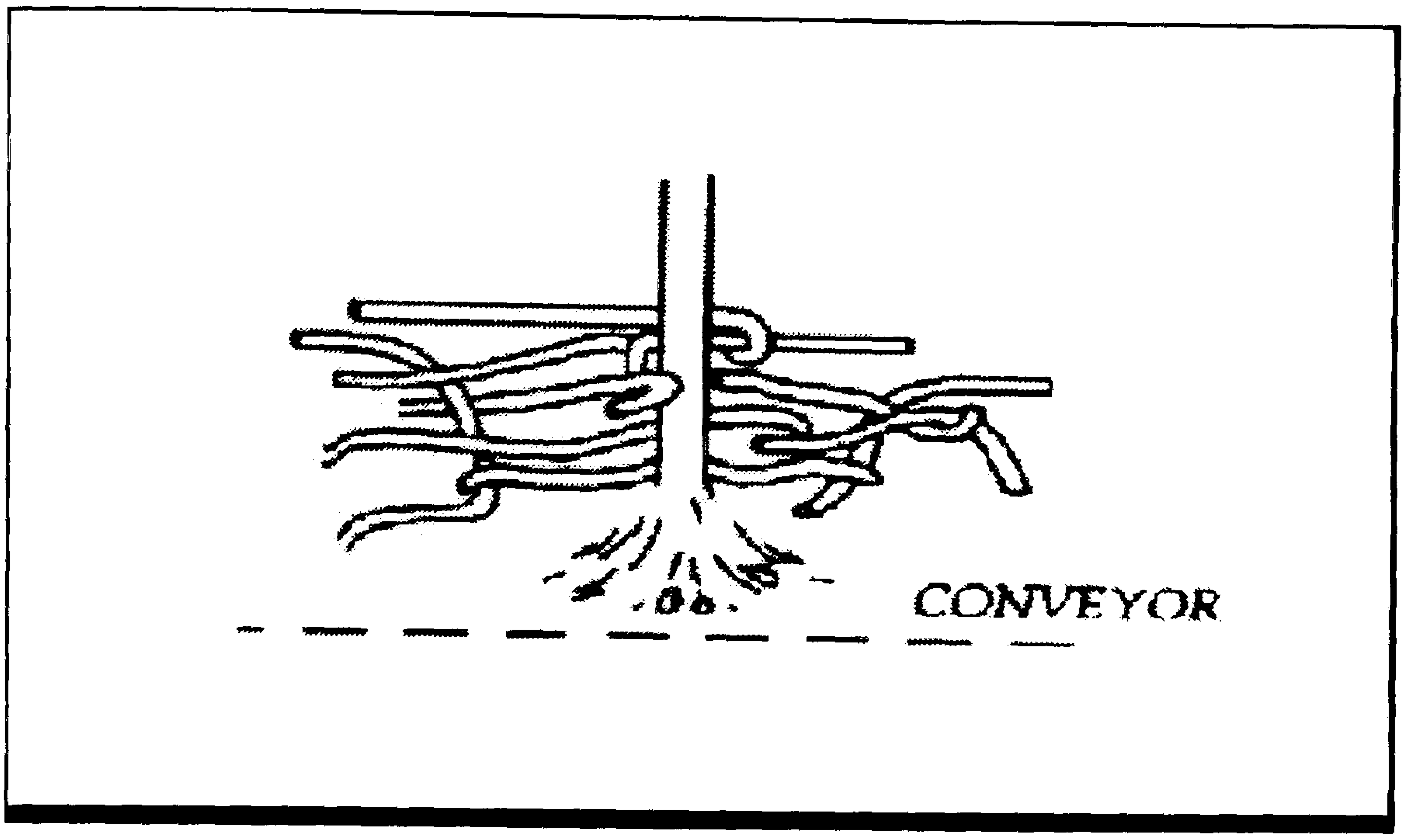


Figure 1.5 Internal Water Jet Turbulence[74]

The second suggested mechanism (water jet/conveyor belt interaction) involves jet rebound. As the water jet reaches the conveyor belt without being dispersed on its passage through the web, it is then deflected by the rigid wires of the belt and is reflected on to the reverse side of the web. The flow patterns created from the conveyor belt will be different from that of the incident jets. Fig.1.6 shows a simplified model of the second mechanism[74].

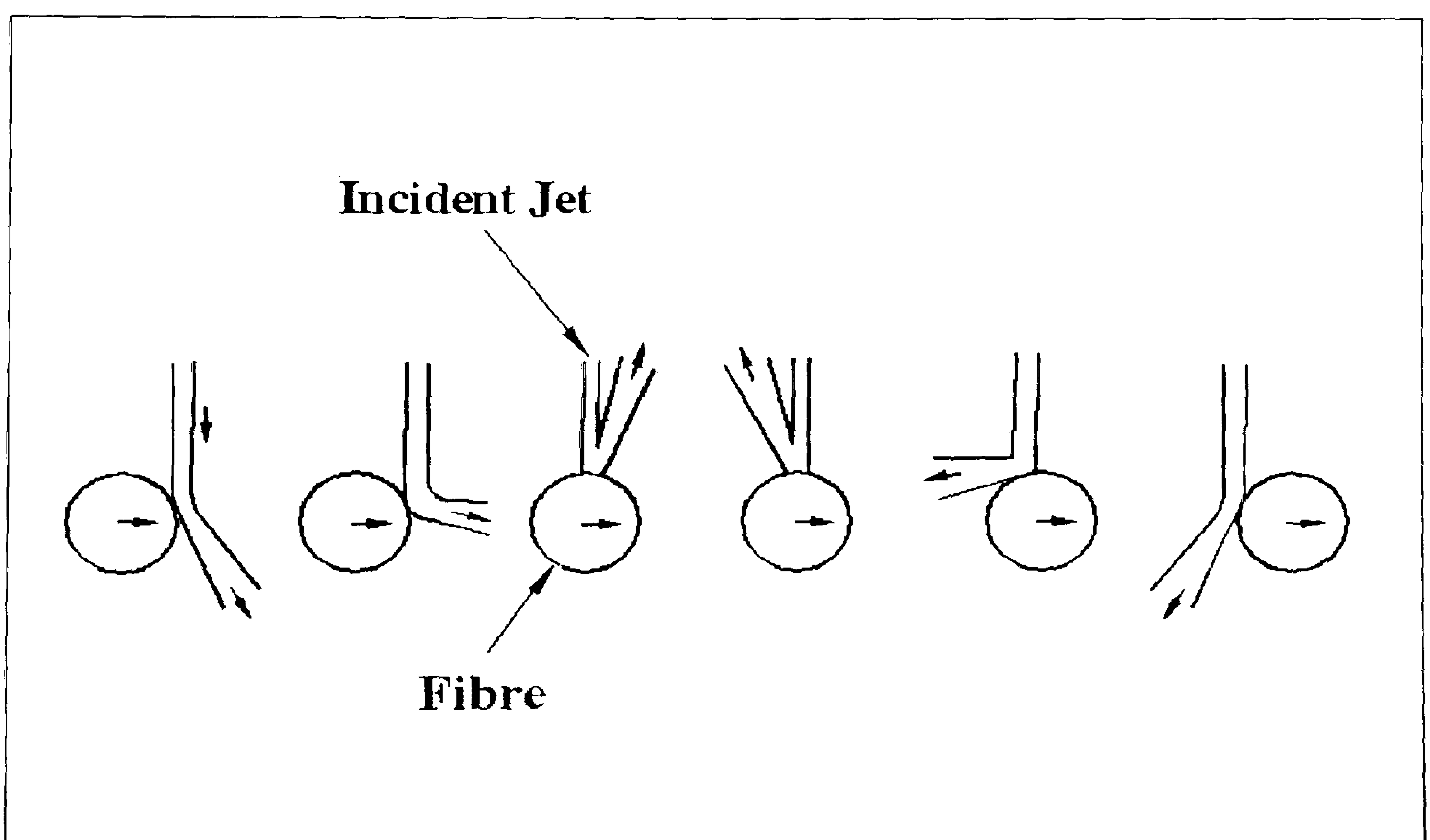


Figure 1.6 Deflection of Water Jet by Conveyor Belt[74]

1.11.1.3 Influence of Fibre Properties

The key elements in the design and production of hydroentangled fabrics are:

1. The fibre properties and the design of the web formation system.
2. The energy imparted to the fibres and the system used to impart it.
3. The nature and the design of the fibre support member[71,75].

The majority of fibre types that can be made into a web can also be hydroentangled. Bartholomew et al.[75] has highlighted the importance of fibre tenacity/extensibility/rigidity and that they are closely linked in the manufacturing process. He established that using low pressure, increased fibre flexibility results in a more efficient entanglement and thus increased fabric tensile strength. Bartholomew et al.[75] also studied the relationship between the frictional properties and cross-sectional shape of fibres and the effect on the hydroentanglement process. It is known[73,74,76] that the fibre cross-sectional shape is important because it affects the fibre rigidity, which in turn affects the ease of hydroentanglement.

Bartholomew et al. also concluded[75] that the ideal fibre to be used in hydroentanglement must possess low friction for easy carding, low wet friction in hydroentanglement to allow the fibres to knot together, and then high friction in the final fabric to minimize slippage under load in order to completely exploit the fibre tensile strength. Bertram[74] also discussed how fibre properties have a direct effect upon those of the fabric. Generally, stronger fibres give stronger fabrics but this cannot be achieved in the case of a strong, but rigid, fibre because it will not readily entangle.

Bertram[74] pointed out that fibre flexibility is therefore the key factor to forming well-consolidated structures as this allows the fibres to produce entanglements with its neighbours and thus maximizes fabric strength. Fibre flexural rigidity measurements are therefore often quoted as a measure of "hydroentanglement efficiency"[74]. This is in agreement with other researchers[75,77].

The wet mobility of a fibre and its ability to bend around others over short radii, can determine the ease of achieving a well-entangled fabric. The factors, which influence the fibre bending, are the wet modulus of the fibre and its moment of inertia. The ability of the fibre to bend and form knots also depends on its cross section, wettability, density, linear density and surface friction[71]. On the other hand, hydroentangled fabric properties depend to a large extent on the web geometry which in turn depends on the web forming mechanism[71,76,77].

Dry–laid, wet-laid, polymer-laid or combinations of these methods of web forming systems can be used to produce precursor webs for hydroentanglement. The method chosen will affect the physical properties of the fabric, the production rates and the fabric cost[76]. White et al.[72] claimed that any nonwoven web forming process could be used to produce webs for hydroentanglement; most applications require the final product to have reasonably equivalent properties in both the MD and CD. Isotropic webs can be produced by various air laying systems or by carding and cross laying (under certain circumstances). Melt blown webs, can also be produced with good squareness of the web and wet formed webs, especially those produced on a former, also have good MD/CD characteristics[72]. More recently, commercial processes involving the formation of hydroentangled fabrics suitable for clothing applications from spunlaid webs have been developed by Perfojet and Freudenberg. The latter fabrics are referred to as "EVOLON" fabrics[20], which are spunlaid and then hydroentangled. Other companies such as Polymer Group Incorporated (PGI), has launched APEX[18,19] technology which are fabrics that are hydroentangled and have the superficial appearance of woven and knitted fabrics due to design of the forming surface.

1.11.1.4 The Influence of Specific Energy

As stated by White[72] et al. and others[68,69,74,75,77] hydroentanglement is an energy transfer process and therefore, it provides a system of transferring high energy using columnar water jets to the precursor web. Traditionally, energy levels used in the process are classified into three main groups[72].

	H.P.-hr/lb	Peak Pressure (lb/in^2)
High	1.00	1500-2000
Medium	0.25-0.5	800-1200
Low	0.1-0.15	400-800

Turi[71] demonstrated that the amount of entanglement is proportional to the energy introduced and is reflected in the tensile strength, surface integrity, elongation and initial modulus of the fabric. Most of the tensile strength is believed to be developed early during hydroentanglement while the surface integrity and the initial modulus are mainly influenced by the final hydroentanglement stages. Heavyweight webs can be treated using higher initial energies than lighter webs.

It is mentioned by many authors, for example Turi[71] that the energy intensity can be varied by changing the water pressure, and since the energy intensity is related to pressure ($P^{1.5}$), any change in the pressure will markedly affect the amount of fibre entanglement until the web is completely bonded.

Previous work conducted by Moschler et al.[77] has also revealed that using a number of injectors produces longitudinal forces which play a part in determining the stress-strain profile of the fabric by increasing the fibre orientation in the machine direction. She[77] also asserts that hydroentanglement process parameters have little influence on previously tightly bonded webs, which already have a high fabric tensile strength.

1.11.1.5 Design of the Fibre Support Member

Hydroentangled fabric properties are influenced by the design and pattern of the support member or screen (this is normally a porous drum or conveyor belt). Using high and medium energy systems, the supporting member is usually water permeable and allows the water to be removed from the site of water jet impact. The important factors in the screen design are:

1. the warp and weft diameters;
2. the weave pattern;
3. the composition of the screen material.

These factors determine the pattern of the fabric and also the life cycle of the screen[71]. Medeiros[76] described one spunlace manufacturing system that uses two types of substrate configurations. The first is a traveling conveyor and the second is a rotating drum. Densely spaced, loosely entangled areas in hydroentangled fabrics that are arranged in straight-line patterns are the result of a combination of such screen patterns and the choice of jet orifice size. In the fabric, these areas will be joined by unentangled bundles of fibres as shown in figure1.7.

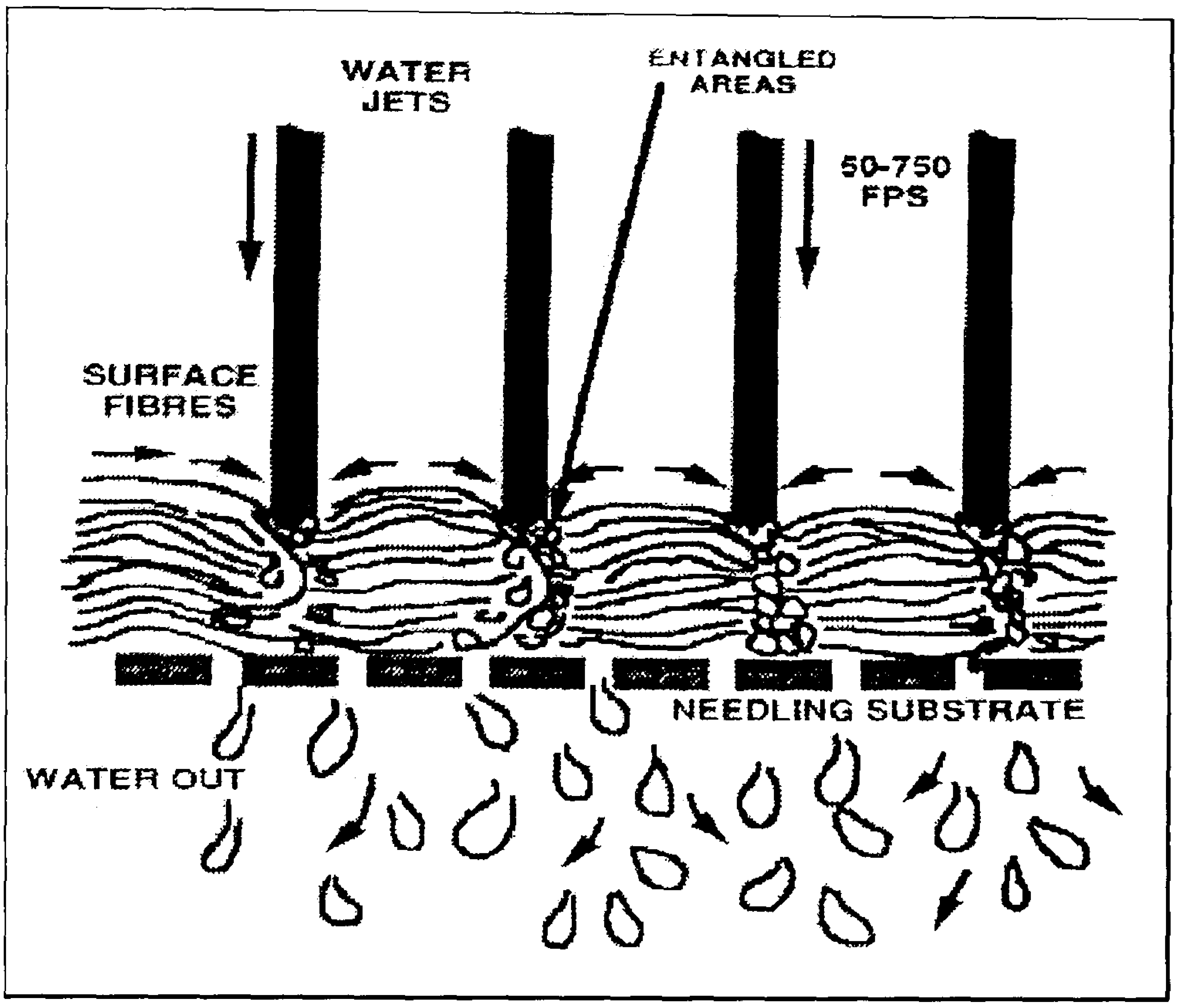


Figure 1.7 Hydroentanglement Process[76]

As a result, this structure has low out-of-plane bending rigidity along any axis and low in-plane shear, tensile and compressive moduli. This results in fabrics with desirable characteristics such as, softness, a flexible hand, drape, limp handle, conformable and moldable, stretchable, high bulk, high strength and good resistance to delamination[76].

1.11.1.6 Mechanical Properties of Hydroentangled Fabrics

Spunlaced fabrics[76] are unique among nonwoven fabrics because of the balance between strength and the shear modulus as shown in figure 1.8. Microscopic examinations of these fabrics have revealed that the points of entanglement are numerous but the fibres are not tightly entangled. During hydroentanglement, fibres from the web surface are driven into the web resulting in high Z-directional strength[76]. Also, microscopic examination[78] of fabric cross sections has provided evidence of twist and migration of fibres within the structure. This has demonstrated that the entanglement can be developed while sustaining a good degree of fibre freedom, which leads to an improved textile feel or hand compared to other nonwoven fabrics.

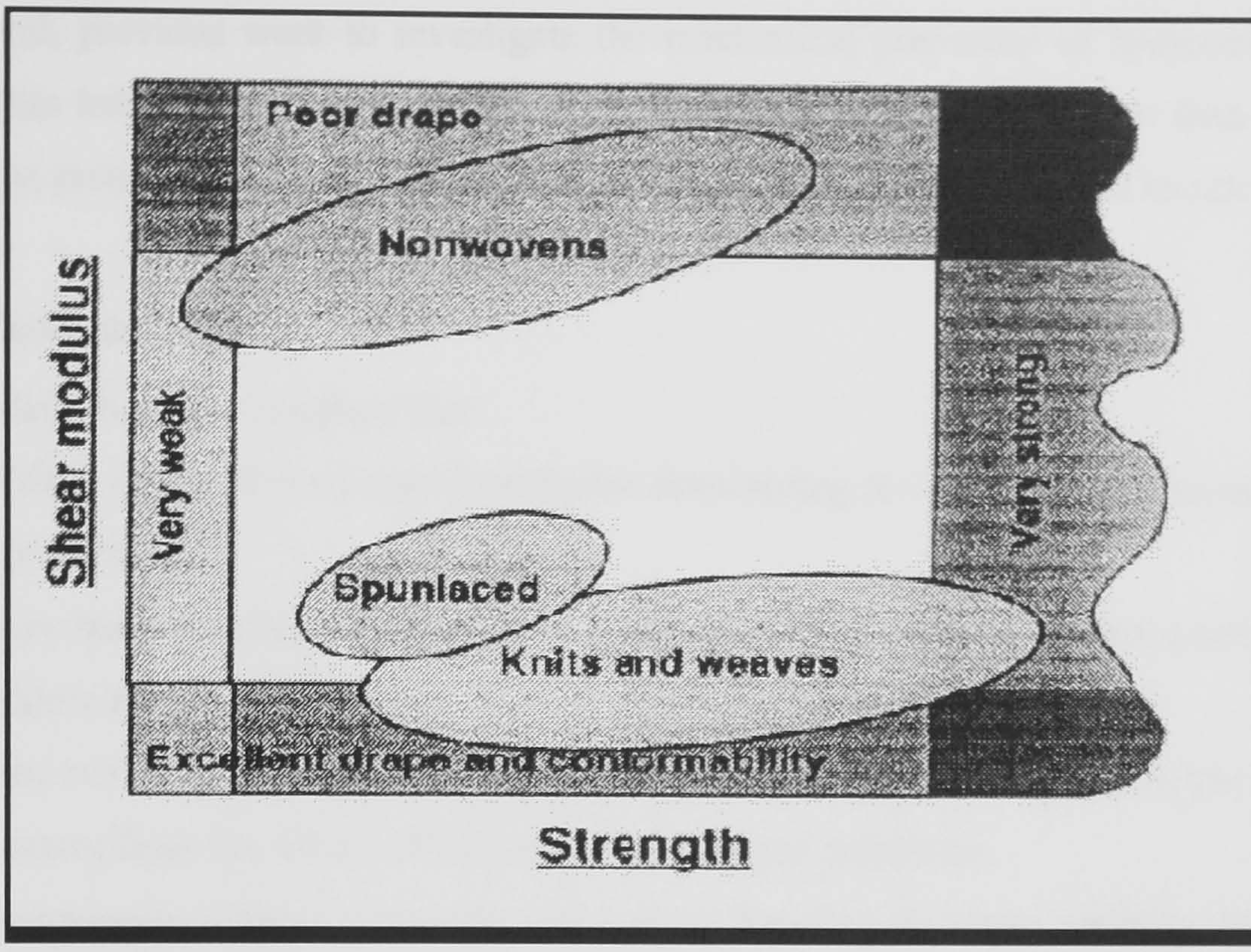


Figure 1.8 Qualitative Map of Shear Modulus and Strength[70,76,79]

Previously attempts have been made to investigate the stiffness of hydroentangled fabrics. Mohammed and Herring[78] reported one comprehensive study, where differently bonded nonwoven fabrics were evaluated including spunlaced fabrics. Their results showed that spunlaced fabrics had the best strength/stiffness ratio for textile purposes. Gilmore et al.[80] studied the effect of specific energy on hydroentangled fabrics composed of unbleached cotton and, he found that increasing the total specific energy resulted in increasing peak tensile load and elongation in the MD. Similarly, the flexural rigidity also increased with an increase in the total specific energy used to make the fabric. The author explained an increase in the bending rigidity as a result of increasing the TSE (total specific energy) and the removal of waxes and oil from the fibre. These results were in agreement with those of Timble et al.[81] although the latter studied polyester/cotton hydroentangled fabrics rather than 100% cotton fabrics.

Qiao[82] obtained results by testing hydroentangled fabrics produced using several energy levels. She concluded that increasing the number of passes would generally result in increased fabric strength until a limiting value. She also concluded that increasing the level of energy obtained by using multiple passes would result in a more uniform fabric appearance.

In general, previous work to investigate the mechanical properties of hydroentangled fabrics has been focused on the properties up to the breaking point rather than on the low stress properties, which are important with respect to fabric drape and handle.

1.12 Conclusions

It is evident from the literature that:

1. fabric structure is an important factor determining the low stress mechanical properties;
2. low stress mechanical properties of fabrics are the main factors that determine fabric handle;
3. the behaviour of fabrics during manufacture and wear can be predicted to some extent from the values of low stress mechanical properties;
4. nonwoven fabrics generally have high bending & shear rigidity and low extensibility and as a result, these fabrics are less suited for apparel applications;
5. the challenge is to engineer nonwoven fabrics, which have high extensibility and low bending & shear rigidity to enable them to be more suited for apparel applications;
6. there is a need to systematically study the effects of process parameters on the low stress mechanical properties of hydroentangled fabrics, as this directly influences fabric structure;
7. investigation of the low stress mechanical properties of nonwoven fabrics is required to enable a further comparison of woven or knitted fabrics;
8. few systematic studies have been conducted into the low stress mechanical properties of nonwoven fabrics.

It is obvious that some researchers have carried out work to investigate the appropriateness of using nonwoven fabrics in clothing. It is evident that hydroentangled fabrics have the closest values of low stress mechanical properties to that of woven and knitted fabrics. To evaluate this further, in this work, the decision was made initially to focus on the low stress mechanical properties of different groups of nonwoven fabrics including hydroentangled fabrics.

1.13 Aims and Objectives

1. To verify the low stress mechanical and dimensional properties of different generic types of nonwoven fabrics;
2. To verify that the hydroentangled fabrics have the greatest potential for use in apparel applications;
3. To quantify the differences in the low stress mechanical and dimensional properties of hydroentangled fabrics resulting from changes in structure and process conditions;
4. To understand the effect of process parameters on the internal architecture of hydroentangled fabrics.

CHAPTER 2

PRELIMINARY STUDIES: INVISTIGATION OF LOW STRESS MECHANICAL PROPERTIES OF COMMERCIAL NONWOVEN FABRICS USING THE FAST INSTRUMENTATION SYSTEM

2.1 Introduction

This chapter describes the use of the FAST instruments to measure the low stress mechanical properties of a set of commercially available nonwoven fabrics.

The commercial nonwoven fabrics consisted of groups of fabrics bonded by different methods including mechanical, chemical, thermal or a combination of bonding methods such as mechanical and chemical bonding methods. The purpose of these tests was to compare the low stress properties of hydroentangled nonwoven fabrics with those produced by different bonding methods to determine whether groups of fabrics exhibited characteristic sets of properties according to their bonding method and to verify whether or not hydroentangled fabrics were most suited for apparel applications.

2.2 The FAST System for Fabric Objective Measurement

2.2.1 Overview of Instrumentation System

FAST (Fabric Assurance by Simple Testing) is a set of instruments and test methods developed by CSIRO's the Division of Wool Technology (Australia) for measuring those fabric properties that influence the appearance and the handle of the garment in wear. In other words, the data generated provides a language with which garment makers and fabric producers can communicate about cloth and garment properties and performance.

The system consists of three simple instruments together with a test method and is designed to be used by fabric manufacturers, finishers and garment makers[46].

2.2.2 FAST-1 Compression Meter

FAST-1 consists of a compression meter, which measures fabric thickness at two predetermined loads of 2 and 100 gf/cm^2. The principle of measurement is shown in figure 2.1.

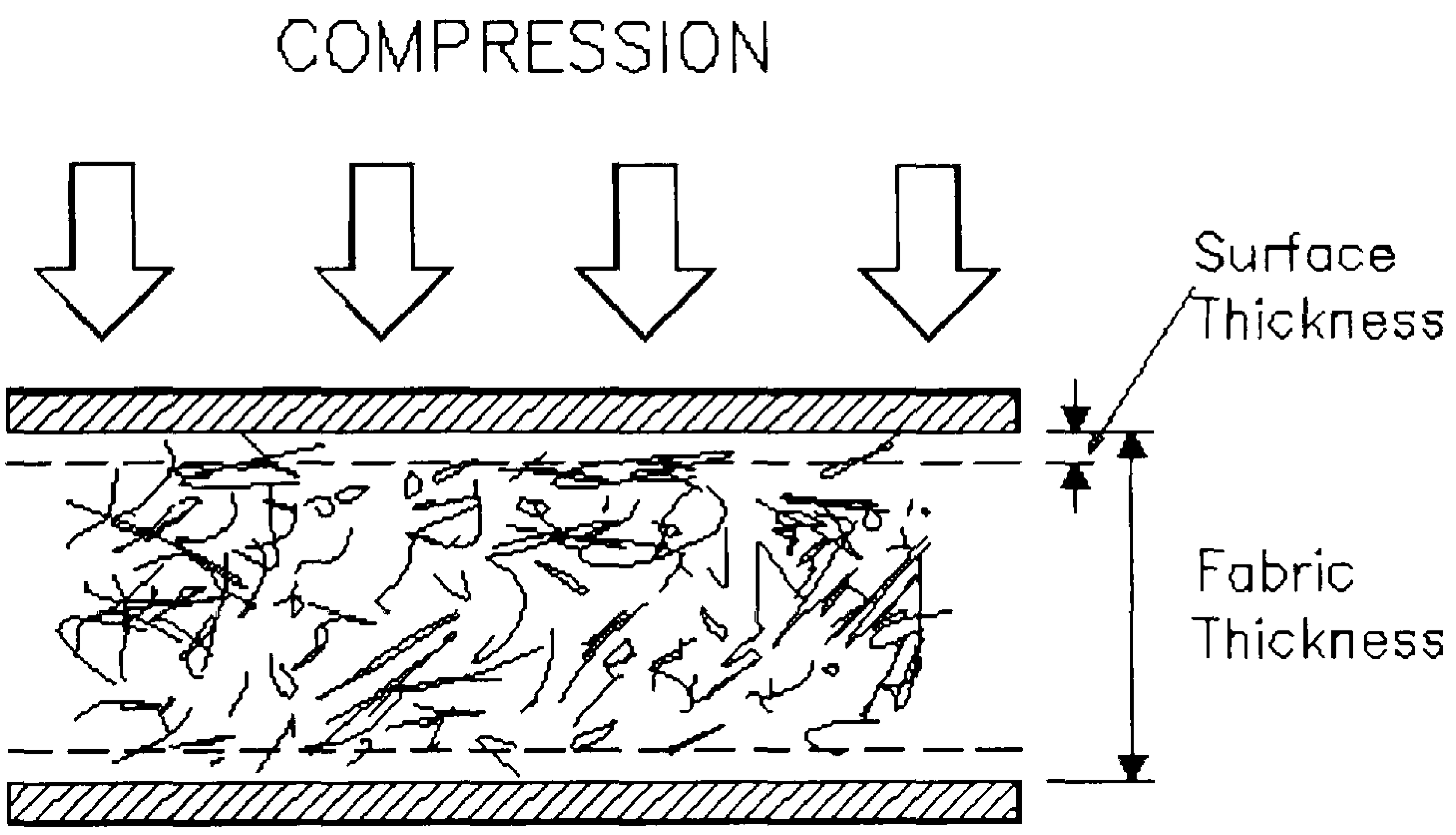


Figure 2.1 Measuring Principle of the FAST-1 Compression Meter[46]

2.2.3 FAST-2 Bending Meter

FAST-2 measures the bending length of the fabric. From this measurement the bending rigidity of the fabric may be calculated. The instrument uses the cantilever bending principle described in British Standard method (BS: 3356 (1961)). However in FAST-2 the tip of the fabric is detected using a photocell, and not by eye, as in some other test instruments that measure bending length to a fixed angle. The photocell determines when the tip of the fabric intersects a 41.5° - bending angle, which makes the instrument simpler to use. The values of the bending length are read directly from a display on the instrument[46]. The principle of measurement is shown in figure 2.2.

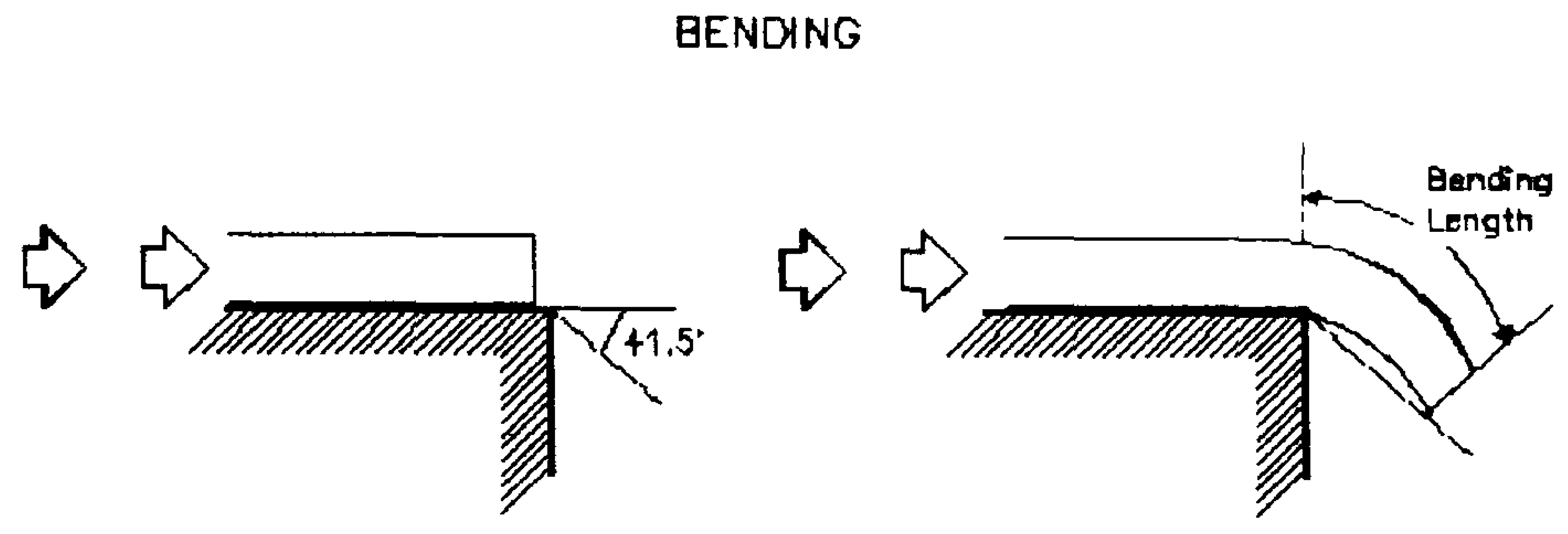


Figure 2.2 Schematic Representation of the Measurement of Bending Length[46]

2.2.4 FAST-3 Extension Meter

FAST-3 is an extension meter, which operates on a simple lever principle. By removing weights from a counterbalancing beam, the extensibility of the fabric can be measured at 3 different loads (5, 20 and 100 gf/cm) (See figure 2.3), thereby simulating the kind of deformation the fabric is likely to undergo during garment manufacture[46]. The extensibility of the fabric can be measured in the warp, weft and bias directions (in the case of woven fabrics), and in the machine direction (MD), cross direction (CD) or bias direction (in the case of nonwoven fabrics).

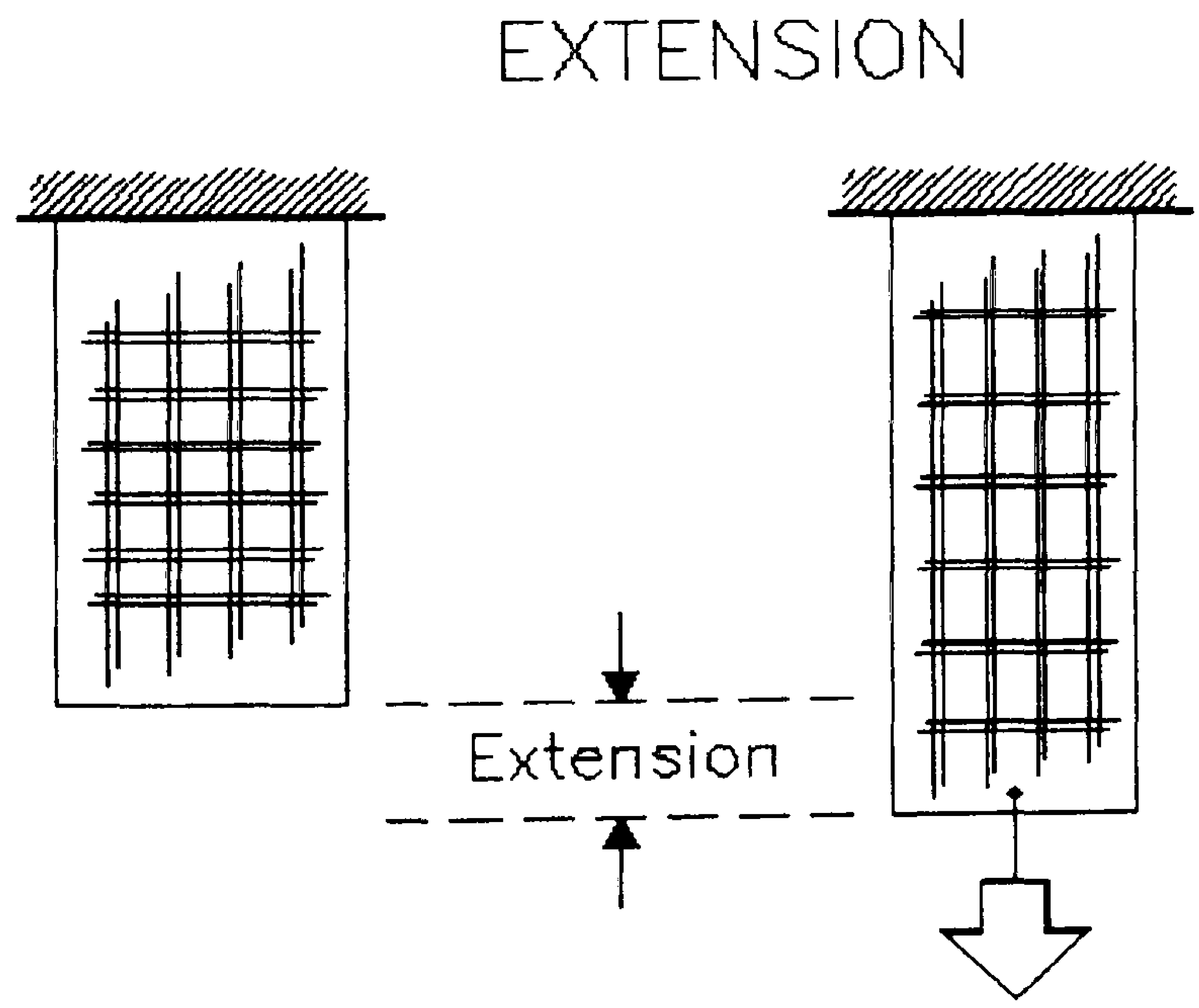


Figure 2.3 Measuring Principle of the FAST-3 Extension Meter[46]

2.2.5 FAST-4 Dimensional Stability Test

The final component of FAST is a test method, which measure the dimensional stability of the fabric. The method involves measurements of the fabric before and after a wet relaxation process. The FAST-4 test can be completed in less than two hours and does not require a conditioned atmosphere.

Since the low stress mechanical properties of the fabrics were of premier interest, only FAST instruments 1 –3 were used.

2.2.6 Preparation Of Test Samples

1. In order to obtain consistent results, fabrics were conditioned overnight in a standard atmosphere (20°C, 65% RH) before cutting;
2. Before cutting out each sample, an arrow was marked on the fabric indicating the machine direction (MD), the cross direction (CD) and the bias direction;
3. Keeping at least 5cm from the selvedges, four squares of 200mm x 200mm were cut (figure 2.4);
4. The first and second squares were used to prepare six bias samples for the FAST-3 Extension Meter (figure 2.4);
5. The third and fourth squares were used to prepare three MD and three CD samples for the FAST-2 Bending Meter and the FAST-3 Extension Meter (figure 2.4);
6. The same samples can be used for the FAST-1 Compression test provided the measurements are performed in the correct order, compression first followed by bending and finally extension.

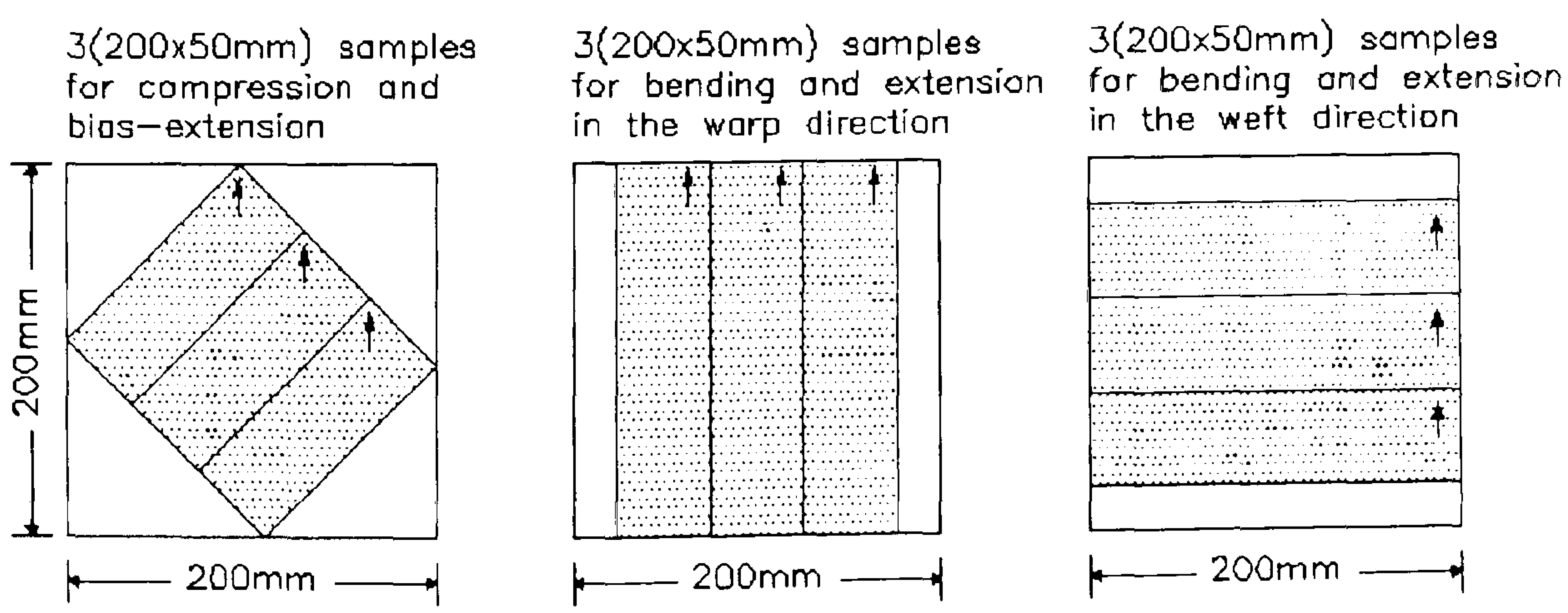


Figure 2.4: Preparation of Test Samples[46]

2.2.7 Definitions of The Properties Measured by The FAST System

The following section defines the fabric properties measured by the FAST system.

a. Thickness/ Surface Thickness (FAST 1)

Using the FAST system, the thickness of the fabric is measured at a compressive load of 2 gf/cm^2 and 100 gf/cm^2. The surface thickness, defined as the difference between the thicknesses at the two loads, is calculated from the measured data

$$ST = T2 - T100$$

Where:

ST = surface thickness

T2 = Fabric thickness at 2 gf/cm^2

T100 = Fabric thickness at 100 gf/cm^2

b. Bending Length, Bending Rigidity and Bending Modulus (FAST 2)

The bending length of the fabric can be measured directly from the bending meter (FAST 2). The bending rigidity of a fabric is defined as the couple required to bend that fabric to unit curvature. The FAST system determines bending rigidity from the cantilever bending length of the fabric, measured using the principal described in BS: 3356(1961), and fabric area density.

$$BR = W \times (BL)^3 \times 9.807 \times 10^{-6}$$

Where: BR = Bending Rigidity in μNm

BL = Bending Length in mm

W = Fabric Area Density in g/m^2

Bending modulus is calculated from bending length, weight and thickness (T100) as follows:

$$BM = \frac{12 \times (BL)^3 \times W \times 10^{-7}}{T100^3}$$

Where:

BL = fabric bending length (mm)

W = Fabric weight per unit area (g/m^2)

T100 = fabric thickness at a load of 100 gf/cm^2 (mm)

c. Extensibility (FAST 3)

The extensibility of a fabric measures the increase in fabric dimensions, which occurs when it is subjected to an applied load. Using the FAST system, extensibility is measured as a percentage increase in length at a sample loading of 5gf/cm (E5%), 20gf/cm (E20%) and 100gf/cm width (98.1 N/m)(E100%). The quoted value for fabric extensibility is that measured at 100gf/cm. The extensibilities in the MD and CD directions measured at 5gf/cm and 20gf/cm are used to calculate fabric formability. Bias extensibility is measured only at 5gf/cm width[46].

d. Shear Rigidity (FAST3)

The shear deformation of a fabric can be described as a trellising motion in which the angle between the MD and CD is changed (from 90 degrees) without imposing an extension on either the MD or CD. The shear rigidity of a fabric is a measure of the force required to deform the fabric in shear. In the FAST system, shear rigidity is calculated from the bias extensibility of the fabric under a load of 5gf/cm as follows:

$$G = 123/EB5$$

Where: G = Shear Rigidity (N/m)

EB5 = Bias Extensibility (%)

f. Formability

The FAST system uses the derived parameter, formability, in the analysis of fabrics. Formability is a measure of the extent to which a fabric can be compressed in its own plane before it will buckle. This parameter is defined as the product of the bending rigidity and the extensibility of the fabric as follows[46]:

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

Where:

F = Formability (mm^{2})

BR = Bending Rigidity (μNm)

(E5, E20) = Extension (%)

g. Fabric Tensile Hysteresis

The method devised to test the fabric elastic recovery (or samples hysteresis) was to plot the resulting extensions for the three loads (E5, E20 and E100) during loading and unloading using the FAST 3 instrument of the sample. Assuming linear connectivity between the points as shown in figure 2.5, the hysteresis was calculated by subtracting the areas under the lines over the range of extension values.

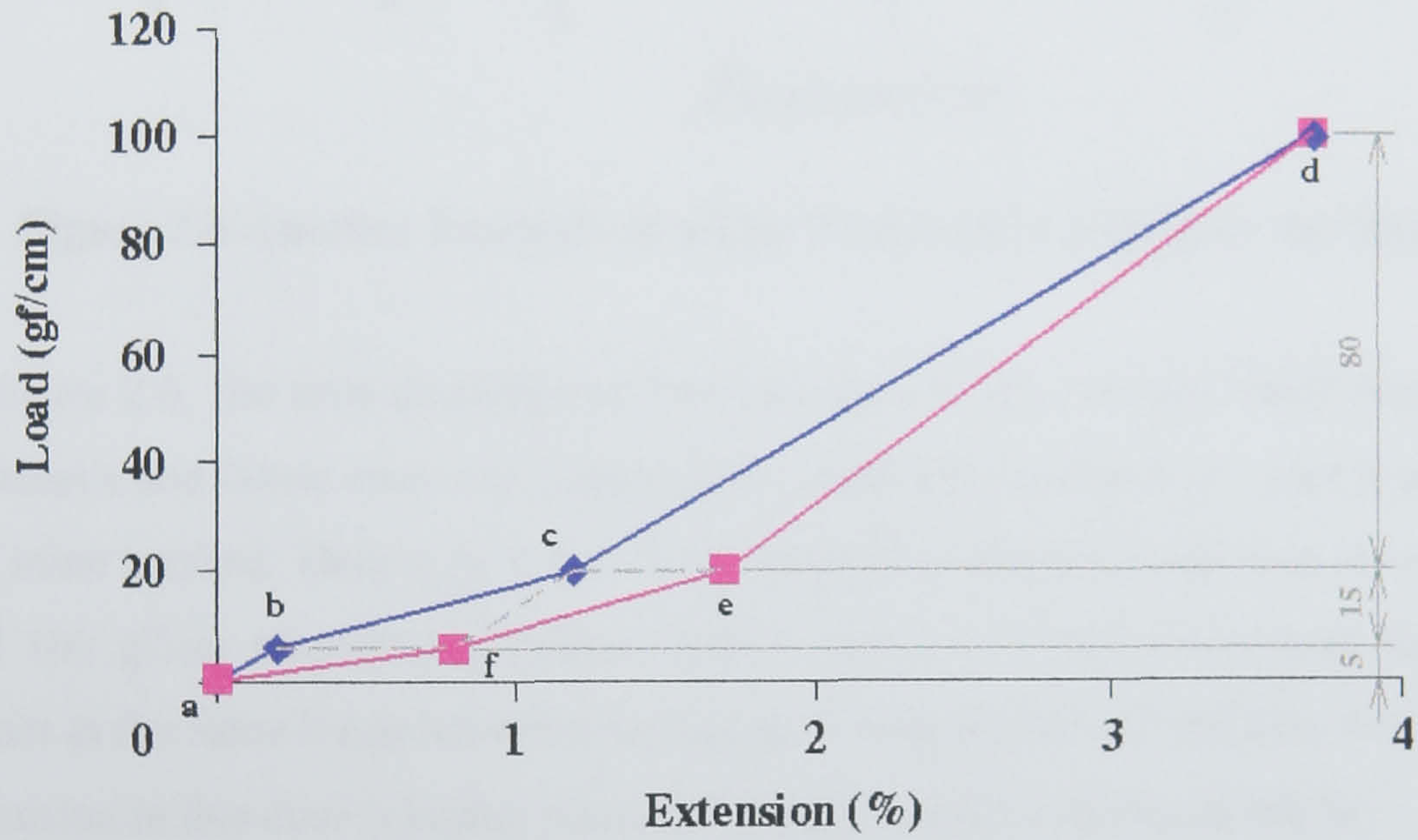


Figure 2.5 An Example of a Plot Produced to Calculate the Hysteresis

Figure 2.5, it is an example of a plot produced using this method. Here a, b, c and d represent the values of extension at loads 0, 5, 20 and 100 gf/cm respectively (when loaded) where e and f represent the extension values at the same loads but when unloaded. The calculation is shown below:

$$\textbf{Area} = 0.5\,[(X_f - X_b) * 5 + (X_f - X_b + X_e - X_c) * 15 + (X_e - X_c) * 80]$$

Using this equation, the area abcdef can be calculated to give a measure of the hysteresis and fabric recovery.

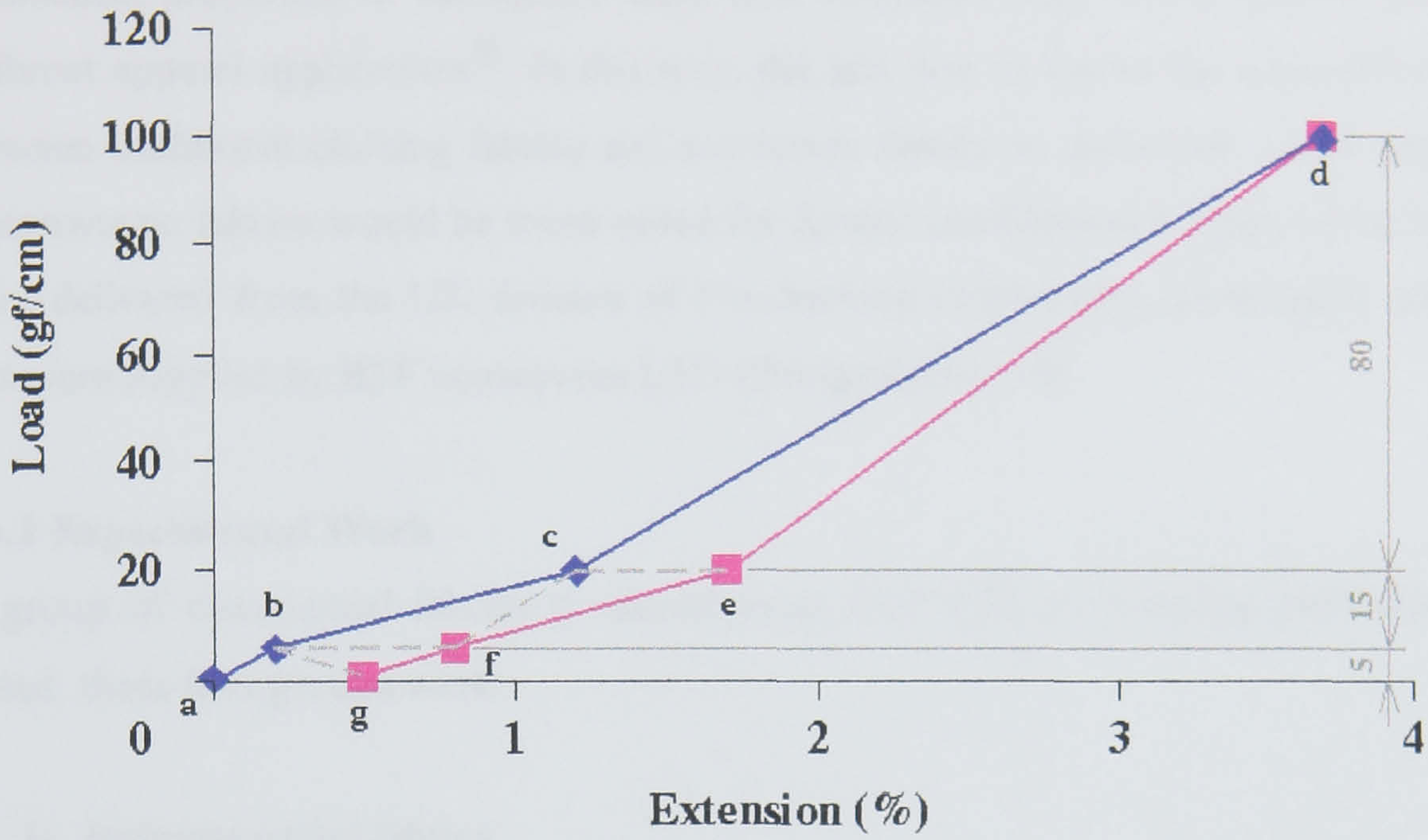


Figure 2.6 Another Example of a Plot Produced to Calculate the Hysteresis

In figure 2.6, the area abcdefg can be calculated to give an additional measure of the hysteresis and fabric recovery. Figure (2.6), is another example of a plot produced using the same method. Here a, b, c and d represent the values of extension at loads 0, 5, 20 and 100 gf/cm respectively (when loaded) where e, f and g represent the extension values at the same loads but when unloaded. It is important to note here that the residual extension in this case is higher than zero. The calculation is shown below:

$$\textbf{Area} = 0.5\ [(X_g + X_f - X_b) * 5 + (X_f - X_b + X_e - X_c) * 15 + (X_e - X_c) * 80]$$

2.3 Testing and Evaluation of Commercial Nonwoven Fabrics

A group of thirty commercial nonwoven fabrics were sourced and tested to establish their mechanical properties using the FAST instrument. Subsequently, the low stress mechanical properties of the fabrics were also compared with woven fabrics used for different apparel applications[83]. In this way, the aim was to assess the main differences between traditional clothing fabrics and nonwoven fabrics to determine which category of nonwoven fabrics would be more suited for further consideration. Most of the fabrics were delivered from the UK division of Freudenberg Nonwovens (Greetland), and the rest were supplied by BFF nonwovens LTD (Bridgewater), UK.

2.3.1 Experimental Work

A group of commercial fabrics produced using four different bonding methods were tested, these four groups were:

1- hydroentangled fabrics;
2- chemically bonded fabrics;
3- thermally bonded fabrics;
4- combined bonding (Hydroentanglement + chemical bonding) fabrics.

The fibre compositions of the fabrics included: Viscose rayon, Polyester, Cotton and Nylon. The fabrics were in the area density range of 40-80 g/m^2.

Samples were prepared for the FAST instrument using the method obtained in section 2.3. Six measurements were made in each direction per sample. Tests were performed in the machine direction (MD), cross direction (CD) and bias direction. Tables 2.1 – 2.4 show the results obtained for the fabrics. The results are defined according to the following key.

Key:

F1 = Formability in Warp Dir. (MD) (mm^2)

F2 = Formability in Weft Dir. (CD) (mm^2)

E5-1= Extension in warp dir. At the load of 5gf/cm (MD) (%)

E5-2= Extension in weft dir. At the load of 5gf/cm (CD) (%)

E20-1= Extension in warp dir. At the load of 20gf/cm (MD) (%)

E20-2= Extension in weft dir. At the load of 20gf/cm (CD) (%)

E100-1= Extension in warp dir. At the load of 100gf/cm (MD) (%)

E100-2= Extension in weft dir. At the load of 100 gf/cm (CD) (%)

EB5 = Extension in bias dir. At the load of 5gf/cm (%)

BL1 = Bending length in warp Dir. (MD) (mm)

BL2 = Bending length in weft Dir. (CD) (mm)

BR1 = Bending Rigidity in warp Dir. (MD) (μN.m)

BR2 = Bending Rigidity in weft Dir. (CD) (μN.m)

G = Shear Rigidity (N/m)

T2 = Fabric thickness at 2 gf/cm^2 (mm)

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

ST = Surface Thickness (mm)

For the purpose of comparison with data on woven fabrics[83], the notation of 1 and 2 will be used for each property (i.e.F1, F2, E5-1, E5-2....etc)

Hydroentangled Fabrics

Fibre Type	Fabric Number	Weight g/m^2	F1 (mm^2)	F2 (mm^2)	E5-1 (%)	E5-2 (%)	E20-1 (%)	E20-2 (%)	E100-1 (%)	E100-2 (%)	EB5 (%)	BL1 (mm)	BL2 (mm)	BR1 (μNm)	BR2 (μNm)	G (N/m)	T2 (mm)	T100 (mm)	ST (mm)
100% Viscose	4	46	0.176	0.057	0.06	2.9	0.37	9.6	0.93	*	1	18.2	9.5	2.720	0.387	123.00	0.34	0.203	0.137
67% Viscse, 33% PET	5	36.5	0.134	0.076	0.2	6.5	0.86	*	2.7	*	2.3	16.8	7.2	1.698	0.134	53.48	0.37	0.212	0.158
100% PET	6	43.5	0.321	0.084	0.1	3.2	0.53	*	1.7	*	1.53	18.9	8.5	2.881	0.262	80.39	0.49	0.25	0.24
50% PET, 50% Viscose	7	57	0.524	0.192	0.17	7	0.93	*	2.93	20	3.4	18.8	9.9	3.716	0.543	36.18	0.68	0.38	0.3
100% Cotton	8	59	1.284	0.245	0	2.6	0.56	13.3	2.13	*	0.6	22.3	14.5	6.419	1.765	205.00	0.68	0.38	0.3
100% PET	20	54.5	0.216	0.153	0	0	0.37	1.3	1.73	7.87	0	22.5	16.6	6.090	2.446	**	0.46	0.29	0.17
	Averages	49.42	0.44	0.13	0.09	3.70	0.60	8.07	2.02	13.93	1.47	19.58	11.03	3.92	0.92	99.6	0.50	0.29	0.22

Table 2.1: Results Obtained of Low Stress Mechanical Properties of Hydroentangled-Bonded Fabrics

* Maximum values obtained by the FAST instrument (21.2 %)

** Infinite values

Chemical bonded Fabrics

Fibre Type	Fabric Number	Weight g/m^2	F1 (mm^2)	F2 (mm^2)	E5-1 (%)	E5-2 (%)	E20-1 (%)	E20-2 (%)	E100-1 (%)	E100-2 (%)	EB5 (%)	BL1 (mm)	BL2 (mm)	BR1 (μNm)	BR2 (μNm)	G (N/m)	T2 (mm)	T100 (mm)	ST (mm)
30% PET, 70% Viscose	9	50	0.367	0.335	0	0	0.1	0.13	0.6	0.83	0	46.5	43.9	49.317	41.499	**	0.396	0.26	0.136
30% PET, 70% Viscose	10	82	3.934	2.031	0	0.06	0.3	1.667	1.6	7.1	0.1	49.83	35.5	99.530	35.989	1230.00	0.907	0.466	0.441
30% PET, 70% Viscose	11	86.5	5.622	6.594	1.8	1.5	9.9	11.3	*	*	2.06	24.16	21.5	11.967	8.433	59.71	2.31	0.78	1.53
100% PET	12	35	0.010	0.032	0	1.57	0.2	5.43	0.77	*	0.33	19	4.8	2.355	0.038	372.73	0.35	0.16	0.19
30% PET, 70% Viscose	13	52	0.110	0.172	0	0	0.067	0.13	0.43	1.03	0	42	29	37.794	12.441	**	0.39	0.26	0.13
30% PET, 70% Viscose	14	55.5	1.128	1.198	0	0.167	0.23	1.9	1.27	8.67	0.167	52	26	76.555	9.569	736.53	0.81	0.34	0.47
30% PET, 70% Viscose	16	37.5	0.023	0.000	0	0	0	0.1	0.23	0.83	0	35.5	20.8	16.458	3.310	**	0.229	0.16	0.069
100% Viscose	22	48.5	***	***	0	0.3	0.3	1.9	1.37	11.17	0.07	***	***	***	***	1757.14	0.56	0.28	0.28
30% PET, 70% Viscose	23	84	***	***	0.03	0	0.03	0.43	0.17	3.3	0	***	***	***	***	**	0.51	0.39	0.12
100% PET	30	41.5	0.000	0.019	0	0	0.033	0	0.1	0.2	0	27.4	24.3	8.375	5.842	**	0.054	0.04	0.014
	Averages	57.25	1.40	1.30	0.18	0.36	1.12	2.30	0.73	4.14	0.27	37.05	25.73	37.79	14.64	831.2	0.65	0.31	0.34

Table 2.2 Results Obtained of Low Stress Mechanical Properties of Chemical Bonded Fabrics

*** Unable to measure due to surface characteristics of the fabrics.

Hydroentangled –Chemical Bonded Fabrics (Combined Bonding)

Fibre Type	Fabric Number	Weight g/m²	F1 (mm²)	F2 (mm²)	E5-1 (%)	E5-2 (%)	E20-1 (%)	E20-2 (%)	E100-1 (%)	E100-2 (%)	EB5 (%)	BL1 (mm)	BL2 (mm)	BR1 (μNm)	BR2 (μNm)	G (N/m)/10	T2 (mm)	T100 (mm)	ST (mm)
100% PET	1	40	0.236	0.032	0.02	2.02	0.23	8.6	1.04	*	0.5	17.9	11.03	2.251	0.527	246.00	0.38	0.27	0.11
100% Viscose	3	39.5	0.195	0.214	0.03	1.56	0.26	6.3	0.85	*	0.35	32.8	11.6	13.674	0.605	351.43	0.39	0.23	0.16
100% PET	17	81.5	1.064	0.490	0.00	3.13	1.03	13.27	3.83	*	1.23	20.6	12.45	6.989	1.543	100.00	1.02	0.58	0.44
	Averages	53.67	0.50	0.25	0.02	2.24	0.51	9.39	1.91	*	0.69	23.77	11.69	7.64	0.89	232.5	0.60	0.36	0.24

Table 2.3: Results Obtained of Low Stress Mechanical Properties of Hydroentangled- Chemical Bonded Fabrics

* Maximum values obtained by the (FAST 3) instrument (21.2 %)

** Infinite values

*** Unable to measure due to surface characteristics of the fabrics.

Thermal Bonded Fabrics

Fibre Type	Fabric Number	Weight g/m^2	F1 (mm^2)	F2 (mm^2)	E5-1 (%)	E5-2 (%)	E20-1 (%)	E20-2 (%)	E100-1 (%)	E100-2 (%)	EB5 (%)	BL1 (mm)	BL2 (mm)	BR1 (μNm)	B2 (μNm)	G (N/m)/10	T2 (mm)	T100 (mm)	ST (mm)
30% PET, 70% Viscose	15	34.5	0.22	0.247	0	0.93	0.23	4.03	1.13	*	0.3	36	14.5	15.79	1.03	410.00	0.44	0.18	0.26
100% Nylon	19	54.5	6.04	2.78	0.53	3.87	2.27	12.8	8.97	*	0.93	35.3	26.5	23.52	9.95	132.26	2.04	0.5	1.54
100% PET	21	56.5	1.51	0.35	0	0.67	0.63	4.37	2.77	17.53	0.27	24.5	22.1	8.15	5.98	455.56	1.6	0.39	1.21
100% PET	24	34.5	0.00	0.00	0.00	0.00	0.00	0	0.27	0.43	0.00	25.7	20.2	5.75	2.79	**	0.04	0.02	0.02
100% PET	25	78	***	***	0.00	0.00	0.00	0.4	0.13	3.37	0.00	***	***	***	***	**	0.39	0.31	0.08
100% PET	28	33	***	0.02	0.00	0.00	0.067	0.033	0.6	0.367	0.00	24.5	***	4.76	***	**	0.095	0.049	0.04
	Averages	48.50	1.94	0.68	0.09	0.91	0.53	3.61	2.31	10.68	0.25	29.20	16.66	11.59	4.94	332.6	0.77	0.24	0.53

Table 2.4: Results Obtained of Low Stress Mechanical Properties of Thermal Bonded Fabrics

* Maximum values obtained by the (FAST 3) instrument (21.2 %)

** Infinite values

*** Unable to measure due to surface characteristics of the fabrics.

2.3.2 Low Stress Mechanical and Dimensional Properties of Commercial Nonwoven Fabrics

The results for all the fabrics show quite a wide variation. However, in order to explore whether the fabrics categories showed distinctive characteristics, the average values of the properties for each of the fabrics in each of the classification, were calculated. For the purpose of comparison, these are summarized in figure 2.7 under each of the four bonding classifications (shown in section 2.2). A comparison of the average of the data shows that hydroentangled fabrics typically presented the lowest values of bending length, bending rigidity and shear rigidity.

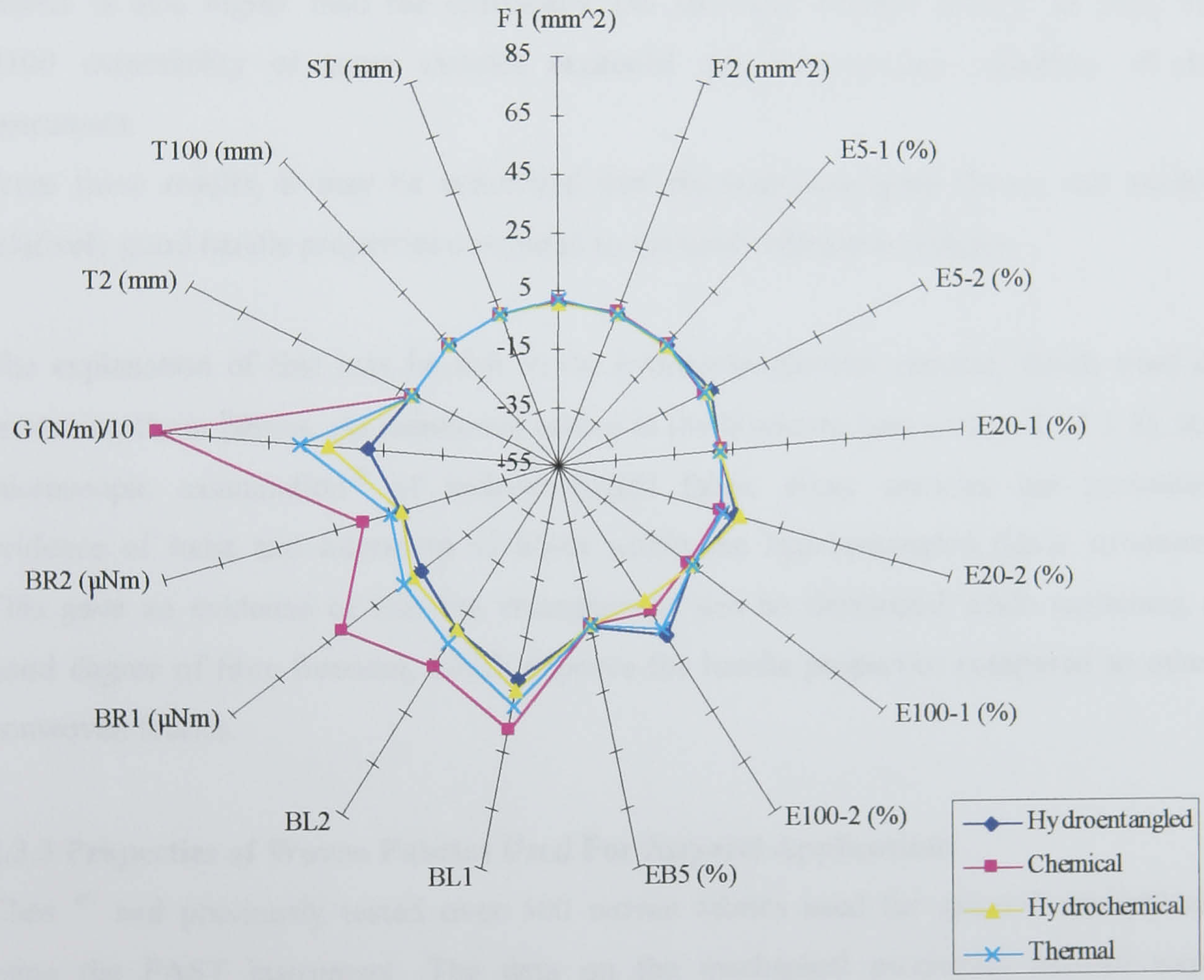


Figure 2.7 Low Stress Mechanical and Dimensional Properties of Commercial Nonwoven Fabrics

It is interesting to note that all the nonwoven fabrics show a similar general profile shape, irrespective of the method of bonding. Whereas many properties (e.g. E5%, E20% and E100%) show no marked differences, there are larger proportional differences in BL1, BL2, BR1, BR2 and G.

The bending length (BL1 and BL2) and the bending rigidity (BR1 and BR2) for the chemically bonded fabrics in both the MD and CD are higher than the other groups of fabrics such as thermally, hydroentangled or combination-bonded fabrics.

In addition, the shear rigidity (G) of the chemically bonded fabrics is markedly higher than that of the other fabrics, which is considered to be a disadvantage in the performance of clothing fabrics.

The hydroentangled fabrics have the lowest values of shear rigidity (G), bending length (BL) and bending rigidity (BR) in both the MD and CD, and the extensibility of these fabrics is also higher than the chemically and thermally bonded fabrics. In fact, the E100 extensibility of some samples exceeded the measurement capability of the instrument.

From these results, it may be concluded that the hydroentangled fabrics will exhibit relatively good handle properties compared to the other nonwoven fabrics.

The explanation of that may be due to the hydroentanglement process, which used in producing these fabrics. As mentioned earlier in the literature (see section 1.11.1.6), the microscopic examination[78] of hydroentangled fabric cross sections has presented evidence of twist and migration of fibres within the hydroentangled fabric structure. This gave an evidence of that the entanglement can be developed while sustaining a good degree of fibre freedom, which improve the handle properties compared to other nonwoven fabrics.

2.3.3 Properties of Woven Fabrics Used For Apparel Applications

Chen [83] had previously tested over 500 woven fabrics used for apparel applications using the FAST instrument. The data on the mechanical properties derived were analyzed and the average mechanical properties of these fabrics were calculated for each group of these clothing woven fabric applications (i.e. Linings, Blouse, Shirts and Pajamas fabrics) within a normal range.

The average weight (fabric area density) of the fabrics in each group is summarized in table 2.5. This was to obtain indicative values for the properties to enable a comparison to be made with equivalent values for the nonwoven fabrics.

Table 2.5: Summary of Average Weight For Clothing Fabrics

Clothing Fabric Application	Average Fabric Weight (g/m^2)
Shirts	110
Pajamas	100
Blouse	91
Linings	50-80

The average mechanical properties values for each group of clothing fabrics, are given in figure 2.8

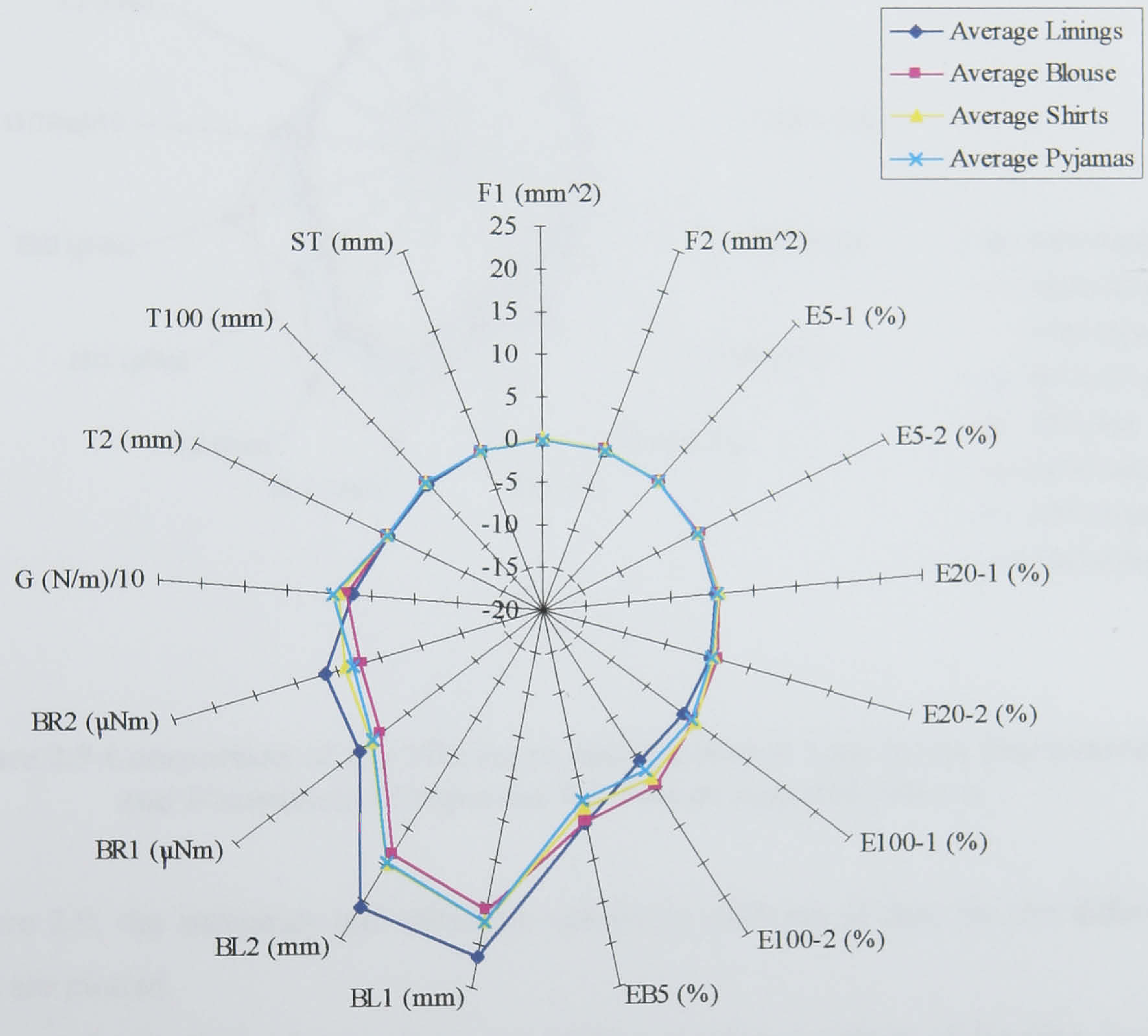


Figure 2.8 Results Obtained for Commercial Woven Fabrics

Figure 2.8 shows that the principle differences in the values obtained for existing clothing fabrics were for the bending length and bending rigidity properties. It is evident that the lining fabrics gave the highest bending lengths and bending rigidity despite having the lowest fabric weights.

2.3.4 Comparison of the Minimum and Maximum Values for Woven Fabrics Used for Apparel Applications

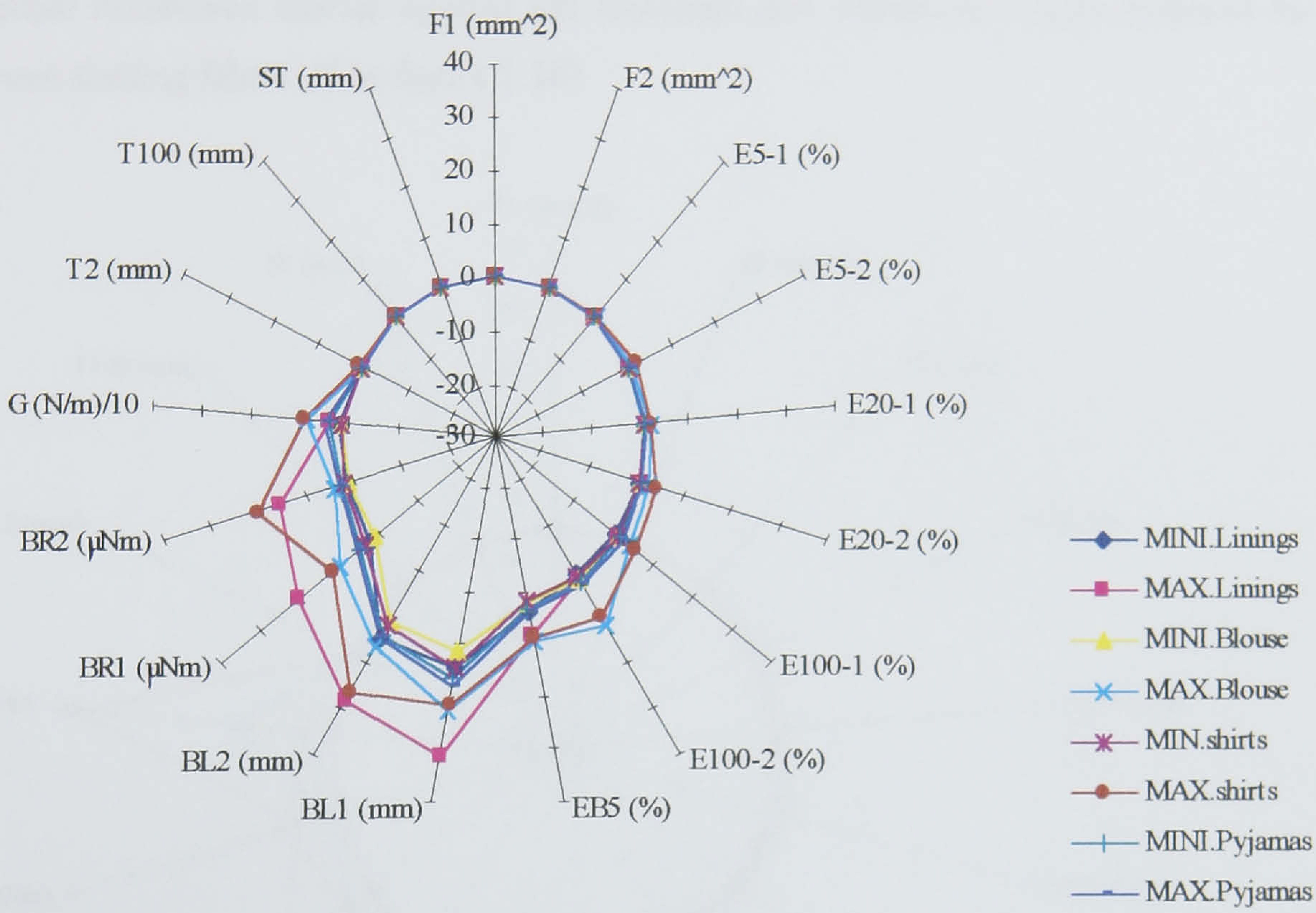


Figure 2.9 Comparison of the Minimum and Maximum Low Stress Mechanical and Dimensional Properties for Woven Apparel Fabrics

In figure 2.9, the maximum and minimum values for each set of data for the different fabrics are plotted.

In figure 2.9, the lining fabrics have the highest maximum values of bending length (BL) and bending rigidity (BR), whereas the blouse fabrics have the lowest bending length and bending rigidity values.

The blouse and shirt fabrics have the highest maximum values of extension (E5%, E20% and E100%) and also shear rigidity (G).

2.3.5 Comparison of Mechanical and Dimensional Properties of Shirting Fabrics and Commercial Nonwoven Fabrics

Despite the variability in properties, some indication of the similarity of the different types of fabrics may be obtained by plotting, the average mechanical properties for commercial nonwoven fabrics against the minimum and maximum values obtained for the woven shirting fabric. (See figure 2.10).

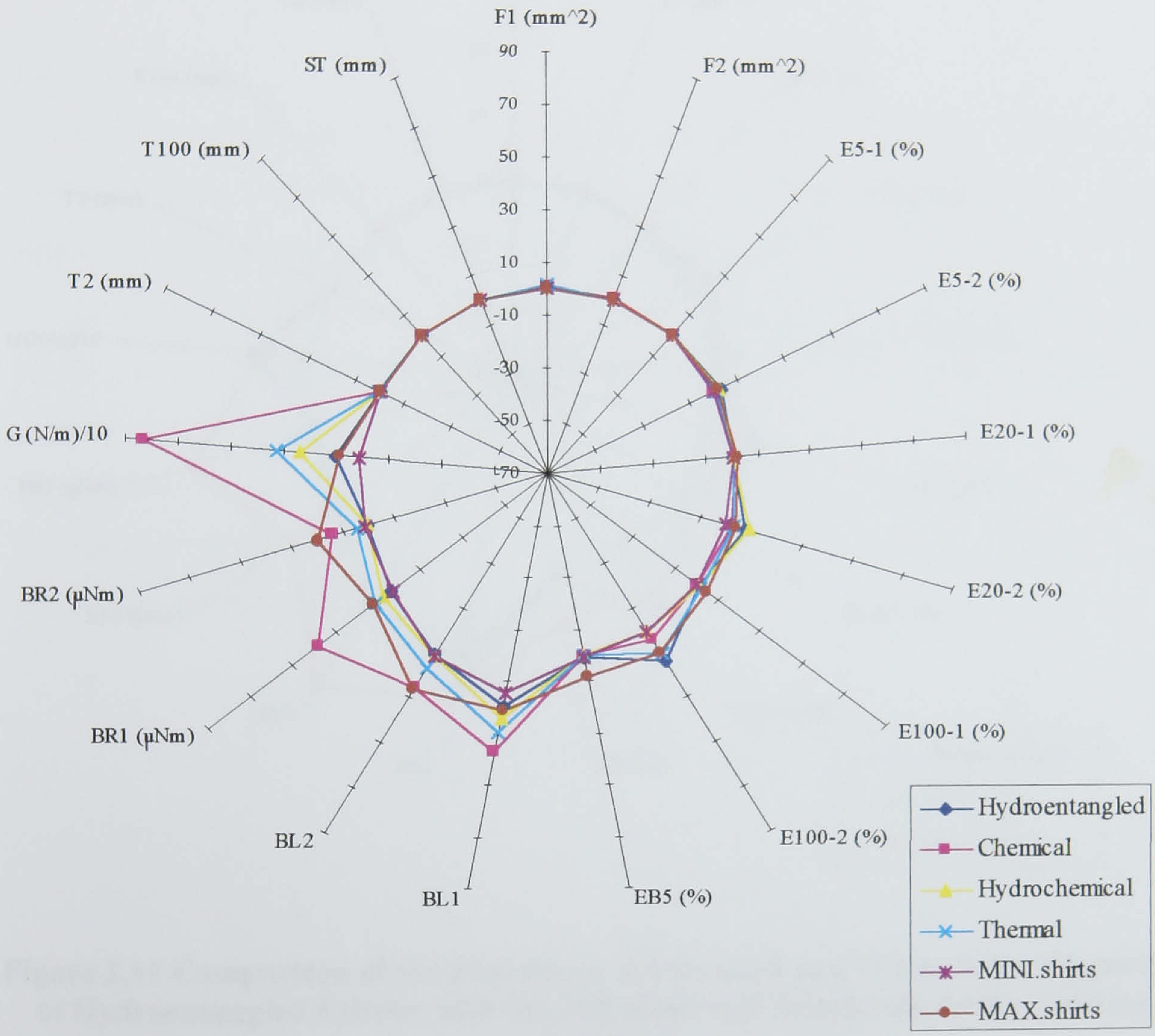


Figure 2.10 Comparison of the Low Stress Mechanical and Dimensional Properties of Commercial Nonwoven Fabrics and Shirting Fabrics

Figure 2.10 shows that in comparison to other nonwoven fabrics, hydroentangled fabrics have values, which are similar to the minimum shirting values, or fall between the minimum and maximum values except for the extension values in the CD (E100-2 %).

2.3.6 Comparison Between Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics and Woven Shirt Fabrics

To improve clarity, minimum and maximum values of the low stress mechanical properties of woven shirt fabrics are plotted separately against the corresponding hydroentangled fabric values. (Figure 2.11).

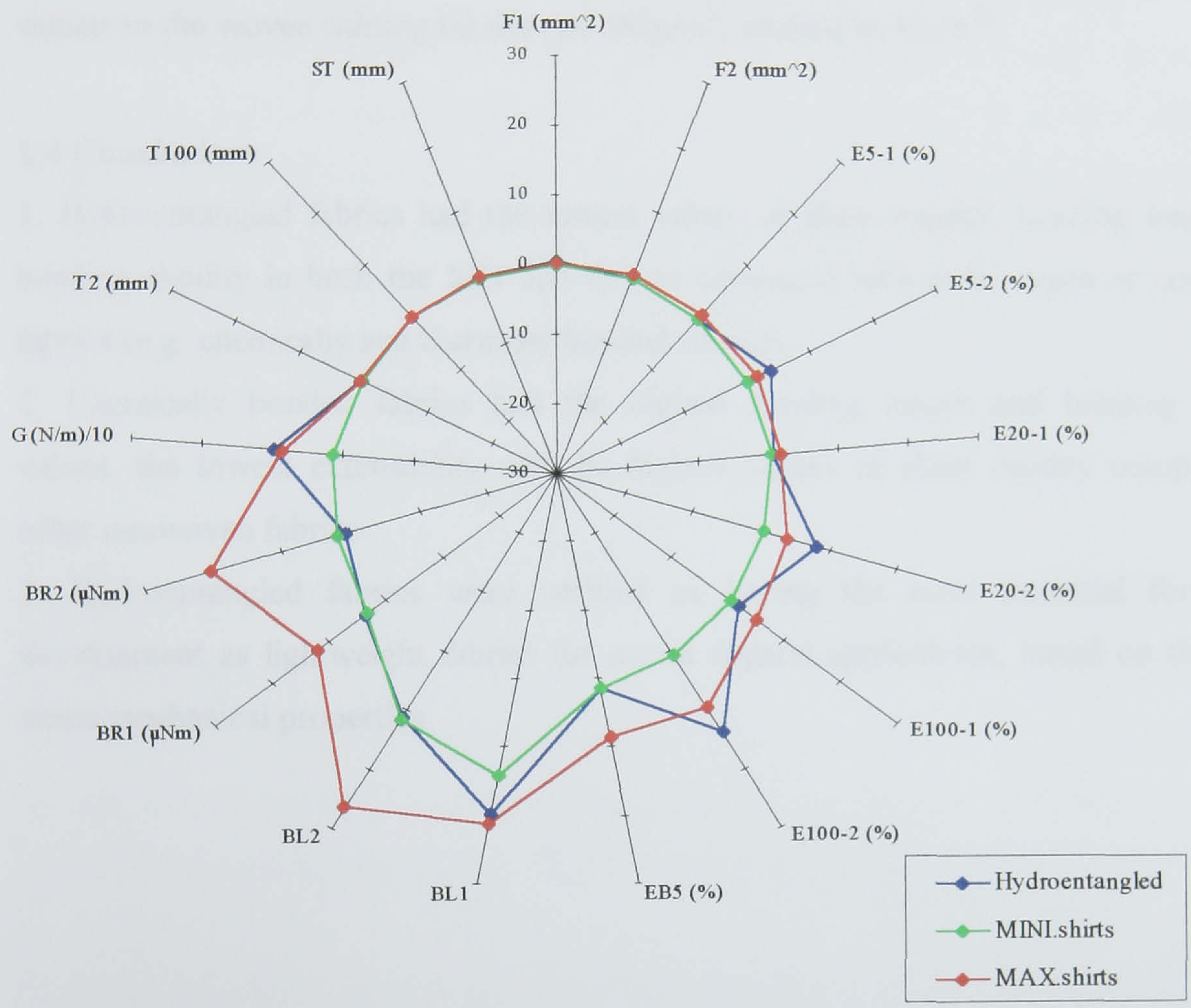


Figure 2.11 Comparison of the Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics with the Minimum and Maximum for the Shirting Fabrics

In figure 2.11, it is evident that the mechanical properties of the hydroentangled fabrics are generally positioned within the maximum and the minimum values of the woven shirt fabrics except for the extension values in the CD (E5-2, E20-2 and E100-2).

This may arise because the range of weights (area density) for the hydroentangled fabrics is slightly lower than that of the shirting fabrics, resulting in higher values of extension. This increase in extension according to lower weight (area density) is expected as increasing the area density usually results in a decrease in the extension when all other variables are constant.

From the analysis in this chapter, it is evident that the hydroentangled fabrics offer the most potential as substitutes for woven shirting fabrics in term of their mechanical properties. In order to explore this further, the experimental work reported in chapter 4 and 5, investigates hydroentangled fabrics produced with fabric weights (area densities) similar to the woven shirting fabrics (i.e. 90 g/m^2) studied by Chen[83].

2.4 Conclusions

1. Hydroentangled fabrics had the lowest values of shear rigidity, bending length and bending rigidity in both the MD and CD as compared with other types of nonwoven fabrics (e.g. chemically and thermally bonded fabrics).
2. Chemically bonded fabrics had the highest bending length and bending rigidity values, the lowest extensibility and the highest values of shear rigidity compared to other nonwoven fabrics.
3. Hydroentangled fabrics were verified as having the most potential for future development as lightweight fabrics for use in apparel applications, based on their low stress mechanical properties.

CHAPTER 3
PREPARATION OF EXPERIMENTAL FABRICS

3.1 Background

A limitation of commercially sourced fabrics is the difficulty in establishing their precise history. Clearly, there is no practical means of fully understanding the settings used during their production, which determine fabric structure and therefore the relationship with the low stress fabric mechanical properties. It is also difficult to establish if such fabrics have been chemically or mechanically finished after bonding. For these reasons, a range of experimental hydroentangled fabrics were produced under controlled conditions using a pilot hydroentanglement machine. The experimental procedures used are reported in this chapter.

3.2 Production of Hydroentangled Fabrics

3.2.1 Raw Materials and Fabric Preparation

The fibres used in this project were white, 38 mm, mean fibre length, 1.7 dtex viscose rayon fibres with 1.57 specific gravity. These fibres were chosen because they have a long history of use in the hydroentanglement industry and can be hydroentangled easily to give a coherent fabric structure. This is largely because viscose rayon fibres have relatively low bending rigidities and high extension compared to some other fibres.

There are two basic steps in the preparation of hydroentangled fabrics, the first is the formation of a web or batt and the second is the process of transforming this tenuous structure into a coherent web (bonding).

The viscose rayon fibres were pre-opened using a small Fearnought opening machine and aerodynamically spread in a blending bin to unify the batch. The opened fibres were then carded on a two-part nonwoven carding machine[84]. The carding machine consisted of a volumetric feed system with microfeed control, a breast unit with three workers and strippers, a main swift with seven workers and strippers and a single doffer. The maximum working width of the machine was one metre. The card was used to produce three cross-laid webs of 100, 138, 165 and 180 g/m^2 nominal area density. Before hydroentanglement, the batts were lightly preneedled. Batt lengths of 5 metres each were needle punched using a needle penetration depth of 12 mm and a punch density 50

P/cm^2 (on one side only). The needled fabric was slit up the middle to make 2 x 0.5m wide fabrics. The purpose of pre-needling was to increase the overall breaking load, to decrease the extension of the hydroentangled fabrics [84,85] and to reduce the bulk of the batt to enable it to pass under the first injector without being disturbed. Because the hydroentanglement machine had no integrated web-forming unit, individual webs were cut to 0.29 x 0.50 m^2 from the batts using a prepared template, and were then fed to the hydroentanglement machine.

3.2.2 Hydroentanglement Machine Specifications

Hydroentanglement is an energy transfer process, in which the energy generated by the water flow is transferred to the web or batt. It also follows that high water pressure imparts larger amounts of energy[81]. The specific energy applied to the web is normally calculated based on the flow parameters of the particular hydroentanglement machine. The procedure is described in section 3.2.3. The hydroentanglement machine used was 0.5m wide and was of the horizontal flatbed type. It was capable of operating at water jet pressures up to 140 bar.

A schematic diagram of the machine is shown in figure 3.1. There are four main sections:

1. the fabric manufacturing section comprising three injectors, the pre-wetting unit and the web support or belt;
2. the high-pressure water supply consisting of a water tank, twin water filters and high-pressure water pump;
3. the suction section consisting of a suction pump and three suction boxes into which the injected water passes;
4. the electrical control section.

Before the first injector, a simple prewetting unit is positioned over the forming belt, which provides water across the width of the machine. The principal purpose of the prewetting unit is to reduce the bulk of the web and to improve the attachment of the web to the belt[80]. A summary of the machine specifications is given in table 3.1

Table 3.1: Hydroentanglement Machine Specifications

Prewetting Injector Specifications	
Pipe Diameter	4 mm (internal)
Water Flow	8.25 litres/min
Height	100 mm above the belt
Conveyor Belt Specifications	
Composition	Polyester monofilament
Thickness	660 μm
Yarn Diameter	180 μm
Structure	4/1 Step 2 Twill with Weft Faced Side Uppermost
Conveyor Belt Speed	8 m/min
Injection System Specifications	
Number Of Injectors	1
Design Of Jet Strip	Single row
Jet Density (Jets/m)	1300
Jet Inlet Diameter (μm)	120
Jet Outlet Diameter (μm)	140

The water used during hydroentanglement is filtered to avoid progressive blocking of the jet strips. Two filters of 1 μm and 0.5 – 0.3 μm were used and a stainless steel water-tank of 1 m^3 is used for storing the filtered water.

A stainless steel triple-plunger pump driven by a 30 KW motor is used to generate water pressures up to 140 bar. However, if more than one injector is used, the maximum pressure available is reduced to 120 bar. Three injectors are normally fitted to the machine. The first injector is connected to an auxiliary pump developing low pressures up to 30 bar, the other two injectors are linked to the main high-pressure water pump, (the triple-plunger pump).

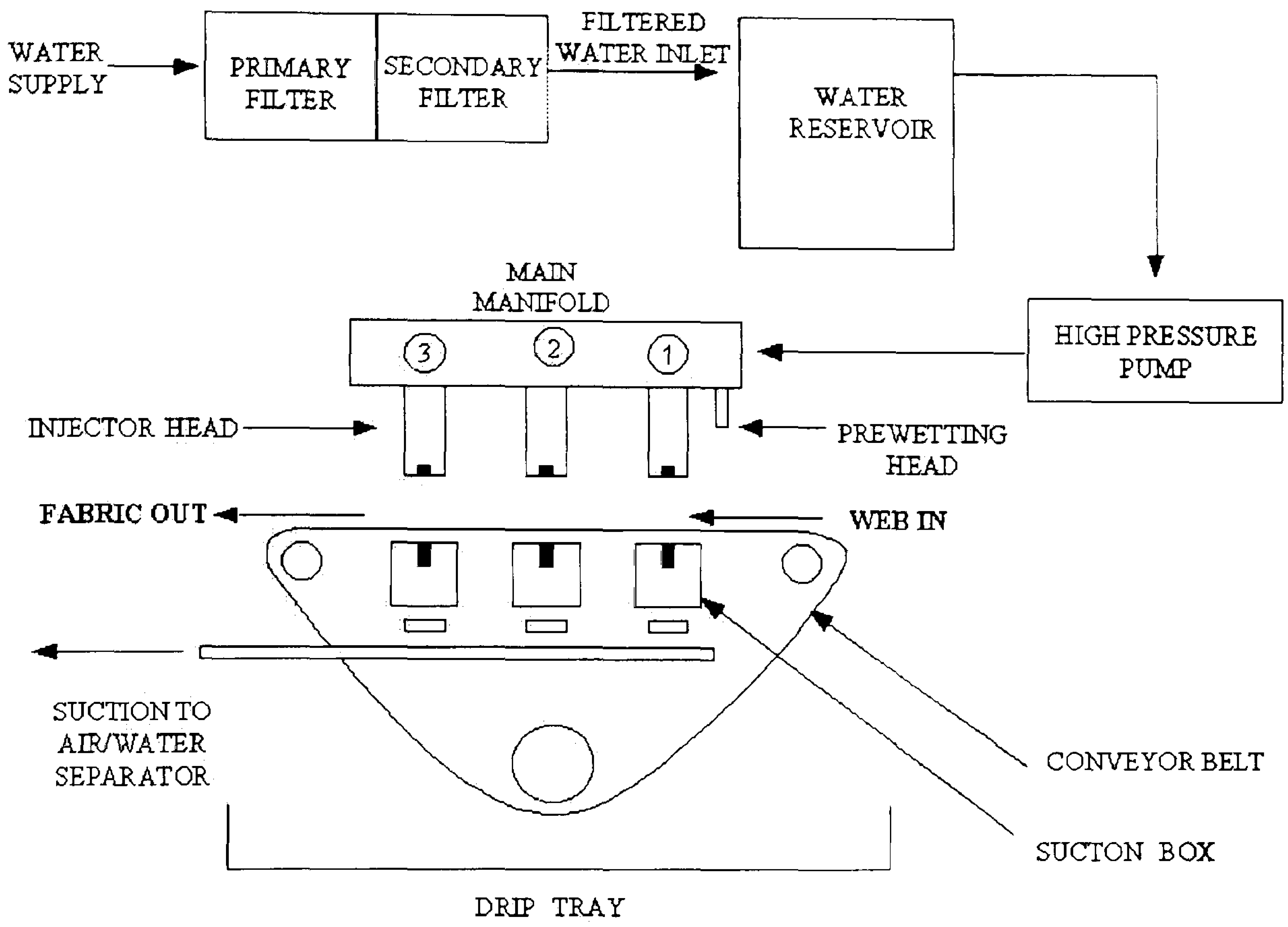


Figure 3.1 Schematic Diagram of the Experimental Machine[85]

3.2.3 Determination of the Specific Energy

The specific energy is an important parameter, which is known to influence both fabric structure and the physical properties of the fabric (see equation 3.1). The specific energy is derived using simple fluid mechanics. In equation 3.1 the coefficient of discharge (C_d) depends on whether the jet (which is conical in shape) is face up or face down or in other words on whether the cone is nose-up or nose-down. The jet dimensions also affect this. The coefficient of discharge value used in this work was obtained experimentally. So that equation 3.2 is obtained after substituting. The specific energy introduced to each web was calculated using equation 3.2. Normally, it is common practice to calculate the specific energy of webs based on the starting weight per unit area of the original web. This could be misleading if more than one injector is used in succession because the weight per unit area of the web usually decreases with increasing applications of energy. Thus, to determine the differences, the magnitude of the changes in weight per unit area was measured and the specific energies were recalculated accordingly after each injector. The procedure that was used is discussed in the following section.

$$E\,(MJ/Kg) = 1.11\,C_d \frac{1}{WS}\sum_{i=1}^{N} n_i d_i^2 p_i^{\frac{3}{2}} \qquad \textbf{(3.1)}$$

Where:

E = Energy introduced to the web (MJ/Kg)

C_d = Discharge coefficient (experimentally found to be 0.66)

W = Material basic weight (Kg/m^2)

S = the delivery speed (m/sec)

P_i = Water pressure for the *ith* injector (bar)

n_i = the number of jet orifices (m) for the *ith* injector

d_i = the diameter of jet orifices (m) for the *ith* injector

Since the values of S, C_d, n_i, d_i are constants, the equation can be simplified as shown in equation 3.2.

$$\textbf{Total Energy (E)} = \frac{136.84\times10^{-6}\times(\sqrt{\Delta P})^3}{W} \qquad \textbf{(3.2)}$$

3.3: Estimation of the Specific Energy Application During Hydroentanglement

3.3.1 Introduction

This section presents a possible alternative approach for estimating the total specific energy applied to the web during hydroentanglement. Normally, such calculations are based on the original web weight per unit area and take no account of the marked decreases in web weight per unit area, which can take place at each injector during the process. This section considers the errors that may occur when calculating the specific energy using the original web weight and multiple injectors. This is because the web weight can decrease after each injector. This section evaluates the errors that may be involved in calculating specific energy using the normal method.

3.3.2 Experimental Procedure

Using the four webs 100, 138, 165 and 180 g/m^2 described in section 3.2.1, three samples from each were cut to dimensions of (64 x 40 cm). Each fabric was then hydroentangled at different water pressures (50, 70 and 90 bar) and using different hydroentangled at different water pressures (50, 70 and 90 bar) and using different numbers of injectors. In total, 36 fabrics with different levels of total specific energy were produced. The machine specifications and settings are given in table 3.1. A summary of the test procedure is given below (stages 1-4).

Stage 1

First, the fabric was hydroentangled using one injector (using a pressure of 50 bar). A sample of dimensions (40 x 16 cm) was cut from this fabric. The fabric was then hydroentangled using the second injector and another sample of the same dimensions was cut for analysis. This process was repeated until four fabric samples were obtained, and each hydroentangled using a different number of passes (and therefore different total specific energies).

Stage 2

After conditioning, the weight per unit area of each web sample was measured. It is important to appreciate that there is a change in weight per unit area of the web after each injector and it is of interest to quantify this change.

Stage 3

After the weight per unit area of the web after each pass has been obtained, it may be possible to more accurately determine the energy applied by subsequent injectors in the process. The total energy is then calculated by summing all the individual energies applied to the fabric. An example of this procedure, for the 165 g/m^2 hydroentangled web processed at 50 bar energy, is summarized in table 3.2.

Web 165 g/m^2

	Pressure = 50 Bar	
	Weight (g/m^2)	Energy (MJ/Kg)
Web	171.22	0
After Pass 1	165.43	0.28
After Pass 2	160.46	0.58
After Pass 3	158.80	0.88
After Pass 4	155.50	1.18

Table 3.2: Calculated Specific Energy Values Based on Changes of Web Weight per Unit Area During Hydroentanglement

Stage 4

The specific energy for each of the fabrics was calculated based on the web weight per unit area after each injector. In this way, an accurate impression of the change in fabric area density with specific energy could be determined. From stage 3 of this procedure, the relationship between specific energy and fabric weight per unit area after each of the four passes could be observed. Most previous researchers appear to have calculated total specific energy based on the original web weight per unit area irrespective of the changes in weight per unit area between injectors. Therefore, this is not necessarily as accurate a procedure in comparison with the approach shown here. Based on the calculated specific energies, the corresponding web and final fabric weight per unit area values are shown in table 3.2 for the nominal fabric area density of 165 g/m^2.

An example of the relationship between web and fabric weight per unit area and the number of passes (injector passes) is illustrated in figure 3.2. It is evident that in general, there is an initial decrease in area density with an increasing number of injector passes.

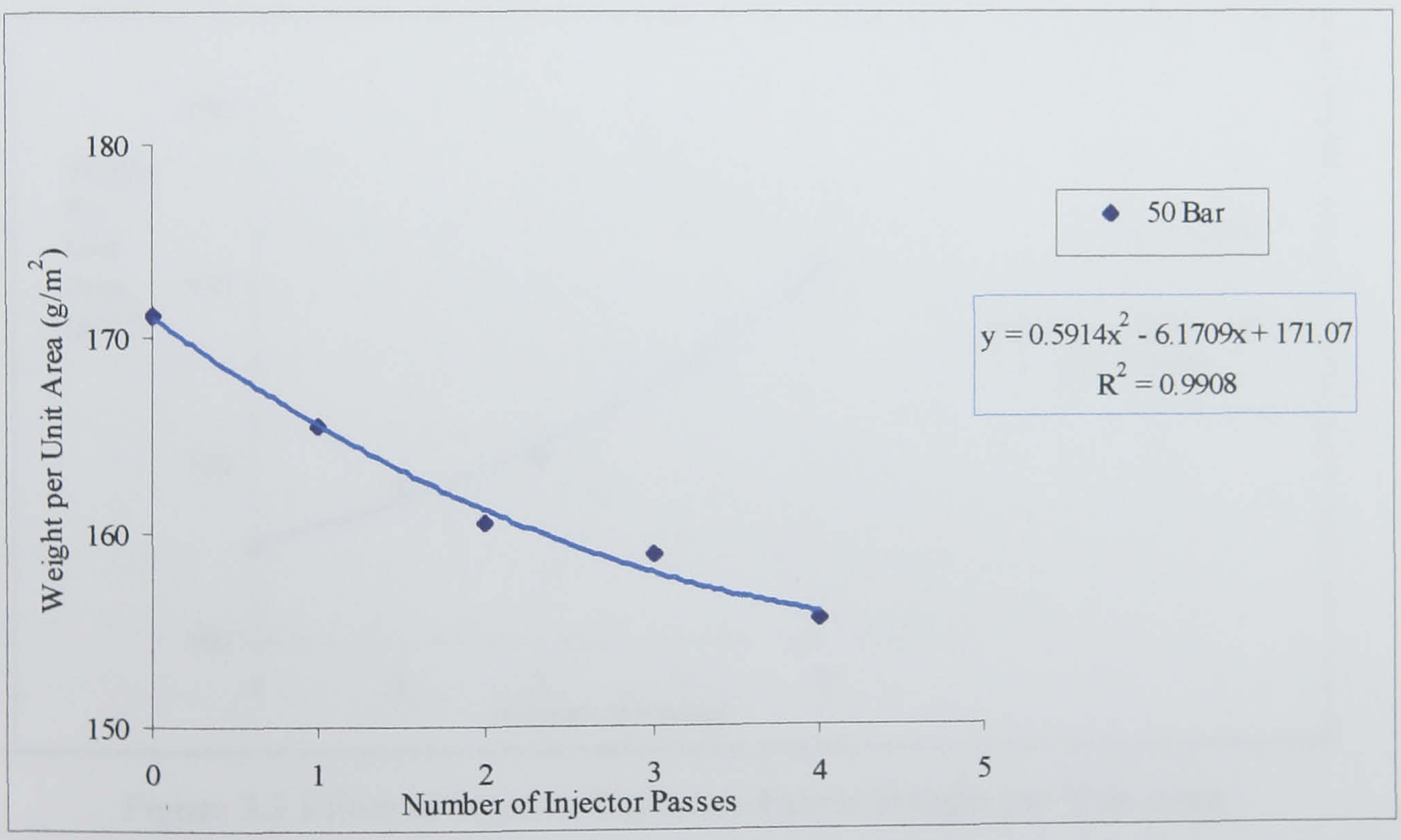


Figure 3.2 Effect of Injector Passes on Fabric Weight per Unit Area 165 g/m^2

In figures 3.2, the effect of increasing the number of injector passes on the fabric weight per unit area (for nominal fabric weight 165 g/m^2) is illustrated

In figure 3.2 a second order polynomial regression equation where y is the fabric or web weight, and x is the number of passes and the constant relates to the web weight per unit area.

3.4 A Method for Estimating the True Web Weight per Unit Area After Each Injector Pass During Hydroentanglement

Of course, in practice, it is not practical to stop the machine to measure the web weight between passes. Therefore, it is useful to find a method of calculating the values. By substituting the values for the fabric weight per unit area after four passes into the equation (figure 3.3) instead of the weight per unit area of the original web it is possible to obtain the fabric weight per unit area after two and three passes as well as the original web weight per unit area (figure 3.2). This is because the web weight per unit area and the fabric weight per unit area after each pass is normally unknown except for the fabric weight after four passes (or the final pass). In this way, the specific energy can be calculated based on improved estimates of the web/fabric weight per unit area after any number of passes.

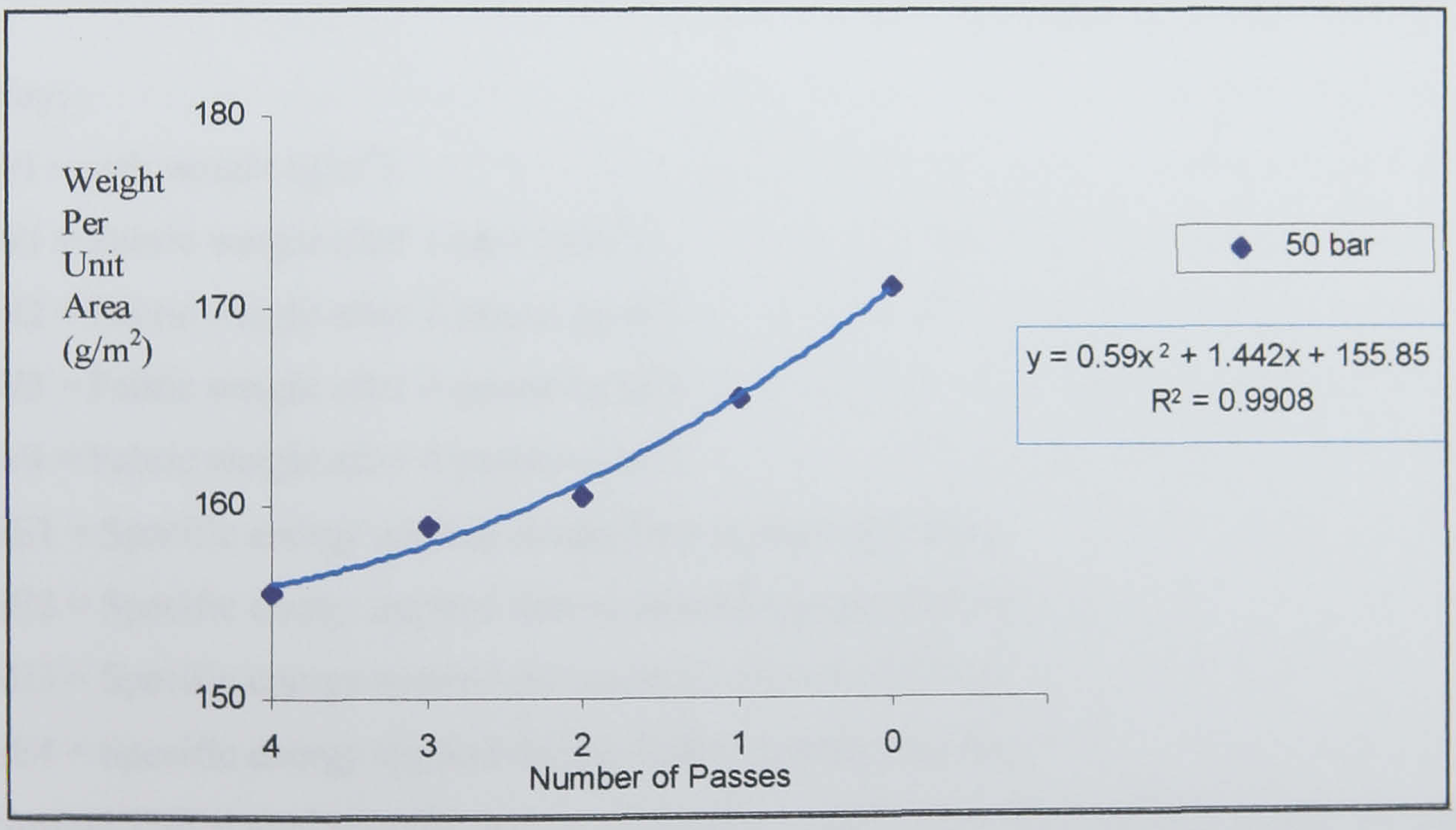


Figure 3.3 Effect of Injector Passes on Fabric Weight per Unit Area 165 g/m²

An example of the calculation to obtain the web weight per unit area after each injector is shown in table 3.3. This new method of calculating the total specific energy applied after 4 injectors, was applied on previously produced fabrics where only the weight of the fabric after four injectors was known. In table 3.3, both total specific energies are calculated and compared according to the two methods. An example for a web of nominal area density of 165 g/m^2 is shown in table 3.3.

Table 3.3 Calculation of Total Specific Energy for Web Weight Per Unit Area 165 g/m^2 at Pressure 50 bar.

50 Bar	Fabric 165 g/m^2 Total Specific Energy (TSE) =136.84*10^-6*50^(3/2)*10^3/Y Y = "Web-Fabric Weight per unit area"											
MD												
	W4	W3	W2	W1	WI	SE4	SE3	SE2	SE1	Calculated TSE (MJ/Kg)	Normal TSE (MJ/Kg)	TSE (Δ)
Mean	163.03	165.06	168.27	172.67	178.25	0.29	0.29	0.28	0.27	**1.13**	**1.09**	**0.05**
CD												
Mean	162.82	164.9	168.07	172.46	178.04	0.29	0.29	0.28	0.27	**1.13**	**1.09**	**0.05**
Bias												
Mean	161.49	163.5	166.73	171.13	176.71	0.30	0.29	0.28	0.27	**1.14**	**1.10**	**0.05**

Key:

WI = web weight (g/m^2).

W1 = Fabric weight after 1 pass (g/m^2).

W2 = Fabric weight after 2 passes (g/m^2).

W3 = Fabric weight after 3 passes (g/m^2).

W4 = Fabric weight after 4 passes (g/m^2).

SE1 = Specific energy applied during first injector (MJ/Kg).

SE2 = Specific energy applied during second injector (MJ/Kg).

SE3 = Specific energy applied during third injector (MJ/Kg).

SE4 = Specific energy applied during fourth injector (MJ/Kg).

Normal TSE = total specific energy calculated based on the original web weight per unit area (MJ/Kg).

Calculated TSE = calculated total specific energy according to the new method based on all weights (MJ/Kg).

As can be observed from table 3.3, once the web weight per unit area after each injector is obtained, the total specific energy can be calculated based on the fabric weight per unit area after each pass (1, 2, 3 and 4). As a result, four specific energies are obtained (SE1,SE2, SE3 and SE4).

By summing these, the total specific energy is calculated (TSE). For the purpose of comparison between this method of analysis and the normal method of calculating the total amount of specific amount of energy based on the original web weight per unit area, the (normal total specific energy) is also calculated. As predicted, the values of the normal total specific energy are lower than those calculated using the new method of estimation. This is expected because the new method takes into consideration the decrease of fabric weight per unit area after each injector pass.

3.5 Summary

It is evident from several experiments and previous results, for example Vaughn [86], that the hydroentanglement process has an effect on the fabric weight per unit area. After several injectors, it is apparent that there is a decrease in the fabric weight per unit area and this influences the accuracy of estimating the specific energy applied during hydroentanglement. Because it is impractical to stop the machine after each pass to measure the actual weight per unit area, a method of recalculating the amount of specific energy applied after a specific number of passes has been presented. After each injector pass, the fabrics were weighed to determine the mean area density and these values were recorded. These values were plotted to produce sets of equations to enable prediction of the web and fabric weight per unit area after each injector pass. Using this method of analysis, it was possible to determine the effect of hydroentanglement on the fabric area density and this provides an alternative approach for calculating the specific energy when multiple injectors and different water pressures are used. It should borne in mind that the small differences arise as a consequence of the small changes in area densities after each hydroentanglement process. If the area density changes are higher, the differences between the energies calculated using the two methods are likely to be significant. However, the differences in specific energy obtained from the two methods are very small (typically less than 5%) and for practical purposes can be ignored (for the range of conditions studied).

CHAPTER 4

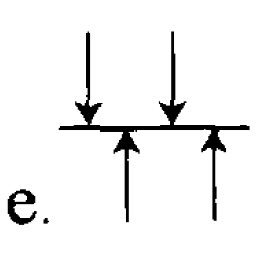
THE INFLUENCE OF PROCESS PARAMETERS AND FABRIC STRUCTURE ON THE FABRIC DIMENSIONAL AND LOW STRESS MECHANICAL PROPERTIES

4.1 Introduction

The fabrics proposed in section 3.2.1 were used to undertake a study of the fabric structural parameters and their influence on the low stress mechanical properties. There have been previous studies of hydroentangled fabric structure as detailed in section 1.11.1, chapter 1. Relevant papers have been published by Vaughn[86], Timble et al.[80,81], Qiao[82] and Jain et al.[49,50]. It has been found[30] that, generally, the mechanical behaviour of a nonwoven fabric is determined by the fibre properties, the binder properties, the web structure and the nature of the association between the fibre and binder. Consequently, the purpose of this chapter is to study the general effects of processing parameters (particularly specific energy) on the dimensional and structural properties of hydroentangled fabrics, which are believed to influence the low stress mechanical properties such as bending length and extension.

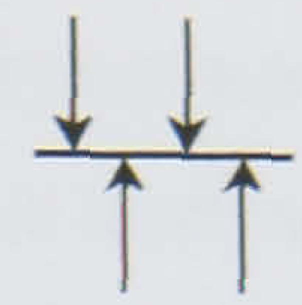
4.1.1 Experimental Procedure

Samples were produced at pressures of 20, 50, 70 and 90 bar for these experiments using 4 injectors at each pressure. The samples had nominal area densities of 100, 138, 165 and 180 g/m^2. The influence of the specific energy on both the dimensional and structural properties of the fabrics was determined using standard methods (Chapter 2, section 2.2.6 and 2.2.7).

An alternating energy profile was used in producing these fabrics i.e. . The results are reported in the following sections.

4.1.2 Fabric Thickness

Figures 4.1 and 4.2 show the effect of increasing the specific energy on the mean fabric thickness obtained at two fabric compression levels of 2 gf/cm^2 (T2) and 100 gf/cm^2 (T100). It is apparent that the fabric thickness initially decreases as the specific energy applied increases. This supports the findings of other workers [82,86,87].



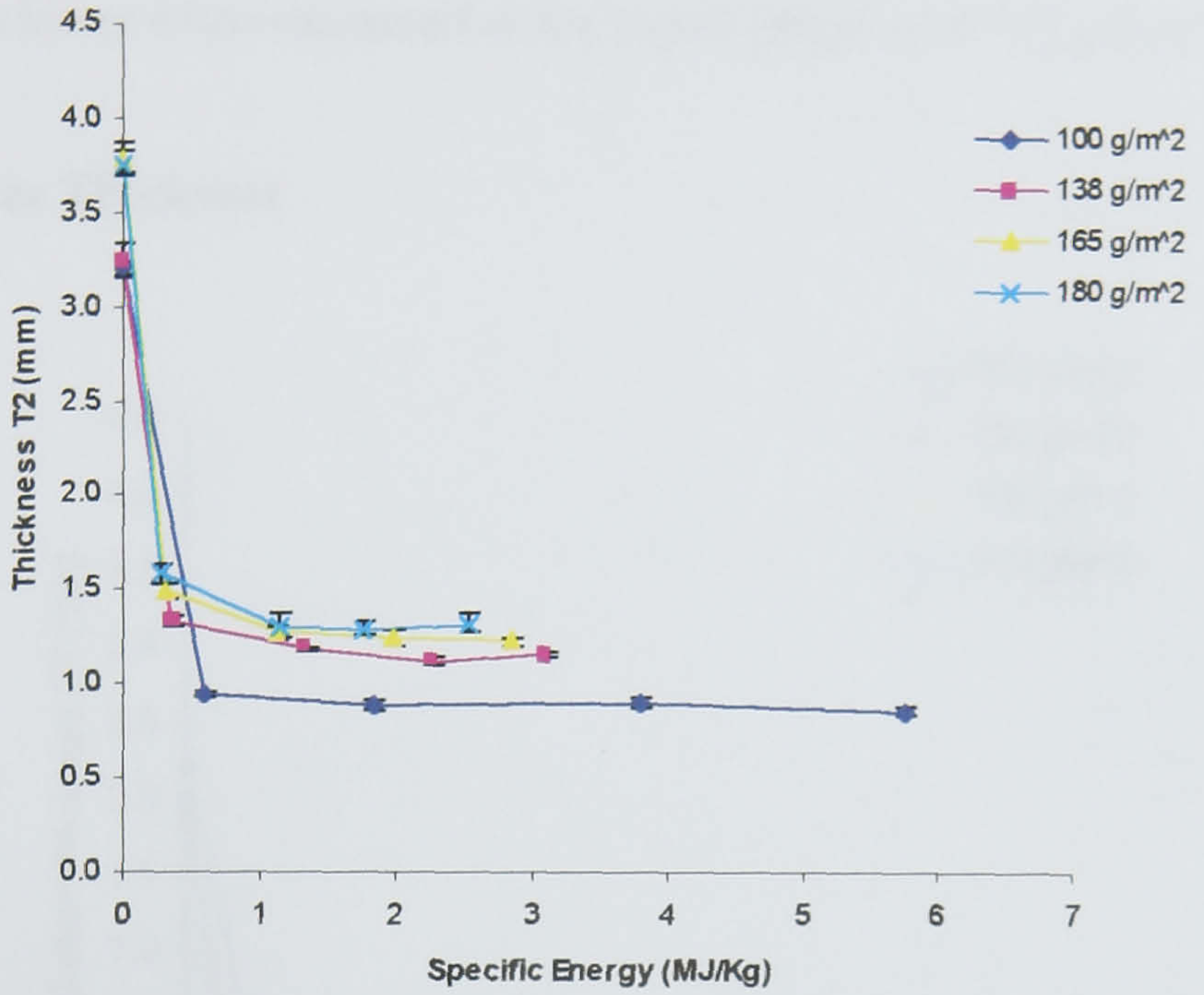


Figure 4.1 Effect of Specific Energy on Mean Thickness at 2 g/cm^2 Pressure (T2)

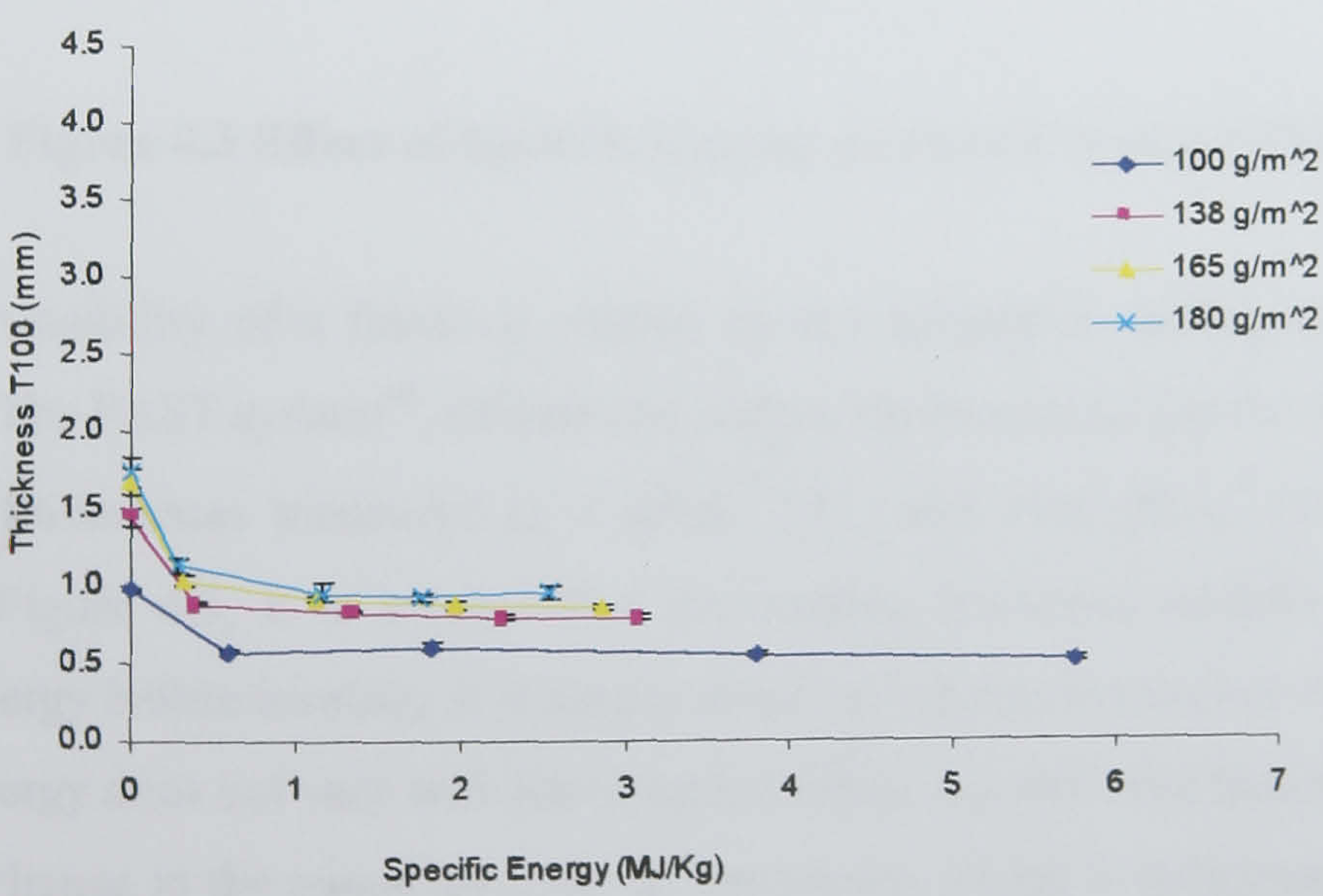


Figure 4.2 Effect of Specific Energy on Mean Thickness at 100 g/cm^2 Pressure (T100)

Figures 4.1 and 4.2 indicate that the relationship appears to be generally exponential, with a large initial decrease in thickness at low specific energy followed by a leveling at higher specific energy, in other words, thickness becomes independent of energy. As expected, the thickness is lower when measured at the higher pressure of 100 gf/cm^2.

4.1.3 Surface Thickness

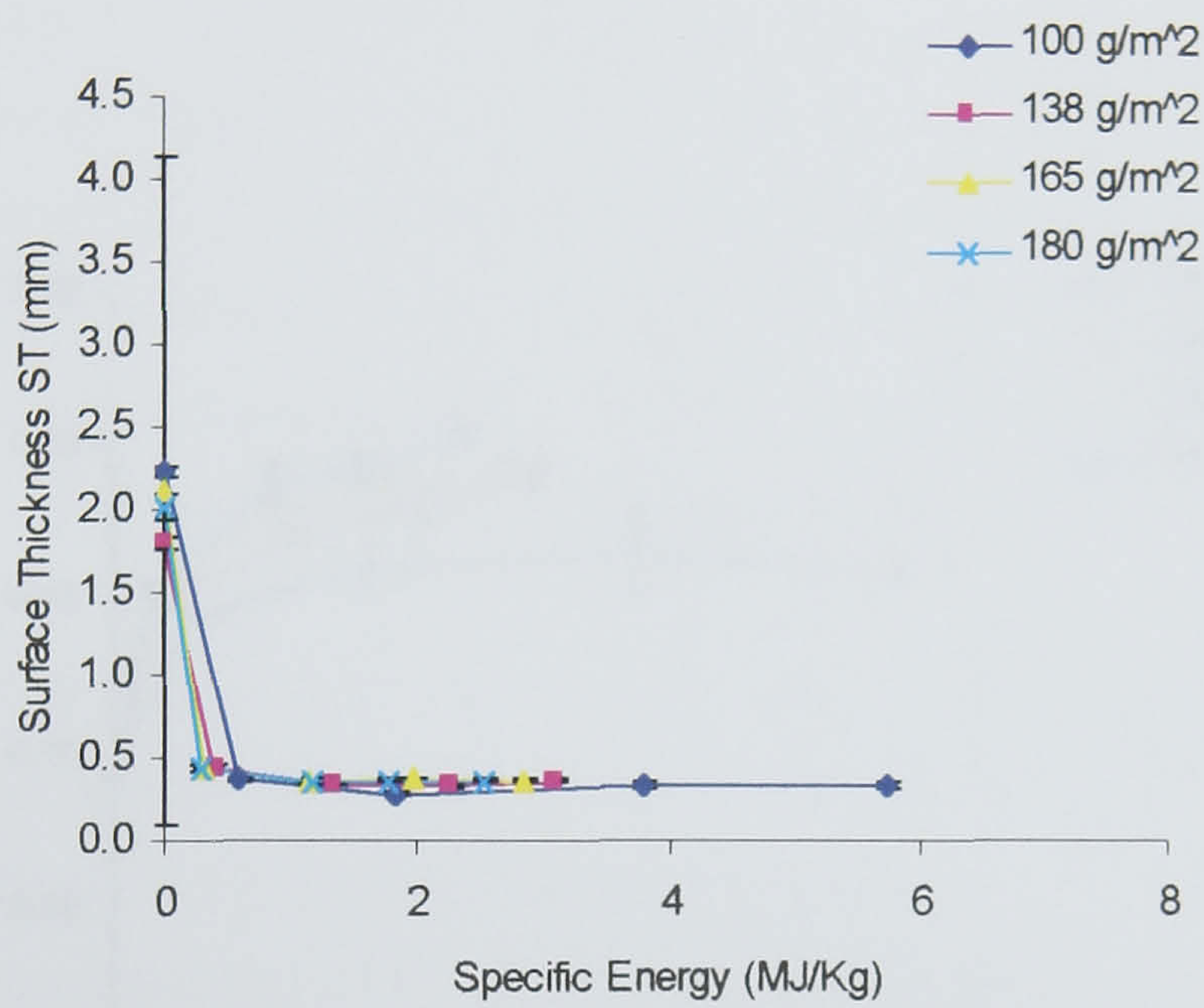


Figure 4.3 Effect of Specific Energy on Fabric Surface Thickness

The compressibility of a fabric is related to the subjective feeling of smoothness and fullness[33]. The FAST system[46], defines the surface thickness (ST) as the difference between the fabric thicknesses measured at 2 gf/cm^2 (T2) and 100 gf/cm^2 (T100) compression levels. In Figure 4.3, it is evident that the surface thickness initially decreases at low specific energy before leveling. It is also interesting to note that surface thickness at a given specific energy does not vary with fabric area density. It is believed that these results reflect the initial change in the compressibility of the fabrics, which is influenced by the degree of fabric consolidation due to hydroentanglement.

4.1.4 Fabric Density

In figure 4.4, it is apparent that after an initial increase in the mean fabric density (Df) with specific energy, further increases in specific energy applied leads to only smaller increases in density. This may be due to a decrease in the compressibility of the fabric at higher specific energy and a decrease in fibre mobility due to the increased consolidation and fibre entanglement, which will inhibit further fibre rearrangement during the hydroentanglement process.

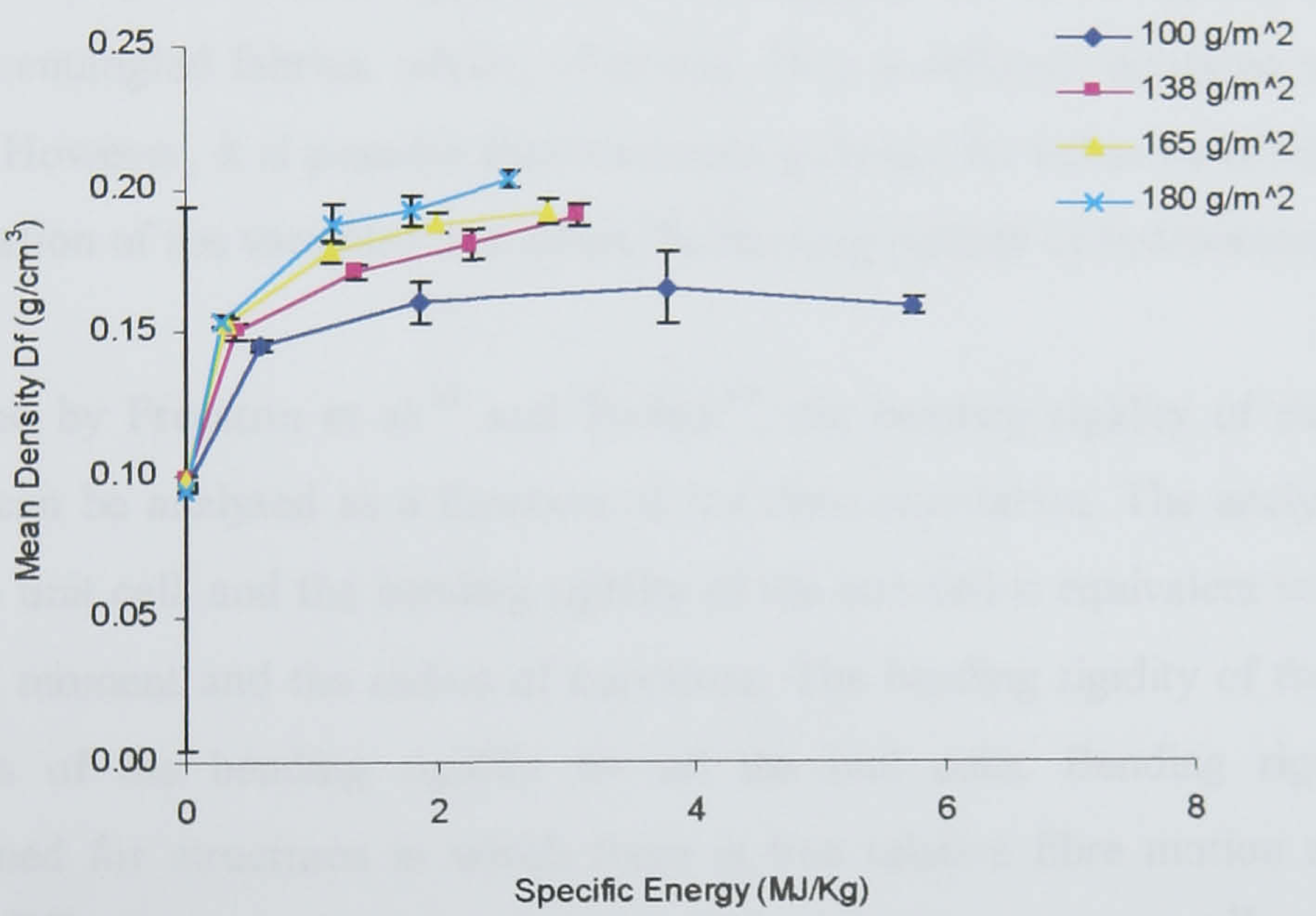


Figure 4.4 Effect of Specific Energy on Mean Fabric Density (Df)

It is also evident that increasing the web weight per unit area yields denser fabrics. This arises because the weight per unit area and thickness do not vary in direct proportion as the specific energy increases. On the other hand, it is evident that the lightest fabrics (100 g/m^2) becomes less dense at the highest specific energy due to the decrease in weight per unit area (See chapter 3- Table 3.2)

4.1.5 Bending Properties

The fabric bending behaviour is an important low stress mechanical property, which clearly has a major influence on fabric handle and aesthetic properties.

4.1.5.1 Bending Mechanics of Fibreweb Structure

In conventional textile materials, Hearle et al.[88] considered the bending rigidity of a yarn to be approximately equal to the sum of the bending rigidities of the constituent fibres. We may expect a comparable way of predicting the bending rigidity of nonwoven fabrics although, as Petterson[28] mentioned, the bending behavior of nonwoven fabrics is determined by a complex interaction between fibre properties and bond characteristics.

Freeston et al.[58] and Turbak[89] presented a theory to explain the bending rigidity of adhesive-bonded fabrics in 1965 which obviously differs from mechanical bonded materials. At present there appears to be no specific theory to explain the bending rigidity of hydroentangled fabrics, which, of course, have a different structure to adhesive bonded fabrics. However, it is possible that the existing theory for adhesive bonded fabrics can give an indication of the variables that affect the bending rigidity of hydroentangled fabrics.

As stated by Freeston et al.[58] and Turbak[89], the bending rigidity of the adhesive bonded fabrics can be analysed as a function of the fibre orientation. The analysis is based on the use of a unit cell, and the bending rigidity of the unit cell is equivalent to the product of the bending moment and the radius of curvature. The bending rigidity of the fabric is taken as the sum of the bending rigidity for all the unit cells. Bending rigidity models were determined for structures in which there is free relative fibre motion and restricted fibre mobility[58,89]. The assumptions made in the work of Freeston et al.[58] and Turbak[89] can be summarized as follows:

- The fibres are initially straight.
- The fibre cross section is cylindrical and the diameter is constant along the fibre length.
- The fibre diameter is small compared to the length (shear stresses in the fibre are negligible).
- The fibre diameter and fabric thickness are small compared to the radius of curvature. The neutral axis of bending coincides with the geometric centerline of the fibre.

- There is an equal angular and numerical distribution of fibres through the thickness of the nonwoven[58,89].

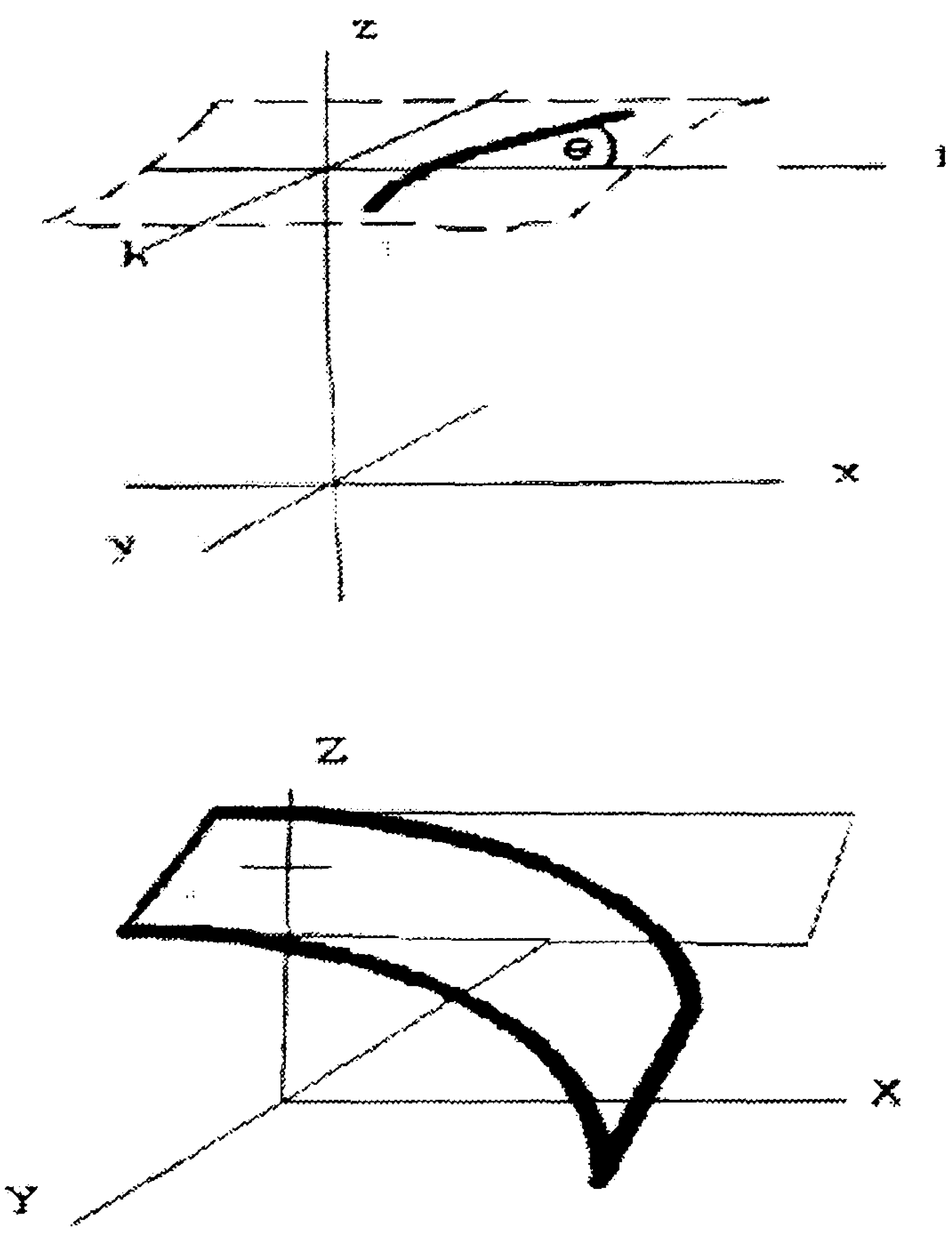


Figure 4.5-a Fabric and Fibre Geometry for Derivation of the Fabric Bending Rigidity Equation[58,89]

Figure 4.5-a shows the geometry used for the evaluation of nonwoven fabrics in bending[58,89].

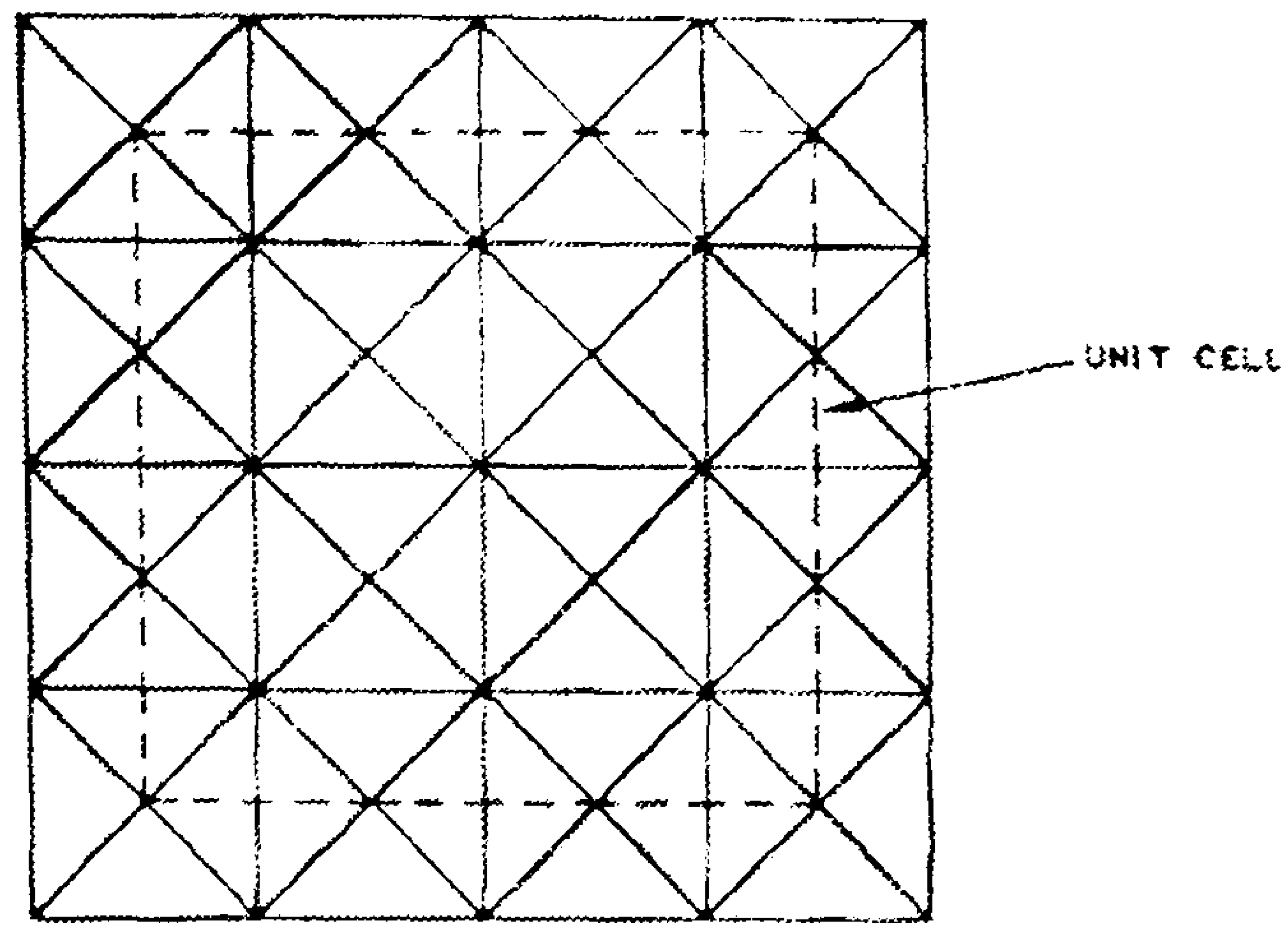


Figure 4.5-b Schematic Diagram of Idealized Nonwoven Fabric[58]

Figure 4.5-b shows a schematic diagram of an idealized nonwoven fabric by considering the fabric as a matrix of bond points whose fibres radiate outward, to other bond points.

Considering the previous assumptions and the case of free relative fibre movement, the unit cell bending rigidity $(EI)_{cell}$ has been determined as follows in equation 4.1[58,89].

$$(EI)_{cell} = N_f \int_{-\pi/2}^{\pi/2} [E_f I_f \cos^4\theta + GI_p \sin^2\theta \cos^2\theta] \, \phi(\theta) \, d\theta \qquad \textbf{4.1}$$

Where:

N_f = The number of fibres in the unit cell

$E_f I_f$ = Fibre bending rigidity around the fibre axis

G = Shear modulus of the fibre

I_p = Polar moment of inertia of the fibre cross section

$\phi(\theta)$ = The fibre orientation distribution relative to the machine direction of the fabric.

If the fibres are free to twist during bending, the torsion term ($GI_p \sin^2\theta \cos^2\theta$) becomes zero. If the freedom of relative fibre motion is severely limited, in other words, assuming there is no freedom of relative fibre motion, the unit cell bending rigidity can be shown in as equation 4.2

$$(EI)_{cell} = \frac{N_f E_f A_f t^2}{12} \int_{-\pi/2}^{\pi/2} \phi(\theta)\cos^4\theta\, d\theta \qquad 4.2$$

Where

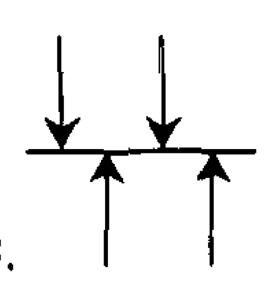
A_f = fibre cross-sectional area

t = nonwoven fabric thickness [58,89]

It can be concluded from Freeston et al. and Turbak[58,89] 's theory that a key parameter in determining the bending properties of nonwoven fabrics is the number of fibres in the cross sectional unit area when all other factors are constant.

It is predictable that the decrease in fabric thickness, which arises during hydroentanglement, will be associated with an increase in the fabric density (Figure 4.4) and therefore there will be an increase in the number of fibres in the cross sectional unit area. Based on equation 4.2, this can be expected to lead to an increase in bending rigidity as well as a decrease in fabric extension. To study this further, the average number of fibres in the cross-section of some experimental hydroentangled fabrics was measured by means of optical microscopy and Scanning Electron Microscopy (SEM technique) (see sections 5.5 and 6.2). The findings of this study are represented in chapter 6.

4.1.5.2 Bending Length

Having established some basic associations between fabric structure and bending rigidity, the next section deals with the effects of the specific energy, when applied using alternating energy profile i.e.  . Also, in this section, the bending properties of the face of the fabrics were measured. Later in chapter 6, differences in the bending properties in the face and back of the fabrics are discussed.

Based on equation 4.2, it is clear that if all other conditions remain constant, the bending properties will depend on the number of fibres in the unit cell and the fabric thickness (N and T^2). Figure 4.6 shows that, for all the fabrics, there was an initial decrease in bending length as the specific energy applied increased followed by a slight increase as the specific energy increased further. It is known that there is a large initial decrease in fabric thickness with pressure or specific energy before leveling (see figure 4.1 and 4.2). It may therefore be suggested that initially the change in bending length is mainly a function of a decrease in fabric thickness, and that subsequently, the bending length is mainly dependent on change in fabric packing density (or in other words, the number of fibres in the unit cell). This will be investigated further in chapter 6.

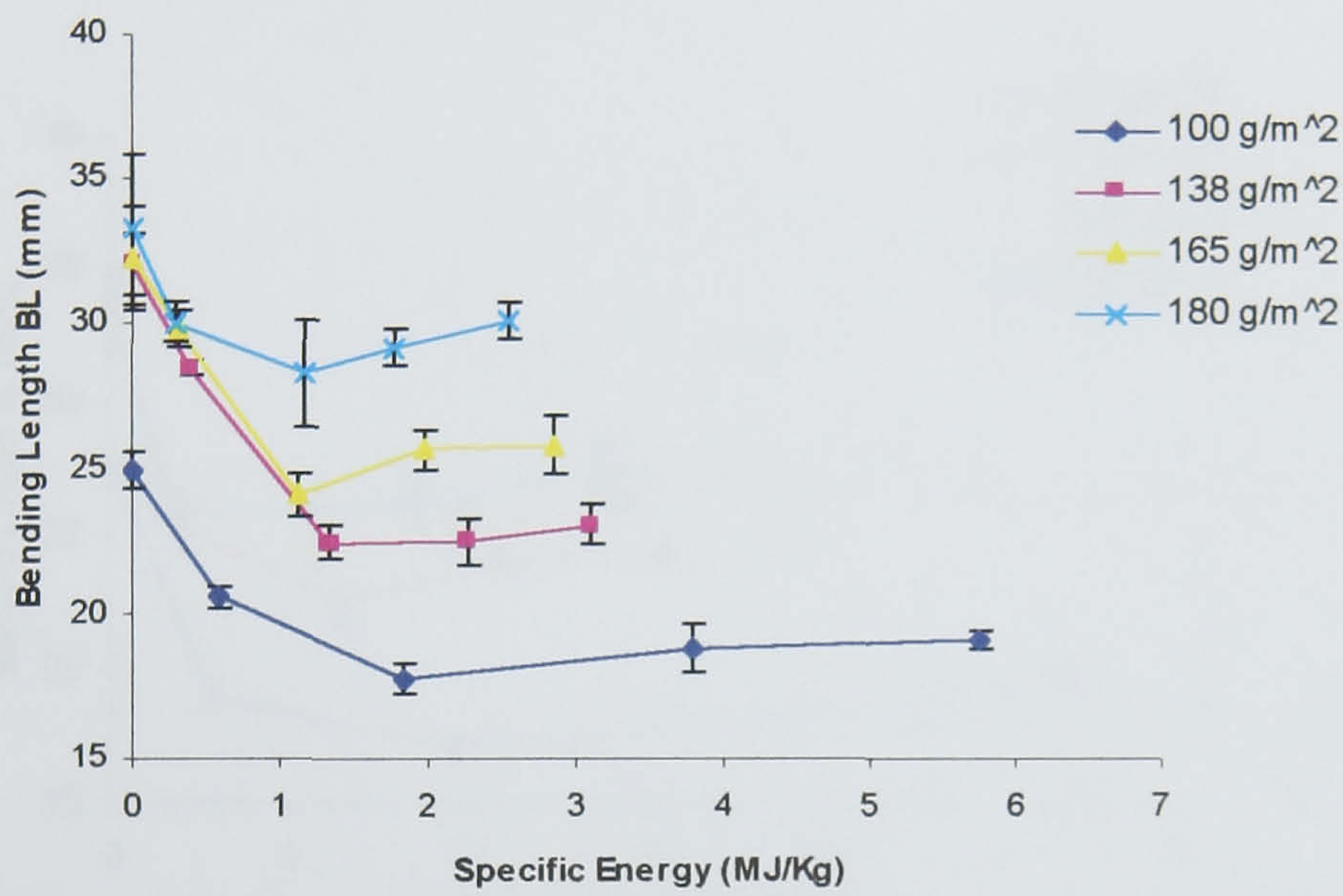


Figure 4.6 Effect of Specific Energy on the Mean Bending Length (MD)

It is also evident from figures 4.6 and 4.7, that increasing the specific energy initially decreases the bending length in both the machine and cross directions. This is followed by a leveling or a slight increase in bending length.

These results can be explained in terms of the corresponding decrease in fabric thickness[82,86] (see figures 4.1 and 4.2). Further increases in the specific energy, results in a slight increase in the bending length for all the fabric weights especially the heaviest. The increase may be due to an increase in the density of the fabrics (see figure 4.4). Again, referring to the theory of bending for nonwoven fabrics proposed by Freeston and others[58,89] the number of fibres in the unit cell will effectively increase, and accordingly as mentioned previously, the bending length of the unit cell can be expected to increase. And as mentioned earlier by Smith et al.[48] (see section 1.10.3), that the properties of nonwoven materials are determined by the fibres used, the bonding agents, and the bond density which can be defined as the number of fibre to fibre bonds per unit area. Increasing the number of bonds prevent the fibres from moving and cause it to be stiff with high strength and low extensibility, whereas, a low bond density yields a more limber fabric with a lower strength[48]. Comparatively, in hydroentangled fabrics, the increase in the number of pillars and depth of pillars will increase the fabric stiffness. This will be discussed in more detail in section 5.9.1 and 5.9.2, chapter 5.

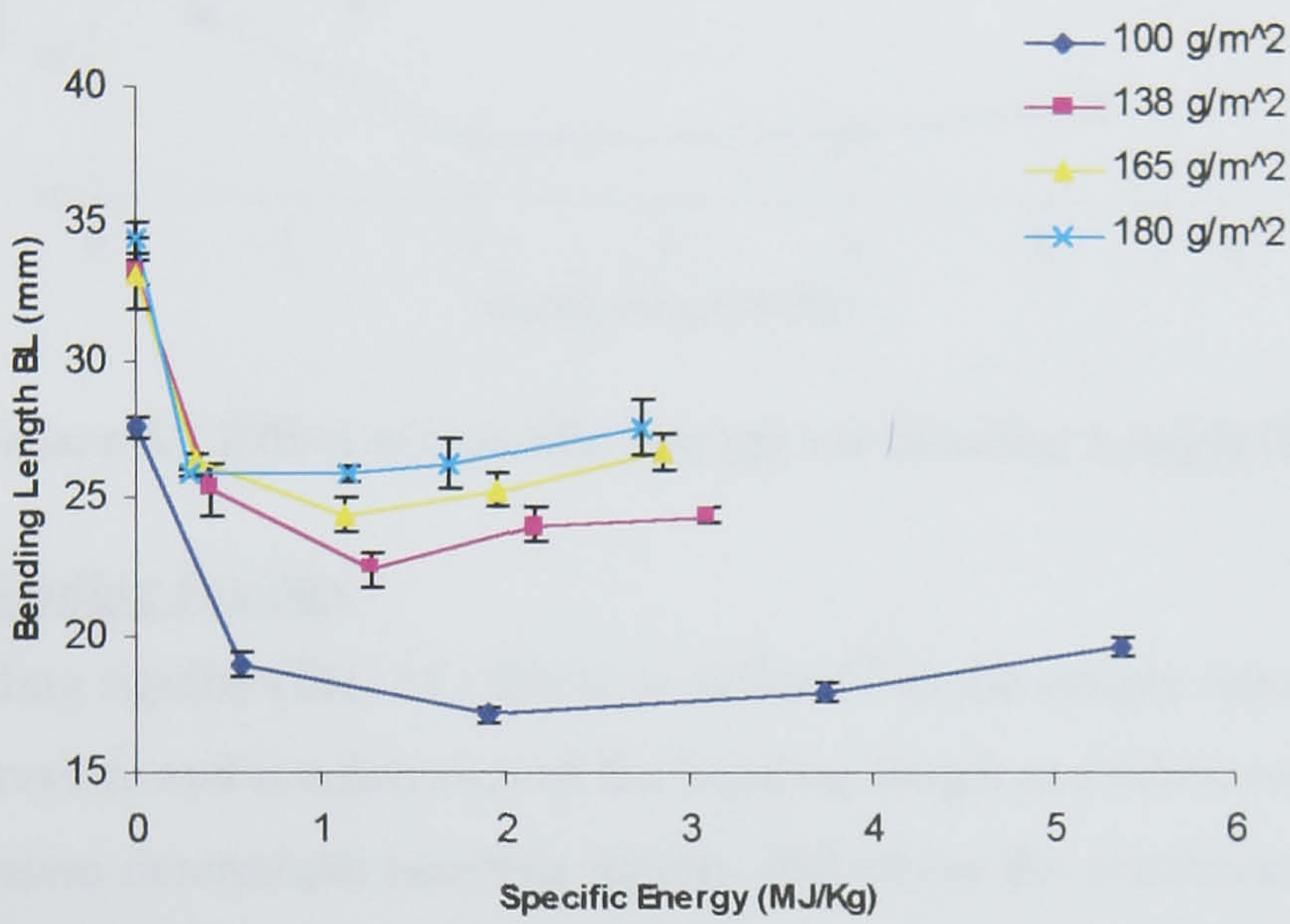


Figure 4.7 Effect of Specific Energy on Bending Length (CD)

Similar trends are observed in the MD, CD and bias direction (comparing Figs.4.6– 4.8). It is interesting to notice that the bending length for the initial webs are similar in the MD, CD and Bias directions suggesting that the structure is initially isotropic. However, after hydroentanglement at the lowest energy of 0.581 MJ/Kg (20 bar), it is evident that the bending length in the CD is lower than in the MD and Bias directions, especially for the heavy weight fabrics (165 and 180 g/m^2). These results can be explained in terms of increasing fibre orientation in the MD as the specific energy increases and therefore the bending length increases. This will result in fabrics that are stiffer in the MD than in the CD. This preferential reorientation of fibres in the MD as the specific energy increases has been noted by Qiao[82] and Moschler et al.[77].

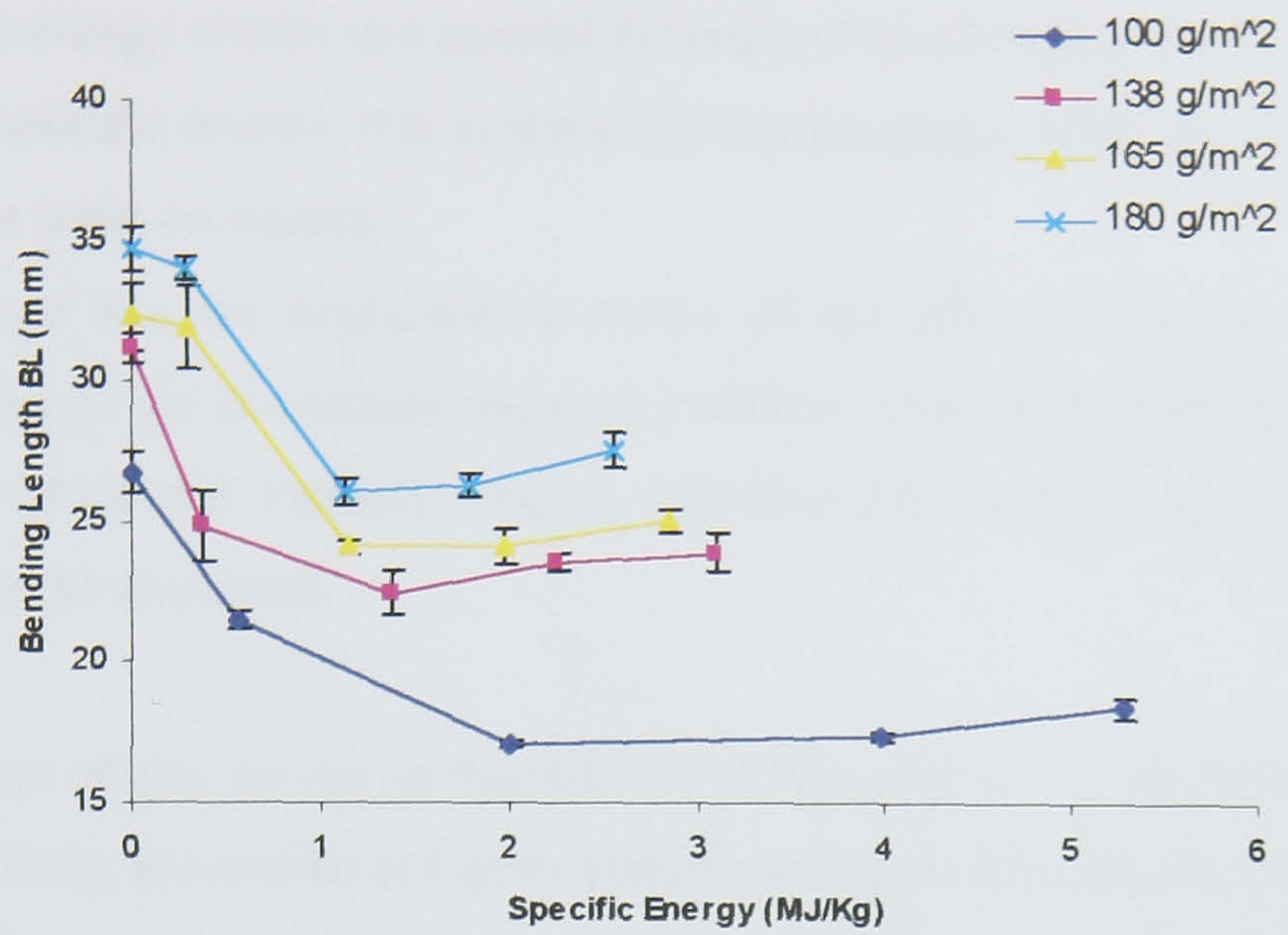


Figure 4.8 Effect of Specific Energy on Bending Length (Bias Direction)

4.1.5.3 Bending Rigidity

The bending rigidity (BR) of a fabric is defined[46] as the couple required to bend a fabric to a unit curvature and is a function of the bending length and fabric weight per unit area. The FAST system determines bending rigidity (BR) from the cantilever bending length of the fabric as indicated in chapter 2, section 2.2.7.

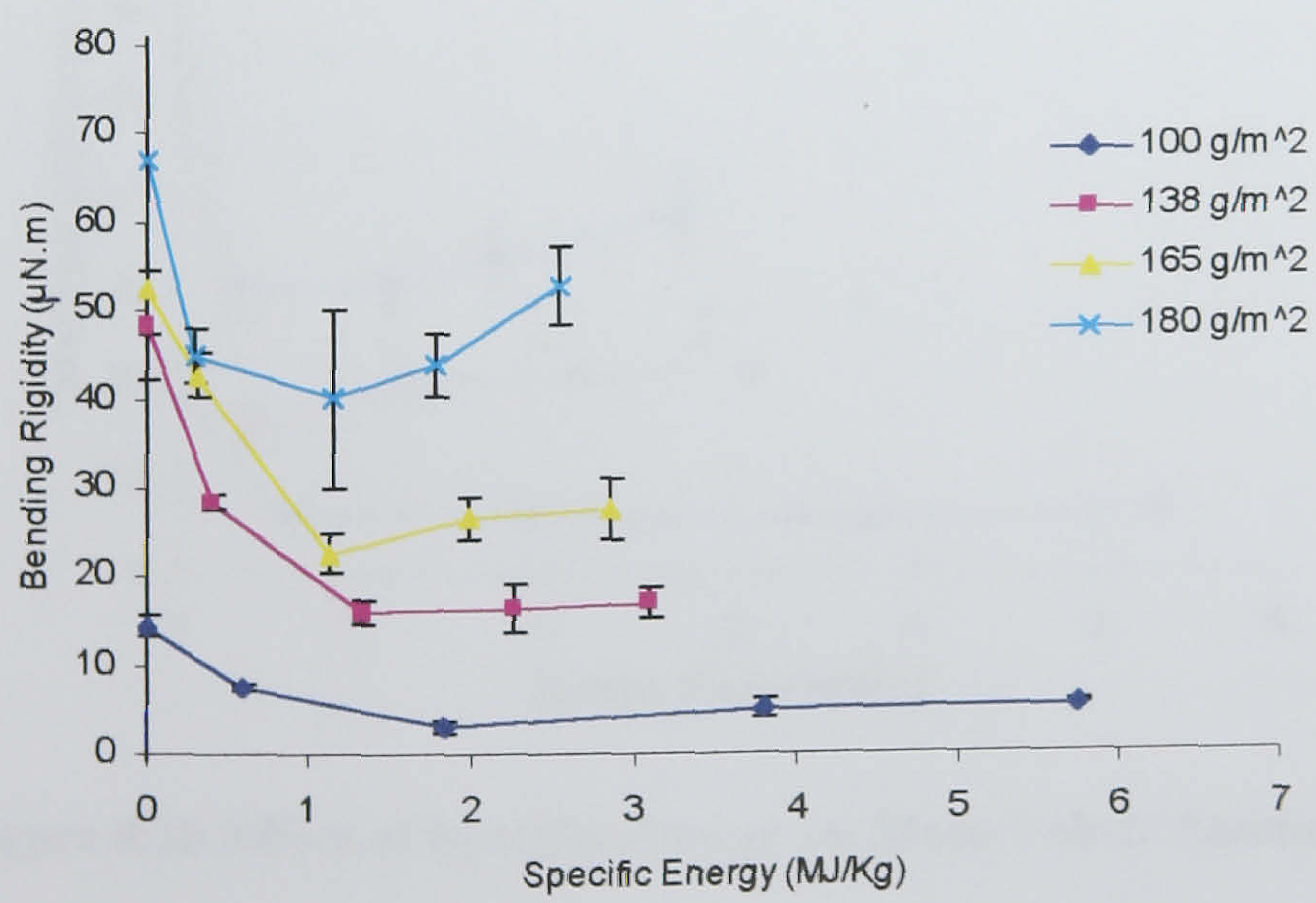


Figure 4.9 Effect of Specific Energy on Mean Fabric Bending Rigidity (MD)

Figure 4.9 shows that for the MD, initially at low specific energies, an increase in the specific energy results in a general decrease in bending rigidity for all the fabric weights. At higher specific energy, it is evident that the bending rigidity for all the fabric weights tends to either level or increase.

The trend can be explained in terms of the fabric bending length, which decreases according to the associated decrease in fabric thickness and the weight per unit area of the fabric. Given the method used to calculate the bending rigidity, such a decrease, can therefore be expected.

The form of the curves in figures 4.9, 4.10 and 4.11 for the MD, CD and bias direction respectively, are similar at higher specific energies. Smaller incremental decreases in fabric thickness are observed (see sections 4.1.2) and the bending length therefore increases probably due to further fabric consolidation and the increase of the fabric density. It is also interesting to note that the increase in bending rigidity associated with the increase in the specific energy appear to increase with fabric weight.

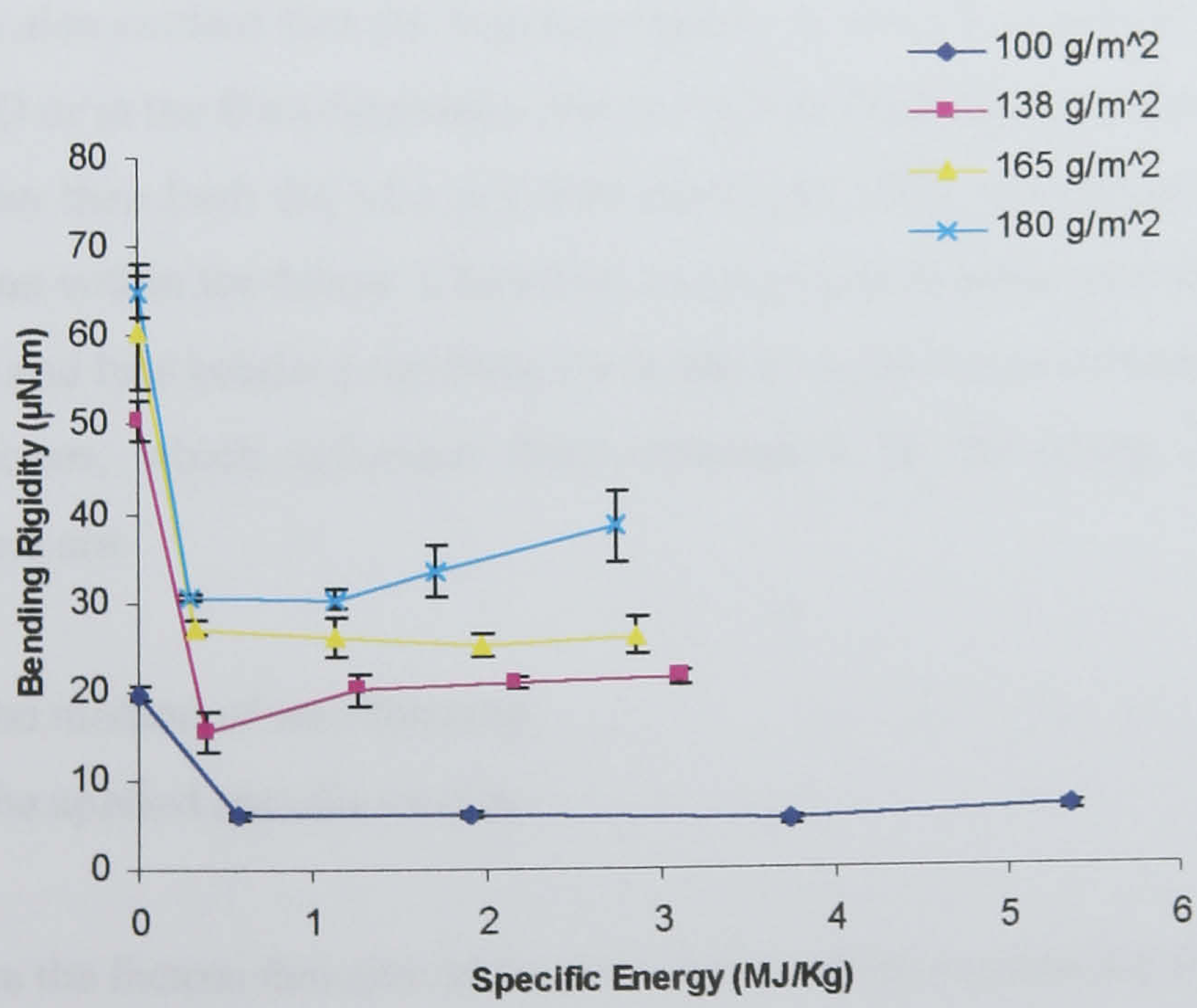


Figure 4.10 Effect of Specific Energy on Mean Fabric Bending Rigidity (CD)

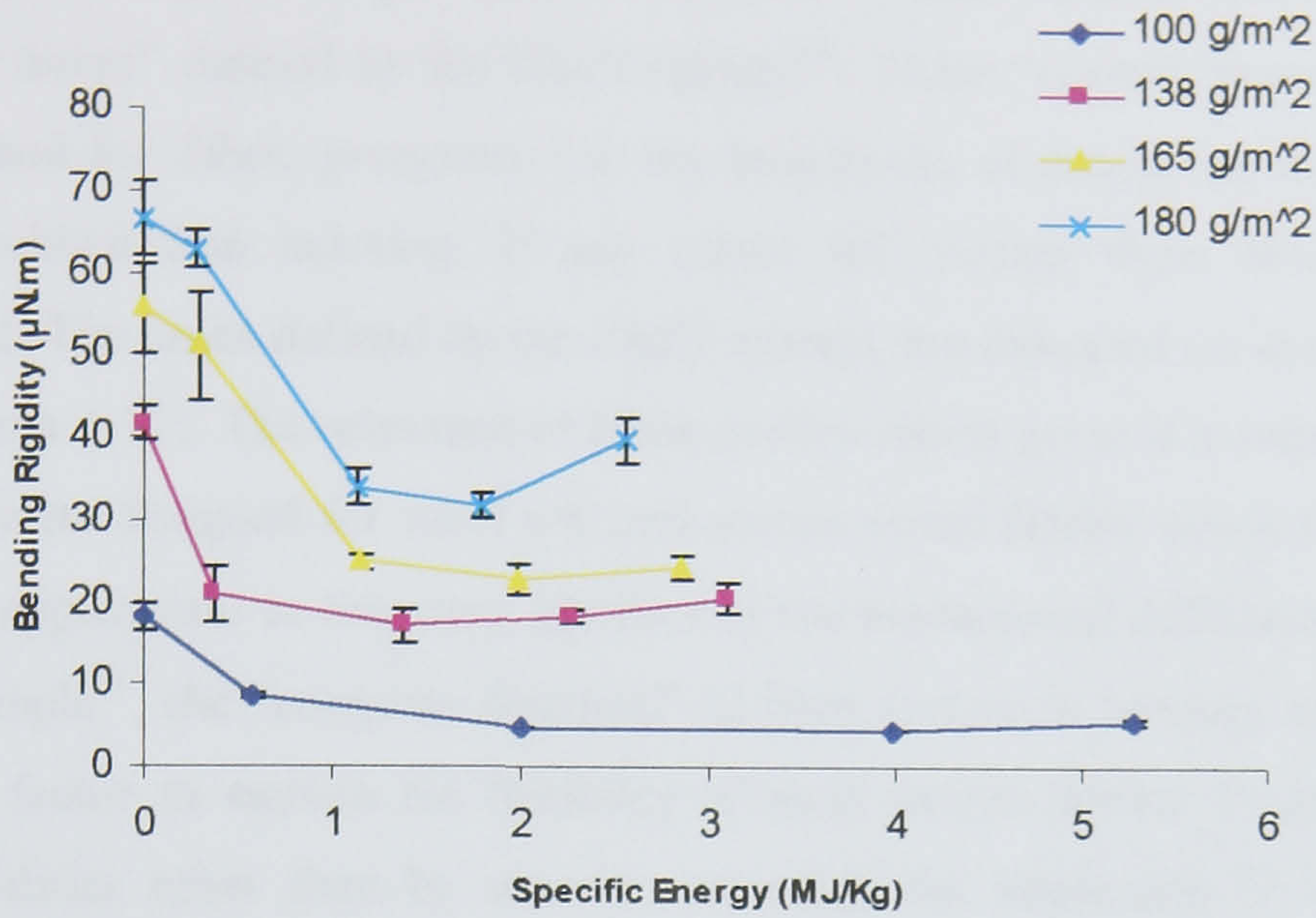


Figure 4.11 Effect of Specific Energy on Mean Fabric Bending Rigidity (Bias)

In figures 4.10 and 4.11, it is evident that similar general trends are evident as for figure 4.9. It is also evident that the bending rigidity in the CD direction is generally lower than in the MD or in the Bias directions that accords with the bending length in the CD, which is also, lower than both the MD and Bias directions. This reflects the anisotropy in the fibre orientation within the fabric. Therefore, it is reasonable to suggest that the difference in the MD, CD and bias bending rigidities (or in other words the anisotropy) will be influenced by those factors, which influence fibre orientation in the fabric. The principal process parameters are:

1. the method of web forming;
2. the applied specific energy.

These are the factors that should be considered when engineering the fabric properties.

Compared with conventional fabrics intended for use in apparel applications (e.g. woven suit fabrics), and according to the FAST system, most of the bending rigidity values for the hydroentangled fabrics produced at relatively higher specific energies would be acceptable, especially the lighter-weight fabrics. In other words, most of the values fall within the "control zones" defined by the FAST manual[46]. These "control zones ", are the limits that are defined for fabric properties (or the boundaries of properties for fabrics) that would offer problem free tailoring. If any values fall outside these limits, problems can be expected. The limits defined by the FAST system, are indicated on each graph for reference (e.g. figure 4.12). The relevance of these control charts given is questionable in this context as they were designed for wool worsted woven suited fabrics which may not, therefore, be entirely appropriate in this case, because of the fundamental differences in fabric structure. For example[55], the "complete freedom" of fibre motion in bending most woven fabrics, is the key factor to explain the flexibility of most woven fabrics. In attempting to produce textile fabrics other than by weaving, as while the interlacing of warp and weft yarns provides a "self-locking" structure of sufficient tensile strength, it is often necessary to introduce a certain amount of interfibre bonding in nonwoven materials to achieve the same result. This bonding[55,58], however, is incompatible with an independent fibre bending mechanism. Accordingly, the drape and handle of many nonwoven fabrics is such that their usage in clothing is still limited[55]. Also the fabrics that made from fibres with high resistance to extension will be stiffer than fabrics that made from fibres, which are easily extended[59]. And as mentioned earlier, (see section 1.10.2, chapter 1) Stevenson[29] claimed that in a nonwoven fabric, the mechanisms of deformation at a bend requires fibre rotation, straightening in the fabric plane, buckling at the bend and bending out of the fabric plane, and bond rotation and bending. Whereas, in woven fabrics, the distortion mechanisms that are presented require little or no elastic strain energy and afford a low resistance to the bending forces[29].

Further comparisons between the mechanical properties of hydroentangled fabrics and that of normal shirting fabrics are shown in section 4.3. Figure 4.12 shows an example of a FAST control chart for a woven fabric with a low bending rigidity. However, it should be borne in mind that the FAST control charts were designed for wool and wool blend woven fabrics so that the limits may not be entirely appropriate for viscose nonwoven fabrics.

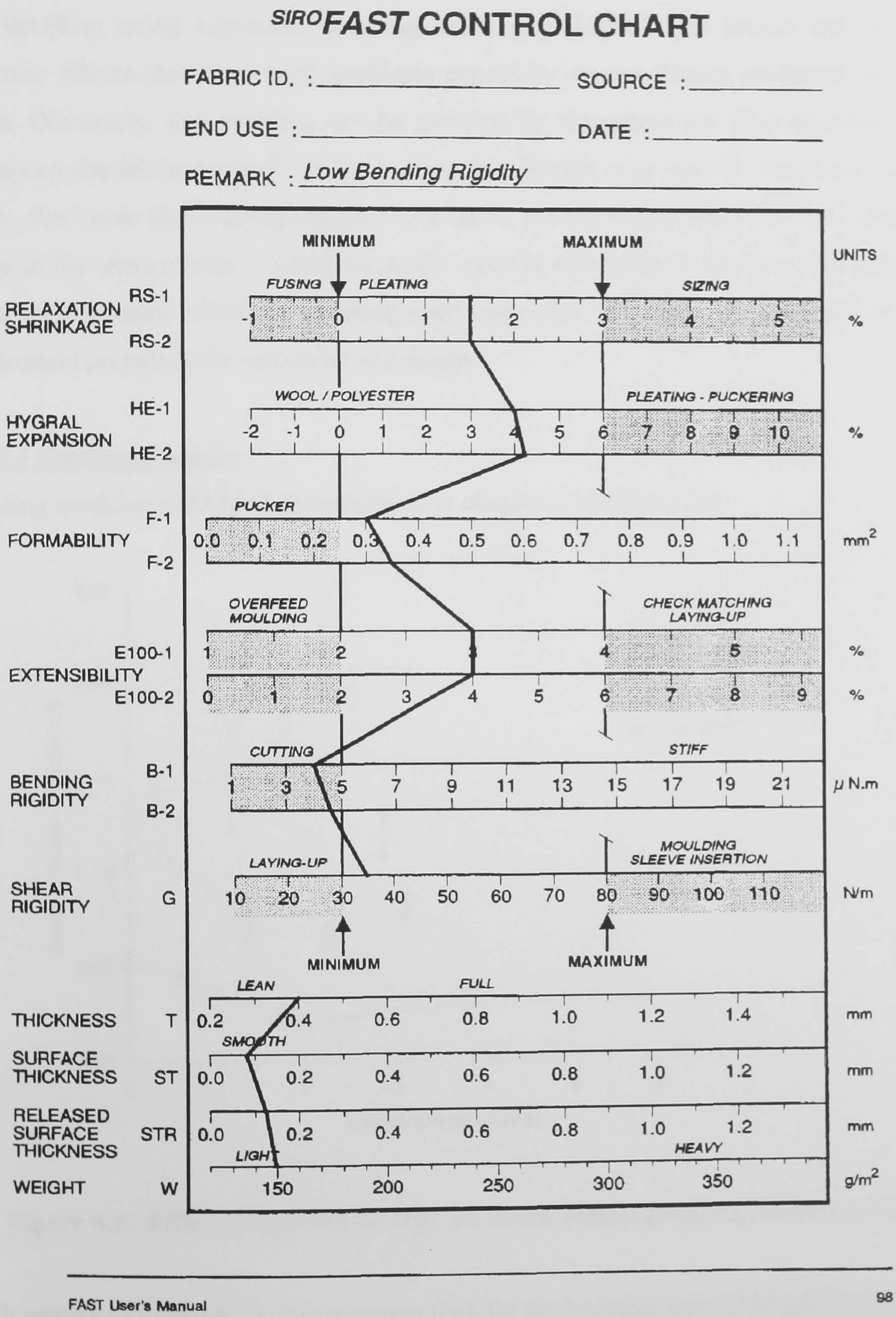


Figure 4.12 FAST Control Chart for a Woven Fabric With Low Bending Rigidity[46]

In figure 4.12, it can be noticed that a low bending rigidity can cause difficulties in cutting and handling using automated tailoring machinery. Lightweight fabrics are the most common fabrics that have such problems especially woven fabrics produced from fine fibres. Obviously, this problem can be avoided by increasing the fibre diameter or by increasing the fabric weight[46]. In hydroentangled fabrics, it is notable that the lighter the fabric, the lower the bending rigidity, low fabric density and a relatively low number of fibres in the cross section. Such fabrics can result in low bending rigidity. This should be taken into account when engineering hydroentangled fabrics with specific low stress mechanical properties for particular end usage.

4.1.5.4 Bending Modulus

Bending modulus is defined as mentioned in chapter 2, section 2.2.7

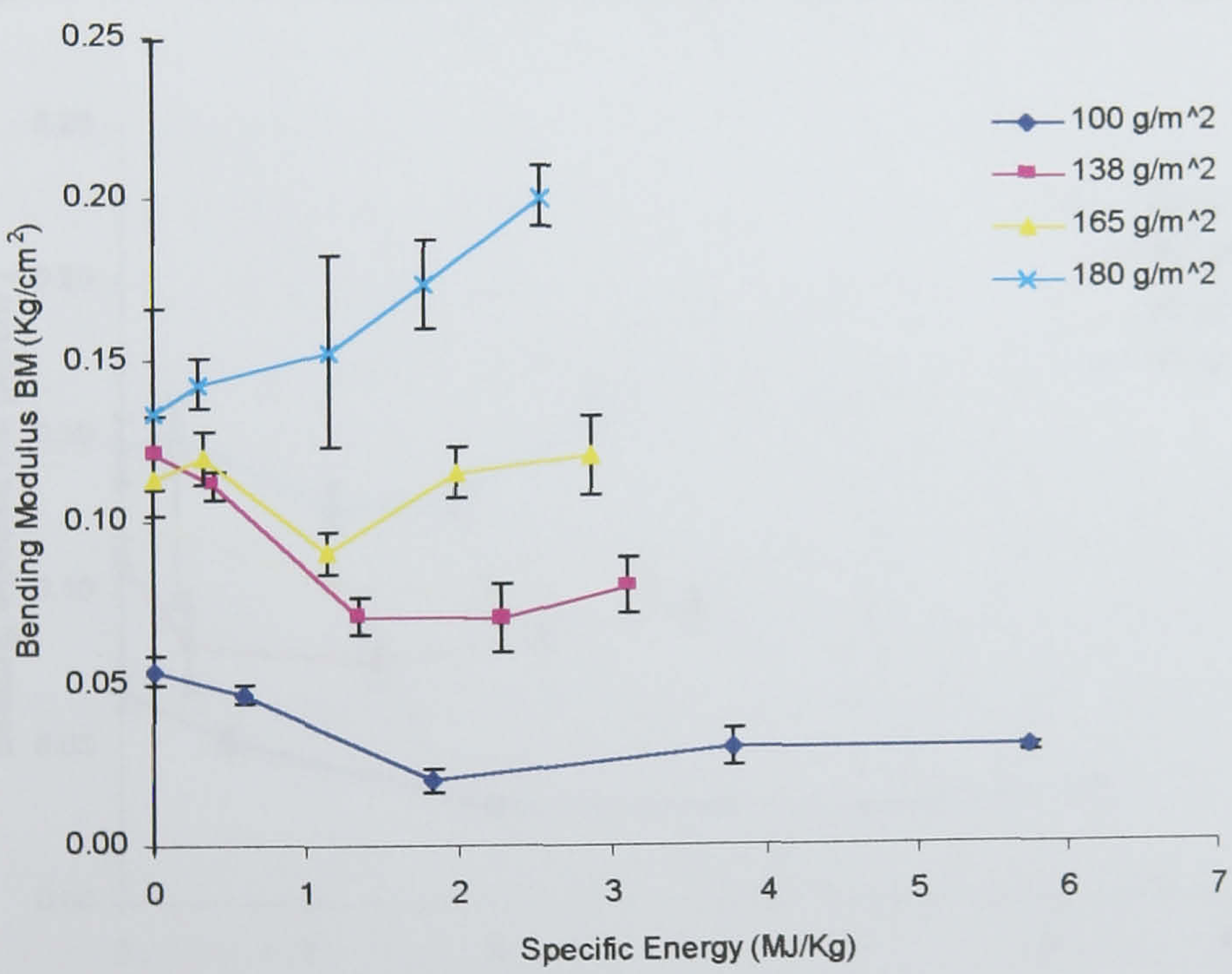


Figure 4.13 Effect of Specific Energy on Mean Fabric Bending Modulus (MD)

With respect to Figure 4.13, it is apparent that, for the heaviest webs (180 g/m^2), increasing the specific energy generally increases the bending modulus. However, the trends are different for the lighter-weight fabrics.

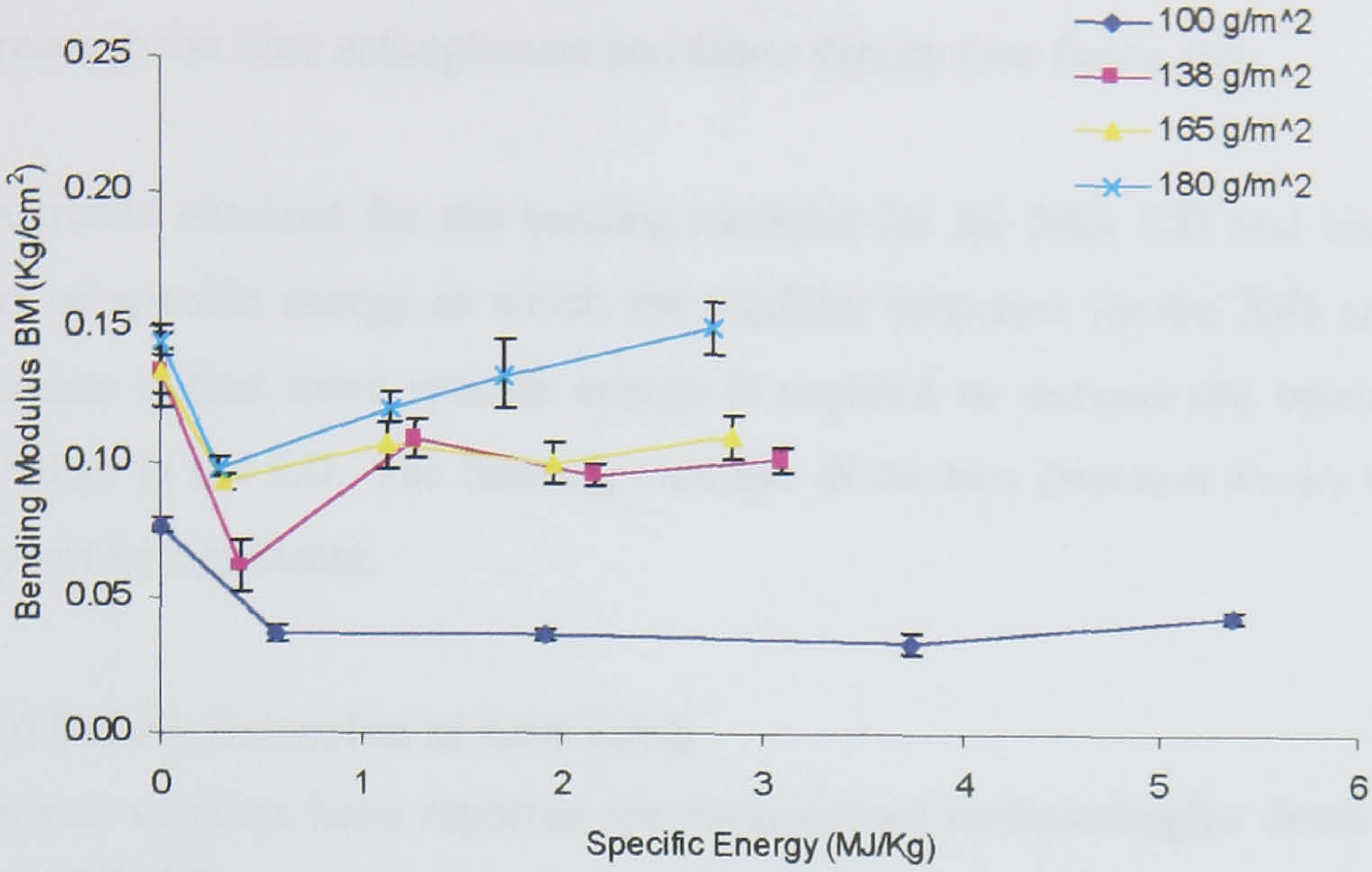


Figure 4.14 Effect of Specific Energy on Mean Fabric Bending Modulus (CD)

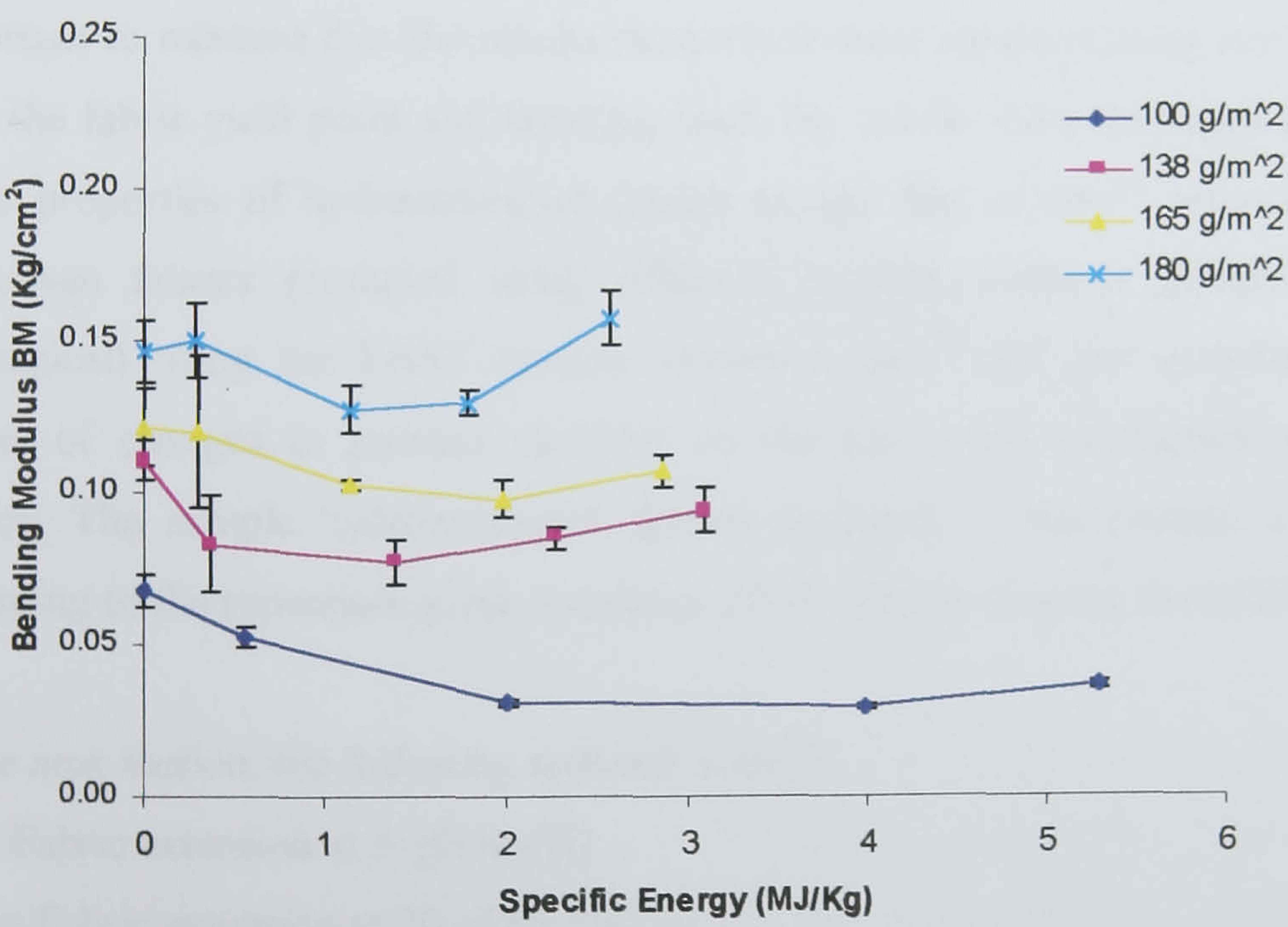


Figure 4.15 Effect of Specific Energy on Mean Fabric Bending Modulus (Bias)

In Figures 4.13, 4.14 and 4.15, the trends obtained are probably due to the rapid decrease in fabric thickness, when the web is initially hydroentangled, which is followed by a leveling for some of the fabrics (especially the lighter weight fabrics). The bending modulus for the other fabric area densities at higher specific energies tends to increase, probably due to an increase in the fibre entanglement and fabric density (see figure 4.4).

The trends obtained for the bending modulus for the MD, CD and bias differ in that the level of specific energy at which the modulus increases for the MD and CD differs. The inference is that more specific energy is required to increase the bending modulus in the MD than in the CD. The bending modulus in the bias direction shows little difference and may not be significant.

4.1.6 Fabric Extension at Low Load

Previous workers have reported the extension of hydroentangled fabrics at peak breaking load [80,81,82,86] and generally have shown that increasing the applied specific energy decreases the tensile fabric extension. While similar results were obtained in the present study, especially when using the higher load of 100 gf/cm (see Figures 4.22 – 4.24), it is important to mention that the results shown here were obtained using low loads well below both the fabric yield point and breaking load. No similar work has been found on the low stress properties of hydroentangled fabrics except that of Jain[50] who tested commercial nonwoven fabrics produced using different bonding methods (chemical, thermal and mechanical) using the FAST system. However, Jain[50] did not systematically study the effects of changes in process variables on the low stress mechanical properties of the fabrics. The sample hydroentangled fabrics produced in the present work were tested according to the procedure given in section 2.2.4, chapter 2, using the FAST system[46].

In the next section, the following notation is used:

E5 = Fabric extension at 5 gf/cm (%)

E20 = Fabric extension at 20 gf/cm (%)

E100 = Fabric extension at 100 gf/cm (%)

4.1.6.1 Fabric Extension at 5 gf/cm

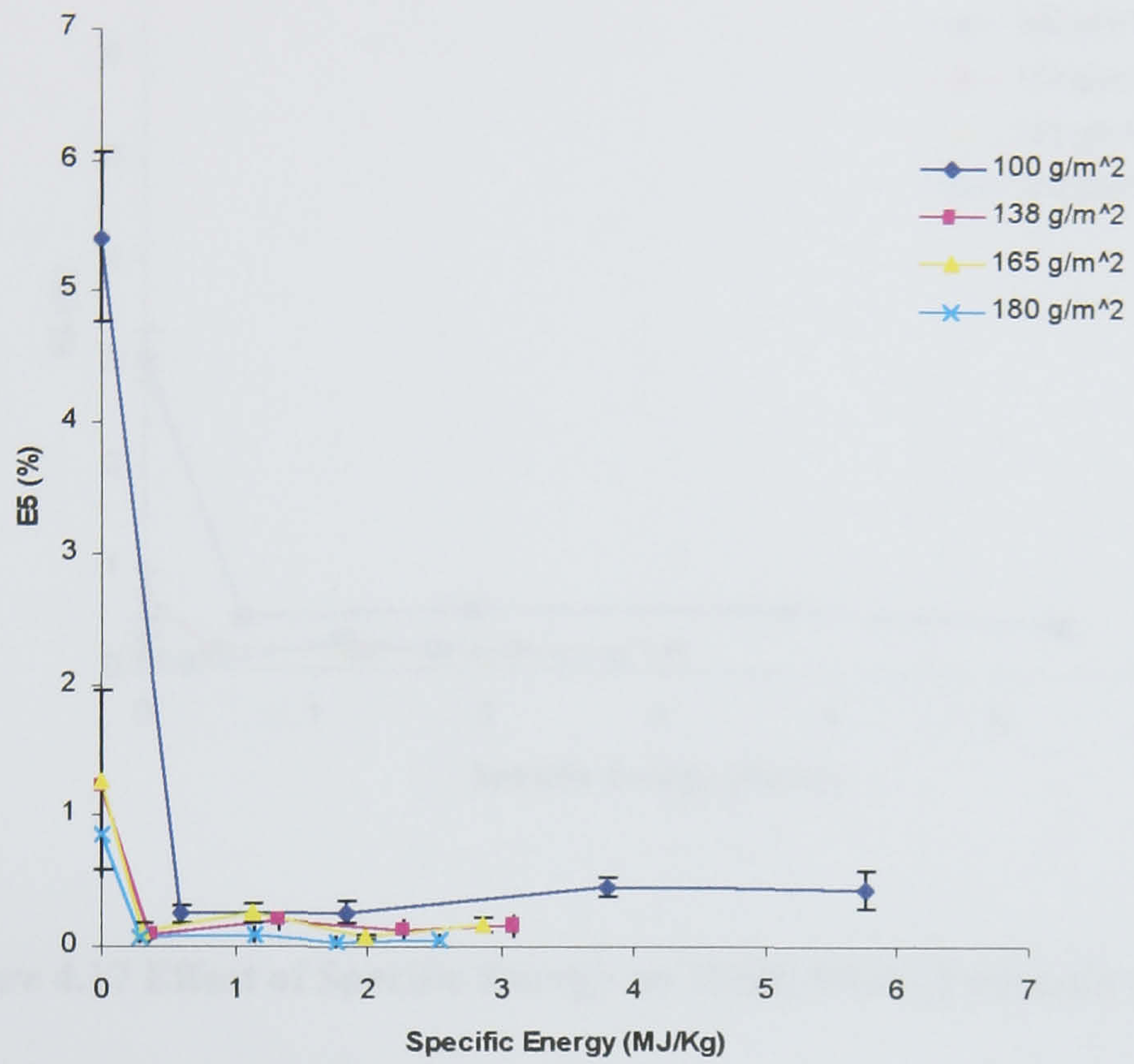


Figure 4.16 Effect of Specific Energy on Mean Fabric Extension at 5 gf/cm (MD)

Comparing figures 4.16- 4.18, it is interesting to note that the extension values tend to converge and are not clearly differentiated by changes in fabric weight per unit area irrespective of the direction of measurement (MD, CD or Bias).

As the load increases, there tends to be greater differentiation between the fabric weight per unit area particularly at 100 gf/cm force. It is to be expected that the lighter-weight fabrics will extend more at low loads due to the low frictional resistance offered by the small number of fibres in the fabric cross-section compared to the heavier fabrics.

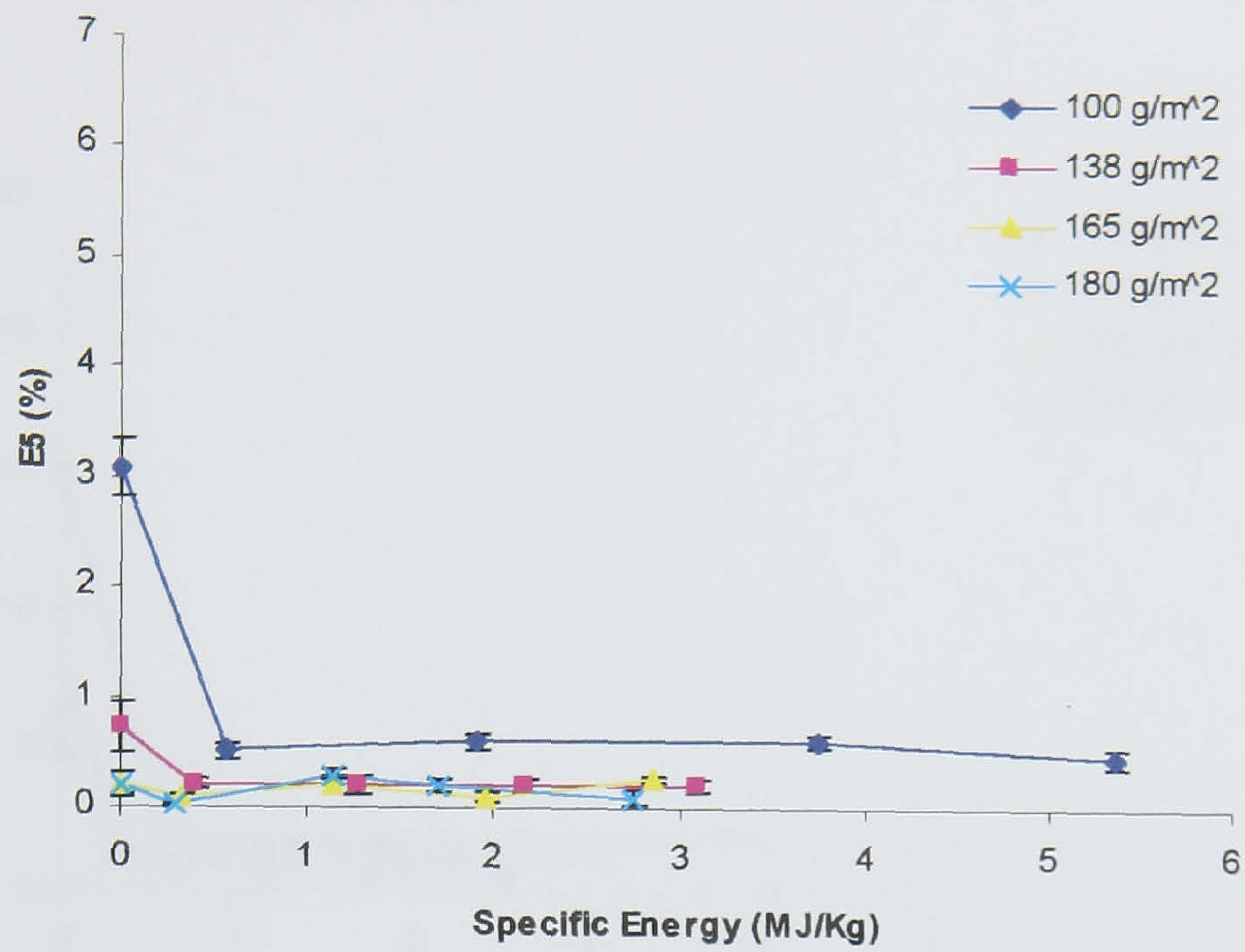


Figure 4.17 Effect of Specific Energy on Mean fabric Extension at 5 gf/cm (CD)

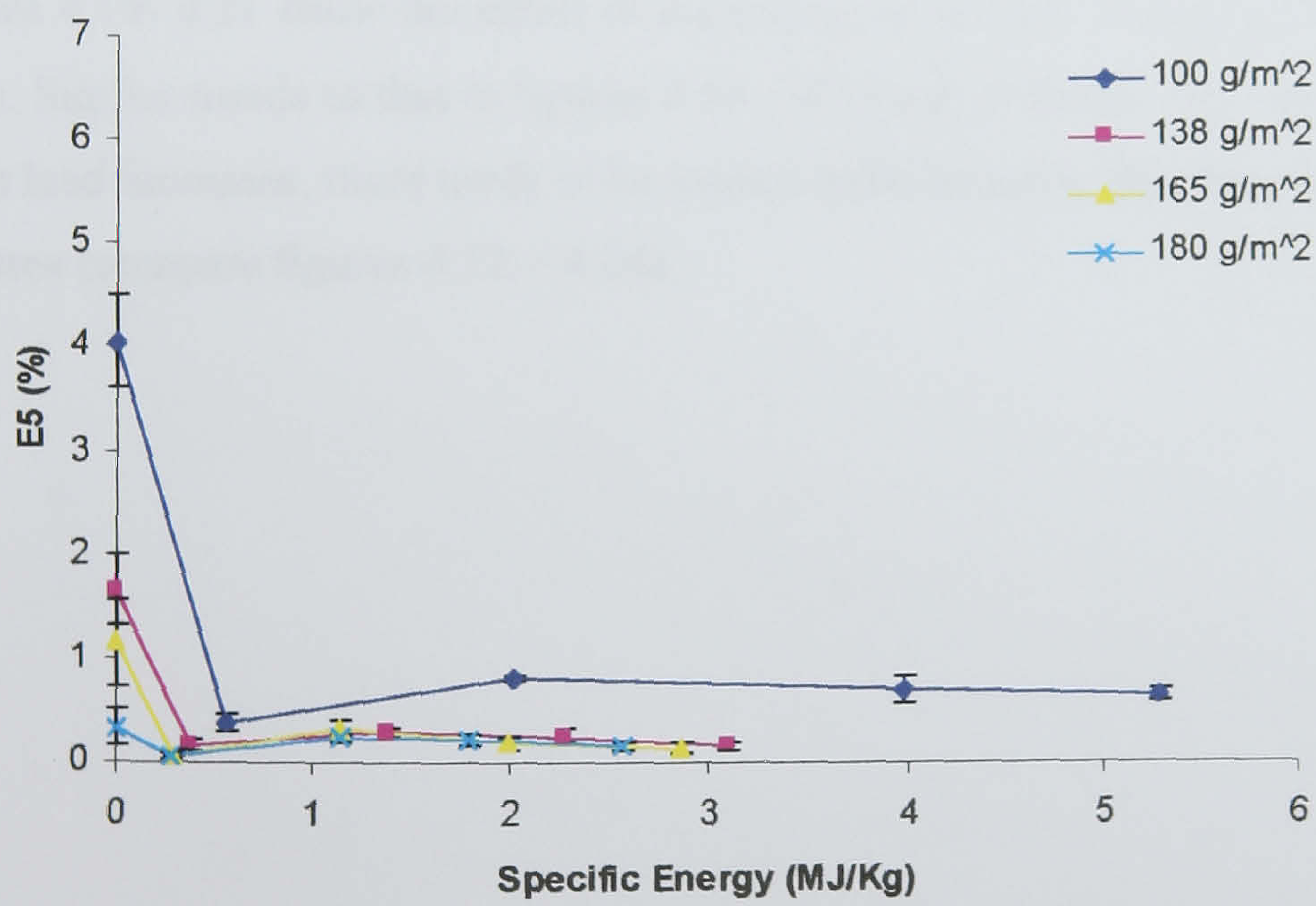


Figure 4.18 Effect of Specific Energy on Mean Fabric Extension at 5 gf/cm (Bias)

4.1.6.2 Fabric Extension at 20 gf/cm

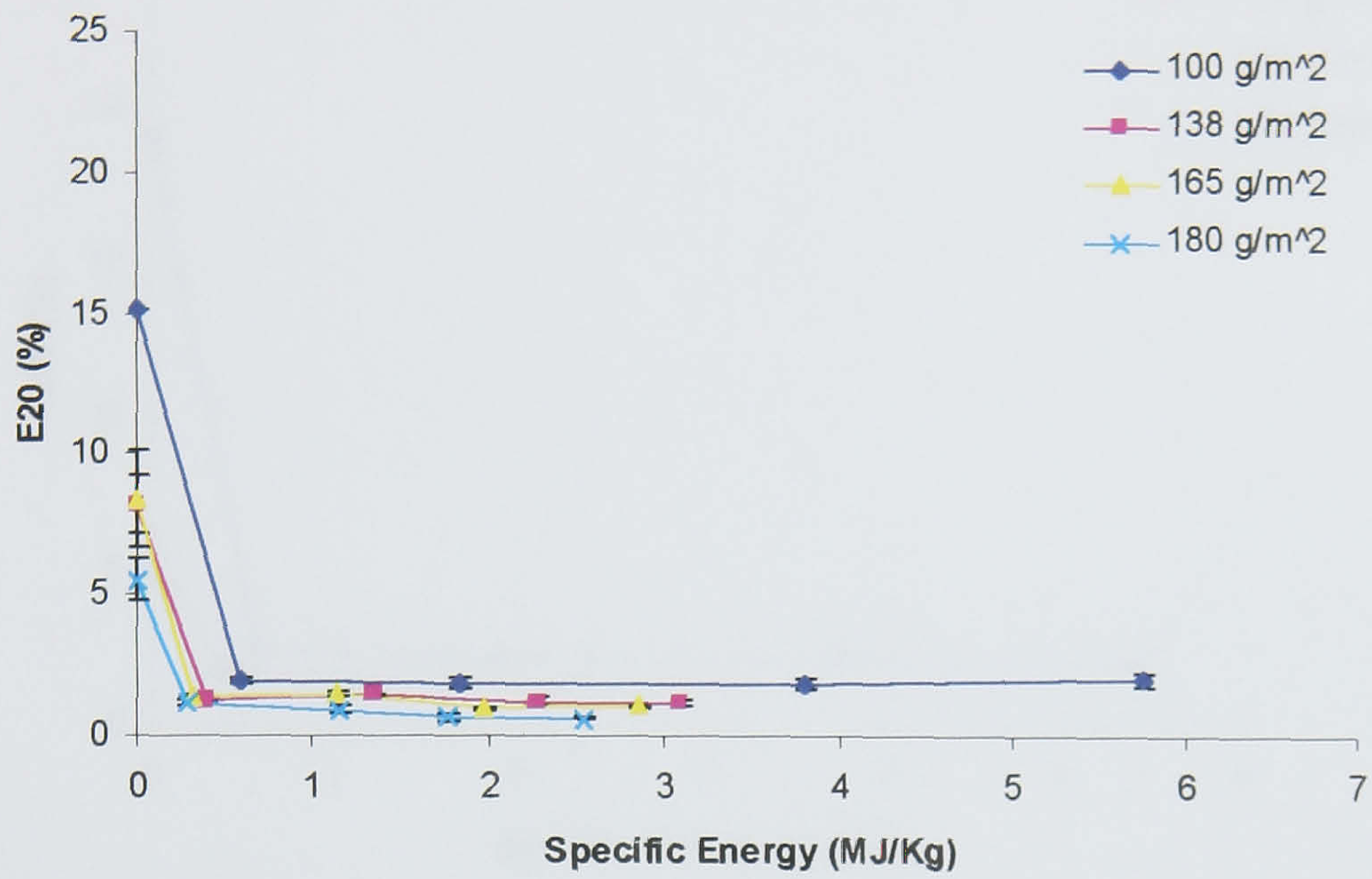


Figure 4.19 Effect of Specific Energy on Mean Fabric Extension at 20 gf/cm (MD)

Figures 4.19- 4.21 show the effect of increasing of specific energy on the extension at 20 gf/cm. Similar trends to that in figures 4.16 – 4.18 are obtained. It is interesting to note that as the load increases, there tends to be greater differentiation between the fabric weight per unit area (compare figures 4.22 – 4.24).

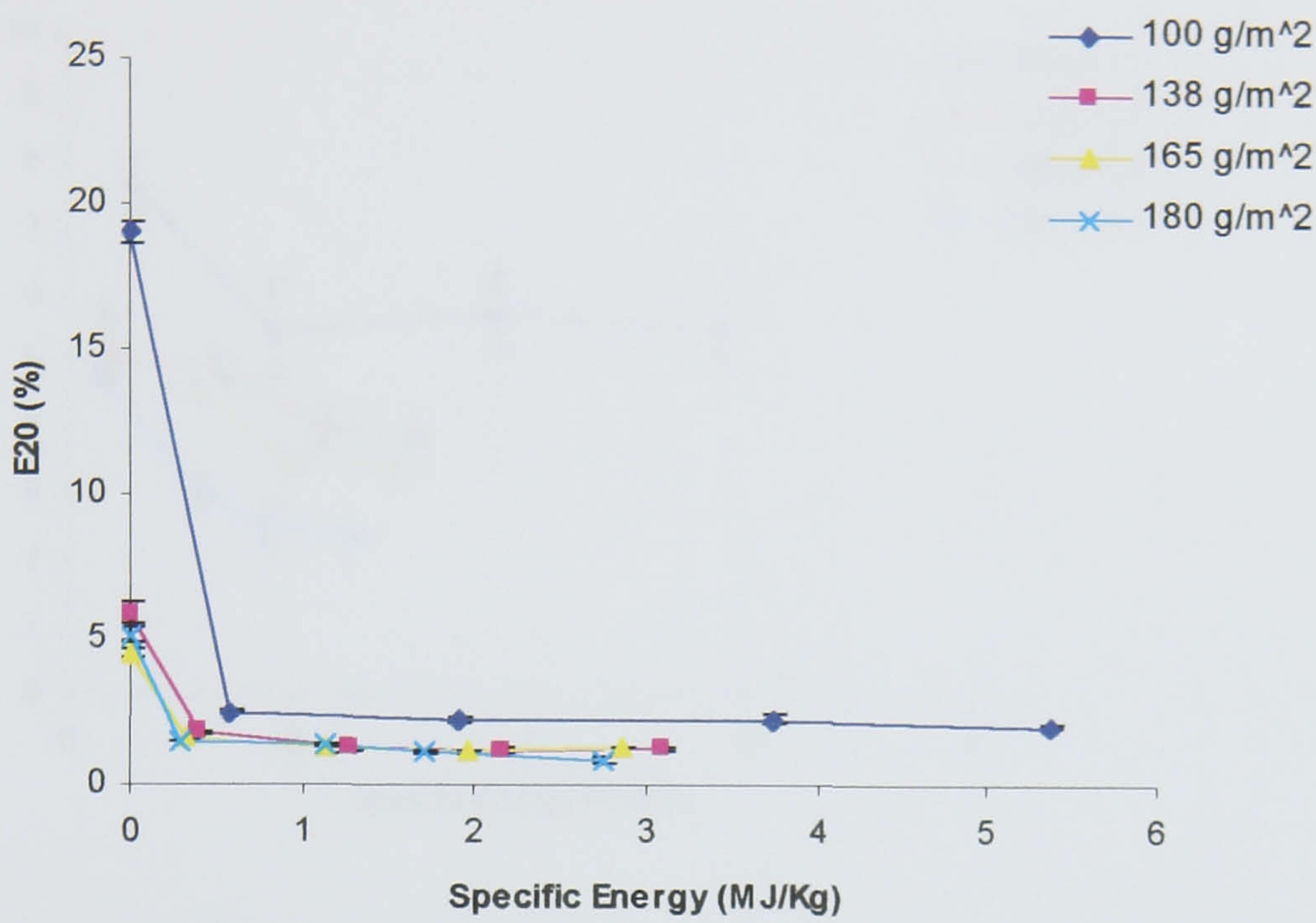


Figure 4.20 Effect of Specific Energy on Mean Fabric Extension at 20 gf/cm (CD)

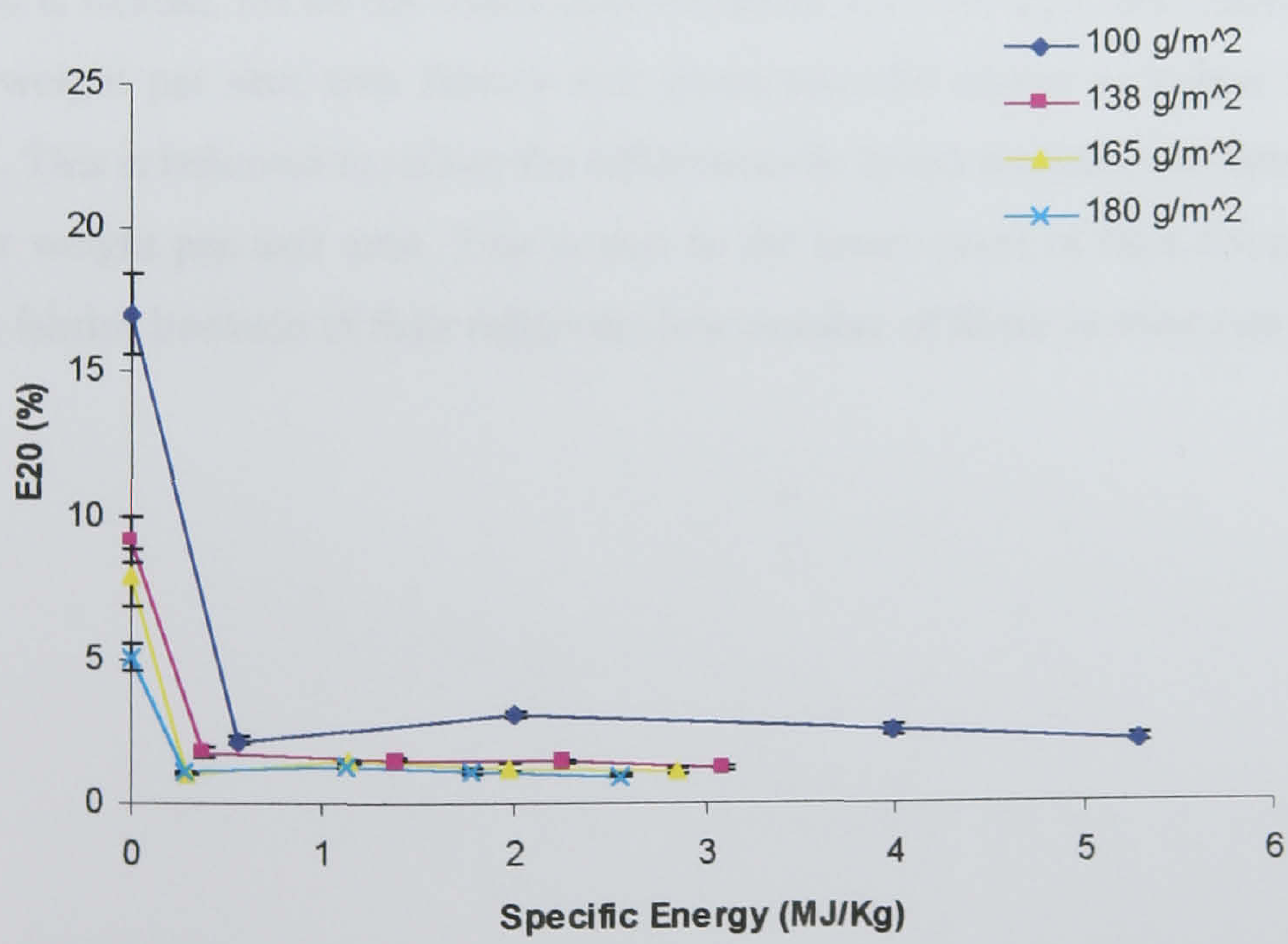


Figure 4.21 Effect of Specific Energy on Mean Fabric Extension at 20 gf/cm (Bias)

4.1.6.3 Extension at 100 gf/cm

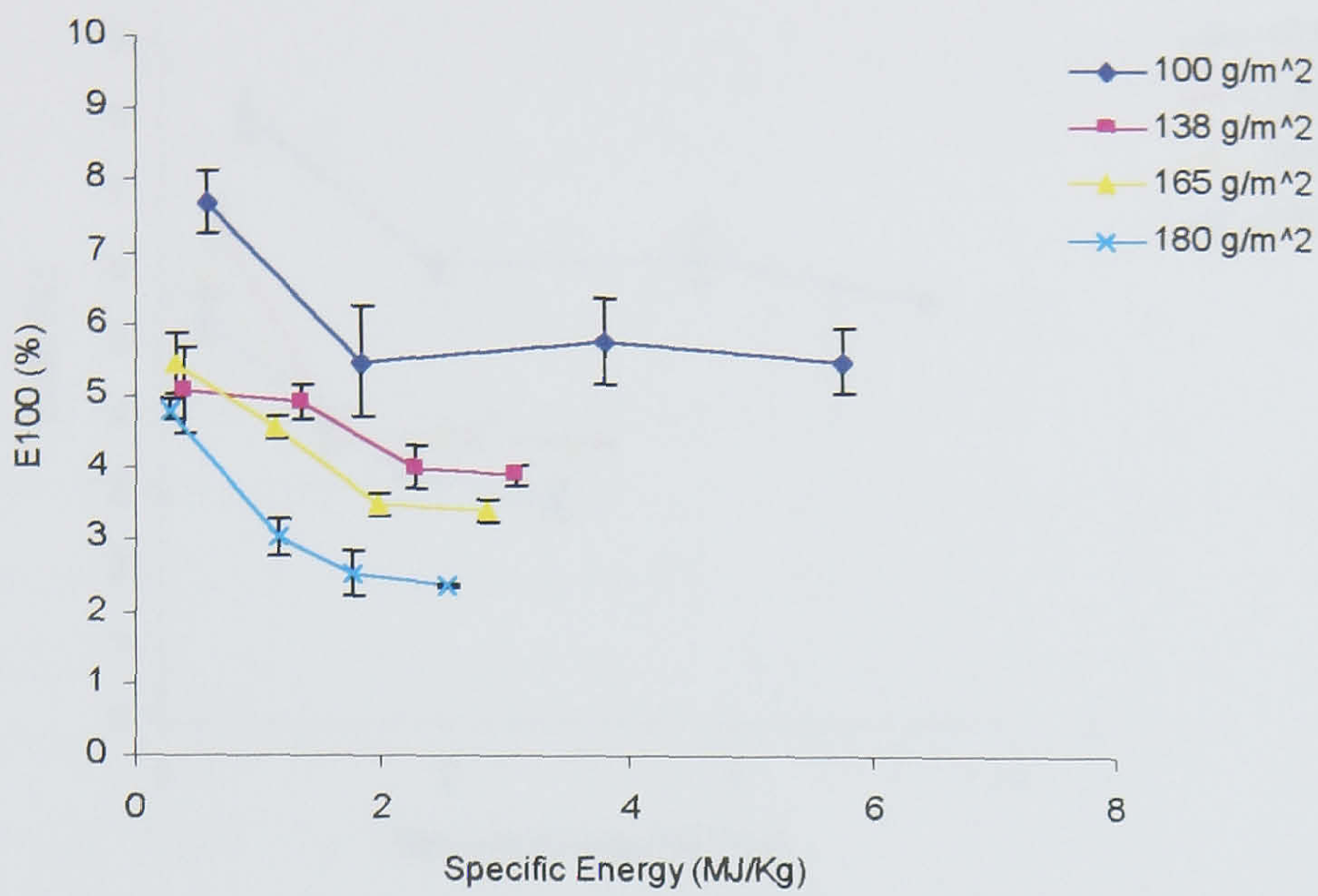


Figure 4.22 Effect of Specific Energy on Extension at 100 gf/cm (MD)

In figures 4.22- 4.24, it is also evident that the values of extension initially decrease when the web is treated, for all the fabric area densities. Furthermore, the extension of the lower fabric weight per unit area fabrics at a given specific energy is higher than the heavier fabrics. This is believed to reflect the differences in fabric resistance to extension according to their weight per unit area. This is due to the lower level of fibre friction in the lighter weight fabrics because of their relatively low number of fibres in the cross sections.

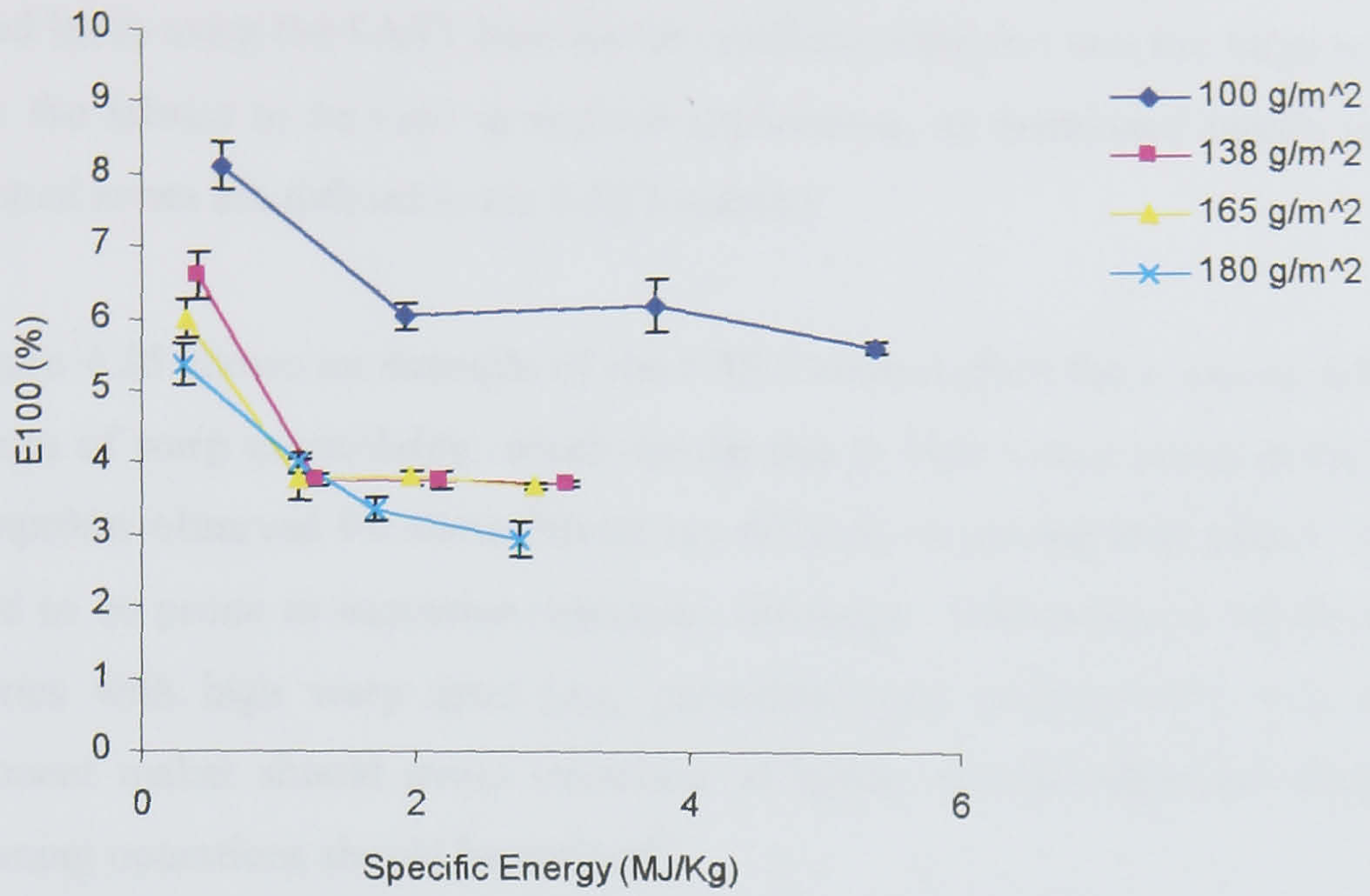


Figure 4.23 Effect of Specific Energy on Mean Fabric Extension at 100 gf/cm (CD)

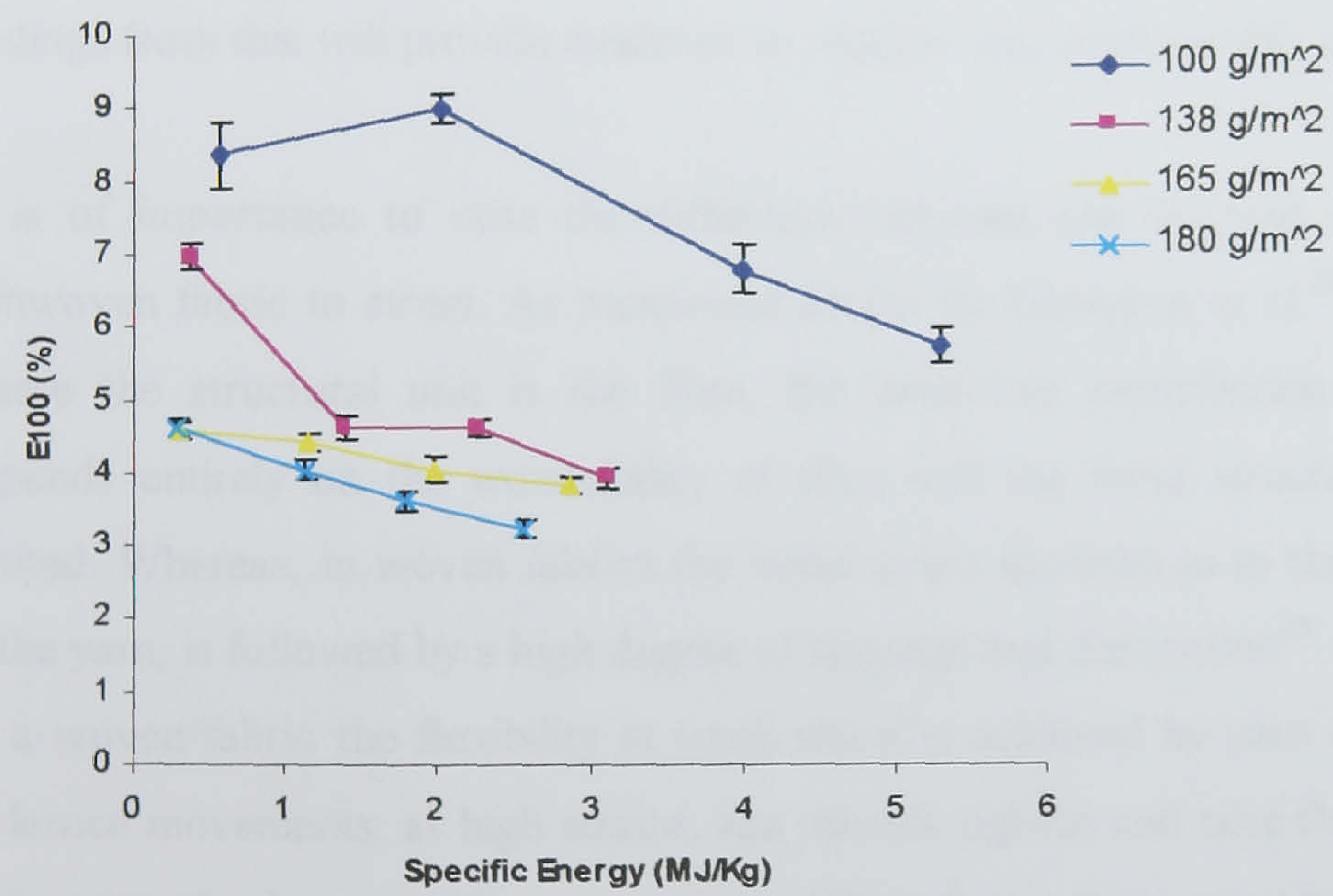


Figure 4.24 Effect of Specific Energy on Mean Fabric Extension at 100 gf/cm (Bias)

Comparing figures 4.22 – 4.24, it is interesting to observe the differences in the MD, CD and bias direction. There is a gradual leveling for all the fabrics per unit areas in all directions, which starts, at different values of specific energy. This is probably due to reaching maximum consolidation.

In figures 4.22 – 4.24, the original webs could not be accurately measured at any of the fixed loads using the FAST because the resulting extension was too large to measure.
For the fabrics to be used in apparel applications, as mentioned before in section 4.1.5.3, control zones are defined in the FAST manual.

Figure 4.25 shows an example of the FAST control chart for a woven fabric that has high values of warp extensibility, which can be due to high weave crimp in the warp yarns. The symptoms observed for these fabrics are difficulty in sewing long seams. Also, such fabrics tend to be prone to excessive relaxation shrinkage. This occurs in unbalanced woven blend fabrics with high warp setts (e.g. gabardines and cavalry twill). For such fabrics, the garment maker should avoid stretching in laying up and additional attention or care for seaming operations should be noticed[46].
In hydroentangled fabrics, high extensibility may be caused by low fabric consolidation resulting in high fibre mobility. Increasing the level of specific energy used to produce the fabrics would tend to reduce the fabric extensibility and increase fabric strength[82]. The findings from this will provide evidence to suggest this, preliminarily at the higher loads.

It is of importance to note the difference between the reaction of the woven and the nonwoven fabric to stress. As mentioned earlier by Petterson et al.[28], in nonwoven fabrics, where the structural unit is the fibre, the collective contribution of neighboring fibres depends entirely on the extensibility of fibre and the bond structure and therefore it is limited. Whereas, in woven fabrics the initial stress application to the structural unit, which is the yarn, is followed by a high degree of slippage and dislocation[28].
In a woven fabric the flexibility at small strain is achieved by yarn crimp and the freedom of lattice movements: at high strains, the threads tighten and take the load together, giving high strength. In contrast, a nonwoven fabric loses these advantages where the cross-members stiffen the structure and the individual elements share the load unevenly to break easily. However, if the bonding is reduced, then fibre slippage becomes very easy, and strength decreases more[65].
Another example of a FAST control chart is given in figure 4.26, which shows the FAST chart for a fabric having low warp extension.

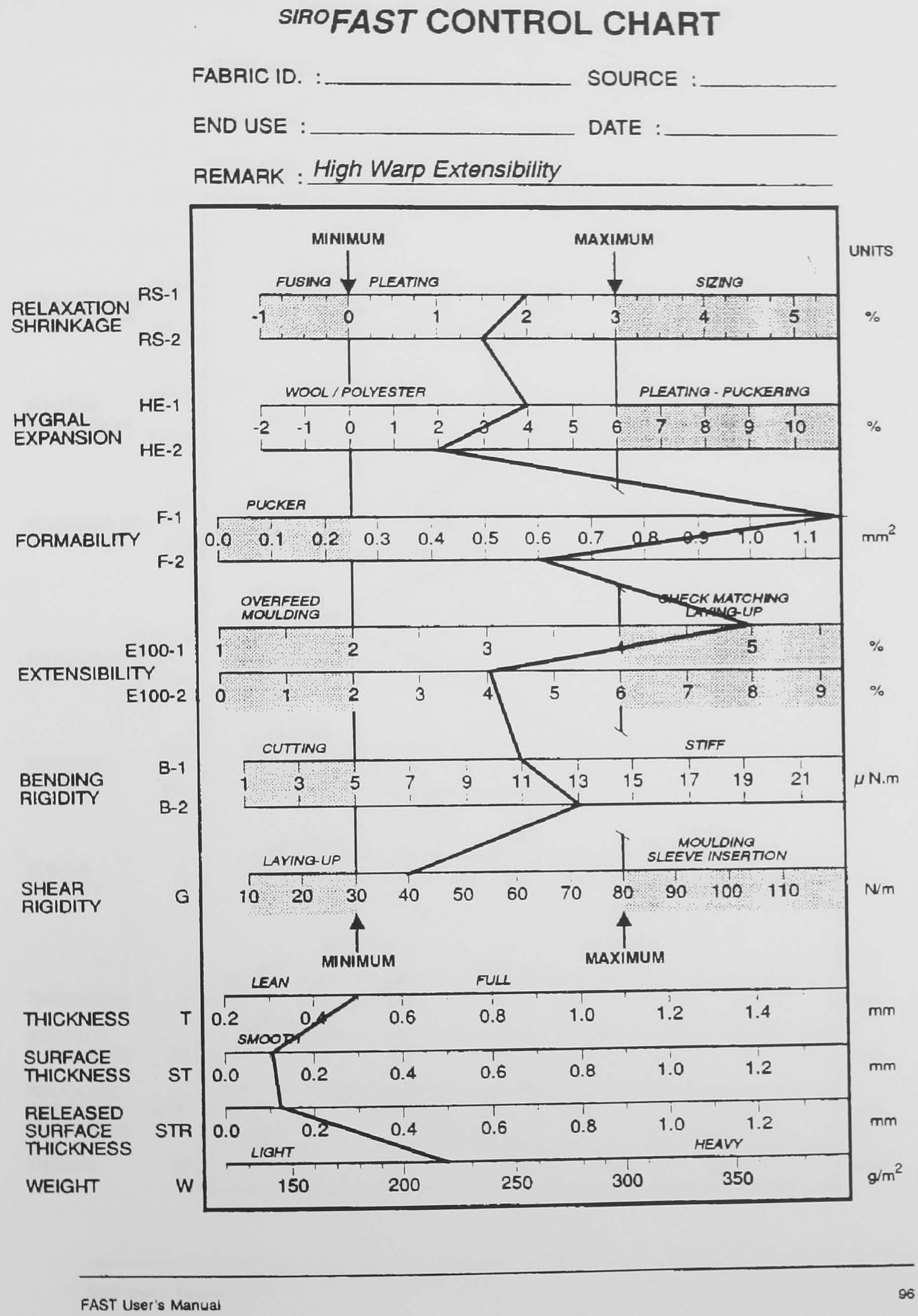


Figure 4.25 FAST Control Chart for a Woven Fabric With High Warp Extensibility[46]

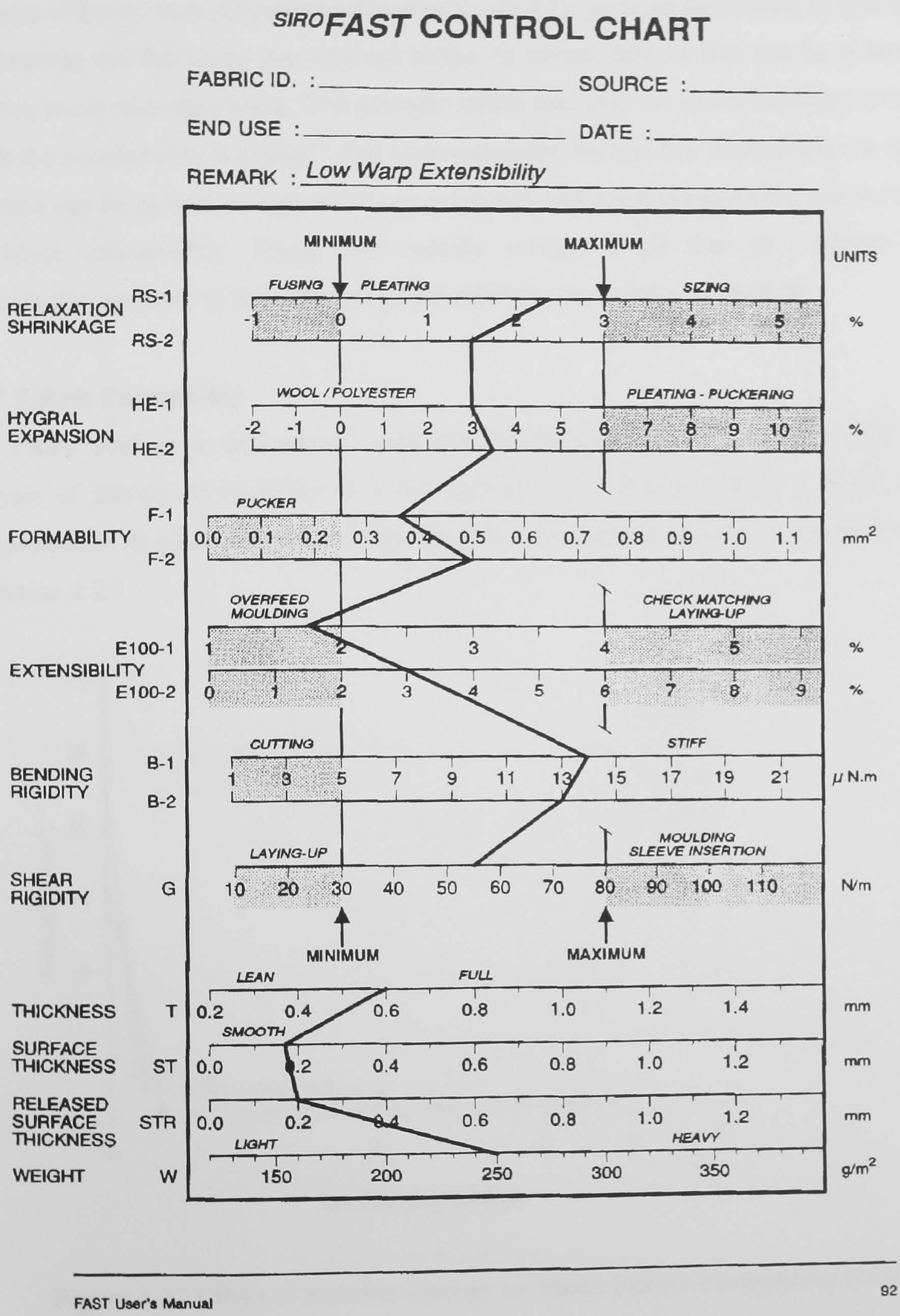


Figure 4.26 FAST Control Chart for a Woven Fabric With Low Warp Extensibility[46]

The type of fabric with properties defined in figure 4.26 presents difficulties in sewing and in moulding the fabrics to the required shape. In woven fabrics, this can be avoided by weaving more ends than picks. The garment maker may also cut seams slightly on the bias where the extensibility is higher[46]. For hydroentangled fabrics, low extensibility in the MD direction can be caused by high fabric consolidation and low fibre mobility, which reduces the fabric extensibility. Using low specific energy levels may give higher fabric extensibility, possibly to the deficient of other fabric properties e.g. strength.

4.1.7 Fabric Formability

The FAST evaluation procedure[46] uses the derived parameter, formability (F), in the analysis of fabrics. Formability is a measure of the extent to which a fabric can be compressed in its plane before it will buckle. This parameter is defined as shown in chapter 2, section 2.2.7.

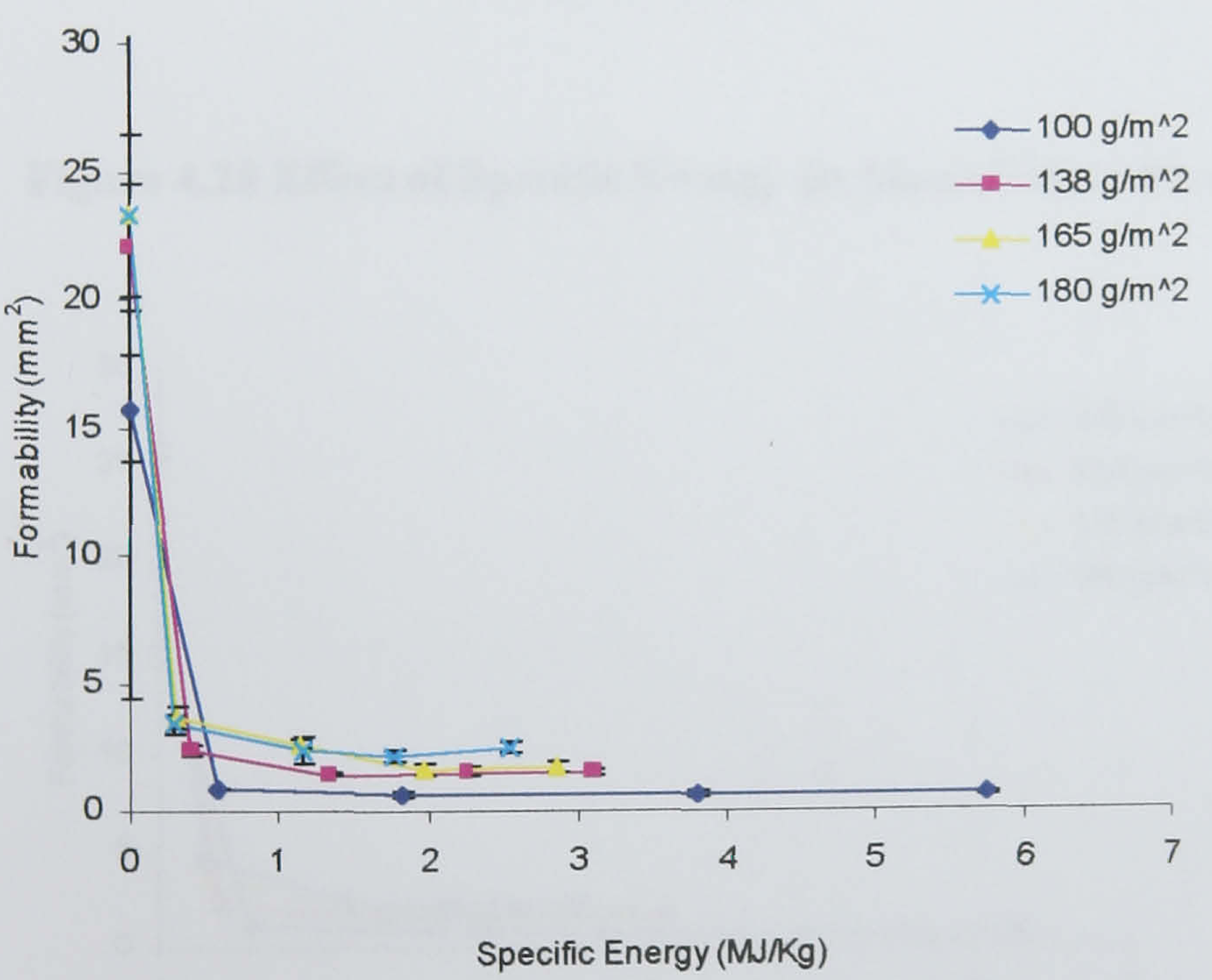


Figure 4.27 Effect of Specific Energy on Mean Fabric Formability (MD)

In general, it is clear that, following a large initial decrease in formability resulting from hydroentanglement of the webs, further increases in specific energy have very little influence on formability. This applies in the MD, CD and Bias directions. The extension values for the fabrics in the bias direction were higher than in the CD or the MD directions (figures 4.16- 4.21). This reflects the minimal effect of the increases in specific energies have on the fabric extensibility at low loads (E5 and E20 %)

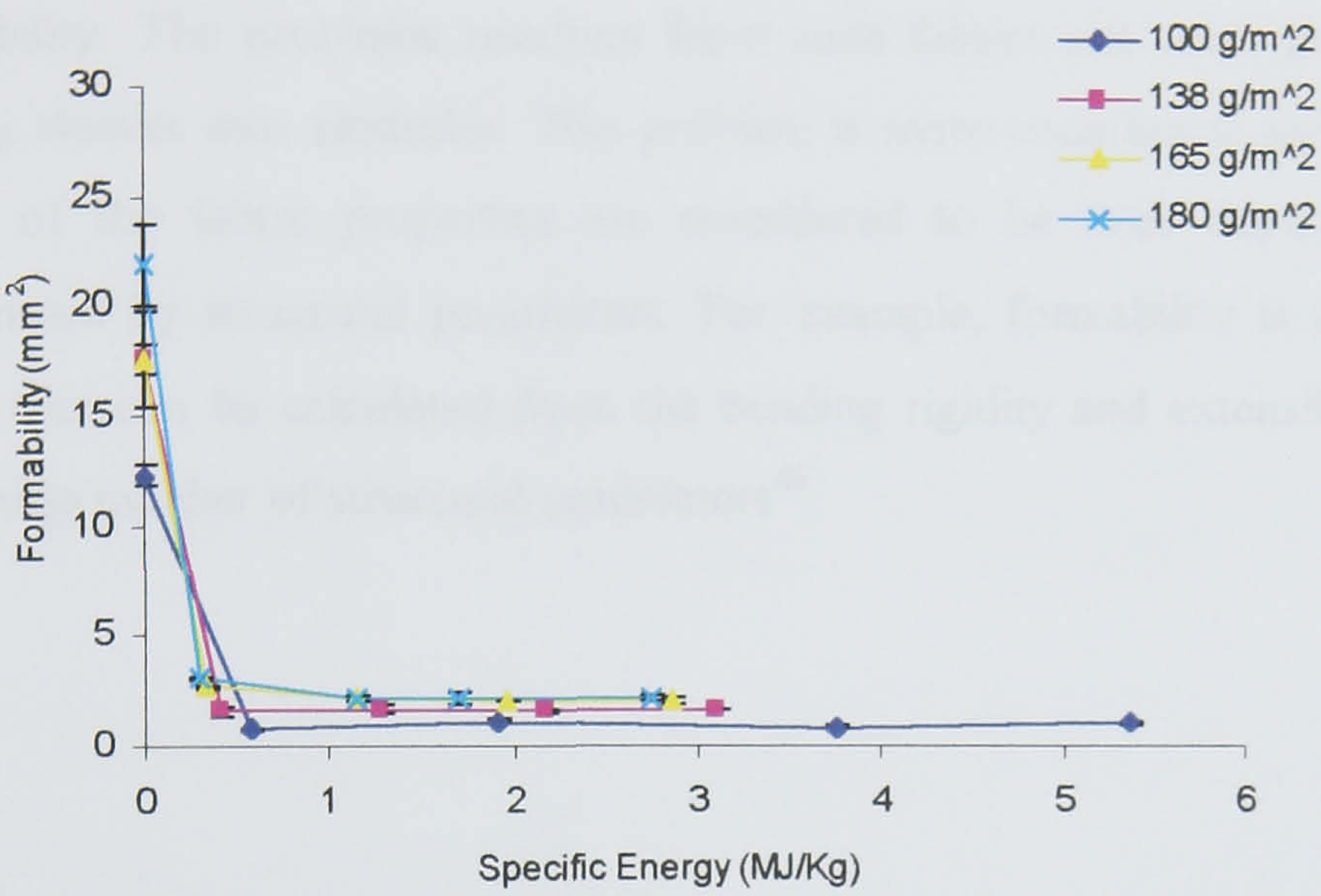


Figure 4.28 Effect of Specific Energy on Mean Fabric Formability (CD)

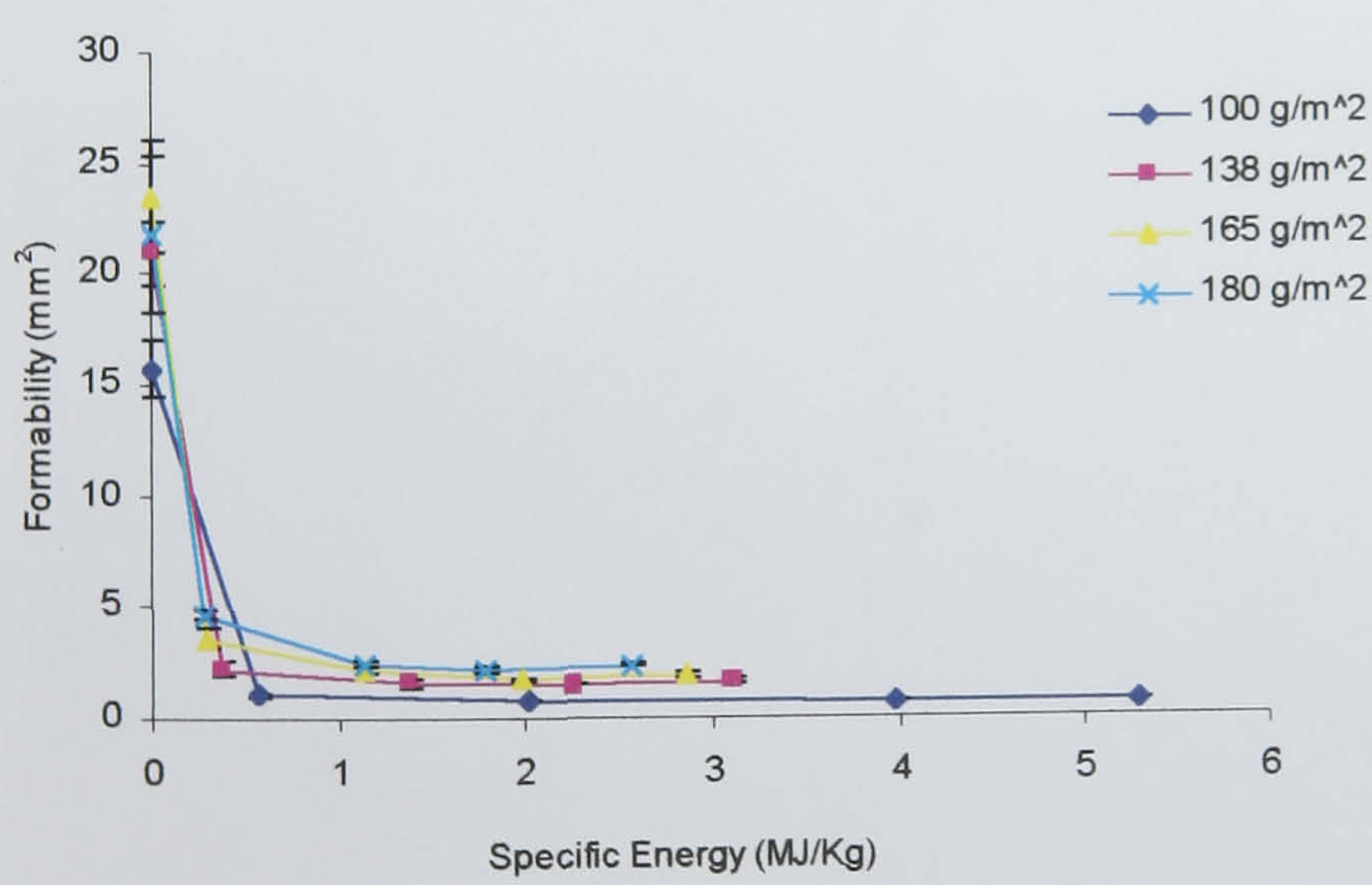


Figure 4.29 Effect of Specific Energy on Mean Fabric Formability (Bias)

It is worthwhile mentioning that the formability values obtained for the hydroentangled fabrics (excluding the webs) would be considered to be acceptable for apparel applications according to the FAST system "control zones"[46].

Figure 4.30 shows a FAST control chart obtained for fabrics that have low warp and weft formability. The problems resulting from such fabrics are seam pucker and difficulties in sewing sleeves into armholes. This problem is more common in lightweight woven fabrics. Many of the fabric properties are considered to be inter dependent because they are determined by structural parameters. For example, formability is a derived property of a fabric that can be calculated from the bending rigidity and extensibility, and thus depends on a large number of structural parameters[46].

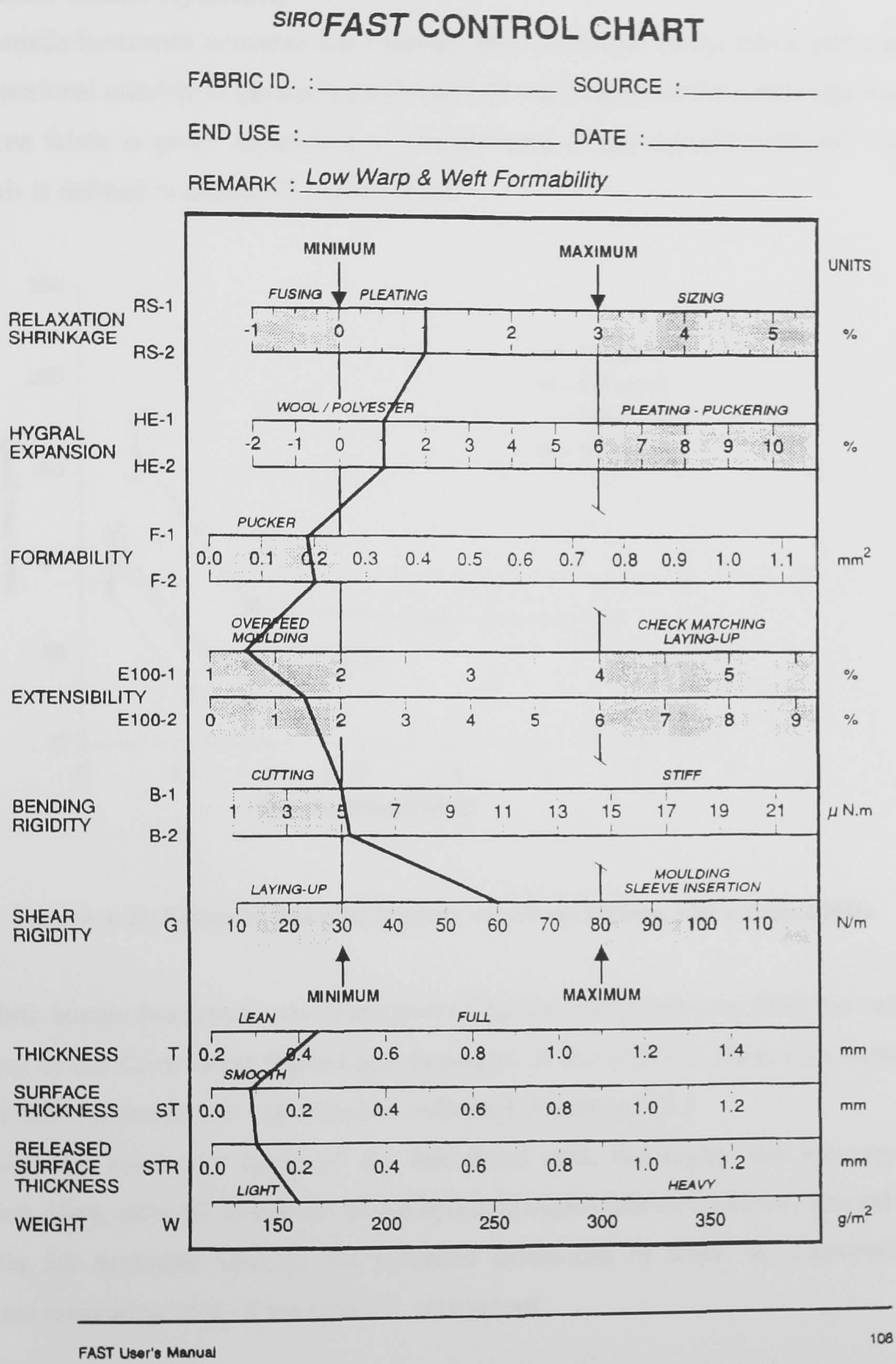


Figure 4.30 FAST Control Chart for a Woven Fabric With Low Warp and Weft Formability[46]

4.1.8 Fabric Tensile Hysteresis

Fabric tensile hysteresis concerns the recovery from extension of the fabric and it affects the dimensional stability of garments produced[31]. It was found that the elastic recovery of a nonwoven fabric is partly dependent on the recovery of the ingredient fibres[30]. Tensile hysteresis is defined in chapter 2, section 2.2.7.

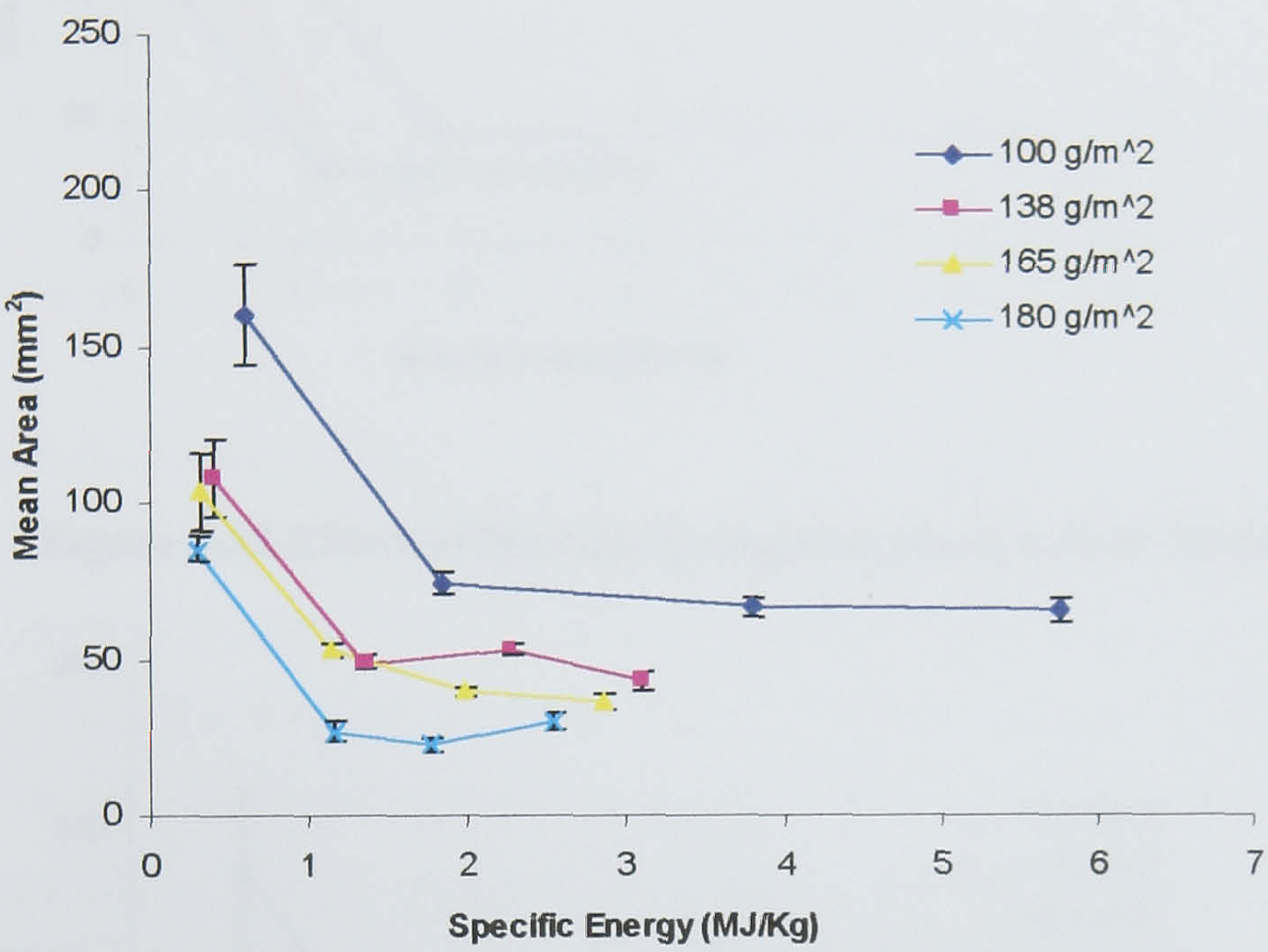


Figure 4.31 Effect of Specific Energy on Mean Fabric Hysteresis (MD)

The fabric tensile hysteresis was characterized by the calculated area from the values of extension of the fabric when loaded and unloaded on the FAST 3, Extension meter. The fabric tensile hysteresis was calculated as indicated in section 2.2.7.

Generally, the lower the value of the calculated area, the higher the recovery from extension. Here, only the hysteresis of the hydroentangled fabrics is shown. The values for the webs are excluded because the recorded extensions of these webs exceeded the maximum measuring limit of the FAST 3, instrument.

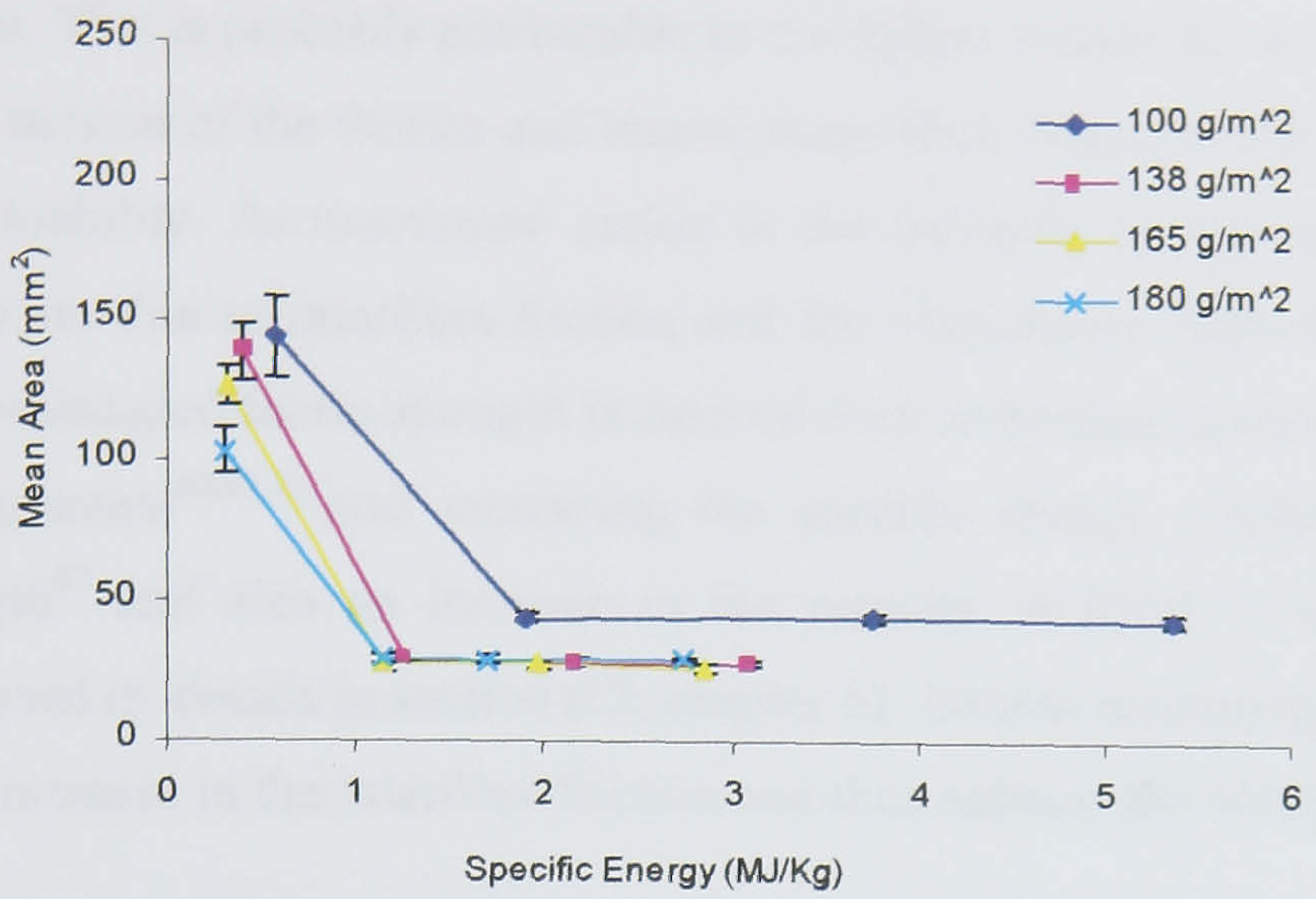


Figure 4.32 Effect of Specific Energy on Mean Fabric Hysteresis (CD)

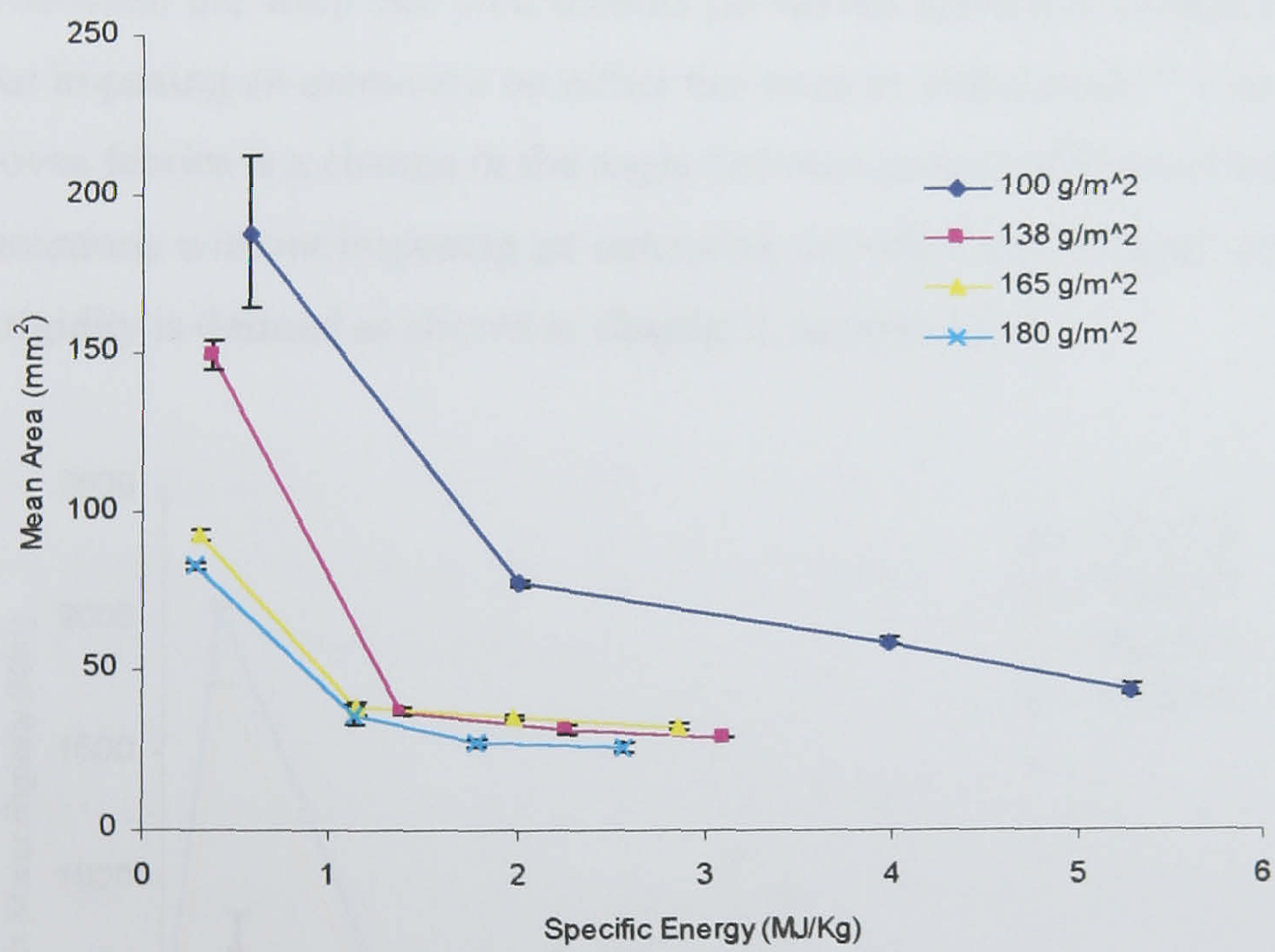


Figure 4.33 Effect of Specific Energy on Mean Fabric Hysteresis (Bias)

Figures 4.31- 4.33 show similar trends. In general, it is observed that the calculated area is higher for the lower weight per unit area fabrics than the heavier fabrics. This can be explained in terms of the higher extension values for the lower weight per unit area fabrics, as compared to the heavier area density fabrics. As a result, the recovery from extension of the heavier weight per unit area fabrics was higher than the lower weight per unit area fabrics. This is probably attributable to the lighter weight fabrics having fewer fibres in the cross section of the fabrics and hence, more fibre slippage within the structures and more fibre mobility. As mentioned earlier in the literature (see section 1.10.8), the hysteresis losses are due to interfibre friction and the viscoelastic behaviour of the fibres[66]. As the hydroentangled fabric strength is derived from inter-fibre friction and is a function of fibre entanglement[68,69,73] and increasing the specific energy results in an increase in fabric strength[82] and also an increase in the number of fibres in the cross-section (will be discussed in details in section 6.2, chapter 6) . So that increasing the specific energy results in an increase in the interfibre friction and thus reduces the hysteresis.

4.1.9 Fabric Shear Rigidity

Shear deformation in a woven fabric can be described as a trellising motion in which the angle between the warp and weft threads (in woven fabrics) is changed (from 90 degrees) without imposing an extension on either the warp or weft threads[46]. The analogy for this in nonwoven fabrics is a change in the angle between groups of fibres oriented in the MD and CD directions without imposing an extension on either set of fibres. In the FAST system, shear rigidity is defined as shown in chapter 2, section 2.2.7.

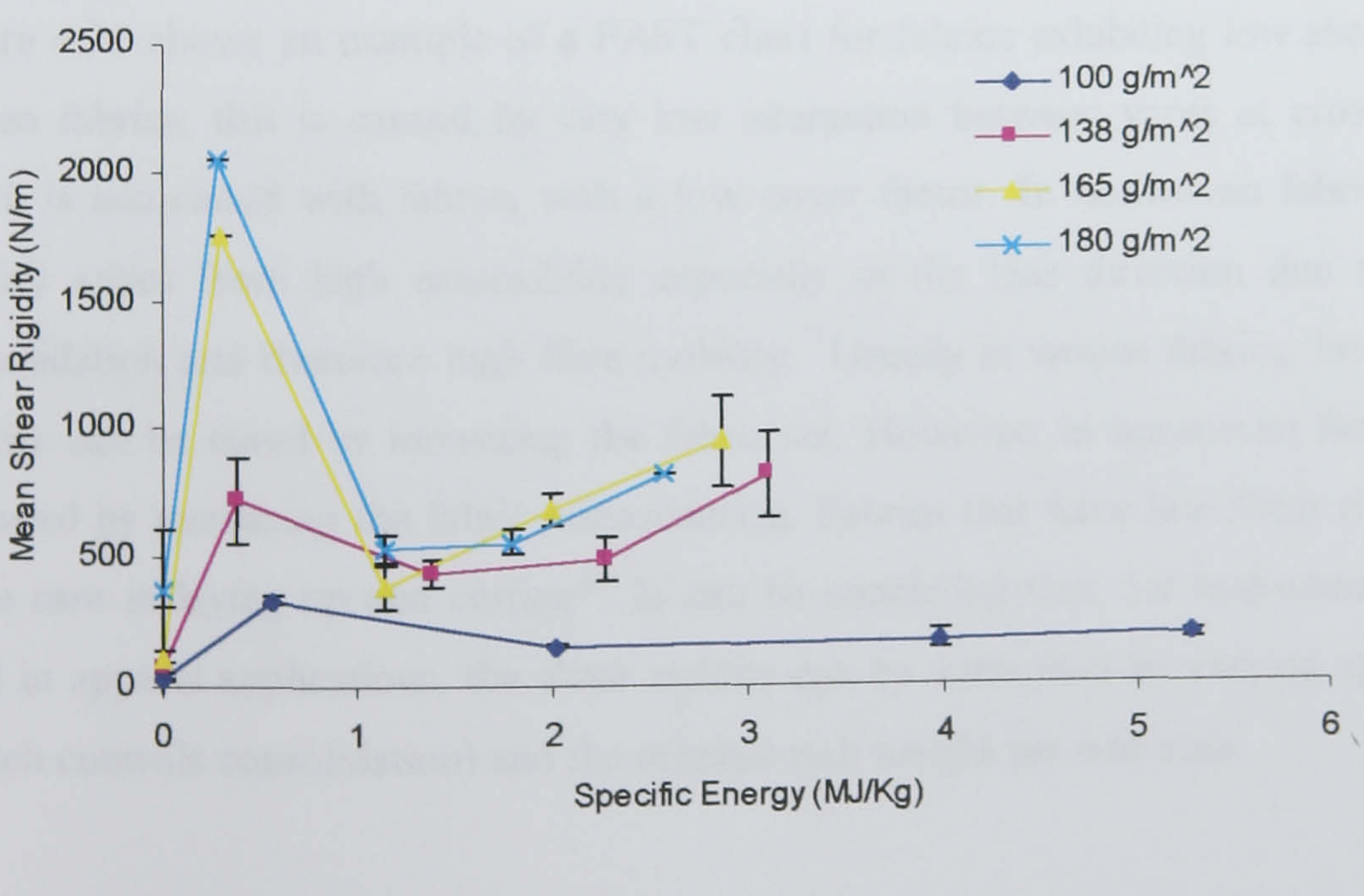


Figure 4.34 Effect of Specific Energy on Mean Fabric Shear Rigidity Properties

In figure 4.34, it can be noticed that increasing the specific energy results in an increase in the shear rigidity, followed by a decrease and subsequently leveling or slight increase for all fabric per unit areas. These changes occurred as a result of the decrease in the fabric extension at a load of 5gf/cm in the bias direction due to increasing the specific energy (see figure 4.18). It is important to mention that any minor change in the values of extension at a load of 5gf/cm in the bias direction will result in marked changes in the values of shear rigidity. Local variations in the bias extensibility of the fabrics due to intrinsic variations in a nonwoven fabric will therefore give rise to local variations in shear rigidity. Generally, in order to minimize the shear rigidity, lighter weight per unit area fabrics should be used.

Figure 4.35 shows an example of the FAST control chart for fabrics having a high shear rigidity. This causes a stiff handle; poor drape characteristics and also, difficulty in shaping and moulding fabrics. High shear rigidity in woven fabrics is caused by excessive interaction between the yarns at crossover points[46]. Whereas, in nonwoven fabrics, high shear rigidity may be caused by a high number of fibres in the cross section or low fibre mobility especially when using a high level of specific energy in the production of hydroentanglement fabrics. As a result, such fabrics obtained generally exhibit low fabric extension especially in the bias direction and, accordingly, high shear rigidity.

Figure 4.36 shows an example of a FAST chart for fabrics exhibiting low shear rigidity. In woven fabrics, this is caused by very low interaction between yarns at crossover points, which is associated with fabrics with a low cover factor. In nonwoven fabrics, low shear rigidity arises from high extensibility especially in the bias direction due to low fabric consolidation and therefore high fibre mobility. Usually in woven fabrics, low fabric shear rigidity can be cured by increasing the fabric set. However, in nonwoven fabrics, it might be cured by increasing the fabric consolidation. Fabrics that have low shear rigidity require more care in laying up and cutting[46]. It can be concluded that, for hydroentangled fabrics used in apparel applications, the shear rigidity can be controlled by varying specific energy (which controls consolidation) and the original web weight per unit area.

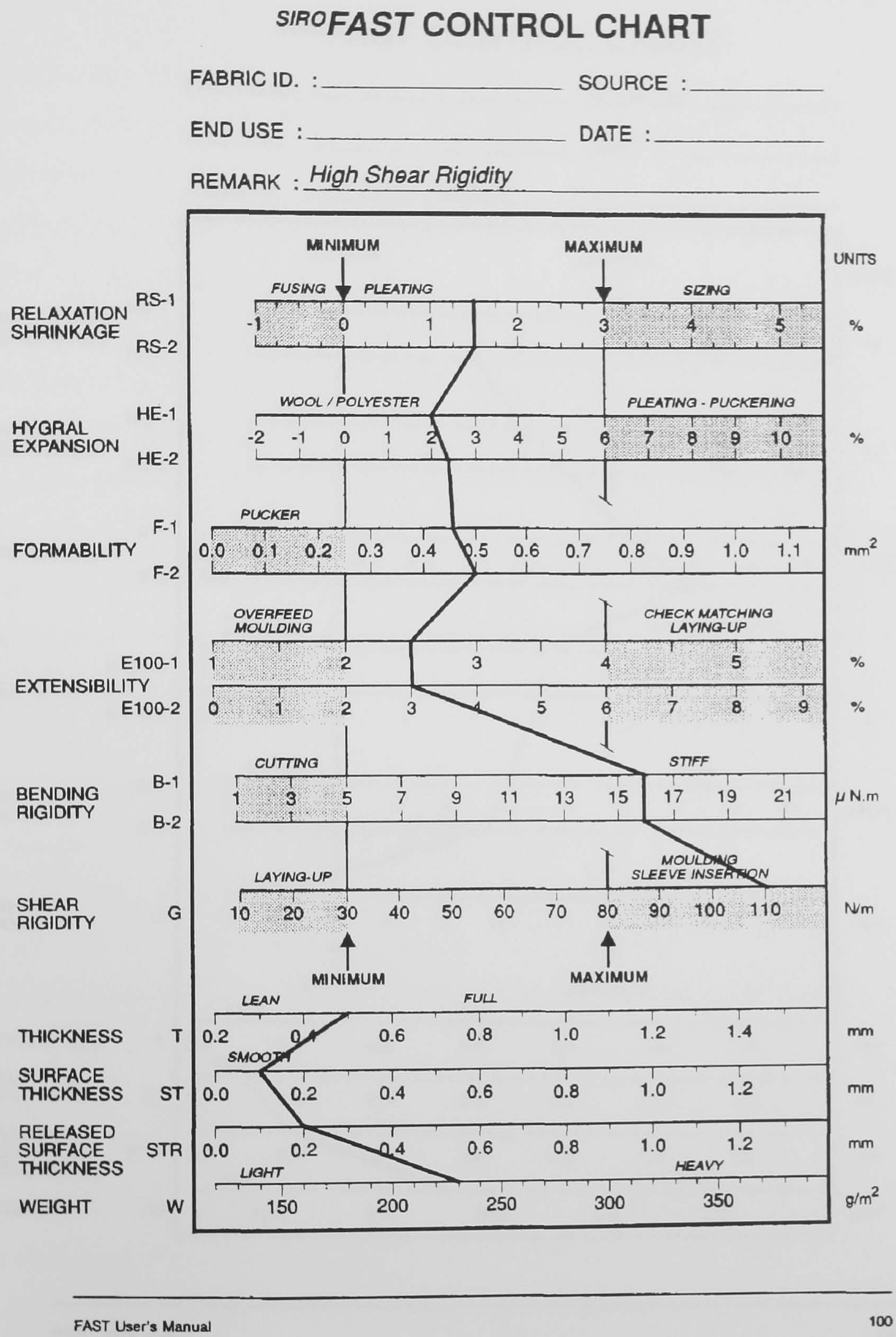


Figure 4.35 FAST Control Chart for a Woven Fabric with High Shear Rigidity Values[46]

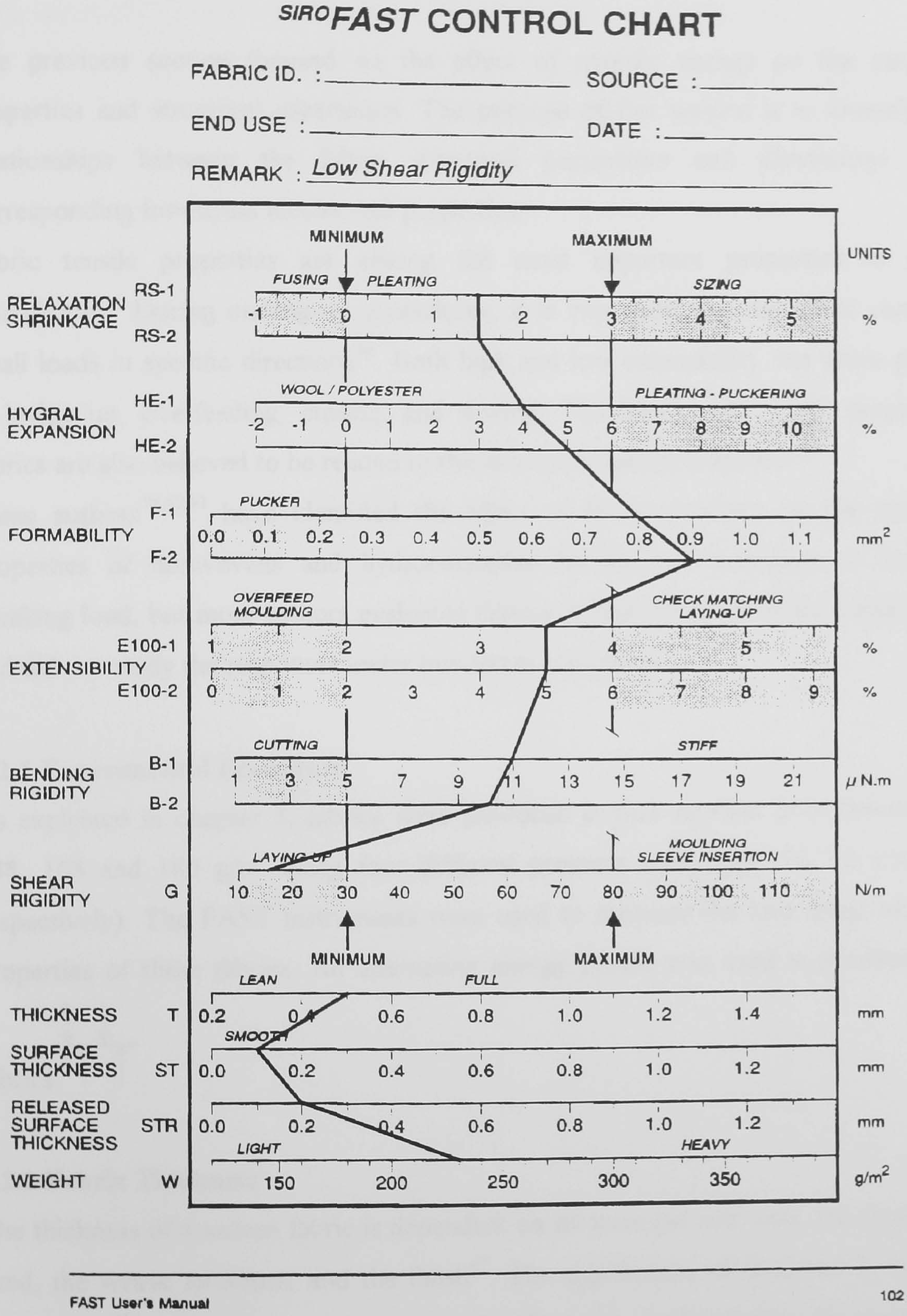


Figure 4.36 FAST Control Chart for a Woven Fabric with Low Shear Rigidity Values[46]

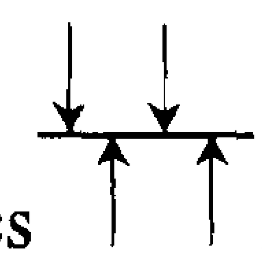
4.2 Fabric Structure and the Low Stress Mechanical Properties of Hydroentangled Fabrics

The previous section focused on the effect of specific energy on the mechanical properties and structural parameters. The purpose of this section is to investigate the relationships between the fabric structural parameters and dimensions on the corresponding low stress mechanical properties.

Fabric tensile properties are among the most important properties in garment manufacture. During making-up procedures, it is important that the fabric can sustain small loads in specific directions[90]. Both high and low extensibility can cause problems in laying up, overfeeding, cutting, and sewing. The handle and tactile properties of fabrics are also believed to be related to the low stress tensile behaviour[46].

Some authors[79,82,91] have identified the effect of fabric structure on the mechanical properties of nonwovens and hydroentangled fabrics e.g. extension at break and breaking load, but most authors evaluated fabrics at high loads i.e. at the breaking point and did not study the responses under low stress conditions.

4.2.1 Experimental Procedure

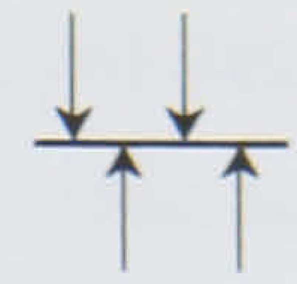
As explained in chapter 3, fabrics were produced at four nominal area densities, 100, 138, 168 and 180 g/m^2 using four different pressure levels (20, 50, 70 and 90 bar respectively). The FAST instruments were used to measure the low stress mechanical properties of these fabrics. An alternating energy profile was used in producing these fabrics  .

4.2.2 Fabric Thickness

The thickness of a woven fabric is dependent on its mass per unit area, the type of yarns used, the weave structure, and the finish[47]. The significance of thickness is defined by Fourt et al.[62] as a prime factor in determining the level of effectiveness for such comfort factors as insulation and water vapor transmission.

Figures 4.37 and 4.38 indicate that the fabric thickness increases with an increase in the fabric area density, which is to be expected. It is evident that even at relatively low pressure there is a marked consolidation of the web resulting in a major decrease in thickness. Typically, the entangled fabric is one-third the thickness of the original web.

Figure 4.1, shows that at a compression of 2 gf/cm^2; the difference in thickness due to area density is small. This is probably due to the low compression used, which only affects the surface fibres, while there is little effect on the bulk of the fabric.



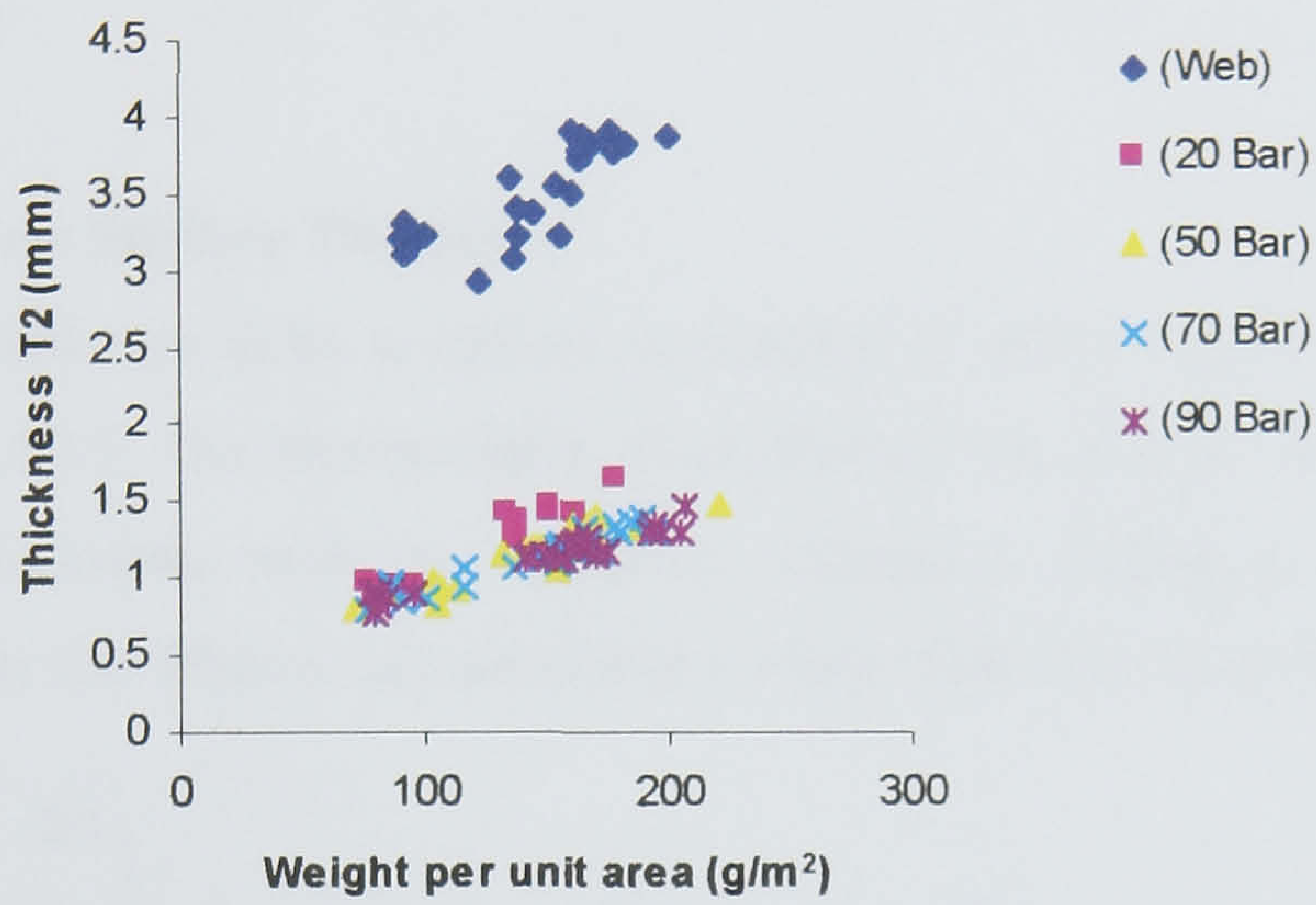


Figure 4.37 Effect of Hydroentangled Fabric Weight per Unit Area on Fabric Thickness at A Pressure of 2 gf/cm^2 (T2)

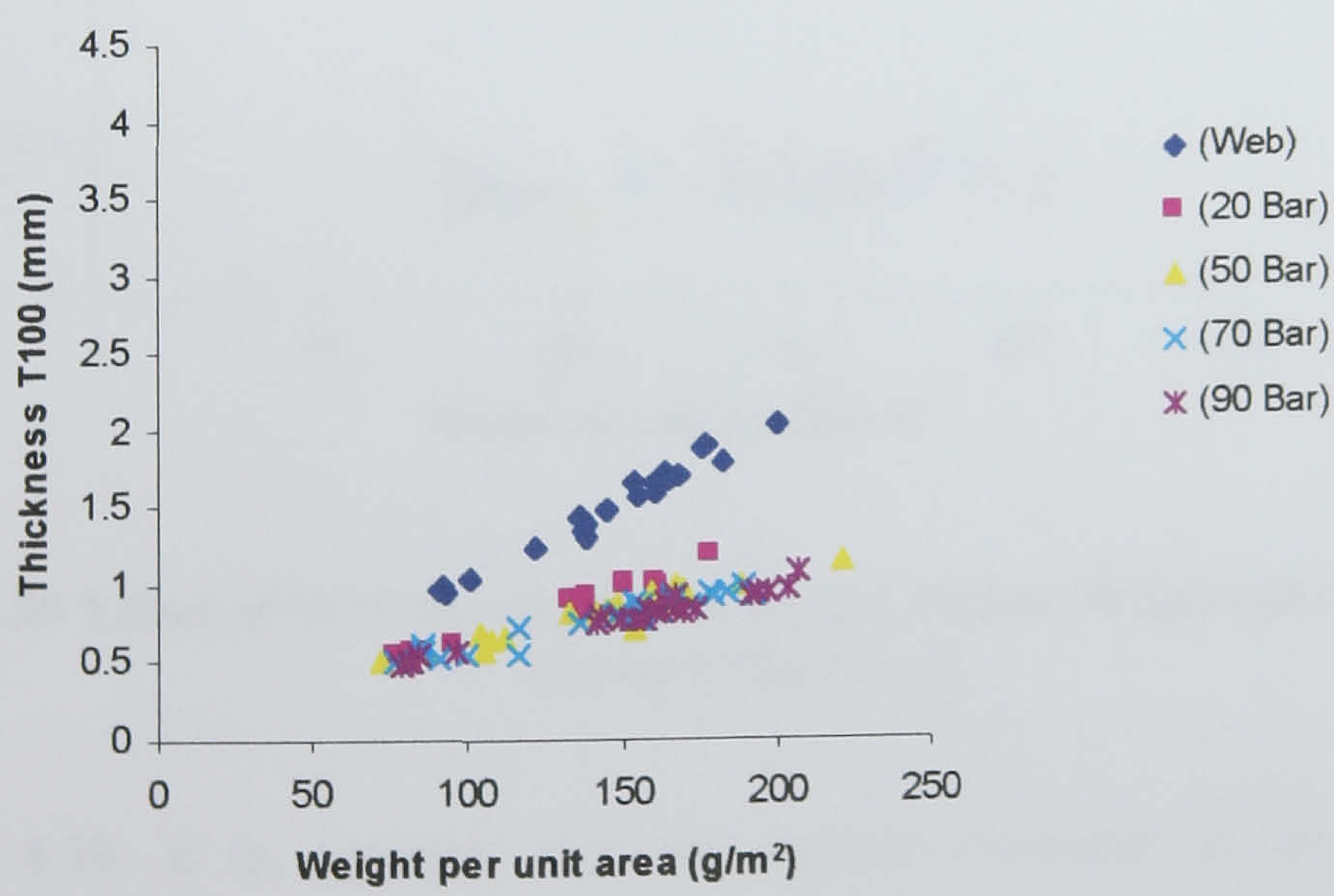


Figure 4.38 Effect of Hydroentangled Fabric Weight Per Unit Area on Fabric Thickness at A Pressure of 100 gf/cm^2 (T100)

Comparing figures 4.37 and 4.38, it is evident that when using a higher load during thickness testing (100 gf/cm^2 rather than 2 gf/cm^2), all the hydroentangled fabrics have a similar thickness vs weight per unit area trend but the curve gradient for the webs (Thickness vs weight per unit area) is steeper in figure 4.38. It may be suggested that this change in gradient is related to the relative resistance to compression of the webs as compared to the bonded fabrics. At a higher weight per unit area, the resistance to compression may be expected to be higher yielding a high thickness value for a given fixed load.

4.2.3 Fabric Surface Thickness

Surface thickness (ST) is defined in chapter 2; section 2.2.7. As mentioned earlier in section 1.10.5, the heavyweight thick fabrics are able to stand greater variation in surface thickness, with no noticeable change in handle or appearance whereas, in lightweight thin fabrics, any change in surface thickness can be easily observed[33].

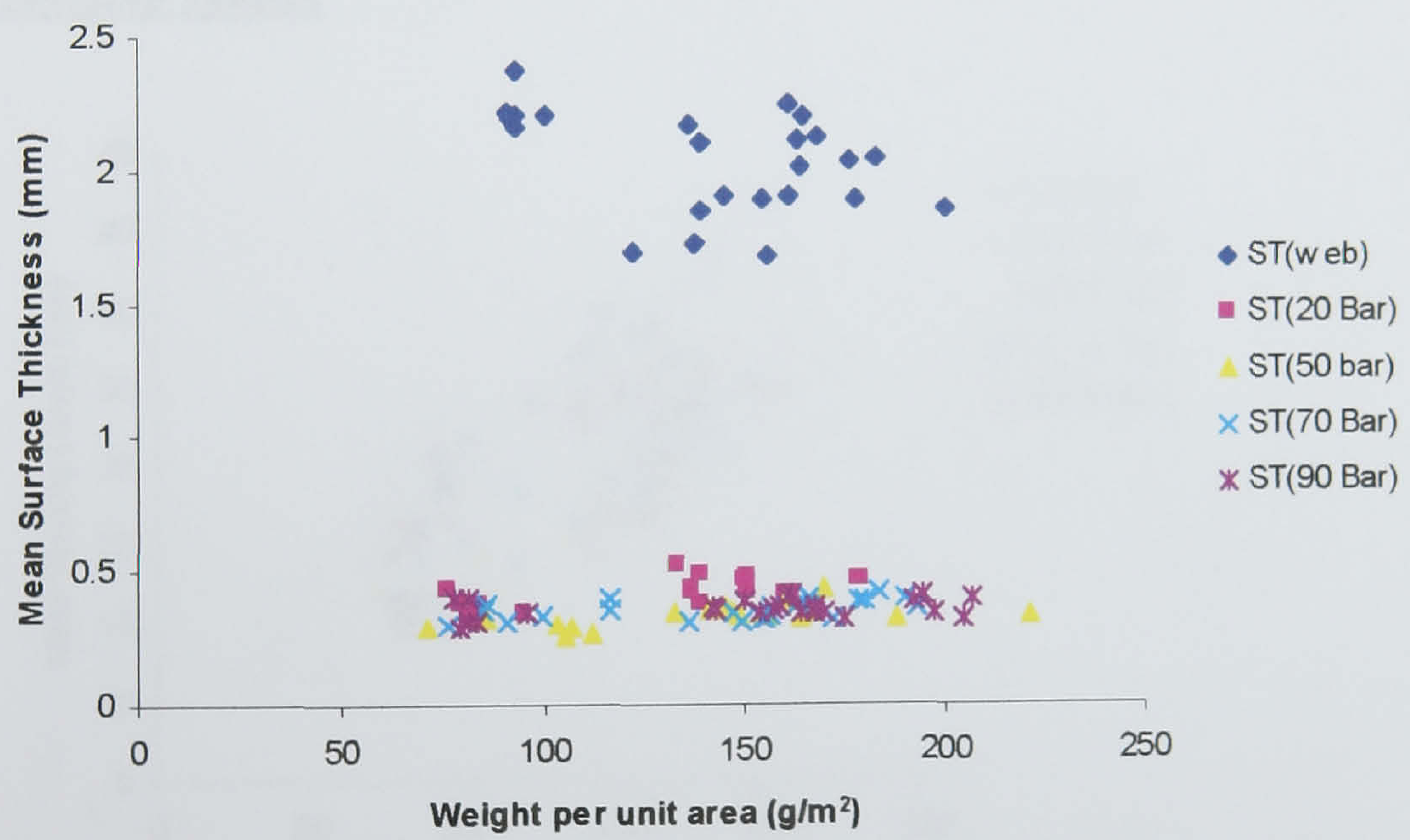


Figure 4.39 Effect of Web and Hydroentangled Fabric Weight (Area Density) on Surface Thickness

In figure 4.39, it is apparent that the surface thickness of the webs and the hydroentangled fabrics are independent of the weight per unit area. It is also clear that the webs and the hydroentangled fabrics group differently which is due to the marked decrease in fabric thickness, which occurs after hydroentanglement.

4.2.4 Bending Properties

As fabric stiffness is a key factor in the study of handle and drape, a number of authors have carried out research in this field[37,54,79,90,92]. For example, Ali[79] has investigated the effect of hydroentangled fabric area density on fabric bending length and bending rigidity. His results are in general agreement with the results of the present study.

It is also interesting to note that the bending length values for the webs range between about 22 - 42 mm whereas they lie between about 13 – 35 mm for the hydroentangled fabrics. As a result, the webs have high bending length values compared to hydroentangled fabrics. It is also of interest to note that, contrary to popular belief, nonwoven fabrics in general and hydroentangled fabrics in particular are not homogenous structures since only parts of the structures are bonded while other regions are left almost web-like. As a result, a considerable amount of variation in the results is always expected (see figures 4.42 and 4.45)

4.2.4.1 Bending Length

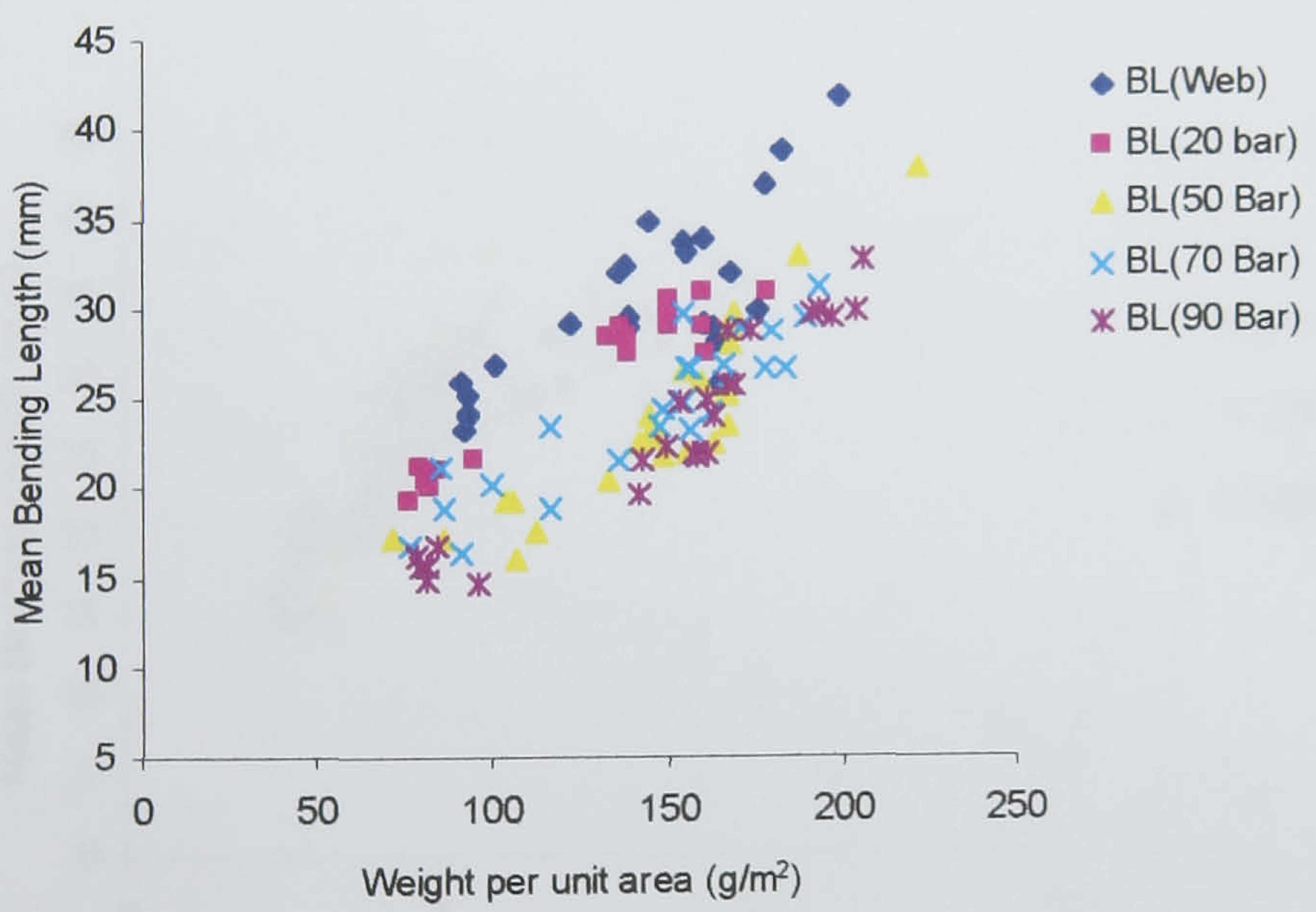


Figure 4.40 Effect of Hydroentangled Fabric Weight per Unit Area on Mean Bending Length

In figure 4.40, it is apparent that in general, an increase in the fabric weight per unit area increases bending length (BL) for both the unbonded webs and the hydroentangled fabrics. It has been found that there is a large influence of fabric weight on drape, and accordingly, on the bending length[59]. As known from the literature[47] the constructional features affecting the stiffness of a woven cloth are mainly its weight, the nature of the fibres, and the compactness or density of the weave.

For a given area density, the webs tended to exhibit higher bending lengths in comparison to the hydroentangled fabrics. Accordingly, it appears that the bonded fabrics are in fact less stiff than the original unbonded webs. This is in contrast to chemical bonded fabrics as studied by Petterson and Stevenson [27,29]. A possible explanation is as follows:

- The webs before hydroentanglement are comparatively thick and since structures that have high values of thickness, also tend to have high values of bending length[56] (See eq. 1.2 and 1.4 in chapter 1), these results are predictable.
- During hydroentanglement, the original webs draft (as well as mechanically bond) and the resulting fabric therefore exhibits a lower area density than the original web as well as a reduced thickness. This will also tend to decrease the measured bending length.

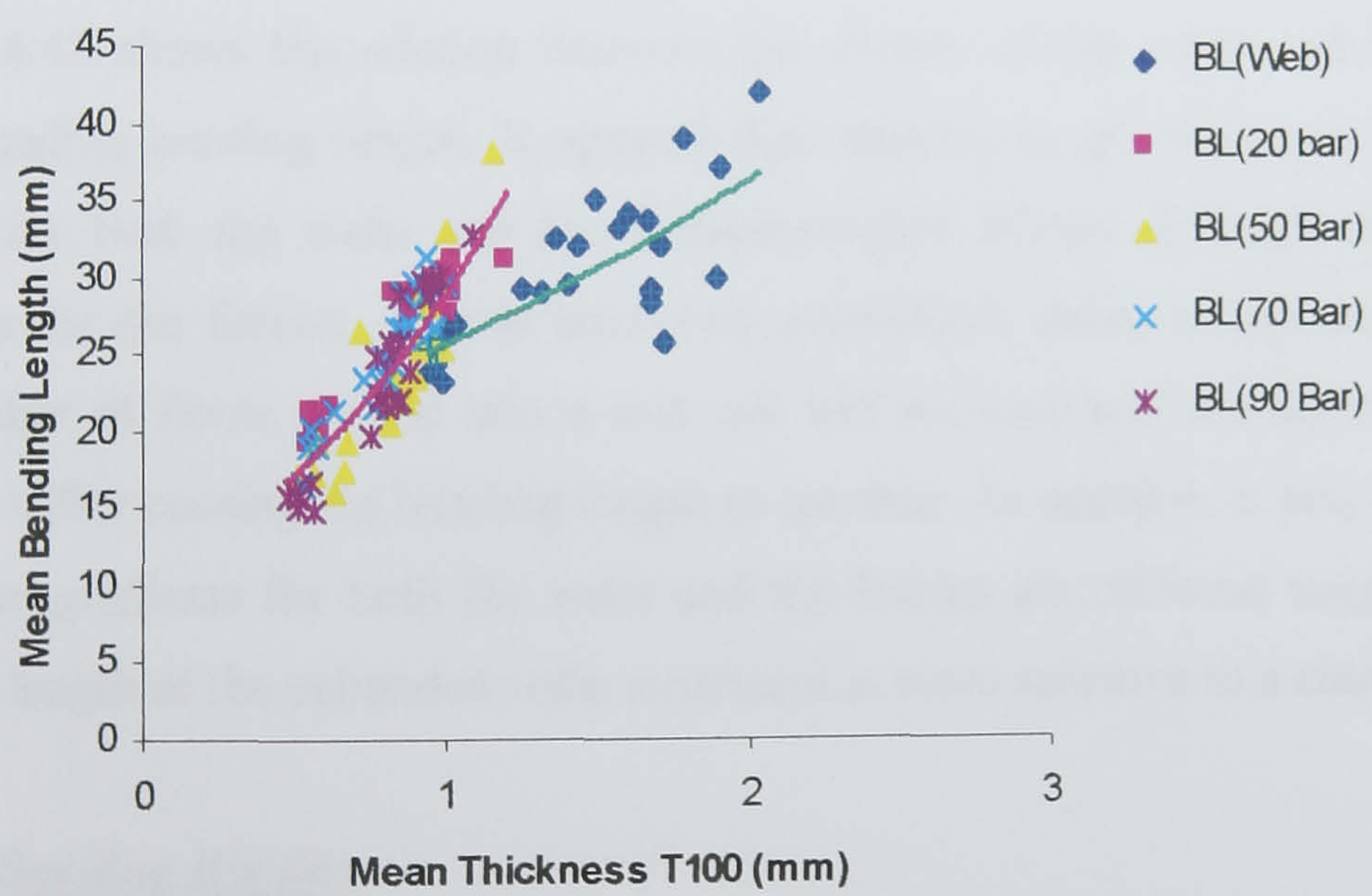


Figure 4.41 Relation Between Hydroentangled Fabric Thickness and Mean Bending Length

Figure 4.41 shows a plot of web and fabric thickness measured at 100 g/cm^2 pressure and the corresponding bending length for the webs. It is apparent that increasing the thickness of both the unbonded webs and the fabrics increases the bending length, although the gradients differ depending on the state of the structure (i.e. web or hydroentangled fabric). These results are consistent with equations 1.2 – 1.4.

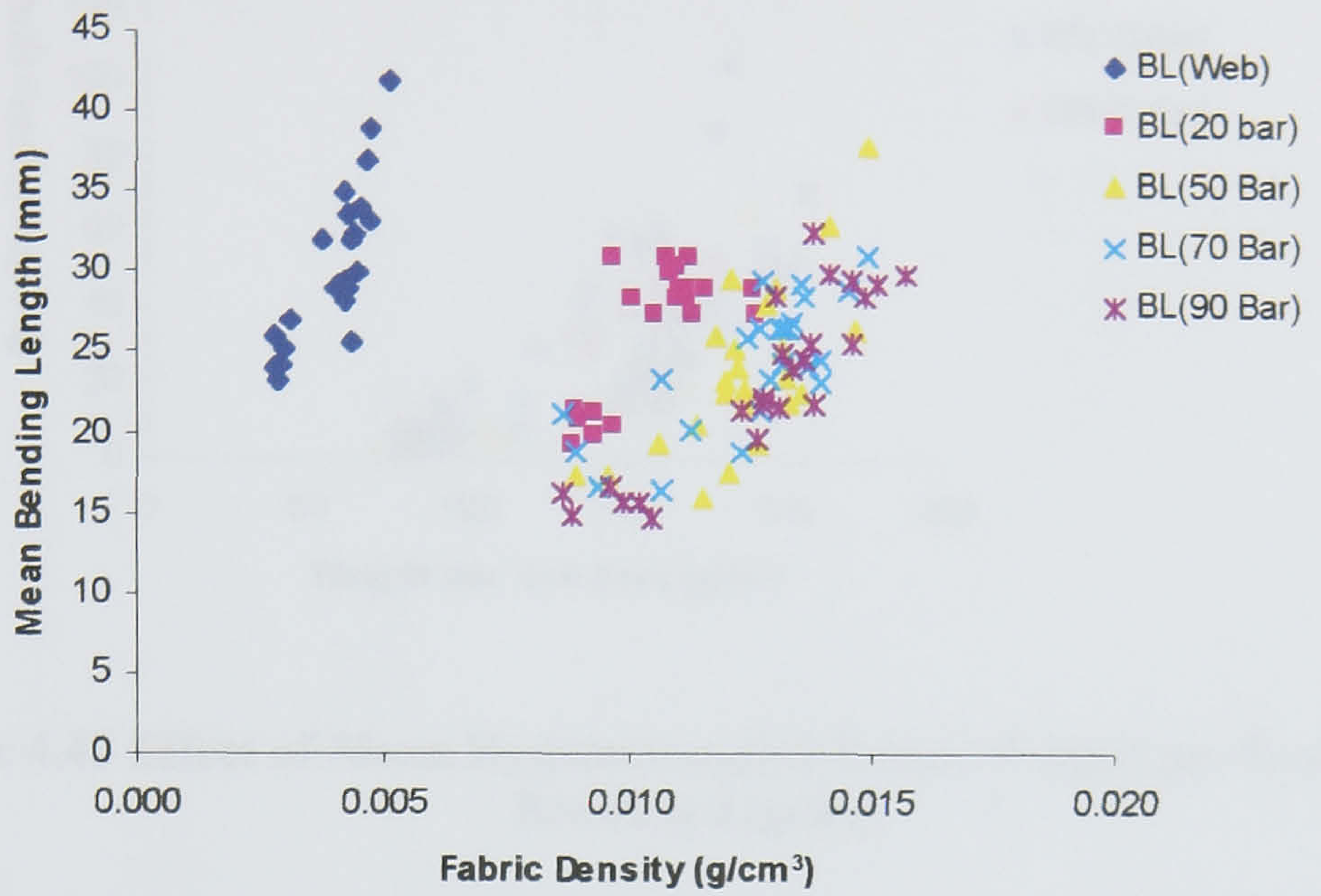


Figure 4.42 Relation Between Web and Hydroentangled Fabric Density on Bending Length

Figure 4.42 shows the relation between the density of the webs and fabrics and the corresponding bending length. It appears that bending length increases with the fabric density for both the webs and the hydroentangled fabrics although there is marked variation for the fabrics. This is intuitively predictable since, as the density increases, the number of fibres packed into a unit cell will increase and the fabric will therefore become stiffer causing the bending length to increase. In addition, it may be noticed that the curve gradients for both the webs and the fabrics are different suggesting that the bending length of the unbonded webs structures is more sensitive to a change in density.

4.2.4.2 Bending Rigidity

Bending rigidity is the quantitative representation of stiffness felt by hand during subjective assessment of the fabric handle[49]. Peirce found that stiffness of a fabric is closely related to the handle and drapability of fabric[35]. Bending rigidity is very important from the point of view of the cutting operation in making-up. High bending rigidity is desirable for a trouble free cutting operation. Since the formability of fabrics is related to the bending rigidity, lower values of bending rigidity may cause seam pucker[83]. Bending rigidity is defined in chapter 2, section 2.2.7

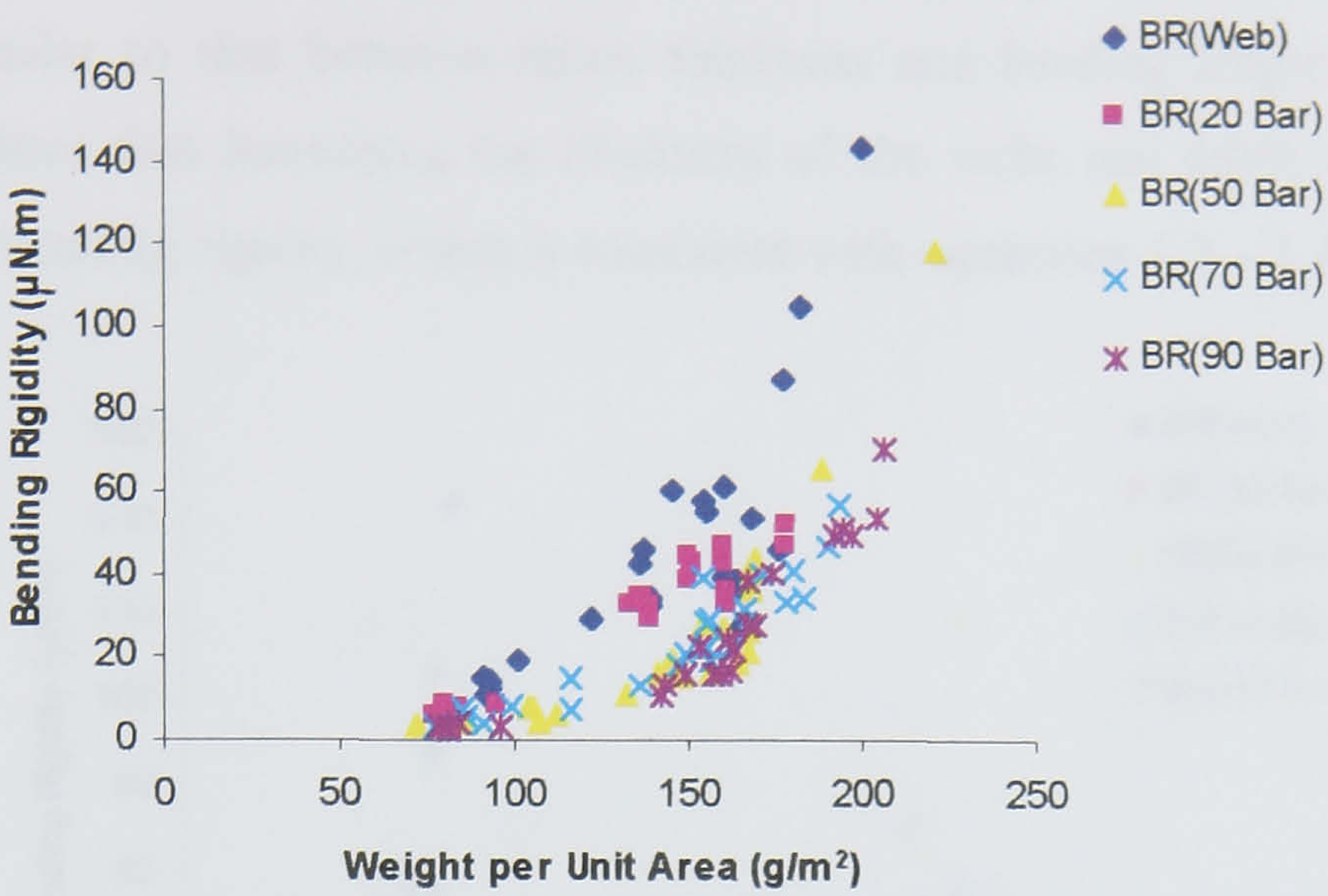


Figure 4.43 Effect of Mean Hydroentangled Fabric Weight per Unit Area on Bending Rigidity

Figure 4.43 shows the bending rigidity for the fabrics plotted against weight per unit area. Increasing the fabric weight per unit area is associated with an increase in bending rigidity. These results are in agreement with other workers who reported the bending properties of spunlaced and apertured fabrics[79].

In this work, the effect of weight on fabric bending rigidity has been investigated using four different water pressures 20,50,70 & 90 bar and compared to the unbonded webs and the same basic trends were observed throughout.

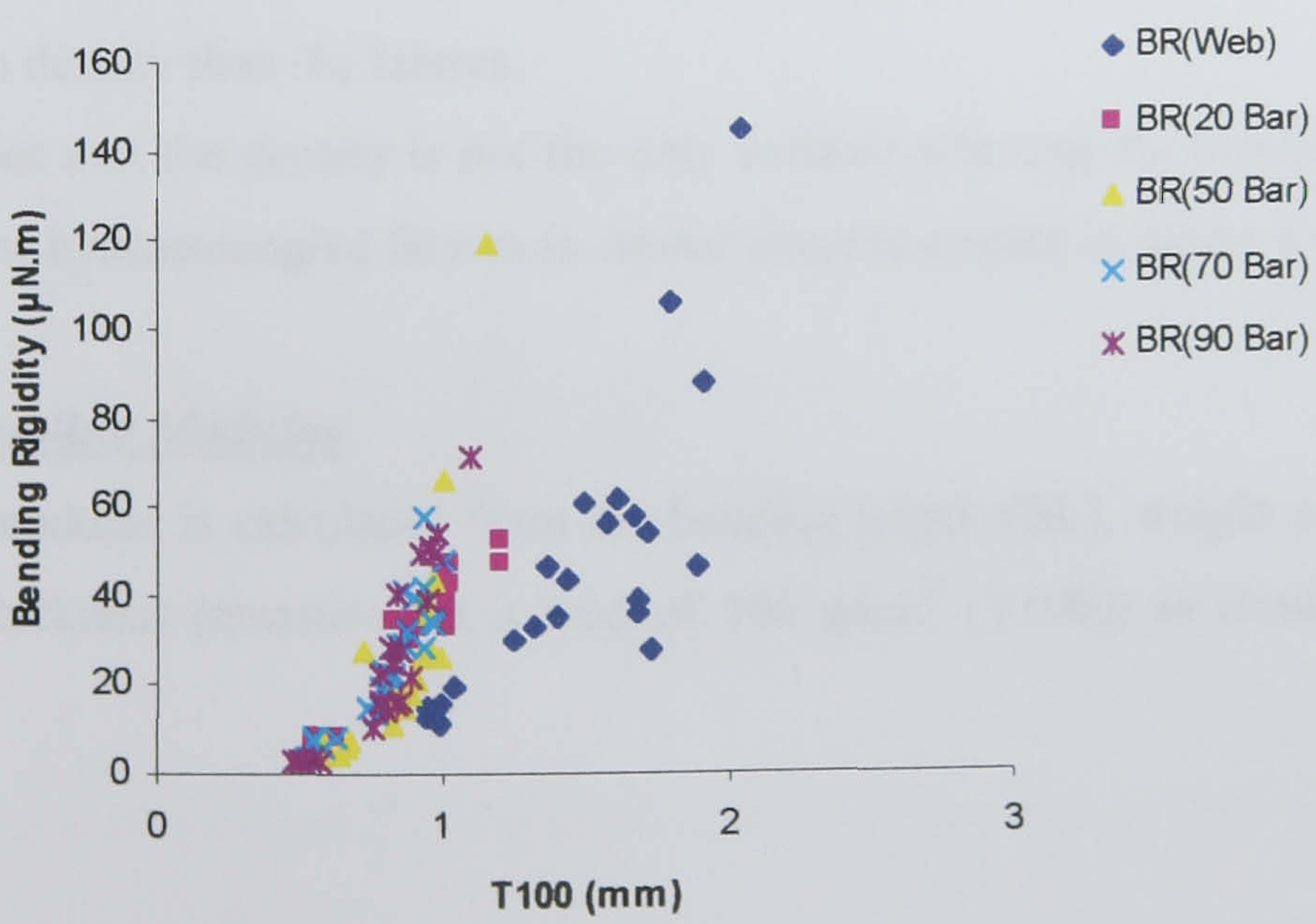


Figure 4.44 Effect of Mean Hydroentangled Fabric Thickness on Bending Rigidity

Figure 4.44 shows a plot of thickness vs bending rigidity. The form of the relationship is almost similar to that between fabric thickness and bending length (see figure 4.41). This confirms that increasing the thickness of the webs and fabrics is associated with increased bending rigidity, which is consistent with equations 1.2 – 1.4.

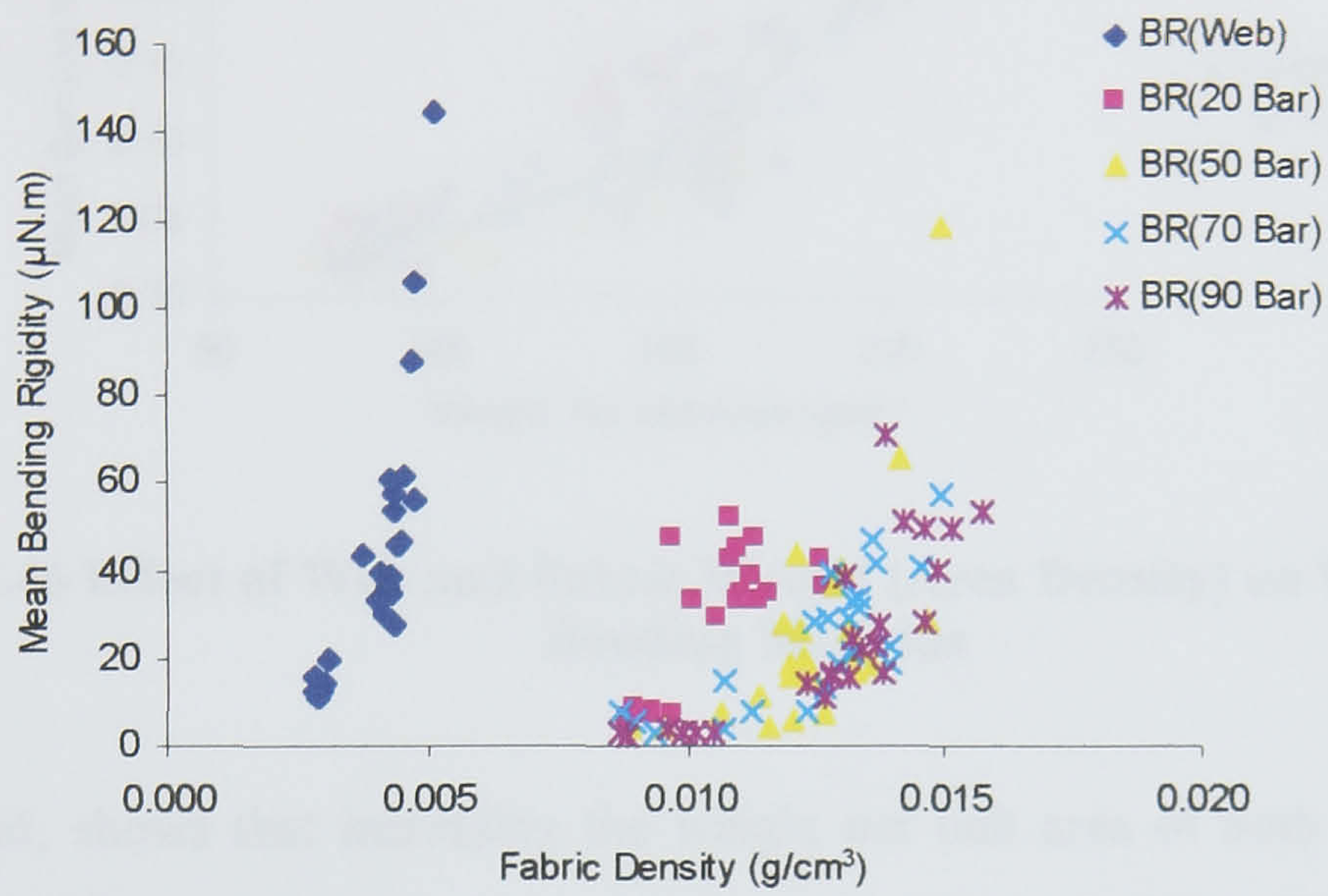


Figure 4.45 Effect of Density on Hydroentangled Fabric Bending Rigidity

Figure 4.45 shows a plot of web and fabric density and bending rigidity. It is apparent that increasing the density is generally associated with a higher bending rigidity, although the relationship is less clear for other structural parameters.

In figure 4.45, it is also interesting to note that the values of the bending rigidity for the webs and fabrics fall into discrete groups and that the webs are more sensitive to an increase in density than the fabrics.

This implies that the density is not the only variable affecting the bending rigidity of the webs or the hydroentangled fabrics (a similar trend is evident in figure 4.41)

4.2.4.3 Bending Modulus

Bending modulus is calculated from the bending length (BL), weight per unit area (W) and the thickness (measured at a load of 100 g/cm^2 (T100)) as mentioned in section 2.2.7.

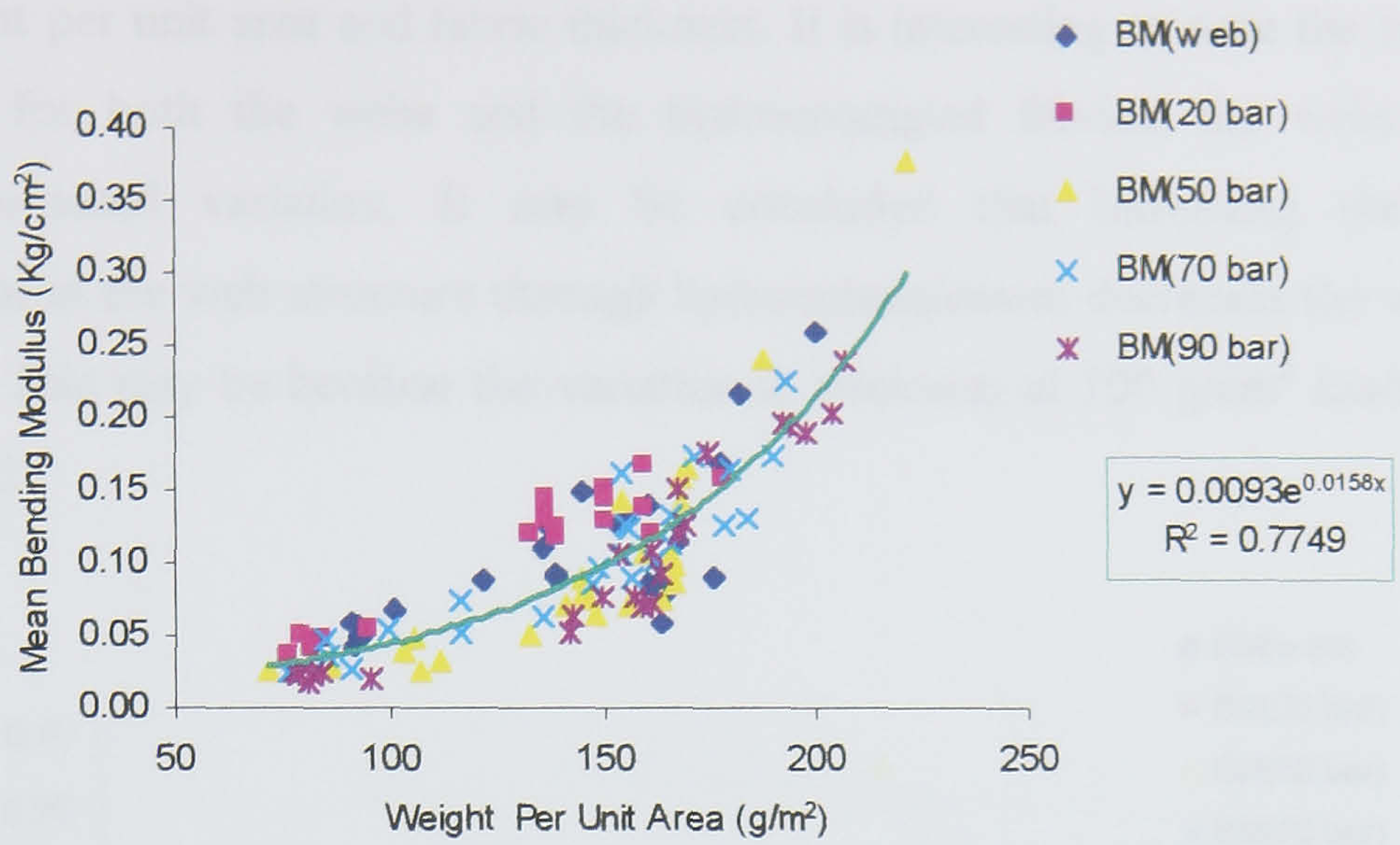


Figure 4.46 Effect of Web and Fabric Weight (Area Density) on Web and Fabric Bending Modulus

Figure 4.46, shows that increasing the weight per unit area of both the webs and the fabrics are associated with an increase in the bending modulus (BM). This is to be expected given the influence of fabric weight per unit area on bending length. In contrast to figure 4.45, both the web and fabric bending moduli values fall on the same trend line. As a result, the bending modulus may be predicted from different area densities with reasonable accuracy using a single equation for different hydroentangling pressures (figure 4.46).

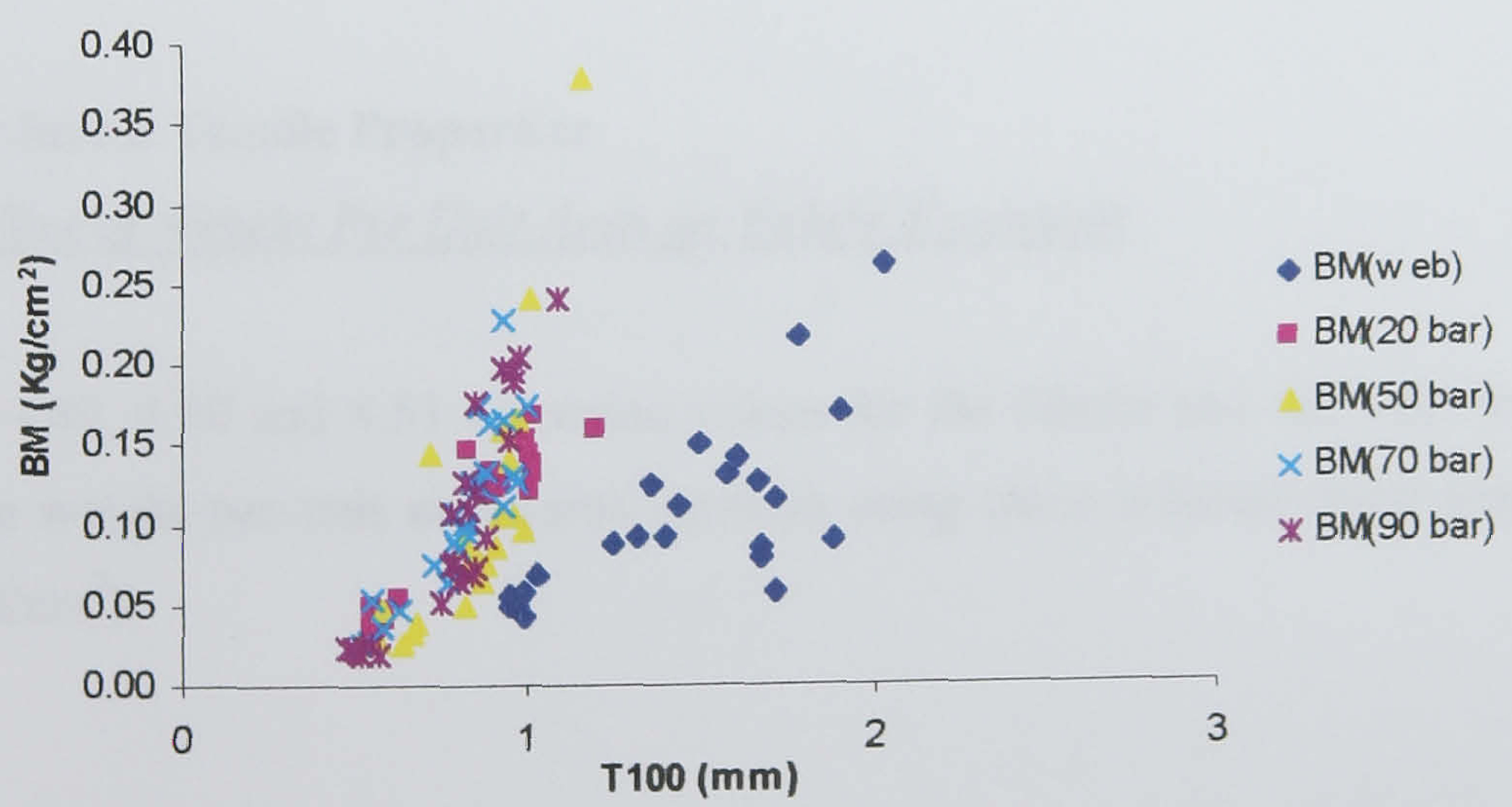


Figure 4.47 Effect of Fabric Thickness (T100) on Fabric Bending Modulus

In figure 4.47, it is evident that increasing the thickness increases the bending modulus (BM). This is not surprising given the strong correlation that exists between increasing fabric weight per unit area and fabric thickness. It is interesting to note the variation in the results for both the webs and the hydroentangled fabrics; the webs generally showing increased variation. It may be concluded that increasing the level of entanglement in the web structure through hydroentanglement decreases the variation in the results. This may be because the variation in thickness at 100 g/cm^2 load (T100) is also reduced.

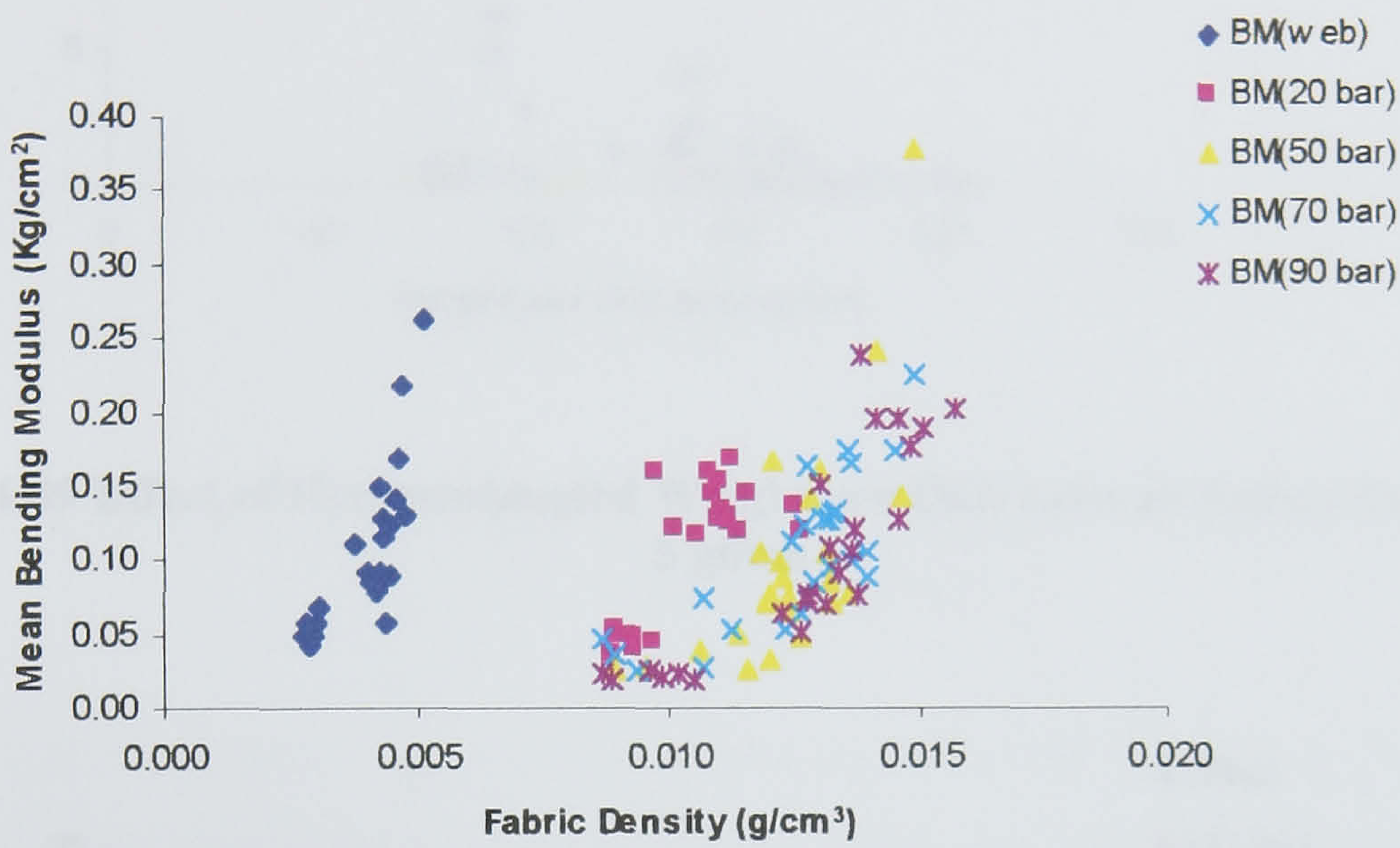


Figure 4.48 Effect of Fabric Density on Fabric Bending Modulus

Figure 4.48, shows similar trends to these observed as in figures 4.42 and 4.45.

4.2.5 Low Stress Tensile Properties

4.2.5.1 Effect of Weight Per Unit Area on Fabric Extension

In figures 4.49, 4.50 and 4.51 extension values for the fabrics and the webs are plotted against the weight per unit area (area density) using three different fixed loads (5, 20 and 100 gf/cm^2).

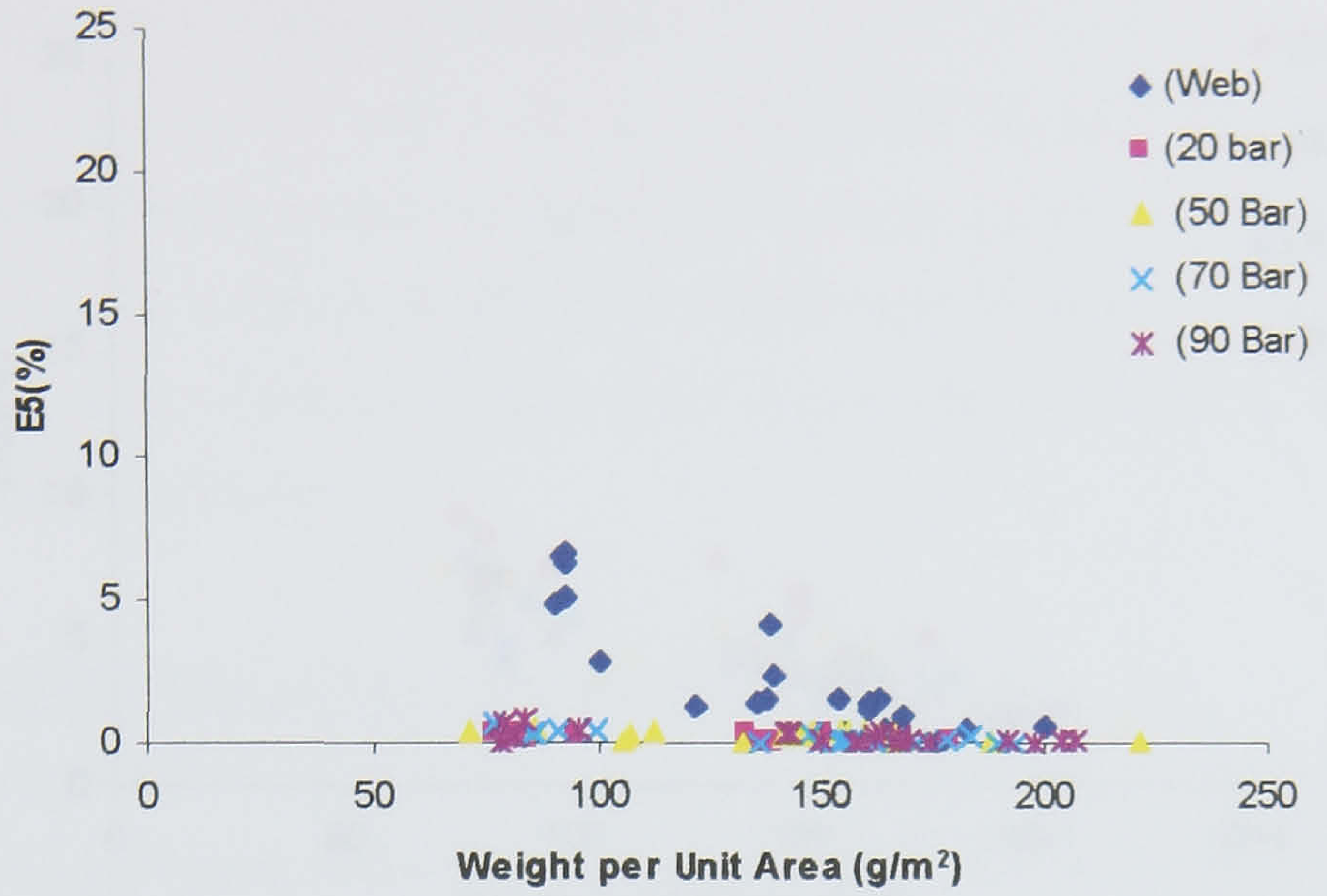


Figure 4.49 Effect of Hydroentangled Weight per Unit Area on Fabric Extension at 5 gf/cm

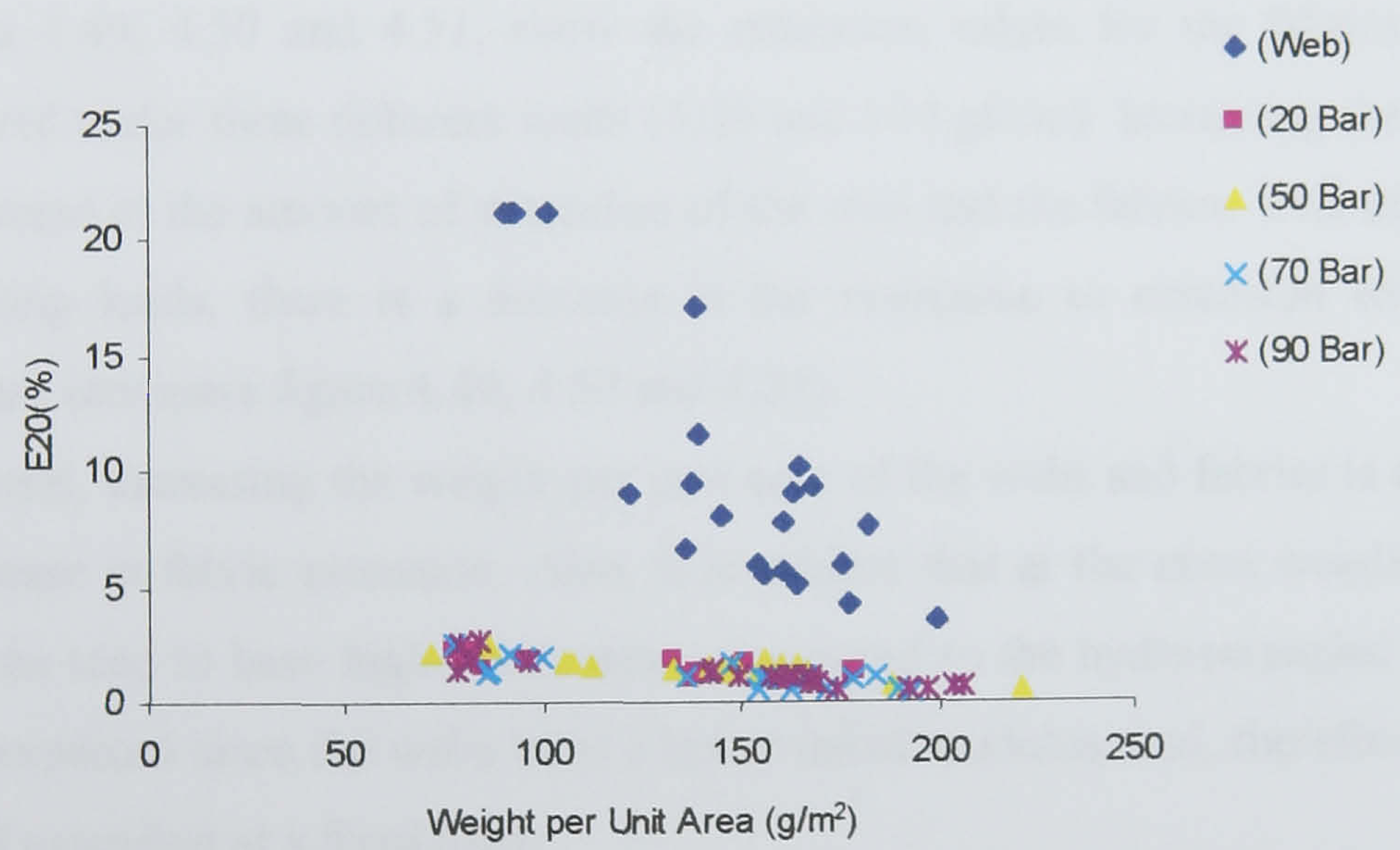


Figure 4.50 Effect of Fabric Weight per Unit Area on Fabric Extension at 20 gf/cm

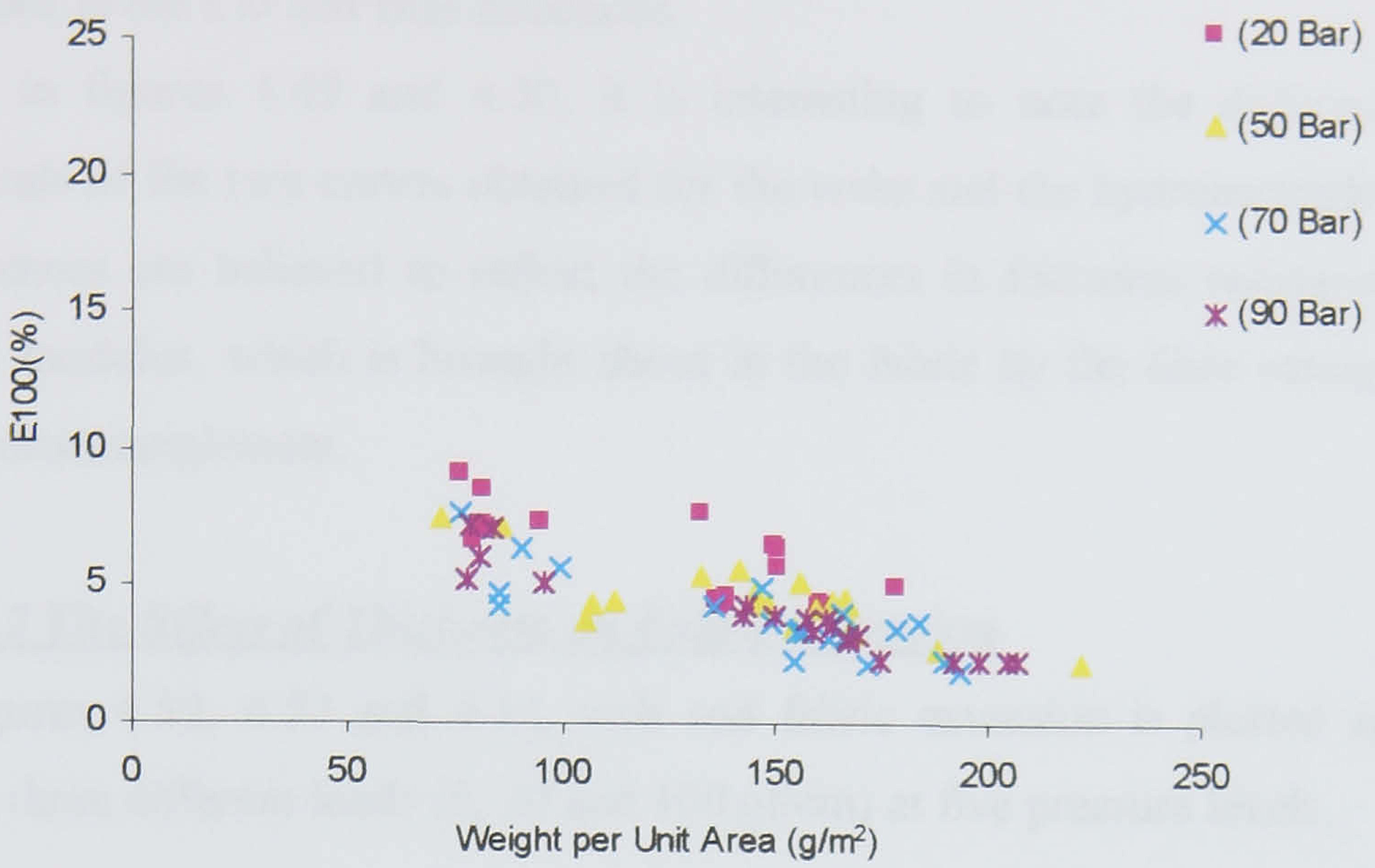


Figure 4.51 Effect of Hydroentangled Fabric Weight per Unit Area on Fabric Extension at 100 gf/cm

Figures 4.49, 4.50 and 4.51, show the extension values for the fabrics and the webs measured under three different loads (5,20 and 100 gf/cm). Increasing the load results in an increase in the amount of extension of the web and the fabrics. This arises because at increasing loads, there is a decrease in the resistance to extension within the fabric structure (compare figure 4.49, 4.50 and 4.51).

In general, increasing the weight per unit area of the webs and fabrics is associated with a decrease in fabric extension. Also, it is evident that at the same weight per unit area, the webs tend to have higher extensions compared to the hydroentangled fabrics. This is to be expected since the webs have a lower initial modulus, and, therefore have a higher overall extension at a fixed load.

On the other hand, increasing the consolidation of the hydroentangled fabrics (for the same fabric weight per unit area) will result in an increase in the fabric strength[82]. As a result, the fabric extension will simultaneously decrease (see figures 4.16 – 4.24). The decrease in fabric extension is also believed to be associated with an increase in the number of fibres in the cross section of the fabric as the area density increases. This leads to an increase in the total friction between the fibres within the fabric cross-section and as a result, an increase in the resistance to extension. Also as the load increases, the results for the webs and the hydroentangled fabrics tend to converge towards the same extension vs weight per unit area trend line. This may be attributable to the higher extension, which takes the fabrics beyond their initial modulus. Similar results are obtained in the CD and Bias directions.

Also, in figures 4.49 and 4.50, it is interesting to note the difference between the gradients of the two curves obtained for the webs and the hydroentangled fabrics. These differences are believed to reflect the differences in frictional resistance and therefore initial modulus, which is brought about in the fabric by the fibre entanglement induced by hydroentanglement.

4.2.5.2 The Effect of Thickness on Fabric Extension

In figures 4.52, 4.53 and 4.54, web and fabric extension is plotted against thickness using three different loads (5, 20 and 100 gf/cm) at five pressure levels.

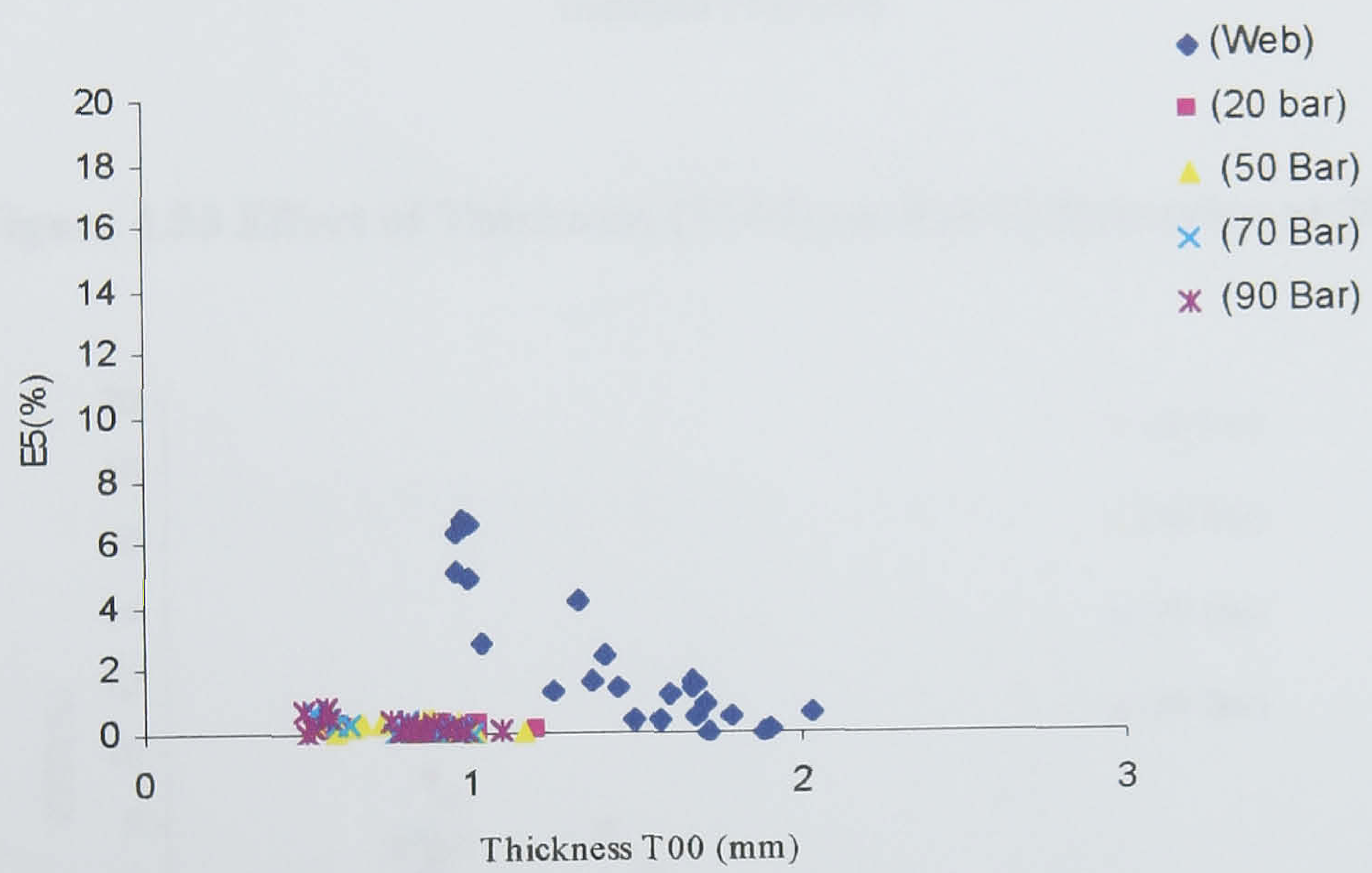


Figure 4.52 Effect of Thickness (T100) on Fabric Extension at 5 gf/cm

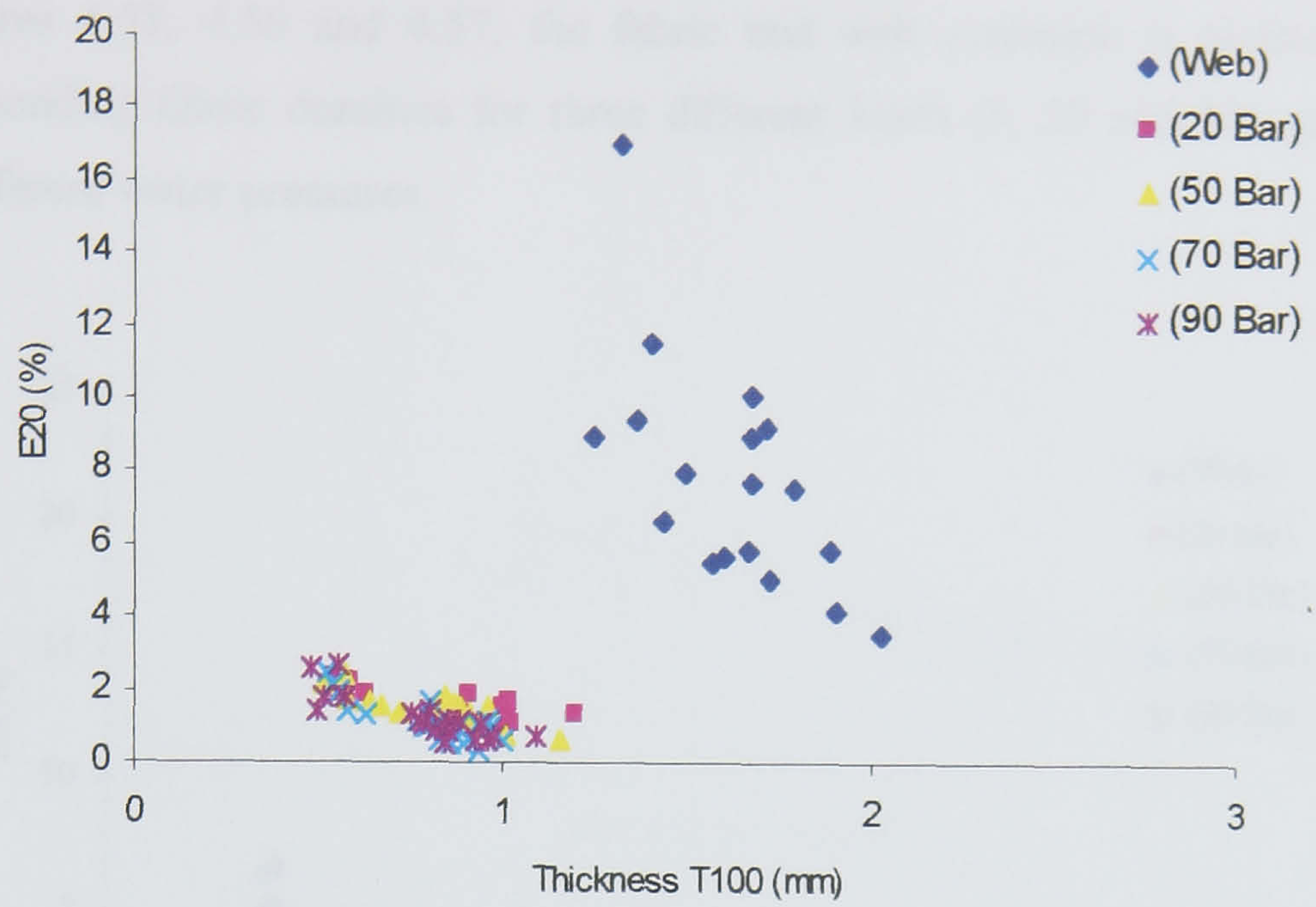


Figure 4.53 Effect of Thickness (T100) on Fabric Extension at 20 gf/cm

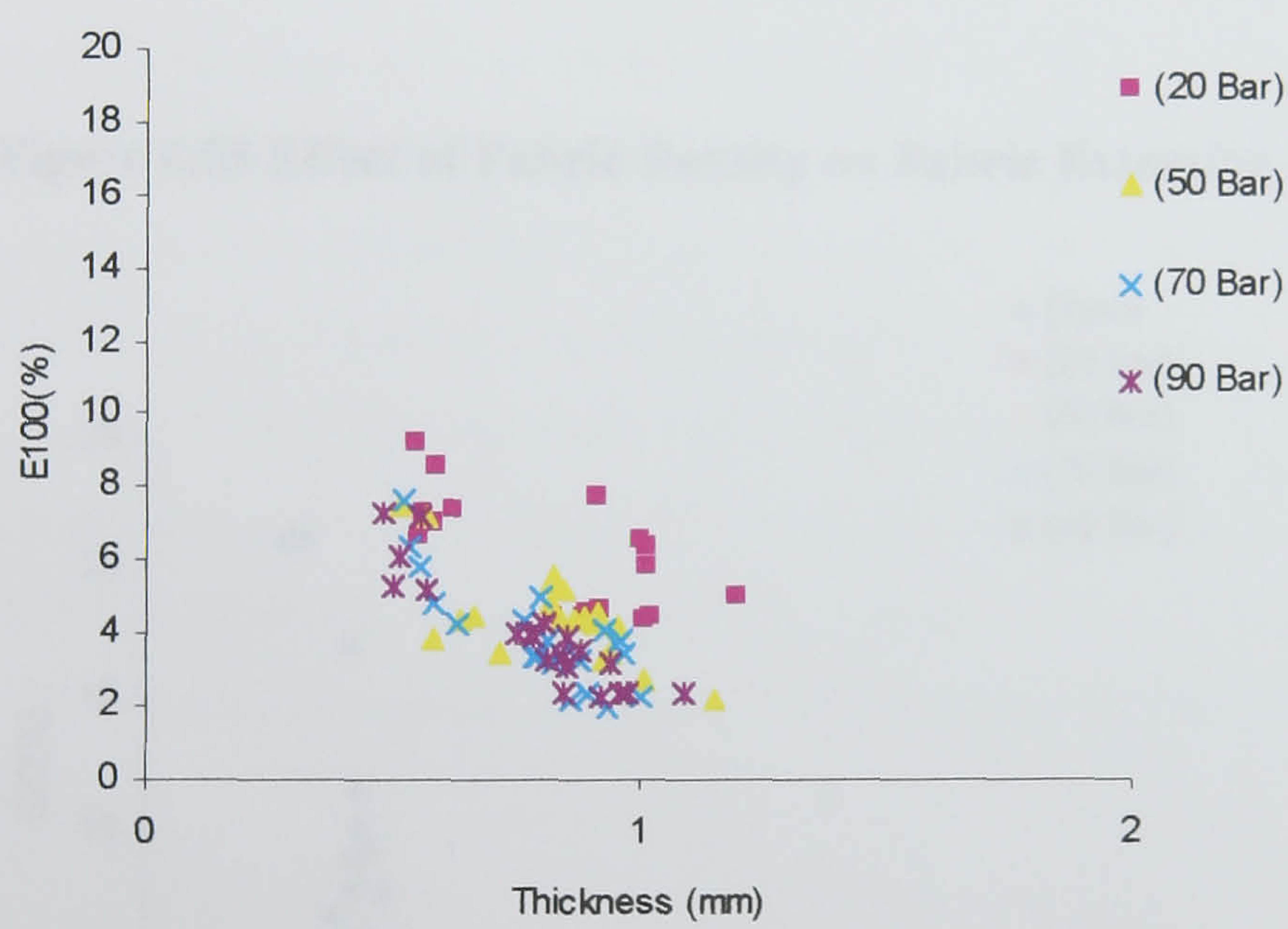


Figure 4.54 Effect of Thickness on Web and Fabric Extension at 100 gf/cm

In figure 4.52, 4.53 and 4.54, generally it is evident that increasing fabric thickness results in a decrease in extension. This may be explained as mentioned in section 4.2.5.1 as the fabric weight per unit area and fabric thickness are related. Also, in figures 4.52, 4.53 and 4.54, it is interesting to note that the trend is more noticeable at higher loads (E100% -figure 4.54) compared with lower loads (E5% and E20% - figures 4.52 and 4.53).

4.2.5.3 Effect of Fabric Density on Fabric Extension

In figures 4.55, 4.56 and 4.57, the fabric and web extension is plotted against the corresponding fabric densities for three different loads (5, 20 and 100 gf/cm) and for five different water pressures.

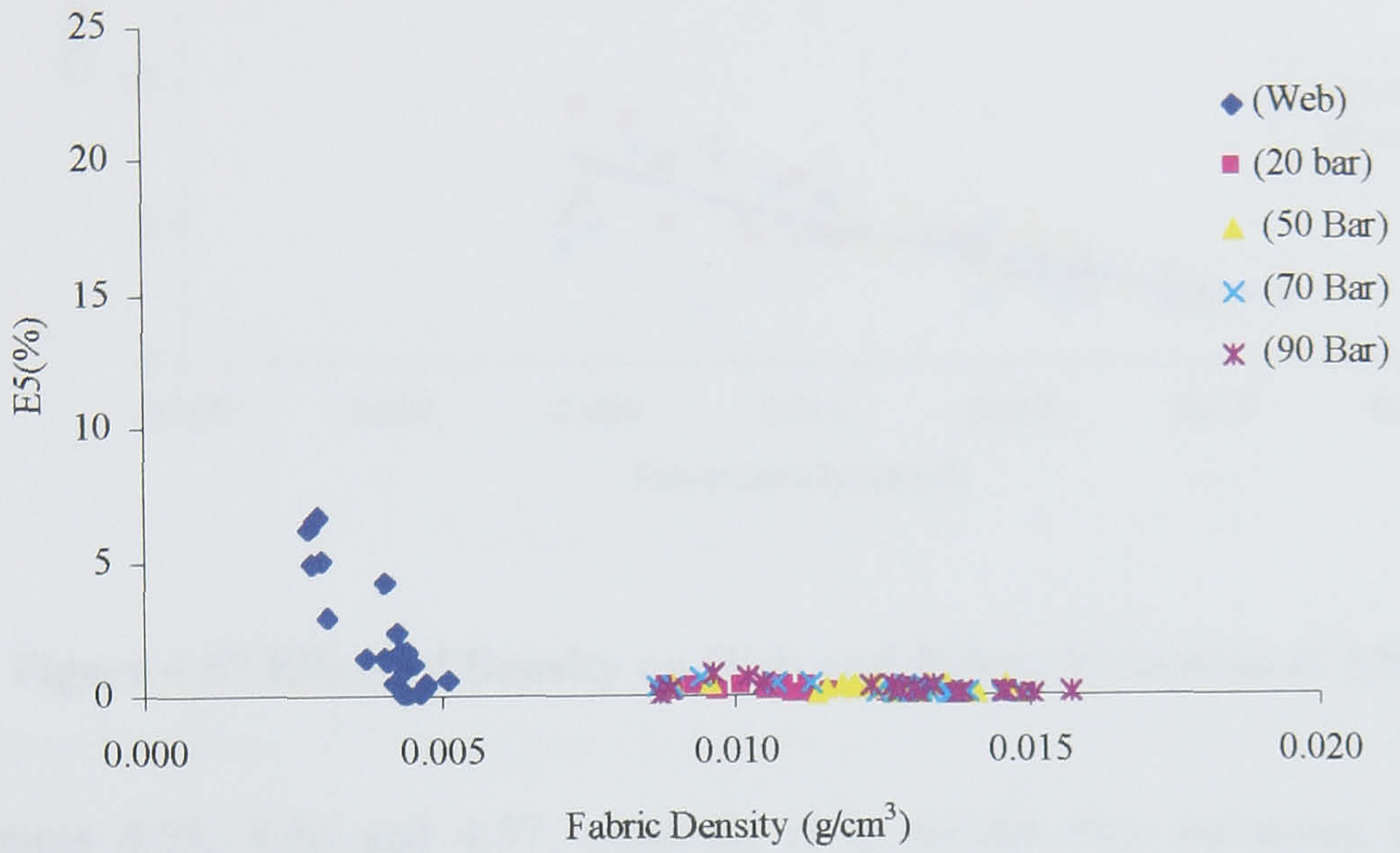


Figure 4.55 Effect of Fabric Density on Fabric Extension at 5 gf/cm

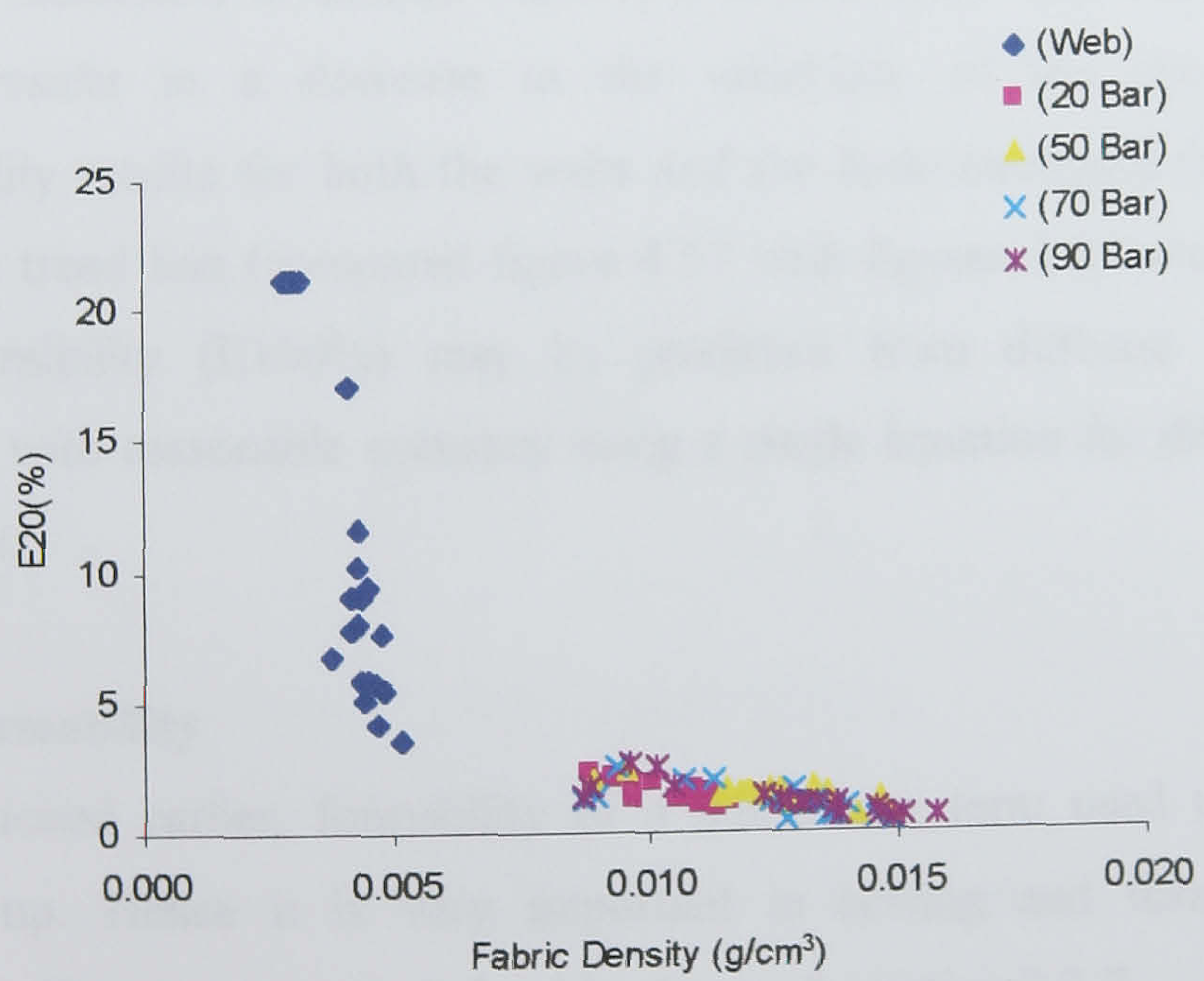


Figure 4.56 Effect of Fabric Density on Fabric Extension at 20 gf/cm

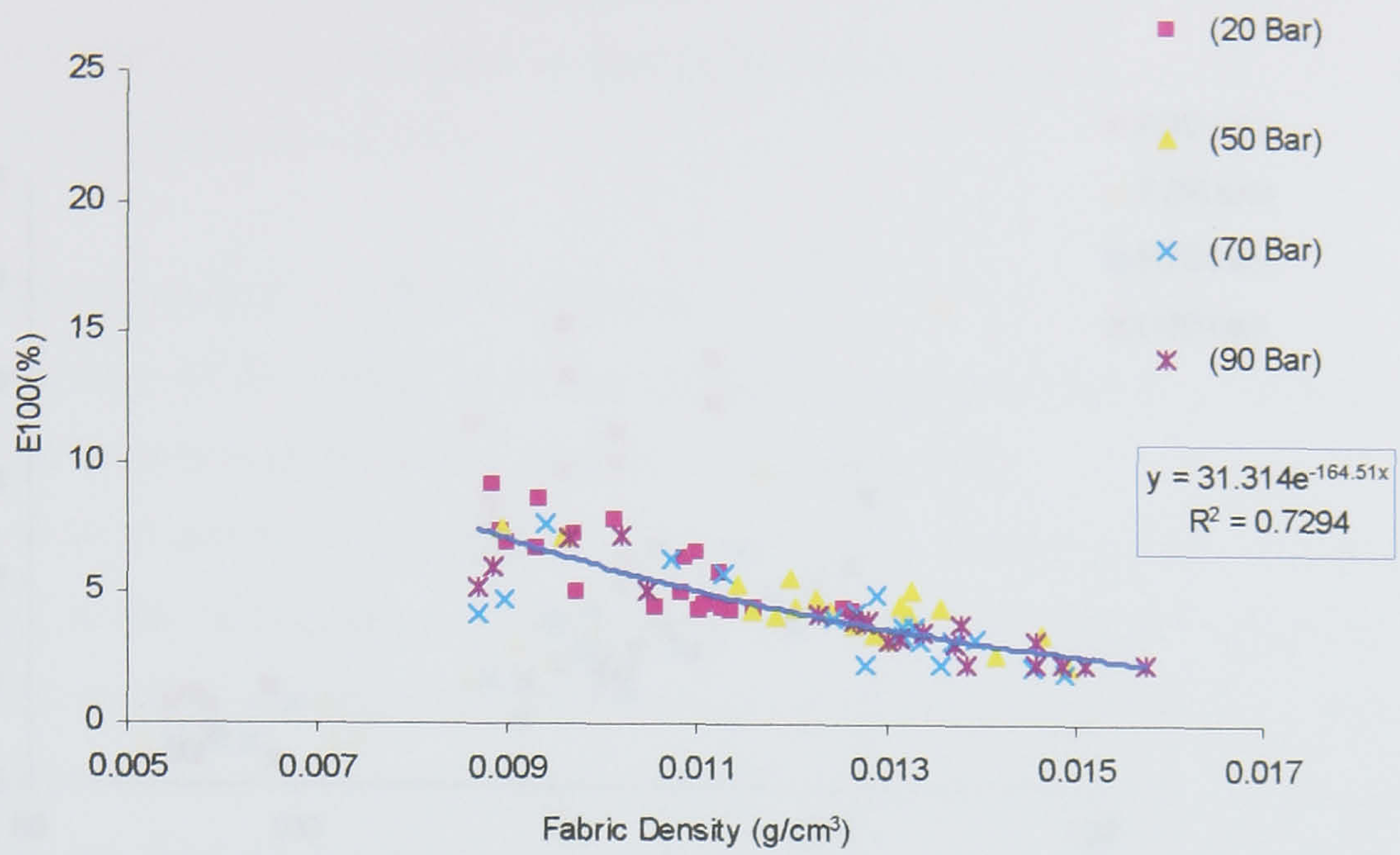


Figure 4.57 Effect of Density on Web and Fabric Extension at 100 gf/cm

In figures 4.55, 4.56 and 4.57, generally it is evident that increasing the density is accompanied by a decrease in extension; however, the effect is quite minimal at low loads in contrast with the webs whose extensibility is very sensitive to fabric density. Also, as mentioned in section 4.2.5.1, it is noticeable that increasing the load during testing results in a decrease in the variability of the results. Accordingly, the extensibility results for both the webs and the hydroentangled fabrics inclined to meet the same trend line (compared figure 4.57 with figures 4.55 and 4.56). In figure 4.57, the extensibility (E100%) may be predicted from different hydroentangled fabric densities with reasonable accuracy using a single equation for different hydroentangling pressures.

4.2.6 Formability

As mentioned earlier, formability of a fabric is a term used to express the ease of making up. Hence it is very important in sewing and forming three-dimensional garments. This parameter is defined in chapter 2, section 2.2.7.

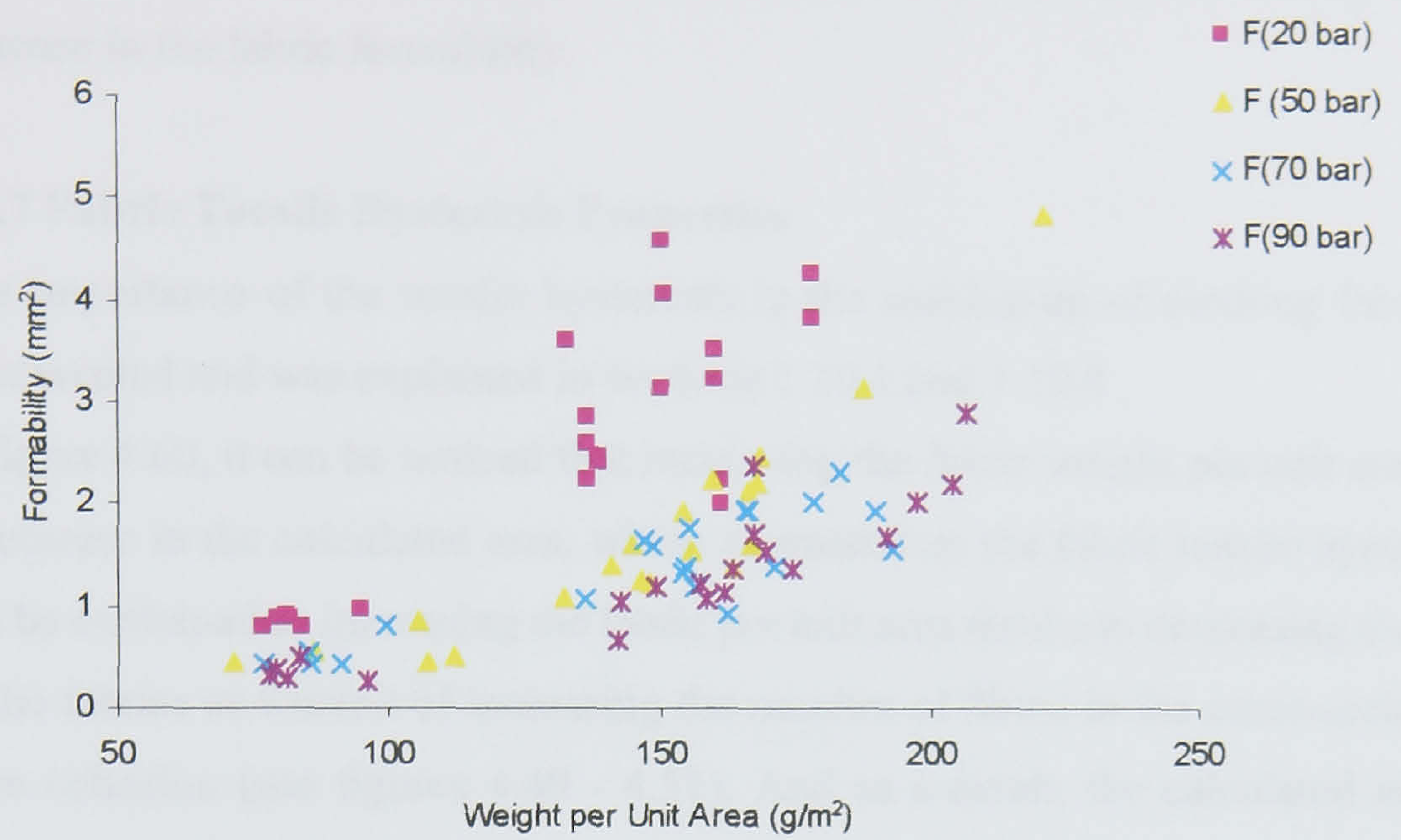


Figure 4.58 Effect of Weight per Unit Area on Hydroentangled Fabric Formability

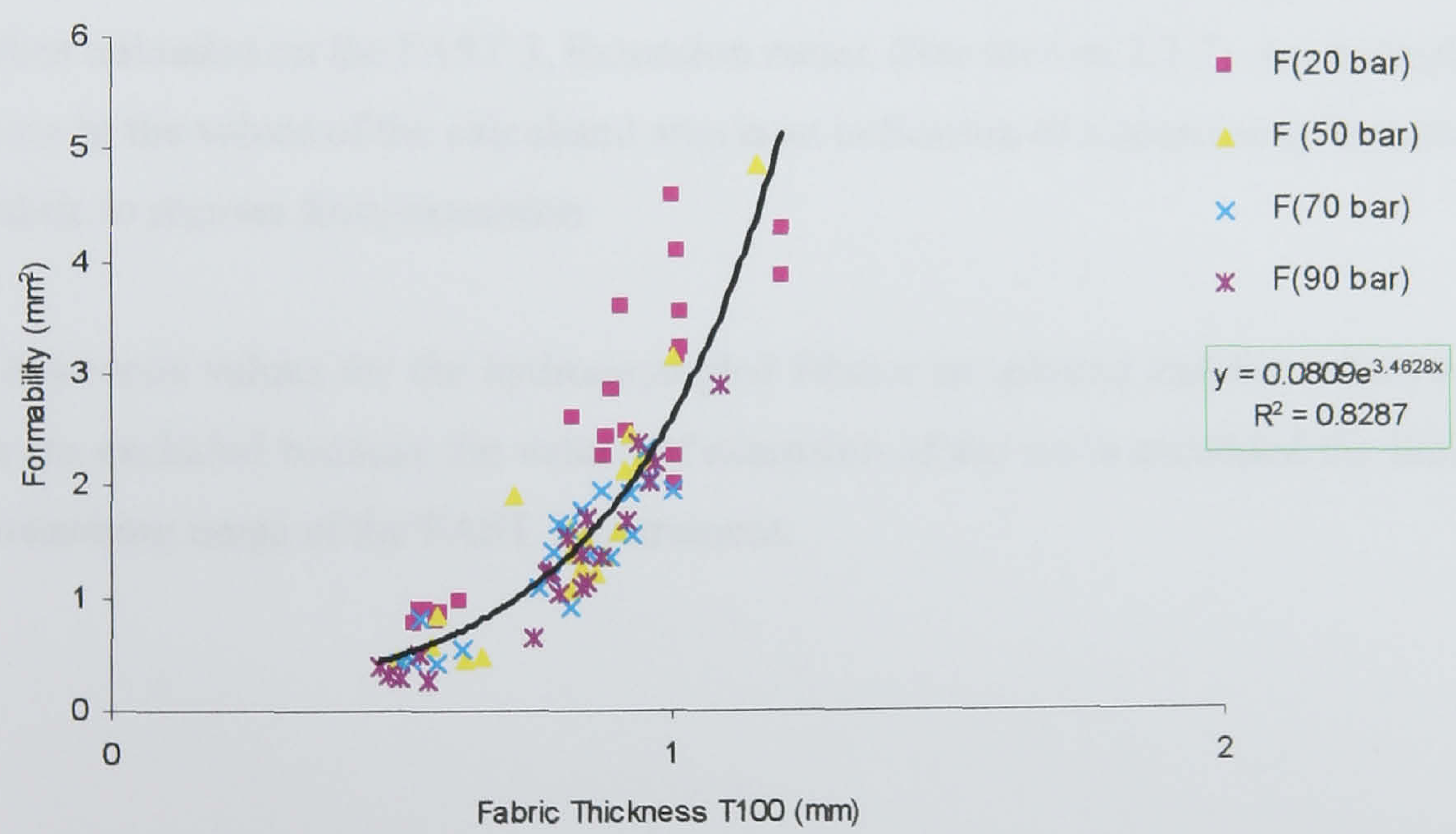


Figure 4.59 Effect of fabric Thickness on Hydroentangled Fabric Formability

In figure 4.58, it is noticeable that increasing the fabric weight per unit area is accompanied by an increase in fabric formability. Also, in figure 4.59, it is shown that fabric formability (F) and thickness (T100) may be related by a single exponential equation for the hydroentangled fabrics. It is important to note here that only the results of the hydroentangled fabrics are plotted and the results of the webs are excluded from these figures. These results can be explained in terms of increasing fabric weight per unit area resulting in an increase in the fabric bending rigidity, and as a result, an increase in the fabric formability.

4.2.7 Fabric Tensile Hysteresis Properties

The importance of the tensile hysteresis in the making-up of clothing fabrics is well documented and was explained in sections 1.10.1 and 1.10.8

In figure 4.60, it can be noticed that increasing the fabric weight per unit area results in a decrease in the calculated area, which characterises the fabric tensile hysteresis. This can be explained as increasing the fabric per unit area results in decreasing the extension of the fabrics as a result of increasing the number of fibres in the cross-section and the fibre cohesion (see figures 4.49 - 4.51). And as a result, the calculated area (tensile hysteresis) will decrease.

It is important to emphasize that the calculated area is a measure of fabric elastic recovery and is calculated from the values of extension when the fabric is first loaded and then unloaded on the FAST 3, Extension meter. (See section 2.2.7). Accordingly, an increase in the values of the calculated area is an indication of a decreasing limitation of the fabric to recover from extension

The hysteresis values for the hydroentangled fabrics are plotted and the values of the webs are excluded because the values of extension of the webs exceeded the limits of the measuring range of the FAST 3 instrument.

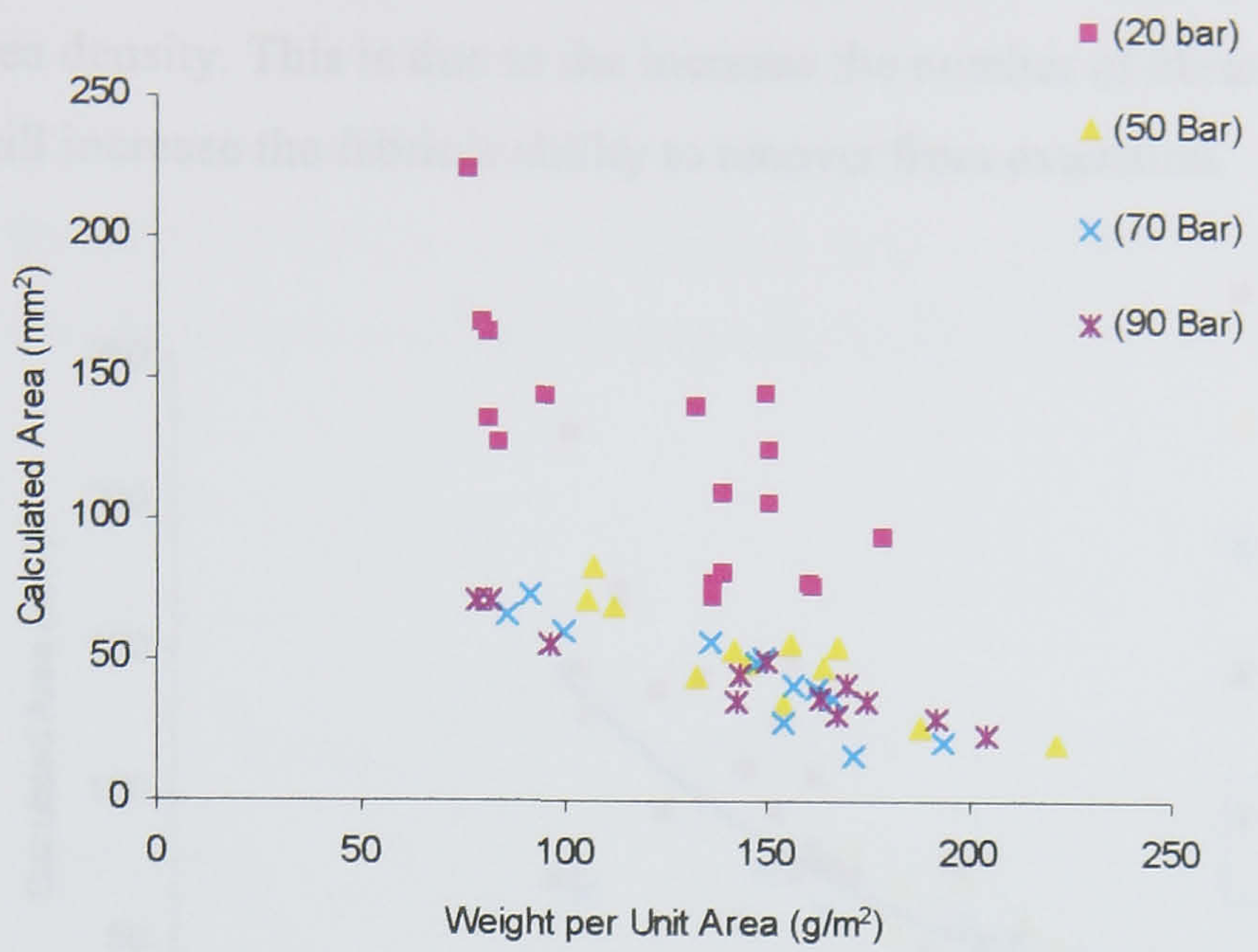


Figure 4.60 Effect of Fabric Weight per Unit Area on Fabric Hysteresis

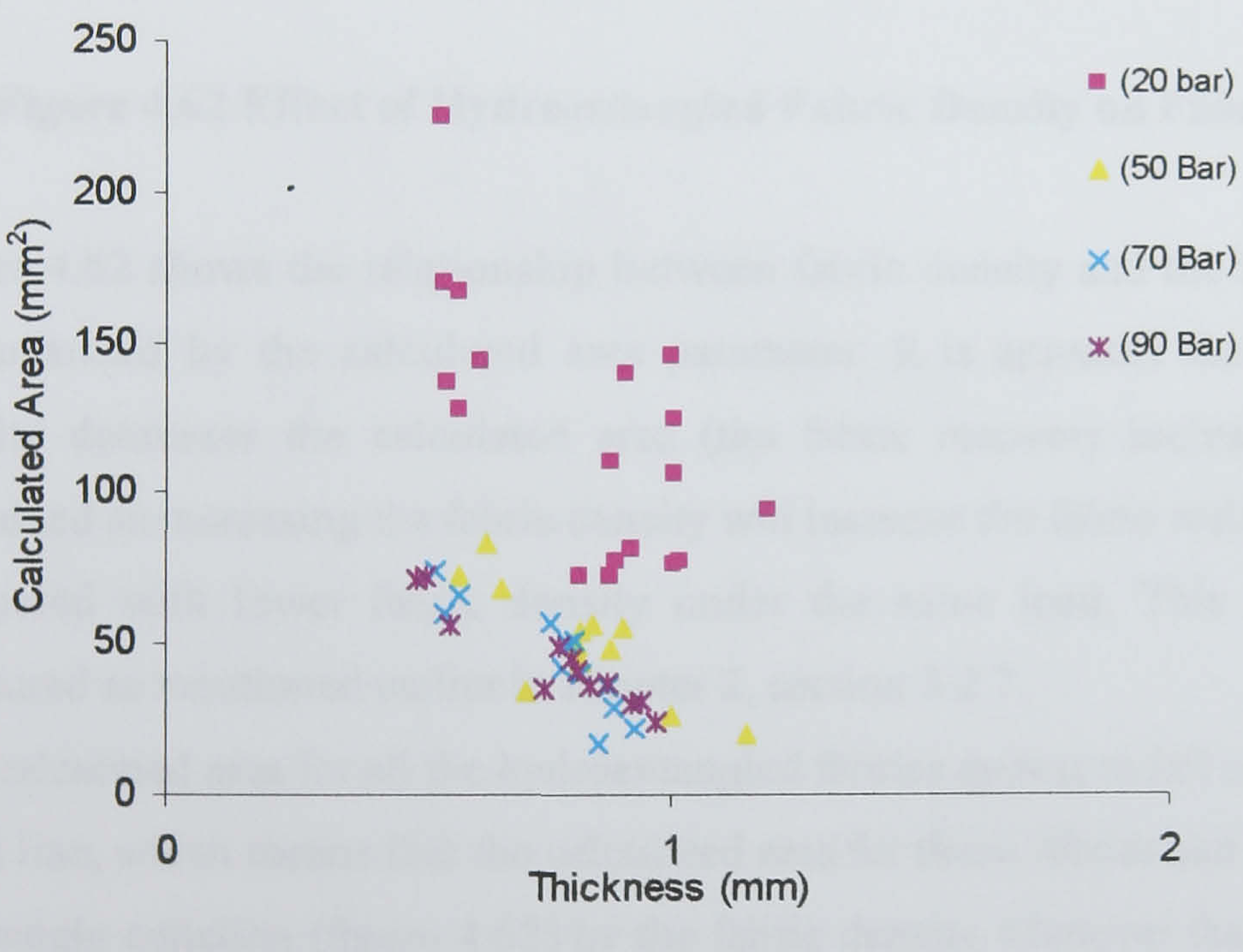


Figure 4.61 Effect of Fabric Thickness (T100) on Fabric Tensile Hysteresis

In Figure 4.61, it is generally apparent that increasing the thickness results in a decrease in the calculated area. In other words, the recovery of the fabrics will increase and this is predictable since fabric weight per unit area and thickness are known to be related. These results can be explained since the increase in fabric per unit area (or fabric thickness) will be accompanied with high fabric recovery from extension compared with low fabric area density under the same load. This also can be described, as the higher fabric area density will have more resistance to extension compared with low fabric area density. This is due to the increase the number of fibres in the cross-section, which will increase the fabric's ability to recover from extension.

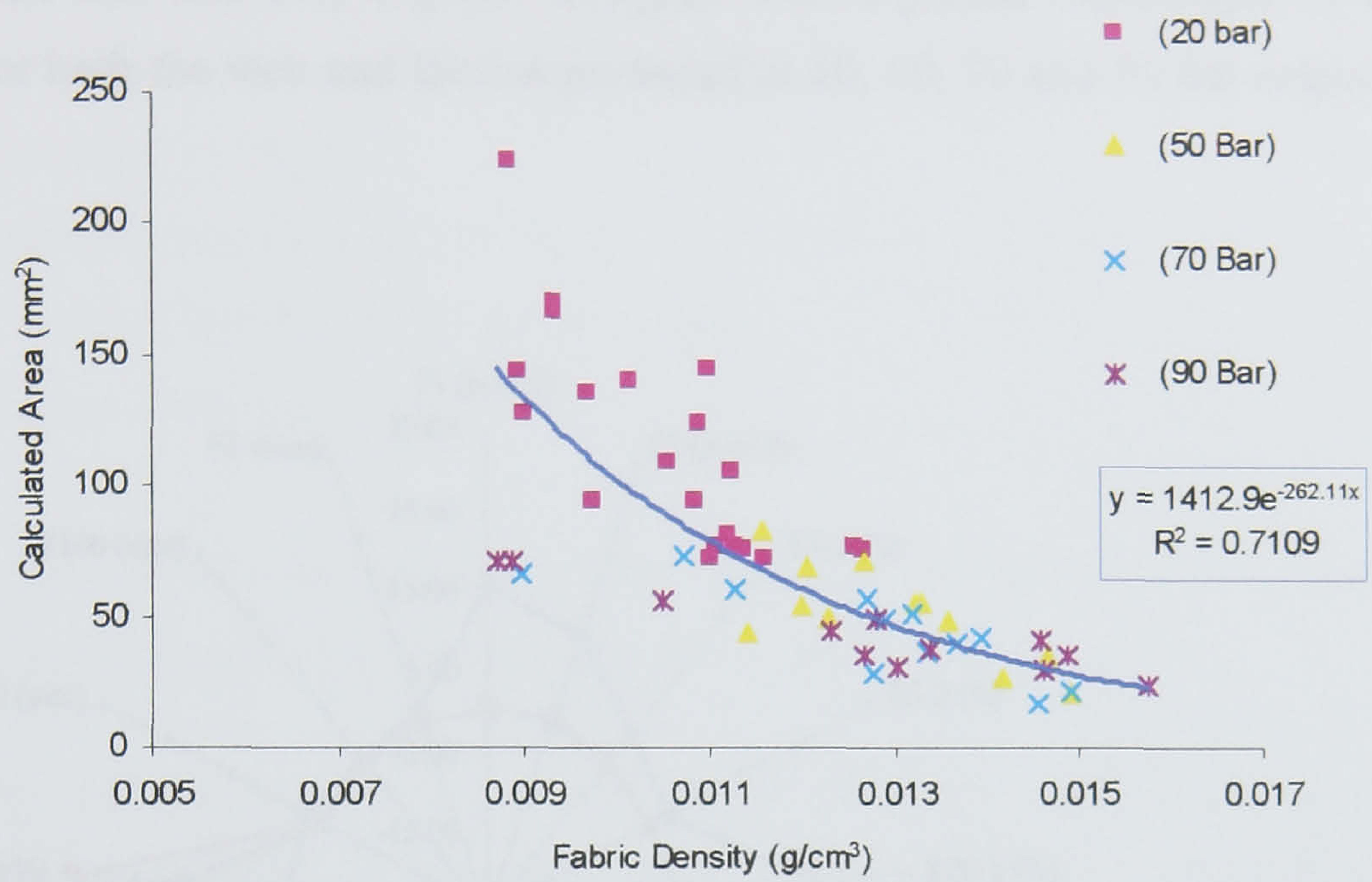


Figure 4.62 Effect of Hydroentangled Fabric Density on Fabric Hysteresis

Figure 4.62 shows the relationship between fabric density and the fabric hysteresis as characterized by the calculated area parameter. It is apparent that increasing fabric density decreases the calculated area (the fabric recovery increases). This can be explained as increasing the fabric density will increase the fabric resistance to extension compared with lower fabric density under the same load. This calculated area is measured as mentioned earlier in chapter 2, section 2.2.7.

The calculated area for all the hydroentangled fabrics appear to fall on the same general trend line, which means that the calculated area for these fabrics can be predicted using one single equation (figure 4.62) by the fabric density whatever the level of energy or water pressure used.

4.3 Comparison of the Low Stress Mechanical Properties of Hydroentangled Fabrics

In this section, an analysis of the low stress mechanical properties for 100 g/m^2 fabrics in both the MD and CD, is given. In figure 4.63, a general comparison of the main results for both the web and fabrics produced at 20, 50, 70 and 90 bar respectively is shown.

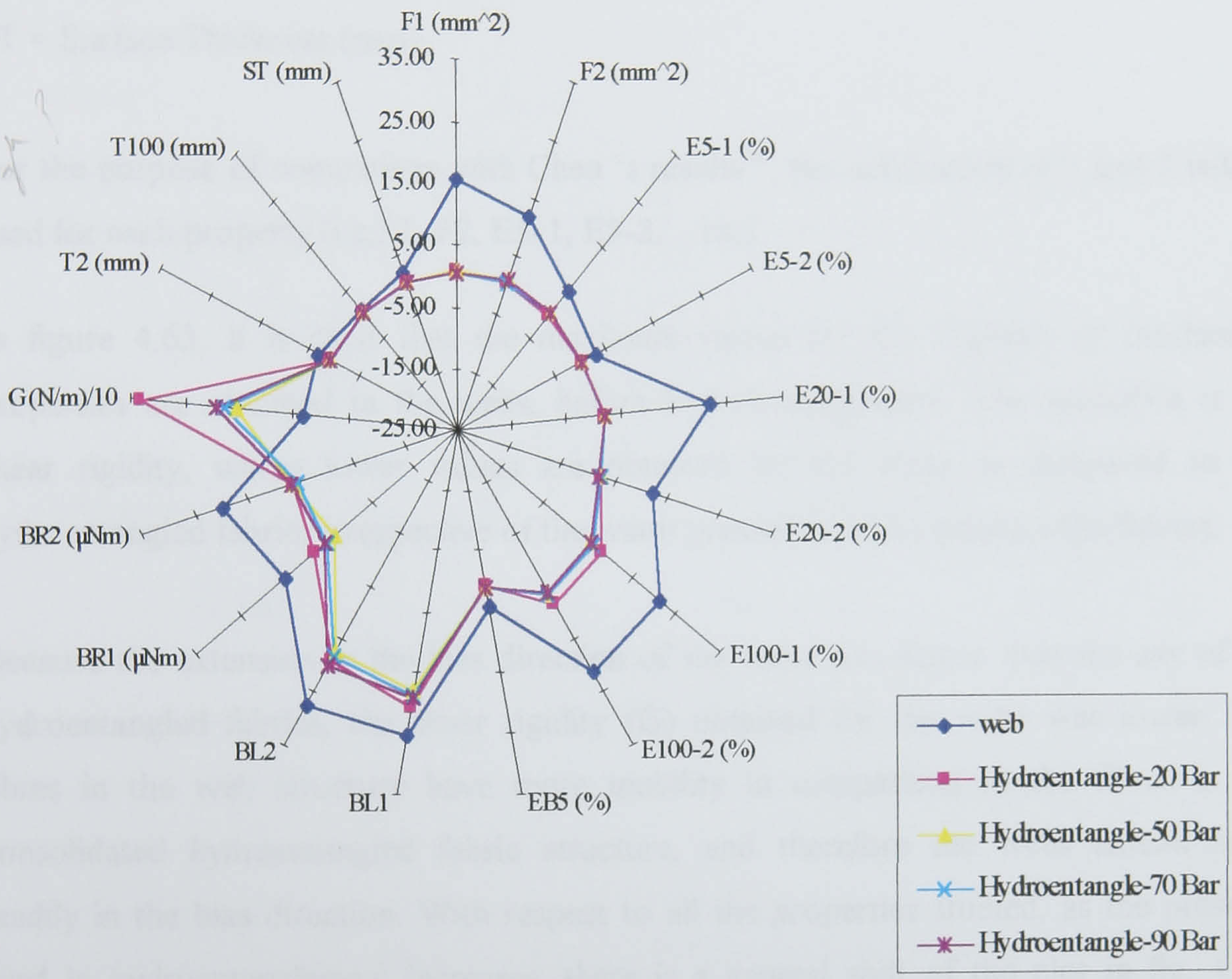


Figure 4.63 Comparison of the Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics and the Original Web

Where:

F1 = Formability in Warp Direction (MD) (mm^2)

F2 = Formability in Weft Direction (CD) (mm^2)

E5-1= Extension in warp direction (MD) at a load of 5gf/cm (%)

E5-2= Extension in weft direction (CD) at a load of 5gf/cm (%)

E20-1= Extension in warp direction (MD) at a load of 20gf/cm (%)

E20-2= Extension in weft direction (CD) at the load of 20gf/cm (%)

E100-1= Extension in warp direction at the load of 100gf/cm (%)

E100-2= Extension in weft direction (CD) at the load of 100 gf/cm (%)

EB5 = Extension in bias direction at the load of 5gf/cm (%)

BL1 = Bending length in warp Direction (MD) (mm)

BL2 = Bending length in weft Direction (CD) (mm)

BR1 = Bending Rigidity in warp Direction (MD) (μN.m)

BR2 = Bending Rigidity in weft Direction (CD) (μN.m)

G = Shear Rigidity (N/m)

T2 = Fabric thickness at 2 gf/cm^2 (mm)

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

ST = Surface Thickness (mm)

For the purpose of comparison with Chen 's results[83], the notification of 1 and 2 will be used for each property (i.e.F1, F2, E5-1, E5-2....etc)

In figure 4.63, it is clear that the maximum values for the majority of mechanical properties are obtained in the webs, before hydroentanglement. The exception is the shear rigidity, where lower values are obtained for the webs as compared to the hydroentangled fabrics irrespective of the water pressure used to produce the fabrics.

Because the extension in the bias direction of the webs was higher than for any of the hydroentangled fabrics, the shear rigidity (G) obtained for the webs was lower. The fibres in the web structure have more mobility in comparison to the fibres in the consolidated hydroentangled fabric structure, and therefore the webs extend more readily in the bias direction. With respect to all the properties studied, as the pressure used in hydroentanglement increases, there is a general shift of the plot in fig. 4.65, towards the centre (i.e. lower values are obtained). However, it is interesting to note that there are only small differences in the values for the hydroentangled fabrics irrespective of the pressure / specific energy used during their manufacture.

4.3.1 Comparison of the Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics with Conventional Shirting Fabrics

Chen[83] investigated the low stress mechanical properties of over 300 woven fabrics used for clothing using the FAST system. These fabrics were of different structures and area densities. From this database[83], a group of woven fabrics used as shirtings in the range

80-100 g/m^2 were selected for comparison with the hydroentangled fabrics produced in the present study. The fabrics selected were of comparable area density to the hydroentangled samples. The purpose was to establish similarities and differences in the low stress mechanical and dimensional properties.

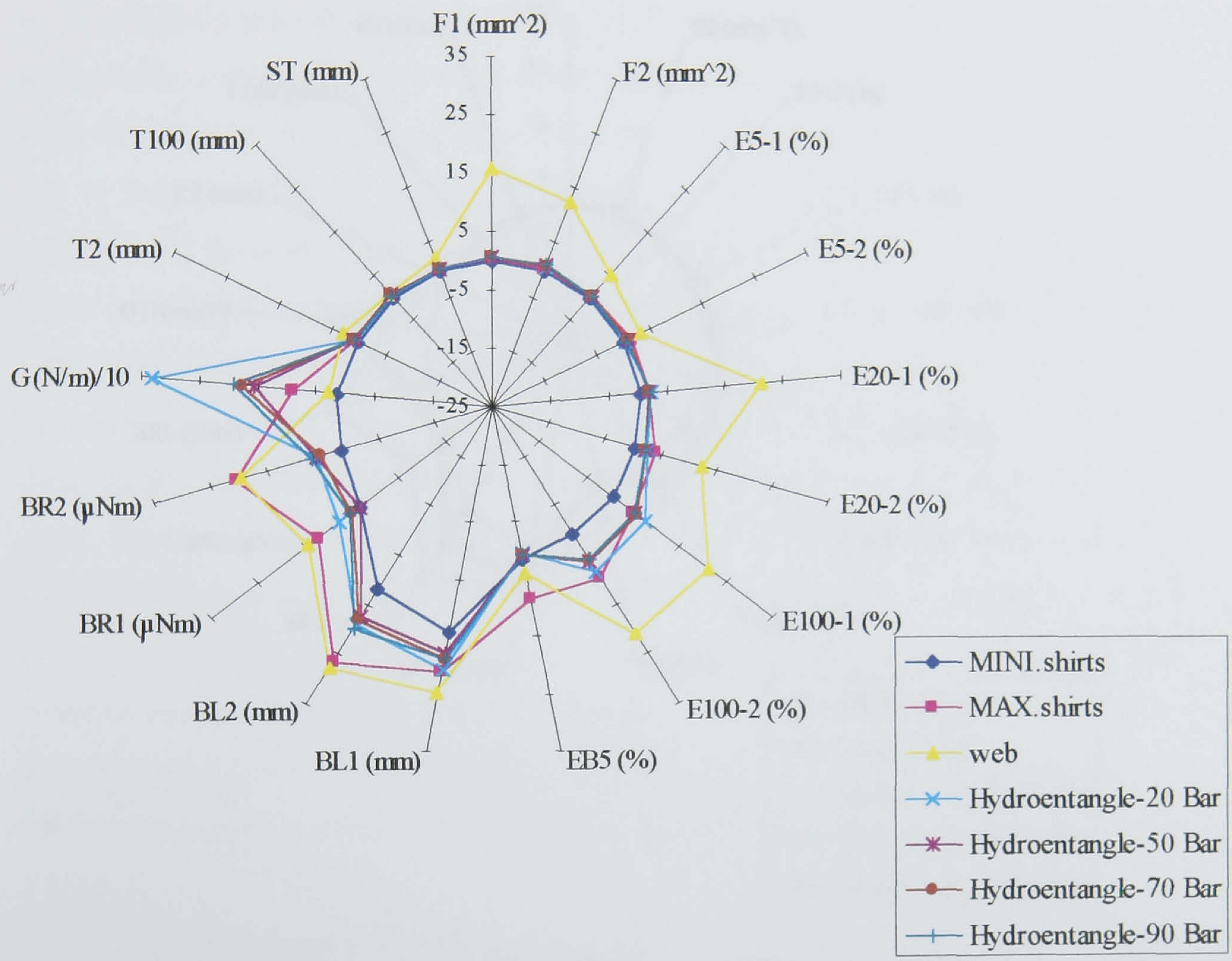


Figure 4.64 Comparison of the Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics and the Maximum and the Minimum Values for Shirt Fabrics

In figure 4.64, a comparison between the low stress mechanical and dimensional properties of the shirting fabrics (the maximum and minimum values are given) [83], and these of the webs and the hydroentangled fabrics produced using 20, 50, 70 and 90 bar respectively is presented.

Not surprisingly, it is evident that the values of most of the parameters for the webs and the fabrics produced at 20 bar water pressure fall outside the maximum acceptable limits for shirt fabrics. Accordingly, in further analysis the results for the webs were excluded (figure 4.64)

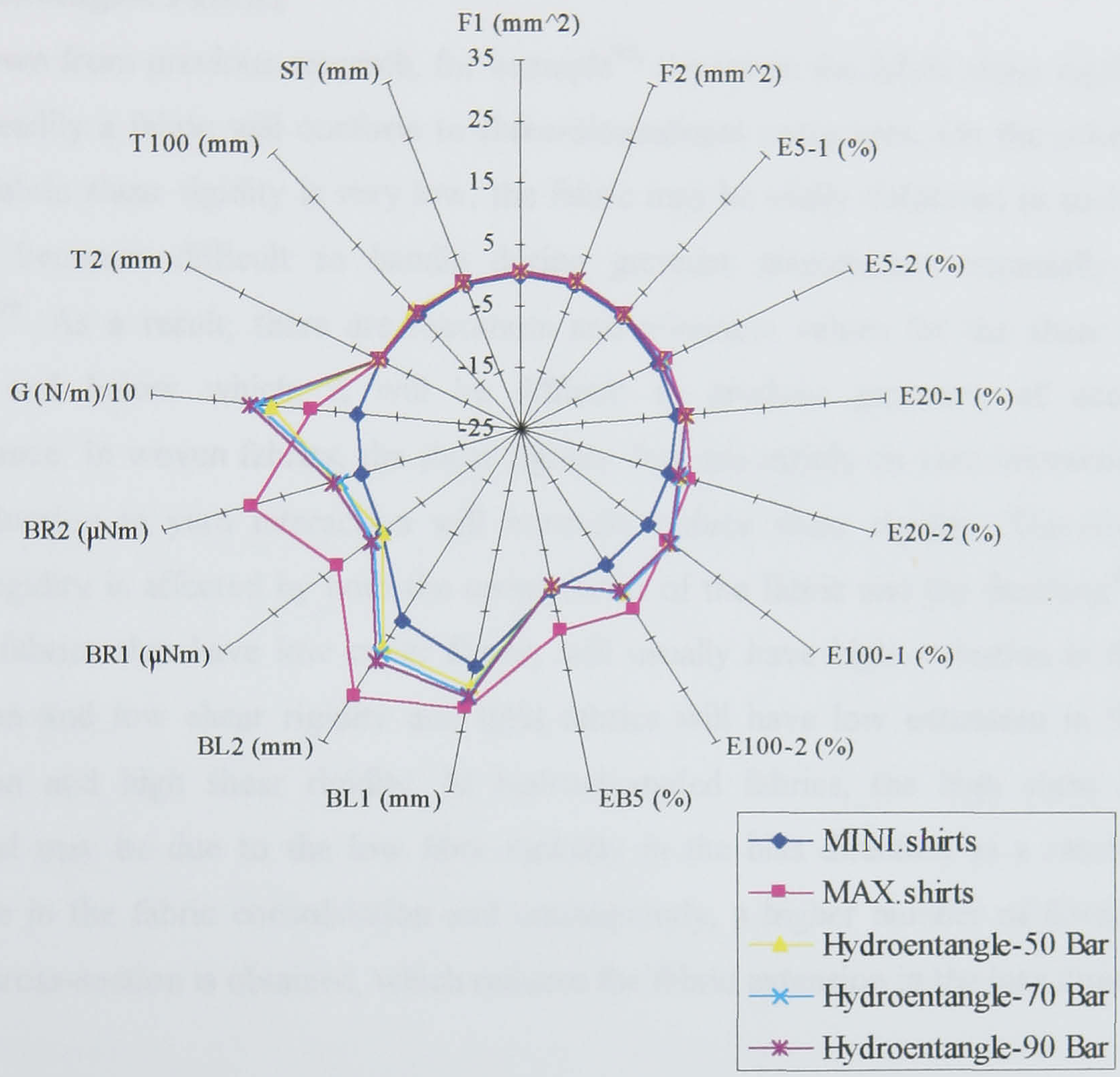


Figure 4.65 Low Stress Mechanical and Dimensional Properties of Hydroentangled Fabrics (50, 70 and 90 bar) and Maximum and Minimum for Shirt Fabrics

In figure 4.65, the values for the webs and the hydroentangled fabrics produced using 20 bar water pressure are excluded from the comparison because they fall outside the maximum acceptable limits for shirt fabrics. Only the hydroentangled fabrics produced using relatively high pressures, and the shirting fabrics are compared.

The values for the hydroentangled fabrics tend to fall within the minimum and maximum values for the shirt fabrics with the exception of the shear rigidity. Therefore, it would appear that hydroentangled fabrics produced using relatively high water pressure have properties comparable to these of woven fabrics apart from the shear rigidity. Further modification to process parameters may be a suitable route for reducing the performance difference between woven and hydroentangled fabrics. This will be explained in the next section.

4.4 Effect of Fabric Geometry on Bending Rigidity (BR) and Shear Rigidity (G) in Hydroentangled Fabrics

As known from previous research, for example[93], the lower the fabric shear rigidity, the more readily a fabric will conform to three-dimensional curvatures. On the other hand, if the fabric shear rigidity is very low, the fabric may be easily deformed in such a way that it becomes difficult to handle during garment manufacture especially during sewing[93]. As a result, there are maximum and minimum values for the shear rigidity above and below which, it will be difficult to produce garments of acceptable appearance. In woven fabrics, the shear rigidity depends mainly on yarn interaction; and the reduction in yarn interaction will normally reduce shear rigidity. Therefore, the shear rigidity is affected by both the cover factor of the fabric and the finishing[46]. As a result, fabrics that have low cover factor, will usually have high extension in the bias direction and low shear rigidity and tight fabrics will have low extension in the bias direction and high shear rigidity. In hydroentangled fabrics, the high shear rigidity obtained may be due to the low fibre mobility in the bias direction as a result of an increase in the fabric consolidation and consequently, a higher number of fibres in the fabric cross-section is obtained, which reduces the fabric extension in the bias direction.

Also, the bending rigidity has an important effect on the handle of the fabric. The most effective approach to control the fabric stiffness is by the right the choice of the fibre type and fineness used, and also, the yarn and fabric construction[46]. For hydroentangled fabrics, the reorientation of the fibres according to the hydroentanglement process has the major influence on the fabric stiffness.

In order to reduce the shear rigidity obtained for the hydroentangled fabrics, a modified approach was needed during fabric manufacture that would lead to fabrics with lower shear rigidities. Some researchers have linked the structure of entangled fibres in hydroentangled fabrics to “pseudo-yarns. i.e. the fibre bundles are entangled into continuous strands running in the MD. This is particularly noticeable in apertured fabrics. If such pseudo-yarns are also produced in the CD, perhaps it will be possible to produce a fabric that, in crude terms, is similar to a woven fabric. Consequently, the bias properties might improve. Therefore, the approach was explored involving the hydroentanglement of fabrics in both the MD and CD directions to produce hydroentangled fabrics that have a structure, which may allow more fibre mobility in the bias direction. The fabrics produced are described in the next section.

4.4.1 Experimental

Three different fabrics of the same range of weight per unit area (100 g/m^2), using the same water pressure applied (50 bar) and the same total specific energy, were produced. Four injectors were used in each fabric sample in different directions. The fabrics were prepared as shown in tables 4.1 –4.3.

Table 4.1: Specifications of Sample 1

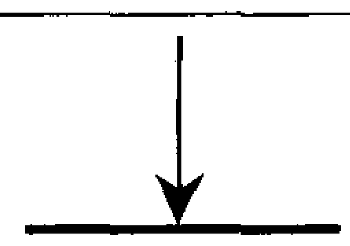
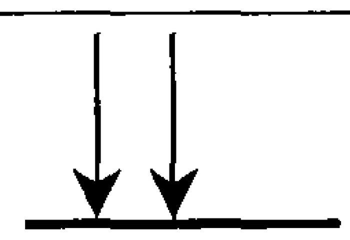
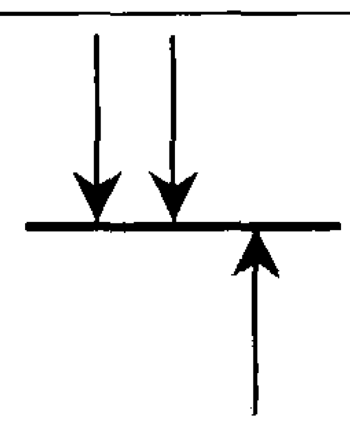
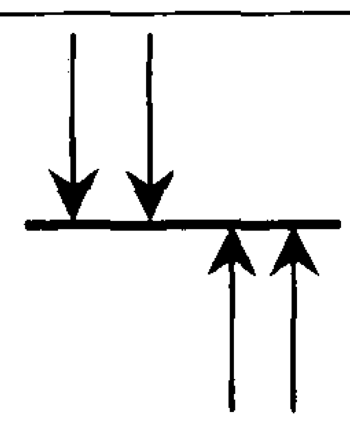
Machine Direction	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
MD (Face)		1 pass- 50 bar	0.578
MD (Face)		2 passes – 50 bar	1.156
MD (Back)		3 passes – 50 bar	1.734
MD (Back)		4 passes – 50 bar	2.312

Table 4.2: Specifications of Sample 2

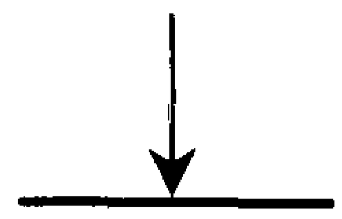
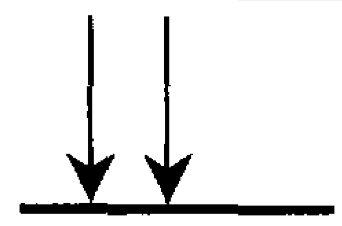
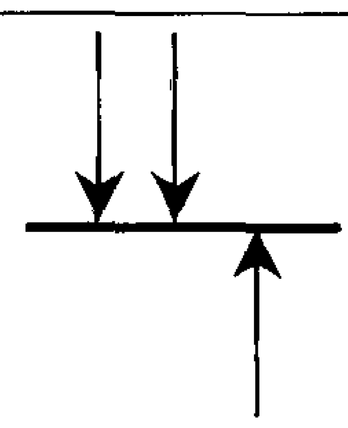
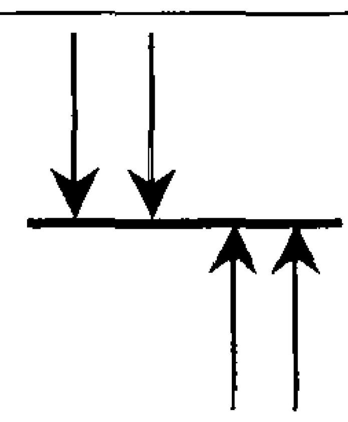
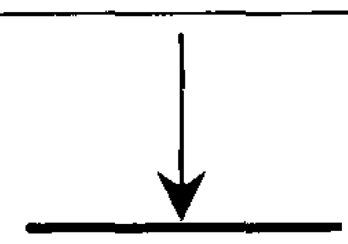
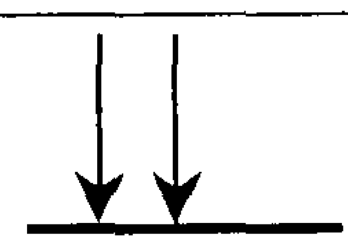
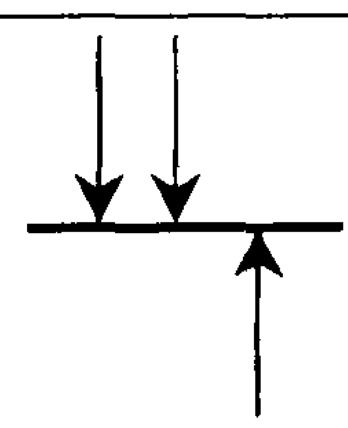
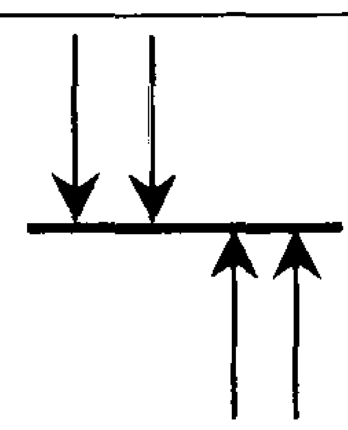
Machine Direction	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
CD (Face)		1 pass- 50 bar	0.578
CD (Face)		2 passes – 50 bar	1.156
CD (Back)		3 passes – 50 bar	1.734
CD (Back)		4 passes – 50 bar	2.321

Table 4.3: Specifications of Sample 3

Machine Direction	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
MD (Face)		1 pass- 50 bar	0.578
CD (Face)		2 passes – 50 bar	1.156
MD (Back)		3 passes – 50 bar	1.734
CD (Back)		4 passes – 50 bar	2.321

The results of the low stress properties of the resulting fabrics (samples 1, 2 and 3) measured are shown in figure 4.66.

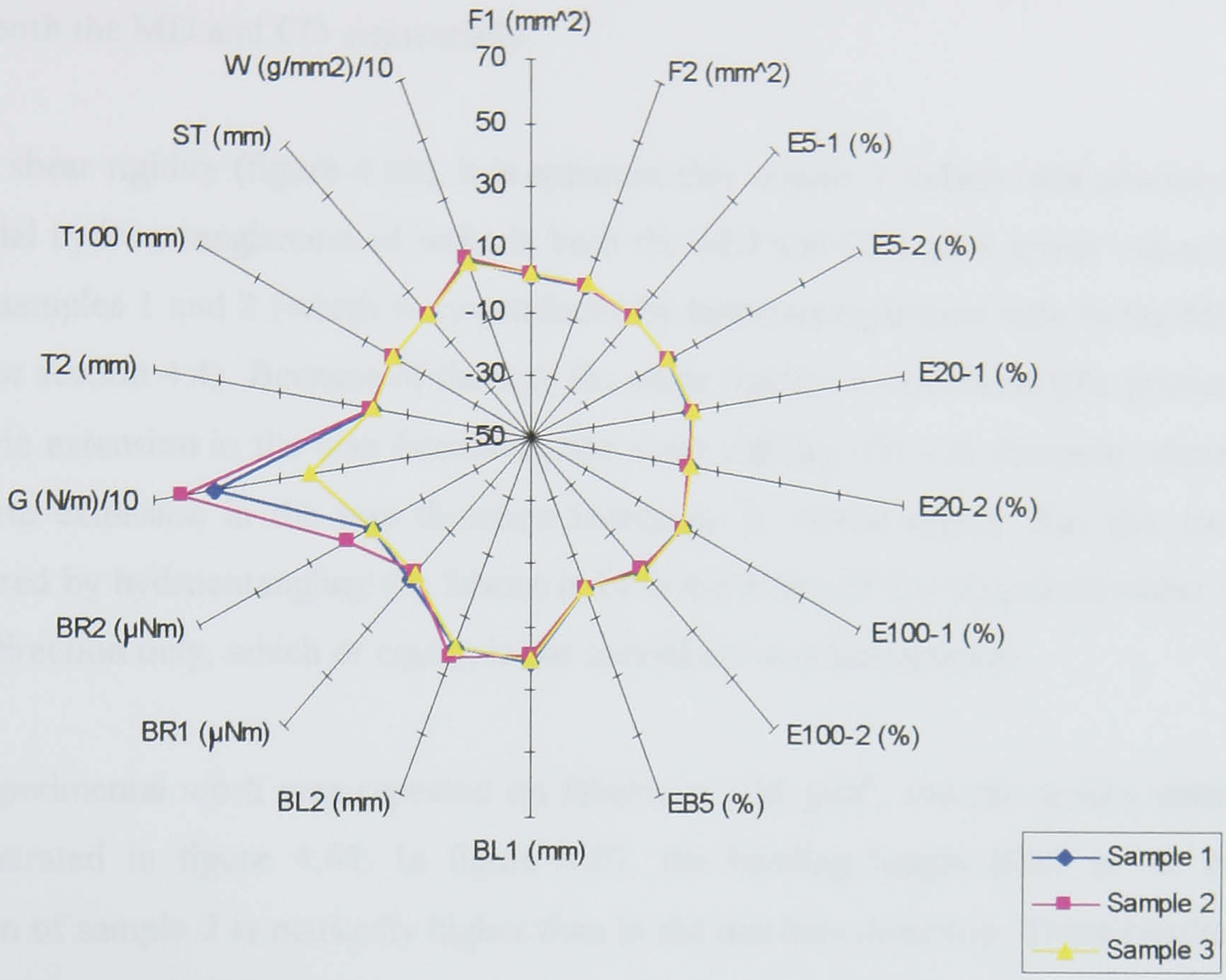


Figure 4.66 Comparison of the Low Stress Mechanical and Dimensional Properties of Samples 1,2 and 3 (100 g/m^2)

In figure 4.66, it apparent that the values are virtually identical for the three samples with the exception of the bending length (BL), bending rigidity (BR) and the shear rigidity (G).

For the bending length, it is known from the results presented in chapter 4, section 4.1.5.3 that the bending length in the MD is generally higher than in the CD when the fabrics are produced in the MD. This is reflected in the results for sample 1.

Conversely, for sample 2 (figure 4.66), the bending length (BL) in the CD is higher than that in the MD and this reflects the direction in which the fabric was hydroentangled. This means that the direction of treatment of the batt and fabrics has a marked effect on the resultant isotropy of fabric bending properties, which tends to negate the influence of the original predominant fibre orientation in the original webs or batts.

For sample 3, it is apparent that the bending length and bending rigidity values are almost the same in the MD and CD. This fabric was produced by hydroentangling the batt in both the MD and CD sequentially.

For the shear rigidity (figure 4.66), it is apparent that sample 3 (which was produced by sequential hydroentanglement of webs in both the MD and CD) gave lower values than that of samples 1 and 2 (which were produced by hydroentanglement only in the MD or CD) (see section 4.4). Because of the way the shear rigidity is calculated (the product of the fabric extension in the bias direction), the shear rigidity (G) will decrease whenever the fabric extension in the bias direction increases. It would appear that this can be engineered by hydroentangling the fabrics in both the MD and CD directions rather than in one direction only, which of course is the normal commercial practice.

This experimental work was repeated on fabrics of 138 g/m^2, and the results obtained are illustrated in figure 4.67. In figure 4.67, the bending length (BL) in the cross direction of sample 2 is markedly higher than in the machine direction. These results are almost similar to these in figure 4.66. In figure 4.67, sample 3 has a lower value of shear rigidity compared with sample 1 and 2, but it is markedly lower in figure 4.66. These results may be explained as for the fabric of 100 g/m^2, there is lower number of fibres in the cross-section compared with fabrics of 138 g/m^2 (see figure 4.4). Thus, the possibility of more fibre mobility in the bias direction is higher than in fabric 138 g/m^2 as a result of high fibre cohesion.

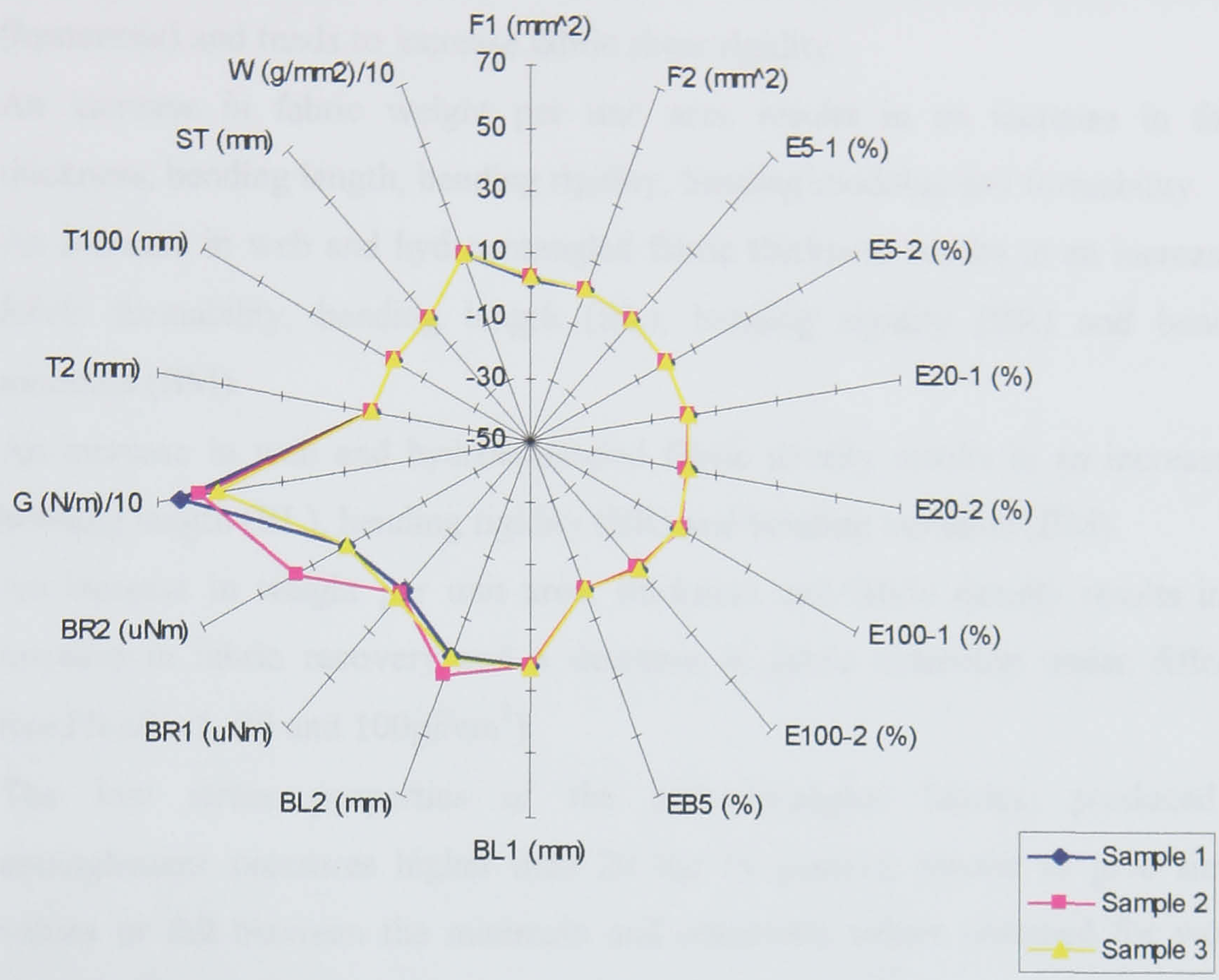


Figure 4.67 Comparison of Low Stress Mechanical and Dimensional Properties of Samples 1,2 and 3 (138 g/m^2)

4.5 Conclusions

For the fabrics tested, the following overall conclusions may be drawn

1. An increase in specific energy applied is associated with an initial decrease in fabric thickness (T2 and T100), and surface thickness (ST) followed by a leveling at higher energies. Also, an increase in specific energy applied is associated with an increase in fabric density.
2. An increase in specific energy applied is associated with a decrease in fabric bending length (BL), bending rigidity (BR) and bending modulus (BM), especially after initial fabric hydroentangling at low specific energy. Further increase in specific energy results in general slight increase in bending length, bending rigidity and bending modulus. Using higher specific energy, the relative changes associated with change in the specific energy appear to increase generally with fabric weight.

3. An increase in specific energy is generally associated with a decrease in fabric extension and formability but results in an increase in fabric recovery (hysteresis) and tends to increase fabric shear rigidity.
4. An increase in fabric weight per unit area results in an increase in fabric thickness, bending length, bending rigidity, bending modulus and formability.
5. An increase in web and hydroentangled fabric thickness results in an increase in fabric formability, bending length (BL), bending rigidity (BR) and bending modulus (BM).
6. An increase in web and hydroentangled fabric density results in an increase of bending length (BL), bending rigidity (BR) and bending modulus (BM).
7. An increase in weight per unit area, thickness and fabric density results in an increase in fabric recovery and a decrease in fabric extension under different fixed loads (5, 20 and 100gf/cm^2).
8. The low stress properties of the hydroentangled fabrics, produced at entanglement pressures higher than 20 bar (4 passes), tended to give similar values or fall between the minimum and maximum values obtained for woven shirting fabrics with the exception of the shear rigidity (G).
9. There is an effect of producing fabrics by hydroentanglement in both MD and CD on the low stress mechanical properties such as fabric bending and shear rigidity.
10. Fabrics produced by hydroentanglement in the MD generally have high bending length in the MD than CD, compared to fabrics produced by hydroentanglement in the CD, which generally have high bending length in the CD than MD.
11. Fabrics produced by hydroentanglement of the webs in the MD or CD only tend to have high shear rigidity (G) compared to woven fabrics used for apparel applications.
12. Hydroentangling fabrics bi-directionally (i.e. in the MD and CD) tends to give fabrics with lower shear rigidity (G) than these hydroentangled uni-directionally in the MD or CD only
13. The formation of the fabrics by hydroentangling the webs in both the MD and CD sequentially tend to decrease the anisotropy of bending behaviour in resultant fabrics especially for the fabric 100 g/m^2.

CHAPTER 5
INVISTIGATION OF FABRIC STRUCTURE USING A TRACER FIBRE TECHNIQUE

5.1 Introduction

The internal structure of a nonwoven fabric is a major influence on the mechanical properties and influences fabric aesthetics including properties such as bending and compression characteristics. Structural changes in the fabric are affected by process variables and adjustments and in particular the applied specific energy level and energy profiles are believed to be important.

In chapter 4, fabrics of different weight per unit area produced using a standard method of introducing the specific energy, were studied.

In this chapter, observations of fibre migration due to changes in the applied specific energy and jet profile are studied using tracer fibres. Image-analysis methods were established to study the microstructural changes in hydroentangled fabrics produced using different conditions. In addition, the cross-sectional structure of different hydroentangled fabrics was also studied.

5.2 Experimental Procedure for Tracer Fibre Studies

A carded web of 100 g/m^2 produced by cross-laying and made of white viscose rayon fibres of 1.7 dtex (mean linear density) and 38mm (mean fibre length) was used. A separate carded web of 4.6 g/m^2 made of black viscose rayon 38mm (mean fibre length), and 1.7 dtex (mean linear density) was carefully rolled on to one or both surfaces of the white web prior to hydroentanglement as explained below. These black tracer fibres were introduced as a method of assessing the reorientation of surface fibres during hydroentanglement using different energy profiles.

To investigate the nature of fibre migration using different energy profiles, each fabric was marked to distinguish four equally sized samples. After each pass, one of the four pieces was cut and retained for analysis. Two of the fabrics were produced with black fibres on the top surface only. The other two fabrics were produced with the black fibres laid on both sides. The purpose of this was to enable the reorientation of fibres into the fabric on both sides during hydroentanglement to be observed.

5.3 Hydroentanglement Machine Settings

The same machine settings as used in chapter 3 – section 3.2.2 were used, except that the webs were pre-wetted at 10 bar pressure to help combine the black and white webs before the main hydroentanglement stage. This low prewetting pressure was used to avoid disturbing the black fibres on the top and (or) bottom of the fabric. Use of an injector operating at such low pressure was preferred rather than a spray head, which operated at a higher pressure than 10 bar (approximately 17 bar), as this would risk disturbing fibres in the web.

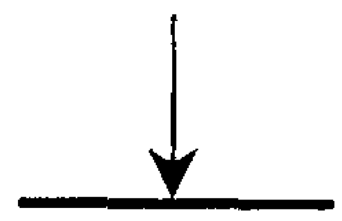
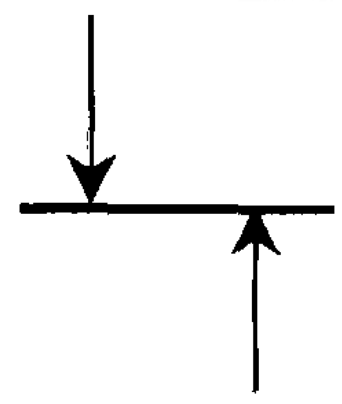
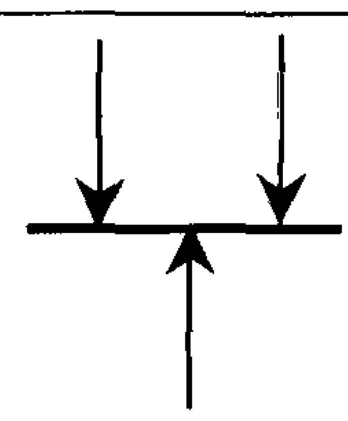
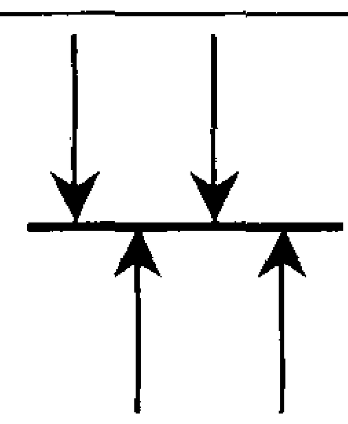
5.4 Experimental Design

Four groups of fabrics were produced, each with four different energy levels. The different energy levels were achieved by multiple passes through the hydroentanglement system. A fixed pressure of 20 bar was used for the hydroentanglement of the first two groups using one injector throughout, whereas, a fixed pressure of 50 bar was used for the second two groups using one injector. It is important to mention here that the four groups of fabrics that were produced at 20 or 50 bar were repositioned on the belt between passes to ensure that the web was treated uniformly. The method of producing each fabric sample is summarized as follows.

5.4.1 Group 1

In this group, four fabrics were produced with four different levels of energy and the pressure used was 20 bar. The black fibre web was placed on both the face and back of the web (See table 5.1).

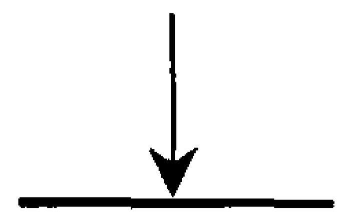
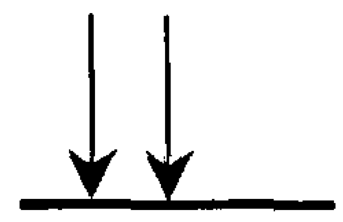
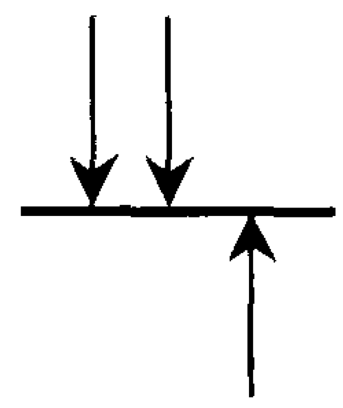
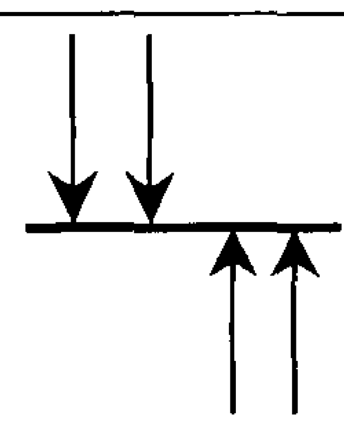
Table 5.1: Specifications of Group 1

Sample Ref. Number	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
S1$_A$		1 pass- 20 bar	0.148
S1$_B$		2 passes – 20 bar	0.296
S1$_C$		3 passes – 20 bar	0.444
S1$_D$		4 passes – 20 bar	0.592

5.4.2 Group 2

As in group 1, four fabrics were produced with four different levels of energy with the pressure set at 20 bar. However, a different set of energy profiles was used as shown in table 5.2. The black fibre web was placed only on the face of the white web.

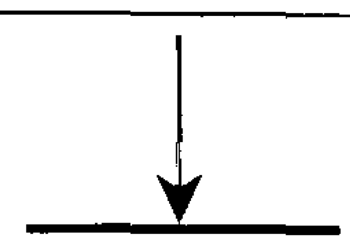
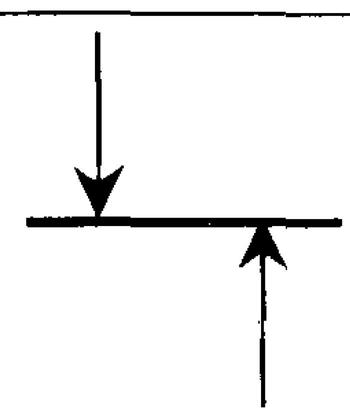
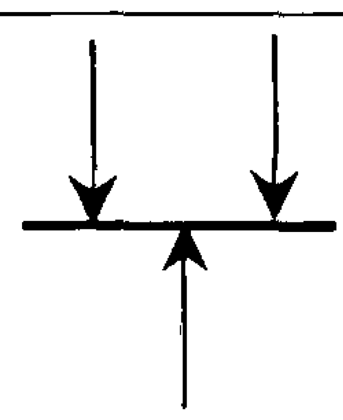
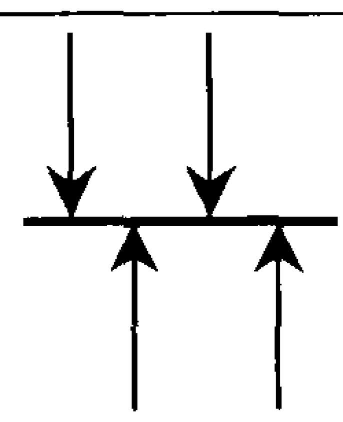
Table 5.2: Specifications of Group 2

Sample Ref. Number	Treatment Type	Number of passes- Pressure Used	Total Specific energy (MJ/Kg)
S2$_A$		1 pass- 20 bar	0.148
S2$_B$		2 passes – 20 bar	0.296
S2$_C$		3 passes – 20 bar	0.444
S2$_D$		4 passes – 20 bar	0.592

5.4.3 Group 3

Four fabrics were produced with four different levels of energy using a pressure of 50 bar. The black fibre web was placed on both the face and on the back of the white web. Thus, the same energy profile as used in group 1 was applied but with a higher pressure (50 bar) (see table 5.3).

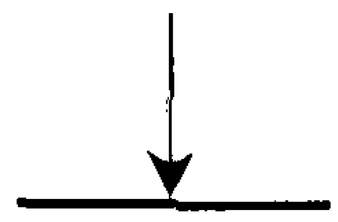
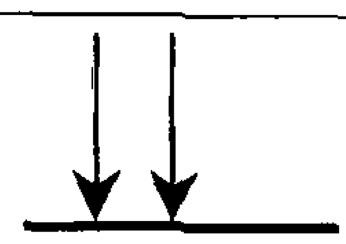
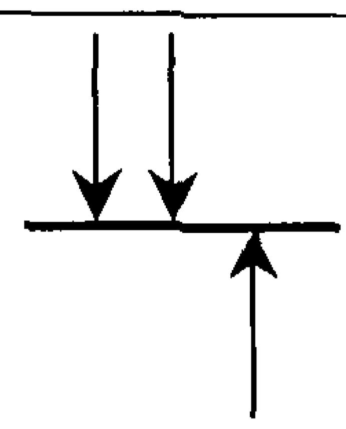
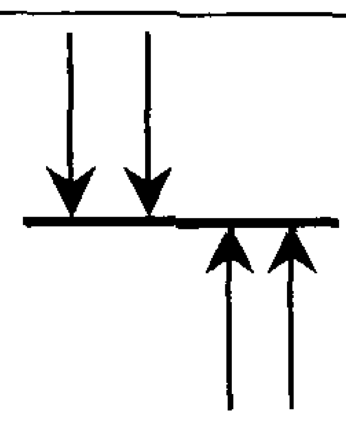
Table 5.3: Specifications of Group 3

Sample Ref. Number	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
$S3_A$		1 pass- 50 bar	0.578
$S3_B$		2 passes – 50 bar	1.156
$S3_C$		3 passes – 50 bar	1.734
$S3_D$		4 passes – 50 bar	2.321

5.4.4 Group 4

Four fabrics were produced with four different of energy levels and the pressure used was 50 bar. The energy profile used was the same as in group 2. The black fibre web was placed on the face side of the white web only (see table 5.4).

Table 5.4: Specifications of Group 4

Sample Ref. Number	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
$S4_A$		1 pass- 50 bar	0.578
$S4_B$		2 passes – 50 bar	1.156
$S4_C$		3 passes – 50 bar	1.734
$S4_D$		4 passes – 50 bar	2.321

5.5 Optical Microscopy of the Hydroentangled Fabrics

Optical microscopy was used to elucidate the differences in the structural arrangement of fibres in the fabric cross-section resulting from the various approaches used to introduce the total specific energy. In the preparation of fabric samples for analysis, it was essential to ensure that the fibres were not disturbed during the cutting process. Accordingly, it was necessary to solidify the structure, prior to cutting, using a resin impregnation procedure, followed by drying, curing and cutting using a microtome. In previous research, a freezing method has been used before sectioning hydroentangled fabric, but it is likely that this will change the volume of the fabric[84]. Other researchers [82,94,95,96,97] have used various resins to satisfactorily solidify fabrics so that they can be cut easily. Two different resins have been used in recent work. Qiao[82] used a LR White embedding kit, and the JB4 embedding kit has been used in other research [94,95,96,97]. In order to obtain high quality cross sections for evaluation, the decision was taken to use the JB4 embedding kit as this has previously given good results[94,95,96,97].

5.5.1 Preparation of Fabrics

Two main stages are required to successfully complete the embedding procedure as described in the following sections:

5.5.2 Preparation of JB-4 Catalyzed Infiltration Resin

A JB4 resin kit was supplied by Agar Scientific Ltd., UK, consisting of two solutions (A & B), and a catalyst (benzoyl peroxide). Solution A is a mixture of hydroxyethyl methacrylate and 2-butoxyethanol, whereas solution B is a mixture of n-dimethylaniline and polyethylene glycol 400. A 100 ml solution of A was mixed with 0.9 g. of benzoyl peroxide and the mixture was stirred until the catalyst completely dissolved[98].

5.5.3 Fabric Embedding System

A 1 ml solution of B was added to 25 ml of fresh catalyzed solution (the mixture) by stirring and placing it into an ice bath to retard premature polymerisation[98]. The fabric sample was then embedded by pouring the final mixture into the mold, which was specially constructed for this research. The mold was then covered tightly. Satisfactory polymerization was achieved after approximately 2 hours. All steps were undertaken in a fume cupboard. Prior to adding the resin mixture, the mold was greased with Vaseline from inside to help remove the sample after polymerization was finished. It is important to mention that a number of trials were undertaken to select the best embedding mold for the fabric. A schematic view of the mold which was eventually designed and constructed is shown in figure 5.1.

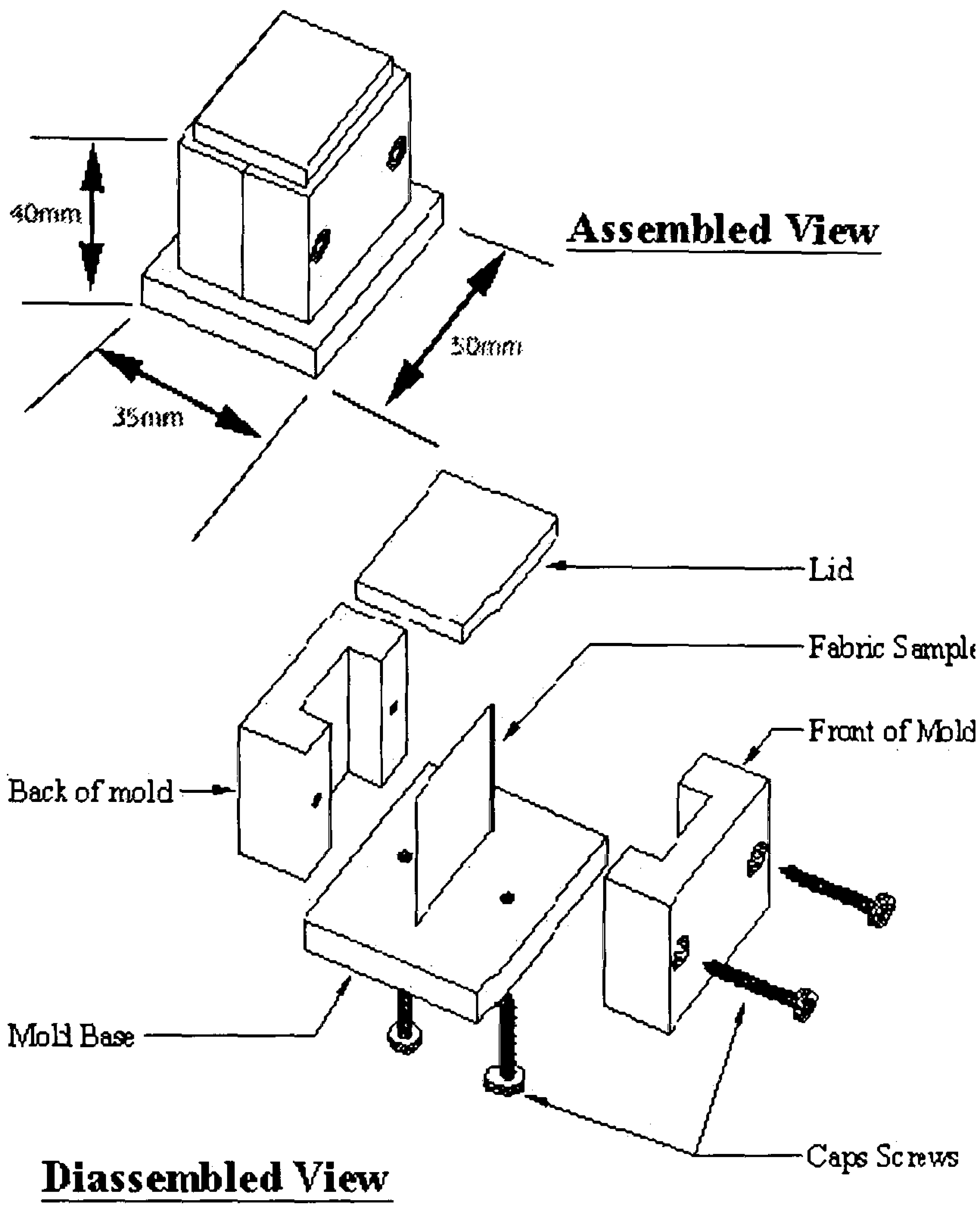


Figure 5.1 Schematic View of the Mold

5.5.4 Advantages of the Mold

The mold shown in figure 5.1 was specially prepared to hold the fabric sample in a vertical position, so that the resin could be laid on both surfaces of the fabric to achieve a more homogenous distribution. At the same time, the black fibres on the surface of the main web were not disturbed. The dimensions of the mold are 35 x 55 x 40 mm (as shown in the assembled view- figure 5.1).

Other advantages of the mold was that it produced a sample with a rectangular shape instead of a cylindrical one, which decreased the labour involved in cutting the extra resin around the fabric after polymerization. To obtain a uniform and complete slice of the fabric, it was necessary to minimise the area that had to be cut using the microtome and also by reducing the amount of friction between the blade and the resin around the fabric. The mold also assisted in reducing the amount of resin needed to a minimum.

5.6 Preparation of Fabric Cross-Sections

After polymerization, the molds were opened and the samples were easily removed. Using a BECK microtome[95,99], it was possible to cut slices of 1 to 15 μm thick. Initially, slices of 10 – 15 μm were cut and placed under an Olympus System BH2 optical microscope, operating with transmitted light. Photomicrographs of the cross-sections were not satisfactory to give a detailed impression of the tracer fibre positions because, with the fine sections, most of the fibres were cut or there were insufficient numbers to give a clear idea of the migration of these fibres inside the fabric.

Therefore, thicker sections of 0.25 to 0.5 mm were cut and a Fujitsu, Digital SLR Camera, using a macro lens, 105 mm – F2.8 (the diameter of the aperture), was used to magnify and record the resulting images. A schematic diagram of the method used is given in figure 5.2. Photographs of the tracer fibres were clearer than the first ones produced by the microscope. The first step was to obtain the photographs using Fuji digital camera, which were transferred as TIFF images to the host computer (PC). Images were imported into the image analysis package (Adobe Photoshop) for trimming and image quality refinement such as contrast, brightness and hue that were adjusted to obtain optimum image clarity.

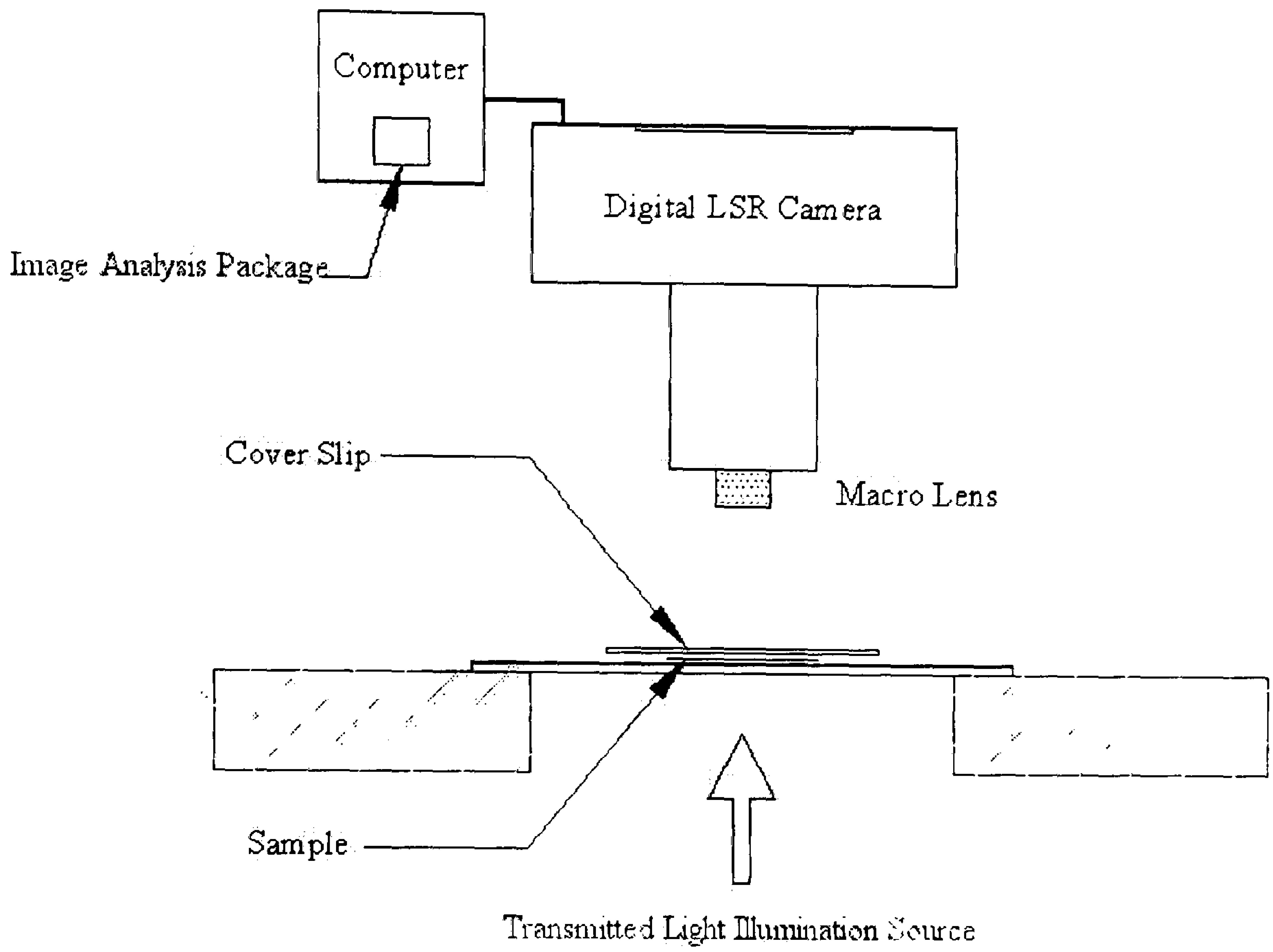


Figure 5.2 Schematic Diagram of the Imaging System

5.7 Optical Observations

Using the BECK microtome, over two hundred sections were cut from each fabric. Six to eight representative slices were selected and the resulting images were obtained.

The images were divided into four groups as mentioned before (figures 5.3- 5.18); each of the two groups can be compared with each other. The first two groups have the same specifications except that the first relates to webs treated at 20 bar pressure whereas the second, relates to those treated at 50 bar pressure (the same total number of passes was applied in both groups).

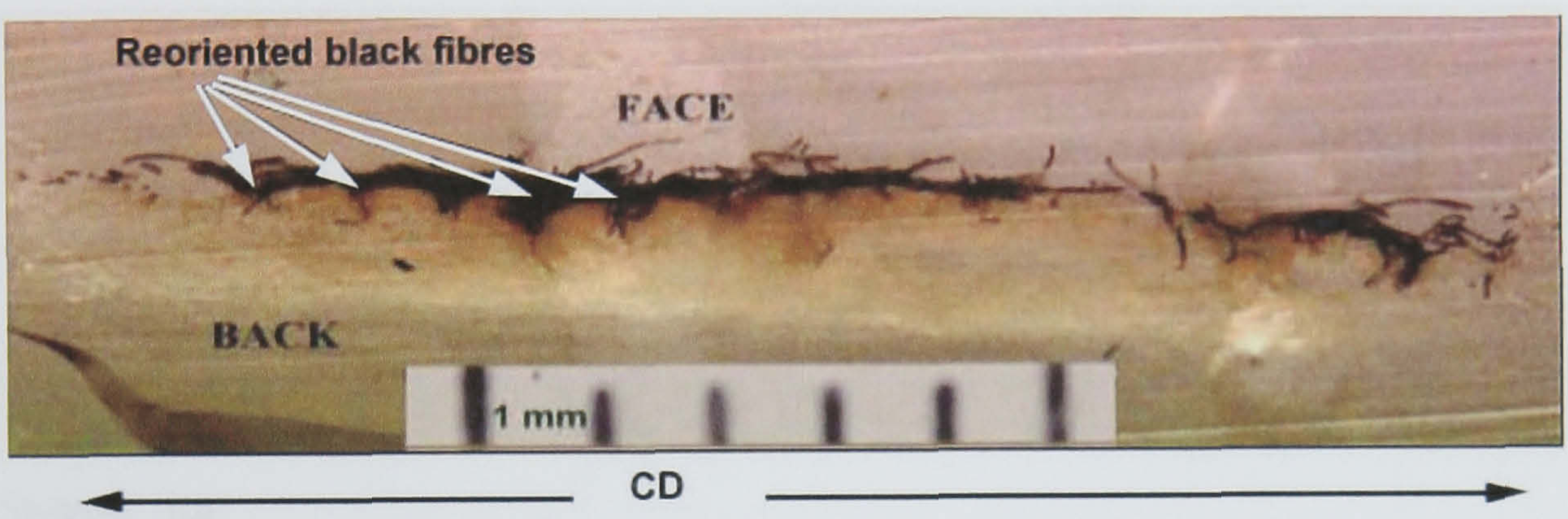
As indicated in section 5.4, the second two groups have similar specifications except that the third relates to fabrics produced using 20 bar pressure and the fourth, was produced using 50 bar. The only difference between the first two groups and the second two groups is that the energy was applied using different energy profiles (See section 5.4)

5.8 Comparison of Fabric Cross Sections

Typical cross sections of the fabrics produced in accordance with the procedure given in 5.4 are shown in figures 5.3 – 5.18

5.8.1 Comparison of Groups 2 (20 bar) and 4 (50 bar) -Tracer Fibres Introduced from One Side

Groups 2 and 4 were produced using a black fibre web on the face side only. In group 2, water pressure at 20 bar was applied to the webs, whereas in group 4, the fabrics were produced using 50 bar.

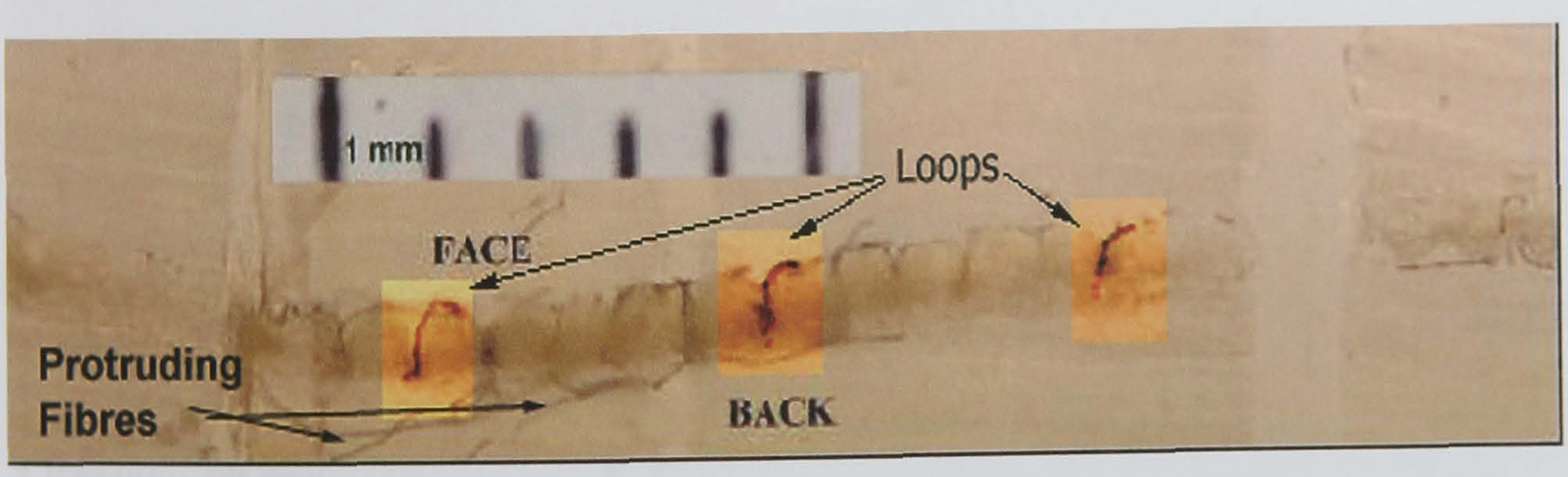


Sample S_{2A}

1 Pass – 20 Bar

Black fibres on face only

Figure 5.3 Cross Section of Sample S_{2A}



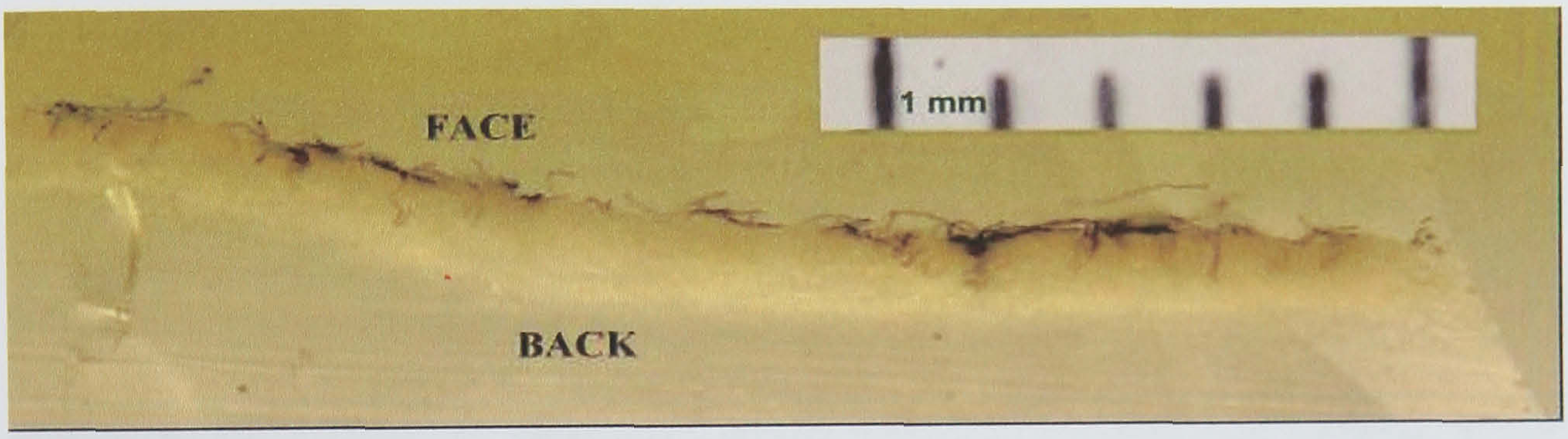
Sample S_{4A}

1 Pass – 50 Bar

Black fibres on face only

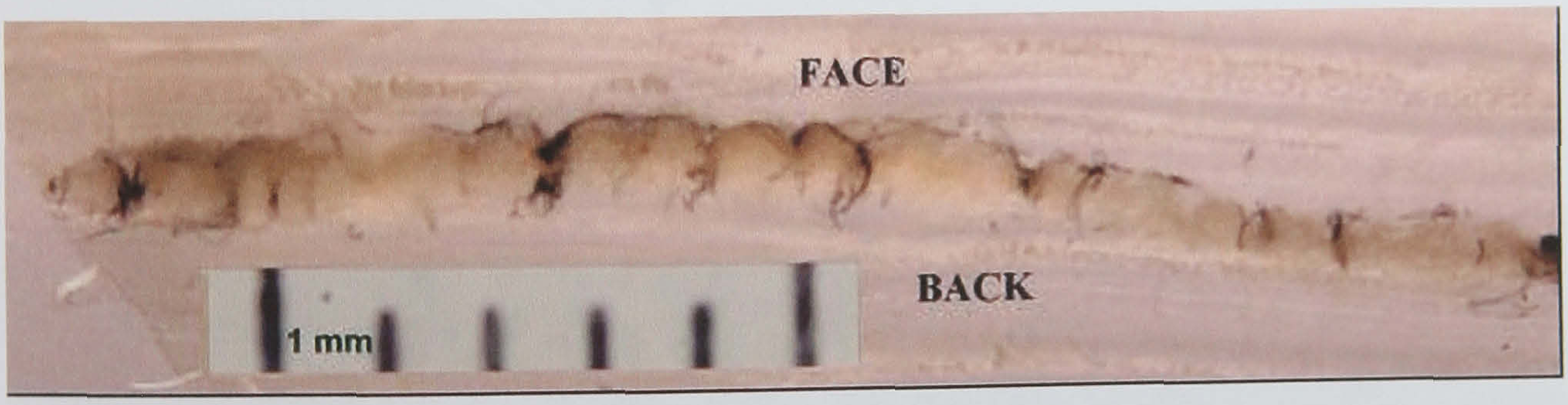
Figure 5.4 Cross Section of Sample S_{4A}

Comparing figures 5.3 and 5.4, it is evident that increasing the pressure used tends to increase the overall penetration depth of the pillars. In some regions, it would appear that the use of the higher pressure results in the migration of surface fibres through the cross-section and out of the reverse side of the fabric. It is clear that fibres are migrated through the entire cross-section of the fabric (figure 5.4). This fibre migration is evident on the fabric surface in contact with the porous conveyor belt and the hydroentangled fabric tends to stick to the conveyor belt. Periodic pillar formation is clearly in evidence. These are approximately in phase with the jet spacing. Looped fibres can clearly be discerned (see figure 5.4).



Sample S_{2B}
2 Passes – 20 bar
Black fibres on face only

Figure 5.5 Cross Section of Sample S_{2B}



Sample S_{4B}
2 Passes – 50 bar
Black fibres on face only

Figure 5.6 Cross Section of Sample S_{4B}

Comparing fabrics S_{2B} and S_{4B} in figures 5.5 and 5.6, and due to increased migration of the fibres through the cross-section, the overall consolidation of the fabric S_{4B} was therefore higher than S_{2B}, and less heterogonous in terms of consolidation.

Also, comparing figure 5.4 and figure 5.5, it can be seen that using one pass of 50 bar on the face of the fabric may result in entanglement of both sides of the fabric (figure 5.4), in other words, pillars can be clearly seen to extend through the cross-section of the fabric. Whereas using 2 passes of 20 bar on one side preferentially affects one side of the fabric (figure 5.5). As a result, using a low number of injectors at a higher pressure results in fabrics that tend to have a more homogenous structure through the cross section compared to fabrics that are produced by applying the jets to one side only at a low pressure.

Sample S_{2C}

3 Passes – 20 Bar

Black fibres on face only

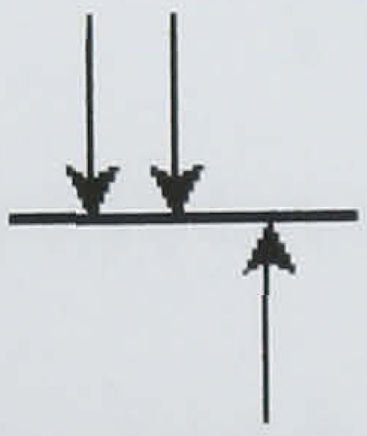
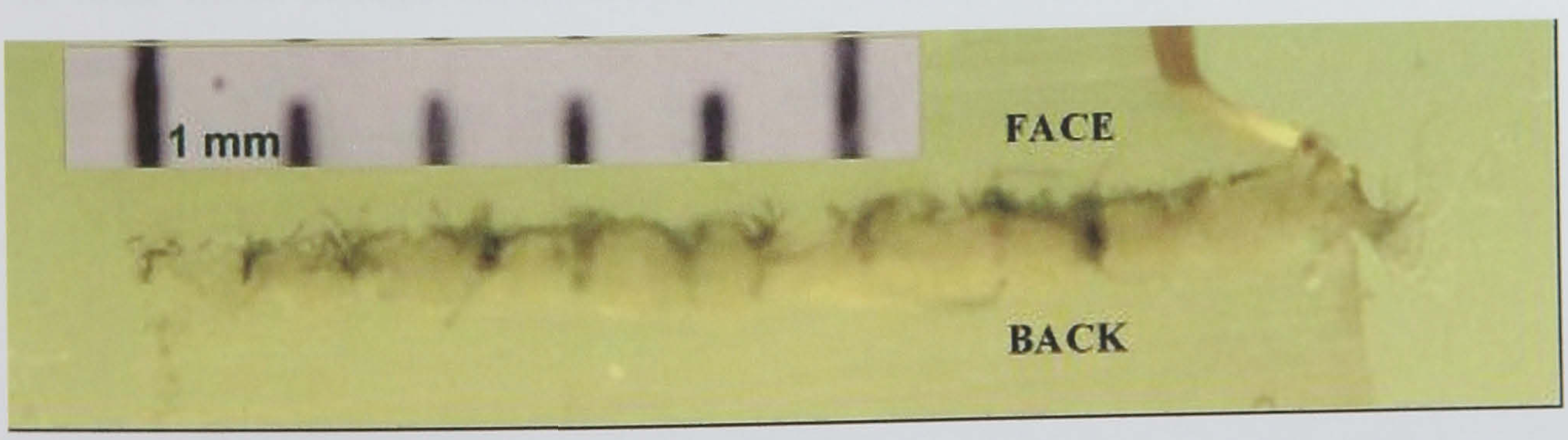


Figure 5.7 Cross Section of Sample S_{2C}



Sample S_{4C}

3 Passes – 50 Bar

Black fibres on face only

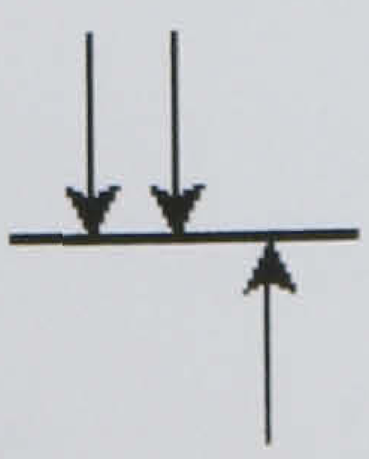
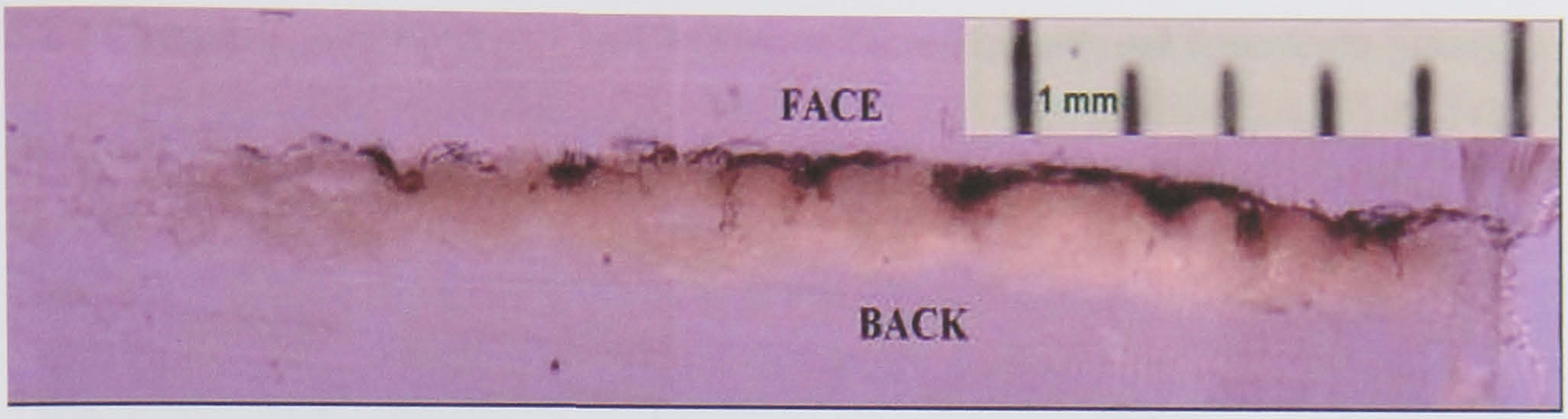


Figure 5.8 Cross Section of Sample S_{4C}



Sample S_{2D}

4 passes – 20 Bar

Black fibres on face only

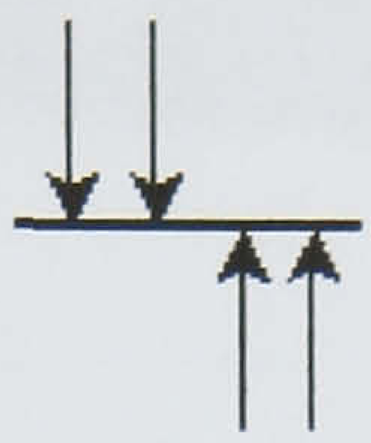
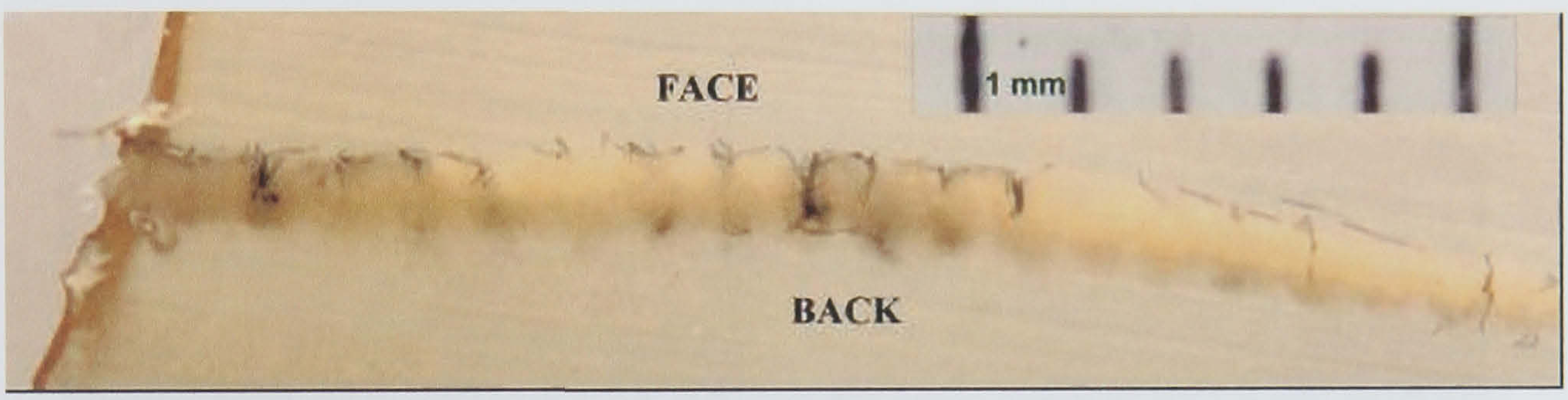


Figure 5.9 Cross Section of Sample S_{2D}



Sample S_{4D}

4 Passes – 50 bar

Black fibres on face only

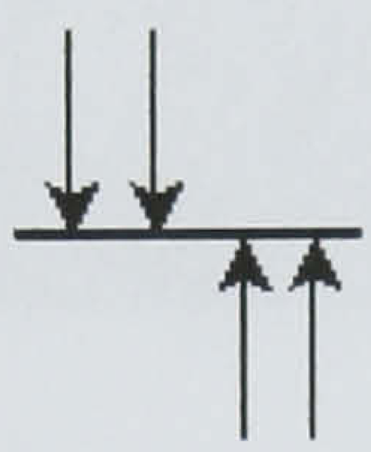
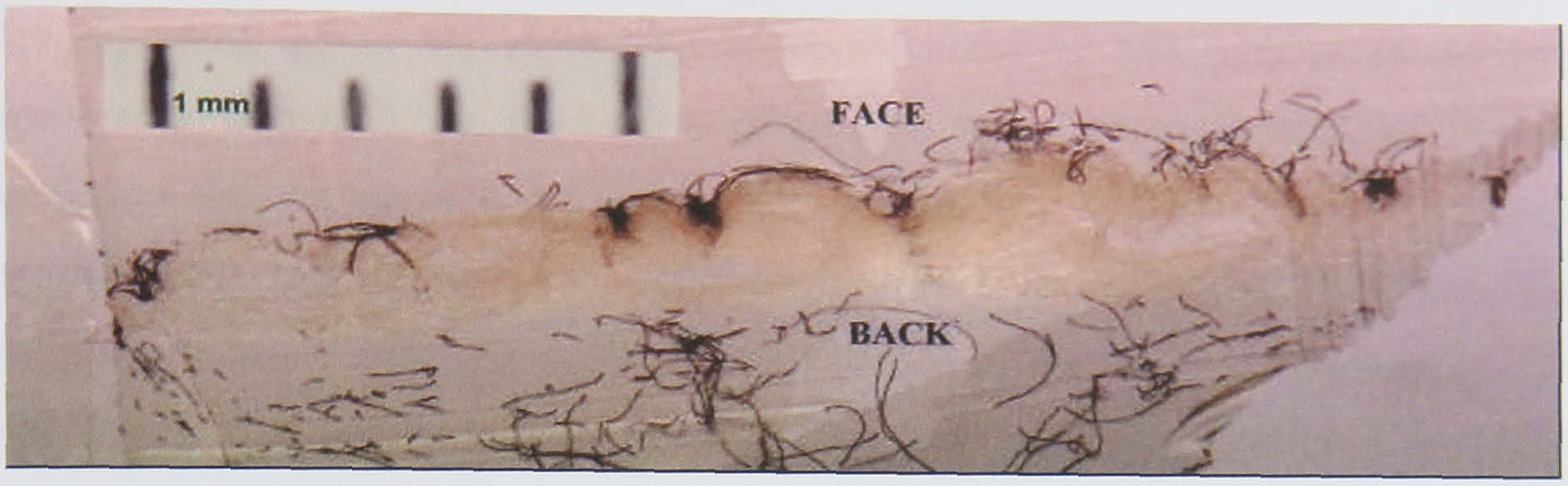


Figure 5.10 Cross Section of Sample S_{4D}

Comparing figures 5.7 & 5.8 and 5.9 & 5.10, it can be seen that the migration depth of the black fibres through the cross-section of the fabrics, are higher with using 50-bar pressure.

5.8.2 Comparison of Groups 1 and 3 (Tracer Fibres Introduced from Both Sides)

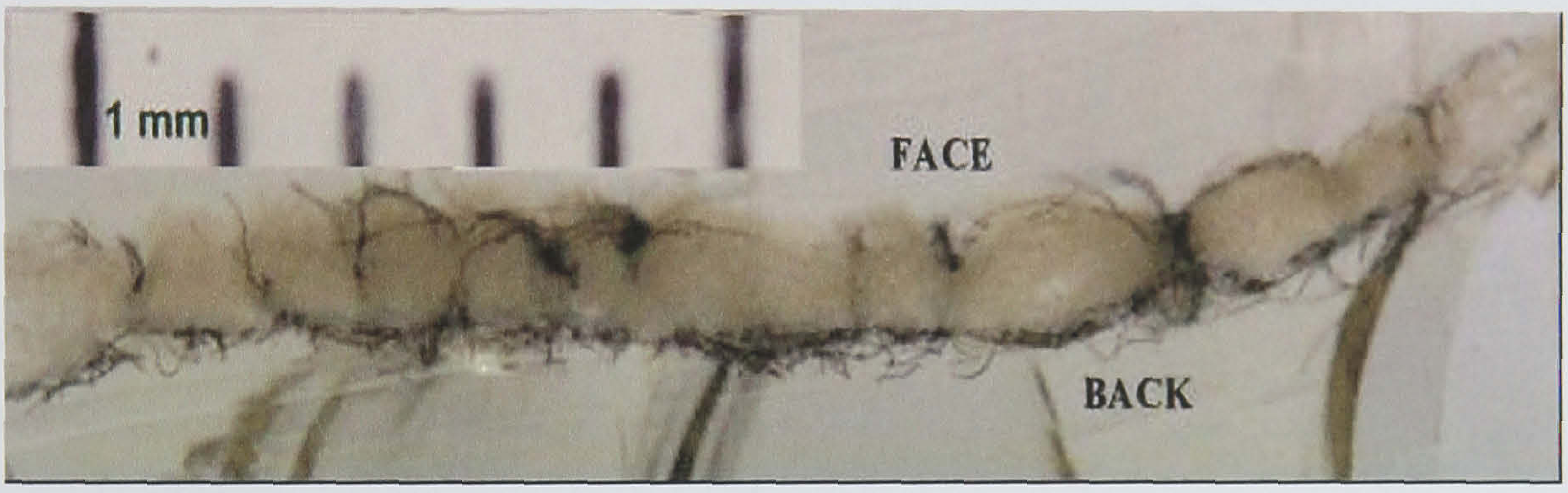


Sample No. S_{1A}

1 pass – 20 Bar

Black fibres on face and back

Figure 5.11 Typical Cross section of Sample $S1_A$



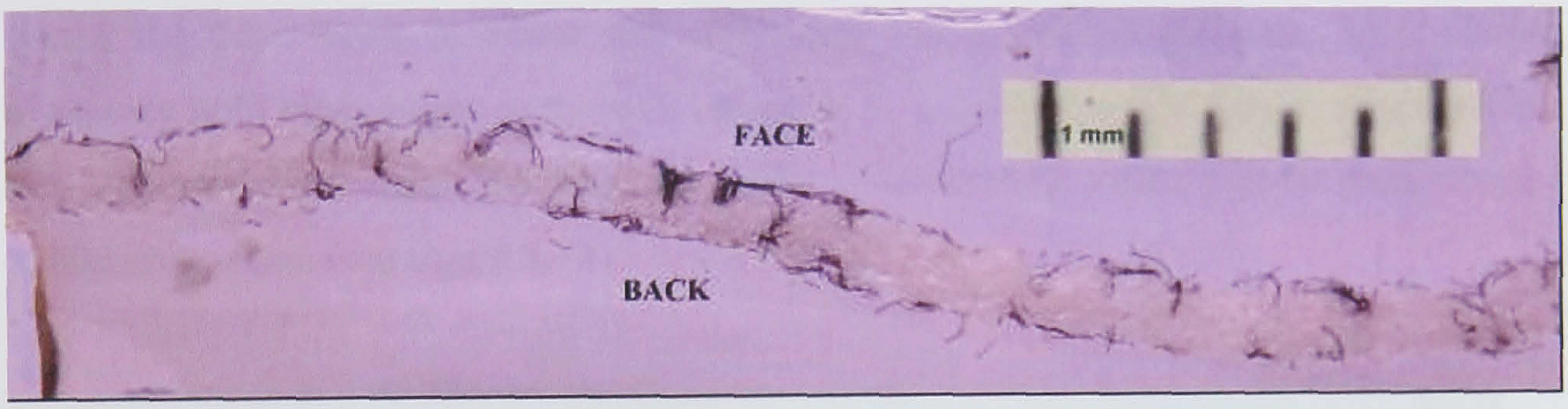
Sample No. S_{3A}

1 pass – 50 bar

Black fibres on face and back

Figure 5.12 Typical Cross Section of Sample S_{3A}

Figures 5.11 and 5.12 show the effect of producing fabrics by applying the jets to one side using different water pressures of 20 and 50 bar respectively. It is evident that at 20 bar (figure 5.11) there is insufficient energy to transfer fibres to the other side of the fabric or completely consolidate the structure. When using 50 bar, some tracer fibres migrated to the reverse side of the fabric although there is marked variation in the migration depth of different pillars. It is also clear that there is variation in the number of fibres associated with each "pillar" but this will also be affected by the uniformity of fibre distribution in the original black web. There is also evidence to suggest that fibres located on the reverse side of the fabric are also entangled to some extent when the jet is introduced from one side only (figure 5.12). This supports the comments of Bertram[74] who suggested that if the water jet reaches the conveyor belt without having been significantly dispersed, the rigid wires of the belt would deflect it back to the web. Deflection will be partially upwards into the web and through other interactions; rebounded jets may be expected to give rise to further entanglement. This mechanism will predominantly affect fibres from the underside of the web and the flow patterns created would be very different to those of the incident jet because of their interaction with the conveyor belt. This phenomenon can be referred to as the water jet/conveyor belt interaction and although it is outside the scope of this work, it requires further elucidation[74,82].

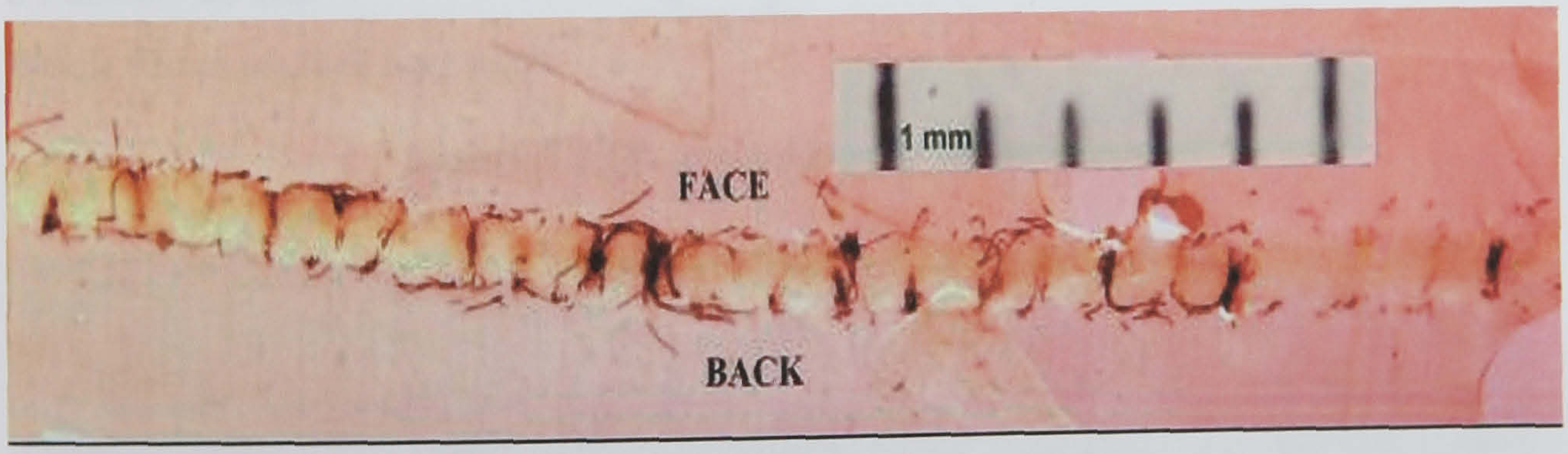


Sample S_{1B}

2 passes- 20 Bar

Black fibres on face and back

Figure 5.13 Typical Cross Section of Sample S_{1B}



Sample S_{3B}

2 Passes – 50 Bar

Black fibres on face and Back

Figure 5.14 Typical Cross Section of Sample S_{3B}

Figures 5.13 and 5.14 typify the different structures produced by introducing the jet energy from both sides of the web. Comparing samples S_{1B} and sample S_{3B}, generally, the use of 50 bar produces z-direction pillars extending from the face to the back of the fabric and interestingly some longitudinal interconnections were evident between adjacent pillars particularly on the reverse side. Greater variation in pillar depth (fibre migration) and fewer longitudinal interconnections were apparent in the fabrics produced at 20 bar. The connection of adjacent fibre loops associated with the pillars is discussed by Ijaiya[70] where, it was observed that full loops were formed by fibres that were initially closer to the top layer of the web; these fibres are subjected to maximum water jet pressure and hence larger drag forces, and they are also more free to move, unlike the inner layer of fibres that may have higher frictional forces. Such fibres obviously hold other fibres in the web structure. It is also clear that fabrics produced in this way produce a chain-like structure in the cross-section, which is most pronounced at higher pressure (see figure 5.14).

Sample S_{1C}

3 Passes – 20 Bar

Black fibres on face and back

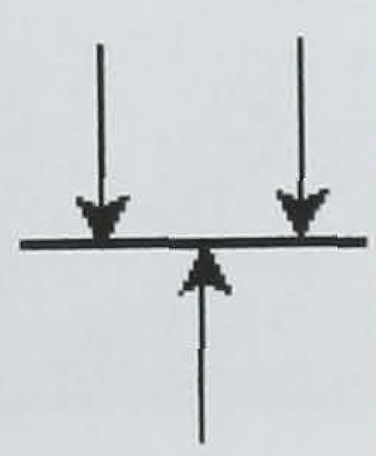
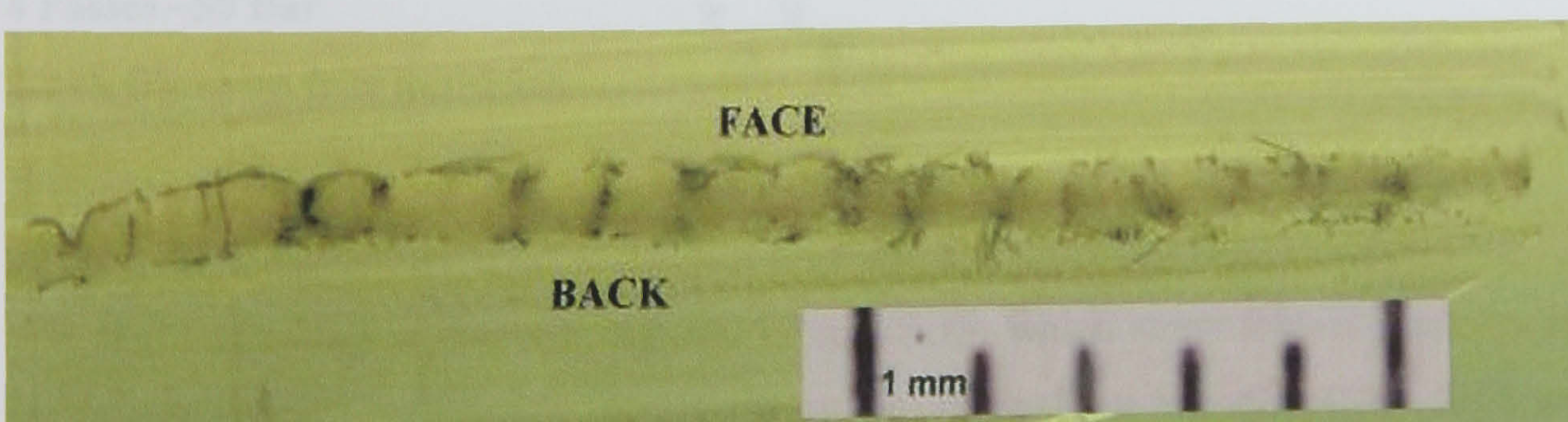


Figure 5.15 Cross Section of Sample S_{1C}



Sample S_{3C}
3 Passes – 50 Bar

Black fibres on face and back

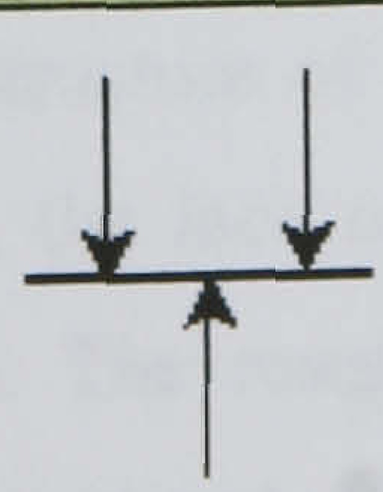
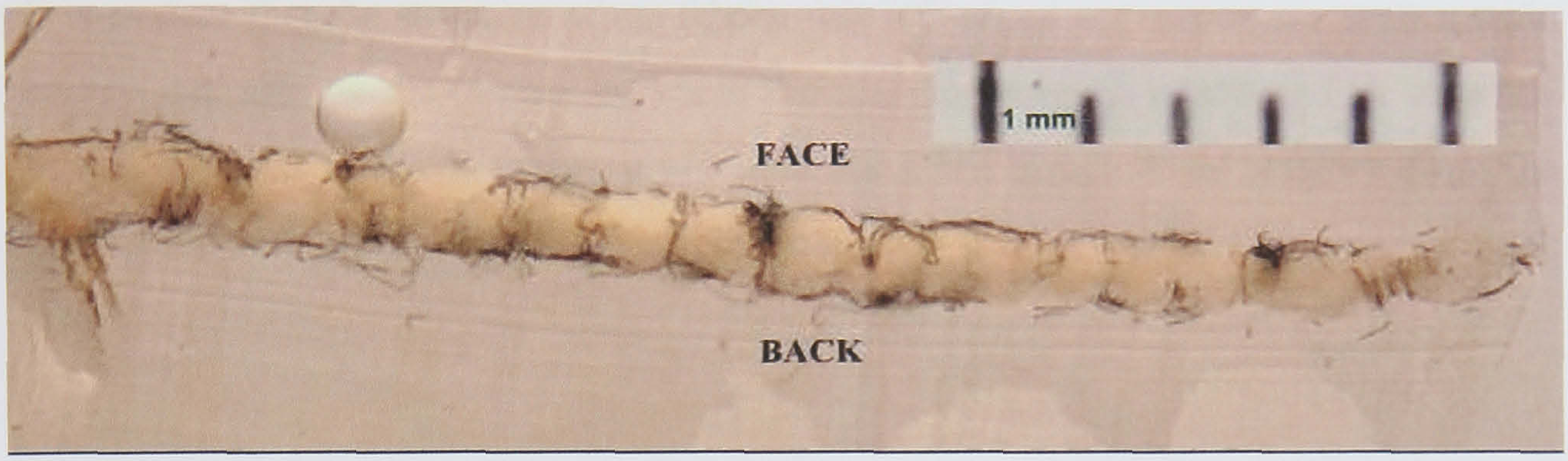


Figure 5.16 Cross Section of Sample 5_{3C}

Figures 5.15 and 5.16 reflect the unequal treatment of the face and back with respect to the pressure profile used. It is evident that in sample S_{1C} (where 20 bar pressure is used), the migration depth of fibres associated with the pillars is generally lower than in sample S_{3C} with respect to the total fabric thickness (where the 50 bar was used).



Sample S_{1D}

4 passes – 20 Bar

Black fibres on face and back

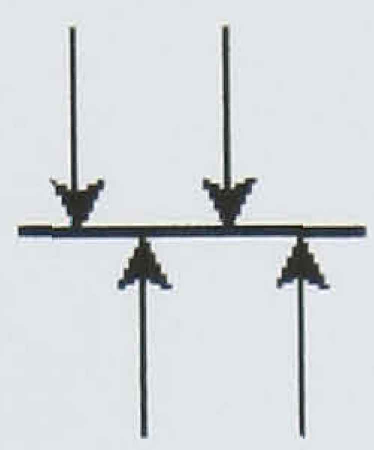
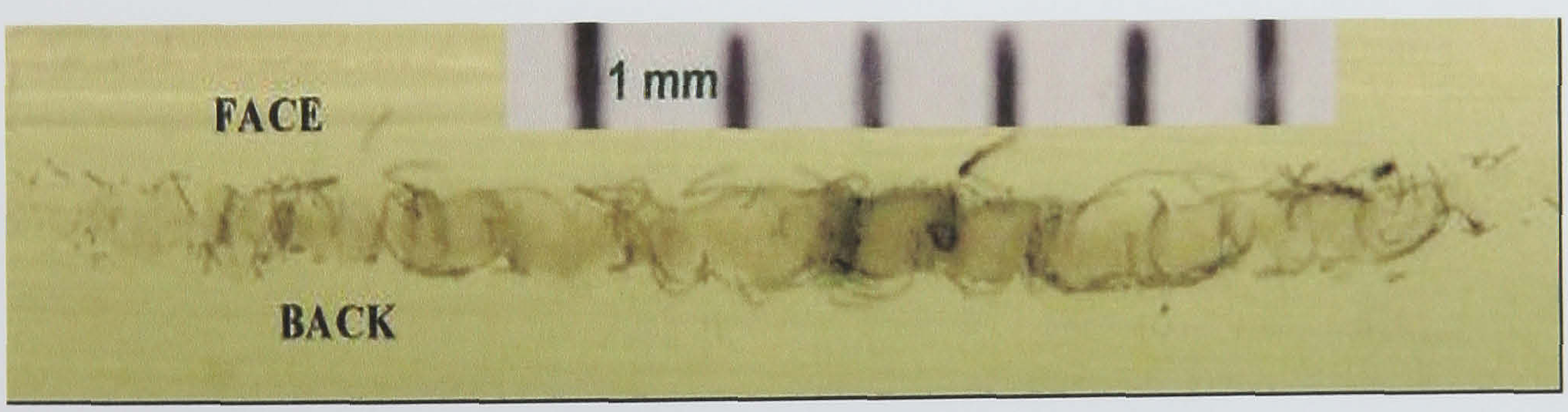


Figure 5.17 Cross Section of Sample S_{1D}



Sample S_{3D}

4 Passes –50 Bar

Black fibres on face and back

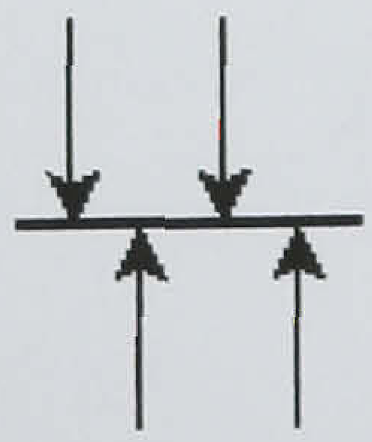


Figure 5.18 Cross Section of Sample S_{3D}

It is also interesting to compare figures 5.5 and 5.13, which show fabrics treated with the same nominal total specific energy (using two passes) but introduced in a different way. It is evident that the internal structure of each fabric is different and depends on the type of treatment. In figure 5.5, the face of the fabric has been produced using 2 passes, and the back is not treated. The resulting fabric has a heterogeneous cross-sectional structure; in which fibre entanglement and migration is apparently more extensive on one side of the fabric. It may be expected that certain low stress mechanical properties of the two structures will differ because of the structural differences in the face and back. This will be examined in chapter 6.

5.9 Analysis of Results

It is evident that the structure of the fabrics was influenced not just by the total specific energy, but also by the manner by which the specific energy is introduced. A summary of the effect of different energy profiles on the fabric structure as obtained from the cross sections is given in tables 5.5 – 5.8.

Table 5.5: Group 2 – Summary of Cross-Section Analysis

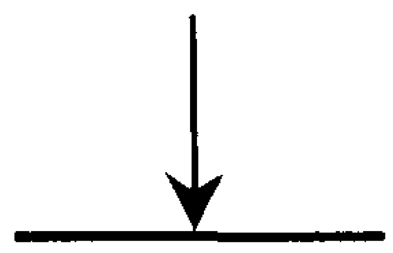
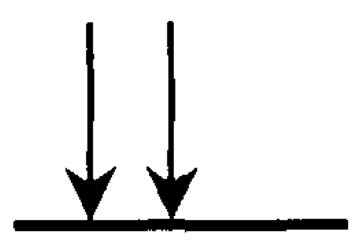
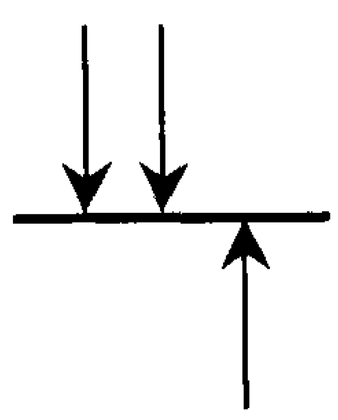
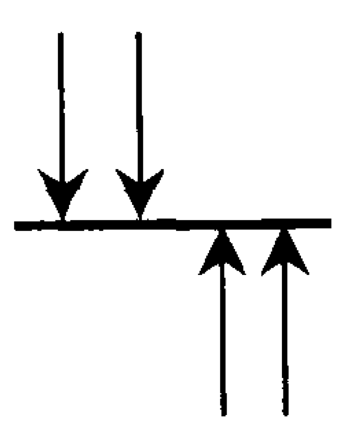
Sample Ref. Number	Treatment Type	Consolidation		Other comments
		Face	Back	
S2$_A$	 1 pass-20 bar	Evidence of entanglement of the face	No sign of any entanglement on the reverse of the fabric.	Different fabric structure in the cross section of the fabric (face and back)
S2$_B$	 2 passes–20 bar	Evidence of entanglement of the face	No evidence of entanglement on the reverse of the fabric.	Entanglement of face only (Different fabric structure in the cross-section compared to sample S1$_B$).
S2$_C$	 3 passes–20 bar	The same observation as in sample S2$_B$ (the face of the fabric)	Little evidence of entanglement on the reverse side of the fabric because there is no black fibres.	Some similarity in the fabric structure on the face and back
S2$_D$	 4 passes–20 bar	Compared with sample S2$_C$, more evidence of homogenous migration on the face and back of the structure.	Evidence of entanglement on the reverse side of the fabric.	The core of the fabric remains effectively unbonded.

Table 5.6: Group 4 – Summary of Cross Section Analysis

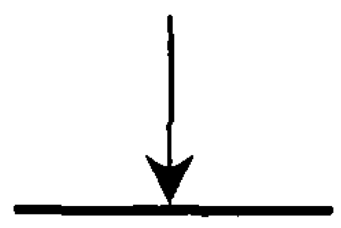
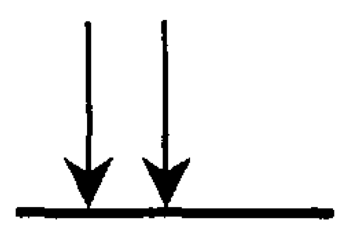
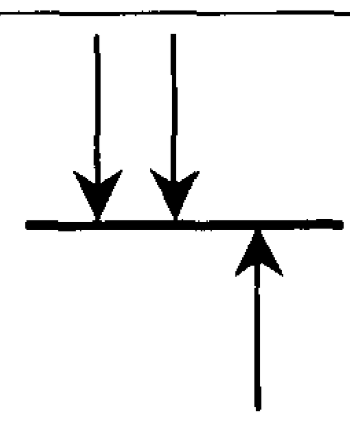
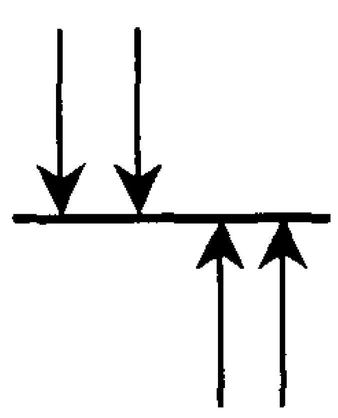
Sample Ref. Number	Treatment Type	Consolidation		Other comments
		Face	Back	
$S4_A$	 1 pass-50 bar	Evidence of consolidation on the face.	Small evidence of entanglement on the reverse side of the fabric	Some evidence of migrated black fibres on the reverse side of the fabric
$S4_B$	 2 passes–50 bar	Evidence of more entanglement on face (compared to $S4_A$)	Evidence of more entanglement on the back (compared to $S4_A$).	A segmented or chain-like structure begins to emerge.
$S4_C$	 3 passes–50 bar	Evidence of more consolidation on face and back (as compared to $S4_B$).	More evidence of consolidation on the back of the fabric	The fabric appears more homogenous in the cross-section compared to $S4_B$.
$S4_D$	 4 passes–50 bar	Evidence of more consolidation on face and back (compared to $S4_C$).	More evidence of consolidation on the back of the fabric (compared to $S4_C$).	More evidence of segmented or chain-like structure (compared to $S4_C$).

Table 5.7: Group 1 – Summary of Cross Section Analysis

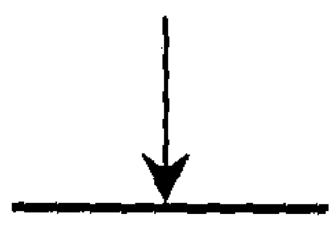
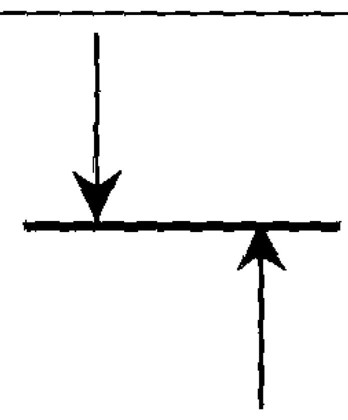
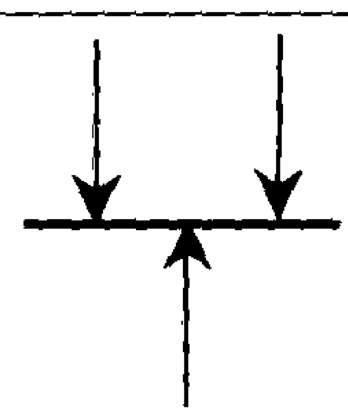
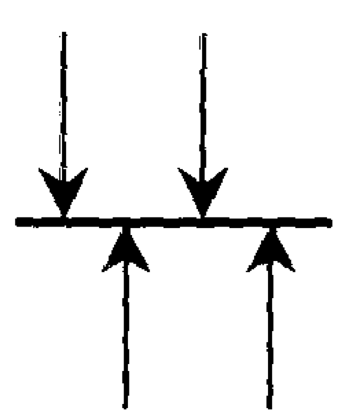
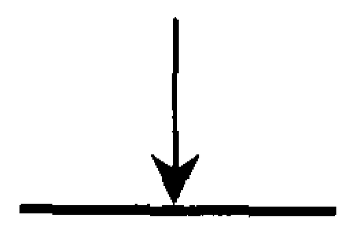
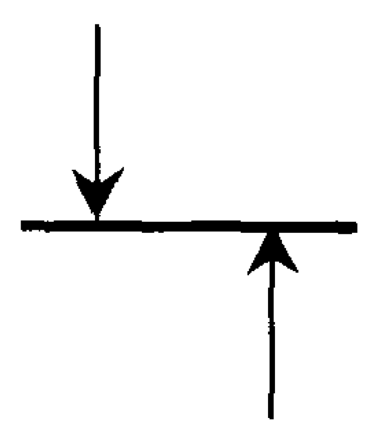
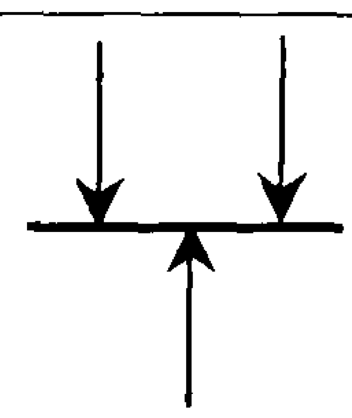
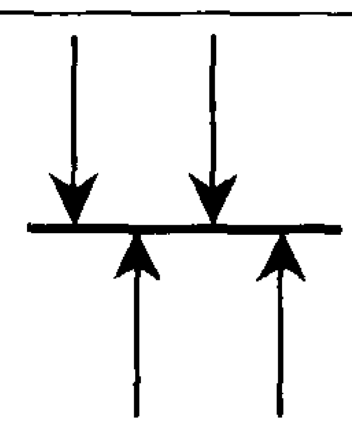
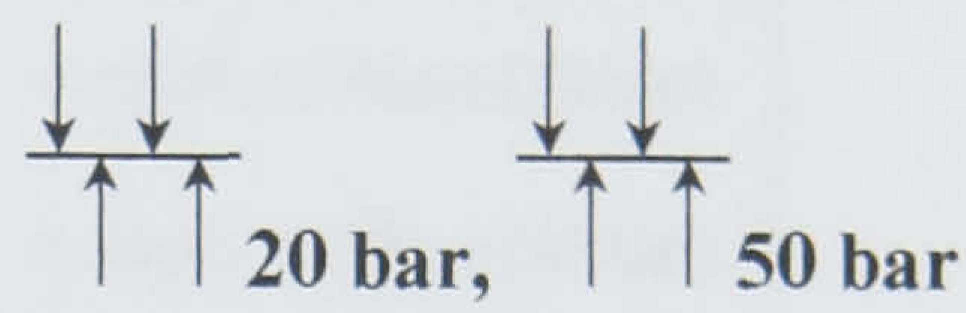
Sample Ref. Number	Treatment Type	Consolidation		Other comments
		Face	Back	
$S1_A$	 1 pass-20 bar	Evidence of entanglement on the face	No evidence of entanglement on the reverse side of the fabric	The black fibres that were mounted on the back were displaced during cutting the slices using the microtome because of the low entanglement on the back of the fabric.
$S1_B$	 2 passes–20 bar	Evidence of the same entanglement on the face	Evidence of entanglement on the back	. Evidence of the entanglement on the face and back of the fabric (compare with sample $S2_B$)
$S1_C$	 3 passes–20 bar	Evidence of more entanglement on the face of the fabric compared to $S1_B$	The back is the same as compared to sample $S1_B$.	Evidence of more consolidation on face compared to the back of the fabric.
$S1_D$	 4 passes–20 bar	Marked entanglement on the face of the fabric	Marked entanglement on back of the fabric	The face and back of the fabric appeared similar and the core of the fabric remained unconsolidated.

Table 5.8: Group 3 – Summary of Cross Section Analysis

Sample Ref. Number	Treatment Type	Consolidation		Other comments
		Face	Back	
$S3_A$	 1 pass-50 bar	Evidence of entanglement on the face	Minor evidence of inward migration on the reverse side of the fabric	The back of the fabric was more consolidated compared with the back of sample $S1_A$
$S3_B$	 2 passes–50 bar	More evidence of entanglement on face as compared to sample $S3_A$ (although the hydroentanglement is on the back)	More evidence of entanglement on back of the fabric.	The fabric structure exhibited some segmented regions or chain-like structures (in the cross-section) (see figure 5.14)
$S3_C$	 3 passes–50 bar	More evidence of consolidation on face as compared to sample $S3_B$	Evidence of consolidation on back of the fabric.	Segmented or chain-like fabric structure (in cross-section) was in evidence.
$S3_D$	 4 passes–50 bar	Evidence of entanglement on face compared to sample $S3_C$	More evidence of entanglement on back compared to sample $S3_C$	Segmented or chain-like fabric structure(in cross-section)

To quantify the effects of specific energy and the pressure profile on the fabric structure, two parameters were identified to characterise the physical changes in the structure resulting from hydroentanglement. The number of pillars per cm in the CD plane and the migration depth of the pillars in the Z direction were determined. The number of pillars per cm was obtained directly from the images of the fabric cross-sections. Ten measurements were made and the average values were calculated with an estimate of the standard error of the mean. The depth of the pillars in the cross-section was also measured and the average was calculated. The standard deviation and the CV% were also calculated. These results were obtained for groups 1 and 3 (Tables 5.7 and 5.8). The thickness of the fabric (T) was determined directly from the optical microscope photographs of the cross-sections. Measurements were taken at fixed intervals along the fabric cross-sections in the CD. Because of the way in which thickness was determined, the resulting average is really an estimate of the surface profile of the fabric (T). The results are shown in figures 5.19-5.21.

5.9.1 Effect of Different Energy Profiles on the Number of Pillars



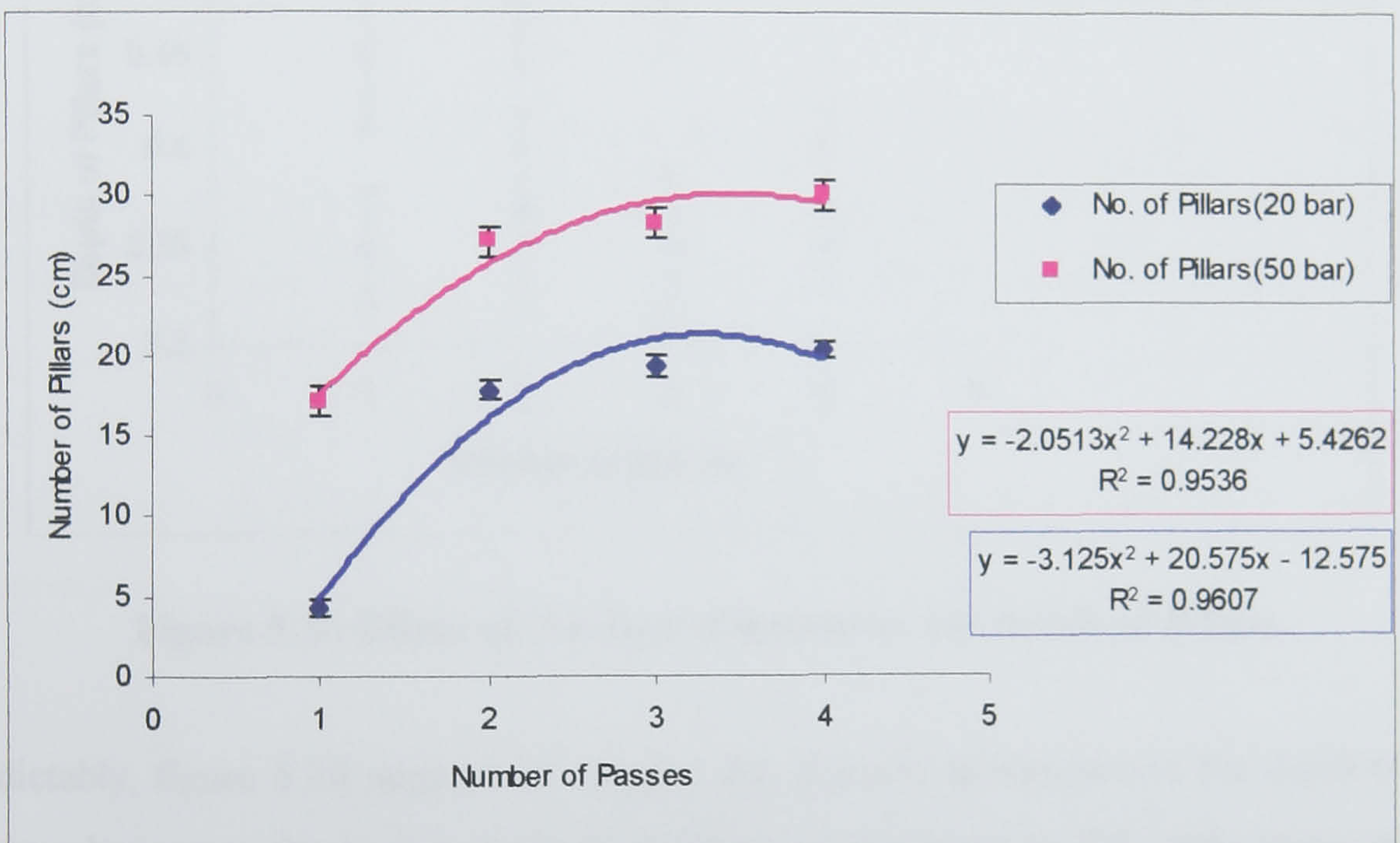


Figure 5.19 Effect of Number of Passes on Number of Pillars

It might be expected that the number of pillars would increase in proportion to the number of passes, providing the jet impact areas in the web were not previously treated in earlier passes. Accordingly, it is evident from figure 5.19 that an increase in the number of passes initially results in a marked increase in the number of pillars for the fabrics produced using both 20 bar and 50 bar (groups 1 and 3). However, after two passes, only marginal increases in the number of pillars is observed although the fabrics were translated across the width of the conveyor between passes (see figure 5.15 and 5.16). Given this situation, the small increase in the number of pillars requires further explanation. It appears that this is due to the confounding effect of pillars in the structure. The black fibres were observed to preferentially migrate in to previously formed needle holes, thereby giving the impression that a new hydroentangled pillar had formed. The possibility of the tracer fibers migrating into these holes appears to be higher when using the higher pressure (50 bar).

5.9.2 Effect of Number of Passes on Depth of Pillars

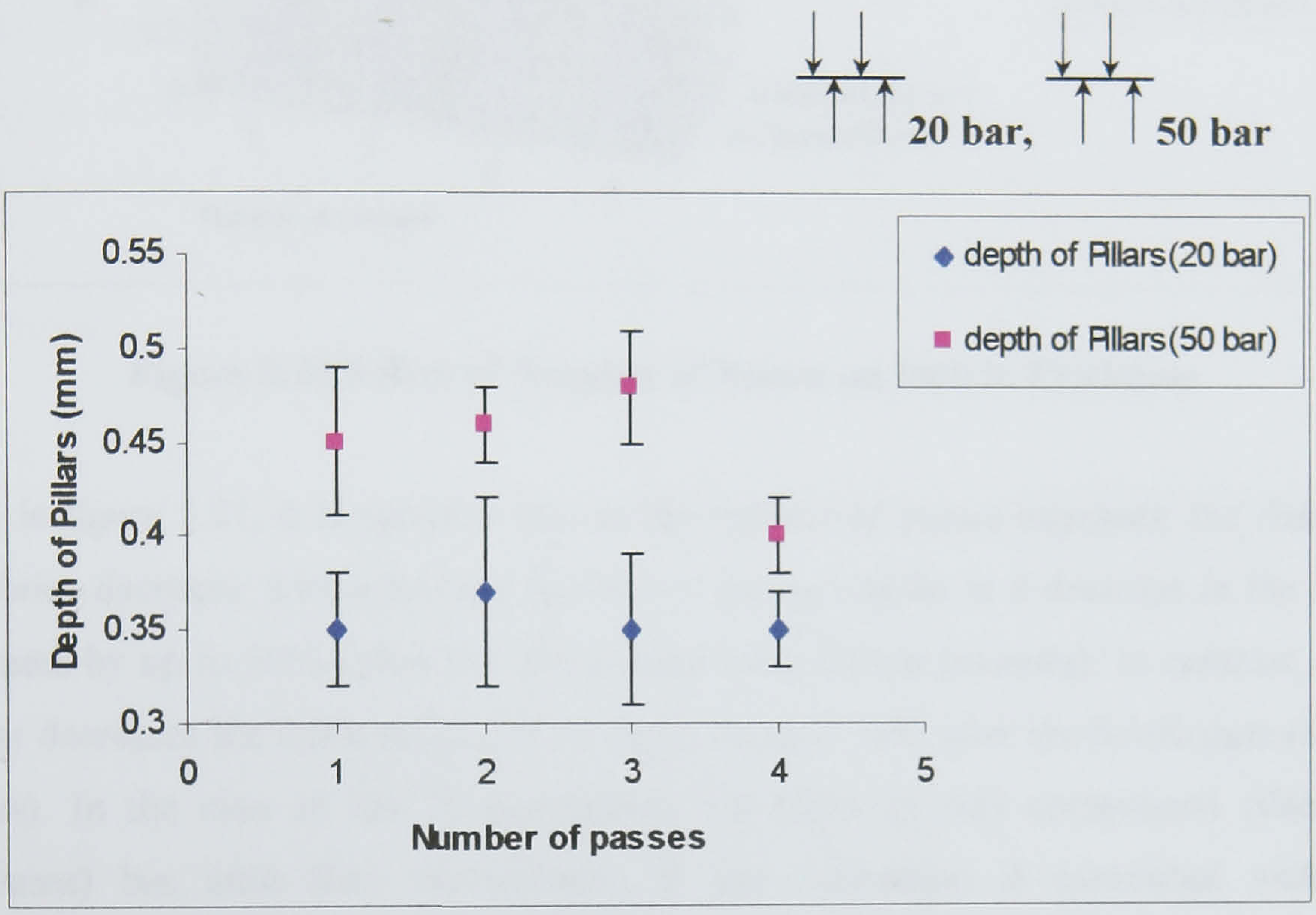


Figure 5.20 Effect of Number of Passes on the Depth of Pillars

Predictably, figure 5.20 appears to suggest that there is an increase in the depth of the pillars when using the higher pressure (50 bar) as compared to the lower pressure (20 bar). It may be that in these experiments, 20 bar is lower than the minimum initiation pressure needed to cause major structural change in the fabrics. It is also evident that at 50 bar, use of more than three passes does not increase pillar depth further. This can be explained in terms of the surface consolidation of the fabric, which prevents the water jets from penetrating the full thickness of the fabric structure. It is likely that a higher pressure would be needed to achieve further increases.

5.9.3 Effect of Number of Passes on Fabric Thickness (T)

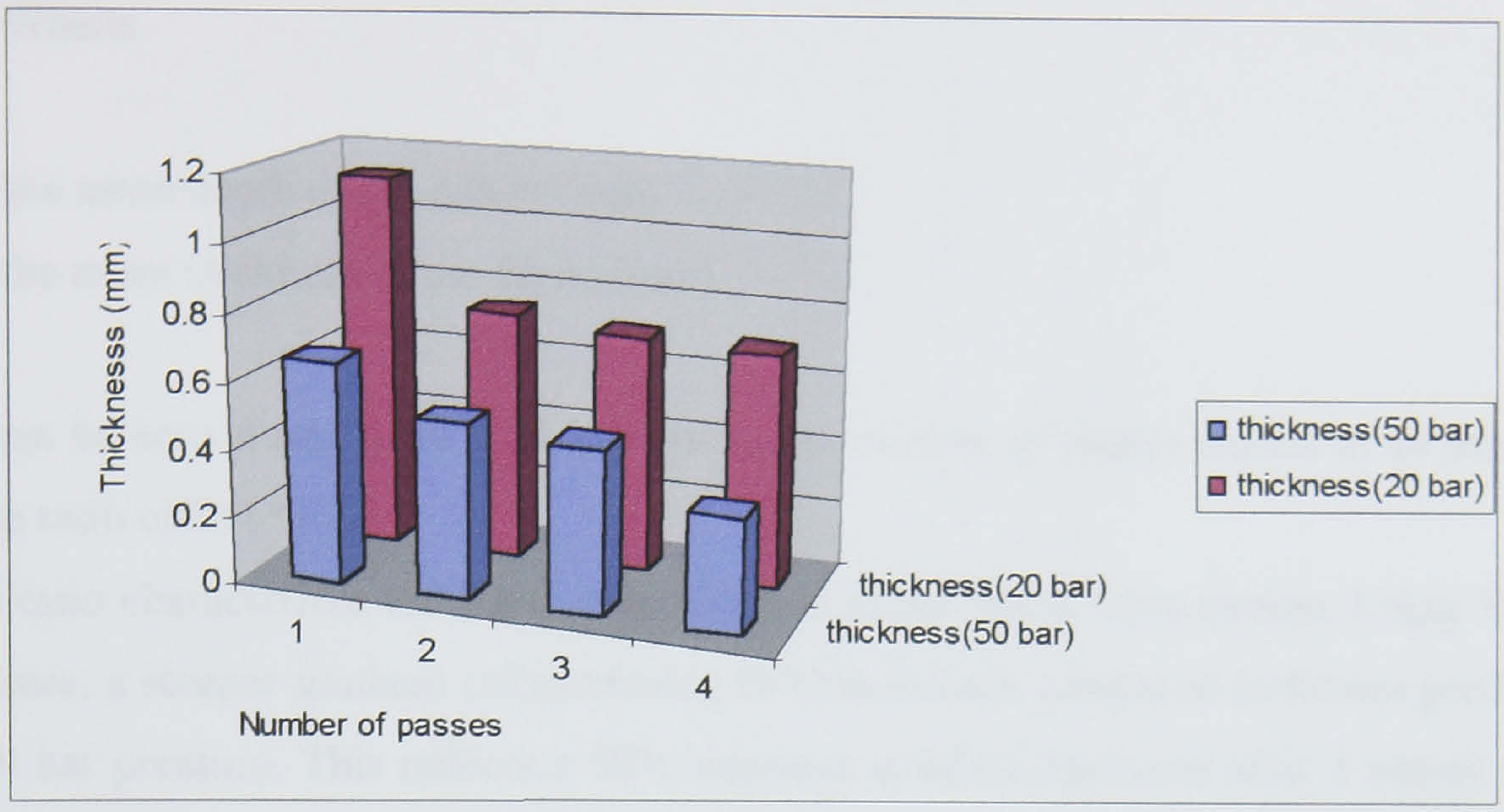


Figure 5:21 Effect of Number of Passes on Fabric Thickness

Also, in figure 5.21, it is apparent that as the number of passes increases, the thickness of fabrics decrease. Increasing the number of passes results in a decrease in the fabric thickness by up to 50% (after the fourth pass using 50 bar pressure). In contrast, using 20 bar decreases the fabric thickness by approximately 38% after the fourth pass (after 4 passes). In the case of the 20 bar fabrics, the fabric is only compressed (thickness decreases) but little fibre reorientation in the z-direction is associated with this compression.

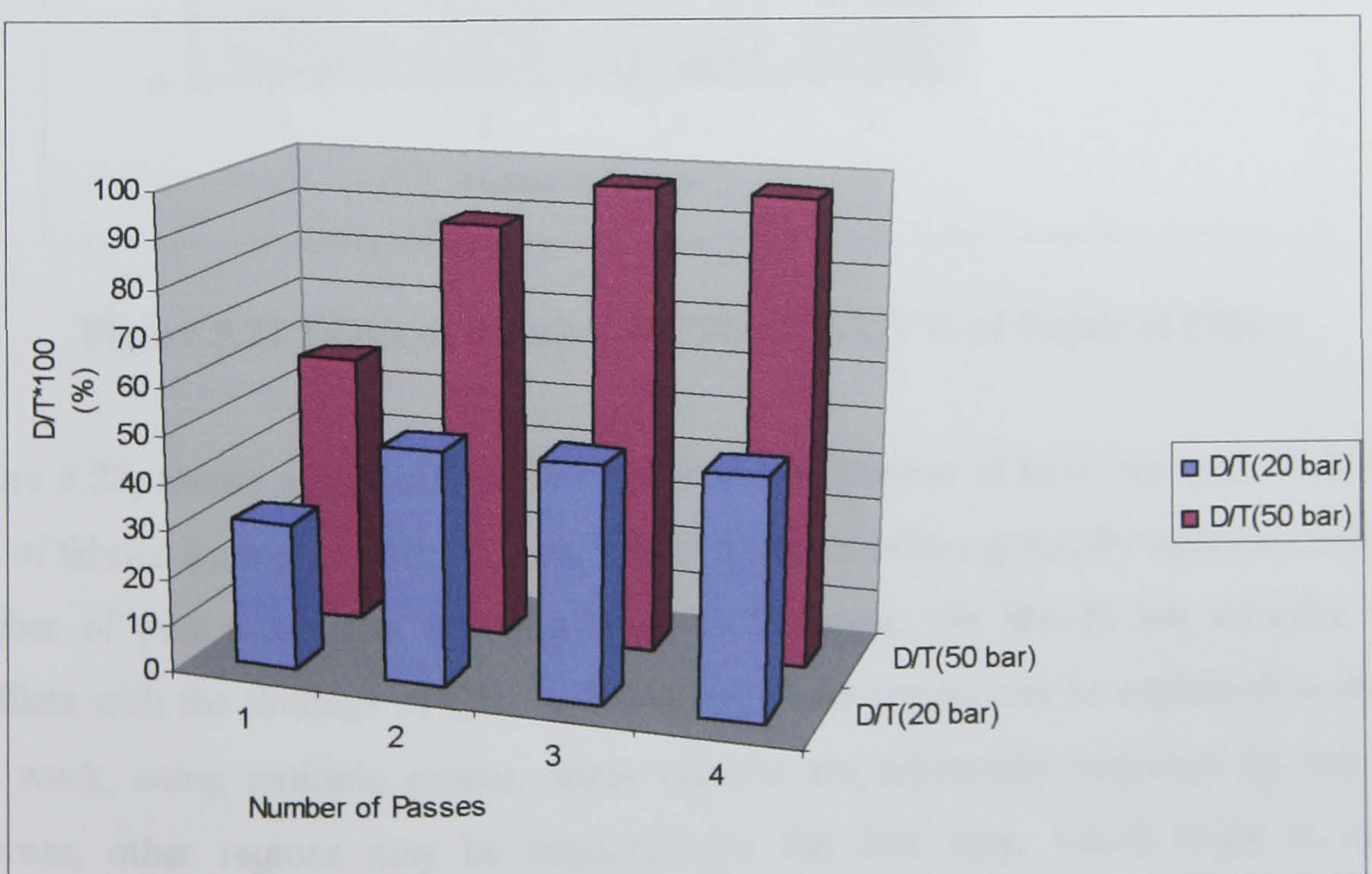


Figure 5.22 Effect of Number of Passes on D/T *100

In figure 5.22, the ratio of D/T was calculated for both the fabrics produced at 20 or 50 bar, Where:

D = the mean depth of the pillars (mm)

T = the mean thickness of the fabric (mm)

As can be seen from figure 5.22 increasing the number of passes results in an increase in the ratio of D/T*100.

This ratio characterizes the fabric consolidation in the fabric cross-section. Using 50 bar pressure, a steeper gradient (of increasing D/T) is evident compared to fabrics produced at 20 bar pressure. This reflects a 50% decrease in fabric thickness after 4 passes at 50 bar pressure.

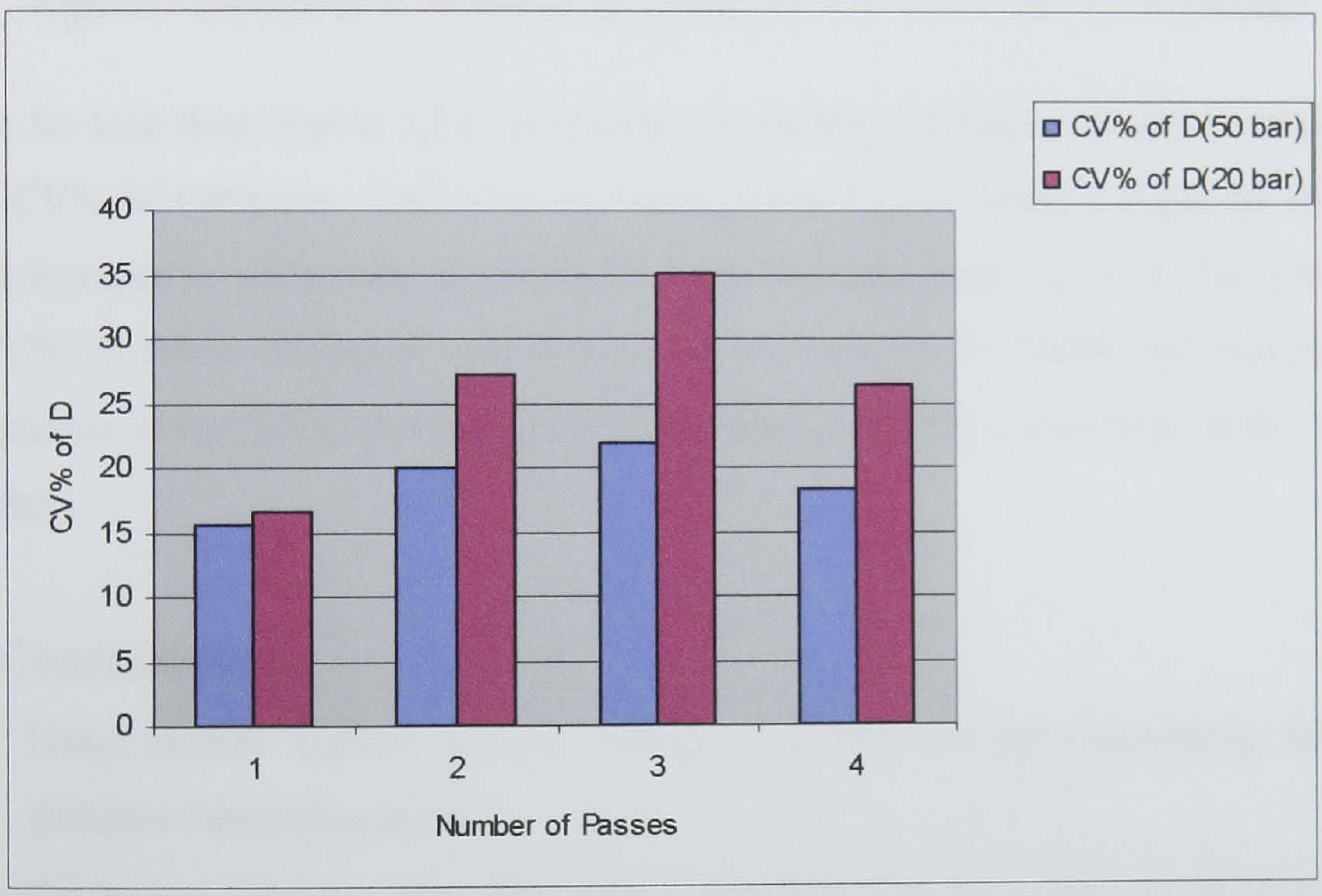


Figure 5.23 Effect of Number of Pillars on CV% of Depth of Pillars

Figure 5.23, shows a plot of the CV% of D vs the number of injectors applied. In both sets of fabrics (groups 1 and 3), the CV% of depth of pillars generally increases with the number of passes and the variation tends to be higher for the 20 bar samples. This conflicts with the findings of Qiao[82]. However, these results can be explained as during this work, using multiple passes, some regions are repeatedly impacted by the jets, whereas, other regions may be impacted for the first time, which tends to create increased heterogeneity. Of course, this situation will depend on the arrangement of successive injector orifices.

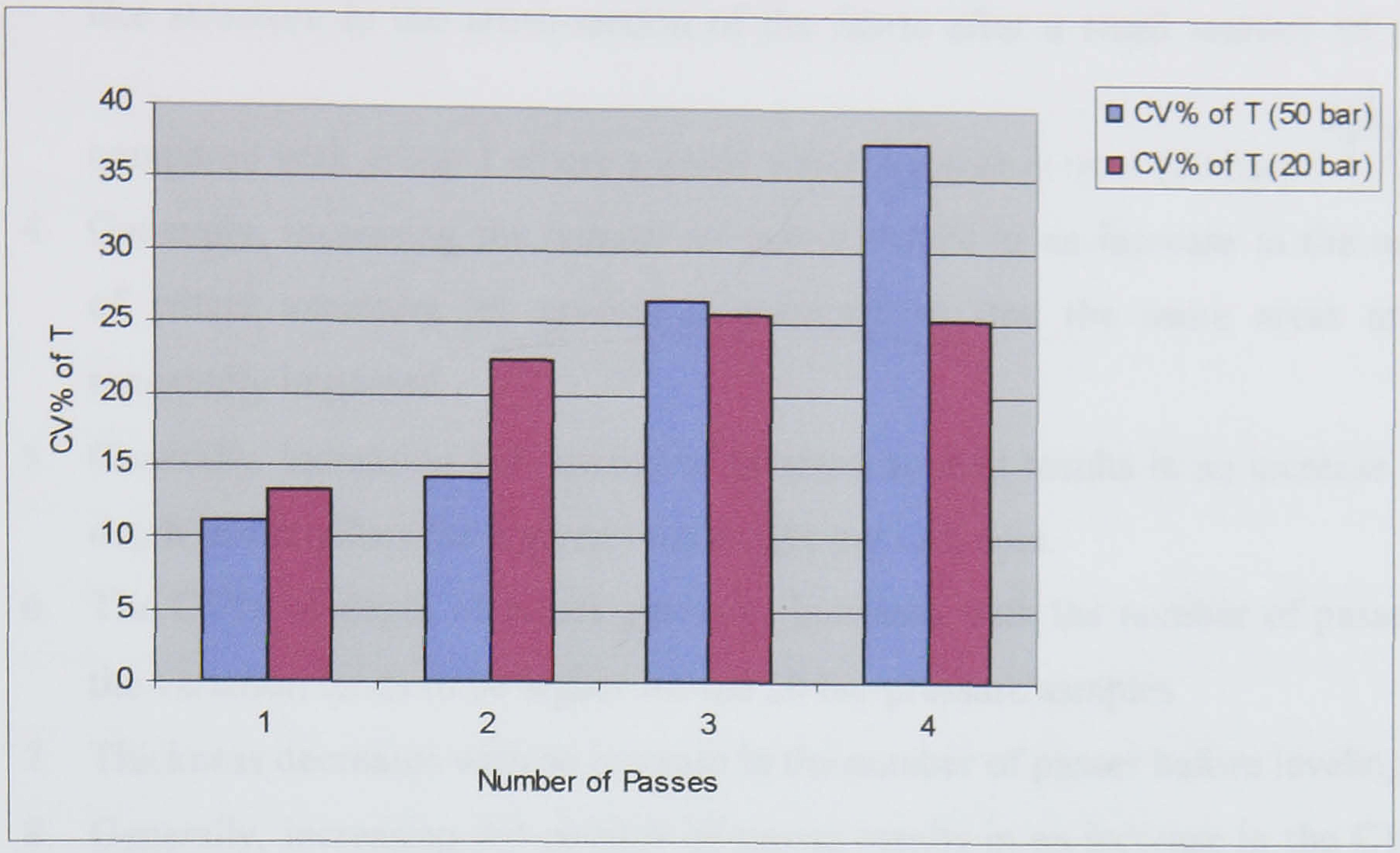
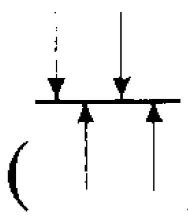


Figure 5.24 Effect of Number of Passes on CV% of Fabric Thickness

As can be seen from figure 5.24, increasing the number of passes results in an increase in the CV% of thickness. This is an interesting observation, since it might be expected that an increase in uniformity would result from multiple passes. In fact, the increase in the CV% of fabric thickness results from an increase in the depth and frequency of corrugations in the fabric surface (jet marks), associated with an increase in the number of passes.

5.10 Conclusions

1. Using similar applied specific energy with different jet sequencing results in different fabric structures.
2. Producing fabrics using low water pressure (20 bar) and an alternating jet sequence as shown in group 1 (↓↓/↑↑ , 20 bar), results in fabrics that have a more compact structure as compared with fabrics produced using the same amount of pressure with a different jet sequence group 2 (↓↓/↑↑ , 20 bar).
3. Producing fabrics using relatively high water pressure (50 bar) and jet sequencing as in group 3 (↓↓/↑↑), results in fabrics that have a uniform, chain-

like structure in the cross-section of the fabric after a small number of passes compared with group 1 where a lower water pressure is used (20 bar) ().

4. Generally, increasing the number of passes results in an increase in the number of pillars assuming jet spacing is arranged so that the same areas are not repeatedly impacted.
5. Generally, increasing the amount of pressure applied results in an increase in the depth of the pillars for a given web weight per unit area.
6. The CV% of depth of pillars generally increases with the number of passes and the variation tends to be higher for the 20 bar pressure samples
7. Thickness decreases with an increase in the number of passes before leveling.
8. Generally, increasing the number of passes results in an increase in the CV% of thickness.

CHAPTER 6

EFFECT OF VARIATION IN PRESSURE PROFILE ON LOW STRESS MECHANICL PROPERTIES AND FABRIC STRUCTURE

This chapter presents a study of the effects of the pressure profile on fabric structure and low stress mechanical properties. This relates specifically to a study of the effects of a different number of passes and sequencing of jets from one or both sides of the web. This is relevant to commercial hydroentanglement installations where injectors are generally arranged on both sides of the web in series. Previous work has shown that the manner in which the energy is applied to the web (the sequence of the jets) influences mechanical properties even if the total specific energy remains constant.

6.1 Experimental Procedure

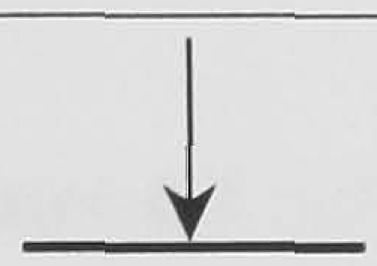
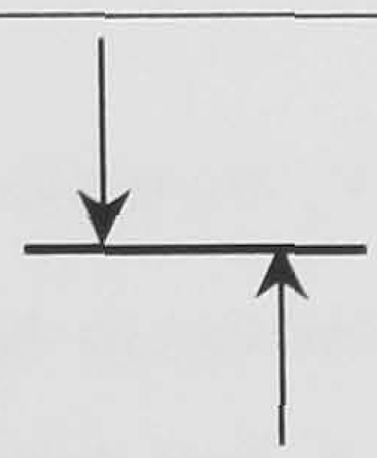
In this work, a carded web of 100 g/m^2 made of viscose rayon fibres of 1.7 dtex linear density and 38mm mean fibre length was used. Three groups of fabrics, each of 100 g/m^2 nominal area density were produced using the general process conditions summarised in chapter 5, section 5.2. The first two groups were produced using two different jet pressure sequences, and each was produced with the same pressure at each stage (Tables 5.1 and 5.2). The third group was produced using higher pressure and the same pressure sequence as group 1 (Table 5.3). The mechanical properties of the fabrics were then determined and where relevant, the properties of the face and back in three fabric directions (MD, CD and Bias direction respectively) were determined. The energy profiles used to prepare the fabric samples in each of the four groups are summarized in Tables 5.1, 5.2 and 5.3 (groups 1-3).

6.2 Identification of the Number of Fibres in the Cross Section Using the Scanning Electron Microscope

Scanning electron microscopy (SEM) was used to identify the number of fibres in the cross section of experimental fabrics of 100 g/m^2 produced at low pressure (20 bar, 1 pass and 2 passes) and at higher pressure (50 bar, 1 pass and 2 passes). The production specifications of these fabrics are shown in tables 6.1 and 6.2.

Figures 6.1, 6.3, 6.4 and 6.5 give examples of typical cross-sections produced for different hydroentangled samples. To permit these observations, it was necessary to prepare samples for cross sectioning. The same procedure as that described in chapter 5, Sections 5.6 and 5.7 was utilised.

Table 6.1: Specifications of fabrics (100 g/m^2) produced at 20 Bar

Sample Ref. Number	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
S1$_A$		1 pass- 20 bar	0.148
S1$_B$		2 passes – 20 bar	0.296

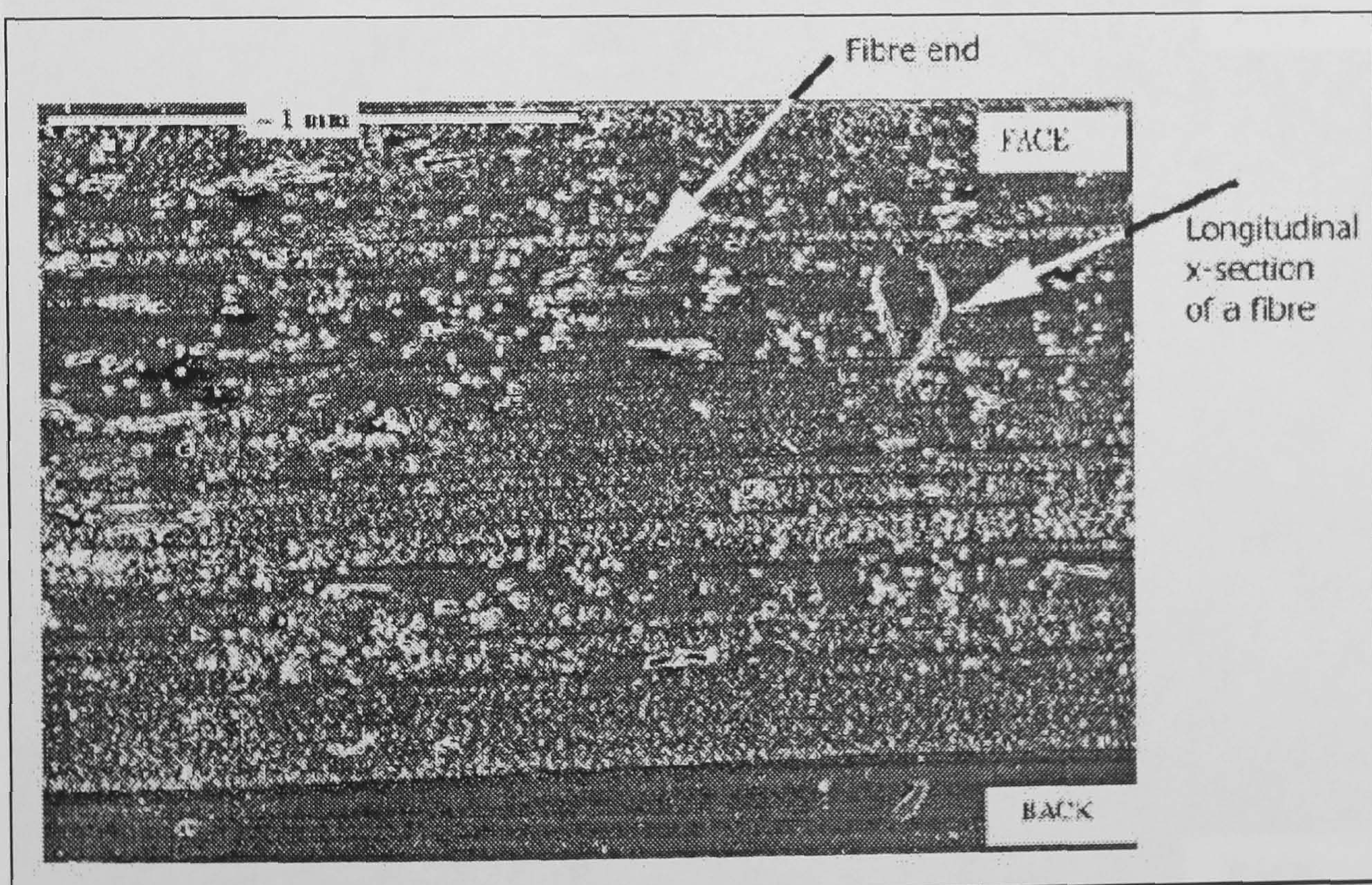


Figure 6.1 Cross Section of the Fabric Sample (S1$_A$) Produced at 20 Bar – 1 Pass (0.148 MJ/Kg)

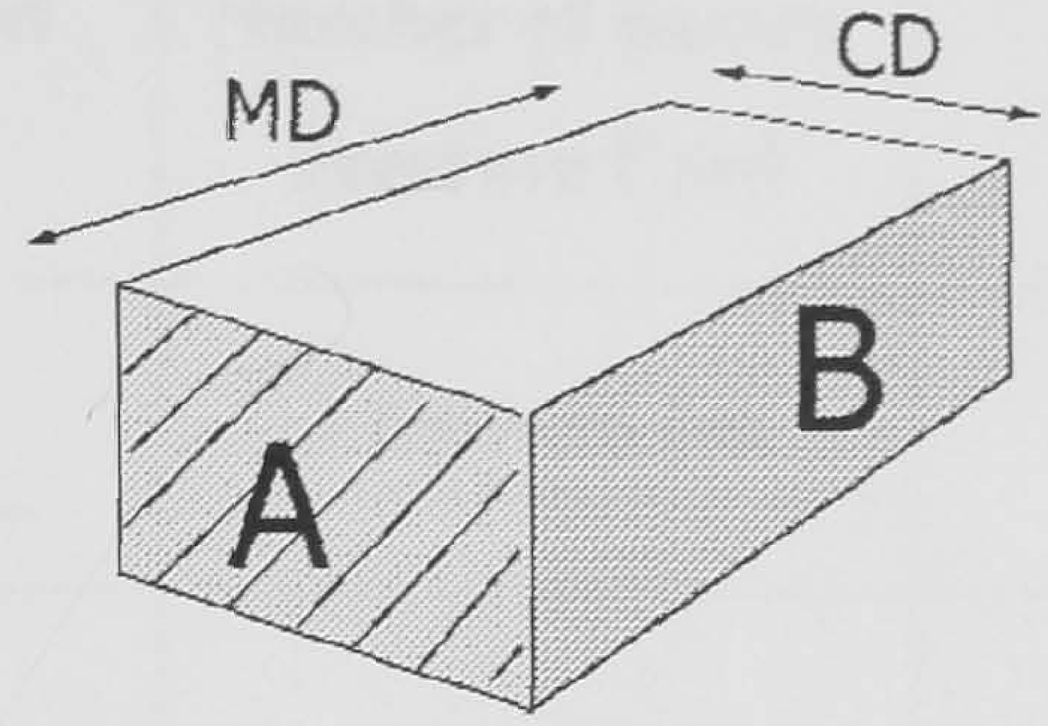


Figure 6.2 Schematic Diagram of a Fabric MD and CD

Figure 6.2 shows a diagram of the fabric MD and CD sections were taken from area A in figure 6.2. Typical cross-sections produced for the different hydroentangled samples are shown in figures 6.1, 6.3, 6.4 and 6.5.

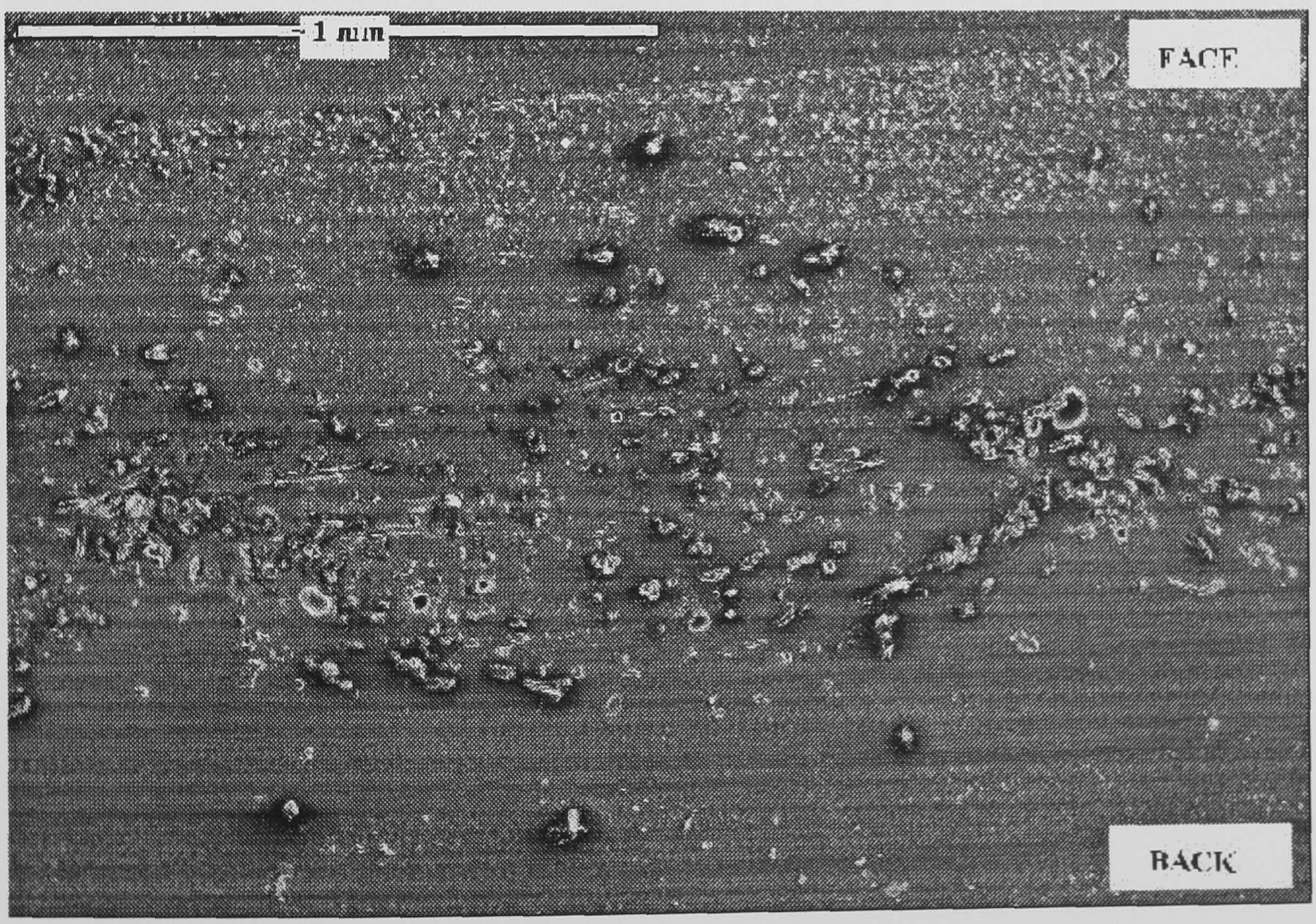
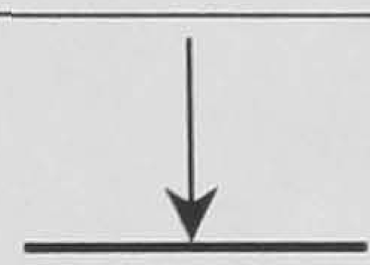
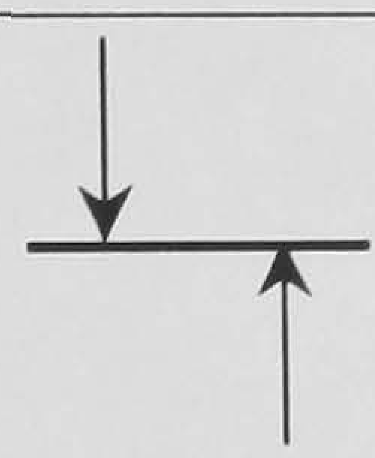


Figure 6.3 Cross Section of the Fabric Sample ($S1_B$) Produced at 20 Bar – 2 Passes (0.296 MJ/Kg)

Table 6.2: Specifications of fabrics (100 g/m^2) Produced at 50 Bar

Sample Ref. Number	Treatment Type	Number of passes-Pressure Used	Total Specific energy (MJ/Kg)
$S3_A$		1 pass- 50 bar	0.578
$S3_B$		2 passes – 50 bar	1.156

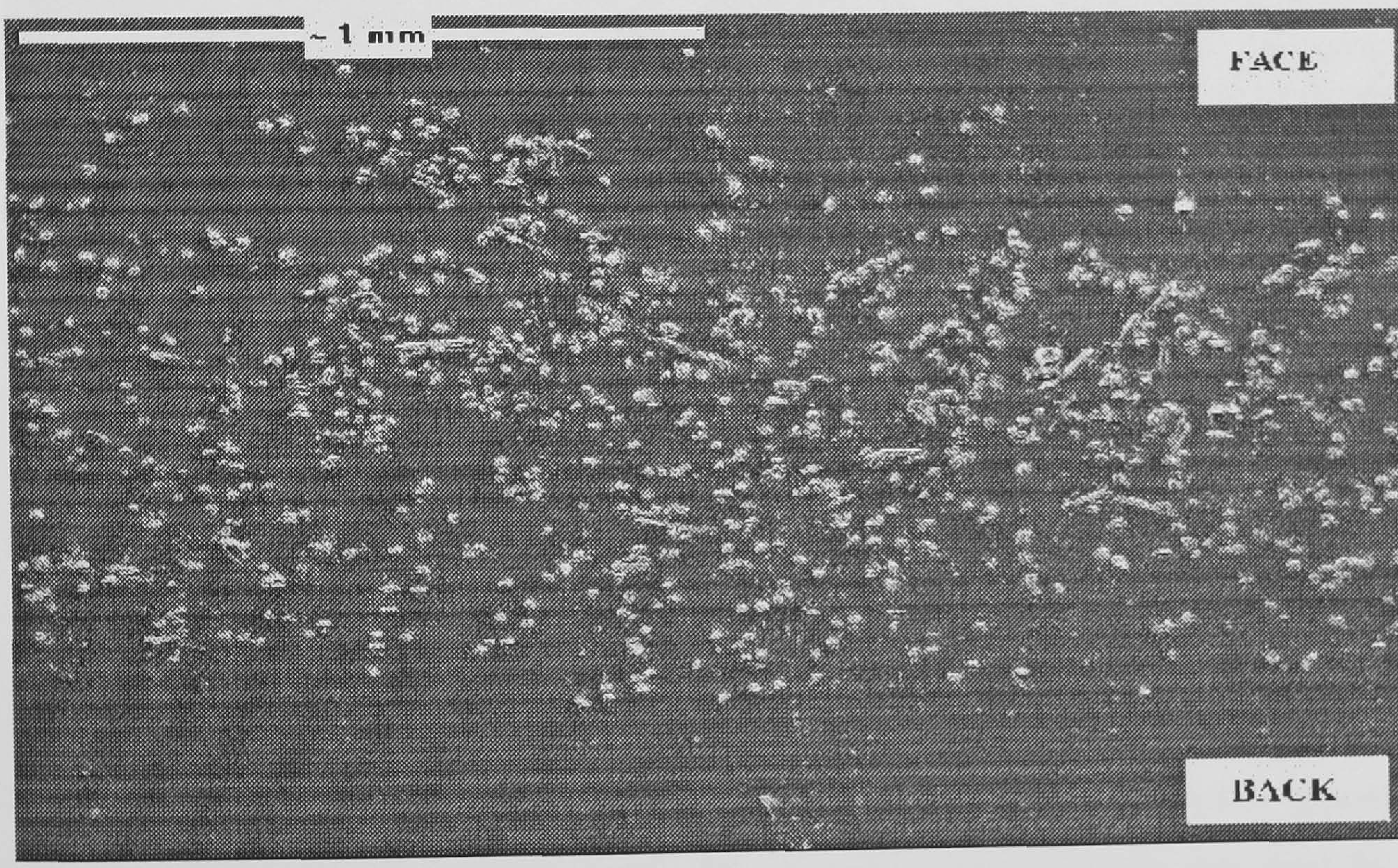


Figure 6.4 Cross Section of the Fabric Sample ($S3_A$) Produced at 50 Bar – 1 Pass (0.578 MJ/Kg)

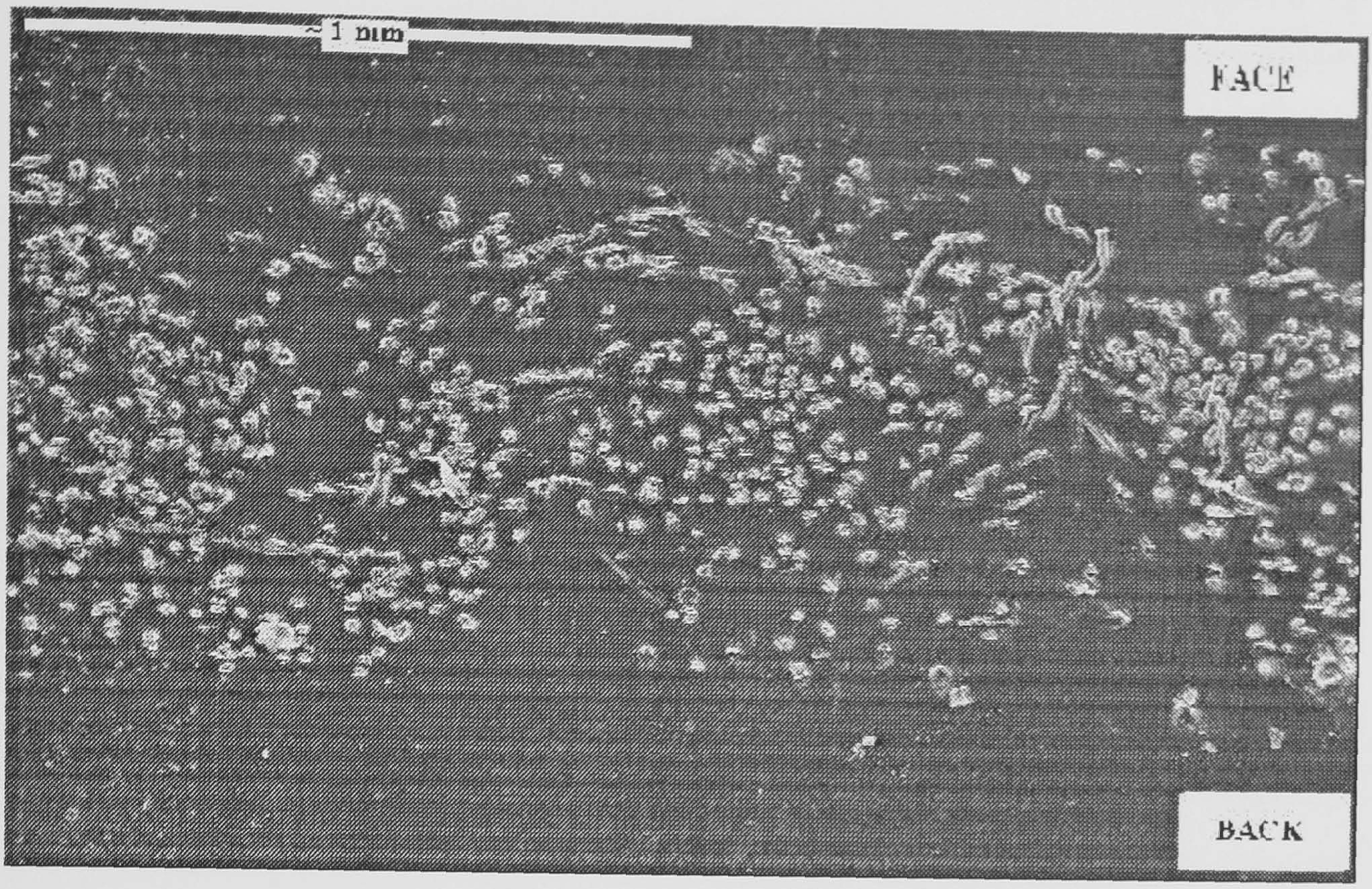


Figure 6.5 Cross Section of the Fabric Sample ($S3_B$) Produced at 50 Bar – 2 Passes (1.156 MJ/Kg)

Figures 6.1, 6.3, 6.4 and 6.5 were analyzed to obtain quantitative data on the structural architecture and the number of fibres in the cross section was determined.

The procedure involved preparing a small window or aperture drawn on a piece of paper and cut to the dimensions of 0.25 mm^2 according to the scale used on the SEM images. The average number of fibres (inside this cell) was determined. The boundary of each fabric section was determined and measurements were taken within the window placed at eight different locations systematically. The average number of fibres measured for each fabric is shown in table 6.3. The total number of fibres in each cell was obtained and an average was calculated together with an estimate of the variation.

Table 6.3: Average Number of Fibres in the 0.25 mm^2 Cross-Sectional Cell (100 g/m^2 Fabric)

	Sample $S1_A$ (20 bar)	Sample $S1_B$ (20 bar)	Sample $S3_A$ (50 bar)	Sample $S3_B$ (50 bar)
	1 pass (0.148 MJ/Kg)	2 passes (0.296 MJ/Kg)	1 passes (0.578 MJ/Kg)	2 passes (1.044 MJ/Kg)
Average	15	22	25	45
SD	4.24	3.37	3.28	6.30
CV%	29.26	15.49	13.27	14.12

It is evident from table 6.3 that the number of fibres in the 0.25 mm^2 cell cross section of the fabric increased as a result of increasing the number of passes used and also as a result of increasing the water pressure used. Figure 6.6-a show the effect of increasing the total specific energy on the fabric packing density. As may be expected, there is a relationship between the increase in the fabric specific energy and the fabric packing density. Figure 6.6-b shows the relationship between the number of fibres in the fabric cross-section unit cell and the fabric packing density. As expected, increasing the number of fibres in the cross section as a result of increasing the specific energy, results in an increase in fabric packing density. The packing density of the fabric is essentially the product of fabric density divided by the specific gravity of the viscose fibres.

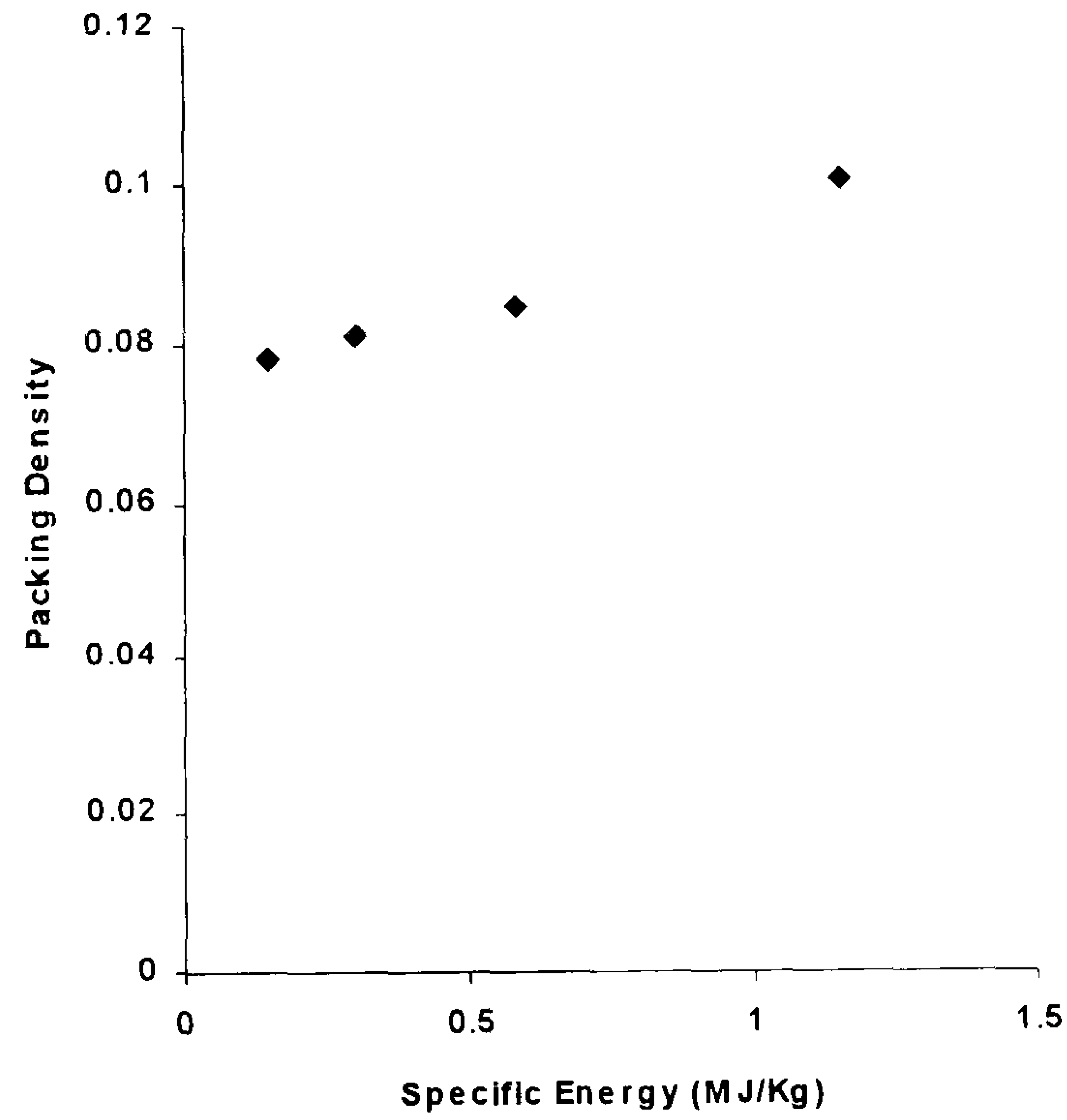


Figure 6.6-a Packing Density vs Fabric Specific Energy

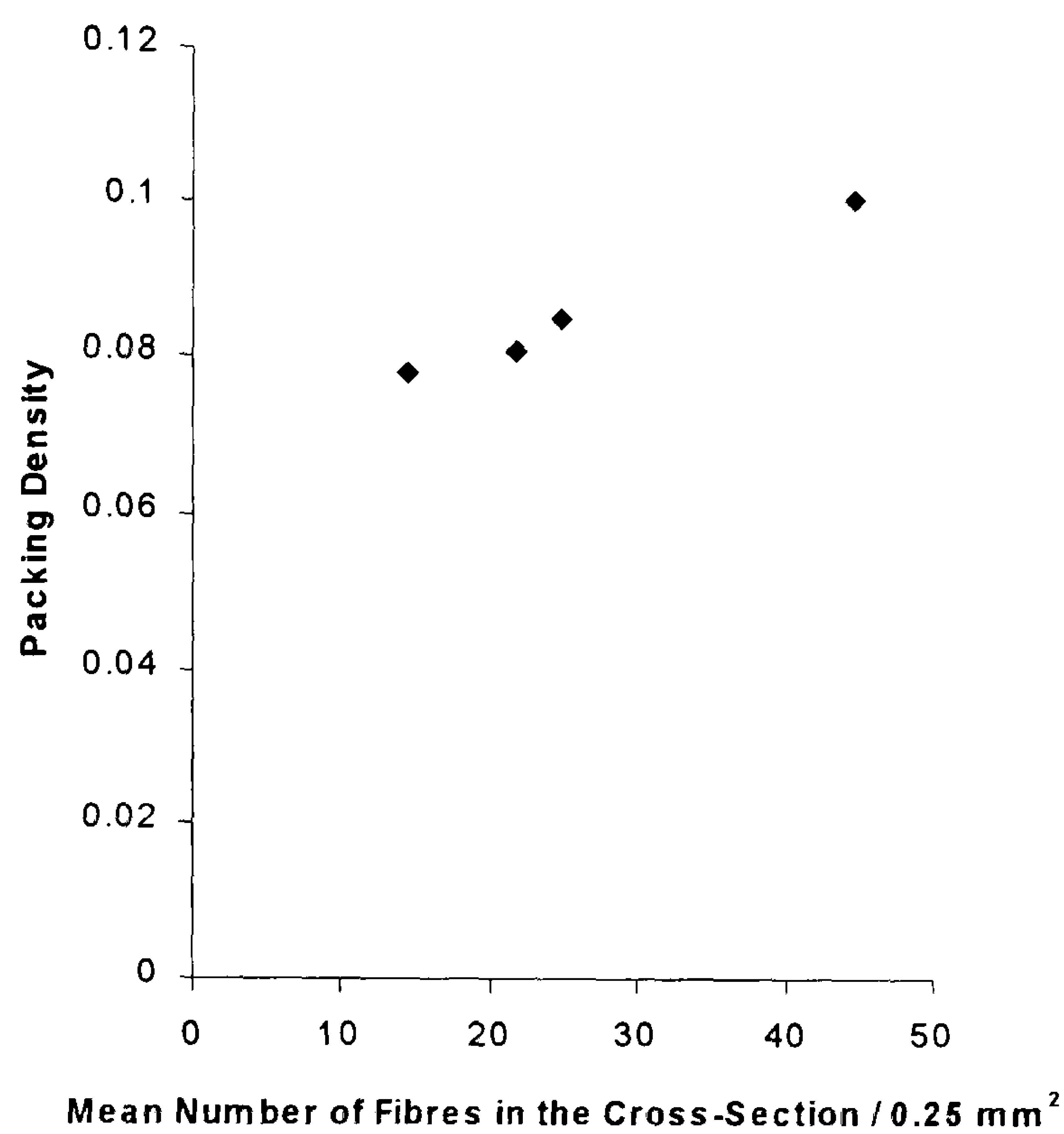


Figure 6.6-b Packing density vs Number of Fibres in the Unit Cell

Assuming an increase in the number of fibres in the cell when substituting in to equation 4.2, and that all other factors are constant, it can be concluded that increasing the pressure or the number of passes will result in an increase in the fabric bending rigidity. According to equation 4.2, assuming all other factors remain constant, increasing the number of fibres in a unit cell of the fabric cross-section will result in an increase in the fabric stiffness. This assumption is tested in the plot shown in figure 6.7, where the fabric bending rigidities for fabrics produced at different energies are plotted against the average number of fibres in the unit cell.

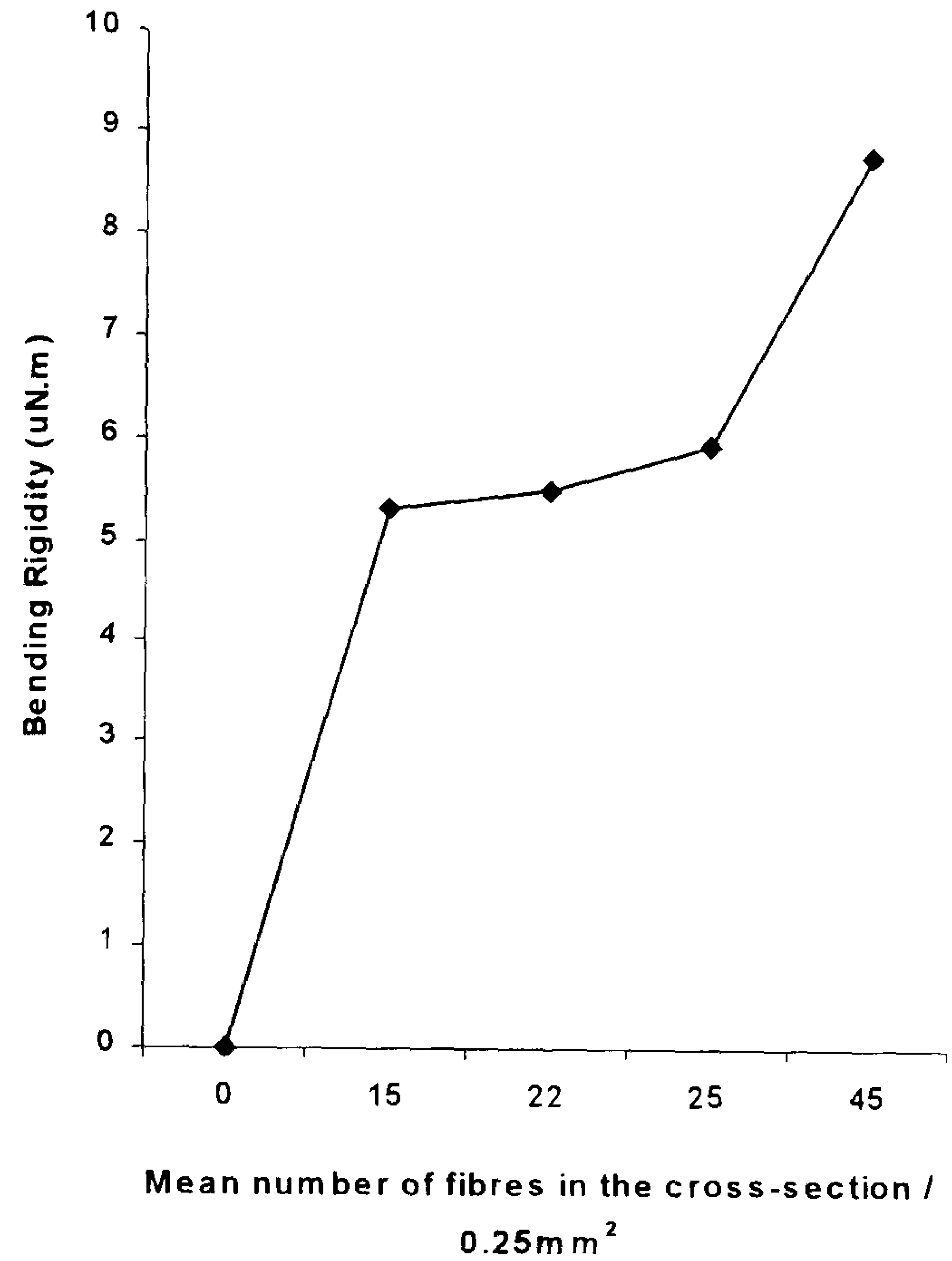


Figure 6.7 Bending Rigidity vs Number of Fibres in the Unit Cell

6.3 Determination of Fabric Structure and the Associated Low Stress Fabric Mechanical Properties

All the fabrics were characterised on the face and back, and in the MD, CD and bias directions using the FAST system. Specifically, fabric thickness (FAST 1), bending length (FAST 2) and extension at a fixed load (FAST 3) were determined. Six specimens were prepared for each sample and in each direction. Conditioning and testing procedures were as indicated in the FAST manual[46], and as explained in chapter 2.

6.3.1 Fabric Thickness (T2, T100)

The effect of increasing the number of passes on fabric thickness was established for groups 1, 2 and 3 (See specification of each group in tables 5.1, 5.2 and 5.3) and is shown in figures 6.8 and 6.9. The T2 and T100 values for the fabrics refer to the two different fabric thicknesses measured at two different loads (2 and 100 gf/cm2), (See chapter 2-section 2.2.2)

6.3.1.1 Fabric Thickness (T2)

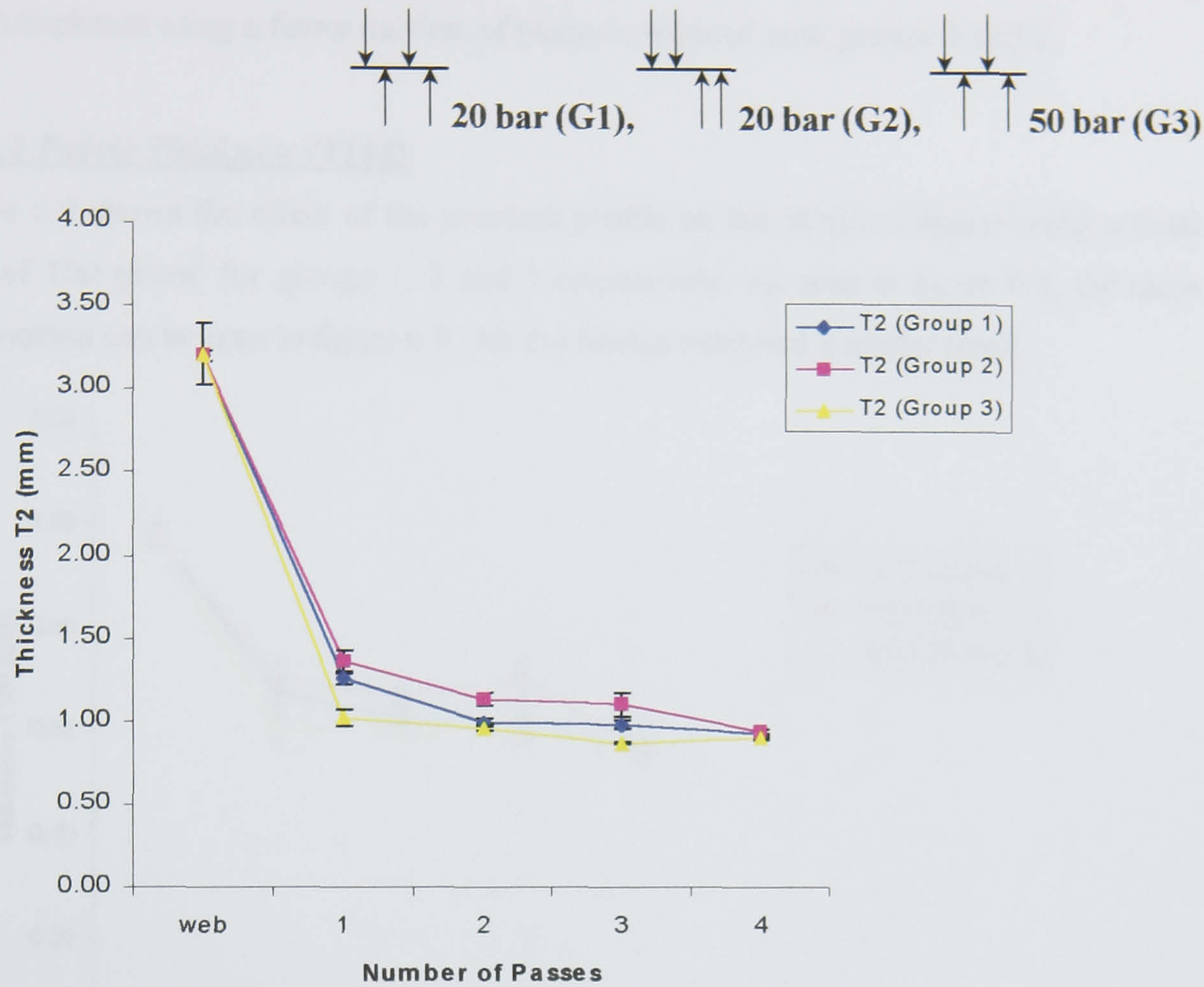


Figure 6.8 Effect of Pressure Profile (Groups 1, 2 and 3) on Fabric Thickness (T2)

In figure 6.8, the effect of the number of passes on fabric thickness, using a fixed load of 2 gf/cm^2 (T2), is presented. It can be noticed that all three groups exhibited a similar trend. After the first pass, an initial decrease occurs and thereafter, fabric thickness tends to a minimum value and levels with further passes.

In group 1, the lowest thickness was obtained after the second pass, whereas in group 2, the lowest thickness was obtained after the fourth pass. In other words, using the pressure sequence in group 2 requires more passes to achieve an equivalent minimum thickness, which means more energy is expended in the process.

It can be concluded from this comparison that treating the fabric on the face and back sequentially after each pass, will result in a more uniform and compacted fabrics using less energy. In group 3, producing the fabric with 50 bar results in the largest decrease in the fabric thickness after the first pass, compared to groups 1 and 2. Therefore, producing fabrics with the pressure profile as in group 3, results in a decrease in the fabric thickness using a fewer number of passes compared with groups 1 and 2.

6.3.1.2 Fabric Thickness (T100)

Figure 6.9 shows the effect of the pressure profile on the fabric thickness using a fixed load of 100 gf/cm^2 for groups 1, 2 and 3 respectively. As seen in figure 6.8, the same observation can be seen in figure 6.9. All the fabrics exhibited a similar trend.

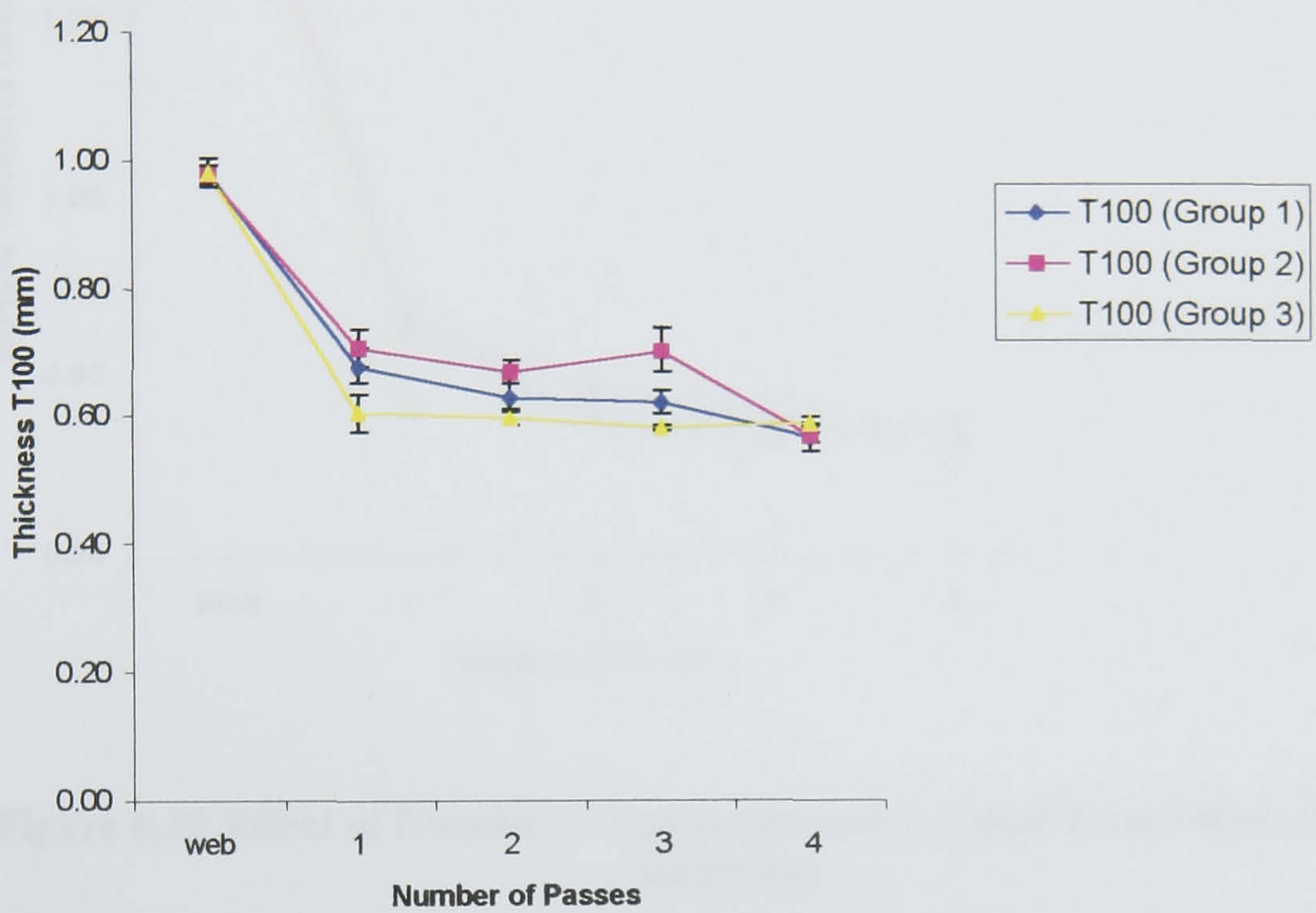


Figure 6.9 Effect of Pressure Profile (Groups 1, 2 and 3) on Fabric Thickness (T100)

Comparing groups 1, 2 and 3, these results can be explained as in section 6.3.1.1 in that applying energy to the face and back of the fabric in the way shown in group 1 (Table 5.1), produces more compact fabrics using less specific energy compared to group 2 (table 5.2). Comparing groups 1, 2 and 3 (Tables 5.5, 5.7 and 5.8), it is noticed that producing the fabric with a higher pressure, of 50 bar, compared with 20 bar in groups 1 and 2, results in a decrease in fabric thickness (T100) to a minimum value after only the first pass.

6.3.2 Fabric Surface Thickness

As explained in section 2.2.7, using the FAST 1 instrument, the surface thickness of the fabric is defined from the thickness measurements at 2 gf/cm^2 and at 100 gf/cm^2 (T2 and T100). From figure 6.10, it is apparent that the web is consolidated heavily after the first pass and further passes produce small absolute changes in the surface thickness.

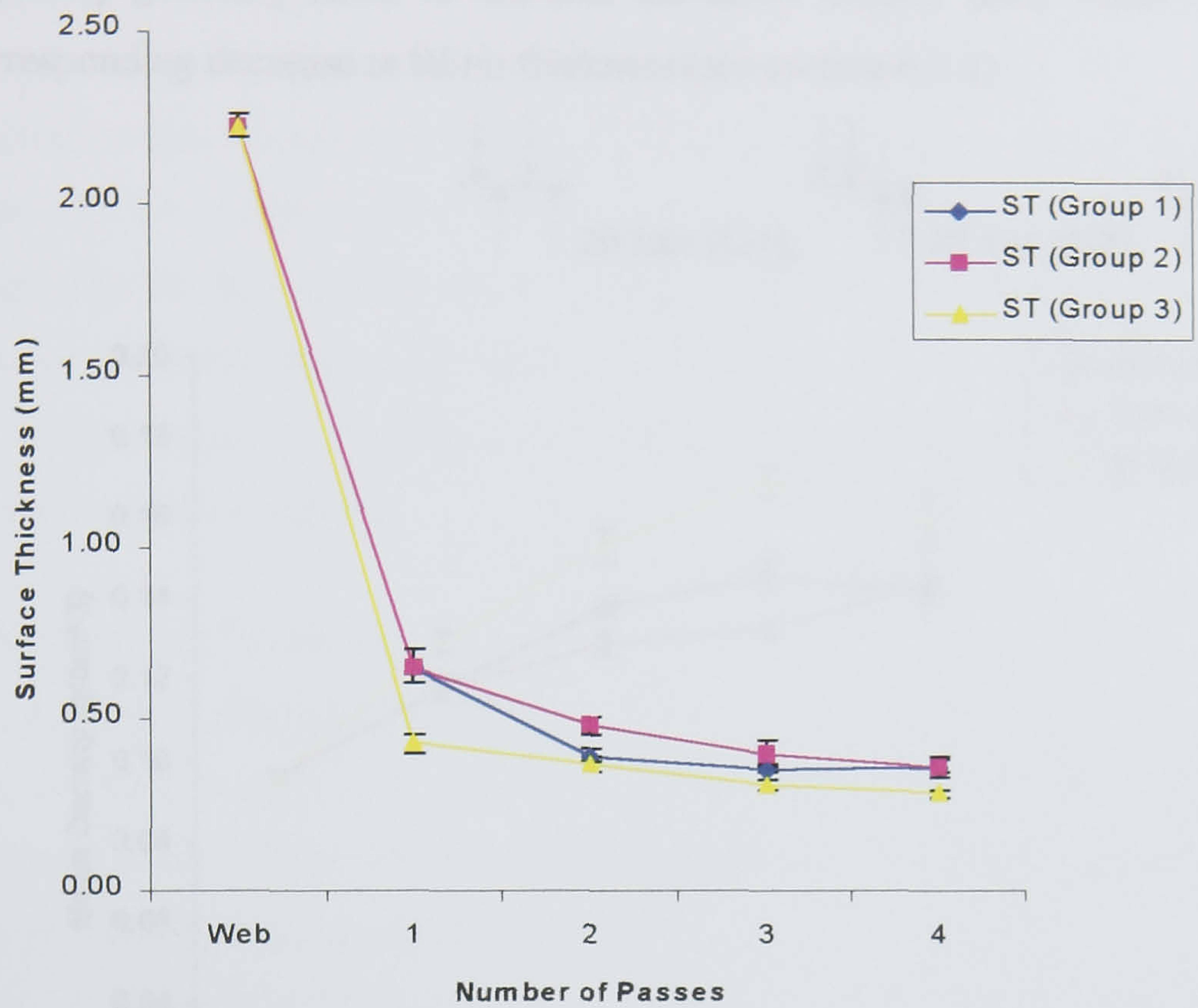


Figure 6.10 Effect of Number of Passes (groups 1, 2 and 3) on Fabric Surface Thickness

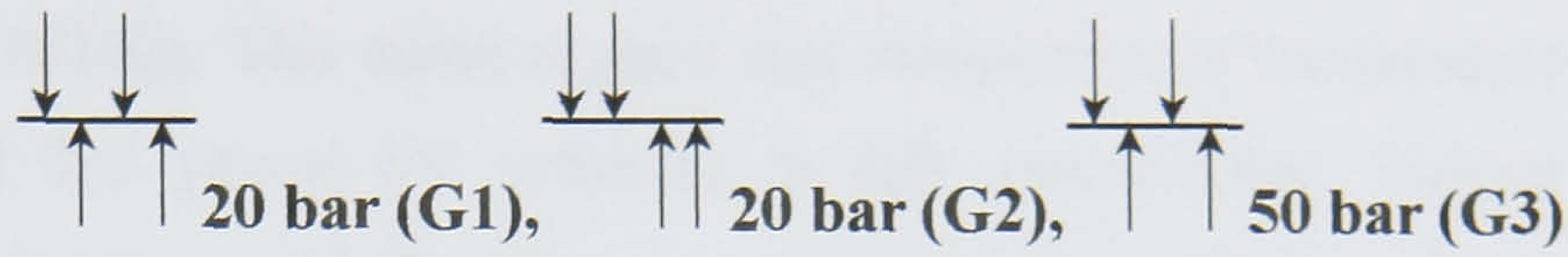
Figure 6.10, also shows a similar trend of decreasing surface thickness with the number of passes is observed. It can be noticed that most of the fabric consolidation and compacting, for all the 3 fabric groups, is achieved after the first hydroentanglement pass.

Comparing group 3 (Table 5.8) with groups 1 and 2 (tables 5.7 and 5.5) in figure 6.10, it is noticeable that the surface thickness decreases by approximately 81% after the first pass in group 3, compared to a decrease of 70% in group 1. These results reflect the use of a higher water pressure in group 3 (50 bar) compared to the lower pressure used in groups 1 or 2 (20 bar).

In general, there is no practical difference in the mean values obtained between each group after two and three passes.

6.3.3 Fabric Density

From figure 6.11, it is apparent that increasing the number of passes up to 3 or 4 injectors) generally tends to increase the fabric density (Df), which results from the corresponding decrease in fabric thickness (see section 6.3.1).



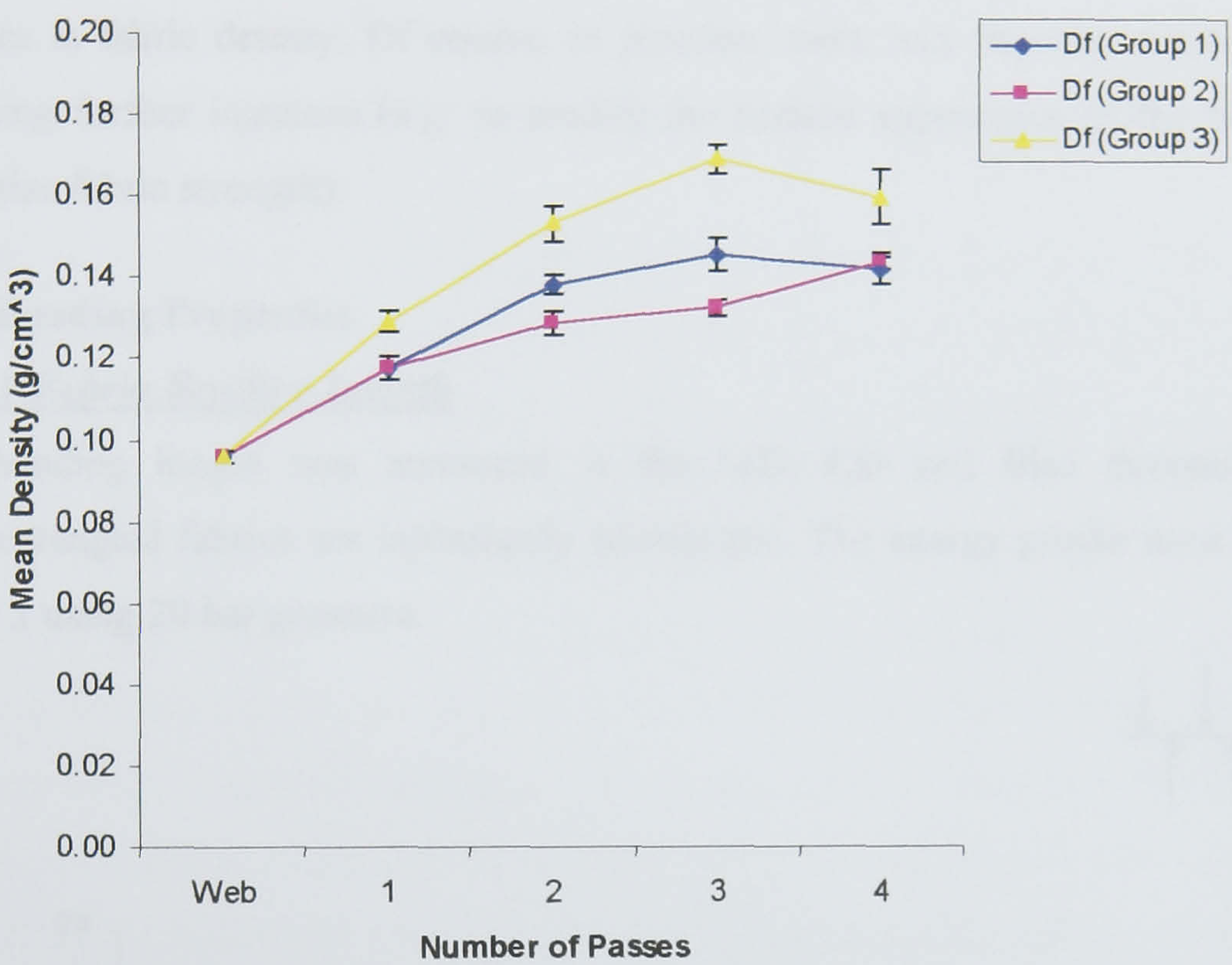


Figure 6.11 Effect of Number of Passes on Fabric Density –Group 1, 2 and 3

For all fabric groups, there was a steady increase in density to a maximum. For groups 1 and 3, the maximum density was achieved after 3 passes. For group 2, the highest density was achieved after 4 passes.

These results reflect the differences that result from applying the energy on the face and back (group 1), which results in greater overall compression of the fabric than in group 2, where the first two passes are applied from the face side only (compare figure 5.5 and 5.13 & 5.13 and 5.14). This implies that the structures of the two fabrics will be different in the cross-section face and back after two passes, which in turn will affect the fabric low stress mechanical properties of both sides. Application of the energy from one side only is therefore likely to lead to a heterogeneous fabric structure in the cross-section, which is most marked when using only a few injectors in total.

In figure 6.11, group 3 fabrics exhibit a similar trend to that of group 1 and 2. The density appears to increase to a maximum at around 2 –3 passes, which approximately corresponds to a specific energy of 1.5 MJ/Kg. Interestingly, in groups 1 and 2, which use a lower pressure, the maximum density was achieved at the same 2-3 passes, but at a lower energy of only 0.45 MJ/Kg. This could suggest that irrespective of the pressure used (20 or 50 bar), after 2-3 passes the structure is fully consolidated. Further treatments at the same pressure would therefore be expected to result in minimal changes in fabric density. Of course, in practice, there may be other technical reasons for using further injectors (e.g. to modify the surface appearance of the fabric and to maximize fabric strength).

6.3.4 Bending Properties

6.3.4.1 Fabric Bending Length

The bending length was measured in the MD, CD and Bias directions because hydroentangled fabrics are intrinsically anisotropic. The energy profile used was that of group 1 using 20 bar pressure.

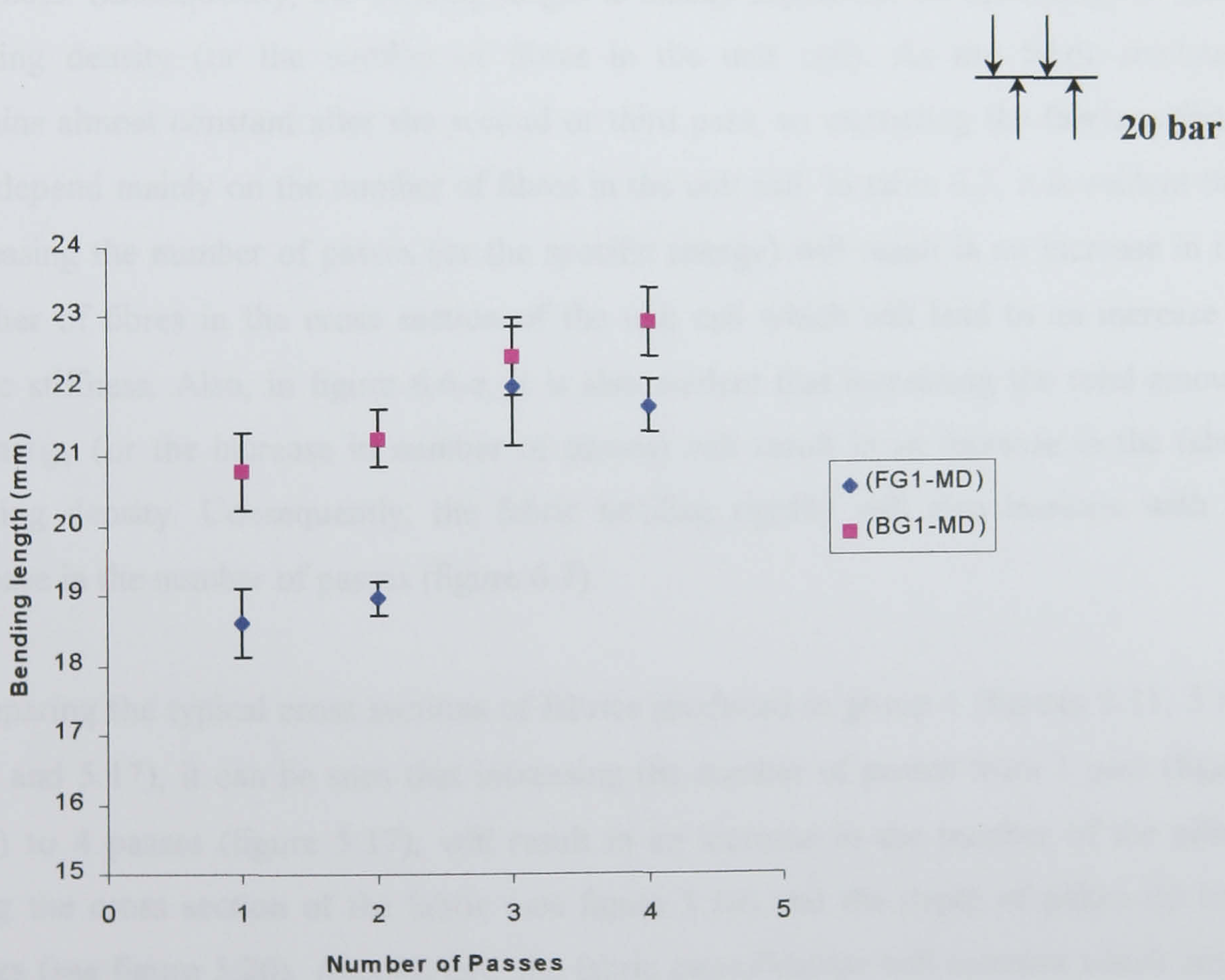


Figure 6.12 Effect of Number of Passes on Fabric Bending Length in Group 1 (Face and Back-MD)

Key:

FG1-MD = face- group 1, tested in the MD

BG1-MD =back- group 1, tested in the MD

Figures 6.12 shows the effect of the number of passes on the bending length of the fabrics in group 1 face and back in the MD. In this figure, the effect of the number of passes using a fixed water pressure of 20 bar (group 1) using the injector sequence shown in table 5.1, on the fabric bending length (Face and Back) is shown. It can be seen that generally, the bending length increases with an increasing number of passes.

Based on equation 4.2, it is obvious that if all other conditions remain constant, the bending properties will depend on the fabric thickness and the number of fibres in the unit cell (T^2 and N). It is known that there is a large initial decrease in fabric thickness with pressure or specific energy before leveling (see figure 6.8 and 6.9). Therefore, initially the change in bending length is mainly a function of a decrease in the fabric thickness. Subsequently, the bending length is mainly dependent on the change in fabric packing density (or the number of fibres in the unit cell). As the fabric thickness remains almost constant after the second or third pass, so increasing the fabric stiffness will depend mainly on the number of fibres in the unit cell. In table 6.3, it is evident that increasing the number of passes (or the specific energy) will result in an increase in the number of fibres in the cross section of the unit cell which will lead to an increase in fabric stiffness. Also, in figure 6.6-a, it is also evident that increasing the total amount of energy (or the increase in number of passes) will result in an increase in the fabric packing density. Consequently, the fabric bending rigidity will also increase with an increase in the number of passes (figure 6.7).

Comparing the typical cross sections of fabrics produced in group 1 (figures 5.11, 5.13, 5.15 and 5.17), it can be seen that increasing the number of passes from 1 pass (figure 5.11) to 4 passes (figure 5.17), will result in an increase in the number of the pillars along the cross section of the fabric (see figure 5.19) and the depth of pillars up to 3 passes (see figure 5.20). Accordingly, the fabric consolidation will increase which could lead to an increase in the fabric stiffness due to the reduced fibre mobility in bending.

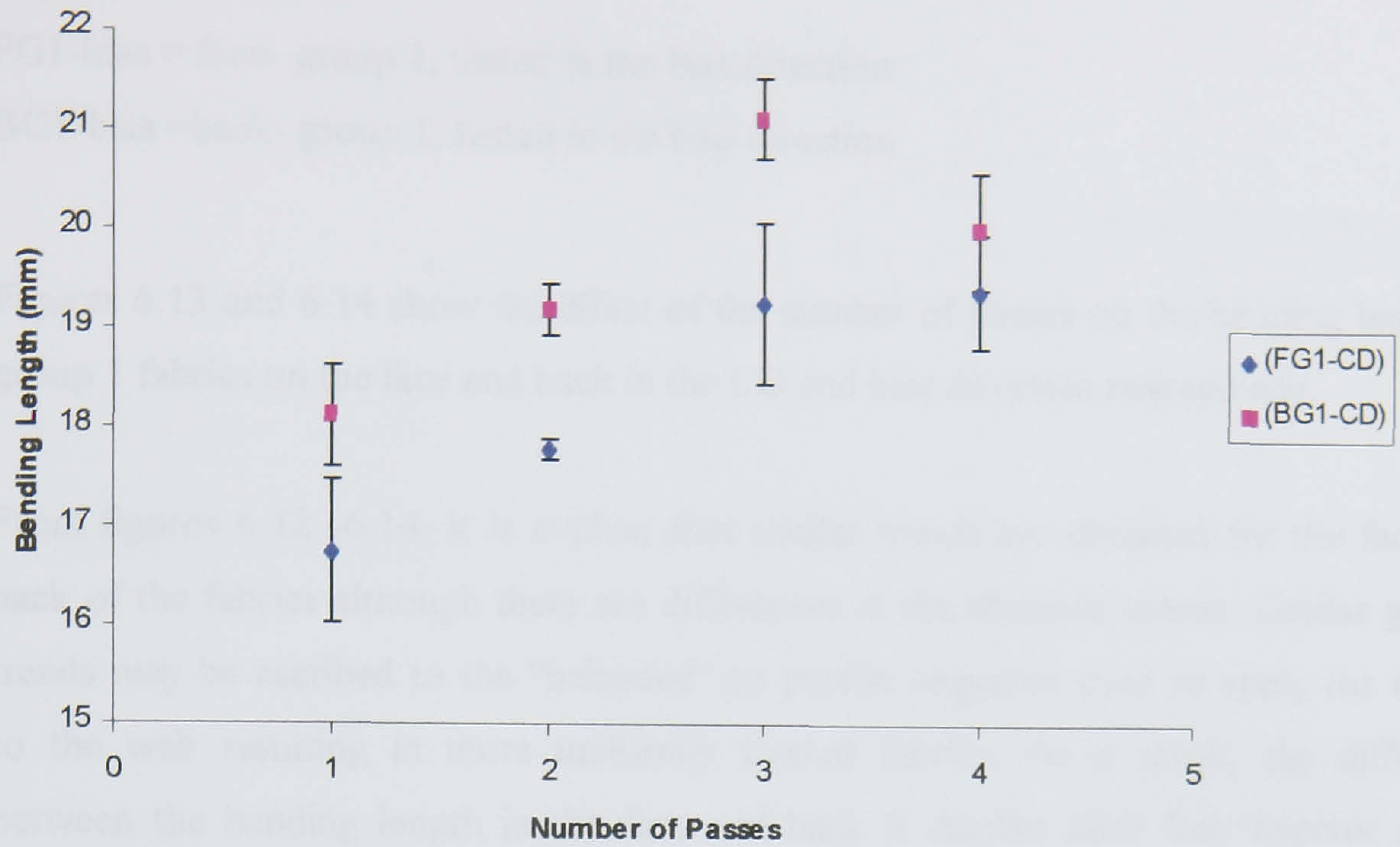


Figure 6.13 Effect of Number of Passes on Fabric Bending Length of Group 1 (Face and Back-CD)

Key:

FG1-CD = face- group 1, tested in the CD

BG1-CD =back- group 1, tested in the CD

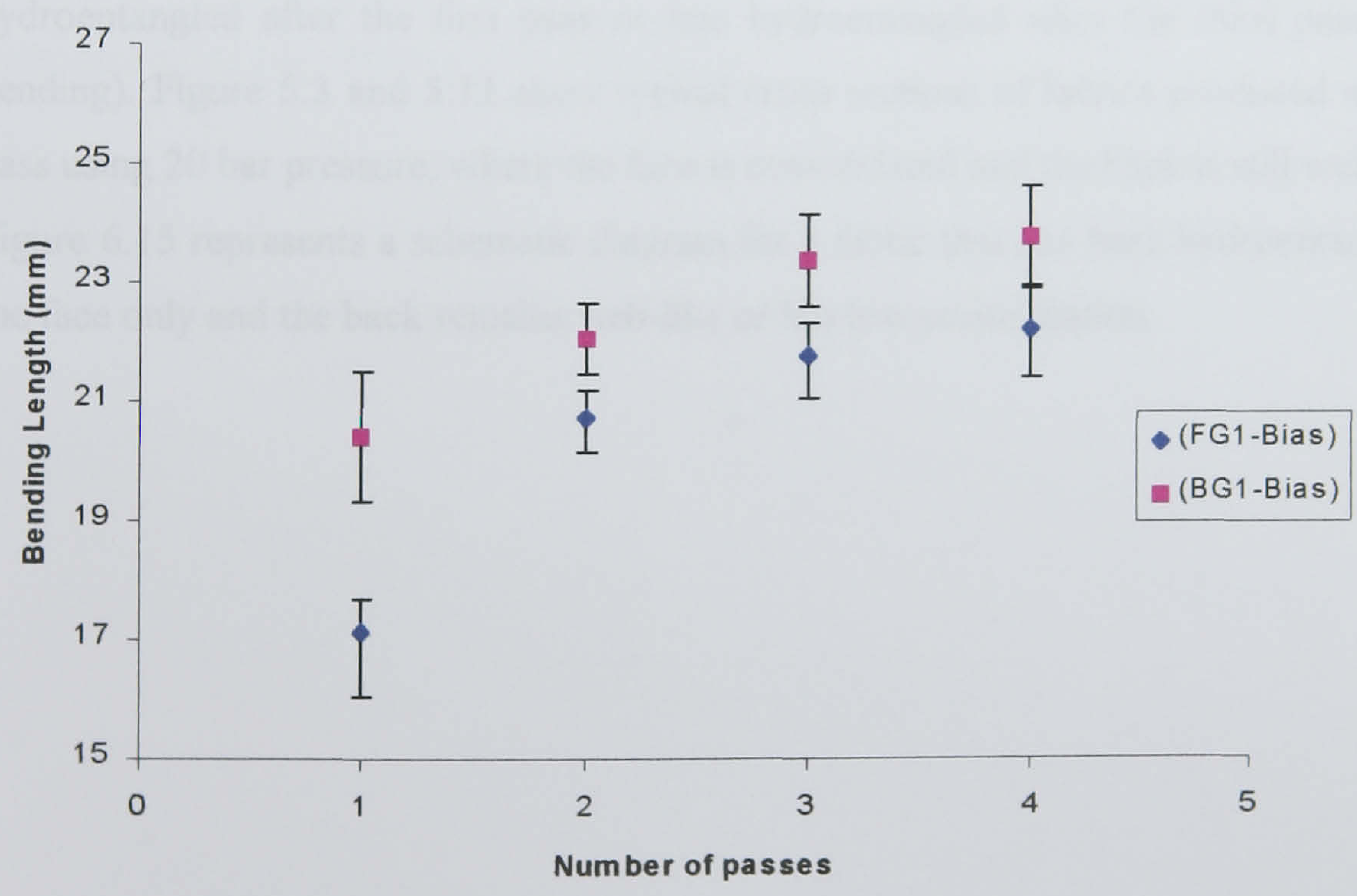


Figure 6.14 Effect of Number of Passes on Fabric Bending Length of Group 1 (Face and Back-Bias)

Key:

FG1-bias = face- group 1, tested in the bias direction

BG1-bias =back- group 1, tested in the bias direction

Figures 6.13 and 6.14 show the effect of the number of passes on the bending length of group 1 fabrics on the face and back in the CD and bias direction respectively.

From figures 6.12 -6.14, it is evident that similar trends are obtained for the face and back of the fabrics although there are differences in the absolute values. Similar general trends may be ascribed to the "balanced" jet profile sequence used to apply the energy to the web resulting in more uniformly treated fabrics. As a result, the difference between the bending length in the face and back is smaller after four injector passes than after the first injector pass especially in the CD and bias directions.

In general, it is noticeable that the bending length of the back of the fabric (the surface to which the water jets are applied after the face side) is generally higher than that obtained for the face. This can be considered in terms of extension of the face (which is hydroentangled) and compression of the back (the fabric layer which is not hydroentangled after the first pass or less hydroentangled after the third pass during bending). Figure 5.3 and 5.11 show typical cross sections of fabrics produced after one pass using 20 bar pressure, where the face is consolidated and the back is still web like. Figure 6.15 represents a schematic diagram for a fabric that has been hydroentangled on the face only and the back remains web-like or has low consolidation.

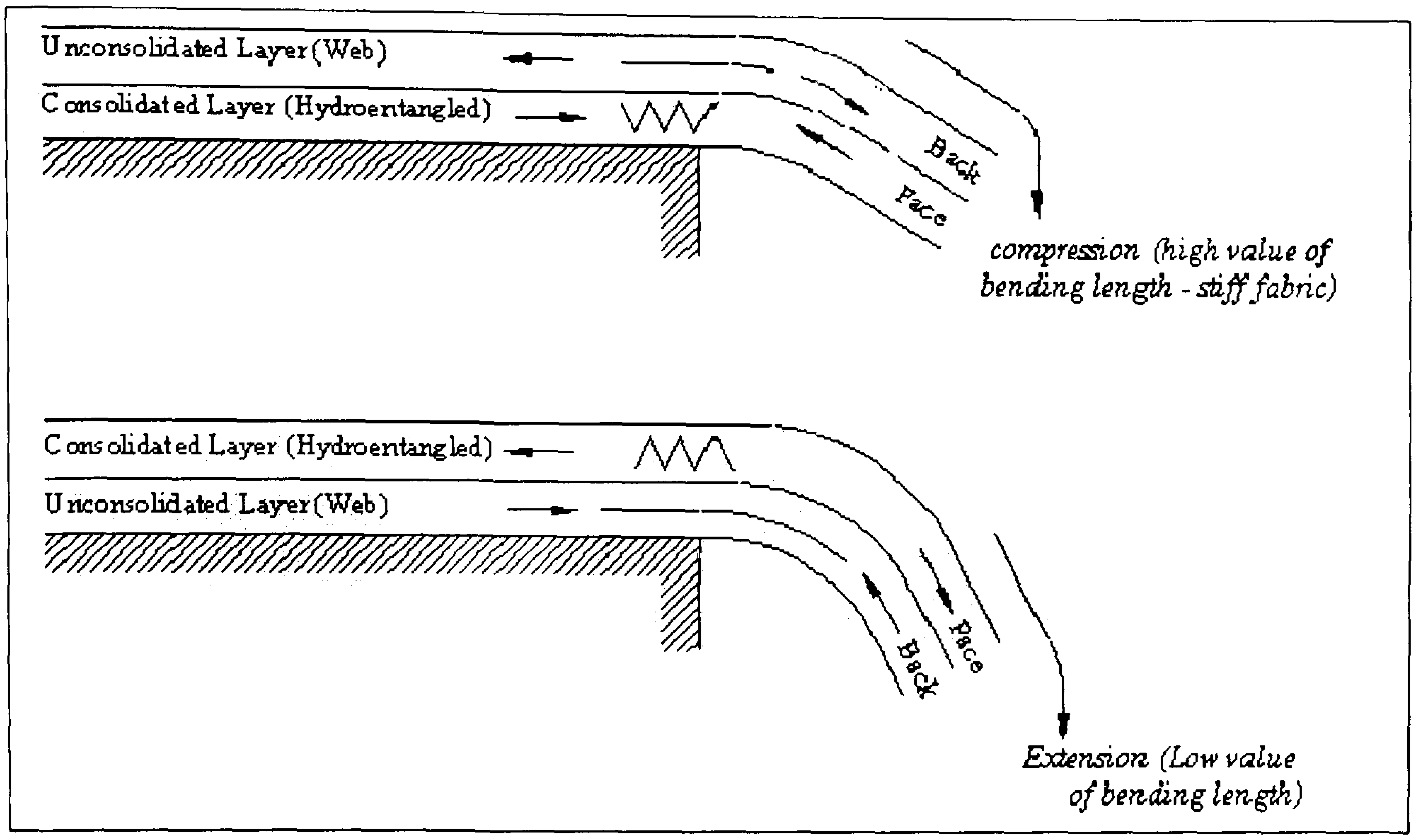
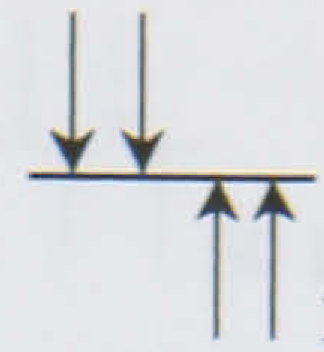


Figure 6.15 Schematic Diagram of Fabric Bending in Both Face and Back

With reference to figure 6.14, in practice, the bending behaviour will depend on the bending (extension) of the upper surface relative to the compression behaviour of the lower surface. From figure 6.15, it may be concluded that the surface that was hydroentangled first will always have the highest consolidation (and a lower bending length, if tested face up) compared with the reverse layer that is subsequently hydroentangled and remains in web-like form.



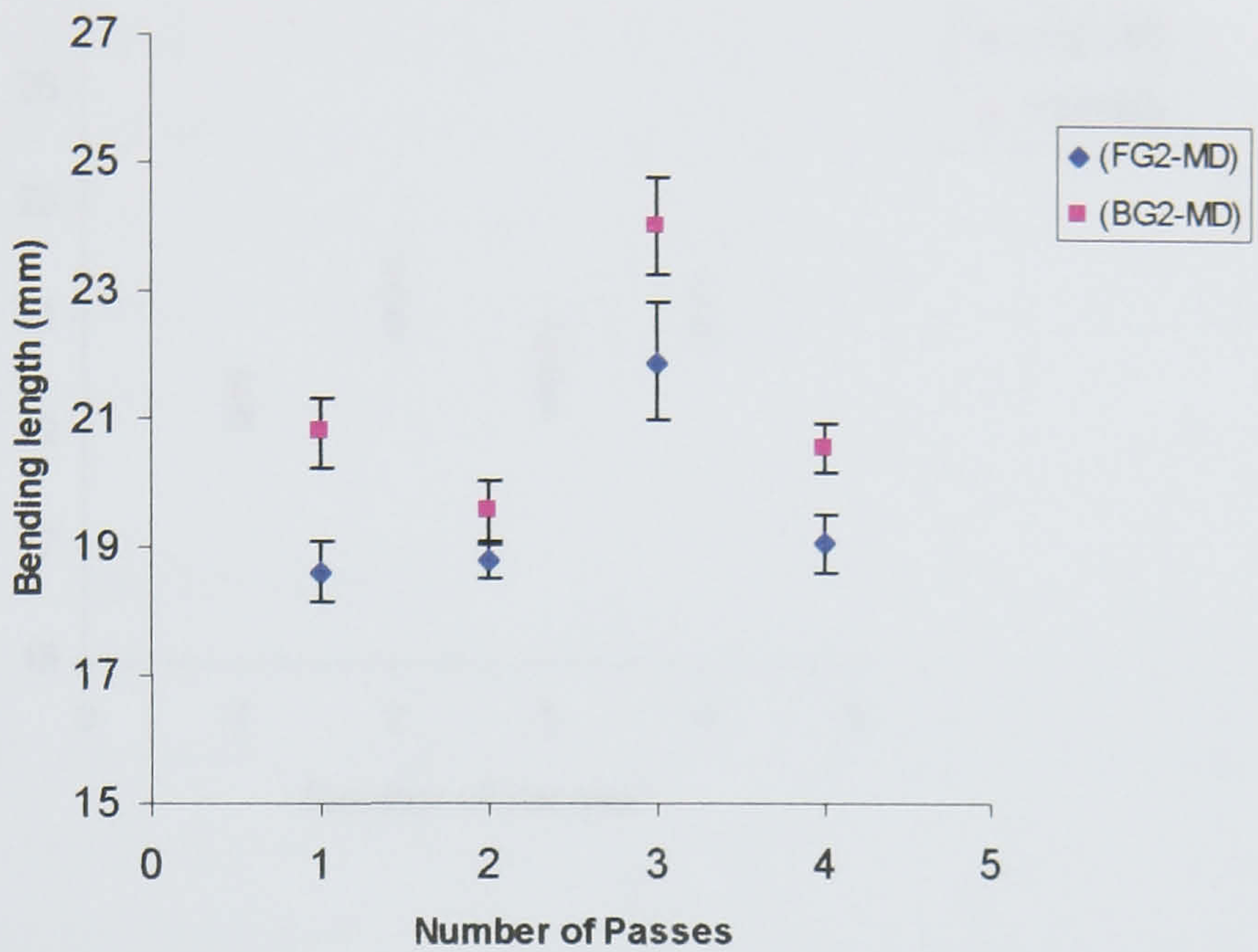


Figure 6.16 Effect of Number of Passes on Fabric Bending Length of Group 2 (Face and Back-MD)

Key:

FG2-MD = face- group 2, tested in the MD

BG2-MD =back- group 2, tested in the MD

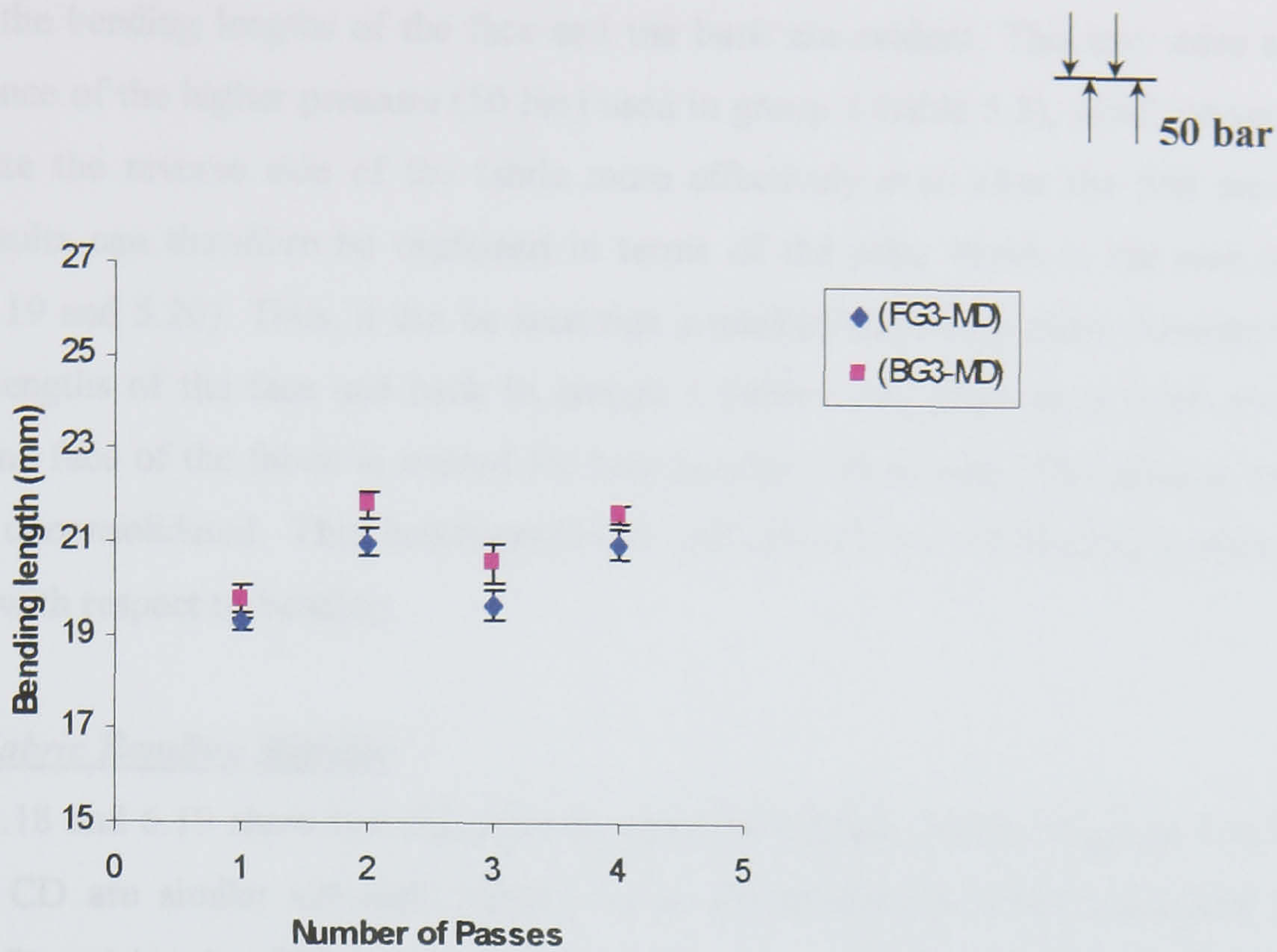


Figure 6.17 Effect of Number of Passes on Fabric Bending Length of Group 3 (Face and Back-MD)

Key:

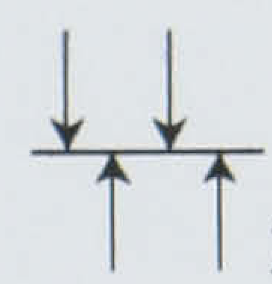
FG3-MD = face- group 2, tested in the MD

BG3-MD =back- group 2, tested in the MD

Figures 6.16 and 6.17 show the effect of the number of passes on the bending length of groups 2 and 3 in the face and back of the fabrics in the MD. Similar trends are obtained for both groups in the CD and bias directions. It is evident that almost similar trends are obtained for the face and back of the fabrics although there are differences in the absolute values. It is interesting to note the difference between the bending length of the face and the back of the fabrics in groups 1, 2 and 3. In figure 6.16, group 2, generally, there is a difference between the bending length for the face and back of the fabric even after the first pass (table 5.2). Similar results are obtained for group 1 (figure 6.12). These findings can be explained by considering the manner in which the energy is introduced to the web. This group (group 2) was produced with the first two passes on the face side only, which results in a change in the fabric structure mainly on the face because the low energy used (20 bar) results in little jet rebound (see figures 5.3, 5.5, 5.7 and 5.9). Such a low pressure is considered too low to affect the reverse side of the web[74,82]. In group 3 fabrics (figure 6.17), it is of interest to note that smaller differences between the bending lengths of the face and the back are evident. This may arise as a consequence of the higher pressure (50 bar) used in group 3 (table 5.3), which serves to consolidate the reverse side of the fabric more effectively even after the first pass[74]. These results can therefore be explained in terms of the pillar depth in the web (see figures 5.19 and 5.20). Thus, it can be seen that a marked difference exists between the bending lengths of the face and back in groups 1 (where low pressure is used) and 2 (where one face of the fabric is treated for two passes). The reverse side remains web-like and unconsolidated. This heterogeneity is reflected in the mechanical properties obtained with respect to bending.

6.3.4.2 Fabric Bending Rigidity

Figures 6.18 and 6.19 show that the general trends of bending rigidity of group 1 in the MD and CD are similar although differences in the anisotropy of the structures are clearly reflected by the differences in the absolute values. Similar trends are obtained for group 1 in the bias direction.



20 bar

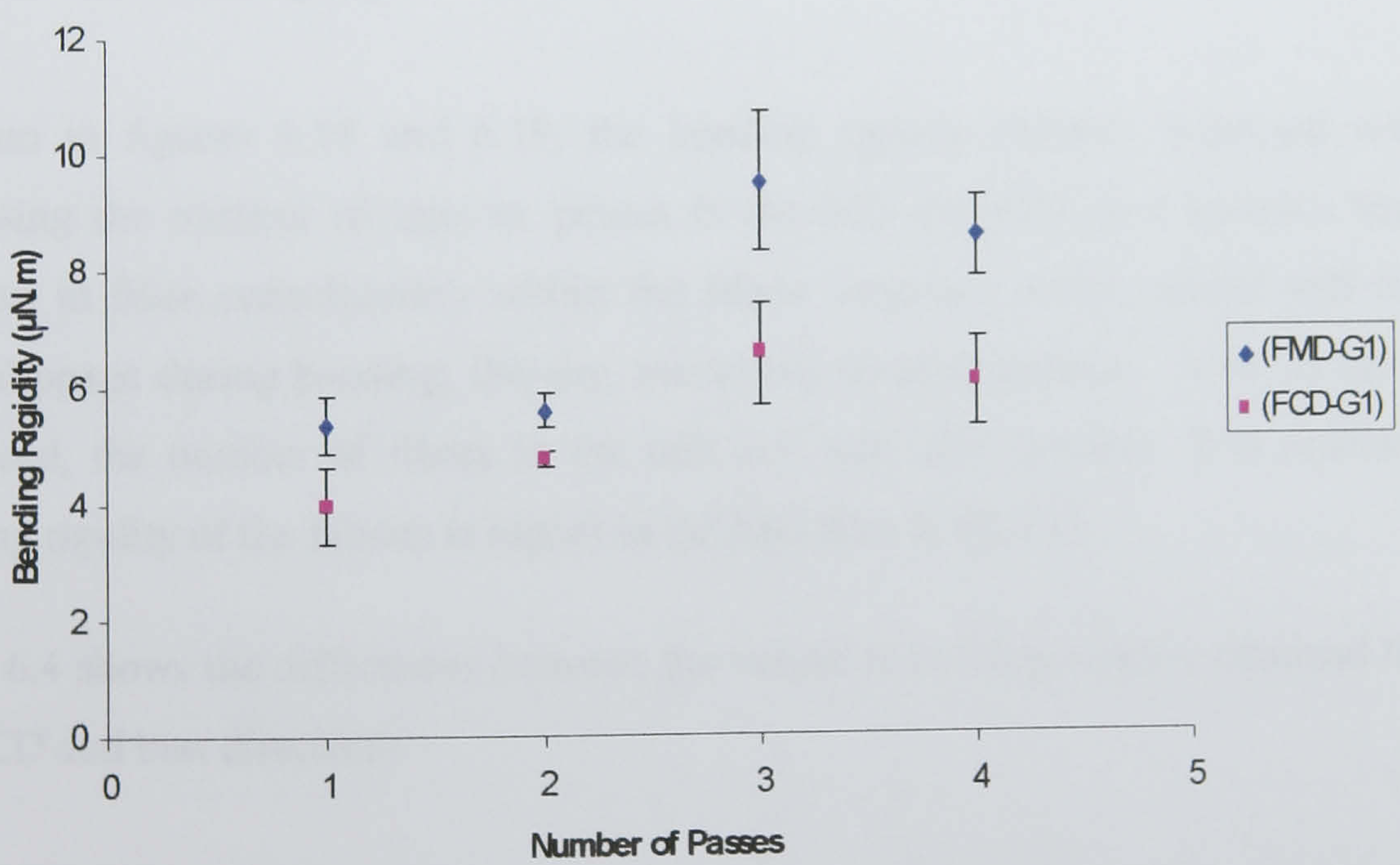


Figure 6.18 Effect of Number of Passes on Fabric Bending Rigidity of Group 1 in the MD and CD

Key:

FMD-G1= face- MD- group 1

FCD-G1= face- CD- group 1

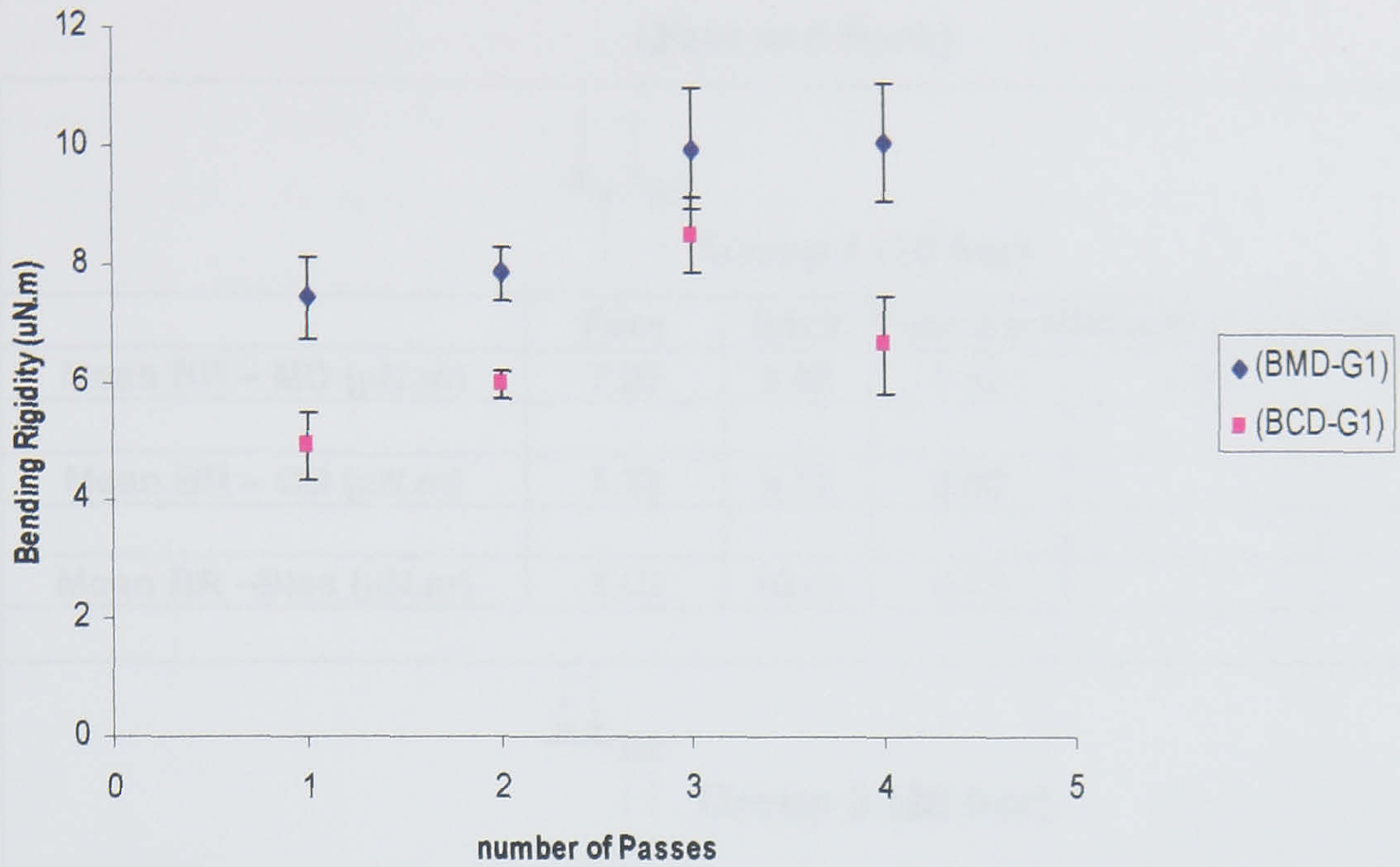


Figure 6.19 Effect of Number of Passes on Fabric Bending Rigidity of Group 1 in the MD and CD

Key:

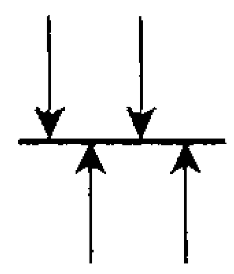
BMD-G1= back- MD- group 1

BCD-G1= back- CD- group 1

As seen in figures 6.18 and 6.19, the bending rigidity initially increased with an increasing the number of injector passes in the MD and CD. It is possible that the increase in fibre consolidation within the fabric structure, which occurs will restrict fibre slippage during bending, thereby, increasing bending rigidity. Also, as has been discussed, the number of fibres in the unit cell will also increase. It is evident that bending rigidity of the fabrics is higher in the MD than in the CD.

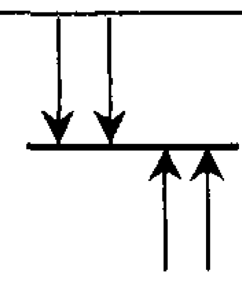
Table 6.4 shows the differences between the values of bending rigidity obtained for the MD, CD and bias directions.

Table 6.4: MD/CD of Bending Rigidity for Groups 1, 2 and 3 (Face and Back)



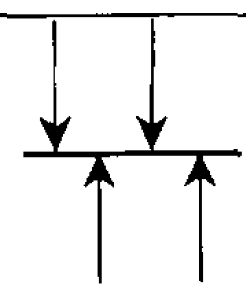
Group 1 (20 bar)

	Face	Back	Face/Back	MD/CD (Face)	MD/CD (Back)
Mean BR – MD (μN.m)	7.26	8.86	0.82	1.36	1.36
Mean BR – CD (μN.m)	5.33	6.52	0.82		
Mean BR –Bias (μN.m)	8.02	10.41	0.77		



Group 2 (20 bar)

	Face	Back	Face/Back	MD/CD (Face)	MD/CD (Back)
Mean BR – MD (μN.m)	6.67	8.50	0.79	1.42	1.52
Mean BR – CD (μN.m)	4.70	5.60	0.84		
Mean BR –Bias (μN.m)	5.68	7.48	0.76		



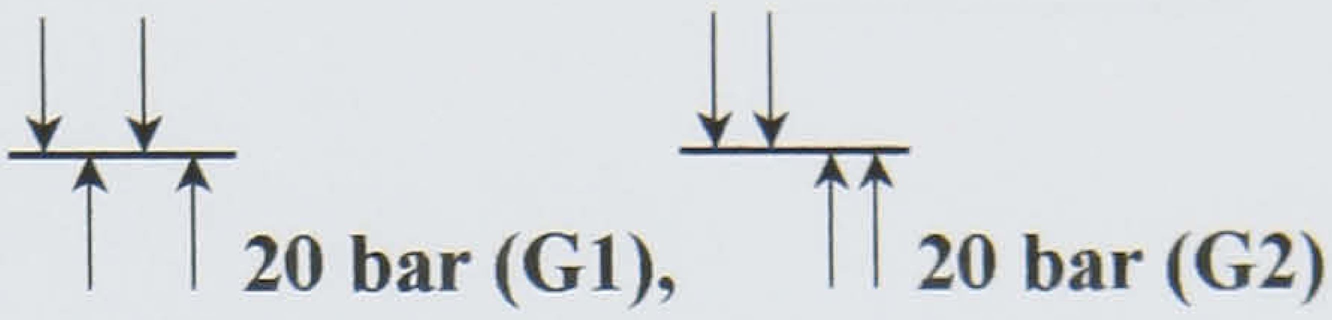
Group 3 (50 bar)

	Face	Back	Face/Back	MD/CD (Face)	MD/CD (Back)
Mean BR – MD (μN.m)	6.76	7.06	0.96	1.26	1.27
Mean BR – CD (μN.m)	5.36	5.55	0.97		
Mean BR –Bias (μN.m)	5.86	6.07	0.96		

From table 6.4, it is noticeable that the bending rigidity of the back of the fabric is always higher than the face for groups 1, 2 and 3 respectively and as a result, the ratio of the face/back bending rigidity is always lower than 1. Also, the bending rigidity of the fabrics in the MD is higher than the CD and as a result, the MD/CD ratio of bending rigidity is always higher than 1. It is of interest to notice that group 2 has the highest MD/CD ratio (anisotropy) compared to the other two groups, where the energy is applied using alternate face and back injectors.

6.3.4.3 Fabric Bending Modulus

Figures 6.20 – 6.23 show the effect of increasing the number of passes on the bending modulus of the hydroentangled fabrics using different injector profiles. Similar trends are obtained for the face and back of the fabrics in the MD, CD and bias directions. It is evident that increasing the number of passes results in a general increase in fabric bending modulus up to a maximum.



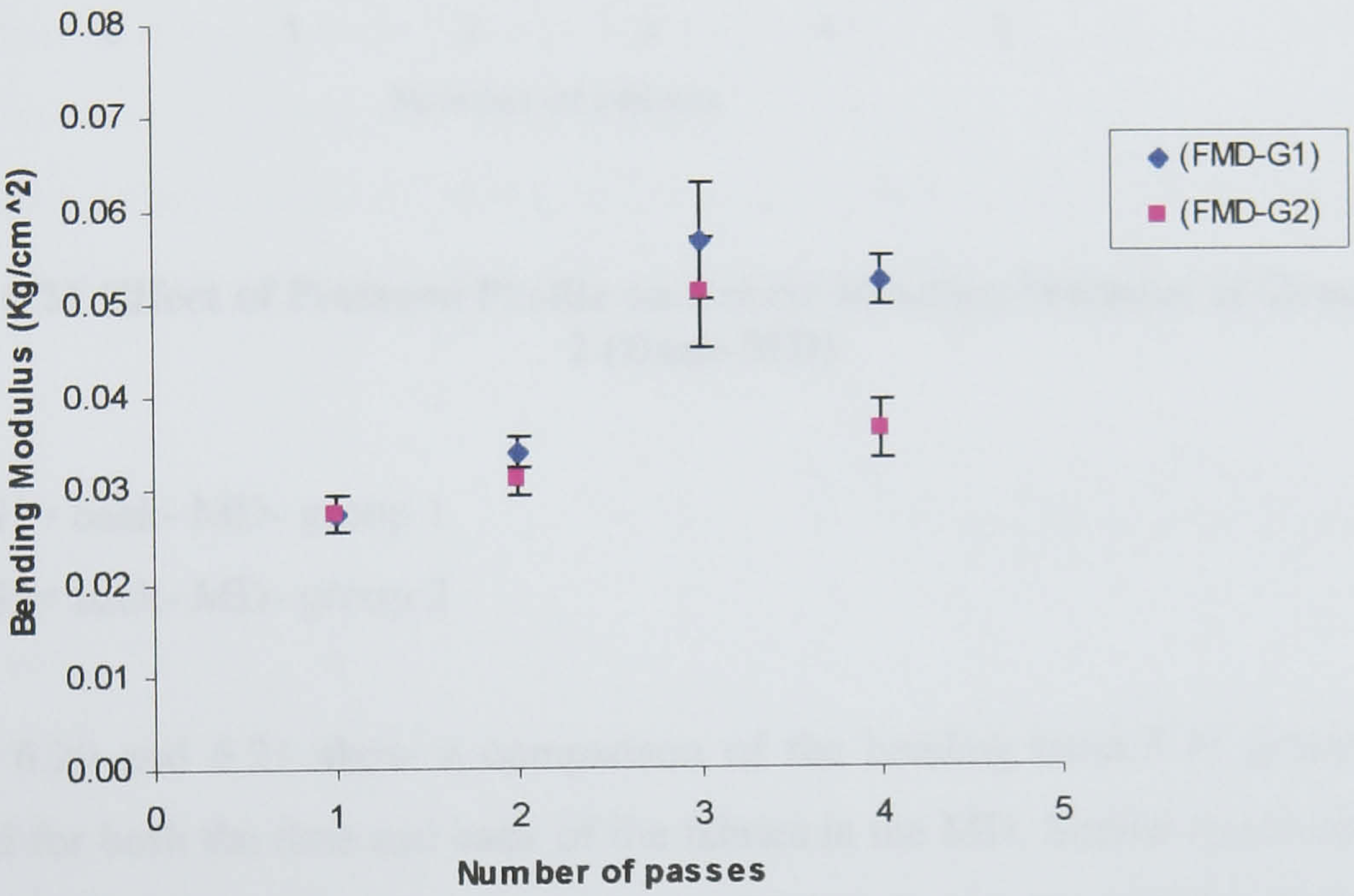


Figure 6.20 Effect of Pressure Profile on Fabric Bending Modulus of Groups 1 and 2 (Face-MD)

Key:

FMD-G1= face- MD- group 1

FMD-G2= face- MD- group 2

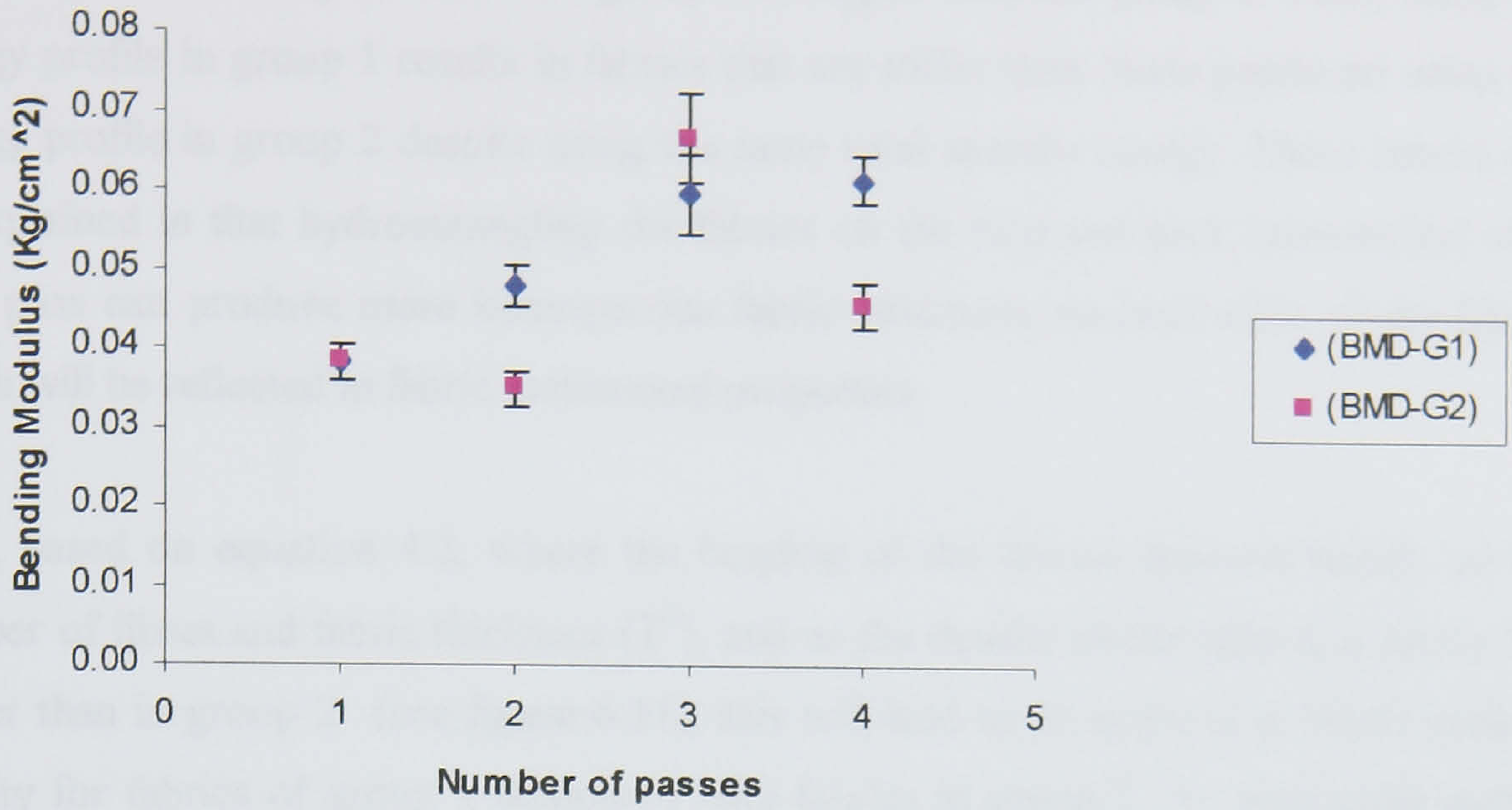


Figure 6.21 Effect of Pressure Profile on Fabric Bending Modulus of Groups 1 and 2 (Back-MD)

Key:

BMD-G1= back- MD- group 1

BMD-G2= back- MD- group 2

Figures 6.20 and 6.21 show a comparison of the bending moduli of groups 1 and 2 obtained for both the face and back of the fabrics in the MD. Similar trends are obtained in the CD and bias direction. In group 1 fabrics, it can be noticed that there is a consistent increase in the fabric bending modulus up to the third injector pass. This can be explained as a result of the manner of applying the energy and the low pressure used (20 bar). This can be noticed from the fabric cross-sections after each injector pass (figures 5.11, 5.13, 5.15 and 5.17).

On the other hand, in group 2 fabrics, no marked changes in the bending modulus of the fabrics after the second pass are observed (especially for the back). Whereas, a marked increase in the bending modulus occurred after the third pass when the fabric is treated from the reverse side for both the face and back of the fabric. This can also be explained as a result of applying the energy on one side for two passes, which will result in softening the fabric (decrease the resistance of the bottom layer to bending – see figure 6.15). As a result, in group 2 fabrics, a slight increase or no increase in bending modulus takes place after the second injector pass.

Generally, the bending modulus for group 1 is higher than for group 2. Thus, using the energy profile in group 1 results in fabrics that are stiffer than those produced using the energy profile in group 2 despite using the same total specific energy. These results can be explained in that hydroentangling the fabrics on the face and back (alternately) after each pass can produce more homogenous fabric structures on both sides of the fabric, which will be reflected in fabric mechanical properties.

Also, based on equation 4.2, where the bending of the fabrics depends mainly on the number of fibres and fabric thickness (T^2), and as the density of the fabrics in group 1 is higher than in group 2 (see figure 6.11), this will lead to an increase in fabric packing density for fabrics of group 1 compared with fabrics in group 2. As mentioned earlier, the bending behaviour of the fabrics will depend mainly on the relationship between N (number of fibres in the unit cell) and T^2 (fabric thickness) in equation 4.2.

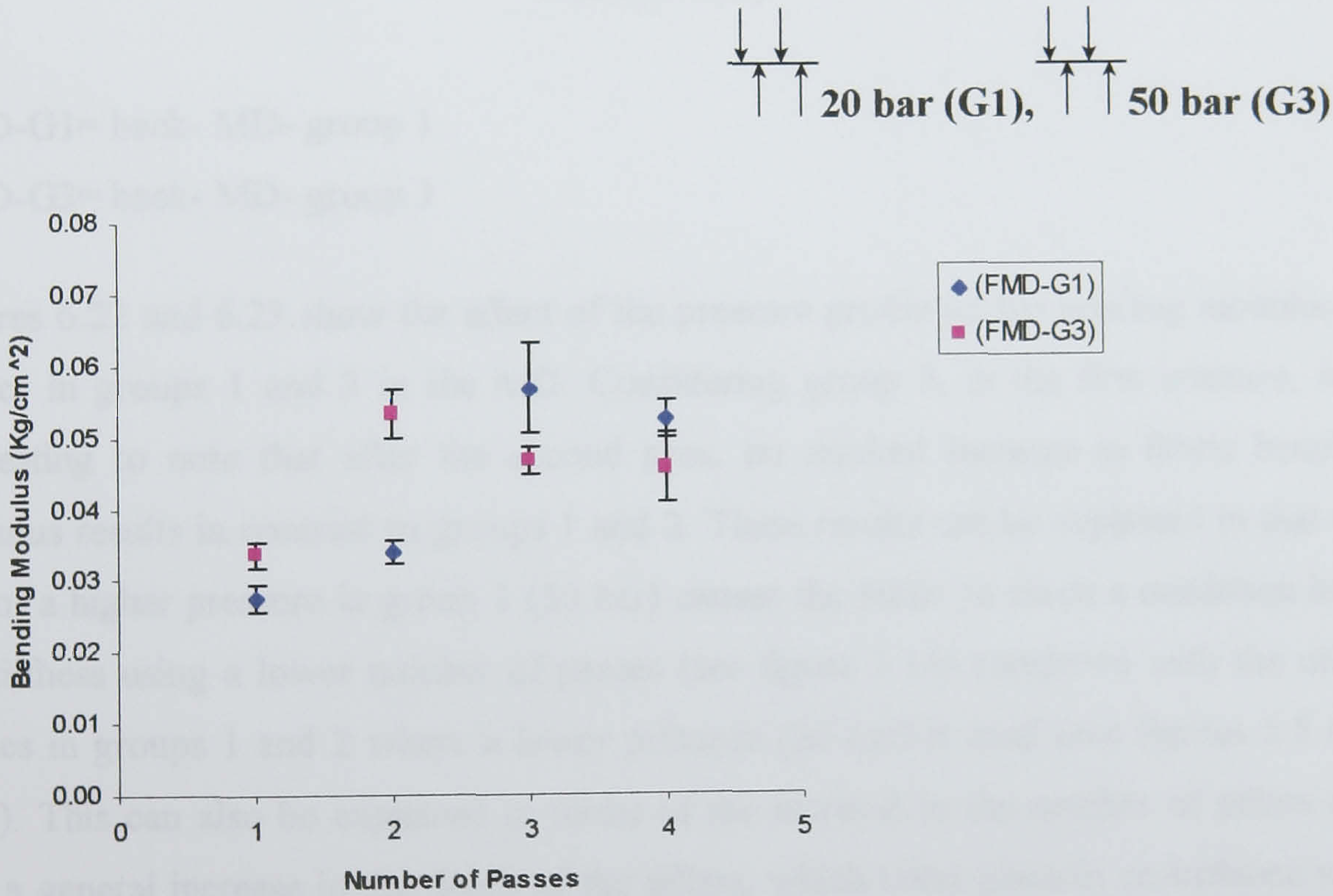


Figure 6.22 Effect of Pressure Profile on Fabric Bending Modulus of Groups 1 and 3 (Face-MD)

Key:

FMD-G1= face- MD- group 1

FMD-G3= face- MD- group 3

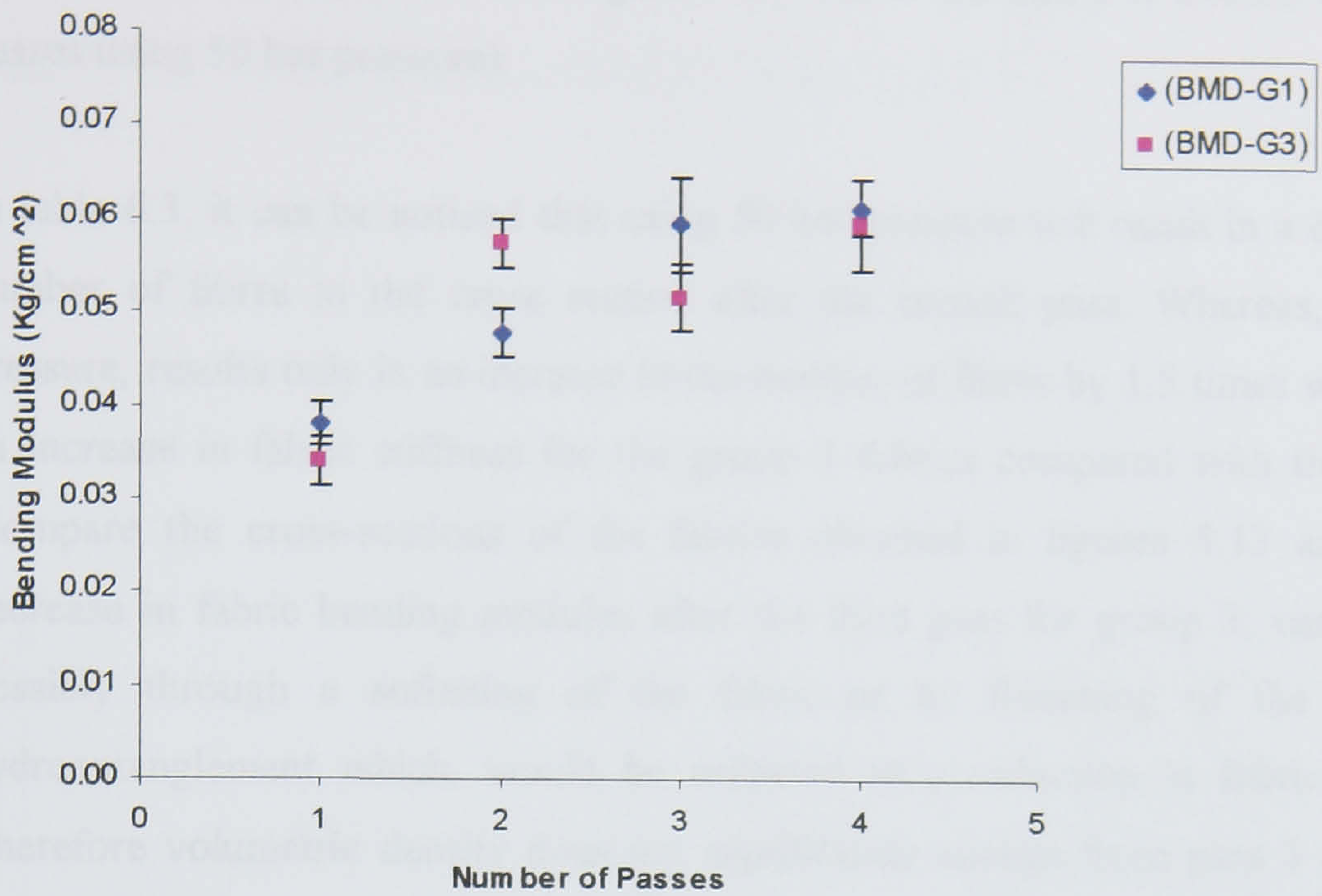


Figure 6.23 Effect of Pressure Profile on Fabric Bending Modulus of Groups 1 and 3 (Back-MD)

Key:

BMD-G1= back- MD- group 1

BMD-G3= back- MD- group 3

Figures 6.22 and 6.23 show the effect of the pressure profile on the bending modulus of fabrics in groups 1 and 3 in the MD. Considering group 3, in the first instance, it is interesting to note that after the second pass, no marked increase in fabric bending modulus results in contrast to groups 1 and 2. These results can be explained in that the use of a higher pressure in group 3 (50 bar) causes the fabric to reach a maximum level of stiffness using a lower number of passes (see figure 5.14) compared with the other fabrics in groups 1 and 2 where a lower pressure (20 bar) is used (see figures 5.5 and 5.13). This can also be explained in terms of the increase in the number of pillars and also a general increase in the depth of the pillars, which takes place in accordance with the increase in pressure applied (50 bar), using the same manner of applying the energy (see figures 5.19 and 5.20). On the other hand, increasing the total specific energy (1.156 MJ/Kg) will lead to a decrease in fabric thickness compared to fabrics produced with lower specific energy (0.296 MJ/Kg) which, will result in producing more compact (see figures 6.8 and 6.9) and stiff fabrics after the second pass. As a result, it can be concluded that increasing the energy applied will lead to an increase in the stiffness of the fabrics up to 2 passes and will produce fabrics of this area density with cross sections that are chain-like (see figure 5.14 where the fabric is treated with 2 injector passes using 50 bar pressure).

In table 6.3, it can be noticed that using 50 bar pressure will result in a doubling of the number of fibres in the cross section after the second pass. Whereas, using 20 bar pressure, results only in an increase in the number of fibres by 1.5 times which results in an increase in fabric stiffness for the group 3 fabrics compared with the group 1 set (compare the cross-sections of the fabrics obtained in figures 5.13 and 5.14). The decrease in fabric bending modulus after the third pass for group 3, can be explained possibly through a softening of the fabric or by flattening of the fabric during hydroentanglement which, would be reflected in a reduction in fabric area density. Therefore volumetric density does not significantly change from pass 3 to pass 4 (see figure 6.11).

6.3.5 Fabric Extension

6.3.5.1 Fabric Extension at 5, 20 and 100 gf/cm in the MD

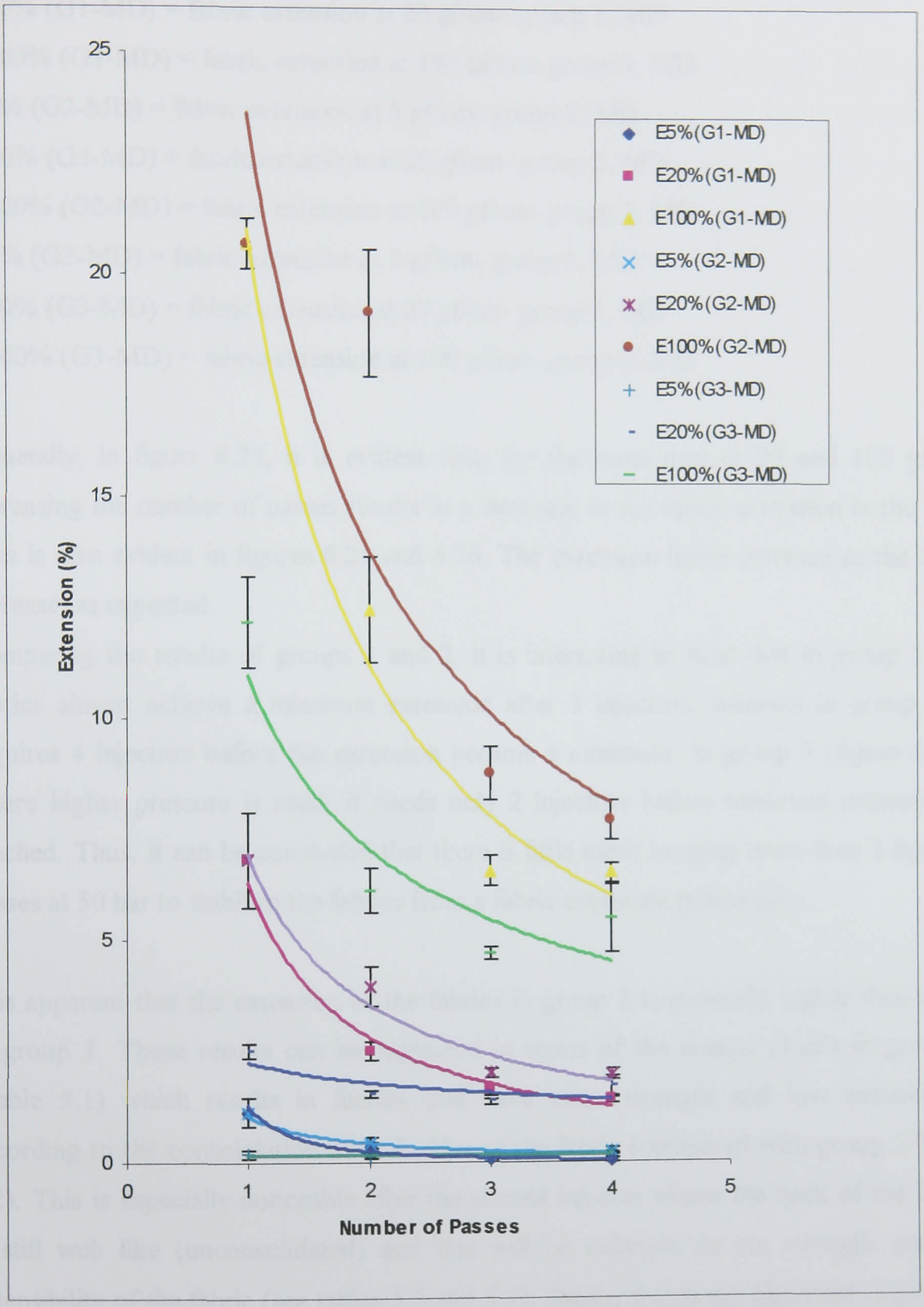


Figure 6.24 Effect of Pressure Profile on Fabric Extension at 5, 20 and 100 gf/cm in the MD For Groups 1, 2 and 3

Key:

E5% (G1-MD) = fabric extension at 5 gf/cm- group 1, MD

E20% (G1-MD) = fabric extension at 20 gf/cm- group 1, MD

E100% (G1-MD) = fabric extension at 100 gf/cm- group 1, MD

E5% (G2-MD) = fabric extension at 5 gf/cm- group 2, MD

E20% (G2-MD) = fabric extension at 20 gf/cm- group 2, MD

E100% (G2-MD) = fabric extension at 100 gf/cm- group 2, MD

E5% (G3-MD) = fabric extension at 5 gf/cm- group 3, MD

E20% (G3-MD) = fabric extension at 20 gf/cm- group 3, MD

E100% (G3-MD) = fabric extension at 100 gf/cm- group 3, MD

Generally, in figure 6.24, it is evident that, for the most part at 20 and 100 gf/cm, increasing the number of passes results in a decrease in the fabric extension in the MD. This is also evident in figures 6.25 and 6.26. The extension levels increase as the loads increase, as expected.

Comparing the results of groups 1 and 2, it is interesting to note that in group 1, the fabrics almost achieve a minimum extension after 3 injectors, whereas in group 2, it requires 4 injectors before the extension became a minimum. In group 3 (figure 6.24), where higher pressure is used, it needs only 2 injectors before minimum extension is reached. Thus, it can be concluded that there is little merit in using more than 2 injector passes at 50 bar to stabilize the fabrics from a fabric extension perspective.

It is apparent that the extension of the fabrics in group 2 is generally higher than those in group 1. These results can be explained in terms of the energy profile in group 1 (Table 5.1) which results in fabrics that have more strength and low extensibility according to the consolidation of both sides of the fabric (compared with group 2-Table 5.2). This is especially noticeable after the second injector where the back of the fabric is still web like (unconsolidated) and this will be reflected in the strength and the extensibility of the fabric (see tables 5.5 and 5.7). Similar trends are observed in group 3 to that of group 1 and 2, but with variation in the form of the curves.

Also, from figure 6.24, compared to groups 1 and 2, it can be noticed that in group 3, a larger initial decrease in the fabric extension occurs after the first injector, this may be explained in terms of the higher pressure used in group 3 (50 bar) as compared to groups 1 and 2, which will tend to lead to greater structural consolidation.

Figure 6.24 also shows a decrease in fabric extension at a load of 100 gf/cm as the number of passes increase. Similar trends to those obtained for the fabric extension at loads of 5 and 20 gf/cm are obtained with different curve gradients. In this case, the group 3 fabrics were the least extensible followed by group 1 then group 2 fabrics for the MD, CD and bias directions. These results reflect the differences in the applied load during extension testing.

6.3.5.2 Fabric Extension at 5, 20 and 100 gf/cm in the CD

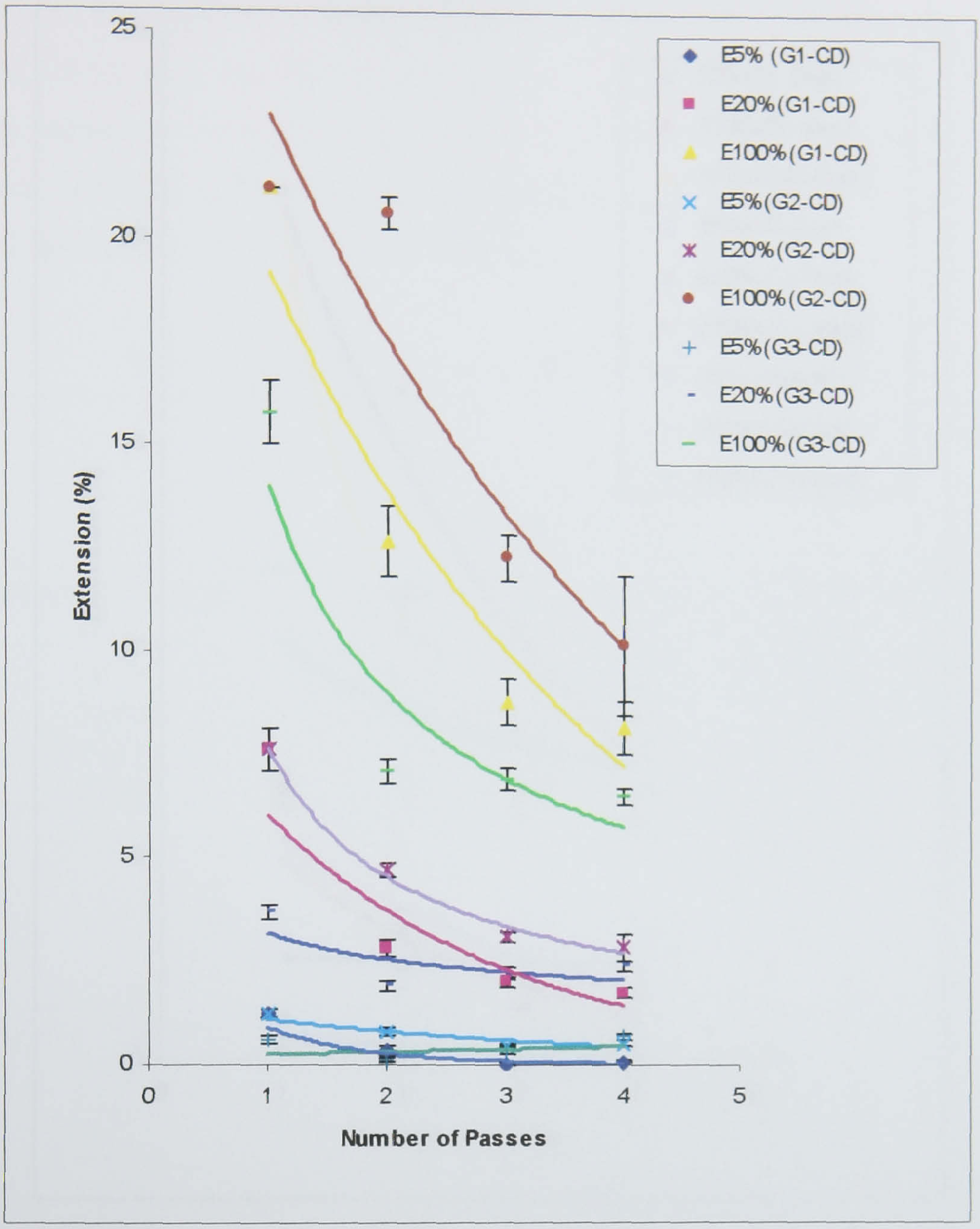


Figure 6.25 Effect of Pressure Profile on Fabric Extension at 5, 20 and 100 gf/cm in the CD For Groups 1,2 and 3

Key:

E5% (G1-CD) = fabric extension at 5 gf/cm- group 1, CD

E20% (G1-CD) = fabric extension at 20 gf/cm- group 1, CD

E100% (G1-CD) = fabric extension at 100 gf/cm- group 1, CD

E5% (G2-CD) = fabric extension at 5 gf/cm- group 2, CD

E20% (G2-CD) = fabric extension at 20 gf/cm- group 2, CD

E100% (G2-CD) = fabric extension at 100 gf/cm- group 2, CD

E5% (G3-CD) = fabric extension at 5 gf/cm- group 3, CD

E20% (G3-CD) = fabric extension at 20 gf/cm- group 3, CD

E100% (G3-CD) = fabric extension at 100 gf/cm- group 3, CD

6.3.5.3 Fabric Extension at 5, 20 and 100 gf/cm in the Bias Direction

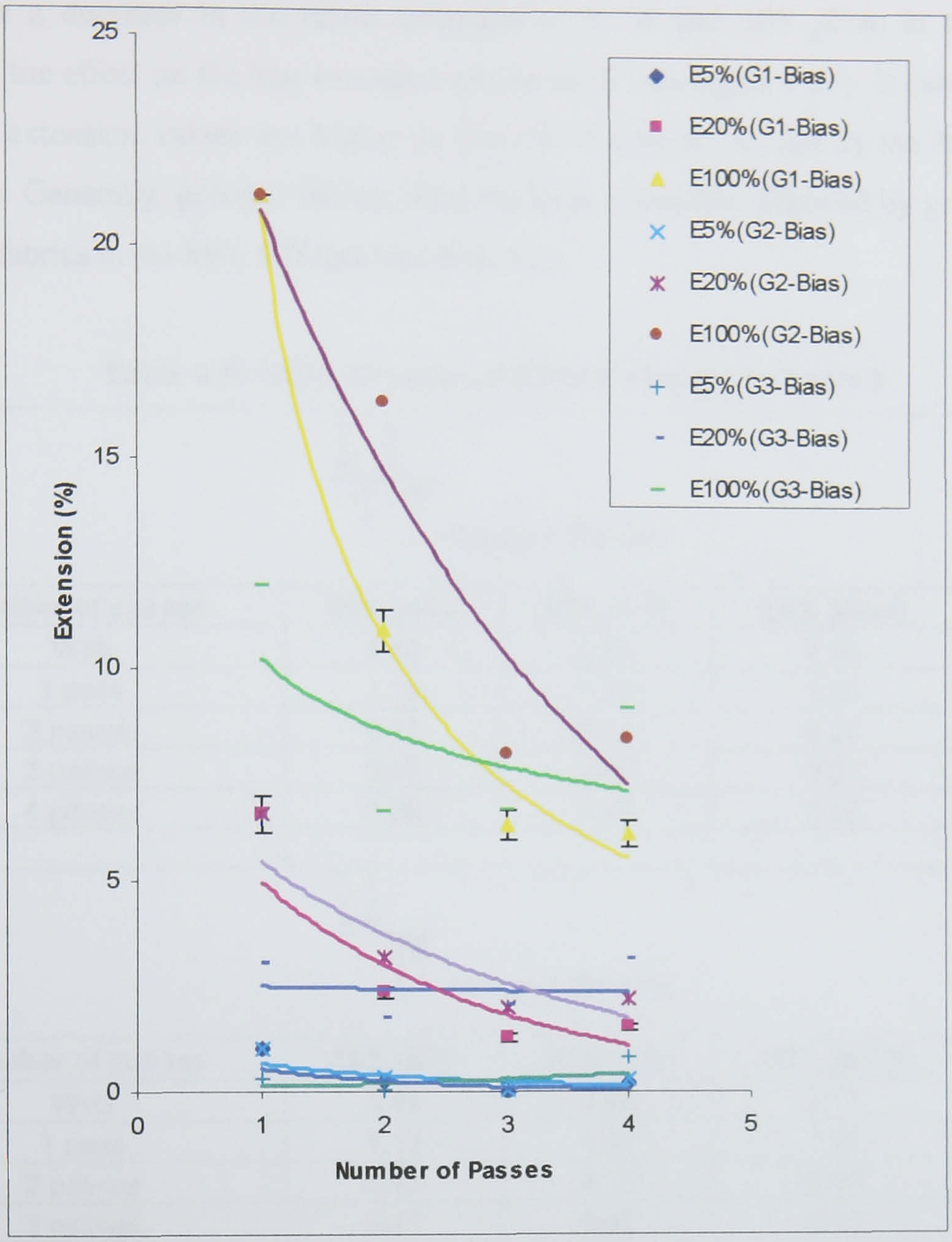


Figure 6.26 Effect of Pressure Profile on Fabric Extension at 5, 20 and 100 gf/cm in the Bias Direction For Groups 1,2 and 3

Key:

E5% (G1-bias) = fabric extension at 5 gf/cm- group 1, bias

E20% (G1-bias) = fabric extension at 20 gf/cm- group 1, bias

E100% (G1-bias) = fabric extension at 100 gf/cm- group 1, bias

E5% (G2-bias) = fabric extension at 5 gf/cm- group 2, bias

E20% (G2-bias) = fabric extension at 20 gf/cm- group 2, bias

E100% (G2-bias) = fabric extension at 100 gf/cm- group 2, bias

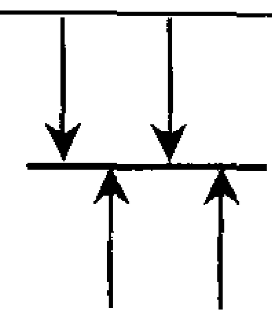
E5% (G3-bias) = fabric extension at 5 gf/cm- group 3, bias

E20% (G3-bias) = fabric extension at 20 gf/cm- group 3, bias

E100% (G3-bias) = fabric extension at 100 gf/cm- group 3, bias

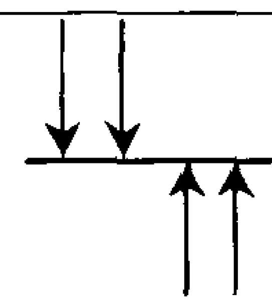
In figures 6.25 and 6.26, generally, it is evident that increasing the number of passes results in a decrease in the fabric extension at 5, 20 and 100 gf/cm in the CD. In contrast, the effect on the bias extension can be small (see figure 6.26). It can be noticed that the extension values are higher in the CD compared to that in the MD or bias direction. Generally, group 3 fabrics were the least extensible followed by group 1 then group 2 fabrics in the MD, CD and bias directions.

Table 6.5: MD/CD ratios of E5%of Groups 1, 2 and 3



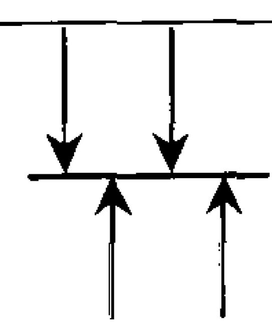
Group 1 (20 bar)

Number of passes	E5% (MD)	E5% (CD)	E5% (Bias)	MD/CD
Web	5.42	3.08	4.05	1.76
1 pass	1.13	1.22	1.05	0.93
2 passes	0.35	0.33	0.25	1.05
3 passes	0.07	0.02	0.07	4.00
4 passes	0.05	0.05	0.20	1.00



Group 2 (20 bar)

Number of passes	E5% (MD)	E5% (CD)	E5% (Bias)	MD/CD
Web	5.42	3.08	4.05	1.76
1 pass	1.13	1.22	1.05	0.93
2 passes	0.43	0.77	0.37	0.57
3 passes	0.17	0.45	0.19	0.37
4 passes	0.25	0.52	0.28	0.48



Group 3 (50 bar)

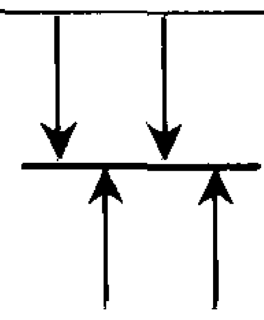
Number of passes	E5% (MD)	E5% (CD)	E5% (Bias)	MD/CD
Web	5.42	3.08	4.05	1.76
1 pass	0.20	0.58	0.30	0.34
2 passes	0.13	0.08	0.07	1.60
3 passes	0.13	0.35	0.10	0.38
4 passes	0.26	0.68	0.80	0.38

These results tend to suggest a decrease in the anisotropy of the hydroentangled fabrics after several injectors. Table 6.5 gives the values of extension at load of 5 gf/cm in the MD, CD and Bias directions and the MD/CD ratios for groups 1, 2 and 3 respectively.

These results indicate that the hydroentangled fabrics are generally more isotropic than the original cross-laid webs in terms of fabric extension.

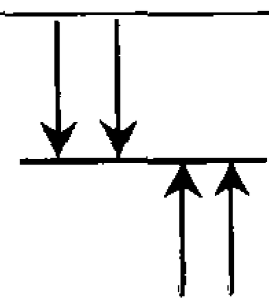
Table 6.6 gives the values of extension at load of 20 gf/cm in the MD, CD and Bias directions and the MD/CD ratios for groups 1, 2 and 3 respectively.

Table 6.6: MD/CD ratios of E20% of Groups 1, 2 and 3.



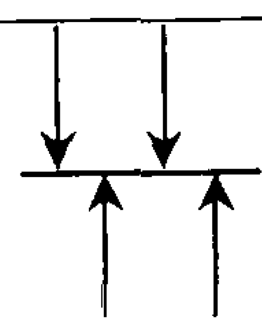
Group 1 (20 bar)

Number of passes	E20% (MD)	E20% (CD)	E20% (Bias)	MD/CD
Web	**	**	***	
1 pass	6.80	7.62	6.57	0.89
2 passes	2.50	2.80	2.35	0.89
3 passes	1.62	2.00	1.27	0.81
4 passes	1.42	1.73	1.52	0.82



Group 2 (20 bar)

Number of passes	E20% (MD)	E20% (CD)	E20% (Bias)	MD/CD
web	**	**	**	
1 pass	6.80	7.62	6.57	0.89
2 passes	3.95	4.70	3.17	0.84
3 passes	2.00	3.08	2.00	0.65
4 passes	1.98	2.83	2.20	0.70



Group 3 (50 bar)

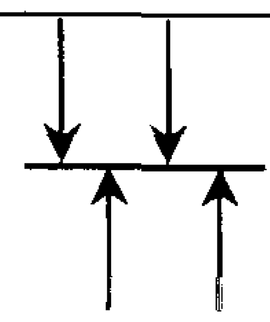
Number of passes	E20% (MD)	E20% (CD)	E20% (Bias)	MD/CD
Web	**	**	**	
1 pass	2.50	3.67	3.03	0.68
2 passes	1.53	1.90	1.75	0.81
3 passes	1.37	2.22	2.05	0.62
4 passes	1.68	2.40	3.13	0.70

**Maximum values obtained by FAST extension instrument

In table 6.6, the MD/CD ratio of the web after hydroentanglement, shows no clear evidence of change in the ratio.

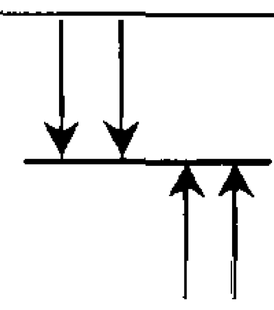
Table 6.7 gives the values of extension at load of 100 gf/cm in the MD. CD and Bias directions and the MD/CD ratios for groups 1, 2 and 3 respectively.

Table 6.7: MD/CD ratios of E100% of Groups 1, 2 and 3.



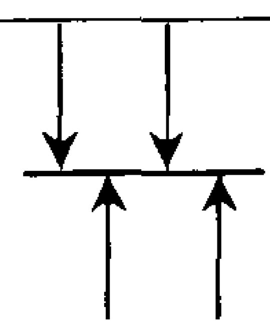
Group 1 (20 bar)

Number of passes	E100% (MD)	E100% (CD)	E100% (Bias)	MD/CD
Web	**	**	**	
1 pass	**	**	**	
2 passes	12.43	12.67	10.92	0.98
3 passes	6.55	8.78	6.32	0.75
4 passes	6.52	8.15	6.12	0.80



Group 2 (20 bar)

Number of passes	E100% (MD)	E100% (CD)	E100% (Bias)	MD/CD
Web	**	**	**	
1 pass	**	**	**	
2 passes	19.13	20.63	16.32	0.93
3 passes	8.75	12.28	8.03	0.71
4 passes	7.70	10.17	8.37	0.76



Group 3 (50 bar)

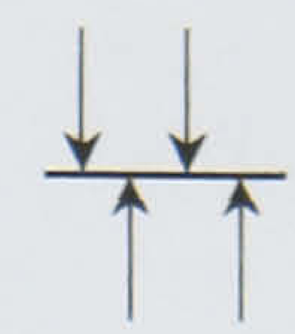
Number of passes	E100% (MD)	E100% (CD)	E100% (Bias)	MD/CD
Web	**	**	**	
1 pass	12.15	15.77	11.98	0.77
2 passes	6.10	7.08	6.62	0.86
3 passes	4.68	6.90	6.65	0.68
4 passes	5.48	6.50	9.08	0.84

**Maximum values obtained by FAST extension instrument

These results of MD/CD ratios of groups 1, 2 and 3 are shown in table 6.7. Similar results are obtained as in table 6.6.

6.3.6 Fabric Formability

Generally, figures 6.27-6.32 show that increasing the number of passes results in decreasing formability for both the face and back of the fabric. Similar trends are evident for both the face and back in the three directions (MD, CD and Bias direction) for all groups (1, 2 and 3).



20 bar (G1)

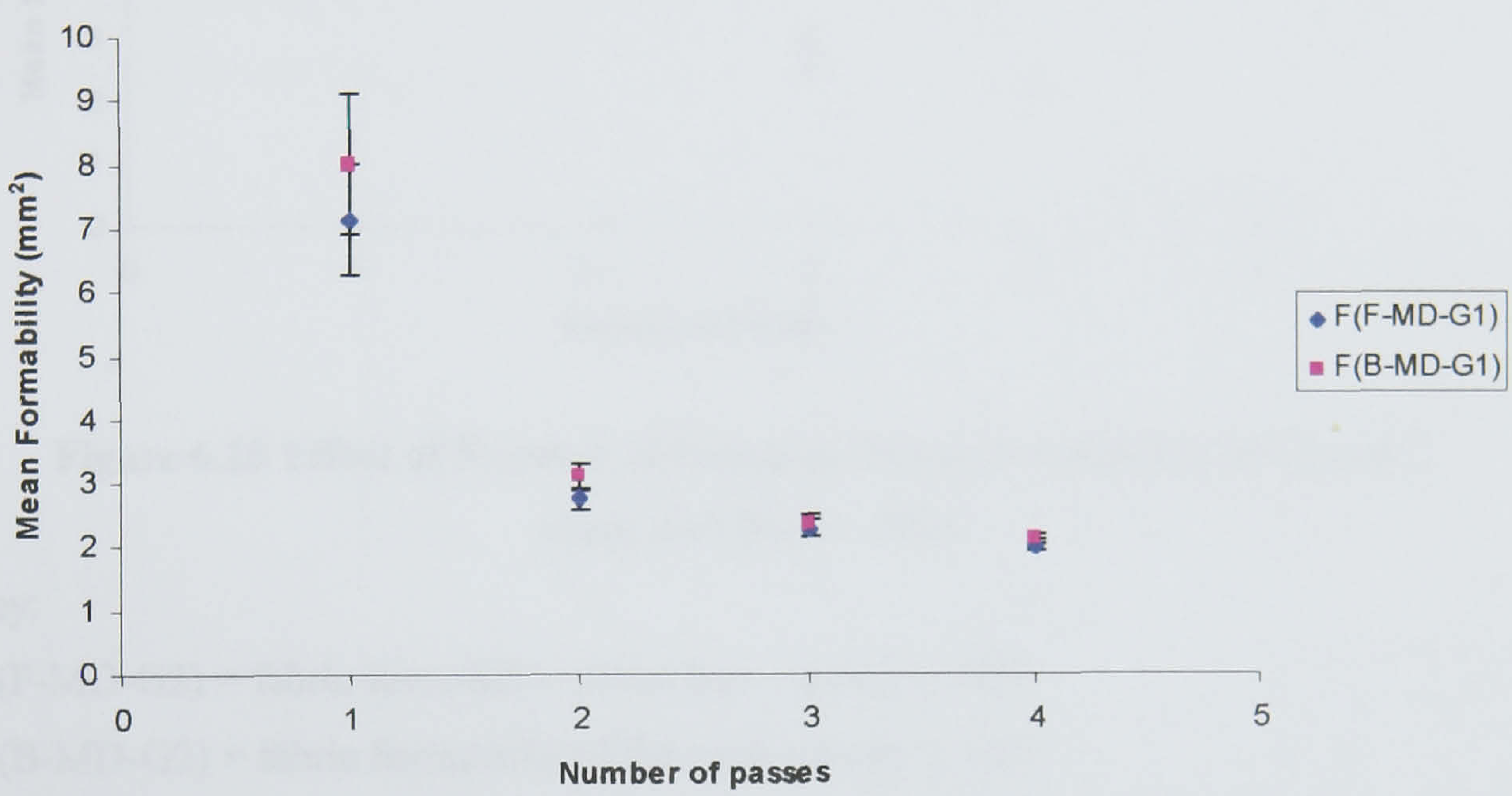


Figure 6.27 Effect of Number of Passes on Fabric Formability of Group 1 (Face and Back - MD)

Key:

F (F-MD-G1) = fabric formability of the face – group 1, MD

F (B-MD-G1) = fabric formability of the back– group 1, MD

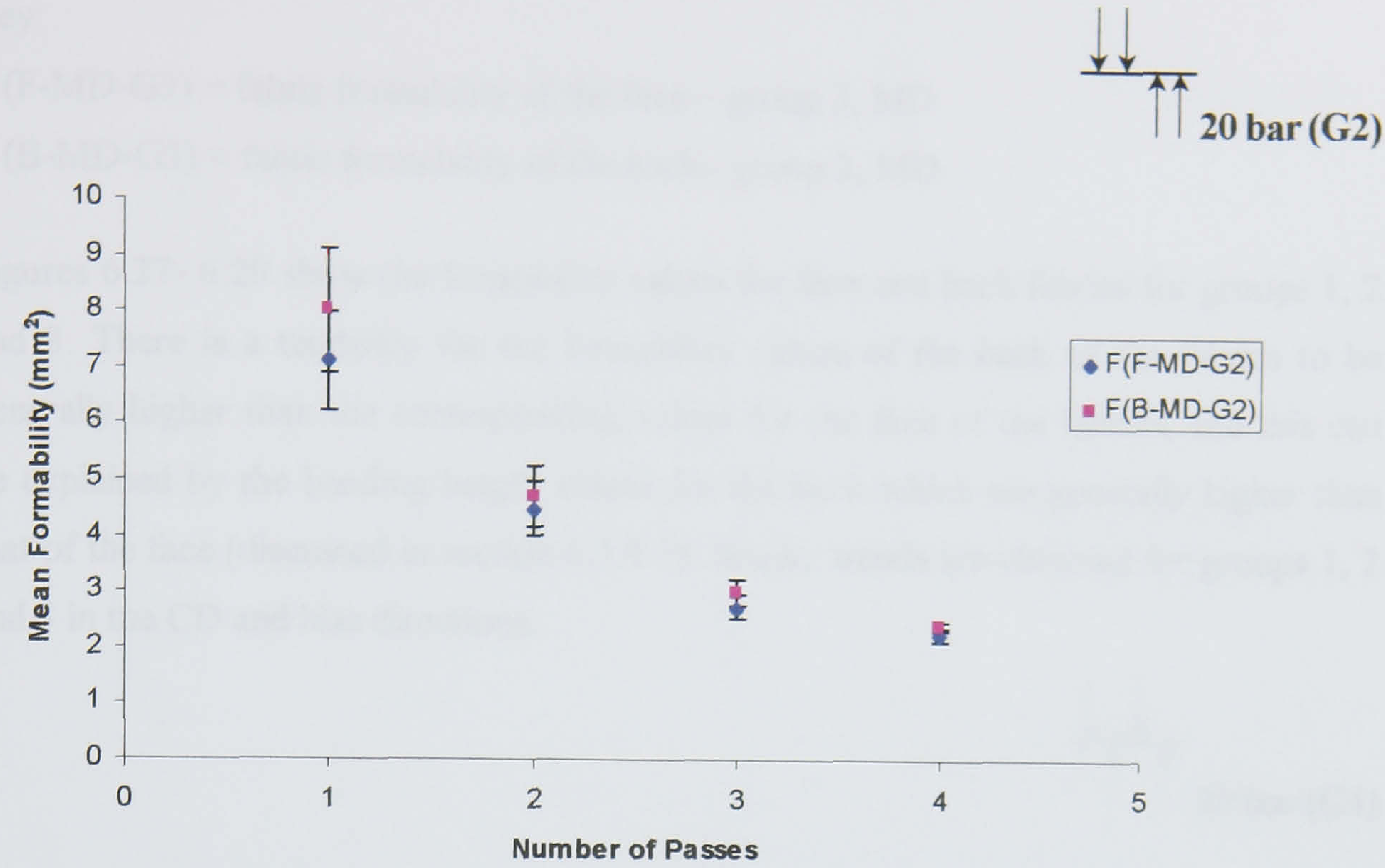


Figure 6.28 Effect of Number of Passes on Fabric Formability of Group 2 (Face and Back - MD)

Key:

F (F-MD-G2) = fabric formability of the face – group 2, MD

F (B-MD-G2) = fabric formability of the back– group 2, MD

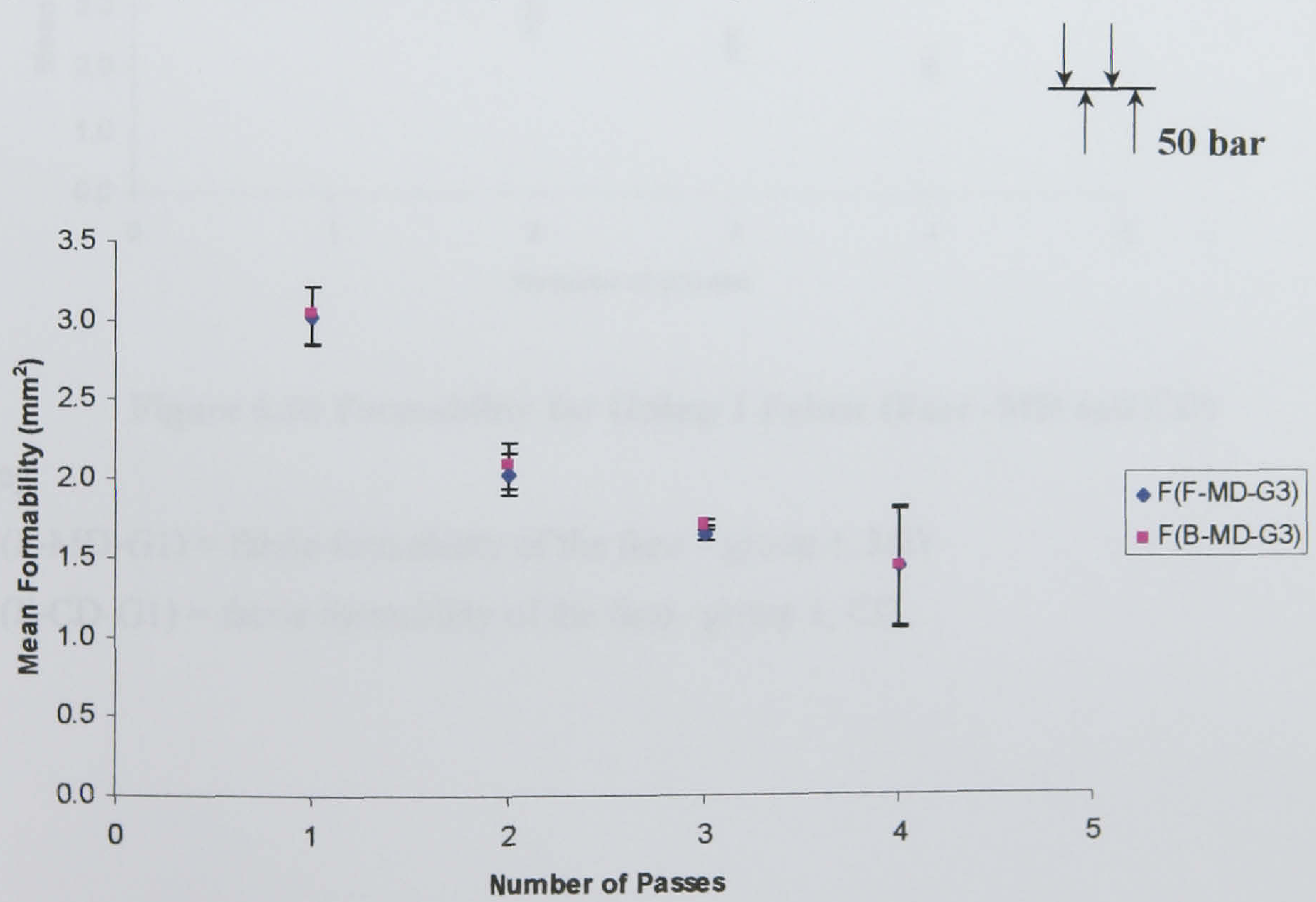


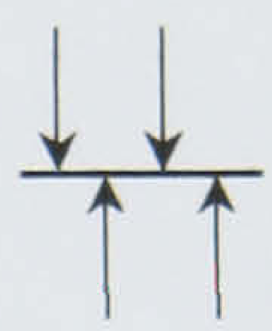
Figure 6.29 Effect of Pressure Profile on Fabric Formability of Group 3 (Face and Back - MD)

Key:

F (F-MD-G3) = fabric formability of the face – group 3, MD

F (B-MD-G3) = fabric formability of the back– group 3, MD

Figures 6.27- 6.29 show the formability values for face and back fabrics for groups 1, 2 and 3. There is a tendency for the formability values of the back of the fabrics to be generally higher than the corresponding values for the face of the fabrics, and this can be explained by the bending length values for the back which are generally higher than that of the face (discussed in section 6.3.4.1). Similar trends are obtained for groups 1, 2 and 3 in the CD and bias directions.



20 bar (G1)

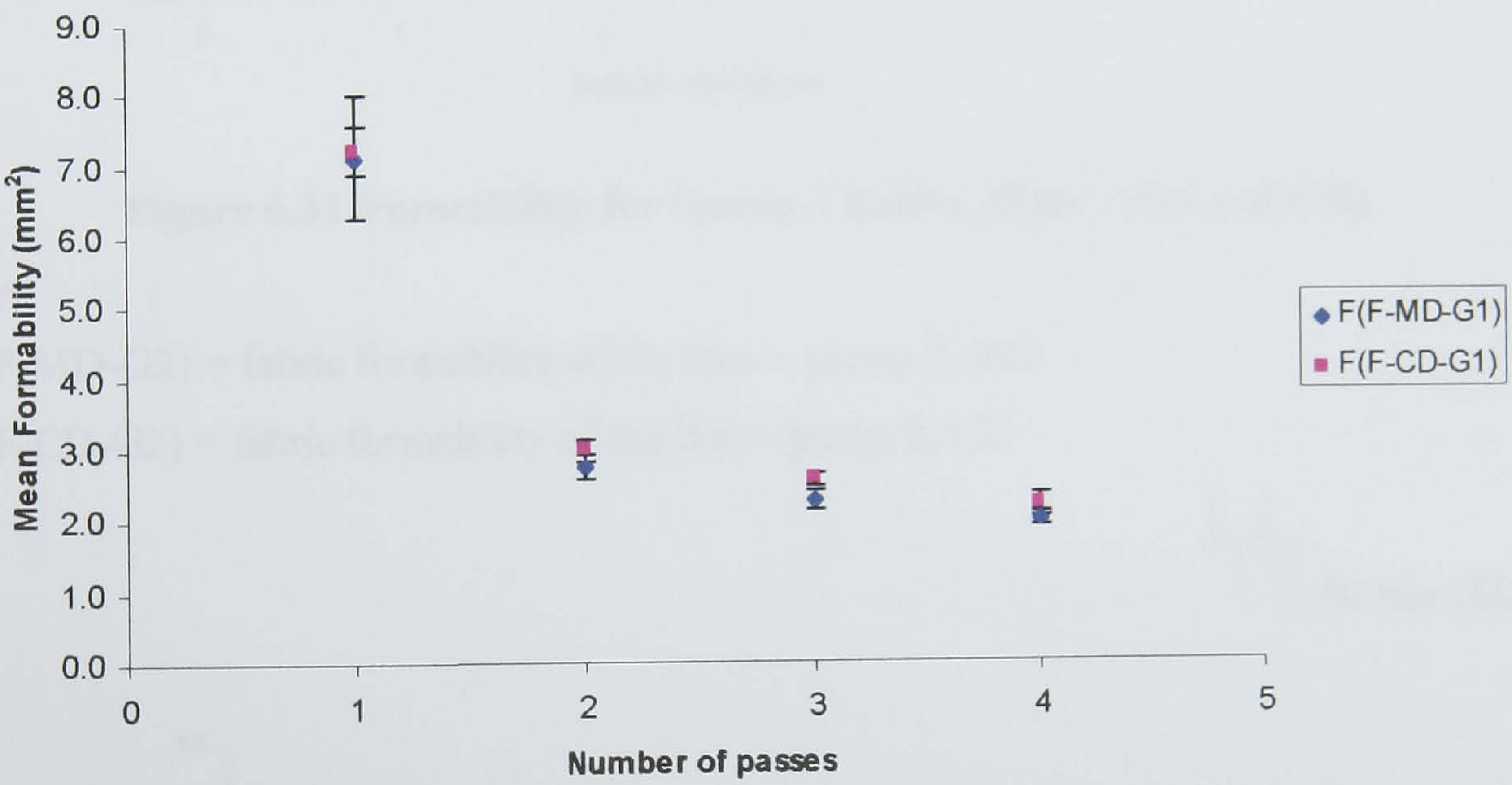


Figure 6.30 Formability for Group 1 Fabric (Face -MD and CD)

Key:

F (F-MD-G1) = fabric formability of the face – group 1, MD

F (F-CD-G1) = fabric formability of the face– group 1, CD

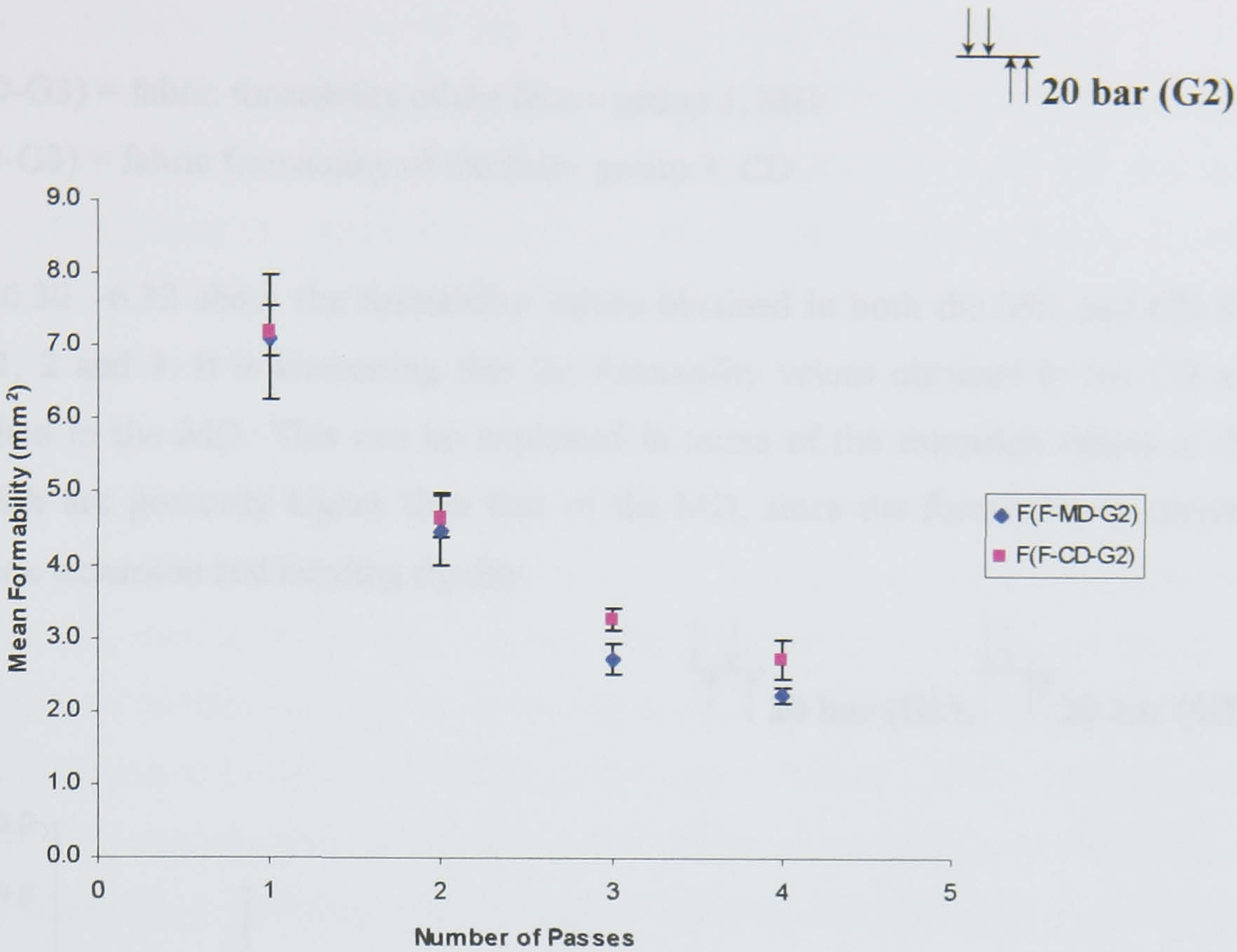


Figure 6.31 Formability for Group 2 Fabric (Face -MD and CD)

Key:

F (F-MD-G2) = fabric formability of the face – group 2, MD

F (F-CD-G2) = fabric formability of the face– group 2, CD

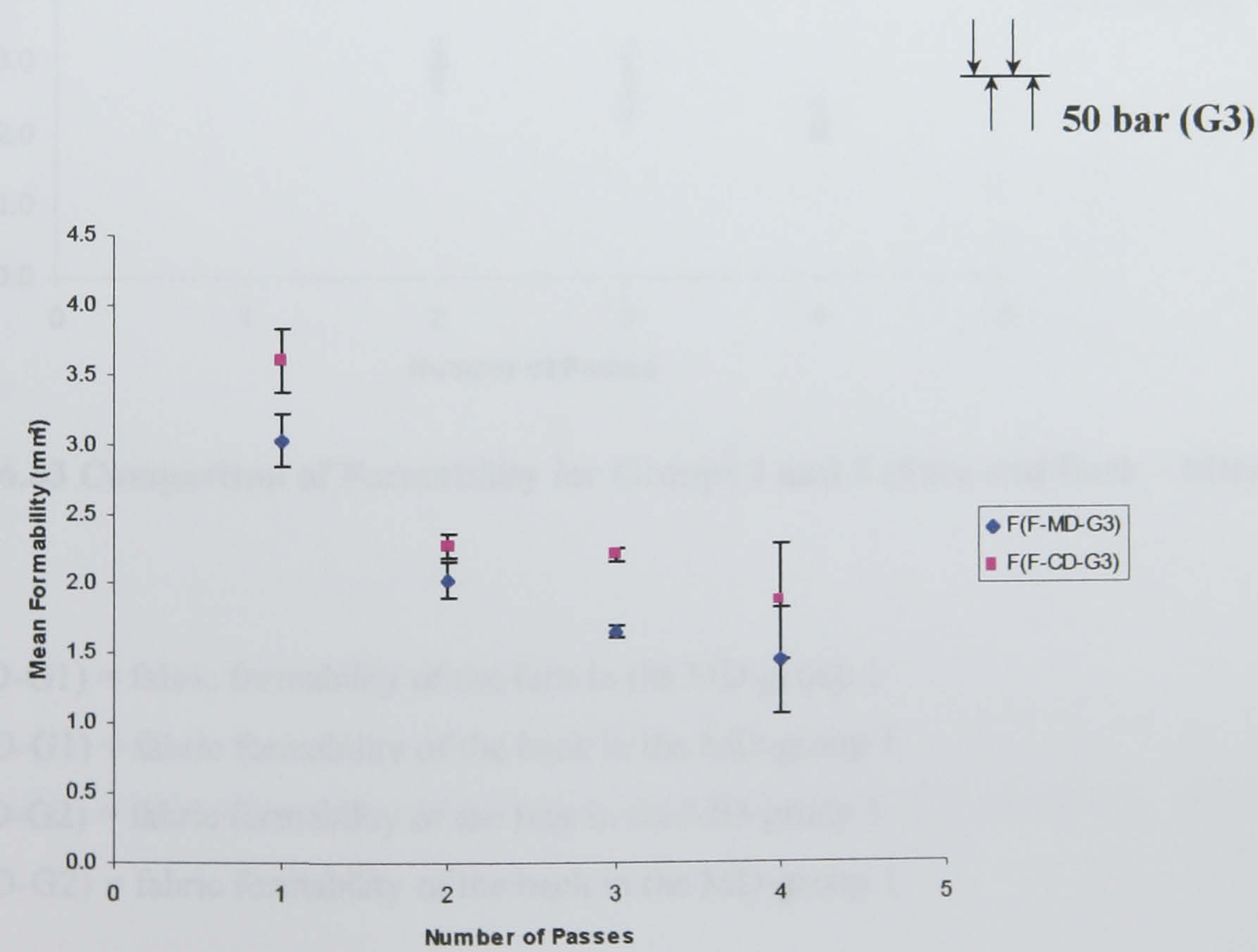


Figure 6.32 Formability for Group 3 Fabric (Face -MD and CD)

Key:

F (F-MD-G3) = fabric formability of the face – group 3, MD

F (F-CD-G3) = fabric formability of the face– group 3, CD

Figures 6.30 –6.32 show the formability values obtained in both the MD and CD for groups 1, 2 and 3. It is interesting that the formability values obtained in the CD are higher than in the MD. This can be explained in terms of the extension values in the CD, which are generally higher than that of the MD, since the formability is derived from fabric extension and bending rigidity.

. 20 bar (G1), 20 bar (G2)

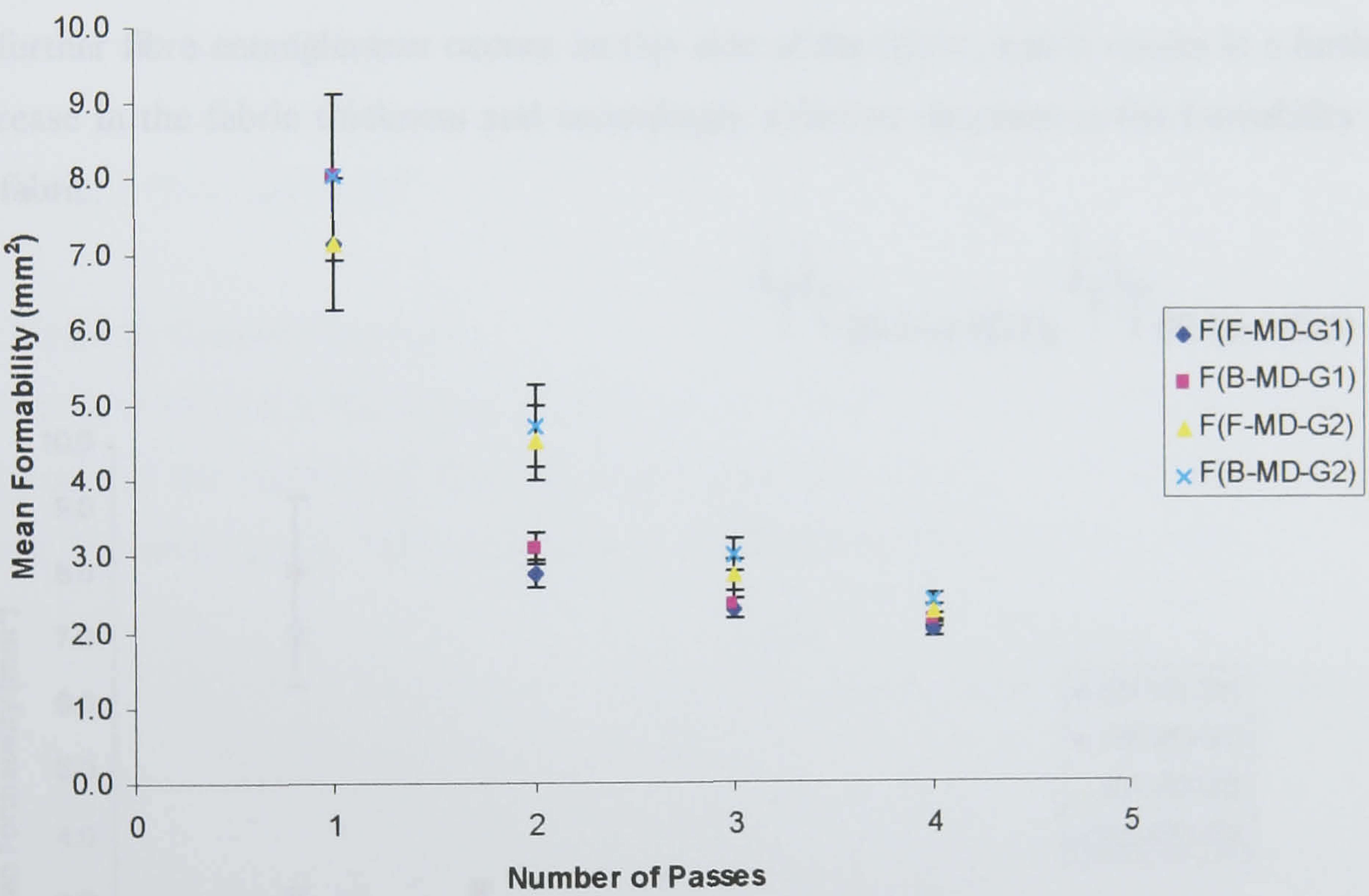


Figure 6.33 Comparison of Formability for Groups 1 and 2 (Face and Back – MD)

Key:

F (F-MD-G1) = fabric formability of the face in the MD-group 1

F (B-MD-G1) = fabric formability of the back in the MD-group 1

F (F-MD-G2) = fabric formability of the face in the MD-group 1

F (B-MD-G2) = fabric formability of the back in the MD-group 1

Figure 6.33 shows a comparison of the formability values obtained for group 1 and 2 (face and back- MD). The same general trends are obtained for group 2 as for group 1 but with different absolute values. Similar trends are obtained in the CD and bias directions. Comparing the results for groups 1 and 2, in figure 6.33, it can be noticed that a decrease in the formability after the third and the fourth pass is small. In group 1, the first two passes involve consolidation of the face and then the back of the fabric, which results in a more homogenous entanglement of the fabric. This appears to be reflected, in the fabric structure, and consequently on fabric mechanical properties such as extension and bending length. On the other hand, in group 2, the first two passes are applied on the face only and both involve low pressure (20 bar), which results in entanglement of the face only (compare the fabric cross–sections of groups 1 and 2 after 2 passes in figures 5.5 and 5.13). After the third pass, when the back is treated (group 2), further fibre entanglement occurs on this side of the fabric, which results in a further decrease in the fabric thickness and accordingly a further decrease in the formability of the fabric.

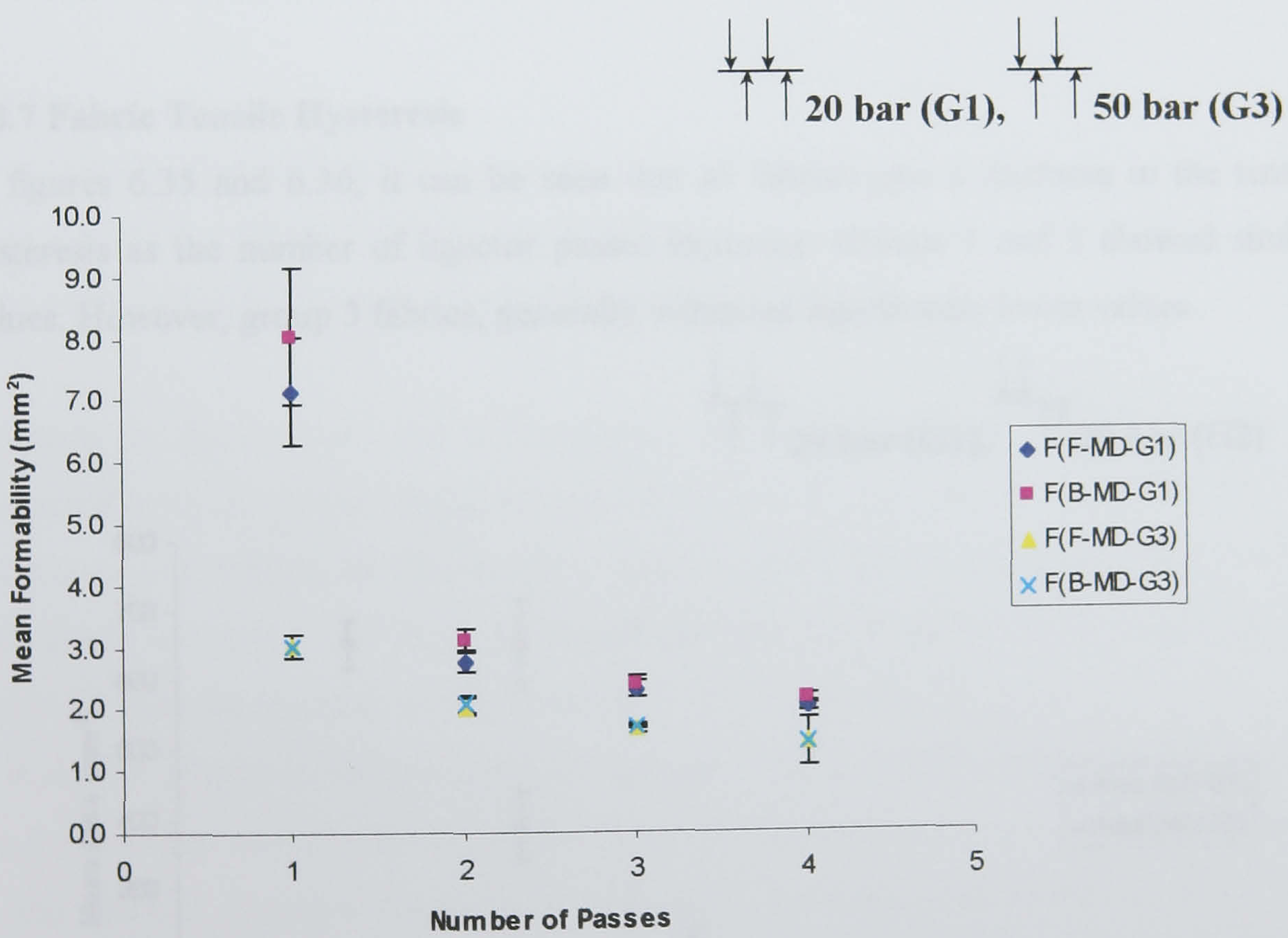


Figure 6.34 Comparison of Formability for Groups 1 and 3 (Face and Back – MD)

Key:

F (F-MD-G1) = fabric formability of the face in the MD-group 1

F (B-MD-G1) = fabric formability of the back in the MD-group 1

F (F-MD-G3) = fabric formability of the face in the MD-group 3

F (B-MD-G3) = fabric formability of the back in the MD-group 3

The trends obtained for group 1 and 3 in figure 6.34 are similar to those of groups 1 and 2 but with different absolute values. Due to the use of a higher pressure (50 bar) in group 3, although the fabrics are produced by applying the energy on the face only (in the first pass), both the face and back produce similar values of formability after only a single injector. These results are in general agreement with the suggestions of Bertram[74]. Thus, it can be concluded that if a higher pressure is used, formability will be similar on the face and back, even if the jets are applied from one side only. In contrast, at lower pressures, alternate or double-sided treatment is needed to minimise differences in the fabric (face and back).

6.3.7 Fabric Tensile Hysteresis

In figures 6.35 and 6.36, it can be seen that all fabrics give a decrease in the tensile hysteresis as the number of injector passes increases. Groups 1 and 2 showed similar values. However, group 3 fabrics, generally, exhibited significantly lower values.

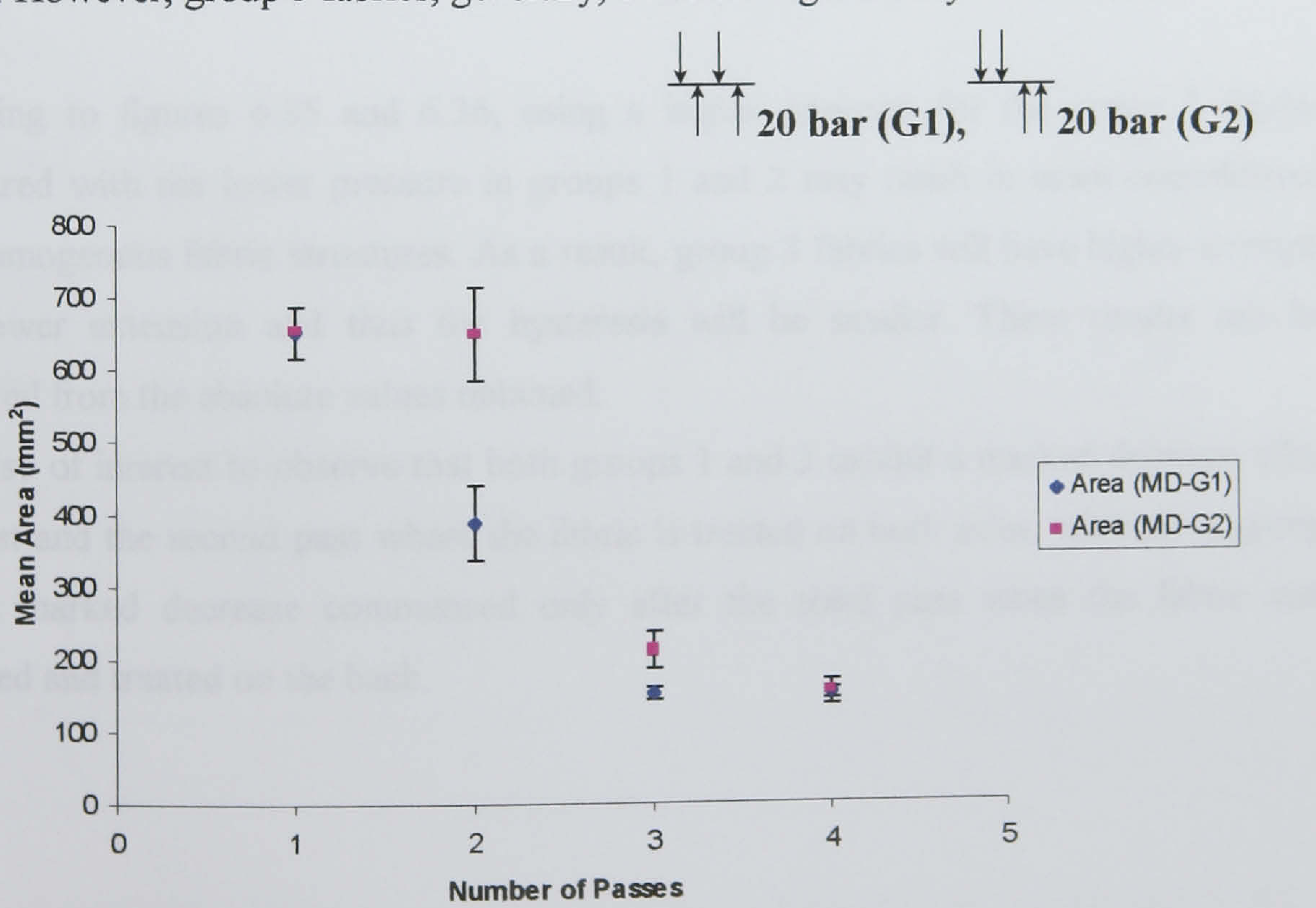


Figure 6.35 Effect of Pressure Profile on Fabric Hysteresis–Groups 1 and 2

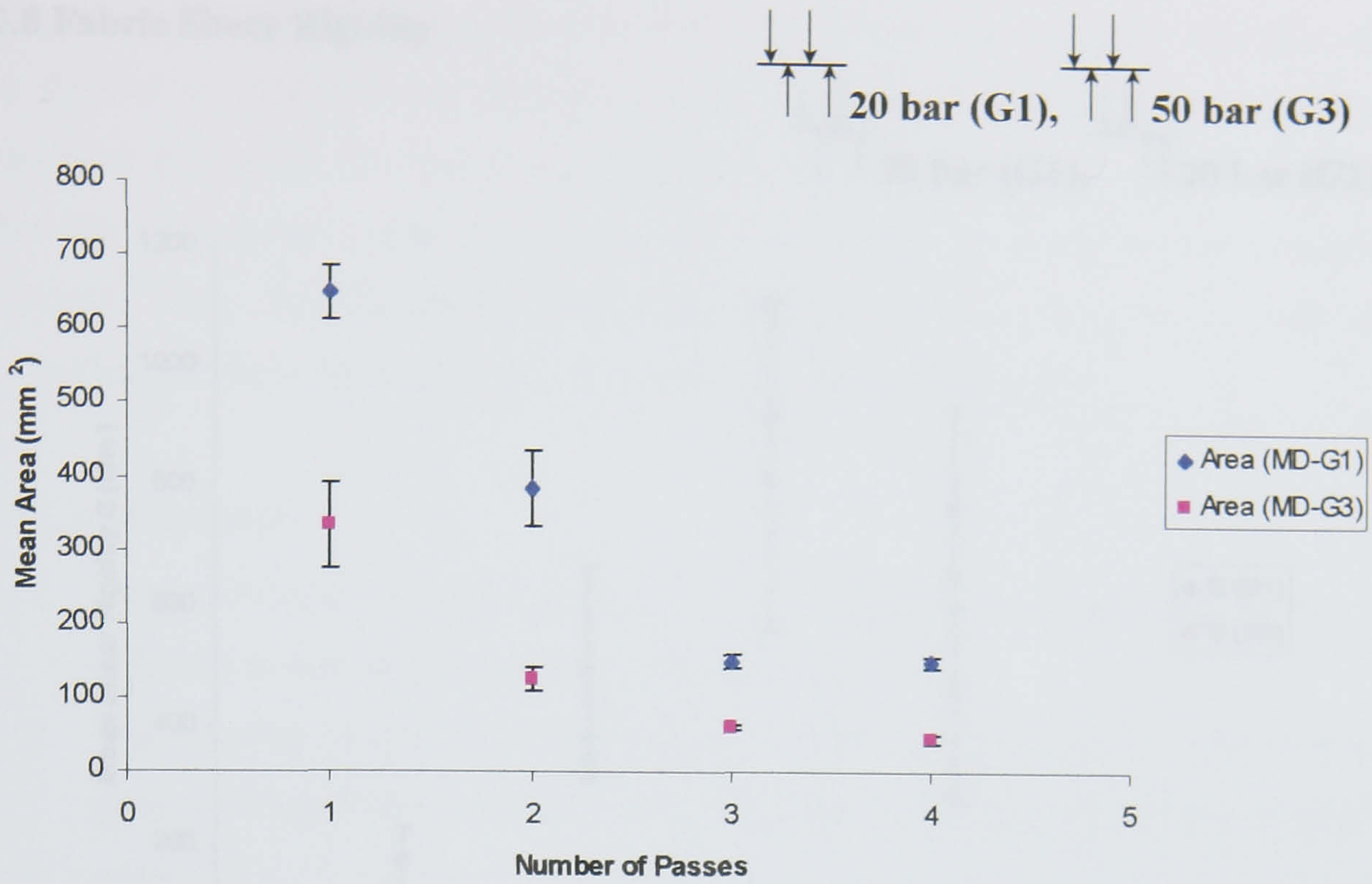


Figure 6.36 Effect of Pressure Profile on Fabric Hysteresis–Groups 1 and 3

Key:

Area (MD-G1) = fabric tensile hysteresis in the MD-group 1

Area (MD-G2) = fabric tensile hysteresis in the MD-group 2

Area (MD-G3) = fabric tensile hysteresis in the MD-group 3

Referring to figures 6.35 and 6.36, using a higher pressure for the group 3 fabrics compared with the lower pressure in groups 1 and 2 may result in more consolidated and homogenous fabric structures. As a result, group 3 fabrics will have higher strength and lower extension and thus the hysteresis will be smaller. These results can be observed from the absolute values obtained.

It is also of interest to observe that both groups 1 and 3 exhibit a marked decrease after the first and the second pass where the fabric is treated on both sides, whereas in group 2, the marked decrease commenced only after the third pass when the fabric was reversed and treated on the back.

6.3.8 Fabric Shear Rigidity

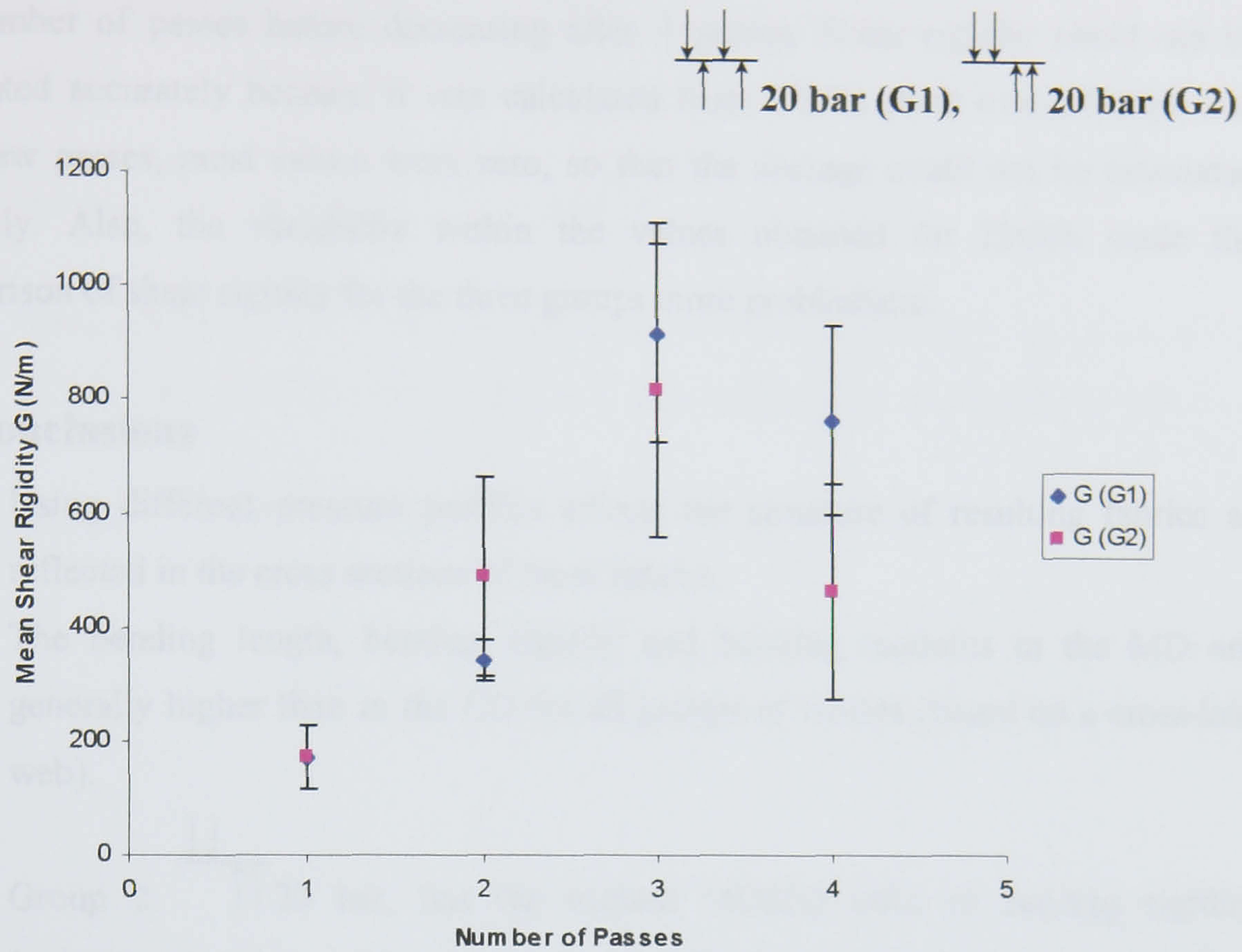


Figure 6.37 Effect of Pressure Profile on Fabric Shear Rigidity–Groups 1 and 2

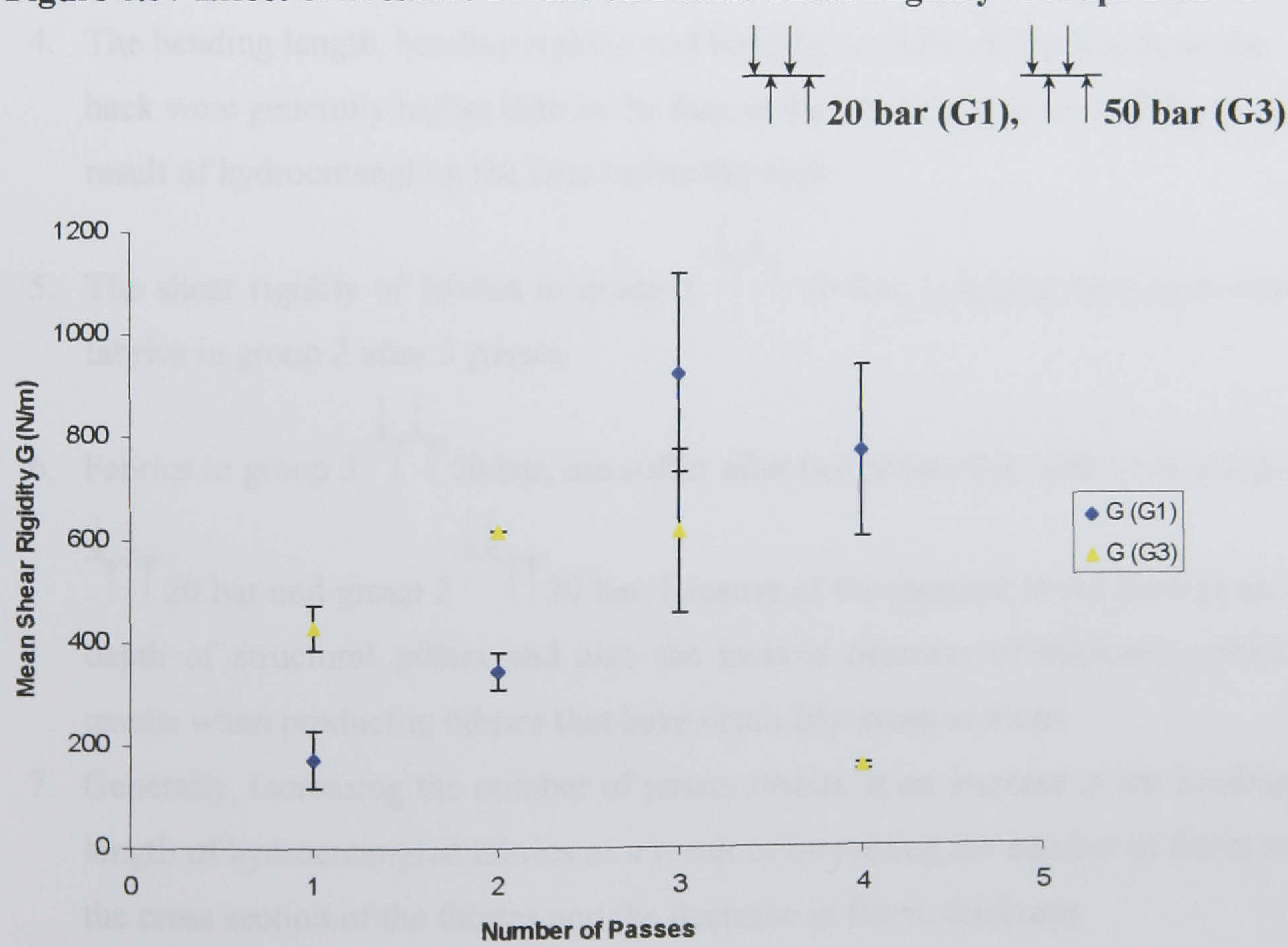
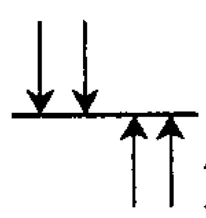
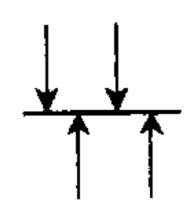
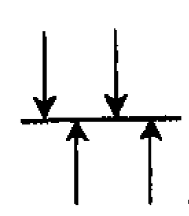
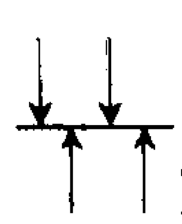
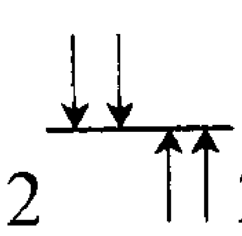
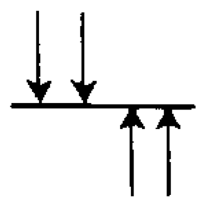
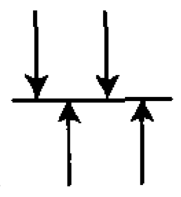
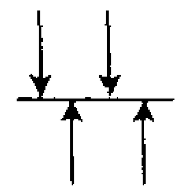


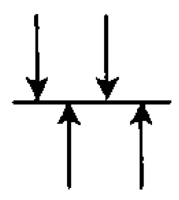
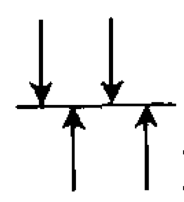
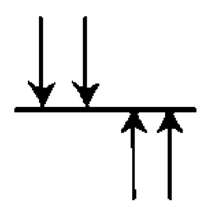
Figure 6.38 Effect of Pressure Profile on Fabric Shear Rigidity–Groups 1 and 3

In figures 6.37 and 6.38, it may be observed that generally, shear rigidity increases with the number of passes before decreasing after 4 passes. Shear rigidity could not be calculated accurately because it was calculated from EB5% (bias extensibility), and after few passes, most values were zero, so that the average could not be calculated precisely. Also, the variability within the values obtained for EB5% made the comparison of shear rigidity for the three groups more problematic.

6.4 Conclusions

1. Using different pressure profiles affects the structure of resulting fabrics as reflected in the cross sections of these fabrics.
2. The bending length, bending rigidity and bending modulus in the MD are generally higher than in the CD for all groups of fabrics (based on a cross-laid web).
3. Group 2  20 bar, has the highest MD/CD ratio of bending rigidity (anisotropy) compared to groups 1 and 3 fabrics, where the energy is applied using alternate face and back injectors.
4. The bending length, bending rigidity and bending modulus of the fabrics on the back were generally higher than in the face of the fabrics for all jet profiles as a result of hydroentangling the face before the back.
5. The shear rigidity of fabrics in group 1  20 bar, is higher compared with fabrics in group 2 after 3 passes.
6. Fabrics in group 3  50 bar, are stiffer after two passes than fabrics in group1  20 bar and group 2  20 bar, because of the increase in the number and depth of structural pillars and also the marked decrease of thickness, which results when producing fabrics that have chain-like cross sections.
7. Generally, increasing the number of passes results in an increase in the bending length of hydroentangled fabrics as a result of increasing the number of fibres in the cross section of the fabrics and the decrease in fabric thickness.

8. Group 2 fabrics  20 bar, generally have higher values of extension (E5%, E20% and E100%), formability and tensile hysteresis compared to fabrics in groups 1  20 bar and 3  50 bar.

9. Group 3 fabrics  50 bar, generally have lower values of extension (E5%, E20% and E100%), formability and tensile hysteresis compared to fabrics in groups 1  20 bar, and 2  20 bar.

CHAPTER 7
MODELING OF LOW STRESS MECHANICAL PROPERTIES OF HYDROENTANGLED FABRICS

7.1 Introduction

This chapter describes the modeling of low stress mechanical properties of hydroentangled nonwoven fabrics and seeks to explain the relationship between fabric structure, process parameters and low stress fabric mechanical properties. There are few previous studies of established models to explain such relationships in hydroentangled fabrics. Existing models demonstrate the relationships between fabric structures or the process parameters on strength and extension but these relate to fabrics tested to breaking point and not under low stress. The relationships between aspects of fabric dimensions and process conditions on the low stress properties is the subject of the present work.

7. 2 Regression Analysis of Low Stress Mechanical Properties of Hydroentangled Fabrics

Regression analysis[100] provides the potential to summarize a collection of sampled data using an empirical model. Each regression model has certain parameters, or variables, which can be adjusted in order to achieve close agreement with the sampled data. These model parameters typically come from derived scientific or statistical theory that the data is supposed to satisfy[100]. The basic idea behind regression analysis is to choose a method of measuring the agreement between a set of data and a regression model with a particular choice of variables.

7.2.1 Nonlinear Regression

Similar to linear regression[100], the goal of nonlinear regression is to determine the best-fit parameters for a model by minimizing a chosen merit function. Where nonlinear regression differs is that the model shows a nonlinear relationship between the parameters, and the process of merit function minimization is an iterative approach. The process is to start with some initial estimates and incorporates algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing[100].

7.2.2 Coefficient of Multiple Determination (R^2)

The goodness of fit of the models is determined by the coefficient of multiple determination (R^2). R^2 measures the proportion of variation in the data points, which is explained by the regression model. A value of $R^2 = 1.0$ means that the curve passes through every data point. A value of $R^2 = 0.0$ means that the regression model does not describe the data any better than a horizontal line passing through the average of the data points[100].
Therefore, R^2 measures the proportion of variation in the data points, which is explained by the regression model. For example, if $R^2 = 0.95$, then 95% of the variation in the dependent, or response variable Y is explained by the regression model.

7.2.3 Dependent and Independent Variables

DataFit software[100] was used to perform regression analysis of the experimental results for the four different fabric groups (defined in terms of their area density) using three-dimensional models. The two sets of variables were:

1. Specific energy and fabric weight (area density);
2. Specific energy and fabric thickness.

These two different sets of variables represent the main process parameter and the fabric dimensions. The dependent variables were the low stress mechanical properties of the hydroentangled fabrics (BL, BR, BM, F, Tensile hysteresis, E5, E20, E100 and G).

Where:
BL = Bending length (mm)
BR =Bending Rigidity (μN.m)
BM = Bending Modulus (Kg/m^2)
Tensile hysteresis = the area within the load extension curves when samples were loaded and when unloaded (mm^2)
E5 = extension (%) of the fabric at load 5 gf /cm (4.9 N/m)

E20 = extension (%) of the fabric at load 20 gf /cm (19.6 N/m)

E100 = extension (%) of the fabric at load 100 gf /cm (98.1 N/m)

G = Shear Rigidity (N/m)

F = Formability (mm^2)

7.3 Data Fit Software

DataFit[100] is a science and engineering tool that simplifies the tasks of data plotting, regression analysis (curve fitting) and statistical analysis. Data can be entered by typing it into a standard spreadsheet interface, by importing it from files created by other applications, or by cutting and pasting it from other Windows based applications. DataFit can solve linear and nonlinear regression models with up to 20 independent variables. There are currently 60 two-dimensional and 242 three-dimensional nonlinear regression models pre-defined in DataFit. The pre-defined nonlinear regression models are those commonly used in scientific, statistical and engineering applications[100].

7.4 Regression Models

DataFit enables the solution of any regression model that defines an independent, or response variable Y as a function of independent, or predictor variable (s) X and at least one fitting parameter. From this 'infinite' set of regression models, a subset of the most commonly used engineering, scientific and statistical regression models, was chosen and compiled into DataFit. This means that the model is pre-defined, that initial estimates are calculated automatically and analytical (exact) derivatives can be used when performing regression analysis.

As mentioned before, the two sets of independent variables were specific energy and weight (area density) and specific energy and thickness. According to the large number of possible models that can be produced for each dependent variable in each direction of the fabric (MD, CD, bias), and for each pressure used (20, 50, 70and 90 bar), the decision was taken to obtain two or three appropriate models for each dependent variable in all directions (MD, CD, Bias) and the water pressures used (20, 50, 70and 90 bar). The selection of the models was determined by the model function that gave the most realistic relationship between the independent variables as denoted by the R^2 value.

It is important to mention here that the fabrics that were not hydroentangled (webs) were also tested using the FAST instrument in the MD, CD and Bias directions, but the results of these tests were not included in the data for preparing the models. The reason for this is that the values obtained when testing the extension of the webs under low stress always exceeded the limits of the extension meter and also because the webs are considered to be a different structure from the hydroentangled fabrics.

It is also important to mention that further samples were produced and tested to give values that could be used to test the validity of the models in terms of their prediction accuracy.

It is evident from the data that the mechanical properties fell into two groups. Some properties were inversely proportional to specific energy applied during hydroentanglement and directly proportional to fabric structure, e.g. bending properties. Others were directly proportional to the energy applied and inversely proportional to the fabric area density / thickness. Therefore, two different sets of equations (models) were selected to reflect this. The equations that were determined to more accurately model the relationships were of the form:

Y=a1+b1*x1+c1*x1^2+d1/x2
Y= a2+b2/x1+c2/x1^2+d2*x2

Where: a1, b1, c1, a2, b2, c2 and d2 are all constants. And:

Y = mechanical property
X1 = area density (g/m^2)
X2 = specific energy (MJ/Kg)

Tables 7.1 (a and b) show the mean values obtained for the regression coefficient for the equation models used for each of the low stress mechanical properties in the MD, CD and bias direction using 20, 50, 70 and 90 water pressures.

Table 7.1 (a)

Model: Y=a+b*x1+c*x1^2+d/x2

Variables	20 Bar			50 Bar			70 Bar			90 Bar			Mean R^2
	MD	CD	Bias	MD	CD	Bias	MD	CD	Bias	MD	CD	Bias	
X1 : Weight **X2 : Energy** **Y : BL**	0.94	0.92	0.96	0.95	0.88	0.94	0.86	0.83	0.93	0.94	0.75	0.90	0.90
X1 : Weight **X2 : Energy** **Y : BM**	0.94	0.89	0.97	0.97	0.86	0.92	0.88	0.79	0.93	0.95	0.74	0.92	0.90
X1 : Weight **X2 : Energy** **Y : BR**	0.96	0.91	0.96	0.97	0.92	0.95	0.91	0.83	0.94	0.95	0.76	0.93	0.92
X1 : Weight **X2 : Energy** **Y : F**	0.80	0.85	0.87	0.95	0.85	0.92	0.74	0.80	0.90	0.87	0.84	0.92	0.86
X1 : Weight **X2 : Energy** **Y : G**			0.56			0.60			0.55			0.71	0.61

Where:

Weight = Area Density (g/m^2)

Energy = Specific energy (MJ/Kg)

BL = Bending length (mm)

BR =Bending Rigidity (μN.m)

BM = Bending Modulus (Kg/m^2)

F = Formability (mm^2)

G = Shear Rigidity (N/m)

Table 7.1 (b)

Model: Y=a+b/x1+c/x1^2+d*x2

Variables	20 Bar			50 Bar			70 Bar			90 Bar			Mean R^2
	MD	CD	Bias	MD	CD	Bias	MD	CD	Bias	MD	CD	Bias	
X1 : Weight X2 : Energy Y : Area	0.70	0.49	0.64	0.94	0.95	0.96	0.86	0.97	0.98	0.91	0.96	0.95	0.86
X1 : Weight X2 : Energy Y : E5	0.35	0.83	0.55	0.15	0.70	0.83	0.68	0.79	0.64	0.42	0.50	0.81	0.60
X1 : Weight X2 : Energy Y : E20	0.64	0.98	0.85	0.77	0.88	0.96	0.63	0.92	0.86	0.79	0.86	0.85	0.83
X1 : Weight X2 : Energy Y : E100	0.62	0.82	0.76	0.62	0.92	0.96	0.68	0.94	0.90	0.91	0.94	0.88	0.83

Where:

Calculated Area = Fabric hysteresis (mm^2)

E5 = extension of the fabric at load 5 gf /cm (4.9 N/m) (%)

E20 = extension of the fabric at load 20 gf /cm (19.6 N/m) (%)

E100 = extension of the fabric at load 100 gf /cm (98.1 N/m) (%)

It is evident from table 7.1 (a), that the equations model the data quite accurately for the bending properties and formability. Generally, the equations showed great accuracy for the properties measured in the machine and bias directions. The equations predict most of the measurement properties with a high degree of accuracy apart from the shear rigidity. Further consideration will be given to the possible reasons for this later.

Table 7.1 (b), shows the values of the regression coefficient for the tensile hysteresis and extensibility. It is evident that, although the correlation is high for the higher extensibility values (obtained at 20 and 100 gf/cm), it is less good for the extensibility measured at 5 gf/cm. This reflects the large variability in the values at this load, which is particularly poor for the fabrics produced at low entanglement pressures.

7.5 Rationalisation of Models

The previous models would require prior selection of water pressure to predict the dependent variables. Further rationalisation to produce unique function models applicable over a wider range of water pressures would be more relevant.

Table 7.2 shows the values of the constants a, b, c, d, derived from the data where weight (area density) and specific energy corresponding to different levels of water pressure (20, 50, 70 and 90 bar) were considered to be independent variables and other low stress mechanical properties of the hydroentangled fabrics are considered to be dependent variables. The bottom of each table shows a single model derived for each property for all the specific energy levels.

Table 7.2

Bending Length (BL)

Model : Y=a+b*x1+c*x1^2+d/x2							X1 = Weight per Unit Area (g/m²) X2 = Energy (MJ/Kg) Y = BL (mm)
	Direction	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
20 Bar	MD	0.94	1.98	0.56	-0.00	-13.84	
	CD	0.92	9.39	-0.21	-0.00	16.15	
	Bias	0.96	44.54	-0.53	0.00	3.16	
	Direction	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
50 Bar	MD	0.95	24.28	0.12	0.00	-47.35	
	CD	0.88	4.68	0.21	-0.00	-3.06	
	Bias	0.94	8.50	0.12	-0.00	-1.19	
	Direction	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
70 Bar	MD	0.86	18.60	-0.43	0.00	141.08	
	CD	0.83	4.72	-0.20	-0.00	139.58	
	Bias	0.93	8.91	-0.20	-0.00	113.95	
	Direction	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
90 Bar	MD	0.94	8.80	0.28	0.00	-102.65	
	CD	0.75	12.79	0.22	-0.00	-69.04	
	Bias	0.90	1.46	0.47	-0.00	-109.62	
	Direction	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.85	15.46	-0.02	0.00	1.74	
	CD	0.79	7.10	0.16	-0.00	0.23	
	Bias	0.89	12.65	0.04	0.00	2.01	

Bending Rigidity (BR)

Model : Y=a+b*x1+c*x1^2+d/x2			X1 = Weight per Unit Area (g/m²) X2 = Energy (MJ/Kg) Y = BR (μN.m)			
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
20 Bar	MD	0.96	-44.80	-15.93	-0.00	816.16
	CD	0.91	-7.61	6.88	0.00	-332.54
	Bias	0.96	114.24	9.39	0.01	-562.80
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
50 Bar	MD	0.97	108.70	-1.06	0.01	-145.45
	CD	0.92	-12.46	0.21	0.00	-7.49
	Bias	0.95	10.64	-0.20	0.00	-7.22
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
70 Bar	MD	0.91	43.38	-2.02	0.00	444.59
	CD	0.83	-3.52	-1.07	-0.00	404.03
	Bias	0.94	14.75	-1.17	0.00	320.07
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
90 Bar	MD	0.95	29.25	0.13	0.00	-359.49
	CD	0.76	16.15	0.25	0.00	-265.78
	Bias	0.93	-29.04	1.48	-0.00	-492.33
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.88	52.19	-1.06	0.01	5.52
	CD	0.80	1.09	-0.07	0.00	1.04
	Bias	0.88	17.27	-0.46	0.00	8.14

Bending Modulus (BM)

Model : Y=a+b*x1+c*x1^2+d/x2	X1 = Weight per Unit Area (g/m^2) X2 = Energy (MJ/Kg) Y = BM (Kg/m^2)

	Direction	R^2	Constants			
			a	b	c	d
20 Bar	MD	0.94	-0.18	-0.04	-0.000	2.60
	CD	0.89	0.01	0.00	0.00	-0.16
	Bias	0.97	0.52	0.02	0.00	-1.21
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
50 Bar	MD	0.97	0.33	-0.00	0.00	-0.62
	CD	0.86	-0.11	0.00	-0.00	-0.06
	Bias	0.92	-0.07	0.00	0.00	-0.01
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
70 Bar	MD	0.88	0.16	-0.01	0.00	1.81
	CD	0.79	-0.07	-0.00	-0.00	1.82
	Bias	0.93	0.03	-0.00	0.00	1.23
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
90 Bar	MD	0.95	-0.08	0.01	0.00	-2.50
	CD	0.74	0.08	-0.00	0.00	-0.32
	Bias	0.92	-0.13	0.01	-0.00	-1.68

	Direction	R^2	Constants			
			a	b	c	d
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.84	0.15	-0.00	0.00	0.01
	CD	0.75	-0.05	0.00	0.00	-0.00
	Bias	0.84	0.06	-0.00	0.00	0.03

Formability (F)

Model : Y=a+b*x1+c*x1^2+d/x2	X1 = Weight per Unit Area (g/m²) X2 = Energy (MJ/Kg) Y = F (mm²)

	Direction	R^2	Constants			
			a	b	c	d
20 Bar	MD	0.80	-3.89	-2.65	-0.00	133.39
	CD	0.85	-0.04	-0.08	0.00	4.02
	Bias	0.87	6.60	0.49	0.00	-29.69
50 Bar	MD	0.95	2.46	-0.01	0.00	-4.69
	CD	0.85	-0.85	0.03	-0.00	-2.23
	Bias	0.92	1.72	-0.02	0.00	-0.56
70 Bar	MD	0.74	-1.15	0.04	-0.00	-8.25
	CD	0.33	0.81	-0.09	0.00	27.79
	Bias	0.90	-0.32	-0.05	-0.00	21.11
90 Bar	MD	0.87	2.17	-0.10	0.00	27.68
	CD	0.84	-1.46	0.09	-0.00	-25.51
	Bias	0.92	-1.78	0.07	-0.00	-15.60

	Direction	R^2	Constants			
			a	b	c	d
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.83	0.47	-0.01	0.00	0.68
	CD	0.82	-0.27	0.00	0.00	0.33
	Bias	0.85	0.37	-0.01	0.00	0.66

Tensile Hysteresis

Model : Y=a+b/x1+c/x1^2+d*x2						X1 = Weight per Unit Area (g/m^2) X2 = Energy (MJ/Kg) Y = Hysteresis (mm^2)
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
20 Bar	MD	0.70	131.12	762596.10	1600985.44	-15913.72
	CD	0.49	38.22	485703.78	-394277.91	-9621.78
	Bias	0.64	-420.56	356706.40	-6155256.39	-4751.90
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
50 Bar	MD	0.94	-57.41	59521.45	-1579888.00	-173.49
	CD	0.95	-8.34	-5998.96	289594.12	54.24
	Bias	0.98	150.97	-25246.38	2679649.83	-49.97
	Direction	**R^2**	**Constants**			
			a	**b**	**C**	**d**
70 Bar	MD	0.86	-141.40	10572.89	-2532202.58	106.10
	CD	0.97	57.78	29706.93	2094670.81	-147.43
	Bias	0.98	-155.26	50015.97	-2113148.15	-18.43
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
90 Bar	MD	0.91	2.87	16125.05	-16149.76	-22.14
	CD	0.96	-3.04	-7175.89	-22455.30	26.43
	Bias	0.95	-33.27	1781.43	-611110.54	26.89
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.78	53.94	-13.60	812189.72	-20.33
	CD	0.73	-4.37	17010.35	-117092.78	-26.81
	Bias	0.70	-92.24	39748.12	-1204766.37	-31.47

Extension at 5 gf/cm (E5%)

Model : Y=a+b/x1+c/x1^2+d*x2							X1 = Weight per Unit Area (g/m²) X2 = Energy (MJ/Kg) Y = E5%
20 Bar	**Direction**	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
	MD	0.35	0.38	-1217.68	6128.69	23.14	
	CD	0.83	-0.25	-1256.39	2235.70	26.47	
	Bias	0.55	-1.22	4584.15	-15050.88	-87.35	
50 Bar	**Direction**	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
	MD	0.15	-0.08	154.09	-3062.95	-0.49	
	CD	0.70	-1.09	-184.33	-2308.65	2.14	
	Bias	0.83	0.80	47.36	11740.33	-1.06	
70 Bar	**Direction**	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
	MD	0.68	0.02	-283.62	906.21	0.90	
	CD	0.83	2.69	-0.05	0.00	6.58	
	Bias	0.64	0.99	317.14	28533.49	-1.94	
90 Bar	**Direction**	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
	MD	0.42	-1.68	34.44	-21475.97	0.84	
	CD	0.79	-0.54	305.74	1909.02	-0.62	
	Bias	0.81	-0.57	-281.24	-2323.56	0.87	
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	**Direction**	**R^2**	**Constants**				
			a	**b**	**c**	**d**	
	MD	0.42	-0.27	61.25	-1385.36	0.04	
	CD	0.59	0.04	-11.81	4825.48	0.02	
	Bias	0.57	-0.18	38.43	1869.52	0.03	

Extension at 20 gf/cm (E20%)

Model : Y=a+b/x1+c/x1^2+d*x2	
	X1 = Weight per Unit Area (g/m^2) X2 = Energy (MJ/Kg) Y = E20%

	Direction	R^2	Constants			
			a	b	c	d
20 Bar	MD	0.64	0.86	10018.65	5960.35	-204.15
	CD	0.98	0.64	3402.76	2093.09	-66.81
	Bias	0.85	-4.95	-1356.68	-75433.26	58.16
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**D**
50 Bar	MD	0.77	-0.61	795.40	-19090.79	-1.97
	CD	0.88	-1.34	-101.15	-5916.87	2.93
	Bias	0.96	2.53	-106.13	37223.60	-1.58
	Direction	**R^2**	**Constants**			
			a	**b**	**C**	**d**
70 Bar	MD	0.63	-0.84	-330.24	-20045.39	2.32
	CD	0.92	0.73	164.35	19993.25	-0.65
	Bias	0.86	0.51	539.46	18134.63	-1.66
	Direction	**R^2**	**Constants**			
			a	**b**	**c**	**d**
90 Bar	MD	0.79	-1.05	1151.86	-13018.67	-1.55
	CD	0.86	-1.56	-33.14	-22637.56	1.31
	Bias	0.85	-0.81	132.17	-11078.14	0.55

	Direction	R^2	Constants			
			a	b	c	D
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	MD	0.73	-0.65	363.43	-11092.64	0.04
	CD	0.85	-0.09	257.12	-1923.12	-0.06
	Bias	0.77	-0.46	331.27	-5165.25	-0.05

Extension at 100 gf/cm (E100%)

Model : Y=a+b/x1+c/x1^2+d*x2		
	X1 =	**Weight per Unit Area (g/m²)**
	X2 =	**Energy (MJ/Kg)**
	Y =	**E100%**

	Direction	**R^2**	**Constants**			
20 Bar			**a**	**b**	**c**	**d**
	MD	0.62	2.99	24822.50	11929.95	-501.79
	CD	0.82	1.87	13237.10	-16056.09	-255.48
	Bias	0.76	-16.22	15761.49	-260496.41	-216.82
50 Bar	**Direction**	**R^2**	**a**	**b**	**c**	**d**
	MD	0.62	1.32	972.65	-7774.28	-2.57
	CD	0.92	-0.89	273.07	-8343.45	2.85
	Bias	0.96	5.39	35.65	77445.67	-3.59
70 Bar	**Direction**	**R^2**	**a**	**b**	**c**	**D**
	MD	0.68	-0.96	-764.98	-43744.87	5.41
	CD	0.94	3.90	-999.24	47978.87	2.15
	Bias	0.90	-0.74	935.10	-21034.08	-0.10
90 Bar	**Direction**	**R^2**	**A**	**b**	**c**	**d**
	MD	0.91	-0.48	2932.90	-10047.67	-4.74
	CD	0.94	-2.39	16.63	-46977.67	2.65
	Bias	0.88	1.25	998.96	-325.43	-1.25

	Direction	**R^2**	**Constants**			
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar			**a**	**b**	**c**	**D**
	MD	0.71	-0.17	879.30	-15857.83	-0.46
	CD	0.83	-0.06	933.00	-15933.46	-0.52
	Bias	0.83	-1.39	1296.05	-30227.07	-0.65

Shear Rigidity (G)

Model : Y=a+b*x1+c*x1^2+d/x2							X1 = Weight per Unit Area (g/m²) X2 = Energy (MJ/Kg) Y = G (N/m)
20 Bar	Direction	R^2	Constants				
			a	b	c	d	
	Bias	0.56	-255.91	232.88	0.02	-11156.45	
50 Bar	Direction	R^2	Constants				
			a	b	c	D	
	Bias	0.60	-912.80	27.75	-0.06	-1697.28	
70 Bar	Direction	R^2	Constants				
			A	b	c	d	
	Bias	0.55	-640.64	13.81	-0.04	-325.27	
90 Bar	Direction	R^2	Constants				
			a	b	c	D	
	Bias	0.71	-2004.52	41.54	-0.08	-4738.15	
(All) 20 Bar, 50 Bar, 70 Bar and 90 Bar	Direction	R^2	Constants				
			a	b	c	d	
	Bias	0.40	-299.12	5.14	0.00	59.13	

7.6 Three Dimensional Plane Models

The plots in Figures 7.1-7.25 show a representation of the regression planes for the three-dimensional models that have been derived compared with the actual data points, in the MD, CD and bas directions. The corresponding data is presented in tables 7.2.

Bending Length (BL)

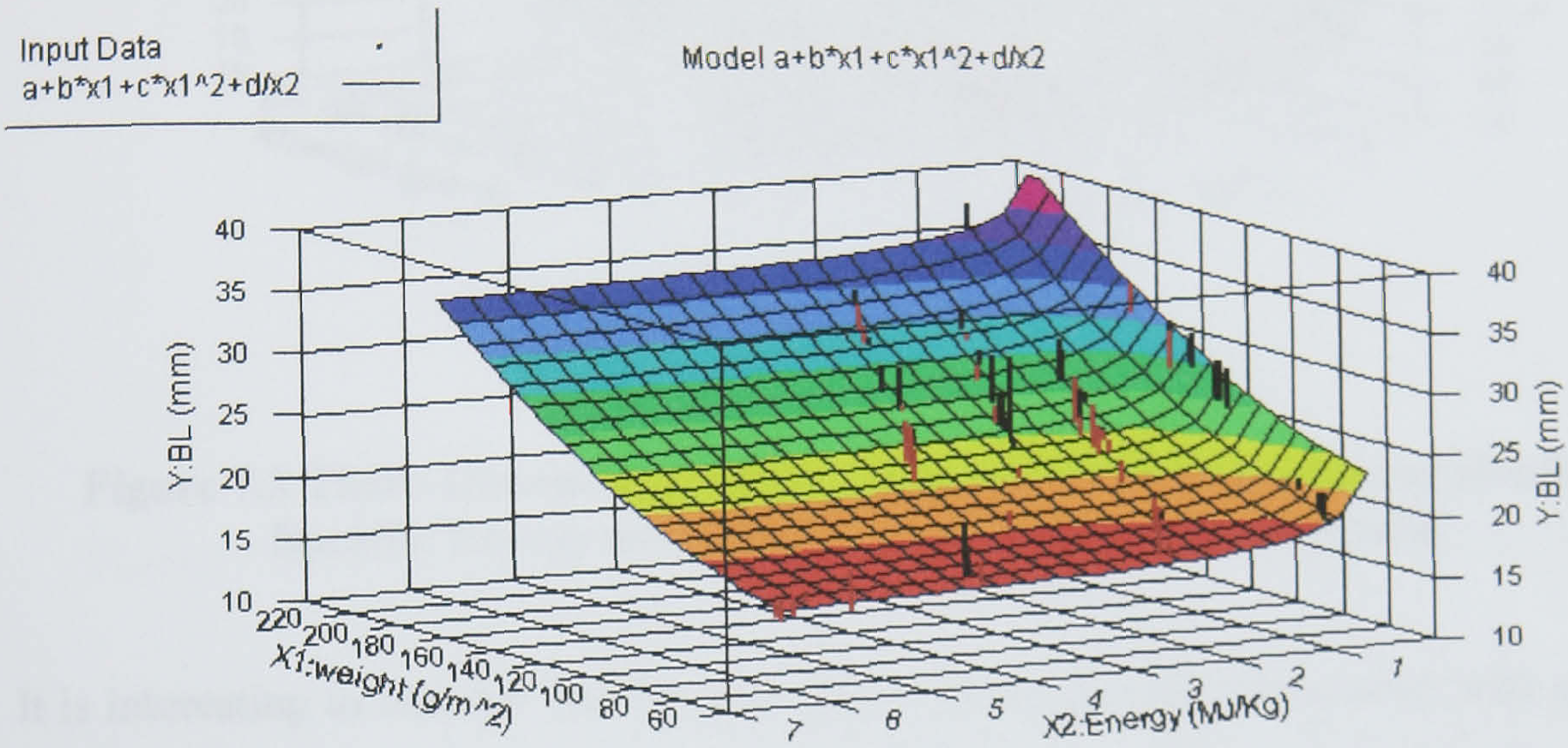


Figure 7.1 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Length in the MD

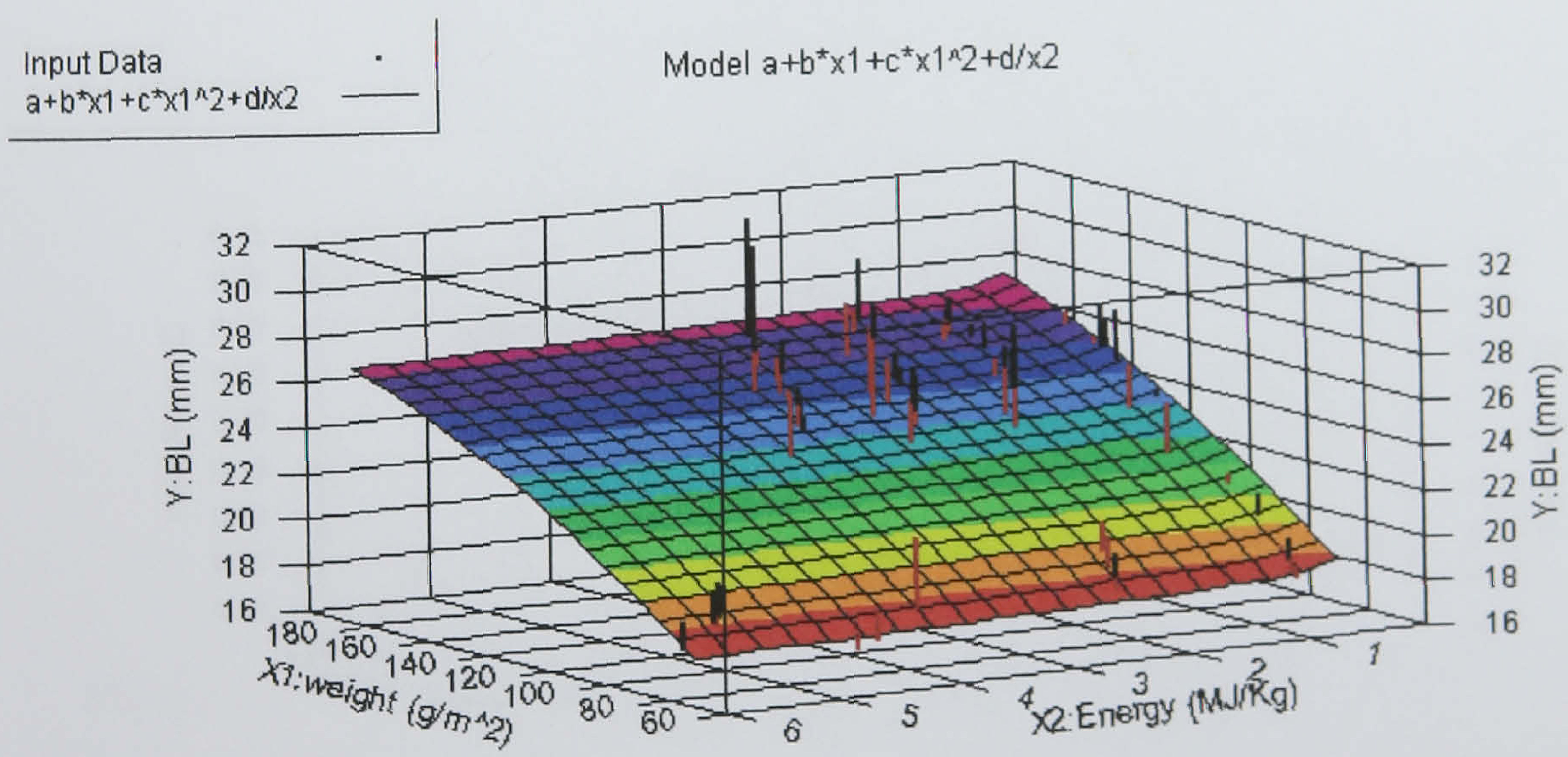


Figure 7.2 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Length in the CD

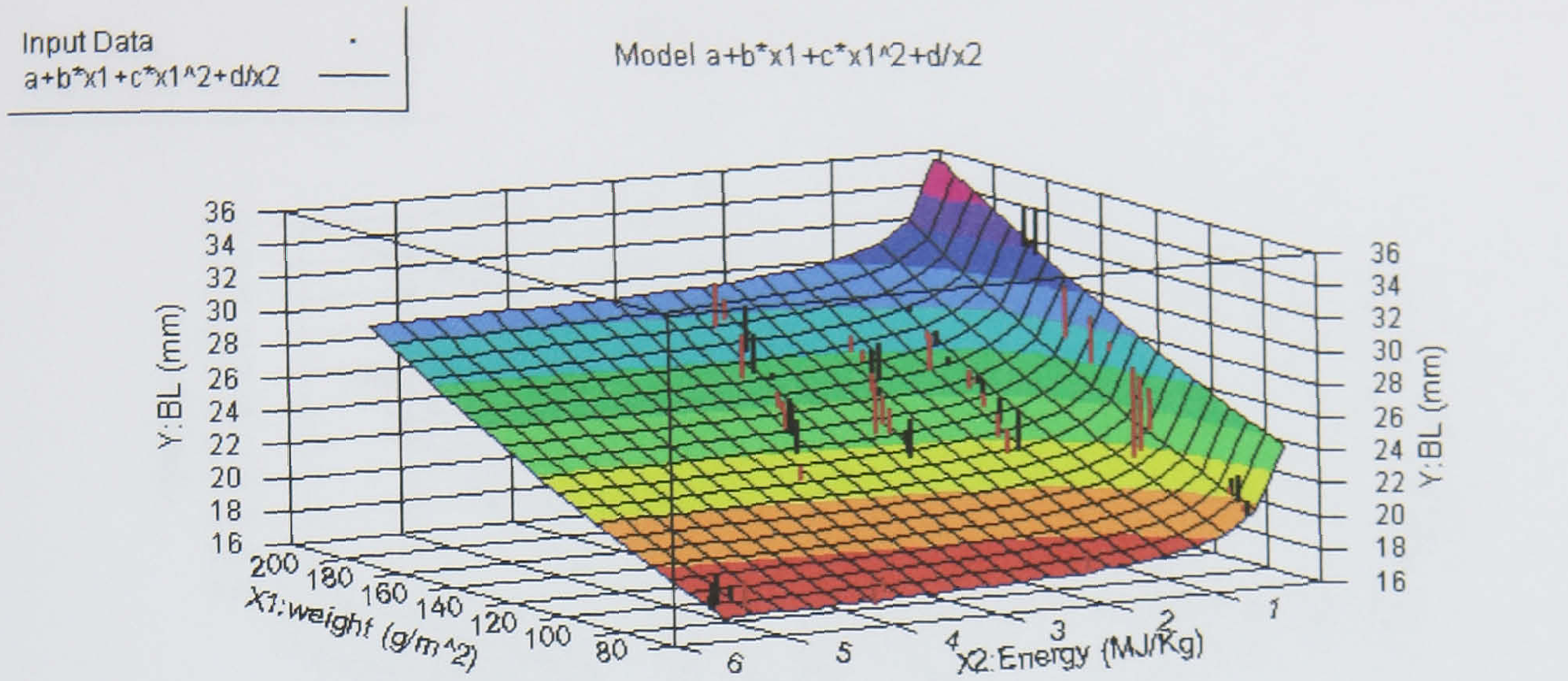


Figure 7.3 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Length in the Bias Direction

It is interesting to observe that the area density dominates the relationship with specific energy, only having a noticeable influence at the lower values, apart from the hysteresis (Figures 7.10-7.12).

Bending Modulus

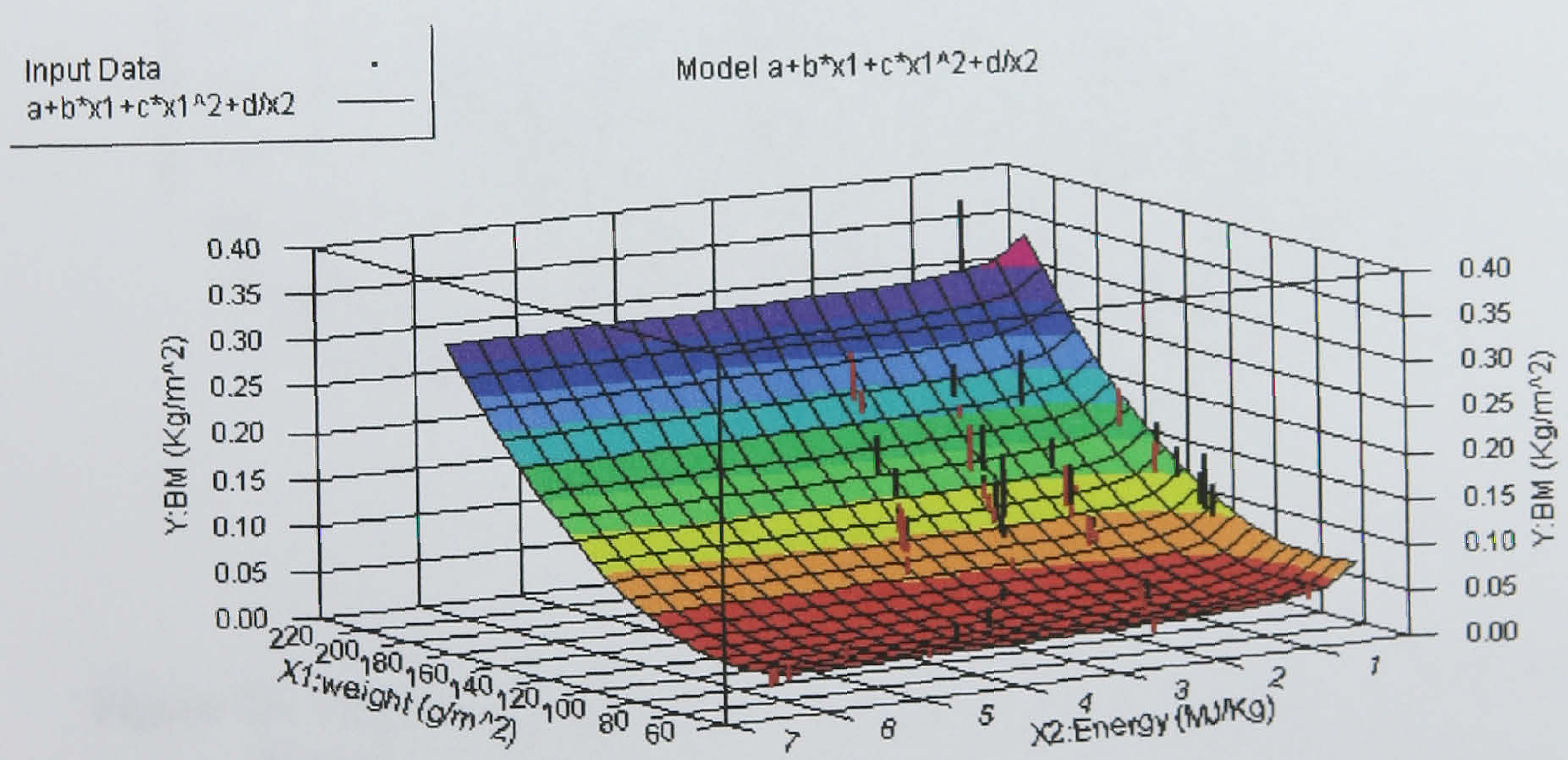


Figure 7.4 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Modulus in the MD

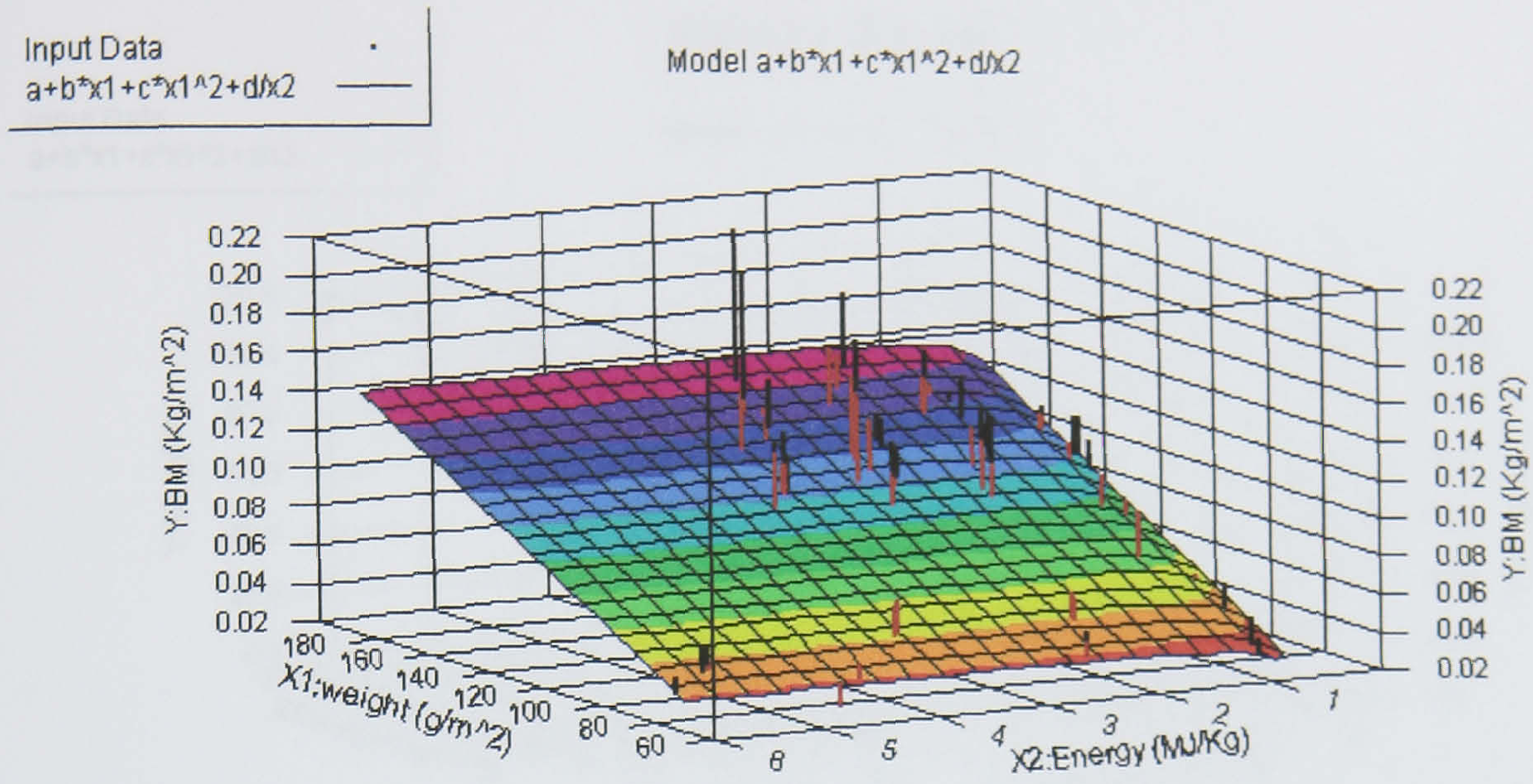


Figure 7.5 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Modulus in the CD

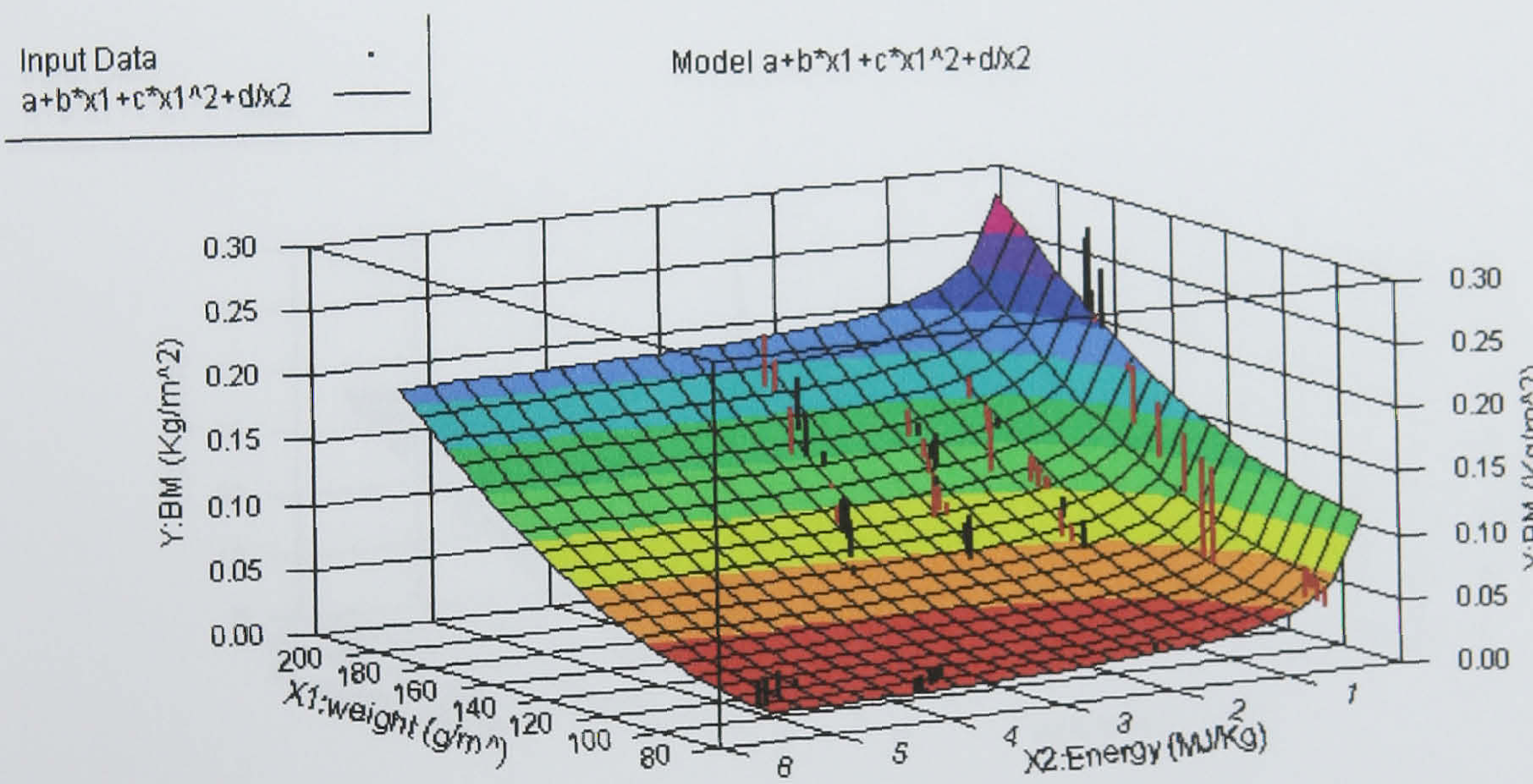


Figure 7.6 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Modulus in the Bias Direction

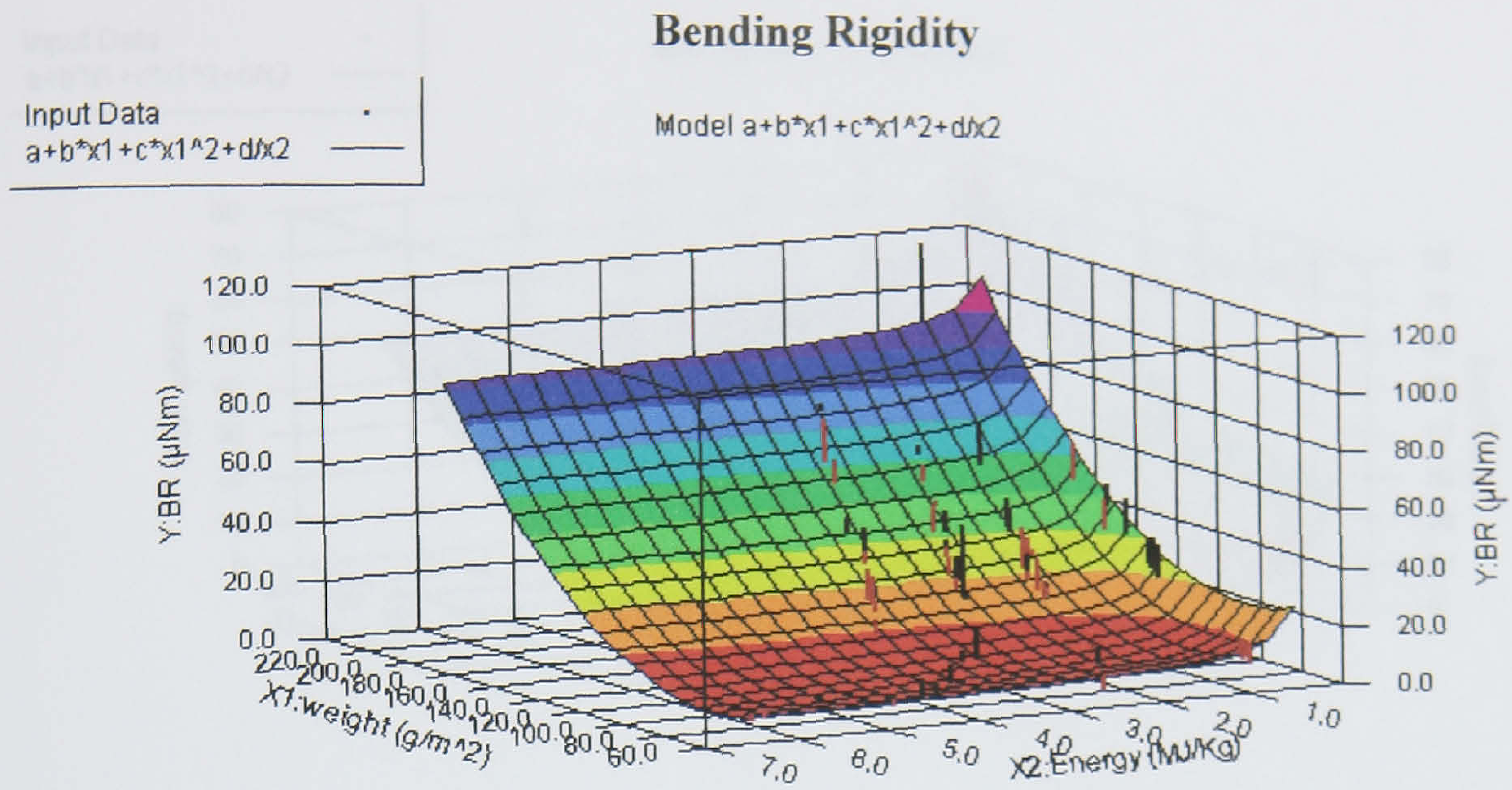


Figure 7.7 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Rigidity in the MD

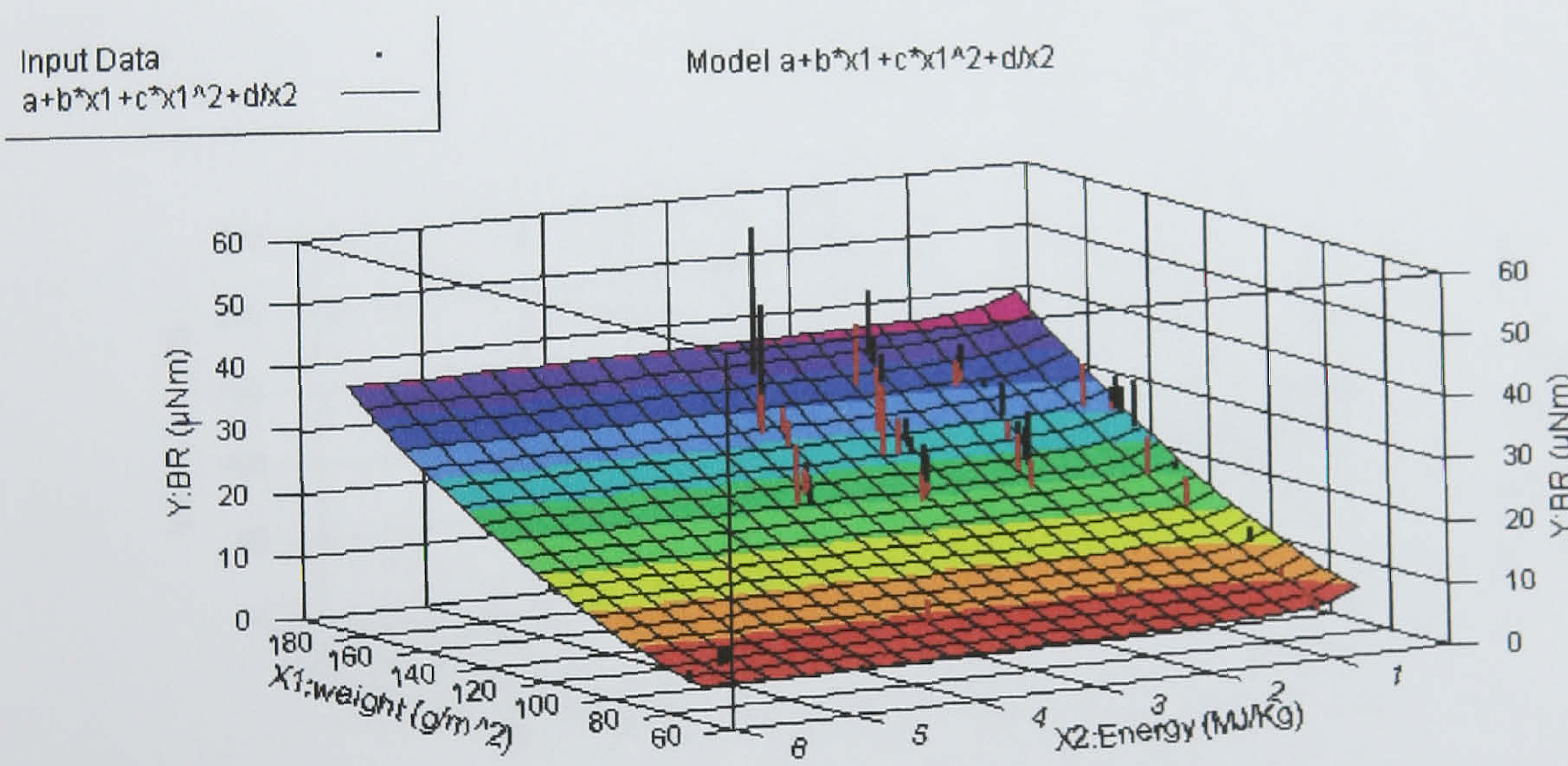


Figure 7.8 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Rigidity in the CD

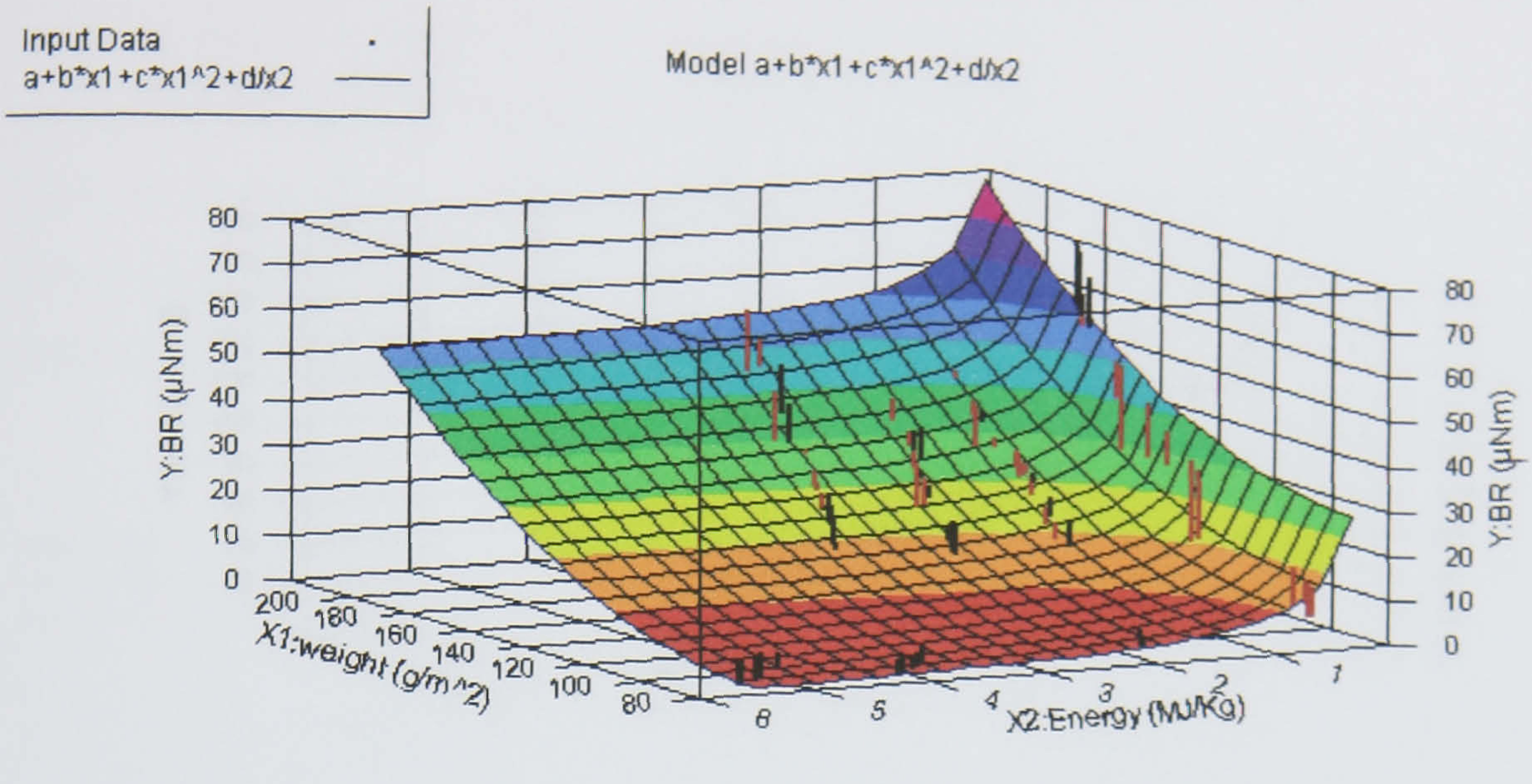


Figure 7.9 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Bending Rigidity in the Bias Direction

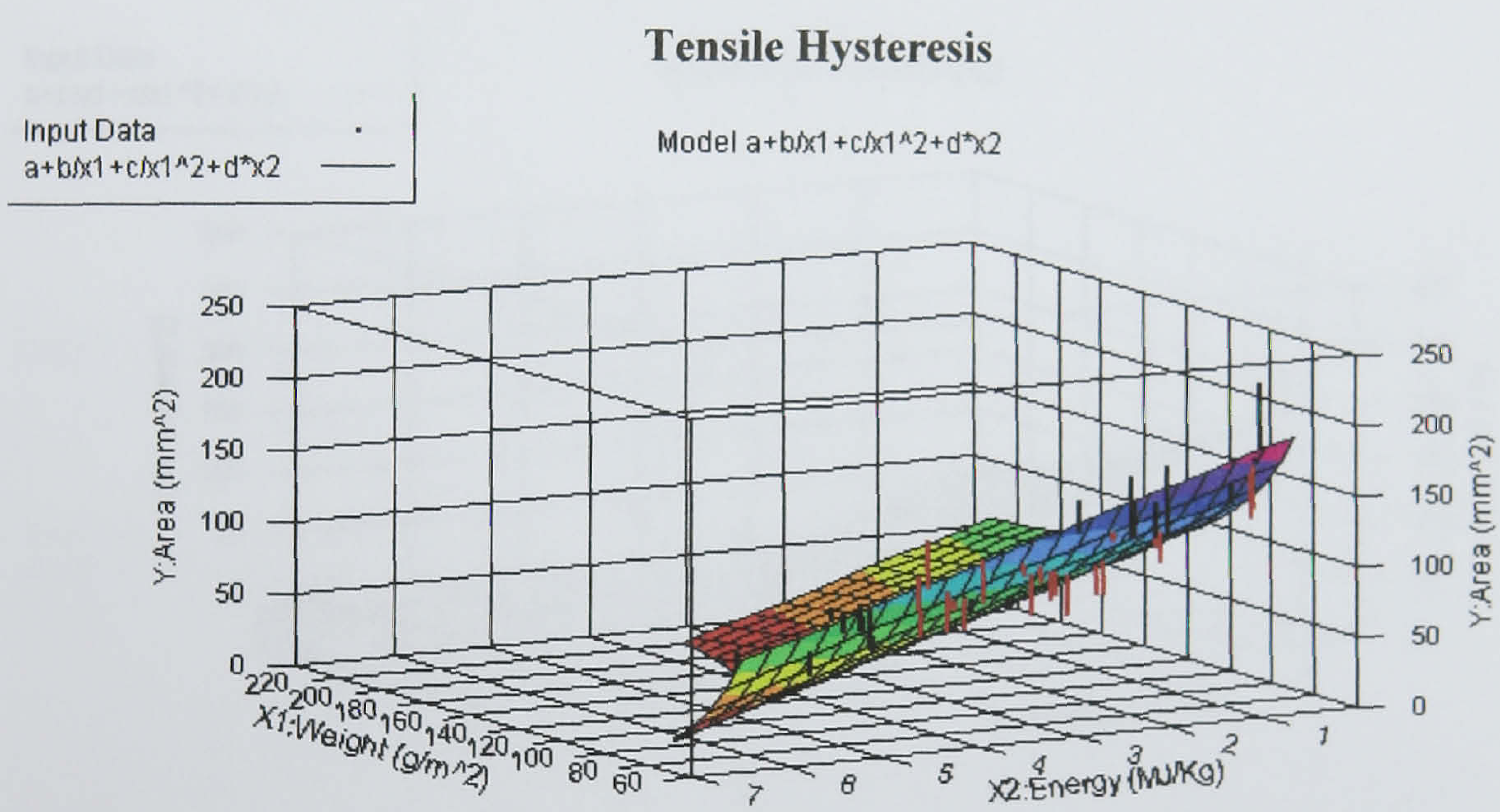


Figure 7.10 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Tensile Hysteresis in the MD

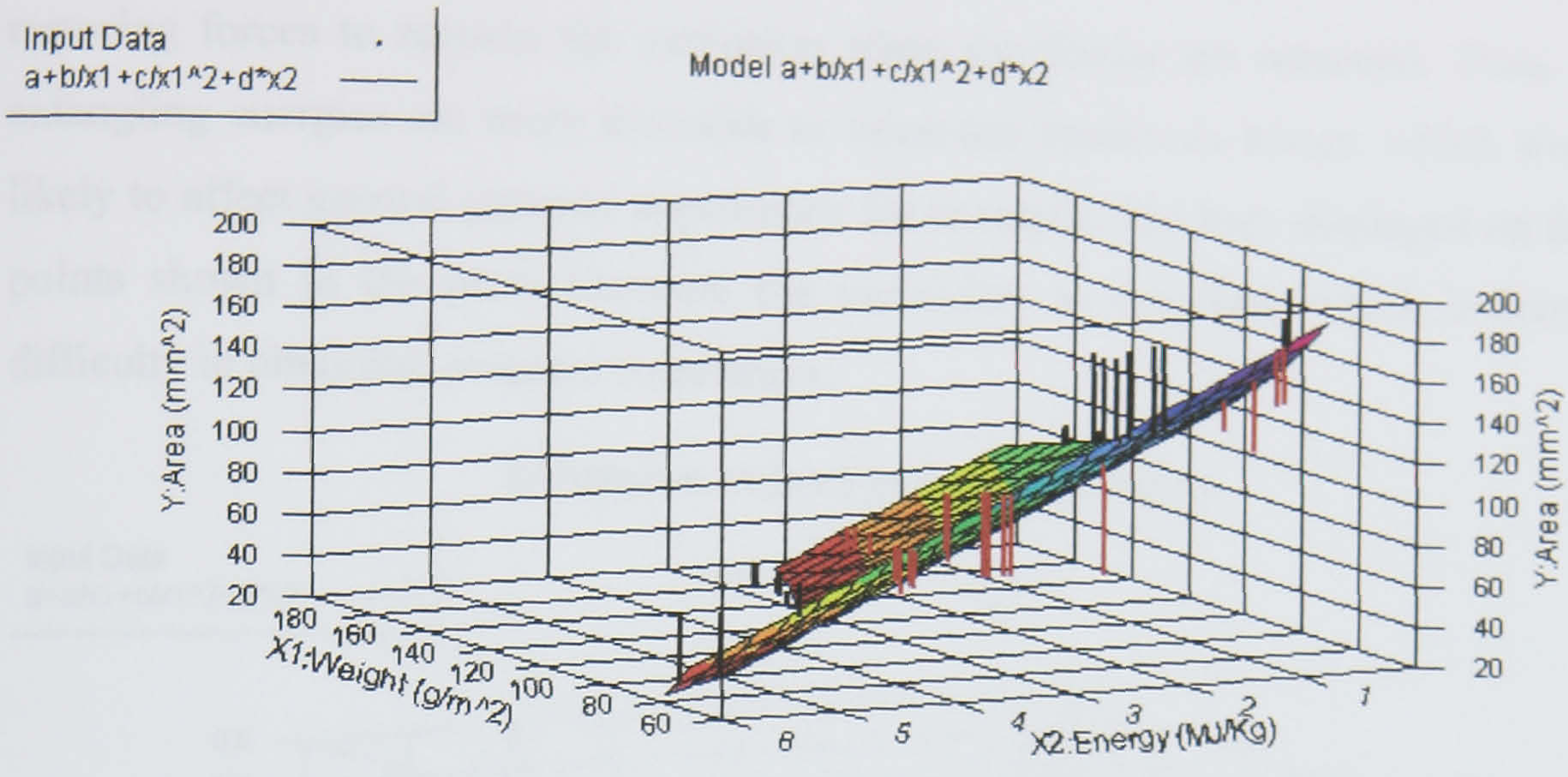


Figure 7.11 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Tensile Hysteresis in the CD

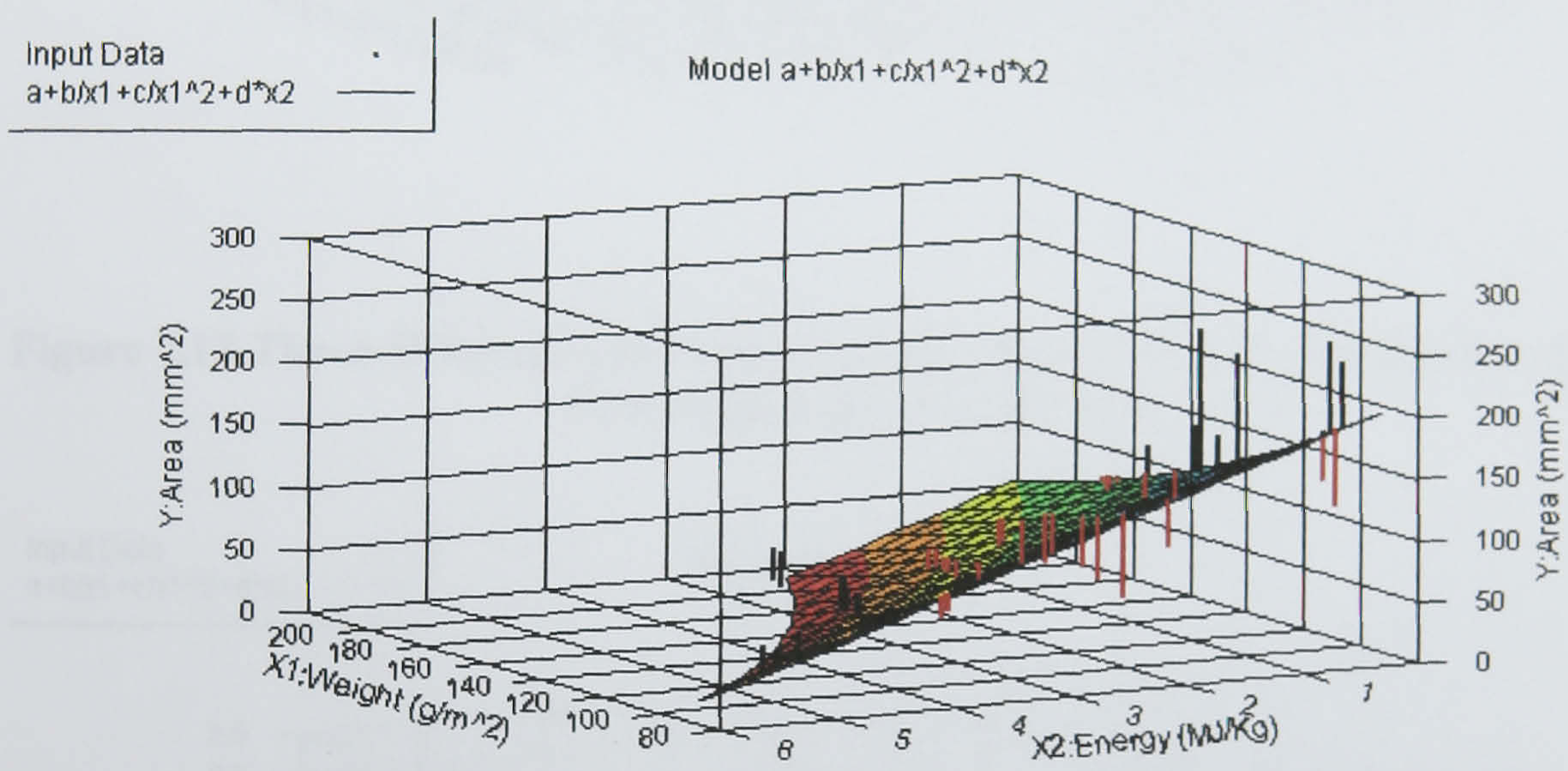


Figure 7.12 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Tensile Hysteresis in the Bias Direction

Figures 7.10 – 7.12 show that the hysteresis in contrast, is more dependent on the specific energy than the area density. The hysteresis is directly proportional to the hydroentanglement energy used. The lower the hydroentanglement energy that is used, the higher hysteresis that is generated. This is probably due to the limited fabric coherence and friction created in the fabric structures at low specific energies. Consequently, during extension the fibres slide over each other with only limited elastic restoring forces to recover the extension when the forces are removed. Thus, higher entangling energies are more desirable to minimise hysteresis losses, which would be likely to affect general garment appearance for example. The bars displayed on the data points shown in the plots illustrate the variability in the data, which indicates the difficulty in obtaining accurate correlation.

Extension at load of 5 gf/cm (E5%)

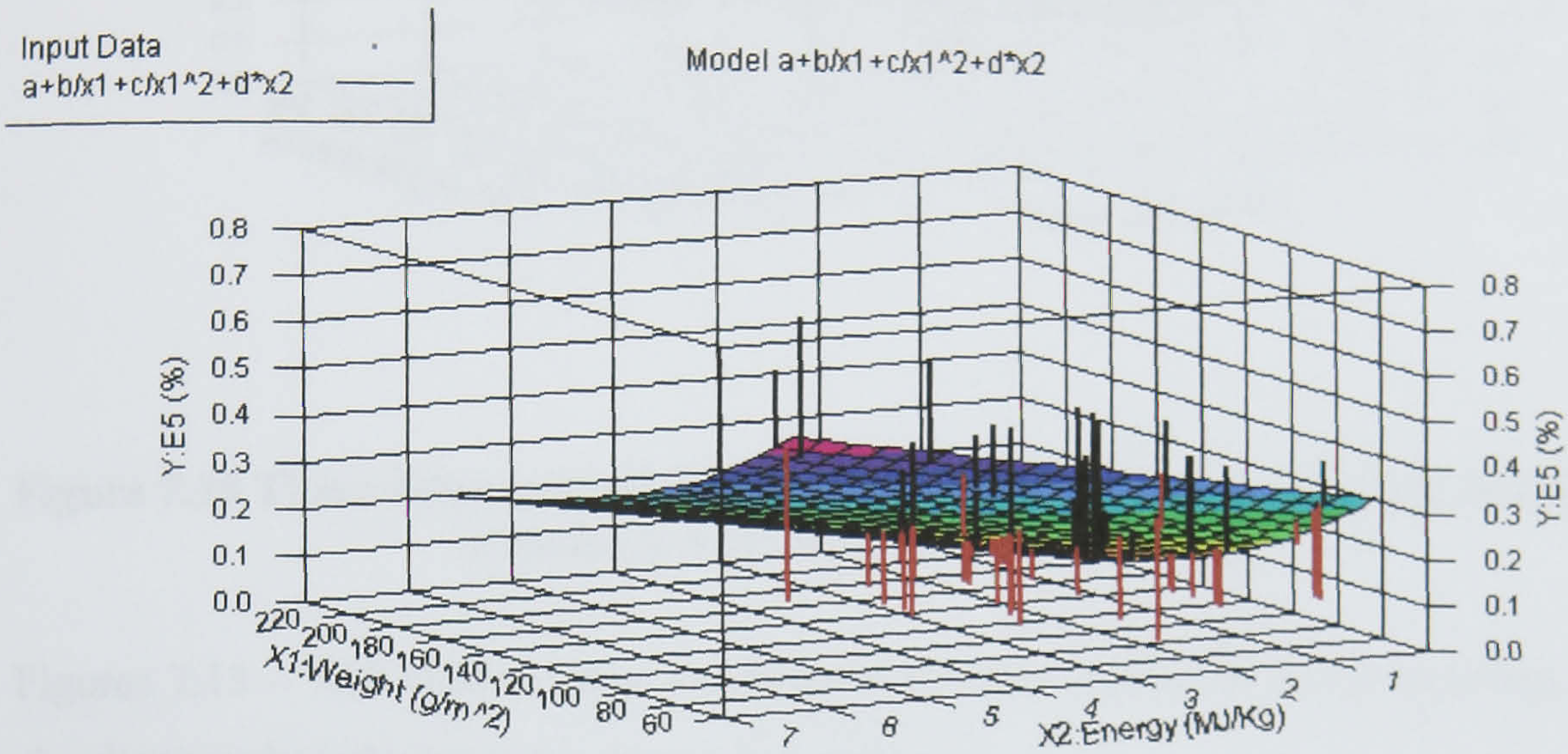


Figure 7.13 Three-Dimensional Model that Correlates Weight, Specific Energy and Extension 5 gf/cm in the MD

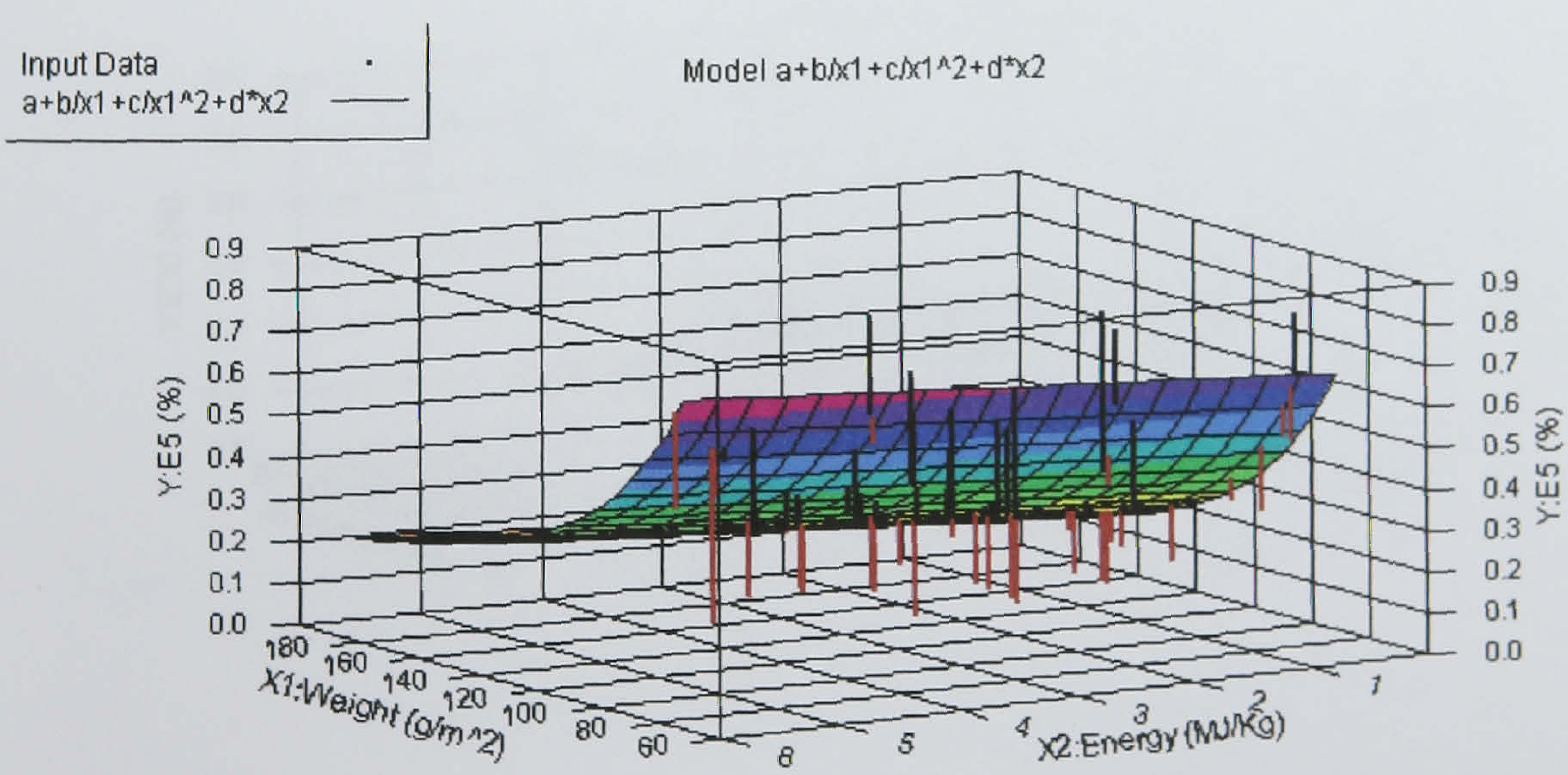


Figure 7.14 Three-Dimensional Model that Correlates Weight, Specific Energy and Extension 5 gf/cm in the CD

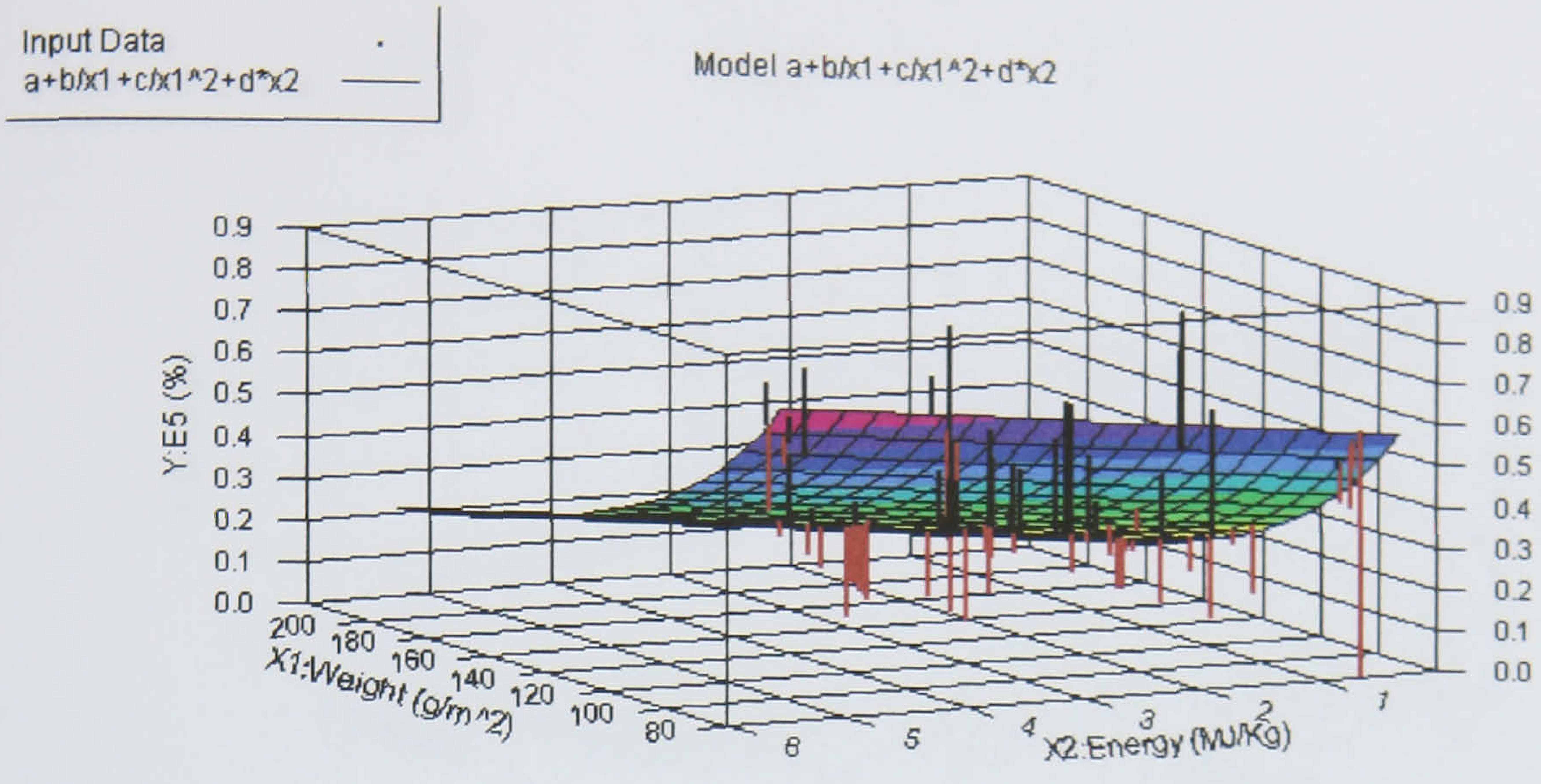


Figure 7.15 Three-Dimensional Model that Correlates Weight, Specific Energy and Extension 5 gf/cm in the Bias Direction

Figures 7.13 – 7.15 show a large variation in the data at low values of extension, which simultaneously influences the regression analysis.

Extension at load of 20 gf/cm (E20%)

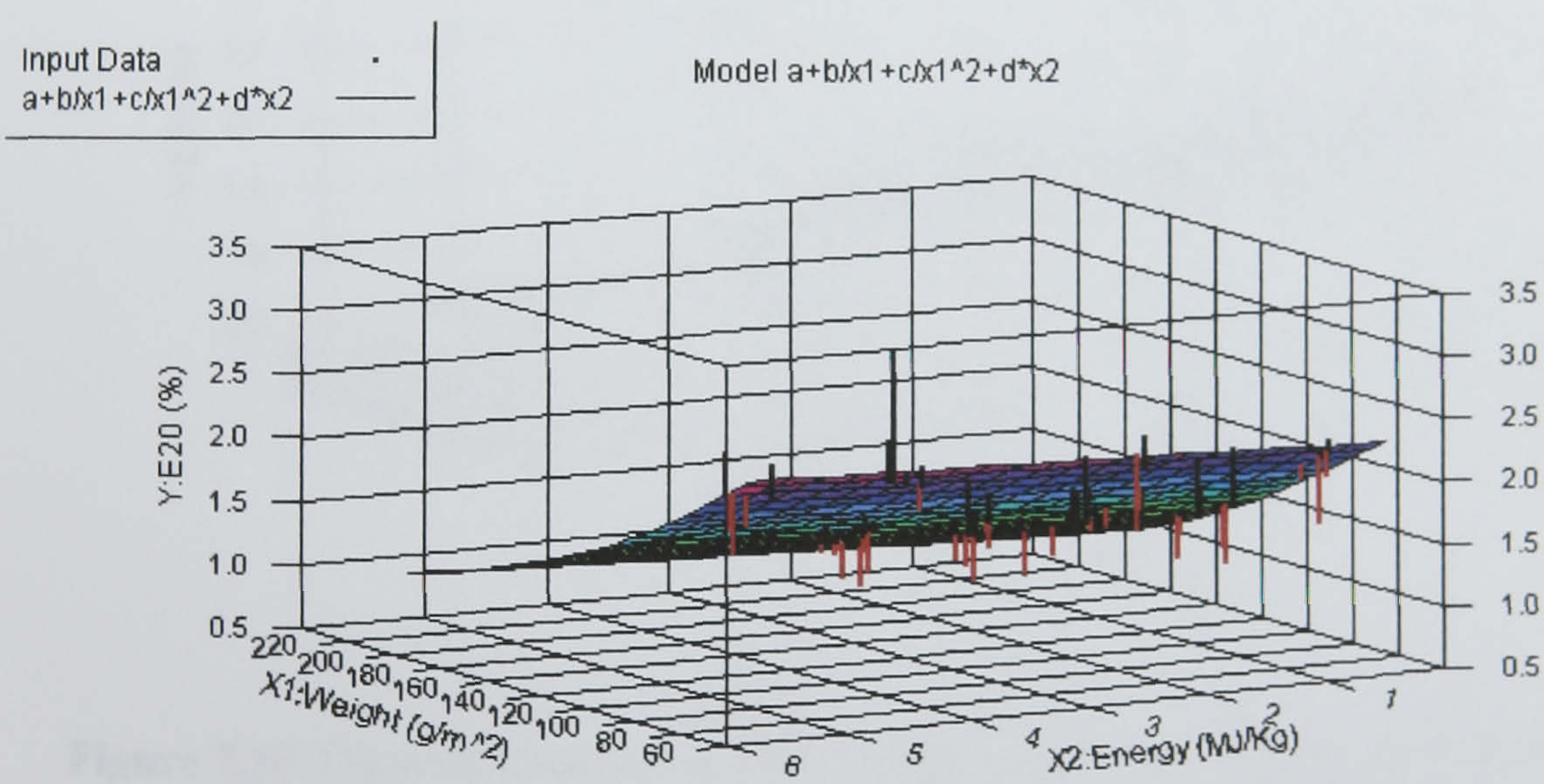


Figure 7.16 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension 20 gf/cm in the MD

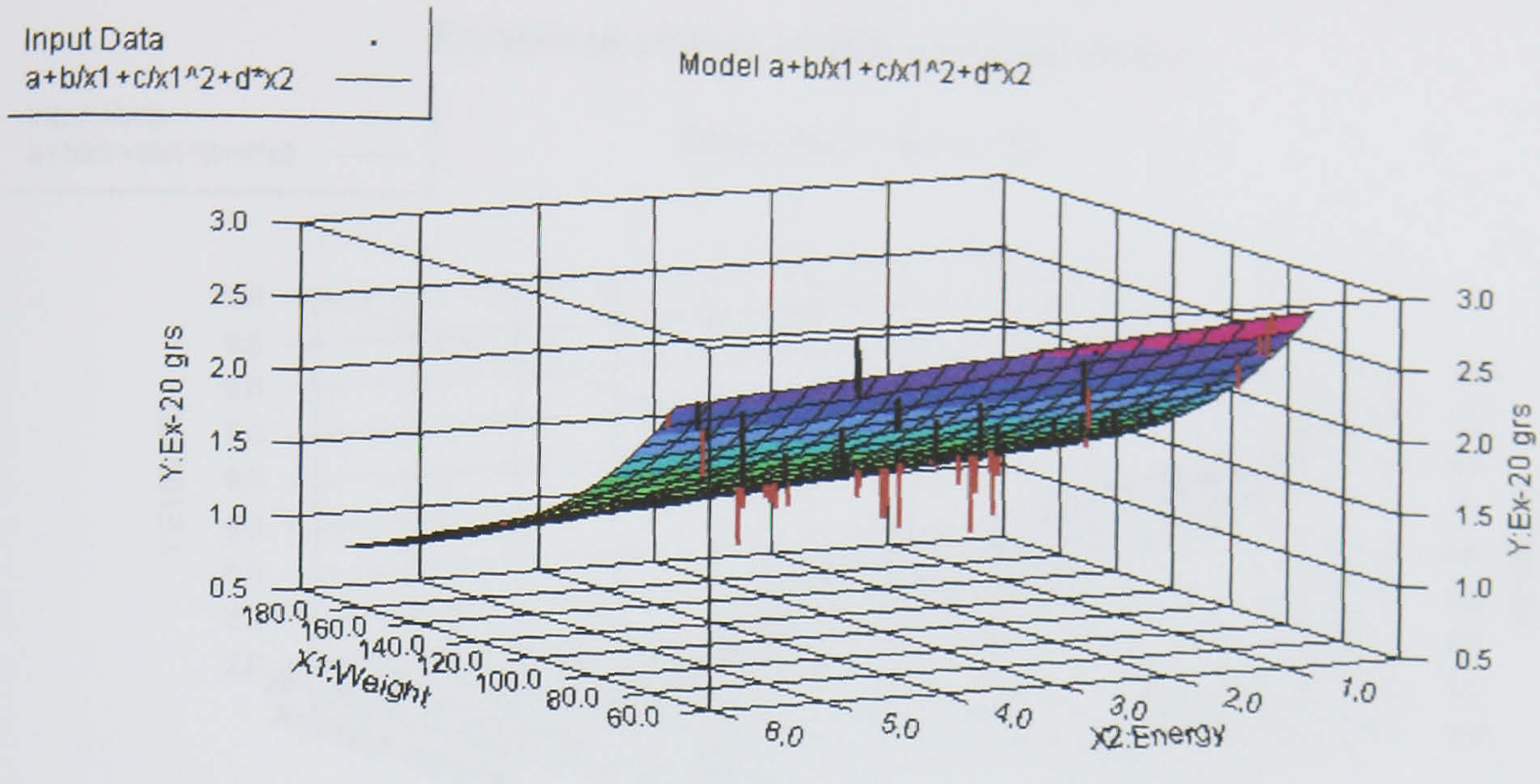


Figure 7.17 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension 20 gf/cm in the CD

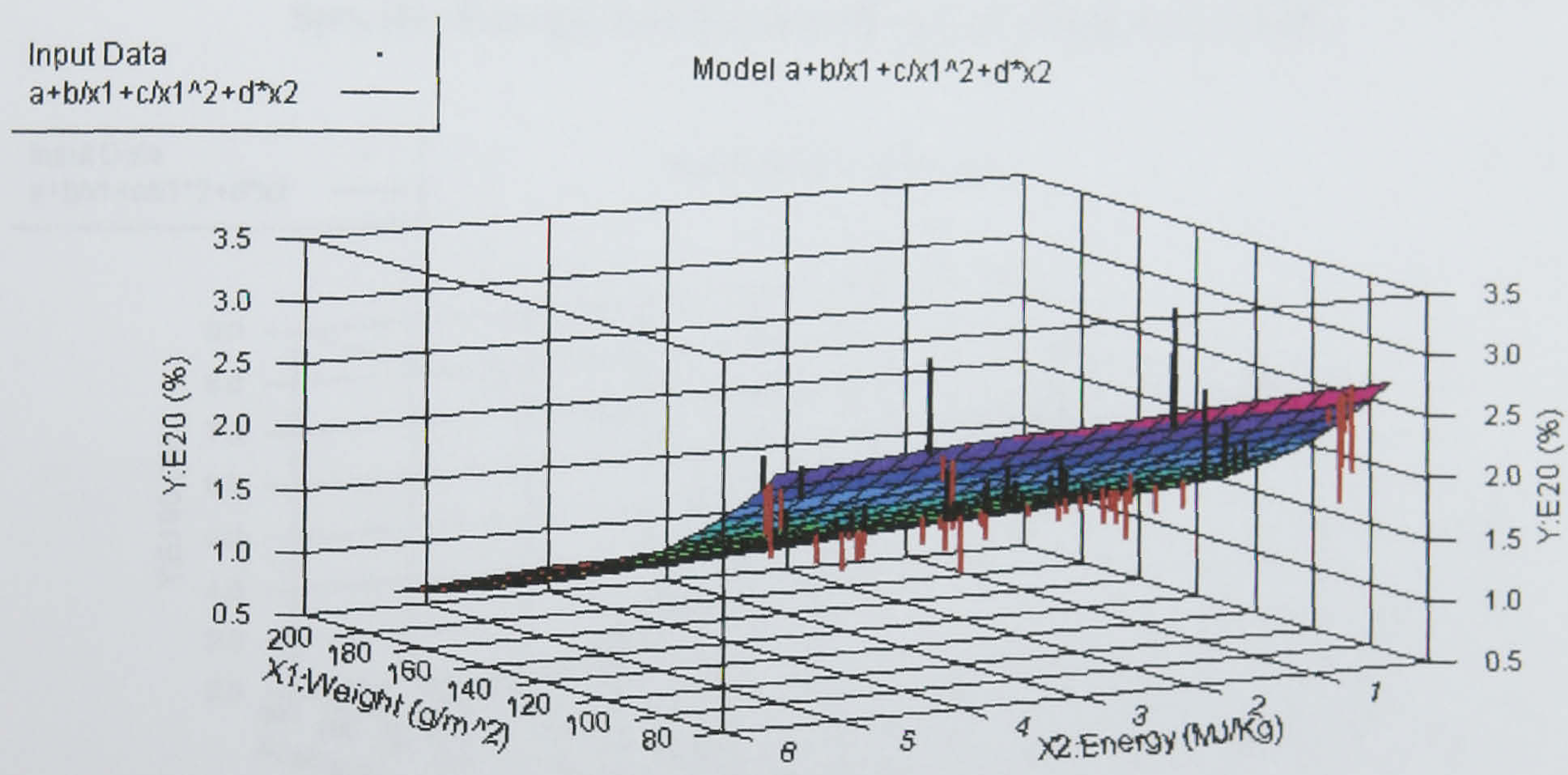


Figure 7.18 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension 20 gf/cm in the Bias Direction

Extension at load of 100 gf/cm (E100%)

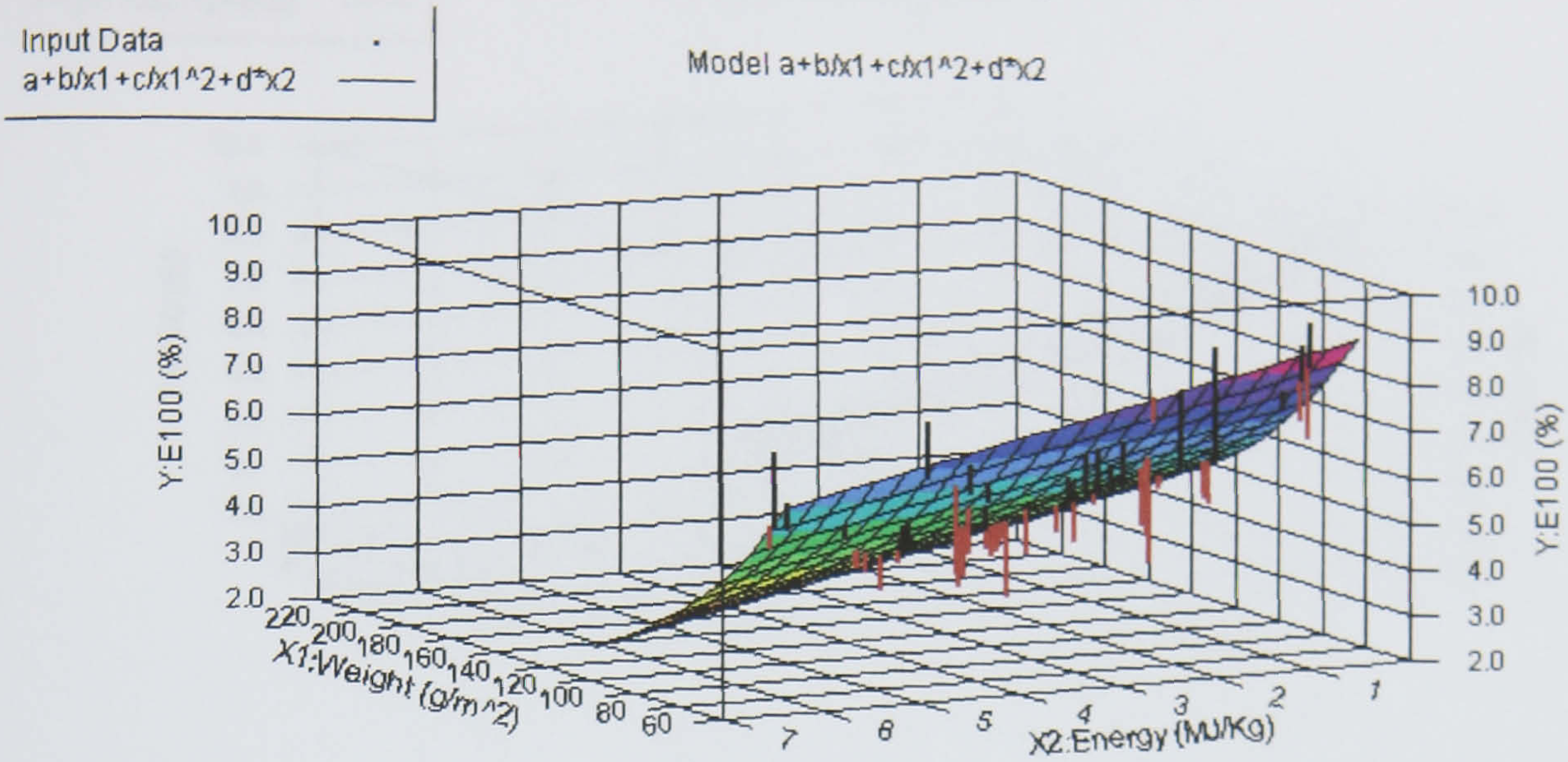


Figure 7.19 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension at 100 gf/cm in the MD

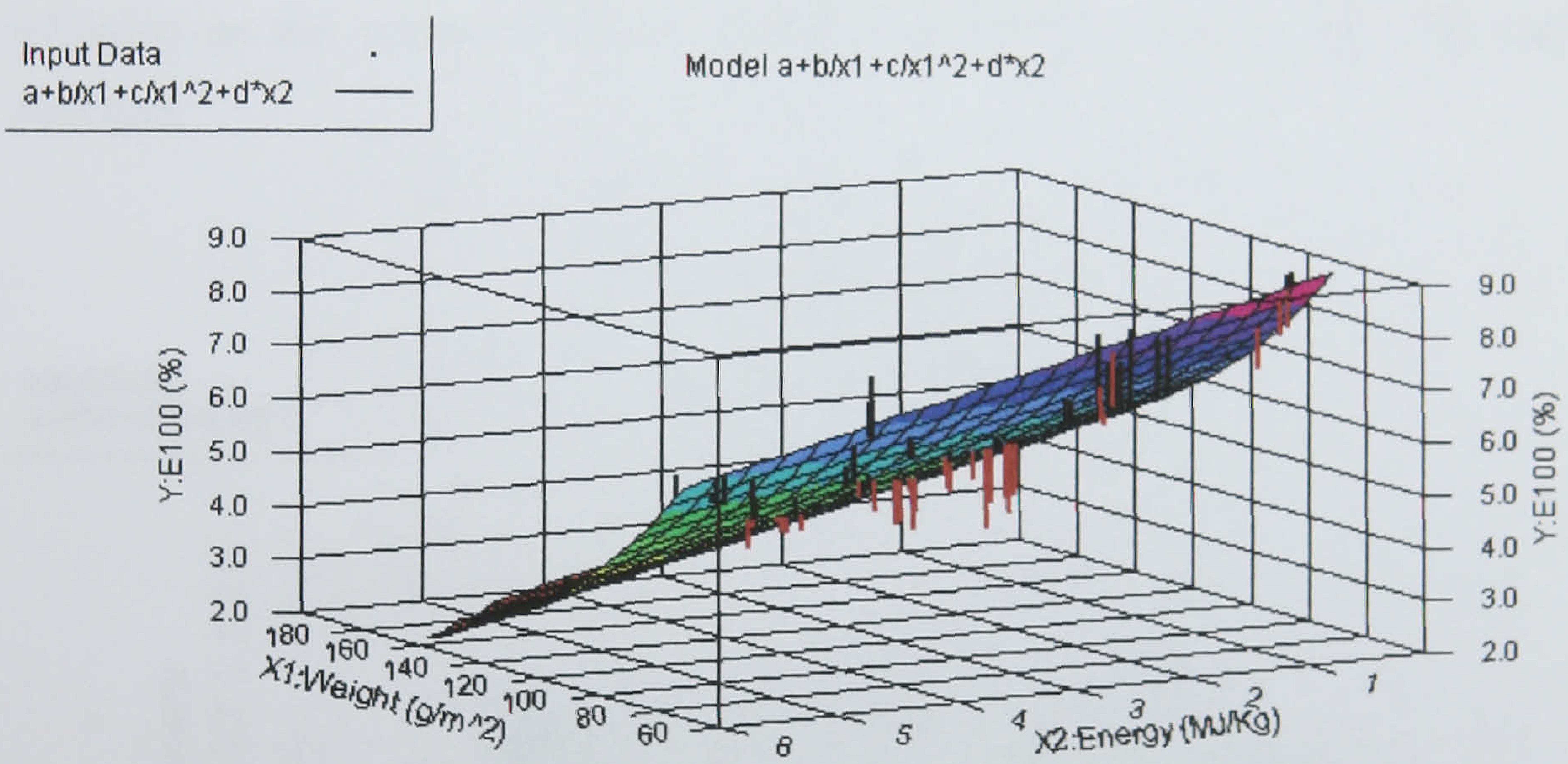


Figure 7.20 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension at 100 gf/cm in the CD

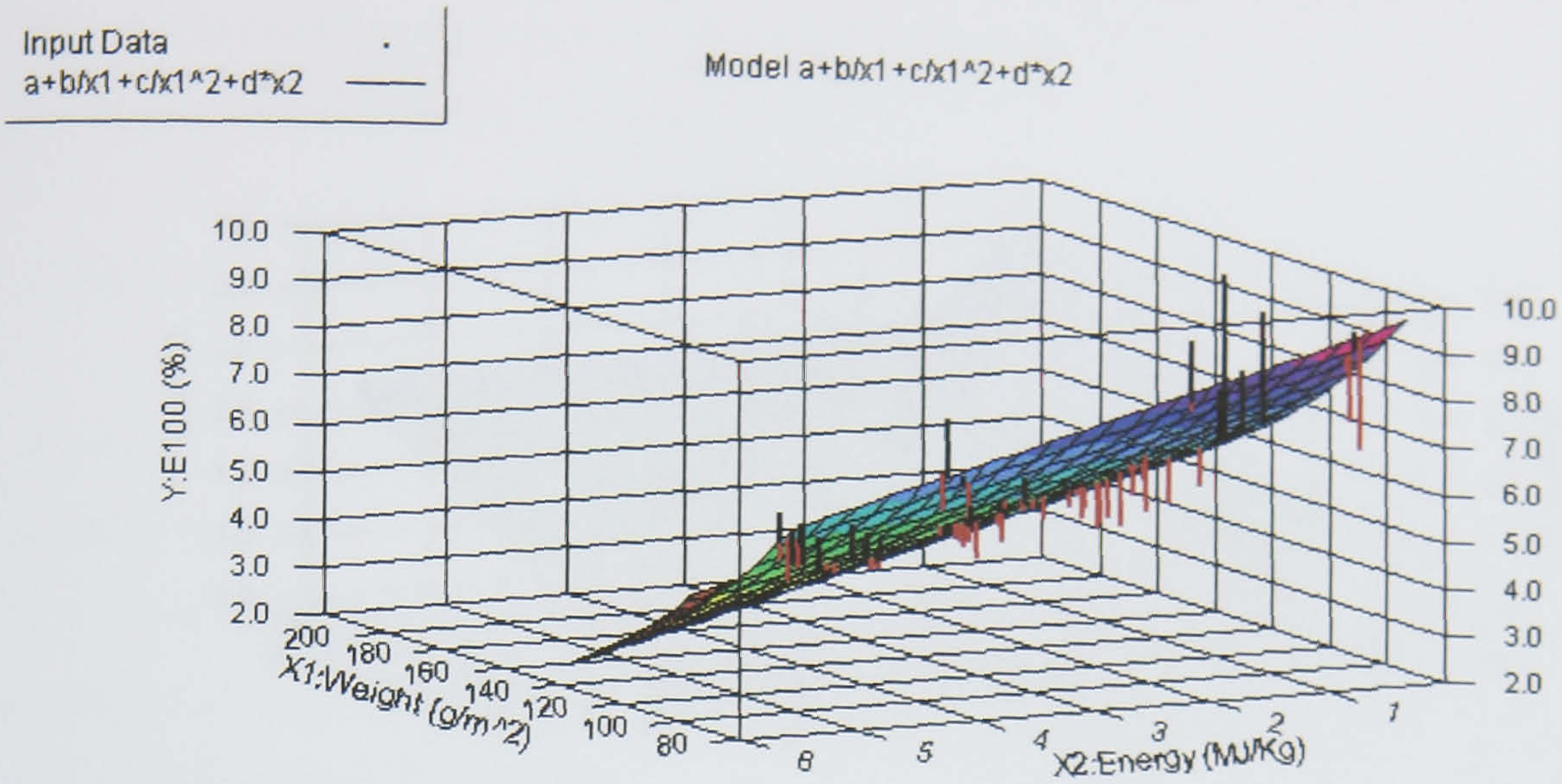


Figure 7.21 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Extension at 100 gf/cm in the Bias Direction

Figures 7.19 – 7.21 show that both the area density and the specific energy have a great influence on the values of fabric extension at 100 gf/cm in the MD, CD and bias direction.

Formability

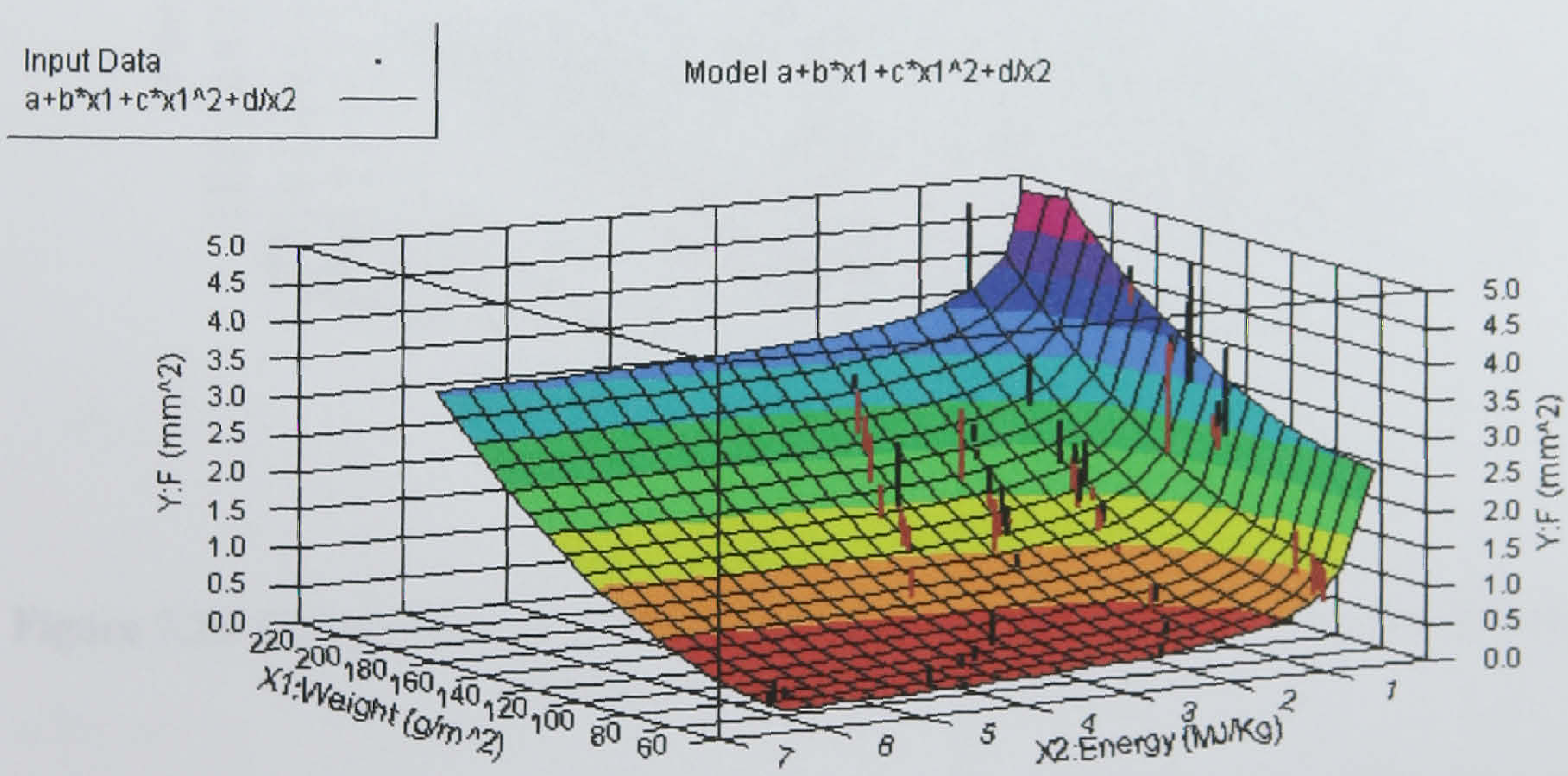


Figure 7.22 Three-Dimensional Model that Correlates Weight (Area Density) Specific Energy and Formability in the MD

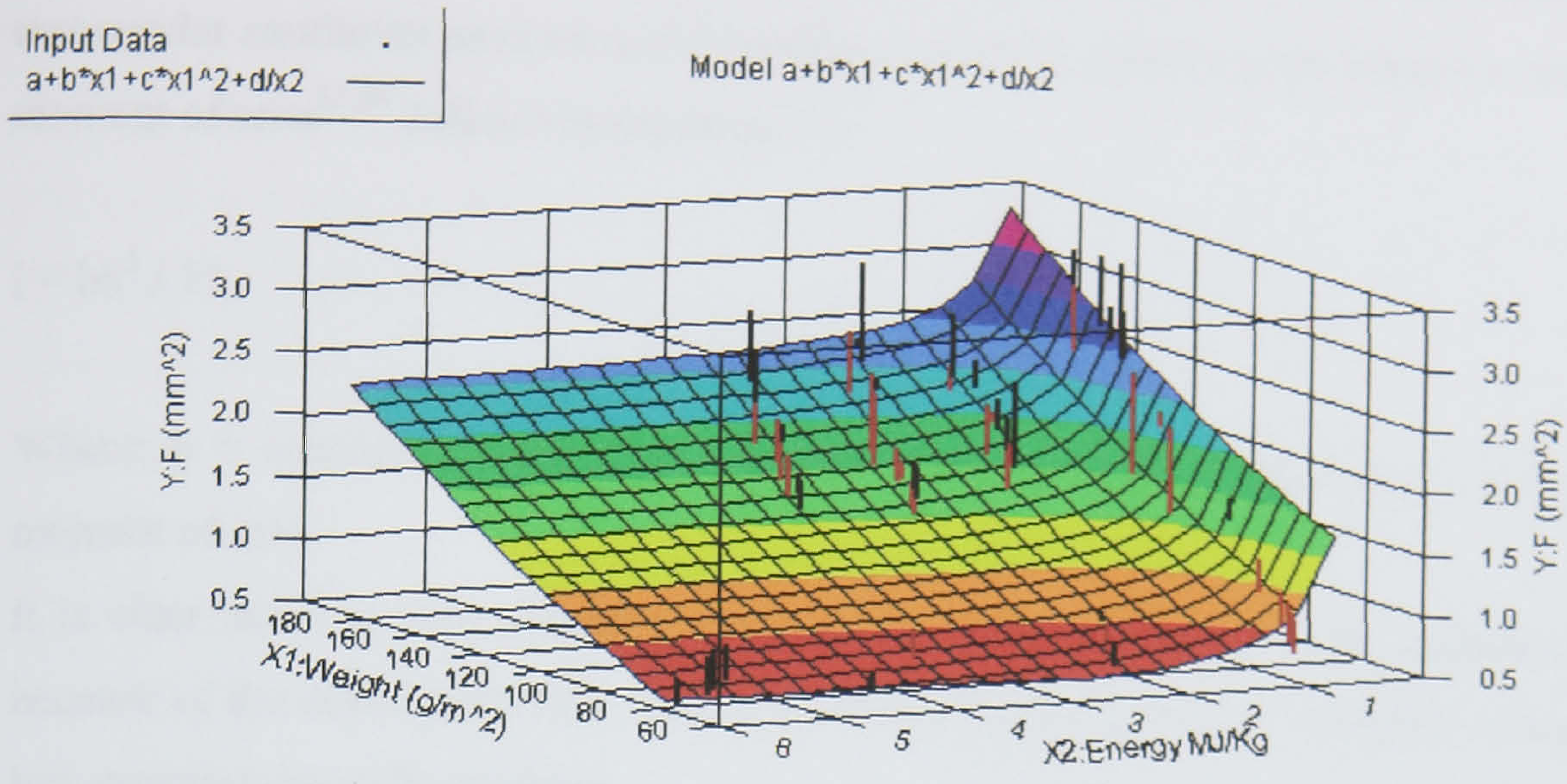


Figure 7.23 Three-Dimensional Model that Correlates Weight, Specific Energy and Formability in the CD

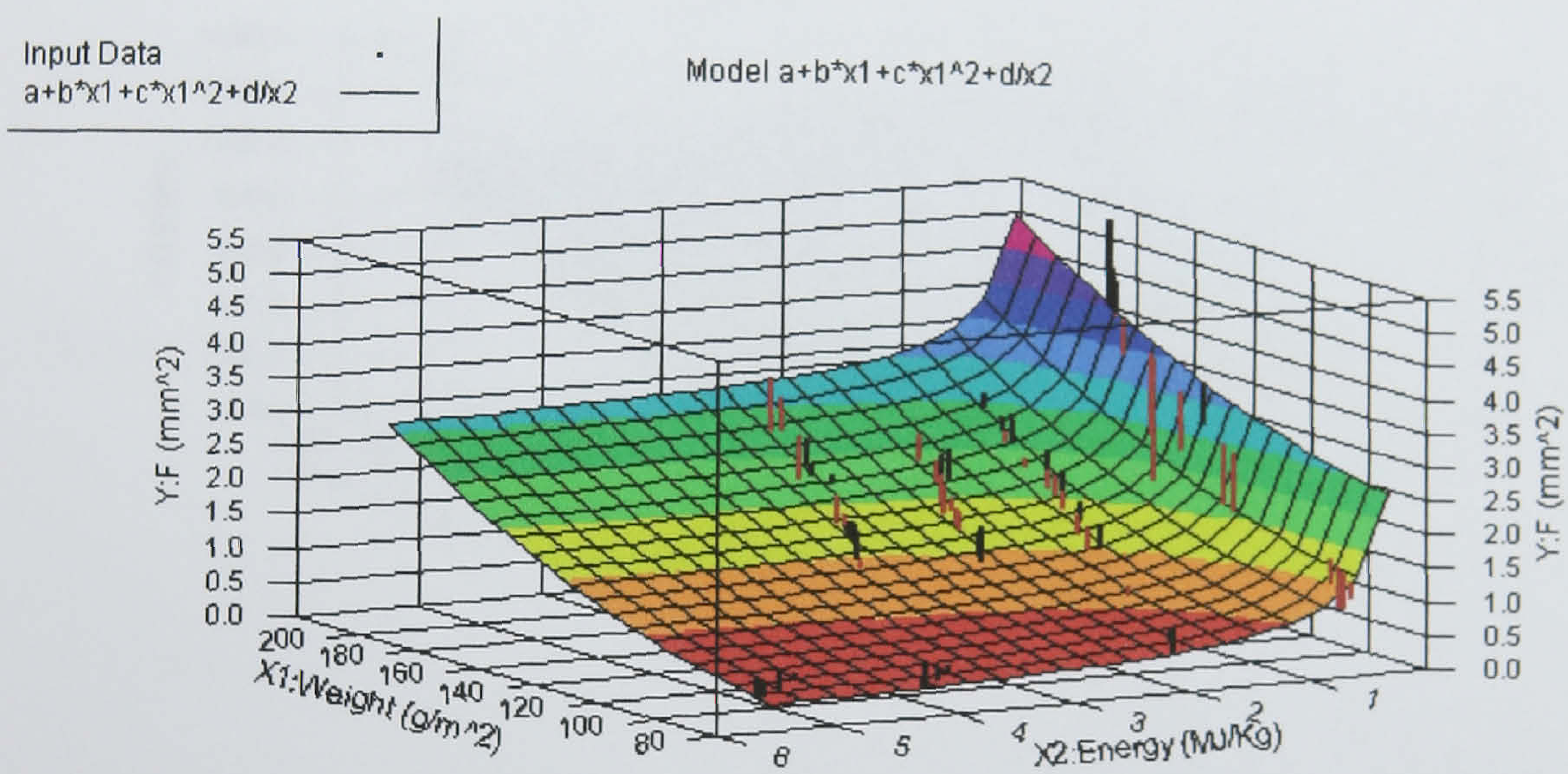


Figure 7.24 Three-Dimensional Model that Correlates Weight, Specific Energy and Formability in the Bias Direction

Figures 7.22 – 7.24 show that the area density of the fabrics has the more dominant effect on the fabric formability apart from at low values of specific energy, where the consolidation of the fabric, is of course, lower. All these values reflect that when there is more opportunity for fibre movement, there will be less elastic recovery (see hysteresis properties), which generates higher formability values. A principal cause of the higher bending rigidity/length properties arises from the larger thickness values. For rectangular cantilever structures the bending rigidity is directly proportional to the polar moment of area[55,56] defined by equation 1.4

$$I = bh^3 / 12$$

Where: b = cantilever width, h = depth or thickness of the sample and I = the polar moment of area.

It is clear that I is very sensitive to the depth or the thickness of the sample (fabric) because of the cubed term (h^3). This is particularly pronounced for samples entangled at low pressures/specific energies.

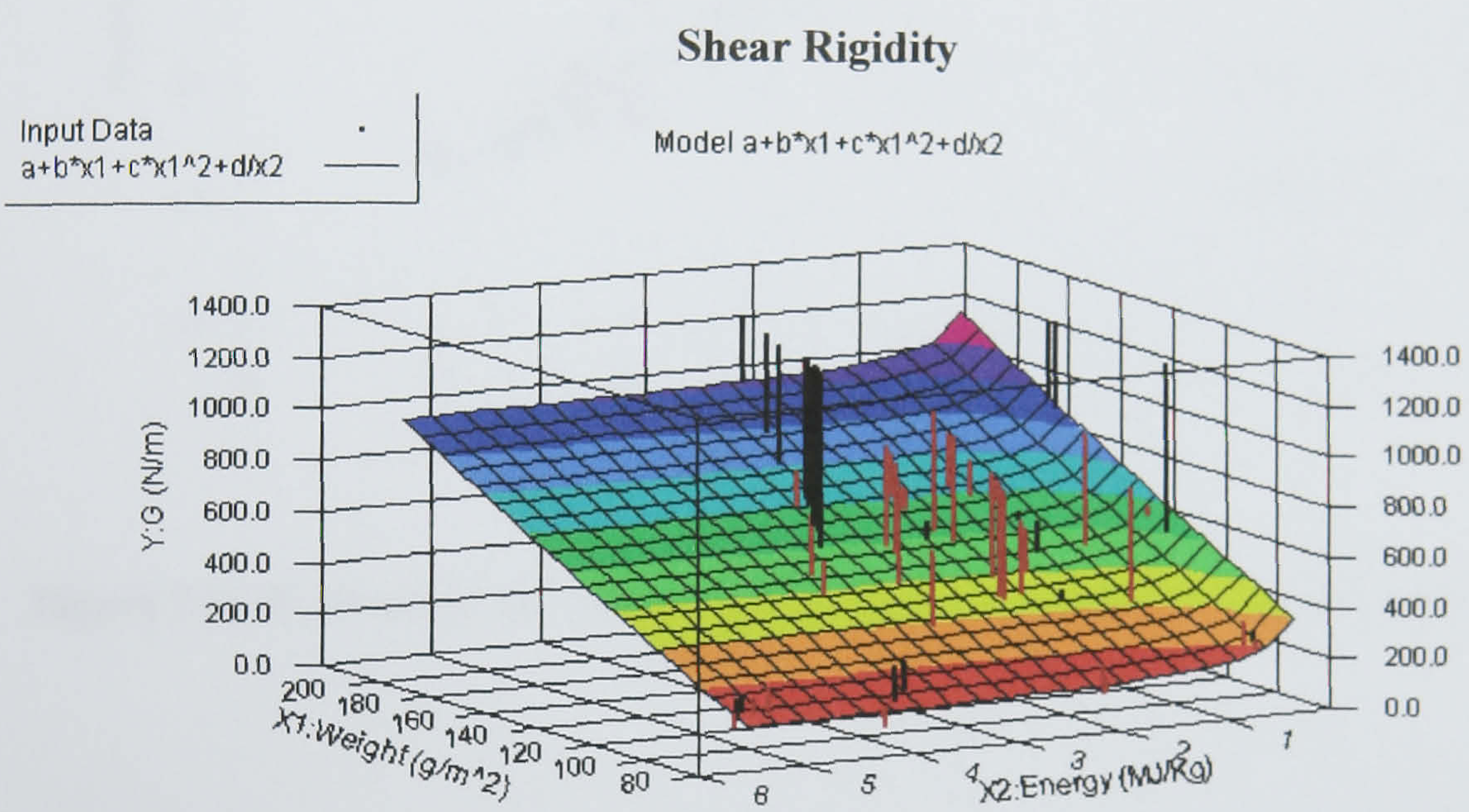


Figure 7.25 Three-Dimensional Model that Correlates Weight (Area Density), Specific Energy and Shear Rigidity in the Bias Direction

In figure 7.25, it is interesting to note that the area density of the fabric has a dominant effect on the fabric shear rigidity rather than the specific energy except for high values of specific energy.

7.7 Evaluation of the Models

For the purpose of evaluation, further samples were produced and the models were used to predict the mechanical property to assess the accuracy of prediction.

7.7.1 Plotting the Evaluated Values

Figures 7.26 – 7.34 show the correlations between the measured values and the predicted data produced by the models for all the mechanical properties of interest (BL, BM, BR, F, E5, E20, E100, Hysteresis and G) in MD, CD and bias directions. This was undertaken in an effort to determine the accuracy of the models.

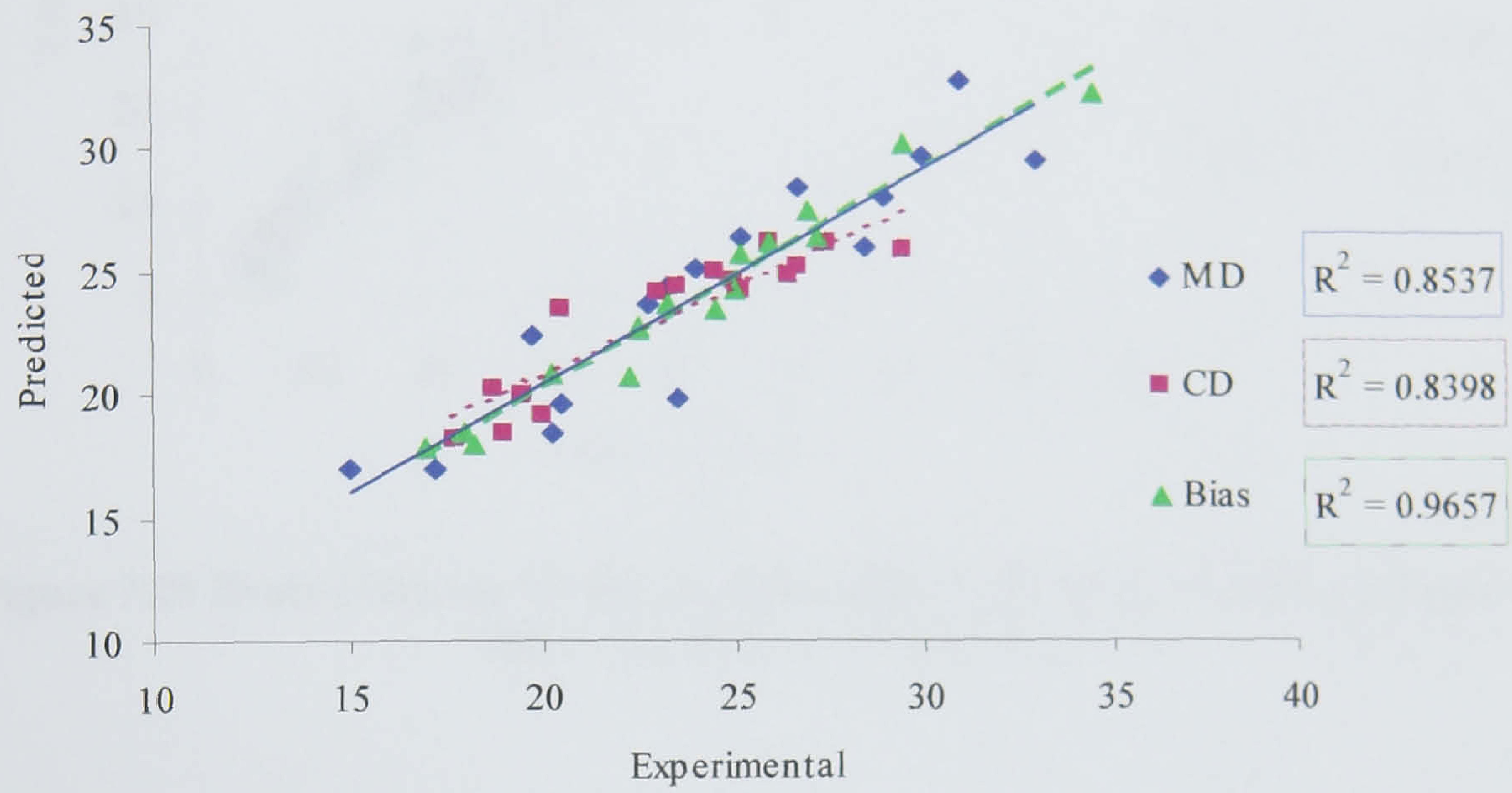


Figure 7.26 Evaluating the Model Produced for the Bending Length (mm) in MD, CD and Bias Directions

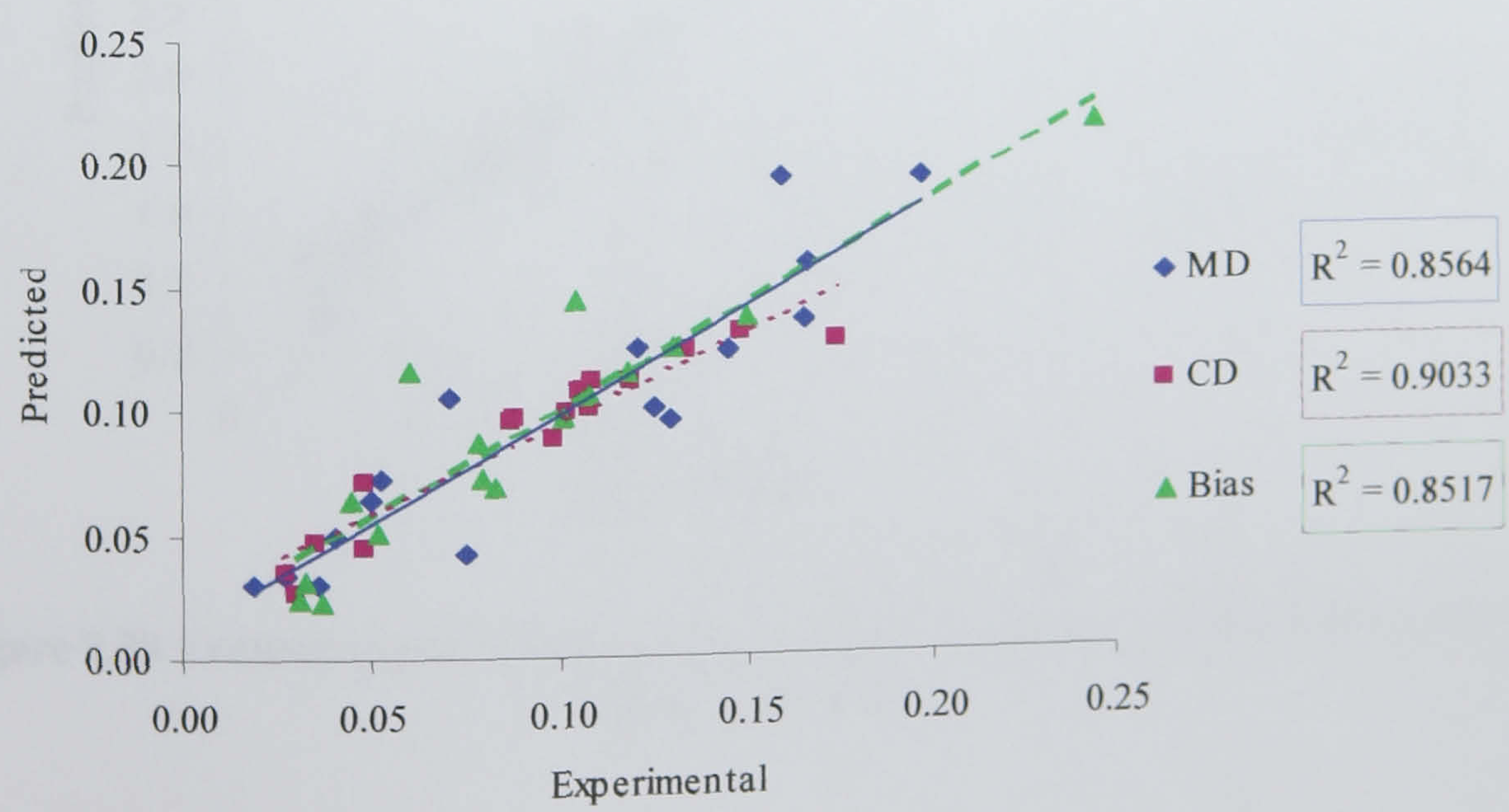


Figure 7.27 Evaluating the Model Produced for the Bending Modulus (Kg/m^2) in MD, CD and Bias Directions

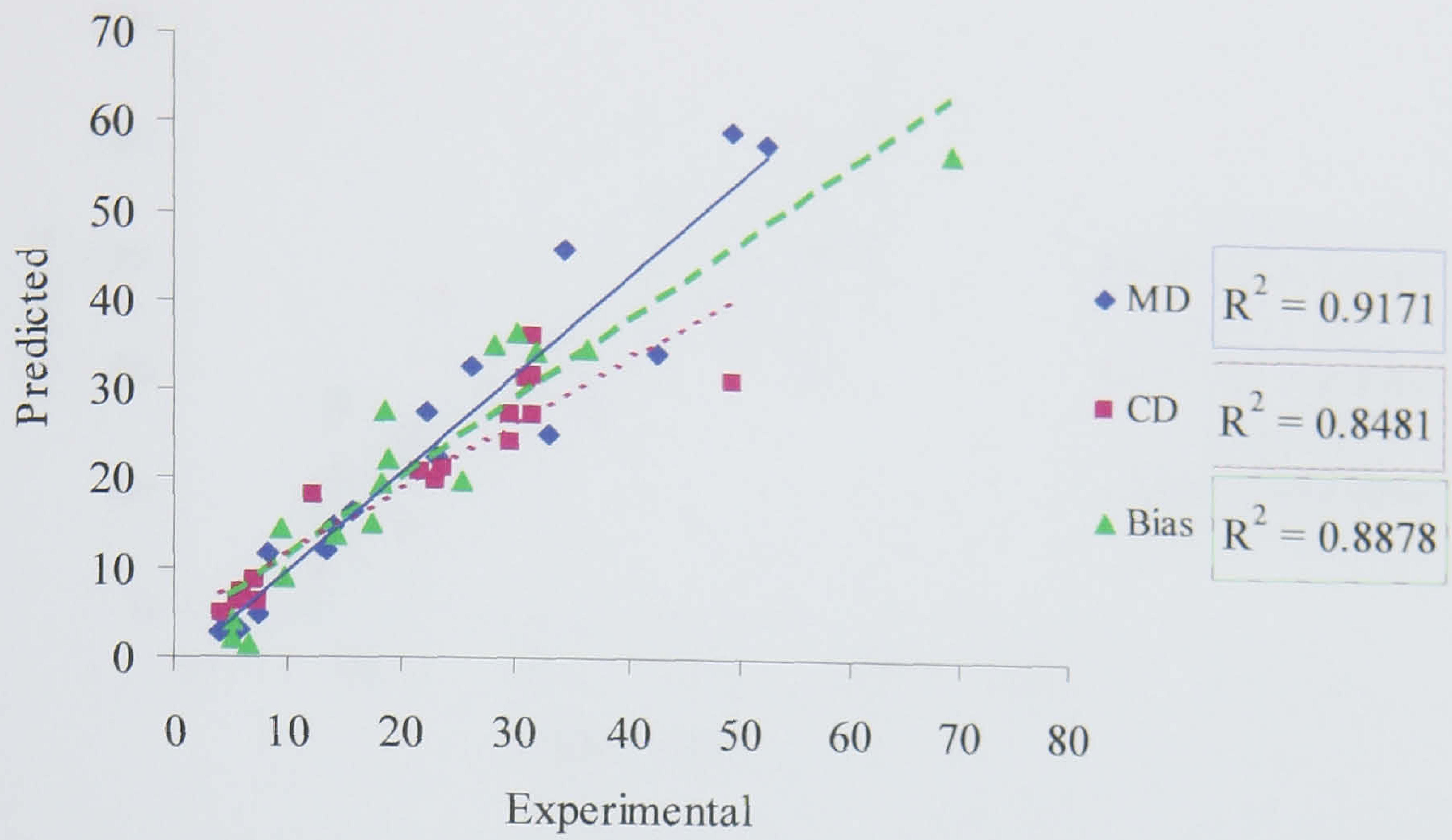


Figure 7.28 Evaluating the Model Produced for the Bending Rigidity (μNm) in MD, CD and Bias Directions

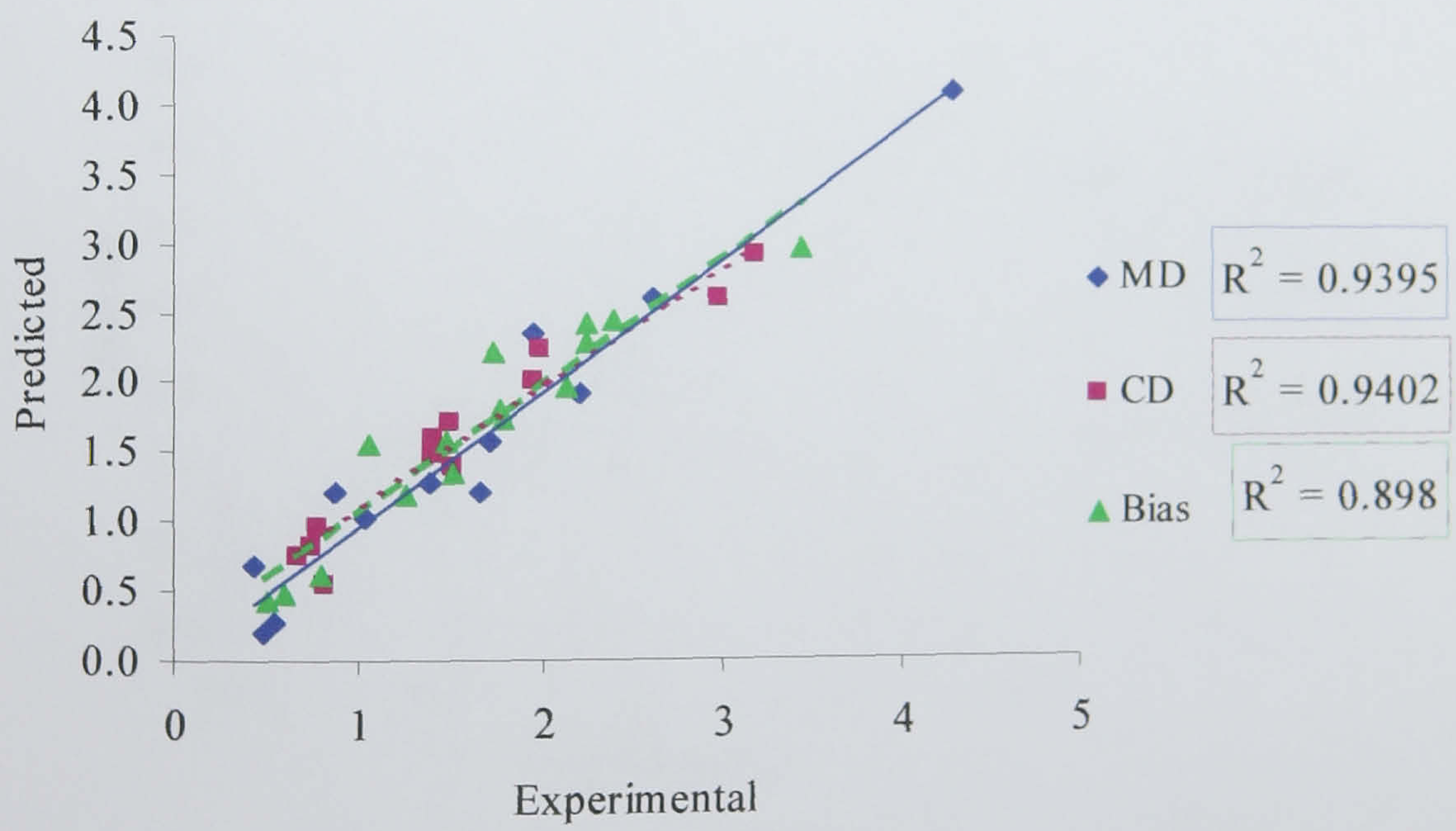


Figure 7.29 Evaluating the Model Produced for Formability in (mm^2) MD, CD and Bias Directions

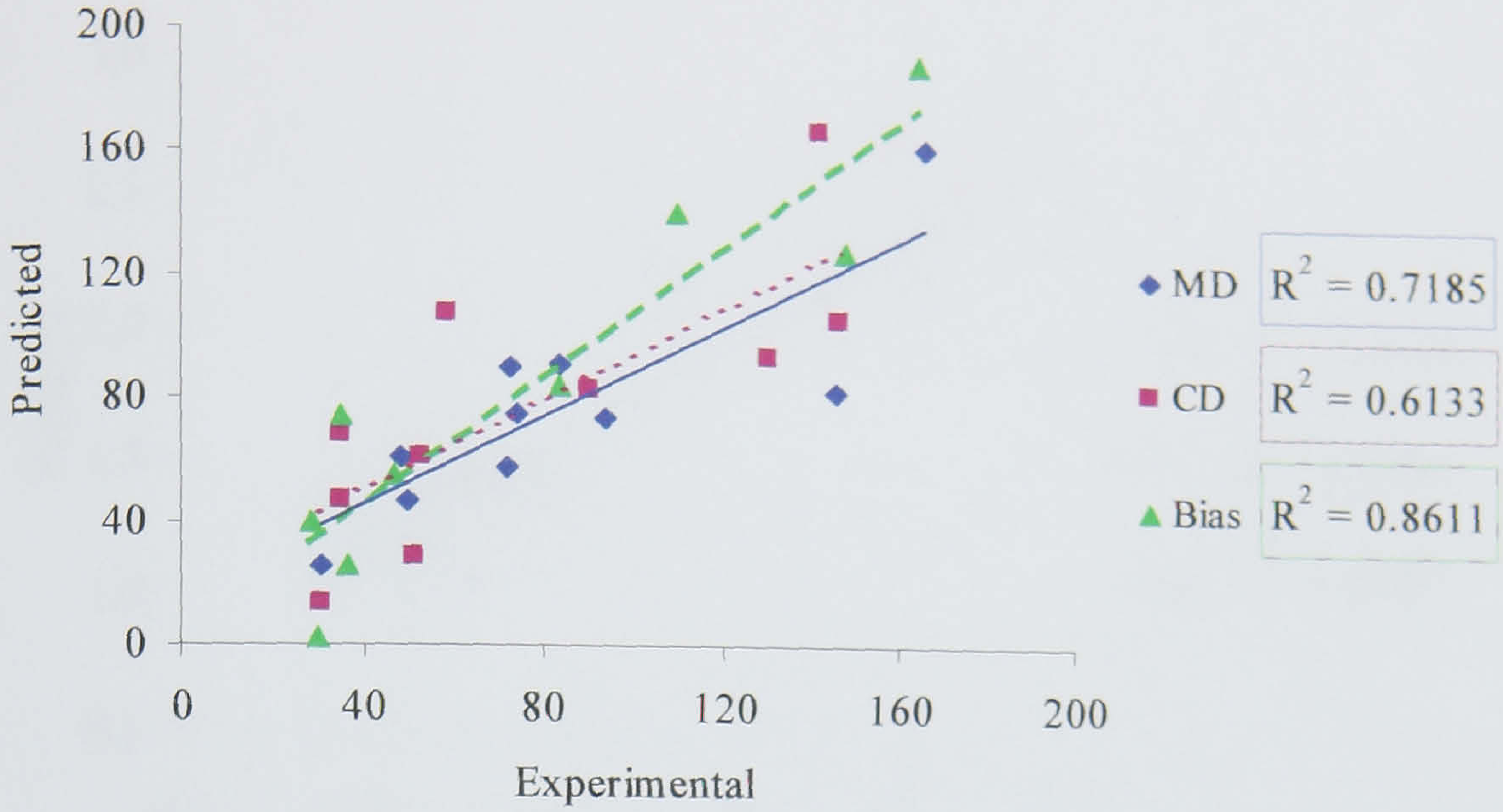


Figure 7.30 Evaluating the Model Produced for the Tensile Hysteresis (mm^2) in MD, CD and Bias Direction

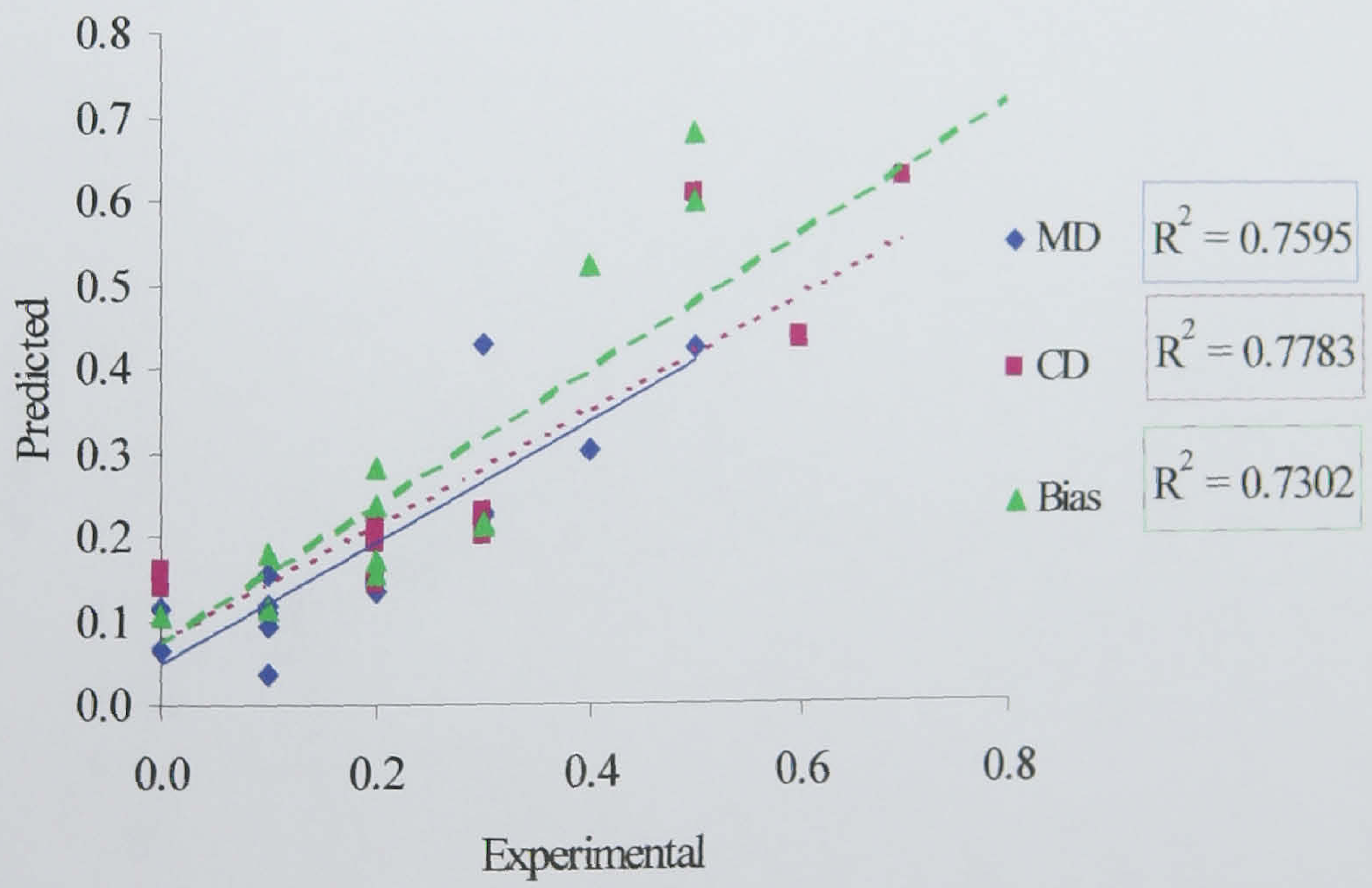


Figure 7.31 Evaluating the Model Produced for Extension at Load 5 gf/cm (%) in MD, CD and Bias Direction

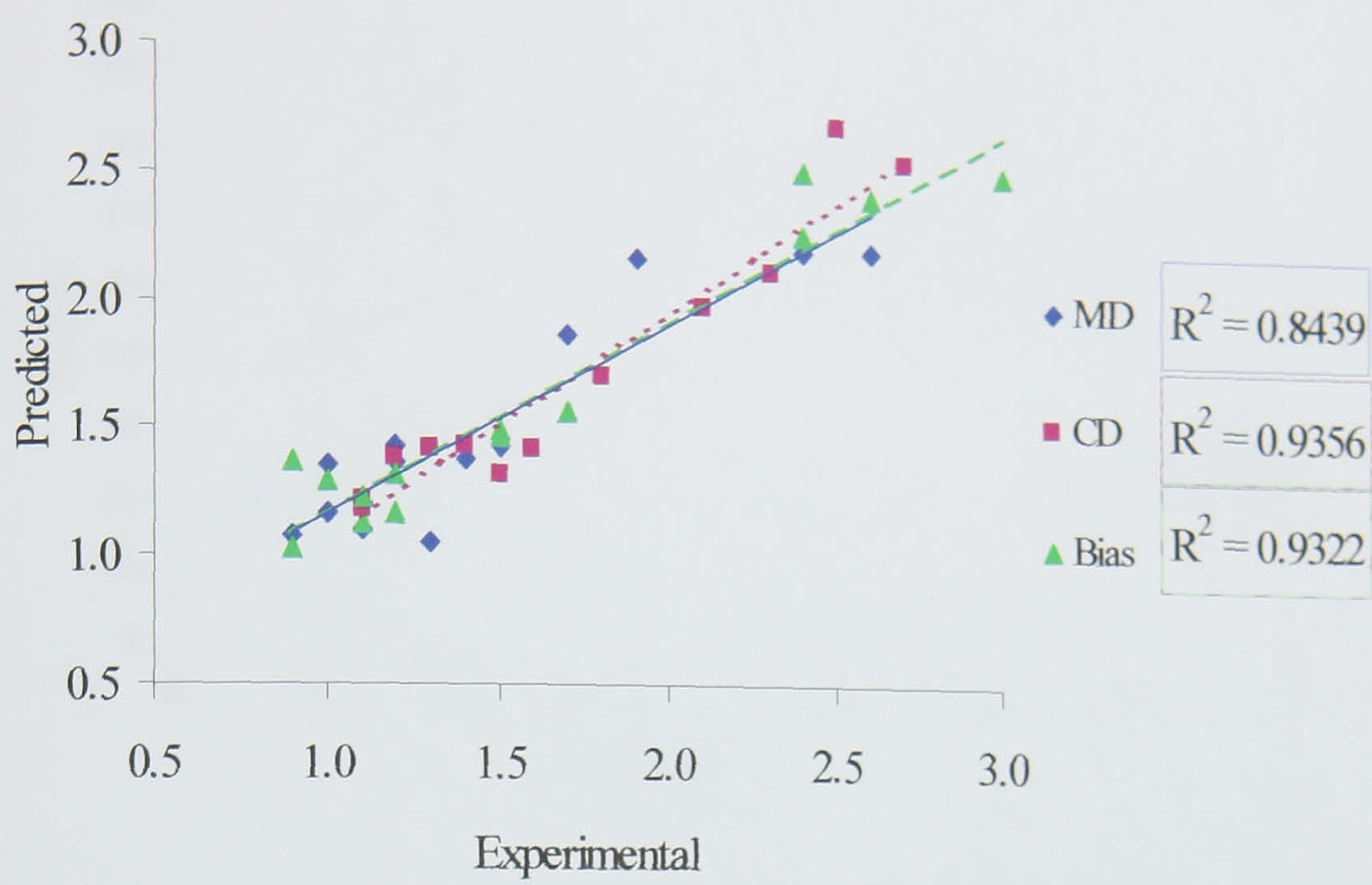


Figure 7.32 Evaluating the model produced for Extension at Load 20 gf/cm (%) in MD, CD and Bias Direction

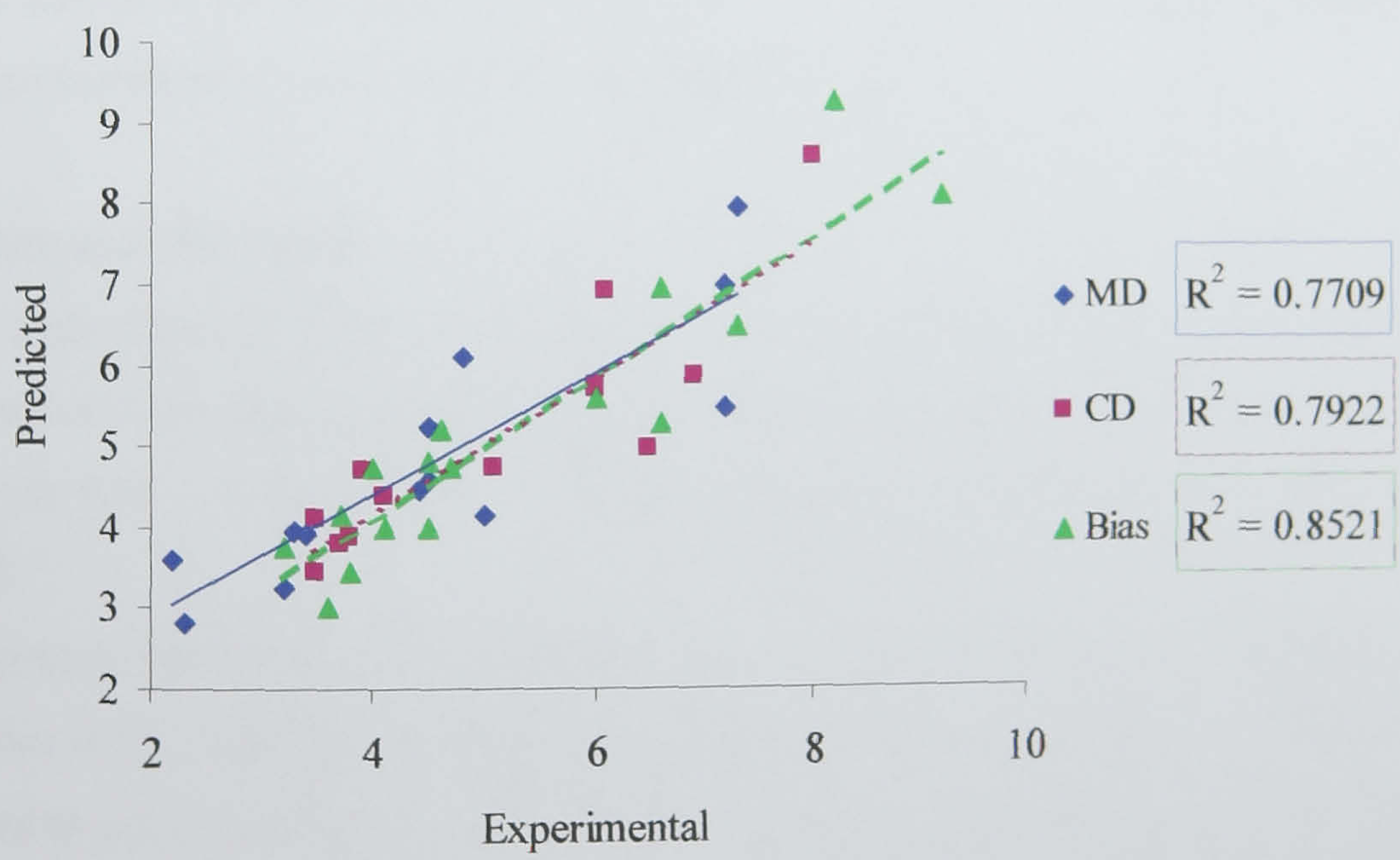


Figure 7.33 Evaluating the model produced for Extension at Load 100 gf/cm (%) in MD, CD and Bias Direction

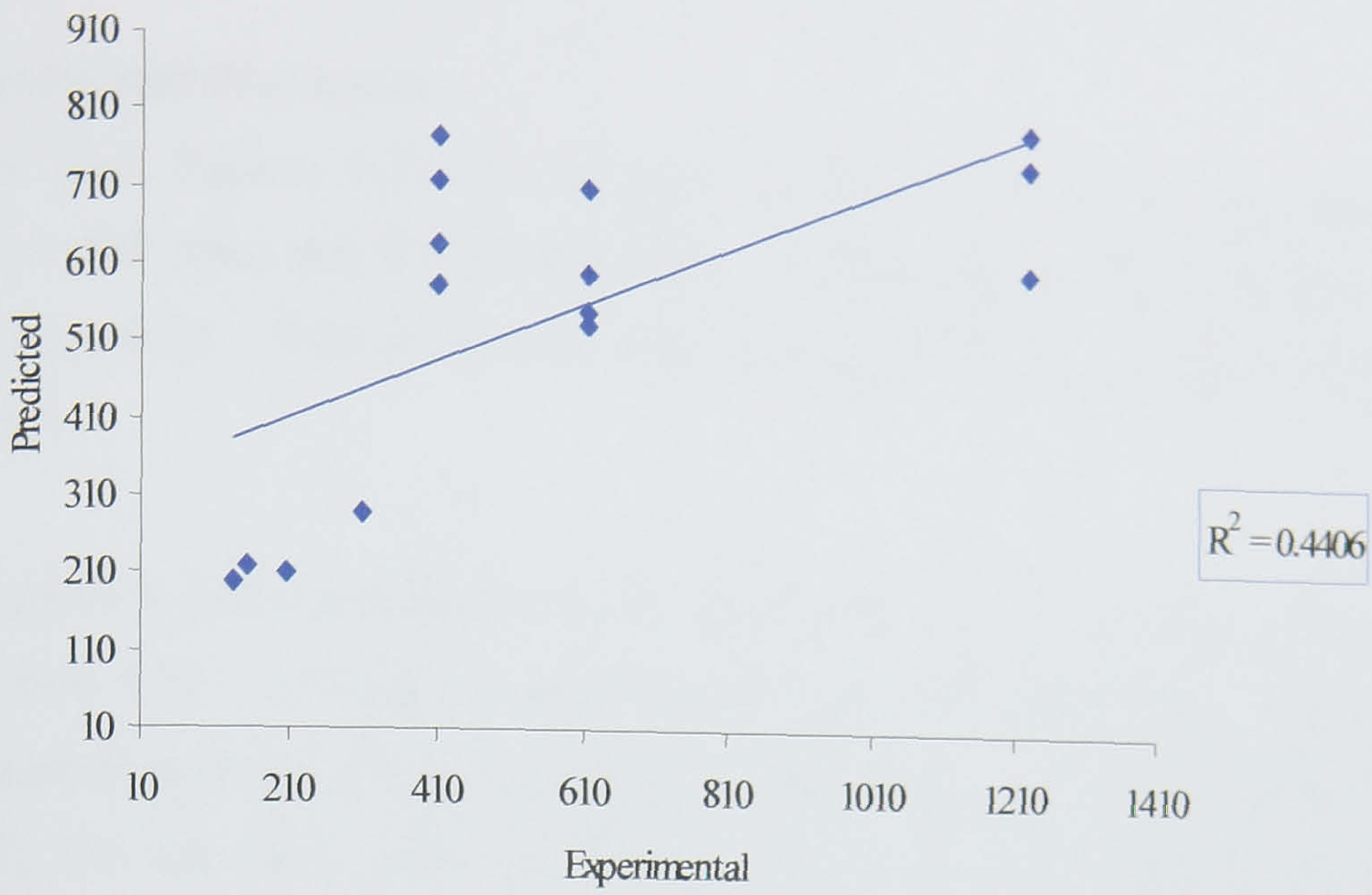


Figure 7.34 Evaluating the Model Produced for Shear Rigidity (μN/m)

Figures 7.26 – 7.34 show the correlations between the measured values and the predicted data produced by the models for all the mechanical properties in the MD, CD and Bias direction for all levels of specific energy used. In these figures, all the data used for generating the models, have been excluded.

7.8 Results and Discussion

As seen from Figures 7.26 – 7.34, there is good agreement between the actual data (experimental data) and the predicted data (from the model). The R^2 values obtained varied from 0.83 – 0.96 in the MD, CD and Bias directions respectively for BL, BM, BR and F.

With respect to fabric extension at different loads (5, 20 and 100 gf/cm respectively), R^2 varied from 0.73 – 0.94 in the MD, CD and Bias directions respectively, which is still considered to be in good agreement and for the hysteresis, R^2 varied from 0.73 – 0.94 in the MD, CD and Bias directions respectively. On the other hand, according to the calculation of the shear rigidity recommended in the FAST manual, (123/ E5% - Bias). The accuracy of prediction was poor with a low value of R^2 (0.44). This results from the low values of extensibility and high variability in the values.

and Bias direction for all levels of specific energy used. In these figures, all the data used for generating the models, have been excluded.

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7.9 Conclusions:

1. There is a good agreement between the measured values for most of the measured low stress mechanical properties predicted from the empirical models except for the shear rigidity. Thus, the equations may be used with confidence to predict most of the mechanical properties and hence enable fabrics to be engineered with specific properties within the data range used.
2. Because the highest value of R^2 for the model that was produced to predict the shear rigidity was less than 0.5, as a result, when evaluating the model, the correlation between the experimental values and the predicted values was poor.
3. The models described a reliable method to engineer fabrics for nonwovens given low stress mechanical properties based on fabric structural and processing parameters. The exception is shear rigidity.
4. For most of the low stress mechanical properties, the area density dominates the relationship with specific energy, only having a noticeable influence at the lower values, apart from the hysteresis and the extension at 100 gf/cm.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Summary

Principally, the objectives of this research were to investigate the low stress mechanical properties of hydroentangled nonwoven fabrics to evaluate their suitability for use in apparel applications. Of principal interest, was to determine the relationship between process and structural parameters and the corresponding low stress mechanical properties.

Chapter 1 dealt with a literature review of previous work on the objective measurement and low stress mechanical properties of woven and nonwoven fabrics. A review of hydroentangled fabrics and their production was also presented. It was concluded that the fabric structure is the most important factor in determining the low stress mechanical properties, and it is these properties that are the main factors determining fabric handle. The behaviour of fabrics during manufacture and wear can also be predicted from the values of the low stress mechanical properties. Many nonwoven fabrics have high bending and shear rigidity and low extensibility and as a result, these fabrics are less suited for apparel applications. Investigation of the suitability of using nonwoven fabrics for outerwear clothing has been carried out by some researchers. It has been suggested that hydroentangled fabrics have the most similar values of low stress mechanical properties compared to woven and knitted fabrics. This was investigated further in chapter 2.

In chapter 2, the physical properties of different types of commercially available nonwoven fabrics produced using different bonding methods were compared with woven fabrics used for apparel applications. It was confirmed that nonwoven fabrics generally have high bending and shear rigidity and low extensibility. Variation in low stress mechanical properties was also observed to be dependent on fabric weight and other factors relating to the structure. These aspects were considered later.

Also, in chapter 2, it was confirmed that, of the fabrics tested, the hydroentangled fabrics had the lowest values of shear rigidity, bending length and bending rigidity in both the MD and CD. The extensibility of these fabrics was higher than the chemically and thermally bonded fabrics tested. As a result, hydroentangled fabrics appeared to have the most potential for future development as lightweight fabrics for use in apparel applications. On the other hand, chemically bonded fabrics exhibited the highest bending length and bending rigidity values, the lowest extensibility and the highest values of shear rigidity compared with other nonwoven fabrics, making them the least suitable for applications where good conformability and drape is required (i.e in clothing fabrics).

In hydroentanglement, the applied specific energy is used to control the level of fibre entanglement (bonding). It is important that the specific energy can be calculated accurately. Chapter 3 dealt with a study of the effect of the hydroentanglement process on the fabric area density. After several injectors, there is generally a decrease in the fabric weight per unit area and this can influence the accuracy of estimating the specific energy applied during hydroentanglement. An alternative method of calculating the amount of specific energy applied after a specific number of injector passes was presented.

Chapter 4 investigated the effect of the specific energy applied on low stress mechanical and dimensional properties. As the specific energy applied was increased, fabric density generally increases, and a decrease in the fabric thickness (T2 and T100), and surface thickness (ST) was observed. The application of increasing specific energy was also associated with a substantial decrease in fabric bending length, bending rigidity and bending modulus during initial hydroentanglement. The application of further specific energy through subsequent hydroentanglement only increased the fabric bending length, bending rigidity and bending modulus. The application of increasing specific energy was generally associated with a decrease in fabric extension and formability; and tended to increase fabric shear rigidity and reduce tensile hysteresis. Thus, there is a trade-off in desirable properties for potential clothing applications.

Also, in chapter 4, it was found that, as the weight per unit area of the fabrics increased, so did the fabric thickness, bending length, bending rigidity, bending modulus and formability. Also, the increases in weight per unit area, thickness and volumetric density were associated with a decrease in fabric tensile hysteresis and extension measured at different fixed loads (5, 20 and 100gf/cm).

An investigation into the effect of the hydroentangled fabric geometry on the low stress mechanical and dimensional properties was also undertaken. Interestingly, it was found that fabrics produced by hydroentangling the webs in the machine or cross direction only tended to have a higher shear rigidity. In contrast, fabrics produced by hydroentangling webs in both the machine and cross directions in sequence, produced fabrics with comparatively low shear rigidity. Hydroentangling the webs in both the MD and CD also tended to decrease the anisotropy of bending behaviour in the resultant fabrics.

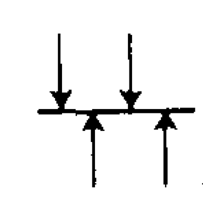
In chapter 5, it was established that changing the energy profiles used to manufacture the fabrics resulted in different fabric structures even if the total energy is constant. Also, increasing the number of injector passes generally results in an increase in the number of structural fibre pillars produced in the z direction. Whereas, increasing the amount of pressure applied resulted in a general increase in the depth of the pillars. The possibility of producing hydroentangled fabrics that have a more uniform structure through the cross section of the fabrics was not feasible when using low water pressure. Increasing the number of injector passes using a low water pressure could not overcome this limitation. In general, to obtain a more homogenous fabric structure along the cross-section, which will subsequently affect the fabric low stress mechanical properties, it appeared preferable to apply a lower number of passes using a high pressure (e.g. 50 bar) than a high number of passes using a low pressure (e.g. 20 bar) for a fabric of 100 g/m^2.

In chapter 6, further investigation of the effect of different energy profiles on the low stress dimensional and mechanical properties was undertaken. Three groups of 100 g/m^2 webs were produced using three different energy profiles and their low stress mechanical properties were measured in the MD, CD and bias directions. It was found that using different energy profiles resulted in different fabric structures for face and back of the fabric and also in the machine or cross direction even when applying the same amount of total specific energy.

In chapter 7, empirical models were developed. Good agreement was found between the values for most of the measured low stress mechanical properties and predicted values obtained from empirical models except for the shear rigidity. Thus, the equations may be used with confidence to predict important low stress mechanical properties and will allow fabrics to be engineered with specific properties. Calculation of shear rigidity according to the FAST manual can not be considered to give an accurate estimation of hydroentangled fabric shear rigidity because of the high variability in the EB5% results

8.2 General Conclusions

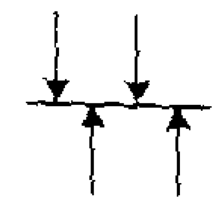
The main findings of this research are summarised below.

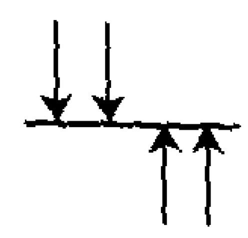
1. The hydroentangled fabrics studied had the lowest values of bending rigidity and bending modulus compared to other nonwoven fabrics such as chemically or thermally bonded fabrics.
2. The hydroentanglement process tends to decrease the web weight per unit area, which influences the accuracy of estimating, the specific energy applied during hydroentanglement. Therefore, an alternative method of calculating the amount of specific energy applied after a specific number of injector passes has been presented, which takes account of the changes in weight per unit area that occur between each injector pass. Providing the original fabric weight changes relatively little during the process, the energy calculated by the different methods were very similar.
3. Using an alternating balanced energy profile i.e. , increasing the applied specific energy resulted in a decrease in fabric bending length, bending rigidity and bending modulus, especially after the initial pass at low specific energy. Using a higher specific energy, the bending length, bending rigidity and bending modulus tended to increase, especially the higher weight fabrics, which tended to be more sensitive to changes in the specific energy, compared with lower weight fabrics.
4. As the weight per unit area of hydroentangled fabrics increased, the fabric thickness, bending length, bending rigidity, bending modulus and formability also increased. On the other hand, the increase in weight per unit area, thickness and volumetric density was associated with a decrease in fabric tensile hysteresis and extension using different fixed loads (5, 20 and 100gf/cm)
5. The low stress properties of hydroentangled fabrics (100 g/m^2), including bending and extension, produced at high energies (2.32 MJ/Kg and above),

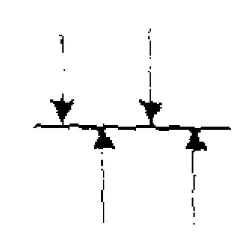
tended to give similar values to those obtained for woven shirting fabrics with the exception of the shear rigidity (G).

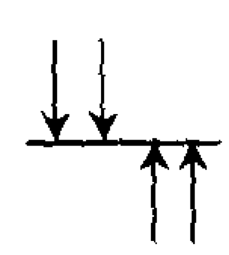
6. Cross-laid fabrics of 100 g/m^2, produced by hydroentanglement in the MD generally had the highest bending length, bending rigidity and bending modulus in the MD, compared to fabrics produced by hydroentanglement in the CD, which generally had the highest bending length, bending rigidity and bending modulus in the CD. It may be suggested that one effect of hydroentanglement is to modify the original dominant fibre orientation in the web.
7. Fabrics produced by hydroentanglement of the webs in either the MD or CD only, tended to have high shear rigidity (G) compared to woven fabrics used for apparel applications. Hydroentangling fabrics bi-directionally (i.e. in both the MD and CD) tended to give fabrics with lower shear rigidity (G) than fabrics hydroentangled uni-directionally in the MD or CD only.
8. The formation of fabrics by hydroentangling webs in both the MD and CD sequentially tended to decrease the anisotropy of bending behaviour in resultant fabrics especially for light-weight fabrics of 100 g/m^2.
9. The structure of hydroentangled fabrics has a major influence on low stress mechanical properties. Therefore, it is important to obtain a homogenous fabric structure along the cross-section of the fabric, which is achieved by consolidation of the fabric using a sufficient level of specific energy (as a minimum 1.156 MJ/Kg for a web of 100 g/m^2).
10. Consolidation of the fabric along the cross section will not be achieved by increasing the number of passes only (total specific energy). The level of water pressure used must be selected carefully to achieve increased fabric consolidation.
11. Using low levels of water pressure (i.e. 20 bar for a web of 100 g m^2) created fabrics with different properties on both sides (different fabric layers) irrespective of the jet application profile.
12. When measuring bending properties using the cantilever method, generally the lowest limits of bending rigidity were obtained when the side treated first was uppermost using 20 bar water pressure.

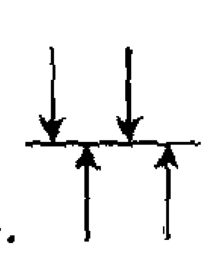
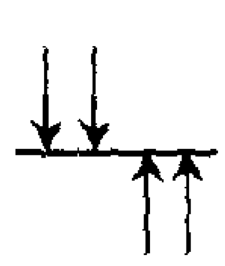
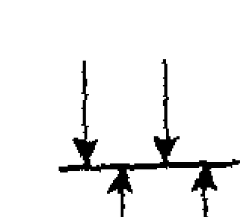
13. Generally, increasing the number of passes resulted in an increase in the number of pillars. Also, increasing the amount of pressure applied generally resulted in an increase in the depth of the pillars.

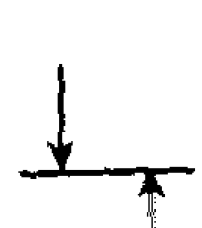
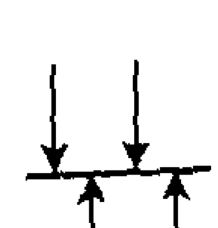
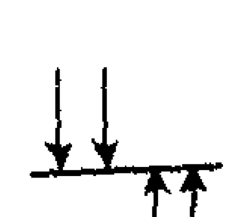
14. Using an alternating energy profile i.e.  (20 bar), with a web of 100 g/m^2, produced fabrics that do not have a homogenous fabric structure along the cross-section of the fabric even after 4 passes.

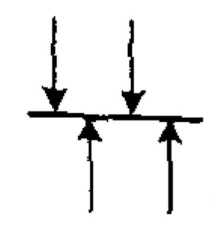
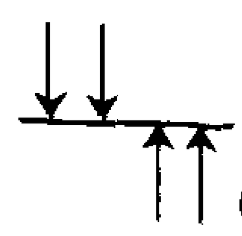
15. Using a paired energy profile i.e.  (20 bar), with a web of 100 g/m^2, produced a fabric in which the core remains effectively unbonded even after 4 passes.

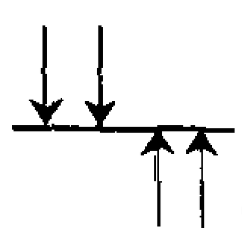
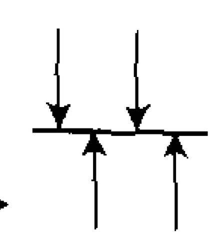
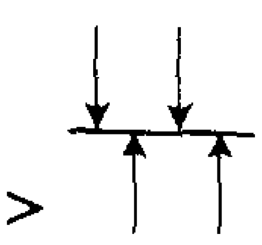
16. Using an alternating energy profile and a higher pressure i.e.  (50 bar), with a web of 100 g/m^2, there was evidence of segmented or chain-like structures within the fabric cross-section, compared with the two energy profiles given in 14 and 15.

17. Using a paired energy profile i.e.  (20 bar), gave the highest anisotropy of bending rigidity as indicated by the MD/CD ratio compared to other energy profiles.

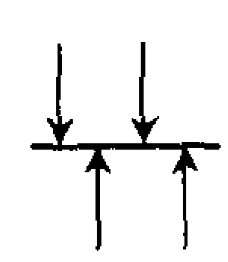
18. Using different energy profiles affected the low stress mechanical properties of hydroentangled fabrics. Fabrics produced with an alternating pressure profile i.e.  (20 bar), tended to give higher bending lengths than paired profiles i.e.  (20 bar), after 4 passes (although the same total amount of specific energy is used). Using an alternating energy profile i.e.  (50 bar), resulted in fabrics that reached maximum bending length after only 2 passes compared with other energy profiles. This can be simplified as follows:

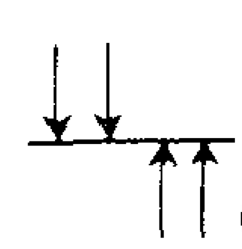
Bending Length (high)  **(50 bar) >**  **(20 bar) >**  **(20 bar) Bending Length (low)**

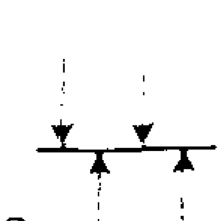
19. Fabrics produced using an alternating pressure profile i.e.  (50 bar), produced the least extensible fabrics, followed by fabrics produced using an alternating pressure profile i.e.  (20 bar), followed by fabrics produced using a paired energy profile  (20 bar), in the MD, CD and bias direction. This can be simplified as follows:

Extensibility (high)  **(20 bar) >**  **(20 bar) >**  **(50 bar) Extensibility (low)**

20. Comparable woven fabrics used for apparel applications (shirt fabrics), have bending rigidities ranging from approximately 5 – 20 μN.m. The hydroentangled fabrics produced in this work gave maximum bending rigidities of about 10.5 μN.m (after any individual pass), which is within the acceptable range.
21. Compared to the extension values for woven shirt fabrics and hydroentangled fabrics produced in this work, it was found that:

    (a) An alternating energy profile  (50 bar) produces fabrics with extension values most similar to woven shirt fabrics (at all loads).

    (b) A paired energy profile using low pressure  (20 bar) gives high extension, compared to woven shirting fabrics.

22. It can be concluded that using an energy profile of the type  (50 bar), may produce fabrics with the most acceptable combination of bending and extension properties compared to woven fabrics of the same range of weight per unit areas
23. Generally, using an alternating rather than a paired energy profile resulted in fabrics with the most suitable combination of low stress mechanical properties for clothing applications.

8.3 Recommendations For Future Work

Further systematic studies are required into the low stress mechanical properties of hydroentangled fabrics produced using a wider range of bonding conditions and the suitability of resulting fabrics for garment production and wear need to be studied. It is also believed that there are opportunities for fabrics, which are bonded using more than one generic type of bonding method in sequence (for example needlepunching and hydroentanglement).

Observations of fibre migration due to changes in the applied specific energy need to be studied further using tracer fibres and other techniques. The optical methods, that have been established to study the microstructural changes in hydroentangled fabrics, proved to be an effective method for identifying changes in fabric structures using different conditions, but these could be further developed.

Additional studies are also required to evaluate the usefulness of other objective measurement systems such as the Kawabata instrument in the characterization of nonwoven fabric handle properties.

To obtain hydroentangled fabrics with minimum variation in low stress mechanical properties, more uniform webs are required to be produced during web formation, which will minimise weight per unit area variations along the length.

Investigation into the "tailorability" of nonwoven hydroentangled fabrics needs to be made. This would enable specific control zones to be developed for nonwovens in order to achieve acceptable quality garments.

Further studies are also required to investigate the dimensional stability of different nonwoven fabrics and specifically hydroentangled fabrics during laundry and ironing (specifically the effects of heat and compression).

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