Effects of Fiber Linear Density on Acrylic Carpet Performance

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ABSTRACT

The appearance of cut-pile carpets deteriorates due to foot traffic and long term heavy loadings. This deterioration is generally seen as a fuzzy appearance due to loose fibers and fuzz on the carpet surface or as thickness loss. The fiber fineness has important effects on a number of yarn properties including cohesion, evenness, strength, stiffness and luster. In this study, three acrylic yarns with different fiber finenesses at the same yarn linear density were used to produce cut-pile carpet samples. The effects of fiber linear density on the amount of loose fibers and fuzz on the carpet surface, thickness loss under prolonged heavy static and dynamic loadings and compression recovery after loading-unloading were investigated. The carpet produced with finest fibers yarns had the lowest amount of loose fibers due to higher cohesion. The carpet samples with the finest fibers exhibited the highest resiliency and lowest thickness loss under static loading. However, the carpet samples with the coarsest fibers showed the least thickness loss under dynamic loading and higher compression recovery after loading-unloading.

Keywords: carpet; fiber linear density; fiber bind; thickness loss; static load; dynamic load; compressibility, loading-unloading

INTRODUCTION

Acrylic and polypropylene fibers are the most commonly used pile materials for Wilton carpet surfaces. Acrylic and polypropylene fibers are used in the form of long-staple and filament. Acrylic fibers are preferred due to their soft handle, good resilience and high light fastness [1-3]. The performance of the fibers affects the carpet performance as well. The lifetime of the carpets can be evaluated by judging their appearance after certain mechanical effects. The carpets undergo static and dynamic compressions due to foot traffic and heavy furniture effects in daily usage. These compression effects cause a bending deformation on the pile yarns causing the appearance of the carpet to deteriorate. The ability of the carpet pile yarns to recover their original state determines the appearance retention and durability performance.

The other parameter that affects the appearance of carpets is the amount of loose fibers and fuzz on the surface. During the face-to-face carpet weaving process, two backing fabrics are woven simultaneously and the pile yarn is interlaced between them to yield a sandwich structure. The pile yarns are cut along the loom width using a reciprocating knife and to obtain two separate cut-pile carpets (*Figure 1*). Since the acrylic yarns used as pile material are manufactured as staple, the short fibers protrude from the yarn structure due to the foot traffic, leading to loose fibers and fuzz on the carpet surface (*Figure 2*). This situation deteriorates the carpet appearance and constitutes a health hazard, especially for babies. In order to decrease the amount of loose fibers, some cleaning or finishing processes are performed after the weaving and backing processes. Nevertheless, the loose fiber problem still occurs for acrylic cut-pile carpets. Carpet manufacturers are in searching for the means to decrease or completely eliminate this problem. However, the parameters affecting the amount of loose acrylic fibers on carpet surfaces as a result of foot traffic have not been adequately defined.

Most of the studies on carpet performance address the compression/recovery performance of carpets under static and dynamic loadings [4-13]. In these studies, the effect of structural parameters such as pile height, pile density, yarn linear density and pile yarn characteristics such as material type and fiber cross section shape have been investigated. Only limited studies found which address carpet performance parameters other than compression [14, 15].

Fiber linear density has an important effect on mechanical and aesthetic properties of textile products [16]. It influences yarn properties such as cohesion, strength, spinning limits, evenness and fabric properties including stiffness and drape. Decreasing fiber linear density used to produce textile products results in softer handle and a more lustrous appearance [16, 17]. Only one study on the effect of fiber linear density on the compression performance of carpets is found in the literature. Sheikhi et al. [18] studied the compression characteristics of acrylic carpet samples made using several blend ratios of fibers of different linear densities. Blend. A compression load was applied by using Instron tensile tester and energy of compression, decompression energy, resilience of carpet compression and relative compressibility were measured. However, thickness loss after static and dynamic loading was not investigated.

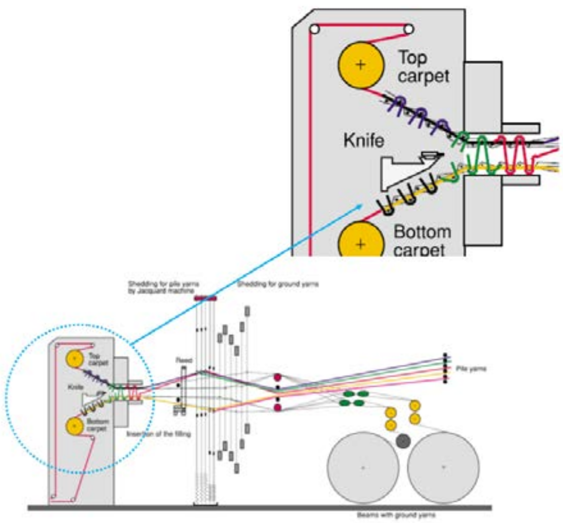

FIGURE 1. Wilton face-to-face carpet weaving technique [3].

FIGURE 2. Loose fibers and fuzz on the carpet surface.

In this study, the effect of fiber linear density on the amount loose fibers and fuzz on the carpet surface, thickness loss after prolonged heavy static and dynamic loadings and compression recovery characteristics after loading-unloading were investigated. Acrylic cut-pile carpet samples with three different fiber linear densities were produced using constant yarn and carpet construction parameters.

MATERIAL AND METHODS

Materials

Three cut-pile carpet samples were manufactured using a Van de Wiele RCI03 Wilton type face-to-face carpet weaving machine. The machine has three rapiers and the production speed is 120 rpm. The samples were produced under identical conditions via the same weaving loom. Acrylic yarns with different fiber linear densities (2.75, 6 and 8 denier) are used as pile material. The fibers were produced by Aksa Akrilik Kimya Sanayii A.Ş. in Turkey. The construction parameters used to produce all cut-pile carpet samples are shown in *Table I*.

Methods

In order to investigate the effect of acrylic fiber linear densities on carpet performance properties, hexapod fiber bind, prolonged heavy static loading, dynamic loading and compressibility tests were performed. Carpet samples were conditioned at standard atmospheric conditions according to ISO 139:2005 [19] (65% ±4% relative humidity and 20°C ±2°C temperature) for 24 h before the tests were conducted.

Hexapod Fiber Bind Test

Fiber bind tests were performed to determine the amount of loose fiber removed from the pile yarn structure due to the foot traffic. The test method was performed using a WIRA Hexapod Tumbler Carpet Tester in accordance with DD ISO/PAS 11856:2003 [20]. The tester consists of a drum, a plastic backing sheet and hexapod. Carpet samples 940 mm X 200 mm in size were fastened to the backing sheet with a double sided adhesive tape. Then, the backing sheet was placed on the inside surface of the drum. The hexapod placed inside the drum has six polyurethane stud feet. As the drum is rotated clockwise and counter clockwise, the hexapod rolls randomly inside the rotating drum and the studs disturb the pile yarns, resulting in loose fibers. The loose fibers on the sample were collected using a light finger tip brush and the weight was recorded every 2000 cycles. Each sample was tested a total of 12000 cycles. At the end of the test, the total mass of the fiber removed from the specimen was calculated in g/m^2 and as a percentage of the mass of pile yarn per meter square above the substrate. The mass of the pile yarn above the substrate was determined in accordance with ISO 8543:1998 [21].

Prolonged Heavy Static Loading Test

In order to determine the effect of fiber linear density on the resilience performance of the carpet, a prolonged heavy static loading test was performed. This test is designed to determine the effect of heavy furniture on carpet thickness loss [1]. The test was performed in accordance with ISO 3416:1986 [22].

TABLE I. Carpet samples construction parameters.

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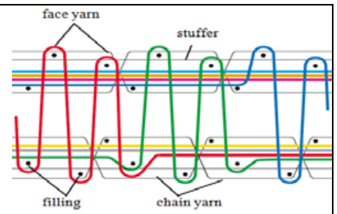

Sample Code	**N2.75**	**N6**	**N8**
Pile Material	Acrylic	Acrylic	Acrylic
Pile Yarn Fiber Chemical Formula	CH_2CHCN	CH_2CHCN	CH_2CHCN
Pile Yarn Count (denier)	1500	1500	1500
Pile Yarn Fiber Linear Density (denier)	2.75	6	8
Pile Height (mm)	13	13	13
Pile Density (piles/m^2)	800000	800000	800000
Warp Sett (ends/10cm)	40	40	40
Weft Sett (picks/10cm)	100	100	100
Average Carpet Weight (g/m^2)	3243.8	3557.3	3301.2

In order to apply the required pressure (700 kPa) on the specimen, weight is hung on a 4.2:1 lever system. The lever system applies force on a pressure foot with a 6 cm^2 area. Five test specimens with 100 mm X 100 mm dimension were prepared from each carpet sample. First, the initial thickness of the specimen before the static loading application was measured under a standard pressure of 2 kPa ± 0.2 kPa according to ISO 1765:1986 [23]. The carpet thickness was measured via an SDL Atlas K094 digital thickness gauge with 0.01 mm accuracy. The standard pressure of 700 kPa was applied to the specimen for 24 hours. The load was removed and the sample thicknesses were measured immediately after removing the load and after 24 h recovery time. The percentage of Thickness Loss (TL) after 24 h compression and 24 h recovery were calculated using Eq. (1). Percent resilience after 24 h recovery was calculated with Eq. (2) [7].

$$Thickness\ Loss\ (\%) = \frac{h_0 - h_c}{h_0} \times 100 \qquad (1)$$

$$Resilience\ (\%) = \frac{h_r - h_c}{h_0 - h_c} \times 100 \qquad (2)$$

where h_0 is the initial thickness, h_c is the thickness after 24 h compression and h_r is the thickness after 24 h recovery time.

Dynamic Loading Test

The dynamic loading test was used to determine the thickness loss of the carpet due to prolonged foot traffic. The test was carried out using a WIRA dynamic loading machine according to BS ISO 2094:1999 [24].

The WIRA dynamic loading machine drops free falling weight on the carpet specimen from a controlled height about every four seconds. The weight has two rectangular steel feet. The carpet specimen is clamped on a metal plate and slowly and continuously traversed to half-overlap of the steel feet at each impact. Five samples of each carpet with 125 mm X 125 mm dimensions were tested; the results are expressed as averages of the 5 tests. The initial thickness of each carpet sample was measured via an SDL Atlas K094 under standard pressure of 2 ±0.2 kPa in accordance with ISO 1765:1986 [23]. The carpet sample was placed in the dynamic loading tester and 50, 100, 200, 1000 and 2000 impacts were applied. The thickness of the sample was measured after each stage of impact. The percentage of TL was calculated by using Eq. (1) where h_c is the thickness of the carpet sample after each stage of impact.

Compressibility Test

The compressibility test is used to determine the compression and recovery characteristic of the carpet sample after different levels of loading and unloading. This determines the compression resistance and resilience of a carpet as a result of foot traffic [2]. The test was performed using an SDL K94 Atlas Digital Thickness Gauge machine according to BS 4098:1975 [25]. The SDL K94 has a pressure foot with 325 mm^2 area and weight settings allowing application of pressures from 5-200 kPa. Five specimens of 75 mm X 75 mm were prepared from each carpet sample and tested. The initial thickness of the sample was measured under 2 kPa pressure in accordance with ISO 1765:1986 [23]. Then, without raising the pressure foot, the extra weights; A: 5kPa, B: 10kPa, C:20 kPa, D: 50kPa, E:100 kPa, F:150 kPa, G:200 kPa were added sequentially. After each weight was added, the thickness value of the sample was read at 30 s intervals as shown in (*Figure 3*). When 200 kPa of pressure was reached, the weights were removed sequentially from G to A at 30 s intervals (*Figure 3*). During the unloading process, the thickness of the carpet sample was read after each weight was removed. The percentage compression recovery of each carpet sample after loading-unloading procedure was calculated using Eq. (3).

$$percentage\ compression\ recovery\ (\%) = \frac{t_r - t_{200}}{t_2 - t_{200}} \times 100 \quad (3)$$

where, t_2 is the thickness under 2 kPa pressure at the beginning of the loading process (*Figure 3*, point A), t_r is the thickness at 2 kPa pressure after unloading all weights (*Figure 3*, point C) and t_{200} is the thickness at 200 kPa pressure (*Figure 3*, point B).

The work of compression in j/m^2 is determined by estimating the area under the loading curve (*Figure 3*, area ADB). Similarly, the work of recovery is measured in j/m^2 by the area under the unloading curve (*Figure 3*, area BEC). The percentage work recovery is calculated by using Eq. (4).

$$percentage\ work\ recovery\ (\%) = \frac{Area_{BEC}}{Area_{ADB}} \times 100 \quad (4)$$

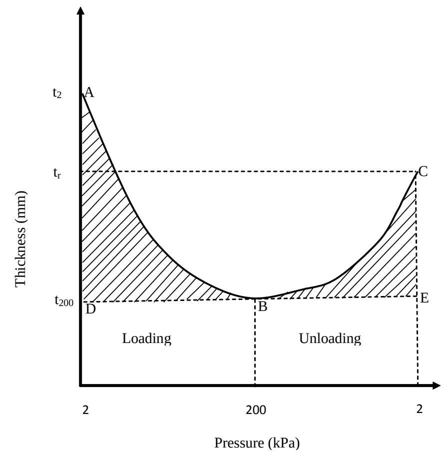

FIGURE 3. Typical thickness versus pressure curve.

In order to understand the statistical importance of fiber linear density on carpet performance properties, ANOVA was performed. The statistical software package SPSS 21.0 was used to interpret the experimental data. All test results were assessed at 95% confidence interval.

RESULTS AND DISCUSSION

Percentage of Loose Fiber after Hexapod Fiber Bind Test

The weight of fiber collected at each 2000 cycle interval and total weight of loose fiber per square meter for each carpet sample are summarized in *Table II*. The weight of loose fiber has a decreasing trend for all carpet samples as cycles increase (*Figure 4*). For all three samples, the amount of loose fiber generated peaks at about 2000 cycles and decreases significantly thereafter. Samples N2.75 and N8 have a sharper decrease between 2000 cycle and 6000 cycle then that of N6. Similarly during the daily usage of acrylic carpet, higher amounts of loose fiber and fuzz are seen on the surface early in the carpet life cycle. The amount of loose fiber generated decreases with time, since some of them are removed after each vacuum cleaning.

TABLE II. Weight of loose fiber at each 2000 cycle stage and total weight per square meter.

	Weight of loose fiber (g)		
Cycles	N2.75	N6	N8
2000	0.7421	0.4068	0.9757
4000	0.5184	0.4756	0.6120
6000	0.3498	0.4499	0.3245
8000	0.2624	0.4224	0.2818
10000	0.2734	0.3904	0.2470
12000	0.2375	0.3012	0.2062
Total (g/m^2)	2.3836	2.4463	2.6472

Since the loose fibers and fuzz on the carpet surface arise from pile yarns, comparing the percentages of the total loose fiber weight with respect to the pile yarn weight is reasonable (*Table III*). The effect of the fiber linear density on the loose fiber percentage

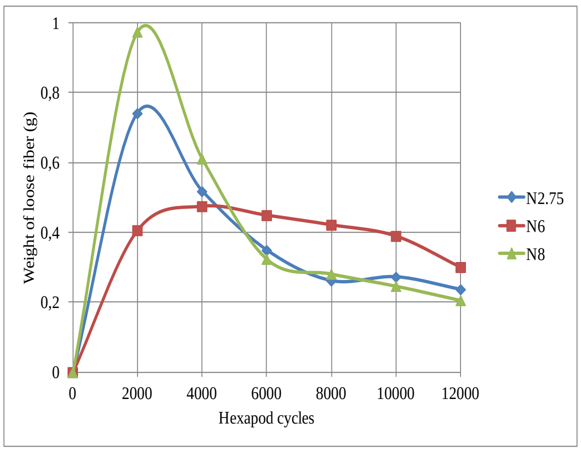

FIGURE 4. Weights of loose fibers versus cycles.

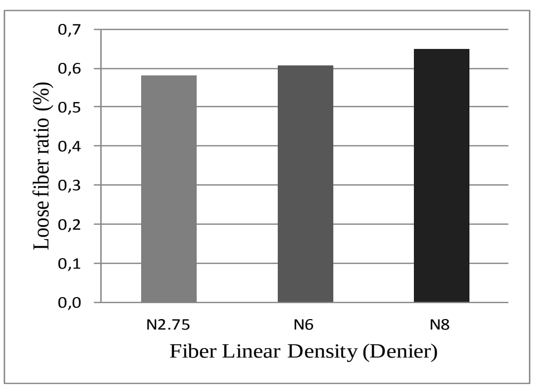

FIGURE 5. Loose fiber ratios versus fiber linear density.

is shown in *Figure 5*. Sample N2.75, made from fibers with the lowest linear density, generated the lowest amount of loose fibers on the carpet surface. Since the linear densities of the pile yarns are the same, the sample with finest fibers has more fibers in the yarn cross section. The increased number of fibers in the yarn cross section results in more contact points in the yarn structure, leading to increased cohesion [26,27]. Thus the lower amount of loose fiber on the carpet surface in the case of finer fibers can be attributed to the better cohesion of the fibers.

TABLE III. Hexapod loose fiber tests.

Sample Code	Mass of pile yarn (g/m^2)	Total mass loose fiber (g/m^2)	Loose fiber ratio (%)
N2.75	2176.99	12.6787	0.58
N6	2144.38	13.0122	0.61
N8	2167.85	14.0809	0.65

Thickness Loss and Resilience after Prolonged Heavy Static Loading

The prolonged heavy static loading test results are presented in *Table IV* where, h_0 is the initial thickness, h_{24h-c} is the thickness immediately after 24 h compression, and h_{24h-r} is the thickness after 24 h recovery time. The TL of each sample after compression is presented in *Figure 6*. The highest TL is obtained for N6. Samples N6 and N8 have approximately the same TL values. The lowest TL is obtained for N2.75. The static compression resistance of N2.75 is better than the other samples. Thus, it should be less deformed by heavy furniture. The highest resilience percentage value is obtained for N2.75 and the lowest is obtained for N8 (*Figure 7*). From *Figure 7*, as the fiber linear density decreases, the recovery capability of the pile yarns after static loading and thus the resilience increases.

ANOVA results for thickness loss and resilience properties after prolonged heavy static loading are seen in *Table V*. Fiber linear density does not have a significant effect on TL ($p=0.176$) whereas it has a significant effect ($p=0.009 < 0.05$) on resilience at a 95% confidence interval.

TABLE IV. Prolonged heavy static loading test results.

Sample code	Thickness (mm)	Mean	SD	TL (%)	Resilience (%)
N2.75	h_0	10.00	0.00	0.00	63.64
	h_{24h-c}	7.25	0.96	27.50	
	h_{24h-r}	9.00	0.00	10.00	
N6	h_0	11.75	0.50	0.00	62.50
	h_{24h-c}	7.75	0.50	34.04	
	h_{24h-r}	10.25	0.50	12.77	
N8	h_0	12.50	0.58	0.00	58.82
	h_{24h-c}	8.25	0.50	34.00	
	h_{24h-r}	10.75	0.82	14.00	

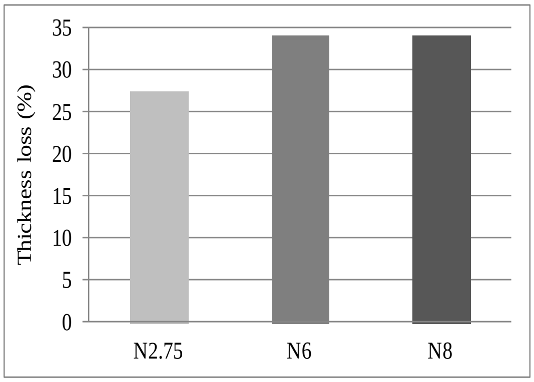

FIGURE 6. TL after 24 h compression.

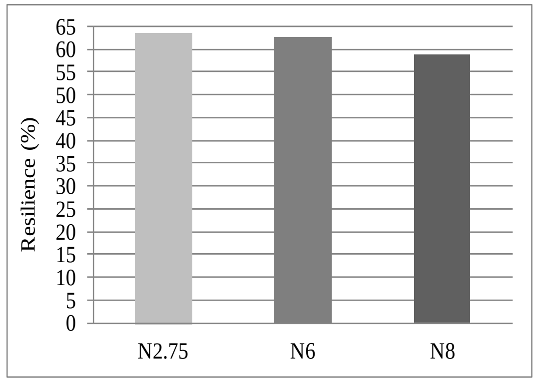

FIGURE 7. Resilience after 24 h recovery time.

TABLE V. ANOVA for thickness loss and resilience properties after prolonged heavy static loading.

		Sum of squares	Degree of freedom	Mean square	F	Significance
Thickness loss	**Between Groups**	2.000	2	1.000	2.118	0.176
	Within Groups	4.250	9	0.472		
	Total	6.250	11			
Resilience	**Between Groups**	6.500	2	3.250	8.357	0.009
	Within Groups	3.500	9	0.389		
	Total	10.000	11			

Thickness Loss after Dynamic Loading

The thickness and TL values of the carpet samples after dynamic loading are given in *Table VI*. Here, h_0 is the initial thickness of the carpet samples before dynamic loading, h_1, h_2, h_3, h_4 and h_5 are the thickness values of the carpet sample after 50, 100, 200, 1000 and 2000 impact treatments respectively. TL percentages versus number of impacts for each carpet sample are shown in *Figure 8*.

TABLE VI. Dynamic loading test results.

Sample code	Carpet thickness (mm)	Mean	SD (Standard deviation)	TL (%)
N2.75	h_0	10.67	0.58	0
	h_1	9.67	0.58	9.37
	h_2	9.33	0.58	12.56
	h_3	8.33	0.58	21.93
	h_4	7.67	0.58	28.12
	h_5	7.33	0.58	31.3
N6	h_0	12	0.1	0
	h_1	11	0.1	8.33
	h_2	11	0.1	8.33
	h_3	9.75	0.5	18.75
	h_4	9	0.1	25
	h_5	8.25	0.5	31.25
N8	h_0	11.33	0.58	0
	h_1	11	0.58	2.91
	h_2	11	0.1	2.91
	h_3	11	0.1	2.91
	h_4	10	0.1	11.74
	h_5	9.67	0.58	14.68

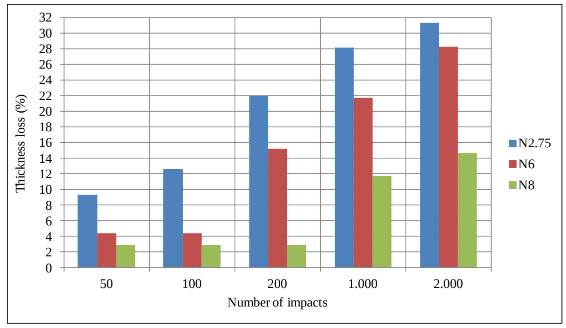

FIGURE 8. TL of carpet samples versus number of impacts.

The highest and the lowest TL values are obtained for samples N2.75 and N8 respectively (*Figure 8*). All three carpet samples have an increasing TL trend as the number of impact is increased. TL values of N2.75 increases gradually as the number of impact is increased. TL values of N6 are constant at 50 and 100 impacts and they increase sharply after that impact treatment. Similarly, TL percentages of N8 are constant until the 200 impact and it sharply increases at 1000 impact and 2000 impact treatments.

The effect of the fiber linear density on TL of the samples after dynamic loading is clearly seen on *Figure 8*. Contrary to the static loading, higher TL values are obtained as the fiber linear density of the pile yarn decreases for all impact treatments. So, it can be concluded that the coarser fibers enhances TL performance of the pile yarn and provides less deformation under dynamic loading.

ANOVA results for thickness loss after dynamic loading for different impact treatments are seen in *Table VII*.

According to ANOVA, fiber linear density has a statistically significant effect on TL for 100 impact ($p=0.019< 0.05$), 200 impact ($p=0.004 < 0.05$), 1000 impact ($p=0.000< 0.05$) and 2000 impact ($p=0.000< 0.05$) levels, in 95% confidence interval. On the other hand, fiber linear density does not have a statistically significant effect on thickness loss for 50 impact ($p=0.095$) level in 95% confidence interval.

TABLE VII. ANOVA for thickness loss property after dynamic loading.

		Sum of squares	Degree of freedom	Mean square	F	Significance
50 impacts	Between Groups	69.773	2	34.887	3.576	0.095
	Within Groups	58.531	6	9.755		
	Total	128.304	8			
100 impacts	Between Groups	161.412	2	80.706	8.273	0.019
	Within Groups	58.531	6	9.755		
	Total	219.943	8			
200 impacts	Between Groups	565.756	2	282.878	15.573	0.004
	Within Groups	108.991	6	18.165		
	Total	674.748	8			
1000 impacts	Between Groups	1032.504	2	516.252	52.808	0
	Within Groups	58.656	6	9.776		
	Total	1091.16	8			
2000 impacts	Between Groups	1424.775	2	712.387	39.214	0
	Within Groups	109	6	18.167		
	Total	1,533,775	8			

Compression and Work Recovery after Compressibility Test

The carpet thickness values under loading-unloading pressures are given in *Figure 9*. The percentage compression recovery value of each sample is calculated using Eq. (3) and presented in *Figure 10*. The highest compression recovery is obtained with sample N8 and the lowest one is obtained with N2.75. Thus, coarser fibers in pile yarns provide better compression recovery performance against foot traffic.

During the loading application, the work is done on the carpet sample by increasing the static pressure, and elastic potential energy is stored. Then, work is done on the carpet by removing the static pressure and the elastic potential energy is dissipated. The difference between these two values indicates the amount of compression deformation.

Thus, the percentage work recovery indicates the resistance of the carpet to compression. A higher percentage work recovery means that the carpet sample has higher resistance to foot traffic. The work of compression and recovery are given in *Table VIII.* The percentage work recovery of the carpet samples are given in *Figure 11*. Sample N8 has the highest work recovery performance. Thus, increasing fiber linear density increases the resistance to dynamic compression.

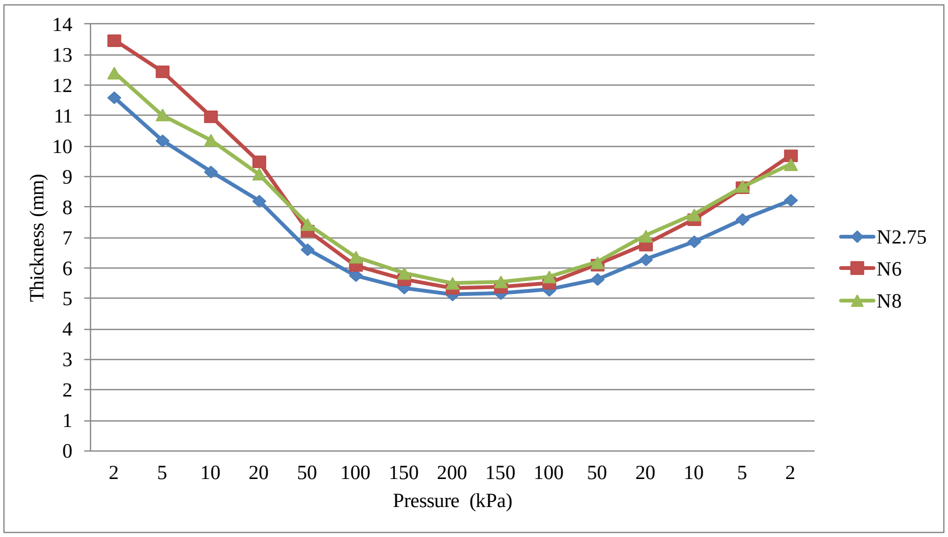

FIGURE 9. Carpet thickness values during loading-unloading treatment.

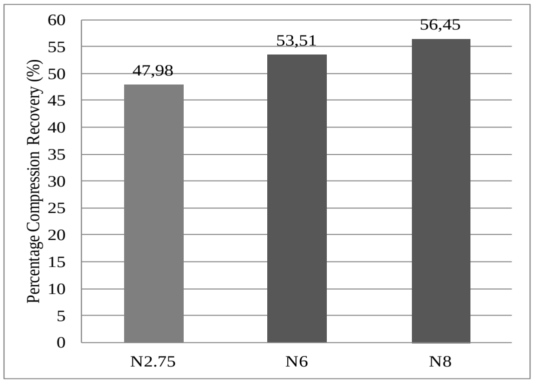

FIGURE 10. Percentage compression recovery of carpets.

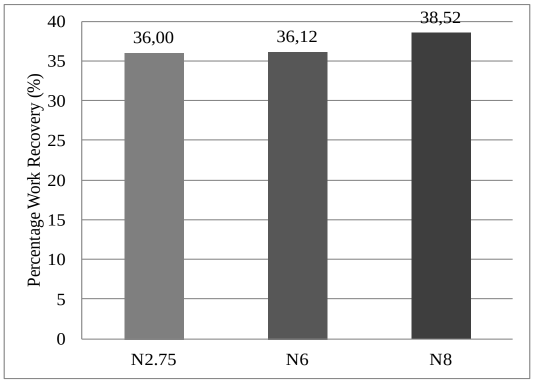

FIGURE 11. Percentage work recovery of carpets.

TABLE VIII. Work of compression and recovery values of the carpet samples.

Sample Code	Work of compression (j/m^2)	Work of recovery (j/m^2)	Percentage Work Recovery (%)
N2.75	223.929	80.604	36.00
N6	292.598	105.68	36.12
N8	275.656	106.179	38.52

ANOVA results for compression recovery, work of compression and work of recovery after compressibility test are given in *Table IX*. ANOVA results indicate that fiber linear density has a statistically significant effect on work of compression ($p=0.000 < 0.05$) and work of recovery ($p=0.007 < 0.05$), whereas fiber linear density does not have a statistically significant effect on compression recovery ($p=0.155$) level at a 95% confidence interval.

CONCLUSION

In the hexapod fiber bind test, the lowest loose fiber ratio is obtained with 2.75 denier fiber. Finer fiber pile yarns have improved fiber bind performance due to higher fiber cohesion. For acrylic carpets, it can be concluded that loose fibers and pilling on the carpet surface due to the foot traffic can be decreased by using finer fibers.

In the static loading test, the highest TL values are obtained for carpet sample with 2.75 denier fibers. The highest resilience values are obtained for carpet samples made from 2.75 denier fibers. It can be concluded that finer fibers enhance the resilience of the pile yarn and the recovery capability after compression.

The lowest TL value and highest compression recovery value were obtained for sample N8. The results of these tests indicate that the compression performance of the carpet samples with coarser fiber is better. Thus, acrylic carpet samples with coarser fiber should be less deformed under foot traffic.

TABLE IX. ANOVA for compression recovery, work of compression and work of recovery.

		Sum of squares	Degree of freedom	Mean square	F	Significance
Compression recovery	Between Groups	168.621	2	84.310	2.191	0.155
	Within Groups	461.797	12	38.483		
	Total	630.418	14			
Work of compression	Between Groups	12796.909	2	6398.455	24.840	0.000
	Within Groups	3091.034	12	257.586		
	Total	15887.943	14			
Work of recovery	Between Groups	2138.559	2	1069.280	7.802	0.007
	Within Groups	1644.647	12	137.054		
	Total	3783.206	14			

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