FINITE ELEMENT SIMULATION ON TENSILE CREEP BEHAVIOUR OF UNDERGROUND SUPPORT LINER

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Abstract: *Polymer-based products are widely used as load-carrying components in different structural applications due to the ease of manufacture, installation, and long lifetime properties. In mining and tunnelling industry, fast-setting, thin polymer-based products are in demand as an underground support liner. Researchers have agreed that the time-dependent material properties of underground support liners have significance for short to long term applications. Although some creep tests were performed in literature, there is no available study on the numerical analysis/simulation of the creep behaviour of underground support liners. In this study, viscoelastic mathematical models developed for two different underground support liners were analyzed in ABAQUS finite element numerical modelling software with a developed subroutine. After the implementation, tensile creep test specimens were modelled to verify the new subroutine. There are two main purposes of the simulation of experiments; Firstly, to verify that the subroutine works in accordance with the actual behaviour of the material, secondly, to obtain realistic creep behaviour results for cases where experiments were not performed. As a result, a good agreement was obtained between the mathematical model predictions and numerical results for different stress levels. The proposed subroutines may create a basement for future numerical studies.*

Keywords: CREEP, THIN SPRAY-ON LINER, MINING, UNDERGROUND SUPPORT, FEM

1. Introduction

Support elements and systems have a crucial role to stabilize excavations and to reduce inward movement of the rock mass. Advancing deeper in underground mining has led to the necessity of different types of support systems by the help of the technological improvements[1]. Researches have extensively focused on the issues of developing support systems. These studies have assisted in the increase of various support systems with different functions. The product "Thin Spray-on Liner" (TSL) is developed as an alternative of widely used surface support materials, mainly shotcrete, in the beginning of 1990s. TSL's are fast-setting multicomponent polymeric materials applied on rock surface with a few mm thickness that have fairly high tensile strength, adhesion, and elongation capabilities. They are recently still being used only at around 150 mines and underground openings all around the world, as the support mechanism and time-dependent material properties are not fully understood yet. Laboratory tests and numerical studies have significant importance to understand the support mechanism and to make a comparison available for TSL products. Many different laboratory test setups are available in the literature. Those are creep, tensile strength, uniaxial compressive strength, punch, bonding strength, double sided shear strength, plate pull, linear block support, gap shear load, and coated core compression tests. In addition to laboratory studies, numerical studies are widely used tools in the last decade to simulate TSL laboratory testing and field conditions. These studies are summarized in Table 1.

Researchers have agreed that creep properties of TSL's being important design parameters and that creep might become a serious problem due to the polymer ingredients. Further research is needed to evaluate the performance of polymer liners under sustained loading conditions[2].

Although some creep tests were performed in literature[3,4], there is no available study on the numerical analysis or simulation of the creep behaviour of underground support liners..

In this study, viscoelastic mathematical models for two different underground support liners were developed and analyzed in ABAQUS finite element numerical modelling software with a developed subroutine. After the implementation, tensile creep test specimens were modelled to verify the new subroutine. There are two main aims of this study. The first one is to verify the subroutine acts in accordance with the actual behaviour of the material. The second is to obtain realistic creep behaviour results where the experiments were not performed.

Table 1: *Numerical TSL Studies in the Literature.*

Authors	Model purpose	Numerical method
Tannant and Wang (2003)[5]	Tensile, Block Punch tests and tunnel model	Discrete element
Malan and Napier (2008)[6]	Fractured underground excavation (square)	Boundary element
Richardson et al. (2009)[7]	Bending, Double sided shear test	Finite difference
Dirige and Archibald (2009)[8]	Underground excavation (horseshoe)	Finite difference
Nater and Mena-Cabrera (2010)[9]	Underground excavation (square)	Distinct element
Guner and Ozturk (2016)[10]	Tensile testing	Discrete element
Guner and Ozturk (2017)[11]	Tensile and compression testing	Finite element
Li et al. (2017) [12]	Gas permeability	Finite difference
Komurlu and Demir (2017) [13]	Linear block support	Finite element
Lee et al. (2018)[14]	Linear block support	Finite element

2. Materials and Creep Model

Numerical models were conducted for two widely used underground support liner products. Product A has two components; the liquid-component is a resin latex and the powder-component is a hydraulically curing powder based on special cement. Components are mixed with 2:1 liquid-powder ratio by weight. The tack-free time of the product was recorded as 30 minutes. Product B is a single component polymer-based powder in spray applications on rock faces for surface support purposes. The suggested mixing ratio is 2:1 powder/ water by weight. The tack-free time of the product was recorded as 5 minutes. It should be noted that Product A has cured for 1 day, on the other hand, Product B has cured for 2 days.

Depending on the loading conditions and environmental effects, polymeric materials can show different mechanical responses. They generally exhibit strong viscoelastic behaviour at room temperature.

Creep is a time and temperature-dependent behaviour and many different theoretical models have been used to describe viscoelastic behaviour of the material. Most of them are based on simple models consisting of springs and/or dashpots and try to describe the viscoelastic behaviour of various polymeric materials.

In this study, the nonlinear multi Kelvin–Voight modelling approach, which can be obtained from rheological models, was followed. The model is represented by Kelvin elements arranged in series, and a single spring. The single spring provides the elastic response and Kelvin elements provide the viscous response as shown in Fig. 1.

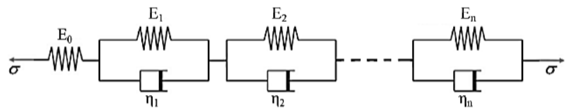

Fig. 1 *Multi Kelvin (Voigt) model*

Each Kelvin element in the series represent time intervals. Therefore, this model approach can be considered as suitable for longer testing periods. Based on the relationship between the constitutive elements, creep behaviour can be calculated as follows:

$$\varepsilon_t(t) = \frac{\sigma_n}{E_0} + \sum_{i=1}^{n} \frac{\sigma_n}{E_i} [1 - \exp(-t/\tau_i)] \quad (1)$$

where σ_n is the applied constant normal stress level, E_0 is the instantaneous elastic modulus, η_i and E_i are the dashpot viscosity and the spring stiffness of $_i$th Kelvin element. η_i/E_i is the retardation time (τ_i). To simplify calculations, researchers generally take retardation times (τ_i) as constant values for different models. In this study, τ1 was taken as 0.2 min and following retardation times were taken as 10 times of the previous Kelvin unit.

The experimental tensile creep test results and creep models used in this work have been reported by Guner and Ozturk (2019)[4]. Equation (1) was used to fit corresponding experimental creep curves using a computer routine providing a Levenberg-Marquardt algorithm. The 4 nonlinear viscoelastic models were generated for each product. Table 2 shows the model coefficients of the Multi Kelvin (Voigt) model.

Table 2: *Model Coefficients for Creep Models*[4]

Product A				
Stress (MPa)	K*	E0	E1	E2
1.06	4	21	1.45E+08	21
0.79	4	38	1.95E+07	72.07
0.53	6	52	9.18E+01	221.46
0.26	6	65	6.57E+01	40.7
Stress (MPa)	E3	E4	E5	E6
1.06	10.5	1.3	-	-
0.79	17.49	4.19	-	-
0.53	26.04	15.87	159.1	16.3
0.26	15.1	20.9	3590	20.4
Product B				
Stress (MPa)	K*	E0	E1	E2
1.46	4	28	5.10E+01	1.25E+02
1.10	4	116	6.59E+01	9.47E+01
0.74	3	140	1.77E+02	4.14E+01
0.37	3	205	3.26E+07	1.41E+02
Stress (MPa)	E3		E4	
1.46	1.94E+00		-	
1.10	7.78E+00		-	
0.74	1.31E+01		1.23E+01	
0.37	1.65E+01		5.68E+01	

*Number of Kelvin Elements

This multi Kelvin model was represented as a subroutine in ABAQUS.

3. FEM Implementation of the Multi Kelvin Model

In ABAQUS software, 5 different creep laws are available. These laws are the power, the hyperbolic-sine, the Anand, the Darveaux, and the double power. Although, these default creep models provide significant convenience to the user, in some practical cases material creep behaviours are typically of very complex form to fit experimental data. Therefore, the creep laws are frequently user-defined via the use of user subroutine CREEP and included in a generic time-dependent, material formulation. Multi Kelvin or Voigt model is not standard model in ABAQUS and hence needed to be incorporated via the CREEP user subroutine.

In order to create the user-defined creep model in ABAQUS, the elastic material behaviour should be defined first. In the creep experiments, the instantaneous strain change that occurs when the samples are sustained under constant load is called elastic strain (ε_e). This elastic strain value also depends on the stress applied in the experiments performed under the same curing time. The parameter which controls the elastic strain behaviour is called the instantaneous elastic modulus (E_0), as mentioned in the previous section. E_0 values, presented in Table 2, depend on the applied stress levels. The relationship between E_0 and applied stress is presented in Fig.2.

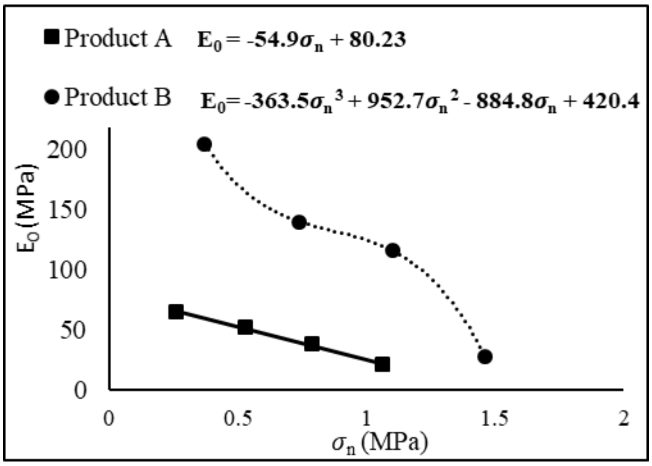

Fig. 2 *The relationship between E_0 and σ_n*

In this context, to specify the predefined field variables (E_0) called "UFIELD" in the software, the user subroutine was prepared by using the relationship presented in Fig 2.

Since the instantaneous strain change occurs when the samples are sustained under constant load, creep is not active in this step. It is recommended that small times step compared to the creep time be used in these steps. Therefore, this time step in which the sample takes instantaneous strain was taken as 0.01 minutes.

CREEP user subroutine defines the increments of inelastic creep strain as functions of the solution dependent variables, such as the deviatoric stress, pressure, temperature, and time increment Δt[15]. A general creep equation (equation 1) is required to be discretized to fit available integration schemes. The derivative of the proposed Multi-Kelvin model has been defined on the assumption that the subroutine will be used with implicit integration. A user subroutine CREEP was coded in Fortran by using the obtained model coefficients. The validation of the developed creep model and the previously extracted parameters was performed using a tensile creep model.

The mesh structure of the tensile creep sample formed in this context is presented in Fig. 3. The meshed geometry consists of rectangles with 20 nodes and 1488 elements (C3D20R). The C3D20R element is a general-purpose quadratic brick element, with reduced integration (2x2x2 integration points).

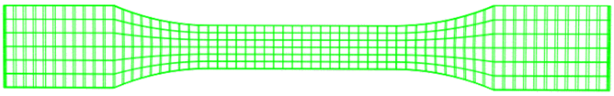

Fig. 3 *The mesh geometry of the specimen*

In FE creep test validation, first of all, the simulations of experiments were carried out for 4 stress levels in which the experiments were performed. It should be noted that validations were carried out with different subroutines for each product. At the end of the analysis, the experimental data were compared with the Multi-Kelvin model and finite element model results and highly consistent results were obtained. The software outputs showing the total strain values and strain distributions at the moment of rupture in the Finite Element validation models prepared for two different TSLs are presented in Fig. 4 and Fig. 5.

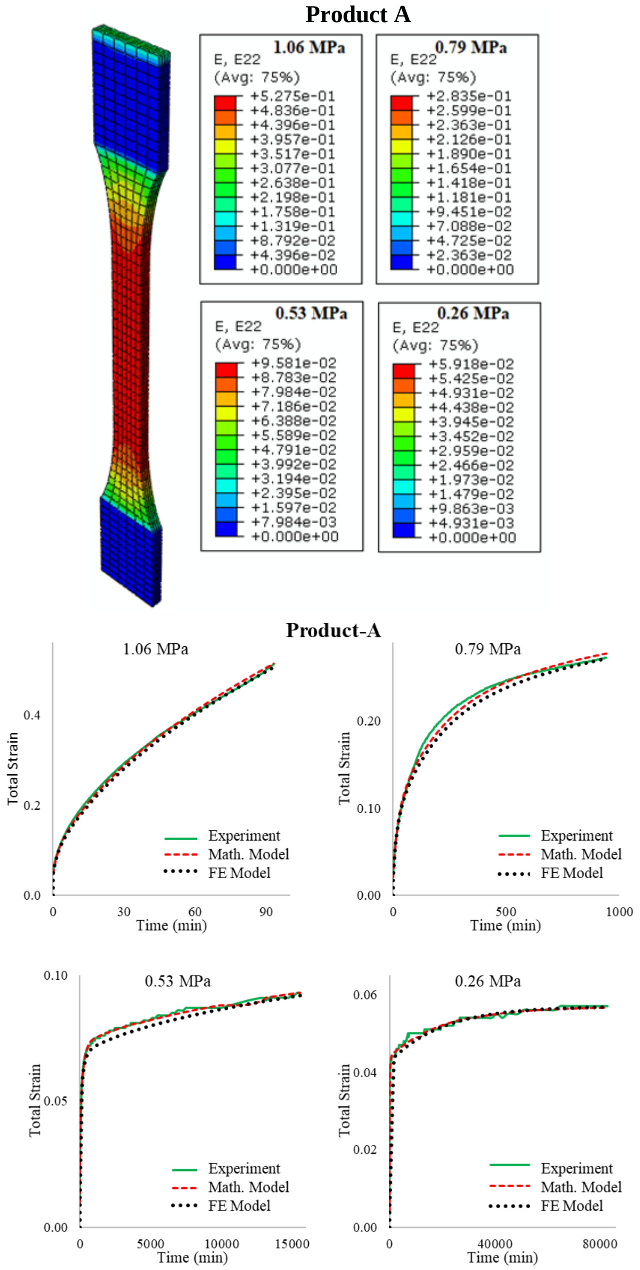

Fig. 4 *FE creep modelling comparisons for Product A*

The second aim of this study is to obtain realistic creep behaviour results for cases where experiments were not performed. Therefore, in addition to the model validation studies, additional validation models for Product B were performed to ensure that the creep behaviour was consistent in the intermediate stress levels.

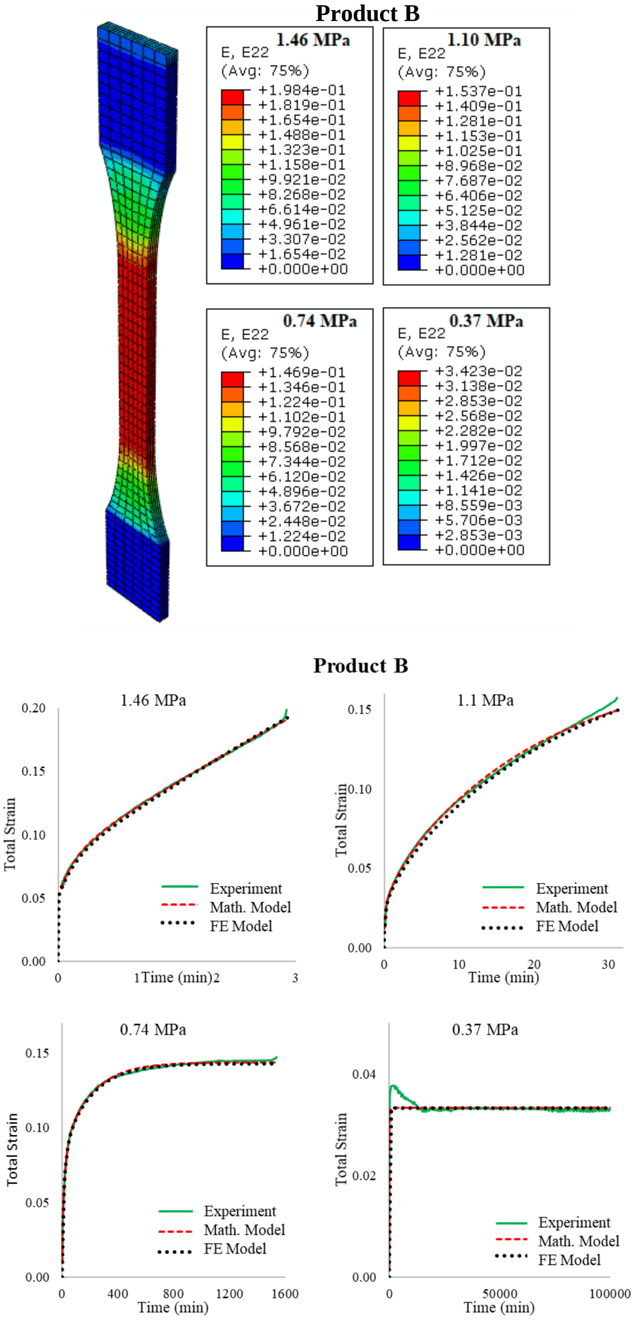

Fig. 5 *FE creep modelling comparisons for Product B*

For additional validation models, constant stress values of 1.27, 0.92, and 0.56 MPa were applied to the sample, respectively. The strain-time graphs of the models under these stress values are presented in Fig. 6. As testing duration varies from a few minutes to 2 months, for the better understanding of the behaviour, the first 100 minutes and the whole graph (log scale) are presented separately. Besides, the failure envelope obtained at the end of the experiments can be seen in the graphs.

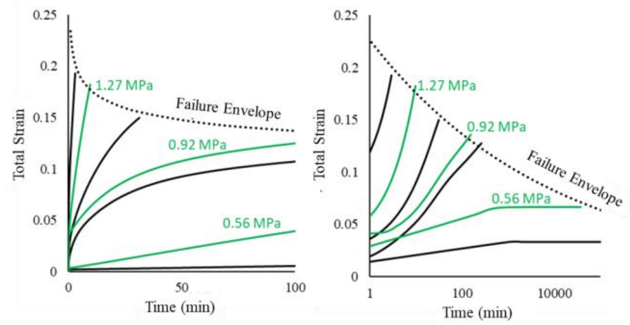

Fig. 5 *FE creep modelling for intermediate stress levels*

As a result of the validation models, The correlation between the experimental creep strain, Multi Kelvin creep model, and numerical creep strain obtained using ABAQUS Finite Element Analysis were found to be adequate.

4. Conclusions

This study presents the numerical model implementation of the generated viscoelastic creep mathematical models for two different underground support liners. Multi Kelvin mathematical models were introduced to ABAQUS finite element numerical modelling software with a developed subroutine. After the implementation, tensile creep test specimens were modelled to verify the new subroutine. Since the instantaneous elastic strain part depends on the applied stress levels, user subroutine UFIELD was used in this section. The creep component was successfully modelled in CREEP user subroutine employing a Multi Kelvin model. The developed subroutines may be used as an input parameter in future large scale numerical studies of time-dependent behaviour of surface support liners.

References

1. Villaescusa, E., 2014. Geotechnical design for sublevel open stoping. CRC Press, London. doi:10.1201/b16702-4.
2. Kuijpers, J.S., Sellers, E.J., Toper, A.Z., Rangasamy, T., Ward, T., Van Rensburg, A.J., Yilmaz, H., Stacey, R., 2004. Required technical specifications and standard testing methodology for thin sprayed linings. SIMRAC Final Report. Research agency: CSIR Division of Mining Technology. Project No: SIM 020206, Report No: 2004-0404.
3. Guner, D., & Ozturk, H. (2018). Creep behaviour investigation of a thin spray-on liner. International Journal of Rock Mechanics and Mining Sciences, 108, 58-66.
4. Guner, D., & Ozturk, H. (2019). Experimental and modelling study on nonlinear time-dependent behaviour of thin spray-on liner. Tunnelling and Underground Space Technology, 84, 306-316.
5. Tannant, D.D, & Wang, C, (2003), “Thin Tunnel Liners Modelled With Particle Flow Code”. Engineering Computations, Vol.21, pp. 318-341.
6. Malan, D.F., & Napier, J.A.L.(2008). Numerıcal Modelling of Tunnel Liner and Fracture Interaction. 6th. International Symposium on Ground Support in Mining and Civil Engineering Construction, SA.
7. Richardson, J., Mitra, R., & Saydam, S., (2009). Investigation of Thin Spray-On Liners using Numerical Modeling”. ARMA, American Rock Mechanics Association, Asheville.
8. Dirige, A., &Archibald, J. (2009), Numerical Modeling Simulations of Spray-on Liners Support Potential in Highly Stressed and Rockburst Prone Rock Conditions”. Proceedings of the 3rd CANUS Rock Mechanics Symposium, Toronto.
9. Nater, P., & Mena-Cabrera, A. (2010). Thin Sprayed Liners - an Approach With Numerical Models. International Society for Rock Mechanics. Eurock 2010.
10. Guner, D. & Ozturk, H. (2016). Experimental and Numerical Analysis of the Effects of Curing Time on Tensile Mechanical Properties of Thin Spray-on Liners Rock Mech Rock Eng (2016) 49: 3205. doi:10.1007/s00603-016-0997-x.
11. Guner, D. & Ozturk, H. (2017). Mechanical Property Comparison of Thin Spray-on Liners Under Tension and Compression. 25th International Congress and Exhibition of Tukey (IMCET 2017), Antalya, Turkey
12. Li, Z., Hussain, F., Mitra, R., & Saydam, S. (2017). A numerical evaluation of using thin spray-on liners for coal mine gas management. Journal of Natural Gas Science and Engineering, 45, 747-760.
13. Komurlu, E., & Demir, AD, (2017). A Numerical Modelling Study on Performance of Thin Spray-on (TSL) Liners. 25th International Congress and Exhibition of Tukey (IMCET 2017), Antalya, Turkey, pp. 105-112
14. Lee, K., Kim, D., Chang, S. H., Choi, S. W., Park, B., & Lee, C. (2018). Numerical approach to assessing the contact characteristics of a polymer-based waterproof membrane. Tunnelling and Underground Space Technology, 79, 242-249.
15. Daver, F., Kajtaz, M., Brandt, M., & Shanks, R. (2016). Creep and recovery behaviour of polyolefin-rubber nanocomposites developed for additive manufacturing. Polymers, 8(12), 437.