SOFTENING THE HABITATS
SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

Proceedings of the TensiNet Symposium 2019
Softening the habitats | 3-5 June 2019, Politecnico di Milano, Milan, Italy
Alessandra Zanelli, Carol Monticelli, Marijke Mollaert, Bernd Stimpfle (Eds.)

Coating of ETFE – Solar Shading for Architectural Applications

Carl MAYWALD*

*Vector Foiltec GmbH
Steinacker 3, 28717 Bremen, Germany
Carl.maywald@vector-foiltec.com

Abstract

Due to the high transmission rate of ethylene tetraflourethylene (ETFE) films over the whole solar spectrum cladding systems for architectural applications may result in heating up inside areas, thus increasing the energy requirements for air conditioning. In order to enhance user comfort and reduce cooling loads the foils have to be specially treated or coated. The low surface energy (23 mN/m) of ETFE foils inhibits surface adhesion thus offering maintenance advantages from self-cleaning effects which simultaneously raises considerable challenges for the design and application of stable coatings. Additionally, ETFE foils as part of the cladding system undergo significant in-service deformation, both plastic and elastic. Coatings have to cope with this specific requirements. This article will provide a brief introduction into the development of coating and printing on ETFE in particular, as well as an introduction into different techniques for solar shading of ETFE cladding systems in architectural buildings. In order to allow for quality assessment of these coatings taking into account elastic and plastic deformation of the target material, a new test procedure for coated ETFE will be introduced.

Keywords ETFE- ethylene tetrafluoroethylene, Texlon® systems in architecture, solar shading, quality assessment of coatings, transmission and reflection

DOI: 10.30448/ts2019.3245.43

Peer-review under responsibility of the TensiNet Association

1. Introduction

Extruded ethylene tetrafluoroethylene (ETFE) films were first identified as an ideal material for transparent building envelopes by Dr. Stefan Lehnert, founder of Vector Foiltec, in 1982 and were subsequently developed as the primary component of a multi-application building cladding system under the brand name "Texlon®". The first project built by employing this technology was the Mangrove Hall of the Burger's Zoo in Arnhem, The Netherlands, in 1982. The basis of a standard Texlon® multilayer system is an airtight cushion formed by welding together a minimum of two ETFE foil layers held within an extruded aluminum alloy perimeter frame, connected to a low pressure (250 Pa) air supply. A more detailed introduction to the technology can be found in "ETFE – Technology and Design" by Annette LeCuyer (LeCuyer A., 2008).

Early architectural projects utilizing the ETFE cladding technology were built with uncoated, clear ETFE films, which are highly transparent across the full band width of the solar spectrum (see Figure 1).

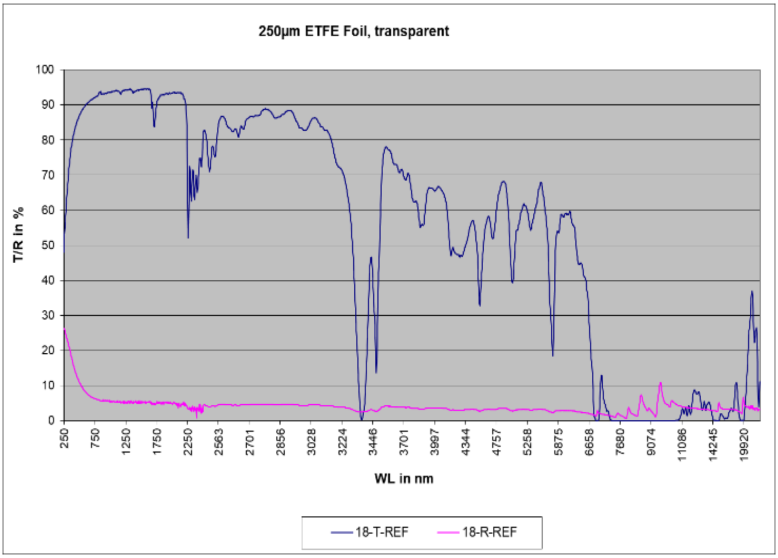

Figure 1: Transmission T and Reflection R of 250 µm ETFE foil up to 20.000 nm wavelength

The transmission of nearly 90 % of photosynthetically active radiation (PAR) is ideal for enhancing plant growth, but for human habitats the high transmission may result in heating of inside areas, thus increasing the required energy for air conditioning. Furthermore, the high surface area to perimeter ratios and the lightweight ETFE cladding panels, which are a significant advantage for sustainability and costs, increase the total solar energy transmission. Therefore careful consideration must be given to any requirement for solar control.

The first solar control for ETFE cladding systems in architecture was the application of a coating on an ETFE film for the atrium roof at the Schlumberger Research Institute in Cambridge, UK, in 1992 (Figure 2a).

Figure 2a: ETFE atrium roof Schlumberger Research Institute, Cambridge, UK, outer foil printed on inner surface, print pattern DM 4:65, light optical density ink (1992)

Figure 2b: Details of stable print pattern, after 23 years installation on the roof of the atrium (2015) .

The application of the print pattern on ETFE film was achieved by the development of a rotogravure, roll to roll printing process by Vector Foiltec. The print pattern employed was a 4 mm dot matrix covering 65 % of the foil surface (DM 4:65) with relatively low optical density. The shading performance though effective was limited and thus supplementary blinds were still required in front of the windows on the ground floor. Despite the technical difficulties mentioned before the detailed view (see fig.2b) exhibits the good status of the coating even after 23 years of exposure (photos taken in 2015) to environmental conditions. In order to protect the ink, the printing is always applied on the inner side of the outer foil of the cushion. In addition, the self-cleaning effect of the outer face of the foil due to the low surface energy is preserved.

Indeed, even though the modification of the transmission for solar radiation is the primary driver for development of coatings on ETFE foils, they have also been utilized for purely aesthetic purposes. Finally, the development of high reflectance printing on ETFE foils was the key technological advance that expanded the application range of Texlon® towards a universal cladding product for high transparency roofs and façades. One example for the success of such a high reflective cushion system is 'The Avenues Mall', the largest shopping mall complex in Kuwait and the second largest in the Middle East. Phase III 'The Grand Avenue' encloses a main boulevard and adjoining side streets under 25.000 m² of ETFE roof (Figure 3) creating a comfortably conditioned space with the experience of an open sky, that is not only a major commercial success but has become a social hub for the whole region (Maywald C., and Riesser,

Figure 3 The Avenues Mall, Kuwait – Texlon® ETFE cladding system printed with DH 7:84 medium

F., 2016) and (Urbán et al., 2016). Since then further phases IVa and IVb have been completed creating a range of additional commercial and social spaces well-protected from the harsh external environment under a total of nearly 100,000 m² of Texlon® ETFE roofing system. Despite the high external temperatures a low overall heat transmission resistance (high U-value) for the roof system has only minor influence due to the temperature stratification effects. In this building category with its full height large volume spaces the warm air is forming a stable inversion layer immediately beneath the roof with comparable or even greater temperature than outside. The temperature gradually decreases downwards to the comfort zone at ground level. During night time the temperatures outside the building are lower. So the loss of thermal energy through the roof is beneficial to reduce daytime cooling demand. However, the necessity for control of radiative solar gain is of paramount importance. The reflective coatings used at The Avenues Mall are a third generation medium opacity ink printed in a 7 mm hexagonal matrix pattern covering 84 % of the foil area (DH 7:84) to the inner surface of the uppermost foil.

For the 3-layer system (200 µm – 80 µm – 200 µm), with outer foil printed on the inner side, the performance is given in Table 1:

	UV-light	Visible light	Solar light
Transmission (%)	16	21	21
Reflectance (%)	44	46	46
Absorption (%)	40	33	33
g-Value/SHGC	0.23		
Shading Coefficient	0.27		
U-Value (W/m^2K)	1.25		

Table 1: Optical and thermal properties of 3-layer cushion system at The Avenues Mall, Kuwait.

2. Printing and Coating on ETFE

Printing and coating on ETFE-foils is highly demanding for both the formulation of the lacquer systems and the physical coating process. This follows from the material characteristics of the foil itself and the wide range of environmental stresses that the printed foil as the primary element of a building envelope cladding system must withstand. The material properties of the ETFE foil that mostly influence the physical and chemical stability of the applied coatings during the printing process and in-service are:

1. Low surface energy ≤ 23 mN/m;
2. Elastic and plastic deformation under load up to 5%;
3. A relatively low melting point of approximately 280° C;
4. Water vapour permeability – approximately 2 $g/(m^2d)$ for a 200 µm ETFE foil;
5. UV transparency – approximately 80 % for a 200 µm ETFE foil.

The installed Texlon® cushion has to withstand a range of extreme environmental stresses:

1. Temperature - ETFE cladding systems have to survive external temperatures between minus 40° C up to plus 50° C.
2. Wind Loads - building envelopes are subject to high wind loads of varying gust durations and load distributions causing high and nonuniform stresses
3. Snow loads – create loading scenarios maintaining high stresses in the ETFE foils over extended periods of time.
4. High humidity, rainfall and condensation can cause vapour pressure gradients in both directions across ETFE membranes.
5. Partial water ponding – certain partial deflation scenarios can result in localised water ponding resulting in very high local loads and associated stresses.
6. Folding, bending and buckling - during the production process, transportation and installation of the ETFE cushions and single layers repeated or sustained folding and buckling can occur.

Both sets of parameters define the requirements for coating formulations, their mechanical and chemical properties, the printing process, and for the treatment systems:

1. Before coating, the surface of ETFE foils should be pre-treated by either corona or plasma discharge to increase the surface energy. The best results regarding adhesion have been identified at a surface energy value of around 56 mN/m. This can be achieved by a corona treatment of a single side of the ETFE foils during the extrusion process. Unfortunately, the surface energy will decrease with time after treatment. Thus, it is strongly recommended to renew this treatment directly before coating.
2. After the coating process the ink must be dried by controlled heating within a drying tunnel. To prevent deformations of the ETFE foil an uniform temperature distribution below 70°C should be applied.
3. The roll to roll process induces longitudinal stress in the foils. However, elongation deformation is not acceptable as multiple pieces of foil with short lengths must be welded together to form larger sheets for cushion production. The print patterns should be aligned across the seams. For this purpose, marks are printed along roll edges to ensure the correct alignment prior to welding.
4. As the primary component of a cladding system foils will be deformed elastically and to some degree plastically during service life. Coating adhesion must be sufficiently robust to withstand shear stresses at the interface between foil and pigments whereas cohesion has to perform sufficiently elastic in order to resist disruption or cracking of the matrix.
5. The coating must remain stable under 100 % humidity within a cushion under simultaneously high external temperatures. Despite pressure from water vapour permeability neither degradation nor generation of plaque due to micro-cracks and micro-channelling is acceptable.
6. The coating must have long-term UV stability
7. The coating must retain adhesion and cohesion
    a. under dynamic stresses from wind loading across a wide material temperature range of -40° C up to +50° C,
    b. in areas of sustained high strain and peripheral buckling induced by snow loads,
    c. in localised zones of high strain caused by folding and buckling during welding as well as production and installation activities.
8. To facilitate many production welding scenarios it is necessary to be able to remove coatings precisely from localised areas of foil. Despite the need for extremely high levels of stability under the circumstances reported above it must also be possible to economically, effectively and safely remove coatings when required as part of the cladding production process.

2.1. Development of ink for printing on ETFE

In close cooperation with a company specializing in the research and production of varnishes and paints Vector Foiltec developed a coating system for use with ETFE foils in 1990 and undertook rigorous testing of its application in an automated gravure printing production process. Eight years after the first architectural application (Schlumberger Research Institute in Cambridge, UK, in 1992) the technology was transferred to a German printing company. Since then it has become the standard system for printing on ETFE for architectural applications. Accordingly, this technology is now used by nearly all suppliers of ETFE cladding systems. With the exception of zoological and botanical buildings where high levels of solar transmission are required, printing is employed in almost all ETFE cladding installations in order to control incoming solar radiation. Vector Foiltec have continuously worked on further optimization of printing ink formulation for exclusive use in their ETFE cladding products with a particular emphasis on enhanced system performance, environmental sustainability and occupational health and safety. In close cooperation with a high-tech printing company in Austria major advances were achieved regarding optical density and reflectivity in 2010. In contrast to the previously used fluoropolymer resin lacquers the new ink is based on an acrylic lacquer enabling the use of much less harmful solvents (bio-ethanol) for the removal of printed ink for welding purposes. The continuous improvement over time in the solar control capabilities of specialist ETFE printing inks is demonstrated in Table 2 below.

Table 2: development of print performance (the more recent acrylic based system is indicated by the prefix H and the former resin system by the prefix R

	T_{UV} %	T_{vis} %	T_{sol} %	R_{UV} %	R_{vis} %	R_{sol} %	ε*	g-value
R01249	41,9	41,7	41,4	30,8	39,9	39,7	0,56	0.46
R01249	9,7	12,6	12,8	38,2	51,5	51,1	0,47	0.25
R78185	6,6	7,2	7,1	48,4	57,7	54	0,43	0.21
H560110	2,5	2,7	2,6	53,9	56,6	55,4	0,40	0.18

For a standard 3-layer ETFE cushion system similar to that deployed in Phase III ‘The Avenues Mall’ Kuwait (200µm transparent outer foil, 80µm transparent middle foil, and 200µm transparent inner foil, outer foil printed on the inner face with DH 4:84, 4mm hexagonal matrix with 84% coverage), the g-values calculated for the 4 different print systems are indicated as well.

It should be noted that transmission and reflectance characteristics for both the visible portion T_{vis} and the solar transmission T_{sol} are closely related. Reduced solar gain resulting from a higher percentage of the surface covered by ink and/or enhanced reflectivity will result in a similar reduction in visible light transmission with these coating systems.

2.2 Texlon® "Vario" system

The Texlon® "Vario" system was developed to provide a cladding solution that could react to changing demands for solar control or visible light transmission in response to customer requirements or variations in the external environment. The system can be triggered to switch modes by automated sensor driven controls or manual push button operation.

In the standard 'Vario' arrangement the two outermost layers of a three layer panel are printed with a complementary offset print on their inward facing surfaces. The middle or innermost printed layer can be moved upwards to rest against the uppermost printed layer or down to meet the bottom layer by pumping air from one side of the middle foil to the other creating a pressurised chamber either below or above the middle foil. A detailed description has been given by Annette LeCuyer (LeCuyer A., 2008, p. 94).

The optical and the thermal performance of a Texlon ® vario system with one of a number of different print pattern combinations (SQM 200-197:45 dark) for open and closed position is given in table 3.

Table 3: optical and thermal performance of a Texlon® vario system for open and closed position. Print pattern is SQM200-197:45

Texlon vario	open			closed		
	UV light	Visible light	Solar light	UV light	Visible light	Solar light
	UV light	Visible light	Solar light	UV light	Visible light	Solar light
	%	%	%	%	%	%
Transmission	15	26	26	5	9	10
Reflectance	14	40	38	14	53	52
Absorption	71	34	35	81	38	39
g-value / SHGC	0,37			0,14		
Shading Coefficient	0,42			0,16		
U-value [W/m²K]	2,78			2,78		

Solar light transmission is 10 % in the closed position and 26 % when open and the associated g-value or Solar Heat Gain Coefficient SHGC are 0.14 closed and 0.37 open. It should be noted that in the standard arrangement the middle foil is always in contact with the uppermost or bottom foil in the closed or open position respectively and therefore for the purpose of thermal insulation this is always a single chamber system with a corresponding U-value of around 2.78 W/m²K.

3. Test procedures for coatings on ETFE

As outlined in section 2.0 the demands on the stability of ETFE coatings for building applications are sophisticated, yet it must still be possible to efficiently remove these coatings as part of the production process. Probably the most demanding of all is the retention of adhesion and cohesion under long and short term deformation, typically up to 3-5 %, under dynamic environmental conditions.

Classic accelerated weathering test methods like EN ISO 4892-2 (2013) and EN ISO 4892-3 (2016) within climate chambers simulating rain, alternating temperatures and UV impact had been applied and revealed no difference in performance for a range of ETFE coatings. However, in-service external exposure in mock-ups and historic installations had led to print degradation or loss of adhesion, showing the limits of the standard test methods for the determination of ageing performance of coatings on ETFE foils. Therefore, a long term corrosion test under stress load and a hysteresis test were developed.

3.1 Long term corrosion test under stress

In the long term corrosion test a 15 mm wide, coated ETFE strip with a foil thickness of 250 µm is loaded by a weight of 6.5 kg fixed at one end of the strip (cf. fig. 4) inducing a nominal stress of approximately 17 N/mm² (HUECK FOLIEN, 2010).

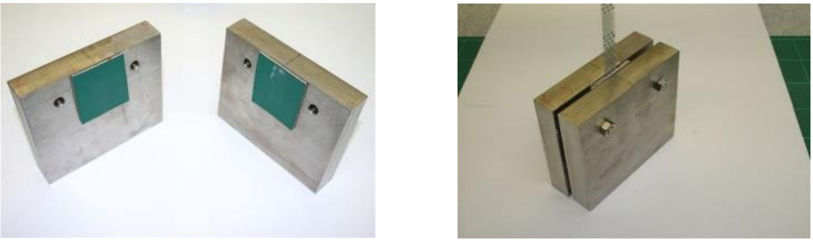

Figure 4: weight for creation of 17 N/mm² load on an ETFE stripe of 15 mm width

Once loaded, the specimen is inserted into a container, which will be filled with 10 mm distilled water and closed afterwards. The strip is led through a slot in the cap of the container, the container is sealed and the strip is tensioned by rolling it up a metal stick (see fig. 5, 6, and 7).

Figure 5: ETFE stripe loaded with weight up to 17 MPa

Figure 6: cap with small opening for ETFE stripe

Figure 7: containment closed with cap

The test assembly is placed into a climate chamber for 10 days at a temperature of 80° C. The tension in the strip was maintained permanently. The ongoing elongation of the strip was corrected by further reeling over the metal stick. Afterwards the stability of the print is determined by applying the Tesa-/Tape-Test (ASTM F2252-3, 2003) (EN ISO 2409, 2013).

The strip has undergone significant elongation (356 % over the period of the test) resulting in a reduced optical density. No defects like cracks or delamination caused by this test were found for any of the H samples, neither for H 318105 nor for H 560110 print system.

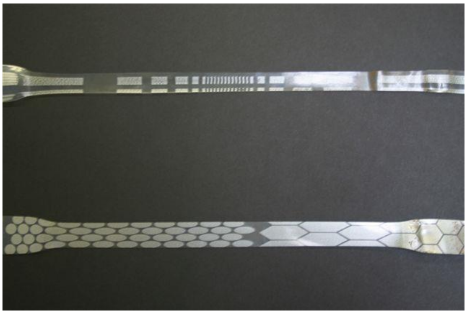

Figure 8: Two strips of ETFE after long-term corrosion test stressed with constant load of 17 N/mm² at 80° C and 100 % humidity

Comparison with results from former ink showed significantly enhanced stability for the new H lacquer.

3.2 Hysteresis Tests

When installed in roof and façade cladding systems ETFE foils undergo frequent exposure to wind loads imposed by a wide range of wind speeds. Gusting wind speeds are typically 40 % higher than basic wind speeds. For the purpose of analysis wind gusts are generally considered to last for about 3 seconds (Eaddy and Melbourne, 2004). Texlon ® ETFE cushion systems are stabilised by an inner air pressure of approximately 250 Pa inducing a permanent pre-stress load of approximately 4 N/mm² to the outermost foils. Single layer systems are pre-stressed to approximately 6 N/mm². In order to simulate these load conditions a hysteresis test procedure using a mono-axial tensile test machine has been designed. In order to simulate extreme wind conditions the load cycling was determined to be between 9 N/mm² and 18 N/mm². The strain-stress diagram is shown in Figure 12. The diagram also illustrates the ageing performance of the ETFE material itself. Cyclic loads will cause reduction of strain with increasing number of cycles even under 18 N/mm² loads. The ETFE foil becomes stiffer with mechanical ageing (Maywald C., and Mißfeld M., 2018)

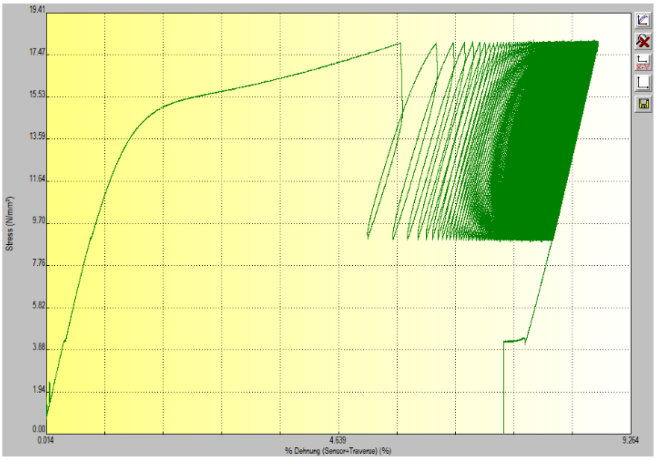

Figure 9: strain-stress diagram 250µm ETFE foil, 300 cycles; test for print stability

After the test strips with the coating under examination have been subjected to 300 load cycles, they are exposed to accelerated weathering tests according to standard norms (EN ISO 4892-2, 2013) and (EN ISO 4892-3, 2016). The load test of various coated samples from different printing companies gave evidence regarding long term stability of the coatings.

4 Summary

Over the last 28 years printing and coating technology on ETFE foils for architectural applications has improved significantly, especially reflectivity and optical density has been increased by more than a factor of 2. For that reason, the g-value of a standard 3-layer ETFE Texlon® cushion was decreased from 0.46 for the first printing generation to a value as low as 0.18 for the state-of-the-art system.

It should be mentioned that foils with embodied pigments introduced into the foil matrix prior to extrusion are also available from ETFE foil manufactures. These embodied pigments also contribute to the selective control of transmission and reflection. The use of coloured ETFE foils in combination with additional printing expands the potential for further solar control is and opens an even wider range for tuning the cladding systems according to local project related requirements. Beside printing and coloured ETFE foils there are approaches towards selective solar shading by metal film sputtering on ETFE foils. However, no solution is currently available to the construction market. This is mainly a consequence of the physical properties of ETFE foils, which are both permeable to water vapour promoting oxidation, and flexible causing micro cracks and delamination of the metallic film coatings.

In order to simulate ageing effects of coatings on ETFE foils new specific methodologies have been developed for laboratory based tests. These tests do not only provide evidence regarding the loss of adhesion of coating on ETFE foil systems resulting from cyclic stretching of the foils under environmental conditions but are essential for the assessment of the in-service ageing characteristics of the material itself. In contrast to most of the other materials used for the building cladding systems foils and membranes are constantly deflected by environmental loads which has a major impact on ageing behaviour and therefore has to be taken into consideration. Therefore, the current test procedures and methods as specified in the standards are not sufficient for quality control of textile membranes and foil treatment systems.

References

ASTM F2252-03 (2003), Standard Practice for Evaluating Ink or Coating Adhesion to Flexible Packaging Materials Using Tape, ASTM International, West Conshohocken, PA, 2003

Eaddy M., Melbourne W.H. (2004), MEL Consultants Pty Ltd Report 30C/02, '*Addendum C to MEL Consultants Report 30/02*, Wind Tunnel Measurements of Pressures on the Proposed Spencer Street Station Redevelopment, Melbourne'

EN ISO 2409:2013-06 (2013), Paints and varnishes - Cross-cut test

EN ISO 4892-2 (2013), Plastics - Methods of exposure to laboratory light sources - Part 2: Xenon-arc lamps

EN ISO 4892-3: 2016-10 (2016), Plastics - Methods of exposure to laboratory light sources – Part 3: Fluorescent UV lamps

HUECK FOLIEN (2010), Baumgartenberg, Austria

LeCuyer A. (2008), ETFE – Technology and Design, *Birkhäuser Verlag AG*, Basel, CH

Maywald C., and Mißfeld M. (2018), Zum Alterungsverhalten von ETFE-Konstruktionen, *Stahlbau 7/18, Wiley Press, Wilhelm Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG*, Berlin, Germany

Maywald C., and Riesser F. (2016), Sustainability – the art of modern architecture, in: *Procedia Engineering, Elsevier*, Vol. 155, pp. 238 – 248

Stranghöner N., Uhlemann J., Llorens J. (2015), CEN/TC 250/WG 5 *Membrane Structures Scientific and Policy Report - SaP-Report*

Urbán D., et.al. (2016), Acoustic comfort in atria covered by novel structural skins, in: *Procedia Engineering*, *Elsevier,* Vol. 155, pp. 361 – 368