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Mechanical properties of ETFE foils: Testing and modelling

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HIGHLIGHTS

- Review of most notable ETFE construction and research projects.
- Creep tests on ETFE foils; effects of stress, type, direction and thickness on the creep strain.
- Comparison between 24-h and 7-day creep responses.
- Tensile stress–strain responses of ETFE foils.
- Modelling of time-dependent behavior of ETFE.

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ABSTRACT

Poly(ethylene tetra fluoroethylene) or ETFE can be extruded into foils, and has been used for cladding and roof applications since the 1980s. ETFE is usually formed into internally pressurized cushions by inflating two or more layers of foil. Creep of ETFE increases with increased axial stress, and axial tensile stress often must be increased in the foils as a means of raising transverse load-carrying capacity. This paper presents results of tests on ETFE foils under tensile loading conditions. Test results of the research described herein consist of creep strain responses over time, and stress–strain responses. Modelling of the time-dependent material response is also included.

1. Introduction

Poly(ethylene tetrafluoroethylene) or ETFE, as it is commonly called, is a copolymer of ethylene and fluoroethylene. It is used for a range of applications including structural cladding, which is the focus of this paper. The material can be extruded into large thin sheets, referred to as foils or films, which can be used in single or multi-layer cladding applications. Films currently in production range in thickness from 50 μm to 300 μm. In single-layer applications the foils are stretched over a structural frame (usually steel) and used as a canopy in areas that do not experience high levels of loading. Multi-layer cladding is created by clamping and sealing two or more layers of foil together at the edges and inflating the space between the foils with air. These cladding systems are called cushions (Fig. 1). In all structural applications ETFE foils are subjected to tension (through pre-tensioning or inflation) in order to be able to carry transverse loads.

ETFE cushions are typically used in skylight and atria applications where glass would traditionally be used. However, this new material has several advantages over glass as noted by Cripps et al. [1], Tanno [2], Moritz [3], Hafner and Moritz [4], and Barthel et al. [5]. ETFE cushions are much lighter than glass panels, and therefore allow for a much lighter and thus less expensive support structure. ETFE allows a 90–97% transmission of visible light, whereas untreated glass only allows for about 81% [6]. It also allows more UV light to pass than glass – 85%, compared to only 58% for untreated double-glazed glass panels – making it preferable for plant growth conditions. The cushions are better insulators than glass panels, owing to the still air pockets contained between the layers of foil. The material is flexible; meaning that under dynamic loading it is less susceptible to failure than glass. In the event that an ETFE cushion does fail, the damage it causes will be minimal compared to a failed glass panel, due to its ductile

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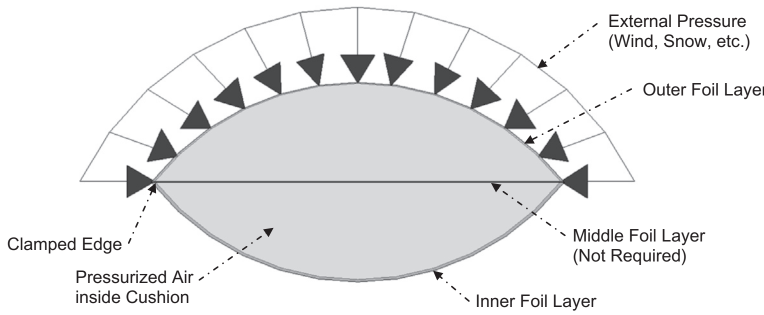

Fig. 1. Schematic ETFE Cushion.

mode of failure and its lightweight. ETFE is a recyclable material. Damaged foils can be added to virgin resin to be reprocessed into new material. The performance of ETFE under fire conditions is unique in that it shrinks away, allowing smoke and fire to be vented to the exterior; instead of melting and dripping onto building occupants, material fragments are swept up with the plume. The material is self-extinguishing, so fire will not spread across it.

Typically glass panels are limited to spans of 3.3 m by roughly 16 m (the length of a standard trailer). ETFE cushions, however, can have much larger spans. In their long direction, they are virtually unlimited in span, as films can be folded or rolled for transportation to site. In their short direction there are varying opinions on maximum spans. Tanno [2] suggests a maximum width of 3.5 m, as do Architekten Landrel (n.d.) [7], while Schöne [8] suggests 4 m as the largest practical span, and Moritz [9] recommends 4.5 m. In practice, cushions as large as 11 m diameter hexagons and 5 m by 17 m rhombuses have been constructed (LeCruyer [10]). Even larger spans can be achieved with the use of secondary support systems such as cable nets. Also, the fact that ETFE cushions have a lower self-weight than glass panels allows for the use of larger clear spans of supporting members.

Cushioned structures can be equipped with sensors that detect events such as heavy snowfall or high winds, and increase the pressure in the cushions accordingly. This allows for energy savings during times of lesser loading conditions. This is in contrast to conventional structures, which are set up at all times to withstand the maximum load, although they will likely only encounter it on rare occasions.

ETFE was first used in construction in 1982 as a replacement for failed fluorinated ethylene propylene (FEP) film on the roof of the Burger's Zoo Mangrove Hall in Arnhem, The Netherlands [10]. This structure remains in service today. Since the introduction of ETFE as a construction material, its popularity has grown rapidly, with usage spreading to nearly every continent. The Allianz Arena in Munich Germany, constructed in 2005, has a façade clad with 66,500 m^2 of ETFE cushions that are fitted with fluorescent lights allowing them to change from white to blue to red to suit the color of the home team using the stadium (Fig. 2). The area directly above the pitch is open, allowing rainwater and sunlight onto the field. The wall cushions are printed with a variable dot pattern, which is densest at the base, reducing the intensity of the lighting at the eye level of drivers and pedestrians. The roof cushions are clear, allowing sunlight onto the pitch even when the sun is not directly overhead [10]. Since its construction, the Allianz Arena has provided examples of potential material performance issues that can arise with ETFE cushions. The large, low slope roof was initially unable to deal with heavy snow loads, leading to the failure of some cushions. To accommodate the heavy loads, inflation pressure can now be increased four times, from 200 Pa to 800 Pa.

Another interesting example is the Eden Project, which consists of a series of ETFE-clad steel geodesic domes, completed in 2001

Fig. 2. Allianz Arena.

(Fig. 3). These domes contain simulated Mediterranean and tropical climates to support the growth of plant life native to those climates (Arup, n.d.) [11]. The Eden Project is the world's largest self-supported transparent envelope. The domes are made of 667 tonnes of steelwork and contain 536 tonnes of air (Vector Foiltec) [12] The largest dome is 110 m in diameter at the base and 45 m high on the inside. The ETFE cushions are mostly hexagonal and up to 11 m in diameter (SKM, 2009) [13]. Of the 831 ETFE panels on the domes, 230 are "intelligently controlled", meaning that their inflation levels are automatically adjusted from 250 Pa to 400 Pa, according to varying climate conditions, and are operable to allow natural ventilation [12].

Other notable examples of the application of ETFE in construction include China's National Aquatics Centre in Beijing, commonly

Fig. 3. Eden Project.

known as the Water Cube, constructed in 2008 for the summer Olympic Games, the DomAquarée atrium roof in Berlin, built in 2003, the Kingsdale School courtyard roof, built in 2009 in London, the Khan Shatyr multi-use entertainment centre, completed in 2010 in Astana, Kazakhstan, and the clearstory of the new BC Place Stadium roof in Vancouver, British Columbia, Canada, constructed in 2012.

Application of ETFE for structures requires that the foils are continuously under tension. Higher tensile stresses in the foils allow higher transverse load-carrying capacities of cushions. ETFE, like all polymers, is prone to large creep deformations when subjected to constant stress. Creep increases with increased axial stress, and axial tensile stress often must be increased in the foils as a means of raising transverse load-carrying capacity. Depending on the stress level, permanent plastic deformation of the foil can result, even after the load is removed. It is therefore important to have a good understanding on the properties of ETFE foil under creep loading. The research results presented herein examine the mechanical response of ETFE foils under tensile loads. Creep strain responses over time, as well as short-term stress–strain responses, are presented and discussed. Models for the time-dependent material response are also included.

2. Chemical and mechanical properties of ETFE

ETFE is a copolymer of ethylene and tetrafluoroethylene. The ETFE polymer chain contains repeating units of alternating ethylene and tetrafluoroethylene monomers, shown in Fig. 4.

Academic and industrial literature contains many references to the mechanical properties of ETFE. The tensile strength of ETFE is estimated by various sources as ranging from 44 MPa to 53 MPa; yield strength is between 20 and 30 MPa. The elongation at break varies from 150% to 600%. Such a large range is due to the fact that elongation depends on a number of factors, including specimen size, shape, orientation, and loading speed. Tear strength is in the range of 400 and 440 MPa. Tensile modulus of elasticity (E) ranges from 300 to 1000 MPa, whereas melt temperatures are within 265–278 °C. These rather large ranges are indicative of the variability in properties of ETFE foils available on the market.

Tensile tests have been performed by numerous researchers and select results are discussed below. Ansell [14] showed a decline in tensile strength as temperature increased. He exposed samples to UV radiation before testing, and found that this did not affect strength. He also tested production-fresh samples and found that yield stress, corresponding strain, and modulus, were approximately 13.1 MPa, 2.9%, and 460 MPa, respectively.

Researchers at DSET Laboratories in Phoenix performed long-term tensile tests on ETFE exposed to the Arizona environment over a period of ten years. The specimens were tested after one, two, three, five, seven, and ten years. The exposure to high temperatures and solar radiation appeared to have little influence on the tensile properties of the foil [3].

Barthel et al. [5] performed uniaxial and biaxial stress–strain tests on an ETFE foil. They found the material to have a uniaxial yield strength of 39.1 MPa in the longitudinal direction, and 40.3 MPa in the transverse direction, and an average elongation at break of 340%. The biaxial tests showed nearly isotropic behavior, with a Poisson's Ratio of 0.45.

DeVries [15] performed uniaxial and biaxial tensile tests. He found the elastic modulus to be 1427 MPa in the longitudinal direction, 1305 MPa in the transverse direction, and 1285 MPa in the diagonal direction. A portion of the uniaxial tests performed on welded samples showed that while the welded samples failed at lower stresses than plain samples, the material yielded before the welds failed. The biaxial tests showed that stress in one direction is not noticeably affected by stress in the other, indicating that uniaxial tests should provide accurate representations of biaxial behavior.

Moritz [3] analyzed uniaxial tensile test data and found the end of the linear-elastic region to be at 16.7 MPa, the start of plastic deformation at 24.8 MPa, the average breaking stress of welded samples at 36.3 MPa, and the average breaking stress of plain samples at 57.3 MPa. The data also showed break stresses decreased somewhat as foil thickness increased.

Creep tests were also performed by several researchers. DuPont published creep results of its Tefzel ETFE product (Dupont, n.d.) [16]. They reported a strain of 0.2–0.3% for exposure to a 6.9 MPa stress over a period of 24 h. They also reported flexural creep results for injection-moulded bars of different ETFE grades at different temperatures and different stress levels.

Ansell [14] performed creep tests at 5 MPa and temperatures of 40, 60 and 100 °C. The tests done at 40 °C lasted for 46 days (1104 h), the tests done at 60 °C lasted 19 days (456 h), and the tests done at 100 °C lasted for only four hours due to excessive flow in the material. At 40 °C and 100% relative humidity, 100 μm film strained 0.6% in the longitudinal direction and 2.8% in the transverse direction by the end of the test, while 300 μm film strained 1.8% in the longitudinal direction and 2.6% in the transverse direction. At 60 °C and with dry air, 100 μm film strained 17.6% in the longitudinal direction and 37.2% in the transverse direction by the end of the test, while 300 μm film strained 20.6% in the longitudinal direction and 32.1% in the transverse direction. At 100 °C and with dry air, 100 μm film strained 13.2% in the longitudinal direction and 11.6% in the transverse direction after two hours, while 300 μm film strained 39.6% in the longitudinal direction and 31.2% in the transverse direction.

Barthel et al. [5] performed creep tests on 225 μm ETFE film at 23 °C and at 5.3, 8.0 and 10.7 MPa stress levels, which were maintained for 1000 h, then discharged and the strain recovery was recorded over a period of 96 h [3]. They found that the creep strain approached a constant value with time. The increase in strain from one stress level to the next was not proportional to the increase in stress. After the load was removed some of the elastic strain recovered instantaneously, but some exhibited a delayed recovery. At a stress level of about 40% of the elastic limit, all strain was recoverable with time.

Liu et al. [17] performed creep tests at stress levels of 3, 6 and 9 MPa and temperatures of 25, 40 and 60 °C for 24 h. The creep strain of the specimen tested at 3 MPa and 25 °C was only 0.49%. The creep strain of the specimen tested at 9 MPa and 60 °C was 13.21%.

Finally, Winkler [18] performed 1000 h biaxial creep tests at 4, 8 and 14 MPa stresses. He developed logarithmic functions to fit his creep data and used them to predict long term behavior. Based on his models, a 200 μm film subjected to 4 MPa of stress would experience 0.3% creep strain after 100 h and 0.6% creep strain after 25 years. After 1000 h at 8 MPa, the predicted elongation was

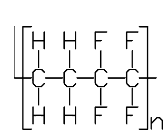

Fig. 4. Poly(ethylene tetrafluoroethylene) chain schematic. C – carbon, H – hydrogen, F – fluoride.

about 1%, and after 25 years about 1.9%. After 1000 h at 14 MPa, the model predicted a creep strain of about 3.7%, whereas after 25 years the creep strain prediction became about 7.4%.

3. Test results

The tests described herein involved a series of 24-h uniaxial creep tests, 7-day creep tests and stress–strain tests on ETFE films. Three brands of film with varying thicknesses were tested. The three brands of ETFE (designated as A, B and C for this study) and their thicknesses are shown in Table 1. The mechanical properties of the films provided by the manufacturers are shown in Table 2. Films A and C were made from the same resin, and therefore have the same resin properties. However, they were extruded by different film manufacturers, so the finished products differ somewhat.

The 24 h creep tests were done on all films at stress levels of 2, 8, 12 and 14 MPa. The stress levels used in this testing were determined based on an estimate of the range of expected stresses of typical ETFE cushions in service [19]. All films were tested in both the longitudinal (the direction of extrusion) and transverse directions. A minimum of two replications were done on each film type, at each stress level and in each direction. The specimens were cut into 50 mm wide by 200 mm long strips to accommodate a 124 mm gauge length. The films were held in place during testing with MTS 100 N Vise-Action Grips. The uniaxial creep tests were performed by attaching a specimen in the top grip and tightening the gripping mechanism. The bottom of the specimen was then placed loosely through the bottom grip and pulled taut from the bottom. The bottom grip was then tightened as well to hold the specimen securely in place. Permanent marks were placed on the specimen just on the inside of the grips to show whether any slippage was occurring within the grips during the test. The placement of the specimen in the test frame and the grips is shown in Fig. 5. The test frame was placed in an insulated enclosure with a heater and thermostat maintaining a constant temperature of 23 °C.

An extensometer was attached to the grips by means of aluminum bars, as shown in Fig. 5. The extensometer could not be attached directly to the specimen because the foils were not sufficiently rigid, but an effort was made to place it as close as possible to the tested specimens.

The specimens were loaded by placing a mass on a platform connected to the grips by a lever arm. The load was placed all at once in order to give an accurate recording of the initial elastic response of the material. The load was left on the specimen for a period of 24 h, during which the extensometer recorded the grip extension at the following time intervals: every 0.25 s for the first minute, every second for the rest of the first hour, every 30 s until the end of the fourth hour, and every 60 s for the remainder of the test.

The long-term (seven day) creep tests were done on film C1 in the longitudinal direction at 2, 8 and 12 MPa. The tests were performed using the same equipment and testing procedure as for the 24-h tests.

Table 1
Summary of testing done on foils.

Foil	Thickness (μm)	Tests[a]		
		24 h creep at 2, 8, 12, 14 MPa	7 day creep at 2, 8, 12 MPa	Tensile tests
A	50	Yes	No	Yes
B	50	Yes	No	Yes
C1	150	Yes	Yes (longitudinal only)	Yes
C2	300	Yes	No	Yes

[a] Tests were done in longitudinal and transverse direction.

Tensile tests were done on all films in both longitudinal and transverse directions. Testing was done at room temperature according to ASTM D882-09 *Standard Test Method for Tensile Properties of Thin Plastic Sheeting* [20]. Five specimens of each film were tested in each direction. An Instron 4465 tensile testing frame was used for all tests. The MTS grips used for the creep tests were used for the tensile tests as well. The specimens were cut to a width of 25 mm and a length of 150 mm to accommodate a gauge length (initial grip separation) of 50 mm. The grips were separated at a rate of 500 mm/min, while their separation distance and the corresponding applied load were recorded at regular intervals. The specimens were tested until failure.

3.1. 24-h creep tests

The strain versus time results of the 24-h creep tests on all films are displayed in Figs. 6–9. Figs. 6–9(a) show the results from the tests done on the longitudinal direction of the films and Figs. 6–9(b) show the results for the transverse direction. Results from two test replications at each stress level are shown.

The creep curves in Figs. 6 through 9 show good reproducibility of results for the two replicates at each stress level. Some creep curve replicates (at the higher stress levels of 12 and 14 MPa) have similar shapes but different values for the elastic portion of the strain (at time 0). It is possible that a small slippage occurred between the specimen and the grips during the initial loading of the specimen, which was not easily visible on the tested foil, but significant enough to appear in the results.

Table 3 summarizes the results from all of the 24-h creep tests. Only the average values from the replicated trials are given.

3.2. Seven-day creep tests

The results of the seven-day creep tests on film C1 are shown in Fig. 10. Also shown in Fig. 10 are the results of the corresponding 24-h tests on film C1 at each of the three stress levels.

The initial 24 h of the 2 MPa and 8 MPa seven-day tests follow the results of the 24-h tests very closely. The creep measured in the 24-h test at 14 MPa, however, is significantly higher than that measured in the first 24 h of the seven-day test. This could again be due to initial slippage of the 24-h specimen in the grips. The

Table 2
Mechanical properties of tested films (from manufacturers).

Film brand	Tensile strength (MPa)[a]	Yield stress (MPa)[a]	Elongation at break (%)	Melt temperature (°C)	Maximum service temperature (°C)	Density (g/cm^3)	Purpose of film
A	46	22	425	267	150	–	Structural
B	41	–	250 (Min)	250–270	–	1.73–1.77	General
C	46	22	425	267	150	–	Structural

[a] At 23 °C, except for tensile strength for film B reported at 25 °C.

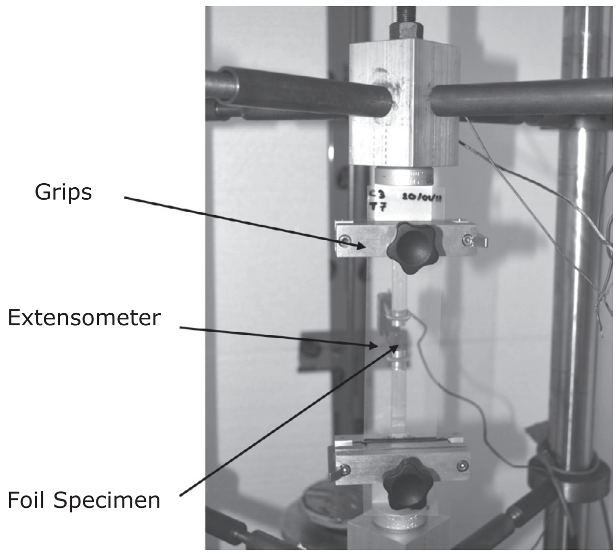

Fig. 5. ETFE specimen in grips.

specimens continued to creep until the seven-day point at all stress levels, rather than reaching a strain plateau before the completion of the tests, but the rate of strain increase did slow down over time.

3.3. Tensile tests

Figs. 11–14 show the stress–strain curves resulting from the tensile tests performed on the films. Tensile tests were done in both directions of the films at a rate of 500 mm/minute until failure.

Table 4 summarizes the average values of yield stress, failure stress and strain for the four films in both directions, and compares them to the values provided by the manufacturers. The tested yield stresses were taken as the values of the initial peaks of the curves.

In nearly every case the measured values were at least as great as the values of the manufacturers. The only cases where the experimental data were lower were the break strain of film A in the longitudinal direction, and the break stress of film C2 in both directions. However, these values were close enough to state that the mechanical properties provided by the manufactures seemed to be reasonable design values for the films.

4. Discussion of test results

From the results in Figs. 6–9, and for all of the films, creep strains increased with stress and time. The curves also became smoother as stress levels increased. This is primarily because the extensometer used for measuring displacements is designed for extensions of up to 12 mm. The lower stresses, especially 2 MPa, produced deformations as low as 0.2 mm over the total 24-h period, meaning that the measurements were at the extreme low end of the extensometer's range, so noise affected the readings.

4.1. Effect of film direction

The films were tested in both the longitudinal and transverse film directions in all of the 24-h creep tests (see Figs. 6–9) and tensile tests (see Figs. 11–14). In nearly every case, more creep strain was observed in the transverse direction than the longitudinal direction, indicating higher material stiffness and less creep deformations in the longitudinal direction. Also, the tensile strength was higher for the longitudinal direction. The least difference was observed for foils C1 and C2 (which are the same ETFE polymer extruded in two different thicknesses), as seen in Figs. 13 and 14.

Similar difference between the tensile behavior of ETFE in the two directions has been observed by Ansell [14] and the DSET Laboratories [3]. Conversely, Galliot and Luchsinger [21] found that

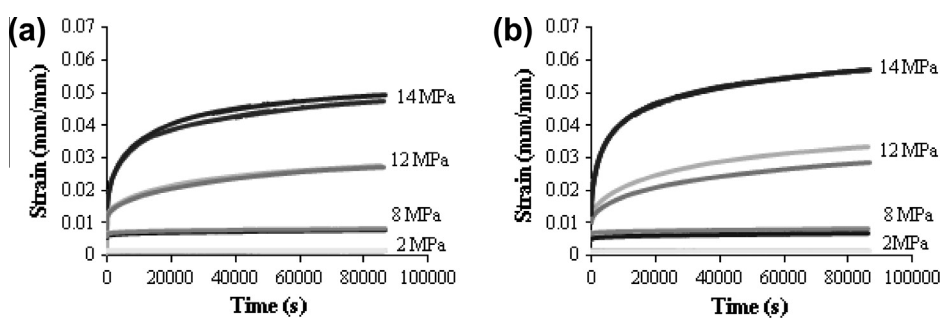

Fig. 6. Strain vs. time results for tests on film A in (a) the longitudinal direction and (b) the transverse direction.

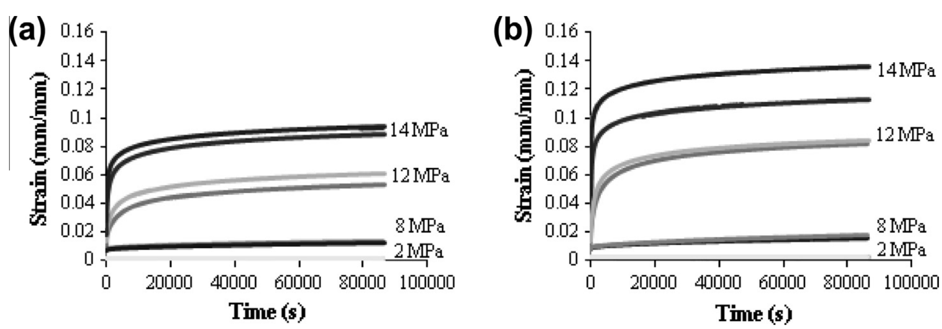

Fig. 7. Strain vs. time results for tests on film B in (a) the longitudinal direction and (b) the transverse direction.

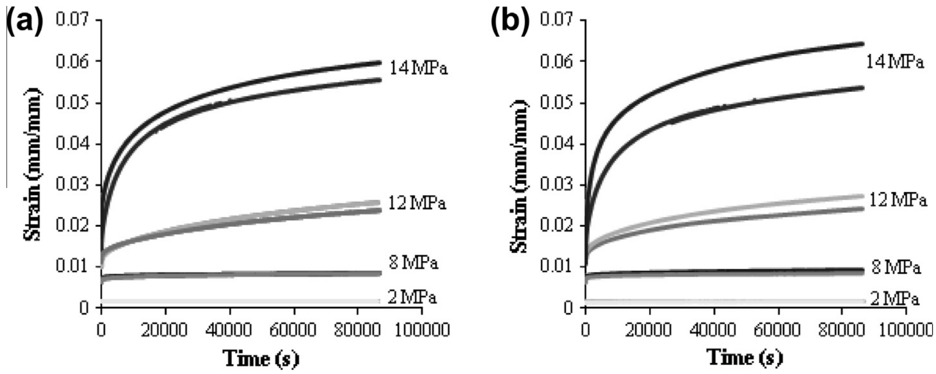

Fig. 8. Strain vs. time results for tests on film C1 in (a) the longitudinal direction and (b) the transverse direction.

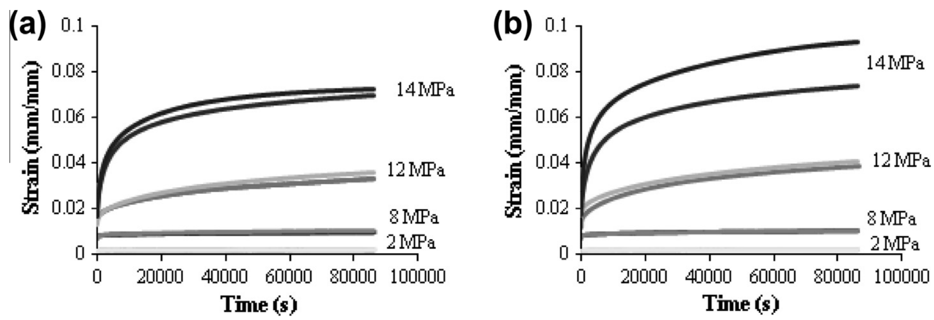

Fig. 9. Strain vs. time results for tests on film C2 in (a) the longitudinal direction and (b) the transverse direction.

uniaxial tensile tests showed a slightly higher yield and ultimate strength for the transverse direction.

The extrusion process by which ETFE film is produced could be responsible for this anisotropic behavior, as it causes the molecules to be aligned and possibly stretched in the direction of extrusion. Since molecular bonds along the polymer chains are much stronger than inter-chain bonds (Van der Waal bonds), any direction parallel to most of the chains should be stronger than other directions. This could also be due to the crystal structure of the molecule, i.e., the degree of crystallinity, the location of the crystalline regions and the orientation of the crystals, or to thermally activated relaxation processes that occur during film processing [22].

4.2. Effect of film thickness

Having two thicknesses of film C (C1 – 150 μm and C2 – 300 μm) allows for an analysis of the effects of film thickness on creep strain, stiffness and strength. In all cases, C2 showed more creep strain in the 24-h tests than film C1 (see Figs. 8 vs 9).

Differences in tensile properties of different thicknesses of the same film have been also observed by other researchers. Ansell [14] found that 100 μm bent film samples had higher average tear strength than 300 μm bent film samples of the same variety. Also, Moritz [3] observed a slightly higher ultimate tensile strength for thinner film samples. However, break strain increased with

Table 3
Summary of results from all 24-h creep tests.

Film	Stress (MPa)	Average strain for all trials (%)					
		Initial at $t = 0$		Total at $t = 24$ h		Creep at $t = 24$ h (Total – Initial)	
		Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
A	2	0.125	0.133	0.144	0.166	0.020	0.033
	8	0.574	0.639	0.822	0.879	0.248	0.240
	12	0.930	1.024	2.737	3.090	1.807	2.066
	14	1.248	1.346	4.833	5.717	3.586	4.371
B	2	0.117	0.186	0.146	0.217	0.029	0.031
	8	0.684	0.810	1.293	1.691	0.610	0.881
	12	1.103	1.249	5.688	8.330	4.586	7.081
	14	2.324	2.073	9.142	12.428	6.818	10.355
C1	2	0.155	0.147	0.170	0.165	0.015	0.018
	8	0.642	0.664	0.845	0.899	0.203	0.235
	12	1.063	1.181	2.481	2.582	1.418	1.401
	14	1.581	1.270	5.754	5.908	4.172	4.638
C2	2	0.163	0.170	0.183	0.197	0.021	0.027
	8	0.737	0.768	1.019	1.066	0.282	0.298
	12	1.345	1.442	3.469	3.972	2.124	2.530
	14	1.577	1.910	7.099	8.348	5.522	6.437

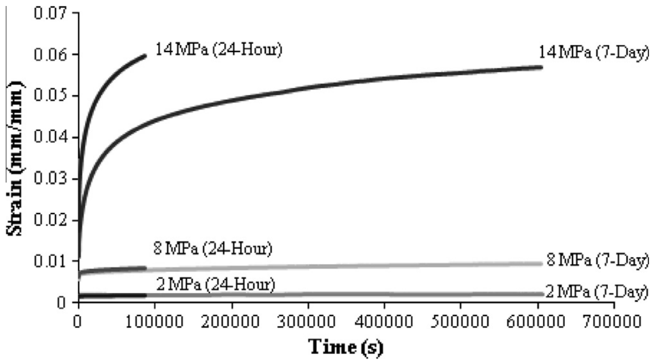

Fig. 10. Results of 7-day creep tests on film C1 contrasted with results of 24-h tests at same stress levels.

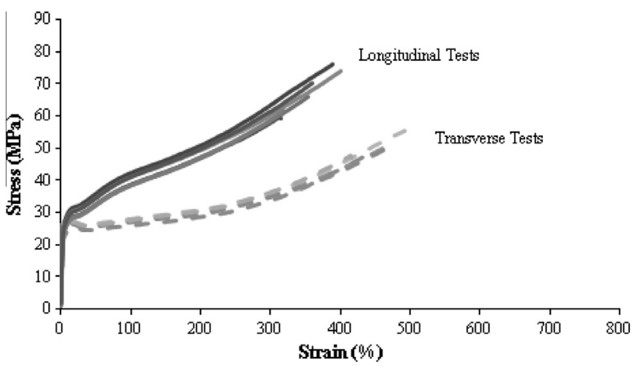

Fig. 11. Tensile test results for Film A.

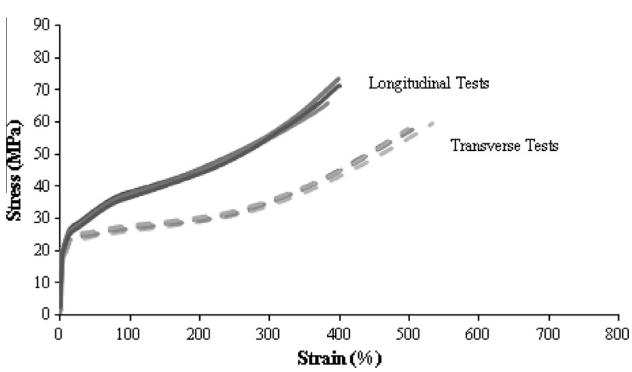

Fig. 12. Tensile test results for Film B.

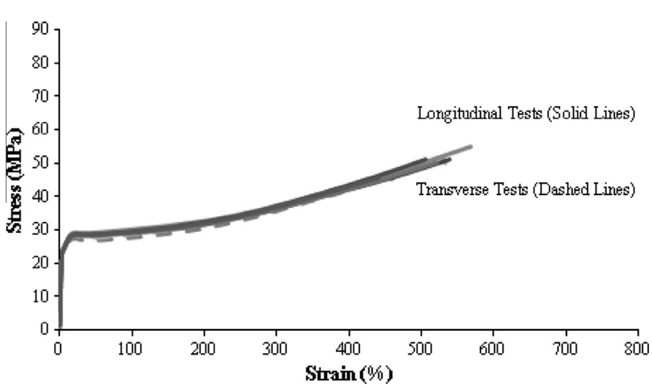

Fig. 13. Tensile test results for Film C1.

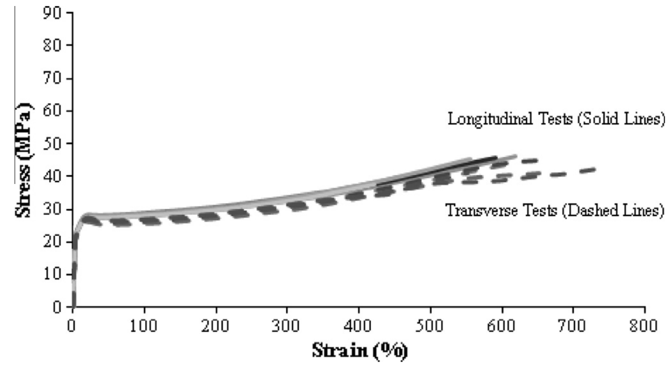

Fig. 14. Tensile test results for Film C2.

thickness. This observation can be the result of the manufacturing process, which favors chain alignment for thinner foils.

4.3. Effect of film type

Three types of film were tested, referred to in this paper as A, B and C. Films A and C are structural-grade films extruded by different manufacturers from the same resin. Film B is a general-purpose film. Mechanical properties supplied by the resin manufacturers are given in Table 2. In general, films A and C displayed similar levels of creep, as would be expected given that they are manufactured from the same resin. Film B generally displayed higher levels of creep than the other films. Fig. 15 shows, as an example, a representative 8 MPa longitudinal creep strain curve for each film.

The creep curves for film A, film C1 and film C2 have very similar shapes. The curves for A and C1 are nearly identical in magnitude; the creep curve for C2 shows higher strains. Possible reasons for this difference are related to the much higher thickness of film C2. The creep curve for film B, on the other hand, has an entirely different shape than the other three and achieves a higher 24-h value of strain. The curve is much steeper than the others, indicating that the creep is continuing at a higher rate, and will likely not level off as quickly as the others. The long-term creep and plastic strains in film B would likely be much higher than in the structural films.

The molecular properties of the resins used to manufacture the films were not provided by the manufacturers. These properties should provide some insight into what influences lower creep strains in structural films. More research focusing on molecular properties and linking them with mechanical behavior is needed to better understand long-term strength and safety of structural ETFE foils.

4.4. Effect of temperature

Although the effects of temperature on creep were not explicitly investigated in this study, an incident during the seven-day creep test on film C1 at 2 MPa provided interesting results that showed the effect of temperature on creep behavior of ETFE. The heater in the insulated enclosure failed to operate consistently when switched on by the controller, resulting in the temperature fluctuating by several degrees over the course of the test. The results of the creep test and the temperature fluctuations are shown in Fig. 16. The temperature is scaled down by a factor of 10,000 in order for both curves to appear on the same plot.

It is interesting to observe that the strain and temperature profiles are similar. At the low stress level of 2 MPa, small temperature fluctuations have a significant impact on strain. Since real

Table 4
Summary of tensile test data, with comparison to manufacturer data.

	Experimental data			Manufacturer data		
	Break		Yield	Break		Yield
	Strain (%)	Stress (MPa)	Stress (MPa)	Strain (%)	Stress (MPa)	Stress (MPa)
A-L	363.93	69.69	28.02	425	46	22
A-T	455.78	50.27	26.60	425	46	22
B-L	388.12	69.73	25.92	250	41	–
B-T	501.67	57.60	24.44	250	41	–
C1-L	515.34	50.64	28.73	425	46	22
C1-T	478.54	47.94	28.46	425	46	22
C2-L	541.67	43.60	27.84	425	46	22
C2-T	641.05	42.71	26.75	425	46	22

L = Longitudinal; T = Transverse.

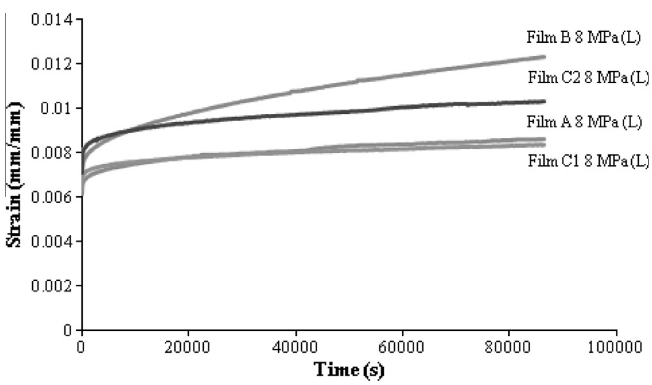

Fig. 15. Creep curves for all film types tested at 8 MPa in the longitudinal direction.

structural applications of ETFE film, such as cushions in buildings, can involve large temperature fluctuations from day to night or from one day to the next, future research should consider temperature effects on creep strain, especially at lower stress levels used in practical applications, where temperature can have a very significant effect on creep strain; possibly more significant than that of stress.

5. Modelling of the observed material response

Practical utilization of polymeric materials in structures requires tools for rational and effective structural analysis. Constitutive modelling, which can be used for structural analysis procedures (e.g., finite element analysis) is required and in this section two such possible modelling approaches are presented. Modelling of the ETFE foils is done using a viscoelastic multi-Kelvin and a viscoplastic power law model. Applicability of linear and nonlinear time dependent modelling is also discussed.

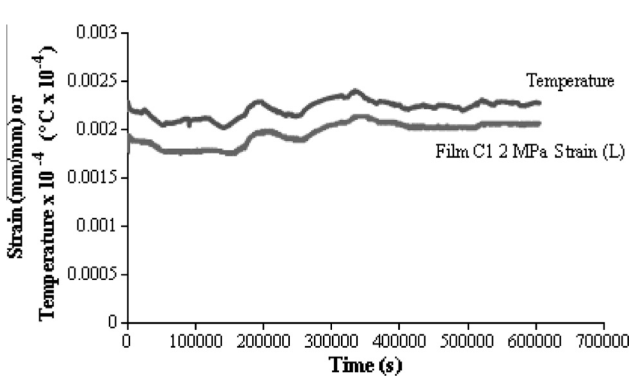

Fig. 16. Seven-day strain and (scaled) temperature profiles for film C1 tested at 2 MPa in the longitudinal direction.

The constitutive modelling procedures used herein follow the formulation presented by Liu et al. [23]. A standard modelling approach for time-dependent material properties, ignoring aging effects, can take on the integral form:

$$\varepsilon(t) = \int_0^t \psi(t-\tau)\dot{\sigma}(\tau)d\tau \tag{1}$$

where ψ is the creep compliance, ε strain, σ stress and t represents time (τ here represents the integrand).

For a constant stress, the strain is:

$$\varepsilon(t) = \sigma_c\psi(t) \tag{2}$$

The material modelling task is to find a function $\psi(t)$ that best fits test results. The 24-h creep tests done as part of this work were used to find creep compliances. The strain versus time curves shown in Figs. 6–9 were first converted into compliance versus time curves by dividing the strain curves by the corresponding constant stress values. Then the appropriate equations for creep compliance presented below were fitted to the experimental data. Materials are considered to be linear when the creep compliance, $\psi(t) = \varepsilon(t)/\sigma_c$, is independent of stress, meaning that it can be described by the same mathematical expression for all stress levels. In practice, most materials, including ETFE, are nonlinear and the compliance is a function of stress, hence a different curve is required to describe it at each stress level.

Viscoelastic materials can be modelled by combinations of spring and dashpot elements, where the springs represent the elastic response of the material and the dashpots represent the viscous response [24,25]. Arranging a spring plus N Kelvin elements in series yields the following equation for creep compliance:

$$\psi(t) = 1/E_0 + \sum_{i=1}^{N} 1/E_i[1-\exp(-t/\tau_i)] \tag{3}$$

where E_0 is the elastic modulus of the material, determined from the initial linear portion of the creep curve, and t represents the time of loading. Each Kelvin element in this model has its own relaxation time τ_i and spring stiffness E_i. The E_i values correspond to the elastic moduli of the springs in each of the elements, and the relaxation times are equivalent to η_i/E_i, where η_i is the viscosity of each dashpot element [25].

In the approach adopted here, the relaxation times are pre-selected for the model such that the entire time spectrum of the test is well represented. Pre-selection of the relaxation times allows for the use of linear least squares fitting for finding the material moduli E_i. A four-element Kelvin chain model was selected and the relaxation times chosen were 20 s, 400 s, 8000 s

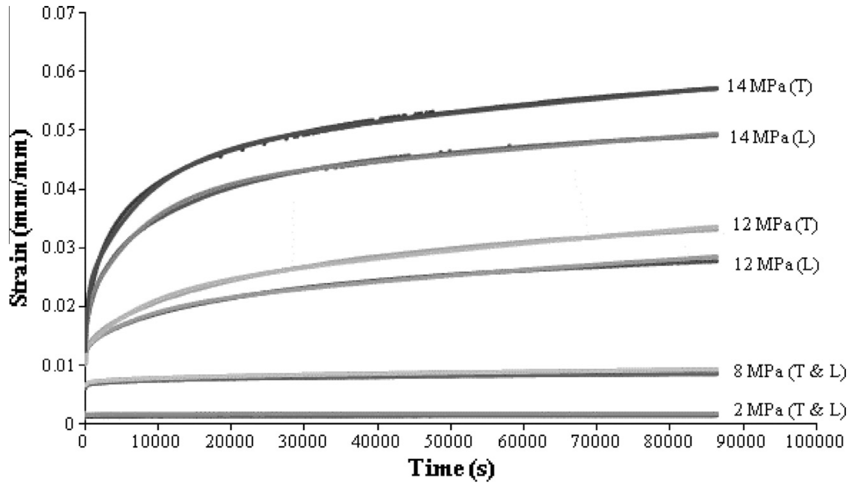

Fig. 17. Measured data and fitted viscoelastic curves for all 24-h creep tests on film A.

and 160,000 s, or $\tau_i = 20^i$. E_0 was evaluated directly from the elastic response portion of the data curves and the E_i values were found using linear least-squares, in terms of their inverses, $x_i = 1/E_i$, as suggested by Liu [26].

Fig. 17 shows an example of the fitted viscoelastic models for strain along with the measured strain data for film A tested at all stresses. It is difficult to distinguish the measured curves from the fitted ones as the models provide a very close fit to the data. Similar curve fittings were done for the creep curves of the other ETFE brands, and good data representation was also shown by these models.

Another approach to find the creep compliance is to assume it follows a power function. This approach is often referred to as viscoplastic modelling as the creep strain does not approach an asymptotic constant value [23]. It results in the following expression for the creep compliance:

$$\psi(t) = 1/E_0 + C_0 t^{C_1} \quad (4)$$

where C_0 and C_1 are the material constants determined from the creep curves using linear least-squares.

Fig. 18 shows the fitted viscoplastic power law models for strain along with the measured strain data for film A tested at all stresses. At the lower stress levels the fitted curves provide a good match to the experimental data, but the 14 MPa models diverge from the measured results. Viscoplastic models for the other ETFE brands provided similar results. Generally, the power law viscoplastic modelling with only two material constants is less accurate than the multi-Kelvin modelling. Curve fitting of the power law model for highly nonlinear creep curves at higher stresses results in inaccurate theoretical curves.

Several issues related to material modelling are important to note. The type of modelling adopted for the representation of the creep compliance determines the ability of the model to represent the long term time-dependent behavior; the multi-Kelvin model converges with time to a constant value of strain (at time $t \gg \tau_{max}$, the strain remains constant and does not increase with time), but the power law model does not converge to a constant strain, meaning the creep modelled by this type of equation does not reach a limit with time. Behavior of most thermoplastic polymers differs depending on the stress level; at lower stresses, creep strains stop increasing with time, but at higher stresses the creep process does not stop. Adopting a proper modelling formulation is then crucial for realistic predictions of long-term strains.

It should also be noted that for each stress level in Figs. 17 and 18 different material constants had to be determined due to the nonlinearity of the behavior of the material. Modelling at stress levels different from the ones used for model development (in this case modelling was done for 2, 8, 12 and 14 MPa stresses) can be done using linear interpolation of material functions between stresses as outlined by Liu et al. [23] or by adopting nonlinear

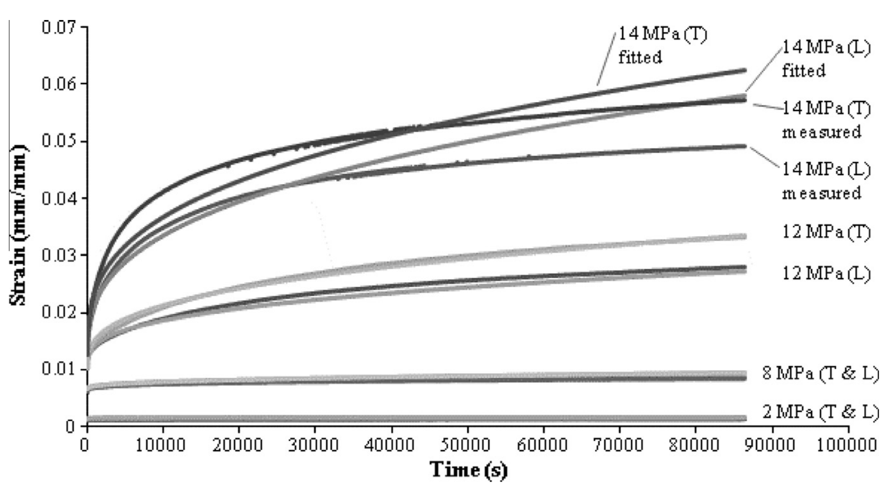

Fig. 18. Measured data and fitted viscoplastic curves for all 24-h creep tests on film A.

functions for material parameters as outlined by Sepiani et al. [27]. Modelling behavior under varying load histories can be done using a modified superposition principle, also presented by Liu et al. [23] and Sepiani et al. [27].

6. Conclusions

This paper presents an experimental investigation into the mechanical behavior of ETFE foils. Testing included creep tensile tests at different stress levels and for different time frames, and tensile stress–strain tests. Experimental work was followed by one dimensional creep modelling using multi-Kelvin and power law models.

ETFE films exhibit short term creep under levels of stress expected in structural applications. The amount of creep strain exhibited by the foils increases with stress level. At 2 MPa, very little creep strain, in the range of 0.015–0.033%, occurs in 24 h. However, at 14 MPa, 24-h creep strains reach values of 3.6–10.4%, an increase of over 100 times for only seven times the stress.

Differences were noted between the responses of films tested in the longitudinal and transverse directions. In general, films tested in the transverse direction experienced higher elastic and creep strains. The extrusion process of the films, together with the molecular structure of ETFE, could be responsible for this behavior.

The different types of film also showed differences in creep behavior. At the same stress levels, structural films A and C had smaller creep strains than the general purpose film B. The rate at which creep strains increased was less for the structural films A and C than for film B.

Temperature effects were observed during the seven-day 2 MPa creep test on film C1. The measured strain fluctuated almost identically to the temperature fluctuations.

Constitutive models were developed to represent the observed creep behavior. Nonlinear viscoelastic and viscoplastic models were developed for each creep test. For the 24-h tests the viscoelastic models provided a very close representation of the data in all cases. The viscoplastic models provided a good representation at low stress levels, but often deviated from the results at higher stress levels.

Tensile tests were also done on the ETFE film. In general, the films yielded and failed at higher stresses in the longitudinal direction than the transverse direction, but were more ductile in the transverse direction. Average yield stresses for all the films ranged from 24 to 29 MPa, and average failure stresses ranged from 42 to 70 MPa.

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