Nevşehir Bilim ve Teknoloji Dergisi

Araştırma Makelesi (Research Article)

Makale Doi: **10.17100/nevbiltek.1880822**

Geliş Tarihi: 03/02/2026 Kabul Tarihi: 06/06/2026

Prediction of the Short – Term Stress Relaxation Behavior of Polypropylene Block Copolymer Material Using an ANSYS Three Network Model Calibrated with Low Quasi – Static Tensile Tests[*]

Şenol ŞAHİN[1], Ferhat AKPINAR[2,3]

[1]*Kocaeli University, Faculty of Engineering, Department of Mechanical Engineering, Kocaeli, Türkiye*

ORCID ID: 0000-0002-7823-2245

[2] *Doğuş University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, Istanbul, Türkiye*

[3]*Kocaeli University, Institute of Science, Department of Mechanical Engineering, Kocaeli, Türkiye*

ORCID ID: 0000-0003-2842-6276

Abstract

The aim of this study is to address the limited number of numerical investigations on pure polypropylene block copolymers (PPB) reported in the literature by developing a high – accuracy finite element approach based on the ANSYS Three Network Model (TNM). This approach is intended to predict the short – term, time – dependent mechanical behavior of PPB and to complement the extensive experimental studies previously reported. Within the scope of this study, Multipurpose test specimens manufactured by injection molding from pure PPB material in accordance with the ISO 3167 Type A standard were subjected to uniaxial tensile tests at low quasi – static strain rates (0.0003 s^{-1}, 0.000725 s^{-1}, and 0.00145 s^{-1}) up to the stress plateau region. Subsequently, stress relaxation tests were performed with a holding time of 600 *s* at the yield strain levels determined for each strain rate. The time – strain – stress data obtained from the uniaxial tensile tests were utilized to calibrated PPB – specific ANSYS TNM parameters through the MCalibration software. High correlations are observed between the simulation and experimental results for both uniaxial tensile and stress relaxation tests, with this agreement quantitatively confirmed by coefficients of determination of $R^2 \geq 0.78$. In conclusion, the proposed ANSYS TNM – based modeling approach has demonstrated a high level of predictive accuracy for the strain – rate – dependent mechanical behavior of semicrystalline polymers such as PPB, while also providing significant gains in terms of time, cost, and labor efficiency in engineering design applications.

Keywords: Polypropylene Block Copolymer; ANSYS Three Network Model; Finite Element Method; Tensile Test; Stress Relaxation.

[*] **Corresponding author e-mail:** sensah@kocaeli.edu.tr This paper was presented as an abstract at the International Yildirim Bayezid Scientific Research and Innovation Symposium – I (2025) under the title "Experimental Investigation of the Effect of Strain Rate on the Tensile Behavior of Polypropylene Block Copolymer Specimens and Numerical Analysis with the ANSYS TN Model". This study is derived from the second author's doctoral dissertation, which was supervised by the first author.

Düşük Yarı Statik Hızlı Çekme Testleri ile Kalibre Edilmiş ANSYS Üç Ağ Modeli Kullanılarak Polipropilen Blok Kopolimer Malzemenin Kısa Vadeli Gerilme Gevşeme Davranışının Tahmini

Öz

Bu çalışmanın amacı, literatürde rapor edilen saf polipropilen blok kopolimerler (PPB) üzerine yapılan sayısal çalışmaların sınırlı olmasını ele alarak, ANSYS Üç Ağ Modeli (TNM) temelli yüksek doğruluklu bir sonlu elemanlar yaklaşımı geliştirmektir. Bu yaklaşım, PPB'nin kısa süreli, zaman bağımlı mekanik davranışını tahmin etmeyi ve daha önce rapor edilmiş kapsamlı deneysel çalışmaları tamamlamayı amaçlamaktadır. Çalışma kapsamında, ISO 3167 Tip A standardına uygun olarak saf PPB malzemeden enjeksiyon kalıplama yöntemiyle üretilen çok amaçlı numuneler, düşük sanki statik genleme hızlarında (0.0003 s^{-1}, 0.000725 s^{-1} ve 0.00145 s^{-1}) gerilme plato bölgesine kadar tek eksenli çekme testlerine tabi tutulmuştur. Ardından, her bir şekil değiştirme hızı için belirlenen akma genleme seviyelerinde 600 s bekleme süresiyle gerilme gevşemesi testleri gerçekleştirilmiştir. Tek eksenli çekme testlerinden elde edilen zaman – genleme – gerilme verileri, MCalibration yazılımı aracılığıyla PPB'ye özgü ANSYS TNM parametrelerinin kalibre edilmesinde kullanılmıştır. Tek eksenli çekme ve gerilme gevşemesi testleri için simülasyon ve deneysel sonuçlar arasında yüksek düzeyde korelasyonlar gözlenmiş olup, bu uyum $R^2 \geq 0.78$ olan regresyon uyum katsayıları ile nicel olarak doğrulanmıştır. Sonuç olarak, önerilen ANSYS TNM tabanlı modelleme yaklaşımıyla PPB gibi yarı kristalin polimerlerin gerinim hızı bağımlı mekanik davranışını yüksek doğrulukla öngörebilme başarımı sergilenmiştir ve aynı zamanda mühendislik tasarım uygulamalarında zaman, maliyet ve iş gücü açısından önemli kazanımlar sağlanmıştır.

Anahtar Kelimeler: Polipropilen Blok Kopolimer; ANSYS Three Network Model; Sonlu Elemanlar; Çekme Testi; Gerilme Gevşemesi Testi.

1. Introduction

Polypropylene (PP) is a thermoplastic polymer belonging to the polyolefin family and characterized by a semicrystalline structure[1]. It is widely utilized across numerous application areas, including packaging, automotive, construction, aerospace, and biomedical industries [2], [3]. Owing to its low cost, lightweight nature, ease of processability, high chemical resistance, and adequate mechanical performance, PP is considered one of the most widely preferred thermoplastic materials in engineering applications [3].

Polypropylene block copolymer (PPB) exhibits favorable impact resistance, ductility, and energy absorption capacity [4-6]. PPB and its derived materials are considered suitable candidates for engineering applications requiring high impact resistance, as a result of these characteristics.

Accurate material characterization and identification of material properties are essential for engineering design, as they directly define the applicable service conditions and performance limits [7]. In this context, a systematic investigation of the mechanical behavior of PPB provides a rational and effective engineering approach for evaluating its suitability in engineering design applications.

The through experimental evaluation under various loading and testing conditions. In this regard, standardized mechanical tests such as tensile, compressive, flexural, creep, impact, and stress relaxation tests are widely employed to assess their performance [8].

The mechanical behavior of PP materials is strongly influenced by factors such as stress level, strain level, and temperature [9-11]. In particular, strain rate is widely recognized as a dominant parameter governing the mechanical response of polymeric materials [12], [13]. Consequently, the accurate representation of strain – rate – sensitive behavior is essential for the robust modeling and engineering design of PP – based materials.

The tensile test, which is one of the fundamental methods employed in investigating the mechanical behavior of materials, enables the reliable determination of key mechanical properties such as elastic modulus, yield stress, elongation capability, and fracture strength, and is therefore one of the most widely adopted techniques in the literature [14]. The tensile behavior of plastic materials is commonly evaluated in accordance with the TS EN ISO 527 – 2 standard [14], [15]. During tensile testing, load and displacement data are recorded as a function of time, from which stress – strain relationships are subsequently calculated. Within the scope of this study, injection – molded specimens manufactured from PPB were prepared as TS EN ISO 3167 Type A multipurpose test specimens and experimentally tested [15].

Stress relaxation testing is one of the characteristic experimental methods used to investigate the mechanical behavior of materials and represents a fundamental technique for characterizing the time – dependent mechanical response of viscoelastic materials. In this test, the specimen is brought to a prescribed constant strain (ε_0) at a constant temperature (T), and the resulting force, and hence the stress $\sigma(t)$, which decreases over time, is recorded while the strain is maintained constant [16]. This behavior is associated with the molecular rearrangement of polymer chains and the time – dependent dissipation of energy arising from internal friction.

Extensive studies have investigated stress relaxation behavior of isotactic polypropylene (iPP), combining experimental and numerical approaches. In one such study, short-term relaxation tests were conducted for 20 minutes (1200 s) in accordance with ASTM E–328, using specimens prepared according to ASTM D – 638. The time – dependent mechanical response was subsequently analyzed numerically using a Viscoplasticity Based on Overstress (VBO) constitutive model. [17], [18]. In another study, the mechanical behavior of iPP under cyclic loading was investigated both experimentally and numerically. Within the study, stress relaxation tests were conducted in accordance with the ASTM E–328 protocol, with a duration of 1200 s. [19].

It has been widely reported in the literature that the strain rate employed in tensile testing plays a crucial role in determining the mechanical properties of thermoplastic materials, particularly polypropylene (PP). According to these studies, variations in strain rate can significantly alter the observed stress – strain response, highlighting the importance of accurately controlling and reporting strain – rate conditions in experimental investigations. Polymeric materials, and PP in particular, exhibit pronounced strain – rate sensitivity, which must be properly accounted for in constitutive modeling and engineering design applications [12], [20-22]. Moreover, not all strain rate regimes are appropriate for every experimental method or testing apparatus; consequently, the literature generally prescribes defined strain rate boundaries. Figure 1 illustrates these boundaries, the associated test modalities, suitable testing equipment, and the regions in which inertial effects become significant [12].

In addition to the strain rate, accurately defining the applicable strain range is a critical research parameter for polymeric materials. In stress – strain curves obtained from tensile tests of semi – crystalline thermoplastic materials, five distinct characteristic regions can be identified. These regions are: linear elastic and linear – viscoelastic, nonlinear – viscoelastic, strain softening, plateau stress, and strain hardening. Depending on the experimental conditions, it may not always be possible to observe all of these regions. Figure 2 illustrates a typical stress – strain curve obtained from the tensile testing of a semi – crystalline thermoplastic material, along with its characteristic regions. [23].

Short – term stress relaxation tests are particularly important for understanding the short – term viscoelastic response of materials under service conditions in engineering applications. Based on the data obtained from these short – term relaxation tests, long – term stress relaxation behavior can be predicted using the time – stress – temperature superposition principle [24].

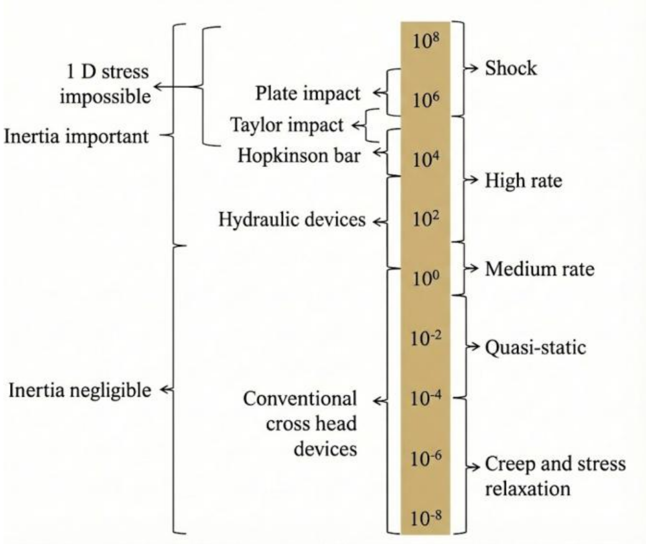


Figure 1. Strain rate ranges, test types, equipment, and inertial effect regions [12]

Material models represent a widely adopted approach in the literature for predicting the mechanical behavior of materials. These models are typically calibrated using a limited set of experimental data, enabling reliable predictions under conditions that have not been directly tested. Consequently, this approach offers substantial advantages in terms of time, labor, and cost efficiency [28-30].

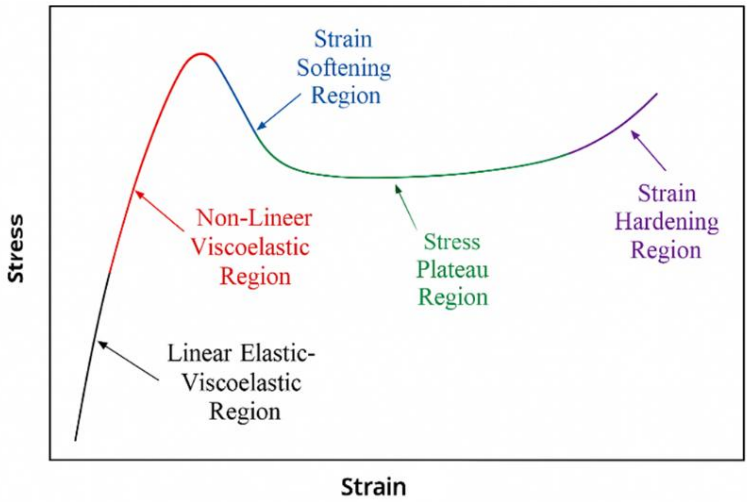


Figure 2. Stress – strain curve and characteristic regions of a semi – crystalline thermoplastic material [23]

In the literature, a wide range of material models has been developed, ranging from basic linear viscoelastic models such as Maxwell, Kelvin – Voigt, and Standard Linear Solid (SLS) to advanced nonlinear viscoplastic models, including the Three Network Model (TNM) and the Three Network Viscoelastic Model (TNV). The determination of an appropriate material model is influenced by several technical factors, including the material class, the finite element analysis software adopted, the targeted mechanical response, the strain regime under consideration, and other relevant criteria [27-33].

Multi – network models have been extensively utilized in the literature for the prediction of material behavior [30], [34-36]. Among these models, TNM stands out as an effective approach for representing the complex mechanical behavior of polymer – based materials, accounting for both elastic and time – dependent deformation components [35], [36]. The model provides a robust representation of the material's mechanical response, capturing the effects of key environmental and mechanical factors, including strain rate dependence and temperature variations [34], [35], [37]. Moreover, the integration of the TNM within commercial finite element method (FEM) software, particularly through its implementation in ANSYS, facilitates its widespread adoption in engineering applications [38]. Due to these advantages, the present study adopts the ANSYS Three Network Model (ANSYS TNM).

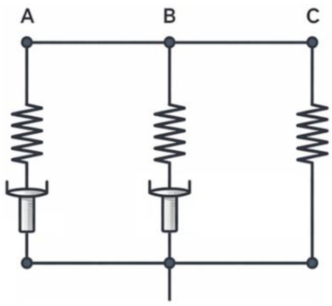


Figure 3 Schematic illustration of the Three – Network Model (TNM) [39]

A schematic illustration of the TNM is shown in Figure 3, highlighting the arrangement of springs, dashpots, and networks that constitute the model. In TNM, total stress is the sum of three parallel networks: A and B capture elastic-viscoplastic behavior, while C represents strain-stiffening at large deformations [39].

The TNM formulation commences with the definition of deformation gradients, wherein the total deformation gradient, F^{appl}, encompasses both the thermal expansion component, F^t, and the mechanical deformation component, F [40].

$$F^{appl} = F^t F \tag{1}$$

$$F^t = [1 + \alpha(\theta - \theta_0)]I \tag{2}$$

In Eq. (2), α denotes the coefficient of thermal expansion, θ is the current temperature, and θ_0 represents the reference temperature [40].

Each network experienced the same deformation, as Networks A, B, and C are configured in parallel [40].

$$F = F_A = F_B = F_C \tag{3}$$

For Networks A and B, the mechanical deformation gradient is multiplicatively decomposed into elastic F_n^e and viscoplastic F_n^v components, with n referring to either network, as expressed in Eq. (4) [40].

$$F_n = F_n^e F_n^v \tag{4}$$

The total Cauchy stress is expressed as Eq. (5) [40].

$$\sigma = \sigma_A + \sigma_B + \sigma_C \tag{5}$$

The Cauchy stress in Networks A and B follows the eight-chain representation, while Network C is defined analogously [40].

$$\sigma_n = \frac{\mu_n}{J_n^e \overline{\lambda_n^{e^*}}}\left[1 + \frac{\theta - \theta_0}{\hat{\theta}}\right] \frac{\mathcal{L}^{-1}\left(\overline{\lambda_n^{e^*}}/\lambda_{lock}\right)}{\mathcal{L}(1/\lambda_{lock})} dev\left[b_n^{e^*}\right] + \kappa(J_n^e - 1)I \tag{6}$$

For Networks A and B, where n denotes either network, $J_n^e = det[F_n^e]$, $b_n^{e^*} = (J_n^e)^{-2/3} F_n^e (F_n^e)^T$ is the Cauchy – Green tensor, $\overline{\lambda_n^{e^*}} = \sqrt{tr[b_n^{e^*}]/3}$ is the effective chain stretch, μ_n is the initial shear modulus, $\hat{\theta}$ is a temperature – dependent material constant, κ is the bulk modulus, θ and θ_0 are the current and reference temperatures, λ_{lock} is the locking stretch representing maximum chain extension, and $\mathcal{L}^{-1}$ is the inverse Langevin function [40].

$$\sigma_C = \frac{1}{1+q}\left\{\frac{\mu_C}{J\overline{\lambda}_C}\left[1 + \frac{\theta - \theta_0}{\hat{\theta}}\right] \frac{\mathcal{L}^{-1}(\overline{\lambda}_C/\lambda_{lock})}{\mathcal{L}(1/\lambda_{lock})} dev[b^*] + \kappa(J-1)I + q\frac{\mu_C}{J}\left[I_1^* b^* - \frac{2I_2^*}{3}I - (b^*)^2\right]\right\} \tag{7}$$

For Network C, $J = det[F]$, $b^* = (J)^{-2/3}F(F)^T$ is the Cauchy–Green tensor, $\overline{\lambda_c} = \sqrt{tr[b^*]/3}$ is the effective chain stretch, and μ_c is its initial shear modulus [40]. I_1 and I_2 denote the first and second invariants of b^*, respectively. q is the relative contribution of I_2 [41].

In Network B, the shear modulus evolves from its initial value μ_{Bi} toward its final value μ_{Bf} in response to viscoplastic flow, as described by the following equation [40].

$$\dot{\mu}_B = -\beta\left[\mu_{Bi} - \mu_{Bf}\right]\dot{\gamma}_A \tag{8}$$

where, $\dot{\gamma}_A$ denotes the effective flow rate of Network A, β is material – dependent evolution constant, μ_{Bi} and μ_{Bf} are the initial and final shear modulus of Network B, respectively [40].

The effective deviatoric flow rate is defined by a reptation – based relation [40].

$$\dot{\gamma}_n = \dot{\gamma}_0\left(\frac{\tau_n}{\hat{\tau}_n + aR(p(n))}\right)^{m_n}\left(\frac{\theta}{\theta_0}\right)^{n_t} \tag{9}$$

Here, n refers to Networks A and B. The constant $\dot{\gamma}_0$ [s^{-1}] introduced for dimensional consistency, $R(x)$ denotes the ramp function, and $p(n)$ represents the hydrostatic pressure. The term τ_n corresponds to the Frobenius norm of the deviatoric part of σ_n , while $\hat{\tau}_n$ defines the flow resistance of network n, indicating the shear stress level at which plastic flow becomes dominant. The material parameters a, m_n and n_t serve distinct roles: m_n is the stress exponent governing strain – rate sensitivity in the power – law formulation, n_t is the temperature exponent, and a characterizes the pressure dependence of the flow behavior [40].

While experimental investigations of polypropylene block copolymers (PPB) are extensive [10], numerical research on their mechanical behavior remains limited. In particular, the application of viscoplastic constitutive models calibrated with low – rate uniaxial tensile tests to predict short – term stress relaxation via ANSYS – based finite element analysis approach is largely unexplored, and this study addresses this gap by developing and validating a predictive approach for the time – dependent mechanical response of pure PPB.

2. Materials and Methods

2.1 Materials

The polypropylene block copolymer (PPB) granular pure material used in this study was supplied by Borealis A/S under the trade name BorECOTM BEC5015. Table 1 presents the mechanical and physical properties of the material as specified by the manufacturer, in accordance with the relevant ISO standards [10].

Table 1. Physical and Mechanical Properties of BorECO™ BEC5015

Density[kg/m³]	MFR [g/10 mins] (230°C/2.16 kg)	Young's Modulus [MPa]	Tensile Strength [MPa]	Elongation at Yield [%]
900	0.3	1500	30	10

2.2 Multi – Purpose Test Specimen Preparation

The injection moulding machine (Engel Victory 330/50 Tech) with a screw diameter of 35 mm and a length – to – diameter ratio (L/D) of 30 was used to produce multi – purpose test specimens from pure PPB materials. The injection molding process was performed in accordance with TS EN ISO 294 – 1, using an injection pressure of 130 bar, a holding pressure of 80 bar, and a holding time of 15 s, resulting in a total cycle time of 60 s, which included a 40 s cooling period and a 5 s mold opening time. The process was carried out under controlled parameters, including barrel temperatures of 210°C, 220°C, 230°C, and 235°C from the feed section to the nozzle, a melt temperature of 235°C, and a mold cooling temperature of 30°C.

A high – precision process chiller equipped with a temperature control unit (Frigel Microgel Duo) was employed to maintain the mold temperature constant at the set value for each multi – purpose test specimen. Type A specimens were produced by direct injection molding using an A – type ISO mold designed in accordance with TS EN ISO 294 – 1, featuring a T – distributor and two cavities, and manufactured from S235JR steel (material number: 1.0038). The resulting test specimens had dimensions of 216 mm × 10 mm × 4 mm, in compliance with TS EN ISO 3167. The dimensions of the injection – molded specimens are shown in Figure 4 [10]. The multipurpose test specimens were produced in accordance with the TS EN ISO 527 – 2 standard to evaluate the tensile behavior of plastic materials.

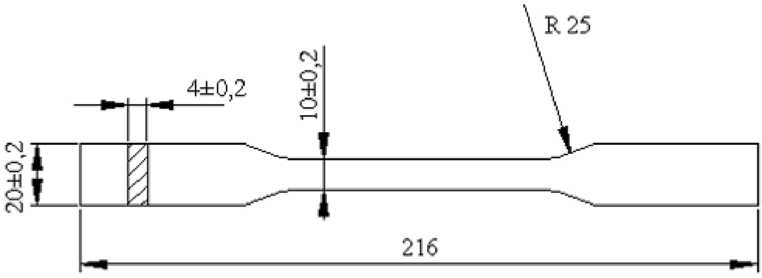


Figure 4. Multi – purpose test specimen dimensions according to TS EN ISO 3167 Type A

2.3 Uniaxial Tensile Test

Uniaxial tensile tests of Type A multipurpose specimens were performed using a 5 kN universal testing machine (Instron 4411) equipped with a static axial clip – on extensometer (Instron 2630 – 111) and computer – controlled Bluehill®2 software, as well as a 10 kN universal testing machine (Shimadzu AGS – X 10) in combination with Trapezium X software.

The multi – purpose test specimens were mounted in the grips of the testing machine along their principal longitudinal axes, with the injection gate region held by the fixed jaw. This configuration ensured that the loading direction during the tensile tests coincided with the injection molding filling direction of the specimens, thereby inducing tensile stresses parallel to the principal longitudinal axis of the specimens, as defined by the L – T orientation in ISO 13586.

Tensile testing of the multi – purpose test specimens was performed in accordance with TS EN ISO 3167. The nominal strain rate $\dot{\varepsilon}$ (s^{-1}), was determined from the ratio of the constant crosshead velocity, v (mm/s), to the initial gauge length (L = 115 mm), according to $\dot{\varepsilon} = v / L$. For the precise evaluation of the Young's modulus, a clip – on static axial extensometer with a gauge length of L_o = 50 mm was employed, and a tensile speed of 1 mm/min (0.0003 s^{-1}) was applied. To characterize other mechanical properties, quasi – static tensile tests were conducted at crosshead velocities of 2, 5, and 10 mm/min, corresponding to nominal strain rates of 0.0003 s^{-1}, 0.000725 s^{-1} and 0.00145 s^{-1} . All tests were carried out up to the plateau stress region. The resulting data enable a comprehensive assessment of the viscoelastic response and strain rate – dependent deformation mechanisms inherent to the PPB material.

All tensile tests were conducted under controlled environmental conditions at $23°C \pm 1°C$ and $50\% \pm 10\%$ relative humidity. For each mean experimental value, a minimum of five specimens was tested. The mean values corresponding to each strain rate were determined through statistical evaluation of the experimental data using Chauvenet's criterion.

The time – strain – stress data obtained from the uniaxial tensile tests were imported into MCalibration software for the calibration of the ANSYS TNM. As a result of the calibration process, the material model for the PPB material was successfully calibrated using the uniaxial tensile data, and the corresponding model parameters were determined.

2.4 Stress Relaxation Test

Stress relaxation experiments were conducted on the multi – purpose specimens to provide a more comprehensive evaluation of the time – dependent mechanical response of the material. These experiments were performed at the same strain rates used in the uniaxial tensile tests and at the corresponding yield strains of 0.088, 0.087, and 0.086 mm/mm, with a hold period of 600 seconds for each strain rate. Although short-term stress-relaxation tests of 1200 seconds are well documented for semi – crystalline polymers [17-19], studies have shown that even shorter tests of around 600 seconds can reliably capture early-stage relaxation [42] .

A significant portion of the stress relaxation response of PPB materials occurs within the first 600 seconds following the loading phase. Consequently, this duration provides a sufficient characteristic timescale to capture the fundamental viscoelastic behavior of PPB, in agreement with the shortened protocols reported for semi – crystalline polymers in the literature.

The stress – time data obtained from the relaxation tests were not utilized for model calibration but were instead employed as validation experiments to assess the predictive accuracy of the finite element simulations performed using the ANSYS TNM.

2.5 Numerical Modelling

The calibrated ANSYS TNM parameters for the pure PPB material were incorporated into the material library of the finite element analysis software. A three – dimensional finite element model, constructed based on the geometry of the experimental specimens, was assigned the calibrated ANSYS TNM material definition and imported into the numerical analysis environment.

Mesh sensivity analizi The mesh was generated with an approximate characteristic element size of 2 mm, comprising a total of 16,750 nodes and 3,078 elements; this resolution was selected to provide an optimal balance between simulation accuracy and computational efficiency. The geometry was discretized using 20 – node quadratic hexahedral elements (SOLID186). The mesh consisted of three elements across the 4 mm thickness.

To replicate the experimental conditions of the uniaxial tensile tests, all degrees of freedom of the nodes on the fixed – grip side were fully constrained, while the nodes corresponding to the movable – grip side were assigned time – dependent displacement boundary conditions equivalent to the applied tensile rate. These boundary conditions and loading configurations were established to enable direct comparison between the simulated stress and displacement fields and those obtained from the experimental tests. In ANSYS platform, boundary condition nodes are defined using named selections and worksheet – based methods.

The simulations of the stress relaxation tests employed the same specimen geometry, mesh configuration, and calibrated ANSYS TNM material parameters as used for the tensile tests. The boundary conditions and loading protocols were configured analogously to those in the uniaxial tensile tests: one grip was fully constrained while the other was displaced until the prescribed strain level was reached. Upon attaining the target strain, the movable grip was held stationary, allowing the stress to decay over time. Subsequently, the movable grip was returned to its initial position to simulate the unloading process. In this manner, the stress relaxation tests were simulated using the existing FEM model framework under conditions consistent with the experimental setup. Figure 5 schematically illustrates the boundary conditions and loading scenarios applied in the finite element simulations of both the tensile and stress relaxation tests.

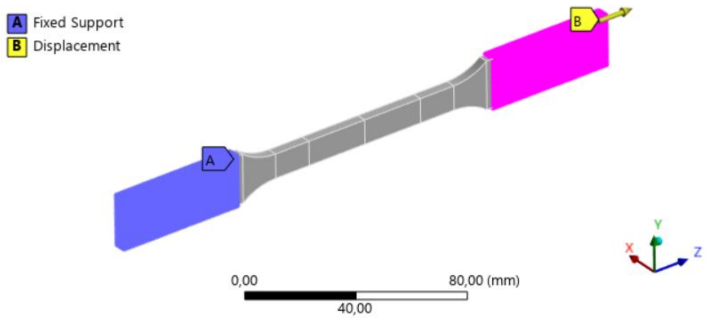


Figure 5. Schematic representation of boundary conditions for tensile and relaxation test simulations

The accuracy of the ANSYS TNM was evaluated by comparing the simulation results of uniaxial tensile and stress relaxation tests with the corresponding experimental data for the PPB material. Although the ANSYS TNM was calibrated exclusively using the tensile test data, it was found to predict the short – term stress relaxation behavior with a high degree of accuracy.

The coefficient of determination (R^2) was employed to evaluate the correlation between the experimental and FEM results. As the FEM dataset contained fewer points, the experimental data were reduced accordingly, and R^2 was computed in MATLAB according to Equation (10) [11] to assess the agreement between the simulation and experimental measurements.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - y_{fit})^2}{\sum_{i=1}^{N}(\bar{y} - y_{fit})^2} \tag{10}$$

3. Results and Discussion

The stress – strain curves obtained from uniaxial tensile tests performed at different quasi – static strain rates are presented in Figure 6. An increase in strain rate led to an increase in the yield stress, accompanied by a decrease in the yield strain. Furthermore, increasing the strain rate caused the nonlinear viscoelastic region of the stress–strain curve to shift toward lower strains, i.e., toward the linear viscoelastic region, accompanied by an increase in the slope of the curve.

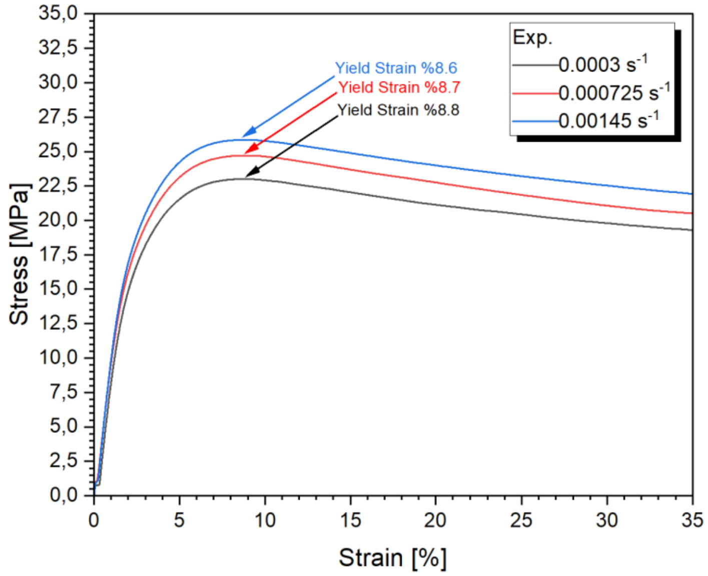


Figure 6. Stress – strain curves of PPB specimens from uniaxial tensile tests at various strain rates

The time – strain – stress data obtained from the uniaxial tensile tests were imported into the MCalibration software to calibrate the ANSYS TNM material model parameters for the PPB material. The calibrated parameter values are presented in Table 2.

In this study, material model parameters were carefully selected and calibrated based on available experimental data. Temperature related parameters and compression loading related parameters ($\hat{\theta}$= 0, α = 0, n = 0, a = 0) and the multiaxial parameter (q = 0) were set to zero, and large-deformation parameters (λ_L) were constrained, as the study focused solely on isothermal, uniaxial tensile behavior and small or moderate deformations.

Table 2. Optimized ANSYS TNM material model parameters for the PPB material

Description	Symbol	Unit	Value
Shear modulus of network A	μ_A	MPa	298.60
Temperature factor	$\hat{\theta}$	K	0.00
Locking stretch	λ_L	–	5.20
Bulk modulus	κ	MPa	1567.40
Flow resistance of network A	$\hat{\tau}_A$	MPa	17.68
Pressure dependence of flow	a	–	0.00
Stress exponent of network A	m_A	–	4.33
Temperature exponent	n	–	0.00
Initial shear modulus of network B	μ_{Bi}	MPa	252.65
Final shear modulus of network B	μ_{Bf}	MPa	68.42
Evolution rate of μB	β	–	21.68
Flow resistance of Network B	$\hat{\tau}_B$	MPa	28.44
Stress exponent of Network B	m_B	–	14.78
Shear modulus of Network C	μ_C	MPa	2.68
Thermal expansion reference temperature	θ_0	K	295.15
Relative contribution of second invariant	q	–	0.00

The calibrated parameter values for the PPB material, as provided in Table 2, were implemented into the finite element analysis software. Subsequently, finite element simulations of the uniaxial tensile tests were performed. Figure 7 presents a comparison between the stress – strain curves obtained from the experimental uniaxial tensile tests and those predicted by the numerical simulations.

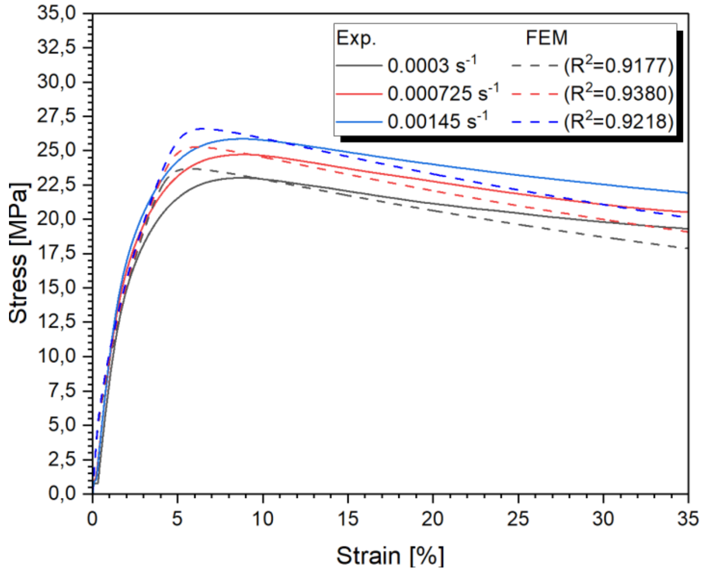


Figure 7. Experimental and FEM stress – strain curves of PPB material at various strain rates

The experimental stress – strain data obtained from uniaxial tensile tests conducted at strain rates of 0.0003 s^{-1}, 0.000725 s^{-1}, and 0.00145 s^{-1} were compared with the stress–strain curves derived from finite element – based simulations using the method of least squares. The resulting coefficients of determination (R^2) were 0.9177, 0.9380, and 0.9218, respectively. These R^2 values indicate that the ANSYS TNM material model accurately captures the mechanical behavior of PPB under uniaxial tensile loading.

Figure 8 presents the stress relaxation test conducted on a uniaxial tensile setup, showing (a) the strain – stress curves and (b) the stress – time curves. In the experiments performed at three different quasi – static strain rates, a decrease in stress over time was observed when the specimen was held at a constant strain. This stress reduction reflects the characteristic behavior of stress relaxation.

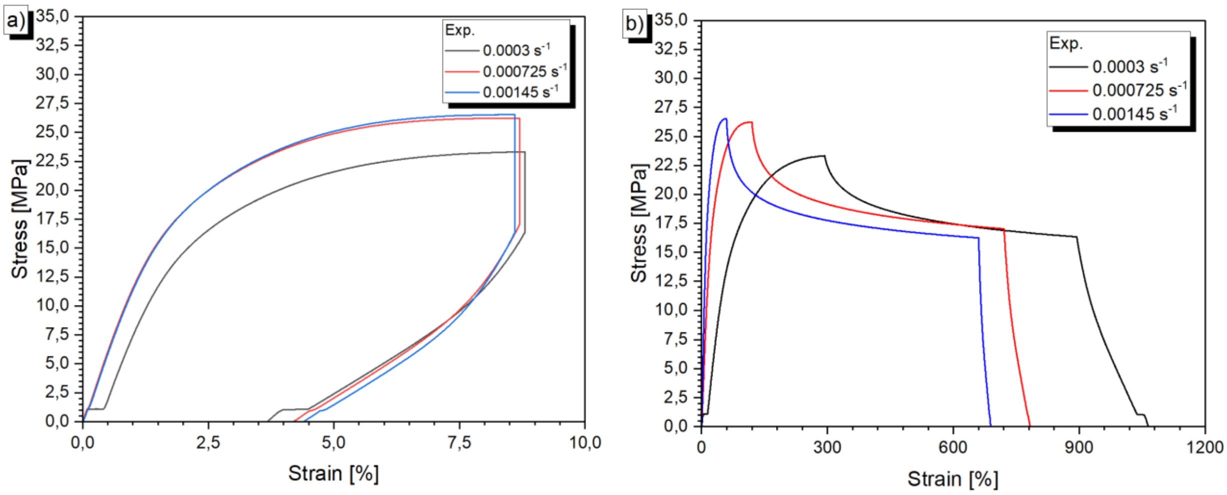
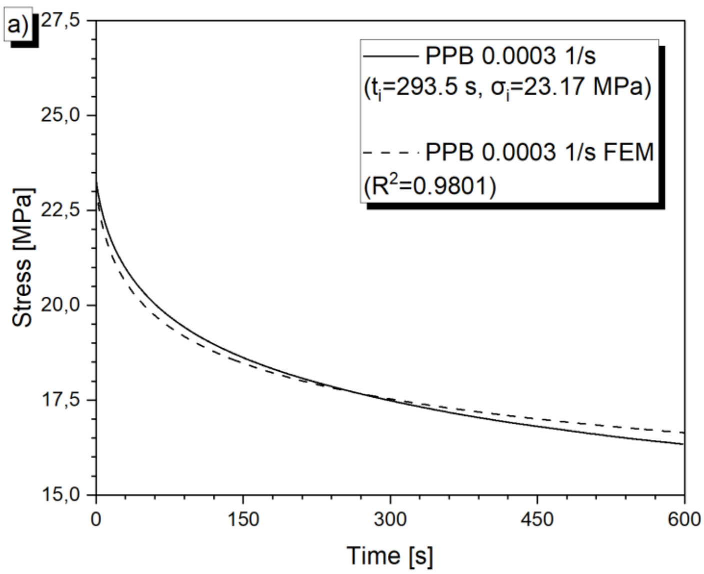


Figure 8. Stress relaxation test: (a) stress – strain curves, (b) stress – time curves

Figure 9 presents a comparison of the stress – time curves obtained from stress relaxation experiments and numerical simulations conducted at different strain rates (a) 0.0003 s^{-1}, (b) 0.000725 s^{-1}, and (c) 0.00145 s^{-1} and under varying initial relaxation stresses. Correlation between the experimental measurements and the finite element simulation results was assessed using the method of least squares. The coefficients of determination (R^2) were found to be 0.9801, 0.7842, and 0.9603 for quasi–static strain rates progressively increasing from low to high. t_i and σ_i are demonstrated



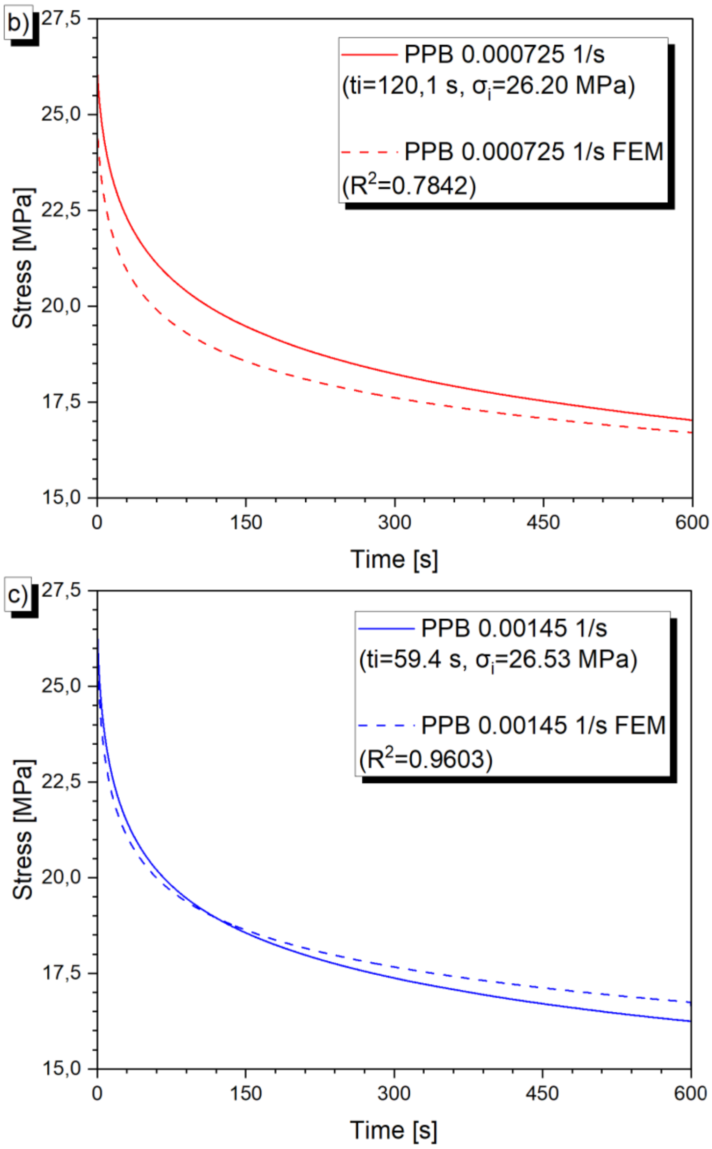


Figure 9. Experimental and finite element stress – time curves of PPB material from stress relaxation tests (a) 0.0003 s^{-1}, (b) 0.000725 s^{-1}, and (c) 0.00145 s^{-1}

Although the stress relaxation experiments were not included in the calibration process, the stress – time curves obtained from finite element – based stress relaxation simulations show a high level of agreement with the experimental data. The coefficients of determination (R^2) exceed 0.7842, indicating that the ANSYS TNM model calibrated for PPB reliably captures the stress relaxation behavior.

4. Conclusion

In this study, the mechanical behavior of pure polypropylene block copolymer (PPB) under low quasi – static strain rates was systematically investigated using a combination of experimental methods and finite element – based numerical simulations. The time – strain – stress data obtained from uniaxial tensile tests at different strain rates were successfully employed, via the MCalibration software, to calibrate ANSYS TNM parameters specific to the pure PPB material.

The mechanical behavior of pure PPB under tensile loading was compared across all examined strain rates using experimental data and tensile test simulations performed in a finite element – based framework. The resulting coefficients of determination ($R^2 \geq 0.91$) demonstrate that the model effectively captures the nonlinear, rate – dependent viscoelastic behavior characteristic of semi – crystalline polymers.

Finite element – based simulations of stress relaxation tests, conducted using ANSYS TNM parameters calibrated from time – strain – stress data obtained in tensile tests of pure PPB, were compared with stress relaxation experiments that were not included in the calibration process. The stress – time curves from both experimental and numerical studies exhibited high coefficients of determination ($R^2 \geq 0.7842$), demonstrating that the simulations accurately reproduce the experimental data.

The results indicate that the mechanical behavior of the material can be reliably predicted using a limited set of experimental data, offering significant advantages in terms of time, cost, and labor for engineering applications. Furthermore, this study contributes to the literature on numerical modeling of the short – term relaxation and rate – dependent tensile behavior of rate – sensitive pure PPB. Overall, the findings demonstrate that ANSYS TNM is an effective tool for predicting the mechanical performance of PPB and similar semi – crystalline polymer materials.

5. Acknowledgments and Author Contributions Statements

The authors gratefully acknowledge the academic software licenses for MCalibration and PolyUMod provided by Numesys Advanced Engineering Services through the facilitation of Ms. Sema Kaya.

This research manuscript represents a collaborative effort, with each author contributing significantly. Ferhat Akpınar was responsible for the optimization of material model parameters and finite element – based simulation studies. Together with Dr. Şenol Şahin, he co – developed the methodological framework and contributed to the interpretation of results. Dr. Şenol Şahin oversaw the execution of experimental activities and provided scientific validation and academic supervision throughout the study. All authors reviewed and approved the final version of the manuscript.

6. References

[1] Uyor, U. O., Popoola, P. A., Popoola, O. M., Aigbodion, V. S. (2023). "A review of recent advances on the properties of polypropylene-carbon nanotubes composites" ***Journal of Thermoplastic Composite Materials***, *36*(9), 3737-3770, 2023, doi: 10.1177/08927057221077868.

[2] Reis, M., Cakan, B. G., Durmuş, A., Reis, M. "Sıcaklık değişimi ve dinamik yol yüklerinin polipropilen gıda depolama kutularının deformasyonuna etkisi" ***Nevşehir Bilim ve Teknoloji Dergisi***, 99-105, 2020, doi: 10.17100/nevbiltek.726470.

[3] Hossain, M. T., Shahid, M. A., Mahmud, N., Habib, A., Rana, M. M., Khan, S. A., Hossain, M. D. "Research and application of polypropylene: a review" ***Discover Nano***, *19*(1), 2, 2024, doi: 10.1186/s11671-023-03952-z.

[4] Murariu, M., Laoutid, F., Paint, Y., Murariu, O., Raquez, J. M., Dubois, P. "Balancing the strength–impact relationship and other key properties in polypropylene copolymer–natural CaSO4 (Anhydrite)-filled composites" ***International Journal of Molecular Sciences***, *24*(16), 12659, 2023, doi: 10.3390/ijms241612659.

[5] Shao, W., Liu, L. Z., Wang, Y., Wang, Y., Shi, Y., Song, L. "Investigation of crystallization, morphology, and mechanical properties of polypropylene/polypropylene-polyethylene block copolymer blends" ***Polymers***, *15*(24), 4680, 2023, doi: 10.3390/polym15244680.

[6] Tang, Y. H., Zhang, N., Bao, W., Jiang, W., Lin, Y., Su, Z. H. "Critical role of ethylene-propylene block copolymer in impact polypropylene copolymer" ***Chinese Journal of Polymer Science***, *42*(3), 344-351, 2024, doi: 10.1007/s10118-023-3058-4.

[7] Deng, Y. M., Edwards, K. L. "The role of materials identification and selection in engineering design" ***Materials & design***, *28*(1), 131-139, 2007, doi: https://doi.org/10.1016/j.matdes.2005.05.003.

[8] Arıcıoğlu, M., Mert, B., Soydan, Y. "Mechanical analysis of polymeric materials" ***Sakarya University Journal of Science***, *4*(1-2), 51-58, 2000, doi: 10.16984/saufbed.75940.

[9] Zhou, Y., Mallick, P. K. "Effects of temperature and strain rate on the tensile behavior of unfilled and talc-filled polypropylene. Part I: Experiments" ***Polymer Engineering & Science***, *42*(12), 2449-2460, 2002, doi: https://doi.org/10.1002/pen.11131.

[10] Aydemir, B., Şahin, Ş., Şahin, T. "Polipropilen kopolimerinde (PPB) kalsiyum karbonat tane boyutunun kısa süreli çekme sürünme özellikleri üzerine etkisi" ***Nevşehir Bilim ve Teknoloji Dergisi***, *7*(2), 206-213, 2018, doi: 10.17100/nevbiltek.368459.

[11] Segura-Méndez, K. L., Puente-Córdova, J. G., Rentería-Baltiérrez, F. Y., Luna-Martínez, J. F., Mohamed-Noriega, N. "Modeling of stress relaxation behavior in HDPE and PP using fractional derivatives" ***Polymers***, *17*(4), 453, 2025, doi: 10.3390/polym17040453.

[12] Siviour, C. R., Jordan, J. L. "High strain rate mechanics of polymers: a review" ***Journal of Dynamic Behavior of Materials***, *2*(1), 15-32, 2016, doi: 10.1007/s40870-016-0052-8.

[13] Farahani, M. F., Bagheri, R. "A new look at tensile yielding in isotactic polypropylene: role of strain rate and thermal softening" ***Polymer Bulletin***, *79*(12), 11157-11176, 2022, doi: 10.1007/s00289-021-03997-z.

[14] B. Aydemir, "Plastiklerin ISO 527 standardına göre çekme özelliklerinin belirlenmesi" in "Mühendislik alanındaki gelişmeler", A. Bideci, Ed., *Turkey: Duvar Kitapevi*, 2022, ch. Chapter 7, pp. 111–128. [Online]. Available: https://www.duvaryayinlari.com/Webkontrol/IcerikYonetimi/Dosyalar/muhendislik-alanindaki-gelismeler_icerik_g3808_nFMAwjoG.pdf

[15] Şahin, Y., Sahin, S., İnal, M. "Modelling of the tensile properties of calcium carbonate filled polypropylene composite materials with Taguchi and artificial neural networks" ***IFAC-PapersOnLine***, *51*(30), 282-286, 2018, doi: https://doi.org/10.1016/j.ifacol.2018.11.302.

[16] Deng, M., Zhou, J. "Effects of temperature and strain level on stress relaxation behaviors of polypropylene sutures" ***Journal of Materials Science: Materials in Medicine***, *17*(4), 365-369, 2006, doi: 10.1007/s10856-006-8239-5.

[17] Drozdov, A. D., Dusunceli, N. "Inverse relaxation in polypropylene" ***Iranian Polymer Journal***, *21*(10), 701-711, 2012, doi: 10.1007/s13726-012-0077-3.

[18] Dusunceli, N. "The unusual creep and relaxation behaviour of polypropylene" ***Journal of Polymer Engineering***, *32*(3), 167, 2012, doi: doi:10.1515/polyeng-2011-0159.

[19] Drozdov, A. D., Dusunceli, N. "Cyclic deformations of polypropylene with a strain-controlled program" ***Polymer Engineering & Science***, *52*(11), 2316-2326, 2012, doi: https://doi.org/10.1002/pen.23188.

[20] K. A. Brown, R. Brooks, and N. A. Warrior, "Characterizing the strain rate sensitivity of the tensile mechanical properties of a thermoplastic composite," ***JOM***, vol. 61, no. 1, pp. 43–46, 2009, doi: 10.1007/s11837-009-0007-9.

[21] Wang, Q., Wang, J., Wang, A., Zhou, C., Hu, J., Pan, F. "Effect of strain rate and temperature on the tensile properties of long glass fiber-reinforced polypropylene composites" ***Polymers***, *15*(15), 3260, 2023, doi: 10.3390/polym15153260.

[22] Amjadi, M., Fatemi, A. "Tensile behavior of high-density polyethylene including the effects of processing technique, thickness, temperature, and strain rate" ***Polymers***, *12*(9), 1857, 2020, doi: 10.3390/polym12091857.

[23] Chowdhury M., "Thin polymer films out of thermodynamic equilibrium," *Albert Ludwigs University - Mathematics and Physics Department, Ph.D Dissertation*, Freiburg, 2012. [Online]. Available: https://www.researchgate.net/publication/279825049_Thin_polymer_films_out_of_thermodynamic_equilibrium

[24] Luo, W., Wang, C., Hu, X., Yang, T. "Long-term creep assessment of viscoelastic polymer by time-temperature-stress superposition" ***Acta Mechanica Solida Sinica***, *25*(6), 571-578, 2012, doi: 10.1016/S0894-9166(12)60052-4.

[25] Tscharnuter, D., Jerabek, M., Major, Z., Pinter, G. "Uniaxial nonlinear viscoelastic viscoplastic modeling of polypropylene" ***Mechanics of Time-Dependent Materials***, *16*(3), 275-286, 2012, doi: 10.1007/s11043-011-9158-5.

[26] Gebrehiwot, S. Z., Espinosa-Leal, L. "Characterising the linear viscoelastic behaviour of an injection moulding grade polypropylene polymer" ***Mechanics of Time-Dependent Materials***, *26*(4), 791-814, 2022, doi: 10.1007/s11043-021-09513-0.

[27] Rosca, N., Najm, S. M., Avrigean, E., Oleksik, M., Trzepieciński, T., Oleksik, V. "Study on the choice of a suitable material model for the numerical simulation of the incremental forming process of polymeric materials" ***Applied Sciences***, *15*(13), 7094, 2025. doi: 10.3390/app15137094.

[28] J. S. Bergström, J. E. Bischoff, "An advanced thermomechanical constitutive model for UHMWPE" **I*nternational Journal of Structural Changes in Solids – Mechanics and Applications***, vol. 2, no. 1, pp. 31–39, 2010.

[29] Dal, H., Kaliske, M. "Bergström–Boyce model for nonlinear finite rubber viscoelasticity: theoretical aspects and algorithmic treatment for the FE method" ***Computational Mechanics***, *44*(6), 809-823, 2009, doi: 10.1007/s00466-009-0407-2.

[30] Bergström, J. S., Boyce, M. C. "Large strain time-dependent behavior of filled elastomers" ***Mechanics of Materials***, *32*(11), 627-644, 2000, doi: https://doi.org/10.1016/S0167-6636(00)00028-4.

[31] Alhourani, A., Barsoum, I., Deveci, S., Sheikh-Ahmad, J., Abdelgawad, A. "Constitutive models for the thermo-mechanical and dynamic behavior of high-density polyethylene" ***Polymer Testing***, 108935, 2025, doi: https://doi.org/10.1016/j.polymertesting.2025.108935.

[32] Mainardi, F., Spada, G. "Creep, relaxation and viscosity properties for basic fractional models in rheology" ***The European Physical Journal Special Topics***, *193*(1), 133-160, 2011, doi: 10.1140/epjst/e2011-01387-1.

[33] Bergström, J. S., Kurtz, S. M., Rimnac, C. M., Edidin, A. A. "Constitutive modeling of ultra-high molecular weight polyethylene under large-deformation and cyclic loading conditions" ***Biomaterials***, *23*(11), 2329-2343, 2002, doi: 10.1016/S0142-9612(01)00367-2.

[34] Almomani, A., Deveci, S., Mourad, A. H. I., Barsoum, I. "Constitutive model calibration for the thermal viscoelastic-viscoplastic behavior of high density polyethylene under monotonic and cyclic loading" ***Polymer Testing***, *118*, 107911, 2023, doi: https://doi.org/10.1016/j.polymertesting.2022.107911.

[35] Mian, S. H., Umer, U., Moiduddin, K., Alkhalefah, H. "Predicting mechanical properties of polymer materials using rate-dependent material models: Finite element analysis of bespoke upper limb orthoses" ***Polymers***, *16*(9), 1220, 2024, doi: 10.3390/polym16091220.

[36] O. Volgin, I. Shishkovsky, "Material modelling of FDM printed PLA part" ***Engineering Solid Mechanics***, 153–160, 2021, doi: 10.5267/j.esm.2020.12.004.

[37] Knight, J., Salim, H., Elemam, H., Elbelbisi, A. "Calibration of thermal viscoelastic material models for the dynamic responses of PVB and SG interlayer materials" ***Polymers***, *16*(13), 1870, 2024, doi: 10.3390/polym16131870.

[38] Kulkarni, S. S., Mocko, G. M. "A finite element simulation model of convective heat-assisted single-point incremental forming of thermoplastics" ***The International Journal of Advanced Manufacturing Technology***, *111*(11), 3305-3317, 2020, doi: 10.1007/s00170-020-06311-9.

[39] Kumar, M., Ravi, K., Singh, S. S. "Predicting the double-yield phenomenon in low-density polyethylene film using three-network viscoplastic model" ***Mechanics of Materials***, *184*, 104736, 2023, doi: https://doi.org/10.1016/j.mechmat.2023.104736.

[40] Bergström J., "*8 - Viscoplasticity Models*" in *Mechanics of Solid Polymers*, J. Bergström, Ed., William Andrew Publishing, 2015, pp. 371–436. doi: https://doi.org/10.1016/B978-0-323-31150-2.00008-X.

[41] ANSYS Inc., "ANSYS Mechanical APDL Material Reference: TNM Theory," ANSYS Help Release 2025 R1. Accessed: Mar. 18, 2026. [Online]. Available: https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/corp/v251/en/ans_mat/aQw8sq22dldm.html

[42] Dusunceli, N., Colak, O. U. "High density polyethylene (HDPE): Experiments and modeling" ***Mechanics of Time-Dependent Materials***, *10*(4), 331-345, 2006, doi: 10.1007/s11043-007-9026-5.