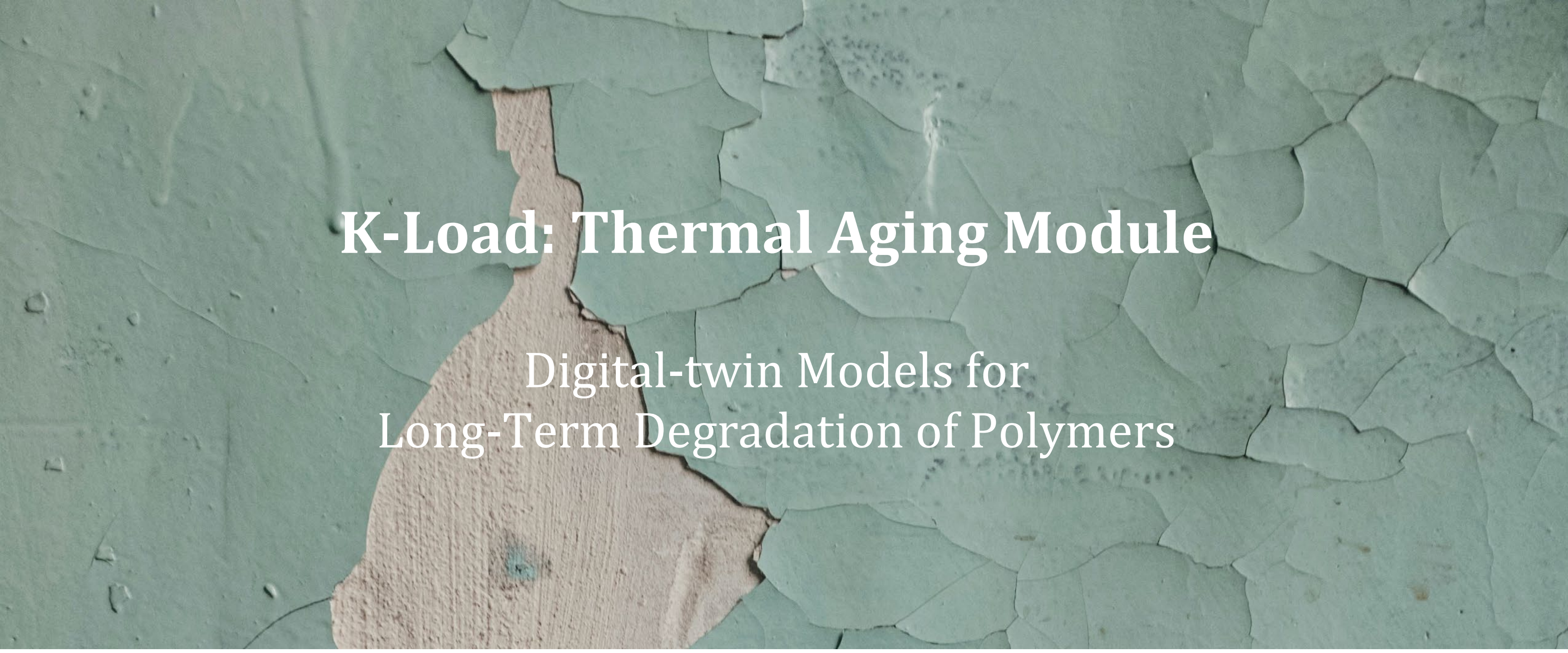


K-Load: Thermal Aging Module

Digital-twin Models for Long-Term Degradation of Polymers

Modern aerospace, automotive, defense, and electronics increasingly rely on polymeric materials whose reliability must be certified over decades of operation. The K-Load Thermal Aging Module provides a rigorous predictive framework that extends far beyond empirical Arrhenius extrapolations.

Valid for a Material Family

Once a digital twin is trained for one representative member of a material family (e.g., a specific epoxy or elastomer), it can be rapidly re-trained for other derivatives in the same family—greatly reducing qualification costs.

Minimized Training Data

Minimum requirement: three to four accelerated aging datasets (stress–strain, relaxation, modulus decay, or weight loss) at elevated yet realistic temperatures. Tests must avoid extreme conditions that trigger secondary degradation mechanisms. Input formats accepted: CSV, Excel.

High Accuracy in Long-term Predictions

Conventional Arrhenius models assume a single activation energy and exponential time–temperature shift. This often underestimates damage in polymers where multiple concurrent kinetics operate. K-Load integrates multi-mechanism kinetics into a hybrid physics-informed ML engine, producing far superior long-term extrapolation.

Couple Theories & Computation

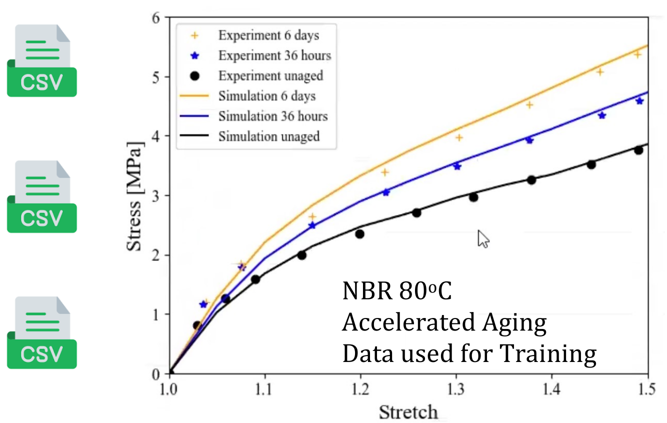
Unlike classical theoretical models that rely on a single governing equation, the hybrid K-Load approach integrates data-driven learning with mechanistic polymer physics. This allows the model to adapt to non-linear kinetics, capture multiple concurrent degradation pathways, and deliver predictions that are both accurate and generalizable across material families.

Stage 1: Experimental Data

- Tracks degradation of modulus, weight loss, and cross-link density under isothermal and cyclic heating.
- Predicts full constitutive stress–strain curves at arbitrary time–temperature histories.
- Validated for elastomers, adhesives, encapsulants, epoxies, and thin films.

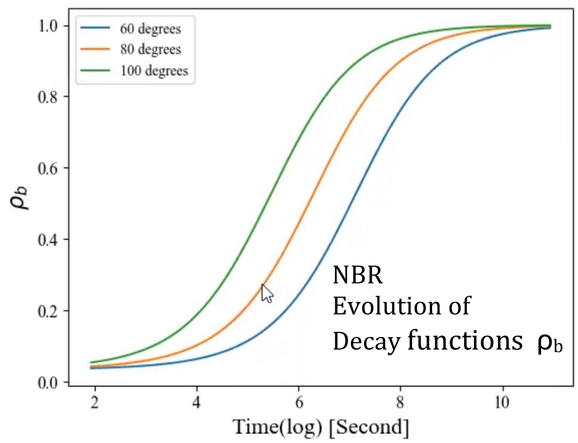
Stage 2: Data Input & Consistency Check

- Automated import of CSV/Excel datasets.
- Replicates compared, discontinuities flagged, outliers filtered statistically.
- Generation of averaged master curves for modulus or relaxation properties.



Stage 3: Fine-Tuning with Material Knowledge

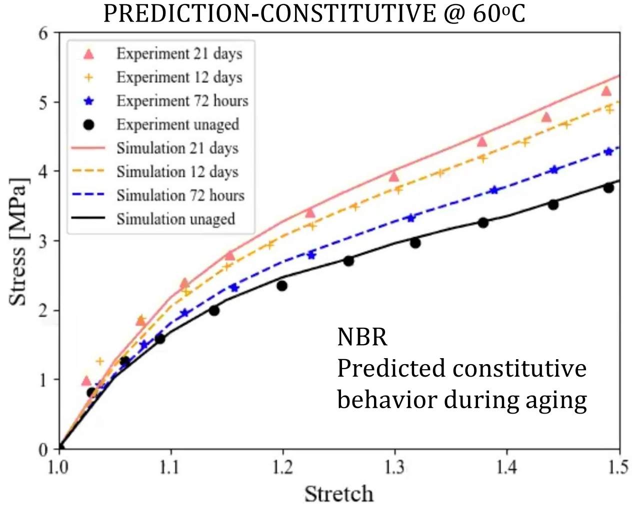
- Incorporates oxidation rate constants, cross-link scission, and filler-modulus interaction.
- Accounts for network structure: linear, branched, filled/unfilled.
- Utilizes literature-based models for chain scission, free-volume evolution, and decay functions ρ_b.
- Merges experimental data with polymer physics in a hybrid engine.



Stage 4: Post-Processing & Simulation

- Constitutive behavior prediction at user-defined time–temperature pairs.
- Stress relaxation under fixed strain; long-term creep/relaxation envelopes.
- Failure thresholds and property retention maps generated automatically using K-Fail.
- Optional coupling with K-Extreme for Survivability analysis against extreme events, such as Burst, fire…

PREDICTION-CONSTITUTIVE @ 60°C



Stage 5: Output Data Generation

- Produces modulus–time plots, relaxation curves, and stress–strain envelopes.
- Multi-format export: Excel spreadsheets, CSV/JSON databases, PDF reports.
- API-ready outputs: tangent stiffness matrices for Abaqus, Ansys, COMSOL.

Next-Step Options

After training and prediction, results can be directly deployed for advanced workflows:
- Excel/CSV Reports: Tabulated outputs for certification dossiers and QA workflows.
- Finite Element Integration: Exported tangent matrices directly embedded into Abaqus, Ansys, COMSOL.
- API Access: Real-time simulation pipelines through REST API integration.
- K-Fail Coupling: Predict survivability under cyclic loading, vibration, and fatigue.
- K-Extreme Coupling: Assess long-term reliability under combined thermal, radiation, and mechanical stressors.

Key Benefits

- Cuts qualification testing by 50–70%.
- Improves accuracy over Arrhenius extrapolation for long-term reliability.
- Enables survivability assessments for mission-critical aerospace and defense polymers.

PREDICTION-RELAXATION AFTER 50 Days