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INVESTIGATIONS INTO THE LONG-TERM BEHAVIOUR OF FABRICS

HASTIA ASADI*, JÖRG UHLEMANN*, THOMAS STEGMAIER†, VOLKMAR VON ARNIM†, NATALIE STRANGHÖNER*

* Institute for Metal and Lightweight Structures
University of Duisburg-Essen
45117 Essen, Germany
Email: iml@uni-due.de, web page: http://www.uni-due.de/iml

† Deutsche Institute für Textil- und Faserforschung (DITF)
73770 Denkendorf, Germany
Email: thomas.stegmaier@ditf.de - Web page: http:// http://www.ditf.de/

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Summary. The design process of membrane buildings and structural fabrics has to consider changes of the material properties due to long-term exposure to the environment. For the structural engineer the loss of tensile strength in the fabric, in the seams and in the mechanical fastenings is of major concern, further variations in tear strength and stiffness should be known. The degradation of the protective coating normally becomes apparent in the decrease of the optical properties, first.

For basic synthetic materials the strength deterioration resulting from certain environmental impacts are known. But the prediction of properties for material compositions typically found in structural membranes are vague and a change of these properties during lifetime due to a time dependent environmental load spectrum containing UV radiation, condensate, rain, temperature and pollutants is not possible without experimental testing.

Regarding long-term loading behaviour of structural membranes, creep-rupture or time-to-failure-tests are state of the art. A reevaluation of existing literature and new experimental results show that these tests do not cover loads with limited duration like snow.

The objective of the present paper is to broaden the data basis for long-term behaviour of typical structural membranes for both environmental impacts and mechanical loading. Both aspects are investigated in contribution to the development of a new European design standard for structural membranes.

PVC-coated polyester (PES) fabrics and PTFE-coated glass fiber fabrics are in the main focus of the standardization work as they cover the gross market for structural fabrics. In this paper, environmental impacts to the top coat, particular due to humidity are discussed for PES/PVC and glass/PTFE fabrics. Furthermore, effects of "long-term loading" but with limited duration are presented for glass/PTFE fabrics. Moreover, consequences on the linked strength reduction factors derived from the test results are analyzed and the implications on the design concept and test methods are discussed.

1 INTRODUCTION

Today, the application of coated fabrics as architectural membrane material for light weight structures is growing dramatically. New generations of membrane materials have been developed over the last decades based on high strength fiber fabrics, coated by high performance materials. For some composites, such as PVC-coated polyester fabric, the coating actually consists of several layers. The main coat made from plasticized PVC protects the fabric and thin top coats on the exterior surface containing e. g. polyvinylidene fluoride (PVDF) protect the main PVC coat. Ideally, the top coat provides a barrier to and from the environment blocking incoming UV radiation, moisture, dirt, corrosive gases and mitigates the plasticizer migration to the surface.

Under weathering, every layer degrades according to its own sensitivity and the permeability of the covering layers with the result of variable functional losses especially concerning the optical and mechanical properties. Until now, rough assumptions are made for testing architectural membranes and calculating strength reduction factors [1, 2].

In this work, PVC coated polyester fiber membranes taken from two dismantled architectural projects located in Germany are investigated by evaluating existing test results available in the Essen Laboratory for Lightweight Structures (ELLF) at the University of Duisburg-Essen. Furthermore, the effect of wetting on the short term tensile strength of PES/PVC and glass/PTFE are assessed.

In addition, changes in top coat structure and chemical composition of PES/PVC membranes due to rapid artificial weathering at the German Institutes of Textile and fiber research (DITF Denkendorf) are shown up, deploying ATR-IR spectroscopy and a dyeing procedure.

In the design practice long-term loading impacts are considered in a simplified manner, using a safe sided strength reduction factor of approximately 2 for glass/PTFE fabrics. The prediction presently based on long-term loading simulations of "unlimited" duration can be improved considering effects of long-term loads with limited duration as for example snow, discussed below for a glass/PTFE fabric.

2 CONSIDERATION OF ENVIRONMENTAL IMPACTS AND STRENGTH REDUCTION FACTORS

2.1 General

In general, environmental impacts can be investigated using three procedures: natural ageing (weathering) of test specimens in natural weathering test rigs, artificially accelerated ageing in weathering chambers and ageing by practical application [3]. The last method means the investigation of dismantled material from a realized project.

In the framework of the German "A-factor"-concept, the reduction factor considering environmental impact is calculated according to equation (1) [4]:

$$A_2 = \frac{n_{23}}{n_{w,23}} \tag{1}$$

where n_{23} is the short term tensile strength at room temperature of 23°C and $n_{w,23}$ is the tensile strength at room temperature of 23°C for a weathered test specimen. One aim of the present research is to quantify this ratio for the typically used materials in textile architecture, considering typical lifetimes of architectural structures made from the common composites PES/PVC and glass/PTFE.

2.2 Assessing strength reduction factors of two dismantled architectural fabrics

Architectural PES/PVC membranes applied in two membrane buildings are evaluated in this chapter, see also [5]. Table 1 gives details about these materials and their background. After each interval of inspection a sample was taken and the mechanical performance was assessed using a CRE (constant rate extension) tensile testing machine according to EN ISO

1421 [6]. The results are presented in Figure 1.

Table 1: General features of projects A and B

Name of the project	Year of installation	Location	Application	Material type
A	1979	Germany	Stand canopy	PES/PVC type V Color green Top coat: Acrylic
B	1994	Germany	Multifunctional stadium roof	PES/PVC type III Color white TiO_2 Top Coat pure PVDF

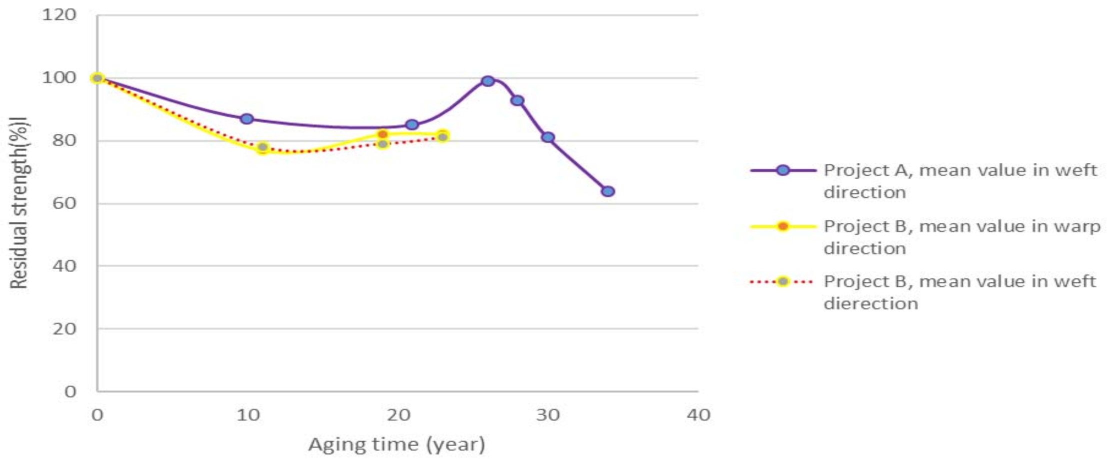

Figure 1: Residual strength-ageing time curves of projects A and B

With curves in Figure 1, the A_2 factors (strength reduction factors) of two projects could be calculated for different ageing duration. But for the designer, the A_2 factor for a specific material considering its typical lifetime is decisive. Presuming a typical service life of 15 years for PES/PVC it results A_2 = 1.18 for material (A) in weft direction and A_2 = 1.32 for Material (B), both in weft and warp direction.

3 CHARACTERIZATION OF WETTING AND WICKING

3.1 General

Many physical properties of fibers are affected by the amount of water absorption such as dimensions, tensile strength and elastic recovery. Pollutants can accompany the water which eases the penetration into the material. The water transport is driven by capillary forces and requires a porous media [7].

In Figure 2 the cross section of a PVC coated membrane is depicted showing the foamy, porous structure of the soft PVC coating. The PVC hardly infiltrates the PES-yarn. The PVDF-topcoat is 15-20 µm thick. In general, the wicking process can be destinguished according to the transport direction in transverse or in-plane wicking[8].

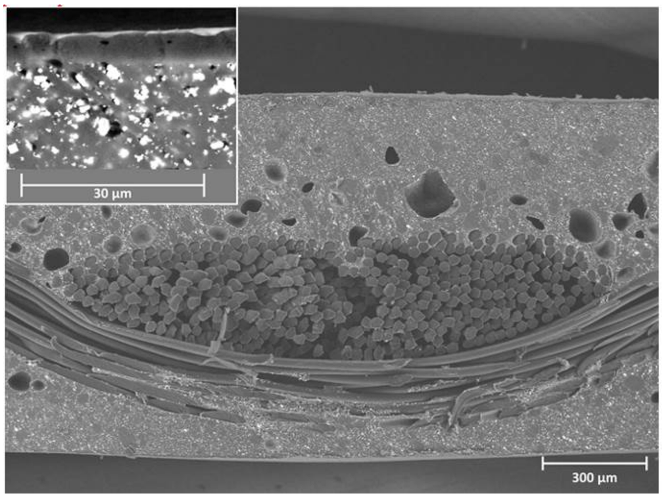

Figure 2: SEM cross section of a PVC coated PES membrane. Enlarged detail shows PVC coating and PVDF topcoat. Bright particles are inorganic fillers in PVC.

3.2 Wetting mechanism in architectural fabrics

In architectural fabrics, the exterior surface is sealed and therefore water (rain or melting snow) should not seep into fabric yarns by passing the coating surface as long as the top coat keeps intact. With the passage of time ageing cracks develop, delamination occurs and the protection is reduced. Via the seams and uncovered edges, in-plane wicking along the yarns which are coated but not filled by PVC or any other materials, might take place. Additionally, these cracks cause transverse wicking and water penetrates through the thickness of the fabric. In many technical polyester fabrics the wicking process is reduced by supplying a "low-wick" system, but as not all materials are equipped and the effectiveness of the low-wick system itself decreases under environmental influence, the impact of humidity or water on the material properties is of interest.

3.3 Effect of water on tensile properties of PES/PVC and glass/PTFE fabrics

The changes of tensile strength due to the influence of water penetration has been examined through wet tests based on EN ISO 1421 [6], carried out on virgin and aged, dismantled PES/PVC fabrics and on virgin glass/PTFE fabric. The dismantled PES/PVC fabric investigated was given from a three-year old inner layer of a biogas plant. The inner layer of biogas plants is affected by some aggressive chemical gases such as hydrogen sulfide. In these tests, test specimens were placed in a bath of water and surfactant for 24 hours, see Figure 3. The surfactant was used in order to lower the surface tension. Comparison samples were kept dry. Dry and wetted test specimens were subsequently tested with the CRE tensile testing machine at the ELLF. Table 2 shows the change of weight after the water bath. With the exception of the dismantled fabric, which has some micro cracks, the average changes in weight of the samples investigated after wetting are almost the same for both PES/PVC and glass/PTFE fabrics.

Table 3 presents the change in tensile strength of the wetted materials related to the dry ones. The amount of mean tensile strength of PES/PVC fabrics after wetting does not decrease dramatically. On the contrary, it increases slightly in some cases. Overall, the changes are rather insignificant. In contrast, for the glass/PTFE fabric, a considerable decrease in tensile strength of 6.81% and 6.64% is observed for warp and weft direction, respectively. This illustrates, that glass/PTFE fabric is more sensitive to water influences, particularly as it absorbed the smallest amount of water of all tested materials, see Table 2. This effect is known as hydrolysis, which leads to stress corrosion cracking of the glass fibers, see e.g. [9]. It can be concluded, that for the weathering test of glass/PTFE fabrics – natural or artificial –it is important to cover edges of the test specimens.

Figure 3 : Wet test procedure, bath of water and surfactant (left) and drying with paper towel (right)

Table 2: Average weight changes (%) of different fabrics after wetting

Name of fabric	Average weight changes after wetting (%)	
	Warp strip specimens	Weft strip specimens
PES/PVC, Type I, Dismantled (3 years old) , Biogas Plant	9.09%	9.06%
PES/PVC, Type I, virgin	4.11%	4.24%
PES/PVC, Type II, virgin	4.96%	4.82%
PES/PVC, Type III, virgin	3.49%	2.79%
Glass/PTFE, Type III, virgin	3.18%	3.23%

Table 3: Average tensile strength changes (%) of different fabrics after wetting

Name of fabric	Change in mean tensile strength after wetting (%) related to the dry state			
	Warp stressing		Weft stressing	
	Increase	Decrease	Increase	Decrease
PES/PVC, Type I, Dismantled, Biogas Plant	3.91%			0.46%
PES/PVC, Type I, virgin		0.89%		1.49%
PES/PVC, Type II, virgin		2.06%		2.72%
PES/PVC, Type III, virgin	4.62%		1.28%	
PES/PVC, Type IV, virgin	1.39%		1.95%	
Glass/PTFE, Type III, virgin		6.81%		6.64%

Table 4 shows the changes in amount of mean tensile strain at breaking point after wetting. It becomes obvious that the differences between virgin samples of PES/PVC and glass/PTFE are not considerable. In constrast, for dismantled biogas PES/PVC samples, these changes are about 6.87% and 4.76% in warp and weft direction, respectively. With reference to Table 2, the highest amount of water seepage belongs to these dismantled samples: 9.09% in warp and

9.06% in weft. It could be concluded that the more water seeps into PES/PVC samples, the more growth in mean tensile strain at break can be observed. But the data are not stringent. For instance, the type II virgin material has a relative high water absorption, but low increase in tensile strain at break.

Table 4: Average breaking tensile strain changes (%) of different fabrics after wetting

Name of fabric	Change in mean tensile strain at break after wetting (%) related to the dry state			
	Warp stressing		Weft stressing	
	increase	decrease	Increase	decrease
PES/PVC, Type I, Dismantled, Biogas Plant	6.87%		4.76%	
PES/PVC, Type I, virgin	1.57%			0.73%
PES/PVC, Type II, virgin	1.55%			1.18%
PES/PVC, Type III, virgin	4.68%		3.02%	
PES/PVC, Type IV, virgin	0%		1.99%	
Glass/PTFE, Type III, virgin		3.75%		2.49%

4 ARTIFICIAL WEATHERING OF TOP COATING

4.1 General functionality

The purpose of a top coat is to increase the appearance, reduce the maintenance and to extend service life. In particular, this is accomplished by blocking environmental penetration of chemicals, moisture and UV radiation; mitigating the loss of plasticizer; increasing the surface quality regarding cracking, crazing and abrasion; reducing the adherence of moisture, dirt, biological films and preserving gloss, color and reducing solar heating.

The durability and effectivity depend on the chemical composition, the thickness and the surface quality of the coating. In general, only limited information concerning the layered build up is published by the manufacturers allowing not more than a rough assignment to the material classes e.g.: PVF-film, PVDF-film, acrylic-resin, resin of acrylic blended with PVDF or other materials, PVDF-resin, TiO_2. Further, the thickness of the resins range in the order of 1 to 10 μm while the films thickness is > 20 μm. The unprecise knowledge of the material composition influences the model concept of the ageing process and influences the examination method for assessing aged materials.

In the following, two methods are presented for examining changes in top coats after artificial weathering in a wet-dry industrial environment characterized by temperature changes between -30 to +70°C with condensing water and sulfur dioxide SO_2 turning into sulfurous acid H_2SO_3. The cycle Global-UV-test is subdivided into four periods with different conditions of temperature, humidity and UV-radiation. During the 10 hour lasting periods I and III the chamber temperature is kept at 50°C, the relative humidity at 90 % and the global UV radiation has an intensity of 50 W/m² on the top surface. Between these periods lays an interval with rain at 30°C without UV-radiation. This cycle is characterized by high UV-irradiation at high humidity under moderate temperature. It simulates an application in a humid tropical or subtropical climate without industrial pollution.

The cycle noxious gas/climate change consists also of four periods with changing conditions of humidity, temperature and concentration of noxious gases. During the 6 hour lasting periods I and III the chamber temperature lays at 70°C, the relative humidity at 90 %

and the concentration of each SO_2 and NO_x at 15 ppm. A 6 hour frost period with –30°C under continuing affection by SO_2/NO_x is simulated in the interval between the periods I and III. The final 6 hour period IV simulates moderate climate conditions wit 20°C at 35 % relative humidity. This cycle is characterized by strong temperature and humidity changings at high concentrations of corrosive gases. It simulates an application in moderate climates with seasonal temperature changings and high industrial pollution.

Table 5: Environmental simulation, cycle Global-UV-test, cycle time 24 h

period		I	II	III	IV
time	[h]	10	2	10	2
temperature	[°C]	50	30	50	30
relative humidity	[%]	90		90	
UV-intensity *	[W/m²]	50	0	50	0
rain		none	+	none	+

* UV-irradiation only on the upper side

Table 6: Environmental simulation, cycle noxious gas/climate change, cycle time 24 h

period		I	II	III	IV
time	[h]	6	6	6	6
temperature	[°C]	70	-30	70	20
relative humidity	[%]	90		90	35
noxious gas SO_2 / NO_x	[ppm]	15 / 15	15 / 15	15 / 15	0

Table 7: Cycle arrangement of series 1 and 2

days		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
series 1(b)	Global-UV-test	X		X		X		X		X		X		X		X		X		X	
	noxious gas/climate change		X		X		X		X		X		X		X		X		X		X
series 2(c)	noxious gas/climate change	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Changes in chemical composition of the top layer can be analyzed deploying an ATR-IR spectroscope. The search for cracks and capillary systems can be analyzed by applying a dyeing procedure.

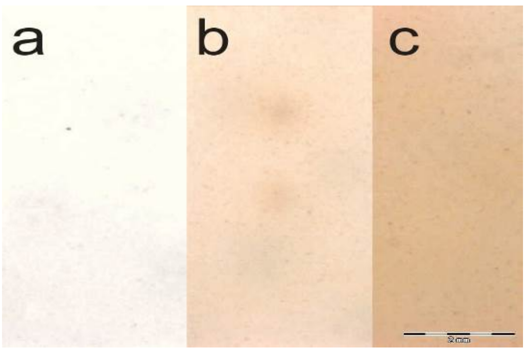

Figure 4: Microscopic picture of material (a) and in condition after 20 days of aging (series 1, b / series 2, c)

A weak yellowing appears on the membrane surfaces from series 1. The edges of the samples show a stronger yellowing effect, which indicates that humidity and noxious gases which penetrate into the laminate along open laying fabrics and layers are more responsible for the yellowing than the UV-radiation.

According to the visual appearance the chosen environmental treatment conditions cause external alterations of the membrane but keep the material functionally intact. This is in harmony with the typical observation that changings in color appear on membranes much earlier before serious material destruction takes place.

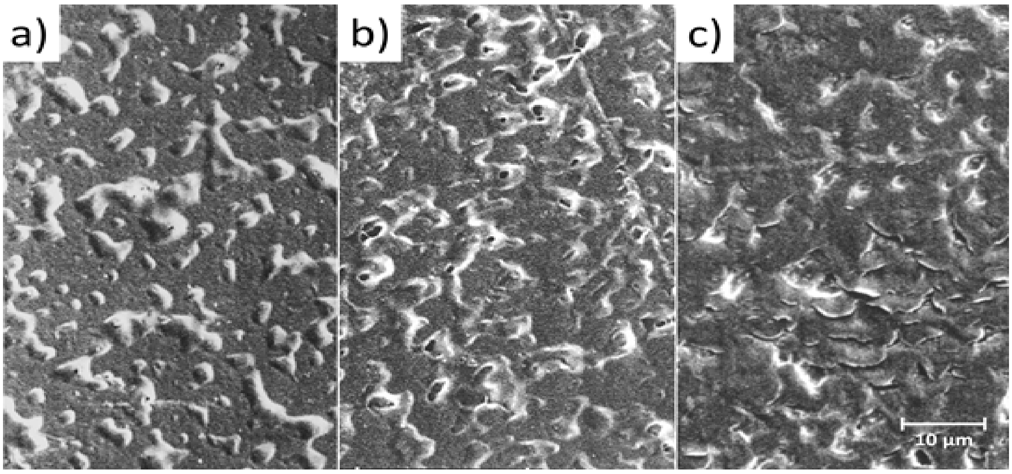

Figure 5: SEM picture of material as-received (a) and in condition after 20 days of aging (series 1, b / series 2,c)

Blisters in the top coat or in layers beneath tend to open up during ageing. This causes pores in the top coat which reduce the function of the top coat as protecting coating and diffusion barrier.

4.2 ATR-IR spectroscopy

The IR spectroscopic examination of the top coat surface containing PVDF has been conducted with a Biorad FT60 spectrometer, a Specac Golden Gate single reflection ATR accessory and a germanium crystal. The high refraction index of the Ge-crystal limits the penetration depth of the IR ray into the material to approximately 1 µm. Thus the chemical information is from the very top layer of the PVDF-top coat. The PVDF coating contains also acrylic binder which results in relatively strong C=O vibration at 1728 cm-1 in the IR-spectrum. After the artificial ageing, especially the samples in series 2 display strong OH-vibrations at 3300 cm-1 and signals at 1640 – 1660 cm-1 in the IR-spectrum of the PVDF-coating. This can be explained with hydrolytic degradation of ester groups. Furthermore, one can recognize that the intensity of the carbonyl vibration at 1728 cm-1 decreases during ageing. Apparently this goes together with an increasing signal at 1660 cm-1. A decreasing signal intensity means that chemical alterations take place with a non (or slow) diffusing component. This might assume that the PVDF coating acts as an efficient diffusion barrier for PVC plasticizers.

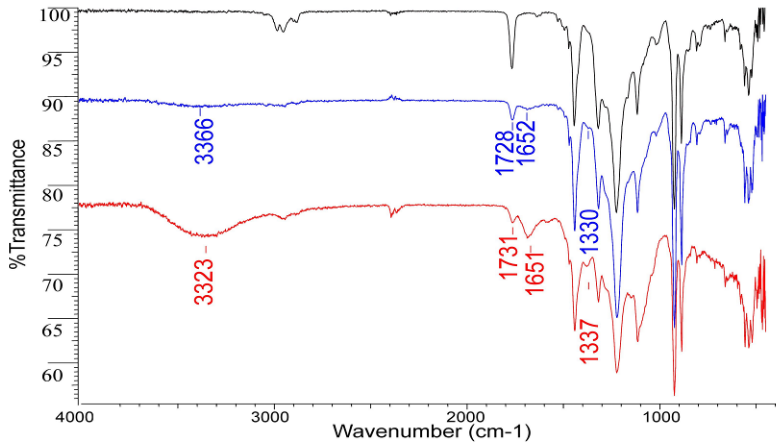

Figure 6: IR spectrum of Membrane PVDF-topcoat surface: as-received (top, black) and in condition after aging (series 1, middle, blue / series 2, bottom, red)

4.3 Dyeing according to the Neocarmin TA-Standard procedure

The varyingly aged membranes were afterwards treated with a dye in the Neocarmin TA process. After the dyeing procedure the surface was investigated with a stereo-microscope, see Figure 7. The penetration of the colored fluid uncovers capillary capabilities of the material and differences in color intensity and color shade depict differences in material and thickness as well as changes in chemical composition during ageing.

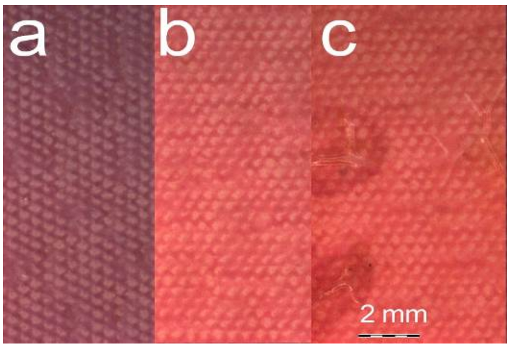

Figure 7: Microscopic picture of dyed material as-received (a) and in condition after 20 days of aging (series 1, b / series 2, c)

5 LONG-TERM LOADING IMPACTS ON GLASS-PTFE FABRICS

In German design practice, long-term loading is typically considered as decreasing the tensile strength and is taken into account by the strength reduction factor A_1 [2]:

$$A_1 = 1.1 \cdot \frac{n_{23}}{n_{t,23}} \tag{2}$$

where n_{23} is the short term tensile strength and $n_{t,23}$ is the tensile strength after long-term loading over time t in “time-to-failure”-tests, both at room temperature (T = 23°C). The “extrapolation factor” of 1.1 was introduced by Minte. It aimed to cover uncertainties of the extrapolation for the time between $t = 10^3$ h und $t = 10^5$ h because only a few tests existed for this period of time.

On the other hand, [5, 10] show for PES/PVC fabrics that “long-term” load of limited duration like snow does not reduce the strength. In order to investigate the effect “long-term” loading of limited duration on PTFE-coated glass fiber fabrics, experimental "long-term" loading tests have been performed in the ELLF on a glass-PTFE fabric type II according to the classification proposed in [4]. In the framework of these tests, the duration of "long-term" is defined as three months, which is able to cover a snow load duration in most regions of Europe. For safety purposes, the magnitude of the membrane stress resulting from the snow load is considered as the maximum design stress, assumed here to be 25 % of the short term tensile strength given in the data sheet. This assumption is deduced from the typical safety factor of 4. Presuming a damaging effect, a subsequent period of 2.5 months at prestress level is scheduled for half of the tests specimens in order to identify a possible recovery after unloading. The prestress level is set to 2 % of the short term tensile strength. The tests were carried out in two phases:

- Phase 1: Loading of all test specimens with the full design stress and holding it constant for three months; for half of the test specimens a subsequent recovery time of 2.5 months on prestress level was scheduled;
- Phase 2: Unloading of the test specimens, removal from the long-term loading test rig and immediate mounting in the 50-kN tensile testing machine for the experimental determination of the residual tensile strength.

In total, 12 test specimens were tested, six warp and six weft specimens. They were mounted on the ELLF creep test stand as shown in Figure 8 on the left.

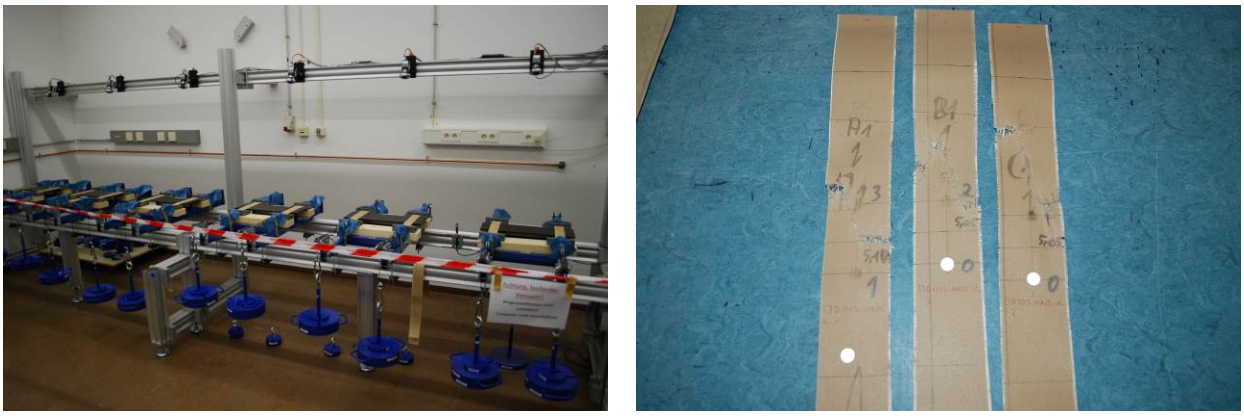

Figure 8: Installation situation of the long-term loaded test specimens in the creep test stand (left), examples of the kind and position of fractures during the tensile tests after long-term loading (right)

In phase 2, every single test specimen was demounted from the long-term test stand individually and mounted immediately in the tensile testing machine within a time period of less than five minutes. Figure 8 on the right gives an example of material fractures obtained in these tensile tests. No clamping fractures occured. For comparison reasons, also virgin material was tested in the tensile testing machine. Table 8 shows the results of the measured residual strengths after three months of full design stress and in comparison the virgin state strengths. The strength did not decrease after three months loading, but instead increased by 4-5 % regarding mean values. Only the 5%-fractile in weft direction shows a constant level. This is due to a slightly higher coefficient of variation after the long term loading in weft direction. But it should be mentioned that the coefficient of variation was generally low with max. $V_x = 3.2$ %.

Table 8: Comparison of virgin tensile strengths to residual tensile strengths after three months loading on full design stress level

	Warp		Weft	
	Mean	5%-Fractile	Mean	5%-Fractile
Short term tensile strength of the virgin material [kN/m]	117,2	113,2	122,8	116,2
Residual strength after three months of full design stress [kN/m]	122,4	121,3	129,4	116,5
Residual strength/virgin strength [%]	104,55	107,16	105,37	100,26

As almost no strength decrease due to long-term loading could be identified, the additional recovery time was valued to be obsolete. However, Table 9 gives the results of the residual strengths after the additional recovery time of 2.5 months on prestress level. For warp as well as for weft direction, the mean tensile strength even rises! But as the deviations are little higher now with V_x = 3-4 %, the 5%-fractiles are more or less on virgin state level again. In warp direction the “usable” strength value in the design even decreased slightly by 2 %.

In summary, long-term loading of limited duration did not damage glass/PTFE fabric. On the contrary, the full design load initially even strengthened the material. But this increase was lost again during the subsequent period at prestress level.

From this it follows, that in the current design practice the impact of long-term loading, considered with a strength reduction factor of approximately A_2 = 2 or more for glass/PTFE fabrics, seems to be much too high and leads to very conservative values. Possibly, the strength reduction factor for long-term loading in the future design standard could be applied on load combinations including prestress, but excluding snow. For the definition of safe strength reduction factors in the framework of the establishment of a Eurocode, further research is recommended.

Table 9: Comparison of virgin tensile strengths to residual tensile strengths after three months loading on full design stress level plus 2.5 months recovery on prestress level

	Warp		Weft	
	Mean	5%-Fractile	Mean	5%-Fractile
Short term tensile strength of the virgin material [kN/m]	117,2	113,2	122,8	116,2
Residual strength after three months of full design stress plus 2.5 months recovery [kN/m]	123,5	111,2	134,5	117,7
Residual strength/virgin strength [%]	105,38	98,23	109,53	101,29

6 CONCLUSIONS

Environmental impact causes some changes in both optical and mechanical properties of building polymers. PVC-coated polyester and PTFE-coated glass fiber fabrics are affected where they are exposed directly to the atmospheric environment during their long-term services in textile architecture structures.

Experimental tests presented in this contribution simulated water seepage from uncovered edges of PES/PVC and glass/PTFE fabrics and investigated the development of tensile strength for the wetted test specimens. All polyester fabrics investigated revealed no significant loss of tensile strength due to water penetration, whereas the glass/PTFE fabric showed a considerable loss of strength of approximately 7 % – although the lowest amount of water was absorbed compared to all other tested material. Due to this sensitivity, it is strongly recommended to cover edges of test samples made from glass fiber fabric in both natural and artificial weathering tests.

Experimental long-term loading tests on glass/PTFE fabric simulating high stress with a load duration of three months revealed that the glass fiber fabric did not respond with a decrease in tensile strength but actually an increase. In fact, this favorable effect got lost when the high stress was withdrawn again. In contrast to the current design practice, it is imaginable that future design rules omit a strength reduction for "long-term" loads with limited duration like snow and only apply it to long-term loads of unlimited duration like prestress.

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