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Research paper

Influence of water soaking on the ultimate tensile strength of polyester-based coated woven fabrics

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Abstract: This research aims to determine the influence of water-soaking on polyester-based coated woven fabrics for ultimate tensile strength and elongation at break under uniaxial tensile tests. The paper begins with a short survey of literature concerning the investigation of the determination of coated woven fabric properties. The authors carried out the uniaxial tensile tests with an application of a flat grip to establish the values of the ultimate tensile strength of groups of specimens treated with different moisture conditions. SEM fractography is performed to determine the cross-section structures of coated woven fabrics. The change in the mechanical properties caused by the influence of water immersion has not been noticed in the performed investigations.

Keywords: coated woven fabric, polyester-based coated woven fabric, construction materials, mechanical properties, uniaxial test

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1. Introduction

Architectural fabrics refer to structurally coated woven fabrics used to form tensile surface structures (Fig. 1), such as canopies, membrane roofs, hanging, and pneumatic structures [1–6]. Different types of coated woven fabrics are manufactured and used in construction. The main differences between different types of coated woven fabrics are in the base materials (e.g. polyester or glass threads), coatings or top coating materials (e.g. PVC (polyvinyl chloride), PVDF (polyvinylidene fluoride) or PTFE (polytetrafluoroethylene)) or differences in the manufacturing process (e.g. Precontraint technology [7, 8]). The membrane building performance, material properties, and structural behaviours are reviewed by [9–12].

a) b)

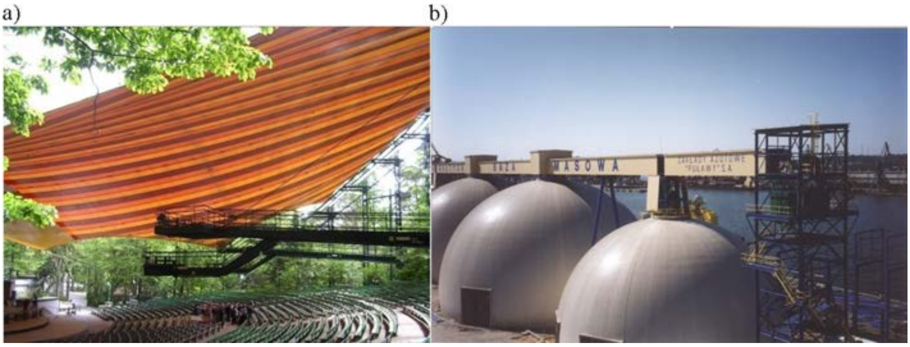

Fig. 1. Membrane polyester structures: a) hanging roof of Forest Opera in Sopot (2006); b) spherical tanks for fertilizers in Gdynia Harbour

The literature concerning the subject of architectural fabrics investigations is very extensive. Performed investigations of the coated woven fabrics have shown that the mechanical parameters are highly influenced by temperature changes [13–15]; changes in behaviour under uniaxial, biaxial and creep loadings [16–21]; glass threads based and PTFE-coated woven fabrics occur a reduction in the tensile strength resulting under waterlogged [22, 23]; prove degradation of the tensile strength exposed to weathering and ageing impacts and cyclic loading [24–27]; exhibits highly material nonlinearity with identified viscoelastic, viscoplastic behaviour [28–34]; puncture resistance strength increases with the increase of weight percentage of fibres and initial notch significantly reduce the ultimate strength [35–38]; the failure strength depends on the stress ratio and off-axial angle [39–42]. The investigations are also performed on: tearing behaviours and tearing strength propagation mechanisms [41, 43–46], off-axis tearing properties [47, 48], achieving 3D strain surfaces on coated woven fabrics, and refined biaxial test procedures [49, 50], modelling multi-scale progressive damage to investigate the damage and failure behaviours [51]. The application of the fast camera in laboratory tests aids in the visualization of the complex composite behaviours of fabrics [52] is also developed.

The present study is aimed at the determination of the influence of water-soaking on the ultimate tensile strength of chosen coated woven fabrics for which the base threads material is polyester under uniaxial tensile tests. The paper is an extension of the former investigations on the water-soaking of coated woven fabrics [23, 53].

2. Materials and methods

For laboratory tests, the authors chose three coated woven fabrics having polyester threads coated by PVC (polyvinyl chloride), PVDF (polyvinylidene fluoride), and cross-linked PVDF (versatile, thermally and chemically ultrastable PVDF material [54]). The main properties declared by the producers are collected in Table 1. The investigated coated fabrics differ in weight, thickness, and tensile strength. Before tests, the fabrics have been stored in the laboratory in room conditions (temperature 20–22°C, humidity 20–50%) for 7–9 years. As declared by the producer the manufacturing process for B-type and C-type coated fabrics is similar. The B-type and C-type coated fabrics are produced with the technology, where the threads of the warp and weft are initially strained during the coating process while A-type is produced without prestressing in the weft direction.

Table 1. Properties of investigated coated woven fabrics

Properties	A-type (Valmex FR1000 type III)	B-type (Precontrain1302S)	C-type (Precontrain TX30 – V)
Total Mass per Unit Area (g/m^2)	1050	1350	1500
Thickness (mm)	0.9	1.02	1.14
Tensile Strength (kN/m) Warp Weft	 120 110	 160 140	 200 160
surface treatment/ top coating	PVDF	S2 PVDF/PVDF	Crosslinked PVDF
yarn	PES Panama Weave P 2/2 1670 Dtex	PES HT 1100/2200 Dtex	PES HT 1670/2200 Dtex

The morphology of coated woven fabric samples (virgin fabrics) was performed by a scanning electron microscope (SEM, type TM3030 Manual Stage, model 55E-0015, Hitachi, Tokyo, Japan). The results of the analysis were documented with the SEM images. SEM fractography was carried out to determine the cross-section structures of coated woven fabrics.

Before the uniaxial tensile tests were carried out the fabric specimens were cut in the warp and weft direction from three types of base materials (virgin fabrics) and were divided into three groups. The first group was the base material specimens. Results for this group are denoted A, B and C regarding A-type, B-type and C-type coated fabrics. The two remaining groups of specimens were immersed in room-temperature water for two weeks. The immersion period was twice longer as that taken by Asadi et al. [22] and the same as in [23]. After two weeks they were taken out of the water. Their surface was dried using absorbent paper. The specimens of the second group were immediately tested. The second group is denoted as A_wet, B_wet and C_wet reference to coated fabrics A-type, B-type and C-type tested as wet (waterlogged). The third group of fabric specimens, after two weeks of water soaking, was left in the room conditions to dry out for the following seven days (one week) and then tested. The last group is denoted as A_air-dried, B_air-dried and C_air-dried concerning A-type, B-type and C-type coated fabrics subjected to waterlogging and the process of air-drying.

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 of gauge distance and flat grips were used. The specimens had 50 ± 1 mm width, and the active length (distance between grips) was equal to 200 ± 1 mm, see Fig. 2). The total length of fabric specimens was 300 ± 1 mm. The mechanical tests were performed according to the ISO 1421:2016 standard [55] for the strip method, with the displacement rate of the upper grip equal to 100 mm/min. Each type of test has been repeated at least five times. Three main groups for three chosen types of coated fabric specimens were tested.

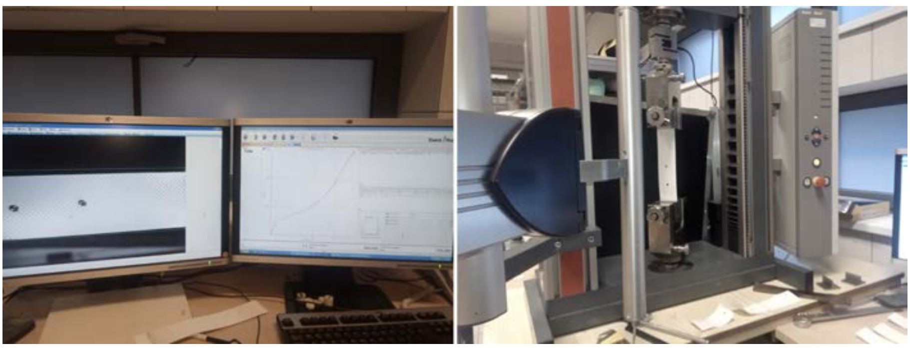

Fig. 2. Uniaxial laboratory tests stand

3. Laboratory test results

3.1. Results of SEM fractography

SEM micrographs of the cross-sections of the coated fabrics are shown in Figs. 3–5. The photo of each fabric has been taken from two perpendicular directions (warp and weft) and with two magnifications. According to the photos, some differences in cross-sections according to the fabric producer can be observed. The reason can be the manufacturing process, especially the prestressing of the threads during covering them with the coating layers. The fabric in Fig. 3 was prestressed during the coating process in the warp direction

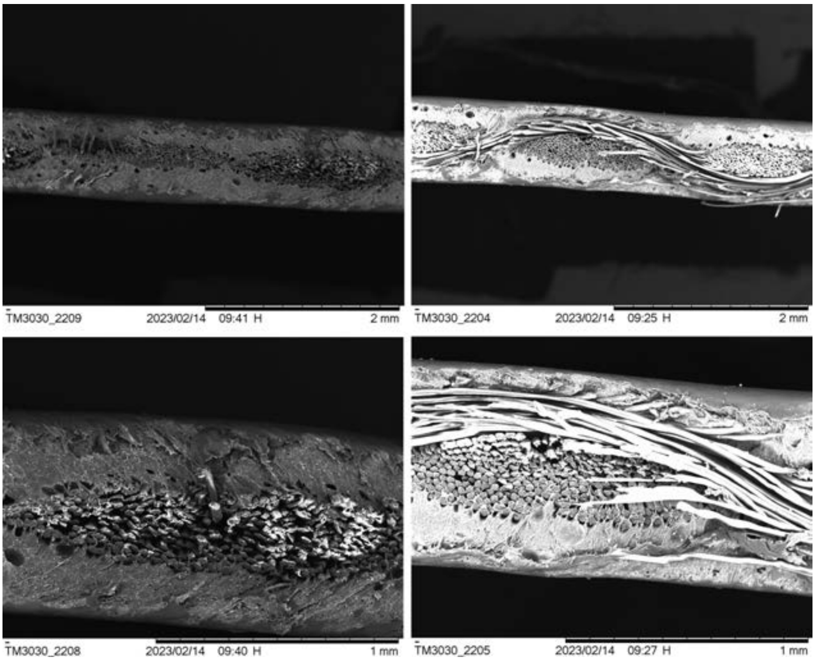

Fig. 3. SEM microscopic images – A-type fabric

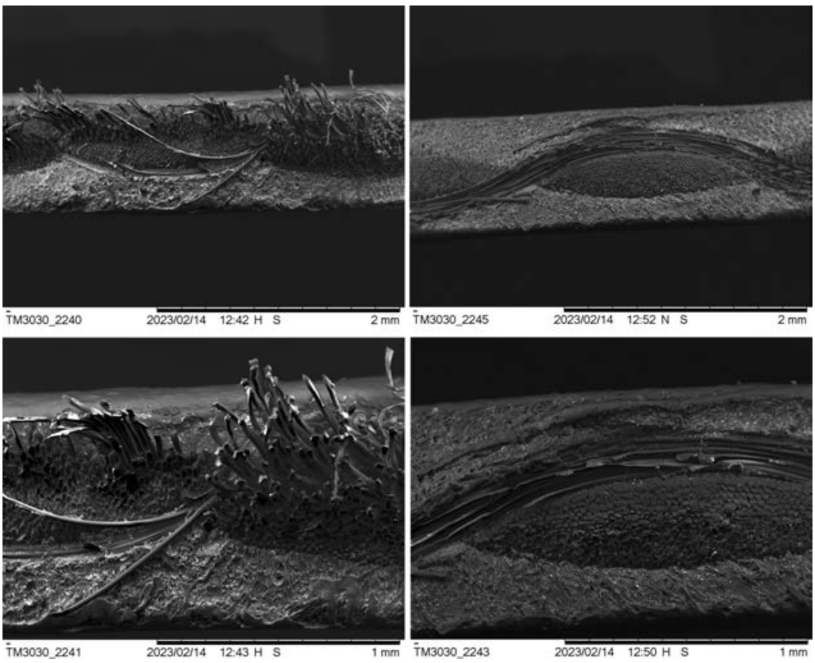

Fig. 4. SEM microscopic images – B-type fabric

only, while two other fabrics have been prestressed in both directions. The cross-sections of all fabrics are dense but porous. There are many micropores and continuous bubbles in the porous structure, most of all in A-type fabric, see Fig. 3. When the coating layer is damaged mainly due to weather conditions (temperature and ultraviolet light have the biggest influence), water can penetrate the threads changing their working conditions, and consequently the fabric mechanical properties. According to the SEM analysis, the microstructure of coated fabrics is anisotropic.

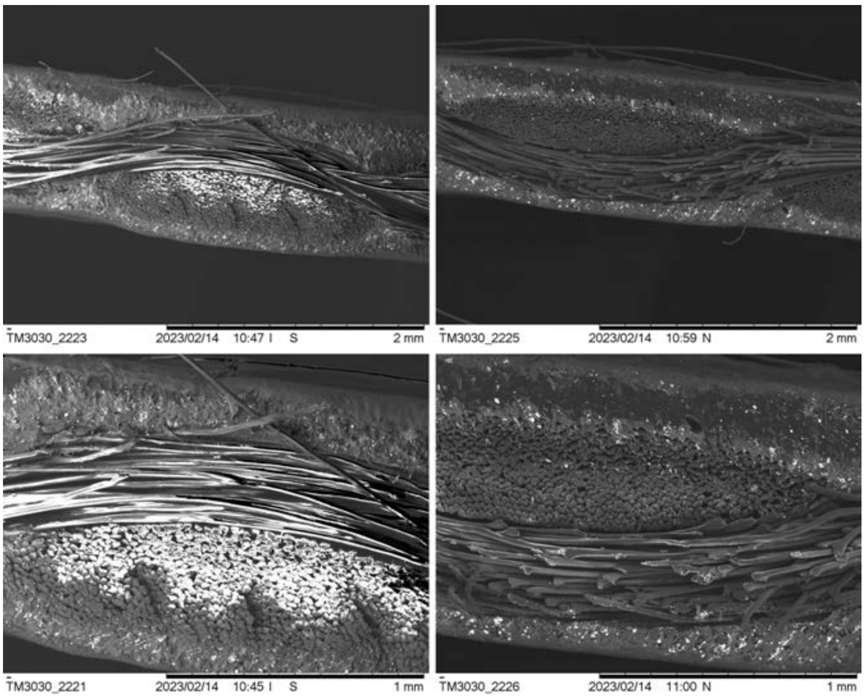

Fig. 5. SEM microscopic images – C-type fabric

3.2. Results of uniaxial tensile tests

The results of the uniaxial tensile tests are presented in the form of the stress-strain curves in Figs. 6–8 for the A-type, B-type and C-type coated fabrics, respectively. The first denotation used on figures concerns the type of fabrics (A, B, or C). The second part of denotation O and W refers to warp and weft directions respectively.

The shape of the stress-strain curves is typical for the investigated type of architectural fabrics with polyester threads [8]. The A-type fabric exhibits more different responses for warp and weft directions while the response of warp and weft directions under uniaxial loads for the B-type and C-type coated fabrics are very similar due to the initial prestressing of warp and weft threads during the coating process.

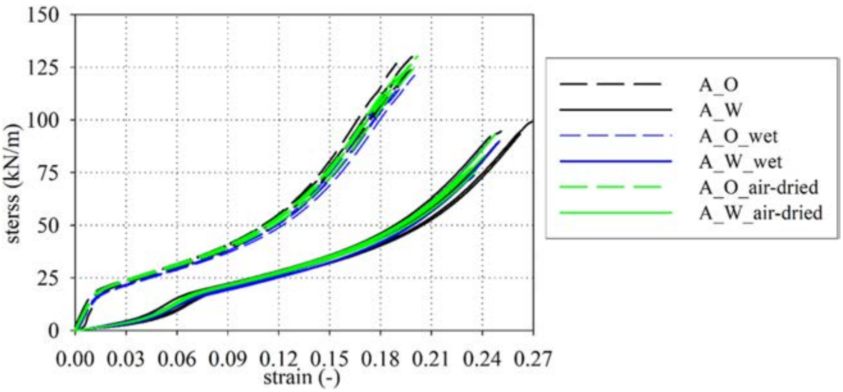

Fig. 6. Uniaxial tensile test results – A-type fabric

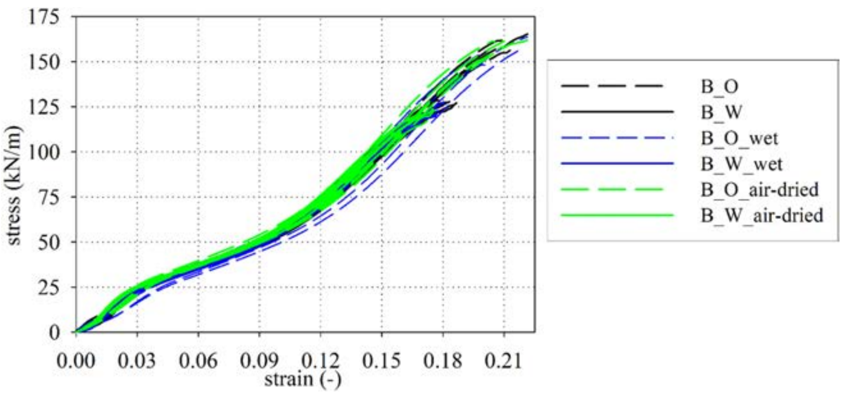

Fig. 7. Uniaxial tensile test results – B-type fabric

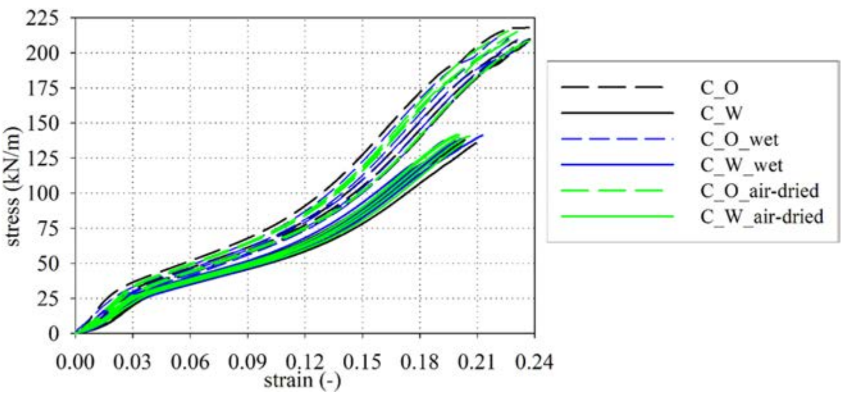

Fig. 8. Uniaxial tensile test results – C-type fabric

3.3. Elongation at break and tensile strength

Based on the performed uniaxial tensile tests the elongation at break (rupture strain) and the tensile strength for each tested specimen is determined and collected in Tables 2–4 for the A-type fabric, in Tables 5–7 for the B-type fabric, and in Tables 8–10 for the

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

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.1907	120.37	0.2630	93.91
2	0.1892	126.76	0.2449	92.36
3	0.1994	125.20	0.2521	94.94
4	0.1997	130.93	0.2698	99.43
5	0.1986	123.90	0.2493	89.44

Table 3. Elongation at break and tensile strength – wet specimens A-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	*	111.83	0.2392	84.9501
2	0.1858	114.20	0.2351	73.7049
3	0.1948	120.07	0.2428	88.8322
4	0.1914	114.63	0.2510	90.7116
5	0.2002	121.26	0.2221	68.2138

* – value missed due to experiment error

Table 4. Elongation at break and tensile strength – air-dried A-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.1919	119.53	0.2415	83.12
2	0.1889	120.66	0.2365	75.66
3	0.2004	128.24	0.2336	77.23
4	0.2023	130.59	0.2270	71.91
5	0.1993	124.31	0.2475	93.04

C-type fabric. The Shapiro-Wilk test [56] for all calculated values was performed to be sure the normal distribution of obtained results (value to reject $P = 0.05$). All investigated quantities fulfil the criterion of normality. The mean values of the calculated properties and their standard deviation are presented in Table 11. The mean values of the tensile strength

Table 5. Elongation at break and tensile strength – base specimens B-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.2124	163.74	0.1839	128.6158
2	0.2095	161.06	0.1817	127.0372
3	0.2219	165.58	0.1818	128.7660
4	0.2136	156.62	0.1943	126.3563
5	0.1966	147.41	0.1867	127.2624

Table 6. Elongation at break and tensile strength – wet specimens B-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.2221	163.77	0.1823	127.65
2	0.2177	156.51	0.1773	121.12
3	0.2016	156.41	0.1787	123.13
4	0.2027	150.62	0.1786	119.96
5	0.2012	148.41	0.1708	121.66

Table 7. Elongation at break and tensile strength – air-dried B-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.1985	151.2454	0.1750	123.9437
2	0.2223	162.0611	0.1764	123.0524
3	0.2056	161.5406	0.1721	117.2304
4	0.2142	160.4520	0.1710	119.1112
5	0.2112	162.0700	0.1696	120.5930

obtained for base coating fabric material during tests are generally higher by 0–5% for warp direction and 10–15% lower for weft direction than specified in Table 1. This difference may be due to the application of the flat grips and the age of the fabrics.

Table 8. Elongation at break and tensile strength – base specimens C-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.2378	209.75	0.2005	135.30
2	0.2310	208.14	0.2028	133.67
3	0.2436	218.06	0.1996	137.26
4	0.2380	209.42	0.2037	137.87
5	0.2290	203.78	0.2108	135.97

Table 9. Elongation at break and tensile strength – wet specimens C-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.2362	205.64	0.2043	139.6789
2	0.2360	209.31	0.1930	137.5461
3	0.2237	213.15	0.1985	136.4190
4	0.2280	211.25	0.2022	138.8742
5	0.2316	209.55	0.2134	141.4161

Table 10. Elongation at break and tensile strength – air-dried C-type fabric

Specimens No.	Warp		Weft	
	Rupture Strain	Tensile Strength	Rupture Strain	Tensile Strength
	–	kN/m	–	kN/m
1	0.2271	215.788	0.2038	136.1117
2	0.2382	208.64	0.2010	139.9382
3	0.2320	215.69	0.2009	141.7092
4	0.2343	206.69	0.2061	140.5940
5	0.2271	209.11	0.2000	142.2226

Table 11. Mean elongation at break and tensile strength results

Fabric type	Test type	Warp		Weft	
		Rupture Strain [–]	Tensile Strength [kN/m]	Rupture Strain [–]	Tensile Strength [kN/m]
A-type	dry	0.1955 ± 0.0051	125.4 ± 3.8	0.2560 ± 0.0103	94.1 ± 3.7
	wet	0.1931 ± 0.0060	116.4 ± 4.1	0.2380 ± 0.0107	81.3 ± 9.8
	air-dried	0.1966 ± 0.0058	124.7 ± 4.8	0.2372 ± 0.0078	80.2 ± 8.2
B-type	dry	0.2108 ± 0.0092	158.9 ± 2.0	0.1857 ± 0.0052	127.6 ± 1.0
	wet	0.2091 ± 0.0100	155.1 ± 6.0	0.1775 ± 0.0042	122.7 ± 3.0
	air-dried	0.2104 ± 0.0090	159.5 ± 4.6	0.1728 ± 0.0028	120.8 ± 2.8
C-type	dry	0.2359 ± 0.0059	209.8 ± 5.2	0.2035 ± 0.0044	136.0 ± 1.6
	wet	0.2311 ± 0.0054	209.8 ± 2.8	0.2033 ± 0.0076	138.8 ± 1.9
	air-dried	0.2318 ± 0.0048	211.2 ± 4.2	0.2024 ± 0.0025	140.1 ± 2.4

4. Discussion

The one-way analysis of variance (ANOVA [57, 58]) was applied to check whether the obtained differences of material properties obtained in investigated conditions (based material, wet and air-dried) are important from the statistical point of view. The ANOVA analysis required checking of the normal distribution by the Shapiro-Wilk test (what was done before), and the equal variance e.g. by the Brown-Forsythe test [59] (value to reject $P = 0.05$). The equal value of the variance for all groups was also obtained.

In Table 12 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 12 by the word YES, otherwise the word NO is used. The obtained values of the P parameter in the Bonferroni t-test analysis [60] are also given.

Generally, it can be concluded that soaking of the fabrics has minor meaning in the warp direction (except for tensile strength for A-type fabric). For the weft direction, the drying process does not influence the change of material properties (the properties of base and dried material are similar). The wet fabric of A and B types changes the value of the rupture strain as well as the tensile strength. They are lower than for the base and dried material. Almost no change in the fabric's stiffness properties for warp and weft directions in all texts has been observed (see Figs. 3–5).

A similar investigation has been performed for two types of architectural fabrics with glass threads and PTFE coating. The results of this research have been presented in [23]. Now the comparison of the soaking properties of both groups of fabrics can be made. It can be concluded that the stiffness of the glass-based fabrics is more sensitive to humidity conditions. Both families of fabrics (polyester and glass) exhibit some decrease of the tensile strength in the weft direction in water immersion conditions, also some reduction of the rupture strain has been noticed. In the warp direction in water influence conditions, the

Table 12. Results of ANOVA analysis

	Warp		Weft	
	Rupture strain	Tensile Strength	Rupture strain	Tensile Strength
A-type				
base/wet	NO ($P = 0.654$)	YES ($P = 0.017$)	YES ($P = 0.039$)	NO ($P = 0.068$)
base/dried	NO ($P = 0.654$)	NO ($P = 1.000$)	YES ($P = 0.031$)	YES ($P = 0.045$)
dried/wet	NO ($P = 0.654$)	YES ($P = 0.029$)	NO ($P = 1.000$)	NO ($P = 1.000$)
B-type				
base/wet	NO ($P = 0.956$)	NO ($P = 0.493$)	YES ($P = 0.029$)	YES ($P = 0.023$)
base/dried	NO ($P = 0.956$)	NO ($P = 0.493$)	YES ($P = 0.001$)	YES ($P = 0.002$)
dried/wet	NO ($P = 0.956$)	NO ($P = 0.493$)	NO ($P = 0.304$)	NO ($P = 0.706$)
C-type				
base/wet	NO ($P = 0.346$)	NO ($P = 0.837$)	NO ($P = 0.920$)	NO ($P = 0.153$)
base/dried	NO ($P = 0.346$)	NO ($P = 0.837$)	NO ($P = 0.920$)	YES ($P = 0.230$)
dried/wet	NO ($P = 0.346$)	NO ($P = 0.837$)	NO ($P = 0.920$)	NO ($P = 0.959$)

tensile strength change has been obtained for the polyester A-type fabric only. Nevertheless, after drying also for this fabric the tensile strength resumes to the value close to the original one. The behaviour of the glass-based fabrics in the warp direction is more complex. After the drying process, their tensile strength is reduced up to 10–14% compared with the virgin one.

5. Conclusion

In the present paper, the investigation of the influence of water-soaking on the ultimate tensile strength of chosen polyester-based 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 for investigated coated woven fabrics resulting from the performed test was not observed.
- A significant difference in the elongation at break for coated fabric under waterlogged was not assigned.
- As the fabrics were 7–9 years old and in the current research the flat grips have been used, the obtained values of the tensile strength can be slightly reduced in comparison to the producer-declared values given in Table 1. Nevertheless, the flat grips usage does not influence the comparison between groups for specimens treated in different soaking conditions.

The present study confirmed the good resistance of the investigated fabrics to humidity conditions. The mechanical properties are similar even after more than 7 years of storage.

The behaviour of the fabrics in the exploitation conditions has been the subject of the ageing experiments presented in [26, 61, 62]. The obtained results encourage the authors to continue the extended research directed towards precisely understanding the influence of water-soaking on the different types of coated woven fabric's behaviour after different levels of loading and also after soaking in acid water or after atmospheric environmental conditions (eg. UV exposure or frost).

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Wpływ wytrzymałości na rozciąganie tkanin powlekanych na bazie poliestru w warunkach moczenia w wodzie

Słowa kluczowe: tkaniny techniczne, poliestrowe tkaniny powlekane, materiały konstrukcyjne, właściwości mechaniczne, testy jednoosiowego rozciagania

Streszczenie:

Niniejsze badania mają na celu określenie wpływu nasiąkania wodą na poliestrowe tkaniny powlekane na wytrzymałość na rozciąganie i wydłużenie przy zerwaniu w próbach jednoosiowego rozciągania. Artykuł rozpoczyna się od krótkiego przeglądu literatury dotyczącej badań nad właściwościami tkanin technicznych. Autorzy przeprowadzili próby rozciągania jednoosiowego z użyciem szczęk płaskich w celu wyznaczenia wartości wytrzymałości na rozciąganie grup próbek poddanych działaniu różnych warunków wilgotnościowych. Wykonano także fraktografie SEM w celu określenia struktury przekrojowej tkanin powlekanych. W przeprowadzonych badaniach nie zauważono zmiany właściwości mechanicznych pod wpływem zanurzenia w wodzie.

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