

Journal of Visualized Experiments

Artificial Thermal Ageing of Polyester Reinforced and Polyvinyl Chloride Coated Technical Fabric

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE60737R2
Full Title:	Artificial Thermal Ageing of Polyester Reinforced and Polyvinyl Chloride Coated Technical Fabric
Section/Category:	JoVE Engineering
Keywords:	mechanical properties, ageing, performance, Arrhenius, composites, technical fabric
Corresponding Author:	Paweł Kłosowski, Dsc. Eng. Politechnika Gdanska Wydział Inżynierii Lądowej i Środowiska Gdańsk, Poland POLAND
Corresponding Author's Institution:	Politechnika Gdanska Wydział Inżynierii Lądowej i Środowiska
Corresponding Author E-Mail:	klosow@pg.edu.pl;pawel.klosowski@gmail.com
Order of Authors:	Paweł Kłosowski, Dsc. Eng. Krzysztof Żerdzicki Krzysztof Woznica
Additional Information:	
Question	Response
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US\$2,400)
Please indicate the city, state/province, and country where this article will be filmed . Please do not use abbreviations.	Gdańsk, Poland

TITLE:

Artificial Thermal Ageing of Polyester Reinforced and Polyvinyl Chloride Coated Technical Fabric

AUTHORS AND AFFILIATIONS:

Pawel Klosowski^{1*}, Krzysztof Zerdzicki¹, Krzysztof Woznica²

¹Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland

²Laboratoire de Mecanique Gabriel Lamé, Institut National des Sciences Appliquées Centre Val de Loire, Blois, France

Corresponding Author:

Pawel Klosowski (klosow@pg.edu.pl)

Email Addresses of Co-Authors:

Krzysztof Zerdzicki (krzysztof.zerdzicki@pg.edu.pl)

Krzysztof Woznica (krzysztof.woznica@insa-cvl.fr)

KEYWORDS:

mechanical properties, ageing, performance, Arrhenius, composites, technical fabric

SUMMARY:

Here, we simulate accelerated thermal ageing of technical fabric and see how this ageing process influences the mechanical properties of the fabric.

ABSTRACT:

Architectural fabric AF9032 has been subjected to artificial thermal ageing to determine changes of the material parameters of the fabric. The proposed method is based on the accelerated ageing approach proposed by Arrhenius. 300 mm x 50 mm samples were cut in the warp and fill directions and placed in a thermal chamber at 80 °C for up to 12 weeks or at 90 °C for up to 6 weeks. Then after one week of conditioning at ambient temperature, the samples were uniaxially tensioned at a constant strain rate. Experimentally, the parameters were determined for the non-linear elastic (linear piecewise) and viscoplastic (Bodner–Partom) models. Changes in these parameters were studied with respect to the ageing temperature and ageing period. In both cases, the linear approximation function was successfully applied using the simplified methodology of Arrhenius. A correlation was obtained for the fill direction between experimental results and the results from the Arrhenius approach. For the warp direction, the extrapolation results exhibited some differences. Increasing and decreasing tendencies have been observed at both temperatures. The Arrhenius law was confirmed by the experimental results only for the fill direction. The proposed method makes it possible to predict real fabric behavior during long term exploitation, which is a critical issue in the design process.

INTRODUCTION:

Polyester based architectural fabrics are commonly used for construction of hanging roofs¹. Being relatively cheap with good mechanical properties, they can be employed in long-term exploitation (e.g., the hanging roof of the Forest Opera in Sopot - Poland). Unfortunately, weather conditions, ultraviolet radiation, biological reasons, and operational purposes (season pre-stressing and loosening²) can affect their mechanical properties. Hanging roofs made of AF9032 are typically seasonal structures subjected to high temperature (especially during sunny days in the summer), regular pre-tensioning and loosening. In order to properly design a hanging roof, fabric parameters must be determined not only at the beginning of exploitation, but also after several years of use.

Ageing analysis measures the ageing indicator and compares the initial and final values of the parameters to assess the impact of ageing. Cash et al.³ proposed one of the simplest methods by comparative analysis of 12 different types of roofing membranes. These membranes were exposed to outdoor weathering for 2 or 4 years. The authors used a rating system of several properties to assess fabric durability. In order to provide an analysis of polymer thermal ageing, the time-temperature superposition principle (TTSP) can be applied⁴. This principle states that the behavior of a material at low temperature and under low strain level resembles its behavior at high temperature and high strain level. The simple multiplicative factor can be used to relate the current temperature properties with the properties at the reference temperature. Graphically, it corresponds to the curve shift on the log time scale. Regarding the temperature, two methods are proposed to combine the shift factor and the ageing temperature: the Williams-Landel-Ferry (WLF) equations, and the Arrhenius law. Both methods are included in the Swedish standard ISO 11346⁵ to estimate the lifetime and maximum operational temperature for rubber, or vulcanized and thermoplastic, materials. Recently, thermal ageing and Arrhenius methodology have been used in the cable lifetime prediction^{6,7}, heating pipes⁸, and polymer glue PMMA⁴. An extension of the Arrhenius law is the Eyring law that takes into account other ageing factors (e.g., voltage, pressure, etc.)⁹. Alternatively, other studies propose and verify simple linear models for a description of ageing (e.g., biosensor ageing¹⁰). Although the Arrhenius method is commonly used, there is discussion on its relevance in the lifetime prediction of every material. Hence, the method must be used with care, especially in terms of initial assumptions and experimental conditions⁶.

Similar to most polymers, the polyester fabrics used in the current research exhibit two distinct transition phases defined by the melting temperature (T_m) and the glass transition temperature (T_g). The melting temperature (T_m) is the temperature when a material changes from its solid state to the liquid one, and the glass transition temperature (T_g) is the boundary between the glass and rubber states¹¹. According to manufacturer's data, the AF9032 fabric is made from polyester threads ($T_g = 100\text{--}180\text{ }^{\circ}\text{C}$ ¹², $T_m = 250\text{--}290\text{ }^{\circ}\text{C}$ ¹³) and PVC coating ($T_g = 80\text{--}87\text{ }^{\circ}\text{C}$ ^{14,15}, $T_m = 160\text{--}260\text{ }^{\circ}\text{C}$ ¹⁶). The ageing temperature T_a should be selected below T_g . During sunny days, the temperature on the top surface of a hanging roof may even reach $90\text{ }^{\circ}\text{C}$; thus, two ageing temperatures ($80\text{ }^{\circ}\text{C}$ and $90\text{ }^{\circ}\text{C}$) are tested here. These temperatures are below the thread T_g and close to the coating T_g .

The performance of the accelerated ageing protocol on technical fabrics is presented in the

current work. Artificial thermal ageing is used to predict changes of the material properties. The article illustrates appropriate laboratory testing routines and a way to extrapolate relatively short-term experimental results.

PROTOCOL:

1. Accelerated thermal ageing experiments on technical fabric

1.1. Overall preparation

1.1.1. Prepare a testing machine with proper software (in order to provide constant strain rate tests) and a video extensometer.

1.1.2. Prepare a thermal chamber providing constant temperature of 80 °C (± 1 °C) and 90 °C (± 1 °C) for at least 12 weeks.

1.2. Specimen preparation

1.2.1. Unroll the technical fabric AF9032 bale. Draw the desired shapes (300 mm x 50 mm) with a soft pencil or marker on the fabric surface parallel to the warp or fill direction.

NOTE: The distribution of specimens on the fabric surface is given elsewhere¹⁷.

1.2.2. Indicate the warp direction on each specimen with a permanent marker. Cut the specimens with a sharp knife or scissors. Use the ruler if a knife is used for cutting.

NOTE: The specimens should be rectangular¹⁷. The major load-carrying elements of the fabric are threads. In the operational phase, the coating material usually exceeds its yield limit, thus not taking part in the stress distribution. The only elements to carry the load are threads spreading from one grip to another. Therefore, it is not reasonable to use sophisticated shapes of specimens (e.g., a dumbbell shape usually used for metals). On the other hand, such sample shapes result in the need for special grips when the ultimate load is investigated, or the use of an extensometer in order to assess material parameters.

1.2.3. Measure the specimen's thickness with a slide caliper and count the number of threads at the short edge of the specimen.

NOTE: For each specimen, take three thickness measurements, and compute the average value. Use the magnifying glass to assess the number of threads if necessary.

1.3. Turn on the thermal chamber, leaving the door open. Using the buttons and the control display, select the temperature (80 °C). Close the thermal chamber door and observe the increase of temperature on the control panel.

1.4. Specimen warming

1.4.1. When the temperature is close to 80 °C, open the thermal chamber door. Insert at least 7 sets of specimens with each set consisting of 6 specimens cut in the warp direction and 6 in the fill direction. Close the door as soon as possible in order to avoid a temperature drop.

NOTE: The experiments should be conducted for three strain rates. For each strain rate, experiments are performed on two specimens in the warp direction and two in the fill direction. Place excess specimens in the chamber in case the experiments are not successful or the results from both tests are highly divergent.

1.4.2. After 1 h, don thermal gloves and remove the first set of specimens (the reference set; 6 specimens in the warp direction and 6 in the fill direction). After every 2 weeks, remove a succeeding set of specimens from the thermal chamber.

NOTE: The entire warming process will take 12 weeks.

1.5. Specimen conditioning

1.5.1. Leave the specimens at room temperature for one week. Cool the specimens to room temperature (i.e., their properties should be stabilized).

1.5.2. Before the test, draw two black marks (dots) using a permanent marker with a lengthwise separation of about 50 mm (L0) in the middle of each specimen.

NOTE: The dots will be used by the video extensometer.

1.6. Testing machine setup

1.6.1. Install four 60 mm flat inserts into the testing machine, two inserts per one grip. The inserts show a fish scale surface type and are used to avoid slipping the specimens out of the grips.

1.6.2. Switch on the machine. Start the software (e.g., TestXpert) that controls the machine. Choose the program dedicated to the tensile tests.

1.6.3. Select the starting position with a 200 mm grip to grip separation in the software. Click the **Starting Position** button to execute the 200 mm grip to grip separation. This grip position is usually called the starting position for a test.

NOTE: The 200 mm distance is required by the ISO standard¹⁷.

1.7. Video extensometer setup

1.7.1. Move the camera of the video extensometer along the supporting bar to situate the lens

of the camera at the level of the middle part of the specimen. Check whether the lens of the camera provides a clear view of the specimen markers during the whole experiment.

NOTE: Perform a similar test before the main test to establish the probable sample elongation range to ensure that the camera will follow the black markers during an entire test.

1.7.2. Select the proper brightness and focus for the lens using the computer screen and the associated software.

1.8. Video extensometer calibration

NOTE: The calibration device is the standard equipment of the video extensometer.

1.8.1. Put the calibration device in the front of the camera and clamp it with the grips.

1.8.2. Using the video extensometer software (e.g., VideoXtens), select the proper type of markers in the **Targets** window (usually black and white).

1.8.3. Select the calibration procedure in the video extensometer software using the **Scale** option and choose the calibration distance in the **Scale** window.

NOTE: The distance should be similar to the separation of markers on the specimens. The calibration device offers three measuring distances: 10, 15 and 40 mm. Due to the 50 mm marker separation, the 40 mm distance is appropriate.

1.8.4. After calibration, change the marker type to **Pattern** in the **Targets** window.

NOTE: This enables the video extensometer to follow the markers indicated on the specimen.

1.9. Test performance

1.9.1. Prepare the test parameters in the TextXpert software.

NOTE: The prepared program must enable a test with a selected strain rate in the uniaxial stress case. It must be correlated with the video extensometer. The recorded parameters are the initial distance of the extensometer markers (L₀), and result functions of time, grip displacements, current extensometer's markers distance, and force. The pre-load force of 50 N¹⁷ is programmed and the L₀ distance is adjusted after preloading.

1.9.2. Put the specimen along the machine main vertical axis and close the grips using the tubular spanner.

NOTE: The specimen must be located symmetrically to the grips in the vertical and horizontal directions.

1.9.3. Perform the tests with the selected constant strain rate until the specimens break (use 0.005, 0.001, and 0.0001 s⁻¹ strain rates). For each strain rate, test at least two specimens in the warp direction and fill direction. Save the test results.

NOTE: The following data are necessary: the initial distance of the extensometer markers (L₀), time functions of the extensometer's marker distance, and the force.

1.10. Repeat steps 1.5–1.9 every two weeks using the other sets of samples (six times, up to 12 weeks).

1.11. Repeat the entire procedure at 90 °C. The total number of specimens does not change. The ageing process lasts 6 weeks. Remove and test subsequent sets of specimens every week.

2. Data preparation

2.1. Knowing the cross section area of the samples, use graphing software (SigmaPlot¹⁸ or similar) to recalculate the registered force and elongation increments according to elementary strength of material equations to the stress-strain relations. Plot a graph of obtained data, separately, for the warp and fill samples and for each of the strain rates.

2.2. Repeat for the 80 °C and 90 °C results.

3. Parameter identification of material models

3.1. Piecewise linear model for non-linear elastic modeling

NOTE: The application of the piecewise linear material model is possible when the stress-strain curve can be split into sections of linear (or approximately linear) shapes. Particular crossing points of the lines at neighboring sections correspond to applicability ranges of the related lines¹⁹.

3.1.1. In the case of every curve obtained in step 2.1, find the strain ranges, detecting the linear or close to linear stress-strain relation.

3.1.2. Using the fit regression option in the graphing software and the least square method, identify the best-fit line in the chosen region.

NOTE: The tangent to this curve corresponds to the stiffness of the material in a particular range.

3.1.3. Denote the tangent as E_{ij} where the index i corresponds to the current direction of the material (W for the warp direction and F for the fill direction) and the index j is a consecutive number of the identified line.

3.1.4. Having parameters of all the lines, find the intersection points between the lines; denote

them as $\epsilon_{k/l}$, where **k** and **l** mark the crossing lines.

NOTE: These points ($\epsilon_{k/l}$) constitute the strain ranges to apply the particular longitudinal stiffness values (E_{ij}) (**Figure 1**).

3.2. Bodner–Partom viscoplastic model

NOTE: The Bodner–Partom constitutive law is used to reflect the elasto-viscoplastic behavior of various materials^{20,21}. The basics and mathematical formulation of the model is given in detail elsewhere^{20–25}. The elementary equations are presented in **Table 1** only to model the uniaxial stress state. The Bodner–Partom model parameters are identified by means of the uniaxial tensile tests conducted with at least three different strain rates. The value of the strain rate must be constant at least in the inelastic part of the experiment. The complete Bodner–Partom model identification procedure modified for technical woven fabrics is widely presented^{24,25}.

3.2.1. Using the graphing software, identify Bodner–Partom model parameters following Klosowski et al.²⁴.

4. Arrhenius extrapolation

NOTE: The Arrhenius law is based on an empirical observation that ambient temperature increase results in acceleration of a number of chemical reactions that may speed up the ageing process as well. The complete mathematical representation of the Arrhenius chemical reaction concept can be found elsewhere^{11,26}. The Arrhenius law in a simplified form is called “the 10 degree rule”²⁷. According to this rule, a surrounding temperature increase of about 10 °C theoretically doubles the rate of the aging process. Hence, the reaction rate f is defined as follows¹⁷:

$$f=2^{\Delta T/10}, \quad (1)$$

where $\Delta T=T-T_{\text{ref}}$ is the difference between the ageing temperature **T** and the service temperature T_{ref} of a material.

4.1. Assume the temperature T_{ref} according to the average value based on the results of the local meteorological station (here, $T_{\text{ref}} = 8 \text{ °C}$ ²⁸). Assume the thermal chamber temperature **T** to be used in the ageing test (here, 80 °C and 90 °C).

NOTE: The temperature level should be registered for a longer time period, at least one year, and then calculated as the mean value of that period, bringing a time average of this period taken as T_{ref} .

4.2. Calculate the reaction rate constant **f** from equation 1 and then extrapolate the ageing time (expressed in weeks) to years (**Table 2**).

NOTE: The extrapolation effects of different ageing time periods conducted within the current research are presented in **Table 3**. For instance, thermal ageing of a specimen in 4 weeks at 90 °C is equal to its ageing in 8 weeks at 80 °C and corresponds to a natural ageing of approximately 23 years.

5. Data representation

5.1. Present the obtained parameter values in the normalized form of X/X^0 , where X denotes a current value of the certain parameter and X^0 corresponds to the initial value of this parameter, with regard to a specimen aged 1 hour only.

NOTE: The time of artificial thermal ageing is set up in hours.

5.2. Plot X/X^0 values on the Y axis versus the ageing time plotted on the X axis to show the evolution of the parameters. Prepare plots for the warp and fill directions of the tested material separately.

5.3. Describe the parameter values plotted over time by linear functions (or different best-fit functions) using the least square method and report R^2 values.

5.4. To evaluate whether the Arrhenius simplified relation is correct for AF9032 fabric, redraw the results obtained for 90 °C with respect to the ageing time recalculated into “real” time according to the Arrhenius law.

REPRESENTATIVE RESULTS:

Figure 2 juxtaposes the stress-strain curves for the warp and fill directions of AF9032 fabric obtained at different ageing times, in the 80 °C temperature level for a strain rate of 0.001 s^{-1} . The difference between the 1 h ageing period (reference test) and the rest of the ageing periods is clear. The ageing time does not seem to substantially affect the material response in the warp direction, as the stress–strain curves are highly repetitive, showing no important differences in the ultimate tensile strength (UTS). It stays contrary to the behavior observed for the fill direction, where the UTS is much lower in the case of artificially aged samples than in the unaged case. Moreover, the achieved stress–strain curves detect divergent trajectories when the strains exceed 0.06.

The results obtained at different temperature levels and the extrapolation of the results for a higher temperature level presented in one graph compress all the data concerning a particular parameter. If the curves representing evolution of the parameters in both temperatures over the ageing time fall into the same trajectory, it confirms that the obtained parameter values actually follow the Arrhenius equation. If the lines are parallel, it suggests that additional experiments are necessary to explain the observed phenomenon or that some correction coefficients should be introduced to the results at one temperature level to make results in both temperatures fall into one path.

Variation images of the PVC coating stiffness and fill ultimate strains over the ageing time are in **Figure 3** and **Figure 4**, respectively. The experimental results at two temperature levels of 80 °C and 90 °C are presented in **Figure 3a** and **Figure 4a**. It was proven before²⁴ that the second linear part of the experimental stress-strain curve of a simple tensile test (denoted here as E_{F0}) corresponds to the stiffness of technical fabric covering made of PVC. The results obtained at the temperature level of 90 °C extrapolated in hours to 12 weeks (2000 hours) and recalculated to “real” years according to the Arrhenius simplified relation are drawn in the same graph in order to compare the results (**Figure 3b** and **Figure 4b**).

The evolution of stiffness of the PVC coating over ageing time is almost linear at temperature levels of 80 °C and 90 °C with a constant increment in time, much greater in 90 °C than in 80 °C. This phenomenon suggests that PVC subjected to relatively high temperature undergoes changes resulting in the growth of its stiffness, as an effect of accelerated ageing. This behavior is possibly caused by physical ageing, specific for polymer materials, like technical fabrics. The ultimate tensile strains values (ϵ_{ult}) exhibit a decreasing trend over ageing time in the fill direction and temperature levels of 80 °C and 90 °C. For the warp direction, the UTS values show no significant variation over ageing time. On the other hand, the ultimate tensile strains (ϵ_{ult}) decrease in 80 °C and grow in 90 °C.

The same procedure has been used to address the Bodner–Partom model parameters. Here, the hardening parameter m_1 in the warp direction and the viscosity parameter n in the fill direction are presented in **Figure 5** and **Figure 6**, respectively.

The final research results are sets of linear functions, which represent certain material parameters or fabric properties over ageing time. Following this, all the basic mechanical properties (stiffness, yield limit, ultimate tensile stress and strain) and Bodner–Partom model parameters (n , D_0 , D_1 , R_0 , R_1 , m_1 , m_2) were identified, put together at temperature levels of 80 °C and 90 °C and analyzed by means of the Arrhenius extrapolation methodology²⁹.

The approximation lines corresponding to the parameter trends throughout ageing time collapse to one line for UTS, ϵ_{ult} , m_1 in the case of fill direction. Other parameter approximation lines in ageing time exhibit parallel tendencies without collapse to one line.

In the case of warp direction, only the approximation lines of UTS, E_{W2} and m_1 collapse into one line, while other parameters show neither clear tendency nor parallel character of the curves. All the parameter values in ageing time for the fill direction express parallel trends or collapse to one line. Thus, the approach of the Arrhenius simplified equation, shown in the present article, has been proven for that direction only.

FIGURE AND TABLE LEGENDS:

Figure 1: Schematic representation of the piecewise linear model for AF9032 fabric.

Figure 2: The impact in thermal ageing case at 80 °C on the stress–strain response in the warp and fill directions of AF9032 fabric, for the strain rate of 0.01 s⁻¹.

Figure 3: Stiffness of the PVC coating at different ageing times in hours (red and blue lines) (a); stiffness values obtained at 90 °C recalculated to time in years according to the Arrhenius simplified equation (blue lines) for the fill direction of AF9032 fabric (b).

Figure 4: Ultimate strains of the PVC coating at different ageing times in (red and blue lines), experiments (a); ultimate strains values obtained at 90 °C recalculated to time in years according to the Arrhenius simplified equation (blue lines) in the fill direction of AF9032 (b).

Figure 5: Bodner–Partom coefficient of isotropic hardening m_1 at different ageing times in hours (red and blue lines), experiments (a); coefficient of isotropic hardening m_1 values obtained at 90 °C recalculated to time in years according to the Arrhenius simplified equation (blue lines) in the warp direction of AF9032 (b).

Figure 6: Bodner–Partom strain rate sensitivity parameter n at different ageing times in hours (red and blue lines) experiments (a); and strain rate sensitivity parameter n values obtained for 90 °C recalculated to time in years according to the Arrhenius simplified equation (blue lines) for the fill direction of the AF9032 (b).

Table 1: Basis Bodner–Partom equations in uniaxial state.

Table 2: Example calculations of the Arrhenius simplified equation.

Table 3: Extrapolation of ageing time recalculated with the Arrhenius equation at temperature levels of 80 °C and 90 °C.

DISCUSSION:

This article includes a detailed experimental protocol to simulate the laboratory accelerated experiments on polyester reinforced and PVC coated fabrics for civil engineering applications. The protocol describes the case of artificial thermal ageing only by the means of raising the ambient temperature. This is an obvious simplification of real weather conditions, as UV radiation and water influence play an additional role in material service ageing.

Generally, the conditions of accelerated ageing performed in the laboratory should be as close as possible to the true weather and service conditions of a tested material. For instance, materials used in aerospace or marine structures undergo hydrothermal ageing, when humidity and temperature primarily act upon the material durability^{30,31}. Regarding the battery degradation level, two ageing factors are usually monitored: temperature and state of charge⁹. In electrical cable insulations, apart from temperature, different voltage and stress levels must be included, while performing accelerated laboratory ageing¹⁴. However, the thermal type of accelerated ageing is the most common one, thus it is easy to reflect it in the laboratory. The calibration of the obtained results with outdoor data of the service aged material creates a reliable tool to predict the future behavior of textile fabrics or other materials.

A drawback of the presented method is the number of samples tested. Because uniaxial tensile experiments with three different constant rates are conducted, two samples were tested in each material direction for each strain rate case. As the analysis has to cover both warp and fill directions of the fabric, tested at two temperature levels, with at least 5 ageing time intervals, a large number of samples is required. Fortunately, the results are very repetitive, displaying very similar tendencies; therefore, the obtained results are considered reliable even if two samples are tested in the same conditions only.

The procedure for conducting the uniaxial tensile tests with constant strain rates and with the video extensometer data registration is presented thoroughly. The European national standard¹ does not require the use of an extensometer for testing technical fabrics. Therefore, the proposed protocol is more precise than the standard requirements; thus, the obtained data are more accurate.

The proposed protocol makes it possible to determine material parameters for fabrics in the future; therefore, it is a suitable tool in design. The method has been successfully validated during the research of the hanging roof of the Forest Opera in Sopot. The samples of the polyester reinforced, and PVC coated fabrics were collected from the roof after 20 years of operation. Samples of unaged material were also obtained from the same manufacturer. Both types of samples proceeded through the same laboratory experiments and parameter identification routines. Results were represented by the parameters of the piecewise linear and Bodner–Partom models. The trends observed in mechanical behavior of material from the Forest Opera resemble trends found in the case of thermal ageing. Thus, the results presented here have been confirmed by the tests of a fabric after 20 years of service²⁸. Nevertheless, for other kinds of technical fabrics, some modifications of the proposed method may be required, thus the experimental protocol should be properly adjusted.

ACKNOWLEDGMENTS:

The publication of this work was supported by the Faculty of Civil and Environmental Engineering at Gdansk University of Technology.

DISCLOSURES:

The authors have nothing to disclose.

REFERENCES:

1. Ambroziak, A. Mechanical properties of Preconstraint 1202S coated fabric under biaxial tensile test with different load ratios. *Construction and Building Materials*. **80**, 210–224 (2015).
2. Żerdzicki, K., Kłosowski, P., Woźnica, K. Analysis of the cyclic load-unload-reload tests of VALMEX aged fabric. In *Shell Structures: Theory and Applications*. Edited by Pietraszkiewicz, W., Witkowski, W., 477–480, CRC Press. Boca Raton, FL (2017).
3. Cash, C. G., Bailey, D. M. *Predictive service life tests for roofing membranes: Phase 2. Durability of Building Materials and Components*. Taylor & Francis. London (2014).
4. Yin, W. et al. Aging behavior and lifetime prediction of PMMA under tensile stress and liquid scintillator conditions. *Advanced Industrial and Engineering Polymer Research*. **2** (2), 82–87

484 (2019).

485 5. Swedish Standards Insitute. Buildings And Constructed Assets - Service Life Planning - Part 7:

486 Performance Evaluation For Feedback Of Service Life Data From Practice. *International*

487 *Organization of Standardization*. 15686-7, 2006 (2017).

488 6. Šaršounová, Z. The Inconveniences Related to Accelerated Thermal Ageing of Cables.

489 *Transportation Research Procedia*. **40**, 90–95 (2019).

490 7. Gong, Y. et al. Comparative study on different methods for determination of activation

491 energies of nuclear cable materials. *Polymer Testing*. **70** (June), 81–91 (2018).

492 8. Vega, A., Yarahmadi, N., Jakubowicz, I. Optimal conditions for accelerated thermal ageing of

493 district heating pipes. *Energy Procedia*. **149**, 79–83 (2018).

494 9. Redondo-Iglesias, E., Venet, P., Pelissier, S. Eyring acceleration model for predicting calendar

495 ageing of lithium-ion batteries. *Journal of Energy Storage*. **13**, 176–183 (2017).

496 10. Panjan, P., Virtanen, V., Sesay, A. M. Determination of stability characteristics for

497 electrochemical biosensors via thermally accelerated ageing. *Talanta*. **170** (April), 331–336

498 (2017).

499 11. Martin, R. *Ageing of Composites*. Woodhead Publishing (2008).

500 12. Mouzakis, D. E., Zoga, H., Galiotis, C. Accelerated environmental ageing study of

501 polyester/glass fiber reinforced composites (GFRPCs). *Composites Part B: Engineering*. **39** (3),

502 467–475 (2008).

503 13. Rosato, D., Rosato, M. *Plastic product material and process selection handbook*. Elsevier:

504 Kidlington, Oxford (2004).

505 14. Brebu, M. et al. Study of the natural ageing of PVC insulation for electrical cables. *Polymer*

506 *Degradation and Stability*. **67** (2), 209–221 (2000).

507 15. Martienssen, W., Warlimont, H. *Handbook of Condensed Matter and Materials Data*. Springer

508 Berlin: Berlin (2005).

509 16. Berard, M.T., Daniels, C.A., Summers, J.W., Wilkes, C.E. *PVC Handbook*. Munchen: Hanser

510 (2005).

511 17. Rubber – or plastics-coated fabrics – Determination of tensile strength and elongation at

512 break. Beauth Publishing. SN EN ISO 1421 (2017).

513 18. Systat Software, Inc. SigmaPlot 12.0 User's Guide (2015).

514 19. Ambroziak, A., Kłosowski, P. Mechanical testing of technical woven fabrics. *Journal of*

515 *Reinforced nad Plastic Composites*. **32** (10), 726–739 (2013).

516 20. Bodner SR, P. Y. Constitutive equations for elastic–viscoplastic strain-hardening materials.

517 *Journla of Applied Mechanics*. **42**, 385–389 (1985).

518 21. Andersson, H. An implicit formulation of the Bodner–Partom constitutive equations.

519 *Computers and Structures*. **81** (13), 1405–1414 (2003).

520 22. Kłosowski, P., Zagubień, A., Woznica, K. Investigation on rheological properties of technical

521 fabric “Panama.” *Archive of Applied Mechanics*. **73** (9–10), 661–681 (2004).

522 23. Zaïri, F., Naït-Abdelaziz, M., Woznica, K., Gloaguen, J. M. Constitutive equations for the

523 viscoplastic-damage behaviour of a rubber-modified polymer. *European Journal of Mechanics,*

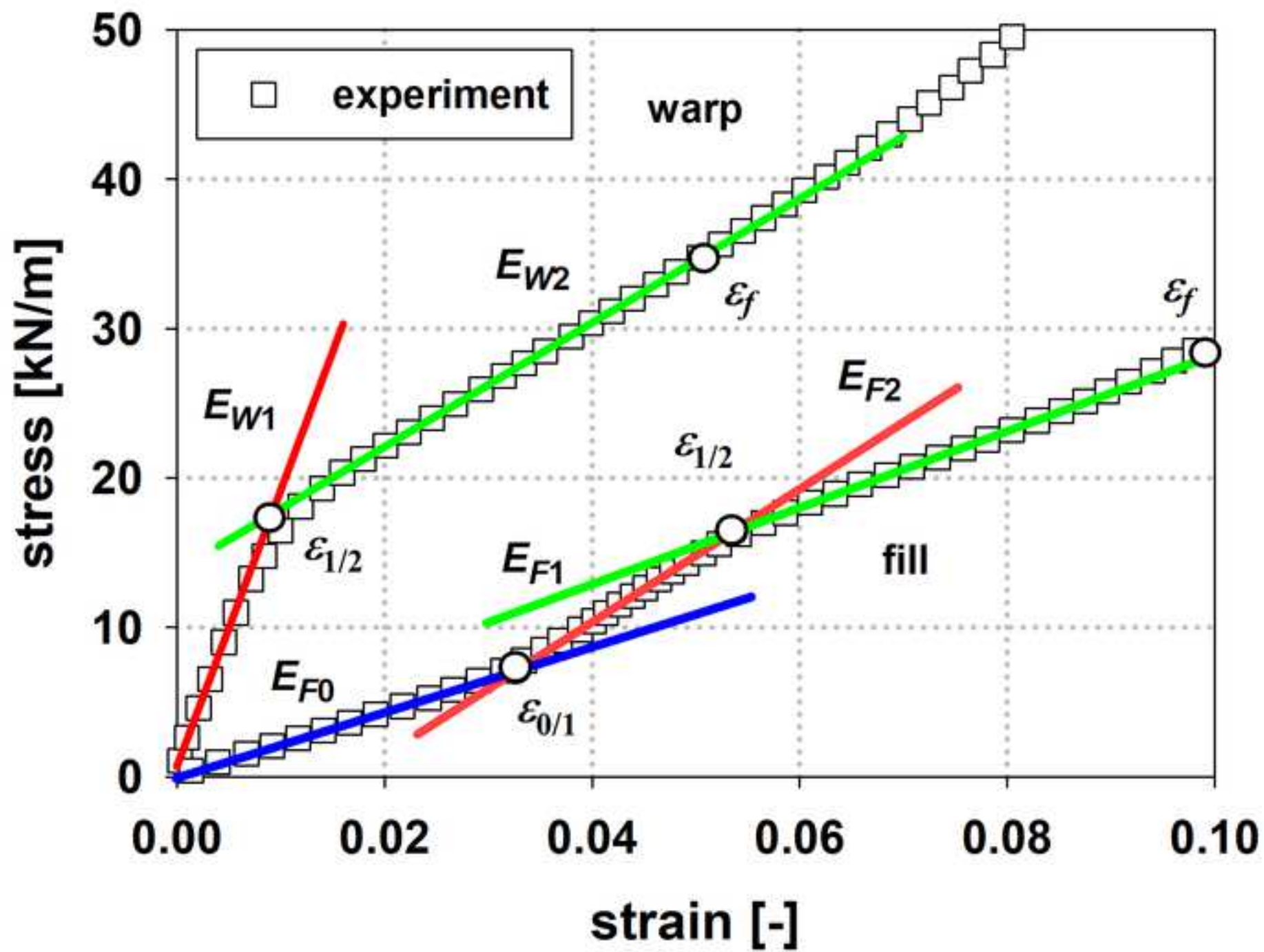
524 *A/Solids*. **24** (1), 169–182 (2005).

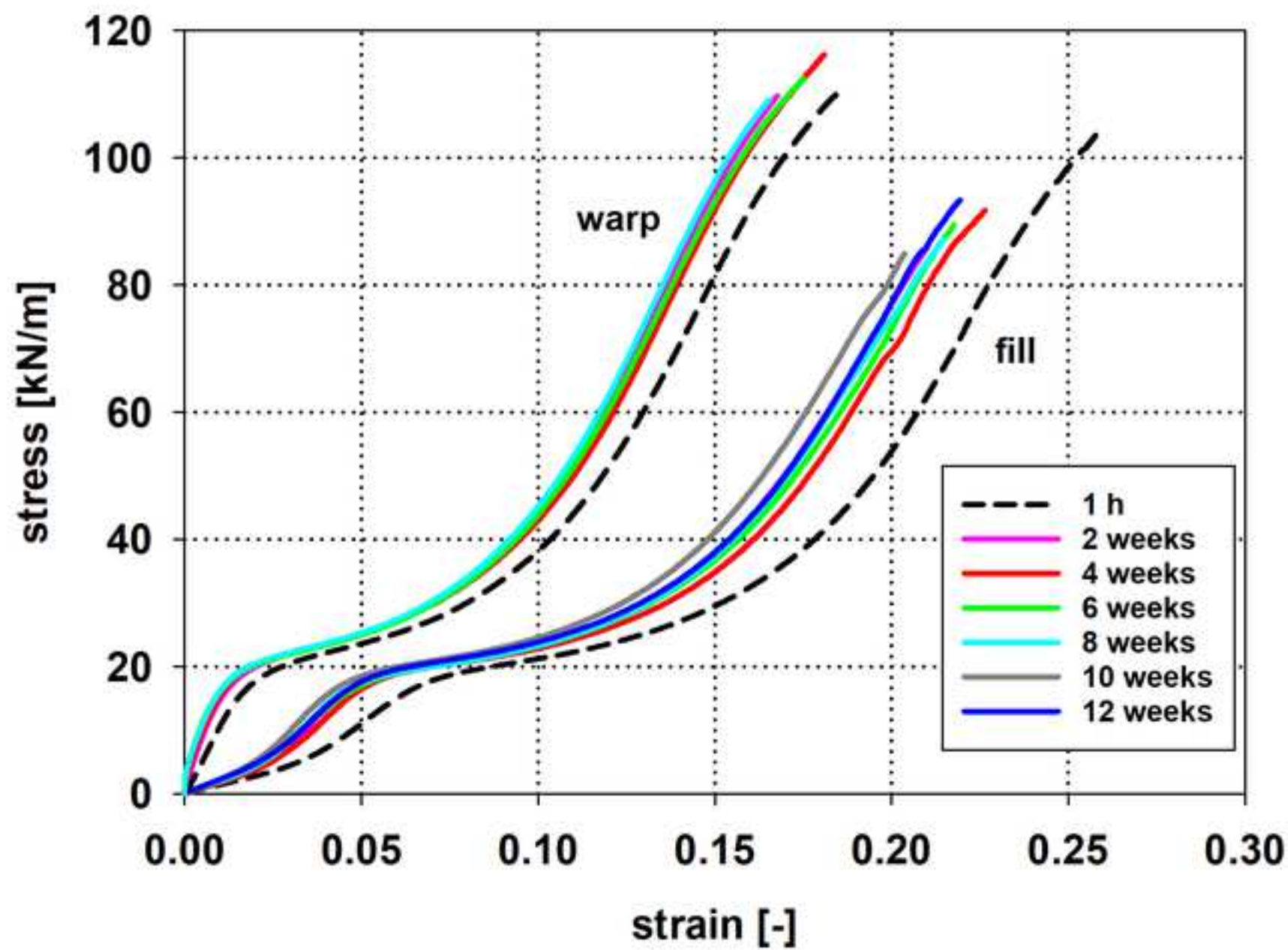
525 24. Kłosowski, P., Zerdzicki, K., Woznica, K. Identification of Bodner–Partom model parameters

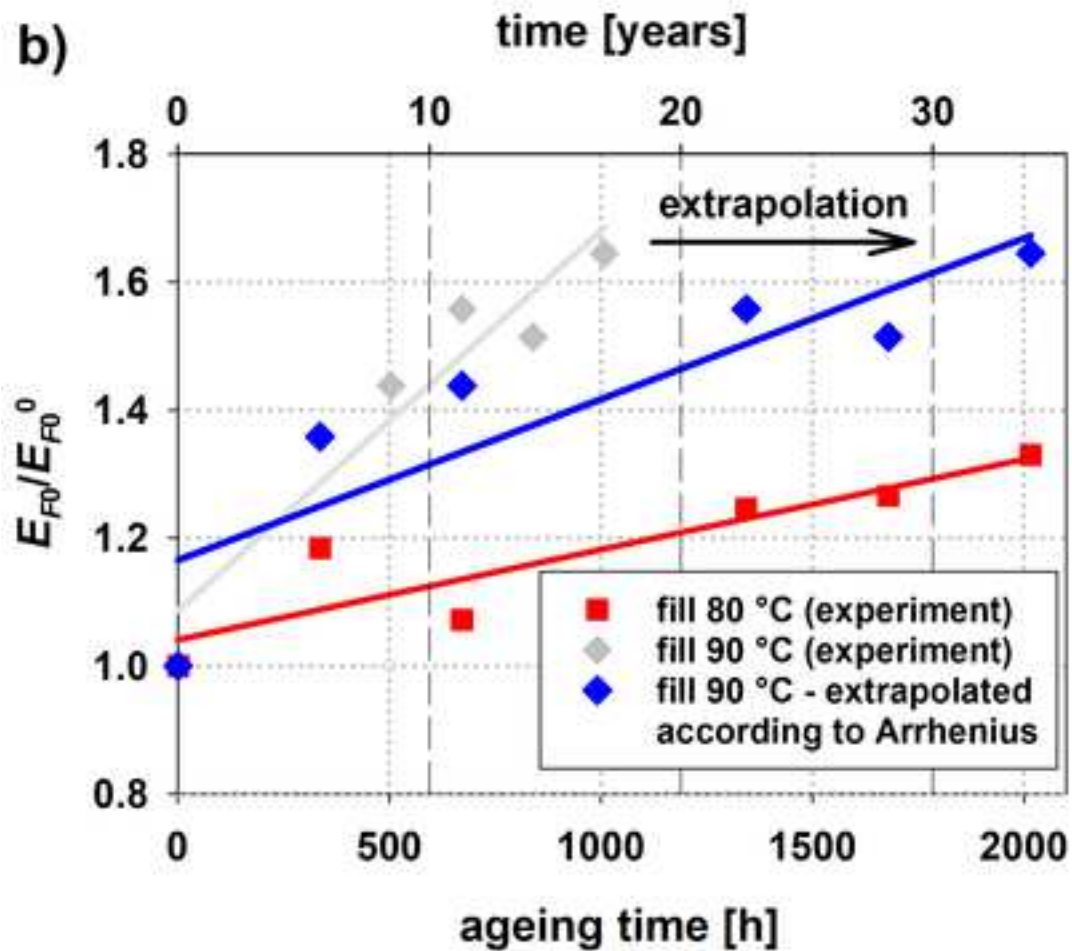
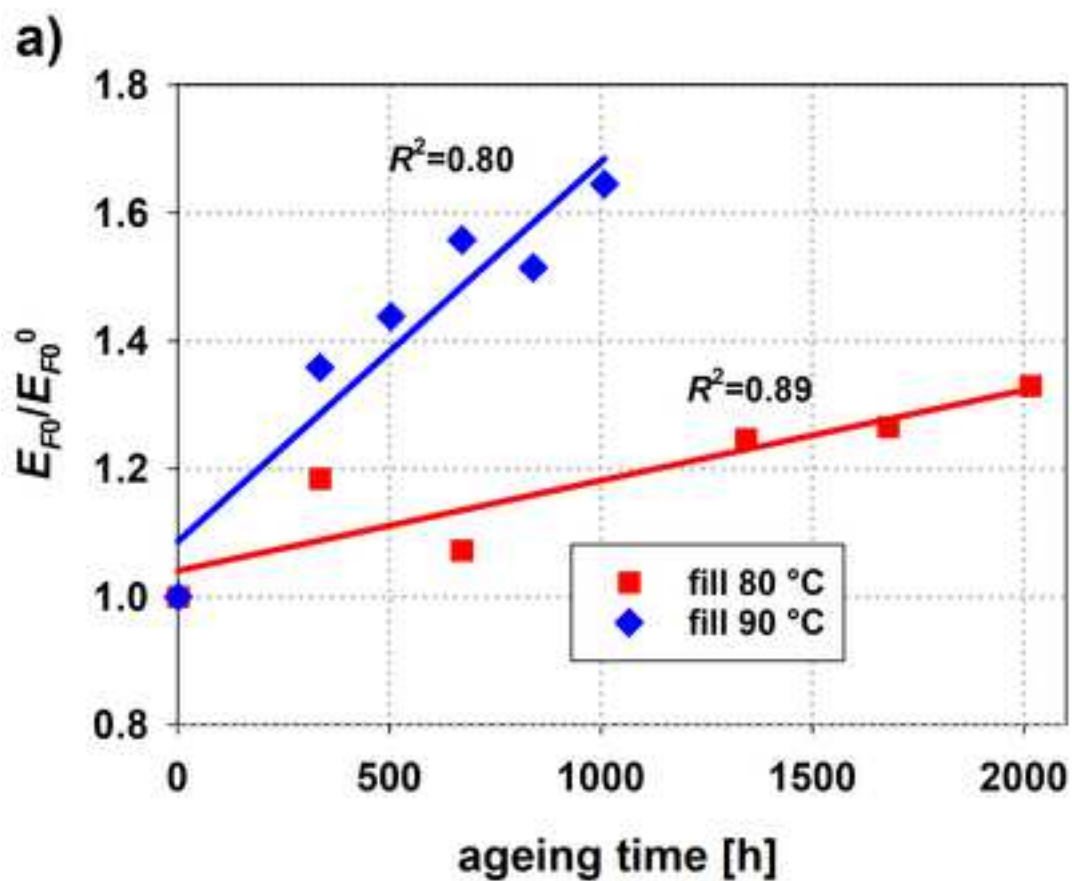
526 for technical fabrics. *Computers and Structures*. **187** (2017).

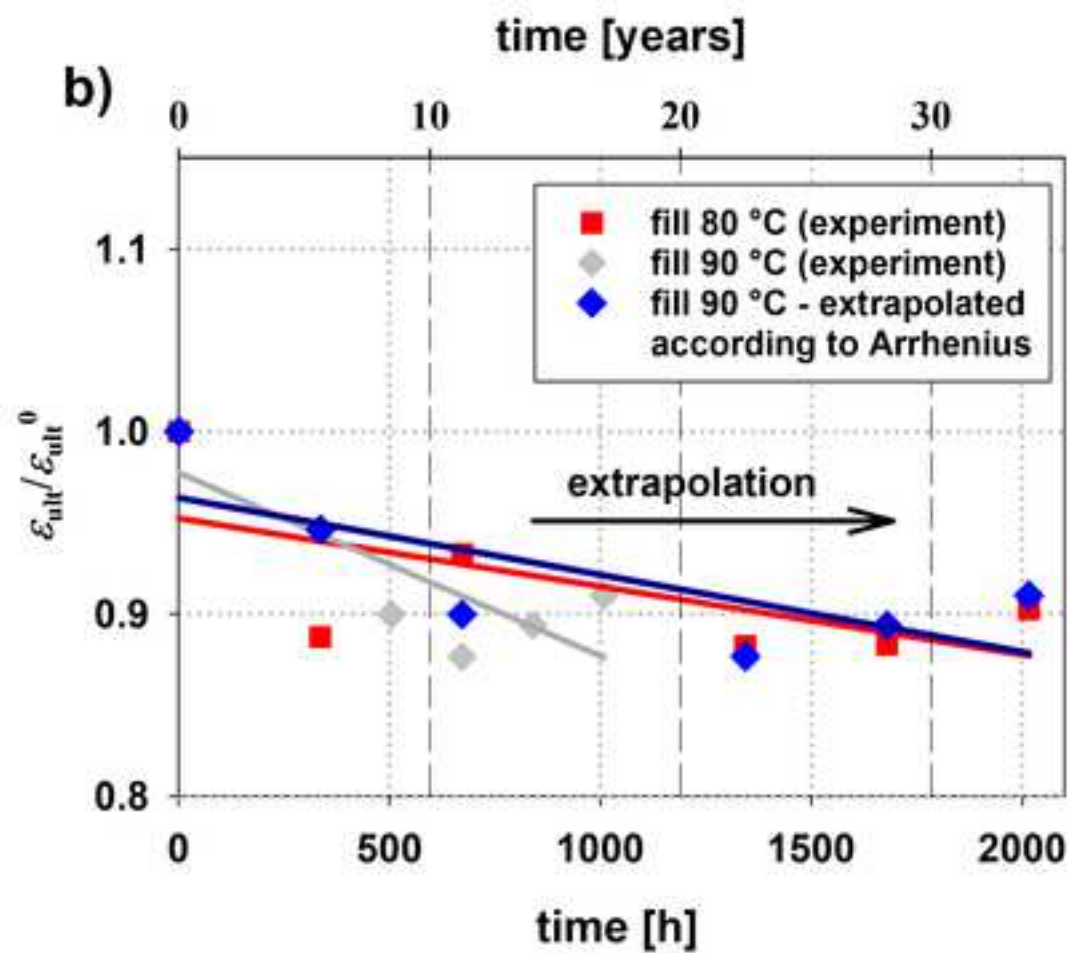
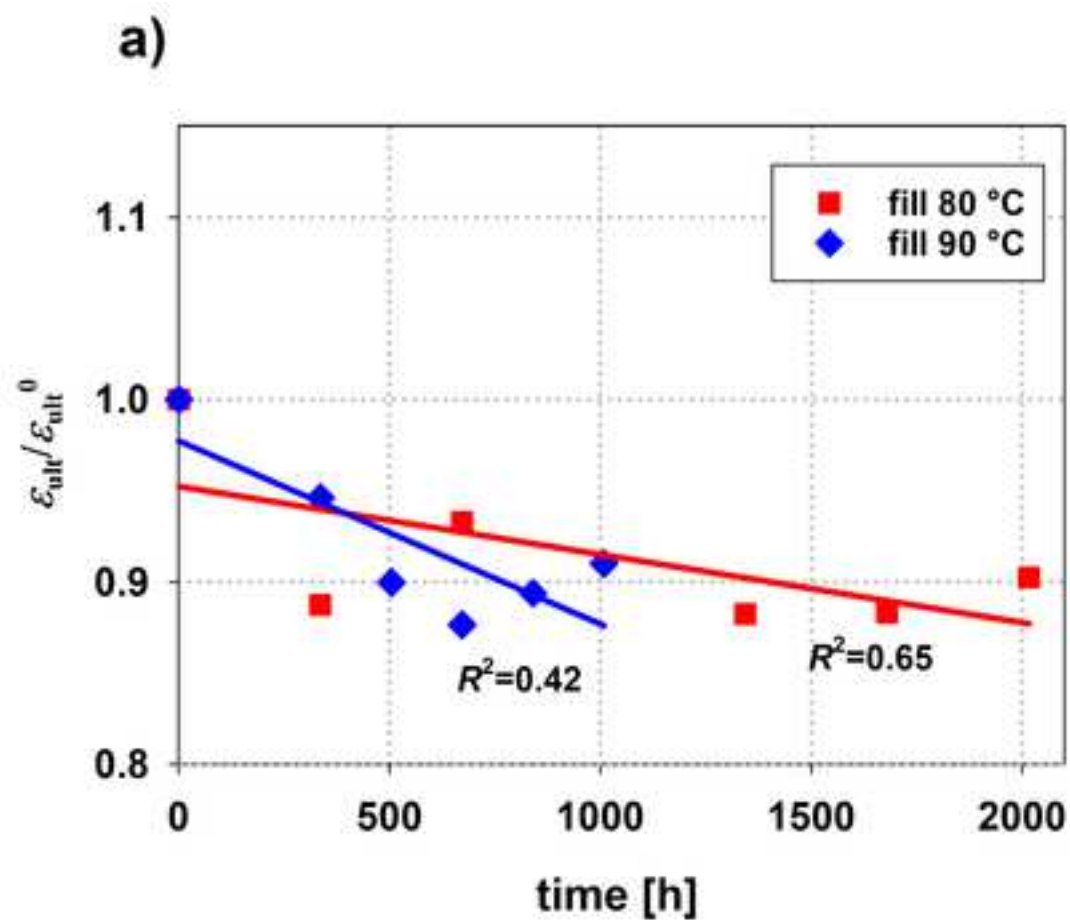
527 25. Zerdzicki, K. Durability evaluation of textile hanging roofs materials. Ph.D Thesis Gdansk

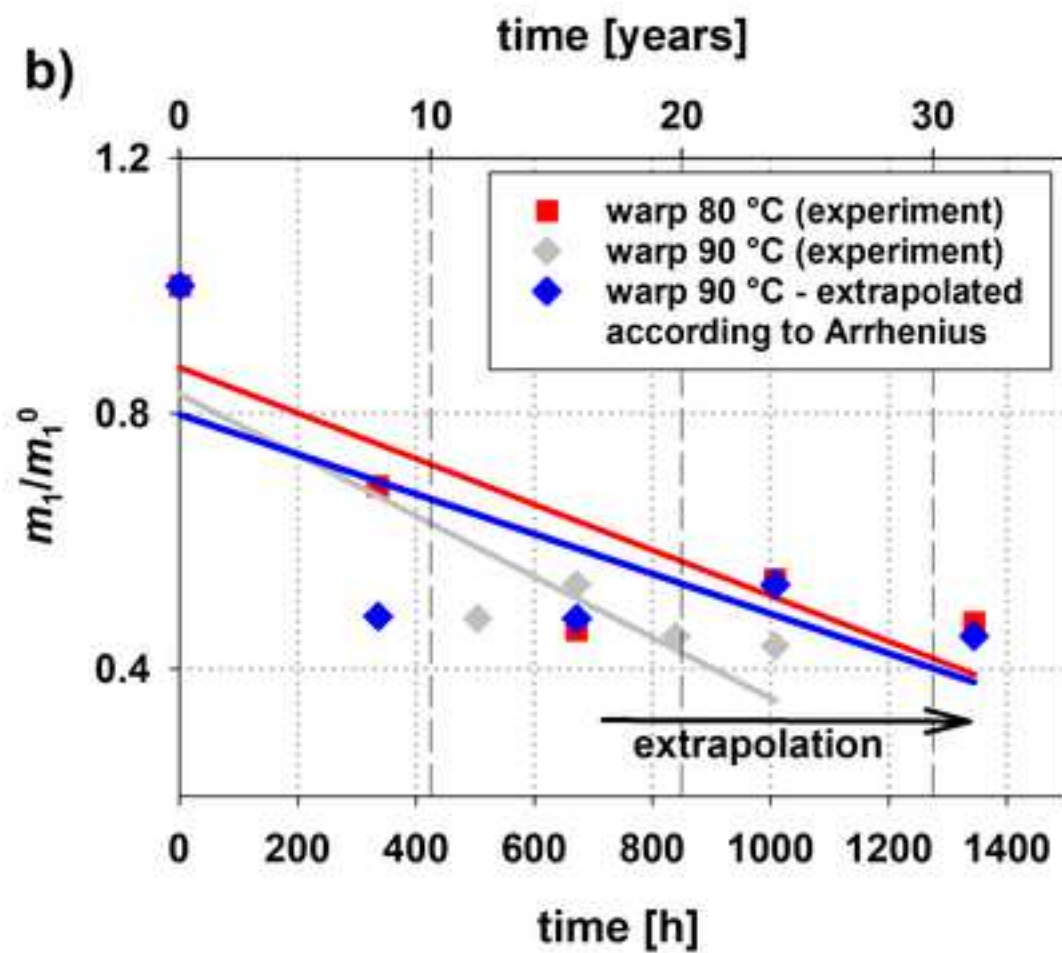
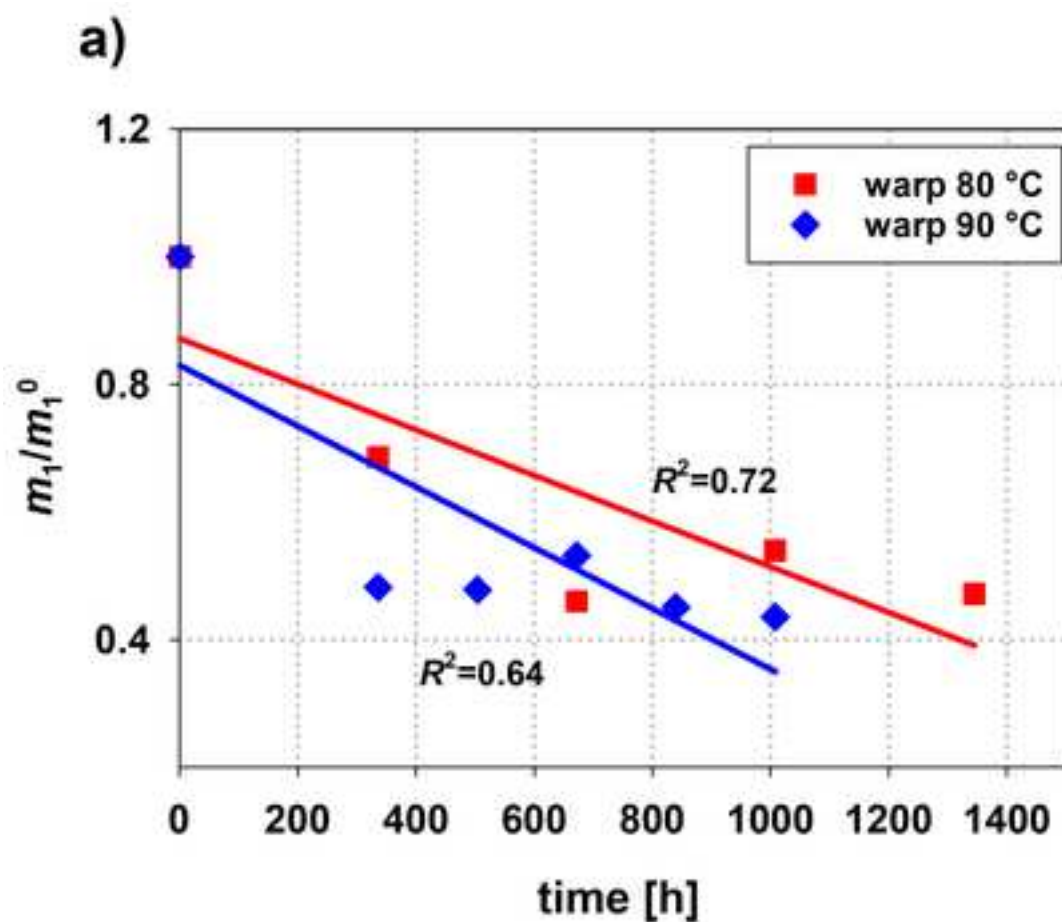
528 University of Technology (2015).
529 26. Bystritskaya, E. V., Pomerantsev, A. L., Rodionova, O. Y. Prediction of the aging of polymer
530 materials. *Chemometrics and Intelligent Laboratory Systems*. **47** (2), 175–178 (1999).
531 27. Hukins, D. W. L., Mahomed, A., Kukureka, S. N. Accelerated aging for testing polymeric
532 biomaterials and medical devices. *Medical Engineering and Physics*. **30** (10), 1270–1274 (2008).
533 28. Zerdzicki, K., Klosowski, P., Woznica, K. Influence of service ageing on polyester-reinforced
534 polyvinyl chloride-coated fabrics reported through mathematical material models. *Textile*
535 *Research Journal*. **89** (8), 1472–1487 (2019).
536 29. Klosowski, P., Zerdzicki, K., Woznica, K. Influence of artificial thermal ageing on polyester-
537 reinforced and polyvinyl chloride coated AF9032 technical fabric. *Textile Research Journal*. **89**
538 (21–22), 4632–4646 (2019).
539 30. Firdosh, S. et al. Durability of GFRP nanocomposites subjected to hygrothermal ageing.
540 *Composites Part B: Engineering*. **69**, 443–451 (2015).
541 31. Le Saux, V., Le Gac, P. Y., Marco, Y., Calloch, S. Limits in the validity of Arrhenius predictions
542 for field ageing of a silica filled polychloroprene in a marine environment. *Polymer Degradation*
543 *and Stability*. **99** (1), 254–261 (2014).
544

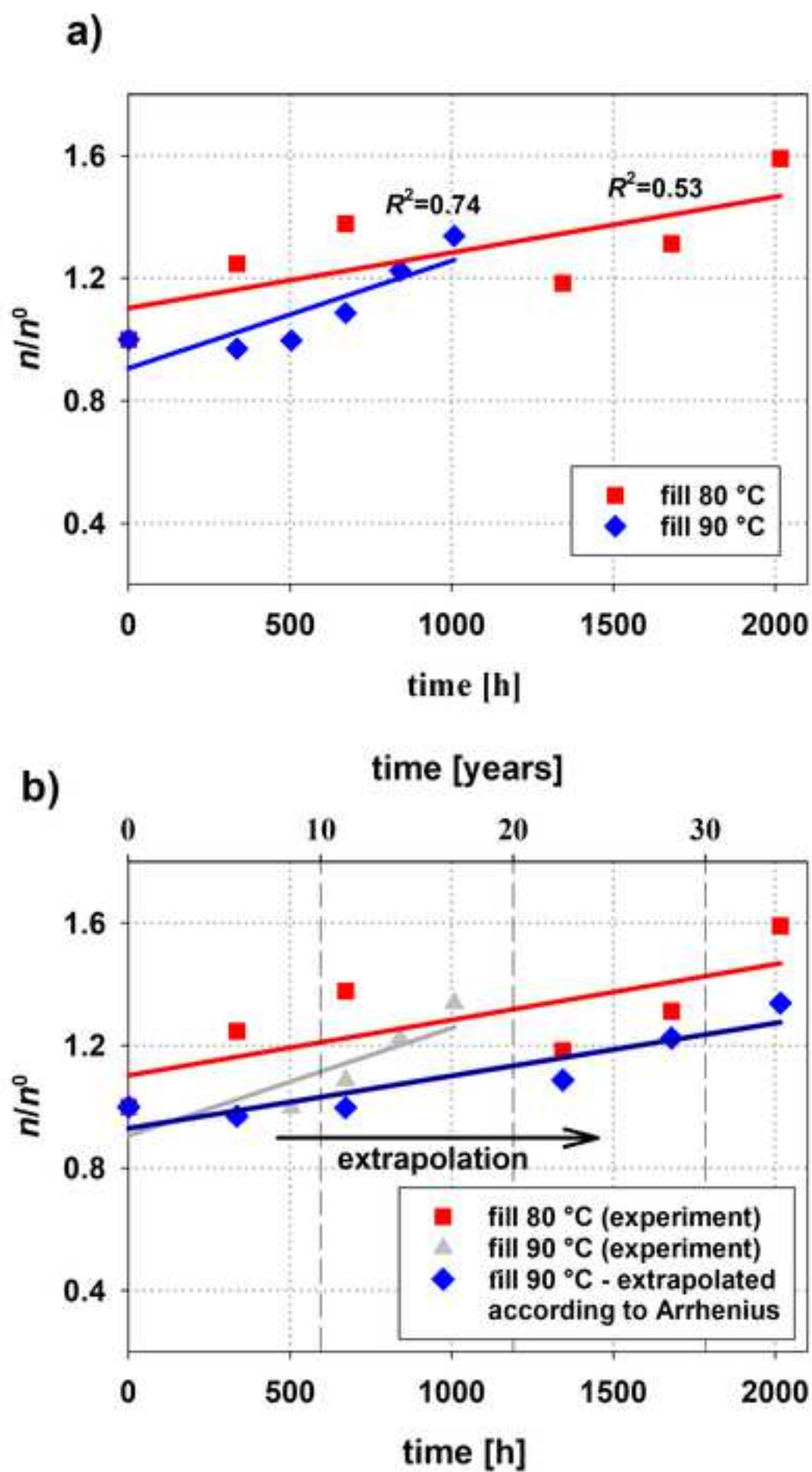












Inelastic strain rate	$\dot{\epsilon}^I = \dot{\rho} \text{sig}(\sigma)$
Cumulated inelastic strain rate	$\dot{\rho} = \frac{2D_0}{\sqrt{3}} \exp \left[- \left(\frac{Z}{ \sigma } \right)^{2n} \frac{n+1}{2n} \right]$
Additional equations	$Z = R + \sqrt{\frac{2}{3}} X \text{sgn}(\sigma)$ $\dot{W}^I = \sigma \dot{\epsilon}^I$
Isotropic hardening	$\dot{R} = m_1 (R_1 - R) \dot{W}^I, \quad R(t=0) = R_0$
Kinematic hardening	$\dot{X} = m_2 \left(\sqrt{\frac{3}{2}} D_1 \text{sgn}(\sigma) - X \right) \dot{W}^I$
Material parameters	$n, D_0, D_1, R_0, R_1, m_1, m_2$

Variable	T _{ref}	T	ΔT	f	Calculation example for 4 weeks of thermal ageing
Formulation	-	-	T-T _{ref}	$2^{(\Delta T/10)}$	f*4/52
Unit	°C	°C	°C	[-]	[years]
Results	8	80	72	147	11.3
		90	82	294	22.6

Laboratory ageing time [weeks]		1	2	3	4	5	6	7	8	9	10	11	12
Time according to Arrhenius [years]	80 °C	2.8	(5.7)	8.5	(11.3)	14.1	(17.0)	19.8	(22.6)	25.4	(28.3)	31.1	(33.9)
	90 °C	(5.7)	(11.3)	(17.0)	(22.6)	(28.3)	(33.9)	39.6	45.2	50.9	56.6	62.2	67.9

() marks the ageing tests performed in the present study and used to identify parameters.

Name of Material/Equipment	Company	Catalog Number	Comments/Description
AF 9032 technical fabric	Shelter-Rite Seaman Corporation		
knife of scissors			
marker			pernament
ruler			
Sigma Plot	Systat Software Inc.	v. 12.5	
Testing machine Z020	Zwick Roell	BT1-FR020TN.A50	
TestXpert II program	Zwick Roell	v. 3.50	
Thermal chamber	Eurotherm Controls	2408	
tubular spanner			13 mm
Video extensometer	Zwick Roell	BTC-EXVIDEO.PAC.3.2.EN	Instead of video extensometer, a mechanical one can be used
VideoXtens	Zwick Roell	5.28.0.0 SP2	

Gdansk University of Technology
Department of Civil and Environmental Engineering
Faculty of Structural Mechanics
ul. Narutowicza 11/12
PL-80-233 Gdańsk
Poland (Polska)
e-mail: klosow@pg.edu.pl

Gdańsk, October 10th 2019

Xiaoyan Cao

Review Editor: Journal of Visualized Experiments

Dear **Xiaoyan Cao**

I have pleasure to send you the new improved version of the manuscript entitled *“Experiments on artificial thermal ageing on polyester reinforced and polyvinyl chloride coated technical fabric”* written by Prof. Krzysztof Woźnica, PhD Krzysztof Żerdzicki and me, to be considered for publication in **JoVE**.

According to your remarks, we improved the manuscript. Due to short period for corrections it was impossible to find the native speaker to check the manuscript, but great amount of changes have been made according to the external language specialist suggestions. We put more details to the protocol, except of problems which need long explanations (in this situation we have made the references to other publications), or which will be clearly visible in the film (like number of grips or inserts of the machine – on the other hand this is the elementary knowledge of testing machines).

I hope you will find the paper after improvements worth to be published in **JoVE**.

Sincerely yours

Prof. Paweł Kłosowski



1 Alewife Center #200
Cambridge, MA 02140
tel. 617.945.9051
www.jove.com

ARTICLE AND VIDEO LICENSE AGREEMENT

Title of Article:

Experiments on artificial thermal ageing on polyester reinforced and

Author(s):

polyvinyl chloride coated technical fabric

Kłosowski Paweł, Żerdzicki Krzysztof, Woznica Krzysztof

Item 1: The Author elects to have the Materials be made available (as described at <http://www.jove.com/publish>) via:

☒ Standard Access

☐ Open Access

Item 2: Please select one of the following items:

☒ The Author is **NOT** a United States government employee.

☐ The Author is a United States government employee and the Materials were prepared in the course of his or her duties as a United States government employee.

☐ The Author is a United States government employee but the Materials were NOT prepared in the course of his or her duties as a United States government employee.

ARTICLE AND VIDEO LICENSE AGREEMENT

1. **Defined Terms.** As used in this Article and Video License Agreement, the following terms shall have the following meanings: **"Agreement"** means this Article and Video License Agreement; **"Article"** means the article specified on the last page of this Agreement, including any associated materials such as texts, figures, tables, artwork, abstracts, or summaries contained therein; **"Author"** means the author who is a signatory to this Agreement; **"Collective Work"** means a work, such as a periodical issue, anthology or encyclopedia, in which the Materials in their entirety in unmodified form, along with a number of other contributions, constituting separate and independent works in themselves, are assembled into a collective whole; **"CRC License"** means the Creative Commons Attribution-Non Commercial-No Derivs 3.0 Unported Agreement, the terms and conditions of which can be found at: <http://creativecommons.org/licenses/by-nc-nd/3.0/legalcode>; **"Derivative Work"** means a work based upon the Materials or upon the Materials and other pre-existing works, such as a translation, musical arrangement, dramatization, fictionalization, motion picture version, sound recording, art reproduction, abridgment, condensation, or any other form in which the Materials may be recast, transformed, or adapted; **"Institution"** means the institution, listed on the last page of this Agreement, by which the Author was employed at the time of the creation of the Materials; **"JoVE"** means MyJoVE Corporation, a Massachusetts corporation and the publisher of The Journal of Visualized Experiments; **"Materials"** means the Article and / or the Video; **"Parties"** means the Author and JoVE; **"Video"** means any video(s) made by the Author, alone or in conjunction with any other parties, or by JoVE or its affiliates or agents, individually or in collaboration with the Author or any other parties, incorporating all or any portion

of the Article, and in which the Author may or may not appear.

2. **Background.** The Author, who is the author of the Article, in order to ensure the dissemination and protection of the Article, desires to have the JoVE publish the Article and create and transmit videos based on the Article. In furtherance of such goals, the Parties desire to memorialize in this Agreement the respective rights of each Party in and to the Article and the Video.

3. **Grant of Rights in Article.** In consideration of JoVE agreeing to publish the Article, the Author hereby grants to JoVE, subject to **Sections 4** and **7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Article in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Article into other languages, create adaptations, summaries or extracts of the Article or other Derivative Works (including, without limitation, the Video) or Collective Works based on all or any portion of the Article and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and (c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. If the "Open Access" box has been checked in **Item 1** above, JoVE and the Author hereby grant to the public all such rights in the Article as provided in, but subject to all limitations and requirements set forth in, the CRC License.

ARTICLE AND VIDEO LICENSE AGREEMENT

4. **Retention of Rights in Article.** Notwithstanding the exclusive license granted to JoVE in **Section 3** above, the Author shall, with respect to the Article, retain the non-exclusive right to use all or part of the Article for the non-commercial purpose of giving lectures, presentations or teaching classes, and to post a copy of the Article on the Institution's website or the Author's personal website, in each case provided that a link to the Article on the JoVE website is provided and notice of JoVE's copyright in the Article is included. All non-copyright intellectual property rights in and to the Article, such as patent rights, shall remain with the Author.

5. **Grant of Rights in Video – Standard Access.** This **Section 5** applies if the "Standard Access" box has been checked in **Item 1** above or if no box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby acknowledges and agrees that, Subject to **Section 7** below, JoVE is and shall be the sole and exclusive owner of all rights of any nature, including, without limitation, all copyrights, in and to the Video. To the extent that, by law, the Author is deemed, now or at any time in the future, to have any rights of any nature in or to the Video, the Author hereby disclaims all such rights and transfers all such rights to JoVE.

6. **Grant of Rights in Video – Open Access.** This **Section 6** applies only if the "Open Access" box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby grants to JoVE, subject to **Section 7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Video in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Video into other languages, create adaptations, summaries or extracts of the Video or other Derivative Works or Collective Works based on all or any portion of the Video and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and (c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. For any Video to which this **Section 6** is applicable, JoVE and the Author hereby grant to the public all such rights in the Video as provided in, but subject to all limitations and requirements set forth in, the CRC License.

7. **Government Employees.** If the Author is a United States government employee and the Article was prepared in the course of his or her duties as a United States government employee, as indicated in **Item 2** above, and any of the licenses or grants granted by the Author hereunder exceed the scope of the 17 U.S.C. 403, then the rights granted hereunder shall be limited to the maximum

rights permitted under such statute. In such case, all provisions contained herein that are not in conflict with such statute shall remain in full force and effect, and all provisions contained herein that do so conflict shall be deemed to be amended so as to provide to JoVE the maximum rights permissible within such statute.

8. **Protection of the Work.** The Author(s) authorize JoVE to take steps in the Author(s) name and on their behalf if JoVE believes some third party could be infringing or might infringe the copyright of either the Author's Article and/or Video.

9. **Likeness, Privacy, Personality.** The Author hereby grants JoVE the right to use the Author's name, voice, likeness, picture, photograph, image, biography and performance in any way, commercial or otherwise, in connection with the Materials and the sale, promotion and distribution thereof. The Author hereby waives any and all rights he or she may have, relating to his or her appearance in the Video or otherwise relating to the Materials, under all applicable privacy, likeness, personality or similar laws.

10. **Author Warranties.** The Author represents and warrants that the Article is original, that it has not been published, that the copyright interest is owned by the Author (or, if more than one author is listed at the beginning of this Agreement, by such authors collectively) and has not been assigned, licensed, or otherwise transferred to any other party. The Author represents and warrants that the author(s) listed at the top of this Agreement are the only authors of the Materials. If more than one author is listed at the top of this Agreement and if any such author has not entered into a separate Article and Video License Agreement with JoVE relating to the Materials, the Author represents and warrants that the Author has been authorized by each of the other such authors to execute this Agreement on his or her behalf and to bind him or her with respect to the terms of this Agreement as if each of them had been a party hereto as an Author. The Author warrants that the use, reproduction, distribution, public or private performance or display, and/or modification of all or any portion of the Materials does not and will not violate, infringe and/or misappropriate the patent, trademark, intellectual property or other rights of any third party. The Author represents and warrants that it has and will continue to comply with all government, institutional and other regulations, including, without limitation all institutional, laboratory, hospital, ethical, human and animal treatment, privacy, and all other rules, regulations, laws, procedures or guidelines, applicable to the Materials, and that all research involving human and animal subjects has been approved by the Author's relevant institutional review board.

11. **JoVE Discretion.** If the Author requests the assistance of JoVE in producing the Video in the Author's facility, the Author shall ensure that the presence of JoVE employees, agents or independent contractors is in accordance with the relevant regulations of the Author's institution. If more than one author is listed at the beginning of this Agreement, JoVE may, in its sole

ARTICLE AND VIDEO LICENSE AGREEMENT

discretion, elect not take any action with respect to the Article until such time as it has received complete, executed Article and Video License Agreements from each such author. JoVE reserves the right, in its absolute and sole discretion and without giving any reason therefore, to accept or decline any work submitted to JoVE. JoVE and its employees, agents and independent contractors shall have full, unfettered access to the facilities of the Author or of the Author's institution as necessary to make the Video, whether actually published or not. JoVE has sole discretion as to the method of making and publishing the Materials, including, without limitation, to all decisions regarding editing, lighting, filming, timing of publication, if any, length, quality, content and the like.

12. **Indemnification.** The Author agrees to indemnify JoVE and/or its successors and assigns from and against any and all claims, costs, and expenses, including attorney's fees, arising out of any breach of any warranty or other representations contained herein. The Author further agrees to indemnify and hold harmless JoVE from and against any and all claims, costs, and expenses, including attorney's fees, resulting from the breach by the Author of any representation or warranty contained herein or from allegations or instances of violation of intellectual property rights, damage to the Author's or the Author's institution's facilities, fraud, libel, defamation, research, equipment, experiments, property damage, personal injury, violations of institutional, laboratory, hospital, ethical, human and animal treatment, privacy or other rules, regulations, laws, procedures or guidelines, liabilities and other losses or damages related in any way to the submission of work to JoVE, making of videos by JoVE, or publication in JoVE or elsewhere by JoVE. The Author shall be responsible for, and shall hold JoVE harmless from, damages caused by lack of sterilization, lack of cleanliness or by contamination due to

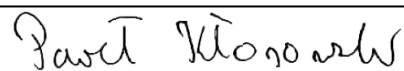
the making of a video by JoVE its employees, agents or independent contractors. All sterilization, cleanliness or decontamination procedures shall be solely the responsibility of the Author and shall be undertaken at the Author's expense. All indemnifications provided herein shall include JoVE's attorney's fees and costs related to said losses or damages. Such indemnification and holding harmless shall include such losses or damages incurred by, or in connection with, acts or omissions of JoVE, its employees, agents or independent contractors.

13. **Fees.** To cover the cost incurred for publication, JoVE must receive payment before production and publication of the Materials. Payment is due in 21 days of invoice. Should the Materials not be published due to an editorial or production decision, these funds will be returned to the Author. Withdrawal by the Author of any submitted Materials after final peer review approval will result in a US\$1,200 fee to cover pre-production expenses incurred by JoVE. If payment is not received by the completion of filming, production and publication of the Materials will be suspended until payment is received.

14. **Transfer, Governing Law.** This Agreement may be assigned by JoVE and shall inure to the benefits of any of JoVE's successors and assignees. This Agreement shall be governed and construed by the internal laws of the Commonwealth of Massachusetts without giving effect to any conflict of law provision thereunder. This Agreement may be executed in counterparts, each of which shall be deemed an original, but all of which together shall be deemed to be one and the same agreement. A signed copy of this Agreement delivered by facsimile, e-mail or other means of electronic transmission shall be deemed to have the same legal effect as delivery of an original signed copy of this Agreement.

A signed copy of this document must be sent with all new submissions. Only one Agreement is required per submission.

CORRESPONDING AUTHOR

Name:	Kłosowski Paweł	
Department:	Faculty of Civil and Environmental Engineering	
Institution:	Gdansk University of Technology	
Title:	Prof. dr hab. eng.	
Signature:		Date: 29.08.2019

Please submit a **signed** and **dated** copy of this license by one of the following three methods:

1. Upload an electronic version on the JoVE submission site
2. Fax the document to +1.866.381.2236
3. Mail the document to JoVE / Attn: JoVE Editorial / 1 Alewife Center #200 / Cambridge, MA 02140