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Long-Term Expectations and Experiences of ETFE-Membrane Constructions

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ABSTRACT

ETFE membrane constructions, ether as single-ply or as pneumatically inflated cushions having two or more membranes, have become the favoured building envelope material for architects. Stadiums, sport arenas, courts, exposition halls, zoo buildings, museums and other public buildings have been erected and their creators were awarded already at the design stage by juries and media. Little is known about real service life, long-term behaviour and maintenance costs of such constructions. In this paper the performance of 3 large buildings will be discussed (Masoala Rain Forest building Zoo Zurich, a pyramid building in Germany and Bush Hall of Burger's Zoo Arnhem NL). The latter, more the 23 years old, has been re-roofed in 2009 because of damages caused by a severe hail storm. Performance, special properties and experiences as well as their life-time assessment of the 3 buildings aforementioned are treated in this publication. In order to assess the Hail Impact Resistance (HIR) of such building materials, a new classification system connected to public register has been introduced by public building insurance companies in Switzerland (see www: hagelregister.ch). It serves primarily as designing tool for roofing & facade architects and engineers.

KEYWORDS

ETFE-membrane, Long-term behaviour, Hail impact, Resistance, Classification.

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1 INTRODUCTION

Since 1980, foils made of the polymer type Ethylen-Tetra-Flour-Ethylen (ETFE) – a thermoplastic polymer copolymer – have been applied as elements of building envelopes more often. All types of customized cushions and shapes can be manufactured of relatively thin foils jointed by a thermo-fusion and thermo-forming process. Inflated cushions may form complete façades, roofs or their segments. Popular applications are stadiums, parking and exhibition roofs, spa halls, museums, atriums, zoo and other buildings mainly for public use. In addition, illumination techniques allow special visual effects in architecture. Therefore, architects are captivated by this material because of its nearly unlimited means of applications [LeCuver 2008]. However, little is known concerning aging behaviour of these constructions. Manufacturers are currently estimating the life-time of ETFE foils to be 50 years or more.

2 MATERIALS AND CONSTRUCTION

2.1 Material and foils

ETFE is a thermoplastic polymer consisting of polyethylene and poly-tetrafluorethlylene, a compound of tetrafluorethylene (4 parts) and of ethylene (one part) with a final density around 1.72 g/cm^3. As a thermoplastic, its melting point ranges at a temperature above 275° C. It can be processed by extrusion technology using fully mixed ETFE granules as raw material. The semi-crystalline polymer structure of foils thicker than 50 microns shows a slightly bluish appearance. The presence of the 4 flour atoms in the chemical structure provides excellent chemical resistance against most physical-chemical influences and fire.

ETFE-foils 1.5 to 2.0 m of width and 50 to 250 microns of thickness can be fused together by a thermo-fusion process to any size of cushion. In the jointed zone, the overlapped surfaces fully melt. With the help of pressure rolls, a solid jointing is created. This zone of 25 mm width is visible because of doubled thickness and surface imprints. CNC-controlled machinery is needed for precise cutting and jointing.

Figure 1 and 2. Jointing of ETFE-foils by hot fusion and inlay of keder in foil boundary loop.

2.2 ETFE-constructions

The construction of a pneumatically supported building consists of multiple elements bridging a stiff engineering structure made of wood, steel, concrete or a combination if all. The gaps between the engineering structures are filled by membrane cushions consisting of 2 or more ETFE layers. The connection to the engineering structure is realised by a linear fixation system called keder. At the boundary, membrane layers are formed to pockets containing plastic rods. The keders fit in EPDM gaskets and slotted aluminium profiles to provide water tightness. The cushions are inflated with dry air where it builds up an internal pressure in the range of 200 – 400 Pa. In order to maintain cushion shape and its adaptation to high wind forces, a detailed air duct system connects all cushions and serves as a mandatory air pressure pump. In case of a membrane leakage, only few elements are connected and an auxiliary air pump provides sufficient air pressure. In case of inflation, the cushion height can exceed 1m or more. If the outside layer is separated from the inside layers by a special spacer profile, the air chambers provide excellent thermal insulation.

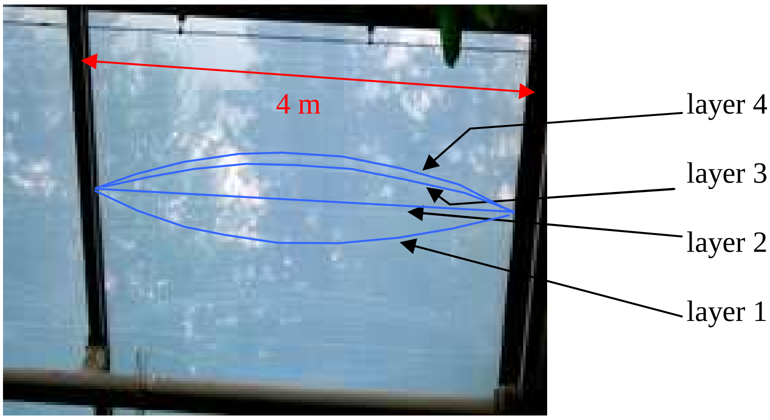


Figure 3. ETFE-cushions with 4 layers of MAS building at Zoo Zurich span 4 m. The 4th layer acts as protection against hail stones.

3 LIFE TIMES OF ETFE-MEMBRANES

3.1 General

Fluor polymers are known as being highly resistant against a large number of chemicals and environmental influences including UV radiation. As thin foils, this polymer was first applied in building envelopes around 1980 and was soon applied also on solar panels. Currently, many successful architectural applications around the world are equipped by ETFE-foils. On the other hand, non-UV-stabilized polyethylene foils for temporary use are known to decay only after a short period of use [Eyerer et al. 2005]. Crack initiation of the polymer chains starts soon after a few months of exposure. Records from outdoor applications of ETFE-membranes over extended time periods, promise a reasonable life-time [Lehnert, Schween 2005]. Therefore they seem to be apt for permanent buildings as well.

3.2 Investigated buildings

ETFE-foils from three buildings in the Netherlands, in Germany and in Switzerland were available for this investigation. The longest exposure time was 22 years at the Bush Hall of Burger's Zoo in Arnhem (BZA) [Fig. 4 an 5]. Whereas, the pyramid spa-hall (PSH) in western Germany was installed 13 years ago and the roof of the Masoala Rain Forest building (MAS) of Zoo Zurich 7 years ago [Fig. 6]. In table 1 the relevant building data are listed. From the MAS and PSH building, new membranes were also available where the results of the installation were taken from as reference data.

Table 1. Data from investigated buildings and thickness of installed ETFE-membranes.

Source of foils	*Year of installation*	*Age* [years]	*Raw material*	*Number of membranes layers*	*Thickness form outside to inside* [microns]
MAS* aged	2002	7	A	4	200/100/180
MAS new	2002	0	A	1	200
PSH**	1987	13	A	2	200/200
PSH new	2002	0	A	1	200
BZA***	1986	22	B	3	150/80/100

* With hail protection foil after hail damage ** damaged by hail storm in 2000
** damaged by hail storm in June 2008

Figure 4, 5 and 6. The roof of bush hall of Burger's Zoo Arnhem NL (left), inside view (centre) and the Masoala Rain Forest building at Zoo of Zurich (right).

3.3 Test methods applied

In order to assess the long-term performance of EFTE membranes, only a limited number of typical tests for polymers were selected in the first test series because of a given cost limit. Therefore, extended testing with sophisticated equipment has been postponed for the second investigatory level. The investigated properties were as follows:

- Surface analysis
- Tension test: E-modulus, extension and stress at yield and at break
- Impact tension test, to sense the loading rate influence
- Tear resistance: to check the reaction to micro-cracking sensibility
- Coefficient of thermal expansion
- Fourier-Transformation-Infra-red FTIR-analysis: to check for material base and physical changes
- Differential-Scanning-Caloriymetry DSC, for melting temperature and enthalpy

4 RESULTS

4.1 Surface analysis

Before analysis, the membrane from the BZA-building was intensely washed with common soap with water in order to remove dirt and bio-residuals stemming from the out-door deposit. All surfaces were visually inspected for defects, cracking and possible chemical attack. Critical spots were investigated by a regular magnifying glass of 6 xs.

Table 2. Results of the visual inspection of the membrane surfaces.

Aspect	*MAS, Zurich*		*BZA, Arnhem**		*PSH, Germany*	
	2002 new	*7y*	*22 y*	*22 y*	*2002 new*	*13 y*
Exposition	outside	outside	outside	inside	new	inside
Thickness	200	200	150	100	200	200
Appearance	new	as new	slightly mat	As new	new	as new
Colour	light bluish	light bluish	light bluish	clear	light bluish	light bluish
Light transparency	transparent	transparent	transparent	transparent	transparent	transparent
Gloss	very high	very high	high, dirt spots	high	very high	high
Contact with water	f. repellent	f. repellent	f. repellent	f. repellent	f. repellent	f. repellent
Defects	none	none	multiple	multiple	none	indents, slits
Deposits	none	none	bio-film, dirty	bio-film both sides	none	dust sticks
Faults /scratches	none	some	multiple	multiple	none	multiple

In general, all membranes were fully water repellent. All were transparent and of a light bluish colour. No signs of oxidation or deterioration were found on any of the membranes [Table 2]. With increasing age, more scratches and defects were located -especially on the BZA-membranes. Due to its application and high humidity on this membrane, a well-developed bio film on both sides of the interior foil was found.

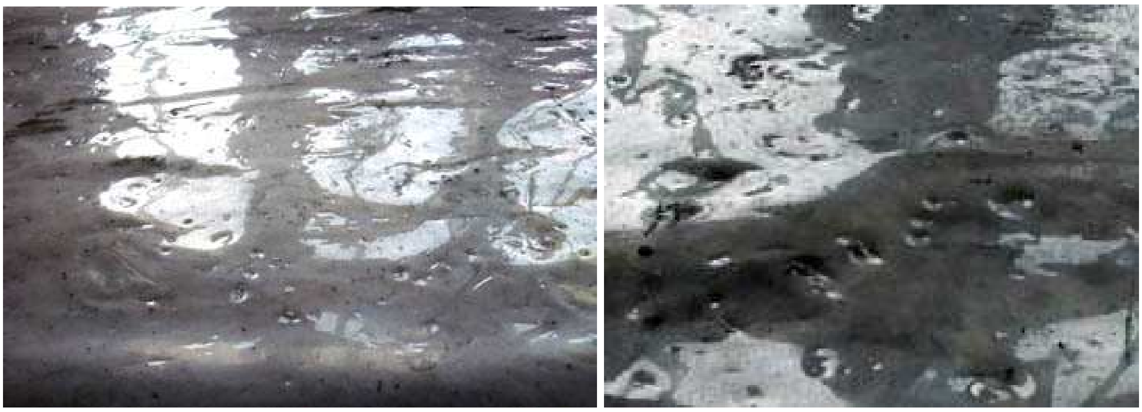


Figure 7 a and 7 b. Appearance of the BZA membrane with various indents, small perforations and surface contaminations.

4.2 Mechanical properties

All membranes were subjected to tension, impact tension and tear resistance. The tests revealed the values were nearly unchanged compared to new membranes. A higher scatter of the standard deviation was observed at the BZA-membrane due to little mechanical defects which were neglected during the test sample extraction. The tension test results of the PSH building showed a certain difference compared to the MAS and BZA building membranes [Figure 8 and 9].

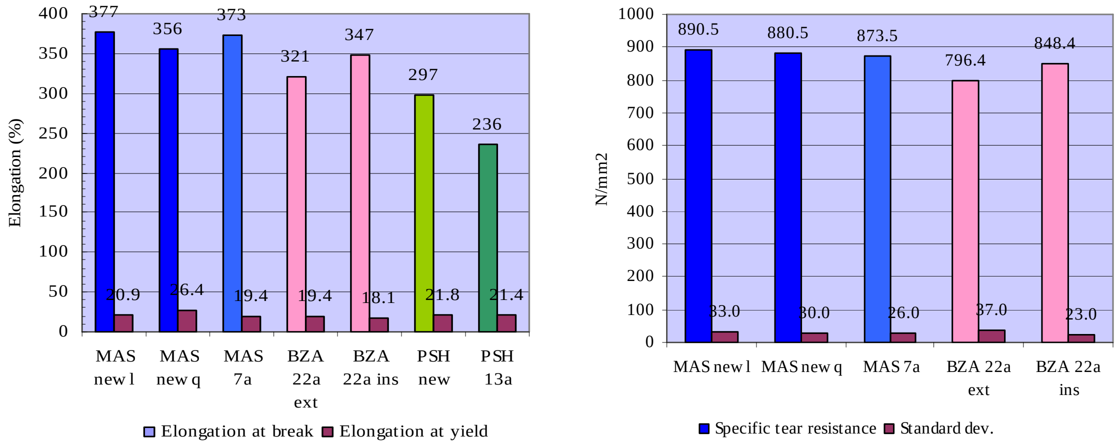
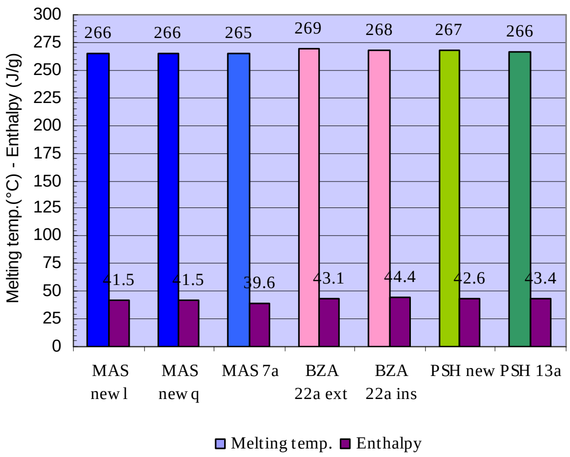


Figure 8 and 9. Elongation at break and at yield from tension tests (left) of all three buildings. Specific tear resistance in N/mm^2 of MAS and BZA buildings.

4.3 Physical properties

The FTIR investigations confirmed the nature of the polymer as Ethylene-Tetraflourethylene ETFE. Only minor differences of the wave number 754 cm^{-1} of BZA and PSH foils lead to the conclusion, that different raw materials were used. It didn't show any sign of aging or oxidative degradation at all.

DSC investigations pointed to the possibility that changes may have been influenced by the stored heat due to longer sun exposure of the BZA-building. However, these changes were minimal but detectable (Fig. 10 and 11).



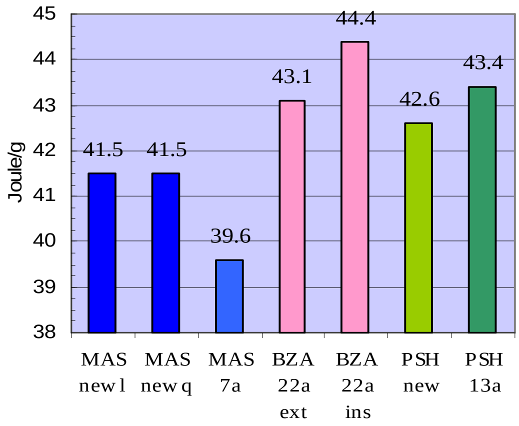


Figure 10 and 11. Melting temperature (° C) and enthalpy (J/g) for new and aged ETFE membranes (left). Enthalpy peaks blown up for better discrimination (right).

5 ASSESSMENTS

All mechanical properties exhibited nearly unchanged values compared to new conditions. Minor deviations could be associated to surface scratches, indentations and perforations. Degradation by physical-chemical influences could not be noticed. However, the surface was heavily contaminated with sticky dirt and fungi. Cleaning with soap water and action pressure was minimally successful. A certain contamination remained on the surface of BZA building. Figure 12 shows an overall assessment of the aging status after the exposed years with an intensity level. The intensity levels are connected to times and priority of measures to be taken. A special view was taken to the feasibility and to remark the early aging indication of the applied test method.

Property	**Aging status**			**Feasability of method**	**Remarques**
	MAS	**BZA**	**SPH**		
Exposure time (years)	7	22	13		
Tension at break	[green]	[pink]	[light orange]	yes	
Tension at yield	[green]	[green]	[green]	yes	
Elongation at break	[green]	[pink]	[pink]	yes, good	early indicator
Elongation at yield	[green]	[green]	[green]	yes	
E-Modulus	[green]	[green]	[green]	yes	
Impact tension	[green]	[light orange]	[green]	excellent	early indicator
Tear resistance	[green]	[pink]	n.t.	excellent	early indicator
Surface analysis	[green]	[light orange]	n.t.	yes	
Coefficician of thermal expansion	[green]	n.t.	n.t.	yes	
FTIR-analysis	[green]	[green]	[green]	excellent	early indicator
Melting temperature	[green]	[green]	[green]	yes, good	difference of run 1 to run 2
Enthalpy	[green]	[green]	n.t.	yes, good	difference of run 1 to run 2

	Aging level		**Measures to be taken**
Remarques:	[green]	none	none
	[light orange]	very little	none
n.t. = not tested	[pink]	little	prepare
	[magenta]	detectable	begin
	[purple]	strong	absolutly necessary

Figure 12. Overview of aging status and feasibility of test methods for early detection, MAS: Masoala Rain forest Building, BZA: Burger's Zoo Arnhem, PSH: Pyramid Spa-Hall.

6 What are life-time terminators of ETFE-membrane structures?

6.1 General

The mechanical properties depend strongly of the material thickness, the temperature, the specific failure mode and the rate of loading. Since the applied material thickness of the ETFE membrane cushions do not exceed more than 250 microns (older buildings only 150 microns) such constructions are highly vulnerable against sharp tools, knifes and sticks, flying foreign objects and animal/human attacks. Damages and vandalisms were already observed during the construction phase and in use. Some buildings required instant repairs or replacements.

6.2 Life-time terminators

Construction using cushions made of ETFE seem to last 3 decades or more. The membranes of the oldest buildings show only minor physical-chemical deterioration, if they are still in use like the Mangrove building of Burger's Zoo. Baring responsibility for this fact, are the strong chemical bonds of Fluor atoms in the molecular chain. The applied proportion of 29 % ethylene and 71 % tetra-Fluor-ethylene seem to function in the exposed environments. Despite that fact that several buildings had to be repaired or re-covered because of mechanical defects caused by snow overload, by impact of wind born debris or by hailstorms. The BZA-building was completely re-roofed in 2009 after a major hailstorm in June 22, 2008. Hail stones of irregular shape of 4 - 5 cm diameter perforated the outer foil. Also, the newly erected Masoala Rain Forest building was re-roofed after a sever hailstorm in June 2002, 14 days after installation was completed. For further protection the insurances required a protection against hail impact damage [Flüeler & Makarova 2002]. This was realised by a fourth, separately inflated ETFE-membrane to be replaced when perforated. In another hailstorm in 2004 only the protection foil was damaged. In 2006, a heavy snow fall deflated 90 % of the membrane cushions and forced an improvement of the air duct inlets.

7 Conclusions

Experience from this work demonstrated that ETFE-membranes exhibit an excellent physical-chemical long-term performance exceeding 30 years. It has also taught the building owners that all three buildings were exposed and damaged by hail impact during the 22 years' period of use. The MAS building suffered from severe damage caused by irregularly shaped hail stones 14 days after installation only and two years later for a second time. Therefore, such constructions need to be protected against hail and impact of sharp objects as well as against vandalism. For designers, owners and insurers the newly established register of hail impact resistant (HIR) building materials of the Swiss association of public building could serve as a know-how tank. In the testing protocol, all materials/systems of a building envelope are tested with -20° C cold ice balls of 1 – 5 cm in diameter. It forms the 5 HIR class systems and represents hail impact resistance of the declared size in centimetres at which no damage occurs. Details can be found in the register [VKF 2008]. For higher safety, thin and soft materials like ETFE-cushions and protection foils have to be evaluated also in regard to impact of irregularly shaped hails stones. Due to changing climate, hail storms will occur more frequently and intensely. They will also strike regions where up to date hail has been unknown.

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