The Journal of The Textile Institute

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjti20

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To cite this article: Abdelhamid R. R. Aboalasaad, Brigita Kolčavová Sirková & Moaaz Eldeeb (2022) Influence of woven bandage composition on its elasticity and durability, The Journal of The Textile Institute, 113:11, 2299-2309, DOI: 10.1080/00405000.2021.1978191

To link to this article: https://doi.org/10.1080/00405000.2021.1978191

Published online: 14 Sep 2021.

THE JOURNAL OF THE TEXTILE INSTITUTE
2022, VOL. 113, NO. 11, 2299–2309
https://doi.org/10.1080/00405000.2021.1978191

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ARTICLE

Influence of woven bandage composition on its elasticity and durability

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ABSTRACT
It is essential to achieve the optimum stretch for the 100% cotton woven compression bandage (WCB), particularly when producing short-stretch bandage (SSB). Since the SSB achieves a high level of working pressure (dynamic or walking) and a low level of resting pressure (supine or sleeping), this study evaluated the effect of ply twist on yarns extension that are being used as warp yarns in WCB. The proposed study investigated the commercial yarns available in the bandage market in addition to yarns spun at a wider range of ply twist. Moreover, the study analysed the influence of yarn material and bandaging technique on corresponding pressure at the ankle and mid-calf positions. Results revealed that the optimum twist for plied yarn should be at least 1800 turns per meter to produce highly extensible WCB. The experimental results of the uniaxial stress test concluded that the elasticity of 100% cotton short-stretch bandage followed the exponential behaviour whereas the cotton-polyamide-polyurethane long-stretch bandage behaved in a linear function due to the higher level of elastic recovery gained by polyurethane (Elastane) filament.

ARTICLE HISTORY
Received 10 December 2020
Accepted 6 September 2021

KEYWORDS
Plied warp yarns; twist level; bandage elasticity; short- and long-stretch woven bandages; durability

1. Introduction

There are two types of WCB that achieve the optimum stretch. The first type typically uses highly twisted plied warp yarns. The resultant bandage, in this case, is a short-stretch bandage (SSB), such as the 100% cotton WCB. Also, it can be fabricated by using two polymeric yarns with different melting points by means of steaming then applying heat setting. The second type uses Elastane filament (Lycra) with Viscose or cotton to produce a long-stretch bandage (LSB). The key factors that influence the WCB elasticity are the characteristics of the fibre, the yarn processing parameters particularly the single and ply twist, the bandage structure, and the WCB application variables.

There is a strong positive correlation between the warp yarns ply twist and the required cotton bandage elasticity. This bandage elasticity can be defined as 'the elastic recovery after extension or compression when the bandage is subjected to repeated stresses and activities. Moreover, the yarn strength is a function of the characteristics of the fibre (mainly the fibre fineness, cross-section, and tenacity) as well as the yarn parameters (i.e. twist coefficient, number of fibres in cross-section, and yarn evenness). This paper sheds light on the effect of ply twist on yarn extension that is being used as warp yarns in woven bandages and discusses the influence of yarn material and bandaging technique on corresponding pressure at the ankle and mid-calf positions.

It is known that the geometrical arrangement of filaments (fibrils) in the structure of twisted fibre bundles can be described by a model of concentric helixes, the so-called ideally helical model (Neckář, 1990). Mertová et al., (2018) considered that peripheral fibres have the shape of a helix with an angle of fibre slope to the multifilament yarn axis (β_D). They confirmed that increasing the twist level has increased the angle of peripheral fibres (β_D) and the angle between the axis of fibres on the surface and the line parallel to the yarn axis (β') increased as well. There was a shortening (twist take-up) of the multifilament yarn because of twisting. It was associated with an increase in yarn count value which was expressed by the substance cross-sectional area of multifilament yarn.

Previous research concluded that increasing the twist level decreased the yarn mass coefficient of variation, yarn diameter, coefficient of variation, and hairiness (Abbasi et al., 2012; Sreenivasan & Shankaranarayana, 1961). Meanwhile, increasing the twist level of staple yarn improved their tenacity, however, the higher twist of multifilament yarns reduced their strength which is an important factor in terms of their end-use, especially for technical applications (Moučková et al., 2018). Altas et al. concluded that, in carded yarns, an increase of twist coefficient increases the evenness, tenacity, and elongation values and decreases hairiness and diameter values significantly. In combed yarns, the increase in twist coefficient increases tenacity and elongation and decreases the number of thick places, neps, hairiness, and diameter values significantly (Altas & Kadoğlu, 2012).

Kotb (2012; Eldeeb Moaaz, 2010), investigated the dependence of yarn quality on the yarn ply twist. At a twist

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ratio of ply twist factor to a single twist factor over 1.1, maximum strength was achieved. Smith and Waters (1985) concluded that yarns of lower twist had lower strength due to fibre slippage, moreover, yarns of very high twist had lower strength because of increased fibre obliquity to the yarn axis. Hence, it is necessary to adopt the optimum twist level for single and plied yarns.

Chattopadhyay, (2008; Essam, 1928; Zulfiqar, 2011), concluded that a higher yarn twist can increase the fabric strength up to a certain extent and decreases the binding effect of the fabric structure by increasing the yarn compactness, and beyond that, the strength fails particularly with close-woven fabrics. Moreover, According to Taylor, (1959; Seo et al., 1993), the fabric strength was increased with the increase in warp and weft linear density by improving the fibre binding relative to the yarn strength since the yarn failure was initiated at the bending points where the highest local strain occurs. However, Essam (1928) reported that the strength of fabric increased with the increase in fabric settings (warp and weft densities) but after certain limits, this increase did not yield a corresponding increase of strength.

There is scarce information concerning the effect of high ply twist on the warp yarns elasticity that are being used in woven bandages (Aboalasaad & Sirková, 2017; Maqsood et al., 2016). Therefore, this study initially investigates the commercial yarns available in the bandage market in addition to yarns spun at a broader range of ply twist. Moreover, the study reveals the influence of bandage material and the number of layers on its elasticity and durability since there are also limited sources in this regard (Kumar et al., 2013; Kwon et al., 2018; Partsch et al., 2008).

Relaxation time is commonly used to describe the stress-relaxation behaviour of a viscoelastic material, which indicates the time required to reach the steady state of the material after an unrelaxed state. Previous research observed that cotton and Viscose fibres have the lowest relaxation time, where the stress decayed fast under constant extension (Kumar et al., 2014). So that it was necessary to study the effect of cyclic stress-relaxation on the applied load by long- and short-stretch woven bandages.

2. Methodology

2.1. Analysis of the mechanical properties of the warp yarns

The methodology plan was divided into two phases, the first was to evaluate the mechanical properties of the plied warp yarns used for producing WCB available in the commercial market. The second was to produce and analyse warp yarns at a certain range of ply twist to achieve the required high extensibility and elasticity of the WCB. The required bandage tension can be adjusted by controlling the optimum bandage extension as a function of warp yarn twist and other variables. As for the first phase, fine (6 Tex) and coarse (21 Tex and 30 Tex) yarns were plied with a high ply twist ranges from 300 to 2300 twist/m (tpm) as shown in Table 1. The yarns were kept in a conditioning room for 24 h at standard temperature (20 ± 2 °C) and relative humidity (65%) before testing.

The load-elongation curve of the warp yarns was obtained according to the ASTM D2256 (ASTM-2256, 2002). Instron 4411 tensile testing machine was used to measure the tension developed in the yarn while keeping a gauge speed of 180 mm/min. The device gauge length was set to 500 mm. The yarn twist per meter was measured on the TWIST LAB-2531C twist testing machine according to standard procedure CSN 80 0701. The yarn linear density was measured from a lea of one hundred meters according to CSN 80 0050 (Aboalasaad & Sirková, 2019).

Afterwards, the yarn tensile properties were evaluated and based on the results, the best single yarn among the commercial yarns was 21 Tex and therefore a new single yarn (20 Tex) was selected to be plied at a wider range of ply twist (600–2200 tpm). As for the second phase, to produce the new proposed 100% cotton WCB, single ring-spun yarns were produced from Egyptian cotton fibres, Giza 86, by using the Rieter G37 ring spinning machine according to the plan shown in Table 2.

The linear density of the weft yarns was kept at 60 Tex for all bandage samples. As far as the warp yarns are concerned, among all above single yarns, the 20 Tex yarns spun in S and Z-direction were chosen to be plied on two plies using DirecTwist twister at a nominal twist level ranges from 600 to 2200 twist/m and at different twist direction to achieve the required high extensibility and elasticity of the WCB as demonstrated in Table 3.

2.2. Evaluation of warp yarns material and bandage structure

To investigate the influence of yarns raw material, 100% cotton SSB and cotton-polyamide-polyurethane (CO-PA-PU) LSB were used, as shown in Figures 1 and 2, respectively. Besides, the WCB pressure was measured using the Microlab PicoPress instrument M-700 at the ankle and mid-calf positions (Aboalasaad & Sirková, 2019). The specifications of the bandage samples are shown in Table 4. To study the influence of the bandaging technique on its elasticity and durability, the bandage was applied on a real leg using two and three bandage-layers (Aboalasaad et al., 2020; Kumar et al., 2013; Kwon et al., 2019).

Testometric M350-5CT instrument was used to measure the SSB and LSB tension at a constant speed of 100 mm/min. The device gauge length was set to 100 mm and the 500 N load cell was used to measure the uniaxial load applied by stretching the WCB according to standard test method ISO 13934-1:1999(E) (E. ISO, 1999) and the load-relaxation test for both bandage types was evaluated according to the experimental setup shown in Figure 3 (Aboalasaad et al., 2020). Moreover, the CO-PA-PU LSB was tested using the same scheme except that it was extended by 60 mm to achieve 120% extension, then 4 s dwell, followed by a 20 mm relaxation.

Table 1. Commercial plied yarn properties.

	Ply yarn twist (twist/m) Twist direction (SS-Z)	Nominal yarn count (Tex)	Actual yarn count (Tex)
Group no. 1	300	6*2	11.78
	600		12.16
	900		12.87
	1200		13.24
	1500		13.71
	1800		13.96
Group no. 2	1850	21*2	49.37
	2100		51.15
	2200	30*2	74.72
	2300		80.27

Table 2. Single yarn process parameters.

Nominal yarn count (Tex)		15	15	20	20	25	25	30	30
Twist direction		S	Z	Z	S	S	Z	Z	S
Actual yarn count (Tex)	Average	14.7	15	19.7	19.8	24.6	24.7	29.5	29.8
	C.V. (%)	1.6	1.7	1.6	1.3	1.2	1.11	1.1	1.04
	Std. (Tex)	0.24	0.26	0.32	0.26	0.30	0.27	0.32	0.31
Twist/m		1031	1062	910	925	803	799	751	748
Twist factor (α_m)	Average	127.3	127.3	127.3	127.3	127.3	127.3	127.3	127.3
	C.V. (%)	3.3	3.1	3	2.7	2.33	2.5	2.3	2.4
	Std. (αm)	4.20	3.95	3.82	3.44	2.97	3.18	2.93	3.06
Tenacity (cN/Tex)	Average	19	19.5	20.3	20.5	22.2	22	21	21.9
	C.V. (%)	6.6	6.15	5.8	6	5.6	5.5	4.4	4.3
	Std. (cN/Tex)	1.254	1.199	1.177	1.23	1.243	1.21	0.924	0.942

Table 3. Newly produced plied yarn properties, 20*2 Tex.

Twist direction					
SS-Z		SZ-Z		ZZ-S	
Ply twist (twists/m)	Actual yarn count (Tex)	Ply twist (twists/m)	Actual yarn count (Tex)	Ply twist (twists/m)	Actual yarn count (Tex)
606	40.03	597	40.87	602	39.63
1181	41.88	1216	42.18	1204	41.29
1761	45.78	1793	46.68	1773	48.40
2185	52.26	2168	55.45	2172	54.42

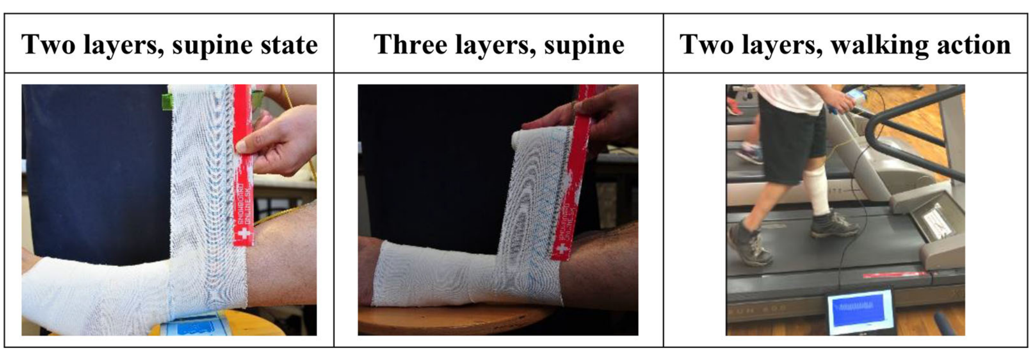


Figure 1. Application of two- and three-layers bandaging on a human leg, 100% bleached cotton short-stretch WCB.

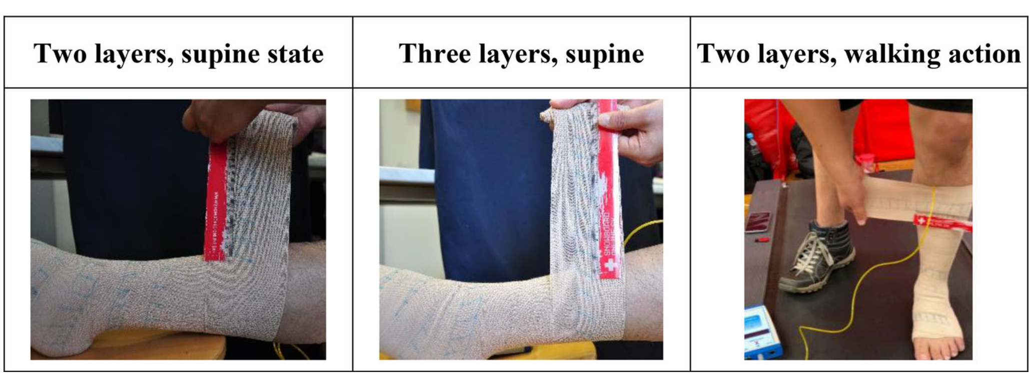


Figure 2. Application of two- and three-layers bandaging on a human leg, cotton-polyamide-polyurethane long-stretch WCB (78-16-6%).

Table 4. The characteristics and specifications of the bandage samples.

(1) Cotton bandage parameters:	(2) CO-PA-PU bandage parameters:
Warp set: 8 ends/cm	Warp set: 11 ends/cm
Weft set: 15 picks/cm	Weft set: 18 picks/cm
Warp count: cotton, 20 × 2 Tex, 1800 twist/m	Warp count: cotton, 10 × 2 Tex / polyamide, 7.8 Tex / polyurethane, 42.5 Tex.
Weft count: cotton, 75 Tex, open-end yarn.	Weft count: cotton, 36.9 Tex.
Fabric weight: 210.25 g/m2	Weight: 236.48 g/m^2
Fabric thickness: 1.06 mm	Thickness: 1.09 mm

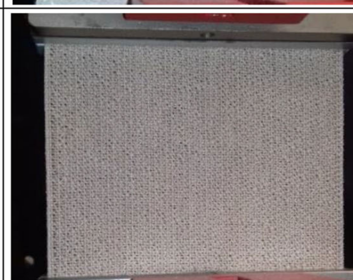
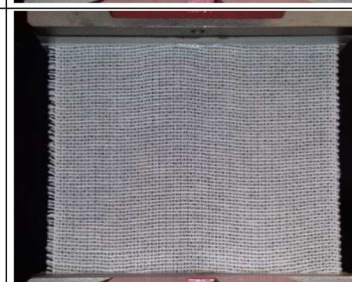
The experimental setup	CO-PA-PU LSB	100% Cotton SSB
Original sample size 100x100 mm^2 and 50 mm gauge length		
Extending the WCB 30 mm to achieve 60% extension, then 2s dwell, followed by a 10 mm relaxation to reduce the extension up to 40%, then the stretch-relaxation continued for 6 cycles		
After 6 cycles of stress-relaxation		
After 5 days of cyclic loading-unloading		

Figure 3. Stress-relaxation test using Testometric M350-5CT.

3. Results and discussion

3.1. Relationship between warp yarn twist and its tensile properties

Load-elongation curves of the commonly used ply twist of warp yarns in the market are illustrated in Figure 4. The 1st group showed a breaking load ranges from 1.9 to 2.3 N at 35 and 23 [mm] elongation respectively, whereas the 2nd group achieved 5.2 to 6.5 N at 53 and 72 [mm] respectively. However, the plied yarn tenacity of group 1 ranges from 16.5 to 24.9 [cN/Tex], and it is significantly higher than group 2 that ranges from 8.5 to 15.5 [cN/Tex], as previously calculated in previous research (Aboalasaad & Sirková, 2019).

Table 5 summarizes the tensile properties of the plied yarns that are commonly used in producing the WCB in the market. Notably, increasing the ply twist from 300 to 1800 twist/m increases the actual plied yarn linear density by 18.51% for fine count 6*2 Tex.

Figures 5 and 6 illustrate that increasing the plied yarn twist, in group 1, from 300 to 600 twist/m increases the yarn tenacity and breaking elongation by 5.16% and 8.21% respectively. After that, the yarn breaking load gradually decreases by increasing the yarn twist from 900 up to 1800 twist/m, on the contrary, the yarn extension significantly increases by 27.48%. Whereas the plied yarn in group 2, at 2100 twist/m yields less tenacity values than 1850 twist/m by 20.86%, moreover the tenacity decreased by 15.73% at 2300 twist/m. These lower values of tenacity are due to the increase in twist angle close to the perpendicular level (wrapping angle is almost 87° at the highest levels of ply twist), as a result, the horizontal component of the forces contributing to yarn strength decreases.

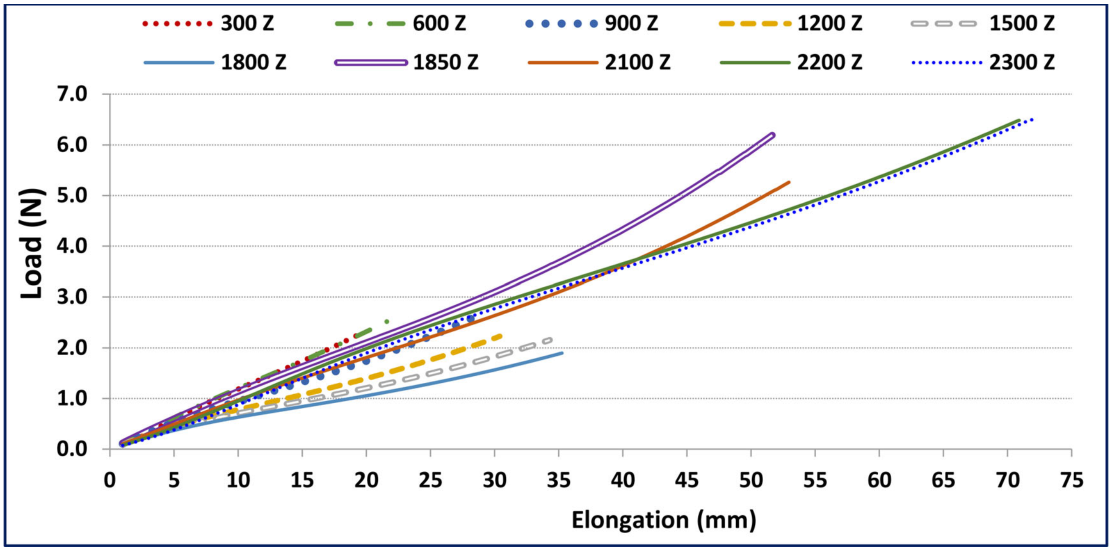


Figure 4. Load-elongation curves of the 1st and 2nd groups of yarns.

Table 5. Commercial plied yarn tensile properties.

				Tenacity		Extension	
	Yarn twist (twist/m)	Actual yarn count (Tex)	Nominal yarn Count (Tex)	Average (cN/Tex)	Std. (cN/Tex)	Extension (%)	Std. (%)
Group no. 1	300	11.78	6*2	23.64	1.4275	4.75	0.6118
	600	12.16		24.86	1.5201	5.14	0.6515
	900	12.87		23.51	1.9156	6.44	0.8210
	1200	13.24		20	1.7504	6.98	0.7502
	1500	13.71		18.09	1.4808	7.67	0.6346
	1800	13.96		16.49	1.5827	8.21	0.6783
Group no. 2	1850	49.37	21*2	15.53	1.2982	12.01	0.6491
	2100	51.15		12.85	1.2596	12.19	0.6298
	2200	74.72	30*2	9.86	1.4965	15.78	0.7483
	2300	80.27		8.52	1.2289	15.77	0.6144

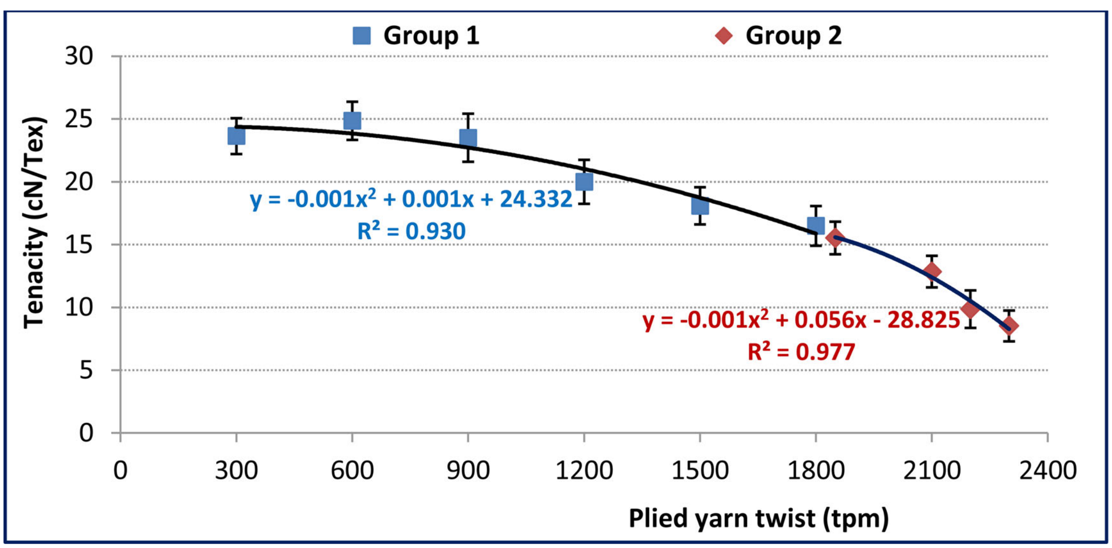


Figure 5. Effect of ply twist on yarn tenacity for commercial bandage yarns.

The obtained results in Figures 5 and 6 contribute to selecting the optimum yarn twist, for the selected commercial yarns at least (1500–1800 twist/m) are required for producing high extension cotton compression bandages, whereas to achieve the highest elasticity of cotton WCB, 2200–2300 twist/m would be used. However, for the 21*2 Tex yarn, the extension has reached an acceptable level of 12% and still improves with the increase in twist, on the other hand, the tenacity has lowered to 15.5 cN/Tex and still deteriorates with the increase in twist. Hence, the 21*2 Tex yarn among all commercial yarns at 1850 tpm would be appropriate for the bandage warp yarn. Thus, the new 20*2 Tex plied yarns would be produced and evaluated to achieve the optimum bandage pressure. Nevertheless, the optimum

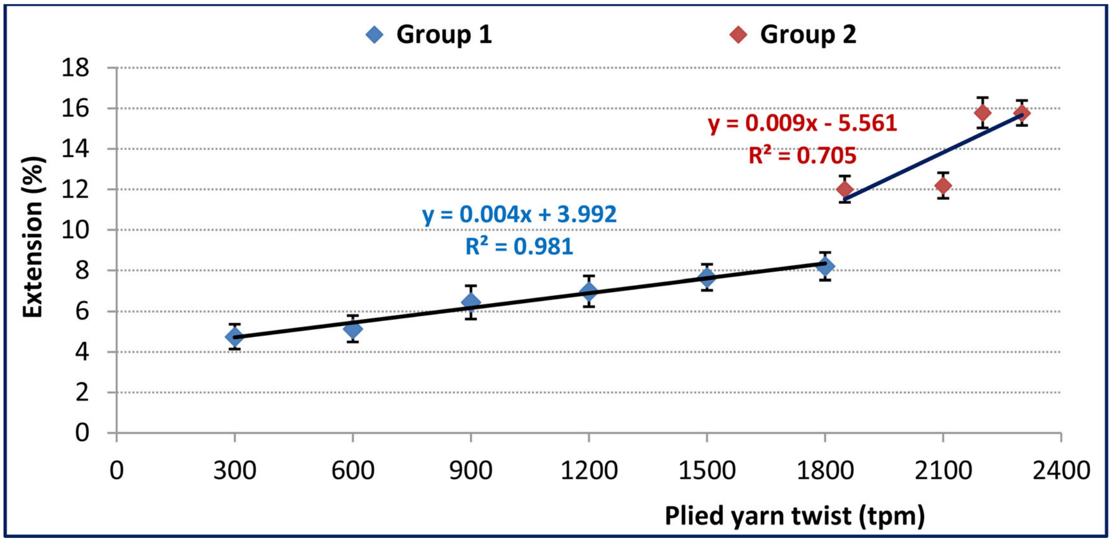


Figure 6. Effect of ply twist on yarn extension for commercial bandage yarns.

extension level and applied load entirely depend on the final end-use of the compression bandage either for venous leg ulcers or athletic performance (Aboalasaad & Sirková, 2019). Yet, these results are not conclusive because the twist range and the yarns count are different.

3.2. Evaluation of the newly produced plied warp yarns

The evaluation of the used plied warp yarns in the market for producing the WCB concluded that the warp yarn tenacity should be greater than 15.5 cN/Tex and its extension should be at least 12% to produce the highly stretched 100% cotton WCB. Since the suitable yarn which is 21*2 Tex was given a limited range of twist, a new 20 Tex yarns spun in S and Z-direction were thoroughly investigated and plied on two plies at a wider twist level ranges from 600 to 2200 twist/m at different twist direction to achieve the required high extensibility and elasticity of the WCB as demonstrated in Table 6, Figures 7 and 8.

Results show that increasing the plied yarn twist from 600 to 1200 twist/m improved the yarn tenacity slightly. After that, the yarn tenacity deteriorates gradually until 2200 tpm. Nevertheless, the yarns extension significantly increases constantly from 600 to 2200 tpm. The results of the newly produced 20*2 Tex yarn were promising because the 21*2 Tex yarn which was tested earlier achieved 15.5 cN/Tex and 12% extension at the 1850–2100 tpm range. But when using the wider range of ply twist, the proposed 20*2 Tex yarn achieved 18–20 cN/Tex and 11.5–12.5% extension at 1500–1800 tpm range. In this way, the newly produced yarns could realize better yarn tensile properties at a lower ply twist level which is good from an economic perspective (Aboalasaad & Sirková, 2019).

As far as the effect of twist direction is concerned, the extension of the sz-z yarns is the highest followed by the extension of the zz-s and ss-z yarns. However, the tenacity of the sz-z yarns is almost the lowest among yarns but yielded no differences at the highest level of twist approximately 2200. Nevertheless, these differences are insignificant compared to the effect of the twist level.

Table 6. Newly produced 20*2 Tex yarn tensile properties.

Ply twist (twists/m)	Actual yarn count (Tex)	Tenacity (cN/Tex)	Std.	Extension (%)
Twist direction, SS-Z				
606	40.03	21.8	1.09	9.37
1181	41.88	23	0.92	10.81
1761	45.78	19	0.912	12.04
2185	52.26	16.2	0.648	12.97
Twist direction, SZ-Z				
597	40.87	20.5	1.0455	9.92
1216	42.18	20	0.86	11.07
1793	46.68	17.9	0.895	12.64
2168	55.45	16	0.48	13.83
Twist direction, ZZ-S				
602	39.63	22	0.99	9.16
1204	41.29	22	1.32	11.31
1773	48.40	17	0.884	12.47
2172	54.42	16.6	0.664	13.53

Figure 9a shows the longitudinal view of single yarns using the Scanning Electron Microscopy (SEM). The yarns were plied to highly twist levels to achieve the required bandage stretch, whereas Figure 9b shows the plied yarn that has a high twist level of 2200 twist/m. The plied yarn twist angle ranges from 64 to 83°. The higher twist levels increase the fibre-to-fibre cohesion, make the tips, or ends of the fibres protruding from the surface of the yarn to contribute to yarn tension, and wrap the cotton fibres to obtain a compact yarn structure, and consequently causing higher extension (Bhargava, 1984).

3.3. Effect of warp yarn material and bandaging technique on bandage elasticity and durability

According to the previous calculation of the compression applied by the 100% cotton SSB and CO-PA-PU LSB (Aboalasaad et al., 2020; Aboalasaad & Sirková, 2019), the cotton bandage required optimum tension of 10.3 N at 60% extension whereas CO-PA-PU was stretched 120% to

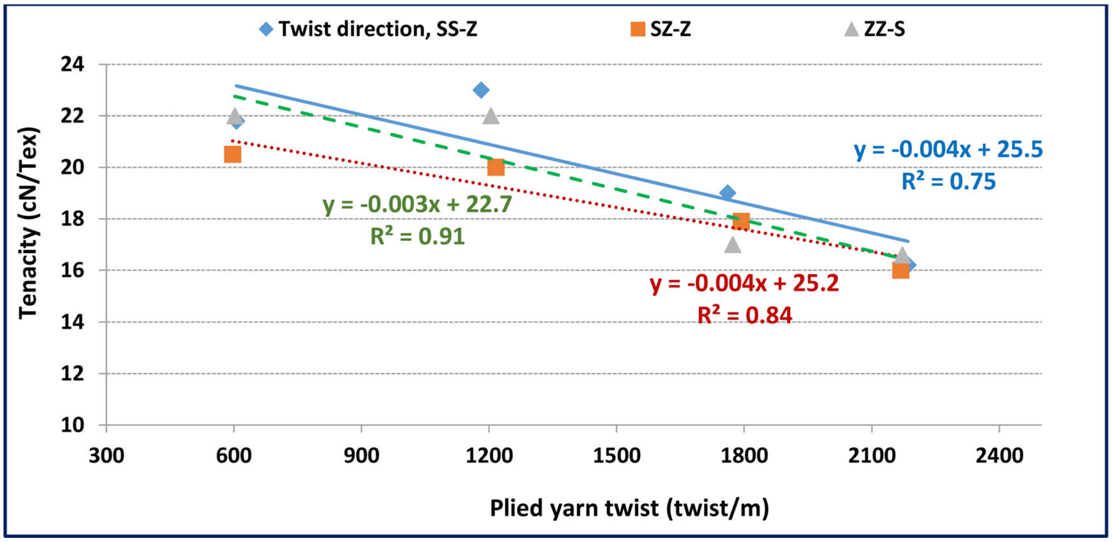


Figure 7. Effect of ply twist on 20*2 Tex bandage warp yarn tenacity.

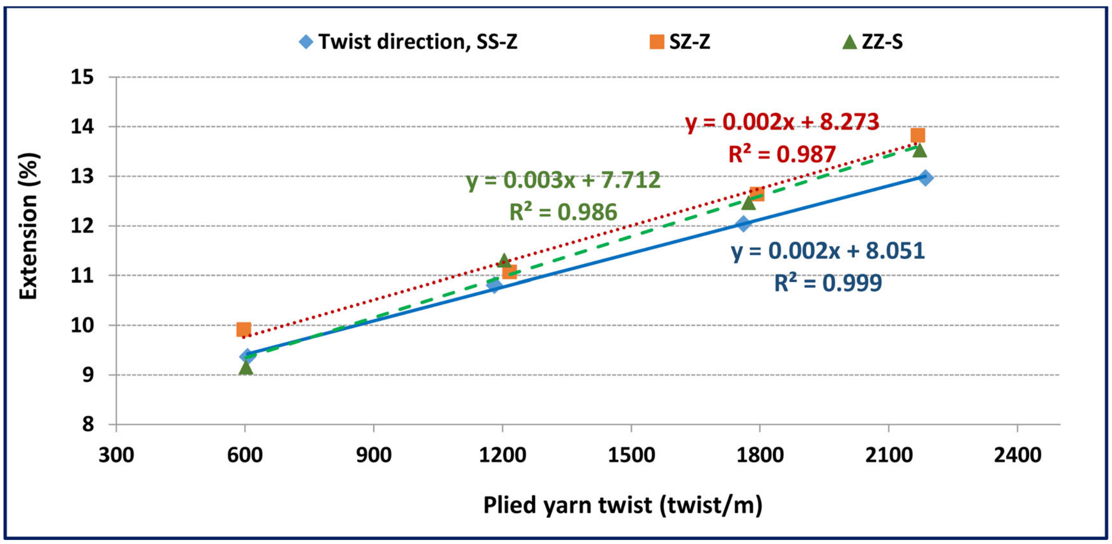


Figure 8. Effect of ply twist on 20*2 Tex bandage warp yarn extension.

achieve 12.2 N, as illustrated in Figure 10. It is obvious that the cotton bandage elasticity follows the behaviour of exponential function whereas the CO-PA-PU behaves in a linear function due to the higher level of elastic recovery caused by the polyurethane filament. Moreover, the highly twisted plied warp yarns enable the cotton bandage to achieve an acceptable value of elasticity at moderate extension levels.

According to the earlier findings shown in Figure 11, regarding the measurement of the applied extension level to achieve the optimum bandage pressure at ankle position (Aboalasaad et al., 2020; Aboalasaad & Sirková, 2019). Cotton SSB achieved approximately 35 mmHg and 52 mmHg for two and three layers, respectively at 60% extension, whereas CO-PA-PU LSB should be stretched up to 120% to obtain 48 mmHg and 72 mmHg, respectively. It is essential for patients or any bandage user to understand the high resting compression applied by the LSB that reaches approximately 20.13 to 30.49 mmHg at ankle position for two and three layers respectively, in case the bandage was stretched to 120% extension then relaxed (Aboalasaad et al., 2020). Hence, the patient should take off the LSB during rest time or sleeping.

Similarly, Figure 12 illustrated the influence of bandage extension on practical pressure at the mid-calf position. The cotton SSB had 23 and 34 mmHg for two and three layers at 60% extension, while CO-PA-PU LSB achieved 33 and 46 mmHg, respectively at 120% extension. The results of Figures 11 and 12 confirmed the gradual decreasing bandage pressure, starting with maximum values at ankle position, reducing at the calf, and finally achieving the minimum compression at the knee position (Aboalasaad & Sirková, 2019).

Figure 13 demonstrates that during the unloading cycle, the minimum applied load by CO-PA-PU LSB reached approximately 1.75 N and 5.15 N at 60% and 120% respectively, which corresponds to a high resting pressure level of approximately 11.5 mmHg and 28.6 mmHg, respectively according to the Laplace equation (Aboalasaad et al., 2020). Whereas cotton SSB has a higher value for working pressure and very low resting compression less than 5 mmHg at

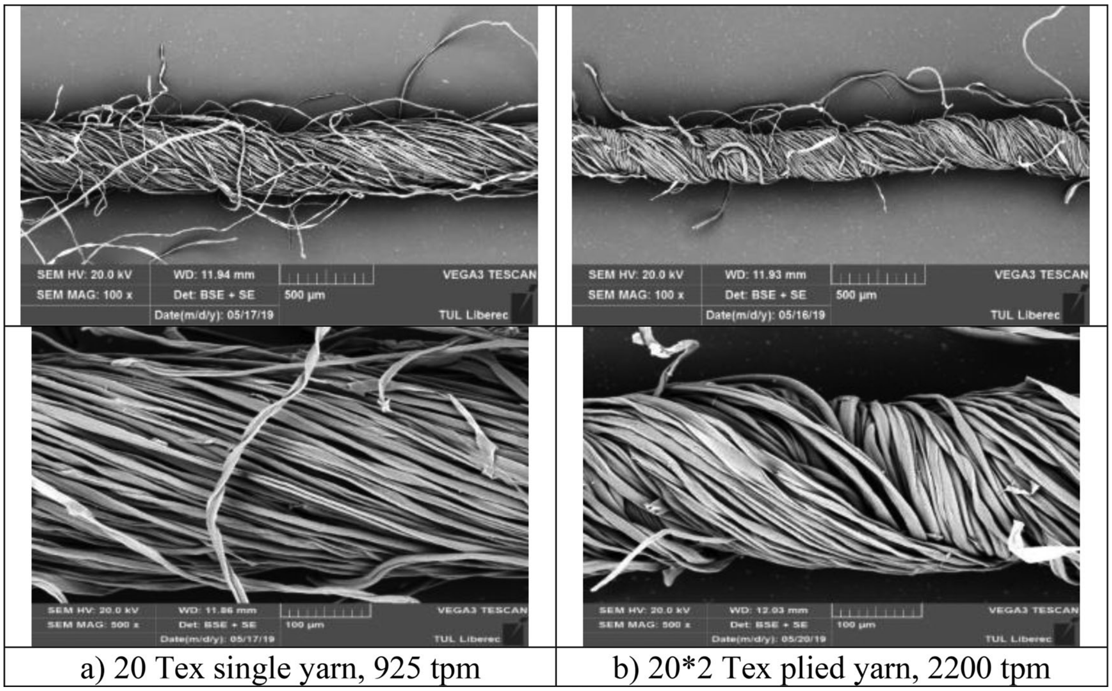


Figure 9. Scanning electron microscopy of the single and plied yarns.

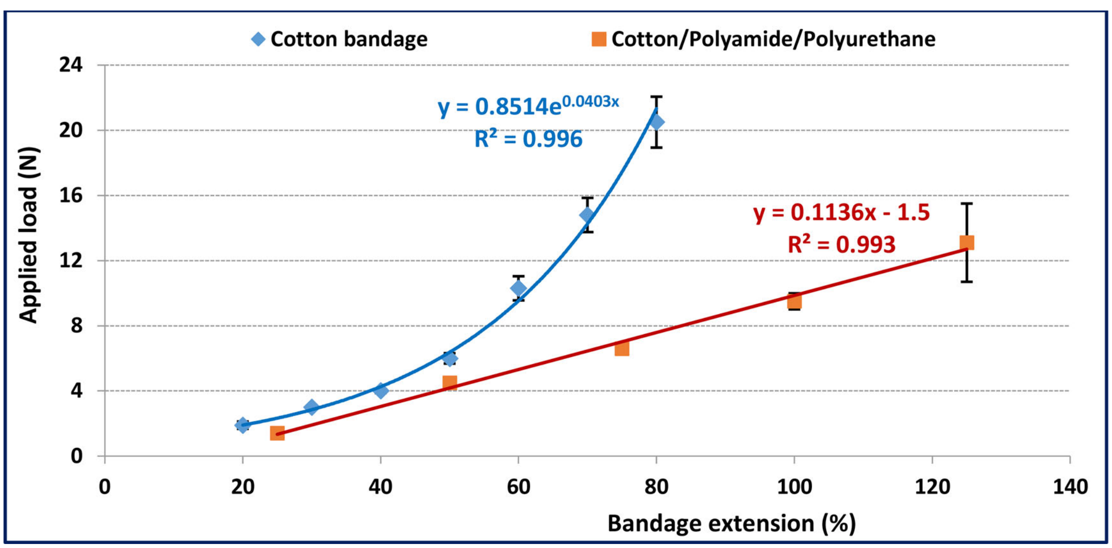


Figure 10. Relationship between applied load and bandage extension for WBC.

0.26 N. When the LSB was wrapped on the human leg for five days (8 h every day), there was non-significant residual deformation, approximately 1.4% after longer treatment time. Whereas the cotton SSB showed a significant residual deformation of approximately 7.2%, see Figure 14 (Aboalasaad et al., 2020).

4. Conclusion

The evaluation of the used plied warp yarns in the market for producing the WCB concluded that the warp yarn tenacity should be greater than 15.5 cN/Tex and its extension should be at least 12%. But when using the wider range of ply twist, the current investigated 20*2 Tex yarn achieved better tenacity 18–20 cN/Tex and better extension 11.5–12.5% at 1500–1800 tpm range. In this way, the newly produced yarns can realize better yarn tensile properties at a lower ply twist level which contributes to a better bandage user experience.

Cotton SSB elasticity followed the exponential function whereas the CO-PA-PU LSB achieved a linear behaviour due to the highest elasticity gained by Elastane filament. The patient or any bandage user should take off the LSB during sleep because of the high resting compression especially at ankle position for three layers bandaging.

CO-PA-PU LSB recovered approximately 98.6% of its original length after the load-relaxation test, this elasticity enabled wearing comfort when applying the LSB for the

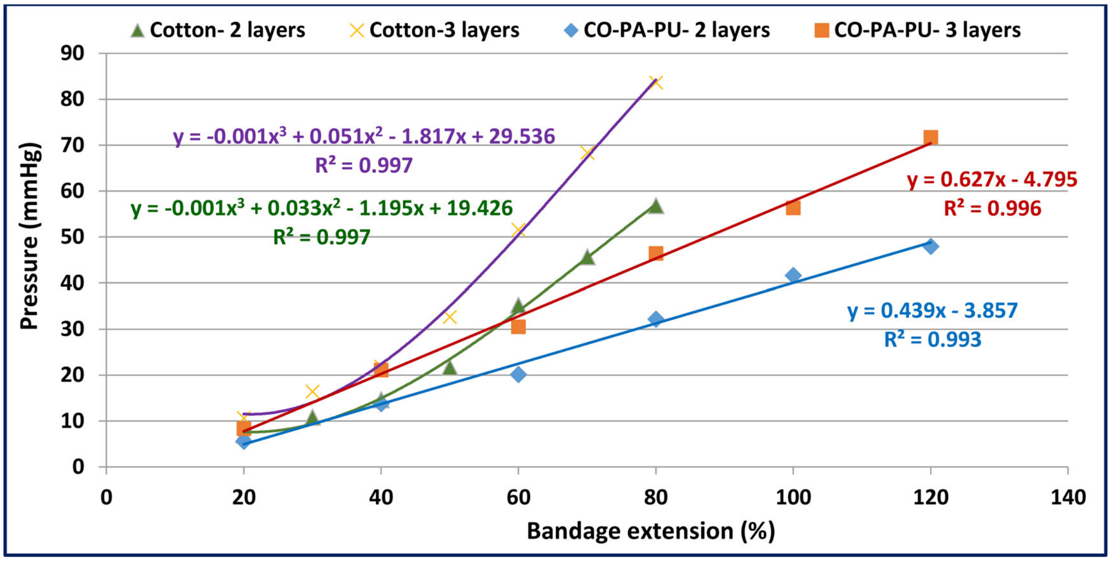


Figure 11. Effect of bandage extension on practical pressure at ankle position for cotton SSB and CO-PA-PU LSB.

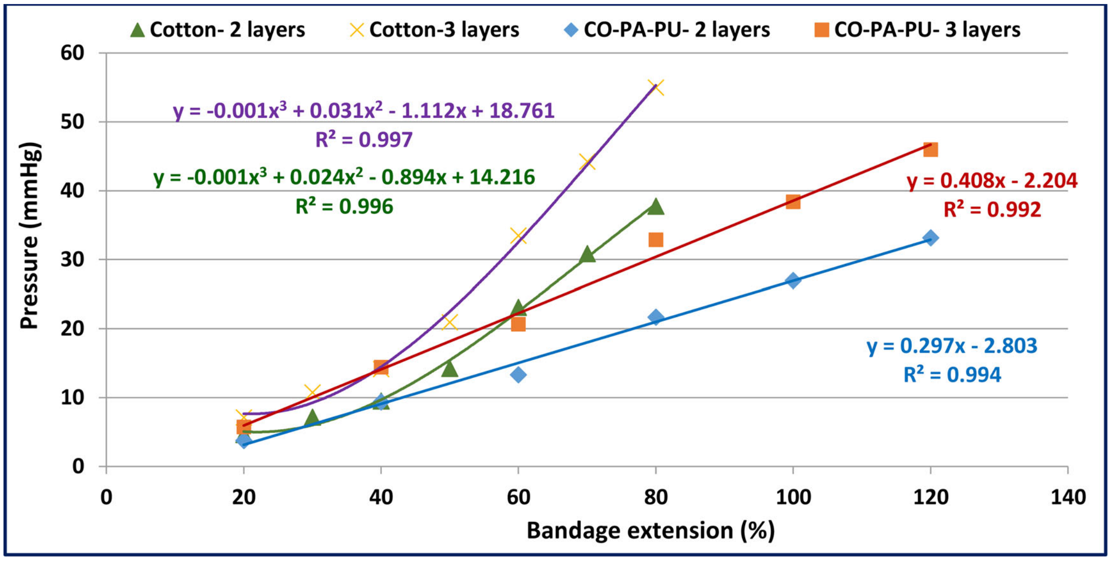


Figure 12. Effect of bandage extension on practical pressure at the mid-calf position for cotton SSB and CO-PA-PU LSB.

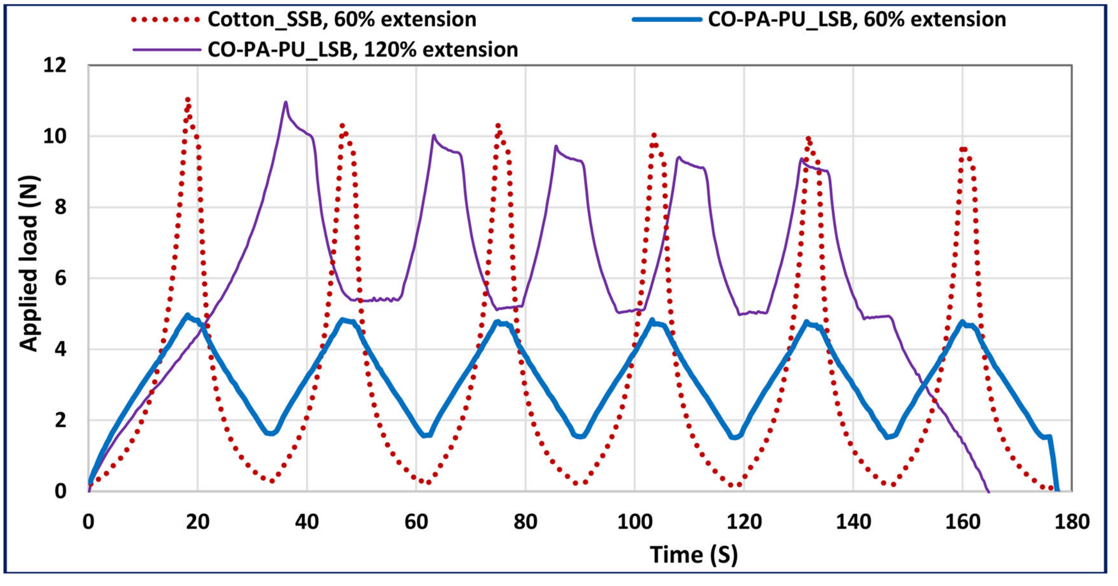


Figure 13. Effect of cyclic loading on applied load by long and short-stretch bandages on the first day.

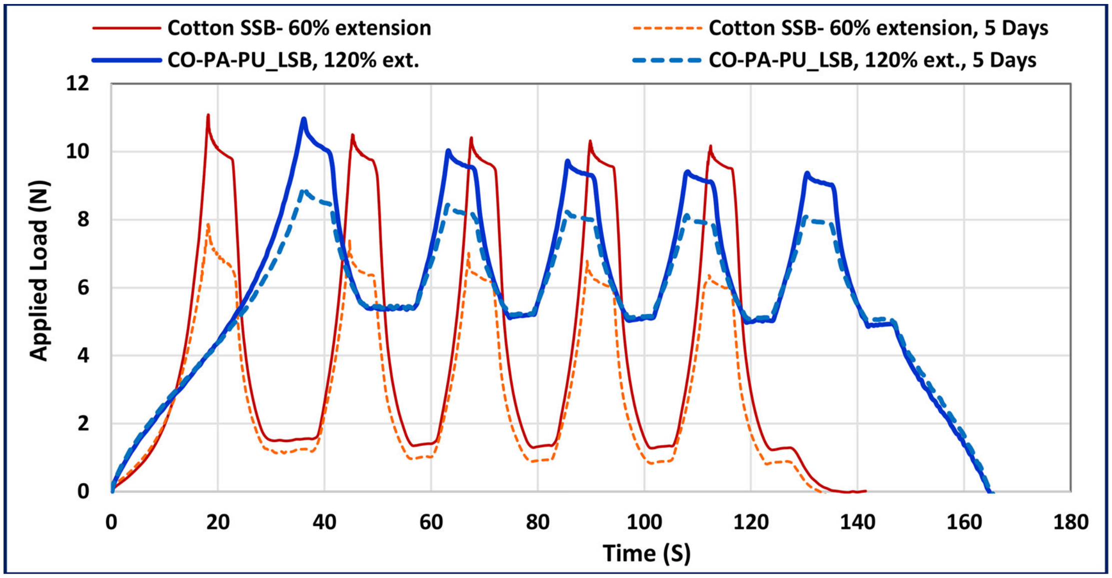


Figure 14. Effect of cyclic stress-relaxation on applied load by long- and short-stretch bandages on the first and fifth day.

patient or during athletic performance, whereas 100% cotton SSB retained only 92.8% of its initial length after 5 days of cyclic stress-relaxation.

Acknowledgments

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic and the European Union—European Structural and Investment Funds in the Frames of Operational Programme Research, Development and Education—Project Hybrid Materials for Hierarchical Structures [HyHi, Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843].

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was funded by ministerstvo školství, mládeže a tělovýchovy.

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