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Heat-setting parameters optimisation of cotton/elastane fabric using response surface methodology

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The effect of heat-setting treatment on the performance of cotton/elastane fabric has been studied. Response surface methodology has been used to design the experiments where temperature (°C), time (s) and fabric width extension (%) are taken as factor variables. Fabric dimension (lengthwise and widthwise), fabric areal density and fabric tension decay are taken as response variables. The findings establish that the optimum heat-setting parameters are 190°C temperature, 75s process time and 13.5% width extension. It is necessary to optimise the heat-setting parameters to achieve better fabric dimensional stability, as overheating damages and deteriorates some of the elastane filaments, resulting in reduced recovery properties after a certain temperature point.

Keywords: Cotton/elastane fabric, Dimensional stability, Elastane, Heat-setting treatment, Knitted fabric, Single jersey fabric, Tension decay

1 Introduction

Elastic fabric is a combination of materials with both elastic and flexible properties. The strands of yarns of each fabric are woven or knitted together to form a remarkable elastic fabric that retains its form even when stretched out. Elastic fibres go by various names, including elastane and lycra. It is derived from synthetic fibres noted for their outstanding stretching characteristics. Elastane cannot be used alone in knitted fabrics; thus, it is wrapped with cotton fibre to create core elastane yarns that interlace with one another to form a knitted fabric. Tights, underwear, sportswear, corsets and medical pressure or compression fabrics are among the fabrics that use elastane yarns[1–4]. For better stretchability of knitted fabric, elastane yarn is added into the fabrics to enhance the elastic properties.

Elastic knitted fabrics are prone to poor dimensional stability due to the compression of the loops in knitted fabric[3,5]. Thus, the elastic knitted fabric finishing process requires a fabric stretching and heat-setting treatment to improve the fabric's dimensional stability and reduce the amount of fabric shrinkage during repeated washing[6,7]. For medical compression garments, the constant stretching of compression fabric will decay the effectiveness of the garment and causes it to lose its ability to exert the correct pressure on the patient, thus reducing its treatment effectiveness[8]. Heat-setting of the knitted fabric serves to set and fix the elastane and reduce the elastane recovery force, because in comparison to fabric without elastane yarn or fibre, fabrics containing elastane are dimensionally unstable. Therefore, heat setting treatment is applied to these fabrics to achieve satisfactory dimensional stability[9].

Heat-setting is conducted at certain temperatures and times. According to previous researchers, elastane yarns have a large number of polymer components with a random molecular structure[5,6,9,10]. Therefore, the application of temperature helps the fibre establish a more rigid and stabilised molecular structure inside the elastane fibres[10]. Senthilkumar *et al*.[5] investigated the effect of heat-setting temperature on the elastic behaviour of cotton/spandex knitted fabric. Fabric samples were set at 180°C, 200°C and 220°C with extension levels ranging from 20% to 50% for 36 *s*. This study concluded that the heat-setting temperature has significantly influenced the elastic behaviour of cotton/spandex knitted fabric. The dynamic work recovery of the fabric increased when the temperature was increased from 180°C to 200°C and then started decreasing from 200°C to 220°C. The fabric dynamic

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work recovery decreased due to the significant loss of its residual energy caused by excessive heating which compromise the structural integrity of the fabric[6]. Few studies found that under-heating causes fabric dimensional stability to be lost over the time, whereas over-heating reduces strength and causes discolouration of fibres[11,12]. To prevent the yellowing of fabric, heat-setting is ideally performed at the early stage of textile processing rather than at the final stage[13].

In the study by Nazir *et al*.[14], heat-setting temperature, time, fabric width extension and fabric overfeed factors were used to optimise the heat-setting process in order to improve the dimensional stability of cotton/elastane knitted fabric. Their findings indicated that if the fabrics are heat-set for a sufficient period above the elastane softening temperature (175-180°C), optimum stability in the dimensions and areal density of cotton/elastane fabrics may be attained after laundering. This is in line with another study which claimed that if the desired effect is to preserve fabric areal density while maintaining good stretch and growth characteristics, a heat-setting temperature of 182°C should be applied[15]. Fabric width extension is also an important factor that decides the effectiveness and efficiency of the heat-setting process[12,14]. At a lower fabric overfeed, a higher width-way fabric shrinkage was noted with a higher fabric width extension parameter setting. Meanwhile, fabric width extension at greater fabric overfeed reduces the fabric length-way shrinkage[14].

In order to ensure an effective and efficient heat-setting process, optimised parameters, such as temperature, time and fabric width extension, must be chosen and carefully monitored[16]. A slight variation in these parameters may cause a significant effect on the properties of the fabric[14].To date, limited scientific and comprehensive studies towards the optimisation of the heat-setting process have been done. Hence, this study is focused on the optimisation of heat-setting parameters of cotton/elastane knitted fabric for better dimensional stability and elastic behaviour. In this study, the response surface optimisation (RSM) approach has been applied. RSM has also been utilised by other researchers to simulate and optimise various textile processes, such as ring spinning, nonwoven and finishing process[17–20]. Ultimately, the optimisation of heat-setting process can help in achieving optimal overall performances of the elastic fabric for the right end-use application.

2 Materials and Methods

2.1 Materials

The fabric used for conducting the experiments in this study was single jersey weft knitted fabric with 90% cotton and 10% elastane fibre contents.

2.2 Fabric Relaxation Process

A fabric composing of cotton and elastanewill relax to a lower energy state. At lower state energy, the yarn will retract back to its original state after the fabric manufacturing process. Regardless of their end uses, the fabric should be relaxed to reduce residual stresses caused by the elastic yarns' tension during the knitting process and determine the fabric's absolute minimum width [15]. In this study, the fabric was relaxed on a flat surface at room conditions of 25 ± 2*°C* and humidity of 65± 2% for 24h to release the knitted stresses. After the fabric was fully relaxed, the width of the fabric was determined according to ASTM D3774-9, where the distance from the outer edge of one selvedge to the outer edge of other selvedge was measured perpendicular to the selvedges while the fabric was held under zero tension and free of folds and wrinkles. The width of the fabric was measured at three points separated by at least 0.3 m along the length of the fabric. The average of all measurements on the specimen was calculated to the nearest 1 mm.

2.3 Heat-setting Process

Twenty samples of fabrics were subjected to heat-setting treatment at different process parameters. Based on previous studies, the process parameters or factors selected for this study were temperature (T), time (t) and fabric width extension (E_w). The coded and actual values of the factor levels are mentioned in Table 1. Each fabric sample was heat-set on a lab-scale stenter according to the experimental plan given in Table 2. The experiments were designed by using the central composite design of response surface methodology on Minitab software.

2.4 Testing Methods

After the heat-setting treatment, the samples were conditioned in a standard atmospheric condition (20°C ± 2, 65% RH ± 2% relative humidity) and then tested for the response variables. Statistical data analysis and modelling were done by using Design-Expert software.

Table 1 — Coded and actual levels of design factors

Factor	Factor symbol	Coded and actual levels				
		-2	-1	0	+1	+2
Temperature (*T*),°C	X_1	180	190	200	210	220
Time (*t*), s	X_2	60	75	90	105	120
Width extension (E_w), %	X_3	9	10.5	12	13.5	15

Table 2 — Heat-setting parameters on dimensional stability, areal density and tension decay of cotton/elastane knitted fabric heat-setting

Exp. No.	Factors			Responses				
	Temp (X_1), °C	Time (X_2), s	Width extension (X_3), %	FD_L, %	FD_w, %	ΔD_r, %	ΔD_w, %	Tension decay %
1	210	105	10.5	0.06	2.87	13.18	11.62	7.53
2	200	90	12	4.03	2.95	11.00	5.32	10.46
3	210	75	13.5	1.10	3.19	15.48	12.47	11.66
4	190	105	13.5	4.40	2.66	10.20	4.19	10.70
5	190	75	10.5	5.00	3.41	1.59	-6.49	5.56
6	200	90	12	1.17	0.48	12.71	11.99	8.09
7	210	105	13.5	-2.93	1.75	15.48	17.17	12.02
8	210	75	10.5	-1.51	-0.34	7.33	9.75	12.33
9	190	75	13.5	4.80	1.51	6.88	1.42	10.17
10	190	105	10.5	3.43	0.97	6.76	3.25	11.33
11	200	90	12	2.28	2.34	11.27	7.88	11.02
12	200	90	12	1.57	2.34	11.17	8.45	9.77
13	200	60	12	0.39	1.57	9.73	8.88	10.24
14	200	90	12	1.51	1.66	9.47	7.30	11.37
15	220	90	12	-3.37	0.07	16.13	19.71	9.64
16	200	90	15	1.05	4.60	15.51	11.32	7.81
17	200	90	9	3.43	1.77	13.03	9.20	11.06
18	200	120	12	1.99	3.13	13.98	10.49	10.68
19	180	90	12	7.52	3.51	4.05	-6.33	10.10
20	200	90	12	1.76	2.70	10.77	7.95	10.82

FD_L – difference in length-way dimension (%) after laundering, FD_W – difference in width-way dimension (%) after laundering, ΔDr – difference (%) in fabric areal density and after dry relaxation, and ΔDW - difference (%) in fabric areal density and after 5 laundering cycles.

2.4.1 Dimensional Stability

The dimensional stability of the samples was determined in accordance with AATCC 135 standard test method using top-loading washing machine (Model:AW-A820M). The original dimension of the specimens was measured before the washing cycle started. Each cycle consisted of 20 knitted cotton/ elastane specimens and sufficient ballast to produce a 1.8 kg load. The loads were washed on a ‘Normal’ setting with the load set to ‘Large’. The water temperature was maintained at 38 ± 2°C and the rinse water temperature at 12 ± 2°C. Commercial detergent (66 ± 1 g) was added to the empty drum before adding the load. After the washing cycle had completed, the specimens were dried by using the Flat-Dry method. The dimension of the specimens after washing was measured. Dimensional change was calculated using the following equation:

$$DC = \frac{X-Y}{X} \times 100\% \qquad \text{... (1)}$$

where DC is the dimensional change (%); *X*, the original dimension of specimen (cm); and *Y*, the dimension of specimen after washing (cm).

2.4.2 Fabric Areal Density

The areal density (mass per unit area) of washed and unwashed fabric samples was determined according to ASTM D 3776. The specimens were cut into 30 cm × 30 cm size and then weighed in grams on a high-precision balance to the nearest 0.1 % of its mass. The areal density of the specimens was calculated using the following equation:

$$\text{Mass per unit area (g/m}^2\text{)} = \frac{\text{Mass of specimen, g}}{\text{Length of specimen} \times \text{width of specimen, m}} \qquad \text{... (2)}$$

Table 3 — Analysis of variance (ANOVA) for effect of input variables on response variables

Parameter	FD_L	FD_w	ΔD_r	ΔD_w	Tension decay
			p-value		
X_1	< 0.0001*	0.1387	0.0003*	< 0.0001*	0.4939
X_2	0.8006	0.4786	0.0223*	0.0858	0.6942
X_3	0.3767	0.1436	0.0175*	0.0973	0.8505
X_1, X_2	0.8850	0.3999	0.6563	0.4817	0.0548
X_1, X_3	0.7330	0.4653	0.7740	0.9440	0.9727
X_2, X_3	0.2159	0.7646	0.2148	0.6205	0.9875
X_1^2	0.9781	0.6007	0.2022	0.2760	0.7699
X_2^2	0.3976	0.9818	0.7585	0.9082	0.9039
X_3^2	0.8461	0.4120	0.2849	0.7235	0.5520

*p-value< 0.05 – statistically significant difference.

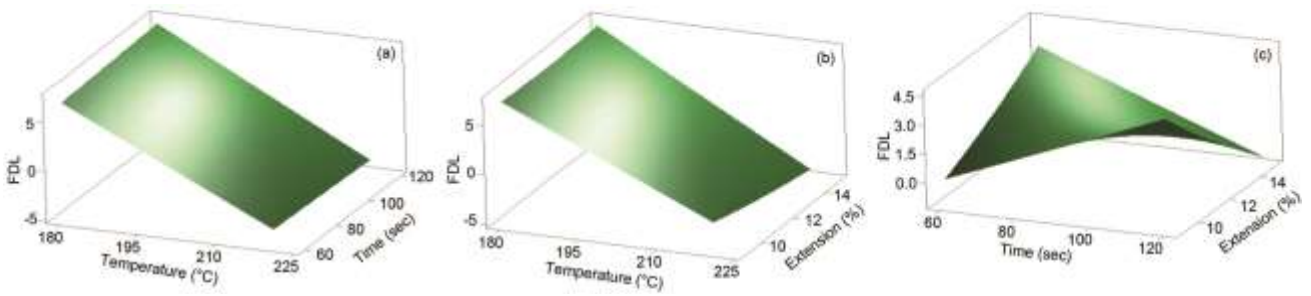

Fig. 1 — Effect of heat-setting parameters on fabric dimension (lengthwise) after laundering (a) dimension *vs*. temperature & time, (b) dimension *vs*. temperature & extension, and (c) dimension *vs*. time & extension

2.4.3 Stress-Strain Analysis

The fabrics were tested for their tensile behaviours and the tension decay after repeated extensions based on ASTM D 4964 – 96 method (CRE principle) at extension levels of 15% strain by using Instron tester. A fabric specimen of 290 mm × 75 mm size was cut and formed into a looped specimen with the loop circumference size of 250 ± 2 mm. The specimen was mounted onto the looped bars of Instron tester manually under zero load, and its position was adjusted around the bar so that the seam lay midway between the bars. The applied load was 500 N at a speed of 500 ± 15 mm/min for 10 cycles. The specimens were cycled 10 times between zero and the specified strain. After completing 10 cycles, the load and extension data were recorded. The percentage of tension decay was calculated according to the following equation:

$$\text{Tension decay} = \frac{(T_0\text{-}T_1)}{T_0} \times 100\% \qquad \text{... (3)}$$

where T_0 is the tension of original fabric (N); and T_1, the tension of fabric after 10 cycles of extension (N).

3 Results and Discussion

The results for the influence of heat-setting parameters on the performance of cotton/elastane knitted fabric are summarised in Table 2. The statistical significance of the effect of each factor, as a function of p-value (at 95% confidence) based on the analysis of variance (ANOVA) of the data are as shown in Table 3.

3.1 Effect of Heat-setting Parameters on Fabric Dimension

The effect of heat-setting parameters on fabric dimension (lengthwise and widthwise) after laundering is depicted in Figs 1 and 2. The analysis of variance (ANOVA) results show that the effect of heat-setting temperature is statistically significant on fabric dimension (lengthwise), where the p-value obtained is < 0.0001. As seen in Fig. 1, the effect of temperature is more prominent than the effect of time and extension. It is also apparent that when the heat-setting temperature is higher than the elastane softening temperature (175-180°C) at which the elastane will soften and experience noticeable changes in the physical properties, the difference in fabric dimension (lengthwise) after laundering is drastically reduced. Meanwhile, the surface area plot of change in fabric dimension (lengthwise) against time and extension (Fig. 1) shows a fluctuation trend as the time and width extension level increase. However, based on ANOVA, these factors do not significantly affect the fabric

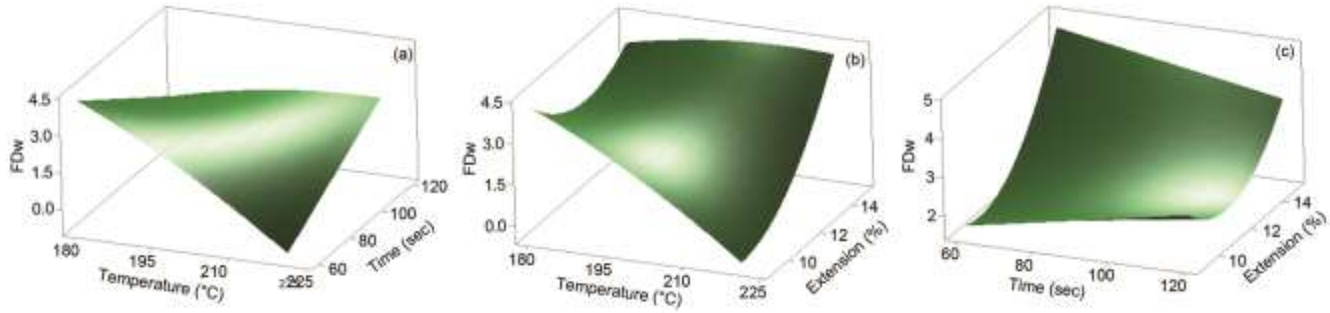

Fig. 2 — Effect of heat-setting parameters on fabric dimension (widthwise) after laundering (a) dimension *vs*. temperature & time, (b) dimension *vs*. temperature & extension, and (c) dimension *vs.* time & extension

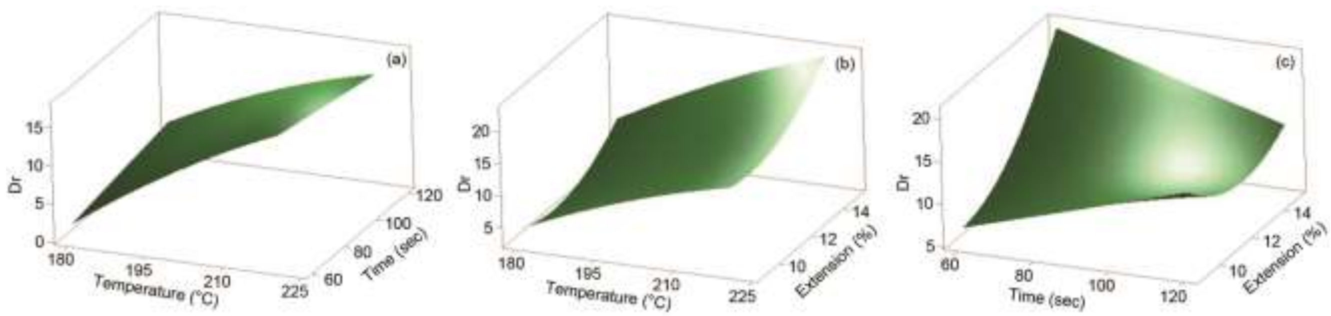

Fig. 3 — Effect of heat-setting parameters on fabric areal density after heat-setting (a) areal density *vs*. temperature & time, (b) areal density *vs*. temperature & extension, and (c) areal density *vs.* time & extension

dimension. Apart from that, the effect of heat-setting parameters on fabric dimension (widthwise) after laundering (Fig. 2) shows a different trend, where the difference in fabric dimension (widthwise) after laundering decreases sharply as the temperature increases. The effect of heat-setting temperature is more noticeable at lower time and lower width extension levels. However, there is no statistically significant interaction between the heat-setting parameters in the widthwise direction.

According to Nazir *et al*.[14], polymeric chains in the fibre do not shift or rearrange significantly below the elastane softening temperature, hindering a more stable molecular chain orientation. Therefore, this contributed to a higher shrinkage or growth in fabric when the chains relax during laundering, resulting in poor dimensional stability. On the contrary, when the fabric is heat-set at temperatures above the elastane softening temperature (175-180°C), the difference in fabric dimension in both lengthwise and width wise directions after laundering is decreased. As reported by previous scholars, this condition is achieved, as heat application stabilises the cotton/elastane yarn by increasing its rigidity and compactness and forming a more stable molecular chains orientation[21]. Although there is no statistically significant relationship between time and fabric width extension, the optimum value of both variables is needed to achieve the least amount of fabric dimensional change in both directions simultaneously.

3.2 Effect of Heat-setting Parameters on Fabric Areal Density after Heat-setting

According to the analysis of variance (ANOVA) results shown in Table 3, all heat-setting parameters significantly influence the fabric areal density after heat-setting. Fig. 3 shows that the changes in fabric areal density (ΔD_r) are lower at lower heat-setting times without being affected much by temperature. The lowest difference in fabric areal density after heat-setting is 1.59% at 190°C, 75s and 10.5% width extension. However, the influence of temperature becomes more significant as the heat-setting time increases. The difference in areal density increases with the increase in temperature and extension at longer process times. Previous studies claimed that better stabilisation of fabric is attributed to higher heat-setting temperature and time, resulting in less relaxation shrinkage after the heat-setting process to cause any increase in fabric areal density. However, it should be noted that overheating will degrade the elasticity of the elastane, making it impossible to achieve the desired and optimised properties of a cotton/elastane knitted fabric[10,22,23]. Since the fabric is

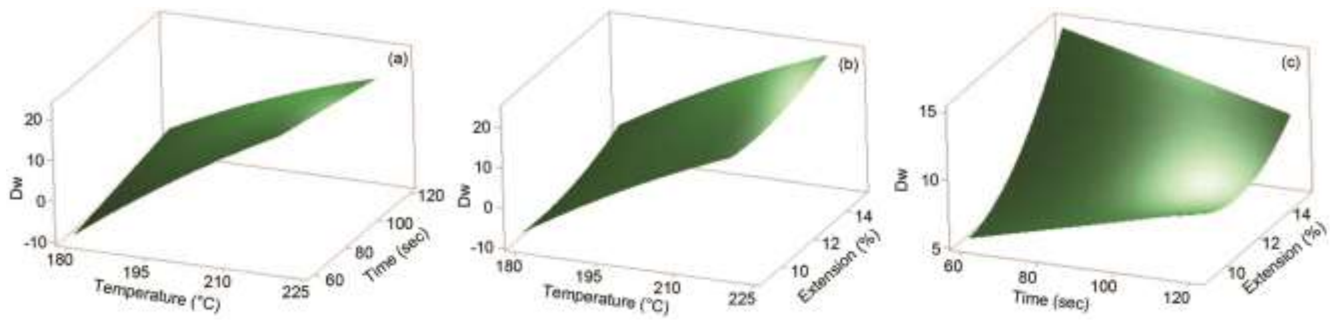

Fig. 4 — Effect of heat-setting parameters on areal density of fabric after laundering (a) areal density *vs.* temperature & time, (b) areal density *vs.* temperature & extension, and (c) areal density *vs.* time & extension

not well-set at higher temperatures and longer periods, it inclines to relax during the heat-setting treatment, increasing the fabric's density.

Apart from that, the effect of width extension during heat-setting on change in density of the fabric is also shown in Fig. 3, where the change in fabric areal density after heat-setting treatment is minimum when the fabrics are heat-set at low width extension. Since the elastane yarns that run primarily along the width are exposed to more heat when heat-setting treatment is achieved at higher fabric width extension, they get better heat-set. Therefore, when the elastane is better heat-set, dry relaxation is reduced, resulting in a minor change in fabric areal density during relaxation[14,24]. Nevertheless, if a higher width extension is applied at a higher temperature beyond the optimum level, the structural integrity of the cotton/elastane knitted fabric would be compromised. As there is a statistically significant influence by all of the heat-setting parameters on the fabric areal density, it is necessary to optimise the heat-setting parameters to achieve better fabric dimensional stability.

3.2 Effect of Heat-setting Parameters on Fabric Areal Density after Laundering

Figure 4 shows the effect of heat-setting parameters on the difference in grey fabric areal density and after five laundering cycles (ΔD_w). When the fabric is heat-set at a higher temperature, time and width extension, the increase in fabric areal density after laundering is noticeably higher. From the analysis of variance (ANOVA) results shown in Table 3, the effect of heat-setting temperature is found statistically significant on fabric areal density after laundering, where p-value obtained is < 0.0001. As seen in Fig.4, the effect of temperature is more prominent than the effect of time and width extension. Based on results obtained in Table 2, the most optimum change in fabric areal density after laundering is 1.42% at 190℃, 75s and 13.5% width extension, which is considerably lower than the changes in fabric areal density after heat-setting treatment. It is important to note that the heat-setting treatment on the knitted fabric serves to set and stabilise the elastane, consequently improving the dimensional stability of the fabric and reducing the changes in areal density after repeated laundering cycles[5,25].

Figure 4 also demonstrates the influence of width extension on the increase in fabric density after laundering. The effect of fabric width extension during heat-setting treatment is not as significant as the effect of time and temperature. An increase in fabric density after laundering is lower when the fabric is heat-set at a higher width extension. Since elastane yarns are exposed to more heat at higher width extensions, they get heat-set more effectively. Nonetheless, the level of width extension should not exceed the optimum level to prevent unacceptable changes in fabric areal density. The findings suggest that heat-setting treatment on cotton/elastane knitted fabric at a sufficiently higher temperature and time with a greater width extension improves the fabric properties to laundering in terms of fabric areal density, which guarantees good dimensional stability of finished fabrics[15,26].

3.3 Effect of Heat-setting Parameters on Fabric Tension Decay after Heat-setting

The effects of heat-setting parameters on the elastic behaviour of cotton/elastane knitted fabric after being subjected to heat-setting treatment are demonstrated in Fig. 5. According to the analysis of variance (ANOVA) results shown in Table 3, there is no statistically significant influence on the fabric tension decay after heat-setting treatment by all the factors where p-value obtained is>0.005. Based on the results (Table 3), the least change in fabric tension decay after heat-setting treatment is 5.56% at 190℃, 75s and 10.5% width

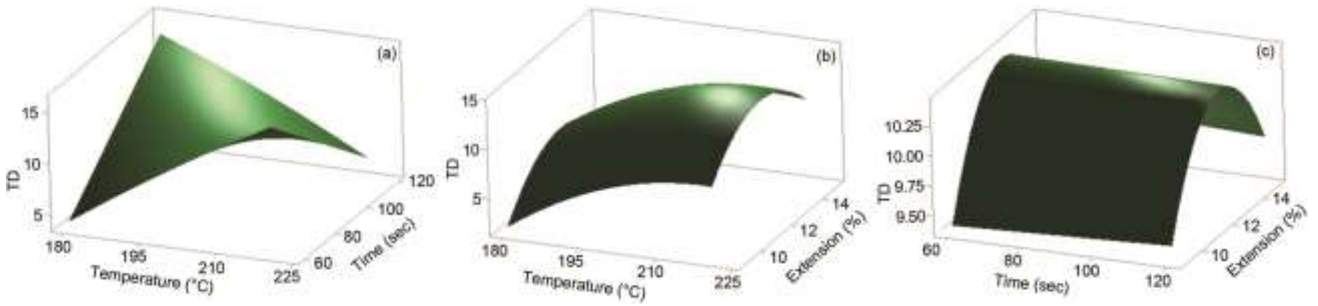

Fig. 5 — Effect of heat-setting parameters on fabric tension decay (a) tension decay *vs*. temperature & time, (b) tension decay *vs.* temperature & extension, (c) tension decay *vs.* time & extension

extension. As seen in Fig.5, there is a significant relationship between temperature and time with fabric tension decay after heat-setting treatment. The relationship between all factors shows fluctuation trends where the lowest fabric tension decay is obtained at lower heat-setting temperatures and a longer time. Meanwhile, the effect of width extension during heat-setting treatment is not as significant as time and temperature on the fabric tension decay. As heat-setting treatment is applied on elastic fabric in an elongated shape, the elastane molecular structure rearranges the fabric, thus lowering the recovery tension. When the heat-setting temperature increases above its softening temperature (175-180°C), the elastane loses its residual energy. The elastane soft segments shrink as they become rigid, compressing the knit loops. Therefore, the higher the heat-setting temperature, the lower will be the fabric tension decay, consequently lowering the dynamic work recovery. Overheating damages and deteriorates some elastane filaments, resulting in reduced recovery properties after a certain temperature point[27,28].

4 Conclusion

This study shows that the heat-setting treatment on cotton/elastane fabrics at a sufficient time above the elastane softening temperature results in maximum stability in fabric dimensions and areal density and fabric tension decay after laundering. An increase in the heat-setting temperatures above the elastane softening temperature(175-180°C), leads to a decrease in the difference in fabric dimension in both lengthwise and width wise directions and better dimensional stability of fabric areal density after laundering. The stability of the fabric areal density to dry relaxation improves as the fabric is heat-set at a low width extension. In terms of fabric tension decay, higher heat-setting temperature results in lower fabric tension decay, consequently lowering the dynamic work recovery. Based on all findings, it can be inferred that the optimum heat-setting parameters are achieved at a temperature of 190*℃*, 75s process time and 13.5% width extension. It is observed that heat-setting treatment compacts the cotton fibres with elastane, stabilising the yarn and improving its elastic properties. Similarly, the cotton elastane yarn is stabilised by heat-setting treatment, which relaxes the residual energy obtained from twisting or spinning.

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