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Compressional behavior of Persian hand knotted wool carpets using response surface methodology

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The effects of knot density, pile height, number of ply in pile yarn and pile yarn twist on compressional behavior (compression and compression recovery) of Persian hand knotted wool carpets has been studied. The influence of variables on compression behavior of carpets has been quantitatively analyzed by using response surface methodology based on the Box-Behnken design of experiment. The minimum compression occurs with the combination of minimum values of pile height (10 mm), knot density (5 knots/inch) & number of ply in pile yarn (2 ply), and maximum value of pile yarn twist (4.5 twists/inch). However the maximum compression recovery is attained with the combination of minimum values of pile height (10 mm) & pile yarn twist (3.5 twists/inch), and maximum values of knot density (7 knots/inch) & number of ply in pile yarn (4 ply).

Keywords: Carpet, Compression behaviour, Hand knotted wool, Persian hand knotted carpet, Response surface methodology, Wool

1 Introduction

Carpet is a three dimensional home furnishing product, used in the decoration of floor, wall and ceiling. It consists of two parts, namely base and pile. The former is created by warp and weft yarns and the latter is created by pile yarns which generate working surface of the complete carpet with desired design and pattern. Basically carpets are divided into two groups on the basis of its manufacturing systems, viz machine made and handmade carpets. Machine made carpet manufacturing systems include tufting, weaving, knitting, braiding, needle felting, fusion bonding and flocking. Handmade carpets are produced in three different types, namely knotted, flat woven and tufted. Knotting is an extensively used method for carpet manufacturing. The texture of hand knotted carpets is produced by the independent knots. Persian or Sehna, Tibetan, Turkish or Ghiordes, Spanish and Kiwi knots are generally used in handmade carpet industry. Among these, Persian knot is extensively used in handmade carpet sector of India[1-4].

Carpet should maintain their appearance and walking comfort throughout its service life. The carpet compressional behaviors influence these properties. Compressibility is a measure of the relative change in the volume of a material as a response to a pressure change. As far as carpet is concerned, the change in thickness is only considered. Researchers have explained elastic and inelastic mechanisms to understand compression and recovery of carpet piles[5].

Compressional behaviors of carpets are collectively influenced by fibre, yarn and carpet constructional parameters. The ratio of compressed thickness to initial thickness gives the measure of carpet compressibility (%). Carpet resiliency is the instant recovery property of carpet pile after removal of compressive stresses. Gupta *et al.*[6] studied the influence of wool fibre diameter and medullation on resiliency of hand-knotted carpets and found that the resiliency increases with the increase in fibre diameter and medullated fibre content in carpet. Sheikhi *et al.*[7] studied the compression properties of acrylic cut-pile carpet consisting of pile yarn with different fibre blend ratios. Arora *et al.*[8] studied the influence of tuft constitution (the number of threads assembled together to form a tuft whether single or plied) on the performance parameters of hand-woven carpets. They found that carpet resiliency increases and compressibility decreases with the increase in the number of folds in the yarn. Ishtiaque *et al.*[9] engineered the carpet yarns to purposefully position different characteristics of fibre across the yarn section using modified SIRO spinning technique on

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worsted spinning system. Carpet resiliency was found to be better for carpets manufactured from engineered yarns. They also developed a new instrument carpet compression tester (CCT) to measure carpet compressional properties, namely carpet thickness, compressibility and resiliency under static and dynamic condition[10].

The influence of carpet constructional parameters on the compressional behaviors has been reported by some researchers. It has been found that pile density and pile height play an important role in determining carpet compression properties. Dayiary *et al.*[11, 12] investigated the behavior of pile yarn under a compressive load. They presented a mechanism of pile deformation under compression and derived the total energy of pile deformation in terms of nonlinear bending and frictional energies. They found that the total number of pile yarns per unit area increases with the increase in pile density, resulting in higher yarn frictional contacts as well as higher energy loss. Moghassem *et al.*[13] investigated the effect of knot density, pile height and percentage of slipe wool on compression behavior of hand woven carpets. They found that compression and matting of the pile yarn is decreased and its elastic recovery is increased with the increase in knot density. Matting of samples decreased with increase in pile height to certain level, but further increase caused increased reduction in matting. Nilgün *et al.*[14] studied the effects of raw material, yarn linear density and number of loop per unit area on compressibility and thickness recovery of carpets. It was found that the compressed thickness of the carpet produced from thicker yarn is higher. Higher loops per unit area increase both the thickness and resistance to compression of the carpet during the loading periods. For denser carpet, the recovered thickness is higher and the thickness loss is lower due to the tightly packed structure. Several researchers[15-17] developed a theoretical model to predict the carpet compressional behavior.

However, the twist and the number of plies in the pile yarn are expected to influence the compressional behavior of handmade carpets. Besides, the yarn parameters (twist level and number of plies) and carpet construction parameters (pile density and pile height) parameters may have some interaction to influence the compressional behavior. There is no reported research where all these important yarn and carpet characteristics have been studied simultaneously. Therefore, in this investigation, an attempt has been made to study the compressional behavior of Persian handmade wool carpets by developing a model using Box-Behnken response surface methodology. The influence of four variables (pile density, pile height, number of ply in pile yarn and pile twist level) and their interactions on the compressional behavior of handmade carpets has also been studied. Using the developed model, it would be possible to find the best combination of yarn and carpet variables to improve the compressional behavior of Persian hand knotted carpets.

2 Materials and Methods

2.1 Materials

Four types of yarns were used for the manufacturing of Persian handmade carpets namely pile, warp, thick weft and thin weft yarns. Among these, pile yarns of 3.90 metric counts (Nm) with 3 different twist levels [3.5, 4.0 and 4.5 twists/inch (tpi)] were produced from 100 % wool fibres using woollen spinning system. Wool fibres having the mean fibre diameter 37.65 μm, fibre diameter CV% 24.4, mean fibre length 75.03 mm, and fibre length CV% 28.5 were used. The specifications of pile yarns are given in Table 1 and specifications of warp, thin weft and thick weft yarns are given in Table 2.

Carpet samples were manufactured by creating Persian knots (also called Sehna knot). Persian knot is an asymmetrical single knot. The Persian knots are created by wrapping the tuft around one warp yarn at an angle of 2π radians and then around another adjacent warp yarn at an angle of π radians as depicted in Fig. 1. A short piece of yarn is tied by hand around two neighbouring warp strands. After

Table 1 — Pile yarn specifications

Nominal metric count	Nominal twists/inch	Actual metric count (CV %)	Actual twists/inch (CV %)	Twist direction
3.90	3.5	3.64 (7.98)	3.63 (9.51)	S
3.90	4.0	3.86 (8.29)	4.02 (9.61)	S
3.90	4.5	3.96 (2.67)	4.62 (6.73)	S

Table 2 — Warp, thin weft and thick weft specifications

Sample	No. of ply	Resultant yarn count Ne (CV %)	Twists/inch (CV %)	Twist direction
Warp	6	0.9 (0.32)	5.5 (2.56)	S
Thin weft	2	1.6 (1.36)	5.1 (2.09)	S
Thick weft	2	0.9 (0.86)	5.1 (1.59)	S

each row of knots is completed, two strands of weft are passed through a complete set of warp strands in alternate shedding. Then the knots and the weft threads are beaten with a comb for securing the knots in place. The weaving process begins at the bottom of the loom and as the knots and weft yarns are added, the carpet moves upwards until it is finished.

A 4-factor 3-level Box-Behnken experimental design plan was used. The variables and their coded and actual levels are given in Table 3. The values of variables at 0 levels are based on the general practice of the handmade carpet industry. Other values at -1 and +1 levels are one step higher and one step lower respectively, than values at 0 levels.

2.2 Methods

2.2.1 Knot Density

Number of knots in Persian handmade wool carpets was determined as per IS: 7877 (Part III) – 1976 (Reaffirmed 1997), which is equivalent to ISO 1763-1973, by using a rule capable of measuring to the nearest millimeter. This parameter was measured at the back of carpet in length-wise and width-wise directions.

2.2.2 Pile Height

The pile height of carpets was measured as per IS: 7877 (Part IV) – 1976 (Reaffirmed 1997), which is equivalent to ISO 2549-1972, using flat metal gauges of known height.

2.2.3 Compressional Properties

The thickness of a carpet specimen was measured as the distance between the reference plate on which carpet rests and a parallel circular presser-foot. Carpet sample size for this test was 125 mm ×125 mm. Specimen was placed on the base plate so that no part of the presser foot was within 20 mm of the edge of the specimen or within 75 mm of any previous measurement. The presser foot was lowered smoothly on the specimen to apply a pressure of 2 kPa and after 30s the gauge reading was noted. Without raising the presser foot, extra mass was added carefully to increase the pressure to 5 kPa and gauge reading was noted after 30s. This procedure was continued for pressure levels of 10, 20, 50, 100, 150 and 200 kPa and the gauge reading, in each case, was noted when the pressure has been applied for 30s. Immediately after taking the gauge reading at the highest pressure, the pressure was reduced to 150 kPa. The gauge reading was again noted after 30s and then pressure was reduced to 100 kPa. The recovery cycle was continued till the original pressure of 2 kPa was reached. For each sample, 5 readings were taken and then the average was calculated. Figure 2 depicts the typical thickness-pressure curve. SDL carpet thickness gauge (Digital) was used for conducting this test as per BS 4098: 1975 (Reaffirmed 1982) standards. Following parameters were calculated with the help of observed readings

- ***Carpet thickness at 2 kPa*** – The mean initial thickness of the carpet at 2 kPa.
- ***Compression (t_2 - t_{200})*** – The change in thickness of the carpet when the pressure is increased from 2 kPa to 200 kPa.
- ***Percentage Compression Recovery*** – The change in thickness when the pressure is reduced from 200 kPa to 2 kPa expressed as a percentage of the compression. Numerically, it is expressed as

$$\left(\frac{t_r - t_{200}}{t_2 - t_{200}}\right)\times 100$$

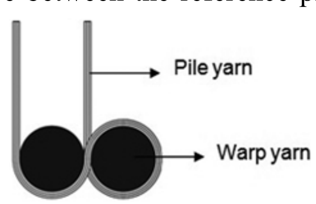

Fig. 1 — Persian knot

Table 3 — Coded and actual levels of variables

Variables code	Variables	Levels		
		-1	0	+1
x_1	Knot density, inch^{-1} (knots/inch in each direction)	5	6	7
x_2	Pile height, mm	10	13	16
x_3	Number of ply (pile yarn)	2	3	4
x_4	Pile yarn twist, tpi	3.5	4	4.5

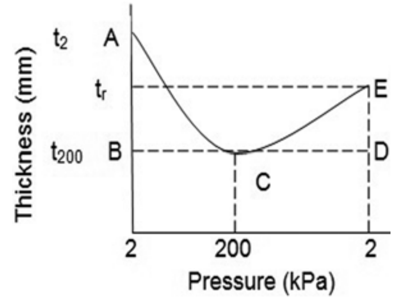

Fig. 2 — Typical thickness-pressure curve for textile floor coverings (Source: BS 4098: 1975)

2.3 Response Surface Methodology

Response surface methodology (RSM) is a set of mathematical and statistical procedures, useful for the modeling and analysis of problems in which a response is influenced by some independent variables. The most common forms of RSM are the first or second order models[18]. A second order (quadratic) model is shown below:

$$y = \beta_0 + \sum_{i=1}^{h} \beta_i x_i + \sum_{i=1}^{h} \beta_{ii} x_i^2 + \sum_{i=1}^{h-1} \sum_{j=i+1}^{h} \beta_{ij} x_i x_j + \varepsilon \quad \ldots (1)$$

where y is the process response; x_1, x_2,… x_h are the independent variables; β_o, β_i, β_{ii} ($i = 1,2,...,h$), β_{ij} ($i = 1, 2,..., h$; $j = 1, 2,..., h$) are the constant term and coefficients for linear, quadratic and interaction terms respectively; and ε is a random experimental error term assumed to have a zero mean. The most common second order RSM design is Box-Behnken design (BBD). This is a three-level design based on the construction of a balanced incomplete block design. The BBD is an efficient option for fitting response surfaces using three evenly spaced levels[19]. In 4-factors and 3-levels BBD, twenty-seven experiments are conducted, whereas in a full factorial design 3^4 or 81 experiments will be needed.

3 Results and Discussion

3.1 Response Surface Model for Compression Behavior

Table 4 presents the details of experimental and predicted results for the compression and compression recovery of Persian hand knotted carpets. From the experimental results (Tables 4-6) the following response surface equations are obtained:

$$\begin{aligned} y = &-120.021 + 18.374x_1 + 3.576x_2 - 5.103x_3 + 28.702x_4 \\ &+0.016x_1x_2 + 0.015x_1x_3 - 1.525x_1x_4 + 0.201x_2x_3 - 0.568x_2x_4 \\ &+1.975x_3x_4 - 0.945x_1^2 - 0.065x_2^2 - 0.785x_3^2 - 2.343x_4^2 \end{aligned} \quad \ldots (2)$$

$[R^2=0.808]$

$$\begin{aligned} y = &-308.010 + 50.978x_1 - 8.722x_2 + 38.992x_3 + 94.705x_4 \\ &+0.241x_1x_2 - 0.914x_1x_3 - 8.215x_1x_4 + 0.478x_2x_3 - 0.355x_2x_4 \\ &-5.640x_3x_4 - 0.956x_1^2 + 0.246x_2^2 - 1.577x_3^2 - 2.898x_4^2 \end{aligned} \quad \ldots (3)$$

$[R^2=0.918]$

These equations contain 14 terms arising from 4, 6 and 4 linear, interaction and quadratic terms respectively.

The coefficient of determination (R^2) of Eq. (2) relating compression of Persian hand knotted carpet with four input parameters is found 0.808. This implies that the model can explain around 81% variability present in the experimental data. Besides, only one sample (out of 27) is showing more than 10 % prediction error. Therefore, it can be inferred that the derived model is quite accurate in terms of prediction accuracy. The coefficient of determination (R^2) of the Eq. (3) relating per cent compression recovery of Persian hand knotted carpets with four input parameters is found 0.918.

The ANOVA results of compression and compression recovery models are shown in Tables 5 and 6 respectively. The significance of the entire model and each of the coefficients was checked by using F-test and the associated p-value. If the p-value is less than 0.05 then the model is statistically significant at 95 % level. The F value of 3.60 for the compression model indicates that it is significant and there is only 1.6 % chance that an F-value as large as this could occur (Table 5). In the ANOVA for compression of Persian handmade wool carpets (Table 5), x_1 (knot density), x_2 (pile height), x_3 (number of ply), interaction term of x_3x_4 (number of ply × pile yarn twist) as well as the quadratic terms x_1 (knot density^2) are statistically significant. If the p-value is greater than 0.1, then the model term is not significant. In this research, knot density has been expressed by the number of knots in one inch length. Therefore, the actual number of knots per unit area can be obtained by multiplying the knot density in warp and weft directions. Therefore, the parameter x_1^2 in compression model [Eq. (2)] becomes significant.

It is observed from ANOVA of per cent compression recovery of Persian hand knotted wool carpets [Table 6] that x_1 (knot density), x_2 (pile height), x_3 (number of ply) and interaction term of x_1x_4 (knot density × pile yarn twist) are statistically significant. The pile yarn twist (x_4) is neither influencing compression nor influencing compression recovery significantly.

3.2 Analysis of Contour Plots

Figure 3 depicts the effect of knot density and number of ply in pile yarn on the initial carpet thickness of Persian hand knotted wool carpets at 2 kPa. It is observed that initial carpet thickness increases with the increase in knot density and number of ply in pile yarn. The maximum initial carpet thickness occurs at the higher values of knot density (7 knots/inch) and number of ply in pile yarn (4 ply) because there is less space between pile yarns for deformation and displacement in dense carpets[13].

Figures 4 and 5 depict the influence of two carpet construction parameters (knot density and pile height) on the compressional behavior of Persian hand knotted wool carpets. It is observed that compression increases with the increase in pile height. This can be attributed to the fact that bending moment increases with the increase in pile height even at the same compressive force[13]. For the same level of pile height, the compression increases with the increase in knot density in Persian hand knotted carpets. The reduction in thickness of the carpet with the increase in pressure

Table 4 — Compression parameters of Persian hand knotted wool carpets

Knot density inch^{-1}	Pile height mm	Number of ply (pile yarn)	Pile yarn twist tpi	Carpet thickness at 2 kPa mm (CV %)	Actual compression mm (CV %)	Predicted compression mm	Error %	Actual compression recovery, % (CV %)	Predicted compression recovery, %	Error %
5	10	3	4	19.15 (2.09)	10.03 (2.21)	9.97	0.65	62.05 (3.36)	62.11	0.10
5	16	3	4	22.34 (5.89)	12.93 (2.72)	11.75	9.15	58.63 (5.30)	55.47	5.39
7	10	3	4	19.09 (2.11)	11.28 (2.75)	12.24	8.54	72.26 (4.75)	74.74	3.44
7	16	3	4	23.26 (1.38)	14.37 (3.13)	14.22	1.06	71.73 (2.77)	70.99	1.03
5	13	2	4	18.32 (6.62)	10.84 (2.18)	9.88	8.85	43.48 (7.81)	46.38	6.67
5	13	4	4	21.14 (1.86)	11.38 (7.10)	11.43	0.45	60.92 (7.86)	63.62	4.43
7	13	2	4	19.92 (2.42)	12.49 (5.61)	12.23	2.12	62.34 (4.40)	62.29	0.09
7	13	4	4	22.23 (1.74)	13.09 (3.34)	13.84	5.69	76.13 (4.53)	75.87	0.34
5	13	3	3.5	17.37 (6.25)	9.53 (5.81)	10.42	9.32	50.92 (6.02)	51.40	0.93
5	13	3	4.5	17.67 (4.03)	9.79 (7.71)	11.29	15.34	63.41 (5.36)	60.31	4.90
7	13	3	3.5	24.59 (1.72)	15.17 (2.13)	14.32	5.62	72.69 (3.42)	73.69	1.38
7	13	3	4.5	20.81 (1.46)	12.38 (2.75)	12.14	1.93	68.75 (2.63)	66.17	3.75
6	10	2	4	18.88 (2.90)	10.63 (5.94)	11.08	4.21	64.44 (1.96)	61.53	4.51
6	10	4	4	20.31 (2.25)	11.08 (5.18)	11.45	3.35	78.01 (3.70)	74.08	5.04
6	16	2	4	19.24 (3.61)	11.47 (5.29)	11.75	2.43	51.65 (6.57)	53.47	3.52
6	16	4	4	25.75 (0.06)	14.33 (5.59)	14.54	1.43	70.95 (7.94)	71.75	1.13
6	10	3	3.5	19.36 (4.04)	11.48 (5.67)	10.94	4.73	68.58 (4.05)	67.78	1.17
6	10	3	4.5	20.88 (2.93)	13.03 (3.69)	11.99	7.98	64.50 (4.05)	69.54	7.81
6	16	3	3.5	21.97 (2.67)	13.69 (6.23)	14.52	6.05	66.05 (7.09)	63.65	3.64
6	16	3	4.5	20.01 (1.89)	11.83 (5.44)	12.16	2.82	59.84 (6.93)	63.28	5.75
6	13	2	3.5	19.52 (8.96)	12.32 (1.69)	12.73	3.29	51.23 (8.21)	51.40	0.32
6	13	2	4.5	17.05 (6.31)	9.79 (8.92)	10.10	3.16	59.82 (4.97)	57.73	3.49
6	13	4	3.5	21.21 (3.37)	12.86 (4.26)	12.33	4.12	71.03 (2.61)	72.45	1.99
6	13	4	4.5	23.39 (2.45)	14.28 (3.55)	13.65	4.38	68.34 (5.04)	67.50	1.22
6	13	3	4	22.28 (5.83)	14.12 (9.03)	13.57	3.87	62.46 (1.25)	64.57	3.38
6	13	3	4	22.19 (4.83)	13.89 (7.16)	13.57	2.28	63.94 (2.41)	64.57	0.99
6	13	3	4	21.11 (1.76)	12.60 (3.68)	13.57	7.72	67.38 (4.37)	64.57	4.17

Table 5 — ANOVA for compression of Persian hand knotted wool carpets

Source	Sum of squares	Degrees of freedom	Mean square	F value	*p*-value Prob > F
Model	52.96	14	3.78	3.60	0.0160
Knot density (x_1)	16.99	1	16.99	16.18	0.0017
Pile height (x_2)	10.25	1	10.25	9.76	0.0088
Number of ply (x_3)	7.49	1	7.49	7.13	0.0204
Pile yarn twist (x_4)	1.30	1	1.30	1.24	0.2877
$x_1 x_2$	9.025E-003	1	9.025E-003	8.592E-003	0.9277
$x_1 x_3$	9.000E-004	1	9.000E-004	8.568E-004	0.9771
$x_1 x_4$	2.33	1	2.33	2.21	0.1626
$x_2 x_3$	1.45	1	1.45	1.38	0.2625
$x_2 x_4$	2.91	1	2.91	2.77	0.1221
$x_3 x_4$	3.90	1	3.90	3.71	0.0780
x_1^2	4.76	1	4.76	4.53	0.0547
x_2^2	1.83	1	1.83	1.74	0.2114
x_3^2	3.28	1	3.28	3.13	0.1025
x_4^2	1.83	1	1.83	1.74	0.2114
Residual	12.60	12	1.05		
Cor Total	65.57	26			

Table 6 — ANOVA for compression recovery of Persian hand knotted wool carpets

Source	Sum of Squares	Degrees of freedom	Mean square	F value	*p*-value Prob > F
Model	1571.47	14	112.25	9.53	0.0002
Knot density (x_1)	594.88	1	594.88	50.53	< 0.0001
Pile height (x_2)	80.03	1	80.03	6.80	0.0229
Number of ply (x_3)	711.79	1	711.79	60.46	< 0.0001
Pile yarn twist (x_4)	1.44	1	1.44	0.12	0.7324
$x_1 x_2$	2.09	1	2.09	0.18	0.6811
$x_1 x_3$	3.33	1	3.33	0.28	0.6045
$x_1 x_4$	67.49	1	67.49	5.73	0.0339
$x_2 x_3$	8.21	1	8.21	0.70	0.4201
$x_2 x_4$	1.13	1	1.13	0.096	0.7616
$x_3 x_4$	31.81	1	31.81	2.70	0.1262
x_1^2	4.87	1	4.87	0.41	0.5321
x_2^2	26.21	1	26.21	2.23	0.1615
x_3^2	13.27	1	13.27	1.13	0.3094
x_4^2	2.80	1	2.80	0.24	0.6346
Residual	141.29	12	11.77		
Cor Total	1712.76	26			

from 2 kPa to 200 kPa is more at higher knot density level due to higher initial carpet thickness at maximum knot density. From Fig. 4, it can be inferred that the lowest compression can be achieved with lower pile density and lower pile height. From Fig. 5, it is observed that when pile height increases, the per cent compression recovery decreases. It has already been reported in literature that at a constant pile density, lower pile height gives less compression and higher per cent compression recovery, whereas higher pile height gives more compression and lower per cent compression recovery[10]. When knot density is increased, the per cent compression recovery increases because the recovered thickness of the denser carpet is higher due to the tightly packed structure[14]. From Fig. 5, it is clearly observed that highest compression recovery can be achieved with higher pile density and lower pile height.

Figures 6 and 7 depict the effect of number of ply in pile yarn and pile yarn twist on compression and compression recovery of Persian hand knotted carpets respectively. The minimum compression occurs at the minimum number of ply (2 ply) in pile yarn and maximum value of pile yarn twist (4.5 tpi). The two

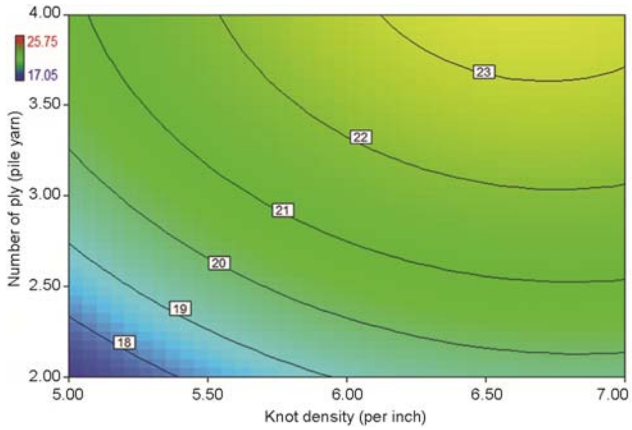

Fig. 3 — Effect of knot density and number of ply in pile yarn on carpet thickness at 2 kPa

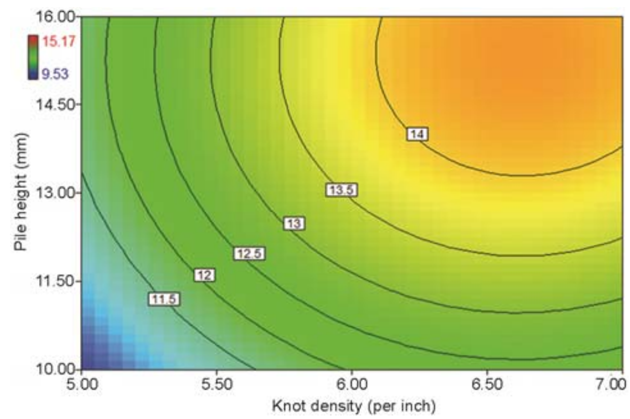

Fig. 4 — Effect of knot density and pile height on compression

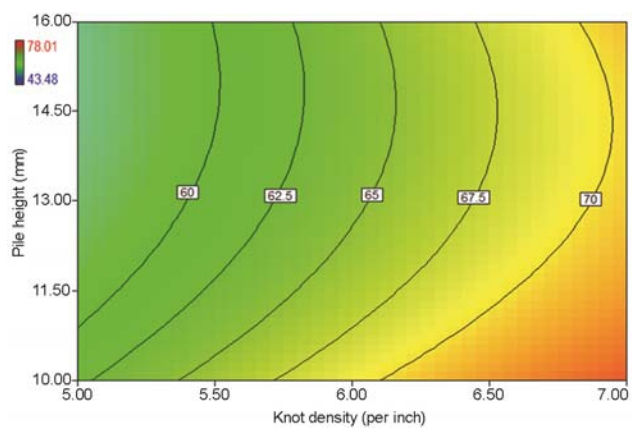

Fig. 5 — Effect of knot density and pile height on per cent compression recovery

ply yarns might have become very stiff with high twist per inch causing less compression. However, maximum compression recovery occurs at the maximum number of ply in pile yarn (4 ply) and the lowest value of pile yarn twist (3.5 tpi). This may be

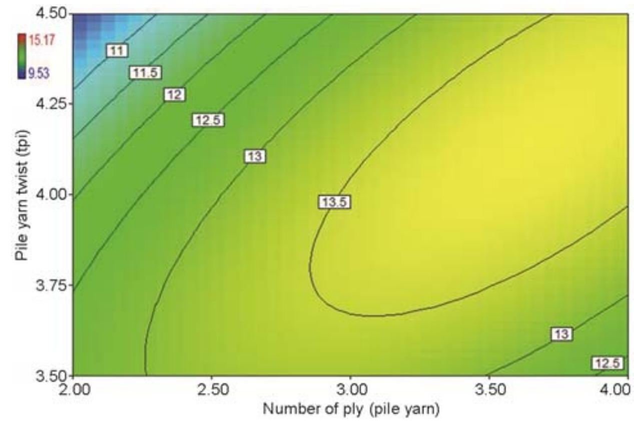

Fig. 6 — Effect of number of ply in pile yarn and pile yarn twist on compression

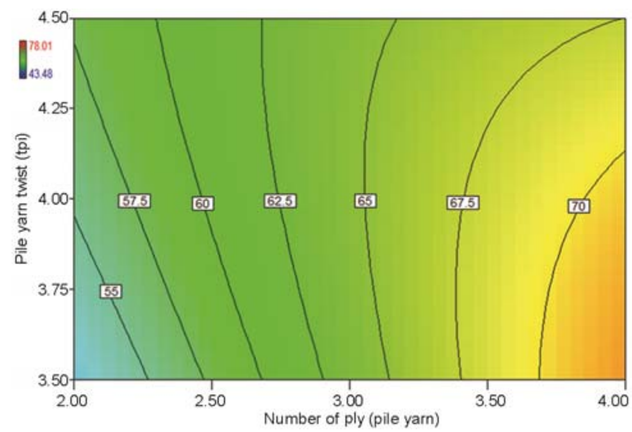

Fig. 7 — Effect of number of ply in pile yarn and pile yarn twist on per cent compression recovery

attributed to the higher capacity of coarse yarn to recover from bending deformation. It is also noted from Fig. 7 that the effect of number of plies in pile yarn is very dominant on compression recovery.

3.3 Contribution of Parameters

Table 7 presents the per cent contribution of various terms on the compressional parameters (compression and per cent compression recovery) of Persian handmade wool carpets. The per cent contribution was calculated by taking individual sum of squares of a term and dividing it by the total sum of squares and then multiplying the resultant value by 100. When all the parameters have the same degrees of freedom, the % contributions can be used to determine which terms are larger contributors than others. Knot density (x_1), pile height (x_2) and number of ply (x_3) contribute 29.13, 17.57 and 12.84 % respectively to compression; whereas knot density (x_1) and number of ply (x_3) contribute 38.40 and 45.94 % respectively to per cent compression recovery. The

Table 7 — Per cent contribution of input parameters on compressional behavior

Parameters	Compression		Per cent compression recovery	
	Sum of squares	Per cent contribution	Sum of squares	Per cent contribution
Knot density (x_1)	16.99	29.13	594.88	38.40
Pile height (x_2)	10.25	17.57	80.03	5.17
Number of ply (x_3)	7.49	12.84	711.79	45.94
Pile yarn twist (x_4)	1.30	2.23	1.44	0.09
$x_1 x_2$	9.025E-003	0.02	2.09	0.14
$x_1 x_3$	9.000E-004	0.0015	3.33	0.22
$x_1 x_4$	2.33	3.99	67.49	4.36
$x_2 x_3$	1.45	2.49	8.21	0.53
$x_2 x_4$	2.91	4.99	1.13	0.07
$x_3 x_4$	3.90	6.69	31.81	2.05
x_1^2	4.76	8.16	4.87	0.31
x_2^2	1.83	3.14	26.21	1.69
x_3^2	3.28	5.62	13.27	0.86
x_4^2	1.83	3.14	2.80	0.18

role of pile yarn twist is almost negligible in explaining the compression behavior.

4 Conclusion

The influence of carpet construction parameters (knot density, pile height) and pile yarn parameters (number of ply in pile yarn and ply yarn twist level) on the compressional behavior of Persian hand knotted wool carpets has been investigated using design of experiment methodology. The compression of Persian hand knotted wool carpets decreases with the reduction in knot density, pile height and number of ply in pile yarn. Another compressional parameter (compression recovery) increases with the increase in knot density and number of ply in pile yarn and reduction in pile height. Therefore, low pile height should be kept for achieving low compression and high compression recovery in Persian hand knotted wool carpets. However, pile density and number of ply in pile yarn need to be optimized to achieve desired level of compression behaviour. The influence of pile yarn twist does not have any significant influence on the compression behaviour of Persian hand knotted wool carpets

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