



Research paper

Influence of cyclic frozen and defrost on mechanical properties of polytetrafluoroethylene (PTFE)-coated woven fabrics

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Abstract: This research aims to determine the influence of the cyclic process of freezing and defrosting on the mechanical properties of the chosen glass fibres and PTFE-coated woven fabrics. The specimens were subjected to freezing at about -20°C for 4 h and thawing by full immersion into the water at about $+20^{\circ}\text{C}$ for 4 h. The fabric samples after 25 and 50 frozen cycles were air-dried at room temperature for one week and then subjected to uniaxial tensile tests. The same tests have been performed on a reference group of specimens, which were not exposed to temperature change. The authors determined the tensile strength, and longitudinal stiffnesses resulting from performed tests. Although the investigated coated woven fabrics expressed a reduction in the tensile strength in water soaking conditions, the performed frozen cycles don't show a significant decrease in strength under uniaxial tensile tests.

Keywords: construction materials, freezer cycles, mechanical properties, PTFE coated woven fabric, uniaxial tensile test

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1. Introduction

The technical woven fabrics, called architectural fabrics, are used for roof construction of the membrane, hanging and pneumatic structures [1–4]. The different types of coated woven fabrics are available on the market for application in tensile structures, e.g.: PVC (polyvinyl chloride)-coated woven fabrics with polyester threads or PTFE (polytetrafluoroethylene)-coated woven fabrics with glass threads. The differences between the types of fabrics result from the use of different materials for the base fabric and coatings or differences in the manufacturing process (e.g. Preconstraint technology [5, 6]). For the investigated PTFE-coated fabric the base material of the fabric is glass fibre threads. The PTFE-coated woven fabrics were applied for example for the membrane roof of the Forest Opera in Sopot (Poland) [7], Fig. 1.



Fig. 1. The Forest Opera membrane hanging roof in Sopot, Poland – co-designed by the authors

The literature concerning the subject of coated woven fabrics is very extensive. Every year new investigations are performed on comprehensive studies on the coated woven fabrics [8–25]. Performed investigations have shown that the mechanical parameters of the coated woven fabrics are highly influenced by temperature changes [26, 27]. Additionally, research investigations indicated that coated woven fabrics occur a reduction in the tensile strength resulting under water-logged [11, 28, 29]. A more extended survey of literature concerning the investigation carried out on coated woven fabrics is performed by Authors in [11].

In the case of permanent membrane or hanging structures used in changing climatic conditions (especially in winter), the sub-zero temperatures may occur cyclically. Based on these observations, the mechanical properties of the architectural fabrics seem necessary to be verified under the process of freezing and thawing cycles.

Due to these characteristics of coated woven fabrics, the present study is aimed at the determination of the influence of freezer and defrost in cycles on the mechanical properties of chosen PTFE-coated woven fabrics identified from the uniaxial tensile tests.

2. Materials and methods

For laboratory tests the authors chose two coated woven fabrics having glass threads coated by PTFE. The properties of the PTFE coated woven fabrics are the same as those investigated by Ambroziak and Kłosowski [11]. The S-type and B-type fabrics' main properties, declared by the producers, are very similar, Table 1. The main difference is related to the manufacturing process, where S-type is produced with the technology, where the threads of the warp and weft are initially strained during coating and B-type fabric with the technology where during coating the fabric is prestressed in warp direction only.

Table 1. Properties of investigated PTFE coated woven fabrics

Properties	S Type	B Type
Total Mass per Unit Area (g/m ²)	1540	1550
Tensile Strength (kN/m)		
Warp	170	160
Weft	156	140
Base Coat	PTFE	PTFE
Weight per Unit Area of Base Fabric (g/m ²)	625	670
Yarn Count (yarn/cm)		
Warp	7.1	8
Weft	7.5	7.5
Translucency at 550 nm (%)	9	8–11

Before the uniaxial tensile tests were carried out the coated woven fabric specimens were subjected to twenty-five and fifty freezer cycles in a freezing chamber with the temperature, and time-controlled refrigerating and heating system. Due to a lack of standard guidelines for the freezer of coated woven fabrics the freezer cycle was performed according to the PN-B-06250 standard [30]. This standard is used generally for the determination of concrete frost resistance [31–33]. The single freezer cycle consisted of freezing at $-18 \pm 2^\circ\text{C}$ for 4 h and thawing by full immersion in water at $+18 \pm 2^\circ\text{C}$ for 4 h. After the specified number of freezer cycles, the fabric specimens were air-dried at in-room temperature for one week and then subjected to mechanical tests.

The uniaxial tensile tests were conducted on the Zwick 020 mechanical testing machine. The video extensometer control (based on the digital image correlation method) with the base of the optical extensometer of about 50 mm and flat grips were used. The specimens had 50 ± 1 mm width, and the active length (distance between flat grips) was equal to 200 ± 1 mm, Fig. 2. The total length of fabric specimens was 300 ± 1 mm. The mechanical tests were performed according to the ISO 1421:2016 standard [34] for the strip method, with the displacement rate of the grip equal to 100 mm/min. Each type of test has been repeated at least six times. Three main groups of coated fabric specimens were tested:



the base specimens of the PTFE-coated fabrics, after 25 frozen cycles and after 50 frozen cycles in the direction of the warp and weft threads.



Fig. 2. Uniaxial laboratory tests stand

3. Laboratory test results

3.1. Uniaxial tensile tests general response

The results of the uniaxial tensile tests are presented in the form of the stress-strain curves in Figs. 3, 4 for the S type and in Figs. 5, 6 for the B type coated fabric, respectively. The denotations S, S_F25 or B_F25 and S_F50 or B_F50 indicated results obtained for the base PTFE-coated fabric material, after 25 freezer cycles and after 50 freezer cycles, respectively.

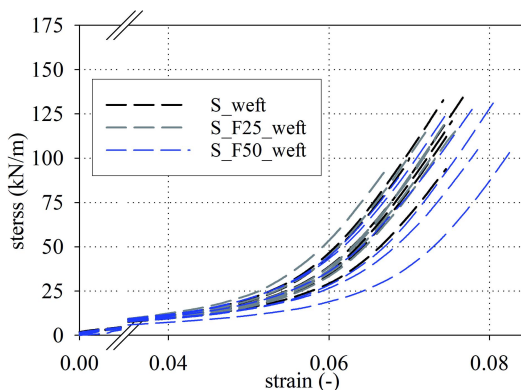


Fig. 3. Uniaxial tensile test results – weft S type fabric

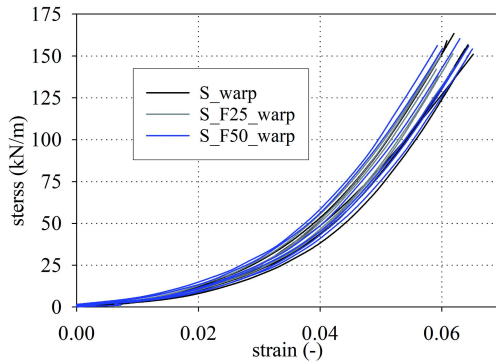


Fig. 4. Uniaxial tensile test results – warp S type fabric

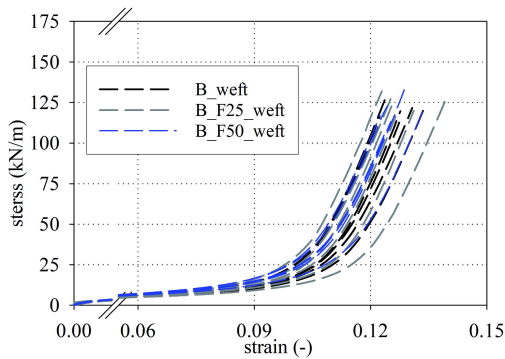


Fig. 5. Uniaxial tensile test results – weft B type fabric

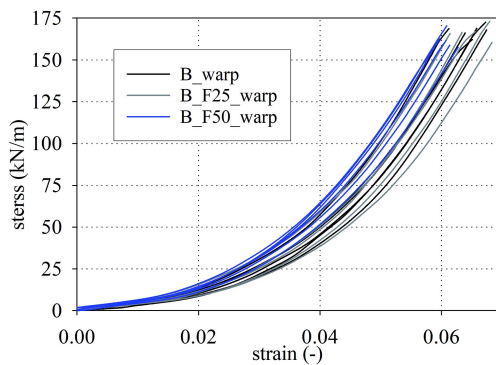


Fig. 6. Uniaxial tensile test results – warp B type fabric

The shape of the stress-strain curves is typical for the investigated type of architectural fabrics with glass threads and PTFE coating [6]. The B type fabric exhibits twice the time higher deformations in the weft direction under the uniaxial loads due to differences related

to the manufacturing process. In the S type fabric, where the threads of warp and weft are initially strained, the difference between deformation in warp and weft direction is much smaller.

3.2. Elongation at break and tensile strength

Based on the performed uniaxial tensile tests two main mechanical properties (the elongation at break and tensile strength) for each tested specimen are determined and collected in Tables 2, 3 for B type fabric and in Tables 4, 5 for the S type fabric. The mean values of the tensile strength obtained during tests are generally lower than specified

Table 2. Elongation at break and tensile strength – base specimens B type fabric

Specimen No.	Weft		Warp	
	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]
1	0.1312	123.8	0.0679	173.3
2	0.1226	117.4	0.0643	170.7
3	0.1277	114.3	0.0654	170.2
4	0.1238	127.6	0.0622	171.3
5	0.1277	119.7	0.0658	163.4
6	0.1343	124.1	0.0680	172.7
mean	0.1279 ± 0.0013	121.1 ± 2.0	0.0656 ± 0.0009	170.3 ± 1.5
median	0.1277	121.7	0.0656	171.0

Table 3. Elongation at break and tensile strength – freezer cycles, B type fabric

Specimen No.	Weft – F25		Weft – F50		Warp – F25		Warp – F50	
	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]
1	0.1261	127.1	0.1338	122.3	0.0641	170.5	0.0600	162.6
2	0.1399	128.8	0.1261	118.2	0.0656	167.1	0.0613	172.3
3	0.1233	132.1	0.1288	133.1	0.0695	175.5	0.0621	166.7
4	0.1272	120.7	0.1247	110.4	0.0615	166.4	0.0642	163.7
5	0.1323	124.1	0.1228	119.5	0.0615	165.2	0.0606	167.3
6	0.1257	130.0	0.1244	123.2	0.0686	162.0	0.0618	161.3
mean	0.1291 ± 0.0025	127.1 ± 1.7	0.1268 ± 0.0016	121.1 ± 3.0	0.0651 ± 0.0014	167.8 ± 1.9	0.0616 ± 0.0006	165.6 ± 1.6
median	0.1266	127.9	0.1254	120.9	0.0649	166.7	0.0616	165.2



by manufacturers. Only the result of tensile strength for the B type fabric in the direction of the warp is about 7% greater than given in Table 1. This difference may be due to the application of the flat grips or the influence of a long storage period of fabric specimens before tests. It should be noted that in the case of the flat grips, damage to specimens close to the grips may be observed. The curved grips cause a more homogeneous stress distribution near the fixing; therefore, higher stress values may be reached under uniaxial tensile tests. On the other hand, the usage of the extensometer restricts the experiment area to the middle part of the fabric specimen only. This part is far from fixing; thus, for the identification of material parameters, the influence of the grips can be neglected [24].

Table 4. Elongation at break and tensile strength – base specimens S type fabric

Specimen No.	Weft		Warp	
	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]
1	0.0750	96.8	0.0664	156.6
2	0.0755	121.9	0.0646	159.1
3	0.0701	101.6	0.0650	160.9
4	0.0751	115.6	0.0609	159.8
5	0.0743	133.3	0.0623	165.4
6	0.0772	137.8	0.0648	153.1
mean	0.0746 ± 0.0010	117.8 ± 6.7	0.0640 ± 0.0008	159.1 ± 1.7
median	0.0751	118.8	0.0647	159.4

Table 5. Elongation at break and tensile strength – freezer cycles, S type fabric

Specimen No.	Weft – F25		Weft – F50		Warp – F25		Warp – F50	
	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]	Rupture Strain [-]	Tensile Strength [kN/m]
1	0.0738	114.0	0.0792	108.5	0.0625	155.6	0.0642	154.7
2	0.0679	98.7	0.0748	126.3	0.0608	158.9	0.0593	156.5
3	0.0733	103.9	0.0780	128.8	0.0626	146.5	0.0655	157.0
4	0.0748	122.0	0.0837	110.8	0.0601	153.6	0.0651	160.0
5	0.0758	115.4	0.0696	94.9	0.0591	142.4	0.0605	156.7
6	0.0725	117.4	0.0810	135.0	0.0600	141.5	0.0638	165.4
mean	0.0730 ± 0.0011	111.9 ± 3.6	0.0777 ± 0.0020	117.4 ± 6.2	0.0608 ± 0.0006	149.7 ± 2.9	0.0631 ± 0.0010	158.4 ± 1.6
median	0.0736	114.7	0.0786	118.5	0.0605	150.0	0.0640	156.8



3.3. Longitudinal stiffnesses

For the S and B types of PTFE-coated fabrics, the longitudinal stiffnesses are specified in Tables 6–9. The longitudinal stiffnesses F_i (kN/m) are determined from the linear approximation of the stress-strain curves using the piecewise linear model [24, 35]. The graphical concept of the piecewise linear model identification is presented in Fig. 7. The

Table 6. Longitudinal stiffnesses – base specimens B type fabric

Specimen No.	Weft		Warp	
	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]
1	88.4	4750	418.1	5230
2	108.6	5140	568.8	5310
3	89.7	4860	518.5	5240
4	115.9	5080	614.8	5510
5	89.9	4970	504.5	4980
6	79.6	4710	433.2	5450
mean	95.3 ± 13.8	4918 ± 175	509.7 ± 76	5286.7 ± 187.9
median	89.8	4915.0	511.5	5275.0
ε_{p1}	0.1053		0.0369	

Table 7. Longitudinal stiffnesses – freezer cycles, B type fabric

Specimen No.	Weft – F25		Warp – F25		Weft – F50		Warp – F50	
	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]
1	96.3	5040	505.9	5480	100.9	4520	665.4	5080
2	69.2	4740	494.1	5030	117.6	4650	593.6	5110
3	125.0	4960	418.0	5210	113.1	4810	599.0	5080
4	94.2	5000	637.0	5220	124.4	4640	530.2	5050
5	85.1	5050	518.0	5210	132.4	4670	628.7	5100
6	109.2	4840	407.6	5100	137.9	4710	562.3	5100
mean	96.5 ± 19.3	4938 ± 123	496.8 ± 82.9	5208 ± 171	121 ± 13.5	4667 ± 95	596.5 ± 47.7	5087 ± 22
median	95.2	4980	500	5210	121	4660	596.3	5090
ε_{p1}	0.1056		0.0363		0.1035		0.0329	



Table 8. Longitudinal stiffnesses – base specimens S type fabric

Specimen No.	Weft		Warp	
	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]
1	226.4	5320	434.4	4346*
2	239.7	5630	379.8	5190
3	254.1	5650	368.4	5190
4	227.8	4970	405.5	5380
5	258.2	5460	421.3	5320
6	245.1	5380	310.1	5370
mean	241.9 ± 13.2	5402 ± 249	386.6 ± 44.9	5290 ± 94
median	242.4	5420	392.7	5255
ε_{p1}	0.0553		0.0366	

Table 9. Longitudinal stiffnesses – freezer cycles, S type fabric

Specimen No.	Weft – F25		Warp – F25		Weft – F50		Warp – F50	
	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]	F_1 [kN/m]	F_2 [kN/m]
1	247.2	6140	380.2	5480	209.5	5290	375.6	5130
2	313.5	5670	437.8	5170	296.2	4810	501.4	5340
3	223.2	5530	374.8	5020	247.7	5270	373.0	5160
4	255.4	5830	402.7	5370	201.3*	5840	385.1	4950
5	226.1	5700	394.2	5200	259.4	5500	466.0	5090
6	269.9	5820	417.9	5320	240.5	5680	420.2	5160
mean	253.1 ± 33.3	5782 ± 207	401.3 ± 23.7	5260 ± 163	250.7 ± 31.5	5398 ± 363	420.2 ± 53.2	5138 ± 126
median	251.3	5760	398.5	5260	247.7	5395	402.7	5145
ε_{p1}	0.0561		0.0350		0.0587		0.0351	

value ε_{p1} (the strain for change of stiffness in the biaxial model) can be calculated according to the formula

$$(3.1) \quad \varepsilon_{p1} = \frac{\sigma_r - F_2 \cdot \varepsilon_r}{F_1 - F_2}$$

where: ε_r is the mean rapture strain and σ_r is the mean tensile strength (from Tables 2–5).



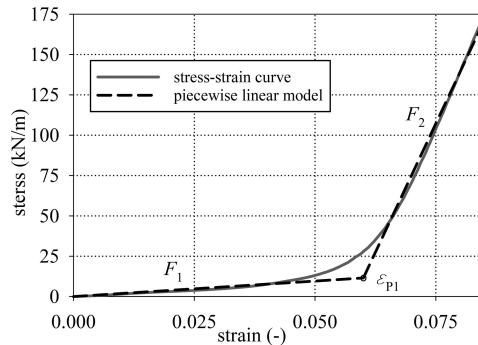


Fig. 7. Graphical concept of the piecewise linear model identification

4. Discussion

The one-way analysis of variance (ANOVA) was used to determine, whether there are any statistically significant differences between the means of the three investigated specimens groups [36, 37]. To perform ANOVA analysis it was necessary to check basic assumptions, which were the normal distribution of the results in the groups and the equal variance of the coated fabric specimens groups. The normal distribution was checked by the Shapiro–Wilk test [38], and the equal variance by the Brown–Forsythe test [39]. It should be noted, that if one of these tests fails the other variance analysis method should be used (e.g. Kruskal–Wallis One-Way Analysis [40]). To obtain the normal distribution of results a few results of the individual tests (with values much different from the others) have to be excluded from the ANOVA investigation (values with “*” in Tables 8–9). After that refinement, all results fulfilled the normal distribution and equal variance tests and therefore could be the subject of the ANOVA analysis.

The One-Way ANOVA compares the means between the groups you are interested in and determines whether any of those means are statistically significantly different from each other. Specifically, it tests the null hypothesis:

$$(4.1) \quad H_0 : m_1 = m_2 = m_3 = \dots m_n$$

where: m_i – the group mean and n – the number of groups.

If, however, the One-Way ANOVA returned a statistically significant result, it is accepted the alternative hypothesis (H1), which is that there were at least two group means that were statistically significantly different from each other. To determine which two groups were statistically significantly different it was necessary to perform one of the post hoc tests. Here the Holm–Sidak method was adopted [41]. In Table 10 the results of the testing hypothesis of significant differences in group results are presented. If the difference is statistically important it is indicated in Table 10 with the word YES, otherwise the word NO is used.

It can be seen that in almost all cases of analysis for S fabric the differences are statistically not important. That means that the properties of the fabric are not changing significantly. That means the fabric has good resistance to cyclic temperature changes.



Table 10. Results of ANOVA analysis

	Fabric B Weft			Fabric B Warp		
	Tensile Strength	Long. Stiff. F_1	Long. Stiff. F_2	Tensile Strength	Long. Stiff. F_1	Long. Stiff. F_2
Base/F50	NO	YES	YES	NO	NO	NO
Base/F25	NO	NO	NO	NO	NO	NO
F25/F50	NO	YES	YES	NO	NO	NO
	Fabric S Weft			Fabric S Warp		
	Tens. Strength	Long. Stiff. F_1	Long. Stiff. F_2	Tensile Strength	Long. Stiff. F_1	Long. Stiff. F_2
Base/F50	NO	NO	NO	NO	NO	NO
Base/F25	NO	NO	NO	YES	NO	NO
F25/F50	NO	NO	NO	YES	NO	NO

For B fabric good frozen cycles resistance in the warp direction also can be confirmed. Nevertheless, the weft direction situation is the opposite. When more than 25 freeze cycles have been applied the changes in material properties should be considered. The explanation for that is the way how both fabrics have been manufactured. During the coating process of S fabric, both directions of the threads have been pre-tensioned. During coating of B fabric, only the threads in warp direction have been pre-tensioned. This causes larger strain values in this direction during exploitation as well as changes in temperature resistance.

5. Conclusions

In the present paper, the investigation of the influence of freezer and defrost in cycles on the mechanical properties of chosen PTFE-coated woven fabrics under uniaxial tensile tests is performed. Based on performed investigation the following conclusions may be drawn:

- A significant reduction in the tensile strength and longitudinal stiffnesses for investigated PTFE-coated woven fabrics resulting from performed frozen cycles was not observed.
- A significant difference in the elongation at break for PTFE-coated fabric under frozen cycles was not assigned.

The present study can be treated as a base for the new investigations on the influence of freezer and defrost in cycles on the architectural coated fabrics. The obtained results encourage the Authors to carry out broad investigations with a larger number of fabric specimens and usage of the curved grips.



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Wpływ cyklicznego zamrażania i rozmrażania na właściwości mechaniczne tkanin technicznych powlekanych politetrafluoroetylenem (PTFE)

Słowa kluczowe: materiały konstrukcyjne, mrozoodporność, właściwości mechaniczne, tkanina techniczna powlekana PTFE, próby jednoosiowego rozciągania

Streszczenie:

Artykuł opisuje badania tkanin technicznych wykonanych z włókna szklanego i powlekanych politetrafluoroetylenem (PTFE) (ang. *PTFE-coated woven fabric*), które mają na celu określenie wpływu cyklicznych procesów zamrażania i rozmrażania na właściwości mechaniczne wybranych tkanin. Próbkę tkanin technicznych zostały poddane zamrażaniu w temperaturze około -20°C przez 4 godziny i rozmrażaniu przez całkowite zanurzenie w wodzie w temperaturze około $+20^{\circ}\text{C}$ przez 4 godziny. Próbkę tkanin technicznych po 25 i 50 cyklach zamrażania suszono na powietrzu w temperaturze pokojowej przez tydzień, a następnie poddano próbom jednoosiowego rozciągania. Na podstawie testów jednoosiowego rozciągania określono wytrzymałość na rozciąganie i moduły sztywności. Pomimo, iż w badanych tkaninach powlekanych następuje spadek wytrzymałości na rozciąganie w warunkach ich namoczenia w wodzie, to wykonane cykle zamrażania nie wykazują znacznego spadku wytrzymałości w próbach jednoosiowego rozciągania.

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