DEVELOPMENT OF AN ADVANCED PERSONAL PROTECTION EQUIPMENT FABRIC

FOR PROTECTION AGAINST SLASHES

BY

KARTHICK KANCHI GOVARTHANAM

B.Tech (Textile Technology); M.Sc (Advanced Materials)

A thesis submitted in partial fulfilment of the requirements of the University of Bolton for the degree of Doctor of Philosophy

June 2012

This thesis is dedicated

to my late father, mother, brother

my beloved wife and daughter

for their love, endless support

and encouragement

DECLARATION

This dissertation has been submitted in partial fulfilment for the award of Doctor of Philosophy in Technical Textiles at the University of Bolton, United Kingdom. I hereby confirm that the work contained in this dissertation is my own and that the work or contributions of others have been fully acknowledged.

Date Karthick Kanchi Govarthanam

ABSTRACT

Knife is the most commonly used single weapon in the UK, being 32% of the weapons employed in a violent incident. Studies reveal that majority (63.3%) of the knife inflicted wounds were slash type and could be disfiguring or life threatening if the blood vessels are ruptured. The stab resistant armours that are currently available do not protect the arms, neck and face as they are very rigid and heavy to be worn comfortably for everyday use for security personnel and are also expensive for the civilian population.

During the research programme, various composite yarns consisting of; a) blends of Spectra® (Ultra High Molecular Weight Polyethylene), glass and polyamide; b) Stainless steel core with wraps of Dyneema® (Ultra High Molecular Weight Polyethylene) and polyester; and c) Kevlar®, in different compositions, were thoroughly investigated to determine the most appropriate yarn for the slash proof materials. The slash proof fabric structures were developed by using knitting technology as it offers significant advantages in terms of cost, design flexibility and versatility. Different fabrics using the appropriate yarn were developed using various knitting criteria. Since there was neither any literature published for slash resistant fabrics nor any comparable fabric availability, the developed fabrics were tested against each other using a test method stipulated for slash proof application. The fabrics were also tested for their thermophysiological and flame resistant properties using a wide range of test methods and procedures. Due to the probable application of slash resistant fabrics, i.e. outer wear in open atmosphere, the developed fabrics were also characterised after exposing 5 years equivalent of UVA/B radiation.

This research programme has led to some extremely successful and innovative outcomes including the granting of a full patent. One of the major findings has been that a two-layered knitted structure produced by using a combination of composite and staple-fibre aramid yarns helps to withstand a higher impact force during the slash attack. It was also established that the designed racked structure in the fabric not only provides resistance to the continuous movement of the knife blade but also increases the overall slash resistance capability of the protective fabric.

The research has also led to some recommendations for further work in order to re-confirm some of the findings established during the study and also to improve the structure by reducing the area density of the slash resistant fabrics further due to the changes in the pass criteria of the slash resistant standard, set as a direct outcome of this research.

ACKNOWLEDGEMENTS

The realisation of this work was only possible due to the collaboration and support of great people to whom I wish to express my gratitude. I am immensely thankful and highly indebted to my Project lead and the Director of studies, Prof. S. C. Anand MBE and my supervisor Dr. S. Rajendran, for the trust deposited in my work and for the motivation demonstrated during this arduous and challenging course. Their advice and support extended during this research programme has been invaluable throughout the studies.

I would like to express my sincere thanks to my industrial supervisor Mr. Aidan Tracy, for his generous supervision, technical support and guidance offered during this research programme. I also wish to express my thanks to Future Textiles, Alfreton, UK, for providing financial support and their production facilities to undertake this research project. I also would take this opportunity to thank Mr. John Simmons and World Fibres Inc, Concord, North Carolina, USA, for their contribution in producing the yarn in accordance to the specifications and criteria’s as required by us and for providing their manufacturing facilities to undertake this research project.

I also wish to thank Mr. Chris Malbon and Mr. John Croft, Home Office Scientific Development Branch for taking into consideration the findings established during the research programme and for their generous support and opinions / recommendationsendeavoured during the research programme.

I am also thankful to the dedication and numerous contributions of Mr. Shahram Shafiee, Mr. Akbar Zarei, Mr Alan Crawshaw, Mrs. Donna Zarei, Mrs. Sue Farrell and all other teaching and non-teaching staff at the Institute for Materials Research and Innovation and other departments in the University, for their support and assistance towards my project.

Finally, I am most indebted to my wife, parents, family and friends for their continued moral support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

GENERAL INTRODUCTION

"The most beautiful thing we can experience is the mysterious.
It is the source of all true art and all science. He to whom this emotion is a
stranger, who can no longer pause to wonder and stand rapt in awe,
is as good as dead: his eyes are closed."

Albert Einstein (1879-1955)
German physicist

Chapter 1. General Introduction

1.1 Background

Law enforcement and medical personnel require a high-level of protection when dealing with physical, chemical and biological threats under various environments. Their demands from protective garments are ever increasing and are more focused on ballistic protection, anti-stab protection and anti-microbial protection.

Knives are the most commonly used weapon in street fights and muggings. Therefore, the law enforcement and medical personnel require a high-level of protection while dealing with physical threats from knives and similar blades. In England, where criminal use of hand guns is not prevalent, it is the security personnel who face assaults from individuals wielding knives, ice picks, and the like. The British Crime Surveys (BCS) conducted between 2001 and 2003 revealed that 12.6 per cent of the people engaged in protective service occupations have been the victims of assault followed by 3.3 per cent of health and social welfare professionals and 1.95 per cent of transport and mobile machine drivers and operatives [1].

The perception of risk for a violent assault at work is also the highest for the protective service occupations followed by the health and social welfare professionals. According to various crime surveys (BCS) over the years 2007 and 2011, on an average, there have been 3225 assaults per 10,000 workers per year in the security and protective services.

Understandably, the risk of violence while at work is the highest for “Security and Protective Services” with a risk percentage of 11.4% while the average risk of violence while at work is only 1.2 per cent. The police are at most risk followed by social workers, probation officers, publicans, bar staff and security guards.

Knife, at 32 per cent, is the most commonly employed weapon in a violent incident. This poses a threat to the officers working in the community, especially the youth and community workers and officers in the protective service occupations. Official statistics suggest that the use of knives in the commission of violent crimes and homicide has remained steady. Available evidence from crime statistics collected by Home Office in the UK indicates that significant a minority of young people carry knives and that this problem may be growing [2].

An investigation by Bleetman et. al. into the real life wounding patterns involving knives has revealed that the majority of the wounds caused were of slash type and the attacks of such type could be disfiguring and could also be life threatening if the blood vessels are involved in the wound. A review of distribution of the wounds in real life attacks revealed that most of the knife assaults are slash attacks at the arms, necks, shoulders and thigh regions [3].

Similarly, the areas in which custodial and corrections officers perform their duties differ greatly from their street counterparts. Cells and hallways are sometimes small or narrow and the ability to move or fight off an attacker is very important. The majority of the threats in these areas are mainly from edged and hand-made weapons. The use of metal or plastic plates in stab resistant vests are therefore not required in such situation as it will restrict an officer’s ability to defend themselves, bend quickly or get up from the floor if knocked down. This inability to defend one’s self can cause more injury than the initial attack.

Ballistic protection is the most evolving field that provides protection against projectile penetration (including the new kind of bullets). Such fabrics use high performance fibres and rely on their strength and stiffness. Anti-stab protection on the other hand relies on tightly woven structures that offer protection from sharp pointed objects with or without sharp cutting edges. Even though stab resistant armour defeats slash attempts, it is impractical to provide stab protection to the arms, neck, shoulder and thigh regions due to the thickness and stiffness required for the armour materials to withstand the force of a stab attack. Slash resistant armours, in contrast, need not be excessively bulky and/or stiff. They can be more flexible and lighter as the maximum load exerted by a slash is approximately 25 per cent of the loads measured in stab attacks.

Even though the currently available protective materials provide protection against such situations, the drawbacks of such devices are that they are very heavy, with limited breathability causing heat stress and discomfort, especially if worn for long periods of time.

1.2 Aims of the research programme

The overall aim of this project was to develop and fully characterise novel and advanced flexible personal protective fabrics that will provide protection against cut and slash attacks.

The major specific objectives of this research programme were:

- To design, develop and characterise novel cut and slash resistant materials for the police and armed forces.
- To engineer, test and analyse lightweight, comfortable and efficient systems which can be utilised for long periods of time.
- To test and analyse these novel materials by using standard test methods and techniques.

The ultimate objective of this research programme was to design a novel and advanced cut resistant and slash proof materials which would be lightweight, comfortable and efficient, that can be utilised for long periods of time for the use of police, armed forces, security personnel and the public who are exposed to a violent environment.

It is the intention to investigate various composite yarns that offer protection against cuts and slashes and incorporate them into suitable cut resistant fabric structures.

1.3 Structure of the thesis

The published literature on the slash and cut resistant materials as well as the different mechanisms involved during a slash and a stab attack are discussed in Chapter Two.

The test methods used to characterise the yarns, the thermophysiological properties of the fabrics and the heat barrier properties of the fabric are discussed in Chapter Three. Chapter Three also discusses in detail about the Home Office Scientific Development Branch (HOSDB) Slash Resistance Standard for the UK Police (2006) that was used to characterise the slash resistant fabrics. In Chapter Four, the selection of the appropriate yarns and the development of the slash resistant materials are discussed in depth. The slash resistant properties of the novel slash resistant materials developed during this research are discussed in detail in Chapters Five. The final conclusions of the work and the major recommendations for future investigations are described in Chapter Six.

The list of publications, conference presentations and the granted patent that has been one of the outcomes of this research programme are listed in Appendix A. A copy of the certifications obtained from the Home Office for the novel slash resistant fabrics are attached in Appendix B while the fabrics that have passed the HOSDB Slash Resistance Standard for the UK Police (2006) are presented in Appendix C.

CHAPTER 2

LITERATURE REVIEW

"The first principle is that you must not fool yourself…

and you are the easiest person to fool."

Richard Feynman (1918–1988),

Nobel Prize in Physics, 1965

Chapter 2. Review of Literature

2.1 Introduction

Currently, knives are being used more commonly in street fights and muggings. Therefore the law enforcement and medical personnel require a high-level of protection when dealing with physical threats. The general public also requires a high-level protection from crimes where, according to the British Crime Survey in 2010/11, a knife was used in 6% of all BCS incidents of violence, similar to the previous year's proportion [4]. The demand for protective garments is ever increasing and is more focused on ballistic protection and anti-stab protection. Ballistic protection provides protection against projectile penetration including the new kind of bullets and anti-stab products offer protection from sharp pointed objects with or without sharp cutting edges such as knives and needles.

2.2 Need for personal protective garments

2.2.1 Resistance against knife

In England, where criminal use of hand guns is not prevalent, it is the police officer who often faces assaults from individuals wielding knives, ice picks, and the like [5]. The British Crime Surveys (BCS) 2001/02 and 2002/03 revealed that 12.6%, of the people engaged in protective service occupations have been the victims of assault followed by 3.3% of health and social welfare professionals and 1.95% of transport and mobile vehicle drivers and operatives. The perception of risk of violent assault at work is also the highest for the protective service occupations at 54% and 28% for the health and social welfare professionals.

A survey conducted with 4715 pupils in school and 687 excluded pupils aged 11-16 revealed that 28% of children in school and 57% of excluded children have carried a knife in the year 2004. This poses a threat to the officers working in the community, especially the youth and community workers and officers in the protective service occupations. Available evidence indicates that significant minority of school children and young people carry knives and this problem may be growing [6].

Between 2005 and 2007, the crimes that involved a knife had more than doubled from 25,500 to 64,000 [7]. The official statistics taken during 2006 suggested that the use of knives in the commission of violent crimes and homicide has remained steady [5]. Due to the significant involvement of knives in offences, data on the number of offences involving the use of a knife or sharp instrument have been collected for a selection of serious violent offences since April 2007. Between September 2010 and September 2011, the threat level was surprisingly as high as 32,500 violent offences that involved use of a knife or sharp instrument [4].

Knife, at 7%, was the most commonly used weapon in the violent offences as per the census taken and this was of similar proportion to previous years [2]. Among homicides, in 2009/10 and 2010/11, knives and other sharp items were the most commonly used implements involved in the physical violence causing death of the victims [8].

2.2.2 Resistance against slash

A review of the real life wounding patterns that investigated 500 patients attending an Accident and Emergency unit in Glasgow, revealed that the majority (63.3%) of the wounds caused by knives were slash type and the attacks of such type could be disfiguring and could also be life threatening if it involves the blood vessels [3].

A review conducted by Bleetman et al, in 2003 also revealed that one third of the assault victims attending hospital were injured by a knife [9]. The majority of those knife injuries were slash-type injuries to the face with fewer affecting the upper limb and the trunk [10]. Less than a quarter of fatal wounds caused by stabs are inflicted in the chest region and the distribution of the wounds suggests that, in real life attacks, most of the knife assaults are slash attacks at the arms, neck, shoulder and thigh regions. UK National Health Service (NHS) data suggests that, in 2010/11, there were 4643 people admitted to hospitals due to assault by sharp objects. The number of admissions was more or less similar in the previous 10 years [11]. Figure 2.1 shows the percentage assaults by injury location.

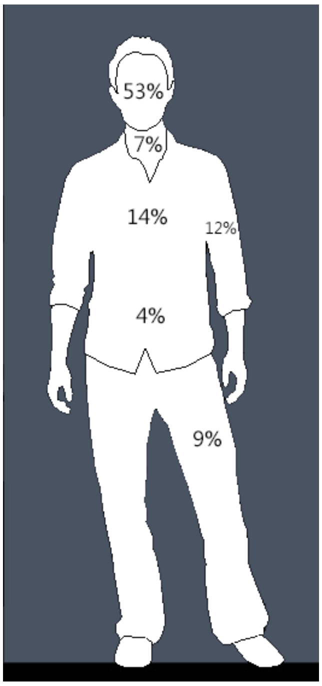


Figure 2.1 Percentage assaults by injury location

Assaults by a sharp object are usually caused as multiple wounds. In an experiment where soldiers were asked to slash a vertical manikin with an intention to wound, 47 per cent of the soldiers delivered multiple slashes [9]. It was also found that eleven per cent of the knife assault victims sustain multiple wounds, especially if the assailant was a male [12].

Even though stab resistant armour defeats slash attempts, it is impractical to provide stab protection to the arms, neck, shoulder and thigh regions due to the thickness and stiffness required for the armour materials to withstand the force of a stab attack. Slash resistant armours, in contrast, need not be bulkier and stiffer. They can be more flexible and lighter as the maximum load exerted by a slash are approximately 25% of the loads measured in stab attacks [3].

The areas in which custodial and corrections officers perform their duties differ greatly from their street counterparts. Cells and hallways are sometimes small or narrow and the ability to move or fight off an attacker is very important but could be quite tricky. The major threat in these areas is mainly from edged and hand-made weapons. The use of metal or plastic plates in stab resistant vests are not required in this situation as it can restrict an officer’s ability to defend himself or herself, manoeuvre quickly or get back up if knocked down. This inability to self-defend can cause more injury than the initial attack.

2.3 Threat and protection levels

2.3.1 Threat levels

The energy developed during a stab attack determines the level of threat. The energy developed mainly depends upon the following factors [13]:

- kinetic energy of the knife / hand / arm system; and
- the muscular force.

The kinetic energy in turn directly depends on:

- the weapon’s mass;
- the weapon’s shape;
- the weapon’s geometry;
- the assailant’s physical strength; and
- the assailant’s emotional state.

2.3.2 Protection levels

The Police Scientific Development Branch (PSDB) body armour standards for UK police (2003) provide three protection levels so that wearers have a choice based on the nature of the risk. Table 2.1 shows the requirements of various energy levels required to withstand different protection levels [14].

The protection levels are categorised into Knife Resistance (KR) and Spike Protection (SP), with three protection levels for each (Level 1, 2 & 3). The maximum penetration is measured with 2 energy levels, E1 and E2, with permissible penetrations of 7 mm and 20 mm respectively.

Table 2.1 Protection levels (PSDB Standards) **[14]**

Protection Level	**Energy Level E1 (joules)**	**Max Penetration at E1 (mm)**	**Energy Level E2 (joules) (n/a for SP)**	**Max Penetration at E2 (mm)**
KR1 (+ SP1)	24	7 (SP1 = 0)	36	20
KR2 (+ SP2)	33	7(SP1 = 0)	50	20
KR3(+ SP3)	43	7(SP1 = 0)	65	20

For spike protection, the material should also pass the knife resistance test and should not allow any penetration of the spike at energy level E1. Spike protection level is investigated in addition to the knife resistance level.

Even though the standard suggests that the maximum energy level required is 65J, studies by Horsfall, et. al, showed that the maximum energy produced could reach up to 115J for an overarm stabbing action and 64J for an underarm stabbing action [13].

2.4 Cut and slash mechanism

Knives are broadly classified into 5 different categories. It is essential to appreciate the various categories to understand the various materials that are used, their specifications, and physical properties; in order to design a fabric that addresses the vast majority of the equipment used [15]. It is important to understand the principle of the slash or stab mechanism as the mechanism involved during a stab attack is different from that is associated with a slash.

2.4.1 Knife or spike penetration mechanism

When a knife or a spike strikes a fabric, the mechanism by which the penetration occurs is different for both devices. A knife, which by definition has a pointed blade with a sharp edge, penetrates the fabric using the tip and then the cutting edge slices through the fibres and cuts the fabric. The fibres that come in contact with the knife edge reduce the drag of the knife thus increasing resistance to the penetration by the knife.

A spike has a round cross-section with a pointed tip, such as an ice pick, awl, nail or needle, which penetrates using the tip and pushes the fibres to the sides and slips through the fabric.

2.4.2 Knife and spike performance

The effectiveness of the blade in terms of cutting is due to the fact that it acts both as a wedge and a lever. As a simple wedge the sharpness of the blade affects the ability to make the incision and the angle between the blade edges governs the degree to which the material being cut will be forced apart. These two factors generally work together and influence the depth of cut. The physical characteristics of the material being cut will play a major part on how these factors work together. The behaviour of slashes will therefore vary depending on the material, thus the fibres of a textile, a metal or a brittle material like glass will be cut in different ways. However, the initial incision is purely a function of sharpness [16].

Sharpness can be defined as the attribute which allows the instrument to perform the cutting operation with the minimum effort. The fundamental mechanism whereby a knife cut is a compressive fracture caused by high pressure from the very small area of the single edge of the knife, for example, a razor blade requires one fine edge, whereas an ice pick requires a sharp point. To achieve maximum sharpness of a blade the edge angle must be low and the tip radius must be small [15].

2.4.3 Principle of knife impact

There are two phases involved in a knife impact.

Firstly, the point of contact of the knife produces 3 actions:

- the target material begins to move away under the force of the knife;
- the knife begins to impede the target material by opening it up; and
- the material begins to make the knife point blunt.

Secondly, once the knife has pierced through the material completely, it causes:

- "run through" – when the knife opens up the material and penetrates through the hole already made

The aim should be to absorb the energy during the first phase, in such a way that the second phase is prevented from happening. The kinetic energy from the penetrating object must be absorbed by the fibrous network and dispersed over a larger area to prevent localised damage.

Horsfall et al classified the threats in terms of Kinetic Energy Density (KED) i.e. incident kinetic energy per unit area, as presented in Table 2.2.

Table 2.2 Threat classification based on Kinetic Energy Density (KED) **[17]**

Threat	**Velocity (m/s)**	**Kinetic Energy (J)**	**Presented Area (mm^2)**	**KED (J/mm^2)**	**Typical Armour Type**
Knife	10	43	2.5 (blunt) 0.2(sharp)	17 210	Speciality Textiles or Plates
Handgun bullet (0.357")	450	1032	65 (initial) 254 (final)	16 4	Textiles
Assault rifle bullet (AK47)	720	2050	45	45	Composites
High velocity bullet (SA80)	940	1805	24	75	Ceramics

Knives apply a relatively modest force but all the energy developed is concentrated over a very small contact area, thus producing the highest energy density. Due to the high energy density, sharp knives and needles have the tendency to pierce through the material.

The tendency of a knife to force through the fabric structure can be resisted by using finer and tighter fabric construction, for example, plain weave. Film lamination and abrasive coatings can be used to improve the penetration resistance on a fabric material. Protection against sharp needles tends to be a problem with any fabric structure due to the porous structure and the fineness of the needles.

2.5 Materials used for slash resistance

2.5.1 Fibres used for slash/cut resistance

The fibres that are used extensively for the armour products are Kevlar®, Spectra®, Dyneema® and Zylon®. A product has been recently introduced by DuPont called Kevlar Correctional® that is 4 times thinner than Kevlar®. The properties of the main fibre types used for slash resistance are summarised in Table 2.3. All the fibres listed provide excellent strength-to-weight (tenacity) property and a high modulus.

Table 2.3 Comparison of fibre properties **[18] [19] [20]**

	Tenacity		**Modulus**		**Breaking Extension**	**Density**	**Moisture Regain**	**LOI**	**Heat Resistance**
	cN/ dtex	**GPa**	**cN/ dtex**	**GPa**	**%**	**g/cm^3**	**%**		**^{0}C**
PBO (Zylon)	37	5.8	1150	180	3.5	1.54	2.0	68	650
UHMWPE (Spectra/ Dyneema)	35	3.5	1300	110	3.5	0.97	0	16.5	150
Aramid (Kevlar)	19	2.8	850	109	2.4	1.44	0.5 - 4.5	29	550

2.5.1.1. Aramid

Aramids are polyamides (Kevlar from DuPont, Twaron from Akzo-Nobel, now Teijin) that are defined as having at least 85% of the amide groups linked to two aromatic rings, see Figure 2.2. They are produced by the polymerisation of long stiff molecules such as para-phenylene terepthalamide achieving molecular weights averaging around 20,000. The stiff aromatic rings and hydrogen bonding cross-links combine the best features of both the polyamides and the polyester in extended chain configuration.

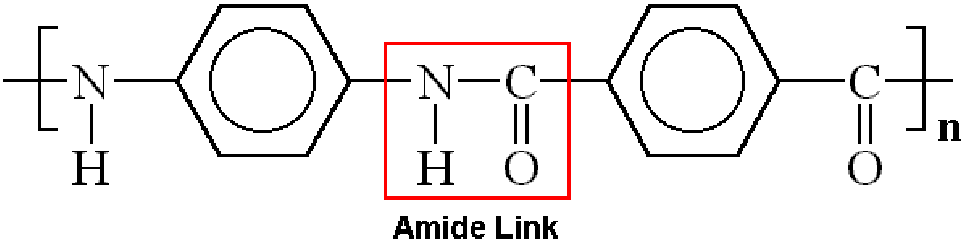


Figure 2.2 Structure of Aramid

In para-aramids, the links are formed on the opposite corners of the rings. Para-aramids do not melt, but decompose above 430^0C. They absorb a small amount of water due to their low moisture regain [18]. Kevlar, in particular, starts to decompose only above 550^0C [21].

2.5.1.2. Ultra High Molecular Weight Polyethylene (UHMWPE)

UHMWPE is a type of polyolefin that is commercially produced in the fibre form as Dyneema® by DSM and as Spectra® by Honeywell. It is produced by gel spinning, a super drawing technique that uses dilute solution of ultra-high molecular weight polymer such as polyethylene to unfold chains further and thus increasing both tensile strength and fibre modulus. These fibres derive their strength from the extremely long chains of polyethylene, with repeats of more than 100,000, that can attain parallel orientation of greater than 95% [22]. See Figure 2.3 for a single repeat structure of UHMWPE.

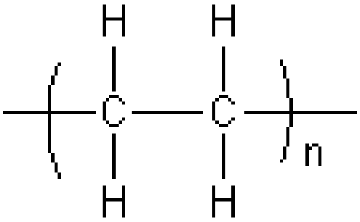


Figure 2.3 Structure of UHMWPE, with n greater than 100,000

The weak Van der Waals bonds between the molecules in UHMWPE give it very poor heat resistance. The fibres melt at 150^0C and their properties deteriorate as the temperature increases above room temperature. Under high stress the fibres tend to creep extensively and can break after short times under load. A secondary slow heating, under tension, when approaching the melting point increases modulus and reduces creep. It is extremely resistant to chemical and biological attack and has better abrasion and fatigue resistance than aramid fibres [23].

2.5.1.3. PBO (Polybenzoxazole)

PBO is produced commercially as Zylon, by dry-jet wet spinning from solution in phosphoric acid. The five membered rings on either side of the benzene ring give a stiffer chain molecule, see Figure 2.4 [19].

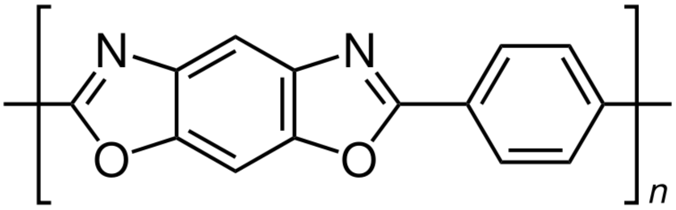


Figure 2.4 Poly(p-phenylene-2,6-benzobisoxazole) PBO

The modulus and strength of the fibre is almost twice as high as aramid fibres with other properties remaining similar. The fibre degrades by hydrolysis in warm and moist condition which makes the fibre unsuitable for applications that expose the material to warm and moist environment.

2.5.2 Yarns used for slash/cut resistance

Several yarn manufacturing methods exist in the textile industry. The characteristics of the yarn that is used in constructing a fabric, highly influences the mechanical properties of the fabric and similarly the yarn characteristics are strongly dependent upon the fibre characteristics and the yarn structure. The yarn can be formed either by using staple fibres or continuous filaments. Several spinning systems exist for processing staple yarns, each of which has a different structure and exhibits different properties. Similarly, continuous filament yarns can be either manufactured from monofilaments or multifilaments, with or without twist imparted into them.

2.5.2.1. Ring spun yarns

Ring spinning is a long established technique used for manufacturing yarns from staple fibres such as cotton, flax, wool, etc. The ring spinning system is the most flexible system, and is the most dominant method of yarn production when using staple fibres. Several literatures exist which describe its know-how for operation and process control [24] [25] [26].

The ring spinning system involves three basic processes to manufacture a yarn from staple fibre. They are,

i) Drafting;

ii) Twisting; and

iii) Winding.

A schematic diagram of the ring spinning system is shown in Figure 2.5. Drafting takes place between the three roller sets in the roller drafting unit where the fibres fed either in a sliver form or a roving form are attenuated to arrange the fibres parallel to each other. The fibre is controlled in the main draft zone by the roller aprons in the middle pair of rollers. Twisting is the process of inserting twist into the attenuated fibres to hold them together. The twist is inserted in to the strand of fibres by the traveller that revolves around the spindle on a ring. The spindle, which holds the yarn package, is positively driven by a belt or tape at constant speed and the traveller are driven by yarn as the yarn is wound on the bobbin [24].

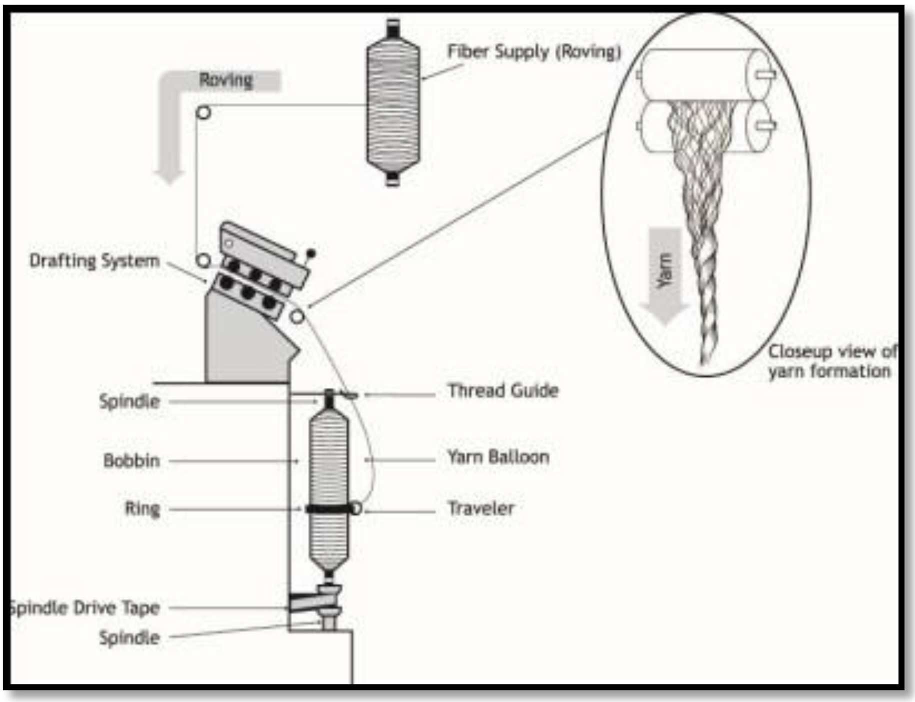


Figure 2.5 Schematic diagram of a ring spinning system [27]

The conventional ring spinning system can be used only with a staple fibre. By slightly modifying the conventional system it can be used to manufacture hybrid yarns such as core spun yarns [28] [29].

2.5.2.2. Composite yarns

Composite yarns can be defined as a structured yarn consisting of a minimum of two strands of yarns, one forming the core, or centre axis, of the yarn, and the other strand(s) forming the cover yarns. To prevent the core from breaking out, the cover members are wrapped around the core in a manner that the successive cover members can be wound over the underlying cover yarns. This second cover member is wound in the opposite direction to the cover member lying underneath it, see Figure 2.6.

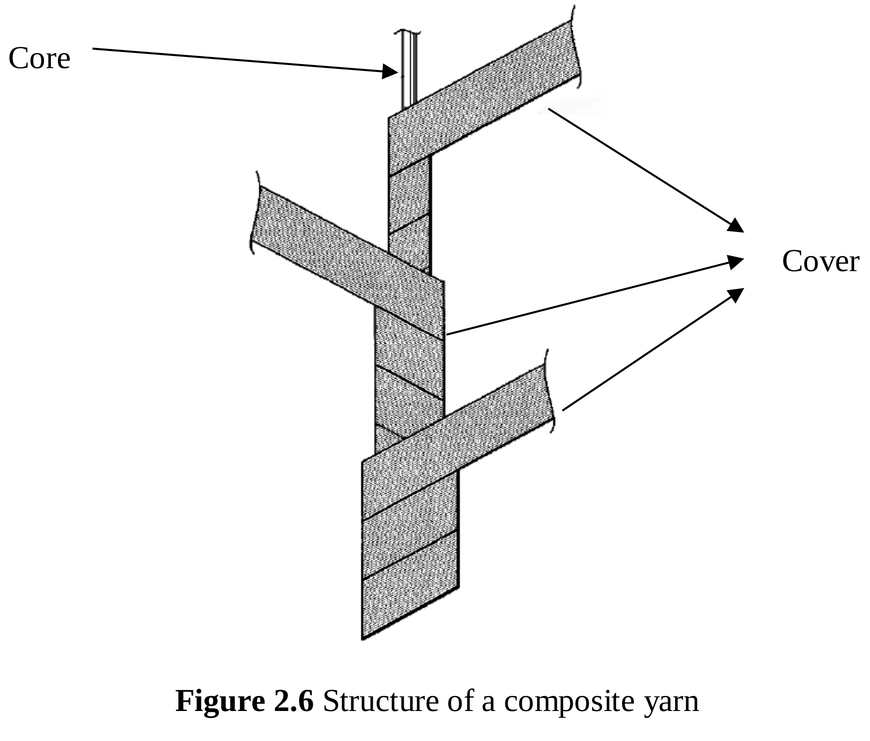


Figure 2.6 Structure of a composite yarn

The first cover member is usually wound in the 'Z'-direction and the second cover member is wound in 'S' direction. The subsequent cover members directions are alternated between 'Z' and 'S' twists.

The classification of the composite yarns is shown in Figure 2.7. Several systems exist to manufacture the different types of composite yarns. Some of the well-known systems are DREF spinning Type I, II & III, Wrap spinning, modified ring spinning, modified core spinning and braided yarns [30] [31] [32] [33].

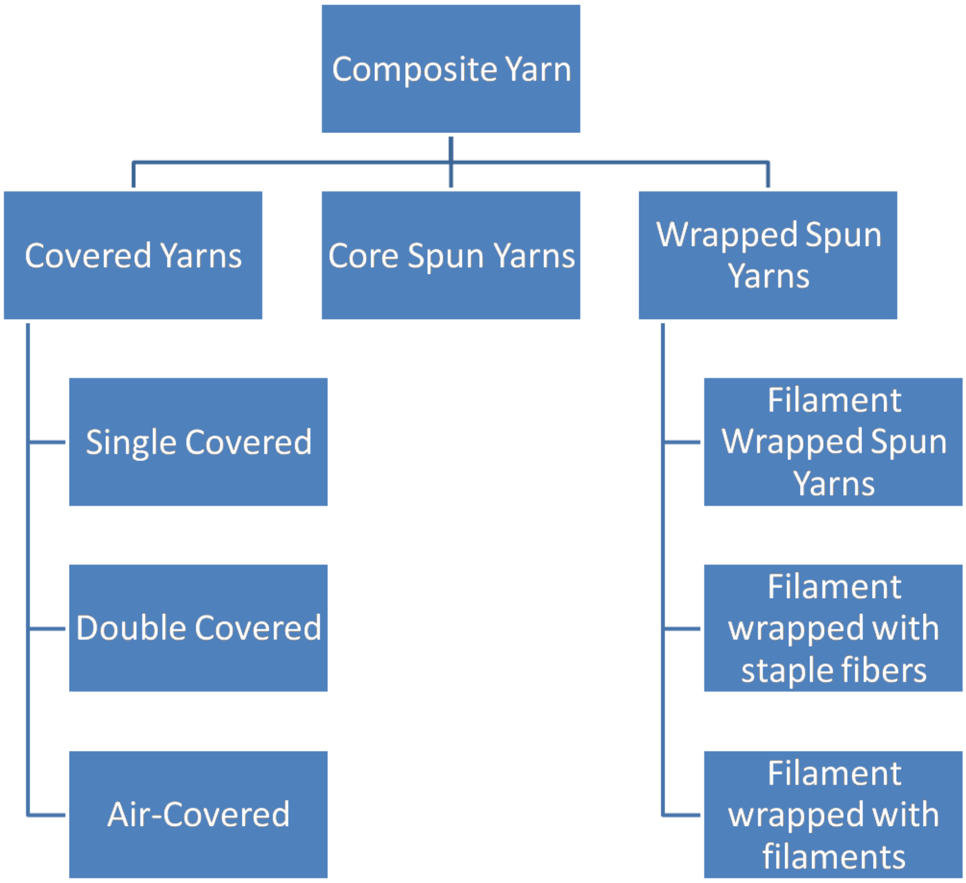


Figure 2.7 Classification of composite yarns

2.5.2.3. Yarn parameters

The yarn characteristics, in general, are dependent upon the following main factors:

- the number of fibres / filaments in the yarn cross section;
- fibre / filament alignment;

- position of the fibres / filaments;
- binding-in (compactness); and
- twist.

In a ring-spun yarn, the number of fibres affected by the twist and the degree of winding influences the mechanical properties and this twist is strongly dependent upon the spinning process parameters. A fully sheath-twisted yarn will have a high tensile strength and a lower abrasion resistance [34].

The properties of the composite yarns differ according to their materials arrangement and the combination of the properties of the different yarns used. They are typically used where high mechanical performance or multi-functional performance is necessary [35] [36]. In a composite yarn, the core filaments contribute the most to the mechanical performance and cover staple fibre or filament yarns contribute the least [37]. The cover staple fibre or filament yarns provide any additional properties such as skin-friendly surface, surface insulation, good handle, etc [38].

Since the yarn used can have high variations with-in its own types, it is essential that the yarn properties are studied before being used in any high performance or speciality fabrics. The analysis of the yarn properties will help in understanding the behaviour exerted by the fabrics.

2.5.3 Fabrics used for slash/cut resistance

Various fabric structures are currently used to provide resistance against stabs and slashes. They include tightly woven structures, woven and nonwoven composites/laminates, as well as warp and weft knitted fabrics.

2.5.3.1. Conventional Fabrics

Weaving is a conventional method of fabric production in which two distinct sets of yarns or threads are interlaced at right angles to form a fabric or cloth. The majority of cut resistant products are created with a plain weave or its derivative, see Figure 2.8.

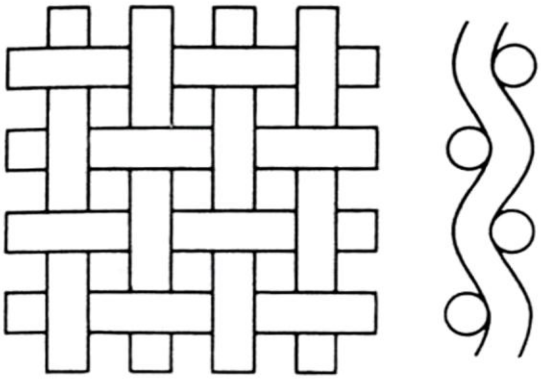


Figure 2.8 Representation of a standard plain weave

Knitting is another method of fabric production where yarns are interlooped to form a flat fabric. Two types of knitting exist namely, warp knitting and weft knitting. Weft knitting is the most common method in use, after weaving, because of its versatility and low capital and floor costs. A weft knitted fabric can be produced by using one single stand of yarn, see Figure 2.9, while a warp knitted fabric or a woven fabric requires the same number yarns as required through the width of the fabric.

Weft knitting technology also offers considerable advantages in terms of cost, flexibility and versatility compared to weaving technique in the production of suitable structures for a contourable protective material. This however has not been proven successful, mostly because of the low initial modulus on a knitted fabric which is due to the high degree of interlocking of the yarns. Since the fabric is formed by interlocking of the yarns, the yarns are flexible and free to move with-in and out of the loops and thus stretch when a load is applied, resulting in low initial modulus.

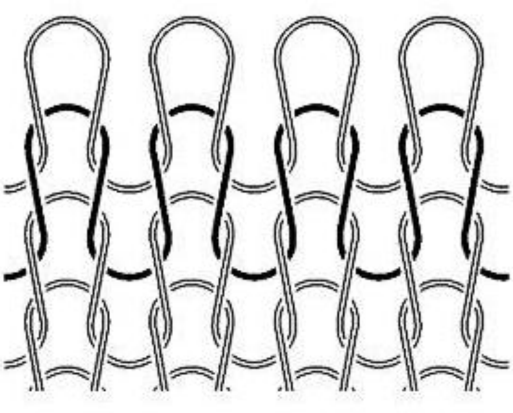


Figure 2.9 Representation of a standard weft knitted structure

2.5.3.2. Laminates

Laminates are composites made by combining two or more natural or artificial materials to maximise the useful properties of the components and minimise the weaknesses of the individual components. A laminate consist of one or more sheets of fibres of one or more material permanently bonded together by heat, pressure, welding or adhesives. Different laminate structures that are used in cut/stab resistant Personal Protective Equipment are discussed in subsequent sub-sections.

2.5.3.2.1. Spectra gold flex

Spectra Gold Flex is a unidirectional laminate made of four layers of aramid polyamide fibre strips, cross plied and sandwiched in a thermoplastic film, see Figure 2.10. The composite produces ultra-thin vests that are very light and comfortable. They are about 25% lighter than Kevlar or Zylon vests but offer high trauma protection. The tight structure of this composite protects from cuts and slashes and to a degree from stabs. This material also offers flame and heat protection and is able to withstand temperatures of up to 500°C.

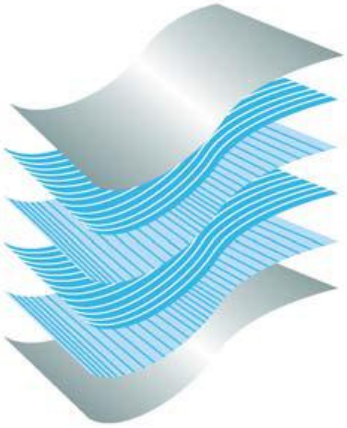


Figure 2.10 Spectra GoldFlex [39]

2.5.3.2.2. Dyneema UD

Dyneema UD is a unidirectional laminate made of two layers of extended chain polyethylene filament tows cross plied and sandwiched in a thermoplastic film, see Figure 2.11. It is one of the strongest [40] [41] [42] and most exclusive fibre laminates designed for ballistic protection. It is very thin and one of the lightest ballistic protection materials available with a relative density lower than that of water [43] [44] [45]. It offers good protection from cuts and slashes and will also help to protect against stabs. It will withstand temperatures of 150°C and maintains its protective properties down to -150°C.

Figure 2.11 Dyneema UD [46]

2.5.3.2.3. Twaron SRM®

Twaron SRM uses silicone carbide particles as a protective coating deposited onto a special matrix composition that coats the Twaron aramid fabric substrate, see Figure 2.12. The major function of the carbide particles is to blunt sharp blades and points, adding to the energy dissipation and penetration resistance of the fabric [47].

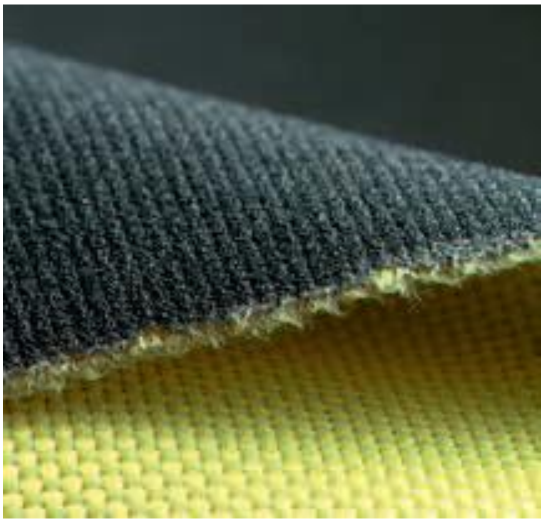


Figure 2.12 Twaron SRM with silicon carbide coating [48]

The major issue with the all the above mentioned slash or stab resistant fabric/laminates is that they are very stiff, which make it impractical to be used on a regular day-to-day basis over long periods of time.

2.5.3.3. Impregnated aramid

Aramid and ultra-high molecular weight polyethylene are used extensively as base materials for ballistic protection. As discussed earlier in Chapter 2, these high performance fibres are characterised by high strength, high energy absorption and low density. However, to meet the protection requirements for typical ballistic threats, approximately 13–50 layers of fabric are required which results in a bulk and stiff armour. The bulkiness limits its comfort, and has restricted its application primarily to torso protection.

To reduce the bulk of the material, Aramids have been impregnated with materials such as colloidal shear thickening fluid (silica particles (450 nm) dispersed in ethylene glycol) or powders with dilatant properties [49] [50]. The results demonstrate a significant enhancement in ballistic penetration resistance [51] . While these impregnated aramids provide better ballistic and stab performance, they have shown very little improvement in cut resistance [52] [53].

2.5.4 Recent innovations

Some recent innovations in stab or cut resistance include the investigations into the following techniques:

- improvements in blunting the knife on contact (Twaron SRM) [48];

- increasing the fibre/knife friction coefficient (PROTEXA) [54];
- reducing the stiffness of resinated textiles to improve drape;
- treating the fabrics with shear thickening fluids (STF) [55]; and
- increasing thermal conductivity of protection textiles to reduce heat build-up of the user [56].

2.6 Thermophysiological properties of PPE

One common issue with all of the PPE garments used for ballistic or stab protection is comfort. Materials that provide protection against knives have an areal density of over 3 kg/m^2 which also adds a thermal burden to person wearing it, especially in moderately warm and humid environments. A human body gains heat by exposure to the environment and through the metabolic heat generated by increased activity [57] . This is usually lost through convection and evaporation, but protective clothing provides significant resistance to such losses due to their thickness and insulation properties. This reduces the thermophysiological comfort of the wearer which might lead the wearer to refuse wearing them over long periods of time.

A Considerable amount of research has been conducted to study the physical factors that affect the comfort properties in functional garments [58] [59] [60]. During normal wear, clothing becomes part of the thermoregulatory system and helps to gradually dissipate and maintain the heat and moisture vapour fluxes that are created [61] [62].

The fabric that is in contact with the skin should be able to manage the perspiration that occurs on the skin. This property is important for thermoregulation and can be measured by studying the heat and moisture transfer properties of the fabric.

The heat and moisture transfer properties are typically associated with fabric breathability. Provided the fabric is breathable, i.e. water vapour permeable, the components used to make up the fabric will not have any significant effect on the thermophysiological properties [63] [64] [65]. Computational fluid dynamic analysis of 3D woven fabrics has shown that weaves with hollow structures are optimal to support ventilation [66].

2.7 Flame retardant properties of PPE

A PPE garment used by the armed and police forces and those used by safety personnel should provide some resistance to flame as the flame/fire is initiated on purpose with an intention to cause harm/injury. Attacks involving fire can be extremely severe and could be targeted on one individual and hence the protective clothing used should be able to withstand flash fire/flame to give enough time to react and escape from the presented threat. It is therefore essential that the fibres used are retardant to fire.

The Limiting Oxygen Index (LOI) is a good indicator of flammability of a textile fibre. It is the minimum concentration of oxygen required for the fibre to sustain a flame after ignition. The LOI’s of the fibres used for development of slash resistant fabric are given in Table 2.3. For a fibre to be fire retardant, the LOI values should be more than 21% which is the percentage concentration of oxygen in the air.

2.8 Test methods

2.8.1 Measurement of cut resistance

There are two European Standards that specify a method of testing cut resistance of a fabric against sharp objects. These are BS EN 388:2003 and BS EN ISO 13997:1997 [67] [68].

BS EN 388:2003 was developed specifically for gloves and it details the test methods for measuring abrasion resistance, blade cut resistance, tear resistance and puncture resistance. BS EN ISO 13997:1997 was developed for any protective clothing and specifies the test method for determination of resistance of a fabric to cutting by sharp objects.

The European standard stipulated for measurement of cuts and stabs is the BS EN 1082-3:2000 [69]. The 3rd part of this standard specifies the impact cut test for fabrics, leather and other materials. It was developed for testing of gloves and arm guards for cut resistance.

Though several test standards exists for measurement of cut resistance, the principles used in these methods do not apply to measuring slash resistance. These methods measure the resistance of a cut where the load applied is continuous. A slash has an instantaneous force which is similar to a stab but one which increases rapidly. This mechanism/working principle of a slash is discussed in detail in section 2.4.3.

2.8.2 Comparison of various test standards

Table 2.4 provides a brief comparison of various test standards that are used for the measurement of cut resistance of a fabric.

Table 2.4 Comparison of standards for cut resistance

BS EN 388:2003	**BS EN ISO 13997:1997**	**BS EN 1082-3:2000**
The cut resistance is measured as a grade of Performance Level (levels 1 to 5)	The cut resistance is measured in Newtons	The cut resistance is measured in mm
Specimens are cut by a counter rotating blade, that moves in an alternating motion under a specified load	Specimens are cut by a sharp blade that is drawn across the specimen	Specimens are cut by a standard knife blade that is held in a guided falling block.
Performance level 4	Cutting load ≥ 13N	Impact energy of the blade is either 0.65 J 1.47J or 2.45 J, based on performance levels expected from the specimen.
Performance level 5	Cutting load ≥ 22N	
Cut resistance is measured as number of cycles required to cut through the material	Cut resistance is measured as the force required to cut through the material during a 20 mm cutting stroke	The cur resistance is measured as depth of penetration in mm
Load is fixed (5 N)	Load is variable	Load is fixed
Circular blade is used to cut the specimen during testing	A sharp knife edge blade is used to cut the specimen during testing	A sharp knife edge blade is used to cut the specimen during testing
Sample size is a strip of (60±6) mm width and (100 ±10) mm length	Sample size is 25mm width and 100mm length (25 x 25 mm specimen can be used for a single cut test)	Specimen is in a tubular form with a length of at least 100 mm and a circular diameter of (100 ± 10) mm

2.8.3 Measurement of slash resistance

The only standard which measures using a principle where the load increases rapidly was released by The Home Office Scientific Development Branch (HOSDB) namely, HOSDB slash resistant standard for the UK Police (2006). It is the first standard in the UK that provides information on the test methodology and protection levels required for slash resistant protection [70]. The principle of testing the slash resistance in the standard is discussed in detail in chapter 3.

CHAPTER 3

EXPERIMENTAL WORK

"That's one small step for man;

One giant leap for mankind."

Neil Armstrong (1930-)

Apollo 11 astronaut

Chapter 3. Experimental Work

3.1 Introduction

The materials currently used for slash and cut resistant applications, their properties and the need for a slash resistant material were reviewed in the previous chapter. Special attention is given to the thermophysiological properties of personal protective equipment garments that are worn to protect from cuts and slashes caused by sharp objects. One of the main aims of this research is to develop a novel lightweight slash and cut resistant material that can be worn for long periods of time on a daily basis.

This chapter discusses the methods used for the production of appropriate yarns and the slash and cut resistant material. It also discusses the test methods used to characterise the yarns, the slash resistance of the novel fabric, the test methods used to study the thermophysiological and heat barrier properties of the fabric.

3.2 Materials

This Section describes the yarns that were used for knitting the fabric and the knitting machine used to construct the slash resistant fabric.

3.2.1 High performance fibres and composite yarn

The high performance fibres that are extensively used for slash and cut resistant products are para-aramids, meta-aramids and Ultra High Molecular Weight

Polyethylene (UHMWPE). The main properties of these fibres are summarised in Table 2.3.

Various yarns, including composite yarns, using the high performance fibres, were used to engineer and develop the slash resistant fabrics. These yarns were thoroughly investigated to determine the most appropriate yarn for the slash proof material. The yarns were first short listed based on its tensile properties. The yarns thus chosen were knitted into fabrics and the ideal yarn for slash resistance was identified by testing their slash resistance properties. The shortlisted yarns that were used in the fabrics are listed in Table 3.1. The process of selecting appropriate yarns for slash resistant application is discussed in detail in Chapter 4.

The yarns were characterised by analysing their tensile properties and also by studying their slash resistant property by means of knitting a fabric with the yarn and testing it against the HOSDB slash resistant standard. For the analysis of the yarns slash resistant property, a jersey knit two layer structures was used for all of the yarns. Spun 2/122 Kevlar was used on one face of the fabric, while the other face was knitted with different yarns.

The test methods used to characterise the yarns are discussed in Section 3.3.

Table 3.1 Yarns used for constructing slash resistant fabrics

Name of Yarn	Description of Yarn	Fibre Composition (%)
WF408	Core: 66 Tex G75 fibreglass	25.3%
	Cover 1: 72 Tex Type 900 Spectra (UHMWPE)	28.5%
	Cover 2: 55 Tex flat polyester	23.0%
	Cover 3: 55 Tex flat polyester	23.2%
WF271	Core 1: 42 Tex type 1000 Spectra (UHMWPE)	48.4%
	Core 2: 11 Tex D450 fibreglass	13.3%
	Cover 1: 17 Tex flat polyester	19.1%
	Cover 2: 17 Tex flat polyester	19.2%
WF528	Core: 11 Tex D450 fibreglass	20.0%
	Cover 1: 24 Tex type 1000 Spectra (UHMWPE)	45.8%
	Cover 2: 8 Tex textured polyamide 66	17.0%
	Cover 3: 8 Tex textured polyamide 66	17.2%
E669	Core 1: 34 Tex ‘E’ Glass (6 micron glass)	13.9%
	Core 2: 50 Micron Stainless steel	41.0%
	Cover 1: 8 Tex false twisted polyamide 66	3.3%
	Cover 2: 8 Tex false twisted polyamide 66	3.3%
	Cover 3: 44 Tex Dyneema (UHMWPE)	18%
	Cover 4: 50 Tex airjet textured high tenacity polyamide	20.5%
K1	61 Tex single ply cotton spun Kevlar	100%
K2	2/122 Tex double ply cotton spun Kevlar	100%
TILSA	57 Tex cotton spun para-aramid	100%

3.2.2 Fabric production

Knitting technology offers considerable advantages in terms of cost, flexibility and versatility in the production of suitable structures for contoured armour, but it has not proved successful, probably because of the high degree of interlocking of the yarns that occur in the knitting process which results in a fabric with low initial modulus.

For slash resistance, it is the low initial modulus which aids in the relative slippage of yarns by distributing stresses over a larger area and hence prevents the blade from striking through the fabric. Therefore, weft knitting technique was utilised to design the slash resistant fabric. Weft knitting process is also attractive when factors such as cost, design potential and versatility are considered.

A series of fabric samples were knitted by using different combinations of various yarns, as listed in Section 3.2.1, and innovative two-layer weft knitted structures. The yarns were used in combination with Kevlar (K2) and the fabrics were knitted with K2 on one face and one of the other yarns, as mentioned in table 3.1, in the other face of the fabric and vice versa. E10 electronic flat knitting machine was used to produce the fabrics.

3.2.3 Knitted structures

The slash resistant test was initially conducted on a single jersey structure. The different structures that were used to construct the slash resistant fabric are as follows:

1. Jersey Knit (Two-layer structure)
2. Racked 1(Two-layer structure with racked wales)
3. Racked 2(Two-layer structure with racked wales with different structure than 2 above)

3.3 Yarn characterisation

All the yarns were conditioned for 24 hours in standard atmosphere of 20^0C and 65% Relative Humidity.

3.3.1 Linear density measurement [BS EN ISO 1889:2009] [71]

A direct method of weighing a definite length of yarn was used to calculate the linear density of the yarns. A microbalance with a 0.0001 gram precision was used to determine the weight of the samples accurately. The mass in grams of 100 metres length of yarn was measured to calculate the linear density of the yarns. 10 specimens were tested per yarn package to determine its linear density in Tex. The linear density in Tex was calculated using the following equation.

$$T = \frac{1000 \text{ x } m}{\mathrm{L}}$$

where,

T = Linear density in Tex;

m = mass in grams; and

L = length of the specimen in metres.

3.3.2 Tensile testing of yarns [BS EN ISO 2062:2009] [72]

The tensile property of the yarn samples was measured on Statimat M tensile tester on a gauge length of 500mm applying a constant rate of extension of 250mm/minute. 10 specimens were tested from each cone of yarn and at least 3 cones were tested per type of yarn. From the load-extension curves, the average breaking strength and percent extension at break were determined. The stress-strain curves were obtained directly from the instrument.

3.4 Evaluation of fabric structures

3.4.1 Measurement of slash resistance

The Home Office Scientific Development Branch (HOSDB) released a Standard, HOSDB Slash Resistant Standard for the UK Police in 2006 that describes a test method for measuring slash resistance. It is the first standard in the UK that provides information on the test methodology and protection levels required for slash resistant protection [70].

3.4.1.1 Principle of slash measurement

The penetration mechanism of a slash attack has been discussed in detail in section 2.4.3. Figure 3.1 shows the different forces applied by a knife attack. It can be observed from Figure 3.1 that the load applied by a knife attack increases rapidly upon contact. Whereas the load applied by different cut resistant test methods are constant load. There is a rapid increase in load when using the standard BS EN 1082-3, but all the load is applied on the pointed tip of the blade while in a slash all the load is applied on the edge of the blade, see Figure 3.2.

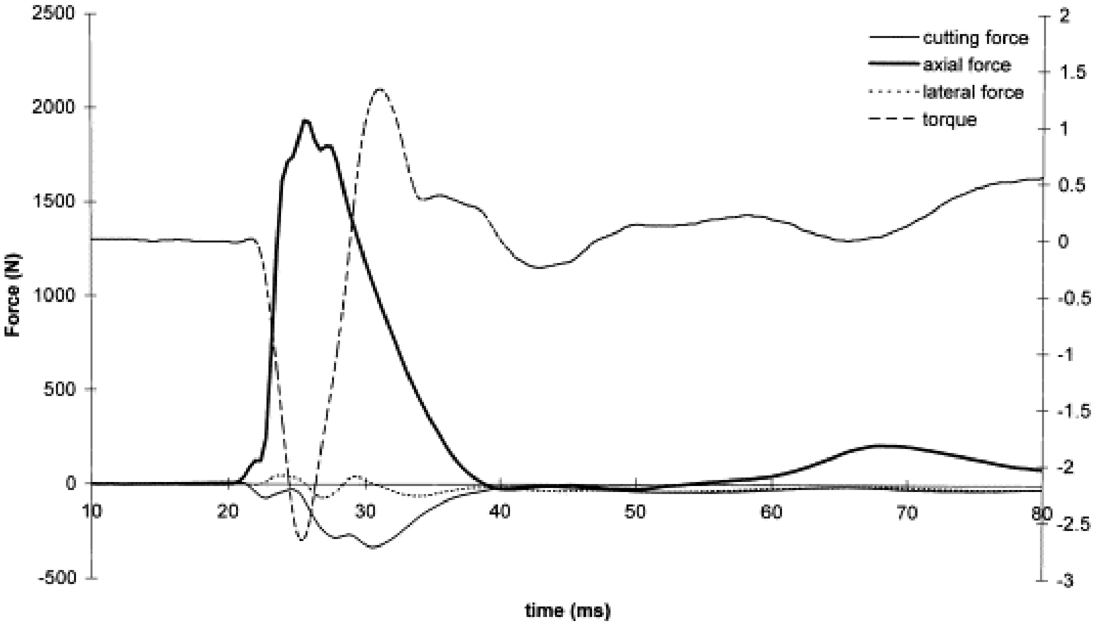
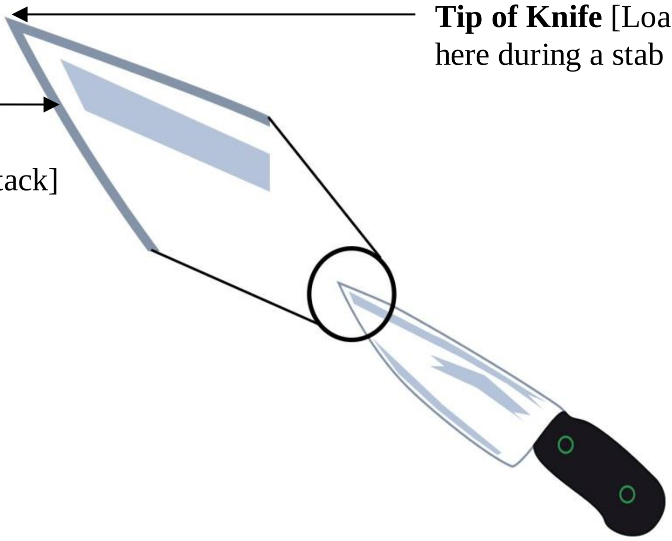


Figure 3.1 Load applied by the knife during a stab/slash attack [16]



Tip of Knife [Load is concentrated here during a stab attack]

Edge of Knife [Load is concentrated here during a slash attack]

Figure 3.2 The edge and tip of a knife

Figure 3.3 shows the load applied on a specimen when tested using the methods described in different cut resistance standards. These loads do not replicate the load applied by a knife attack.

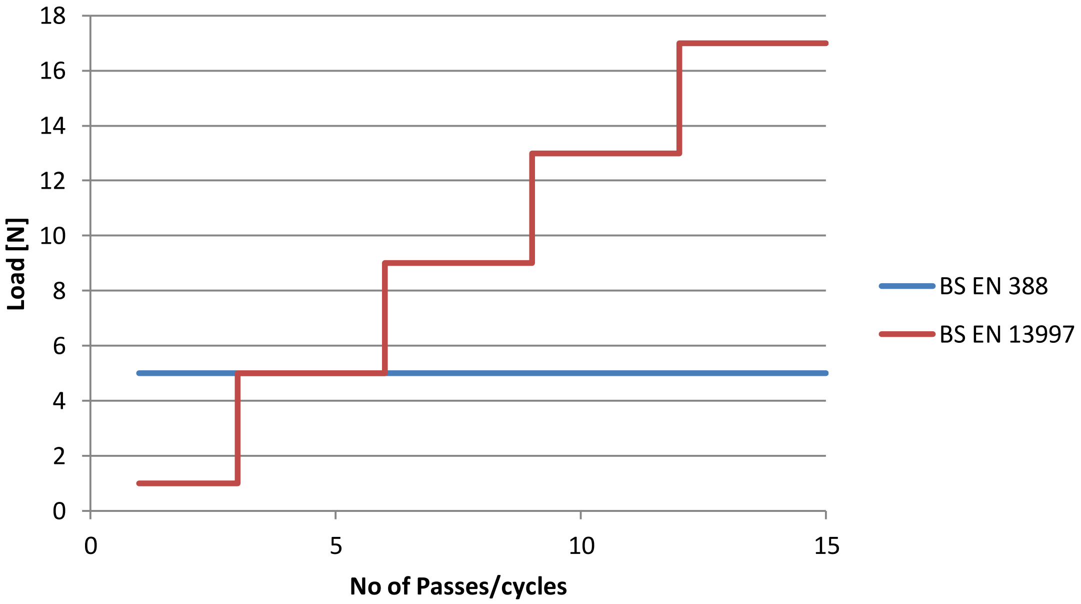


Figure 3.3 Load applied during different cut resistant tests

Figure 3.4 shows the load applied on a specimen during testing when using the method described in the slash resistant standard. Since the blade is held at an angle on the housing, as opposed to the bottom of the housing in the method described in BS EN 1082-3, the load is transmitted to the specimen through the edge of the blade.

A load applied by a slash attack typically starts as a stab at the point of contact and continues to behave like a cut with the sliding motion.

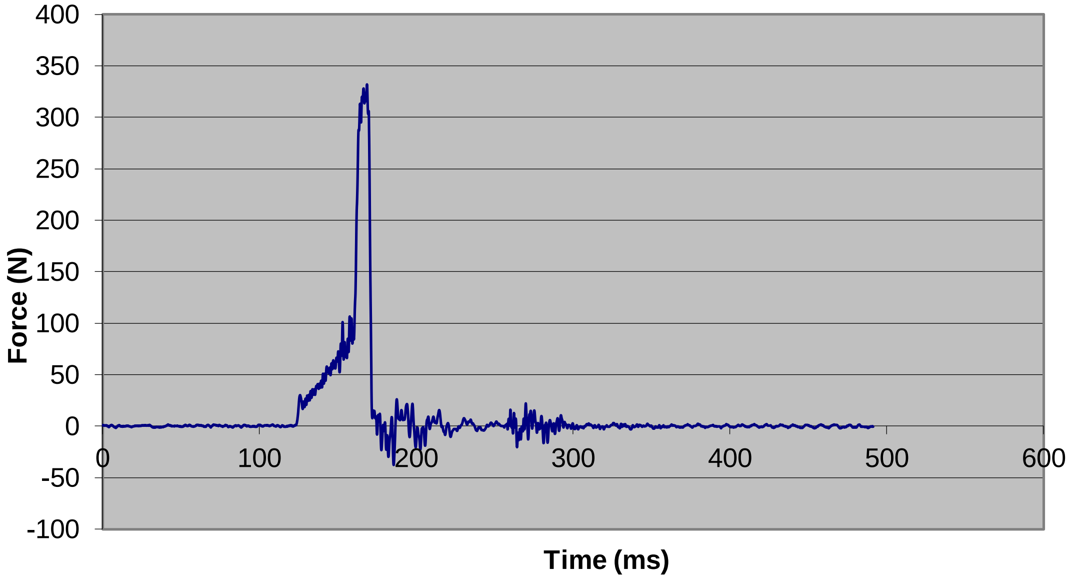


Figure 3.4 Load applied during an HOSDB slash resistant test

3.4.1.2 Test equipment

The test equipment consists of a guided drop assembly, a force table and a slash missile, see Figure 3.5. The slash missile has a mass of 2.0 kg ± 0.1 kg and houses the test blade. The missile is guided by the guide rails to drop under the influence of gravity. The blade contacts the force table at 2^{o} from vertical. The guided drop assembly prevents the slash missile from rotating about its vertical axis during its descent.

The blade is a standard Stanley® knife blade model 1992 that is held at an angle of 30° ± 1° from the horizontal by the supporting arm, see Figures 3.5a – 3.5c, which is free to move around the pivot point. An electrical connection exists between the force table and the supporting arm to form a contact circuit.

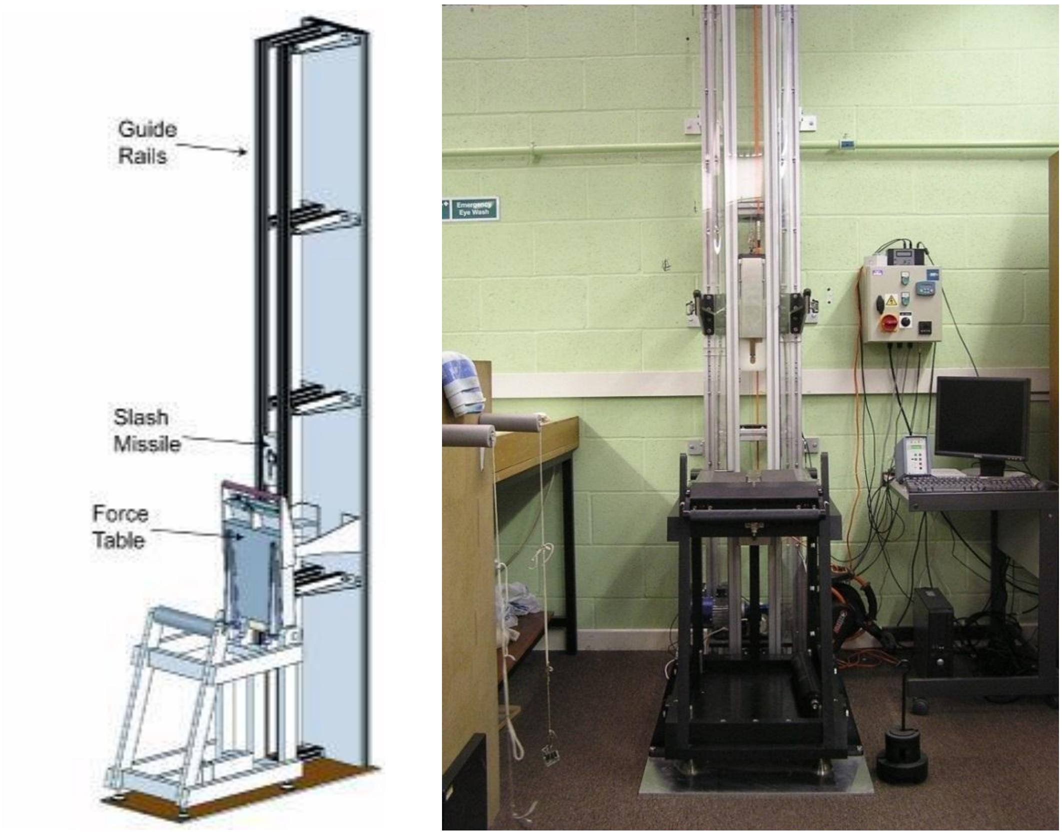


Figure 3.5(a) Slash resistance test assembly

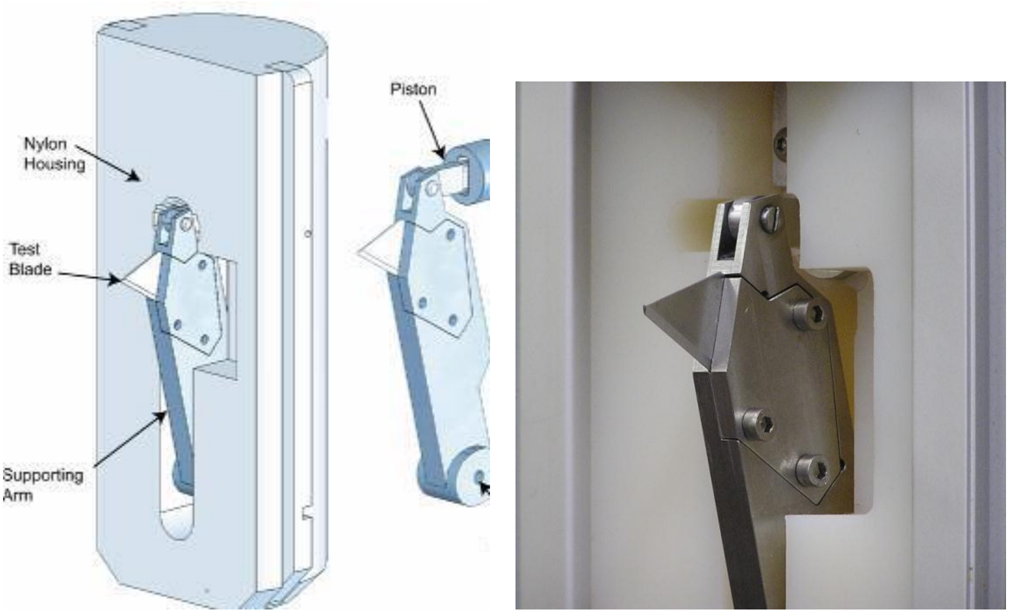


Figure 3.5 (b) Slash missile and Supporting arm

Figure 3.5 (c) Force table

The force table consists of two load cells, preloaded to a force of 30% of their rated value. The force table is mounted at an angle in such a way that the blade tip force reaches the minimum force required to cut through the specimen within a distance of 200mm from the point of contact.

3.4.1.3 Test specimen

Three test packs are required for a single slash compliance test. Each pack must contain a specimen of 500mm length and 300mm width. The construction of the specimen must conform precisely to the description specified in the declaration. If the slash resistant pack is manufactured from more than one layer, all layers of the test specimen should be stitched together along each edge in addition to any stitching pattern which is inherent to the protection provided by the panel. If the design or pattern of the materials used in the slash resistant panel is not homogeneous, one panel must be supplied to the size required with the design or pattern rotated through 90°. The design or pattern directions should be clearly marked by the manufacturer or supplier for compliance testing.

3.4.1.4 Test Procedure

The test requires three test packs with three specimens in each pack. During the test the vertical edges of the specimen are aligned parallel to the force plate in the first set, perpendicular in the second and at an angle of 30^o to the long axis of the force table in the third set. In each set, the slashes are made at 50 ± 5mm from the right edge, 50 ± 5mm from the left edge and then one in the centre of the specimen. An individual slash should be performed using a new blade, using only one tip of the blade.

3.4.1.5 UK Home Office stipulated pass criteria

To pass the specification, the test specimen that is placed on the force table should not have penetration at an average of 80N force and a minimum of 60N force in the following three directions,

- Machine direction (0^0)
- Perpendicular to machine direction (90^0), and
- 30^0 diagonal to the machine direction.

3.4.2 Mechanical testing

3.4.2.1 Dimensional properties

An average of 10 specimens of exactly 10 cm X 10 cm were weighed and multiplied by 100 to calculate the mass per unit area (gm^{-2}). By using the thickness calculated by the Alambeta thermal testing apparatus, the bulk densities of the specimens were also calculated in gcm^{-3}. The thickness was also verified using a standard thickness tester after applying a pressure of 10 grams per centimetre [73].

3.4.2.2 Tensile Properties

The tensile properties of the two-layered slash resistant weft knitted material were tested. These tests not only determine the breaking force of the materials, but the isotropicity of the materials, which can influence their comfort properties. It is well known that the fabric hand, in particular the fabric's tensile/shear properties or stiffness, have a direct influence on the fabric's sensorial comfort [74].

15 strips of 5cm X 30cm size of the knitted material were taken and 10 specimens each were tested for machine direction, cross direction and 45^{o} directions for their load/elongation profiles on an Instron® 4303 model tensile testing machine. Figure 3.6 shows the schematic diagram of a tensile testing machine.

The fabric was held between the two clamps at a gauge length of 200 mm. A 100 kN load cell was used and the rate of transverse of the machine was 200 mm/min.

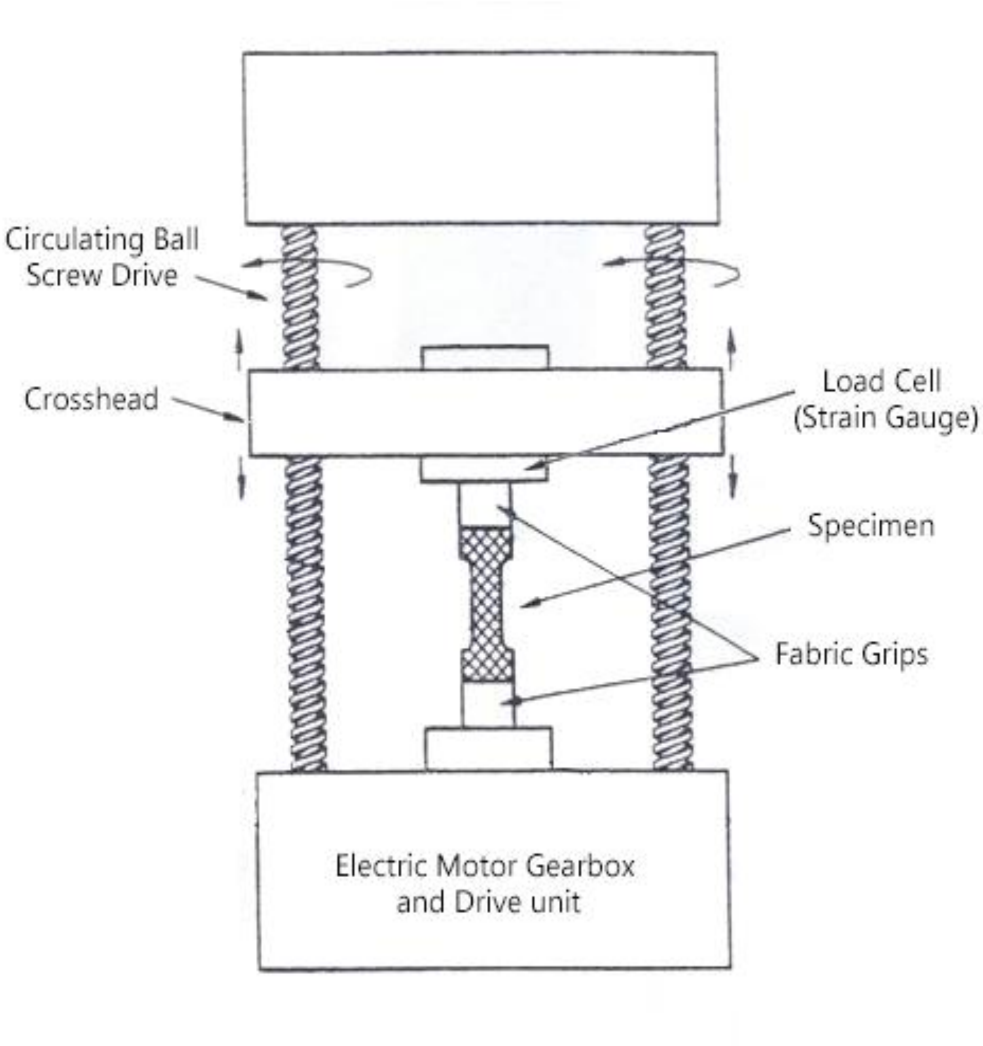


Figure 3.6 Schematic diagram of a tensile testing machine

The mass per unit length of the materials, known as the linear density, was calculated before determining the load/elongation properties of the material so that the following properties could be obtained from the stress-strain curves, see Figure 3.7.

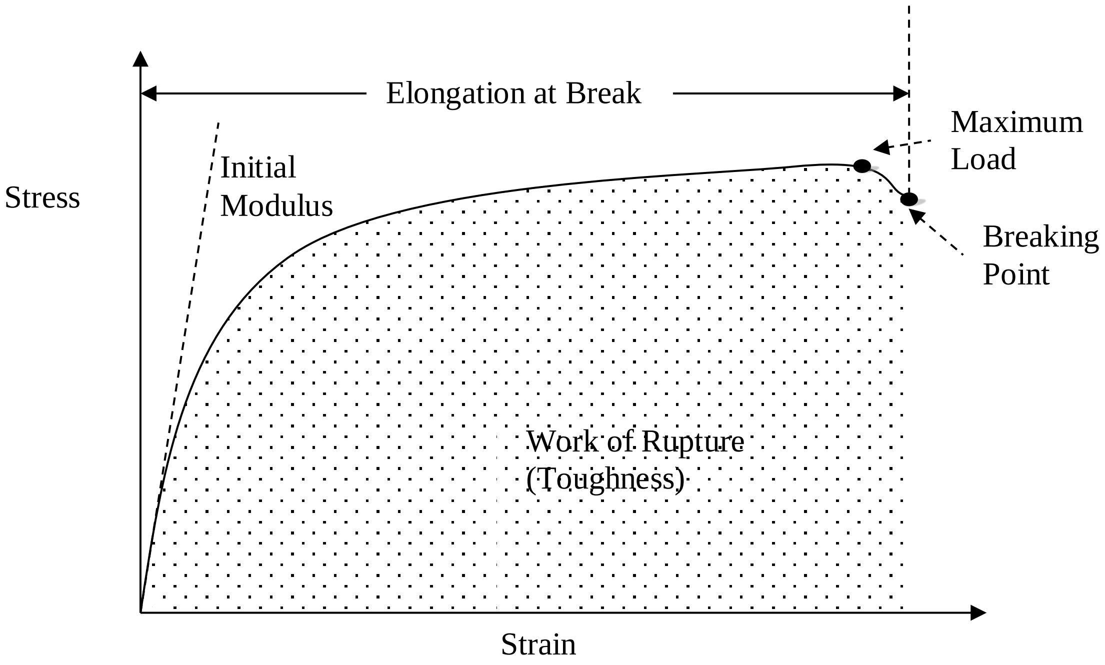


Figure 3.7 Stress-strain curve

1. Specific strength or tenacity ($Ntex^{-1}$): the ratio of the breaking force of a fabric to its linear density.

2. Strain at break or breaking strain (%): the increase in length of a specimen produced by the breaking force, expressed as a percentage of the original nominal length.

3. Work to rupture (N.cm): the area contained by the force/elongation curve up to the point where the breaking force is reached, which is a measure of the toughness of a fabric.

4. Elastic modulus ($Ntex^{-1}$): defined as the modulus in the elastic region of the diagram in which strain changes are still reversible. It is calculated from the slope of the initial straight line portion of the stress strain curve.

Hooke's law: $\sigma = E\,\varepsilon$

$$E = \frac{\sigma}{\varepsilon} \quad \left(\frac{N}{m^2}\right)$$

ε is considered as cNdtex^{-1} for yarns and Ndtex^{-1} in case of fabrics

10 samples were tested for each fabric and the average values were reported with standard deviations.

3.4.3 Thermophysiological testing

The thermophysiological properties of a garment provide comfort by maintaining body temperature and moisture output close to their normal levels. Comfort is related to the materials interaction with the body and the ambient conditions. This is based on how the material moves with or restricts body movement; retains or conducts body or environmental heat; absorbs or repels moisture next to the skin; and allows or restricts access of still or moving air to skin [65] [75] [76].

3.4.3.1 Alambeta thermal analysis

The Alambeta thermal testing equipment uses the same basic principle of the apparatus used for measuring Tog rating [77]. This is the same principle as explain in British Standard BS 4745 Determination of the thermal resistance of textiles. The Alambeta is designed to measure the thermal resistance in Km^2 W^{-1} x 10^{-3} (Tog), thermal conductivity (Wm K^{-1} X 10^{-3}), thermal diffusivity (m^{2}s^{-1}) and thickness (mm) of the test specimens. The schematic representation of Alambeta thermal testing apparatus is shown in Figure 3.8.

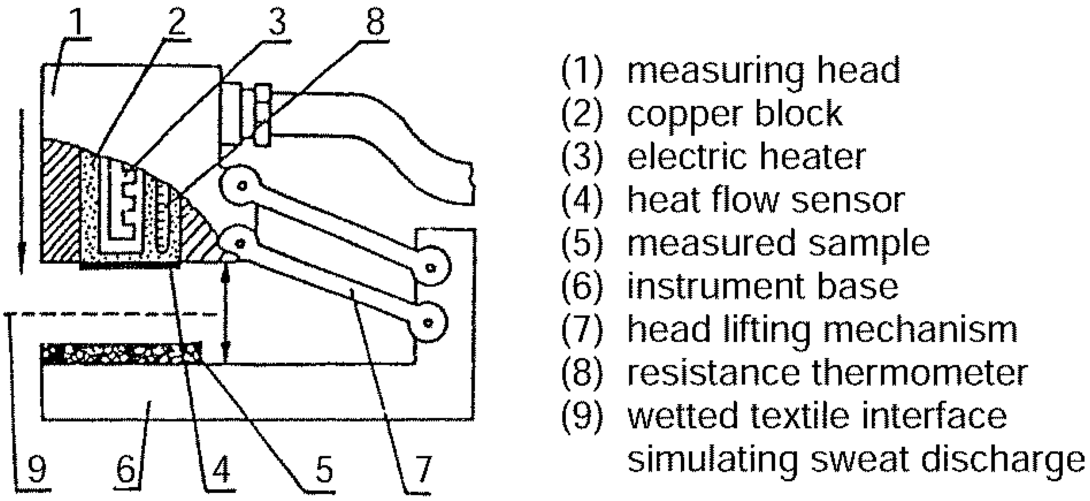


Figure 3.8 Schematics of Alambeta thermal testing apparatus [78]

Specimens of around 15 cm X 15 cm were roughly cut to have total coverage underneath the 100 mm diameter heating plate of the apparatus.

During testing, the top plate is heated to 10^{o}C above ambient conditions and the bottom plate contains temperature sensors. Heat flows from the top plate to the bottom plate through the fabric. Samples are initially tested when dry, then 0.2ml of water is placed on the top of the sample to represent moisture from the skin and the sample is tested after 4 minutes to represent them being in a ‘Wet’ and ‘Dry’ state. When the test is initiated and once the temperature gradient has stabilised, the parameters described earlier are calculated and displayed on the screen in succession.

3.4.3.2 Permatest

The Sensora Permatest instrument uses the same principle as the apparatus specified in ISO 11092 [79] developed by the Hohenstein Institute but employs different conditions and is claimed to be a much faster method. This is a new fast response measuring instrument (skin model) for the non-destructive determination of water-vapour and thermal resistance or permeability of textile fabrics, nonwovens, foils and paper sheets [75] [80] [81].

A heated porous membrane is used to simulate sweating skin. A current of air removes the micro-climate that develops above the surface of the membrane, see Figure 3.9 for a schematic representation of the testing instrument. The heat required for evaporating the water from the membrane with and without a test fabric covering is measured. The fabric produces resistance to evaporation and therefore less heat is required. The results are used to calculate the relative water vapour permeability as a percentage of the control test without the fabric covering, and the resistance to evaporative heat loss in m^2PaW^{-1}.

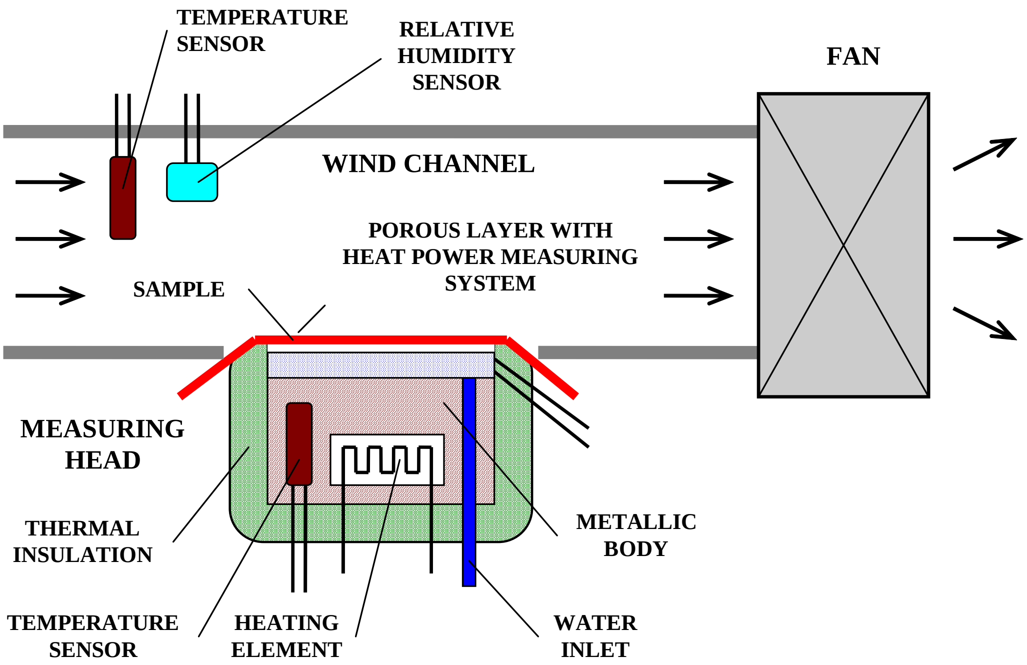


Figure 3.9 Permatest skin model for water vapour permeability testing [82]

The specimens that were used for measuring the thermal properties in the Alambeta instrument were also used for testing on the Permatest apparatus. Firstly a 0.2ml of deionised water was sprayed over the membrane that simulates the skin until there is total coverage and the specimen is mounted onto the plate. The machine is operated without a specimen until the message ‘steady state reached’ is displayed on the computer. A specimen is then placed over the simulated skin by pulling the measuring head and placing the fabric between the bottom of the air channel and the measuring head. Upon measurement, the water vapour resistance is shown in m^2Pa/W and the water vapour relative permeability is shown in %. This test was repeated ten times for each specimen. Though a direct value is calculated by the instrument, values could also be calculated using the following formula:

Relative water vapour permeability (P_{wv})

$$P_{wv} = \frac{100\,u_1}{u_0}\ \%$$

Resistance to evaporative heat loss (E_r)

$$E_r = (P_{plate} - P_{air}) \times \frac{1}{S}\,(1/U_{plate\,+\,fabric} - 1/U_{plate})\quad m^2PaW\text{-}1$$

where,

P_{plate} = Saturated water vapour pressure at wet plate surface at ambient temperature

P_{air} = Water vapour pressure of ambient air

S = Instrument heat sensor constant

$U_{plate\,+\,fabric}$ = millivolt output with fabric

U_{plate} = millivolt output without fabric

In standard atmospheric conditions of 20^0C and 65% RH

Saturated vapour pressure (P_{plate}) = 2.337 kPa

Vapour pressure of ambient air (P_{air}) = 2.337 x 0.65 = 1.519 kPa

3.4.3.3 Absorption testing

Absorption capacity of the fabrics were determined by a static immersion principle as described in BS 3449-1990, Method for resistance of fabrics to water absorption (Static immersion test) [83]. To determine the absorption capacity, a piece of apparatus that helps to hold the specimen immersed in a liquid was used, see Figure 3.10, to immerse a specimen of known mass in water for 20 minutes. The specimens were then hanged for 5 minutes for the excess water to drain and were re-weighed to calculate the percentage absorption capacity (gg^{-1}).

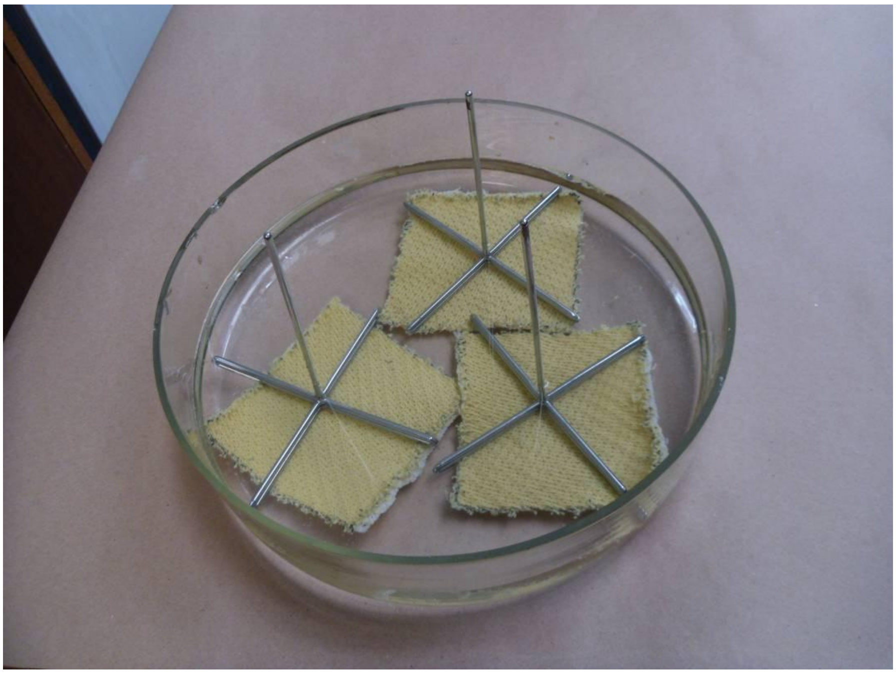


Figure 3.10 Absorption testing

Three 10 cm X 10 cm specimens were prepared for analysis. The mass of each individual specimen were taken and recorded. The specimens were then immersed fully in water for 20 minutes and then hung over the water for 5 minutes to drain excess water. After the allotted time the specimens were reweighed and the absorption capacity was calculated using the following formula:

$$\text{Absorption capacity} = \frac{(\mathrm{M2} - \mathrm{M1})}{\mathrm{M1}}\ x\ 100$$

where,

M1 = Mass of dry specimen

M2 = Mass after water absorption

3.4.3.4 Wicking test

The wicking characteristics of the material were determined by taking a 15cm x 2.5cm specimen strip of known mass and hanging the specimen vertically with one cm of the bottom edge of the specimen immersed in water, see Figure 3.11. After a set period of time any liquid that has vertically wicked up the length of the test specimen is identified. The specimen is also reweighed to measure the amount of liquid that has wicked up the length of the fabric. This is based on the British Standard BS 3424-18 Testing coated fabrics, Methods for determination of resistance to wicking and lateral leakage [84].

Five specimens of 15 cm X 2.5 cm each of the different samples were prepared. The test specimen was weighed to obtain the dry mass (M1). The specimen was hung vertically into the water until one cm of the specimen was immersed into the water. Wicking is allowed to take place for six minutes.

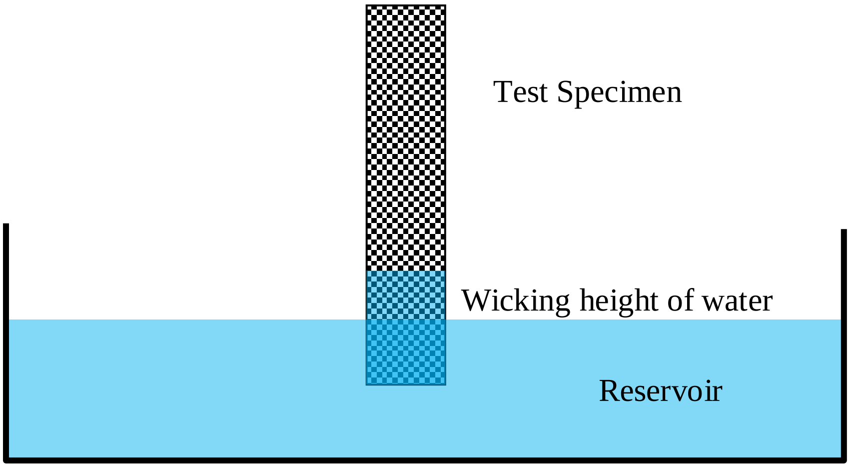


Figure 3.11 Schematic of vertical wicking test

The specimen is then taken out and the one cm section that was immersed in the water is cut off and discarded. The height (H) of the rise of water is noted and the fabric is then reweighed (M2). Then the wicking characteristic of the fabric is measured using the formula:

Wicking = H x (M2-M3) g cm

where,

M3 = 14/15 x M1 (this is to take into account the 1cm length that was cut off from the original specimen before measuring M2)

The wicking height is also compared on its own as a thick sample may have poor wicking height but a high value by this method so doesn't show its true wicking potential.

3.4.4 Ageing of fabrics

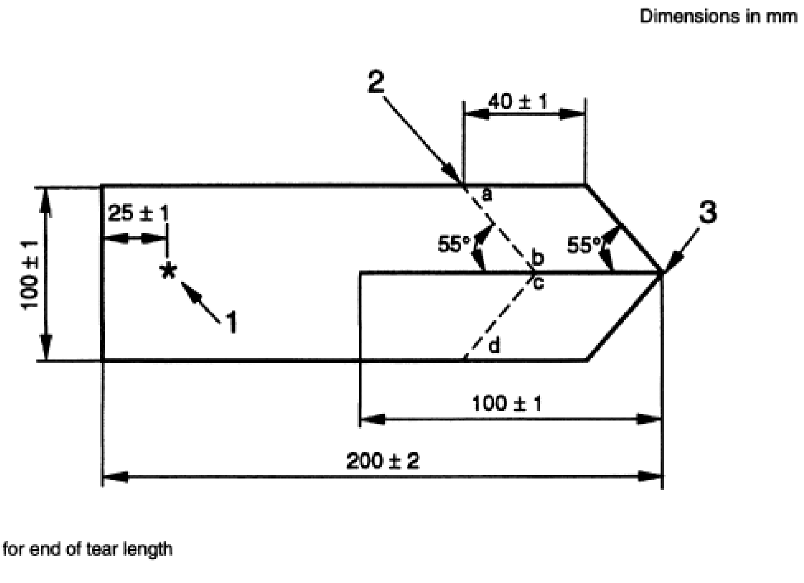
To study the effect of ageing the materials were subjected to UV radiation by exposing it to 450W Xenon arc lamp at a distance of 300mm for 90 hours. This is equivalent to 5 years of everyday exposure at 8 hours per day [85]. The xenon test chamber reproduces the entire spectrum of sunlight (295 nm-800 nm), including ultraviolet (UV), visible light and infrared (IR).

The exposure apparatus consists of a corrosion resistant climatic test chamber containing the optical light source, a filter system and holders for the test specimen. The specimen is exposed on only one side to the xenon arc lamp which serves as the light source. The spectral energy distribution of the light source is as described in BS EN ISO 105-B06:2004 [86] .

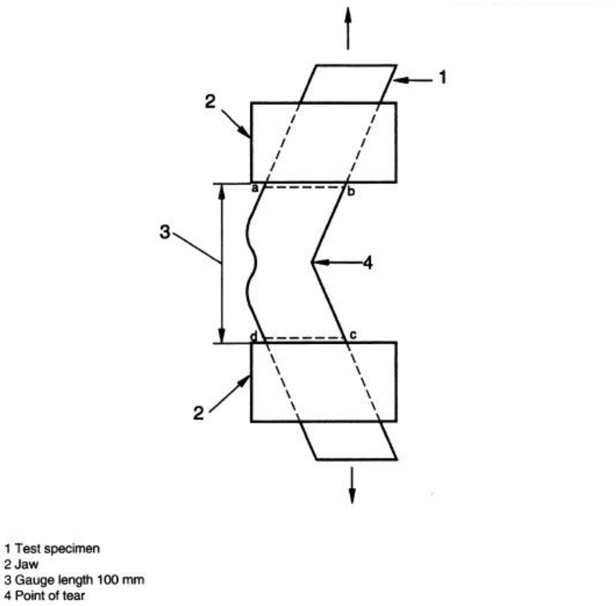
3.4.4.1 Tear strength test

The tear strength was used as one of the method to study the effect of aging on the slash resistant fabrics. The determination of tear force was carried out on wing-shaped specimen as described in BS EN ISO 13937-3:2000 [87]. The tear force is the force required to propagate a specifically shaped pre-initiated tear, see Figure 3.12, to form two wings on one side. Each wing is mechanically stressed using a Constant Rate of Extension (CRE) tensile strength tester, Instron 4303 in this case, such that the stress is concentrated at the cut in such a way as to cause tearing in the desired direction. The wings of the specimen are clamped inclined to the direction of the threads to be torn.

The tear force is calculated by taking the arithmetic mean of all the recorded force peaks for the specimen.



(a) Wing-shaped test specimen

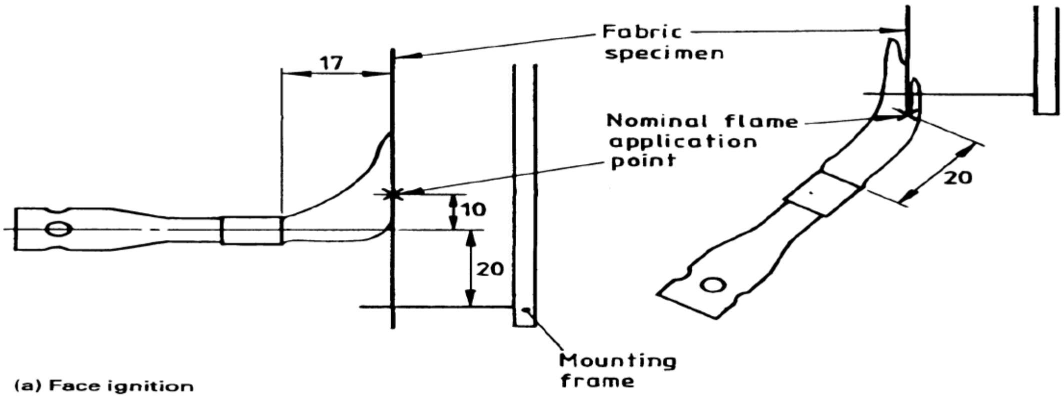


(b) Clamping arrangement

Figure 3.12 Tear strength testing

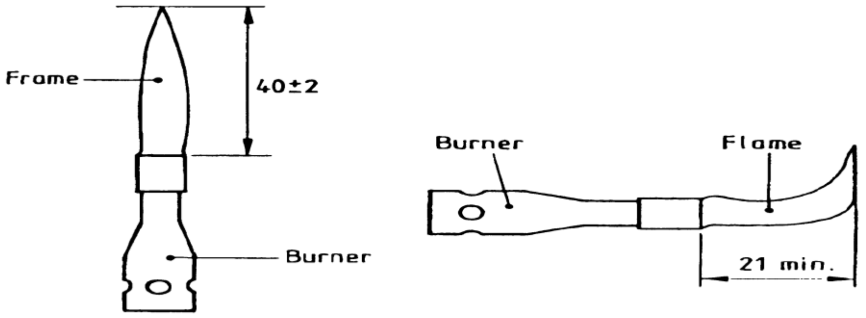
3.4.4.2 Flammability testing

The flammability characteristics on the material was carried out, based on the British Standard BS 5438:1989 , by applying a small igniting flame with a horizontal flame length of 21mm to the face of the fabric for a minimum of 10 seconds [88]. Figure 3.13 shows the test apparatus setup for testing of a specimen for flammability as described in BS 5438:1989. 30 second exposure is generally used for the high performing fabrics and therefore the ignition flame was applied for 30 seconds in these experiments.   .



(a) Face ignition

(b) Bottom edge ignition



(c) Vertical flame height

(d) Horizontal reach

All dimension in millimetres.

Figure 3.13 Flammability test apparatus [88]

CHAPTER 4

CONTRIBUTION OF YARNS AND STRUCTURES IN DEVELOPING SLASH RESISTANT MATERIALS

"The art of discovery consists in seeing what everyone else has seen and then thinking what nobody else has thought"

A. Szent Györgyi (1893-1986),
Nobel Prize for Physiology or Medicine, 1937

4. Contribution of Yarns and Structures in Developing Slash Resistant Materials

4.1 Introduction

In this Chapter, the selection of the yarns used for constructing the slash resistant materials is discussed in depth along with the development of different knitted structures by using an electronic weft knitting machine.

4.2 Development of yarns for slash resistant fabrics

In a PPE fabric, especially a knitted fabric, it is the yarns which absorb the majority of the load. Hence, it is highly essential that a right yarn is chosen for the development of a slash resistant fabric. The yarns should be able to provide the following functions:

- absorb the force exerted by the knife;
- resist from being sheared at the point of contact;
- start blunting the knife edge;
- be dyeable/printable so that the fabric can be manufactured in different colours;

It is well known and scientifically proven that para-aramid fibres and UHMWPE fibres have excellent energy absorbance properties but they cannot be dyed once they have been extruded and they are available only in certain colours, namely yellow and black for aramids and white for UHMWPE [29] [47] [56] [66] [21]. Due to their energy absorbance properties, different varieties of para-aramid yarns where researched from 4 different manufacturers, namely DuPont, Teijin, Tilsatec and Руслан. Staple spun aramids were used in the development of slash resistant fabric as they provide the versatility required when used in a weft knitting machine. They also have a greater number of fibres across the section which provides more resistance to shearing on impact. The spun yarns, on the other hand, have better comfort properties when compared to continuous filament yarns [65] [33] [89].

Staple spun aramid yarns are produced by reducing a continuous multifilament yarn to a bundle of staple fibres by means of stretch breaking and then spinning them into a yarn using the ring spinning system. The sources of different ring spun yarns that were initially analysed are given in Table 4.1.

Table 4.1 Sources of ring-spun yarns

Yarn Name	Fibre constituents	Manufacturer
Twaron Series	100% single and double ply staple spun Twaron	Aramex Garne GmbH, Germany
Kevlar Series	100% single and double ply staple spun Kevlar	Aramex Garne GmbH, Germany
Руслан Aramid	100% continuous filament twisted aramid yarn	JSC KamenskVolokno, Russia
Tilsa series	Staple spun para-aramid of various counts	Tilsatec, UK

Since no single fibre can provide all the properties expected for a highly protective and yet comfortable product, composite yarns comprising of different compositions was developed. The composition of various materials in the composite yarn was provided to different manufacturers based on the equipment available at their respective site. The sources of different composite yarns that were initially analysed are listed in Table 4.2.

Spun Kevlar yarns with two different linear densities was sourced from Aramex-Garne, Singen, Germany and one of the yarn was doubled locally without any twist, coded as K2. This was mainly to increase the linear density of the yarn to enable use of thicker yarn. Tilsa is a para-aramid yarn from Tilsatec, with a similar linear density to that of the Kevlar yarns from Aramex Garne. Several dope dyed para-aramid yarns were sourced from Tilsatec in various linear densities.

Table 4.2 Sources of composite yarns

Yarn Name	Fibre constituents	Manufacturer
Tilsa series	Continuous filament double ply yarns	Tilsatec, UK
Wykes E669	Composite yarn with steel core	Wykes, UK
WF Series	Composite yarns with a minimum of three components	World Fibre Inc, USA

Wykes E669 is a development composite yarn that was spun at Wykes, UK. This yarn was mainly used to study the effect of stainless steel core which is widely used in knitting to provide cut resistant properties.

Composite yarns in the WF series of yarns were spun specifically for the purpose of this research using a vertical hollow spindle covering machine of a type manufactured by H.H. Arnold Company. This machine has been modified using a proprietary technique as described in the US Patent No. 6,413,636 [90].

Figure 4.1 Vertical hollow spindle covering machine by H.H.Arnold

The components in the WF series yarns are glass fibres and UHMWPE. They were constructed in different weight (linear density) combinations to analyse a range of permutations. The composite yarns were double covered with either polyester or polyamide to have a better handle and also enable dyeing the external surface of the fabric. Polyamide 6,6 was used as the covering yarn as it has a higher melting point (263^0 C) than polyamide 6 (216^0 C). Polyamide 6,6 also provides excellent wear resistance and frictional properties [25] [29].

Although, there are methods available to study the cut resistance of yarn [91], there are no standardised methods or methods that are well established. Hence, the initial analysis of the yarns was based on its tensile properties. The yarns were shortlisted based on the stress/strain analysis and these yarns were used in the manufacture of the slash resistant fabric. The ideal yarn for the slash resistant fabric was chosen based on its performance in the fabric against the slash resistant test.

4.2.1 Analysis of yarns using tensile properties

The tensile properties of the yarns listed in Table 4.3 were determined by using Statimat M instrument at a gauge length of 500mm and at a speed of 300mm/min. The average values of 10 specimens [10 tests per cone specimen] tested for each yarn are summarised in Table 4.3. The Standard Deviation is rounded off to the nearest whole number for breaking force, tenacity and work of rupture.

Owing to the different compositions used in the manufacture of the yarns, each yarn has different linear density and exhibits different tensile performance.

Table 4.3 Physical properties of composite and ring-spun yarns

Yarn	Linear Density (Tex)	Breaking Force (cN)	Tenacity (cN/Tex)	Work of Rupture (cN*cm)	Elongation (%)	Breaking Time (s)
TWARON 25-2s	74.6 ± 3.8	5425 ± 355	72.73 ± 4.8	4157 ± 363	4.19 ± 0.1	4.2
KEVLAR (K2)	122.2 ± 4.4	8709 ± 342	71.39 ± 2.8	7332 ± 537	4.51 ± 0.12	4.5
PYCNAH Aramid	62.3 ± 1.2	10573 ± 2655	170.54 ± 42.8	1644 ± 976	3.63 ± 0.96	0.7
S1-TW-1	60.6 ± 4.7	4803 ± 308	79.30 ± 5.1	4249 ± 403	4.81 ± 0.24	4.8
TWARON-98T	98.1 ± 1.7	7632 ± 274	77.89 ± 2.8	6963 ± 345	5.05 ± 0.09	5.1
KEVLAR-60T	61 ± 2	4660 ± 240	76.4 ± 3.2	6843± 487	4.68 ± 0.6	4.7
KEVLAR-96T	96.1 ± 2.1	6172 ± 362	64.22 ± 3.8	5625 ± 471	5.11 ± 0.13	5.1
KEVLAR-101T	100.3 ± 1.8	5971 ± 357	59.72 ± 3.6	5281 ± 439	4.99 ± 0.16	5.0
TILSA (GREEN) 14/1	58.3 ± 0.7	1916 ± 185	33.05 ± 3.2	1662 ± 193	3.98 ± 0.15	4.0
TILSA-WHITE-D92	57.9 ± 0.9	6263 ± 291	109.89 ± 5.1	6606 ± 438	7.33 ± 0.23	7.4
TILSATEC-T62-GREEN	62.6 ± 1.0	1756 ± 186	28.34 ± 3.0	1535 ± 252	3.94 ± 0.28	3.9

Continued…

Yarn	Linear Density (Tex)	Breaking Force (cN)	Tenacity (cN/Tex)	Work of Rupture (cN*cm)	Elongation (%)	Breaking Time (s)
TILSATEC-B145-BLACK	149.0 ± 1.6	3412 ± 47.16	22.90 ± 0.3	27902 ± 1272	24.28 ± 0.96	24.4
TILSATEC-YELLOW-RHINO-C128 [Ne92/2]	132.4 ± 1.6	5561 ± 1638	42.13 ± 12.4	5498 ± 1805	6.43 ± 0.85	6.5
WF520	127.2 ± 4.7	7776 ± 288	61.13 ± 23.4	6792 ± 490	4.75 ± 0.32	4.8
WF408	268.4 ± 6.7	15182 ± 364	56.48 ± 1.4	16485 ± 6178	3.98 ± 0.91	4.0
WF334	221.6 ± 2.3	1072 ± 210	48.42 ± 9.5	1016 ± 346	2.24 ± 0.47	3.8
WF271	95.4 ± 1.9	7549 ± 238	79.30 ± 2.5	6729 ± 617	4.19 ± 0.38	4.2
WF521	128.3 ± 3.6	8559 ± 571	66.87 ± 4.4	7573 ± 813	4.76 ± 0.26	4.8
WYKES E669	201.8 ± 14.6	5191 ± 439	25.83 ± 2.2	20772 ± 2377	15.25 ± 0.99	15.3
Dyneema Composite Yarn (Tilsatec)	113.7 ± 6.9	3635 ± 704	32.00 ± 6.2	8734 ± 4274	10.21 ± 3.89	10.2
WF159	232.0 ± 7.6	15580 ± 529	67.16 ± 2.3	18094 ± 1476	4.74 ± 0.24	4.8
WF528	55.3 ± 3.4	5936 ± 189	107.44 ± 3.4	3821 ± 275	3.24 ± 0.08	3.2

Since the objective was to create a flexible slash resistant fabric that has several properties such as protection against slash, comfort and print/dyeability, yarns that supported such properties were required to be made or sourced. Knitting technology that enabled knitting of a two-layered fabric was declared to be the ideal choice for making the fabric, as discussed in section 3.2. For this purpose, firstly two different yarns that when combined gives all the above properties had to be chosen.

Since para-aramid yarn is the most widely used yarn in cut resistance fabrics, and for the reasons mentioned in section 4.2, ring spun aramid yarns was chosen to be used in one face of the weft knitted fabric. A composite yarn had to be used for the other face of the fabric. It is imperative that the most suitable yarns for each face of the fabric are chosen.

4.2.1.1 Selection of spun aramid yarn

Spun aramid yarns were sourced from three different manufacturers in various linear densities. The stress/strain curves of the 100% aramid yarns are shown in Figure 4.2. It can be observed from the figure that the initial modulus of all the spun aramids are more or less the same. The exception being the russian made PYNAH aramid which is a continous filament yarn with 200 filaments and 100 twists per metre. Though the initial modulus for all the spun aramids are the same, the yarns made by Tilsatec exhibited very low tenacity and required the least effort (work of rupture) to break the yarn. This was the case with the PYNAH yarn too as it required just 1644 cNcm to break the yarn compared to 5281- 7332 cNcm for the other spun aramid yarns. The difference between the work of rupture and tenacity for different counts of 100% Kevlar and 100% Twaron was insignificant, hence only one yarn was chosen among them, namely the 60 Tex (Ne 10/1) Kevlar (K1). The same yarn was doubled locally to provide a yarn with higher linear density that will require a higher breaking force. The tensile properties of the doubled Kevlar (K2) is also shown in Table 4.3.

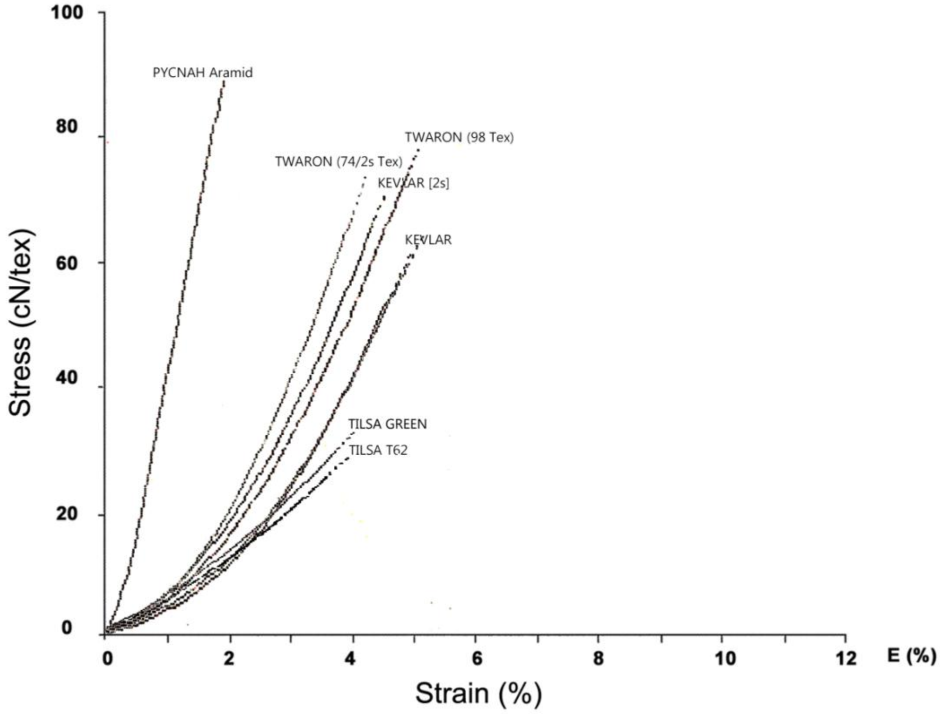


Figure 4.2 Stress/Strain curves of 100% aramid yarns

4.2.1.2 Selection of composite yarn with stainless steel core

It is well established in the industry that yarns with stainless steel core provide highest cut resistance in gloves [91] [92]. Figure 4.3 shows the cut resistance values of various gloves tested against the standard ASTM 1790-05-2005. The highest cut resistance is exhibited by the gloves made from yarns containing stainless steel core. Several patents applied or granted for cut resistance yarns or cut resistance materials contain a component with a stainless steel core in them [93] [94] [95] [96] [97] [98].

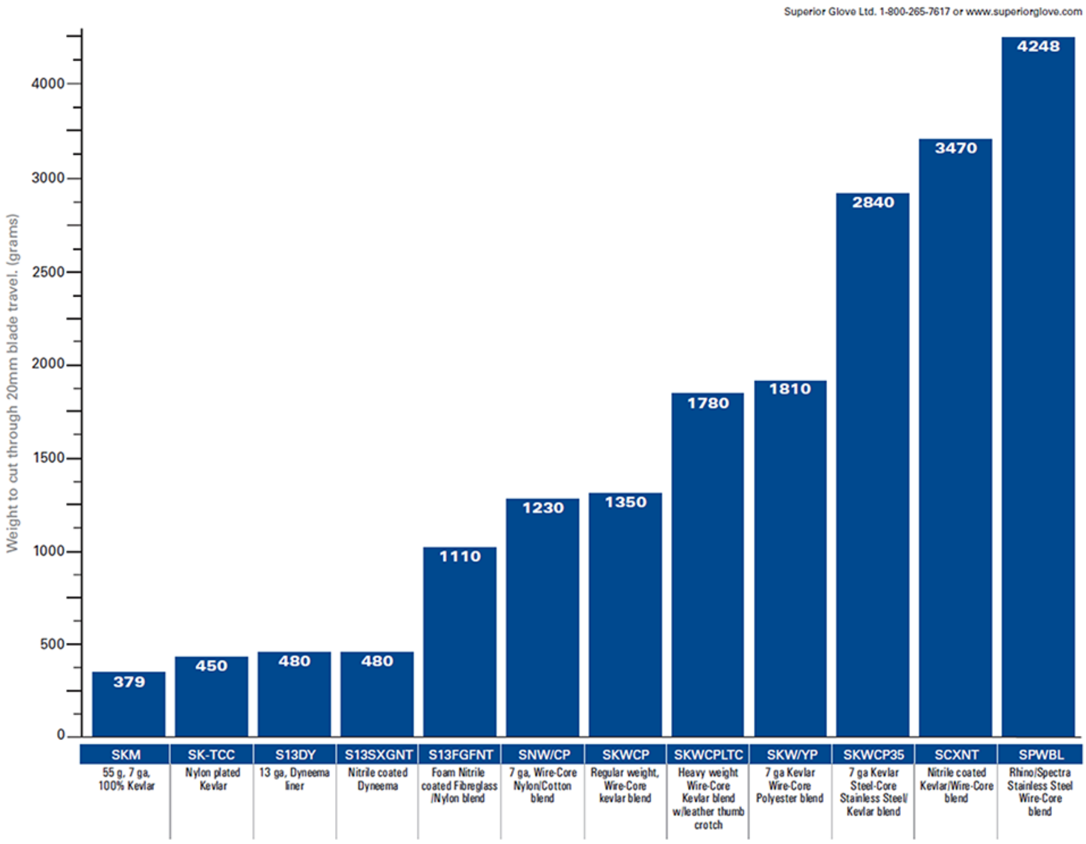


Figure 4.3 Cut resistance of various glove materials [92]

Though the stainless steel yarns provide the hardness for resistance against cuts/slash which requires the highest amount of work for a breakage, 27902 cNcm for Tilsatec B145 and 20772 cNcm for Wykes E669, they also had the least tenacity with 22.90 cN/Tex and 25.83 cN/tex respectively. The high extent of work required to break is mainly due to the intermittent breakage displayed by them, see Figure 4.4. This indicates that yarns with stainless steel core do not provide a better protection than the aramid yarns during a slash attack where the load increases rapidly. For similar protection, in comparison to aramid yarns, composite yarns with a stainless steel core will increase the weight of the fabric and hence is not suitable for a lightweight fabric. They also lead to potential issues during the cut make and trim of the fabric to form a garment.

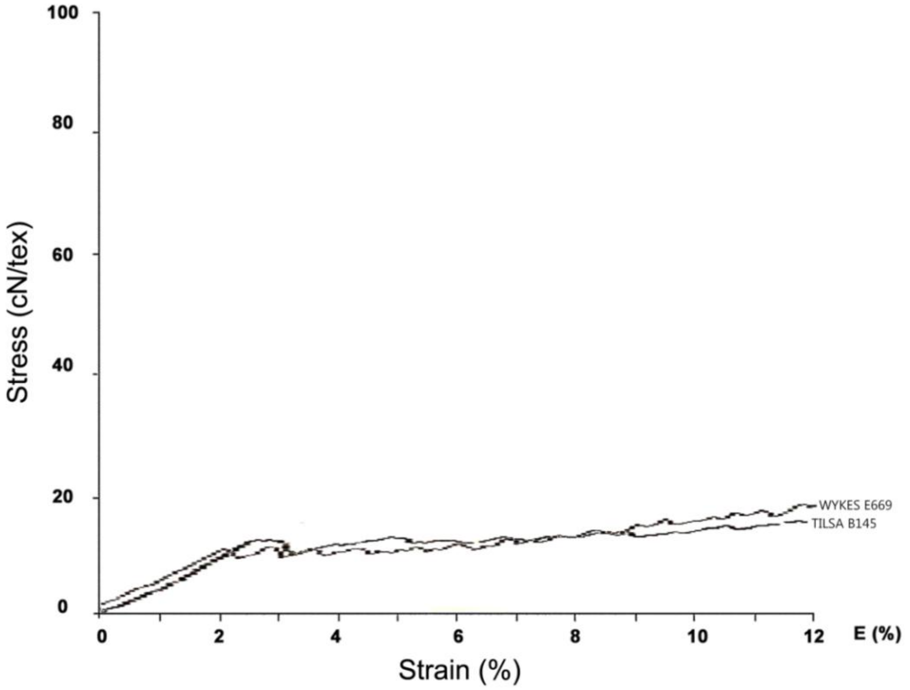


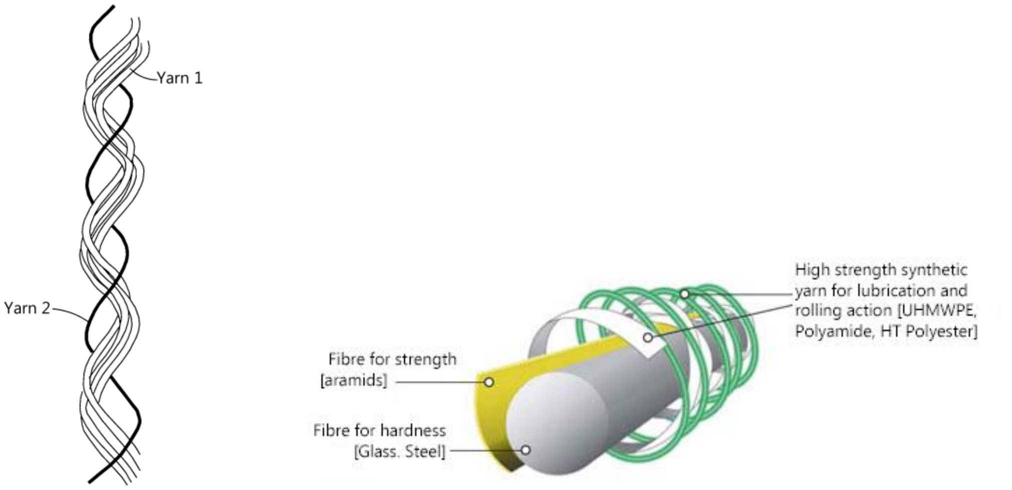
Figure 4.4 Stress/Strain curves of composite yarns with stainless steel core

Both Wykes E669 and Tilsa B145 registered a breaking force of 5191 cN and 3412 cN within the first 4 seconds, but due to its intermittent breakage, it took longer to complete the test. The steel cores used in both these yarns have high modulus of elasticity of 180 cN and hence breaks quicker than the other yarns. The presence of polyamide 6,6 and

UHMWPE (Dyneema) yarns used as the cover yarns prevent the yarn from breaking completely giving the ‘slip-stick’ pattern.

4.2.1.3 Selection of advanced composite yarn

Apart from yarns containing stainless steel core, two other types of composite yarns were tested. The first one being a two ply yarn, where two types of yarns were twisted together and the second one was an advanced composite yarn, where a minimum of three components are used to make up a yarn. The schematic diagram of both types of composite yarns is shown in Figure 4.5(a) and 4.5(b).



(a) Two-ply composite yarn **(b)** Advanced composite yarn [Source: World Fibre Inc]

Figure 4.5 Composite yarns

Glass fibres have low density (2.58 gm/cc) compared to stainless steel (8.00 gm/cc), but exhibit very good tensile and thermal properties. One major drawback with the glass fibres is that they are known to cause irritation and have relatively low fatigue resistance

[99]. In order to overcome this, they have to be double wound with other yarns so that they do not come in contact with the skin. This double winding also protects the glass fibre from abrading which usually leads to reduced strength.

Several different compositions of advanced composite yarns were manufactured to compare their tensile properties. The load/elongation curve for those fibres is shown in Figure 4.6. The Tilsatec yarns are two ply composite yarns and WF series yarns are advanced composite yarns.

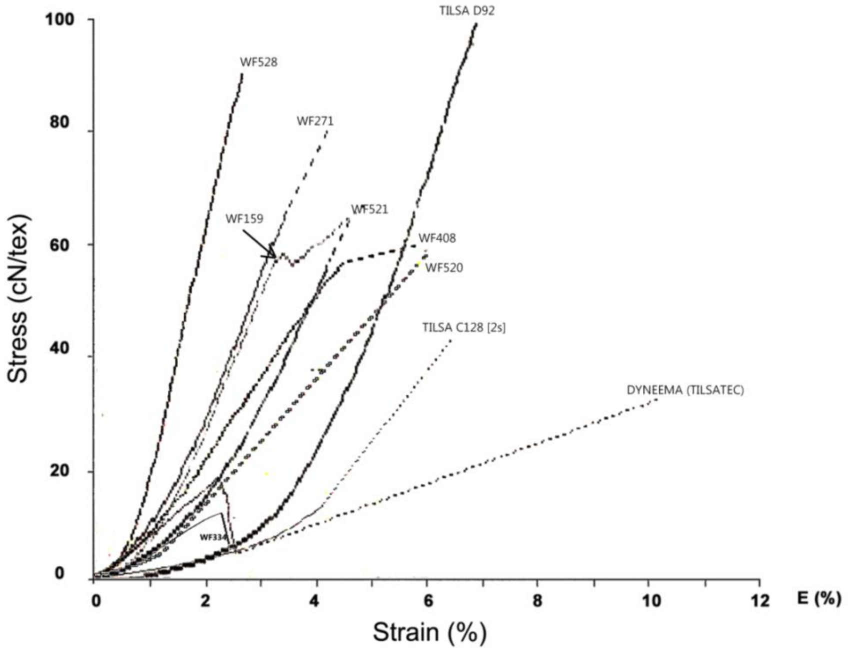


Figure 4.6 Stress/Strain curves for two-ply and advanced composite yarns

It can be observed from the stress/strain curves that Spectra WF528 yarn possesses high tenacity and it has the second highest specific modulus. It can be explained that the presence of fibreglass in its core, along the yarn axis, helps it to contribute more to the tensile strength when compared with the staple-fibre Kevlar yarns. Although Tilsa D92 exhibits highest tenacity, it has a low initial modulus which will make the yarn stretch on impact and thus let the sharp edge of a knife penetrate easily.

The maximum breaking force is withstood by Spectra WF408 which is also the thickest yarn among all the tested yarn samples. It consists of 66 Tex G75 glass fibre in its core and is covered by 72 Tex Type 900 Spectra. The 66 Tex glass fibre is the thickest core used in the samples. The maximum breaking loads endured by the other yarns are much lower than Spectra WF408, but these yarns also have lower linear densities.

It can be inferred, from Table 4.3, that the highest tenacity amongst the ten composite yarns (WF series, Wykes E669, Tilsatec Rhino and Dyneema Composite) was achieved by Spectra WF528, that itself being the yarn with the lowest linear density. The breaking extension of the WF528 is also the second lowest amongst the ten yarns with a value of 3.24%. The maximum force required to break the yarn is only 5633 cN. The yarn that required the highest breaking force is WF408 at 15182 cN, but it also has the highest linear density (268.4 Tex) which reduced its tenacity to 56.48 cN/Tex. The Wykes E669 yarn has the least tenacity of all with 25.83 cN/Tex.

4.2.2 Conclusions

Different yarns that were intended for the manufacture of slash resistant materials were tested for their tensile properties. Based on the tensile properties, a selection of yarns has been shortlisted which is expected to provide the slash resistance performance and at the same time be lightweight and comfortable. The selected yarns will be used to make the slash resistant fabric and their performance analysed based on the outcome of the slash resistance tests. This preliminary selection was based on the performance of the yarn based on its tensile properties and the same performance cannot be expected in the fabric stage for slash resistance as the cover yarns could have a significant effect on the slash resistance, although higher initial modulus absorbs and spreads the load better than those with lower initial modulus. If the yarns can absorb the load, it will help in dissipating the force exerted by a slash attack much more effectively and this will be complimented by the flexible structure of the knitted fabrics. The performance of the yarns based on their slash resistance capabilities is discussed in detail in Chapter 5.

4.3 Development of knitted structures

A series of fabric samples were knitted by using different combinations of various yarns in an innovative two-layer weft knitted jersey structure. Two basic variations of the structure were mainly used to characterise the yarns. They are ‘jersey structure’ and ‘racked structure’ which are described in detail in the subsequent sections. The fabrics were knitted with 2 ply Kevlar yarn on one face and one of the other yarns in the other face and vice versa. The 2-ply Kevlar yarn was doubled from a single Kevlar staple-fibre yarn since a higher linear density Kevlar could not be sourced commercially.

4.3.1 Jersey structure

The ‘Jersey Structure ’is a single piece of knitted fabric that has a genuine two layered structure. The knitting machine that was used to produce the fabrics was an E10 gauge fully electronic flat knitting machine [Make: Stoll; Model: CMS 440]. The structure of the “jersey structure” is illustrated in Figure 4.7.

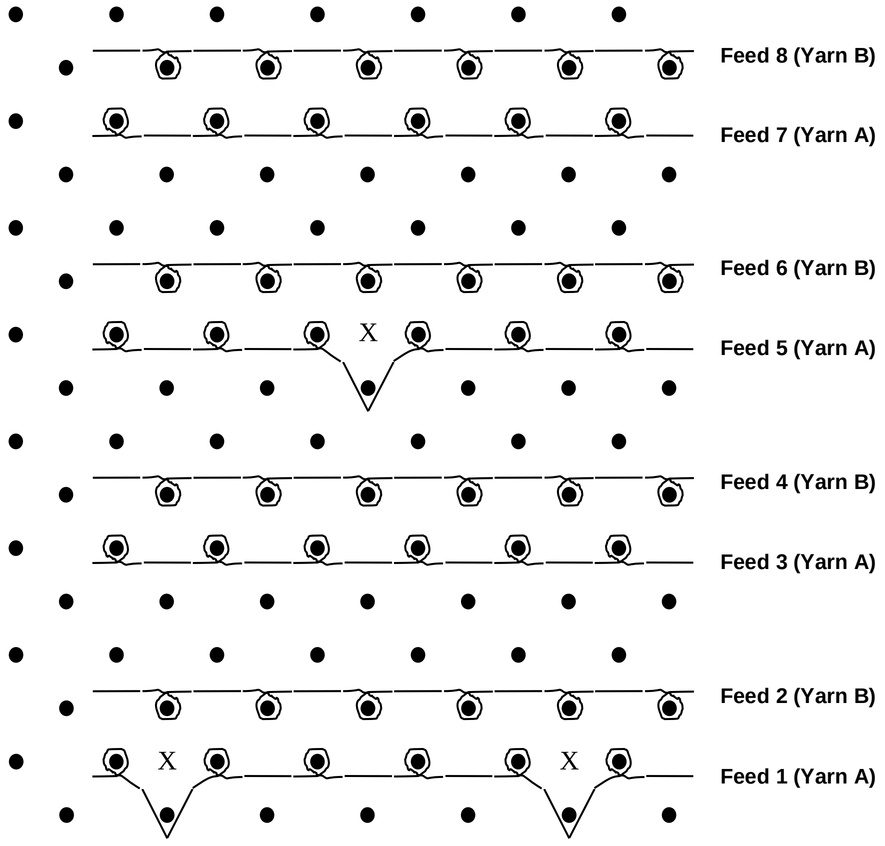


Figure 4.7 Knitting structure of ‘jersey structure’

This structure forms a two layer structure by tucking of yarn from one face of the fabric with the other face of the fabric. Since the knits are tucked at certain intervals, only one yarn is visible on any face of the fabric thus providing a ‘true’ two layer structure.

4.3.2 Racked structures

The ‘Racked Structure’ was also knitted using the same E10 gauge electronic flat knitting machine. The back needle bed of the machine was racked in the following sequence: First, it was racked to the left by 8 needles (one needle per traverse), then it was racked to the right by 8 needles (one needle per traverse). The back needle bed was then racked by 8 needles to the right (one needle per traverse) and finally the needle bed was racked back to the left by 8 needles (one needle per traverse). In this position, the needle bed was back to the normal position, as in the beginning of the sequence. This sequence is continued throughout the fabric. The knitting diagram of the racked knitted structure is shown in Figure 4.8.

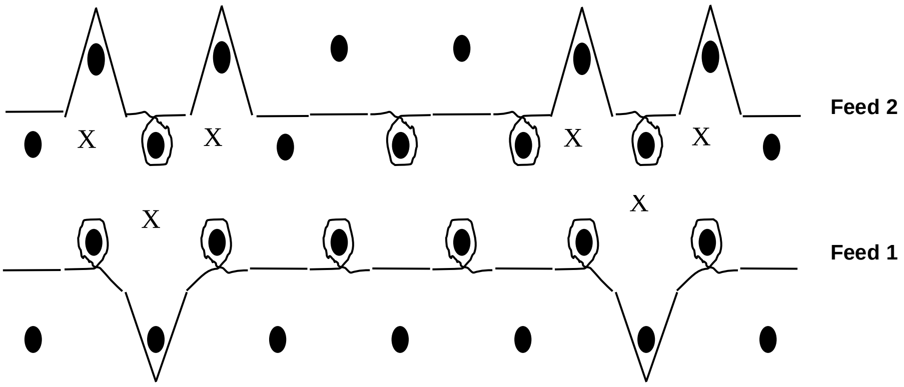


Figure 4.8 Knitting structure of the ‘racked structure’

The difference between the ‘Racked structure 1’ & ‘Racked structure 2’ is the number of racks performed before changing the direction of the rack. Racked structure 1 had 8 racks on either side of movement giving a total of 16 racks in one direction and ‘Racked structure 2’ had 4 racks on either side giving a total of 8 racks per direction.

The effect of stitch length on slash resistance was also analysed by keeping the fabric structure the same and increasing or decreasing the stitch length by 2.5%, 5%, 7.5% and 10%.

CHAPTER 5

SLASH RESISTANCE, TENSILE, THERMAL AND COMFORT PROPERTIES

"My goal is simple. It is a complete understanding of the Universe, why it is as it is and why it exists at all."

Stephen Hawking (1942 -),
Physicist and Mathematician

Chapter 5. Slash Resistance, Tensile, Thermal and Comfort Properties

5.1 Introduction

One of the main objectives of this research programme was to develop and characterise novel cut resistant and slash proof materials that are lightweight, comfortable and efficient. Official statistics showing that knife is the most commonly used weapon employed in violent incidents in the UK, and studies that reveal slash wounds inflicted using knives are disfiguring and sometimes life threatening were discussed in detail in Chapter 2.

In Chapter 4, the analysis of different yarns used for the manufacturing of different knitted structures and the designing of the knitted fabrics by using a flatbed electronic E10 weft knitting machine was discussed. The materials thus formed were tested against the HOSBD slash resistant standard, the principle and procedure of this test standard have been described in detail in Chapter 3.

For slash resistance, the fabric should have a low initial modulus that will aid in the relative slippage of the yarns and thereby assists in distributing the stresses over a larger area and hence prevents the blade from striking through. Fabrics manufactured by using knitting technology will have a high degree of interlocking of the yarns which results in a fabric with a very low initial modulus. Weft knitting technology offers considerable advantages in terms of cost, design flexibility and versatility in the production of suitable structures for slash resistant fabrics.

In this Chapter, the development of slash resistant fabrics is described in detail. The performance of different yarns used for the development of the slash resistant fabrics against the HOSDB slash resistant standard has been compared, followed by the optimisation of the fabric design parameters to obtain light weight slash resistant fabrics.

5.2 Analysis of a slash resistance test results

The fabric specimens were tested against the HOSDB Slash Resistant Standard for the UK Police (2006) [70]. The working principle, test methodology and protection levels required have already been described in detail in Chapter Three.

Figure 5.1 shows a typical graph that is obtained from a single slash. A total of nine slashes, three per direction, were obtained per specimen.

The Y axis shows the force that is applied by the tip of the blade on the fabric during a slash and the X axis shows the time in milliseconds during which the force is applied. The blade travels at 6.5 metres per second and the actual contact time of the blade and the fabric is a maximum of 200 milliseconds, unless the blade is stopped by the test specimen.

A strike-through is whenever the blade comes in contact with the force plate. This is depicted in the graph by the red lines, with a value of 1 when there is a strike-though and 0 when there is no strike-through.

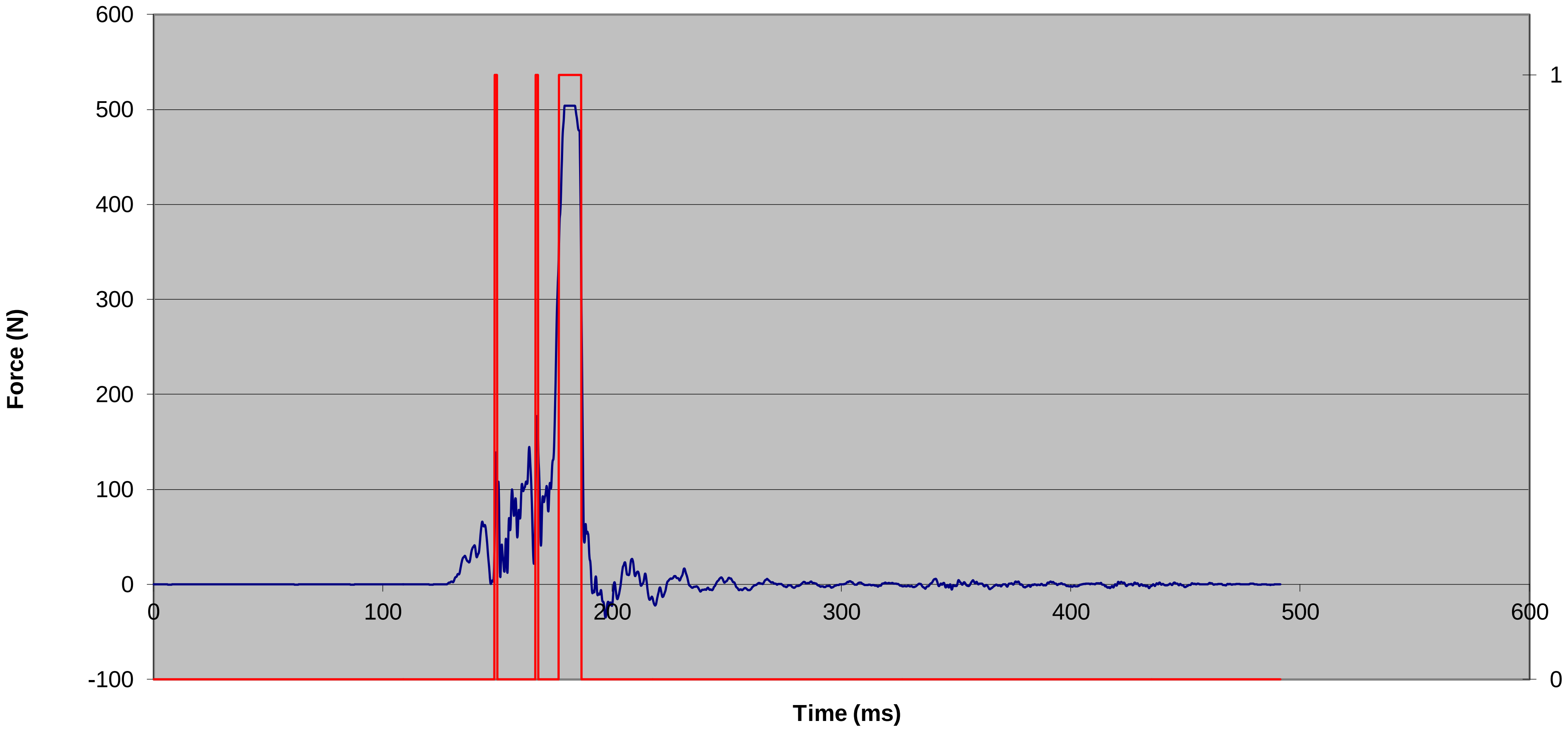


Figure 5.1 Representative graph from a single slash resistant test

5.3 Comparison of different yarns of the knitted fabrics

A series of fabric samples were knitted by using different combinations of the various yarns that were shortlisted by studying their tensile properties. The yarns were used to form an innovative two-layer weft knitted structure that is described section 4.3.1. The yarns that were short listed based on their tensile properties in Chapter 4 were used in the development of the slash resistant fabrics. The tensile properties of these yarns are listed in Table 4.3. The shortlisted yarns are:

- WF408.
- WF528.
- Wykes E669.
- Tilsa; and
- Kevlar.

Table 5.1 shows the results from the initial set of tests that were carried out to compare the various two-layer weft knitted structures and are discussed in the subsequent sections.

The slash test was conducted in three different directions and they are referenced in the discussion as below:

Walewise – slash tested in the machine direction (0^0);

Coursewise – slash tested perpendicular to the machine direction (90^0); and

Crosswise – slash tested 30^0 to the machine direction (30^0);

Table 5.1 Initial slash test results to compare yarn properties

Test Face	Face Yarn	Test Direction	Force (N)		Test Face	Face Yarn	Test Direction	Force (N)
Fabric 1: KEVLAR / WF408 (GSM 1292.4)								
Racked	Kevlar	Walewise	45.37±12.3		Jersey	WF408	Walewise	22.68±4.5
Racked	Kevlar	Coursewise	88.7±7.8		Jersey	WF408	Coursewise	86.57±12.6
Fabric 2: WF408 / KEVLAR (GSM1248.1)								
Jersey	Kevlar	Walewise	84.49±13.5		Racked	WF408	Walewise	24.25±3.2
Jersey	Kevlar	Coursewise	61.24±20.5		Racked	WF408	Coursewise	91.18±20.9
Jersey	Kevlar	Crosswise	59.08±14.5		Racked	WF408	Crosswise	112.71±22.4
Fabric 3: KEVLAR / WF528 (GSM 879.5)								
Racked	Kevlar	Walewise	23.99±9.9		Jersey	WF528	Walewise	27.49±7.4
Racked	Kevlar	Coursewise	86.52±18.8		Jersey	WF528	Coursewise	319.25±35.5
Fabric 4: WF528 / KEVLAR (GSM 759.5)								
Jersey	Kevlar	Walewise	21.52±4.6		Racked	WF528	Walewise	29.18±2.1
Jersey	Kevlar	Coursewise	28.3±6.8		Racked	WF528	Coursewise	16.95±3.4
Jersey	Kevlar	Crosswise	19±4.7		Racked	WF528	Crosswise	30.54±9.3
Fabric 5: KEVLAR / TILSA (GSM 838.8)								
Racked	Kevlar	Walewise	16.47±6.8		Jersey	Tilsa	Walewise	73.43±13.9
Racked	Kevlar	Coursewise	43.22±11.5		Jersey	Tilsa	Coursewise	30.22±6.4
Fabric 6: WF528 / TILSA (GSM 881.6)								
Racked	WF528	Walewise	18.24±3.5		Jersey	Tilsa	Walewise	26.28±4.1
Racked	WF528	Coursewise	64.16±12.9		Jersey	Tilsa	Coursewise	19.97±4.2
Racked	WF528	Crosswise	29.58±8.0		Jersey	Tilsa	Crosswise	19.8±6.7
Fabric 7: KEVLAR / E669 (1089.1)								
Racked	Kevlar	Walewise	47.66±8.4		Jersey	E669	Walewise	17.23±5.2
Racked	Kevlar	Coursewise	84.77±12.5		Jersey	E669	Coursewise	65.97±23.9
Racked	Kevlar	Crosswise	91.84±26.5		Jersey	E669	Crosswise	67.81±20.7
Fabric 8: E669 / KEVLAR (GSM 997.5)								
Jersey	Kevlar	Walewise	15.03±6.5		Racked	E669	Walewise	52.51±15.5
Jersey	Kevlar	Coursewise	234.4±95.0		Racked	E669	Coursewise	22.28±8.6
Jersey	Kevlar	Crosswise	56.8±14.4		Racked	E669	Crosswise	32.43±18.4

Note: Jersey: Straight wales; Racked: Tucked wales; and Test face: Fabric face under test.

5.3.1 Analysis of the various yarn's performance

All the fabric samples were knitted with spun two-ply Kevlar yarn on one face and one of the other yarns in the other face and vice versa. The summary of the test results are shown in Figures 5.2 to 5.5.

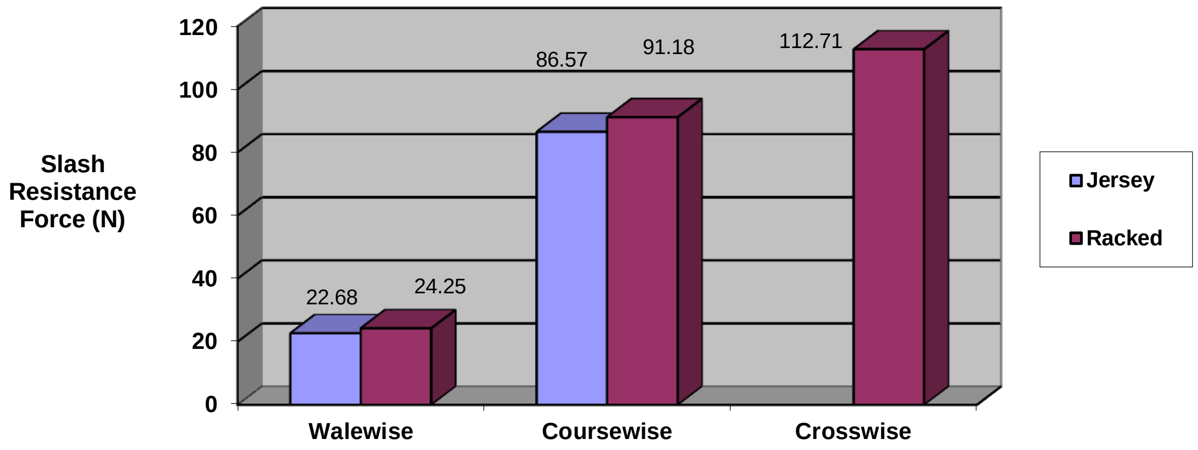


Figure 5.2 Slash force for WF408 yarn

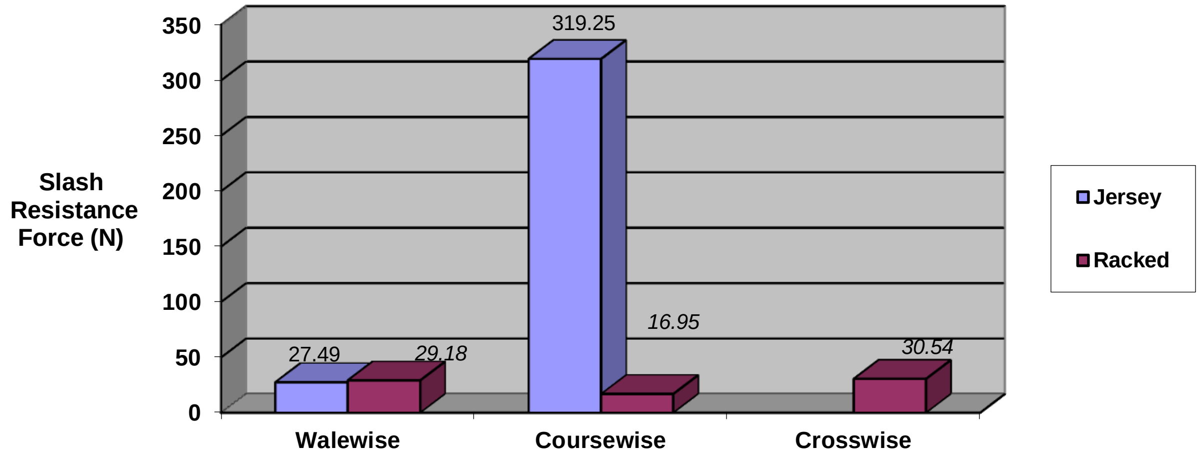


Figure 5.3 Slash force for WF528 yarn

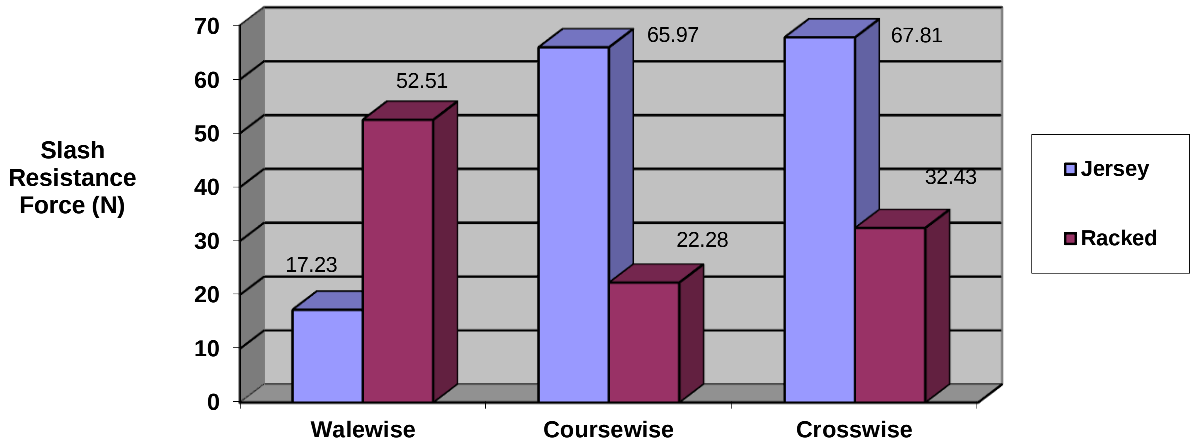


Figure 5.4 Slash force for Wykes E669 yarn

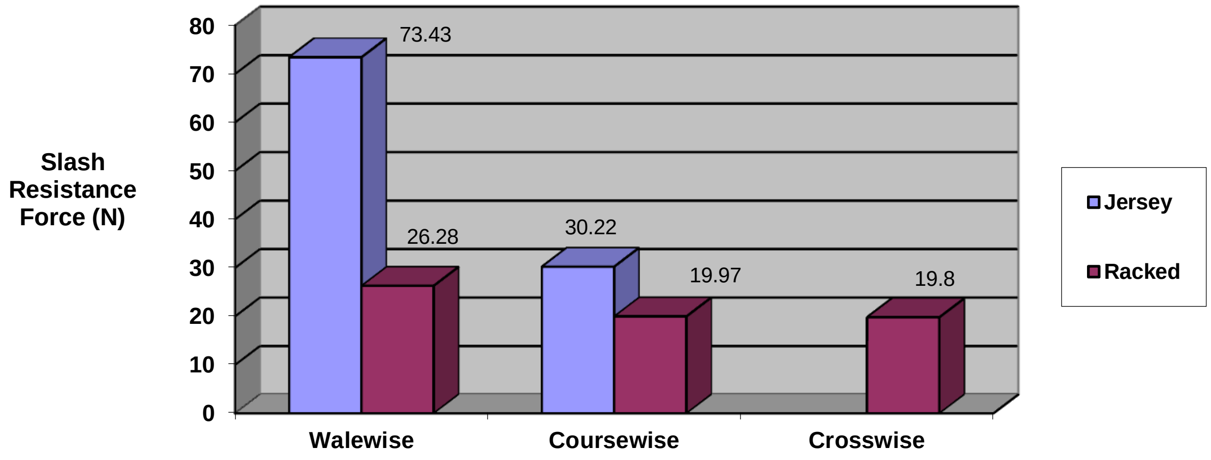


Figure 5.5 Slash force for Tilsa yarn

The results show that the fabrics had better resistance to slashes or cuts in the coursewise direction and in the crosswise direction. A close examination of the tested samples revealed that the resistance in the wales direction was low as the test blade tends to slip in between the columns of the loops in the walewise direction and cut through the fabric very easily. The columns of loops helped in resisting the blade in the other two directions, see Figure 5.6.

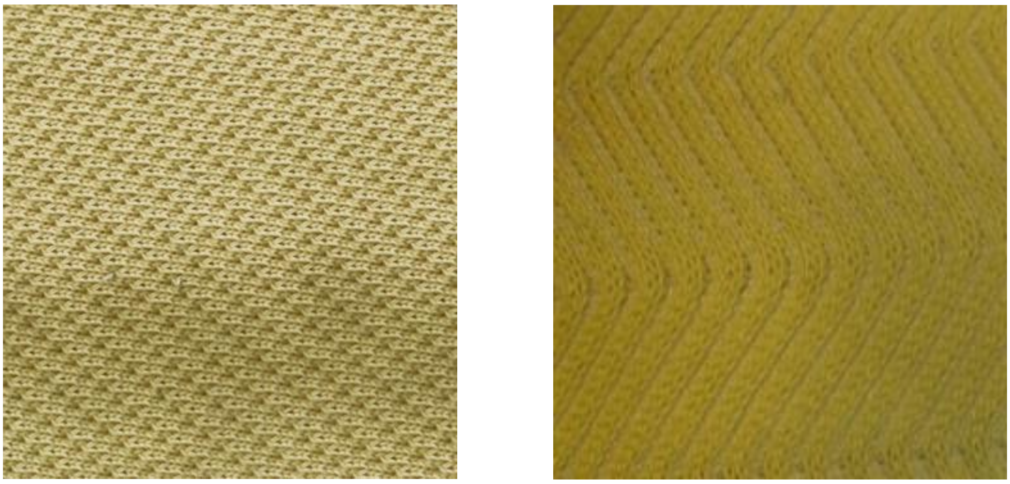


Figure 5.6 Column of loops in different structures

5.3.2 Performance of Kevlar with different yarns

Figure 5.7 shows that the performance of Kevlar was better with a racked structure on average, even though the highest resistance was exhibited by the jersey structure in the course direction. This is due to the accumulation of the yarns which makes the blade jump. This jumping of the blade can be seen in Figure 5.8, where the force exerted on the blade fluctuates from 164.48N to 89.74N. This fluctuation in the slash force can be observed in all the slash tests that were performed during this research programme.

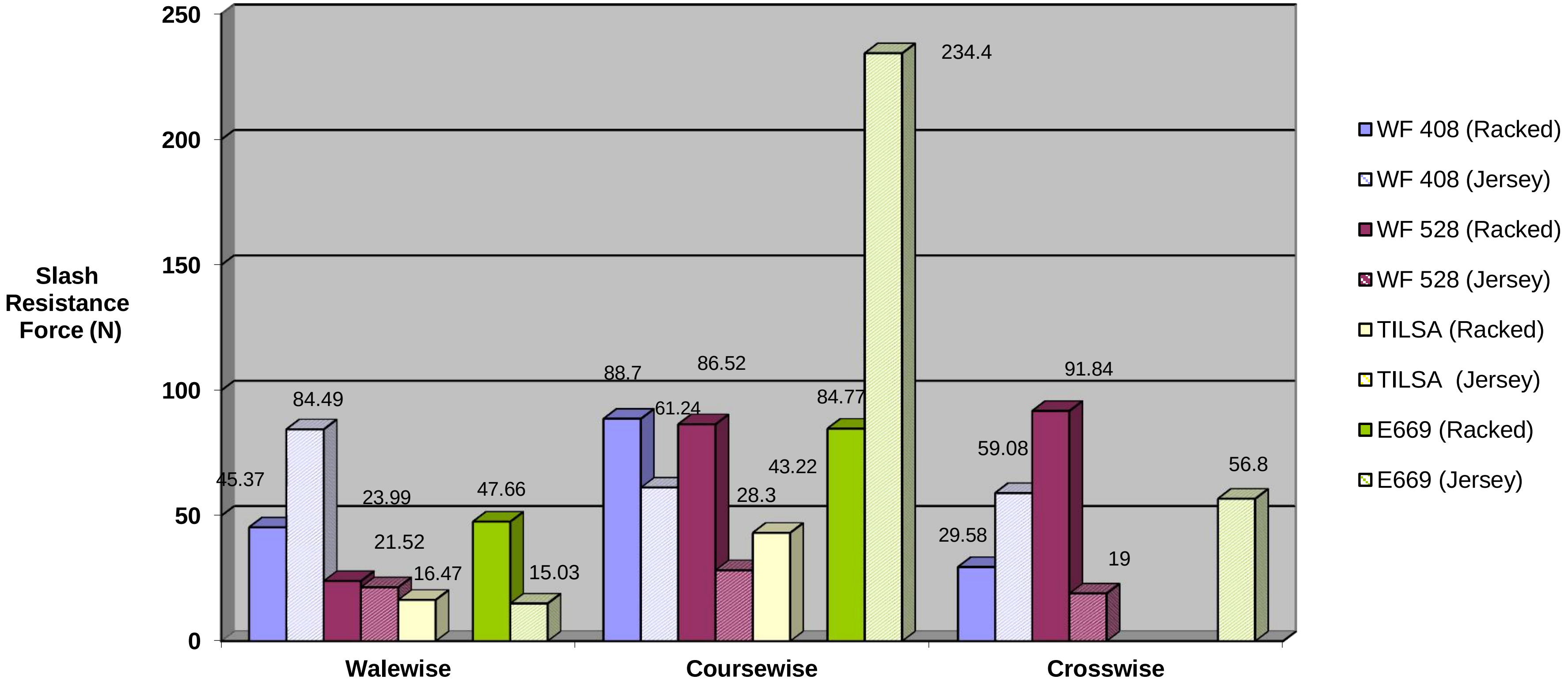


Figure 5.7 Slash force for Kevlar yarn

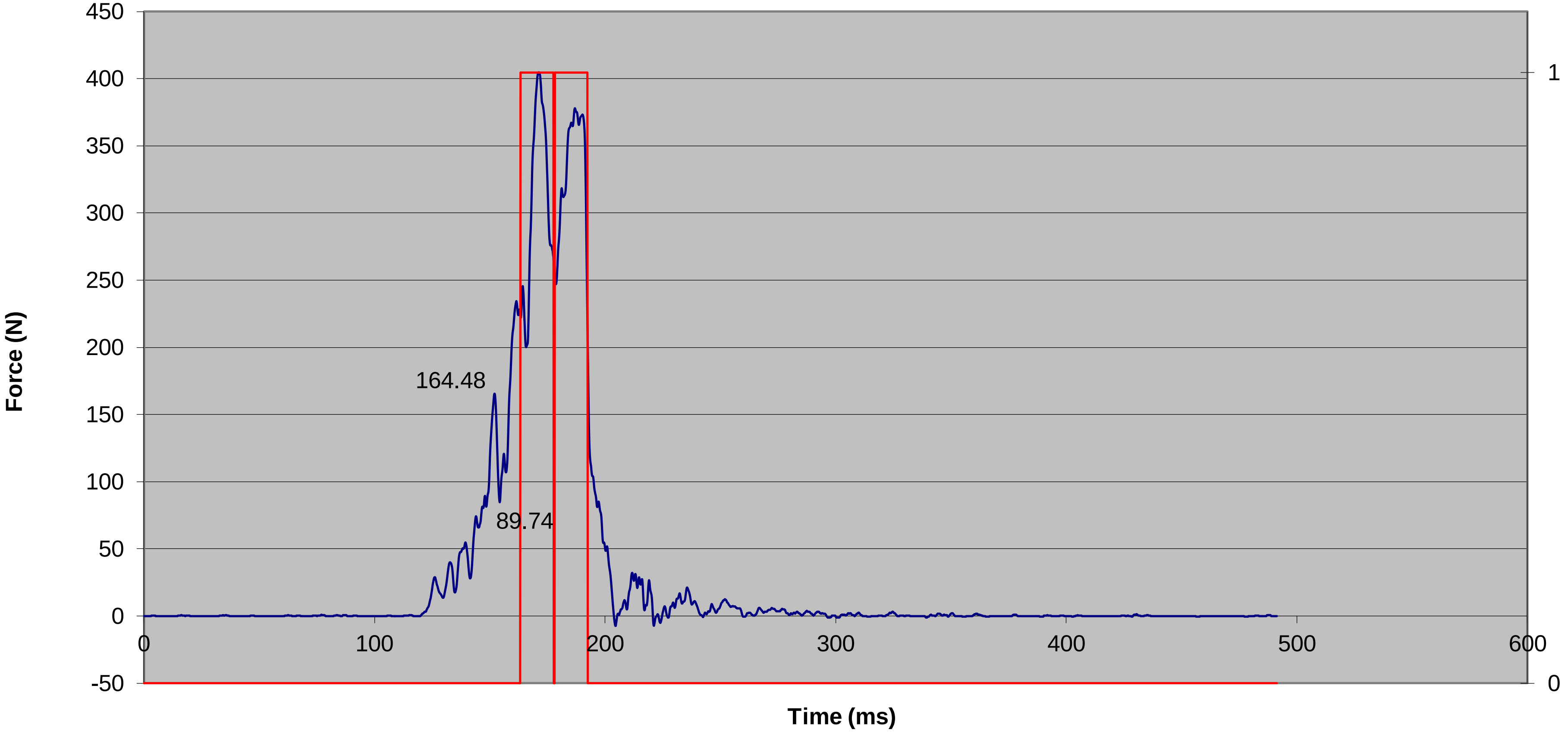


Figure 5.8 Slash Resistance force of a single slash on fabric kitted with Kevlar and Wykes E699

The WF408 and E669 yarns were the closest to passing the test with a short come of 1N in the crosswise direction for jersey Kevlar in the other face for WF408 yarn and 4N in the walewise direction with racked Kevlar in the other face for E669 yarn.

The Kevlar fabric with E669 on the other face had a better average of slash resistance (74.75N) than with WF408 on the other face (68.27N). The highest average of 76.04N was exhibited by racked WF408 yarn on the face with jersey Kevlar on the back. It was however largely let down by the resistance in walewise direction with a value of 24.25N.

5.4 Analysis of knitted structure

The fabrics with two-ply untwisted Kevlar yarn and E669 yarn were knitted in two different knitting structures. The first set was a plain single-jersey fabric and the other one was with a racked structure on the face knitted with Kevlar yarn. The results from this fabric in all three directions are shown in Figure 5.9.

The high value of 234.4 N in the course direction in the single jersey structure has been closely analysed and it was concluded that it is a valid result. There was a cut through even before the contact point at 234.4N, but the blade didn’t make contact with the force plate as the fabric was pulled by the blade and the accumulation of the loops made the blade jump.

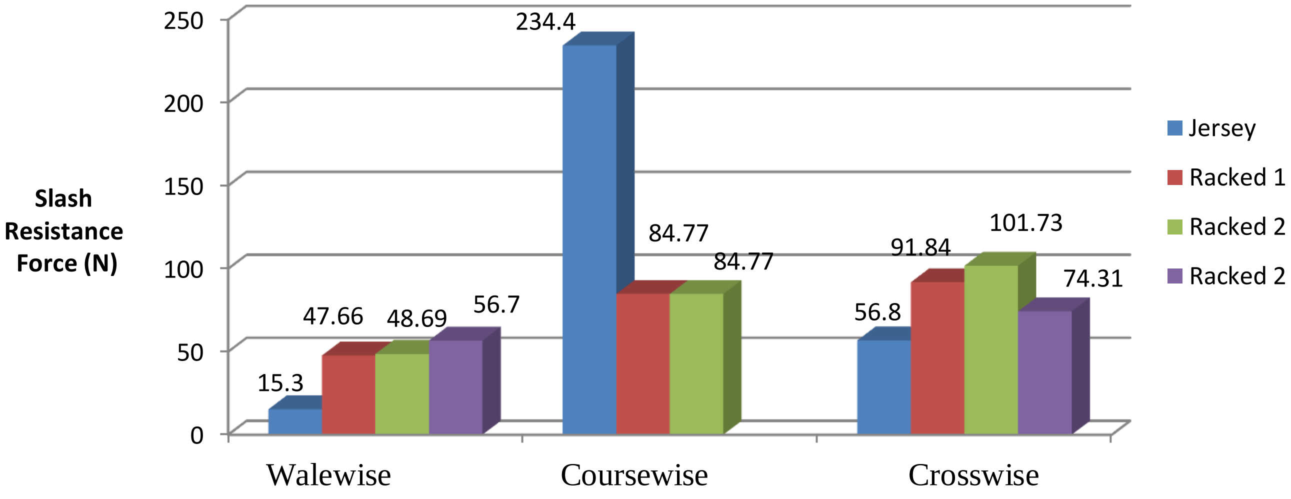


Figure 5.9 Comparison of Slash resistance force for Kevlar/E669 fabric based on different structures

The same phenomenon had occurred in the course direction of the fabric samples where Kevlar and Spectra WF528 yarns were used. It required a force of 319.25N to strike through the single jersey face fabric with Kevlar yarn on the other face.

5.4.1 Effect of structure on slash direction

It can be seen in Table 5.2 that for a single jersey structure, there was a high variance in the slash resistance between the directions of slash performed on a specimen. The cause for the high variance was later identified and this has been addressed in section 5.6. Since the variances between the slash application directions, two-sample t-test was conducted assuming unequal variances. The results are tabulated in Table 5.3.

Table 5.2 Single factor ANOVA by slash test direction on jersey structure

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Median*	*Variance*
Walewise	114	9150.945	80.27145	46	5215.26
Coursewise	110	14841.92	134.9266	108	13436.7
Crosswise	97	10954.71	112.9351	102	7497.667

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	169524.9	2	84762.47	9.717873	8.01E-05	2.319339
Within Groups	2773700	318	8722.328			
Total	2943225	320				

Table 5.3 Two-sample t-test analysis by slash test direction

	Walewise vs Coursewise	**Walewise vs Crosswise**	**Coursewise vs Crosswise**
df	181	192	200
t Stat	-4.21799477	-2.87813275	1.643409259
P(T<=t) one-tail	1.94532E-05	0.002226841	0.050934703
t Critical one-tail	1.286246299	1.285976384	1.285798794
P(T<=t) two-tail	3.89065E-05	0.004453683	0.101869406
t Critical two-tail	1.653315758	1.652828589	1.652508101

It can be observed from Table 5.2 that the slash resistance values were significantly lower in the walewise direction compared to coursewise direction and crosswise direction. The median value of slash resistance in the walewise direction was only 46 N when compared to 108 and 102 of coursewise and crosswise direction respectively. It could be explained that the consistent failure (pass criteria being > 60N) in the walewise direction is due to the blade slipping between the course column and thus having just one layer of fabric to go through. The black line in Figure 5.10 shows the gap between the course columns in walewise direction between which the blade slips.

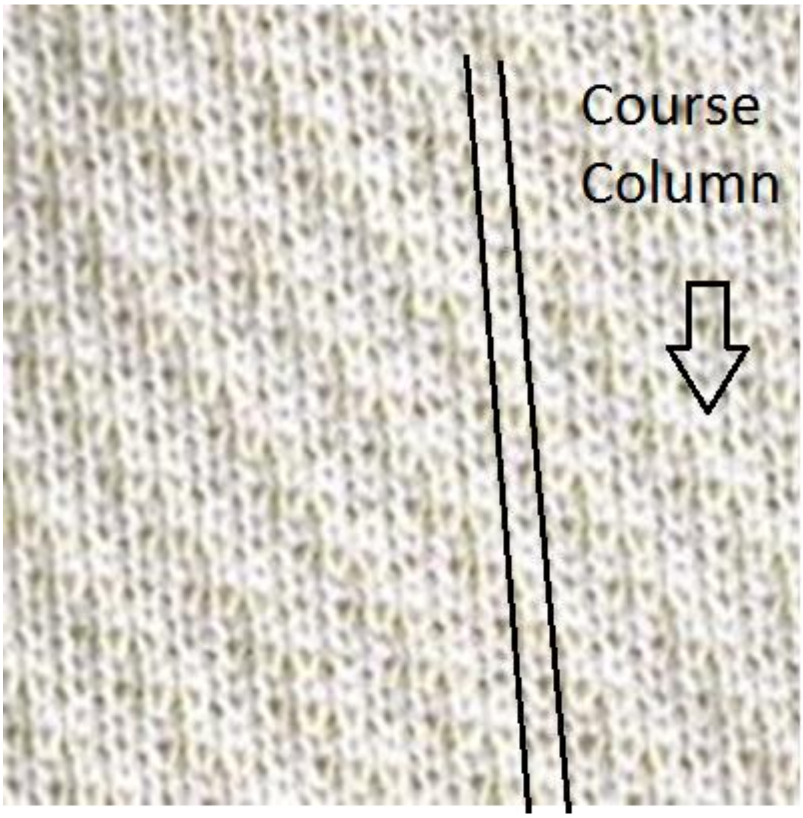


Figure 5.10 Gaps between the course columns causing blade slippage

5.4.2 Development of racked structures

Even though the single jersey structure was passing the slash resistant standard criteria in two out of the three directions, it was observed that it was failing with very low slash resistant values in walewise direction. So, a racked structure was designed so as to prevent the blade from slipping between the course columns. The racked structure prevents the blade from sliding continuously between the columns since the structure is designed in such a way that there is no continuous course column.

Four types of racked structure were achieved using a single design notation that is shown in Figure 4.8. The different racked structures were achieved by racking one set of needle bed (back) by 0, 4, 6 and 8 positions on each side. The ANOVA analysis on racked structure, irrespective of number of racks, statistically prove that the racked structure increased the average slash resistance values to be over the slash resistant standard pass criteria, see Table 5.4.

Table 5.4 Single factor ANOVA by slash test direction on racked structure

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Walewise	25	1583	63.32	1871.31
Coursewise	24	2427	101.125	9663.94
Crosswise	19	2026	106.6316	12419.69

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25917.75	2	12958.87	1.716455	0.187746	2.386114
Within Groups	490736.5	65	7549.792			
Total	516654.2	67				

5.5 Slash resistant personal protective equipment garment

Apart from the Kevlar yarn, the best resistance to slash was recorded by using Spectra WF408 yarn, but this was replaced by three ends of WF528 yarn which reduced the linear density of the yarn used by 30% while maintaining the same breaking force. This in turn reduced the area density of the knitted fabric by 250 g m^{-2} thus making it lighter and potentially more comfortable to wear.

The slash resistant fabrics that passed the standard were officially named as SARK. The first fabric was named SARK-1 and the subsequent fabrics SARK-2 and SARK-3.

The novel two-layer structure, named SARK-1, which passed the HOSDB Slash Resistant Standard for the UK Police on both the faces, was a knitted fabric with two ends of Kevlar yarn as the racked face and three ends of WF528 yarn as the other face. The results of this fabric are shown in Tables 5.5 and 5.6.

Table 5.5 HOSDB slash resistance test results for SARK-1 with Kevlar yarn as face

Slash Test Direction	**Failure Force (N)**	
	Test 1	**Test 2**
Walewise	71.64	62.44
Coursewise	293.77	389.41
Crosswise	109.74	-
Average Force:	**158.38**	**-**

The results of the slash tests shown in Table 5.5 reveal that a minimum failure force of 71.64 N and an average failure force of 158.38 N were achieved. The average force of 158.38 N was almost twice the minimum average required to pass the test.

A second set of walewise and coursewise slash tests were performed to substantiate the results obtained. The same was not repeated on the samples with WF528 yarn used as the test face as there was not enough sample left to conduct the second set of the slash tests. The test results from SARK-1 tested on the WF-528 face are shown in Table 5.6.

Table 5.6 HOSDB slash resistance test results for SARK-1 with WF528 yarn as face

Slash Test Direction	Force (N)
Walewise	65.81
Coursewise	122.17
Crosswise	61.61
Average Force:	**83.20**

The SARK-1 fabric also passed the slash resistance standard with the WF528 yarn as the test face. It passed with a force of 65.81 N in the walewise direction, 122.17 N in the coursewise direction and 61.61 N in the crosswise direction. The high resistance of 122.17 N to slash in the coursewise direction enabled the fabric to obtain the required average of 80 N and above.

The results in Table 5.5 and Table 5.6 are those obtained for the jersey structure named SARK-1. Modifications were made to the SARK-1 structure to achieve a special racked structure in one of the faces, results of which are shown in Table 5.7 and Table 5.8. This racked structure was named as 'SARK-2' in this research work.

Table 5.7 HOSDB slash resistant test results for SARK-2 with Kevlar as face

Slash Test Direction	Force (N)
Walewise	92.49
Coursewise	84.25
Crosswise	97.68
Average Force:	**91.47**

Table 5.8 HOSDB slash resistant test results for SARK-2 with WF528 as face

Slash Direction	Force (N)
Walewise	115.78
Coursewise	144.41
Crosswise	64.89
Average :	**108.36**

The novel two-layer racked structure SARK-2 passed the standard on both faces of the fabric with an average value of 91.47N on the Kevlar yarn face and 108.36N on the WF528 yarn face. SARK-2 achieved similar slash performance in all three directions, as shown in Table 5.8. This indicates that the structure is more or less isotropic with regard to this property.

5.6 Changes in the test pass criteria

Attempts were made to further reduce the fabric area density by modifying the stitch lengths in the fabric structure. The stitch length was decreased in steps of 2.5% for each yarn feed until the fabric became too tight to knit successfully. These fabrics were tested for slash resistance and a detailed analysis of the test results revealed that the slash resistant force obtained for a particular fabric was highly variable and inconsistent. Detailed analysis of the individual graphs revealed that this was due to the accumulation of the knitted loops as explained in Section 5.4. Table 5.9 shows one example where high variability and inconsistence in the slash test results were very obvious.

Table 5.9 Inconsistency in the HOSDB slash resistant test results for sample S39

	Face Fabric	Walewise Direction	Coursewise Direction	Crosswise Direction	Average (N)
Test 1	Kevlar	89.82	23.48	29.58	47.63
Test 2	Kevlar	56.27	59.87	81.88	66.01

The two sets of slashes performed were on the same fabric with all the conditions kept the same and yet there was a high variance from 59.87N to 23.48N in the coursewise direction and from 29.58 to 81.88 in the crosswise direction.

It was understood that the point of contact makes a huge difference, but saying that, when looking into the mechanics of the interaction between the blade tip and the fabric, the test should not show such huge differences. Due to the high cost involved in testing the fabrics and obtaining yarns, enough number of tests could not be performed to study the behaviour of the test method and hence the results and the observation were passed on to HOSDB so that further research could be carried on.

Due to the inconsistency noticed by the HOSDB, when they tested with a plain woven 100% Kevlar yarn fabric, they allowed a strike through of a certain length for textile fabrics.

The current stab resistant standards, such as National Institute of Justice Stab Resistance for Personal Body Armour (NIJ 0115) [100] and Part 3 of the PSDB's Body Armour Standard for UK Police (2003), Knife and Spike Resistance [14], allow an initial penetration of 7 mm across all protection levels. Based on the same principle, the length of slash allowed for the single strikethrough was calculated to be 8.44mm which equates to a total penetration time of 1 millisecond, see Figure 5.11.

Due to the inconsistent behaviour of the textile materials, one of the strike-throughs, among the nine slashes, was allowed to be up to 1.20 milliseconds. A letter confirming the same is attached in Appendix C.

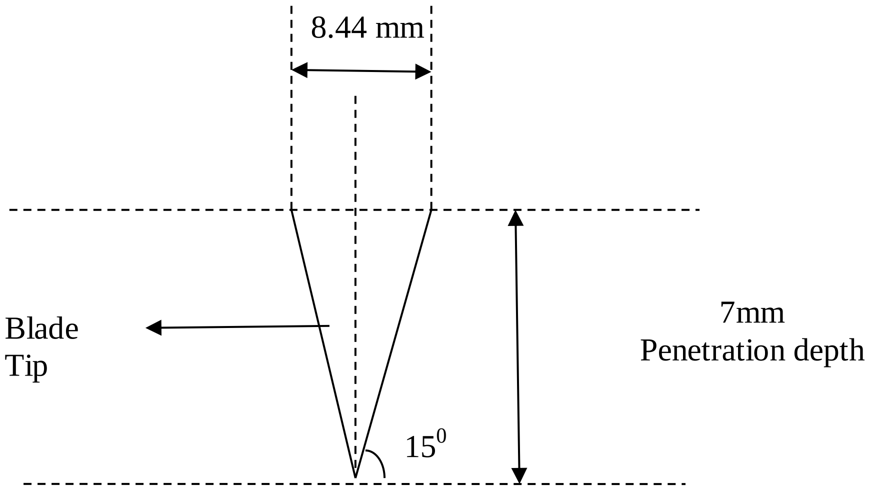


Figure 5.11 Blade penetration depth

Tables 5.10 and 5.11 show two examples where the pass criteria were recalculated. These recalculations were not applied to the previous fabrics as all the previous fabrics tested before this had higher area densities.

Similar phenomenon of inconsistent test results with knitted fabrics was observed during the evaluation of the effect of blade speed. While developing a new method to evaluate the cut resistance of protective glove materials, it was found that the CV% of the test outcomes on knitted Kevlar were between 27% and 38%. The CV% for the same tests on neoprene was between 2% and 16%. When testing the effects of sample holder geometry and load on the cut resistance results, the CV% were between 7 and 78% for knitted materials and 5-11% for neoprene. This test method was later standardised as the ISO blade cut resistance [101].

Table 5.10 Recalculated slash results for SARK-3 on Kevlar face(1x Kevlar yarn; 2xWF528 yarn)

Slash Direction		Actual Force (N)	Start Time	End Time	Total Time (ms)	Next Max. Force (N)	Comments
Walewise	Left	22	39.763199	40.063999	0.3008	93	
	Centre	18	38.463999	39.276799	0.8128	90	
	Right	26	51.468799	52.661199	1.1924	164	<1.20ms applied here
					Average:	**116**	
Coursewise	Centre	67	51.775999	53.094399	1.3184	67	Actual Force Taken
	Right	52	51.052799	52.723199	1.6704	**52**	Actual Force Taken
	Left	29	41.593599	42.470399	0.8768	71	
					Average	**93**	
Crosswise	Centre	134	58.975999	59.884799	0.9088	134	Actual Force Taken
	Left	95	59.417599	60.748799	1.3312	95	Actual Force Taken
	Right	97	68.083199	69.638399	1.5552	97	Actual Force Taken
					Average:	**109**	

Table 5.11 Recalculated slash results for SARK-3 on WF528 face (2x WF528 yarn; 1x Kevlar yarn)

Slash Direction		**Actual Force (N)**	**Start Time**	**End Time**	**Total Time (ms)**	**Next Max. Force (N)**	**Comments**
Walewise	Left	12	39.225599	40.403199	1.1776	84	<1.20ms applied here
	Centre	15	42.860799	43.679999	0.8192	112	
	Right	24	40.230399	41.292799	**1.0624**	97	
					Average:	**98**	
Coursewise	Centre	110	58.681599	59.494399	0.8128	123	
	Right	76	62.431999	63.571199	1.1392	76	Actual Force Taken
	Left	76	55.980799	57.587199	1.6064	76	Actual Force Taken
					Average	**92**	
Crosswise	Centre	144	64.614399	65.292799	0.6784	144	
	Left	27	40.294399	41.196799	0.9024	84	
	Right	86	60.908799	61.951999	1.0432	86	Actual Force Taken
					Average:	**105**	

5.7 Effect of ageing on slash performance

The novel slash resistant fabrics were developed to be worn over long periods of time, especially outdoors. Hence, it was necessary to study the performance of the fabric after exposure to external atmosphere for a certain period of time. It is well known that once extensively used fibre, PBO, in stab resistant materials was not tested for stab resistant properties after extensive exposure to light, which was later found to have degraded their tensile properties due to exposure to UV radiation [102] [103] [104]. This led to the decertification of PBO fibres for ballistic use [105].

Hence, to study the effect of ageing, the fabric SARK-1, which passed the stringent HOSDB Slash Resistance Standard was subjected to UV radiation by the method described in Section 3.4.4.

Due to the costs involved in testing the samples and the inconsistencies observed during the time of research, the exposed and unexposed samples were compared by studying their tensile and flame retardant properties. Studies by Walsh et. al and Lu et. al, have shown that the effect of UV radiation is primarily hydrolysis of the material near the fibre surface which affects the tensile properties of the fibre [103] [104] . Since the slash resistant fabric will be used extensively in direct sunlight, the effect of sunlight on its flammability properties were also studied.

5.7.1 Flammability of slash resistant fabrics

The ignition test on both the treated and untreated fabrics was carried out, based on the British Standard BS EN 5438:1989 [88], by applying a small igniting flame with a horizontal flame length of 21mm to the face of the fabric for a minimum of 10 seconds. 30 seconds is generally used for the high performing fabrics and therefore the ignition flame was applied for 30 seconds and then extended to 60 seconds in case of Kevlar face in these experiments.

Table 5.12 compares the ignition test results of the slash resistant fabrics that were exposed to entire spectrum of sunlight (295 nm-800 nm), including ultraviolet (UVA & UVB), visible light and infrared (IR) with the unexposed fabric. It can be observed that the fabric is resisting ignition for at least up to 60 seconds with the Kevlar yarn used as the face.

Table 5.12 Ignition test results for SARK-1 exposed to entire spectrum of sunlight

	Kevlar Face	**Composite WF528 Face**
Untreated Fabric	No Ignition	Ignites at 24 Seconds
Exposed to 5 years of UV radiation on Kevlar yarn side	No Ignition (tested up to 60 seconds)	-
Exposed to 5 years of UV radiation on WF528 yarn side	-	Ignites at 20 Seconds

On the other face, the polyamide cover of the composite yarn WF528 retains the heat, melts and ignites the fabric after 20 seconds of exposure to the flame. If allowed to continue to burn, it takes over 5 minutes (322 seconds) to completely burn a vertically held 15 x 8.5 cm fabric sample. Once the fabric started burning, the flame travelled only upwards. Once the fabric is completely burned, the structure of the fabric is held intact by Kevlar and the Glass fibres. Figures 5.12 and 5.13 show the fabrics tested with Kevlar yarn face and WF528 yarn face respectively.

Figure 5.12 Slash resistant fabric tested for ignition with Kevlar yarn face

Results reveal that for the usage of this fabric as a flame retardant (FR) layer, the Kevlar yarn side of the fabric has to be used as the outer layer and the face with the WF528 yarn can be used for other purposes.

Figure 5.13 Slash resistant fabric tested for ignition with WF528 yarn face

It must be stated that the heat transferred through the fabric might be higher than that stipulated for flame retardant and heat barrier materials to be worn by humans. Since it was not a part of this research objective, this specific aspect has not been investigated further.

5.7.2 Tear strength of slash resistant fabrics

The tear strength of the novel slash resistant fabrics was tested as per BS EN ISO 13937-3:2000 [87] before and after exposing the different faces to the entire spectrum of sunlight (295 nm-800 nm) and the compiled results are shown in Table 5.13.

Table 5.13 Tear Strength of fabrics exposed to entire spectrum of sunlight

	SARK-1	SARK-1 UV exposed on WF528 yarn face	SARK-1 UV exposed on Kevlar yarn face
Tear Properties			
Tear Strength - at Break (N)			
Walewise	**2798±199**	**2873±162**	**3136±112**
Coursewise	**2444±168**	**2917±211**	**3157±174**
Crosswise	**2939±198**	**2423±111**	**3165±168**
Tear Strength - at Maximum (N)			
Walewise	**5052±223**	**3572±124**	**4890±147**
Coursewise	**3357±145**	**3398±154**	**3577±211**
Crosswise	**4080±191**	**3698±96**	**3791±158**
Elongation at Tear - at Break (%)			
Walewise	**115±16**	**114±15**	**116±13**
Coursewise	**114±21**	**125±26**	**116±22**
Crosswise	**122±18**	**143±21**	**143±19**
Elongation at Tear - at Maximum (%)			
Walewise	**162±26**	**153±23**	**153±19**
Coursewise	**155±24**	**158±31**	**142±24**
Crosswise	**157±21**	**193±35**	**185±39**

It can be observed from table 5.13 that tear strength at break of the fabric exposed in the Kevlar yarn face has reduced by a maximum of 17.5% in the crosswise direction but has gained by 19.4% in the coursewise direction. When an average of all the three directions is considered, it is less than 0.45. The fabric that has been exposed on the WF528 face has an increase in performance by 15.6%.

An unpaired *t*-test between the tear strength at break of unexposed SARK-1 with SARK-1 exposed on WF528 yarn face in walewise direction gives a two-tailed P value of 0.3676 which is considered to be statistically insignificant. The case is similar when the difference between the elongations at tear is considered in all three directions for both WF528 yarn and Kevlar yarn face exposures. The difference is statistically significant for tear strength when comparing unexposed fabric against exposed fabric on both WF528 yarn face and Kevlar face, with a two-tailed P value of less than 0.0001.

The tear strength of fabrics exposed on the Kevlar yarn side is unaffected by the radiations, but an increase of 16% is observed in the fabrics exposed to UV radiation on the WF528 yarn face where the contribution of polyamide constitutes only 13.6% of the structure. It is known that polyamide fibres are susceptible to UV radiation and continuous exposure to UV or sunlight facilitates the destruction of amide linkage and consequently this influences the fabric strength [106] [107] [108] [109].

In this research the increase in tear strength for fabrics exposed to UV radiation on the WF528 yarn side may perhaps be the contribution of glass fibres and UHMWPE fibres and not polyamide fibres. Even though the polyamide is affected by the UV radiation, considering the amount of polyamide fibres present in the fabric, at 13.6%, the overall tear strength is not affected due to the polyamide fibres.

5.7.3 Tensile properties of slash resistant fabrics

The dimensional and tensile properties of the novel slash resistant fabric SARK-1 were tested before and after exposing the different faces to whole spectrum sunlight, including IR, UVA and UVB radiation, the results of which are shown in Table 5.14.

The bulk density of the unexposed and exposed fabrics is very similar which confirms that there is no structural change in the fabric. However, it can be observed from Table 5.14 that there is a significant change (unpaired *t*-test P value < 0.0001) in the maximum breaking load sustained by the fabrics exposed to UV radiation. This could be due to the changes in the amide linkages caused by UV radiations. The S.D values for tenacity are not provided as they were calculated directly from the average of area density and maximum breaking load.

The increase in tenacity across all three directions is about 40.0 % for fabrics exposed on the Kevlar yarn face and 49.1% for fabrics exposed on the WF528 yarn face. The modulus of all the fabrics is more or less similar which means that when the treated fabrics are subjected to slash, they will perform similarly or better than the unexposed fabrics, as the modulus is an important factor for slash resistance.

Table 5.14 Tensile properties for fabrics exposed to entire spectrum of sunlight

	SARK-1	**SARK-1 UV exposed on WF528 yarn face**	**SARK-1 UV exposed on Kevlar yarn face**
Dimensional properties			
Area Density (g m^{-2})	**1083±13**	**1085±20**	**1083±22**
Thickness (mm)	**3.68±0.12**	**3.60±0.12**	**3.62±0.11**
Bulk Density (g cm^{-3})	**0.294**	**0.301**	**0.299**
Tensile Properties			
Breaking Load (N)			
Walewise	**11804±423**	**16231±812**	**16955±912**
Coursewise	**9835±615**	**13328±845**	**14244±424**
Crosswise	**9791±399**	**13289±689**	**14230±365**
Tenacity (N tex^{-1})			
Walewise	**0.21**	**0.29**	**0.30**
Coursewise	**0.17**	**0.24**	**0.27**
Crosswise	**0.17**	**0.24**	**0.25**
Breaking Extension (%)			
Walewise	**103±22**	**99±28**	**103±31**
Coursewise	**155±12**	**143±12**	**133±15**
Crosswise	**86±18**	**109±22**	**117±29**
Modulus (N)			
Walewise	**15.84±2.37**	**15.59±1.93**	**14.45±1.97**
Coursewise	**6.98±1.95**	**8.27±1.46**	**8.89±2.45**
Crosswise	**16.45±1.89**	**11.09±1.42**	**9.99±2.01**
Specific Modulus (N tex^{-1})			
Walewise	**0.00028**	**0.00028**	**0.00025**
Coursewise	**0.00012**	**0.00015**	**0.00017**
Crosswise	**0.00028**	**0.00020**	**0.00018**

Since the main objective of this research programme was to develop a slash resistant fabric that can be worn for long periods of time, the tensile tests were carried out mainly to ascertain that the fabric's slash performance does not degrade over time, on exposure to sunlight. It is evident from the results presented in Section 5.7 that the fabrics do not degrade on exposure.

5.8 Comfort properties of slash resistant fabrics

The intended environment of use for a protective garment should always be considered. A protective garment has two environments attached to it, one is the external environment and the other is the internal environment between the protective garment and the user [110]. The internal environment is affected by the temperature and humidity generated by the wearer. Though this internal environment is considered not to affect the performance of the protective garment, it does affect the wear ability of the protective garment over a prolonged period.

The warm or cool feeling that is obtained when human skin touches any object, including a textile fabric or garment, is due to the thermal conductivity and the thermal absorptivity properties of the material. This transient thermal feeling that is experienced during that instant greatly affects the decision of choosing a fabric to be worn on a regular basis. Since the novel slash resistant garments were developed to be worn on a regular basis, it was essential that the thermophysiological properties of the garments be analysed in order to understand the wear ability of the garments [111]. The results obtained from measuring the thermal properties of the fabric are tabulated in Table 5.15.

Table 5.15 Comfort properties of novel slash resistant fabrics

Comfort properties	**SARK 1**	**SARK 2**	**Property range for base layers**
Alambeta			
Thermal Resistance (W^{-1} K m^2 x 10^{-3})			
Dry -Kevlar Face down	**48.7±3.2**	**48.7±5.1**	**19.5-36.1**
-WF528 Face down	**47.5±5.2**	**45.7±5.0**	
Wet (4 min) - Kevlar Face down	**34.2±3.5**	**43.2±3.2**	**8.5-24.04**
- WF528 Face down	**26.6±4.2**	**30.4±4.1**	
% Recovery after 4 mins of wetting	**63.2**	**77.9**	**42.4 – 95.2**
Thermal Absorpitivity (W m^{-2} S 1/2 K^{-1})			
Dry - Kevlar Face down	**166.6±21.4**	**110.7±26.5**	**68.9 – 85.4**
- WF528 Face down	**184.6±23.8**	**193.0±19.9**	
Wet (4 min) - Kevlar Face down	**258.6±33.6**	**207.8±26.4**	**108 – 375**
- WF528 Face down	**32** [66] [60]**2.6±23.1**	**298.0±31.5**	
% loss in warmth-to-touch from dry to 4 min wetting	**65.4**	**66.5±**	**24.1 – 91.4**
Permatest			
Water Vapour Permeability (%)			**31.6 – 42.4**
- Kevlar Face down	**16.75±2.1**	**12.50±1.6**	
- WF528 Face down	**14.50±2.8**	**12.50±2.4**	
Resistance to Evaporative Heat Loss (m^2 Pa W^{-1})			**1.33 – 4.81**
- Kevlar Face down	**6.31±0.8**	**9.01±0.6**	
- WF528 Face down	**7.40±0.4**	**9.14±0.6**	
Absorption (g g^{-1})	**1.29±0.33**	**1.17±0.23**	**3.0 – 4.5**
Wicking (g cm)			**2.4 – 6.6**
Walewise	**20.28±2.2**	**16.78±2.5**	
Coursewise	**14.32±2.4**	**12.13±2.9**	
Wicking Height (mm)			**30 - 60**
Walewise	**88±7.5**	**82±6.3**	
Coursewise	**78±8.1**	**71±8.2**	

Since no other flexible slash resistant materials exist, it could not be compared directly with a similar material. Due to the nature of the body armours or stab resistant vests, which are generally made up of several layers of fabric either stitched together or formed into a composite [112], their comfort properties cannot be compared directly with the slash resistant fabrics.

Studies show that the bulletproof vests become uncomfortable and the wearer starts to sweat moderately in less than 100 minutes of continuous wear while performing a simulated industrial protocol [113]. The compiled comfort properties of various base layer (next to skin) materials from several previous works are provided as a range for comparison with the comfort properties of the slash resistant fabric in Table 5.15 [58] [60] [114] [115] [116] [117] [118] [119] [120]. The properties of base layer materials compiled in Table 5.15 are of materials such as 220 GSM 100% cotton base layer, 150 GSM 95% polyester and 5% polyamide single jersey fabric, 200 GSM 100% CoolMax Interlock fabric and 100% Merino wool base layer. Most of the cut resistant materials that exist in the market or those that are studied for academic/research purposes focus only on their cut resistant performance.

It can be observed from Table 5.15 that both the SARK fabrics, in spite of being bulky, exhibit very low retention of water with gram-per-gram retention values of 1.29 and 1.17 for every gram of fabric immersed in water for SARK-1 and SARK-2 respectively. This is due to the predominant presence of aramid, UHMWPE and glass fibres. Since all afore mentioned fibres are highly crystalline, they do not retain any water.

The thermal resistance values are slightly on the warmer side with the values of both the fabrics being in between 45 and 49 compared to 36.1 for a 100% cotton base layer. This is due to the ability of the two-layered fabric to trap air between the layers. Understandably, once they are wetted, the value reduces to 30 and below for the WF528 face of the fabric. This reduction in thermal resistance is due to the presence of composite yarns, the multi-component structure of, which enables to trap more moisture.

The percent recovery values after 4 minutes of wetting are very high at 63.2% and 77.9%. The higher value of the thermal recovery indicates that the fabric is relatively quick to dry. This is further substantiated by the low gram-per-gram values.

Similarly, the percentage loss in, warmth-to-touch feeling after wetting for 4 minutes with water was lower for both the fabrics, mainly due to the fabrics characteristic of drying out relatively quickly as indicated by the reasonably high thermal absoptivity values when wet.

Though the fabrics have poor water vapour permeability, both the fabrics have a good resistance to evaporative heat loss, meaning that the body temperature will be maintained well during cold conditions.

The wicking is comparable to some of the fabrics used in every-day wear such as knitted fleece fabrics and tracksuits [121] [81] and this could be due to the presence of ring-spun yarn which wick away the water through capillary action (adsorption) [122]. Since a thick sample may have poor wicking height but a high value by this method, it should be taken in context with the wicking height which is much higher (over 70mm) than any base layer fabric (30-60mm).

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

"The future belongs to those who believe

in the beauty of their dreams."

Eleanor Roosevelt (1884-1962)
Mrs. Franklin D. Roosevelt

Chapter 6. Conclusions and Suggestions for Further Work

6.1 Introduction

The main aim of this chapter is to discuss the major conclusions drawn from the work presented in this thesis and to highlight the significant contribution, as well as the innovative and unique aspects of this research programme. The recommendations for future work with the scope for further development on these products for making it suitable for various other applications are also presented.

6.2 Conclusions

The demand for protective garments is ever so increasing among the law enforcement officers and medical personnel. With knives being used more commonly now-a-days in street fights and muggings, the demand for personal protective garments against knives is escalating among the general public.

Crimes involving knives are increasing on a day-to-day basis in the UK with knife being the most commonly used weapon at 32 percentage. The need for slash resistant materials is ever increasing as the body armours currently worn by the security and protective services personnel do not protect the arm, shoulders, neck and face as they are very rigid and heavy to be worn comfortably over long periods of time.

This research programme was undertaken to develop and fully characterise advanced personal protective fabrics that will provide protection against cut and slash attacks while being lightweight and comfortable to wear for continuous long hours on a day to day basis.

6.2.1 Yarn properties

A selection of fibres currently used for constructing Personnel Protective Equipment (PPE) was identified and these fibres were used to develop different combinations of composite yarns and ring-spun yarns. The tensile and slash resistant properties of these yarns were tested and analysed to understand their contribution in the fabric form.

The results, shown in Figures 4.2 - 4.6 and Table 4.3 in Chapter 4, demonstrated that the composite yarn WF528, containing a core of 11 DTex D450 fibreglass, covered with 24 Tex type 100 Spectra in the ‘S’ direction and then double covered by 8 Tex textured polyamide 66, exhibited the highest tenacity of 98.49 cN/Tex. It was found that the yarns with higher linear densities, owing to the presence of thicker fibre glass or steel yarn core, had the least tenacity among the yarns tested. The presence of steel core in the E669 yarn contributed to a high modulus of elasticity of 180 cN but due to its least extension, the yarn broke quicker than the other tested composite yarns.

The results demonstrated that Spectra WF528 yarn will exhibit the highest tensile properties and at the same time enables the production of lightweight fabrics.

6.2.2 Slash resistance properties

A series of fabric samples were knitted by using different combinations of the various yarns using two innovative two-layer weft knitted jersey structures, namely, ‘jersey structure’ and ‘racked structure’ that are described in detail in Section 4.3 of Chapter 4. These two structures are illustrated in Figure 4.7 and 4.8 respectively.

The developed fabric structures were tested against the HOSDB Slash Resistant Standard for the UK Police (2006) and it was observed that, among all the combinations used, Kevlar yarn had the highest slash resistance with an average value of 74.75 N. Next to Kevlar yarn, the best slash resistance was recorded with the WF408 yarn. Based on the results obtained from the tensile properties of the yarns, the WF408 yarn was replaced by three ends of WF528 which reduced the linear density by 30% thus reducing the area density of the knitted fabric by 250 g m^{-2}, making it lighter and theoretically more comfortable to wear compared to rigid body armours that also provide slash resistant protection.

Three fabrics were produced by varying the rack structure by changing the rack sequence and were officially designated as SARK fabrics: SARK-1, SARK-2 and SARK-3. When tested for slash resistance, the first two variants passed in all three directions on both faces of the fabric and the third variant passed on the WF528 face. Among all the tests carried out, the failure force was always lower in the walewise direction and hence modifications were made to the above structure to achieve a special racked structure in one of the faces. This racked structure provided resistance in the continuous movement of the blade, thus increasing the slash resistance. The slash resistance results obtained for these structures were more isotropic in nature (see Table 5.7 in Chapter 5).

Further reduction of the fabric area density was attempted by altering the stitch length of the yarns in the knitted structure. The results revealed that the slash resistance force were highly inconsistent as the accumulation of the knitted loops made the blade jump and perform a stab action instead of the slash action. Since the purpose of this standard is to test resistance to slash, the test pass criteria were modified for fabrics such that any strike-through due to the stab action is ignored. The changes in the pass criteria, were described in detail in Section 5.6 of Chapter 5.

One of the aims of these slash resistant materials is to be suitable for wear over long periods of time, which means that they will be exposed to UVA and UVB radiation. Hence, the performance of these slash resistant materials was studied by comparing the tensile and flame retardant properties of the fabrics before and after exposing them to 5 years of UVA and UVB radiation. The flame, when exposed to the Kevlar yarn face of the fabric did not ignite even after exposing it for over 60 seconds. There was no visible difference between the unexposed and exposed fabrics.

There was also no significant difference in the tear strength between exposed and unexposed fabrics on the Kevlar yarn side. However, the fabrics that were exposed on the WF528 yarn face exhibited a significant increase (15.6%) in performance.

A significant change (43.4%) was observed in the breaking load of the fabrics exposed to UV radiation. Across all three directions, fabrics exposed on the Kevlar yarn side showed a 40% increase in tenacity and the fabrics exposed on the WF528 yarn side showed 49.1% increase in tenacity.

6.3 Unique features of the slash resistant fabric

A number of unique and innovative outcomes arising from this research programme are listed below:

1. A number of special yarns have been developed, characterised and utilised in these innovative materials.
2. Standard electronic E10 flat weft knitting equipment has been utilised to produce the novel two-layer structures.
3. Although different yarn types were used on the two faces of the two-layer structures, both faces exhibited similar performance.
4. These fabrics have successfully passed the most stringent test method stipulated for such products and applications, namely, the Home Office Scientific Development Branch (HOSDB) Slash Resistance Standard for the UK Police.

5. This unique material is relatively lighter than stab resistant body armours.
6. Based on measured comfort properties, the fabric will be comfortable to the wearer for long periods of continuous use on comparison with 100% cotton base layers.

The novel fabric structures are a two-layer material which, theoretically, will be comfortable to the user with similar slash or cut resistance performance when tested on both faces in spite of using two completely different yarn types on the two faces.

6.4 Recommendations for further work

During this research programme, novel and advanced two-layered slash resistant fabric structures that are light weight and comfortable to be worn over long periods of time have been developed and fully characterised for slash and cut resistance applications, similar to that of body armour, mainly to cover arms, legs and neck, gloves, balaclava, to name a few.

As a part of this programme, composite yarns were developed and the results showed that the properties of the yarns greatly influence the slash resistant properties. Further work could be conducted concentrating solely on the yarns and in studying the cut resistant properties of the yarns. The combination of fibres used in the composite yarns could be altered to further reduce the fabric area density and also to enhance the comfort of the fabric.

Considering the mechanism of a slash, a staple yarn is more resistant to slash than a continuous filament yarn as the staple-fibre yarns help to dissipate the force over a larger area. Hence, further blends of spun high performance fibres could be developed. The fabric can be functionally enhanced by applying an antimicrobial finish and studying its durability over a number of washes.

The fabrics that were exposed to UVA and UVB radiations showed a significant increase in their tensile properties. This aspect could be further investigated to elucidate the reasons why there were 40% and 49.1% increases after exposure. This can be further studied by analysing the changes in molecular levels and in the crystalline regions of the fibres after exposure.

Since the scope of this research programme was to develop slash resistant fabrics that can be worn over long periods of time, the comparison was done mainly to ascertain that the fabrics’ slash performance does not degrade over time on exposure to sunlight. Since it is evident from the results, discussed in section 5.7, that the fabrics do not degrade on exposure, this aspect of the resistance to slash was not studied further. The exposed fabrics need to be tested against the HOSDB Slash Resistant Standard for the UK Police (2006) to ascertain if similar increase in performance could be achieved in slash resistance and if so, whether the fabric area density could be reduced further in order to make it more lighter and comfortable.

REFERENCES

"Nothing in this world is to be feared…

only understood."

Marie Curie (1867-1934)

Nobel Prize in Physics (1903) and Chemistry (1911)

References

[1] J. Simmons, “Crime in England and Wales 2001/2002,” Patterns of Crime Group, London, July 2002.

[2] P. Taylor and R. Chaplin, “Crime detected in England and Wales 2010/11, Home Office Statistical Bulletin 11/11,” Home Office Statistics, London, 2011.

[3] A. Bleetman, C. H. Watson, I. Horsfall and S. M. Champion, “Wounding patterns and human performance in knife attacks: Optimising the protection provided by knife-resistant body armour,” *Journal of Clinical Forensic Medicine,* vol. 10, no. 4, pp. 243-248, December 2003.

[4] G. Berman, “Knife Crime Statistics 2011,” Home Office, London, 2012.

[5] Anonymous, *‘Knife Crime’:In-effective reactions to a distracting problem,* The Centre for Crime and Justice Studies, 2006.

[6] “MORI youth survey 2004,” Youth Justice Board for England and Wales, 2005.

[7] D. Wooding, *Anarchy in UK: Have the yobs taken over?,* 2007, p. 4.

[8] K. Smith, S. Osbourne, I. Lau and A. Britton, “Homicides, Firearm Offences and Intimate Violence 2010/11,” Home Office Statistics, London, 2012.

[9] A. Bleetman, H. Hughes and V. Gupta, “Assailant technique in knife slash attacks,” *Journal of Clinical Forensic Medicine,* vol. 10, pp. 1-3, 2003.

[10] J. P. Shepherd, M. Shapland, N. X. Pearce and C. Scully, “Pattern, severity and acticology of injuries in victims of assault,” *Journal of Royal Society of Medicine,* vol. 83, pp. 75-78, February 1990.

[11] “Hospital Episode Statistics (HES),” National Health Service, [Online]. Available: http://www.hesonline.nhs.uk. [Accessed Aug-Sep 2012].

[12] A. C. Hunt and R. J. Cowling, “Murder by stabbing,” *Forensic Science International,* vol. 52, pp. 107-112, 1991.

[13] I. Horsfall, P. D. Prosser, C. H. Watson and S. M. Champion, “An assessment of human performance in stabbing,” *Forensic Science International,* vol. 102, no. 2-3, pp. 79-89, June 1999.

[14] J. Croft, "PSDB Body Armour Standards for UK Police," Home Office Police Scientific Development Branch, St Albans, 2003.

[15] P. Fenne, "Protection against knives and other weapons," in *Textiles for Protection*, R. A. Scott, Ed., Cambridge, Woodhead Publishing, 2005.

[16] E. K. J. Chadwick, A. C. Nicol, J. V. Lane and T. G. F. Gray, "Biomechanics of knife stab attacks," *Forensic Science International,* vol. 105, pp. 35-44, 1999.

[17] I. Horsfall and C. H. Watson, *Ballistic and stab protection,* Manchester-UMIST, 2003.

[18] H. H. Yang, Kevlar Aramid Fibre, New York: Wiley & Sons, 1993.

[19] R. J. Young and C. L. So, "PBO and related polymers," in *High Performance Fibres*, J. W. S. Hearle, Ed., Cambridge, Woodhead Publishing.

[20] B. Harris, "Strong Fibres," in *Engineering Composite Materials*, London, The Institute of Materials, 1999.

[21] DuPont, "Technical Guide - Kevlar Aramid Fiber," DuPont, [Online]. Available: http://www2.dupont.com/Kevlar/en_US/assets/downloads/KEVLAR_Technical_Guide.pdf. [Accessed Sep 2012].

[22] H. L. Stein, "Ultrahigh molecular weight polyethylenes (uhmwpe)," in *Engineered Materials Handbook*, 1998, pp. 167-171.

[23] M. Miraftab, "Technical fibres," in *Handbook of Technical Textiles,* A. R. Horrocks and S. C. Anand, Eds., Cambridge, Woodhead Publishing, 2000, pp. 29-30.

[24] W. Klein, Manual of Textile Technology. Short-Staple Spinning Series, Vol.4: A Practical Guide to Rinbg Spinning, Machester: The Textile Institute, 1987.

[25] R. P. Lord, Handbook of Yarn Production, Manchester: Woodhead Publishing Ltd, 2003.

[26] C. A. Lawrence, Ed., Advances in yarn spinning technology, Manchester: Woodhead Publishing Ltd, 2010.

[27] International Trade Centre, "Cotton Guide - Yarn Formation," June 2012. [Online]. Available: http://www.cottonguide.org/cotton-guide/cotton-value-addition-yarn-formation/.

[28] R. Audivert and E. Fortuyny, “Filament feeding in spinning of staple fiber yarns covered with continuous filament,” *Textile Research Journal,* vol. 50, no. 12, p. 754.

[29] R. Alagirusamy, R. Fangueiro, V. Ogale and N. Padaki, “Hybrid Yarns and Textile Preforming for Thermoplastic Composites,” *Textiel Progress,* vol. 38, no. 4, pp. 1-71, 2006.

[30] A. P. S. Sawhney, G. F. Ruppenicker, L. B. Kimmel and L. Q. Robert, “Comparison of filament-core spun yarns produced by new and conventional methods,” *Textile Research Journal,* vol. 62, no. 2, pp. 67-73, 1992.

[31] F. Pouresfandiari, S. Fushimi, A. Sakaguchi, H. Saito, K. Toriumi, T. Nishimatsu, Y. Shimizu, H. Shirai, Y. I. Matsumoto and H. Gong, “Spinning conditions and characteristics of open-end rotor spun hybrid yarns,” *Textile Research Journal,* vol. 72, no. 1, pp. 61-70, 2002.

[32] E. Fehrer, “Engineered Yarns with DREF Friction Spinning Technology,,” *Canadian Textile Journal,* vol. 104, no. 8, pp. 14-15, 1987.

[33] W. Klein, Shot Staple Spinning Series Vol 5, New Spinning Systems, Manchester: The Textile Institute, 1993.

[34] A. P. S. Sawhney, G. F. Ruppenicker, L. B. Kimmel and K. Q. Robert, “Comparison of filament-core spun yarns produced by new and conventional methods,” *Textile Research Journal,* vol. 62, pp. 67-73, 1992.

[35] N. Balasubramanian and K. Bhatnagar, “The effect of spinning conditions on the tensile properties of core-spun yarns,” *Journal of Textile Institute,* vol. 61, no. 11, pp. 534-554, 1970.

[36] S. K. Suk, E. S. Lee, J. R. Lee and J. K. Lee, “A study on the physical properties of the core-spun yarn,” *Journal of Korean Fiber Society,* vol. 15, no. 1, pp. 23-31, 1978.

[37] G. M. Abbott, “Force-extension behavior of helically wrapped elastic core yarns,” *Textile Research Journal,* vol. 54, pp. 204-223, 1984.

[38] G. F. Ruppenicker, R. J. Harper, A. P. S. Sawhney and K. Q. Robert, “Comparison of cotton/polyester core and staple blend yarns and fabrics,” *Textile Research Journal,* vol. 59, pp. 12-17, 1989.

[39] Honeywell, “Product Sheet Downloads,” [Online]. Available: http://www51.honeywell.com/sm/afc/common/documents/PP_AFC_Spectra_shie

ld_II_SA_4144_Product_information_sheet.pdf. [Accessed 17 02 2012].

[40] M. Padovani, J. H. Meulman and D. Louwers, “Effect of Real Aging on Ballistic Articles made of Dyneema® UD,” DSM Dyneema, 2011.

[41] S. Chabba, M. van Es, E. J. van Kilnen, M. J. Jongedijik, D. Vanek, P. Gijsman and A. C. L. M. van der Waals, “Accelerated ageing study of ultrahigh molecular weight poly ethylene yarn and unidirectional composites for ballistic applications,” *Journal of Materials Science,* vol. 42, pp. 2891-2893, 2007.

[42] J. Karger-Kocsis and T. Bárány, “Polyolefin Fiber- and Tape-Reinforced Polymeric Composites,” vol. 1, 2012.

[43] J. L. J. van Dingenen, “High performance dyneema fibres in composites,” *Materials & Design,* vol. 10, no. 2, pp. 101-104, March-April 1989.

[44] D. Burger, A. Rocha De Faria, S. F. M. De Almeida, F. C. L. De Melo and M. V. Donadon, “Ballistic impact simulation of an armour-piercing projectile on hybrid ceramic/fiber reinforced composite armours,” *International Journal of Impact Engineering,* vol. 43, pp. 63-77, 2012.

[45] M. Afshari, D. J. Sikkema, K. Lee and M. Bogle, “High performance fibers based on rigid and flexible polymers,” *Polymer Reviews,* vol. 48, no. 2, pp. 230-274, 2008.

[46] DSM, “Dyneema UniDirectional,” 2012. [Online]. Available: http://www.dyneema.com/americas/explore-dyneema/formats-and-applications/dyneema-unidirectional.aspx. [Accessed 21 Feb 2012].

[47] C. Bottger, *Twaron SRM – A novel type of stab resistant material,* The royal military college of science, 1999.

[48] Teijin Aramid, “Ballistics material handbook,” Arnhem, Netherlands, 2012.

[49] Z. Dong, J. M. Manimala and C. T. Sun, “Mechanical Behavior of Silica Nanoparticle-Impregnated Kevlar Fabrics,” *Journal of Mechanics of Materials and Structures,* vol. 5, no. 4, pp. 529-548, 2010.

[50] L. Dischler, J. B. Henson and T. B. Moyer, “Dilatant powder coated fabric and containment articles formed therefrom”. United States of America Patent US 5776839 A, 7 July 1998.

[51] Y. S. Lee, E. D. Wetzel and N. J. Wagner, “The ballistic impact characteristics of Kevlar woven fabrics impregnated with a colloidal shear thickening fluid,” *Journal of Materials Science,* vol. 38, pp. 2825-2833, 2003.

[52] R. G. Egres, M. J. Decker, C. J. Halbach, Y. S. Lee, J. E. Kirkwood, K. M. Kirkwood and N. J. Wagner, “Stab Resistance of Shear Thickening Fluid (STF) - Kevlar Composites for Body Armmour Applications,” in *Proceedings of the 24th Army Science Conference*, Orlando, 2004.

[53] B. A. Cheeseman and T. A. Bogetti, “Ballistic impact into fabric and compliant composite laminates,” *Composite Structures,* vol. 61, pp. 161-173, 2003.

[54] Y. Wang and T. Mabe, “Flexible spike and ballistic resistant panel”. United States of America Patent US7958812 B2, 14 June 2011.

[55] M. J. Decker, C. J. Halbach, C. H. Nam, N. J. Wagner and E. D. Wetzel, “Stab resistance of shear thickening fluid (STF)-treated fabrics,” *Composites Science and Technology,* vol. 67, pp. 565-578, 2007.

[56] C. Buster, “Body armor update,” *Law & Order,* vol. 55, no. 1, pp. 50-62, January 2007.

[57] S. L. Märtha, C. Forsberg and L. K. Wahren, “ Normal oral, rectal, tympanic and axillary body temperature in adult men and women: a systematic literature review.,” *Scandinavian Journal of Caring Sciences,* vol. 16, no. 2, p. 122, 2002.

[58] R. P. Clark and O. Gustaf Edholm, Man and His Thermal Environment, London: Edward Arnold, 1985.

[59] W. H. Rees, “Physical Factors Determining the Comfort Performance of Textiles,” in *Third Shirley International Seminar: Textiles for Comfort*, Manchester, 1971.

[60] A. P. Gagge and R. R. Gonzalez, “Physiological and Physical Factors Associated with Warm Discomfort and Sedentary Man,” *Environmental Research,* vol. 7, no. 230, 1974.

[61] P. O. Fanger, Thermal Comfort, New York: McGraw Hill, 1970.

[62] M. M. Adler and W. K. Walsh , “Mechanisms of Transient Moisture Transport Between Fabrics,,” *Textile Research Journal,* vol. 54, pp. 334-343, 1984.

[63] S. Yoo and R. L. Barker, “Comfort Properties of Heat-Resistant Protective Workwear in Varying Conditions of Physical Activity and Environment. Part I: Thermophysical and Sensorial Properties of Fabrics,” *Textile Research Journal,* vol. 75, pp. 523-532, 2005.

[64] K. L. Hatch, S. S. Woo , R. L. Barker , P. Radhakrishnaiah, N. L. Markee and H. I. Maibach, “In Vivo Cutaneous and Perceived Comfort Response to Fabric Part

I: Thermophysiological Comfort Determinations for Three Experimental Knit Fabrics," *Textile Research Journal,* vol. 60, pp. 405-412, 1990.

[65] G. Havenith, "Heat Balance When Wearing Protective Clothing," *The Annals of Occupational Hygiene,* vol. 43, pp. 289-296, 1999.

[66] X. Chen and E. Kunz, "Analysis of 3D woven structure as a device for improving thermal comfort of ballistic vests," *International Journal of Clothing Science and Technology,* vol. 17, no. 3/4, pp. 215-224, 2005.

[67] British Standards Institution, "BS EN 388:2003, Protective gloves against mechanical risks," London, 2003.

[68] British Standards Institution, "BS EN ISO 13997:1999, Protective clothing — Mechanical properties — Determination of resistance to cutting by sharp objects," London, 1999.

[69] British Standards Institution, "BS EN 1082-3:2000, Protective clothing - Gloves and arm guards protecting against cuts and stabs by hand knives," London, 2000.

[70] C. Malbon and J. Croft, *HOSDB slash resistance standard for UK police (2006),* London: Home Office Scientific Development Branch.

[71] British Standards Institution, "Reinforcement yarns — Determination of linear density," London, 2009.

[72] British Standards Institution, "BS EN ISO 2062:2009. Textiles. Yarns from packages. Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) tester," London, 2009.

[73] British Standards Institution, "BS EN ISO 5084:1997. Textiles. Determination of thickness of textiles and textile products," London, 1997.

[74] S. Kawabata, The Standardisation and analysis of hand evaluation, 2nd Ed ed., Osaka: The Textile Machinery Society of Japan, 1980.

[75] L. Hes, "Recent developments in the field of user-friendly testing of mechnaical and comfort properties of textile fabrics and garments," in *World Textile Congress of the Textile Institute*, Cairo, 2002.

[76] S. J. Kadolph, Quality assurance for textiles and apparel, New York: Fairchild, 1993, p. 193.

[77] British Standards Institution, "BS 4745:2005, Determination of the thermal resistance of textiles," London, 2005.

[78] L. Hes, “Optimisation of shirt fabrics’ composition from the point of view of their appearance and thermal comfort,” *International Journal of Clothing Science and Technology*, vol. 11, no. 2/3, pp. 105-119, 1999.

[79] British Standards Institution, “BS EN 31092:1993, Measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded-hotplate test),” London, 1993.

[80] A. Miravete, 3-D Textile Reinforcements in Composite Materials, Cambridge: Woodhead Publishing Limited, 1999, p. 308.

[81] L. Hes and J. Martins, “Experimental investigation of heat transfer in textile fabric by radiation,” in *3rd World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, USA, 1993.

[82] L. Hes and I. Araujo, “Simulation of the effect of air gaps between the skin and a wet fabric on resulting cooling flow,” *Textile Research Journal*, vol. 80, no. 14, pp. 1488-1490, 2010.

[83] British Standards Institution, “BS 3449:1990, Method for resistance of fabrics to water absorption (Static immersion test),” London, 1990.

[84] British Standards Institution, “BS 3424-18:1986, Testing coated fabrics. Methods 21A and 21B. Methods for determination of resistance to wicking and lateral leakage,” London, 1986.

[85] National Lighting Product Information Program, “Full-Spectrum Light Sources,” Rensselaer Polytechnic Institute, Troy, NY, 2003.

[86] British Standards Institution, “BS EN ISO 105-B06:2004.Textiles. Tests for colour fastness. Colour fastness and ageing to artificial light at high temperatures: Xenon arc fading lamp test,” London, 2004.

[87] British Standards Institution, “BS EN ISO 13937-3:2000. Textiles. Tear properties of fabrics. Determination of tear force of wing-shaped test specimens (single tear method),” British Standards Institution, London, 2000.

[88] British Standards Institution, “BS 5438:1989. Methods of test for flammability of textile fabrics when subjected to a small igniting flame applied to the face or bottom edge of vertically oriented specimens,” London, 1989.

[89] D. J. Spencer , Knitting Technology, 3rd Edition ed., Cambridge: Woodhead Publishing Limited, 2001.

[90] M. A. Andrews and V. A. . Gregory, “Protective yarn”. United States of America Patent US6413636 B1, 2 July 2002.

[91] H. S. Shin, D. C. Erlich, J. W. Simons and D. A. Shockey, “Cut Resistance of High-strength Yarns,” *Textile Research Journal,* no. 76, p. 607, 2006.

[92] Superior Glove Works Ltd, “The Superior Book of Cut Protection,” Superior Glove Works Ltd, New York, 2008.

[93] G. Bontemps, M. Francois, J. Guevel and J. E. A. Kriele, “Composite yarn with high cut resistance and articles comprising said composite yarn”. Europe Patent EP0445872 B1, 11 December 1996.

[94] H. R. Young and R. Zhu, “Ply-twisted yarn for cut resistant fabrics”. United States of America Patent US7127879 B2, 31 October 2006.

[95] G. J. E. Hensen and J. E. A. Kriele, “Cut resistant yarn”. Europe Patent EP1862572 A1, 5 December 2007.

[96] K. Blake, “Composite cut- resistant yarn and garments made from such yarn”. International Patent WO2008102130 A1, 28 August 2008.

[97] K. Chakravarthi, “Cut resistant yarn and apparel”. United States of America Patent US6266951 B1, 31 July 2001.

[98] G. J. I. Henssen, “Cut resistant yarn and apparel”. Europe Patent EP2393968 A1, 14 December 2011.

[99] F. T. Wallenberger and P. A. Bingham , Fiberglass and Glass Technology: Energy-Friendly Compositions and Applications, New York: Springer, 2010.

[100] National Institute of Justice, “NIJ Standard–0115.00. Stab Resistance of Personal Body Armor,” National Institute of Justice, Washington, September 2000.

[101] J. Lara, D. Turcott, R. Daigle and J. Boutin, “A New Test Method to Evaluate the Cut Resistance of Glove Materials,” in *Performance of Protective Clothing:Fifth Edition, ASTM STP 1237,* J. S. Johnson and S. Z. Mansdorf, Eds., American Society for Testing and Materials, 1996.

[102] G. A. Holmes, E. S. Park, J. H. Kim, W. G. McDonough, J. R. Sieber, H. Kobayashi, M. A. Riley and Rice K D, “The effect of environmental and mechanical mechanisms on the performance fo soft body armor,” in *International Committee on Composite Materials (ICCM-17),* Edinburgh, 27-31 July 2009.

[103] P. J. Walsh, X. Hu, P. Cunniff and A. J. Lesser, "Environmental Effects on Poly-p-phenylenebenzobisoxazole Fibers. I. Mechanisms of Degradation," *Journal of Applied Polymer Science,* vol. 102, pp. 3517-3525, 2006.

[104] X. Liu and W. Yu, "Degradation of PBO Fiber by Heat and Light," *Research Journal of Textile and Apparel,* vol. 10, no. 1, pp. 26-32, 2006.

[105] D. Tompkins, "Body Armor Safety Initiative: To Protect and Serve…Better," *NIJ Journal No. 254,* July 2006.

[106] B. S. Stowe, B. S. Salvin, R. E. Fornes and R. D. Gilbert, "The effect of near-ultraviolet radiation on the morphology of Nylon 66," *Textile Research Journal,* vol. 43, pp. 704-714, December 1973.

[107] R. E. Fornes, R. D. Gilbert, B. S. Stowe and G. P. Cheek, "Photodegradation of Nylon 66 exposed to near-UV radiation," *Textile Research Journal,* vol. 43, no. 12, pp. 714-715, December 1973.

[108] G. Hargreaves and J. H. Bowen, "Combined effects of gamma and ultraviolet radiation plus heat on fibrous polyamides," *Textile Research Journal,* vol. 43, no. 10, pp. 568-576, October 1973.

[109] K. Gotoh and M. Hayashiya, "Improvement of serviceability properties of synthetic textile fabrics using 172 nm ultraviolet excimer lamp," *Textile Research Journal,* vol. 78, no. 1, pp. 37-44, January 2008.

[110] J. R R, "Overview of Skin Structure, Function and Toxicology," in *Chemical Protective Clothing - Volume I,* J. James S and K. J. Anderson, Eds., Akron OH, American Industrial Hygiene Association, 1990.

[111] A. Mukhopadhyay and V. K. Midha, "A review on designing the waterproof breathable fabrics part I: fundamental principles and designing aspects of breathable fabrics," *Journal of Industrial Textiles,* vol. 37, no. 3, pp. 225-262, January 2008.

[112] R. A. Scott, "Textiles in defence," in *Handbook of Technical Textiles,* Cambridge, Woodhead Publishing Limited, 2000, pp. 425-458.

[113] J. Wickwire, P. A. Bishop , J. M. Green, M. T. Richardson, R. G. Lomax, C. Casaru, M. Curther-Smith and B. Doss, "Physiological and comfort effects of commercial ''wicking'' clothing under a bulletproof vest," *International Journal of Industrial Ergonomics,* vol. 37, pp. 643-651, 2007.

[114] "Textile Materials and Products for Activewear and Sportswear," Textiles

Intelligence, Wimslow, 2003.

[115] S. C. Anand, “Recent Advances in Textile Materials and Products for Activewear and Sportswear,” *Textile Today,* 2011.

[116] P. Gibson, “Water-repellent Treatment on Military Uniform Fabrics: Physiological and Comfort Implications,” *Journal of Industrial Textiles,* vol. 38, p. 43, 2008.

[117] O. Troynikov and W. Wardiningsih, “Moisture management properties of wool/ polyester and wool/bamboo knitted fabrics for the sportswear base layer,” *Textile Research Journal,* vol. 81, p. 621, 2011.

[118] S. Yoo and R. L. Barker, “Comfort Properties of Heat-Resistant Protective Workwear in Varying Conditions of Physical Activity and Environment. Part I: Thermophysical and Sensorial Properties of Fabrics,” *Textile Research Journal,* vol. 75, p. 523, 2005.

[119] J. Fan and W. K. Tsang, “Effect of Clothing Thermal Properties on the Thermal Comfort Sensation During Active Sports,” *Textile Research Journal,* vol. 78, no. 2, pp. 111-118, 2008.

[120] S. Cimilli, B. U. Nergis, C. Candan and M. Ozdemir, “A Comparative Study of Some Comfort-related Properties of Socks of Different Fiber Types,” *Textile Research Journal,* vol. 80, no. 10, pp. 948-957, 2010.

[121] S. Gunesoglu, S. Meric and C. Gunesoglu, “Thermal contact properties of 2-yarn fleece knitted fabrics,” *Fibres & Textiles,* vol. 13, no. 2, pp. 46-50, 2005.

[122] M. Yoneda and S. Kawabata, “Analysis of transient heat conduction in textiles and its applications,” *Journal of Textile Machinery Society of Japan,* vol. 31, pp. 73-81, 1983.

[123] L. Hes and I. Dolezal, “New method and equipment for measuring thermal properties of textiles,” *Journal of Textile Machinery Society of Japan,* vol. 42, pp. 124-128, 1989.

APPENDICES

"The whole of science is nothing more

than a refinement of everyday thinking."

Albert Einstein (1879-1955)
German physicist

Appendix A:

Publications Arising From Thesis

Patents

Anand, S.C., Tracey, A., Rajendran, S., and Kanchi Govarthanam, K, Future Textiles Limited (2012) Protective Fabrics, GB 2478208. [To be fully granted on 20th June 2012]

Publication in peer-reviewed journals

Kanchi Govarthanam, K., Anand, S.C., and Rajendran, S., Development of Advanced Personal Protective Equipment Fabrics for Protection Against Slashes and Pathogenic Bacteria Part 1: Development and Evaluation of Slash-resistant Garments, Journal of Industrial Textiles, October 2010; vol. 40, 2: pp. 139-155., first published on May 26, 2010

Kanchi Govarthanam, K., Anand, S.C., and Rajendran, S., Development of Advanced Personal Protective Equipment Fabrics for Protection Against Slashes and Pathogenic Bacteria Part 2: Development of Antimicrobial Hygiene Garments and their Characterization, Journal of Industrial Textiles, January 2011; vol. 40, 3: pp. 281-296., first published on July 9, 2010

Literature review publications

Kanchi Govarthanam, K., Anand, S.C., and Rajendran, S., Stab and slash resistance in personal protective garments – I, Technical Textiles International, October/November 2008, 17-22.

Kanchi Govarthanam, K., Anand, S.C., and Rajendran, S., Stab and slash resistance in personal protective garments – II, Technical Textiles International, December 2008, 33-37.

Conference publications

86th Textile Institute World Conference,Hong Kong International Trade and Exhibition Centre, Hong Kong. Nov 2008

Research Forum Presentation, The University of Bolton, UK. Jun 2009 & Apr 2008.

SPARC 2010, University of Salford, 11th June

HEAT 2010, International Conference on Healthcare and Hygiene Textiles & Clothing, Coimbatore, India. 30-31 July 2010.

Textile Institute Centenary Conference, Manchester, UK. 3-4 November 2010.

Appendix B:

Home Office Scientific Development Branch Compliance Certifications

Home Office
Scientific
Development Branch

CONFIRMATION OF COMPLIANCE TO
THE HOSDB SLASH RESISTANCE STANDARD FOR UK
POLICE 2006
(PUBLICATION NUMBER 48/05)
ISSUED TO:

Future Textiles

Unit 2, Major House, Wimsey Way, Alfreton, Derbyshire, DE55 4LS

Model: SARK-1

Test Reference: HOSDB-S16-07/04/09

Date of Issue: 16th April 2009

Areal Density: 1.0354 kg/m^2

This document confirms Slash Resistance compliance of a construction unique to its model designation. Any products manufactured using this model designation, must be in strict accordance with the submitted declaration. This document is issued on condition that any product marketed under the above model designation must be clearly marked with the manufacturer's name, model and test reference given above and in accordance with publication 48/05 Page 3 Section 2.1

Home Office
Scientific
Development Branch

CONFIRMATION OF COMPLIANCE TO
THE HOSDB SLASH RESISTANCE STANDARD FOR UK
POLICE 2006
(PUBLICATION NUMBER 48/05)
ISSUED TO:

Future Textiles

Unit 2, Major House, Wimsey Way, Alfreton, Derbyshire, DE55 4LS

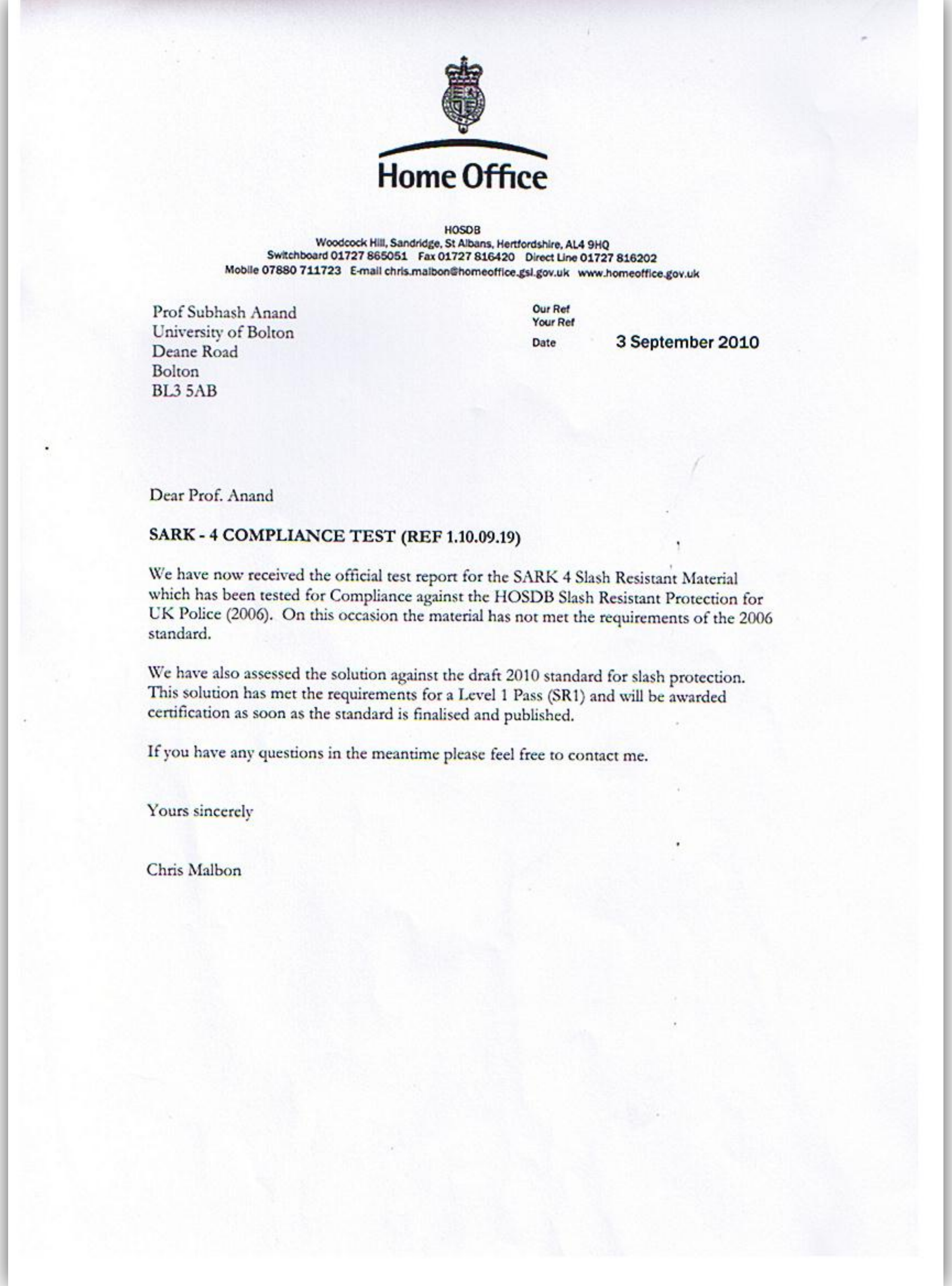
Model: SARK-2

Test Reference: HOSDB-S18-07/04/09

Date of Issue: 16th April 2009

Areal Density: 0.966 kg/m²

This document confirms Slash Resistance compliance of a construction unique to its model designation. Any products manufactured using this model designation, must be in strict accordance with the submitted declaration. This document is issued on condition that any product marketed under the above model designation must be clearly marked with the manufacturer's name, model and test reference given above and in accordance with publication 48/05 Page 3 Section 2.1



Home Office

HOSDB
Woodcock Hill, Sandridge, St Albans, Hertfordshire, AL4 9HQ
Switchboard 01727 865051 Fax 01727 816420 Direct Line 01727 816202
Mobile 07880 711723 E-mail chris.malbon@homeoffice.gsi.gov.uk www.homeoffice.gov.uk

Prof Subhash Anand
University of Bolton
Deane Road
Bolton
BL3 5AB

Our Ref
Your Ref
Date 3 September 2010

Dear Prof. Anand

SARK - 4 COMPLIANCE TEST (REF 1.10.09.19)

We have now received the official test report for the SARK 4 Slash Resistant Material which has been tested for Compliance against the HOSDB Slash Resistant Protection for UK Police (2006). On this occasion the material has not met the requirements of the 2006 standard.

We have also assessed the solution against the draft 2010 standard for slash protection. This solution has met the requirements for a Level 1 Pass (SR1) and will be awarded certification as soon as the standard is finalised and published.

If you have any questions in the meantime please feel free to contact me.

Yours sincerely

Chris Malbon

Appendix C:

SARK Product Images

Appendix D:

SARK Fabric Samples

SARK-1

SARK-2

SARK-3