tile fibres and his results show that the stroke, frequency of cyclic loading, and temperature affect fatigue behaviour. He has observed that the number of cycles that a textile fibre sample withstands before rupture increases with increasing the frequency, even though the time to rupture decreases. He has also shown that at constant frequency, there is a consistent decline in average lifetime with increase in stroke.

The same result was reported by Prevorsek and Lyons [3,4] who have investigated the effect of stroke on the fatigue lifetime of a number of man-made fibres under tensile fatigue.

Frank and Singleton [5] have studied the factors influencing tensile fatigue behaviour of yarns. They have found that plasticizers in the form of heat and/or water tend to increase the fatigue life of yarns. They have also observed that withstanding of nylon, polyester, and viscose rayon yarns against the cyclic deformation based on the frequency of cyclic straining, temperature, ambient humidity differs in each case, and is dependent on the structure and physical properties (regain and thermoplastic property) of each specific yarn.

Anandjiwala et al. [6,7] have studied the tensile fatigue behaviour of staple yarns under cyclical elongation accompanied by abrasion. They have found that the increase in the base tension decreases the resistance of the yarn under applied fatigue and abrasion. They have also observed that increase in fatiguing speed and strain amplitude also tend to decrease the yarn lifetime.

Seo et al. [8] have studied wear and fatigue of nylon and polyester mooring lines. They considered the relative durability of nylon versus polyester lines as the lines are subjected to tensile cycling under storm conditions. They dealt with the structural interactions that occur during tensile cycling of marine ropes, and attempt to model the combined effect of fatigue and wear in some common rope systems.

Jeddi et al. [9] have investigated the tensile fatigue behaviour of cotton and cotton-polyester blended yarns at two strains. They have concluded that the polyester component in blended yarn causes significant improvement in the fatigue resistance of the yarn against tensile cyclic loading. They have also observed that with higher strain percentage during cyclic loading, there are greater variations in yarn viscoelastic properties.

Jamshidi [10] has studied the effect of tensile fatigue on the mechanical properties of polyester, nylon, and polypropylene filament yarns at two strokes and two frequencies. He has observed that for all yarns and loading conditions, the storage modulus of the yarn increases and under all loading conditions the loss modulus of nylon and polypropylene yarns decreases. He has also observed that after dynamic loading, the initial modulus of the yarns increases while the extension-at-break decreases.

Kobliakov et al. [11] have studied the effects of stroke and frequency of cyclic straining on the tensile fatigue behaviour of woven and knitted fabrics. They have found that the fabrics deformation (i.e., the ratio of non-recoverable elongation to initial length of specimen) decreases by increasing the frequency of cyclic loading while it increases by increasing the stroke. They have also shown that knitted fabrics deform more than woven fabrics and weft knitted fabrics reach the final deformation earlier than the woven fabrics.

Jeddi et al. [12] have investigated the effect of structural parameters on the tensile fatigue behaviour of double guide bar warp knitted fabrics with different structures. They have found that geometry of fabric structure affects fabric fatigue and the final deformation and modulus of the fabrics increase by increasing the number of fatigue cycles, while the percentage of tensile breaking extension decreases.

A new dynamic fatigue tester which simulates knitted fabric deformation during use was developed by Ben Abdessalem et al. [13]. They have tested a plain knitted fabric made of cotton, with the fatigue device at different cycles accompanied by relaxations. They have observed that repeated elongation which was involved by permanent deformation depends widely on relaxation and number of cycles. They have concluded that deformation involved by fatigue test corresponds to a displacement and a lengthening of the yarn composing the loop.

The aim of this research is to investigate the deformation of the tubular woven fabric as well as changes in the fabric mechanical properties under tensile fatigue. This kind of fabric is used for vascular prosthesis, which is exposed to mechanical fatigue due to blood pulsating flow. Therefore, in this study the influence of weave density as well as strain and frequency changes were investigated on the variations of woven fabric mechanical properties under tensile fatigue.

EXPERIMENTAL

Theoretical Background

The term viscoelasticity is commonly applied to materials that are neither ideal solids nor liquids, but in fact possess characteristics that are typical of both. When, a stress is applied to viscoelastic materials, they will show time dependent deformation. Any viscoelastic material, at a given time, would flow when a stress is applied. The material would not fully recover when the stress is removed. The portion of strain that is recovered represents the energy stored or the elastic portion of the material response. The portion of the strain that is not recovered represents the energy dissipated or viscose portion of the material response.

Viscoelastic behaviour is particularly related to the concept of hysteresis and hysteresis friction [14]. For simplicity, this work will be confined to the theory of linear viscoelasticity. The strain introduced into a linear viscoelastic material may be expressed in terms of the applied stress σ by the following general equation:

$$\frac{\sigma}{\varepsilon} = k' + jk'' = k^* \quad (1)$$

Where k^* is a complex value. The ratio of stress to strain comprises a real component or storage part k' and an imaginary component or loss contribution k'' which are in-phase and out-of-phase components, respectively. For in-phase component the phase shift between the stress and strain is zero and for out-of-phase component it is 90°. In general, the complex value k^* and its components are functions of frequency (ω) and temperature (T). Furthermore, the ratio k''/k' which determines the phase relationship of σ and ε is described as the damping factor thus, that we can write:

$$k^* = k' + jk'' = k'(1 + j\delta) \quad (2)$$

For a viscoelastic material in tension or bending, k^* becomes the complex young's modulus E^* as:

$$E^* = E' + jE'' = E'(1 + j\delta_E) \quad (3)$$

$$E' = E^* \cos\delta \quad (4)$$

$$E'' = E^* \sin\delta \quad (5)$$

$$\tan\delta = \frac{E''}{E'} \quad (6)$$

E' is the storage modulus and represents the accumulated energy in elastic form. E'' is the loss modulus and represents the energy dissipated in the material by internal frictions of the macromolecular chains. δ is the loss angle, and tan δ is defined as the ratio of E'' and E'.

Instrumentation

In this research a dynamic mechanical analyzer DMA 2980 was used for studying fatigue behaviour of fabrics. This apparatus consists of two major parts, the DMA cabinet and the DMA assembly. In the DMA multi-frequency mode, at constant amplitude DMA (oscillatory stress and strain) experiments are performed on samples as a function of time, temperature, and frequency of oscillation. Storage and loss modulus, tan delta, viscosities, and with some clamps, displacement and static force (preload force) are the results of multi-frequency mode. No drifting was observed in the measuring of the apparatus.

Materials and Methods

Five different plain tubular woven fabrics varying in weft density were produced using 300 denier twisted textured polyester yarn as warp yarn and 150 denier intermingle textured polyester yarn as weft yarn. The diameter of the tubes was 1.6 cm. Fabrics tensile strength along the weft direction was measured using fabric tensile strength tester (Instron 5566) with a cross-head speed of 25 mm/min and a gauge length of 3 cm. Because of small diameter of the tubular fabric, there was limitation in specimen dimensions. From each fabric structure 10 strip specimens of the size 5 × 1 cm were cut in the weft direction and tested. The average fabrics characteristics are given in Table 1. After the general characterization analysis, the fatigue behaviour of fabrics was studied by using DMA 2980, along the weft direction. The mechanical fatigue in vascular prosthesis is caused by repeated circumferential stress on its wall. For this reason and also in order to investigate the effect of weft density on the mechanical properties of these fabrics under tensile fatigue, we tested the fabrics in the weft direction. The dimensions of each specimen were 5 × 1 cm and gauge length was around 1.7 cm (the maximum gauge length of specimen in DMA can be 3 cm),

Table 1. Fabrics characteristics.

Sample ID	Warp density (Warp/cm)	Weft density (Weft/cm)	Load-at-break (N)	Extension-at-break (mm)	Breaking-strain (%)	Tenacity* (N/tex)
1	34	24	101.20	7.96	26.50	0.25
2	34	25	113.30	7.97	26.60	0.27
3	34	26	124.90	9.10	30.40	0.29
4	34	28	126.0	8.90	29.80	0.27
5	34	29	139.20	9.50	31.80	0.29

Tenacity= load at break / (weft yarn count ×weft density × fabric's width).

initial load was 0.73 N, the duration of fatigue test was 90 min, the film tension clamp was used to grip the fabric strips and the DMA single frequency mode was selected. The temperature of the experiment was kept constant at 37ºC and two specimens from each structure of fabric were tested at 0.5% strain and 1 Hz frequency. In order to investigate the effect of strain and frequency changes, the same test was performed at 1% strain and 1 Hz frequency and also 0.5% strain and 3 Hz frequency, respectively. The average results of the variations of the fabrics viscoelastic properties such as storage modulus (E'), loss modulus (E''), tanδ, and percentage elongation are illustrated in Figures 1- 4.

RESULTS AND DISCUSSION

When a woven fabric is subjected to tensile loading in static form or cyclic loading, its dimension and mechanical properties show changes. The range of this change depends on two major factors. The internal factor that is related to the structure and material of the fabric, such as yarn count, weave density, weave pattern, etc and second, the external factor that is dependent on the test conditions, such as time, number of cycles, strain percent, etc. On the other hand, the dimensional changes of the fabric under loading depend on some factors that can be classified as yarn slippage in the fabric and yarn elongation.

Fabric Storage Modulus

The variations of storage modulus of woven fabrics against time, during tensile fatigue performance are shown in Figures 1a-1c.

The phenomenon of fabric fatigue seems to be due to the following factors: yarn slippage in the fabric and yarn elongation. As it is demonstrated in Figure 1, the former factor causes rapid variations of the fabric viscoelastic properties, while the latter causes gradual variations against fatigue cycles.

Generally speaking, Figures 1a-1c shows that the fabrics with higher density lead to higher fabric storage modulus, due to the fact that fabrics with higher density are stiffer, thus exhibit more elastic response.

It is also seen that storage modulus increases with increasing time length. This can be attributed to decrease in fabric recovery from extension as the number of fatigue cycles increases, which make the fabric stiffer and consequently increases its storage modulus.

Comparison between Figure 1a and 1b reveals that for all fabric structures except sample 1 (weft density: 24 weft/cm) the storage modulus is lower at 0.5% strain than at 1% strain. This means that fabrics at low strain have better recovery from extension and greater stability against repeated tensile fatigues.

Comparison between Figure 1a and 1c shows that for all fabric structures except sample 5 (weft density: 29 weft/cm) the storage modulus is higher at 1 Hz frequency than that at 3 Hz frequency. This can be explained by the fact that by increasing frequency, the allotted time for each cycle of loading decreases. Thus, the fabric would not respond properly to the load.

Fabric Loss Modulus

Figure 2 demonstrates the variations of loss modulus of woven fabrics versus time during tensile fatigue per-

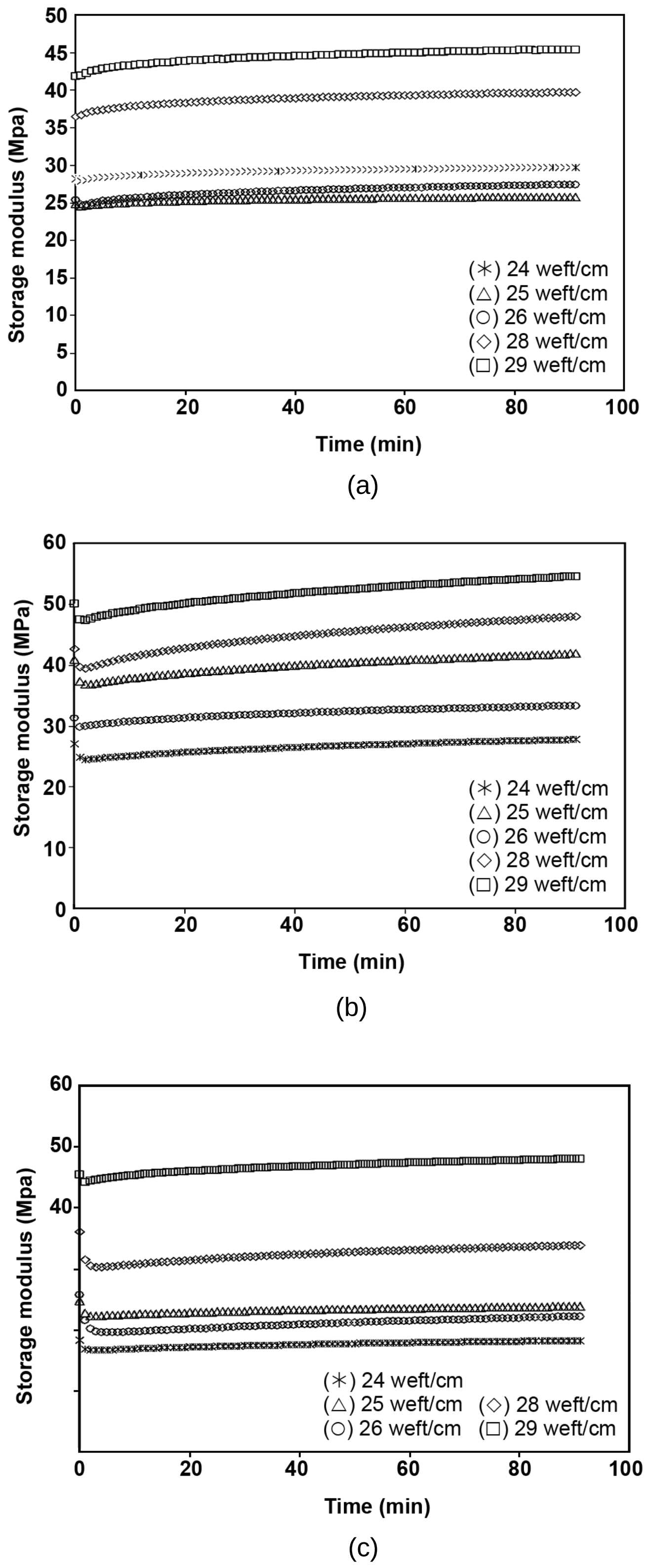

Figure 1. The variations of storage modulus of plain woven fabrics with different weft densities against time at: **(a)** 0.5% strain, 1 Hz frequency; **(b)** 1% strain, 1 Hz frequency; **(c)** 0.5% strain, 3 Hz frequency.

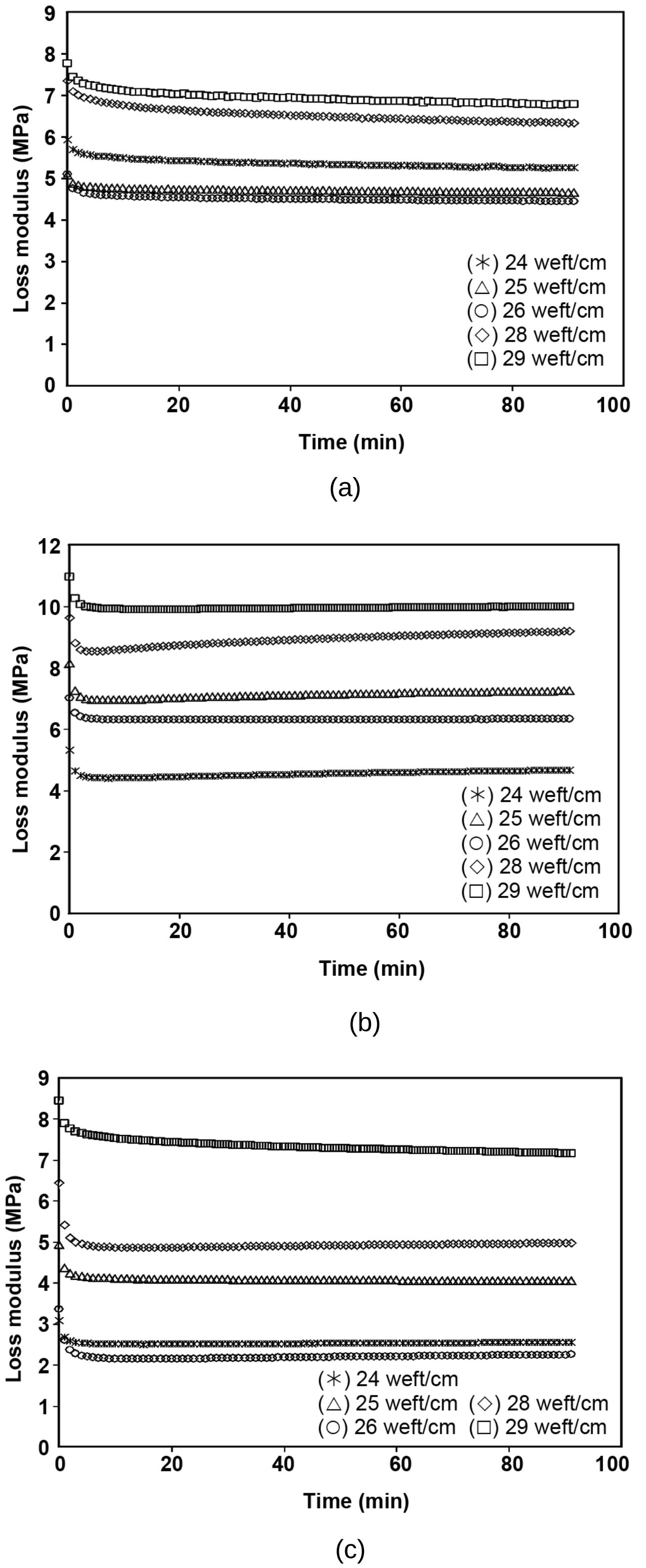

Figure 2. The variations of loss modulus of plain woven fabrics with different weft densities against time at: **(a)** 0.5% strain, 1 Hz frequency; **(b)** 1% strain, 1 Hz frequency; **(c)** 0.5% strain, 3 Hz frequency.

formance which shows a similar trend i.e., a rapid variation is occurred at the beginning of the tests because of yarn slippage, and then variation is continued in a steady state due to yarn elongation.

Generally speaking Figures 2a-2c illustrate that the fabric loss modulus increases with increasing weft density. This can be attributed to more energy dissipation due to interyarn frictions in fabrics with higher weave density.

Comparison between Figures 2a and 2b shows that for all fabric structures, the loss modulus is lower at 0.5% strain than at 1% strain. This means that fabrics at low strain have better recovery from extension and greater stability against repeated tensile fatigues.

Comparison between Figures 2a and 2c reveals that for all fabric structures except sample 5 (weft density: 29 weft/cm) the loss modulus is higher at 1 Hz frequency than that at 3 Hz frequency. The reason is the same for describing the storage modulus.

Fabric Damping Factor

The power of dynamic testing is that, by using the measured phase angle the stress can be separated into two parts, that is elastic stress (σ') and (σ'') viscose stress. The elastic modulus or storage modulus (E') and the viscose modulus or loss modulus (E'') can then be calculated directly from the elastic and viscose stresses, respectively. The damping factor is more commonly referred to as the tangent of the phase angle δ which is a measure of the damping ability of a material. For metals, the damping factor is small (~0.0005) whereas, for viscoelastic materials such as rubber and elastomers it may exceed the unity.

The ratio of (E''/E') was calculated and it is graphically shown in Figures 3a-3c. It is evident in all Figures that the damping factor decreases rapidly at the beginning of the tests, and then continued steadily with time. The decrease of damping factor can be due to the fact that by increasing the number of cycling the fabric becomes stiffer while the dissipated energy decreases due to better recovery from extension.

As it is observed, at 0.5% strain and 1 Hz frequency, with increasing weft density, there is a decrease in fabrics damping factor which corresponds to increase in fabrics storage modulus. A certain trend is not observed for variations of fabric damping factor with weave density at 1% strain and 1 Hz frequency, and also at 0.5%

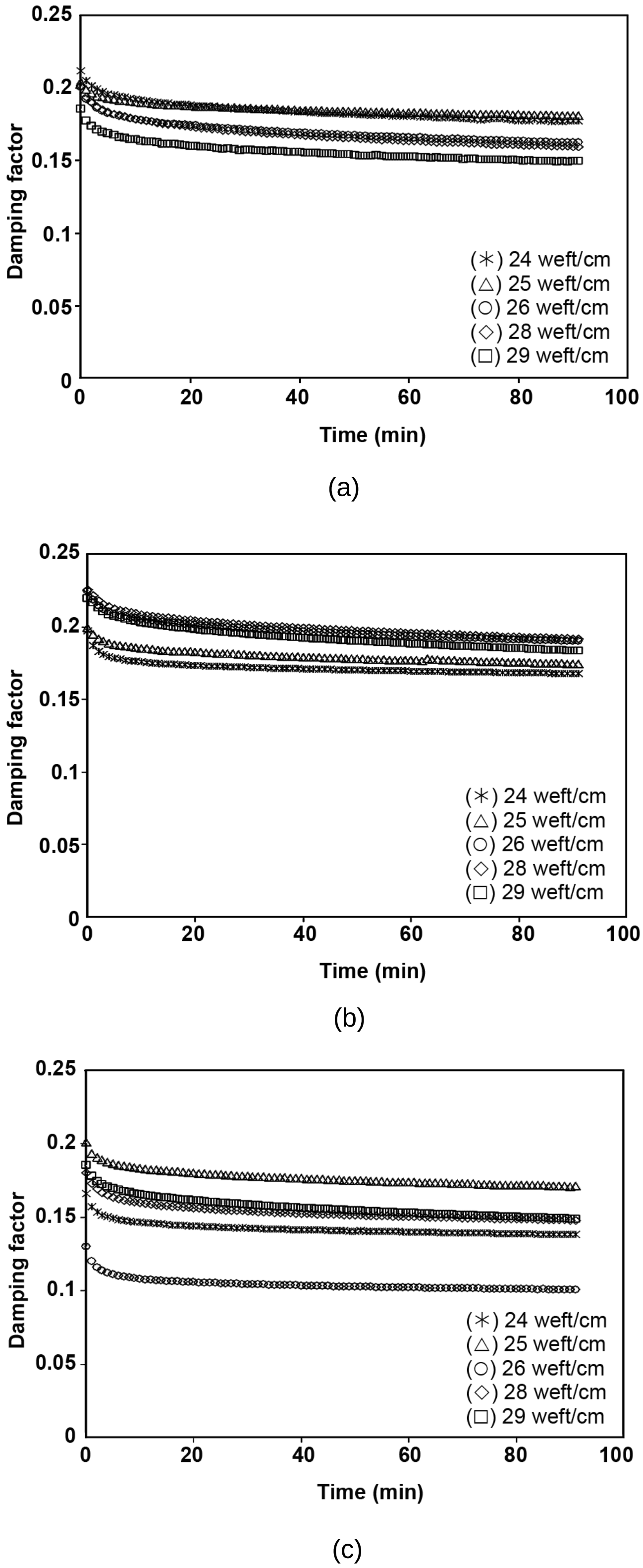

Figure 3. The variations of damping factor of plain woven fabrics with different weft densities against time at: **(a)** 0.5% strain, 1 Hz frequency; **(b)** 1% strain, 1 Hz frequency; **(c)** 0.5% strain, 3 Hz frequency.

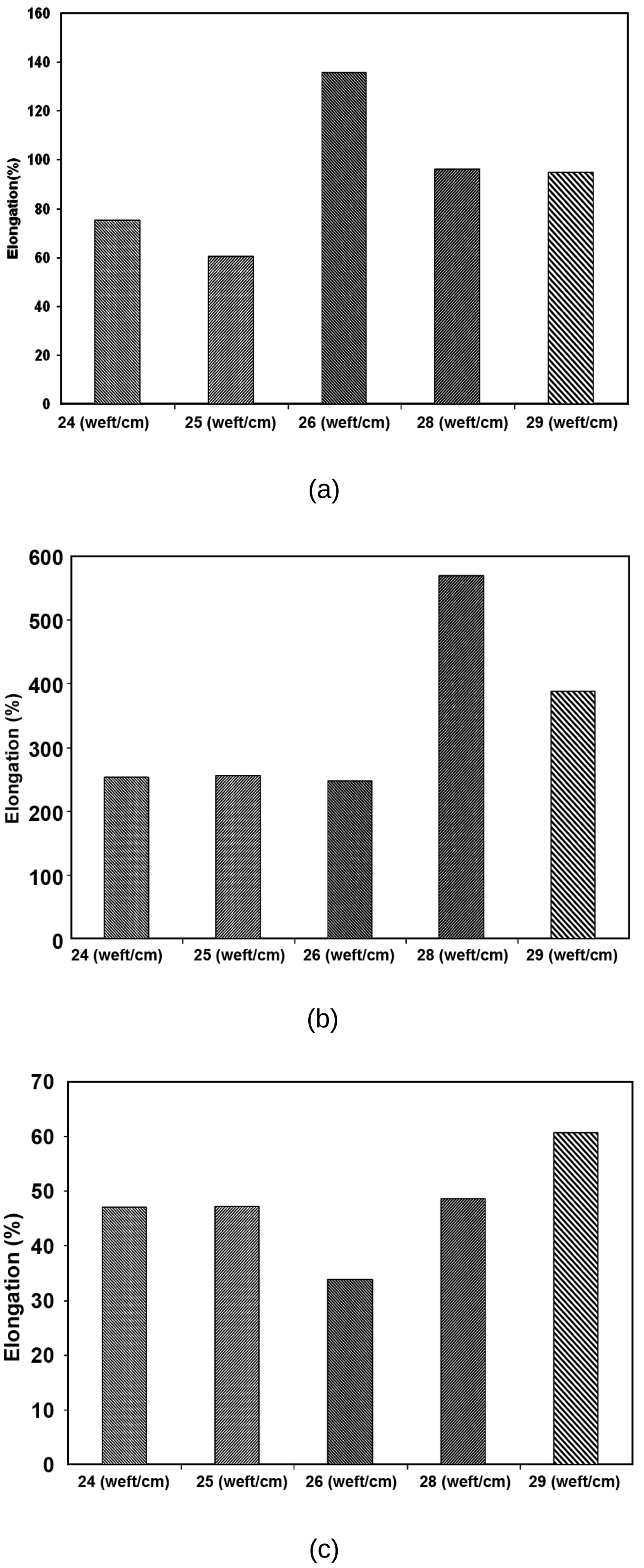

Figure 4. The percentage elongation of plain woven fabrics with different weft densities at the end of fatigue test at: **(a)** 0.5% strain, 1 Hz frequency; **(b)** 1% strain, 1 Hz frequency; **(c)** 0.5% strain, 3 Hz frequency.

strain and 3 Hz frequency.

Comparison between Figure 3a and 3b shows that at higher strain, contrary to tighter fabrics which lead to higher damping factor the looser fabrics show lower damping factor. Since by increasing the strain, both storage and loss modulus increase, this reveals that in tighter fabrics the effect of loss modulus is dominant in storage modulus while in looser fabrics it is reversed.

Comparison between Figure 3a and 3c shows that for all fabric structures the damping factor is higher at 1 Hz frequency than at 3 Hz frequency. Since by decreasing the frequency, both storage and loss modulus increase, this reveals that the effect of loss modulus is dominant in storage modulus.

Fabric Elongation Percentage

The percentage elongation of the fabric at the end of fatigue test (90 min) is demonstrated in Figures 4a-4c. There is no certain trend for variations of fabric percentage elongation with weave density, but for all fabric structures the percentage elongation is higher at 1% strain than at 0.5% strain, which has been confirmed by previous works [1-4,6,9,11]. Thus, it can be concluded that fabrics at high strain have poor recovery from extension and less stability against repeated tensile fatigue.

It is also observed that for all fabric structures (except sample 4) the percentage elongation is higher at 1 Hz frequency than at 3 Hz frequency, which is in accordance with Kobliakov et al. [11]. This can be explained by the fact that by increasing frequency, the allotted time for each cycle of loading decreases. Thus, the fabric would not respond properly to the load, and therefore it can be concluded that there is an increase in lifetime (the lifetime is the decay time of mechanical properties under cyclic loading) with increasing frequency changes

CONCLUSION

In this study, the mechanical properties of plain woven fabrics have been investigated under tensile fatigue loading. The phenomenon of fabric fatigue seems to be due to the following factors; yarn slippage in the fabric, and yarn elongation. The yarn slippage in the fabric occurs at the beginning of the test. This factor which arises from interyarn friction in the fabric structure causes rapid variations of the fabric viscoelastic properties. Following the second mechanism, i.e., yarn elongation appears and causes gradual variations with fatigue cycles.

It was concluded that with increasing weft density, fabrics storage modulus and loss modulus increase for all testing conditions, while damping factor decreases at 0.5% strain and 1 Hz frequency. No particular trend was observed for variations of fabric percentage elongation with weave density.

It has been shown that for all fabric structures, storage modulus, loss modulus and percentage elongation of the fabric are lower at 0.5% strain than at 1% strain, while fabric damping factor is higher at 0.5% strain. It means that fabrics at low strain have better recovery from extension and greater stability against repeated tensile fatigues.

It was observed that for all fabric structures, storage modulus, loss modulus, and percentage elongation of the fabric are higher at 1 Hz frequency than 3 Hz frequency. Thus, it is implied that there is an increase in lifetime with increases in frequency.

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