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Optimizing filtration efficiency of needle-punched recycled polyester fabrics

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ABSTRACT
In the present study, the polyester channel texture is inventively prepared in two sets to investigate the filtration properties for practical application in automotive filters. In the set first (set-I) three different parameters namely grams/m^2 (GSM), needling density and blend ratio with three different levels and in the second set (set-II) three different parameters calender roller pressure, calender roller temperature and calender roller speed with three different levels are used. For the first set fabrics it has been seen that the filtration efficiency increased with the increase in GSM, needling density as well increase of virgin polyester fibre in the blend. In the second set increase in calender roller pressure, calender roller temperature caused increase in filtration efficiency. The study of two sets of fabrics reveals that by judicial selection of calendering parameters high filtration efficiency can be obtained for set II (550 GSM) fabrics resulting cost reduction by the way of lesser requirement of fibers in the manufacturing of needle bonded filter fabrics.
We trust that such an endeavour will be useful for pragmatic utilization of virgin and reused polyester filaments and address the issues of domestic filter markets. Moreover, it can expand the application field and increment the additional estimation of reused polyesters.
Keywords: Blend ratio, virgin, judicial, needle bonded, filter fabrics

I. INTRODUCTION

While manufacturing any fabric, the manufacturing procedure and finishing parameters play important role in deciding fabric characteristics. In case of needle bonded fabrics the filtration efficiency is based on the fibers properties, web attributes and machine parameters.

On going through the reviewing of the published work it is observed that earlier researchers have considered fibre characteristics and machine parameters but none has made study using the blend of virgin and recycled polyester fibers also using different calendaring parameters while finishing the fabrics.

Looking to all these in the present study two sets of fabrics have been taken. Set I carries GSM, blend and machine parameter whereas II set of fabrics includes calender finishing parameters. The aim of the present study is to find the guidelines to optimize filtration efficiency with the aim of cost reduction of automotive filters. In this way, so as to meet the prerequisites of automotive filer market, it is essential to develop new, economical filters of optimum filtration efficiency in conjunction with environmental sustainability using recycled polyester waste materials.

II. MATERIAL AND METHODS

2.1 Materials

Virgin polyester fibers and reused polyester fibers both having a similar denier (1.5), same staple length (42 mm) and same crimps (10 crimps/cm) were utilized.

2.1.1 Method utilized for nonwoven texture advancement

2.1.1.1 Preparation of samples

Two sets of samples (15 each) were prepared in which the first set of 15 samples were readied as per Box-Behnken plan (Table 1).

While the second set of 15 samples each of 550 GSM were prepared using virgin: recycled (50:50) blend ratio, punched at needling density of 250 punches/cm^2. These second set of 15 samples were finished on calender roller machine as per Box-Behnken (Table 2).

Independent variables for the first 15 sets of samples were web weight (GSM), needling density (ND) and blend ratio (BR) as indicated in Table 1.

Table 1. Factors with their levels according to Box-Bhenken structure.

Variables	Levels		
Independent Variables	-1	0	+1
Web weight (GSM)	500	550	600
Needling density (ND) in punches/cm^2	125	250	375
Blend ratio (%)	25:75	50:50	75:25

The independent variables for the second 15 sets of samples were calender roller pressure (CRP), calender roller temperature (CRT) and calender roller speed (CRS), the same has been indicated in Table 2.

Table 2. Factors with their levels according to Box-Behnken structure.

Variables	Levels		
Independent Variables	-1	0	+1
Calender roller pressure (CRP) in bar	0.5	1	1.5
Calender roller temperature (CRT) in degree Celsius	160	200	240
Calender roller speed (CRS) in rpm	2	5	8

Scrim texture [31] was used as invigorating material for the nonwoven channel surface, to thwart damage of the surface and besides to extend life of channel. Fortifying material extend distortion security and nature of channel surface. Moreover, usage of scrim texture causes higher extension and brings down break %, likewise settles the free nonwoven structure.

The sequence for manufacturing the first fifteen sets of needle punched nonwoven filter fabrics were as follows:

2.1.2 Web preparation

Networks of required GSM and mix proportions were set up on the carding machine utilizing fibers of following particular: 1.5 denier, staple length 42 mm and 10 crimps/cm.

2.1.3 Fabric readiness

15 samples of needled automotive channels were readied utilizing the different GSM networks individually on the Erko needle loom 1 and 2 in couple. Loom 1 was utilized for introductory attaching, pre-solidification and minimization of stringy web at similarly lower needling density of 45 punches/cm^2 while loom 2 was utilized for conclusive union of the various networks got from loom 1 during which scrim texture was midway sandwiched between the webs of changing GSM which were punched at required needling density (125, 250 and 375 punches/cm^2) to acquire the nonwoven textures of desired properties separately.

2.1.4 Finishing of samples

The needled samples were calendered over a 3 roller pair calendering machine set at pressure 1.0 bar, calender roller temperature of 200^{o}C running at a speed of 5 revolutions per minute (rpm).

The sequences for manufacturing the second set of fifteen samples of needled samples were as follows:

2.2.1 Web formulation

Networks of GSM 250 and mix proportion V:R::50:50 were set up on the carding machine utilizing fibers of following details: 1.5 denier, staple length 42 mm and 10 crimps/cm.

2.2.2 Fabric formulation

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15 needled channels were readied utilizing the 250 GSM networks individually on the Erko needle loom 1 and 2 in tendem. Loom 1 was utilized for starting attaching, pre-combination and minimization of sinewy web while loom 2 was utilized for conclusive solidification of the various networks got from loom 1 during which scrim texture (50 GSM) was midway sandwiched between the webs of 250 GSM which were punched at 250 punches/cm^2 to get the nonwoven textures of suitable properties.

2.2.3 Finishing of samples

All above obtained 15 sets of needled samples were calendered according Box-Behnken design of experiment one by one over 3 roller calendering machine of varying calendering specifications as mentioned in Table 2.

III. PHYSICAL PROPERTIES OF FIBERS

All the tests were adapted under standard environmental condition kept up at 65% ± 2% RH and 20±2^{o}C as fiber properties changes with differing temperature and relative humidity. The samples were conditioned for 72 hr in the previously mentioned conditions before assessment [32].

Since, the properties of fibers decide the properties of fabrics all major physical properties of the both type fibers (virgin and recycled) including tensile, elongation, and fineness were determined using Lenzing Vibrodyn 500 instrument [31]. An average of 50 fibers was considered as depicted in Table 3.

Table 3. Calculated values for tensile, elongation and fineness of fibers.

Fiber type	Tensile (gram force) ASTM D 3822	Elongation (%) ASTM D 3822	Fineness (dinear) ASTM D 1577-07
Virgin polyester	10.40	22	1.50
Recycled polyester	9.06	26	1.51

IV. PHYSICAL PROPERTIES OF FABRICS

4.1 Web weight (GSM)

IS: 1964-2001 method was utilized for deciding the GSM of needled samples. Test specimens of measurement 10.0x10.0 cm were taken self-assertively from different parts and their weight was estimated utilizing electronic offset set with a precision of 0.005 g and the normal of five readings was resolved.

4.2 Filtration efficiency

The filtration efficiency percentage was worked out using the following formula:

$$F\eta = \frac{(w_{ft} - w_{fi})}{w_{df}} \times 100$$

where, w_{ft} is weight of the fabric with accumulated dust at the end of test; w_{fi} is initial weight of the fabric and w_{df} is mass of total dust fed during the test.

An average of ten readings was considered.

5 Analysis of the results

The test aftereffects of the samples were examined by utilizing the Design-Expert 12 programming. Statistical significance tests (ANOVA) were utilized to discover test of significance.

Table 4. Filtration efficiency report for Ist set of fabrics.

Run	Factor 1	Factor 2	Factor 3	Response 1
	A:GSM	B:Needing density	C:Blend ratio (V:R)	Filtration efficiency
	grams/m^2	punches/cm^2	%	%
1	500	125	50:50	91.11
2	600	125	50:50	93.44
3	500	375	50:50	90.32
4	600	375	50:50	92.65
5	500	250	25:75	93.55

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6	600	250	25:75	93.81
7	500	250	75:25	94.67
8	600	250	75:25	95.01
9	550	125	25:75	94.23
10	550	375	25:75	93.66
11	550	125	75:25	96.01
12	550	375	75:25	95.80
13	550	250	50:50	95.69
14	550	250	50:50	96.71
15	550	250	50:50	95.63

*GSM: g/m^2

Table 5. Filtration efficiency results for IInd set of fabrics.

Run	Factor 1	Factor 2	Factor 3	Response 1
	A:Calender roller pressure	B:Calender roller temperature	C:Calender roller speed	Filtration efficiency
	bar	degree Celsius	rpm	%
1	0.5	160	5	85.11
2	1.5	160	5	89.40
3	0.5	240	5	88.32
4	1.5	240	5	93.47
5	0.5	200	2	87.20
6	1.5	200	2	92.19
7	0.5	200	8	85.39
8	1.5	200	8	90.55
9	1	160	2	91.63
10	1	240	2	97.30
11	1	160	8	86.51
12	1	240	8	94.22
13	1	200	5	95.63
14	1	200	5	96.50
15	1	200	5	95.49

V. RESULTS AND DISCUSSION

Tables 4 and 5 present different responses with respect to the independent variables (fabric GSM, needling density, blend ratio) while Table 5 present responses with respect to variables calender roller pressure, calender roller temperature and calender roller speed for needled filters made from virgin and reused polyester strands, separately. The test results were analyzed progressively.

5.1 Effect of fabric weight (GSM), needling density and blend ratio on filtration efficiency for fabrics: set I

The pattern obtained from the Figure 1i uncovers that the filtration efficiency of nonwoven texture declines with the expansion in GSM. The least filtration efficiency is observed within the range of GSM 580-600 and needling density 175-275. While maximum filtration efficiency is obtained for GSM varying between 500-520 at varying needling densities of 125-175 and 325-375 punches/cm^2. It is additionally seen that the degree of increment of filtration efficiency was at first lesser and it later increased. The underlying decrement in filtration efficiency with expanding needling density might be because of better interlocking of the strands. The increased filtration efficiency during later stage might be because of the breakage of filaments caused because of an expanded needling density. As needle punching is fundamentally the interlocking or circling of filaments to frame a web, a higher pace of needling density brings about progressively irregular circling of strands inside the structure, bringing about intelligible and more stronger webs networks. Another conceivable clarification could be that, because of better fibers interlocking, the load bearing limit of individual filaments increments, bringing about lower filtration efficiency at higher needling density [3].

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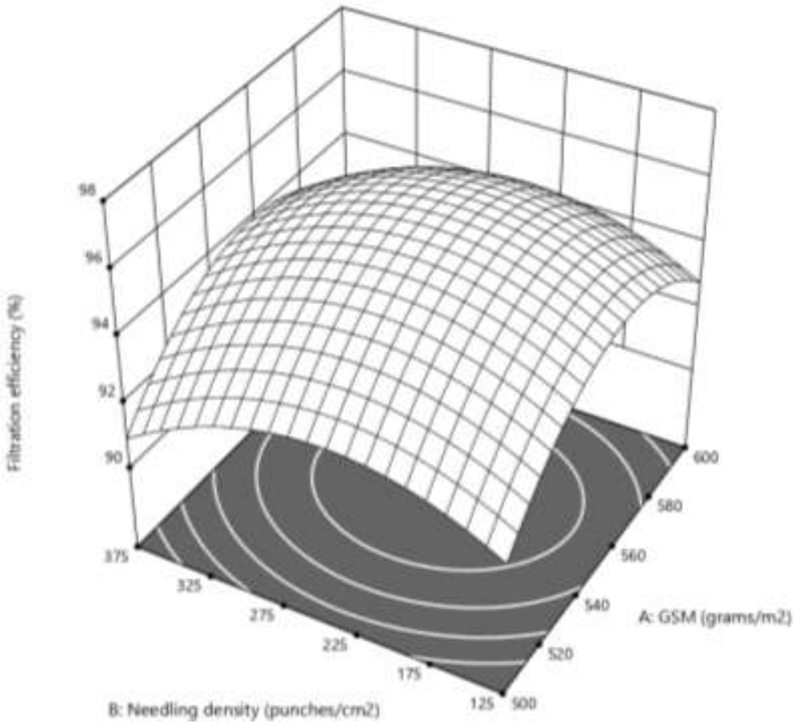

Figure 1i. 3D surface plot of filtration efficiency against needling density and GSM.

The pattern noticed from the Figure 1ii uncovers that the filtration efficiency of needled texture declines with the expansion in GSM. While, for the mix proportion of virgin and reused polyester, it has been seen increment in filtration efficiency with the expanded virgin fibers content in the mixed texture. The minimum filtration efficiency is observed within the range of GSM 580-600 and varying blend ratio V:R::25:75 to V:R::45:55. This may be due to higher higher surface roughness of the virgin fibre [31]. Thus, with the increased proportion of virgin fibre in the blended fabric the filtration efficiency is found minimum. While maximum filtration efficiency is obtained for GSM varying between 500-520 at varying blend ratio of V:R::55:45 to V:R::75:25. It is additionally seen that the degree of decrement of filtration efficiency was at first more and it later increased at higher GSM. The all through decrement in filtration efficiency with expanding extent of virgin filaments in the mixed texture might be because of expanded cohesiveness and better bury fibers frictional powers caused because of higher roughness.

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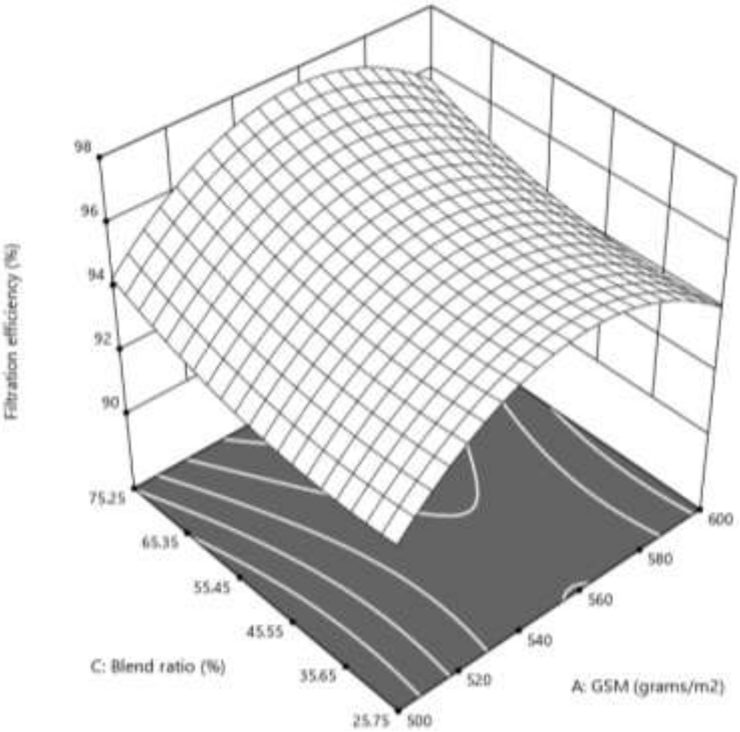

Figure 1ii. 3D surface plot of filtration efficiency against blend ratio and GSM.

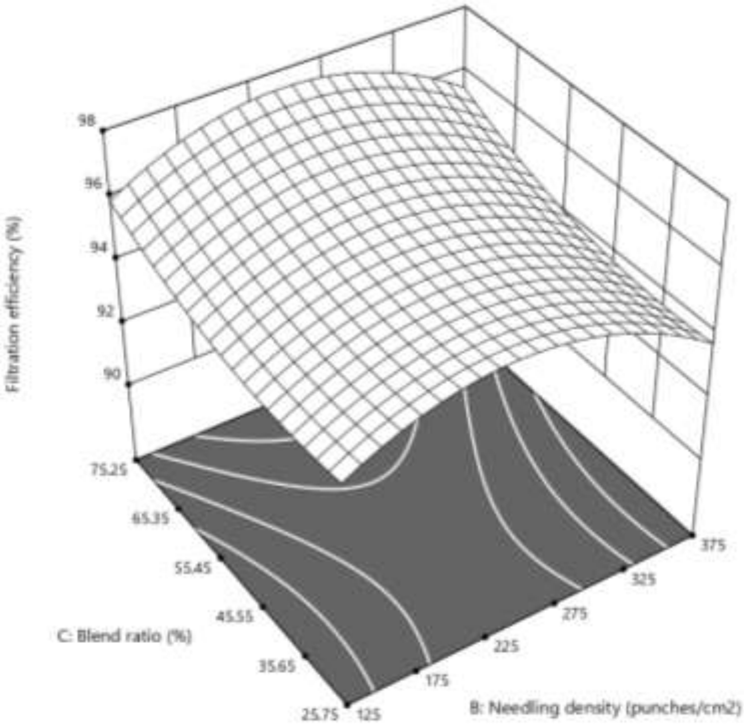

Figure 1iii. 3D surface plot of filtration efficiency against blend ratio and needling density.

Figure 1iii uncovers that the filtration efficiency of nonwoven texture declines with the expansion in virgin strands in the mixed texture. Minimum filtration efficiency is observed within the range of varying blend ratio V:R::75:25 to V:R::55:45 and needling density of 175-275 punches/cm^2. The maximum filtration efficiency is

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observed for blend ratio of V:R::25:75 to V:R::35:65 at needling density of more than 325. It is further observed that the extent of decrease in filtration efficiency was initially more and it later increased at higher needling density. The throughout decrement in filtration efficiency with expanding blend proportion of virgin fibers in the blended fabric may be due to higher cohesiveness and better inter fibre frictional forces caused due to higher roughness of virgin polyester fibers.

5.2 Effect of calender roller pressure, calender roller temperature and calender roller speed on filtration efficiency for fabrics: set II

The pattern obtained from Figure 2i uncovers that the optimum filtration efficiency is observed within the range of 0.9-1.1 bar and 200-220°C. At optimum range of calendar pressure and temperature the fibers in the fabrics gets mechanically adhered resulting optimum filtration efficiency.

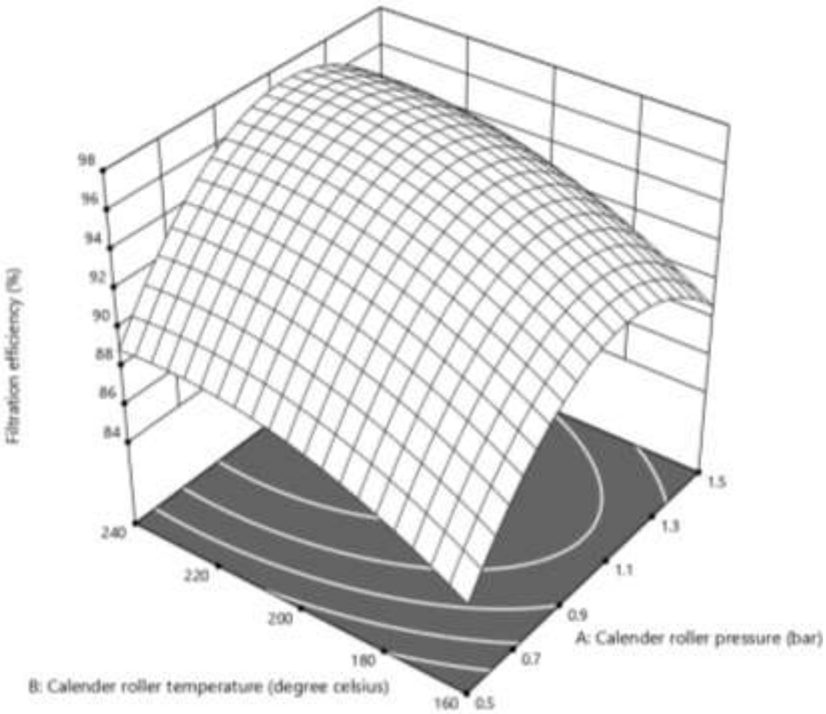

Figure 2i. 3D surface plot of filtration efficiency against calender roller temperature and calender roller pressure.

The pattern obtained from the Figure 2ii uncovers that the maximum filtration efficiency of nonwoven texture is obtained at calender roller speed varying between 7-8 rpm at 0.5-0.7 bar. While optimum value of filtration efficiency is obtained at calender roller speed varying between 4-5 rpm and calendar roller pressure varying between 0.9-1.1 bar. The reason for such trend may be that at lower roller speed and higher pressure fabrics gets enough time to be pressed against calender rollers resulting in compact structure with reduced filtration efficiency.

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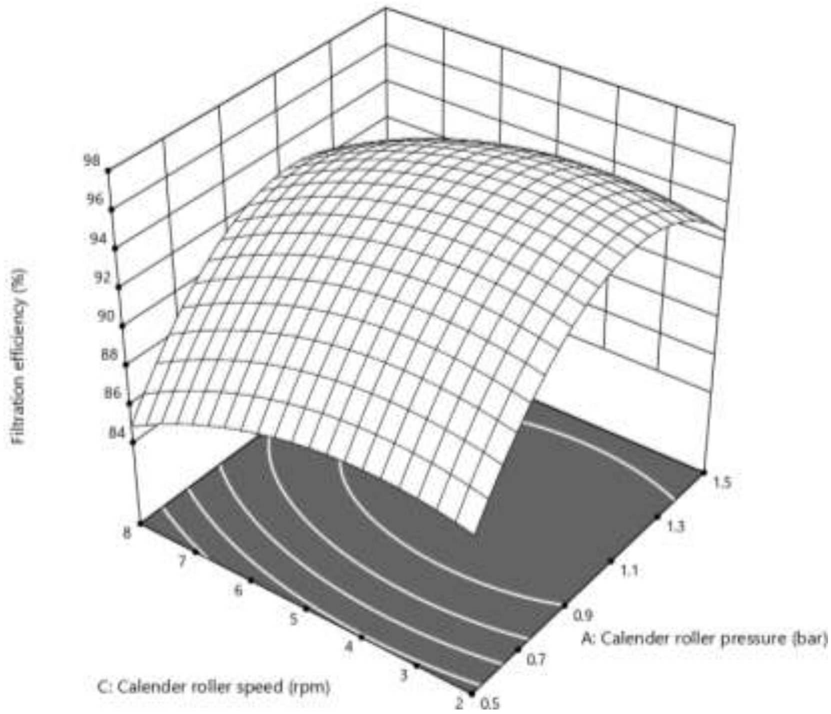

Figure 2ii. 3D surface plot of filtration efficiency against calender roller speed and calender roller pressure.

The pattern obtained from the Figure 2iii uncovers that the higher filtration efficiency of nonwoven texture is obtained at higher range of calender roller speed varying from 7-8 rpm. Also it increased with the increase in roller temperature till around 220^{o}C and thereafter it slightly decreased.

Reduced filtration efficiency with increased calender roller temperature and decreased roller speed may be due to softening of fibers at higher temperature, fabrics gets enough time to be pressed against hot calender rollers, thereby the fibers in it gets mechanically adhered and thermally bonded by hot rollers.

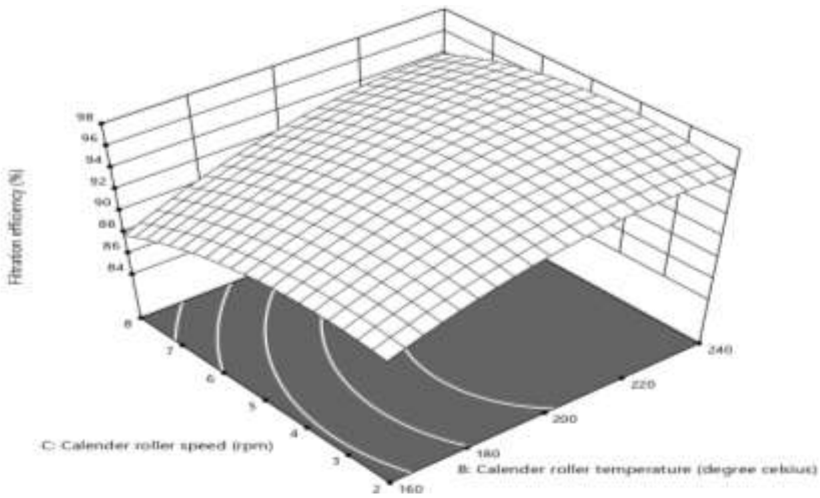

Figure 2iii. 3D surface plot of filtration efficiency against calender roller speed and calender roller temperature.

5.3 Advancing key indicator factors for filtration efficiency: fabrics set I

5.3.1 Filtration efficiency: for fabrics set I

The after-effects of the past segment show that the GSM, needling density, blend ratio, are the significant factors which can straightforwardly influence properties of channel texture. Utilizing Box-Behnken plan of analyses, these factors have been analyzed below.

Table 6. Examination of change for FE: fabrics set I.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	42.50	9	4.72	7.38	0.0202	significant
A-GSM	3.46	1	3.46	5.41	0.0676	
B-Needling density	0.6962	1	0.6962	1.09	0.3445	
C-Blend ratio	4.87	1	4.87	7.61	0.0399	
AB	7.105E-15	1	7.105E-15	1.111E-14	1.0000	
AC	0.0016	1	0.0016	0.0025	0.9620	
BC	0.0324	1	0.0324	0.0507	0.8308	
A^2	21.22	1	21.22	33.19	0.0022	
B^2	11.08	1	11.08	17.33	0.0088	
C^2	1.55	1	1.55	2.42	0.1805	
Residual	3.20	5	0.6394			
Lack of Fit	2.46	3	0.8201	2.23	0.3249	not significant
Pure Error	0.7368	2	0.3684			
Cor Total	45.69	14				

*FE: filtration efficiency
Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 7.38 implies the model is significant. There is only a 2.02% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case C, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The **Lack of Fit F-value** of 2.23 implies the Lack of Fit is not significant relative to the pure error. There is a 32.49% chance that a Lack of Fit F-value this large could occur due to noise.

Table 7. Coefficient as coded factors for FE: fabrics set I.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	96.01	1	0.4617	94.82	97.20	
A-GSM	0.6575	1	0.2827	-0.0693	1.38	1.0000
B-Needling density	-0.2950	1	0.2827	-1.02	0.4318	1.0000
C-Blend ratio	0.7800	1	0.2827	0.0532	1.51	1.0000
AB	0.0000	1	0.3998	-1.03	1.03	1.0000
AC	0.0200	1	0.3998	-1.01	1.05	1.0000
BC	0.0900	1	0.3998	-0.9378	1.12	1.0000
A^2	-2.40	1	0.4162	-3.47	-1.33	1.01
B^2	-1.73	1	0.4162	-2.80	-0.6627	1.01
C^2	0.6475	1	0.4162	-0.4223	1.72	1.01

(* VIF: variance inflation factor, CI: confidence interval)

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multi-co linearity, the higher the VIF the

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more severe the correlation of factors. VIFs less than 10 are tolerable (Table 7).

Final equation in terms of coded factors for filtration efficiency (fabrics set I) is as depicted below

Filtration efficiency = $+96.01+0.6575*A-0.2950*B+0.7800*C+0.0000AB+0.0200*AC+0.0900*BC-2.40*A^2-1.73*B^2+0.6475*C^2$……….. (1)

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

5.34.2 Optimization for filtration efficiency results for fabrics: set I and II

Numerical enhancement of filtration efficiency for fabrics set I (Figure 3i) uncovers that minimum filtration efficiency (150.9 $cm^3/cm^2/sec$) can be acquired approximately at GSM: 599, needling density: 259 (punches/cm^2) and blend ratio V:R::74:26. While for fabrics set II (Figure 6ii), optimum filtration efficiency (202.6 $cm^3/cm^2/sec$) can be attained approximately at calendar roller pressure: 1.3 bar, calendar roller temperature: 206^{o}C and calendar roller speed: 3 rpm.

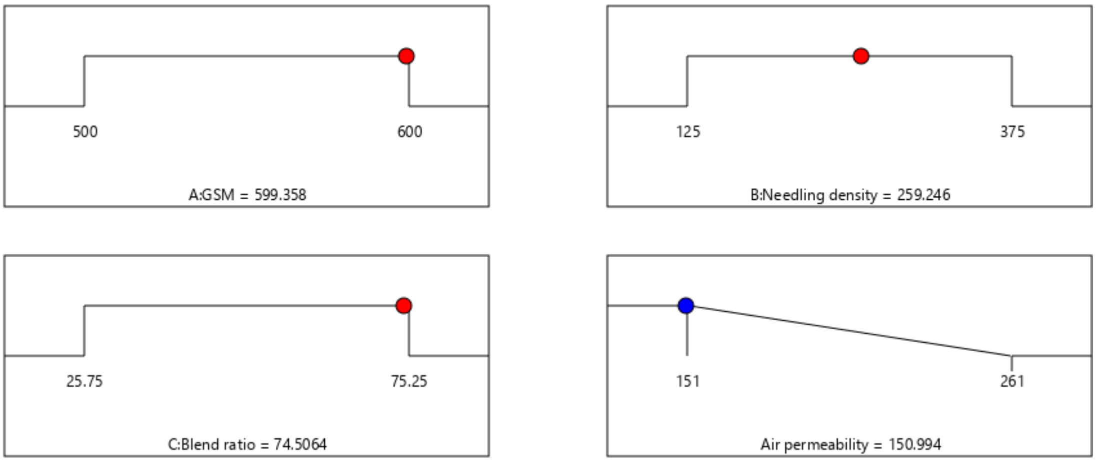

Figure 3 i. Optimization for filtration efficiency (fabrics: set I).

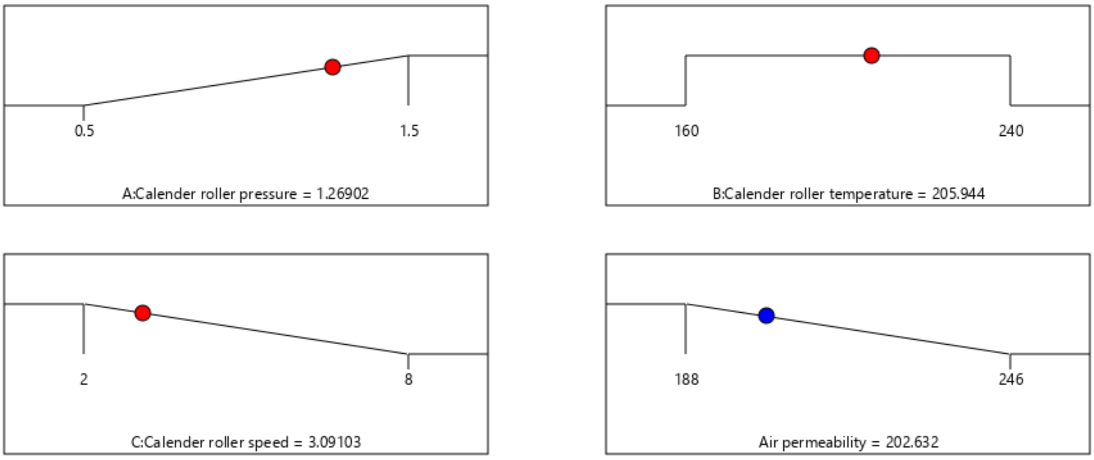

Figure 3 ii. Optimization for filtration efficiency (fabrics: set II).

Figure 3. Optimization of filtration efficiency for fabrics set I and II.

VI. CONCLUSIONS

For fabrics: set I

1. Filtration efficiency reduced with the expansion in GSM.
2. Filtration efficiency reduced at first with the expansion in needling density thereafter subsequently increased.
3. Filtration efficiency reduced with the increased proportion of virgin polyester fibers in the blended fabrics and vice-versa.

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4. Least filtration efficiency (150.9 $cm^3/cm^2/sec$) can be acquired approximately at GSM: 599, needling density: 259 (punches/cm^2) and blend ratio V:R::74:26.

For fabrics: set II

1. Filtration efficiency reduced with the expansion in calender roller pressure subsequently it decreased slightly.
2. Filtration efficiency reduced with the increase in calender roller temperature subsequently it decreased slightly during later stages.
3. Filtration efficiency increased with the increase in calender roller speed and vice-versa
4. Optimum filtration efficiency (202.6 $cm^3/cm^2/sec$) can be attained approximately at calendar roller pressure: 1.3 bar, calendar roller temperature: 206^oC and calendar roller speed: 3 rpm.

From the conclusions of both sets of fabrics it can be analyzed that low values of filtration efficiency may be obtained at lower GSM (550- set II) just by judicial selection of the various parameters of calendering process. Thus instead opting for higher GSM (600- set I), low filtration efficiency can be obtained for set- II fabrics. Thus there is less fibers requirement for set-II (550 GSM fabrics) resulting cost reduction with optimum filtration efficiency characteristics.

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