

## Technical Report

## Optimal designing of soft body armour materials using shear thickening fluid

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## ARTICLE INFO

## Article history:

Received 24 August 2012

Accepted 15 October 2012

Available online 26 October 2012

## ABSTRACT

This paper deals with the optimal design of soft body armour materials by treating Kevlar (para-aramid) fabrics with silica nano-particle based shear thickening fluid (STF). Box and Behnken design of experiment (DOE) plan in conjunction with contour analysis has been used to study the effect of silica concentration, padding pressure and diluent: STF ratio (solvent ratio) on STF add-on% and impact energy absorption. Silica concentration, solvent ratio and square of solvent ratio were found to be statistically significant terms influencing the STF add-on% on Kevlar fabrics. On the other hand, silica concentration, padding pressure and the square of solvent ratio were the statistically significant terms influencing the impact energy absorption. Higher padding pressure enhances the impact energy absorption by the STF treated Kevlar fabrics although it does not influence the STF add-on% significantly. Higher STF add-on% is a necessary but not the sufficient condition for improving the impact resistance performance of Kevlar fabrics.

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## 1. Introduction

Kevlar woven fabrics are often used for soft body armour applications. In soft body armours, approximately 20–50 layers of Kevlar fabric are used to stop a bullet fired by a shotgun or revolver. This makes the body armour heavy, inflexible and uncomfortable to the wearer. It is a challenge for the researchers and scientists to develop materials for soft body armour so that it remains light-weight, flexible and bullet-resistant. Application of shear thickening fluid (STF) enhances the impact resistance performance of the Kevlar fabric [1,2]. Shear thickening fluids are non-Newtonian fluids which show drastic increase in viscosity beyond a critical shear rate [3–7]. Thus, the liquid dispersion is transformed into a material with solid-like properties and thereby facilitating the impact energy absorption. Shear thickening is exhibited by the nano sized particles of certain materials (silica, calcium carbonate, poly methyl methacrylate, etc.) when they are dispersed in a carrier fluid. Shear thickening behavior is reversible, making the body armour flexible enough for normal mobility of the soldier.

In the last decade, significant amount of research works have been done on the application of STF on Kevlar fabrics for improving the impact, puncture or stab resistance performances. Lee et al. [1,8], Kang et al. [9] and Srivastava et al. [10] have used silica nano-particles based STF to improve the impact resistance performance of Kevlar woven fabrics whereas Egres et al. [11] used it for enhancing the puncture resistance against hypodermic needles. Decker et al. [12] reported significant improvement in stab resistance performance during knife drop tower test. They found that

the extent of fabric damage was less in case of STF treated Kevlar fabrics. Tan et al. [13] reported that the ballistic performance of aramid fabrics can be improved by impregnating it with a colloidal silica water suspension (SWS) of different particle concentrations. Wetzel et al. [14] also researched on the influence of particle shape anisotropy on the performance of STF treated Kevlar fabrics. They reported that as the aspect ratio of the particles increases, requirement of the solid volume fraction to reach the critical shear rate decreases. Kalman et al. [15] compared the STFs made with hard silica and softer PMMA (poly methyl methacrylate) particles for improving the impact resistance performance of Kevlar fabrics. They found that the STF based on PMMA exhibited less effective shear thickening as compared to STF based on hard silica particles. Thus silica based STF treated fabrics showed better ballistic resistance than that of PMMA based STF treated fabrics. Rosen et al. [16] used Kaolin clay (platelet like structure) dispersed in ethylene glycol as STF which improved the spike, stab and needle resistances. In recent researches, Hassan et al. [17,18] and Maufez et al. [19] have developed a sonochemical method for the synthesis of STF in a single step. They found that the spike resistance of Kevlar fabrics increased from 85 N to 573 N after the treatment with the STF. Park et al. [20,21] reported the effect of laminating sequence, fabric count and shot location on the impact performance of STF treated Kevlar fabrics.

Optimisation of structure and properties of engineering materials is a very exciting domain of research. Various quantitative techniques like Design of Experiments [22], Taguchi [23,24], multi-criteria decision making [25,26] and genetic algorithm [27] have been used by the researchers for modeling and optimisation of material properties. Although substantial amount of research has been done to improve the impact performance of Kevlar fabrics

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as soft body armour materials, no information is available in published literature about the optimal choice of process parameters. Besides, the correlation between the amount of STF add-on% and impact energy absorption is yet to be explored. It can be presumed that higher STF add-on% coupled with its uniform distribution within the yarn and fabric structures will make shear thickening more effective and thereby the impact resistance performance of STF treated Kevlar fabrics will be enhanced. Therefore, the effects of STF concentration, padding (squeezing) pressure and diluent to STF ratio (solvent ratio) on STF add-on% and impact energy absorption have been explored in this research. Box and Behnken [28] design of experiment plan has been used to minimize the number of experiments. Contour plot analysis has also been done for better understanding of the interaction effects of these parameters.

## 2. Materials and methods

### 2.1. Materials

Plain woven Kevlar fabrics having areal density of 200 g/m<sup>2</sup> were used in this research. The linear density of the yarns was 1000 denier. The number of yarns per inch was 22 in both the directions of the fabric. Silica nano-particles, MP1040, in aqueous dispersion (40% w/v), were obtained from Nissan Chemicals (Japan). The average size of silica particle was 100 nm. Polyethylene glycol or PEG (MW 200) was used as a medium to disperse the silica particles. Three STF were prepared by keeping silica concentration at 50%, 60% and 70% (w/w). Since STFs are highly concentrated dispersions having high viscosity and surface tension, it is difficult to treat textile fabrics uniformly with it and ensure its proper penetration into the fabric. To improve the wettability of the Kevlar fabrics with STFs, these dispersions are diluted with ethanol before application onto the Kevlar fabrics. Dilution reduces the viscosity as well as the surface tension of STFs, thus improving its penetration into Kevlar fabric structure. In subsequent discussions, the ratio of STF to ethanol would be denoted by the term solvent ratio.

### 2.2. Preparation of STF treated Kevlar fabrics

Kevlar fabrics were treated with the STF by using a padding mangle. Schematic representation of padding process is given in Fig. 1. The fabric soaked in STF is passed through the nip of two rubber rollers under certain pressure so that the STF is distributed uniformly and the excess fluid is squeezed out. The padding pressure was 1, 2 and 3 bar. A three factor-three level factorial design proposed by Box and Behnken [22] was used to analyze the role of silica concentration, padding pressure and solvent ratio on STF

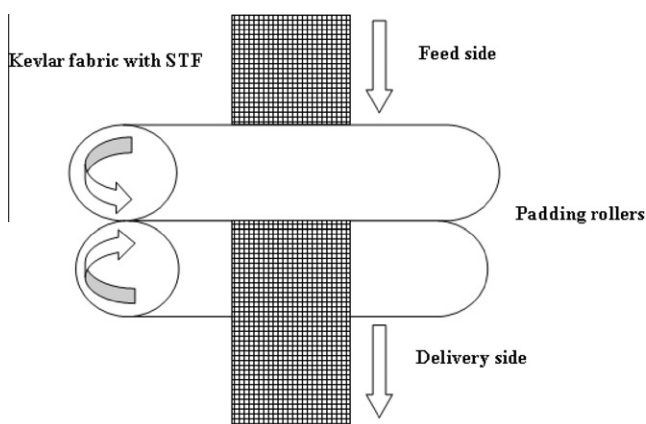


Fig. 1. Schematic representation of Kevlar fabric padding with STF.

**Table 1**  
Variables and levels used in the experiments.

Factors	Levels		
	Low	Medium	High
Silica concentration, % ( $X_1$ )	50	60	70
Padding pressure, bar ( $X_2$ )	1.0	2.0	3.0
Solvent ratio ( $X_3$ )	3:1	4:1	5:1

**Table 2**  
Box and Behnken design plan.

Standard order	$X_1$	$X_2$	$X_3$
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

add-on% and impact energy absorption of Kevlar fabrics. For each factor, three levels (low, medium and high) were chosen. In case of full factorial design, 27 ( $3^3$ ) samples have to be prepared. However, Box and Behnken design plan reduces the number of samples to 15 only. The actual values of the three variables corresponding to the coded levels are given in Table 1. Table 2 shows the Box and Behnken design plan for sample preparation. According to this plan 15 samples were prepared by varying three process variables namely silica concentration, padding pressure and solvent ratio.

The mathematical relationship between the response values (add-on% and impact energy) and the process variables can be described by the following nonlinear equation:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{23} X_2 X_3 + \beta_{31} X_1 X_3 + \varepsilon \quad (1)$$

where  $y$  denotes response values (add-on% or impact energy),  $X_1$ ,  $X_2$  and  $X_3$  indicate silica concentration, padding pressure and solvent ratio, respectively,  $\beta_0$  is constant,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$  are linear coefficients,  $\beta_{11}$ ,  $\beta_{22}$  and  $\beta_{33}$  are pure quadratic coefficients for silica concentration, padding pressure and solvent ratio, respectively,  $\beta_{12}$ ,  $\beta_{23}$  and  $\beta_{31}$  are mixed quadratic coefficients and  $\varepsilon$  is the error term of the model. Design Expert® software was used to develop the equation and contour plots.

### 2.3. Characterization

The rheological tests of STF were done using Anton Parr Physica MCR 101 stress controlled rheometer. Temperature was kept constant at 25 °C and the shear rate was increased from 0 to 500 s<sup>-1</sup> and corresponding viscosity was recorded. The rheological results of STF having 50%, 60% and 70% (w/w) silica concentrations are shown in Fig. 2. It was observed that 70% concentration of silica particles shows the most prominent shear thickening behavior after a critical shear rate of 80 s<sup>-1</sup> and the viscosity rises up to 300 Pa s. Silica concentration of 60% shows comparatively subdued shear thickening behavior where viscosity goes up to 120 Pa s.

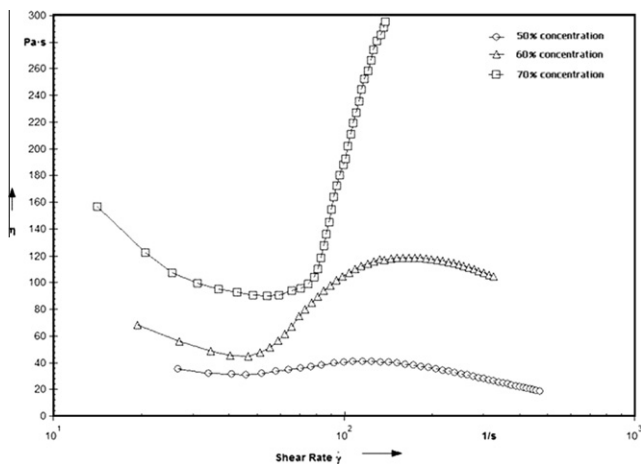


Fig. 2. Rheological behavior of STF at different silica concentrations.

However at 50% concentration, shear thickening is almost insignificant. Therefore, it can be concluded that shear thickening behavior is facilitated with higher concentration of silica particles.

The surface characteristics of STF treated Kevlar fabrics were studied with scanning electron microscope (ZEISS, model: EVO 50) images. The samples were first coated with a silver layer to provide surface conduction before their scanning.

The STF add-on% was calculated using the following expression to express the actual amount of STF present on the treated fabric.

$$\text{Add-on\%} = \frac{\text{Mass of fabric after treatment} - \text{Mass of fabric before treatment}}{\text{Mass of fabric before treatment}} \times 100 \tag{2}$$

2.4. Dynamic impact resistance test

Dynamic impact tests were conducted on untreated as well as STF treated Kevlar fabrics by using drop-weight testing instrument (CEAST, Model: FRACTOVIS PLUS). ‘ASTM: D3763’ standard has been followed for the dynamic impact test. Fig. 3 shows the schematic representation of dynamic impact testing set up. Six bar pneumatic pressure was maintained to grip the fabric samples, having 160 mm × 160 mm dimension, between two circular jaws. The inner and outer diameters of the circular jaws were 76 mm and 108 mm respectively. The diameter of the impactor, which

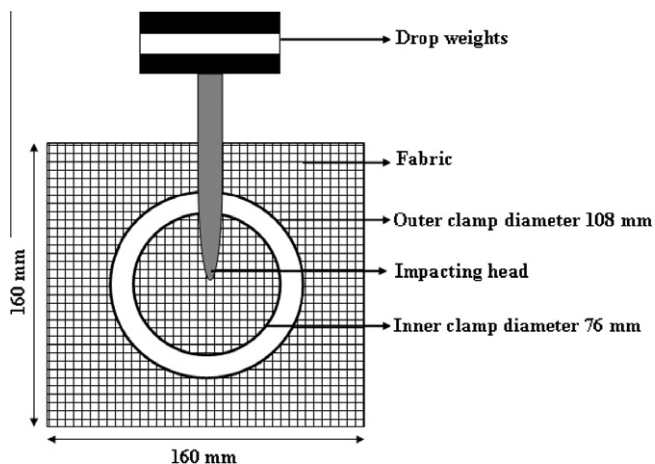


Fig. 3. Dynamic impact testing set up.

Table 3 Add-on% and impact energy absorption for STF treated 200 GSM Kevlar fabrics.

Run	Concentration, % (X <sub>1</sub> )	Padding pressure, bar (X <sub>2</sub> )	Solvent ratio (X <sub>3</sub> )	Add-on%	Impact energy (J)
1	50	1.0	4:1	5.58	37.55
2	70	1.0	4:1	5.83	38.81
3	50	3.0	4:1	5.34	41.20
4	70	3.0	4:1	5.68	43.18
5	50	2.0	3:1	5.80	41.13
6	70	2.0	3:1	8.67	54.48
7	50	2.0	5:1	5.01	34.83
8	70	2.0	5:1	7.97	53.44
9	60	1.0	3:1	7.49	44.80
10	60	3.0	3:1	7.36	53.92
11	60	1.0	5:1	5.74	40.87
12	60	3.0	5:1	5.29	48.43
13	60	2.0	4:1	4.26	33.72
14	60	2.0	4:1	4.02	32.64
15	60	2.0	4:1	4.89	34.08

has a hemispherical head, was 13 mm. The drop weight assembly, which carries the impacting head, adjusts its height automatically based on the chosen velocity of impact. In this case, the velocity of impact was 6 m/s. The instrument measures the impact energy in Joules.

3. Results and discussion

3.1. Models for add-on% and impact energy absorption of STF treated Kevlar fabrics

Table 3 shows the STF add-on% and impact energy absorption for the 15 samples. Table 4 shows the initial ANOVA (analysis of variance), which includes all the nine terms, for the STF add-on%. It is noted that this model is statistically not significant as the p-value is 0.1544 which implies that there is 15.44% probability that the model F-value of 2.582 has occurred due to chance. A close look

Table 4 Initial ANOVA for STF add-on% of 200 GSM Kevlar fabrics.

Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-Value
Model	20.999	9	2.333	2.582	0.1544
X <sub>1</sub>	5.152	1	5.152	5.700	0.0626
X <sub>2</sub>	0.118	1	0.118	0.130	0.7330
X <sub>3</sub>	3.525	1	3.525	3.900	0.1053
X <sub>1</sub> X <sub>2</sub>	0.002	1	0.002	0.002	0.9641
X <sub>2</sub> X <sub>3</sub>	0.002	1	0.002	0.002	0.9641
X <sub>1</sub> X <sub>3</sub>	0.026	1	0.026	0.028	0.8729
X <sub>1</sub> <sup>2</sup>	2.393	1	2.393	2.647	0.1647
X <sub>2</sub> <sup>2</sup>	0.628	1	0.628	0.695	0.4424
X <sub>3</sub> <sup>2</sup>	10.267	1	10.267	11.359	0.0199
Residual	4.519	5	0.904		

Table 5 Final ANOVA for STF add-on% of 200 GSM Kevlar fabrics.

Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-Value
Model	20.970	6	3.495	6.147	0.0111
X <sub>1</sub>	5.152	1	5.152	9.061	0.0168
X <sub>2</sub>	0.118	1	0.118	0.207	0.6613
X <sub>3</sub>	3.525	1	3.525	6.199	0.0375
X <sub>1</sub> <sup>2</sup>	2.393	1	2.393	4.208	0.0744
X <sub>2</sub> <sup>2</sup>	0.628	1	0.628	1.105	0.3239
X <sub>3</sub> <sup>2</sup>	10.267	1	10.267	18.056	0.0028
Residual	4.549	8	0.569		

**Table 6**  
Initial ANOVA for impact energy absorption of STF treated 200 GSM Kevlar fabrics.

Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-Value
Model	667.468	9	74.163	3.249	0.1038
$X_1$	154.880	1	154.880	6.784	0.0480
$X_2$	76.261	1	76.261	3.341	0.1271
$X_3$	35.112	1	35.112	1.538	0.2699
$X_1X_2$	0.130	1	0.130	0.006	0.9429
$X_2X_3$	6.917	1	6.917	0.303	0.6057
$X_1X_3$	0.608	1	0.608	0.027	0.8767
$X_1^2$	29.676	1	29.676	1.300	0.3059
$X_2^2$	55.299	1	55.299	2.422	0.1803
$X_3^2$	344.193	1	344.193	15.077	0.0116
Residual	114.1433	5	22.82865		

**Table 7**  
Final ANOVA for impact energy absorption of 200 GSM Kevlar fabrics.

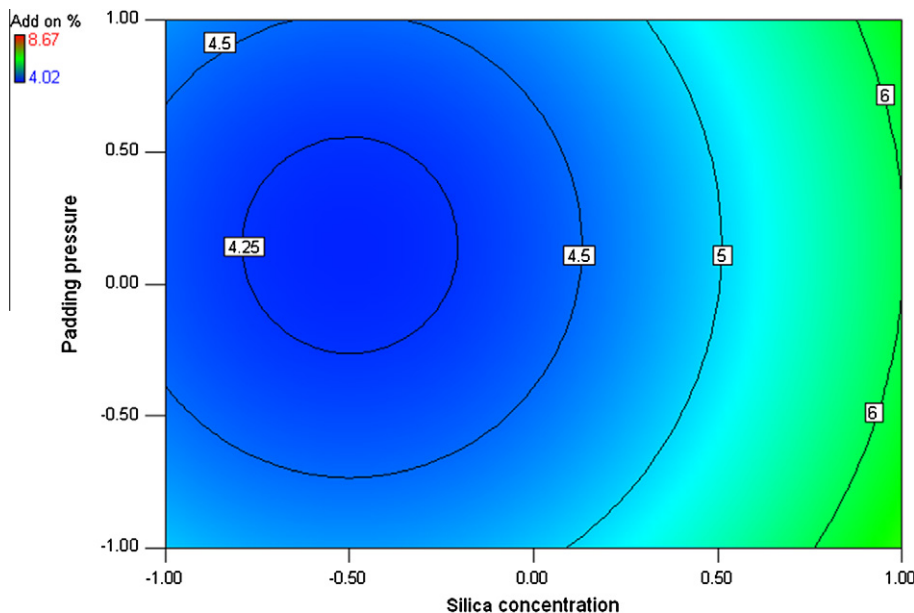
Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-Value
Model	659.813	6	109.969	7.223	0.0068
$X_1$	154.880	1	154.880	10.173	0.0128
$X_2$	76.261	1	76.261	5.009	0.0556
$X_3$	35.112	1	35.112	2.306	0.1673
$X_1^2$	29.676	1	29.676	1.949	0.2002
$X_2^2$	55.299	1	55.299	3.632	0.0931
$X_3^2$	344.193	1	344.193	22.607	0.0014
Residual	121.7982	8	15.225		

at the Table 4 reveals that all the interaction terms ( $X_1X_2$ ,  $X_2X_3$  and  $X_1X_3$ ) are statistically insignificant as the  $p$ -values are much higher than 0.1. Therefore, the interaction terms were eliminated from the model in a stepwise manner. In the first step,  $X_1X_2$  was eliminated from the model as the  $p$ -value was 0.9641 which is the maximum among all the terms of the model. In the next step,  $X_2X_3$  was eliminated followed by  $X_1X_3$ . Table 5 shows the final ANOVA for STF add-on%. The final model, having six terms, is statistically significant as the  $p$ -value is 0.0111 which implies that there is only

1.11% chance that the model  $F$ -value of 6.147 has occurred due to chance. Table 5 reveals that silica concentration ( $X_1$ ), solvent ratio ( $X_3$ ) and the quadratic term of solvent ratio ( $X_3^2$ ) are the statistically significant terms ( $p < 0.05$ ) influencing the STF add-on% on Kevlar fabrics.

The nonlinear model for the impact energy absorption was developed in the same manner as it was done for STF add-on%. Table 6 shows the initial ANOVA, which includes all the nine terms, for the impact energy absorption. It is noted that this model is statistically not significant as the  $p$ -value is 0.1038 which implies that there is 10.38% probability that the model  $F$ -value of 3.249 has occurred due to chance. Table 6 reveals that the interaction terms  $X_1X_2$ ,  $X_2X_3$  and  $X_1X_3$  have  $p$ -values of 0.9429, 0.6057 and 0.8767 respectively. All these interaction terms are statistically insignificant as the  $p$ -values are much higher than 0.05. Therefore,  $X_1X_2$  was eliminated from the model followed by  $X_1X_3$  and  $X_2X_3$ . Table 7 shows the final ANOVA for impact energy absorption. The truncated model, having six terms, is statistically significant as the  $p$ -value is 0.0068 which signifies that there is only 0.68% chance that the model  $F$ -value of 7.223 has occurred due to chance. Table 7 also reveals that silica concentration ( $X_1$ ), padding pressure ( $X_2$ ) and the quadratic term of solvent ratio ( $X_3^2$ ) are the statistically significant terms ( $p < 0.5$ ) influencing the impact energy absorption. The positive effect of higher silica concentration on shear thickening has also been reported by Lee et al. [8]. They found that 62% volume fraction of silica showed more prominent shear thickening even at lower shear rate as compared to 57% volume fraction. Here, the padding pressure is not influencing the STF add-on% significantly although it is influencing the impact energy absorption significantly. In an earlier work [10], it was noticed that higher padding pressure reduces the STF add-on% which may seem contradictory with the present findings. However, it must be kept in mind that the range of pressure used here (1–3 bar) is different from that used in the previous work. Besides, one extra variable (solvent ratio) has been introduced here in the Box and Behnken experimental design plan. These factors might have played their role in making the effect of padding pressure insignificant in case of STF add-on%.

The final response surface equations for add-on% and impact energy absorption are given below (statistically significant terms have been indicated with \*):



**Fig. 4.** Contour plots showing the effect of silica concentration and padding pressure on add-on%.

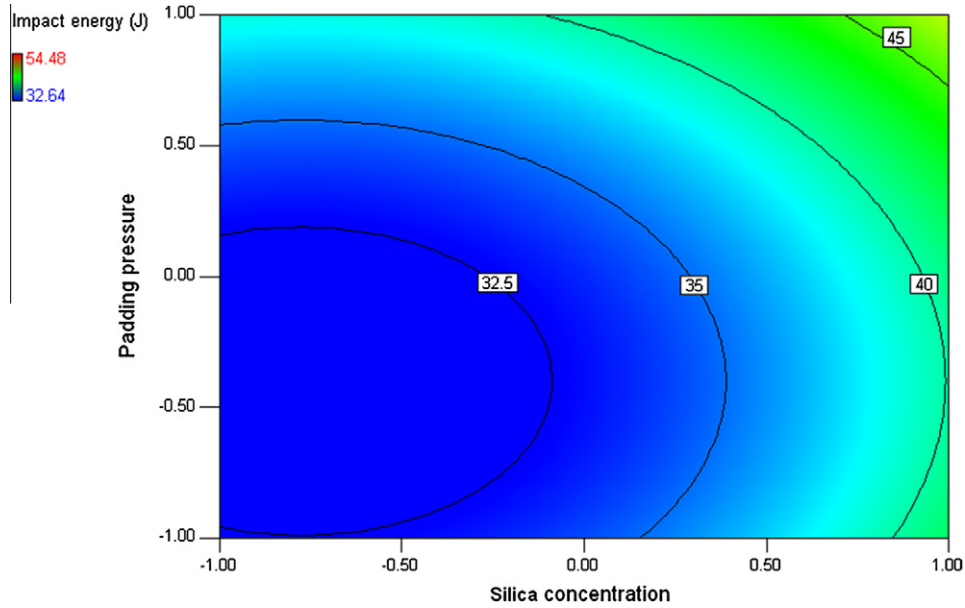


Fig. 5. Contour plots showing the effect of silica concentration and padding pressure on impact energy absorption.

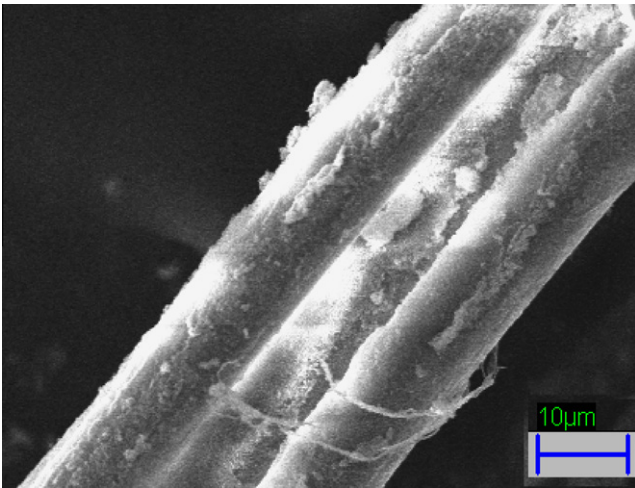


Fig. 6. Filaments extracted from Kevlar fabric treated with STF at 1 bar padding pressure.

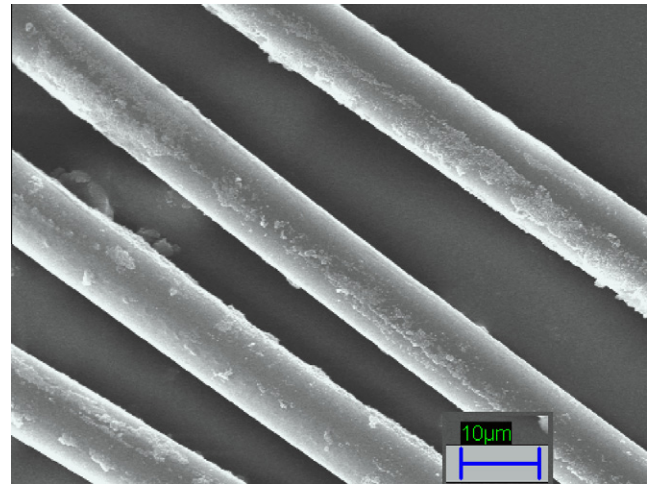


Fig. 7. Filaments extracted from Kevlar fabric treated with STF at 2 bar padding pressure.

$$\text{Add on\%} = 4.39 + 0.803X_1 * -0.121X_2 - 0.664X_3 * + 0.805X_1^2 + 0.413X_2^2 + 1.668X_3^2 * \quad [R^2 = 0.823] \quad (3)$$

$$\text{Impact energy absorption} = 33.48 + 4.40X_1 * +3.088X_2 * -2.095X_3 + 2.835X_1^2 + 3.87X_2^2 + 9.655X_3^2 * \quad [R^2 = 0.845] \quad (4)$$

It is important to note that silica concentration ( $X_1$ ) and square of solvent ratio ( $X_3^2$ ) are not only statistically significant for both STF add-on% and impact energy absorption but their directions of influence as indicated by the respective signs (positive or negative) of coefficients are also same. Therefore, the silica concentration and square term of solvent ratio will influence the STF add-on% and impact energy absorption in the same way. In other words, if the change in silica concentration (or square of solvent ratio) increases the add-on%, then it will also result in increase of impact energy absorption. However, similar inference cannot be drawn

for padding pressure ( $X_2$ ) as the sign of its coefficient is negative and positive for add-on% and impact energy absorption respectively. Therefore, it can be concluded that higher STF add-on% is generally, but not always, associated with higher impact energy absorption by the STF treated Kevlar fabrics. The above equations can explain 82.3% and 84.5% variability of add-on% and impact energy absorption of STF treated 200 GSM Kevlar fabrics.

### 3.2. Analysis of contour plots

The contour plots of STF add-on% and impact energy absorption at different coded levels of silica concentration and padding pressure are shown in Figs. 4 and 5 respectively. It is observed from Fig. 4 that add-on% increases with increase in silica concentration. However, pressure seems to play rather insignificant role in influencing add-on% within the range of the experiment (1–3 bar). From the contours presented in Fig. 5, it can be understood that impact energy absorption increases with the increase in silica concentration and padding pressure. Therefore, it can be summarized

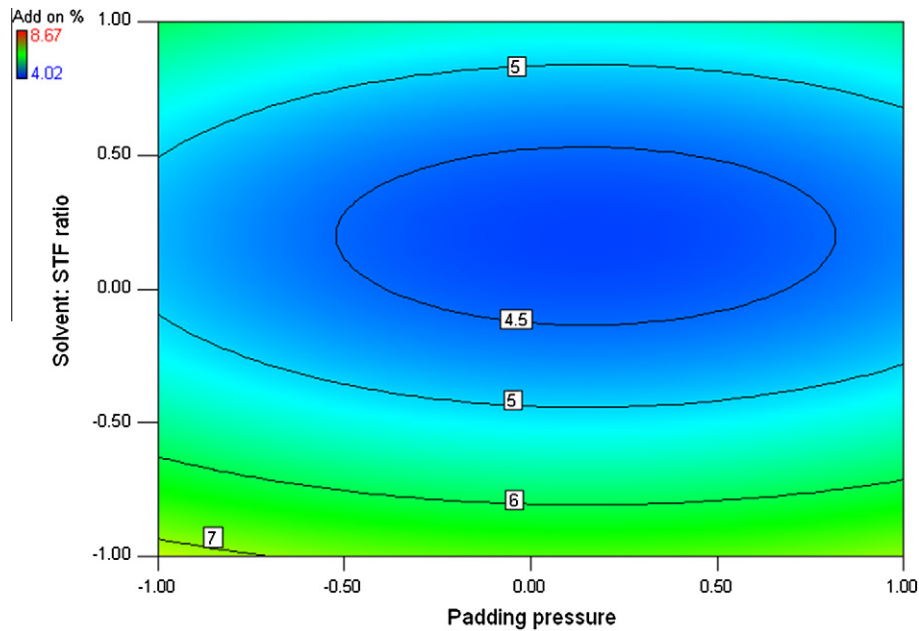


Fig. 8. Contour plots showing the effect of padding pressure and solvent ratio on add-on%.

that the higher padding pressure is causing higher impact energy absorption without causing any significant change in the STF add-on%. Similar effect of padding pressure on impact energy absorption was also reported by Srivastava et al. [10]. Thus, higher padding pressure must have some beneficial role in causing uniform distribution and better penetration of STF within the yarn and fabric structures. Figs. 6 and 7 show scanning electron micrographs of filaments extracted from Kevlar fabrics treated with STF at 1 bar and 2 bar pressure respectively. At lower pressure (1 bar), STF is not distributed uniformly over the filaments and clusters are prominently visible. In contrast, at higher pressure (2 bar and 3 bar), STF is very uniformly distributed over all the filaments. This uniform distribution of STF probably causes more effective shear

thickening resulting in improved impact energy absorption at higher padding pressure.

The contour plots of add-on% and impact energy absorption at different coded levels of padding pressure and solvent ratio have been shown in Figs. 8 and 9 respectively. It is observed from Fig. 8 that add-on% increases significantly with the reduction of solvent ratio beyond the coded level of 0 i.e. 4:1. However, similar to the trend depicted in Fig. 5, pressure seems to have rather insignificant role on STF add-on%. From Fig. 8, it is noted that maximum add-on% is obtained when the padding pressure and solvent ratio both are at their respective minimum levels. However, Fig. 9 shows that the maximum impact energy is absorbed when padding pressure is the maximum and solvent ratio is the minimum. This again

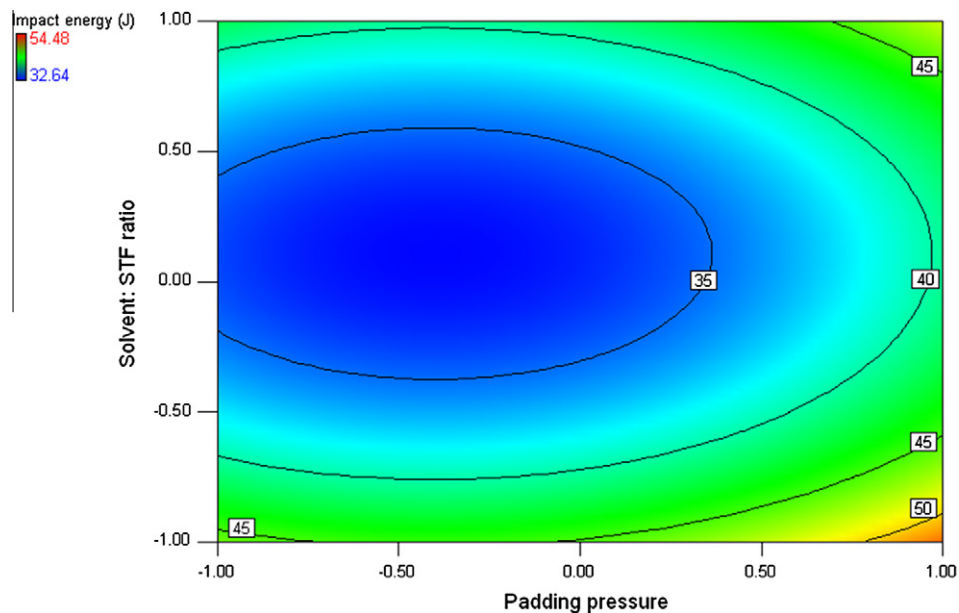


Fig. 9. Contour plots showing the effect of padding pressure and solvent ratio on impact energy absorption.

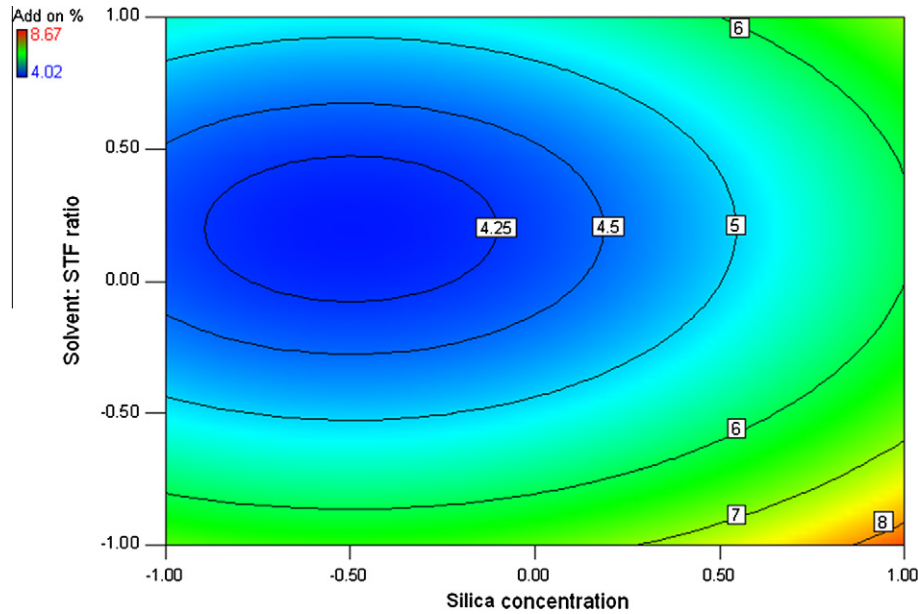


Fig. 10. Contour plots showing the effect of silica concentration and solvent ratio on add-on%.

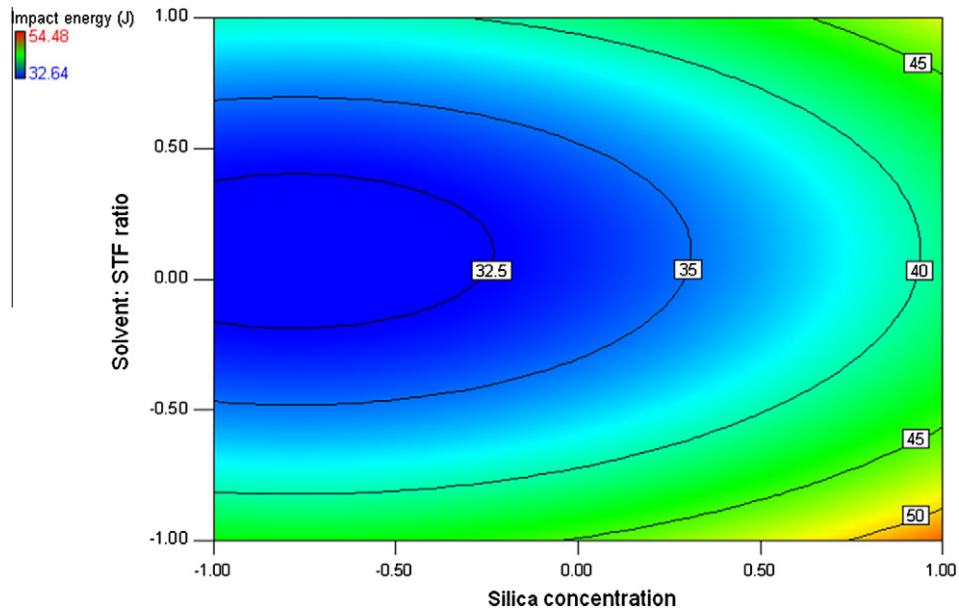


Fig. 11. Contour plots showing the effect of silica concentration and solvent ratio on impact energy absorption.

supports the fact that higher add-on% is a necessary but not the sufficient condition for attaining higher impact energy absorption. The uniform distribution and better penetration of STF induced by the higher padding pressure play pivotal role in determining the impact performance of STF treated Kevlar fabrics.

The contour plots of add-on% and impact energy absorption at different coded levels of silica concentration and solvent ratio are shown in Figs. 10 and 11 respectively. It is observed from Fig. 10 that add-on% increases with the increase in silica concentration. For any given level of silica concentration, the add-on% is the minimum when solvent ratio is at the coded level of 0 i.e. 4:1. The add-on% increases prominently as the solvent ratio is reduced. This may be attributed to the higher viscosity of the STF when it is diluted with lower amount of solvent. The maximum impact energy absorption is yielded when silica concentration is the maximum and solvent ratio is the minimum (bottom-right corner of

Fig. 11). Fig. 10 reveals that add-on% is also the maximum in the same zone. Overall, it can be inferred that the nature of influence of silica concentration and solvent ratio is similar for STF add-on% and impact energy absorption. Higher silica concentration, higher padding pressure and lower solvent ratio facilitate the enhancement of impact energy absorption.

#### 4. Conclusions

Optimization of three process parameters (silica concentration, padding pressure and solvent ratio) for STF application on Kevlar fabrics has been attempted in this research by using Box and Behnen experimental design plan. Fifteen Kevlar fabric samples were prepared as per the Box and Behnen design plan by varying the silica concentration, padding pressure and solvent ratio. The response surface equations were developed to relate the STF

add-on% and impact energy absorption with the three process parameters. Silica concentration, solvent ratio and the square of solvent ratio were found to be statistically significant terms influencing the STF add-on% on Kevlar fabrics. On the other hand, silica concentration, padding pressure and the square of solvent ratio are the statistically significant terms influencing the impact energy absorption. Thus, there are two common terms (STF concentration and square of solvent ratio) which influence the add-on% and impact energy absorption in a similar manner. Contour plots were generated to explain the simultaneous role of two process parameters on STF add-on% and impact energy absorption. Contour plots revealed that higher padding pressure has rather insignificant role in influencing STF add-on%. However, higher padding pressure is essential for maximizing the impact energy absorption. Overall, it was found that higher silica concentration, higher padding pressure and lower solvent ratio facilitate higher impact energy absorption by the STF treated Kevlar fabrics.

### Acknowledgement

The authors are thankful to SERC division of Department of Science and Technology, New Delhi, for providing financial assistance for this research work (SR/FTP/ETA-29/2).

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