

**STUDIES ON IMPACT RESISTANCE BEHAVIOR
OF WOVEN TEXTILE STRUCTURES TREATED
WITH SHEAR THICKENING FLUIDS**

ANKITA SRIVASTAVA



**DEPARTMENT OF TEXTILE TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI - 110016**

AUGUST 2012

STUDIES ON IMPACT RESISTANCE BEHAVIOR OF WOVEN TEXTILE STRUCTURES TREATED WITH SHEAR THICKENING FLUIDS

by

ANKITA SRIVASTAVA
Department of Textile Technology

Submitted
In fulfillment of the requirements of the degree of
Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

August, 2012

CERTIFICATE

This is to certify that the thesis titled **Studies on impact resistance behavior of woven textile structures treated with shear thickening fluids**, being submitted by Mrs. Ankita Srivastava to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by her. She has worked under our guidance and supervision and fulfilled the requirements for submission of the thesis which has attained the standard required for a Ph.D. degree of this institute.

The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

Dr. Bhupendra Singh Butola
Assistant Professor
Department of Textile Technology
Indian Institute of Technology Delhi
Hauz Khas
New Delhi 110016
India

Dr. Abhijit Majumdar
Assistant Professor
Department of Textile Technology
Indian Institute of Technology Delhi
Hauz Khas
New Delhi 110016
India

ACKNOWLEDGEMENTS

I would like to profoundly thank my supervisors Dr. B. S. Butola and Dr. A. Majumdar for their constant interest, encouragement and invaluable co-operation throughout my research work. I am indebted to them for their invaluable guidance and support that they bestowed on me right from the inception to the successful completion of this endeavor.

My sincere gratitude also goes to members of my research committee Prof. B. L. Deopura, Prof. R. Chattopadhyay and Prof. P. Mahajan who have encouraged me a lot throughout the course of this research. I also express my sincere gratitude to all other faculty members of Department of Textile Technology, IIT Delhi for their invaluable support and assistance.

I thank the staff members of all the laboratories of the Department of Textile Technology, IIT Delhi, for extending a helping hand whenever needed.

I extend my gratitude to the Department of Science and Technology, Govt. of India, New Delhi for funding the project entitled ‘Development of woven fabrics with improved impact resistance using shear thickening fluid’ and Institution of Engineers (IEI), India, for funding the project entitled ‘Development of a textile composite structure using shear thickening fluid for ballistic applications’.

I thank Mr. Abhijit Mondal and management of MKU, Kanpur for providing Kevlar fabrics used throughout the study. I am grateful to Dr. Manjit Singh (Director TBRL, Chandigarh),

Dr. Debarati Bhattacharya and Mrs. Ipshita Biswas of TBRL, Chandigarh extending various testing facilities.

Keeping my composure through all these years would not have been possible without the aid of friends. I am grateful to my friends Syamal Maiti, Moumita Bera, Arun Pradhan, Swapna Mishra, Roopali Agarwal, Shalini Singh and all my fellow postgraduate students as without their constant support it would have been impossible to complete this task.

Last but, not the least, I would like to thank my parents and my husband Mr. Ankur Saxena for their love, support and patience throughout my research work.

Ankita Srivastava

Dedicated To my Daughter- Sanvi

ABSTRACT

Use of shear thickening fluids (STF) to improve the impact resistance performance of soft body armor materials like woven Kevlar fabrics is a novel and relatively new concept which has generated a lot of interest among scientific community. However, there is still no clear understanding about the mechanism behind this improvement primarily because the textile fabrics are complex structures whose combination with STFs can lead to very complex interactions.

It can be assumed that the degree of penetration and uniformity of distribution of STF in yarn and fabric structures would play a key role in such enhancements. Since the distribution of STF in yarn and fabric structures would depend a lot on application process parameters like padding pressure and solvent to STF ratio, their role in influencing the impact resistance performance of Kevlar fabrics becomes important. However, no such study has been conducted so far which is an important missing link in this area.

This thesis is an attempt to investigate the role of different process parameters of STF application in improving impact resistance performance of Kevlar fabrics and optimization of the process parameters using the design of experiment methodology.

The materials chosen for this study were 200 and 465 GSM plain woven Kevlar fabrics with and without a water repellent fluorocarbon finish respectively. Shear thickening fluid was prepared by mixing 100 nm size silica with PEG at 50, 60 and 70% w/w concentrations. The STFs were diluted by ethanol and then applied on Kevlar fabrics using a padding mangle at pressures of 0.5, 1 and 2 bar. The characterization and testing of the treated fabrics were done

by STF add-on %, SEM, yarn pull-out test, dynamic impact test and low velocity ballistic test.

Rheological analysis of STFs revealed that after initial shear thinning, shear thickening takes place. Critical shear rate decreases with increase in silica concentration and reduction in temperature.

It was found that STF application significantly enhances the impact resistance performance of Kevlar fabrics. It was also seen that higher silica concentration and lower padding pressure increase the add-on % of STF which results in higher yarn pull-out force. However, impact resistance measured with dynamic impact tester shows a different trend where higher silica concentration and higher padding pressure result in higher impact resistance performance. It is postulated that higher padding pressure facilitates uniform distribution and penetration of STF within yarn and fabric structures. Hence, even though add-on % of STF may be lower at higher padding pressures, it helps to improve impact resistance. This behavior suggests that friction (represented by yarn pull-out force) plays only a partial role and shear thickening plays a more pivotal role in improving impact energy absorption.

A new treatment method was designed to study the effect of sequential padding on impact energy absorption by subjecting the Kevlar fabrics to the process of padding twice with a given STF at different padding pressure combinations. It was found that impact resistance performance increases significantly with sequential padding as compared to untreated and single padding processes. Better results were obtained when the first padding pressure was higher even with same combination of pressures. A low velocity ballistic test also confirmed

the findings as sequentially padded fabric showed almost 125% increase in impact energy absorption than untreated Kevlar fabrics.

Optimization of three parameters (silica concentration, padding pressure and solvent: STF ratio) was carried out using Box and Behnken experimental design plan. Contour plots were generated to analyze the interactive effect of process parameters on STF add-on % and impact energy absorption. It was found that higher silica concentration, higher padding pressure and lower solvent: STF ratio contributed to the higher impact energy absorption. It could also be concluded that higher STF add-on % is a necessary but not the sufficient condition for achieving higher impact energy absorption.

Impact energy absorption modes were analyzed for untreated and STF treated Kevlar fabrics. Three distinct zones of energy absorption were identified. In untreated Kevlar fabrics, failure was dominated by pull-out of primary yarns and there was negligible contribution of secondary yarns in energy absorption. However, in case in STF treated Kevlar fabrics, failure was dominated by the rupture of primary yarns and there was significant contribution of secondary yarns in impact energy absorption. It is postulated that STF helps to engage the secondary yarns in energy absorption during impact and thus the entire fabric structure contributes to it.

CONTENTS

	Page No.
Certificate	i
Acknowledgements	ii
Abstract	iv
Contents	vii
List of Figures	xii
List of Tables	xvi
Chapter 1 Introduction	
1.1 Impact Resistance Behavior in Textiles	1
1.2 Application of Shear Thickening Fluid for Improving Impact Resistance Behavior	2
1.3 Motivation for the Work	2
1.4 Objectives	3
1.5 Organization of the Thesis	4
Chapter 2 Literature Review	
2.1 Introduction	7
2.2 Classification of Body Armors	9
2.2.1 <i>Hard Body Armors</i>	9
2.2.2 <i>Soft Body Armors</i>	9
2.3 Requirements of Body Armors	10
2.4 Damage/failure Mechanism of Body Armors	10
2.5 Effect of Fiber and Yarn Properties on Impact Resistance	12

	Behavior	
2.6	Effect of Fabric Properties on Impact Resistance Behavior	14
2.6.1	<i>Weave Structure and Cover Factor</i>	14
2.6.2	<i>Friction</i>	16
2.6.3	<i>Crimp</i>	20
2.6.4	<i>Twist</i>	22
2.6.5	<i>Number of Layers</i>	22
2.6.6	<i>Boundary Condition</i>	24
2.7	Effect of Projectile Parameters on Impact Resistance Behavior	26
2.7.1	<i>Projectile Geometry</i>	26
2.7.2	<i>Impact Velocity</i>	28
2.7.3	<i>Impact Angle</i>	29
2.8	Shear Thickening Fluids and its Mechanism	29
2.8.1	<i>Order-disorder Theory</i>	30
2.8.2	<i>Hydrodynamic Clustering Theory</i>	32
2.9	Rheological Properties of STFs	35
2.10	Effect of Particle Parameters on Shear Thickening Behavior	37
2.11	Application of STF on Textiles: The Mechanism for Enhancement in Impact Resistance	46
2.12	Ballistic Test Standards	57
2.13	Methods for Performance Evaluation	58
2.13.1	<i>Ballistic Performance Testing</i>	58
2.13.2	<i>Yarn Pull-out Testing</i>	60
2.13.3	<i>Blunt Trauma Testing</i>	62
2.13.4	<i>High Speed Photography</i>	63

2.14	Summary	64
------	---------	----

Chapter 3 Materials and Methods

3.1	Introduction	65
3.2	Materials	65
3.3	Treatment of Kevlar Fabrics with STFs	66
3.4	Characterization Techniques and Testing Methods	66
3.4.1	<i>Add-on % of STF on Kevlar Fabrics</i>	66
3.4.2	<i>Thermogravimetric Analysis</i>	67
3.4.3	<i>Rheological Analysis of STF</i>	67
3.4.4	<i>Particle Size Analysis</i>	68
3.4.5	<i>SEM Image Analysis</i>	68
3.4.6	<i>Yarn Pull-out Force</i>	68
3.4.7	<i>Dynamic Impact Resistance Test</i>	69
3.4.8	<i>Low Velocity Ballistic Test</i>	71
3.5	Summary	73

Chapter 4 Synthesis of Shear Thickening Fluids and Their Rheological Behavior

4.1	Introduction	75
4.2	Particle Size Analysis	76
4.3	Synthesis of Shear Thickening Fluids	76
4.4	STF Characterization by Thermo Gravimetric Analysis (TGA)	78
4.5	Rheological Analysis	79

4.5	Summary	81
Chapter 5	Development of STF Treated Kevlar Fabrics and Its Impact Behavior	
5.1	Introduction	83
5.2	Application of STF on Kevlar Fabrics	83
5.3	Scanning Electron Micrographs	84
5.4	Influence of Padding Pressure and Silica Concentration on Add-on %	84
5.5	Influence of Padding Pressure and Silica Concentration on Yarn Pull-Out Force	86
5.6	Influence of Padding Pressure and Silica Concentration on Impact Energy Absorption	89
5.7	Overall Performance - Process Parameter Matrix	91
5.8	Impact Performance of Multi layered Kevlar Fabric Panels	92
5.9	Yarn Pull-out Force and Impact Energy Absorption by Kevlar Fabrics Treated with STF, Silica-water Suspension, PEG and PVA	94
5.10	Role of Shear Thickening in Enhancing Impact Resistance Performance	96
5.11	Effect of Temperature on Impact Energy Absorption by STF Treated Kevlar Fabrics	100
5.12	Summary	102
Chapter 6	Sequential Padding of Kevlar Fabrics and Weapon Test Results	
6.1	Introduction	105
6.2	Sequential Padding Method	105
6.3	Sequential Padding Results	106

6.4	Low Velocity Ballistic Test	111
6.5	Summary	113
Chapter 7	Optimization of Process Parameters for STF Application on Kevlar Fabrics	
7.1	Introduction	115
7.2	Preparation of STF Treated Kevlar Fabrics	115
7.3	Models for Add-on % and Impact Energy Absorption of STF Treated Kevlar Fabrics	117
7.4	Analysis of Contour Plots	121
7.5	Summary	126
Chapter 8	Analysis of Impact Energy Absorption Modes	
8.1	Introduction	129
8.2	Impact Energy Absorption Modes and their Analysis	129
8.3	Summary	137
Chapter 9	Conclusions	139
Chapter 10	Suggestions for Further Work	141
References		143
Bio-data		155

LIST OF FIGURES

Figure No.	Figure Caption	Page No.
2.1	Generation of waves into a single fiber while impact	11
2.2	Effect of weave on ballistic performance	16
2.3	Effect of yarn friction on energy absorption by the fabric	18
2.4	Projectile velocity for the three different friction conditions	20
2.5	Effect of fabric layers on the trauma depth and diameter	23
2.6	Energy absorption mechanisms for the two cases with four edges clamped	25
2.7	Energy absorption mechanisms for the two cases with four edges free	26
2.8	Different shape and dimensions of projectiles	27
2.9	Effect of impact velocity on energy absorption	29
2.10	Schematic representation of particles in a STF during shear thinning and shear thickening w.r.t. increasing shear rate	30
2.11	Illustration of a typical flow curve of viscosity (η) vs shear rate ($\dot{\gamma}$) for a stable suspension of Brownian hard particles, showing three regions of structure: rest state (I), high shear region (II), and the abrupt change to the shear thickening region (III)	31
2.12	Shear thickening behavior of colloidal silica of average particle size of 450 nm dispersed in ethylene glycol for steady shear flow at volume fractions of 0.57 and 0.62	38
2.13	Viscosity vs. shear rate for 2:1 aspect ratio CaCO_3 -STF at various particle volume fractions	39
2.14	Viscosity vs. shear rate for 7:1 aspect ratio CaCO_3 -STF at various particle volume fractions	40
2.15	Effect of particle shape on shear thickening for solid volume fraction of 0.2	41
2.16	Effect of average particle size on critical shear rate	42
2.17	Shear thickening behavior of 65 wt% colloidal silica particles dispersed in PEG of 100 nm, 300 nm and 500 nm	42

2.18	Viscosity of Clays A and B at different mixing ratios as a function of shear rate at solid volume fraction of 0.44 (Particle A-9 μm and particle B-0.7 μm)	43
2.19	Viscosity of Clay A and B and their 50/50 mixture as a function of solids content. Brookfield 10 r.p.m.	44
2.20	Schematic representation of the effect of chemically induced flocculation on shear thickening behavior	45
2.21	Specific ballistic energy of single, double and quadruple ply Kevlar fabrics treated with different SWS particle concentrations	48
2.22	Impact energy absorption for double ply Kevlar fabric for neat and impregnated with 40 wt% SWS	48
2.23	Effect of fluid volume on impact energy dissipation of STF and Ethylene glycol impregnated Kevlar fabrics	50
2.24	Knife drop tower results for untreated Kevlar and silica-STF treated Kevlar fabrics	52
2.25	Spike drop tower results for untreated Kevlar and silica-STF treated Kevlar fabrics	53
2.26	Rheological behavior of silica-STF with volume fraction of 0.52 and PMMA-STF with volume fraction of 0.49	54
2.27	Comparison of quasi-static spike test results for PMMA-STF treated Kevlar and silica-STF treated Kevlar with neat Kevlar fabric	54
2.28	Comparison of V50 ballistic test results for PMMA-STF treated Kevlar and silica-STF treated Kevlar with untreated Kevlar fabric. The untreated Kevlar and S-STF-Kevlar are 10-shot V50, while the PMMA-STF-Kevlar is a 6-shot V50	56
2.29	V ₅₀ testing methods	59
2.30	Schematic diagram of ballistic test set-up	60
2.31	Fabric behavior during yarn pull-out test	61
2.32	(a) Comparison of measured and fitted curves (b) 3-D model of trauma obtained by curve fitting	62
2.33	Experimental layout for high-speed photograph	63
3.1	Schematic representation of Kevlar fabric padding with STF	67

3.2	Schematic representations of quasi-static yarn pull-out test set up	69
3.3	Dynamic impact testing instrument	70
3.4	Schematic diagrams of top view and side view of impact zone (a) Side view (b) Top view	70
3.5	Ballistic test set up	72
3.6	Schematic representation of ballistic test zone	72
4.1	Particle size analysis of silica	76
4.2	TGA curve of STFs with different compositions	79
4.3	Rheological behavior of STF for different silica concentrations	80
4.4	Rheological behavior of STF (70%) at different temperatures	81
5.1	Scanning electron micrograph of STF (70%) treated Kevlar filaments of 200 GSM fabrics (a) 0.5 bar pressure (b) 2.0 bar pressure	84
5.2	Add-on % for 200 GSM Kevlar fabrics treated with STF	86
5.3	Add-on % for 465 GSM Kevlar fabrics treated with STF	86
5.4	Yarn pull-out force for 200 GSM Kevlar fabrics treated with STF	88
5.5	Yarn pull-out force for 465 GSM Kevlar fabrics treated with STF	88
5.6	Impact energy absorption by 200 GSM Kevlar fabrics treated with STF	90
5.7	Impact energy absorption by 465 GSM Kevlar fabrics treated with STF	91
5.8	Yarn pull-out force for 465 GSM Kevlar fabrics with different treatments	95
5.9	Impact energy absorption by 465 GSM Kevlar fabrics with different treatments	95
5.10	Deformed Kevlar fabric after dynamic impact testing (a) Untreated (b) STF treated	98
5.11	Schematic representation of shear thickening behavior (a) before impact and (b) after impact	99
5.12	Impact energy absorption by STF (70%) treated 200 GSM Kevlar fabrics	101

	at different temperatures	
5.13	Impact energy absorption by STF (70%) treated 465 GSM Kevlar fabrics at different temperatures	102
6.1	Plan for sequential padding process	106
6.2	Add-on % of STF on Kevlar fabrics in sequential padding process	108
6.3	Impact energy absorption (J) at different pressure combinations in sequential padding process	109
6.4	STF add-on % vs impact energy absorption in sequential padding process	111
6.5	Ballistic impact energy absorbed by untreated and STF treated 200 GSM Kevlar fabrics	112
7.1	Contour plots showing the effect of silica concentration and padding pressure on add-on %	122
7.2	Contour plots showing the effect of silica concentration and padding pressure on impact energy absorption	123
7.3	Contour plots showing the effect of padding pressure and solvent ratio on add-on %	124
7.4	Contour plots showing the effect of padding pressure and solvent ratio on impact energy absorption	125
7.5	Contour plots showing the effect of silica concentration and solvent ratio on add-on %	125
7.6	Contour plots showing the effect of silica concentration and solvent ratio on impact energy absorption	126
8.1	Force generation and energy absorption graphs of 200 GSM (a) untreated, (b) STF treated (50%, 2.0 bar) (c) STF treated (60%, 2.0 bar) (d) STF treated (70%, 2.0 bar) and (e) STF treated (70%, sequentially padded-2.0 bar, 0.5 bar) Kevlar fabrics	130
8.2	Kevlar fabrics deformed during impact testing (a) Untreated Kevlar fabric (b) STF treated Kevlar fabric	135

LIST OF TABLES

Table No.	Table Caption	Page No.
2.1	Typical properties of high performance fibers	14
2.2	NIJ Standard 0101.04 performance test summary	58
3.1	Specification of Kevlar fabrics	66
5.1	Add-on % of STF at different levels of padding pressure and silica concentration	85
5.2	Yarn pull-out force of 200 GSM and 465 GSM Kevlar fabrics	87
5.3	Impact energy absorbed by 200 GSM and 465 GSM Kevlar fabrics	90
5.4	Performance matrix representing the effect of process parameters	91
5.5	Impact energy absorption by multilayered Kevlar panels	93
5.6	Normalized impact energy absorption by multilayered Kevlar panels	93
5.7	Yarn pull-out force for 465 GSM Kevlar fabrics with different treatments	94
5.8	Impact energy absorption by STF (70%) treated Kevlar fabrics at different temperatures	101
6.1	STF add-on % and impact energy absorption of Kevlar fabrics in sequential padding process	110
6.2	Ballistic impact energy absorbed by untreated and STF treated 200 GSM Kevlar fabrics	112
7.1	Variables and levels used in the experiments	116
7.2	Box and Behnken design plan	116
7.3	Add-on % and impact energy absorption for STF treated 200 GSM Kevlar fabrics	117
7.4	Initial ANOVA for STF add-on % of 200 GSM Kevlar fabrics	118
7.5	Final ANOVA for STF add-on % of 200 GSM Kevlar fabrics	119
7.6	Initial ANOVA for impact energy absorption of STF treated 200 GSM Kevlar fabrics	120

7.7	Final ANOVA for impact energy absorption of 200 GSM Kevlar fabrics	120
8.1	Time, force build up and energy absorption by Kevlar fabrics in the Zone 1	133
8.2	Peak force and energy absorption related parameters in Zone 2	134
8.3	Differences in the failure modes of untreated and STF treated Kevlar fabrics	137