On the Pressure Behavior of Tubular Weft Knitted Fabrics Constructed from Textured Polyester Yarns

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ABSTRACT
This study attempts to investigate the pressure behavior of tubular knitted fabrics after a long period of time. For this purpose, two kinds of knitted fabric (plain and interlock) with various stitch lengths were chosen and the interfacial pressure and pressure reduction of fabrics after 48 hours were analyzed at different strain percents. The same tests were performed on the same specimens after repeated washing and repeated usage. Finally, the experimental pressure values were compared with the theoretical results obtained from Laplace's law. The results reveal that the stitch length and strain percent are important factors affecting the interfacial pressure and pressure reduction of both plain and interlock fabrics. As the results of statistical analysis, the repeated washing and repeated usage have significant effect on interfacial pressure and pressure reduction of both fabrics. The comparison between experimental pressure values and theoretical values calculated from Laplace's law shows a considerable difference in both plain and interlock fabrics.

Keywords: interfacial pressure, pressure reduction, knitted fabric, Laplace's law.

INTRODUCTION
Compression stockings are known as an effective nonsurgical option for preventing and treating lower limb varicose veins [1]. These kinds of stockings exert an external pressure on limbs, which lead to reduce the vein diameter and increase blood flow [2, 3]. The flat and circular knitting is used as the knitting techniques to produce compression hosieries. In circular knitting technology, the diameter of the machine and the number of needles are fixed during production of a particular product. Diameter of the

product can be changed by altering the tension of the inlay yarn and varying stitch length or using machines with different diameters. These garments are mostly knitted as plain knitted structure [4, 5].

The compression stockings should be able to preserve its compressive pressure even after being worn for an entire day and do not lose their elastic stretch recovery [6]. However, Fabrics show viscoelastic properties and their recovery depends on the drawn ratio. So the exerted loads in the production process and during application of fabrics cause to stretch and let deformations in the fabric. At the beginning of drawing a fabric, the deformation is completely recoverable, but increasing the load on the fabric lead to movement of fibers in the yarn core, this causes time-dependent deformation. The time-dependent deformation is also recoverable, which recovers with time and depends on the initial load [7]. The degree of deformation depends on the several factors such as chemical composition, construction, mass, and thickness of the fabric [8]. Since in the production process and during application the lower loads are exerted, resulting deformations are not permanent. It means that the initial deformation of the fabric after loading consists of two elements, the recoverable deformation (elastic deformation) and deformations, which are recoverable in time (primary creep) [9]. Thus if a fabric is under tension over a long period of time, some of the stresses in it will be relieved, with a consequent reduction in the skin-and-garment interfacial pressure [10]. This is the fabric problematic of having a viscoelastic response to an applied load and is very important, especially in medical pressure garments such as compression stockings. For clinical treatments, it is critical to maintain the pressure on the scar area, within a certain range according to instructions from doctors or therapists. The decline of pressure in the elastic fabrics affects the clinical efficiency of pressure garments [11]. A study by Cheng et al. demonstrated that there is a gradual decrease in skin-and-garment interfacial pressure when patients wear the pressure garments over a period of time [12]. Views of doctors, therapists, and patients support their findings. Slackening occurs in pressure garments when the patient wears them for a long time because the tension of the fabrics is time-dependent [10].

Therefore, it is essential for pressure garments to have the well holding capacity during application and also be suitable for repeated usages. Furthermore, these properties can be improved if the creep behavior and constructional parameters of fabrics are optimized to give the required levels of pressure for specific ailments. In the present work, an attempt has been performed to study the effect of the stitch length, strain value, washing operation and repeated usage on interfacial pressure and pressure reduction of tubular knitted fabrics.

MATERIAL

Fabric Samples

Two different kinds of knitted fabric, plain, and interlock which constructed from textured polyester yarn (16.66 Tex) are studied, and their characteristics are demonstrated in *Table I*. The interlock fabric was knitted on a double jersey MAYER & CIE circular knitting machine with the gauge of 24, and plain fabric was knitted on a single jersey MAYER & CIE circular knitting machine with the gauge of 22.

METHOD

The pressure behavior of weft knitted fabrics was investigated at different stitch lengths, various strain values, repeated washing, and repeated usage. In order to prove the changes in the interfacial pressure under a steady amount of stretch in the course wise fabric direction over a prolonged the period of time, i.e. 48 hours, the following tests were performed.

Pressure Measuring Device

The Kikuhime pressure measuring device (TT Medi Trade) was used to determine the interfacial pressure of tubular fabrics. The small, flexible and air-filled pressure sensor was applied, which has 3cm diameter and about 3 mm thickness. This device is usually used to measure the sub bandage pressure [13, 14].

Tubular Fabric Specimen Preparation Three sizes of tubular fabric specimens were chosen for this study that their diameter was smaller (15%, 20%, and 25%) than the size of the cylindrical tube model (34.54 cm circumference). In fact, the specimens were stretched with 15, 20, and 25 percent of strain. This range of strain was determined assuming pressure garment use. The existing pressure garment is stretched to relatively low strains [10, 11]. Three samples were prepared for each specimen size. The specimens were cut and sewn into the tubular form with a height of 15 cm, which is shown in *Figure 1*. The wale wise direction of the fabric sample refers to the direction that is parallel to the edges, because the test focused on the course wise direction of the fabric.

Measuring Interfacial Pressure

In order to measuring the interfacial pressure of fabric specimens, the samples were put on to the cylindrical tube. After 10 minutes the pressure sensor was inserted between the fabric and cylindrical tube. Then the interfacial pressure was recorded after 1 minute, which allowed the fabric tube to relax sufficiently before measuring. Three measurements were averaged for each specimen size. The diameter of the specimen that had been stretched for 48 hours was measured under zero stresses after it had relaxed for 30 minutes.

Interfacial Pressure after Repeated Washing

The same tests were performed again on the same samples after repeated washings. After the samples were washed and dried, the diameter of the tubular specimen was measured for shrinkage. The washing operation was repeated for seven times and after each washing the interfacial pressure was measured.

TABLE I. Characteristics of fabrics.

Knit type	Code	Stitch length (cm)	Course per cm	Wale per cm	Weight (g/m2)	Thickness (mm)
Plain	P1	0.22	28	12	156	0.54
	P2	0.25	22	12	138.8	0.57
	P3	0.27	18	12	131.2	0.59
Interlock	I1	0.25	22	14	276.4	0.77
	I2	0.29	17	14	245.2	0.82
	I3	0.32	13	14	217.2	1.02

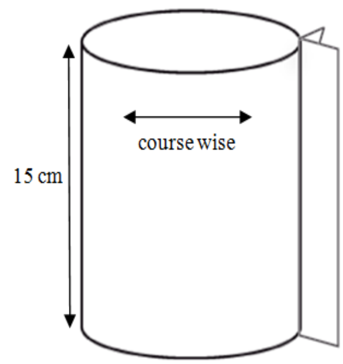


FIGURE1. Prepared tubular fabric specimen.

Interfacial Pressure after Repeated Usage

The design of the test was organized based on usage conditions. As the pressure garment is worn continuously for a period of time in daily duration, correspondingly the fabric is under stress at a certain given strain. When the patient puts off the garment, the tension is released and actually the fabric is under the zero stress. In order to study of the interfacial pressure changes after this repeated usages and relaxations, nine samples were prepared from plain knitted fabric on three different stitch lengths and 25% strain. The test was repeated in nine stages. After each stage, the samples were placed on a smooth surface under zero stresses for 48 hours. Then the sample diameter was measured after 48-hour relaxation.

THEORETICAL BACKGROUND

Laplace's Law

At the early in the 19th century, M. Laplace presented his theory of capillary attraction to the institute of France, in which the wall tension of a container is dependent on both pressure of the container's contents and its radius [15, 16]. Nearly two centuries later, this law was found its direct application in surgical therapy for congestive heart failure [15]. By definition of the Laplace's law, the pressure P can be expressed as Eq. (1).

$$P=T/R \qquad (1)$$

Where T = the tension per unit width and R = the radius of the cylinder [10].

Laplace's law, which relates the pressure, the circumference tension, and the radius of the limb, is used to predict the pressure of the medical compression hosiery in resting position [17]. Due to this equation, interfacial pressure under compression hosieries diminishes gradually with increasing radius from the distal to the proximal leg [18]. In fact, when a fabric is applied with the same constant tension on leg, the pressure values achieved at the ankle will be higher than those exerted at the calf [19].

RESULTS AND DISCUSSION

To consider the influence of different parameters .i.e., stitch length, strain percentage, washing operation, and repeated usage on pressure behavior of fabrics, the statistical analysis was performed.

The ANOVA tests are arranged in SPSS software, and the results are summarized in *Tables II-V*. For all statistical tests, the 95% significance level (α=5%) is chosen.

In the ANOVA tables *Tables II-V*, the final column gives the significance of the F ratio (p value). When p value is less than or equal to α level (5%), the null hypothesis (different levels of the source factor have relatively equal effect on the results), can be rejected. If the p value is greater than 0.05, can be concluded that there is no statistically significant difference between conditions. The significance value shows that there is a significant difference between two treatments, but does not tell us which treatments produced this effect. In these situations, the post hoc tests are designed to provide specific information on means that is significantly different from each other. In this analysis, the Tukey test is used.

The pressure reduction percentage is calculated by using Eq. (2).

$$\left(\frac{P_{10}^{i}-P_{2880}^{i}}{P_{10}^{i}}\right)\times 100 \qquad (2)$$

Where P_{10} = the pressure value after 10 minutes (first measuring) and P_{2880} = the pressure value after 48 hours (2880 minutes) and i= number of washes.

The Effect of Stitch Length on Interfacial Pressure and Pressure Reduction

According to the variance analysis of plain and interlock fabrics, stitch length is an important factor affecting pressure values, because p value (0.00) is less than the critical level (0.05) and so the effect is significant *Tables II, III*. In both kinds of fabrics, when the stitch length increases, there is a significant decline in pressure values *Figure 2*. Thus the samples with the lowest stitch length exert the greatest pressure.

The ANOVA results of pressure reduction of plain and interlock fabrics reveal that the effect of stitch length on pressure reduction over the period of time (48 hours) is significant ($p<0.05$) *Tables IV, V*. In pressure reduction changes, plain and interlock fabrics show opposite behavior. In plain fabric, the samples with the lowest stitch length show more pressure reduction after 48 hours. However, in interlock fabric, in the opposite of plain structure, the sample with the highest stitch length has more pressure reduction *Figure 3*.

If the plain fabrics at three different stitch lengths are stretched by similar strain percentage, the specimen with lower stitch length has more deformations, because there is not sufficient space for yarn movement within the fabric structure. Therefore, the imposed load causes also in the movement of fibers in the yarn structure and consequently, time-dependent deformation happens.

Regarding interlock fabric, because of its special knit structure, the available space for yarn movement is more than plain fabric. It means that in these range of stitch lengths, exerted load due to extension isn't enough to cause fiber movement. Thus the probability of time-dependent deformation is less than plain structure. The interlock sample with higher stitch length presents more space for yarn movement. Therefore, more deformations happen.

The Effect of Strain Percentage on Interfacial Pressure and Pressure Reduction

The variance analysis results *Tables II, III* show that the strain percent has a significant effect on interfacial pressure values in both kinds of fabrics ($p<0.05$). The smaller size of tubular samples causes more extension and consequently, higher interfacial pressure *Figure 4*, because the exerted load via tubular sample on cylinder increases.

Table IV shows that the strain percentage is a significant factor affecting pressure reduction of plain fabric ($p<0.05$), but the effect of strain values up to 25% on pressure reduction of interlock fabric is insignificant *Table V*.

The plain fabrics with the highest strain value show more pressure reduction after 48 hours *Figure 5*. In this fabric with a certain stitch length, the sample which stretched with more strain value shows more deformations after 48 hours. Therefore, its pressure reduction over the prolonged time is more. In the examined range of strains, the imposed load due to extension isn't sufficient to create the considerable difference between pressure reductions of samples with various strain values.

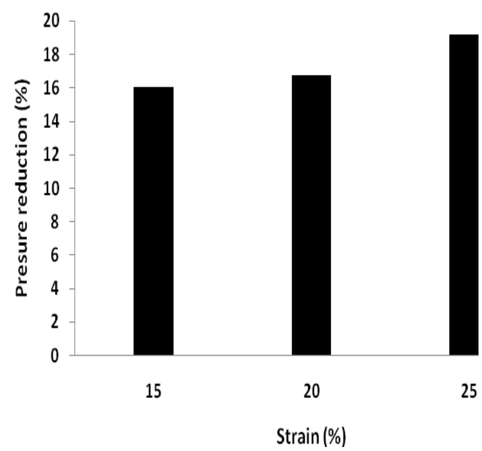


FIGURE 5. Pressure reduction values of plain knitted fabric at three different strain percents.

TABLE II. The results of ANOVA test for interfacial pressure (mmHg) of plain fabric

Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Stitch Length	83096.855	2	41548.428	23011.385	.000
%Strain	10154.054	2	5077.027	2811.886	.000
Repeated Washing	1904.046	7	272.007	150.649	.000
Error	8850.853	4902	1.806		
Total	510472.000	4913			

TABLE III. The results of ANOVA test for interfacial pressure (mmHg) of interlock fabric

Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Stitch Length	107000.827	2	53500.414	23416.556	.000
%Strain	8761.590	2	4380.795	1917.427	.000
Repeated Washing	15628.683	7	2232.669	977.215	.000
Error	9952.266	4356	2.285		
Total	613205.000	4367			

TABLE IV. The results of ANOVA test for pressure reduction (%) of plain fabric

Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Stitch Length	196.542	2	98.271	19.819	.000
%Strain	127.729	2	63.864	12.880	.000
Repeated Washing	2485.544	7	355.078	71.610	.000
Error	297.512	60	4.959		
Total	24701.210	71			

TABLE V. The results of ANOVA test for pressure reduction (%) of interlock fabric

Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Stitch Length	281.817	2	140.908	3.914	.026
%Strain	7.418	2	3.709	.103	.902
Repeated Washing	9267.907	7	1323.987	36.781	.000
Error	1871.829	52	35.997		
Total	38342.690	63			

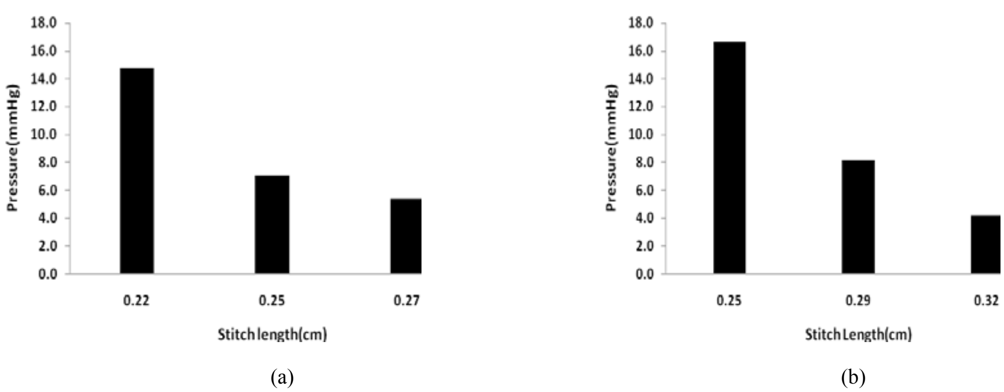
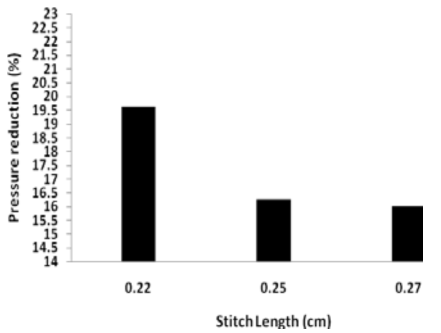


FIGURE 2. Interfacial pressure values of a) Plain knitted fabric b) Interlock knitted fabric at three different stitch lengths.



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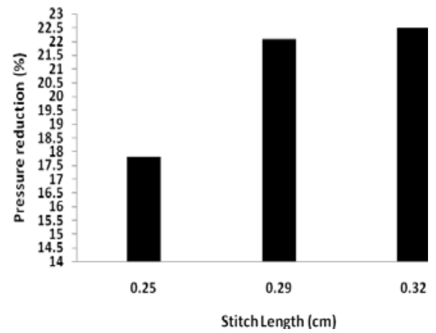

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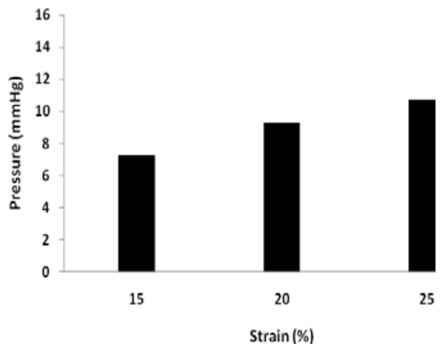
FIGURE 3. Pressure reduction values of a) Plain knitted fabric b) Interlock knitted fabric at three different stitch lengths.



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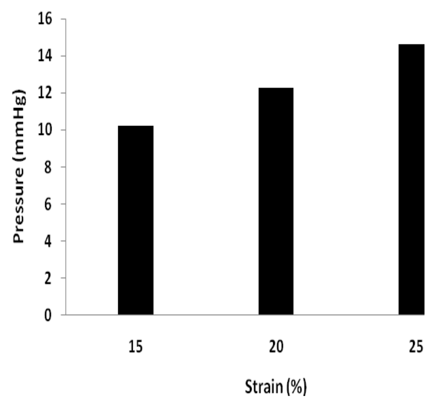


(b)

FIGURE 4. Interfacial pressure values of a) Plain knitted fabric b) Interlock knitted fabric at three different strains.

The Effect of Washing Operation on Interfacial Pressure and Pressure Reduction

The ANOVA results shown in *Tables II-V* compare the pressure behavior of the tubular samples before and after repeated washing. It observes that, the interfacial pressure and pressure reduction values are affected significantly by repeated washing ($p<0.05$).

The interfacial pressure changes during seven washing stages are plotted in *Figure 6.* In both plain and interlock structures, the interfacial pressure of washed samples is higher than the pressure before washing. This is due to the specimens having shrunk to a smaller size but having stretched back to the original extension.

In plain fabric, the pressure has increased until third washing. By third wash up to seventh, as clear in *Figure 6-a,* the results show no considerable changes on interfacial pressure. In accordance with 6-b, in interlock fabric, the interfacial pressure increases until third washing too. Afterwards up to seventh wash, the slight fall is observed. These behaviors are related to the shrinkage phenomenon. It is observed that, in both fabrics, since third wash up to seventh the shrinkage changes were not significant.

Figure 7 indicates the pressure reduction values in each washing stage. In both types of unwashed fabric, great pressure reduction is observed. Washing operation causes to shrinkage and this phenomenon reduces pressure reduction. In plain fabric, as illustrated in *Figure 7-a*, due to shrinkage, there is a steep decline up to third wash. Since then until fifth wash there has been a slight decrease in pressure reduction of fabric. However, then there is a steady increase up to seventh wash, because in these stages, there is no more shrinkage due to washing operation. Therefore, continuing washing causes to deformation and so the pressure reduction increases compared to early stages. Regarding interlock structure, as cleared on *Figure 7-b*, there is a significant decline in pressure reduction of tubular specimens until fifth wash. After that, up to seventh stage, a constant trend is followed.

The Effect of Repeated Usage on Interfacial Pressure and Pressure Reduction

According to the variance analysis results of plain knitted fabric, the repeated usages and relaxations have a significant effect on interfacial pressure and pressure reduction of tubular samples ($p<0.05$). *Table VI* shows the results of TUKEY test to investigate the effect of repeated usage on interfacial pressure of plain knitted fabric. The greatest value of pressure is related to first stage of experiments. Then due to elongation, the pressure has decreased up to the forth test. Since forth the test until ninth, the interfacial pressure does not have significant change.

Table VII indicates the influence of repeated usage on pressure reduction of plain fabrics over a prolonged time. In the first stage, the highest percentage of pressure reduction is observed. The values of pressure reduction decrease up to fifth step subsequently. Since fifth stage until ninth, there have been no considerable changes, because the elongation has not been changed considerably.

TABLE VI. The results of TUKEY test to investigate the effect of repeated usage on interfacial pressure of plain knitted fabric.

Number of Repeated Test	N	Subset		
		1	2	3
9th	39	8.5410		
8th	39	8.5462		
7th	39	8.5872		
6th	39	8.6026		
5th	39	8.6462		
4th	39	8.6667		
2th	39		8.8410	
3th	39		8.9564	8.9564
1th	39			9.0103
Sig.		.187	.289	.970

Comparison between the Experimental Pressure Values and the Theoretical Values Obtained from Laplace's law

The pressure values which were measured by pressure meter and calculated from Laplace's law at three different strains have been compared in Table VIII. According to these values as revealed, there is a considerable difference between theory and experimental in both plain and interlock fabrics (50%-60% for plain fabric and 15%-45% for interlock fabric). The experimental results are less than the obtained values from Laplace's law. These results are in agreement with the recent research which has been performed on rubber shell [20].

CONCLUSIONS

The aim of this study is to investigate the effects of stitch length, strain, washing operation and repeated usage on pressure behavior of knitted fabrics.

The variance analysis results reveal that for both plain and interlock fabrics, stitch length is a significant factor affecting interfacial pressure values and pressure reduction percents over a prolonged time (48 hours). When the stitch length increases, there is a significant decline in pressure values. In plain fabric, the samples have the lowest stitch length show more pressure reduction after 48 hours. Unlike plain fabric, in the interlock fabric, the sample with the greatest stitch length shows more pressure reduction.

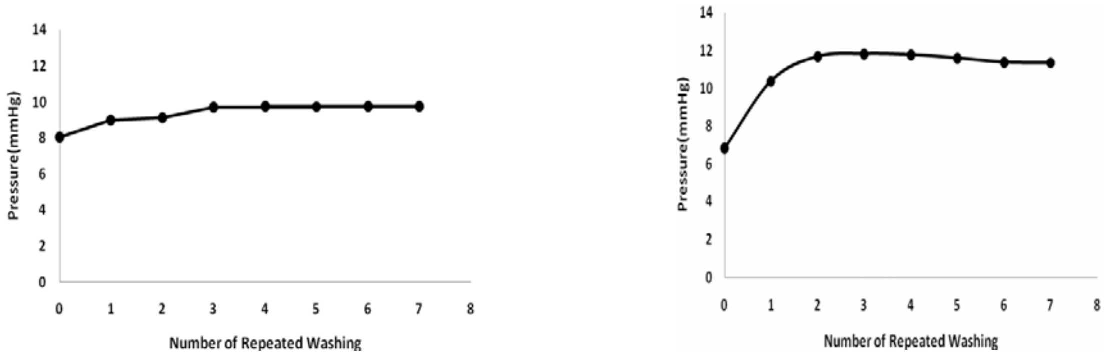
In the both fabrics, more extension causes higher interfacial pressure. The strain percent is a significant factor affecting pressure reduction of plain fabric. The sample with the highest strain value shows more pressure reduction after 48 hours, but the effect of strain values on pressure reduction of interlock fabric is insignificant.

TABLE VIII. The difference percentage between experimental and Laplace's law pressure with 15, 20, and 25% strain of the fabric specimens.

Knit type	Code	Strain percentage	Difference values between experimental and Laplace's law (%)
Plain	P_1	15%	54.4
		20%	58.8
		25%	65.6
	P_2	15%	57.4
		20%	61.6
		25%	68.3
	P_3	15%	49.8
		20%	59
		25%	60.4
Interlock	I_1	15%	26.9
		20%	36.8
		25%	45.1
	I_2	15%	14.4
		20%	29.6
		25%	32.6
	I_3	15%	18.7
		20%	21.3
		25%	28.8

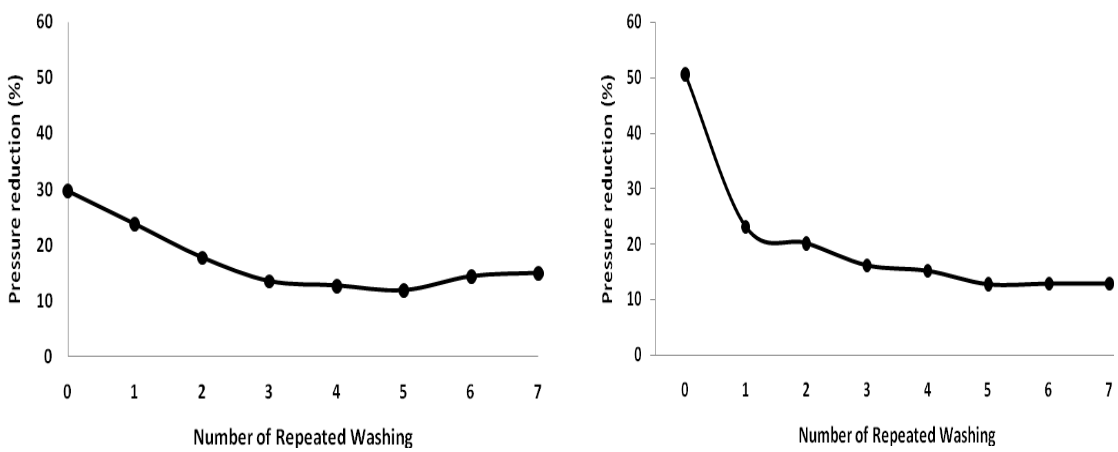
From the ANOVA results, the interfacial pressure and pressure reduction values are affected by repeated washing. In both plain and interlock structures, because of shrinkage, the interfacial pressure after washing is higher than the pressure before washing. The repeated usages and relaxations have a significant effect on interfacial pressure and pressure reduction of tubular samples.

The comparison between experimental pressure values and theoretical results obtained from Laplace's law indicates considerable differences.



(a) (b)

FIGURE 6. Interfacial pressure values of a) Plain knitted fabric b) Interlock knitted fabric after 7 repeated washing operations.



(a) (b)

FIGURE 7. Pressure reduction values of a) Plain knitted fabric b) Interlock knitted fabric after 7 repeated washing operations.

TABLE VII. The results of TUKEY test to investigate the effect of repeated usage on pressure reduction (%) of plain knitted fabric.

Number of Repeated Test	N	Subset				
		1	2	3	4	5
8th	3	5.8667				
9th	3	5.8667				
7th	3	7.1000	7.1000			
6th	3	7.3333	7.3333			
5th	3	7.8333	7.8333			
4th	3		10.2667	10.2667		
3th	3			11.6667	11.6667	
2th	3				13.8000	
1th	3					32.3000
Sig.		.533	.080	.858	.435	1.000

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