LONG-TERM BEHAVIOR OF ETFE FILMS - 100,000-HOUR CREEP TEST WITH SUBSEQUENT RECOVERY

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Abstract: The contribution evaluates the uniaxial creep and recovery behavior of an ETFE film product using long-term laboratory tests. Samples were installed in a long-term test rig in 2010 and subjected to constant loading at various uniaxial stress states (6, 9, and 12 MPa) for more than 100,000 hours, with strains measured. After 109,705 hours, the loads were removed. Recovery was then measured over 14,400 hours, indicating that no further recovery was expected. Finally, the samples underwent short-term uniaxial tensile tests and the results were compared with those of unloaded samples from the same material batch from 2010. The analysis provides important insights into the long-term behavior of ETFE films under continuous loading.

1 INTRODUCTION

ETFE films, used as prestressed, lightweight, and transparent or translucent facade and roof constructions, withstand high wind and snow loads over a wide temperature range. Tests on removed ETFE films show no significant changes in their optical and mechanical properties even after extended periods of use [1], [20], [21]. To demonstrate their durability and load-bearing capacity, the long-term mechanical behavior of the film must be known as precisely as possible. This is particularly true for single-layer, mechanically prestressed constructions. The following presents the execution and results of long-term laboratory tests over more than 100,000 hours on the commonly used ETFE film (NOWOFLON ET6235Z, 250 µm, clear). The aim of the long-term investigation was to obtain data for implementation in FE simulations in order to model the time- and load-dependent mechanical behavior computationally as accurately as possible and to derive an upper application limit under uniaxial prestressing. The comparison of the results of uniaxial short-term tensile tests before and after long-term loading should provide information on whether and to what extent the mechanical properties of the film have changed.

2 BASICS

2.1 MATERIAL (PRODUCT) AND LOAD

The samples examined came from a batch of material used for an approximately 9,000 square meter ETFE foil cushion roof in Munich. The project was completed in 2011. The ETFE foils are still intact today. For building authority approval (ZiE) of the foil cushions, long-term tests of the foil material over 1,000 hours were carried out in 2010. These tests were intended to assess the creep behavior of the foil. For this purpose, 18 foil samples were installed in a long-term test rig at the material testing laboratory of seele cover GmbH and loaded with constant weights (**Figs. 1, 2**).

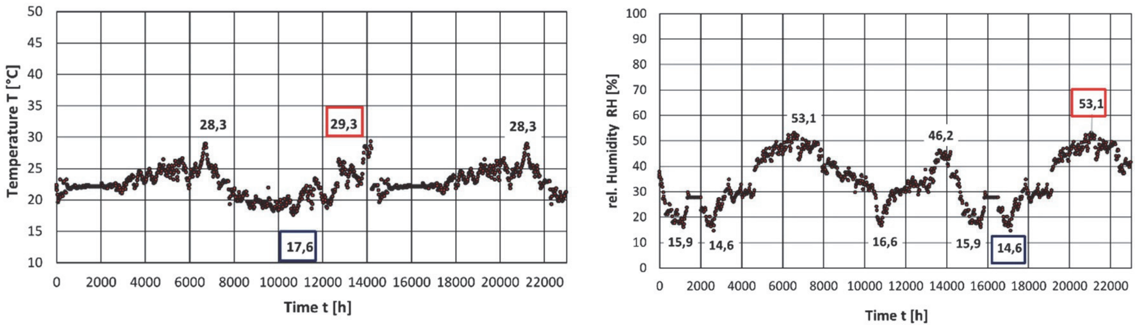
Fig. 1: Long-term test rig for creep tests on 18 ETFE film samples under room climate conditions, seele cover GmbH (today: se cover GmbH)

The 18 weights yielded calculated stresses of 6, 9, and 12 MPa. They were weighed using a calibrated laboratory balance (accuracy ± 0.5 g). At each of the three load levels, three samples were clamped in the extrusion direction (MD) and three in the transverse direction (TD). The tests were not terminated after the planned 1,000 h but continued for more than a decade. The last 12 of the 18 samples were removed after more than 12 years (109,705 h). Their strains were then measured for almost 20 months (14,400 h). Finally, the samples were tested in uniaxial short-term tensile tests (strip samples according to specimen type 2) in accordance with the test standards ISO 527-1 [2] and ISO 527-3 [3]. The results were compared with the in-house monitoring tests from 2010.

Fig. 2: Conditioning, cutting and marking of the 18 ETFE film samples

2.2 INFLUENCE OF TEMPERATURE AND HUMIDITY

In membrane construction, the nominal or reference temperature (t_{nom} or T_{ref}) is 23°C. The forthcoming Eurocode 12 for membrane structures will also refer to this reference temperature [9], [10]. In the long-term tests carried out here, the reference temperature of 23°C could only be maintained with a tolerance of approximately ± 6°C (**Fig. 3 a**). The creep test deviates from the tolerance specified in ISO 899-1 [11] (± 2°C). Therefore, these are results of indicative laboratory tests.



a) b)

Fig. 3: Test-conditions: a) room temperature T [°C] and b) relative humidity RH [%] with minimum and maximum (measurement period 23,000 h)

Indeed, increases and decreases in strain were observed, which can be explained by fluctuations in room temperature and humidity. Nevertheless, the results presented here are very insightful due to the long duration of the tests. The authors are unaware of any results from uniaxial or even biaxial creep or relaxation tests on ETFE films with such a long duration.

Biaxial long-term tests in the moderate air temperature range relevant to our climate zone (with air temperaturas approx. between -20°C and +40°C) are complex at the limits of this range, or even beyond, as they are usually carried out in a climate chamber. The accommodation of the samples, weights, and instruments for measuring temperature, humidity, and the strain of each individual sample requires a sufficiently large climate chamber. This is because the climate chamber must be heated or cooled depending on the temperature. The air humidity should also be kept as constant as possible, in accordance with ISO 62 [12].

Moisture imbalance can influence creep behavior, with excessively dry samples experiencing additional strain due to water absorption, and excessively moist samples exhibiting contraction due to water desorption. Therefore, a 90-minute period of conditioning is recommended [11], [12]. This recommendation has been followed here; however, not only the room temperature but also the ambient humidity fluctuated (**Fig. 3 b**).

Results of biaxial creep and relaxation tests at different temperature levels and stress states would be particularly helpful for the static design of single-layer, mechanically prestressed ETFE films and for defining prestressing corridors. In regions with extreme temperatures, they are even indispensable. DIN CEN/TS 19102 [9] therefore recommends long-term tests if the user does not wish to rely on the suggested k_{mod} values to account for the influence of temperature.

2.3 CREEP MODULUS

The creep modulus E_C is calculated as the ratio of the constant load (stress) to the time-dependent strain ε. Analogous to the Young's modulus (short-term tensile test), the creep modulus (long-term tensile test) is defined as the slope of the secant through the respective point on the stress-strain curve (tan α) for a specific time curve t (**Fig. 4**). The creep modulus E_C [15] described in the relevant literature has only been supplemented in equation (1) by the dependence of the strain ε on the relative humidity RH.

$$E_c\ [MPa] = \tan\alpha = \frac{\sigma_0}{\varepsilon(t,\vartheta,RH,\sigma_0)} = \frac{F \cdot l_0}{A_0 \cdot \Delta l(t,\vartheta,RH)} \tag{1}$$

In equation (1), Ec = creep modulus [MPa], ε (t, φ, RH, σ0) = strain as a function of time t, temperature ϑ, relative humidity RH, and of the constant stress σ_0. Stress and strain can be expressed by the force F, the initial cross-section A_0, the initial length l_0 of the sample and the change in length Δl.

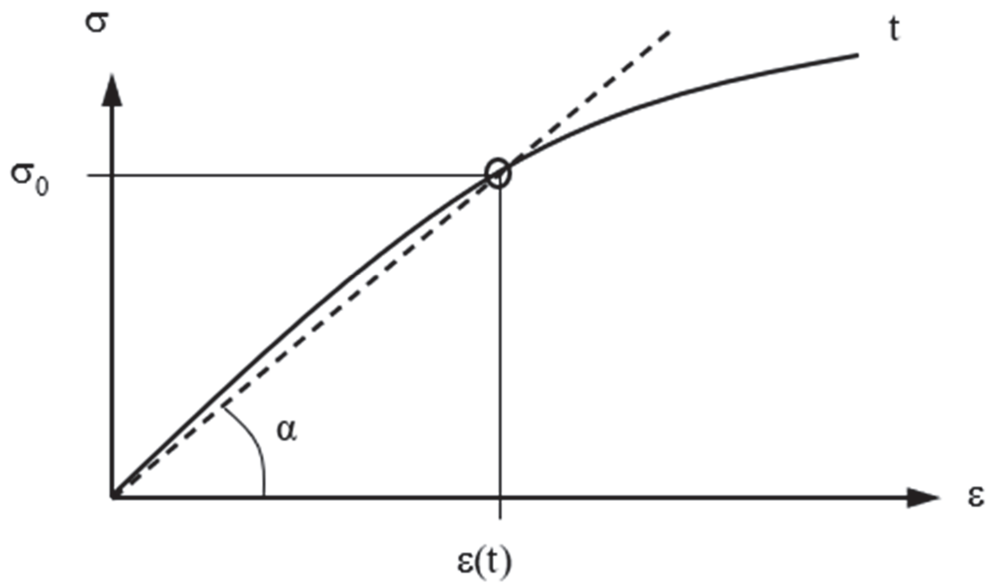


Fig. 4: Determination of the creep modulus E_c as the secant modulus for a specific time curve t

The creep modulus Ec describes the time-, temperature-, and humidity-dependent deformation of materials under constant load, including viscoelastic, respectively viscoplastic ETFE-films. This allows, for example, the assessment of deformations, stresses, and the long- term dimensional stability of ETFE film cushions under internal pressure. This is not possible with the Young's modulus Et, as it is determined from the short-term tensile test and therefore does not capture the time-dependent properties of the ETFE film. At the beginning of the long- term tensile test, the creep modulus Ec corresponds to the Young's modulus Et [MPa] determined in the short-term tensile test.

3 CREEP TESTS

3.1 TESTING CONDITIONS AND STANDARDS

The uniaxial creep test is based on the ISO 899-1 [11] standard for the creep rupture test. The ASTM D2990 [14] standard is also generally applicable to plastic films. It differs from ISO 899-1 [11] primarily in the type of load, the test methods, and the material types it covers.

Laboratory	seele cover GmbH, Obing (today: se cover GmbH in Rosenheim, Germany)
Date of the tests	November 18, 2010 – May 25, 2023 (load phase) May 25, 2023 – January 14, 2025 (recovery phase)
Product (ETFE-Film)	NOWOFOL, NOWOFLON ET 6235Z, clear/unprinted, 250 µm
Number of samples	3 load levels (6, 9, and 12 MPa) x 2 directions (MD, TD) x 3 samples = 18 samples in total (from each group, one out of three samples was selected for preliminary testings in 2021, so that in the end two-thirds of the samples were still available for this evaluation)
Sample size	Sample width: 100mm ± 1 mm, free length between clamps: 200 mm (± 3 mm), measuring tool: Metal measuring tape, accuracy approx. ± 1 mm
Load (weight)	Weight plates, supplemented with aluminum rings, accuracy ± 5 g Measurement using laboratory balance, accuracy ± 0.5 g
Measurement of room temperature and relative humidity	USB sensor with data storage, accuracy ± 0.5°C (temperature), ± 2 RH [%] (relative humidity)

Tab. 1: Test conditions and measurement tools

3.2 RESULTS (GRAPHS)

Figures 5 and 6 show the mean values of the measured strains for the three load stages of 6, 9, and 12 MPa during the creep test (loading pase, 109,705 h) and the subsequent recovery test (unloaded phase, 14,400 h). After the samples were unloaded, some of the previously observed strains decreased again. The measurements were stopped after the recovery phase, as no further changes in strain were expected.

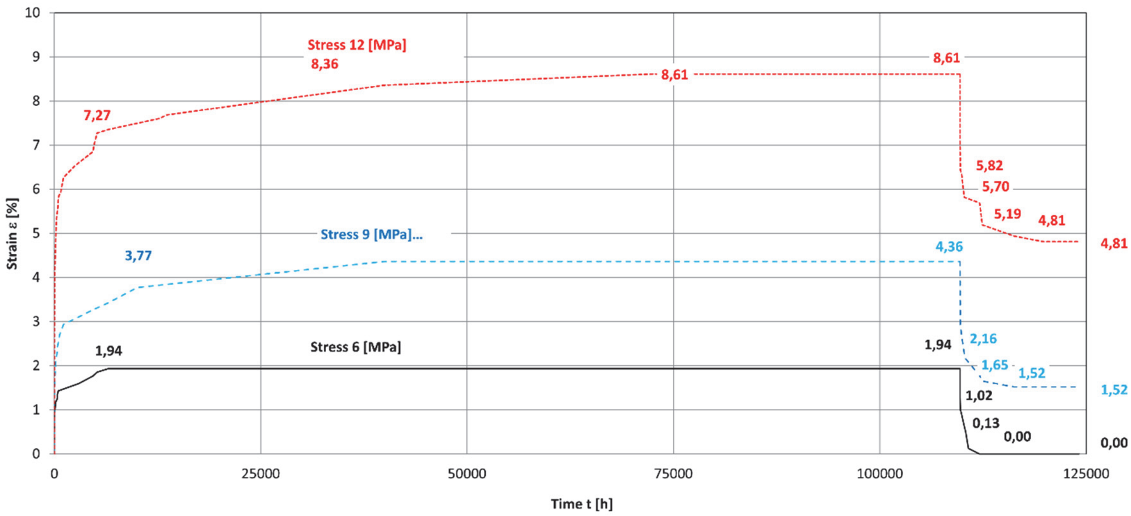


Fig. 5: Creep test with subsequent recovery phase, strain-time diagram (extrusion direction MD, mean)

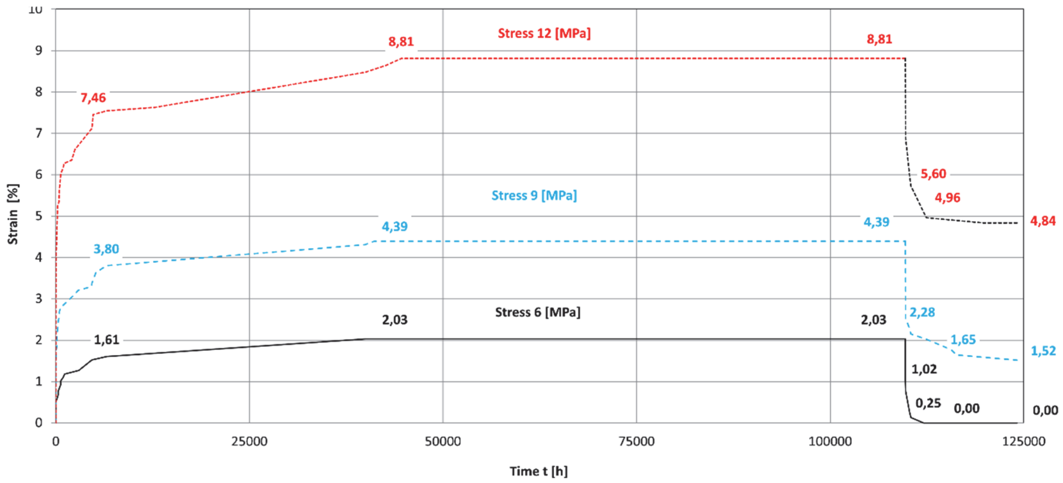


Fig. 6: Creep test with subsequent recovery phase, strain-time diagram (extrusion direction TD, mean)

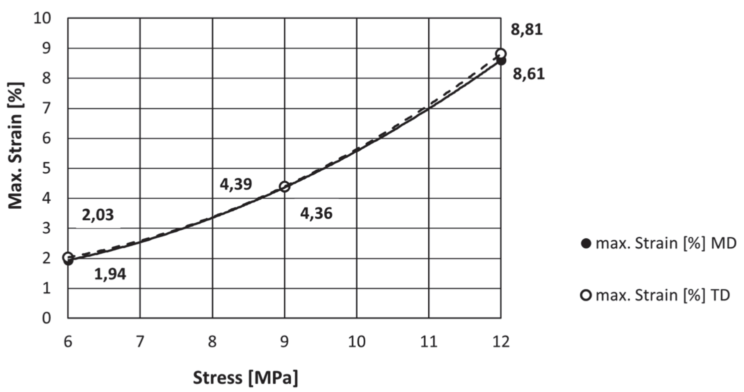


Fig. 7: Creep test - limit strains (MD, TD, mean)

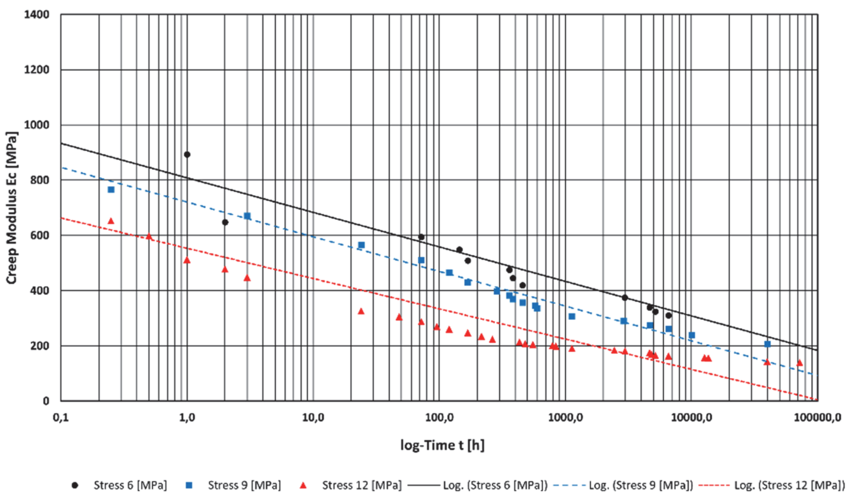


Fig. 8: Creep test - creep module - log-time diagram (MD, mean, logarithmic time axis)

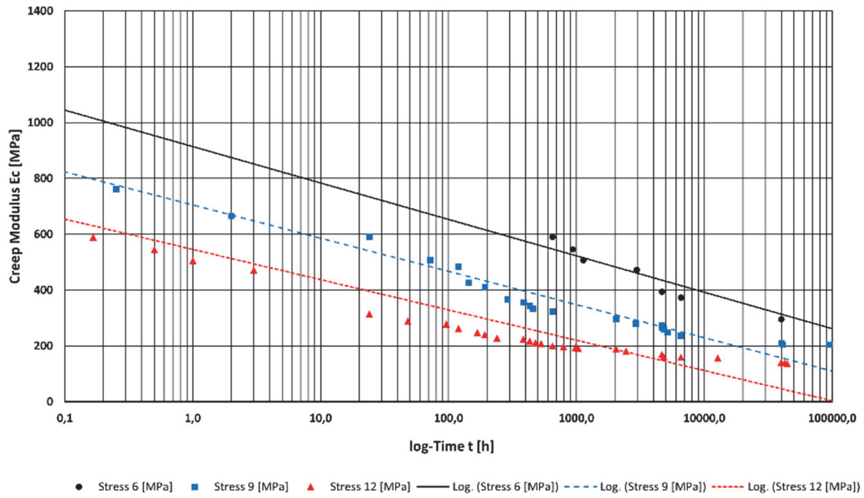


Fig. 9: Creep test - creep module - log-time diagram (TD, mean, logarithmic time axis)

Load levels (stress)	Max. strains (limit-strains) (MD/TD) [%]	Time until reaching the limit strain (MD/TD) [h]	Creep Modulus Ec [MPa] (t = 0.0028 h)	Creep Modulus Ec [MPa] (t = 109,705 h)
6 MPa	1.9/2.0 %	~ 6,500 h	1188/1182	310/295
9 MPa	4.4/4.4 %	~ 40,000 h	1074/1066	206/205
12 MPa	8.6/8.8 %	~ 70,000 h	1191/1180	139/136

Tab. 2: Characteristic values - creep test (loading phase), maximum strains (limit strains), time to reach the limit strain and creep modulus at the beginning and the end of the creep test (t = 0.0028 h and t = 109,705 h)

3.3 CREEP TESTS (LOAD PHASE) – RESULTS / CONCLUSIONS

- The **strains** are load-dependent, non-linear, and finite (up to the investigated stress of 12 MPa). They each reach a load-dependent maximum value (limit strain) (**Figs. 5, 6, 7**), which was not reached after the usual 1,000 h but only after approximately 6,600 h (6 MPa). Assuming that the long time until the limit strain is reached is not solely due to fluctuations in temperature and/or humidity, creep tests should therefore take longer than previously assumed, depending on the load.
- **Deviations of the strains** from the theoretical ideal curves over time indicate a temporary increase in room temperature or relative humidity. Whether the maximum strain should be attributed to the maximum temperature (29.3°C) or the average temperature (approx. 23°C) depends on whether the strain variations resulting from temperature and humidity fluctuations are reversible. This depends on the load [19].
- The results only allow conclusions to be drawn about **uniaxial stress states**. Strains under biaxial stress states are expected to be significantly lower [4], [5], [17], [19]. The authors are unaware of any sufficiently long biaxial creep tests

on ETFE films with a subsequent recovery phase, nor of any relaxation tests. This also applies to tests at different temperatures and humidity levels. Such tests would be extremely helpful for estimating the application limits under continuous loads (prestressing).

- It is recommended that **measurements** be taken regularly and ideally automatically. Especially at the beginning of the experiment, they should be taken at very short intervals. The rapid increase in strain during the first few seconds of the long-term test makes accurate manual measurement difficult. The temperature should deviate by a maximum of ± 2°C from the temperature under investigation [11]. Due to the fluctuating environmental conditions (room temperature and humidity) [11], [12], [13], [14], and the manual reading of the strains, the presented experiments should be considered preliminary laboratory tests. However, due to the very long duration of the tests, they are still very informative.
- At the beginning of the creep tests, i.e., at time t → 0, the **uniaxial creep modulus E_c** corresponds to the **uniaxial Young's modulus E_t** obtained from uniaxial short-term tensile tests. For the investigated film product NOWOFLON ET6235Z, the Young's modulus Et is approximately between 900 and 1,200 MPa, depending on the test conditions [4], [5], [6], [7], [8], [16], [17], [18], [19]. The creep modulus decreases sharply with the duration of the loading (**Figs. 8, 9**).

4. RECOVERY TESTS (UNLOADED PHASE)

4.1 TESTING CONDITIONS AND STANDARDS

After the loading phase of 109,705 hours, the samples were unloaded and the recovery was measured over 14,400 hours at room temperature and ambient humidity. The recovery curve (mean of two samples) over time is shown in **Figs. 10, 11** (extrusion direction MD and transverse direction TD). The recovery test time begins with the removal of the weights (0.00 hours). After 14,400 hours, the strain measurements were stopped since further strain reductions didn't proceed any more.

4.2 RESULTS (GRAPHS)

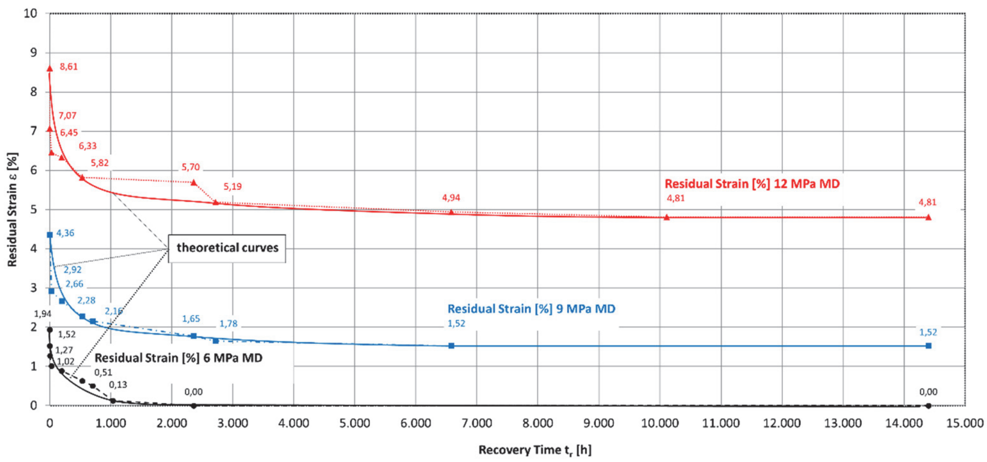


Fig. 10: Recovery test, residual strain-recovery time diagram (MD, mean)

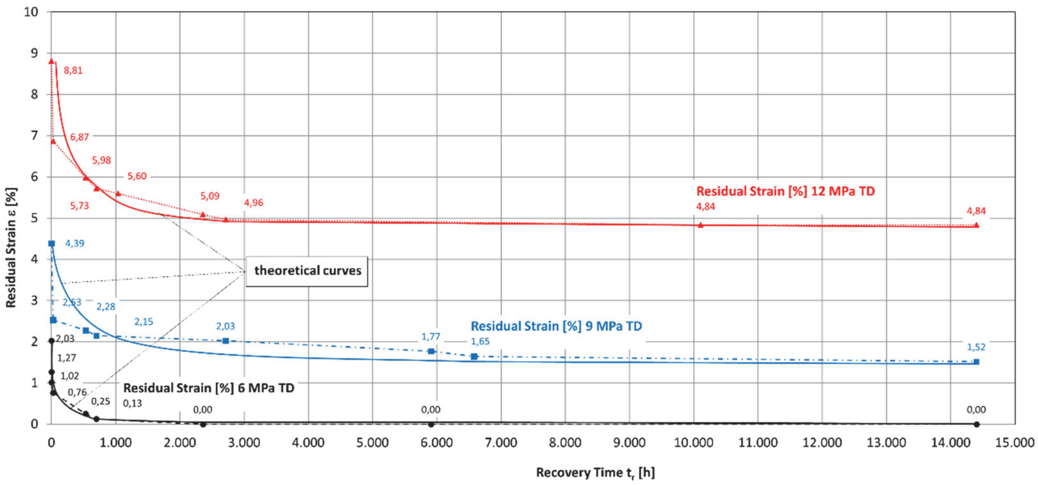


Fig. 11: Recovery test, residual strain-recovery time diagram (TD, mean)

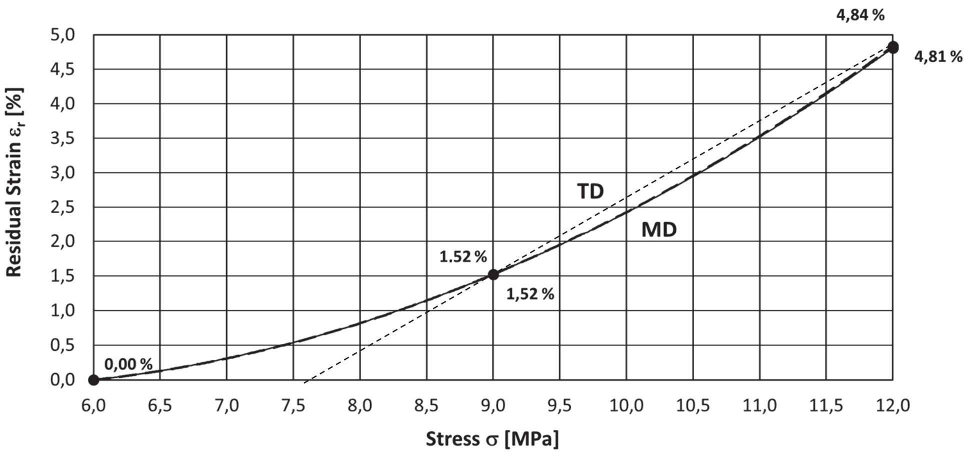


Fig. 12: Recovery test, residual strain-stress diagram (MD and TD, mean)

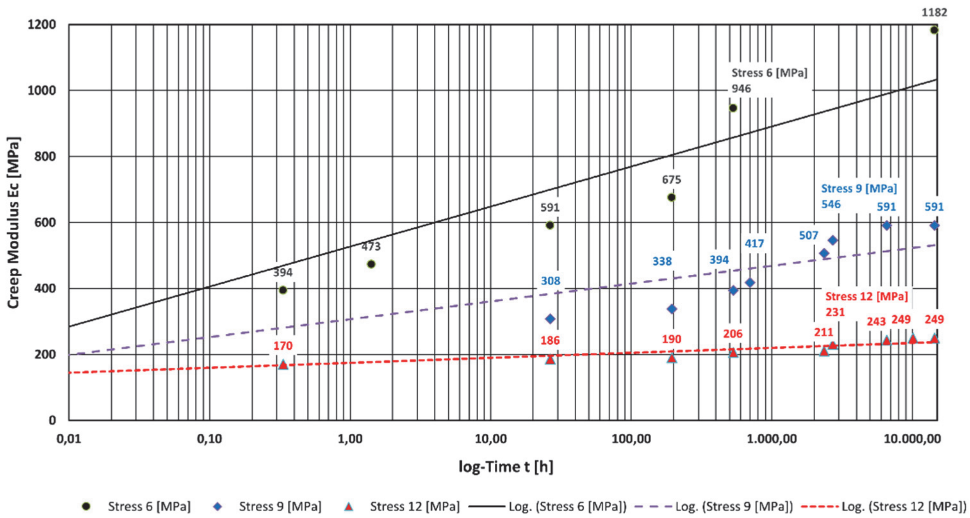


Fig. 13: Recovery test, creep modulus-log-time diagram (MD, mean, logarithmic time axis)

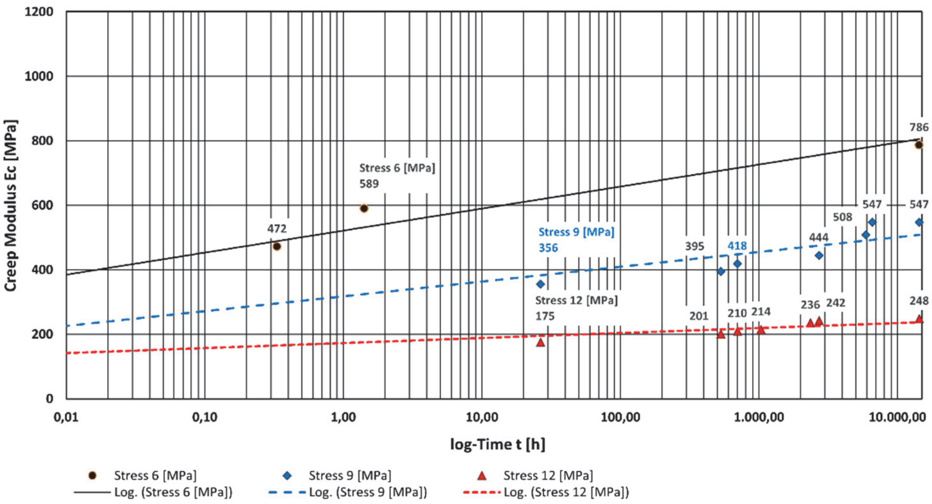


Fig. 14: Recovery test, creep modulus-log-time diagram (MD, mean, logarithmic time axis)

Load levels (stress)	**Residual strains (MD/TD) [%]**	**Time until reaching the residual strains (MD/TD) [h]**	**Creep Modulus [MPa] at the beginning of the recovery phase (t_r = 0 h, t = 109,705 h)**	**Creep Modulus [MPa] at the end of the recovery phase (t_r = 14,400 h)**
6 MPa	0.00/0.00 %	~ 2,300 h	310/295	1182/786
9 MPa	1.52/1.52 %	~ 6,600 h	206/205	591/547
12 MPa	4.81/4.84 %	~ 10,100 h	139/136	249/248

Tab. 3: Characteristic values – residual strains and time until reaching the residual strain the first time as well as creep modulus E_c at the beginning (t_r = 0.00 h) and at the end of the recovery phase (t_r = 14,400 h)

4.3 RECOVERY TESTS - DISCUSSION OF RESULTS AND CONCLUSIONS

- The **strain reduction** during the recovery phase is also load-dependent, non-linear, and finite. The time until the recovery stagnates depends on the load (Figs. 10, 11). The recovery strains are similar in the extrusion direction (MD) and in the transverse direction (TD), a further indication of approximately isotropic behavior.
- In contrast to the tests at 9 and 12 MPa, the test at 6 MPa sustained stress shows no residual strain after approximately 6,600 h following unloading. At least up to this stress level, purely elastic strains occur, while from 9 MPa onwards, plastic strains increasingly appear and, by definition, remain permanently. The stress level between 6 and 9 MPa at which the **residual strain** returns to zero is unknown due to the undefined curve shape (**Fig. 12**).
- Due to their **entropy elasticity**, the chain molecules of ETFE films tend to return to their original configuration, which was established during solidification after extrusion. This tendency is clearly demonstrated by the stretching back into shape. However, the original configuration can only be achieved if the ETFE bonds have

not been damaged by the stress.

- With the recovery of the samples, the **creep modulus Ec** for the stress level 6 MPa increases back to its original level due to purely elastic strains, so that it corresponds approximately to the Young's modulus Et again. This does not apply to the stress levels of 9 and 12 MPa due to the plastic strain components (**Figs.13, 14**).
- According to relevant literature, semi-crystalline thermoplastics, including ETFE, have a so-called **creep limit** at approximately 40–50% of their yield strength [19], [22]. Below this limit, by definition, only elastic strains occur, even under sustained loads. The recovery strains measured here indicate that the creep limit is also applicable to ETFE.
- Experience has shown that the **uniaxial yield stress** in short-term tensile tests (23°C, 100-200 mm/min) is approximately 15-16 MPa [4], [5], [6], [7], [8], [16], [17], [18],
- [19] – characterized by the first yield point of the stress-strain curve. The creep limit would therefore be found at 7.5-8.0 MPa, which approximately corresponds to the results of the long-term tests presented here (min. 6.0-MPa up to 7.6, **Fig. 12**). Whether the creep limit has the same dependence on temperature and humidity as the yield stress remains to be demonstrated.

5 COMPARATIVE UNIAXIAL TENSION TESTS BEFORE AND AFTER THE CREEP AND RECOVERY TESTS

5.1 TEST CONDITIONS AND STANDARDS

The project-related self-monitoring tests were carried out in 2010 at the se cover GmbH laboratory (**Figs. 1, 2, 15, 16 a), Tab. 4 left column**). The batch numbers and test reports are still available. All tests presented here were performed on the same batch of material. The comparison tests are done at the laboratory of NOVUM Membranes in 2025 **(Fig. 16 b), Tab. 4 right column)**.

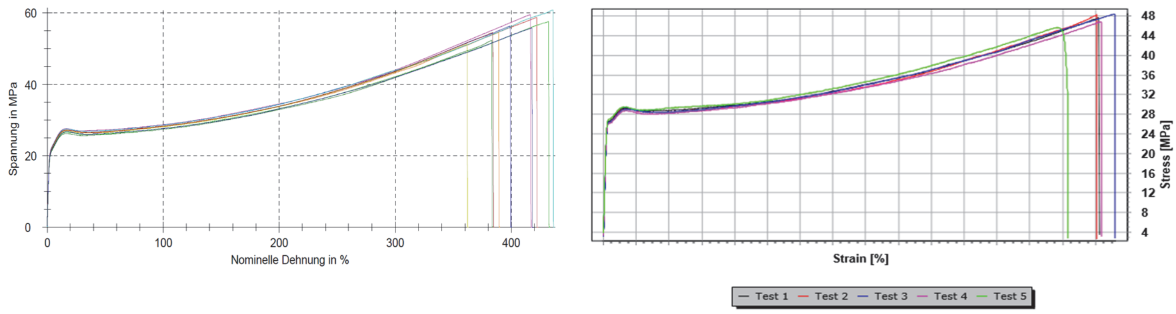
Laboratory	Seele cover GmbH, Obing, Germany (today: se cover GmbH, Rosenheim, Germany)	NOVUM Membranes, Edersleben, Germany
Date of uniaxial short-term tensile tests	October 6-11, 2010 (before the long-term tests started)	June 26, 2025 (after the long-term tests ended)
Testing machine	ZWICK ROELL Z020, 20KN	H&P Inspect table blue 20 KN
Room temperature and relative humidity	23°C ± 2°C / 46% RH (documented, air-conditioned laboratory)	23°C ± 2°C (documented)
Product ETFE-film	NOWOFOL – NOWOFLON ET 6235Z, clear film, unprinted, 250 µm	
Batch-No.	610 B 4131 R8/R12	
Young's Modulus E_t	995 MPa (MD) / 997 MPa (TD) (2x10 samples (MD, TD), mean	
Sample clamps	ZWICK ROELL vulkollan-flat/aluminium-convex	
Standard and sample size	In accordance with ISO 527-1 [2] and ISO 527-3 [3], sample type 2 (strip geometry) with sample width 15 mm and free length between clamps 80 mm	
Test speed and pre-load	200 mm/min (preload 1 N, preload-speed: 10 mm/min)	

Tab. 4: Test conditions of the comparative uniaxial tensile tests

Fig. 15: Uniaxial tensile testing machine ZWICK ROELL Z020 with temperature-controlled chamber (-40°C to +100°C) for testing technical textiles, films, clamping profiles and other components, seele cover GmbH, Obing, 2010

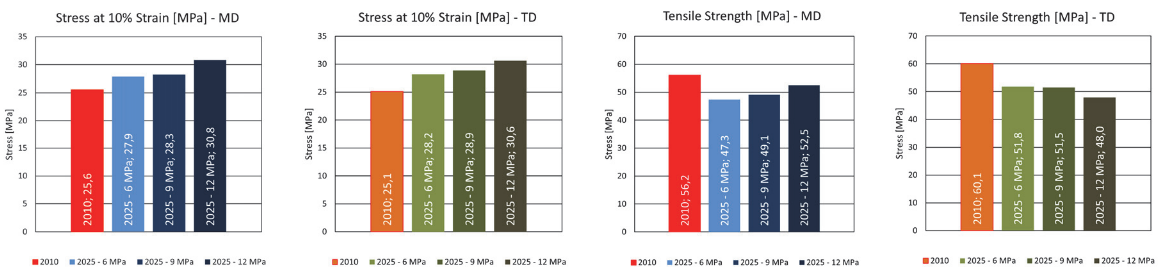
5.2 RESULTS (GRAPHS)

All uniaxial short-term tensile tests were carried out in accordance with the test standard series of the ISO 527 [2], [3] (**Figs. 15, 16**). The results of the uniaxial tensile tests presented here show whether the mechanical properties of the ETFE film have changed due to long-term stress.



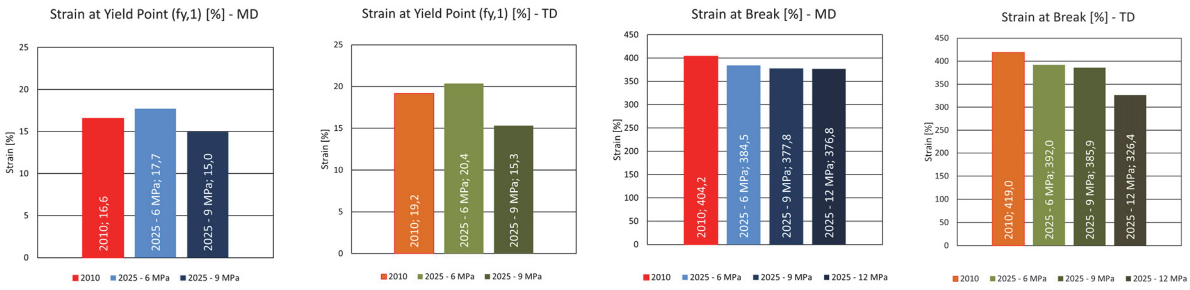
a) b)

Fig. 16: Short-term tensile tests, exemplary graphs for comparison: a) 2010, MD, b) 2025 (6 MPa, MD)



b) b) c) d)

Fig. 17: Short-term tensile tests, comparison of stresses at 10% strain in MD (a) and TD (b), and tensile strengths in MD (c) and TD (d) - before long-term loading with the three load stages 6, 9, and 12 MPa (2010, red/light brown) and after the recovery phase (2025, blue/green)



a) b) c) d)

Fig. 18: Short-term tensile tests, comparison of strains at the yield point (1st yield point, $f_{y,1}$) in MD (a) and TD (b) (load level 12 MPa was not evaluable), and the strains at rupture in MD (c) and TD (d) - before long-term stress with the two load levels 6 and 9 MPa (2010, red/light brown) and after the recovery phase (2025, blue/green)

5.3 COMPARATIVE SHORT-TERM TENSILE TESTS BEFORE AND AFTER THE LONG-TERM TESTS - DISCUSSION OF THE RESULTS AND CONCLUSIONS

- The **stresses at 10% strain** are higher after long-term loading than before. Furthermore, they increase with the magnitude of the sustained load (**Fig. 17 a, b**). No significant differences in MD and TD are discernible, which supports the assumption of approximate isotropy up to the yield stress.
- The **tensile strengths** are lower after long-term loading than before at all three load levels. While they increase with the level of sustained load in MD, they decrease in TD (**Fig. 17 c, d**). Above the yield stress, the isotropy of the ETFE film no longer appears to hold.
- While the **strains at the yield stress** in MD and TD were greater after the sustained load of 6 MPa than before the long-term loading, they decreased significantly with increasing sustained load (9 MPa) and fell below the original value from 2010 (**Fig. 18 a, b**). Unfortunately, no evaluable results were obtained at 12 MPa.
- The **strains at break** are lower after continuous loading in both MD and TD than before. They decrease further with increasing continuous loading (**Fig. 18 c, d**).
- The fact that the strain increased upon reaching the yield stress after a sustained load of 6 MPa, even though it is completely elastic (according to the recovery test), indicates that **two types of exposure** are superimposed: firstly, **long-term loading**, and secondly, **aging (without loading)**. Due to the observed completely elastic strain, the aging effect may dominate at 6 MPa. In contrast, the sustained load effect dominates in the samples loaded with 9 MPa and 12 MPa. Unfortunately, no stored, unloaded samples from the same material batch were available to seperate the two effects. The combination of sustained loading and aging has a noticeable influence on the mechanical properties of the ETFE film.

- The results also show that the approximate isotropy of the film above the yield stress is disrupted with increasing load. This is not surprising, since the chain molecules of the ETFE exhibit a slight orientation in the extrusion direction due to the extrusion process, which can be detected using scanning electron microscopy [21], [22]. The higher the continuous load above the creep limit, the greater the damage to the molecular chains or their bonds can be expected in the crystalline phase of the ETFE film.

6 CONCLUSIONS

The preliminary laboratory tests provide important results regarding the long-term behavior of the ETFE film under continuous loading at room temperature. Due to the extremely long test duration of over 100,000 hours, the results are very informative. They show, for instance, that the limiting strain is not reached after the usual 1,000 hours. The recovery tests over 14,400 hours show that the strains under continuous loading at room temperature are purely elastic up to a uniaxial stress of at least 6 MPa. Because of the applied uniaxial stress conditions, the results cannot be directly extrapolated to biaxial stress conditions. Therefore, it would be very helpful for planners to carry out sufficiently long biaxial creep and relaxation tests on the ETFE foil products for different loads and stress conditions, but also at different temperatures and humidity levels – a big task.

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