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Reliable simulation of PTFE seals: Bridging short- and long-term performance

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Reliable simulation-driven development of sealing solutions requires material models that remain predictive over a wide range of thermomechanical conditions encountered during both assembly and service. PTFE-based sealing materials are particularly challenging in this regard because of their strong dependence on strain, strain rate and temperature. This study builds on and further validates a previously proposed phenomenological constitutive model for PTFE, based on a multi-process rheological framework combined with the SKF strain-modified Eyring formulation. Model parameters are identified from short-term quasi-static uniaxial tensile experiments on unfilled and glass-filled PTFE. The calibrated model is shown to accurately predict the long-term relaxation behaviour under uniaxial tension over a broad range of temperatures and strain levels. Consequently, the model demonstrates outstanding ability to replicate seal radial load response across different shaft diameters and temperatures for both unfilled and glass-filled PTFE seals, highlighting its predictive capability under application-relevant conditions. The framework was further extended to bronze-filled PTFE, where the same modelling methodology yields excellent agreement between model predictions and experimental measurements.

1 Introduction

Driven by the digitalization megatrend, the increasing use of virtual simulation tools in product and process development has made material modelling a key enabler. In sealing applications, this requires material models that remain valid over a broad range of thermomechanical conditions encountered during both assembly and operation. Their reliability, however, ultimately depends on how well they capture the short- and long-term deformation mechanisms governing the material response.

Developing such models is particularly challenging for polymeric sealing materials, whose mechanical response depends strongly on temperature, strain rate and strain level. For polytetrafluoroethylene (PTFE), a widely used sealing material due to its chemical inertness and thermal stability [1], this complexity is further increased by its semicrystalline morphology and the associated molecular transition mechanisms in the amorphous and crystalline phases. Consequently, conventional modelling approaches often fail to capture all relevant dependencies within a single framework.

To address these challenges, a phenomenological constitutive model for PTFE was previously presented at the 22nd International Sealing Conference (ISC) [2]. Built on a multi-process rheological framework, the model incorporates a novel SKF strain-modified Eyring formulation in which the kinetic parameters evolve with accumulated plastic strain. This enables the model to capture the pronounced strain dependence of PTFE together with its sensitivity to strain rate and temperature.

Building on this earlier work, the present study focuses on extending the validation of this framework to other PTFE materials and sealing applications. Model parameters are identified from short-term quasi-static tensile experiments, and the calibrated model is subsequently used, without additional fitting, to predict long-term stress relaxation over a range of temperatures and strain levels. Its predictive capability is further validated through comparison with radial load measurements on PTFE seals for different shaft diameters and temperatures. By validating the model against actual seal performance, this study examines the extent to which short-term laboratory characterisation can be translated into reliable predictions of seal behaviour under application relevant conditions.

2 Experimental method

2.1 Uniaxial tension for material characterization

Two materials were investigated in this study: Unfilled PTFE and 30 wt.% glass filled PTFE. Uniaxial tensile experiments were conducted using a universal testing machine equipped with a 10 kN load cell. The testing procedure consisted of two subsequential phases: a **loading phase** followed by a **stress relaxation phase**. During the loading phase, samples were subjected to a constant crosshead displacement rate until a predefined strain level was reached. In the relaxation phase, the imposed strain was held constant for a period of one hour, during which the decay of stress over time was recorded. This experimental approach is designed to replicate service-relevant conditions encountered in sealing applications. Specifically, the loading phase simulates the assembly of a seal onto a shaft causing a sealing lip force, whereas the relaxation phase reflects the gradual reduction of seal stresses and resulting lip force under operating conditions after installation.

To investigate strain-rate sensitivity, two nominal strain rates of 0.1 s^{-1} and 0.02 s^{-1} were applied during the loading phase, controlled using the crosshead. The influence of temperature was also examined by conducting experiments at various controlled temperatures using a thermal chamber. Liquid nitrogen was used to achieve and precisely control temperatures below ambient conditions. During the relaxation phase, the effect of strain level on stress relaxation behaviour was assessed by stopping the loading phase at three distinct strain levels for each combination of strain rate and temperature. The complete test matrix, including all experimental conditions, is summarized in **Table 1**. For each test condition, two specimens were tested to ensure repeatability.

Tensile test samples were prepared in a stripe geometry, as illustrated in **Figure 1**, with dimensions of 40*10*2 mm^3. A gauge length of 20 mm was defined, with an additional gripping length of 10 mm on either side of the gauge. To prevent slippage during testing, sandpaper (SP) tabs were used in the gripping region. Strain measurements were obtained using a video extensometer, ensuring high accuracy, with a measurement gauge length of 10 mm. Following each experiment, the recorded engineering stress-strain data were converted to true stress and true strain using the expressions provided in equation (**1**).

$$\varepsilon_t = \ln(1+\varepsilon) \; ; \; \sigma_t = \sigma(1+\varepsilon) \qquad (1)$$

where ε_t is the true strain and σ_t is the true stress, ε is the engineering strain measured via the video extensometer and σ is the engineering stress measured via the load cell.

Table 1: Test matrix for unfilled and filled PTFE materials. An asterisk (*) indicates temperatures at which no stress-relaxation experiments were performed.

Material	Temperatures [°C]	Strain rates [s^{-1}]	True strains [%]
Unfilled PTFE	5*, 23, 50, 80, 100*, 120, 150*	0.1, 0.02	5, 16, 28
Glass filled PTFE	23, 50, 80, 100, 120*, 150*	0.1, 0.02	5, 16, 28

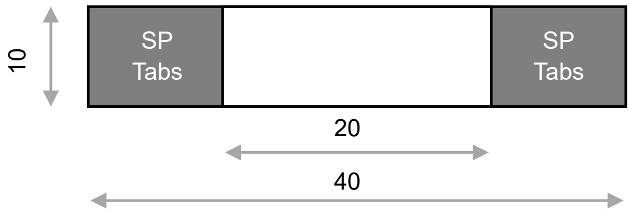

Figure 1: Schematic representation of tensile test samples. All dimensions in mm.

2.2 Radial load measurement for model validation

To evaluate the reliability and accuracy of the developed material model, its predictive capability was validated against experimentally measured seal behaviour. Radial load measurements, as illustrated in **Figure 2**, were conducted on both unfilled and glass-filled PTFE seals. The effect of temperature was evaluated by performing experiments at three temperatures: ambient temperature, 65°C, and 90°C.

The elevated test temperatures were carefully chosen to be different from those used for model calibration, thereby providing an independent validation of the model. Furthermore, at elevated temperatures, the seals were conditioned in the temperature chamber for 10 minutes to ensure thermal equilibrium before being mounted on the shaft. For each test condition, measurements were carried out on two seals to check the repeatability of the results and the reliability of the experimental setup.

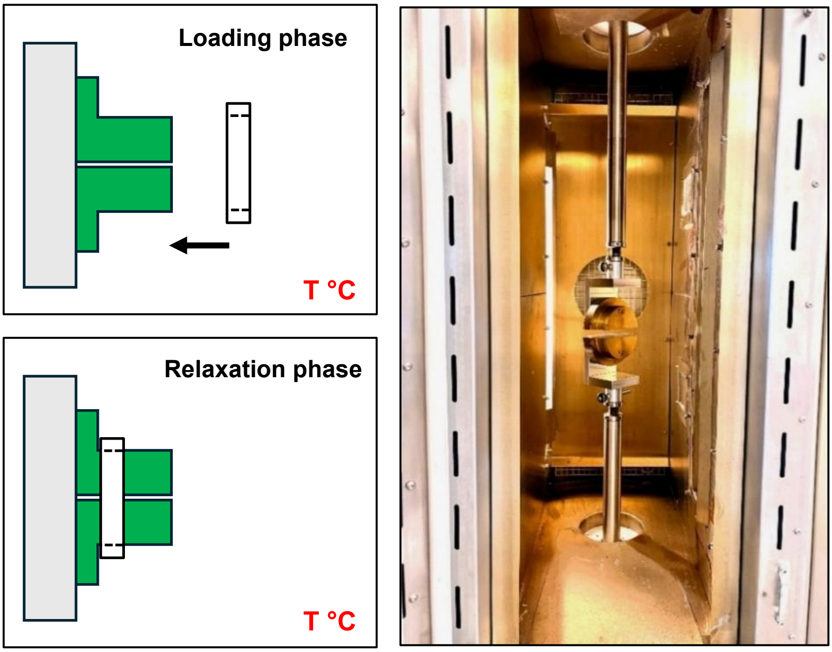

Figure 2: Radial load testing of PTFE seals at different temperatures

3 Model framework for the time-dependent behaviour of PTFE

In order to capture the complex, non-linear elastoviscoplastic behaviour of PTFE, a constitutive model was presented previously in the 22nd International Sealing Conference [2]. The proposed model follows the phenomenological decomposition of the total stress (σ) by Haward and Thackray [3]: A **driving stress** (σ_d) governing intermolecular interactions at small deformations, and a **hardening stress** (σ_h) capturing strain hardening from the entanglement network at large deformations as shown in equation (**2**).

$$\sigma = \sigma_d + \sigma_h \qquad (\mathbf{2})$$

The driving stress is represented by a hyperelastic spring connected in series with a non-linear dashpot while the hardening stress is modelled as a standalone hyperelastic spring. Moreover, both our previous work and findings reported in the literature have shown that PTFE exhibits thermorheologically complex behaviour, with stress contributions arising from two distinct molecular processes: the α-relaxation of the amorphous phase and the β-transition of the crystalline phase [2],

[4]. In the model architecture, each process is represented by multiple spring-dashpot branches, accommodating a spectrum of relaxation times. The final mechanical analogue of the proposed model is illustrated in **Figure 3**.

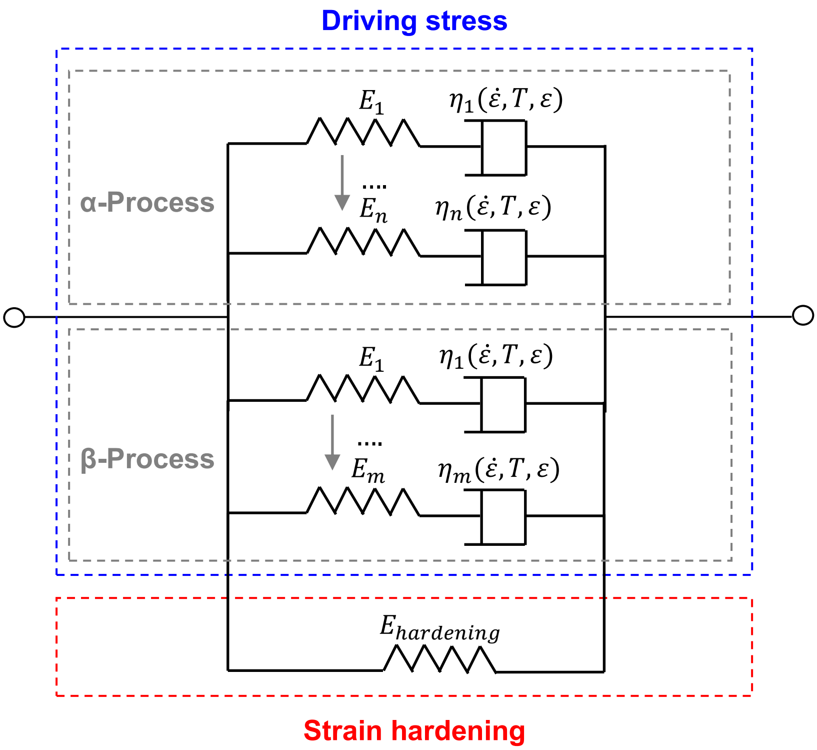

***Figure 3**: Mechanical analogue of a two process model for PTFE*

The yield kinetics are described using the Ree-Eyring equation [5], where both processes are known to act simultaneously with the stresses being additive in nature, as shown below in equation (**3**).

$$\sigma_y = \sum_{i=\alpha,\beta} \frac{kT}{V_i^*} \sinh^{-1}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0,i}} \exp\left(\frac{\Delta U_i}{RT}\right)\right) \quad (\mathbf{3})$$

However, it was also shown that the conventional Ree-Eyring formulation has a limitation in capturing the strong strain dependency of PTFE, particularly in the post-yield regime [2]. To address this, a novel **SKF strain modified Eyring equation** was introduced [2] as depicted in equation (**4**), wherein the thermodynamic constant ($\dot{\varepsilon}_0$), the activation energy (ΔU) and the activation volume (V^*) evolve continuously with plastic strain (ε_p), transitioning from initial to final value as expressed in equations

(**5**), (**6**) and (**7**). This modification enables the model to consistently capture strain rate-, temperature-, and strain-dependent behaviour across both short-term quasi-static loading and long-term transient relaxation regimes.

$$\dot{\varepsilon} = \dot{\varepsilon}_0(\varepsilon_p) * \sinh\left(\frac{qV^*(\varepsilon_p)}{kT}\right) \exp\left(\frac{\Delta U(\varepsilon_p)}{R}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}}\right)\right) \quad (4)$$

$$V^*(\varepsilon_p) = f(V^*_{\mathrm{initial}}, V^*_{\mathrm{final}}, \varepsilon_p, \varepsilon_0) \quad (5)$$

$$\Delta U(\varepsilon_p) = f(\Delta U_{\mathrm{initial}}, \Delta U_{\mathrm{final}}, \varepsilon_p, \varepsilon_0) \quad (6)$$

$$\dot{\varepsilon}_0(\varepsilon_p) = f(\dot{\varepsilon}_{0,\mathrm{initial}}, \dot{\varepsilon}_{0,\mathrm{final}}, \varepsilon_p, \varepsilon_0) \quad (7)$$

Furthermore, the model is implemented within the Parallel Rheological Framework available in the ABAQUS finite element software package. It is worth noting that the framework is inherently modular, enabling systematic simplification depending on the material of interest. For example, the strain dependency can be deactivated for simpler linear viscoelastic materials, the dashpot can be reduced to a Newtonian formulation when sufficient, and the model can be confined to a single-process version for thermorheologically simple polymers. Owing to this flexibility, the proposed formulation offers a general constitutive framework applicable to a broad class of polymeric sealing materials, including elastomers and thermoplastic polyurethanes (TPUs) and across various application conditions

4 Results and discussion

4.1 Analysis and identification of model parameters under short-term quasi-static behaviour

In order to identify the parameters for both the materials under study, the model was calibrated using the short-term uniaxial true stress-strain data obtained during the loading phase. These datasets, depicted in **Figure 4** (a) and (b) for unfilled and glass filled PTFE respectively, highlight the pronounced sensitivity of the stress response to loading conditions. This behaviour reflects the inherent time-dependent nature of PTFE, where an increase in strain rate or a decrease in temperature leads to higher stress levels at a given strain, and vice versa.

A clear yield point cannot be directly identified from the true stress–strain curves in **Figure 4** (a) and (b). Instead, the yield point was approximated by the intersection of two characteristic slopes: the initial slope associated with the viscoelastic regime and the subsequent slope corresponding to strain hardening at larger deformations [2]. Based on this approach, the yield kinetics of unfilled and glass-filled PTFE are illustrated in **Figure 4** (c) and (d) respectively, where markers are experimental data and solid lines are fit using equation (**3**) and parameters listed in **Table 2**.

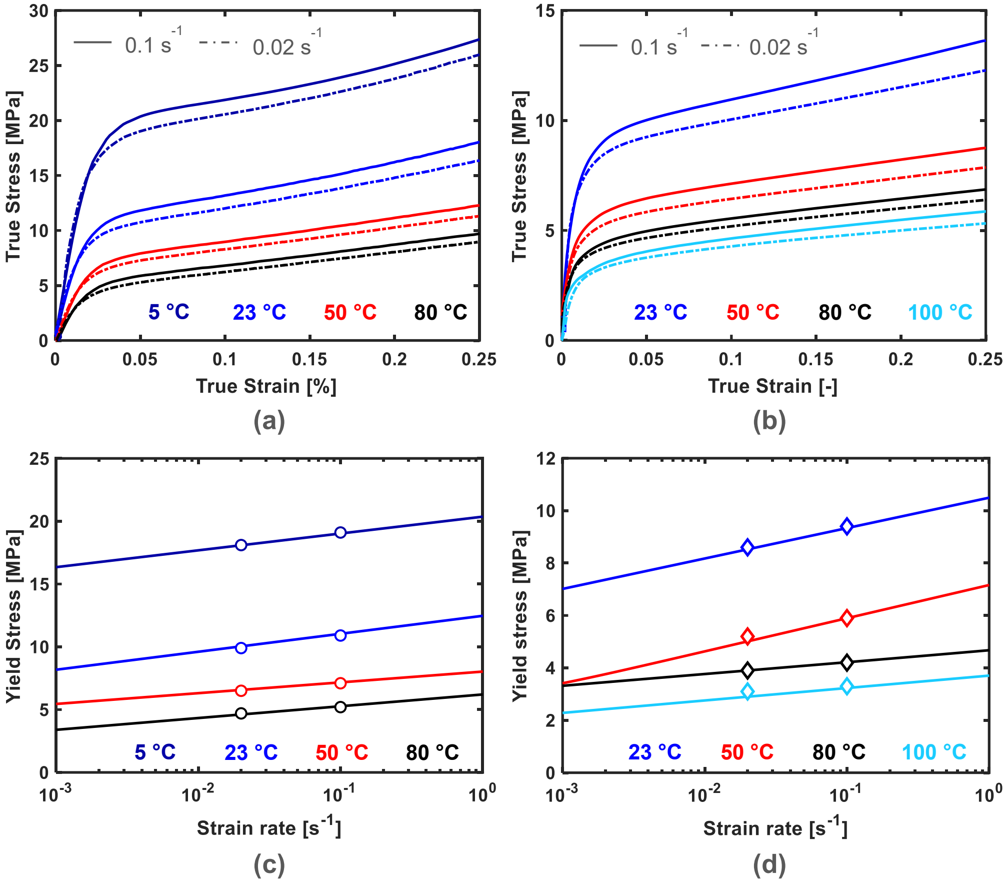

Figure 4: True stress strain response at four different temperatures and two strain rates for (a) Unfilled PTFE and (b) Glass-filled PTFE. Yield stress dependence on strain rate visualized on a semi-log scale for (c) Unfilled PTFE and (d) Glass-filled PTFE. Markers are data and solid lines are fit using equation (3) and parameters listed in Table 2.

Table 2: Eyring parameters needed to fit the observed yield kinetics

Material	Process	V^* [nm^3]	$\dot{\varepsilon}_0$ [s^{-1}]	ΔU [KJmol^{-1}]
Unfilled PTFE	α-process	12	$2*10^{23}$	205
	β-process	14.7	$6*10^{164}$	950
Glass-filled PTFE	α-process	25	$1*10^{38}$	325
	β-process	12	$8*10^{51}$	340

The results in **Figure 4** clearly reveal two distinct regions. In Region I, corresponding to lower temperatures, the material exhibits a pronounced strain rate dependence. In contrast, Region II, associated with higher temperatures, shows reduced strain rate sensitivity. As discussed earlier, this behaviour reflects the interplay of multiple molecular mechanisms in PTFE, arising from contributions of both the amorphous phase (α-relaxation) and the crystalline phase (β-relaxation).

In Region I, the stress response is governed by contributions from both the α and β processes. However, in Region II, the response is predominantly controlled by the α-process. From a modelling standpoint, it is therefore essential to accurately identify the temperature at which the β-process is activated, ensuring that the individual stress contributions of each mechanism are appropriately captured.

To quantify this transition, Differential Scanning Calorimetry (DSC) measurements were performed on both materials. As a thermal analysis technique, DSC enables precise detection of the thermally activated β-transition. Experiments were carried out using a Mettler Toledo DSC system. Cylindrical samples were punched out from tensile stripes, each weighing approximately between 8 mg and 12 mg. Each specimen was heated to a temperature above the melting point of PTFE inside an Aluminium crucible, at a heating rate of 10 °C/min, followed by cooling to ambient temperature at the same rate. The onset of the β-transition was identified during the heating cycle as the point of deviation from the baseline of the heat flow signal as depicted for both the materials in **Figure 5**. This temperature, T_β, was identified to be 50 °C for unfilled PTFE and 80 °C for glass filled PTFE. This was subsequently incorporated into the model as the activation threshold for the β process, defining the onset of its contribution to the overall stress response.

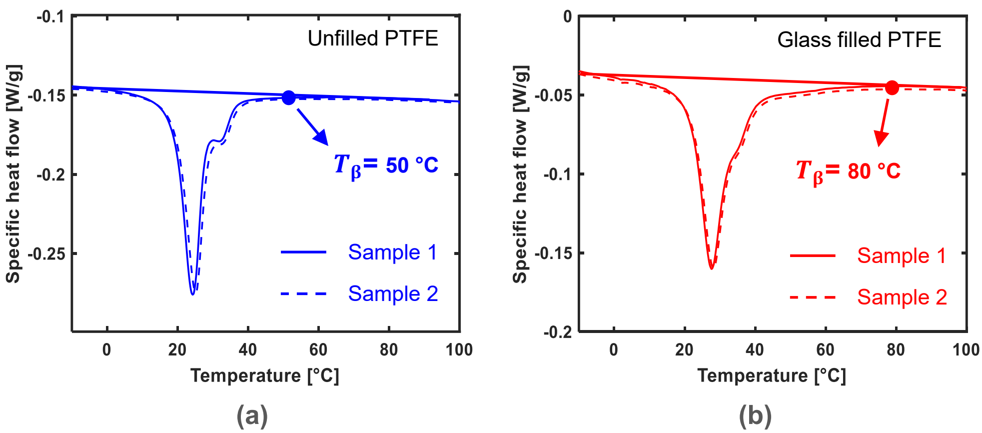

Figure 5: DSC heating curves of (a)Unfilled PTFE and (b) Glass filled PTFE with a heating rate of 10°C/min to identify the onset of beta transition.Two samples were tested to ensure repeatability of the measurements.

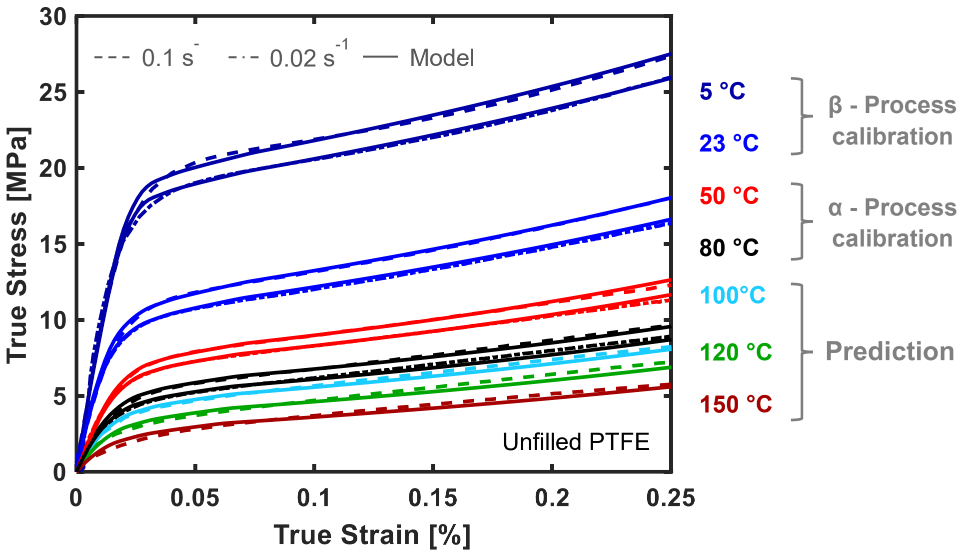

Figure 6: Comparison of model predictions and true stress–strain data for unfilled PTFE under uniaxial tension across all tested temperatures, including conditions outside the calibration window.

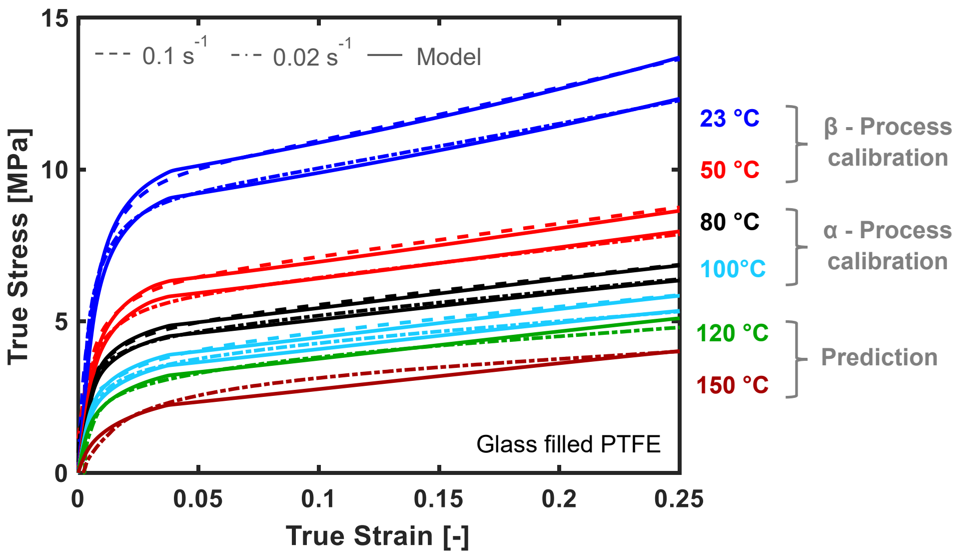

Figure 7: Comparison of model predictions and true stress–strain data for glass-filled PTFE under uniaxial tension across all tested temperatures, including conditions outside the calibration window.

Given that the quasi-static mechanical response and DSC analysis consistently confirm the presence of two underlying molecular processes, a two-process modelling framework, as illustrated in **Figure 3**, was adopted. The initial Eyring parameters for both processes were taken from **Table 2**. The approach proposed by Kadin and Schaake [6] was employed to determine the stiffness of the hyperelastic spring elements, along with the initial Eyring parameters of the dashpots in each branch of the model.

For unfilled PTFE, the parameters associated with the α-process were identified using true stress–strain data obtained at 50 °C and 80 °C. In the case of the glass-filled material, the corresponding parameters were derived from experiments conducted at 80 °C and 100 °C. The final set of Eyring parameters for the α-process was subsequently refined for both materials by fitting the model to the post-yield response at these temperatures. After obtaining all the necessary parameters for the α-process, a similar procedure was followed for the β-process. The spring stiffness, as well as the initial and final Eyring parameters of the corresponding spring–dashpot branches, were calibrated using data obtained at lower temperatures. Specifically, for unfilled PTFE, datasets at 5 °C and 23 °C were used, whereas for the glass-filled material, calibration was based on measurements at 23 °C and 50 °C.

The identified parameter set provides an excellent description of the experimental response, as shown in **Figure 6** for unfilled PTFE and in **Figure 7** for glass filled PTFE. Following calibration, the model's predictive capability is evaluated at temperatures outside the calibration range, where it continues to show excellent agreement with experimental true stress–strain data for both materials. This demonstrates that the model has a predictive capability beyond the calibration domain. As established in previous work [2], achieving this level of accuracy over the entire strain range across strain rates and temperatures can only be achieved through the incorporation of the SKF strain-modified Eyring formulation. These results provide a strong basis for the next step of the study, in which the same calibrated parameter set is used to predict the long-term stress relaxation response under uniaxial tension.

4.2 Predicting long-term relaxation behaviour using identified parameters

After calibrating the full set of model parameters, as detailed in the preceding section, finite element simulations were performed within the ABAQUS framework to evaluate the model's ability to predict long-term stress relaxation behaviour. It is important to emphasize that all parameters were identified exclusively from short-term quasi-static data, and no additional fitting was performed for the relaxation response. Consequently, the model predictions output for stress relaxation represent a purely predictive assessment of the proposed framework. **Figure 8** and **Figure 9** demonstrate an excellent agreement between the experimental measurements and model predictions[1] across all tested strain levels and temperatures, under a strain

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[1] Comparison between data and model predictions for both materials under a strain rate of 0.1 s^{-1} is presented in **Figure 16** and **Figure 17** under Appendix 1.

rate of 0.02 s⁻¹. In addition to accurately capture the strain rate, temperature, and strain dependence of PTFE, as established in prior work [2], the model also successfully describes the behaviour of glass-filled PTFE (Figure 9). Notably, despite the presence of glass fibre reinforcement, the relaxation behaviour is observed to be governed by the underlying molecular mechanisms of the base PTFE polymer. By explicitly capturing these mechanisms within the constitutive formulation, the model is able to reliably account for the influence of fillers without the need for any additional parameters.

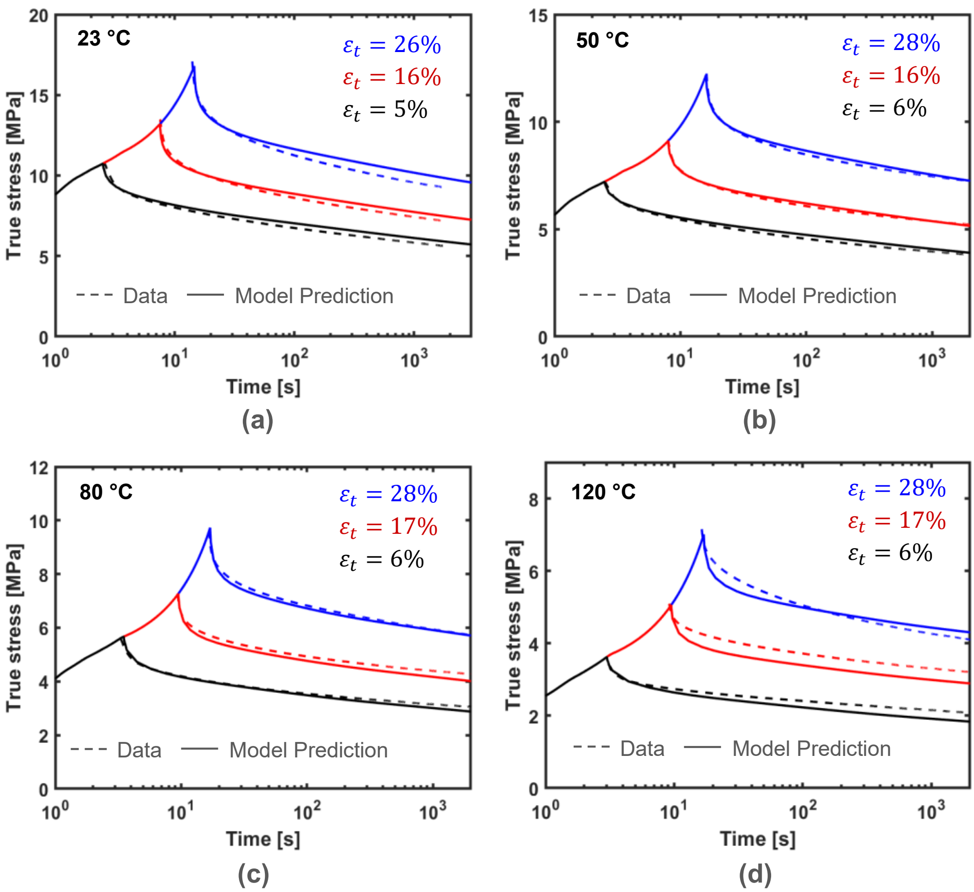

Figure 8: Stress relaxation response of unfilled PTFE at a strain rate of 0.02 s⁻¹, measured at four different temperatures and three strain levels for each condition. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

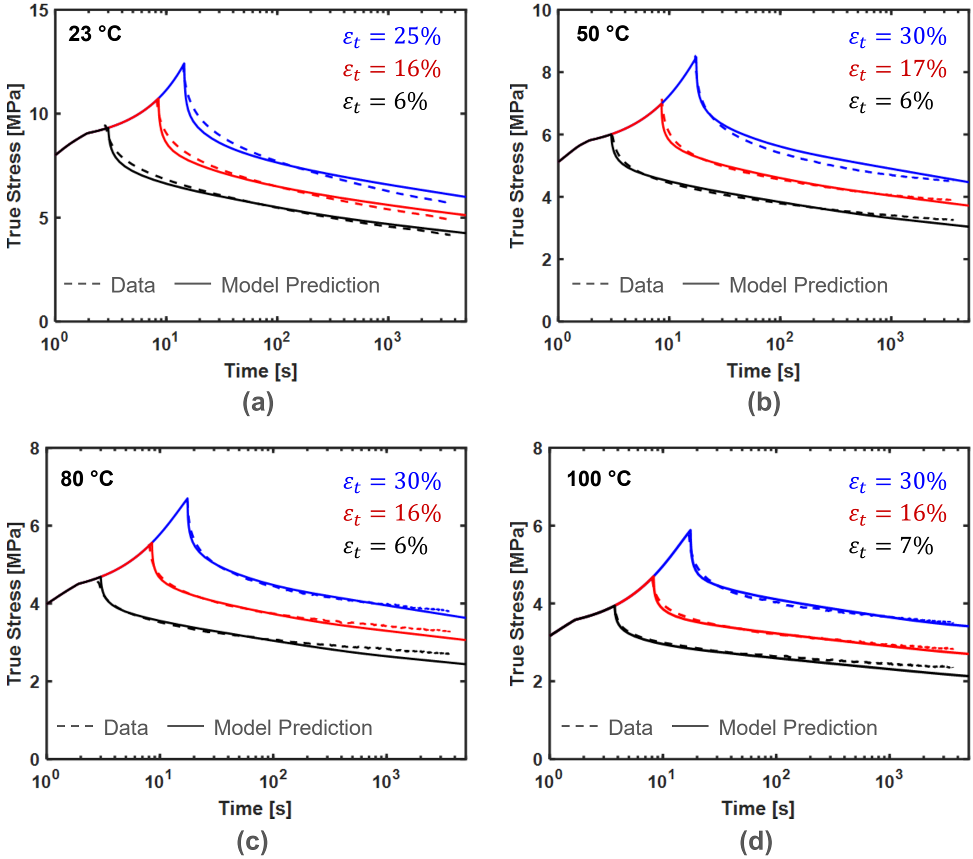

Figure 9: Stress relaxation response of glass filled PTFE at a strain rate of 0.02 s ⁻¹, measured at four different temperatures and three strain levels for each condition. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

4.3 Model validation through seal radial load measurement

Having established the capability of the model to accurately predict the long-term stress relaxation behaviour under uniaxial tension, its applicability for predicting seal performance is subsequently evaluated. This validation is carried out through radial load measurements on both unfilled and glass-filled PTFE seals using a split-shaft configuration, as explained in Section 2.2. Furthermore, the model parameters obtained during the calibration stage were retained without any additional adjustment based on the seal measurements.

Finite element simulations were performed using ABAQUS. An axisymmetric model was adopted to reduce computational effort while preserving the essential features of the problem. The boundary and loading conditions were defined to closely replicate the experimental split-shaft setup. The reaction force acting on the shaft, extracted from the simulation output, was directly compared with the measured radial load data. Given the emphasis on long-term relaxation behaviour, the results are presented using a linear time scale, rather than adopting a logarithmic scale, for the time axis.

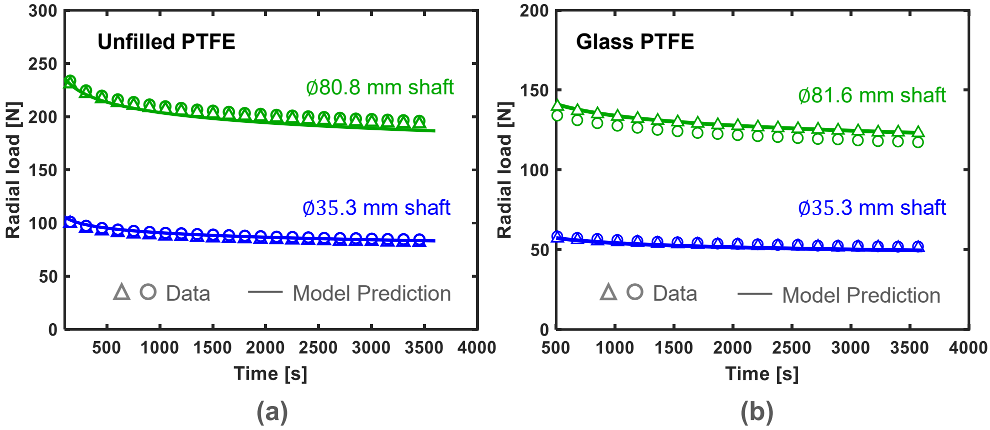

Figure 10: Radial load measurements (markers) at ambient conditions, for seals designed for two different shaft diameters. The model predictions (solid lines) are in close agreement with the data for both unfilled PTFE and glass filled PTFE.

Figure 10 presents the comparison between the measured and predicted radial load response at ambient temperature for both unfilled and glass-filled PTFE seals, evaluated for two different shaft diameters. The model predictions, shown as solid lines, exhibit excellent agreement with the experimental data, shown as markers, across all conditions considered. In particular, the model successfully describes the behaviour of glass-filled PTFE, despite the added complexity arising from fibre reinforcement. The agreement observed across different shaft sizes further indicates that the model successfully captures geometry-dependent effects without the need for additional parameter adjustment, which is highly relevant in practical applications where variations in seal dimensions are inevitable.

Following the successful validation at ambient conditions, the model was further assessed using radial load experiments on the larger-diameter seals at elevated temperatures. The experiments were conducted at 65 °C and 90 °C, deliberately chosen to avoid overlap with the temperatures used for model calibration from short-term quasi-static uniaxial tensile data. Moreover, this analysis enables a comprehensive evaluation of the model under combined thermomechanical loading, where the relative contributions of the α-relaxation and β-transition vary with temperature.

Remarkably, the model continues to exhibit strong predictive performance, with close agreement between the predicted and measured radial loads as illustrated in **Figure 11**. This consistent agreement demonstrates the reliability of the proposed phenomenological framework and once again highlights the importance of the strain-modified Eyring formulation in capturing the molecular mechanisms that govern the macroscopic response of PTFE seals, including the filled material. Overall, the results show that this enhanced model calibrated only from short-term quasi-static uniaxial tensile data can be used to reliably predict the long-term behaviour of seals under application-relevant geometries and operating conditions.

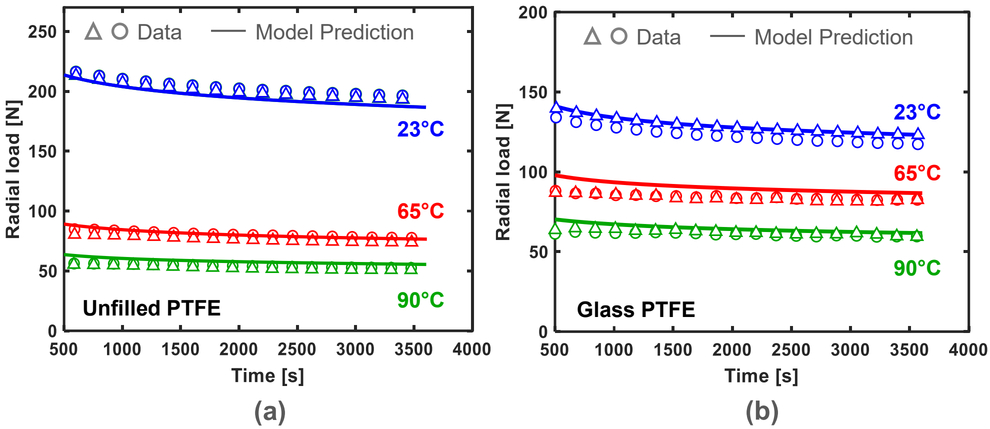

Figure 11: Radial load measurements (markers) at ambient conditions, for seals designed for 80.8 mm shaft. The model predictions (solid lines) are in close agreement with the data for both (a) unfilled PTFE and (b) glass filled PTFE, across all temperatures tested.

4.4 Model extension to Bronze filled PTFE

Following validation for unfilled and glass-filled PTFE seals, the applicability of the model to other filled PTFE grades was examined. Bronze-filled PTFE serves as a representative case to evaluate the generality of the constitutive framework for a different filler system, without modification to the modelling approach.To achieve this, uniaxial tensile experiments were carried out following the methodology described in Section 2.1, previously applied to both unfilled and glass-filled PTFE.

Model parameters were identified from short-term uniaxial quasi-static data shown in **Figure 12** (a). The corresponding yield kinetics, presented in **Figure 12** (b), indicate that the total stress response of bronze-filled PTFE also arises from contributions associated with the α-relaxation of the amorphous phase and the β-transition of the crystalline phase. To determine the onset of the β-transition more accurately, DSC analysis was performed following the same procedure described earlier in Section 4.1 and the resulting curve is depicted in **Figure 13**.

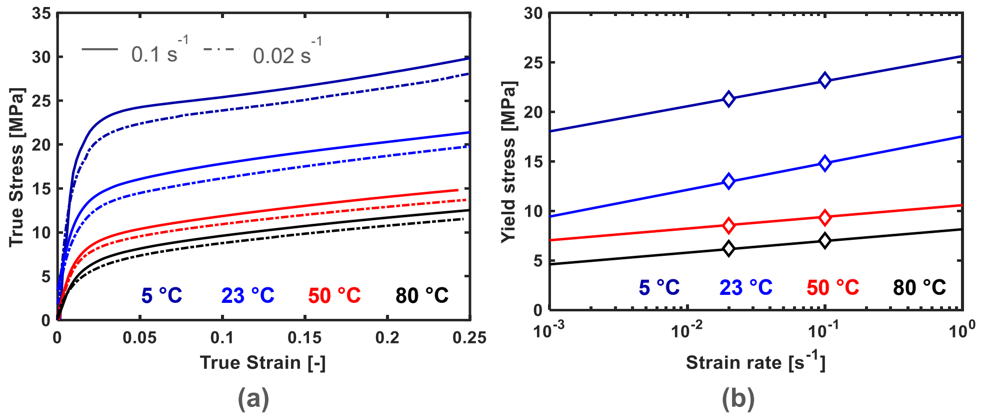

Figure 12: (a) True stress strain response at four different temperatures and two strain rates for Bronze-filled PTFE. (b) Yield stress dependence on strain rate visualized on a semi-log scale. Markers are data and solid lines are fit using equation (3) and parameters listed in Table 3.

***Table 3**: Eyring parameters needed to fit the observed yield kinetics of bronze filled PTFE*

Process	V^* [nm³]	$\dot{\varepsilon}_0$ [s⁻¹]	ΔU [KJmol⁻¹]
α-process	12	$2*10^{23}$	205
β-process	14.7	$6*10^{164}$	950

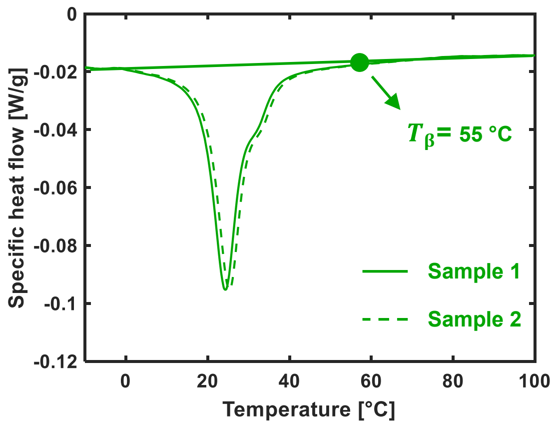

Figure 13: DSC heating curves of bronze filled PTFE with a heating rate of 10°C/min.

Following the results observed in both the quasi-static mechanical data and the DSC thermal data, a two process modelling framework was incorporated with the SKF strain modified Eyring formulation for the dashpot. The approach proposed by Kadin and Schaake [6] was employed to determine the stiffness of the hyperelastic spring elements, along with the initial Eyring parameters of the dashpots in each branch of the model.

The parameters associated with the α-process were identified from true stress–strain data obtained at 50 °C and 80 °C, after which the final α-process parameters were refined by fitting the post-yield response at these temperatures. A similar procedure was then followed for the β-process, with the corresponding spring stiffness and the initial and final Eyring parameters calibrated using the lower-temperature datasets at 5 °C and 23 °C.

The resulting parameter set provides an excellent description of the short-term quasi-static response, both within the calibration window and beyond it, as shown in **Figure 14**. This is fully consistent with the observations made earlier for unfilled and glass-filled PTFE. Consequently, the predictive ability of the model for the long-term relaxation behaviour is assessed.

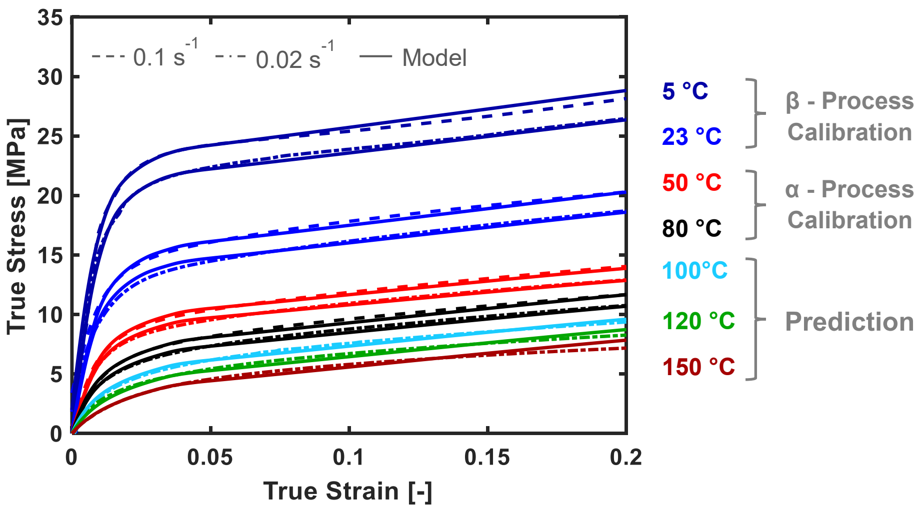

Figure 14: Comparison of model predictions and true stress–strain data for bronze filled PTFE under uniaxial tension across all tested temperatures, including conditions outside the calibration window. Excellent agreement is observed between model predictions and experimental data across all tested temperatures and strain rates.

Figure 15 demonstrates excellent agreement between the experimental measurements and model predictions[2] across all tested strain levels and temperatures, under a strain rate of 0.02 s^{-1}. These results confirm that the model is able to account for the influence of temperature, strain rate, and strain level not only in the short-term response, but also in the long-term relaxation behaviour successfully. More importantly, this provides further evidence that the proposed approach is not limited to a specific PTFE grade, but can serve as a more general framework for the modelling of PTFE sealing materials.

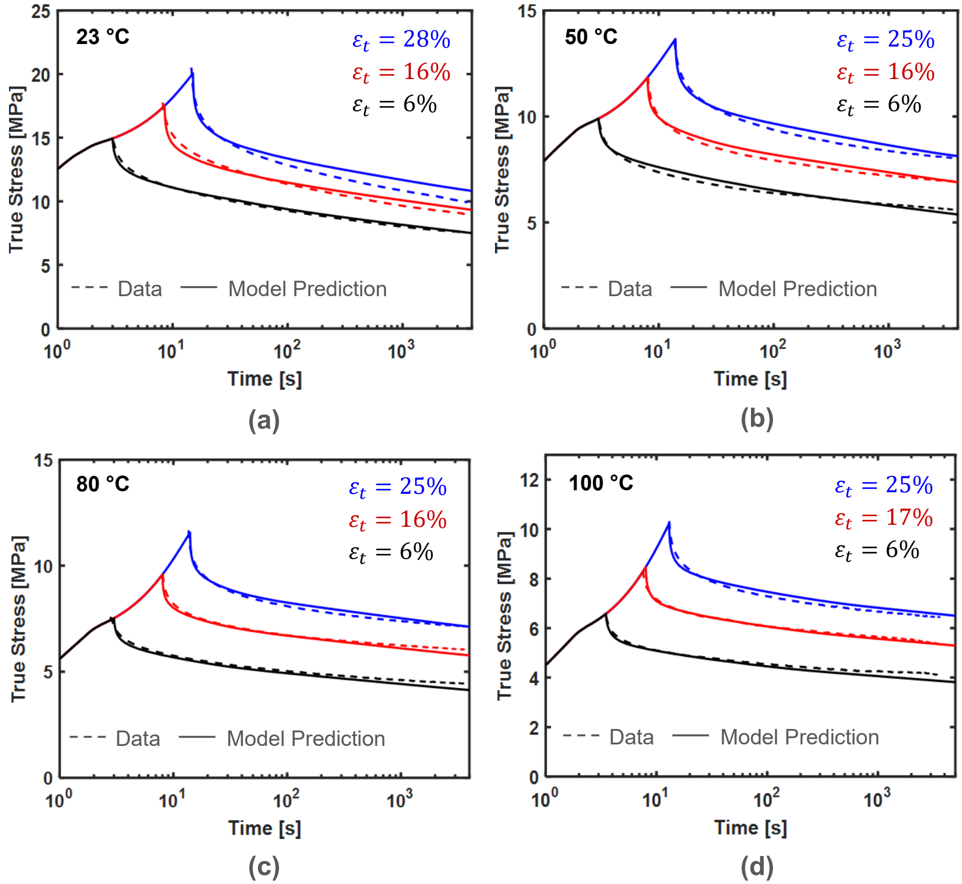

Figure 15: Stress relaxation response of bronze filled PTFE at a strain rate of 0.02 s^{-1}, measured at four different temperatures and three strain levels for each condition. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

[2] Comparison between data and model predictions for both materials under a strain rate of 0.1 s^{-1} is presented in under Appendix 1.

5 Summary and Conclusion

A phenomenological constitutive model based on a multi-process rheological framework and the SKF strain-modified Eyring formulation was validated for PTFE sealing materials. Model parameters were identified from short-term quasi-static uniaxial tensile experiments. The calibrated model accurately described the short-term response of both unfilled and glass-filled PTFE, not only within the calibration range but also at temperatures outside the calibration window. It also predicted long-term stress relaxation under uniaxial tension with excellent agreement across different temperatures, strain rates and strain levels.

The applicability of the framework was further validated through radial load measurements on PTFE seals. Remarkably, for both unfilled and glass-filled PTFE, the model accurately predicted the measured seal response for different shaft diameters and temperatures. These results show that using the adopted modelling approach, short-term material characterization can be translated into reliable predictions of seal behaviour under application-relevant conditions.

Finally, the framework was extended to another filled grade, namely bronze-filled PTFE. Excellent agreement was again observed between experiments and model predictions for both the short-term quasi-static response and the long-term stress relaxation behaviour. Overall, this work showcases and validates a robust and versatile material modelling framework for polymeric sealing materials, further enabling seal digitalization by driving more simulation-driven development processes with reduced dependence on extensive experimental testing.

6 Acknowledgement

The authors would like to express their sincere appreciation to Polymer Competence Centre Leoben GmbH for their invaluable collaboration. All the uniaxial tensile experimental data on unfilled PTFE presented in this paper were performed at their state-of-the-art research facility.

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9 Additional data and model predictions

Appendix 1: Stress relaxation behaviour obtained at a strain rate of 0.1 s^{-1} and compared against model predictions

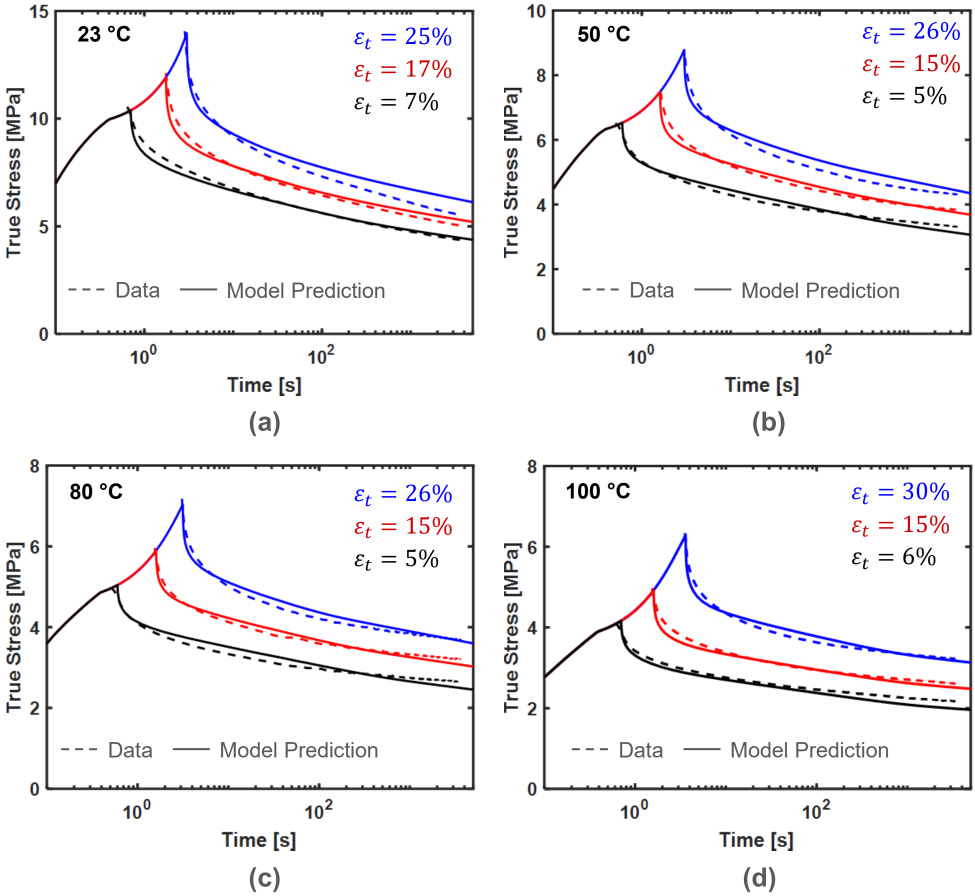

Figure 16: Stress relaxation response of glass filled PTFE at a strain rate of 0.1 s^{-1}, measured at four different temperatures and three strain levels for each condition. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

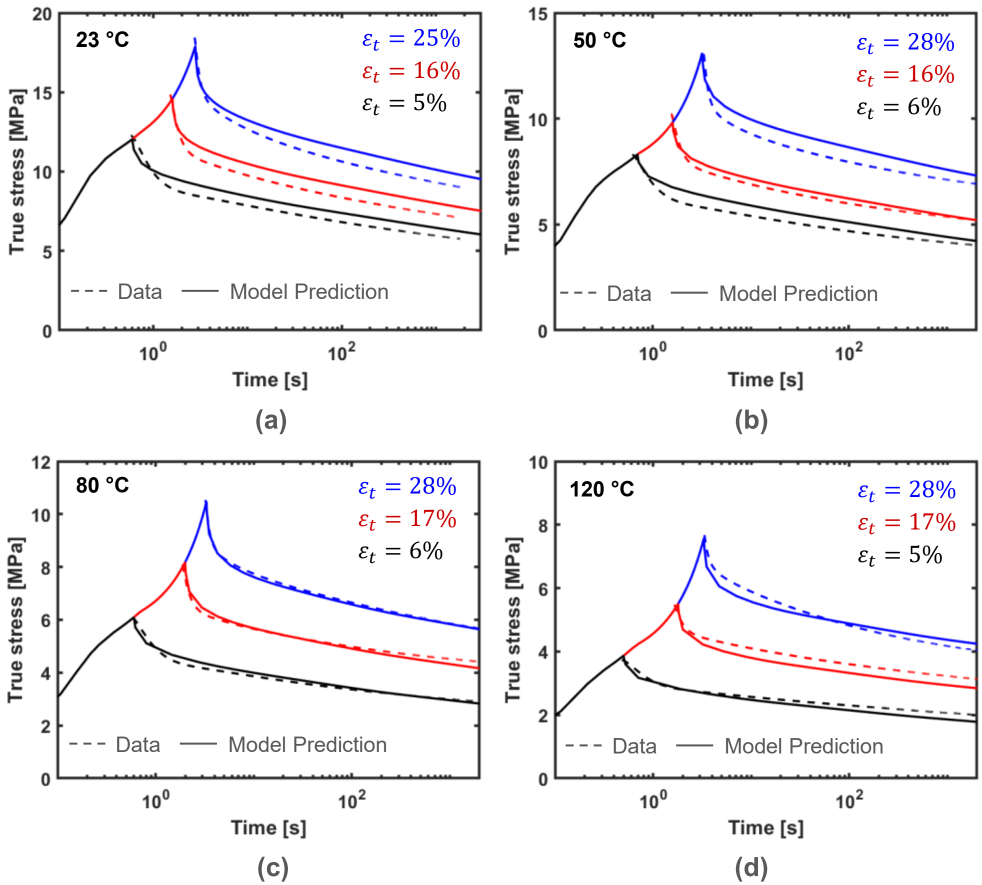

Figure 17: Stress relaxation behaviour of unfilled PTFE at three different strain levels at a strain rate of 0.1 s-1 and four different temperatures. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

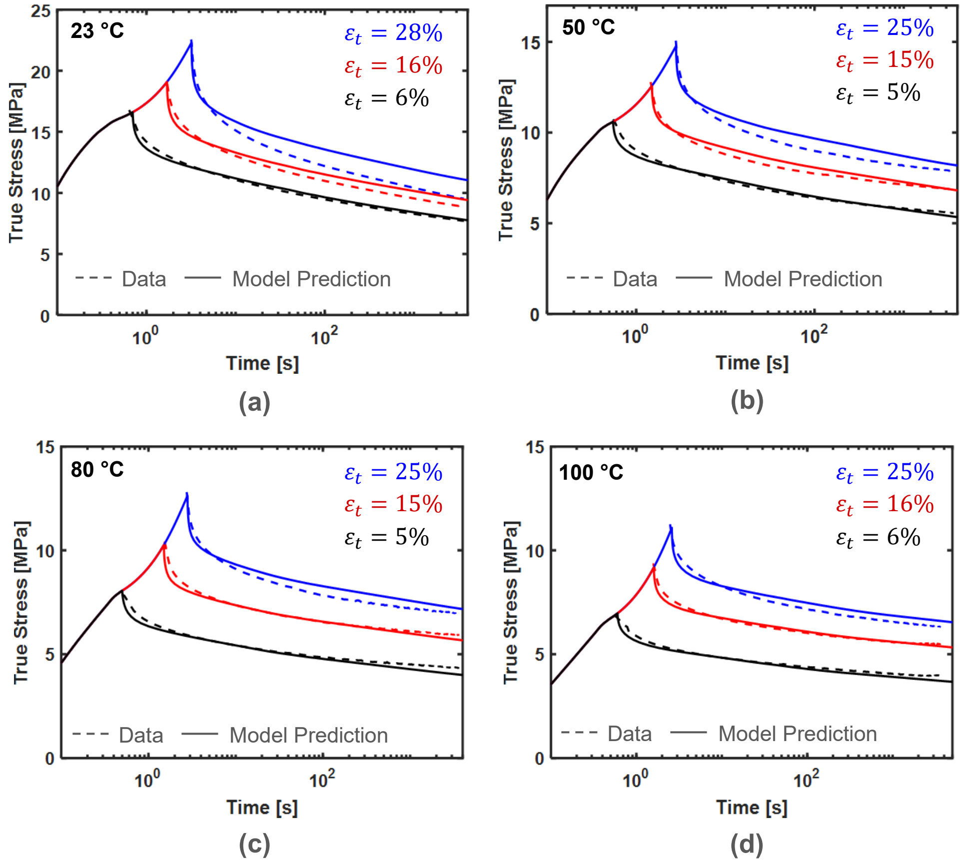

Figure 18: Stress relaxation response of bronze filled PTFE at a strain rate of 0.1 s^{-1}, measured at four different temperatures and three strain levels for each condition. The model predictions, shown as solid lines, exhibit very close agreement with the experimental data.

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