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Investigation of Compressional Creep Behaviour of Persian Hand-woven Carpet During Simulated Storage under Different Environmental Conditions

Abstract

In this research, an apparatus was designed and constructed in order to simulate the storage behaviour of hand-woven carpet under different environmental conditions. Hand-woven carpet ("Isfahan") with 127×83 cm dimensions and 79×84 knot per 10 cm was selected and then inserted into a designed packing simulator with two different laying configurations: flat and folded. The environmental conditions were adjusted at 3 different climatic conditions: 25 ± 5% r.h and 30 ± 2 °C (July-Tehran-Dry), 65 ± 5% r.h and 6 ± 2 °C (February-Tehran-humid), 40 ± 5% r.h and 19 ± 2 °C (October –Tehran-mild). The carpet sample was compressed under constant loads of 170 and 190 kg for folded and flat configurations, respectively. The variation of carpet thickness with time in different parts of the carpet was continuously measured using a data acquisition system. The result of the experiment shows that carpet thickness suddenly decreases in a short period of time, and then reaches a stable condition. The variation trend of carpet thickness with time is in accordance with a logarithm equation ($y=a \times \ln(t)-b$), which is in complete agreement with the Eyring model proposed in creep theory. Generally, in humid conditions, maximum carpet thickness variation occurred at the folded point of the folded configuration. On the other hand, carpet thickness variations in dry conditions are less than those in humid and mild conditions. In addition, carpet thickness in dry conditions more quickly reaches a stable state condition than those in humid and mild conditions.

Key words: persian hand-made carpet, environmental conditions, creep, eyring model, simulation.

Introduction

How to store carpets

Hand-woven Iranian carpets are stored and preserved in a variety of ways and methods before export. The most important ones are flat; placing carpets of the same dimension on each other horizontally, and folded using a method in which the carpets are folded and placed on each other lengthwise [1].

In this method the carpets are sorted out in accordance with their origin, mate-

rial, size and weave style. They are then placed on a slatted wooden pallet, which is 20 cm above the ground. The height of the packed carpets in this method is about 110 cm and the approximate force being exerted on the last carpet underneath would be related 190 kg. In the folded method, the general height remains unchanged; the force being applied to the last underneath carpet would be related to 170 kg; and the folds of each carpet would be similar, which therefore reduces the occupied space to one half of the space needed by the flat method [2].

Though economically advantageous from this point of view, the folded method, depending on the environmental conditions and the duration of remaining folded, would change the physical features of the carpets [3].

The duration of storage under such conditions would last 2 - 7 days, and the stores are mostly in bazaars, where there is no control over the rate of moisture and temperature [2]. Figure 1 shows two methods of storage.

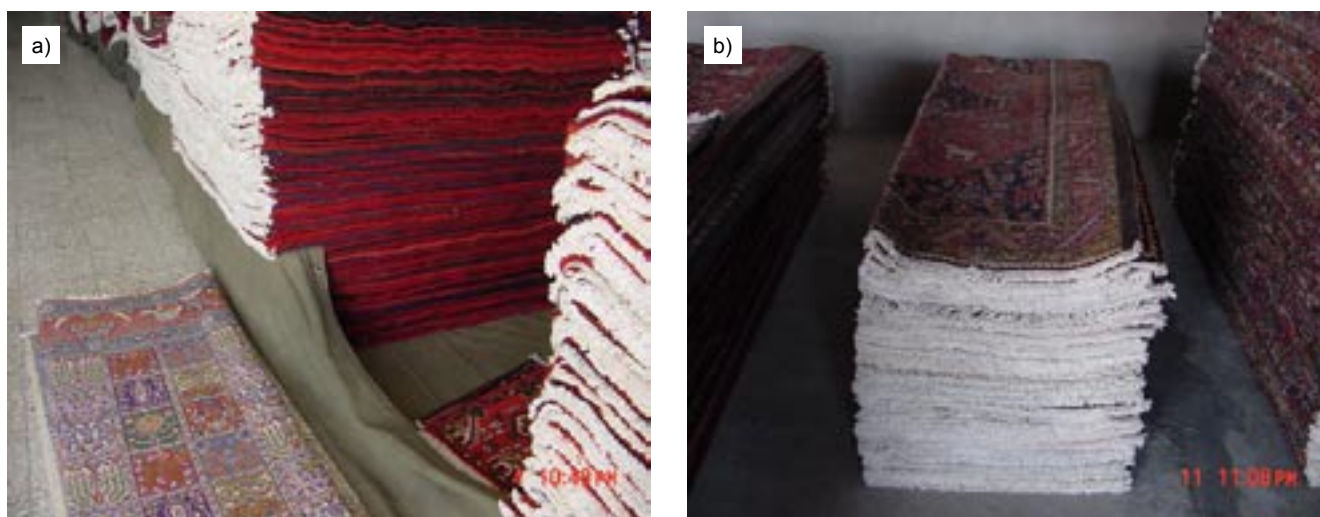


Figure 1. Methods of storage; a) flat, b) folded.

Table 1. Specifications of the Persian carpet (average values).

Dimensions, cm × cm	127.73×83.46
numbers of knots per 10×10 cm	79×84
Pile height, mm	3.96
Thickness, mm	6.46

Table 2. Environmental conditions.

Climate	Moisture, %	Temperature, °C
Mild	40 ± 5	19 ± 2
Humid	65 ± 5	6 ± 2
Dry	25 ± 5	30 ± 2

■ Compressional creep

In 1989, Carnaby and Wood placed a carpet under gradual compression to study the thickness changes after compression recovery. The experiment revealed a reduction in the thickness in the early phase, but then stopped despite the continuation of the increase in the compressing force. After the removal of this force, the thickness resumed increasing [4]. Another experiment was also carried out and showed a non-linear relationship between the applied pressure and resulting strain for a pile of carpets [4].

In 2002, Mir-Jalili studied the thickness variations of a Persian hand-woven carpet with 25 and 35 knots per 6.5×6.5 cm² area, under the effect of a 24 hour static load of 7 kg/cm². The results indicate that much of the changes in thickness occurred in the early stages of compression and then slows down to a steady state condition. The experiment also showed that the rate of decrease in thickness is inversely proportional to an increase in the number of knots per unit area. This, however, has no effect on the trend of thickness changes in the early hours of carpet loading [5].

In 2003, Bassam measured the changes in the thickness of Persian hand-made

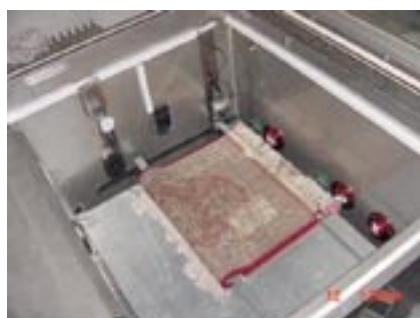


Figure 2. Typical photos of the simulator apparatus to measure the compression creep behaviour of carpet.

carpets with different numbers of knots per unit area [6]. This experiment was carried out under the conditions of a constant load of 1.5 kg for a duration of 2 hours and a circular area of 3.5cm diameter. The results show that the thickness change in carpets with asymmetrical knots is less than that of carpets with symmetrical knots. This research also revealed that carpets with symmetrical and asymmetrical knots could lose half of their thickness in less than half an hour of static loading [6].

It may be considered that there is no published research work to study the compression creep behaviour of Persian hand-made carpet under different environmental conditions. Therefore, the objectives of this research are to investigate the compressional creep behaviour of Persian hand-woven carpet ("*Isfahan*") under different environmental conditions in order to obtain suitable storage for carpets. In this work, a packing simulator apparatus was designed and constructed in order to simulate the storage behaviour of hand-woven carpet under three different environmental conditions (dry, humid and mild). Thus, the compressional creep behaviour of Isfahan hand-woven carpet with two flat and folded laying configurations was investigated using a data acquisition system.

■ Material and method

In this research, a hand-woven Persian carpet, "*Isfahan*", was used. Two different ways of flat and folded configurations and three environmental conditions; mild, humid, and dry, were considered. The thickness of the carpet was measured under two different constant loads of 190 kg (for flat) and 170 kg (for folded) for 48 hours.

The specification of the carpet used in this research is given in Table (1). The

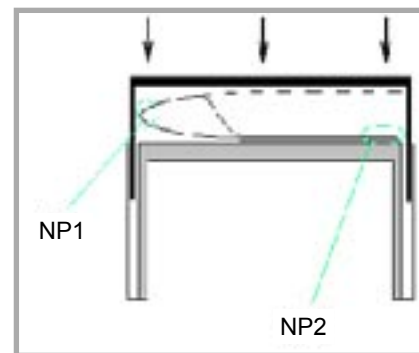


Figure 3. A schematic diagram of the experimental set-up for carpet compression.

Warp and weft of the carpet were silk and cotton yarns, respectively. The carpet pile was mainly of wool yarn and partially of silk yarn. The Persian carpet used in this research had a "ZEL-ol-Soltan" pattern; its knot was asymmetrical; and in every carpet row, there were two wefts involved. The dimensions and the number of knots per unit area were measured with a precision of 0.5 mm, based on Iranian Standards No. 500 and No. 456. The height of the pile and primary thickness were also measured based on Standards ISO2949 and ISO1765 respectively.

To determine the environmental conditions for this research, changes in the environmental conditions in the city of Tehran were obtained from 13 synoptic sites of the Meteorological Bauer, and the average of the temperature degrees in the course of a whole year was computed. Then, the months of October, February, and July were chosen as the months when environmental conditions would demonstrate fully mild, humid and dry cases. Table 2 shows the environmental conditions considered in the current research work.

To investigate the compression creep behaviour of the Persian hand-made carpet under the different environmental conditions, a packing simulator with a dimension of 185×125×135 cm was designed and constructed. A typical picture of this apparatus is shown in Figure 2. This simulator has an inside chamber with dimensions of 110×110×110 cm. A pressing system with a surface area of 70×80 cm was installed, which has the capability of taking loaded with loads of 35 kg to 350 kg. A schematic picture of this pressing system is shown in Figure 3. In this set-up, the environmental conditions, including the temperature and relative humidity of the chamber,

Table 3. Regression equations for the compression creep behaviour of Persian carpet in different environmental and laying configurations.

area condition	(NP1)	(NP2)	(TP)
Mild	0.4364 ln(x) - 0.4963 R ² = 0.8615	0.1521 ln(x) - 0.5021 R ² = 0.4228	0.2879 ln(x) - 1.4275 R ² = 0.8139
Humid	0.5931 ln(x) - 1.6829 R ² = 0.9187	0.4259 ln(x) - 2.5468 R ² = 0.8187	0.5481 ln(x) - 2.6085 R ² = 0.7518
Dry	0.4458 ln(x) - 3.0537 R ² = 0.7439	0.1151 ln(x) - 0.3964 R ² = 0.1815	0.2568 ln(x) - 1.4231 R ² = 0.8173

can be changed from zero to 60 °C and 10% to 95% r.h, respectively.

In order to measure the carpet thickness variation, a special aluminum bar with dimensions of 30×90×0.5 cm was used and placed in the area of compression loading. In the case of flat configuration, the bar is usually placed at a distance of 63 ± 5 cm from the end of the carpet (called Tp area). In the case of folded configuration, the bar is placed at the folded point (known as NP1), and also at a distance of 115 ± 5 cm from the end of the carpet, which is referred to as the NP2 area. The variation height of the bar is registered using an indicator and data acquisition system. Each indicator is connected through an Interface (RS232C) to the serial ports of a PC, through which the average changes in the thickness of the carpet is transferred regularly, every 10 minutes by the serial commands of a multi-timer designed (C.K.Ts) placed into the PC. The first data are given to the PC, 30 ± 5 seconds after loading the carpet. Therefore, two different ways of flat and folded configurations and three environmental conditions; mild, humid, and dry, was considered, and carpet thicknesses were measured under two different constant loads of 190 and 170 kg, respectively, for flat and folded configurations over 48 hours. Thus, the compressional creep behaviour of carpet is measured and studied in this research.

Statistical curve fitting method

To determine the best linear equation, which may fit on the curve, the least square method was used. In this method, three concretely linear and two non-linear forms were fitted to the data in order to select the best fit by means of 'Evaluation-of-All-Available Equation'.

■ A concretely linear, linear form:

$$Y = a \times X \quad (1)$$

■ Concretely linear, non-linear forms

$$Y = a \times X^2 \pm b \times X \quad (2)$$

$$Y = a \times \ln(X) - b \quad (3)$$

■ Non-linear, concretely non-linear forms

$$Y = a \times X^b \quad (4)$$

$$Y = a \times e^X \quad (5)$$

In this method, the curve fitted to the data was first hypothesised in the form of a 'Linear Equation of Growth' or a 'Catalectic, Logarithmic Non-Linear Equation' and then subjected to analysis.

In the method of 'Evaluation-of-all-the Available-Equations', the equations with maximum coefficient correlation were first selected so as to remove the descending or emphatically descending ones; then, the equation whose computed (s²) was approximately zero was chosen for computation of their Mallow's coefficient, and those which have the closest to the unit value were picked out. In all computations, care must be taken to find and analyse non-standard data by means of 'Estevansky's equation' and remove them from the batch, which is to be considered in the process of computation. Based on the hypothesised 'Growth Equation' for the curve fitted to the data, the equations whose correlation coefficient was much too small and nominal, and the equation which has the least non-standard and non-collective data, were picked out without taking into consideration their rate of R².

$$C_p = R_{ssp} + s^2 \quad (6)$$

$$d_i = e_i + \sqrt{MSD} \quad (7)$$

(Estevansky Equation)

where:

C_p - Mallow's Coefficient

R_{ssp} - standard deviation of standardised residual square.

$$e_i = Y_i - \hat{Y}_i \quad (8)$$

$$s^2 = \sum e_i + (N - 2 \times P) \quad (9)$$

where:

N - the number of given data

P - the number of the related variables representing time and is always equal to one.

MSD - mean square difference

$$MSD = \sum e_i + (N - 2) \quad (10)$$

and as a result it is always equal to S².

Result and discussion

Modelling of the compression creep behaviour of Persian carpet for different environmental and folding configurations:

Table 3 represents regression equations that explain the compression creep behaviour of Persian carpet. These equations are obtained through the process of curve fitting to measured data.

Figures 4 to 6 show the compression creep trend of Persian carpet under different environmental conditions and laying configurations. Regarding the regression equations obtained, it can be considered that all the equations are in the non-linear, concretely linear form of

$$Y = a_1 \times \ln(t) - b_1,$$

which is very similar to that of the equation proposed in the Eyring model to describe the creep behaviour of textile fibres. It is also shown that only in dry environmental conditions within the area NP2, where the lowest compression strain occurs, the lowest correlation coefficient is obtained.

Based on the Eyring model, the following equation is presented to explain the creep behaviour of textile fibres [7]:

$$Y = (y_\infty/\alpha) \times f_c \times \ln(1 + At) + y_0 \quad (11)$$

in which,

$$A = \left[\alpha \times \kappa \times f_c \times \left(1 - \frac{y_0}{y_\infty} \right) \right] \times \left[Y_\infty \times \ln \left(\coth \left[\frac{\alpha \times f_c \times \left(1 - \frac{y_0}{y_\infty} \right)}{2} \right] \right) \right] \quad (12)$$

were:

T - time,

Y₀ - immediate strain,

Y_∞ - ultimate strain,

f_c - constant Force, and

α & κ are constant coefficients.

Now, assuming that $a = Y_\infty/\alpha \times f_c$, it can be concluded that

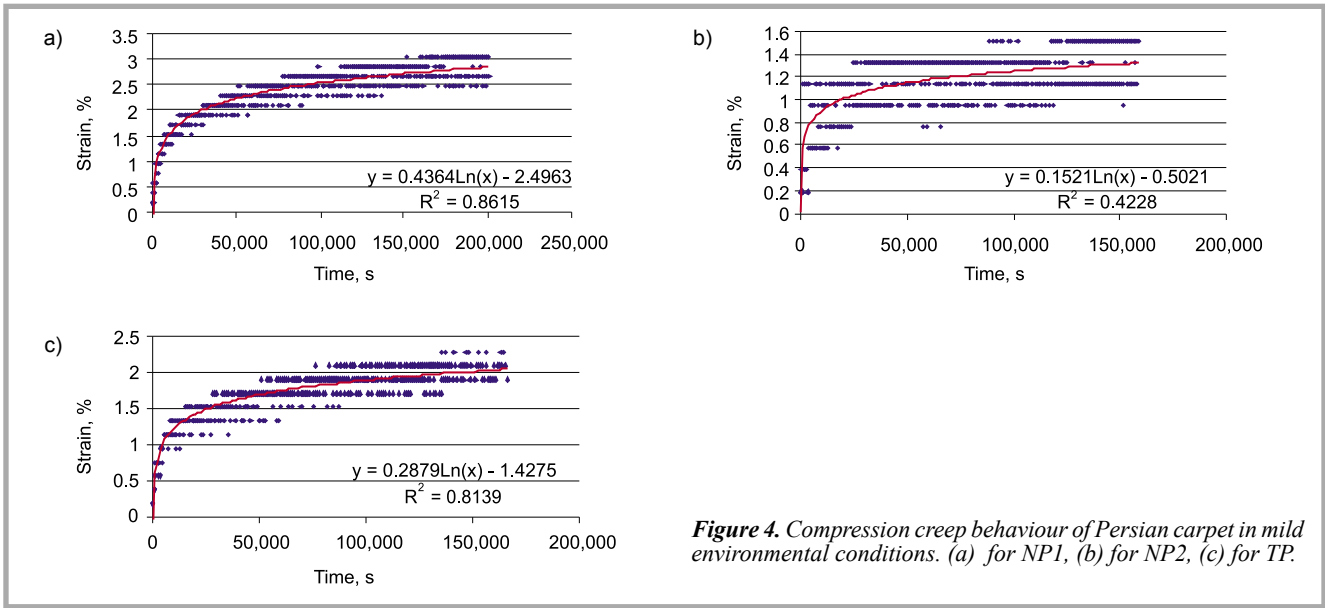


Figure 4. Compression creep behaviour of Persian carpet in mild environmental conditions. (a) for NP1, (b) for NP2, (c) for TP.

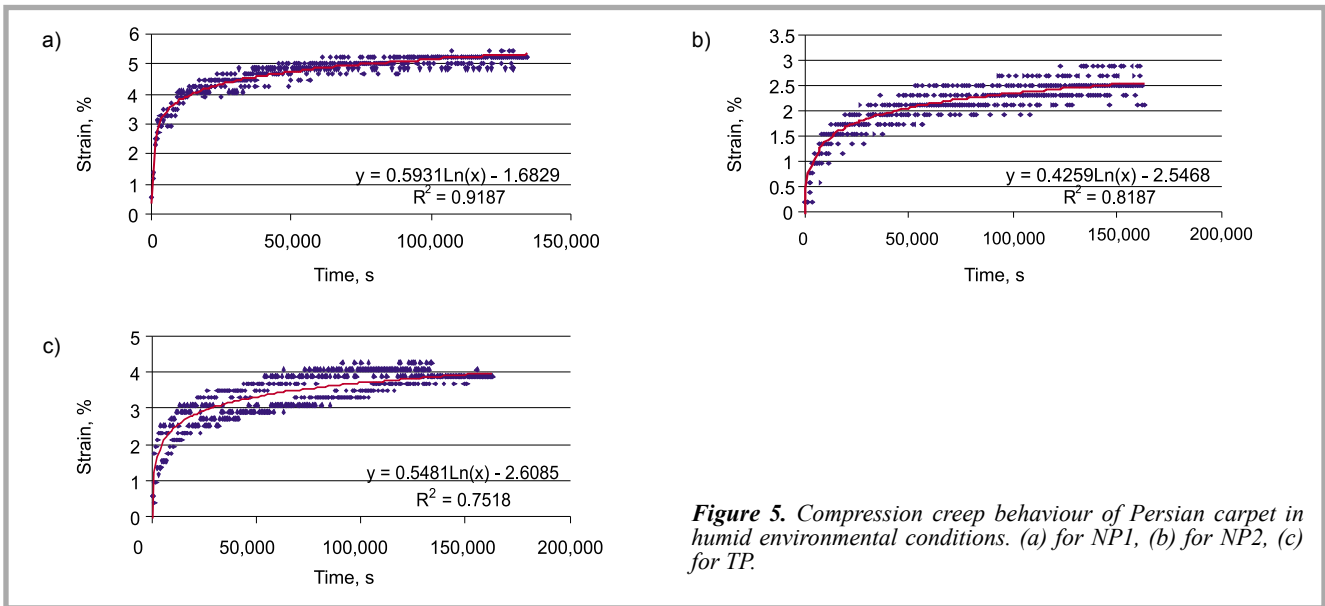


Figure 5. Compression creep behaviour of Persian carpet in humid environmental conditions. (a) for NP1, (b) for NP2, (c) for TP.

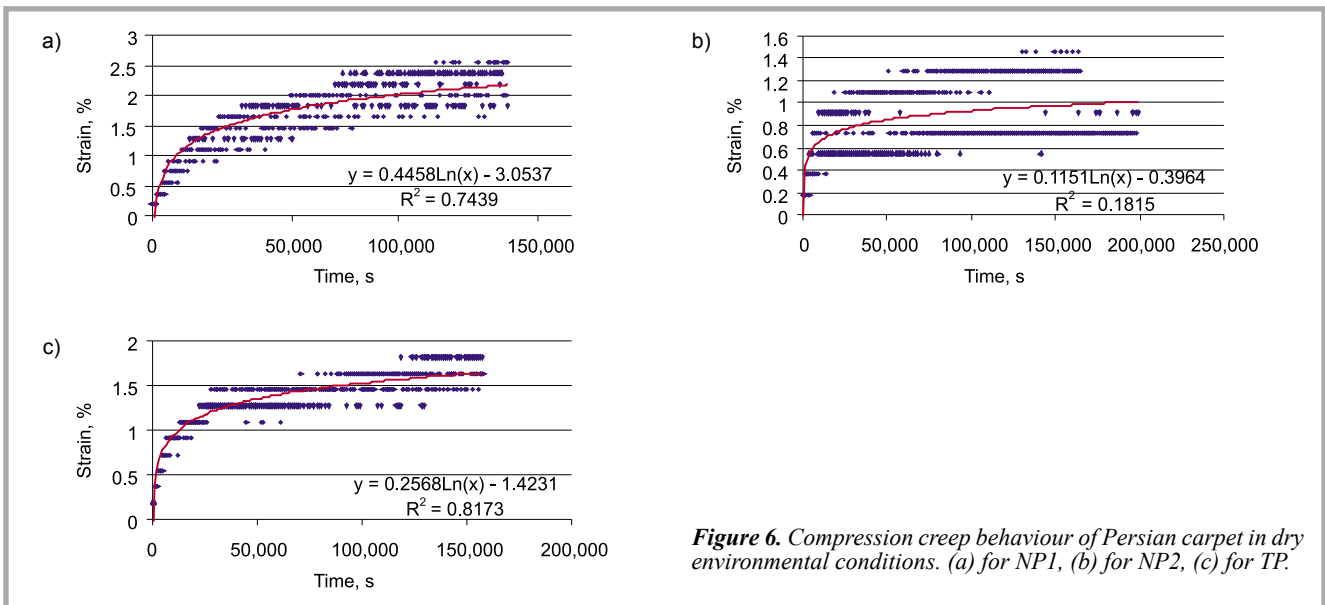


Figure 6. Compression creep behaviour of Persian carpet in dry environmental conditions. (a) for NP1, (b) for NP2, (c) for TP.

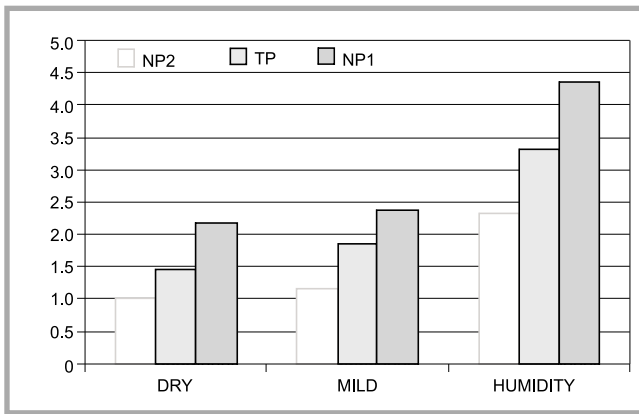


Figure 7. Carpet compressibility values obtained for different methods of folding configurations along with different environmental conditions.

$$y = a \times \ln(T) - y_0 \quad (13)$$

in which T is the function t and A .

In this case, the form of compression creep is virtually the same as equation (13). It should be noted that the computed form is only true for describing the primary creep and if the immediate strain ' y_0 ' is added to both sides, the resulting form could be regarded as similar the equation (13).

$$y_1 + y_0 = a_1 \times \ln(t) + (y_0 - b_1) \quad (14)$$

$$Y = a_1 \times \ln(t) + Y_0 \quad (15)$$

In this case,

$$Y = y_1 + y_0 \quad (16)$$

$$Y_0 = (y_0 - b_1) \quad (17)$$

By comparing equations (13) and (15), it can be implicated that the parameter ' a_1 ' is a variable that depends on the final strain as well as the constant force; and the parameter ' b ' is the error of measurement and fitness, which was affected by the immediate strain. The value of the immediate strain is not constant and varies as long as the environmental conditions and constant force change.

Comparison of compressibility of persian carpet for different environmental and folding configurations

To compare the compressibility of Persian carpet for different environmental and folding configurations, the ratio of maximum compression thickness varia-

tions to initial carpet thickness was calculated and represented as carpet compressibility. The carpet compressibility values obtained for different methods of folding configurations along with different environmental conditions are shown in Table 4 and Figure 7.

According to the experimental results, the maximum carpet compressibility values are obtained within the NP1 area, while the minimum values are obtained within the NP2 area. It is shown that the carpet compressibility obtained within the TP area is always less than that of NP1 and higher than that of NP2.

An analysis of variance for the average values of compressibility within the different areas, under the same environmental conditions as well as within a specific area under different environmental conditions, was performed. The statistical analysis results show that the measured compressibility values are significantly different for mild and humid environmental conditions within the different areas, but in dry environmental conditions within areas NP1 and NP2, only at the level of 95% confidence limit are the values similar. In addition, the measured compression strain values are also similar within the NP2 area under mild and dry environmental conditions, at a 95% confidence limit.

In general, it may be considered that carpet compressibility increases as the environmental conditions transforms from

dry to humid. It is shown that the increase in carpet compressibility within all of the carpet area gradually occurred from dry to mild conditions. However, the highest carpet compressibility is obtained in humid conditions. This result is attributed to the effect of moisture absorption on fibre mechanical properties [7]. It was shown that with an increase in fibre moisture absorption, the slope of the tensile stress-strain curve of the fibre decreases, which in turn leads to a decrease in fibre tensile and bending rigidity [7].

Comparison of compression creep behaviour of Persian carpet:

In order to compare the compression creep behaviour of Persian carpets tested under different environment and folding configurations, the slope, intercept and correlation coefficients of the equations proposed were statistically analysed and a hypothesis test was performed. It was found that the slope of the equations fitted to all of the areas, under dry and humid environmental conditions, is similar. In addition, the slope of the equations fitted to the NP1 and TP areas, under humid environmental conditions, is similar. However, the slopes of the equations within NP2 is even less than that in the case of TP. Comparing the slope of creep curve for different environmental conditions, it is shown that the slope value for humid conditions is always higher than that of dry conditions.

It is shown that the rate of increase of compression strain with an increase in the amount of moisture in the flat (TP) and NP1 areas of folded configurations are similar. As a result, it is predicted that the compression strain could be similar for a short storage time within the TP and NP1 areas. Investigation of the correlation coefficient of the equations fitted to the different areas with various environmental conditions suggests that the correlation coefficient for dry conditions is significantly lower than those of other environmental conditions. It is also shown that the highest correlation coefficient is obtained in humid conditions within the NP1 area. In addition, the correlation coefficient for a flat configuration under different environmental conditions, even in dry conditions, is also fairly high.

Conclusion

The result of the experiment shows that the carpet thickness suddenly decreases in a short period of time and then reaches a stable condition. The variation trend of carpet thickness with time in is accordance with the logarithm equation ($y = a \times \ln(t) - b$),

Table 4. Carpet compressibility values under different environmental and folding conditions (average values).

area/condition	(NP1)	(NP2)	(TP)
Mild	2.39%	1.16%	1.85%
Humid	4.33%	2.32%	3.32%
Dry	2.16	1.00%	1.47%

which is in complete agreement with the Eyring model proposed in textile creep theory.

In general, in humid conditions, maximum carpet thickness variation occurs in a folded configuration within the folded area. On the other hand, carpet thickness variations in dry conditions are less than those of in humid or mild conditions. In addition, carpet thickness in dry conditions more quickly reaches a stable condition than that in humid or mild conditions.

The results of this research revealed that storing of hand-woven Persian carpet (Isfahan) in a folded configuration under dry and mild environmental conditions would lead to a higher resistance against the compression force within a none-folded area. Where it is possible to control the strain within the folded area of a folded configuration, it is suggested that hand-woven Persian carpet (Isfahan) be stored in a folded configuration. In order to control the compressional strain within the folded area of a folded configuration, it is recommended that the empty spaces of the folded configuration during the storing of carpet be filled with two smaller carpets of similar material in a way that the piles of carpets are laid on one another in the opposite direction of their nap sides.



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Received 23.07.2006 Reviewed 16.04.2007

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