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Effect of Traffic Exposure on Toughness Characteristics of Hand-Knotted Carpets

Abstract
Compression performance is a major factor in determining the life wear of each carpet. The toughness of the pile surface, as one of the compression properties of carpets, changes when exposed to wear in use. The main aim of this study was to predict the toughness characteristics of the surface piles of hand-knotted carpets at different levels of traffic exposure. Two types of hand-knotted carpet samples with symmetric and asymmetric knots and similar structural specifications were produced. A Hexapod tumbler tester was used to impose controlled worn out at different traffic exposures (drum revolutions). The samples were then tested with a tensile tester in the compression mode, and load-crush curves were obtained. The compression toughness characteristics and loss rate of toughness of the carpet samples were determined at 0 (new carpet), 4000, 8000, 12000 and 16000 revolutions of the Hexapod tumbler tester. Regression analysis was used to find the correlation between the traffic exposure (drum revolutions) and compression toughness characteristics. The results showed that knot type affects the toughness characteristics of the carpet. However, this effect is not statistically significant at the 5% level. On the other hand, different traffic exposure significantly affects the toughness characteristics at the 5% level.

Key words: *hand-knotted carpet, traffic exposure, toughness, toughness loss rate, regression analysis, turkish knot, persian knot.*

Introduction

The weaving methods of hand-knotted carpet are, basically, the same as procedures used to be hundreds years ago. Only the structures of the looms have changed a little over time [1]. On the other hand, the hand-knotted carpet industry has seen vast improvement in pertinent areas such as standardisation, serviceability, competitiveness, and delivery time. The weaver wraps and ties pile yarns around the pairs of warp threads under one of the common knot types: symmetric (Turkish) or asymmetric (Persian) knots [2]. Carpets wear out due to traffic exposure in use. Compression loading of the pile surface is the most common mechanical contact of carpets in human daily activities like standing and walking, and static and dynamic pressure by massive goods such as moving furniture and other household products. The dynamic response of the pile surface or recovery has an effective role in the stability of the compression properties expected [3, 4]. Appropriate compression performance of carpet increases its lifetime, especially the walking comfort and appearance retention [5]. Usually changes in the compression performance have been measured by the rate of thickness loss or decrease in the resilience of surface piles [4, 6]. Moghassem et al. [7] analyzsed two soft computing modelling methodologies for predicting the thickness loss of Persian hand-knotted carpets.

The total energy of pile deformation and recovery energy are determined by calculating the area under the compression and recovery curve, respectively [8]. With sinusoidal vibration loading within the frequency range of around 0.5 Hz, Horino et al. [9] measured the energy absorption or hysteresis effect by calculating the area of a steady loop obtained from repeated loading and unloading curves. If a carpet has a higher resilience to compression loading, it resists more against damping and energy absorption is lower [10]. Wu et al. [11] used carpet compliance, which is defined as the reciprocal of the compressive modulus, as a mechanical property in their study of carpet performance. They concluded that the more compliant carpets provided better perceived comfort, in particular when ankles and feet impact on the surface piles. The compressive modulus was measured as the slop of the initial linear portion of the load-deformation curve. Similarly the ability of the textile structure to withstand shock or impact loads depends mostly on its toughness or energy absorption ability.

Laughlin and Cusick [12] introduced a transition region in the stress-strain curves of machine carpet samples with the pile yarns of different fibers (wool, acrylic, nylon and polypropylene) after traffic exposure by a Tetrapod walker under cycling loading. They defined the transition region as where the slope of the curve at both low and high forces was changed. Thus this transition region could be an idea to define a new measurable compression property of the carpet pile surface.

Numerous factors affect the compression performance loss of a carpet. Erdoğan [13] studied the effect of the pile fiber cross section shape on the compression properties of polypropylene carpets under short and long-term static loadings. However, the degree of wear certainly plays a major role. Sheikhi et.al [14] investigated the compression properties of acrylic cut-pile carpet consisting of pile yarn with different fibre blend ratios. They concluded that with an increase in the coarse acrylic fibre ratio (16.48 dtex fibre) the specific yarn volume first decreases and then increases.

The effects of wear can be attributed in terms of changes in the surface texture and colour. Phenomena such as pile flattening, pile entangling, surface roughness, fiber shedding and tuft morphology are caused by changes in the surface texture, which can deteriorate the mechanical performance of carpet [15, 16].

The main aim of this study was to investigate the effect of different levels of traffic exposure or wear on the compression toughness characteristics of hand-knotted carpets with two common knot types i.e. the symmetric knot and asymmetric knot. Regression analysis was used to determine the most accurate equations to predict the toughness characteristics and loss rate of toughness parameters under different wear levels. For validating the regression models, two categories of samples with an arbitrary traffic exposure level were prepared. The experimental results of the validating samples were compared with those from the predicting regression models.

Materials and methods

Carpet materials specifications

To carry out the experiments, different types of hand-knotted carpets were prepared. In order to produce pile yarn, virgin wool fibers were selected from a type of Asian wool breed. The specifications of wool fibers are shown in ***Table 1***. The woolen pile yarns were dyed under similar condition with vegetable dyestuff by a traditional method.

Table 1. *Wool fiber specifications.*

Diameter, μm		Length, mm		Crimps/2.5 cm		Medullated fibers, %	
Mean	%CV	Mean	%CV	Mean	%CV	Non	Coarsely
29.43	28.43	98.9	20.51	4.4	6.54	88	4

Table 2. *Structural specifications of hand-knotted carpet samples.* Note: Count of ply yarn.*

Knot density, 1/dm²	Pile yarn		Warp yarn		Thick weft yarn		Thin weft yarn	
	N_m*	%CV	N_e*	%CV	N_e*	%CV	N_e*	%CV
54 × 54	6/2	3.56	20/12	2.57	10/14	2.73	20/3	2.14

Table 3. *Toughness characteristics of carpet samples at different wear levels.* ***Note***: ** Data in brackets are standard deviation values.*

Characteristics	0 (New carpet)		4000		8000		12000		16000	
	Turkish	Persian	Turkish	Persian	Turkish	Persian	Turkish	Persian	Turkish	Persian
WC, N.m	971.0	914.4	918.6	878.1	853.5	824.7	740.0	754.2	664.1	663.0
	(19.1)*	(16.16)	(13.4)	(14.6)	(15.2)	(14.5)	(28.4)	(16.3)	(17.1)	(17.4)
WL. N.m	473.2	451.6	448.3	425.8	413.2	399.4	388.8	372.9	367.1	356.5
	(7.73)	(9.98)	(7.02)	(8.12)	(7.59)	(7.99)	(8.64)	(7.36)	(7.84)	(6.76)
CL, %	83.10	84.45	84.69	84.99	85.90	86.98	88.05	88.19	89.08	89.41
	(1.06)	(0.82)	(0.61)	(0.68)	(0.71)	(0.98)	(0.95)	(0.91)	(0.78)	(1.05)

Moreover, depending on the knot density of the carpet samples, proportional warp and weft yarns were chosen. Structural specifications of the carpet samples are shown in ***Table 2***.

Hand-knotted carpet samples were prepared with two common types of knots i.e. the Persian knot and Turkish knot. Carpets were woven based on a simple pattern. The average pile height was adjusted to 9 mm.

Test methods

Compression tests were performed using a uni-axial tensile testing machine (Zwick universal testing machine 1446-60) under standard conditions, as shown in ***Figure 1*** (Dayiary, Shaikhzadeh Najar & Shamsi, [8]). The carpet sample was placed between two parallel steel plates. The bottom set consists of a flat steel plate (23 × 23 cm) attached to the bottom jaw, and the upper set comprises a circular steel plate (13.5 cm in diameter) attached to the top jaw. The tester was set to work in the compression mode. The rate of compression was 50 mm per minute. The maximum compression load was set to 680 N (average weight of the person). The load-crush curve of the compressed sample was then obtained. After the load reaches the maximum value, the reverse compression test is performed automatically. ***Figure 2*** (see page 66) shows a typical curve of Load-Crush, in which curve P refers to the loading mode and curve P' - the recovery mode. In each case, five tests were performed.

The energy of pile deformation under compression is regarded as toughness and is determined by calculating the area under the compression curve. In order to consider the influence of wearing out the pile surface of the carpet sample on its compression toughness characteristics after a period of usage, samples were subjected to accelerated mechanical wear to simulate traffic exposure. This simulation is performed by a Hexapod tumbler tester according to the ISO 10361 standard. Each carpet sample (a rectangle with dimensions of 20 by 22.5 cm) was worn out from short to long wear levels (Onder & Berkalp, [15]). Compression tests were carried out at five levels of wear i.e. 0 (new carpet), 4000, 8000, 12000 and 16000 revolutions (drum revolutions of the Hexapod tumbler tester).

Calculation of toughness characteristics

Data from the load–crush curves were used to find the area under the curves. The toughness of the materials was determined by finding the area under the load-deformation curve by integration from the curves. The total area under the compression loading curves (Joule or Nm) is defined as the compression toughness (WC). Numerical methods in Matlab® software were used to perform the calculations.

Results and discussion

Toughness characteristics of carpet samples under different wear levels were calculated, the results of which for all samples are shown in ***Table 3***.

According to ***Figure 2***, it seems that in the early stage of compression, the load increases slowly with increasing deformation. The carpet shows a low compression modulus in this region. After a certain point, the compression load tends

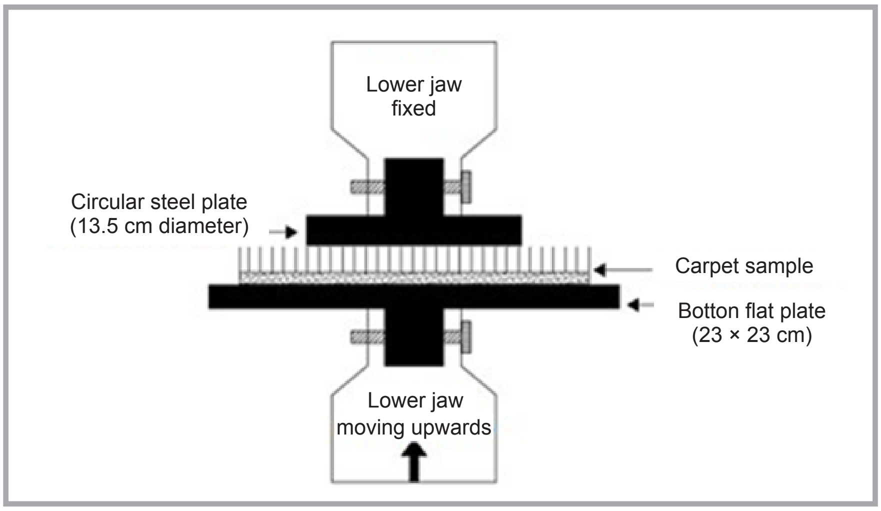

Figure 1. *Installations on Zwick tester jaws.*

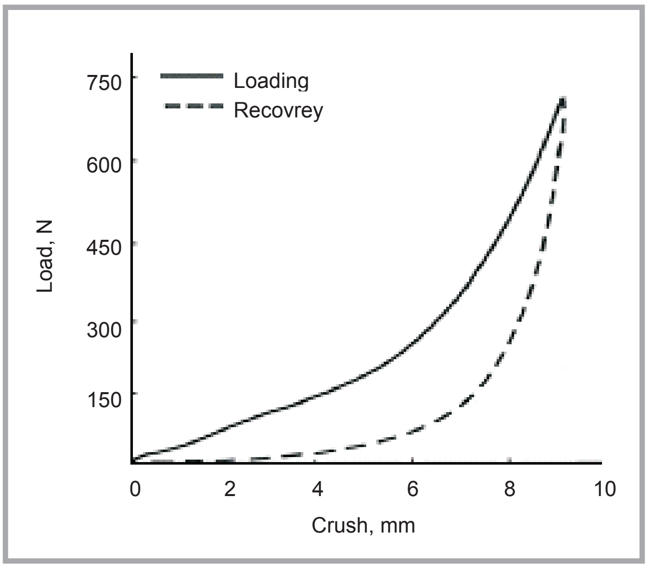

Figure 2. Typical diagram of compression test on a new carpet sample with the Turkish knot.

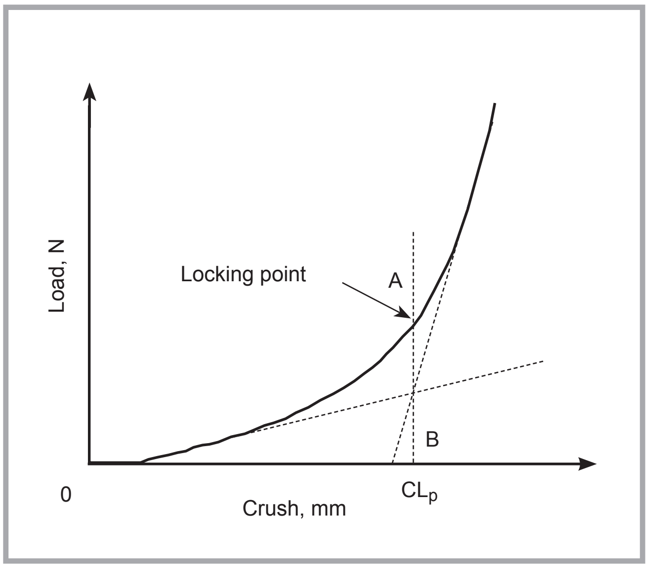

Figure 3. Definition of locking point and locking crush (CL_P).

to increase rapidly with a steep gradient, with the carpet showing a high compression modulus in this region. The reason for this is that at first the piles are free to move in all directions and the resistance to compression is low. As the compression increases, pile yarns become compressed and compact. Then free spaces decrease, and the fibers and yarns are locked to each other. This, in turn, leads to more compactness of the materials and the resistance to compression increases. As can be seen from ***Figure 3***, there is a certain region in the compression curves where the low gradient changes to a steep curve. The locking point is considered in this region. Therefore this transition region could be used to define a new measurable compression property of carpet. To define the transition point (locking point) in this region, the initial and final compressive moduli are considered. The crush at the locking point is defined as equal as the crush at the intersecting point of a hypothetical bilinear curve consists only of the lowest and highest modulus lines of the compression curve.

The significance of the locking point reveals its role when the compression behaviour and performance of a hand-knotted carpet are considered, which can play a significant role in the comfort of a person perceived while walking on a carpet.

To construct this point, as shown in ***Figure 3***, the intersecting point of the lowest and highest tangents to the compression curve is found. From this point, a line is drawn parallel to the load axes until it cuts the compression curve. This point is regarded as the locking point. The crush at the locking point is defined as the locking crush (CL). The percentage of locking crush is determined by dividing the crush value (mm) by the pile height i.e. 9 mm. The toughness at the locking point (WL) is that up to the locking point in Nm. Matlab® software was used to perform the operations.

Statistical methods

Regression analysis is the most common statistical method for the analysing and modelling of dependent variables as a function of one or more independent variables. This method has the advantage of simplicity in describing the quantitative relationship between textile material properties for prediction purposes [17].

The correlations between carpet toughness and worn out parameters were determined. Wear levels or drum revolutions were defined as independent variables (x) and each compression property defined as a dependent variable. Regression analysis was performed for both symmetric and asymmetric knots. ***Equations 1*** to ***6*** in ***Table 4*** represent the best correlation between independent variable and dependent variables with the maximum R-square determined by SPSS® software. Indices *t* and *p* refer to the Turkish and Persian knots, respectively. The regression curves are shown in ***Figures 4*** to ***6***. A one-way ANOVA test was applied to determine the effect of knot type of carpet samples and traffic exposure values on toughness characteristics. It was considered that the knot type affects the loss rate of toughness. However, this effect is not statistically significant. Different traffic exposure significantly affects the loss rate of toughness parameters at the 5% level.

Table 4. Regression equations of toughness characteristics of carpet samples at different wear levels.

Knot type	Model type		Regression equations	R^2	Eq.
Turkish	Quadratic	WCt	$y = 974.26 – 0.013\,x – 4.26×10^{-7}\,x^2$	0.970	(1)
		WLt	$y = 474.97 – 0.008\,x + 7.69×10^{-8}\,x^2$	0.965	(2)
	Linear	CLt	$y = 83.10 + 3.78×10^{-4}\,x$	0.886	(3)
Persian	Quadratic	WCp	$y = 914.13 – 0.007\,x – 5.66×10^{-7}\,x^2$	0.976	(4)
		WLp	$y = 452.52 – 0.007\,x + 8.37×10^{-8}\,x^2$	0.956	(5)
	Linear	CLp	$y = 84.18 + 3.21×10^{-4}\,x$	0.828	(6)

As can be seen from ***Figures 4*** and ***5***, all the data points show a quadratic correlation with high regression coefficients. It is clear that the curvature sign is opposite in the case of compression toughness and locking toughness. The reduction rate of compression toughness is higher in the early stages of traffic exposure and tends to increase at the higher exposure. Contrarilythe locking toughness decreases faster in the early stages of traffic exposure and tends to reach a constant

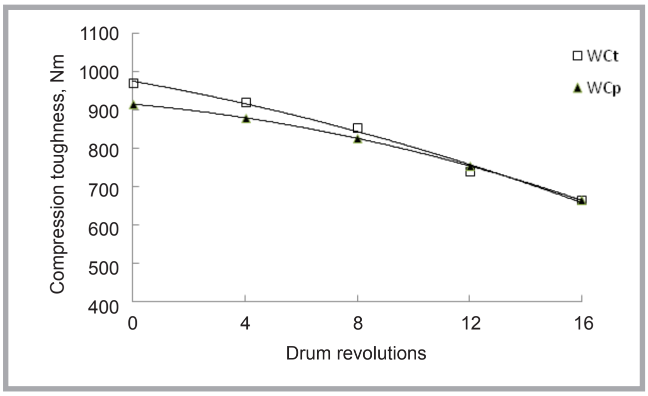

Figure 4. Variation in compression toughness with drum revolutions.

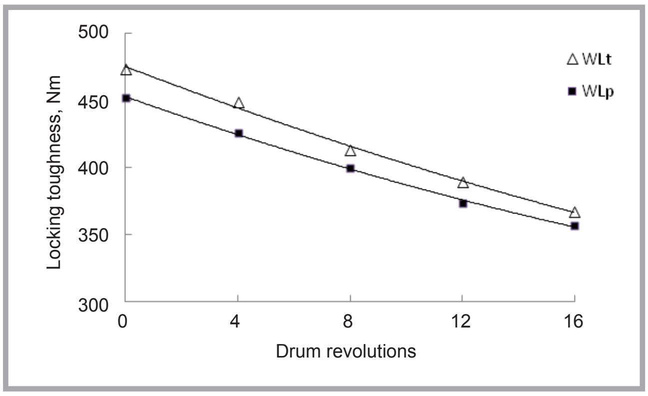

Figure 5. Variation in locking toughness with drum revolutions.

value at the higher and final exposure. The difference between the compression toughness is higher in new carpets. The results show that this difference tends to decrease at higher traffic exposures. The Turkish knot shows slightly higher compression toughness and locking toughness in new carpet in comparison to the Persian knot. It seems that they tend to reach to the same value at higher traffic exposure. However, statistical analysis showed no significant difference between the Turkish and Persian knot in the case of compression toughness and locking toughness.

Figure 6 shows the linear correlation between the traffic exposure and crush in % at the locking point. Increasing the locking crush accompanied by a decrease in toughness implies that the total compression toughness of the carpet decreases at higher traffic exposures and the initial compression modulus decreases.

Loss rate of compression toughness

The durability, performance and lifetime of a hand-knotted carpet are evaluated by the rate of deterioration in its properties during the course of wear out. Traffic exposure may deteriorate the toughness characteristics of the carpet. In this work, the loss rate of toughness parameters are defined as:

Loss rate of WC = $(1 - Ct_i/Ct_0) \times 100\%$ (7)

were, Ct_i - Compression toughness in each worn out, Ct_0 - Compression toughness at zero worn out.

Loss rate of WL = $(1 - Lt_i/Lt_0) \times 100\%$ (8)

were, Lt_i - Locking toughness in each worn out, Lt_0 - Locking toughness at zero worn out.

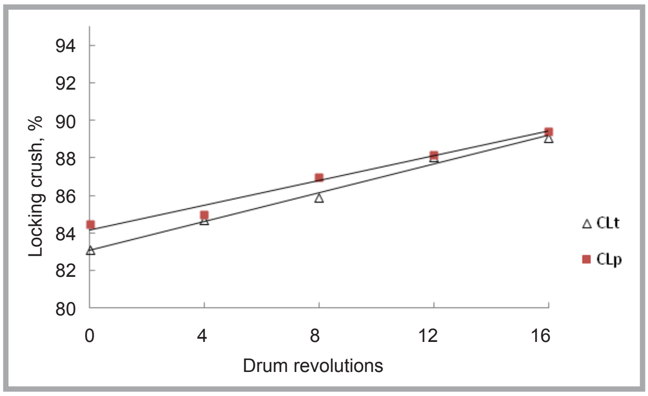

Figure 6. Variation in locking crush with drum revolutions.

Table 5. Loss rate of toughness in % parameters for carpet samples at different wear levels.

	Knot type	0 (New carpet)	4000	8000	12000	16000
Loss rate of WC	Turkish	0	5.40	12.10	23.79	31.60
	Persian	0	3.97	9.81	17.53	27.49
Loss rate of WL	Turkish	0	5.27	12.70	17.86	22.44
	Persian	0	5.73	11.57	17.42	21.07

Table 6. Regression equations of the loss rate of toughness parameters of samples at different wear levels.

Knot type	Model type		Regression equations	R^2	Equation
Turkish	Quadratic	Lost Rate of WCt	$y = 1.34\times10^{-3} x + 4.38\times10^{-8} x^2$	0.974	(9)
	Quadratic	Lost Rate of WLt	$y = 1.70\times10^{-3} x - 1.63\times10^{-8} x^2$	0.971	(10)
Persian	Quadratic	Lost Rate of WCp	$y = 7.24\times10^{-4} x + 6.19\times10^{-8} x^2$	0.981	(11)
	Quadratic	Lost Rate of WLp	$y = 1.64\times10^{-3} x - 1.85\times10^{-8} x^2$	0.968	(12)

In each case of sample type, loss rate of toughness parameters in various knot types were determined and are presented in ***Table 5***.

Correlations between the loss rates of toughness in various traffic exposures for Turkish and Persian knot types were determined. Drum revolutions (x) are defined as an independent variable and the loss rate of WC and that of WL are defined as dependent variables. Indices *t* and *p* refer to the Turkish and Persian knots, respectively. ***Equations 9*** to ***12*** in ***Table 6*** represent the best relationship between the independent variable and dependent variables based on the maximum R-square determined by SPSS® software. The regression curves are shown in ***Figures 7*** and ***8*** (see page 68).

According to ***Figures 7*** and ***8***, data points show a quadratic correlation with a high regression coefficient (R^2). It can be concluded that with an increase in wear levels, the loss rate of toughness parameters increase. The curvature sign of the curves are opposite in the case of compression toughness and locking toughness. This increase is slightly more for carpet sam-

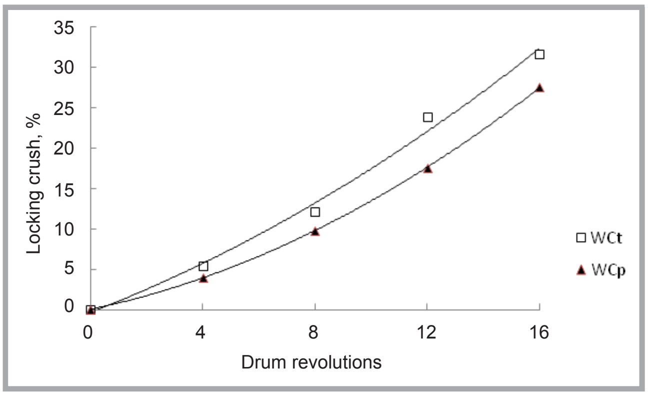

Figure 7. Variation in the loss rate of compression toughness (WC) with drum revolutions.

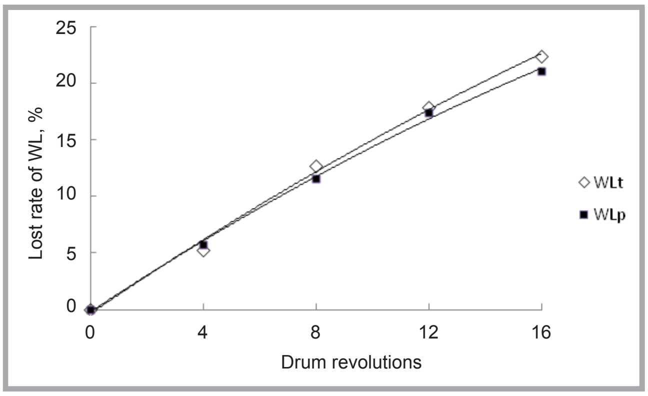

Figure 8. Variation in the loss rate of locking toughness (WL) with drum revolutions.

ples with a symmetric knot. A one-way ANOVA test was applied to determine the effect of knot type and traffic exposure values on the loss rate of toughness parameters. It was considered that the knot type affects the loss rate of toughness. However, this effect is not statistically significant. Different traffic exposure significantly affects the loss rate of toughness parameters at the 5% level.

Conclusions

In this study, we investigated the toughness characteristics and loss rate of toughness parameters of hand-knotted carpets exposed to different wear levels. Five different traffic exposures were used. Based on the experimental study and analysis carried out on the toughness characteristics of carpet samples, the following conclusions can be drawn;

1. Evaluation of the carpet performance is highly influenced by toughness characteristics such as compression and locking toughness.
2. Hand-knotted carpets with a asymmetric (Persian) knot have a lower loss rate of toughness parameters.
3. Hand-knotted carpets with an asymmetric (Persian) knot present higher compression performance than those with a symmetric (Turkish) knot; but this difference is not statistically significant.
4. The best regression models with a maximum R-square were used to correlate the traffic exposure to toughness characteristics. Investigation of validating the regression models showed that the experimental values are close to those estimated from the regression models. The method proposed can estimate the toughness characteristics of hand-knotted carpet under different wear levels with acceptable accuracy.

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