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Viscoelastic Creep Characterization of LDPE Under Multilevel Stress and Temperature Using Time-Temperature Superposition and Constitutive Modeling

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Abstract

This study addresses the difficulty of accurately characterizing the long-term viscoelastic creep of low-density polyethylene (LDPE) when sustained stress, temperature, and exposure time vary simultaneously, while conventional short-term testing and single-condition constitutive models provide limited representation of service behavior. The purpose was to quantify multilevel stress-temperature effects on LDPE creep and integrate experimental response, time-temperature superposition (TTS), statistical modeling, and constitutive validation within one framework. A quantitative, cross-sectional, experimental case-based design was adopted using commercial-grade LDPE specimen-condition cases exposed to stresses of 2–10 MPa and temperatures of 25–65°C, with 45°C selected as the TTS reference temperature. Key variables included stress, temperature, creep time, creep strain, creep compliance, creep rate, temperature shift factor, reduced time, and constitutive parameters. Analysis combined descriptive statistics, Pearson correlations, multiple regression, Cronbach's alpha, TTS master-curve construction, and Burgers-type/generalized viscoelastic model calibration and validation using R^2, adjusted R^2, F-statistics, RMSE, and MAE. Findings showed that creep strain increased from 2.84% to 9.67%, creep rate from 0.018% h^{-1} to 0.071% h^{-1}, and compliance from 0.46 to 1.38 MPa^{-1}. Stress correlated strongly with creep strain ($r = 0.76$), as did temperature ($r = 0.71$), both $p < 0.001$. Regression explained 68.4% of creep-strain variance (adjusted $R^2 = 0.672$; $F = 58.27$, $p < 0.001$), with stress ($\beta = 0.49$) and temperature ($\beta = 0.41$) significant. Shift factors ranged from 5.62 to 0.18, extending the creep domain to 0.18–562 h, while constitutive validation achieved $R^2 = 0.94$, RMSE = 0.37%, and MAE = 0.29%. Overall scale reliability was high (Cronbach's alpha = 0.88), supporting consistency of the quantitative assessment across measured analytical constructs. The findings support more reliable long-term LDPE design, material assessment, and engineering prediction under coupled thermomechanical loading.

Keywords: *Low-Density Polyethylene (LDPE); Viscoelastic Creep; Time-Temperature Superposition; Constitutive Modeling; Stress-Temperature Effects*

INTRODUCTION

Viscoelasticity refers to the mechanical behavior of materials that exhibit both recoverable elastic deformation and time-dependent viscous deformation when subjected to load, while creep is the progressive accumulation of strain under a sustained stress. Low-density polyethylene (LDPE) is a semicrystalline thermoplastic whose long-chain branching, crystalline lamellae, amorphous regions, molecular entanglements, and temperature-sensitive chain mobility give rise to pronounced time-dependent mechanical behavior. Consequently, the deformation of LDPE cannot be described adequately by a purely elastic stress-strain relationship when loading is maintained over extended periods. In *Viscoelastic Model of Cross-Linked Polyethylene Including Effects of Temperature and Crystallinity* (pp. 23-44), the dependence of polyethylene viscoelastic response on temperature and crystalline structure established the importance of treating thermal condition and morphology as integral components of mechanical characterization (Olasz & Gudmundson, 2005). Mechanical analogues containing elastic springs and viscous dashpots have similarly demonstrated that creep, recovery, and stress relaxation can be represented through combinations of recoverable and irreversible time-dependent components (Fancey, 2005). Experimental investigations of HDPE under tensile and compressive loading have further shown that modulus, deformation, relaxation, and creep compliance depend on loading rate, stress magnitude, and elapsed time, confirming the intrinsic viscoelastic character of the polyethylene family (Dusunceli & Colak, 2006; Elleuch & Taktak, 2006). At the constitutive level, semicrystalline polymers have also been described through coupled viscoelastic and viscoplastic mechanisms in which molecular rearrangement, slippage of mesoscopic domains, and deformation of crystalline and amorphous phases jointly control macroscopic strain development (Drozdov, 2007). These characteristics are internationally important because polyethylene materials are employed in packaging films, piping, electrical insulation, liners, containers, biomedical components, structural membranes, and numerous load-bearing polymer applications in which dimensional stability over time remains a fundamental material requirement. Polyethylene creep therefore represents a material-characterization problem linking molecular-scale mobility with measurable engineering deformation under sustained service loading (Khelif et al., 2007; Liu et al., 2008).

The creep response of LDPE is particularly sensitive to both applied stress and temperature because these variables alter the rate and extent of molecular rearrangement within its heterogeneous semicrystalline morphology. Under sustained stress, an initial deformation can be followed by progressively evolving strain as amorphous chains rotate, uncoil, disentangle, and rearrange while crystalline regions and tie molecules resist or redistribute the applied load. Increasing stress can move the response from approximately linear viscoelastic behavior toward nonlinear viscoelastic or viscoplastic deformation, making characterization at a single stress level insufficient for representing the full mechanical response. In *A Practical Approach to Modeling Time-Dependent Nonlinear Creep Behavior of Polyethylene for Structural Applications* (pp. 159-167), creep tests performed across polyethylene materials demonstrated that stress-dependent nonlinear behavior can be represented by combining multi-Kelvin elements with power-law formulations, highlighting the value of multilevel loading for constitutive identification (Liu et al., 2008). Temperature produces an equally important influence because thermal energy modifies segmental mobility, relaxation rates, viscosity, and resistance to deformation. Experimental creep testing of medium-density polyethylene across multiple stresses and temperatures reported that instantaneous deformation and creep behavior vary systematically as mechanical and thermal activation conditions change (Sahebian et al., 2011). Comparable polyethylene investigations have shown strong associations among temperature, morphology, crystallinity, creep compliance, and deformation resistance (Alothman et al., 2014; Bozorg-Haddad & Iskander, 2011). Molecular architecture is also central to this response. Long-chain branching, molecular-weight distribution, and branching topology strongly influence relaxation time, viscosity, elastic response, and thermorheological behavior in LDPE and related polyethylene systems (Delgadillo-Velázquez et al., 2008; Keßner et al., 2010). More recent characterization of industrial LDPE has confirmed that crystallization behavior, dynamic mechanical response, and linear and nonlinear rheology vary with molecular morphology, while constitutive predictions can reproduce important stress responses when an appropriate material framework is employed (Poh et al., 2022). The combined dependence on stress, temperature, morphology, and time therefore requires experimental

characterization that separates and then statistically examines these interacting sources of creep variation.

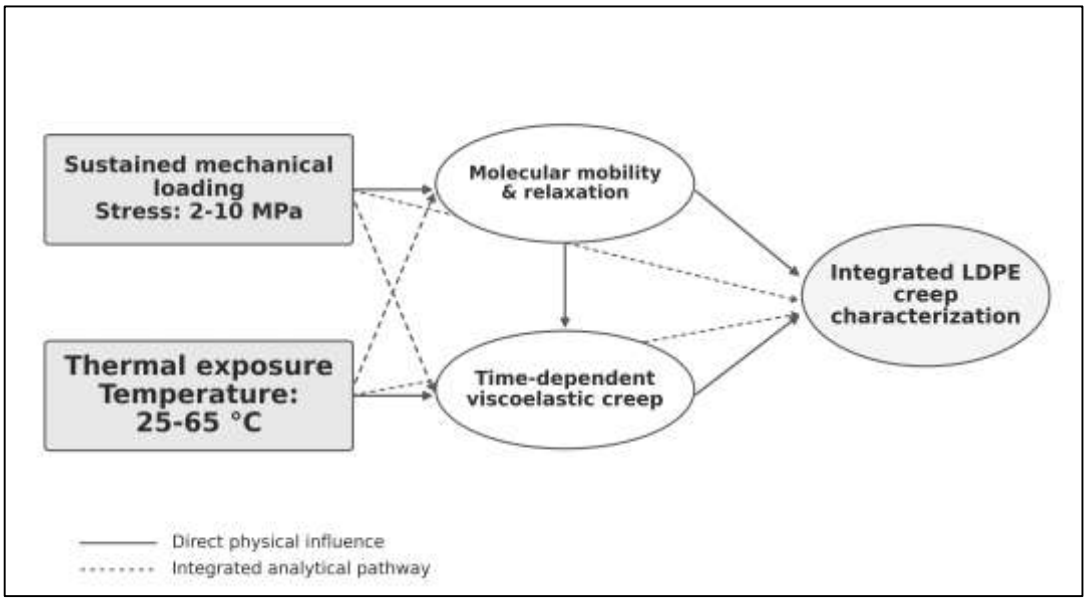
A major difficulty in creep characterization arises from the difference between practical laboratory testing durations and the much longer time scales over which polymer deformation can develop. Time-temperature superposition (TTS) addresses this problem by exploiting the temperature dependence of molecular relaxation so that measurements performed over accessible experimental time or frequency windows can be shifted to construct a broader master representation at a selected reference temperature. In *Isothermal Viscoelastic Properties of PMMA and LDPE over 11 Decades of Frequency and Time* (pp. 777-786), isothermal measurements on LDPE were examined over an exceptionally wide temporal and frequency domain, providing direct evidence for evaluating the applicability and limitations of time-temperature superposition in LDPE (Capodagli & Lakes, 2008). Under TTS, experimentally measured curves obtained at different temperatures are shifted horizontally through temperature-dependent shift factors, transforming physical time into reduced time while retaining the reference-temperature representation of the viscoelastic response. The procedure depends on thermorheological compatibility because different molecular relaxation processes do not necessarily possess identical temperature sensitivities across all thermal domains. Thermorheological studies of LLDPE/LDPE systems have demonstrated that polymer architecture and long-chain branching materially influence shift behavior and activation characteristics (Delgadillo-Velázquez et al., 2008; Dordinejad & Jafari, 2013). Research evaluating WLF, Arrhenius, and related temperature-shift descriptions has likewise established that the mathematical description of temperature dependence must correspond to the relevant relaxation regime rather than being selected independently of material response (Nakada et al., 2011; Shangguan et al., 2017). In *Thermorheological Behavior of Various Short- and Long-Chain Branched Polyethylenes* (pp. 7341-7350), variations in activation energy were associated with polyethylene molecular structure, reinforcing the connection between macromolecular architecture and thermal shifting behavior (Keßner et al., 2010). Statistical examination of TTS has additionally emphasized uncertainty associated with curve shifting and master-curve construction, making quantitative model assessment important when extrapolated creep behavior is derived from experimental observations (Maiti, 2019; Feroz, 2025).

Constitutive modeling provides the mathematical connection between experimental creep observations and the underlying time-dependent mechanical response of polyethylene. Classical viscoelastic representations employ combinations of Maxwell and Kelvin-Voigt elements to distinguish instantaneous elastic deformation, delayed elastic deformation, and viscous flow, while generalized networks introduce multiple retardation or relaxation times to capture broader response spectra. More advanced formulations incorporate nonlinear viscoelasticity, viscoplasticity, temperature dependence, molecular-network concepts, free-volume effects, or stress-dependent parameters. In *Thermoviscoelastic Models for Polyethylene Thin Films* (pp. 13-43), experimental creep, tensile, and biaxial tests were integrated with a nonlinear thermoviscoelastic framework based on free-volume concepts, demonstrating how constitutive parameters can be identified from polyethylene behavior across temperature and loading conditions (Li et al., 2016; Chandra, 2025). Multilevel creep testing is particularly valuable for this purpose because a model calibrated only under one stress can conceal stress dependence in retardation time, viscosity, or compliance. Morphology-controlled HDPE experiments conducted at different stresses and temperatures showed that creep deformation could be represented satisfactorily through a generalized Kelvin-Voigt formulation, while substantial differences in creep resistance emerged from different internal morphologies (Pervaz, 2025; Pan et al., 2016). Short-term creep data have also been fitted using Burgers, stretched-Burgers, Findley, and related phenomenological descriptions, demonstrating how individual constitutive structures represent distinct components of time-dependent response (Kaium, 2025; Pereira et al., 2018). In *Modeling Short- and Long-Term Time-Dependent Nonlinear Behavior of Polyethylene* (pp. 600-610), constitutive parameters obtained from short-duration tests were used to describe nonlinear viscoelastic and viscoplastic polyethylene response over extended time domains (Sepiani et al., 2018). More recent work has combined creep-derived master curves with multi-Kelvin and power-law components for polyethylene, further linking experimental shifting procedures with constitutive parameterization (Kühl & Polak, 2021; Arif Uz et al., 2025). LDPE-specific constitutive research has also shown that

changes in material structure can be represented through visco-hyperelastic-viscoplastic formulations, emphasizing the need for model parameters that remain physically connected to the polymer response being characterized (Ayoub et al., 2020; Mashiat, 2025).

The international literature therefore presents LDPE and related polyethylene creep as a multivariable mechanical phenomenon in which stress, temperature, time, morphology, and constitutive parameters operate simultaneously rather than as independent material descriptors. In *Compression Creep and Thermal Ratcheting Behavior of High Density Polyethylene* (Article 156), increased load and temperature were associated with marked increases in creep strain and reductions in creep modulus, directly demonstrating the need to assess mechanical and thermal variables together rather than through isolated tests (Jeya & Bouzid, 2018). Creep experiments on polyethylene exposed to different environments have also demonstrated that material condition can alter compliance, stiffness, viscosity, and stationary creep rate, illustrating the sensitivity of constitutive parameters to changes in molecular mobility (Habas-Ulloa et al., 2010; Pereira et al., 2018). Rheological investigation of LDPE has further demonstrated that its time-dependent stress response is controlled simultaneously by strain and deformation rate, reinforcing its characterization as a material with strong memory-dependent mechanical behavior (Huang, 2021; Mashfiqur, 2025). Recent constitutive investigations of HDPE have used tensile, relaxation, and creep experiments at multiple stress levels to identify viscoelastoplastic parameters and test model predictions against independent creep observations, indicating that parameter identification and validation should remain separate analytical stages (Drozdov et al., 2023; Mostari, 2025). Related structure-rheology research across LDPE and LLDPE has shown that long-chain branching can increase zero-shear viscosity, storage modulus, relaxation time, activation energy, and strain-hardening behavior, demonstrating that measurable viscoelastic response is closely connected to macromolecular architecture (Jannatul, 2025; Li et al., 2023). The present research is therefore centered on quantitative characterization of LDPE subjected to multilevel stress and temperature conditions, with creep strain, creep rate, compliance, temperature shift factors, reduced time, master-curve behavior, and constitutive parameters treated as interconnected measurable variables. Descriptive statistics, correlation analysis, regression modeling, time-temperature superposition, and constitutive calibration provide distinct analytical routes for examining these variables while maintaining the experimental focus on the stress-temperature-time dependence of LDPE viscoelastic creep.

Figure 1: Overview of the Integrated LDPE Creep Characterization Framework



Background of the Study

Low-density polyethylene (LDPE) is one of the most widely used thermoplastic polymers because of its flexibility, low density, chemical resistance, processability, impact resistance, and relatively low production cost. Its molecular structure contains a substantial degree of chain branching, which limits

close molecular packing and produces a semicrystalline material with both crystalline and amorphous regions. This heterogeneous morphology strongly influences its mechanical behavior under sustained loading. Unlike ideally elastic materials, LDPE does not respond to mechanical stress through an instantaneous and fully recoverable deformation alone. Instead, it exhibits viscoelastic behavior in which deformation develops progressively with time because molecular chains, entanglements, crystalline domains, and amorphous segments continuously rearrange under load. This time-dependent deformation is commonly described as creep and becomes especially important when LDPE components are exposed to mechanical stress for long service periods. The magnitude of creep deformation is not controlled by time alone. Applied stress and environmental temperature can substantially alter the rate of molecular mobility, segmental rearrangement, viscous flow, and resistance to deformation. Higher stress can intensify chain slippage and produce nonlinear deformation, while increased temperature generally accelerates molecular motion and shortens characteristic relaxation times. Consequently, creep measured under one stress or temperature condition may not adequately describe LDPE performance under other operating conditions. Long-term experimental creep testing can also be difficult because direct observation over service-relevant durations requires substantial time and resources. Time-temperature superposition offers a useful means of extending experimentally accessible creep data by shifting responses obtained at different temperatures to a common reference condition and constructing a master curve over an enlarged time domain. Constitutive modeling complements this process by representing the mechanical response through mathematical parameters associated with elastic, delayed elastic, and viscous deformation. The present study is therefore centered on the integrated characterization of LDPE creep under multilevel stress and temperature conditions. By combining experimental creep response, time-temperature superposition, shift-factor analysis, master-curve construction, constitutive modeling, descriptive statistics, correlation analysis, regression modeling, and structured quantitative assessment, the study provides a unified basis for examining how stress, temperature, and time govern the viscoelastic deformation of LDPE.

Problem Statement

The long-term mechanical performance of LDPE is difficult to characterize accurately because its deformation under sustained loading is strongly dependent on stress level, temperature, exposure duration, and the viscoelastic characteristics of the material. Conventional mechanical properties obtained from short-term tensile or compression tests do not fully represent the progressive deformation that develops when LDPE is exposed to constant or quasi-constant loading. Creep behavior can become particularly complex when both stress and temperature change, because the mechanisms responsible for molecular movement and strain accumulation may not remain constant across different loading conditions. A material response observed at low stress may appear approximately linear, whereas a higher stress level can produce nonlinear viscoelastic or viscoplastic behavior. Similarly, increasing temperature can accelerate molecular mobility, reduce resistance to deformation, modify relaxation processes, and change the apparent time scale over which creep occurs. These effects create a major characterization problem because a constitutive model calibrated under a single condition may not accurately reproduce LDPE behavior across other stress-temperature combinations. Direct long-duration testing also creates practical limitations because experimentally reproducing years of creep deformation is difficult within conventional laboratory schedules. Time-temperature superposition can extend the observable response, yet its accuracy depends on suitable reference-temperature selection, reliable shift factors, and the degree to which the investigated LDPE behaves thermorheologically consistently across the selected temperature range. In addition, statistical relationships among stress, temperature, creep strain, creep rate, and model-prediction performance are often examined separately rather than through an integrated analytical framework. Therefore, there is a need for a systematic study that characterizes LDPE under multiple stress and temperature levels, develops a time-temperature master curve, calibrates an appropriate constitutive model, and quantitatively evaluates the relationships among experimental and modeled variables. Addressing this problem requires a framework capable of linking experimental creep observations with statistical analysis and constitutive prediction while maintaining consistent interpretation across all investigated loading conditions.

Purpose and Objectives of the Study

The principal purpose of this study is to quantitatively characterize the viscoelastic creep behavior of LDPE under multilevel stress and temperature conditions and to develop an integrated analytical framework in which experimental creep data, time-temperature superposition, constitutive modeling, and statistical analysis are examined together. The study specifically seeks to determine how changes in applied stress affect creep strain, creep compliance, and creep rate and how these responses vary when temperature is simultaneously changed. A further objective is to establish the statistical relationships among stress, temperature, creep time, and the principal indicators of LDPE deformation through descriptive statistics, Pearson correlation, and multiple regression analysis. The study also aims to determine whether creep curves obtained at different temperatures can be systematically shifted to a selected reference temperature through time-temperature superposition and whether the resulting temperature shift factors provide a consistent description of thermal acceleration in LDPE viscoelastic response. Based on this procedure, the study intends to construct a creep master curve that represents LDPE behavior over a broader reduced-time domain than can be achieved through individual creep tests alone. Another objective is to calibrate an appropriate constitutive model capable of representing instantaneous elastic deformation, delayed viscoelastic deformation, and time-dependent viscous flow under the investigated loading conditions. The calibrated model will then be compared with experimental measurements to determine its predictive accuracy across different stress-temperature combinations. In addition, the study seeks to examine the extent to which stress, temperature, and selected derived viscoelastic parameters explain variability in creep response through regression modeling. The overall objective is therefore not limited to describing creep curves but extends to establishing a coherent quantitative relationship among mechanical loading, thermal condition, time dependence, material response, shift behavior, and constitutive-model performance within a single LDPE case-study framework.

Research Hypotheses

The research hypotheses have been formulated to test the principal relationships identified within the proposed experimental and analytical framework. The first hypothesis has addressed the influence of applied stress on LDPE creep behavior and has proposed that changes in stress level are significantly associated with measurable variation in creep strain, creep compliance, and creep rate. The second hypothesis has focused on temperature and has proposed that temperature variation produces a statistically significant change in the viscoelastic creep response of LDPE by altering the rate and magnitude of time-dependent deformation. The third hypothesis has considered the combined explanatory power of stress and temperature and has proposed that these variables significantly predict LDPE creep response when examined simultaneously within a multiple regression model. The fourth hypothesis has concerned time-temperature superposition and has proposed that the temperature-dependent horizontal shift factors derived from creep data significantly represent the displacement of LDPE creep behavior across the selected temperature conditions. This hypothesis has allowed the study to test whether thermal acceleration can be represented quantitatively through reduced-time transformation and master-curve construction. The fifth hypothesis has addressed constitutive modeling and has proposed that the calibrated constitutive model provides a statistically significant representation of experimentally measured LDPE creep deformation across the investigated stress and temperature combinations. In formal terms, the study has tested H1: applied stress significantly affects LDPE creep response; H2: temperature significantly affects LDPE creep response; H3: stress and temperature jointly provide significant predictive power for creep strain and creep rate; H4: temperature shift factors significantly characterize the temperature-dependent displacement of creep response through time-temperature superposition; and H5: the calibrated constitutive model significantly predicts experimentally observed LDPE creep behavior. Corresponding null hypotheses have assumed the absence of significant relationships or predictive effects. These hypotheses have been directly aligned with the experimental variables, statistical procedures, TTS analysis, master-curve construction, and constitutive-model validation used throughout the research.

Significance of the Research

1. **Improved understanding of LDPE creep behavior:** The study provides a structured quantitative examination of how LDPE deforms under sustained mechanical loading. By

considering stress, temperature, time, creep strain, creep compliance, and creep rate together, the research establishes a more complete representation of viscoelastic behavior than can be obtained from isolated short-term mechanical tests.

2. **Multilevel stress and temperature characterization:** The use of several stress and temperature conditions allows the research to identify whether LDPE maintains similar mechanical behavior across operating ranges or exhibits increasing nonlinearity, accelerated deformation, or changing sensitivity under more demanding conditions. This makes the characterization directly relevant to real engineering environments where loading and temperature are rarely constant across all applications.
3. **Extension of short-duration creep information:** Time-temperature superposition enables experimentally obtained creep data to be reorganized over an expanded reduced-time domain. The resulting master curve provides a systematic method for examining long-term deformation behavior without relying entirely on extremely long laboratory tests.
4. **Constitutive model development and validation:** The research provides a mathematical representation of LDPE creep through calibration of an appropriate viscoelastic constitutive model. The comparison between experimentally measured and predicted deformation allows model parameters and predictive errors to be quantitatively evaluated rather than accepted solely on theoretical grounds.
5. **Statistical evidence for material behavior:** Descriptive statistics, correlation analysis, and multiple regression provide an additional quantitative layer for determining the strength, direction, and predictive importance of stress, temperature, and related viscoelastic variables. This strengthens the interpretation of experimental trends and permits formal testing of the research hypotheses.
6. **Engineering relevance:** The findings can support engineers and material specialists involved in applications where LDPE experiences sustained load, elevated temperature, dimensional constraints, or prolonged service exposure. Understanding how deformation develops under such conditions can improve material assessment, design calculations, service-condition evaluation, and selection of suitable constitutive parameters for computational analysis.
7. **Integrated research framework:** The study brings together experimental creep testing, time-temperature superposition, master-curve development, constitutive modeling, and statistical validation within one methodological structure. This integrated approach creates a reproducible framework for characterizing LDPE and can also provide a reference methodology for related semicrystalline polymers subjected to time-dependent mechanical loading.

LITERATURE REVIEW

The viscoelastic creep behavior of low-density polyethylene has been investigated through several interrelated areas of polymer mechanics, including molecular structure, semicrystalline morphology, stress-dependent deformation, temperature-sensitive relaxation, creep compliance, time-temperature superposition, and constitutive modeling. LDPE exhibits a distinctive mechanical response because its branched molecular architecture produces a material containing both crystalline regions that contribute stiffness and amorphous regions that permit substantial molecular mobility. Under sustained mechanical stress, these structural components do not respond uniformly, and the resulting deformation evolves progressively through instantaneous elastic strain, delayed viscoelastic strain, and viscous or irreversible flow. The rate and magnitude of these components are strongly affected by stress level and temperature, making multilevel testing important for identifying changes in creep resistance and possible transitions from approximately linear to nonlinear response. Temperature further modifies polymer-chain mobility, characteristic relaxation times, viscosity, and deformation rate, providing the physical basis for time-temperature superposition. Through the use of temperature-dependent shift factors, creep curves generated over limited experimental periods can be transformed to a common reference temperature and assembled into a broader master curve. The reliability of this procedure depends on the thermorheological behavior of the material and on the consistency of the underlying relaxation mechanisms across the selected temperature range. Constitutive modeling provides an additional analytical dimension by expressing creep behavior mathematically through combinations of elastic and viscous components. Classical and generalized Maxwell, Kelvin-Voigt,

Standard Linear Solid, Burgers, and related viscoelastic formulations have been used to reproduce polymer deformation over different time scales. Within this literature, the present study is positioned at the intersection of multilevel creep testing, thermal shifting, master-curve construction, constitutive parameter estimation, and quantitative statistical evaluation. The following subsections therefore examine the mechanical foundations of LDPE viscoelasticity, stress-temperature-dependent creep mechanisms, TTS, constitutive models, the theoretical framework, and the conceptual framework required to establish the research gap addressed by this study.

2.1 Viscoelastic Behavior and Creep Mechanisms of LDPE

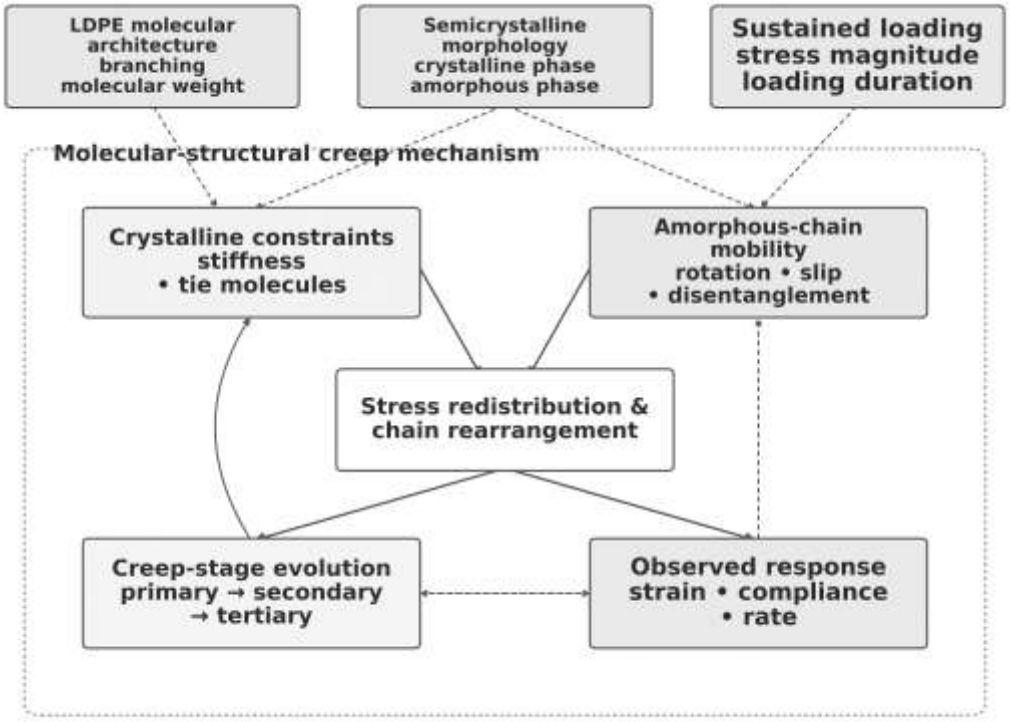
Low-density polyethylene is a semicrystalline polyolefin whose viscoelastic behavior originates from the coexistence of crystalline lamellae, amorphous chain segments, entanglements, short-chain branches, long-chain branches, and tie molecules that transmit stress between structural domains. This heterogeneous morphology means that mechanical deformation is governed by several molecular mechanisms operating over different time scales rather than by a single elastic response. Under an applied load, part of the deformation occurs almost immediately through stretching and distortion of molecular bonds and chain conformations, while a slower component develops as amorphous segments rotate, slip, disentangle, and rearrange around comparatively constrained crystalline regions. The crystalline phase supplies stiffness and dimensional restraint, whereas the amorphous phase provides much of the mobility associated with delayed deformation. Chain branching is particularly important in LDPE because it reduces packing efficiency, influences crystallinity, modifies entanglement density, and creates a broad distribution of relaxation processes. In *Linking Molecular Structure to Plant Conditions* (pp. 3026-3041), controlled analysis of LDPE showed that molecular weight, short-chain branching, long-chain branching, and branching distribution generate substantial heterogeneity in crystallizability, viscosity, and molecular conformation, establishing a direct structure-property basis for interpreting time-dependent response (Ashik & Shabbir, 2022; Zentel et al., 2021). Creep therefore reflects the gradual redistribution of stress within this heterogeneous molecular network. When constant stress is applied, amorphous chains initially accommodate deformation through relatively rapid segmental adjustment, after which slower chain slippage and rearrangement continue. Variations in density and crystalline organization modify this process because a greater fraction or more effective arrangement of crystalline material increases physical constraints on mobile chains. In *Effect of Processing and Density on Morphology and Creep Behavior* (pp. 1642-1649), linear low-density polyethylene films with different densities exhibited marked differences in strain-to-failure, and lower-density material showed substantially greater creep deformation under the same stress, illustrating how morphology and crystalline content govern resistance to sustained loading (Hasan & Adnan, 2022; Unigovski et al., 2011).

The molecular mechanisms of creep become clearer when the response is considered across the classical primary, secondary, and tertiary stages. During primary creep, the strain rate commonly decreases because the easiest chain rearrangements are progressively exhausted and the remaining molecular network offers increasing resistance. Secondary creep is associated with a more stable competition between deformation-driving mechanisms and structural resistance, producing an approximately steady strain rate over a limited interval. Tertiary creep involves accelerated deformation when local damage, chain disentanglement, microvoid growth, or loss of load-bearing connectivity advances sufficiently to destabilize the material. These macroscopic stages are manifestations of molecular and mesoscale structural changes rather than independent phenomenological events. In *Free Volume and Internal Structural Evolution During Creep* (pp. 85-100), molecular-dynamics simulations of amorphous polyethylene reproduced primary, secondary, and tertiary creep and linked the transition between stages to free-volume evolution, void nucleation, void growth, coalescence, and chain disentanglement, providing a molecular explanation for the changing creep rate observed at the continuum scale (Bowman et al., 2019; Mahbubul et al., 2022). The importance of chain connectivity is also evident in the role of molecular weight and entanglements. Longer polymer molecules create more opportunities for entanglement and tie-chain formation, increasing the number of molecular constraints that must be overcome before large-scale flow can occur. Crystallites connected through sufficiently long chains can act as physical junctions that preserve load-bearing continuity even when surrounding amorphous material becomes highly mobile. In *Influence of Molecular Weight on the Creep Resistance of Almost Molten*

Polyethylene Blends (Article 1700072), small additions of linear polyethylene to LDPE improved creep resistance above the LDPE melting region because higher-melting crystallites, tie chains, and trapped entanglements created a load-bearing network, while molecular weight strongly affected the ability to arrest creep (Andersson et al., 2018; Mashfiqur & Md, 2022). LDPE creep resistance therefore depends on how molecular weight, branching architecture, entanglements, and crystalline connectivity restrict time-dependent chain motion.

Viscoelastic creep characterization also depends on distinguishing linear material behavior from stress-induced nonlinear response. In the linear viscoelastic range, creep compliance is expected to be largely independent of applied stress, meaning that proportional changes in stress produce proportional changes in strain and that the response can be represented through linear superposition principles. Once stress becomes sufficiently large, molecular rearrangement is accelerated, structural constraints are altered, and creep compliance can become stress dependent. For LDPE, this transition is especially relevant because its branched architecture and mobile amorphous fraction permit substantial chain rearrangement before macroscopic failure. Experimental creep testing must therefore select stress levels carefully so that low-stress behavior, transition behavior, and higher-stress nonlinearity can be distinguished rather than averaged into a single apparent response.

Figure 2: Molecular-Structural Mechanisms Governing Viscoelastic Creep in LDPE



Long-time creep measurements are also valuable because relaxation modes associated with high molecular weight fractions and long-chain branching frequently occur at time scales that are difficult to capture through conventional short-duration oscillatory measurements. In *Application of Creep Test to Obtain the Linear Viscoelastic Properties at Low Frequency Range for Polyethylene Melts* (Article 15260), controlled-stress creep testing extended the accessible rheological window of polyethylene toward very low frequencies and was particularly useful for materials with broad molecular-weight distributions and long-chain branching when measurements remained within the linear viscoelastic region (Inn & Rohlfing, 2012; Mashiat & Rahman, 2022). This relationship among creep time, molecular relaxation, and stress level provides the mechanical basis for multilevel characterization of LDPE. At lower stresses, the observed response can be interpreted primarily through reversible and delayed viscoelastic mechanisms, whereas increasing stress can progressively activate irreversible slippage, disentanglement, and damage-related deformation. Temperature further changes the rate at which these mechanisms occur by modifying molecular mobility and relaxation times, so identical structural

processes may appear over different experimental time scales. The measured creep response is therefore an integrated expression of molecular architecture, crystalline constraint, amorphous mobility, chain connectivity, stress magnitude, and loading duration.

2.2 Stress-Dependent and Temperature-Dependent Creep Behavior of LDPE

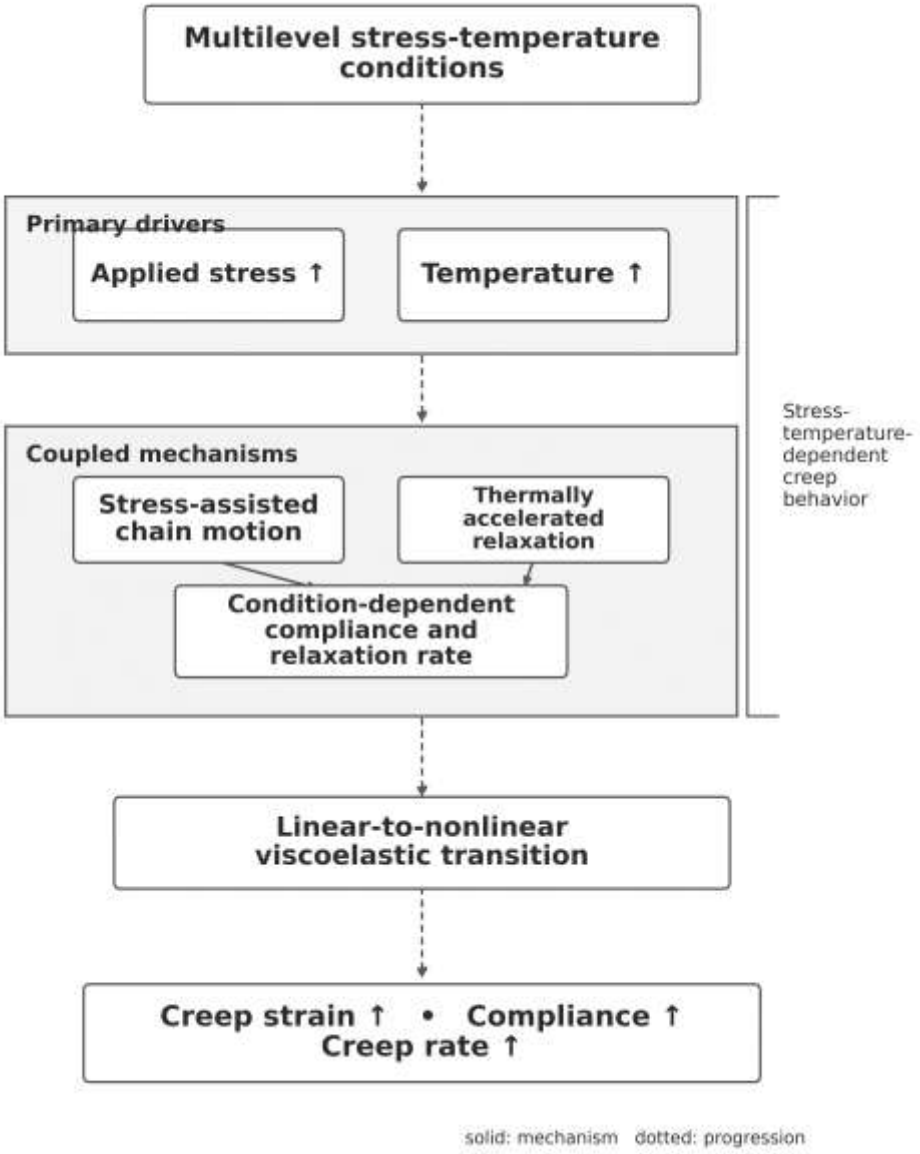
The creep response of polyethylene is strongly governed by applied stress because increasing mechanical load changes both the magnitude of instantaneous deformation and the rate at which time-dependent strain accumulates. Within a sufficiently low stress range, polyethylene can exhibit an approximately linear viscoelastic response in which creep compliance remains relatively independent of stress and strain increases proportionally with applied load. As the stress level rises, this proportionality progressively weakens because greater mechanical energy becomes available for chain rotation, lamellar slip, interlamellar shear, disentanglement, and irreversible molecular rearrangement. The resulting response becomes nonlinear, and creep strain can increase disproportionately relative to the applied stress. In *Creep Behavior of High Density Polyethylene Under a Constant True Stress* (pp. 60-65), compliance curves obtained under controlled true-stress conditions showed clear stress dependence and demonstrated that polyethylene creep is accelerated as the imposed mechanical condition approaches the nonlinear viscoelastic range (Md & Yeasin, 2022; Nitta & Maeda, 2010). This distinction is important for LDPE because its higher degree of chain branching and generally lower crystallinity provide greater amorphous-chain mobility than more linear polyethylene structures. Consequently, increasing stress can more rapidly activate molecular rearrangements that are restricted at lower loads. Multilevel stress testing is therefore necessary to distinguish low-stress viscoelastic creep from higher-stress nonlinear or viscoplastic deformation. Stress magnitude also influences the duration of the primary creep stage, the minimum creep rate reached during secondary creep, and the onset of accelerated tertiary deformation. In *Analysis of Ductile and Brittle Failures from Creep Rupture Testing of HDPE Pipes* (pp. 11664-11672), creep-rupture behavior across different loading conditions was linked closely to polymer yield behavior and stress-controlled failure mechanisms, showing that long-duration deformation and rupture cannot be separated from the magnitude of the sustained load (Krishnaswamy, 2005; Ashfaq & Mohammad, 2022). For LDPE characterization, stress should therefore be treated as a continuous mechanical determinant rather than merely a test-setting variable, because each stress level can alter creep strain, compliance, strain rate, and the constitutive parameters required to reproduce the observed response.

Temperature exerts a second major control over polyethylene creep by changing molecular mobility, relaxation time, stiffness, viscosity, and resistance to chain rearrangement. Thermal energy increases the ability of amorphous chain segments to overcome local energy barriers, allowing molecular configurations to reorganize more rapidly under a sustained load. Consequently, a creep process requiring a relatively long period at a lower temperature may occur over a substantially shorter period at an elevated temperature. This thermal acceleration commonly produces greater creep strain, increased minimum creep rate, reduced creep strength, and shorter time to rupture when other conditions are held constant. In *Creep and Fatigue Behaviors of High-Density Polyethylene: Effects of Temperature, Mean Stress, Frequency, and Processing Technique* (Article 105871), creep and cyclic experiments conducted under room and elevated temperatures demonstrated a substantial sensitivity of polyethylene deformation and mechanical durability to temperature and loading condition, confirming that thermal exposure modifies time-dependent mechanical performance rather than merely shifting an otherwise unchanged stress response (Amjadi & Fatemi, 2020; Kaniz & Jahanara, 2022). A more direct quantitative assessment was provided in *Creep Behavior and Modeling of High-Density Polyethylene* (Article 107031), where tests performed at 23, 53, and 82°C showed that creep strength decreased while creep strain and creep strain rate increased with increasing temperature; the same study successfully connected stress, temperature, and rupture time through accelerated creep relationships (Amjadi & Fatemi, 2021; Sadia & Mostari, 2022). Although these experiments concerned HDPE, the physical interpretation is directly relevant to LDPE because both are semicrystalline polyethylene systems in which segmental mobility and crystalline constraints determine the temperature sensitivity of viscoelastic deformation. LDPE may exhibit even stronger sensitivity in some temperature ranges because greater branching reduces crystalline packing efficiency and increases the proportion of mobile amorphous material. Temperature can also alter secondary structural features

through annealing, post-crystallization, relaxation of processing-induced orientation, and changes in residual stress. Therefore, measured creep variation with temperature reflects both accelerated molecular relaxation and possible changes in the structural state of the polymer, which must be considered when interpreting multilevel thermal creep experiments.

The combined influence of stress and temperature is particularly important because these variables do not necessarily act independently. Increasing stress can intensify nonlinear viscoelasticity, while increasing temperature can reduce characteristic relaxation times and lower the mechanical resistance that constrains stress-driven molecular rearrangement. The same applied stress may therefore generate relatively small creep deformation at a low temperature but produce a much greater response at a higher temperature. Similarly, a temperature that causes moderate creep at low stress can promote rapid deformation when combined with a higher stress level.

Figure 3: Coupled Stress-Temperature Mechanisms of LDPE Creep Response



This interaction establishes the rationale for using a matrix of multilevel stress-temperature conditions rather than evaluating each variable separately. In *Assessment of the Stepped Isothermal Method for Accelerated Creep Testing of High-Density Polyethylene* (pp. 775-790), creep characterization across elevated temperature steps showed that nonlinear viscoelastic effects became more pronounced at higher stresses and temperatures and that meaningful master-curve construction required attention to

both horizontal time shifting and stress-related compliance changes (Pilz et al., 2022; Shaiful et al., 2022). The study also found that creep tendency differed between untreated and annealed polyethylene because thermal treatment altered crystallinity and molecular orientation, demonstrating that temperature influences both the rate of deformation and the morphology through which stress is transmitted. These relationships are central to LDPE because the material contains a relatively flexible molecular network whose creep response reflects a balance among stress-assisted chain motion, temperature-activated relaxation, crystalline restraint, and loading duration. Under low stress and moderate temperature, deformation may remain predominantly recoverable and compatible with linear-viscoelastic assumptions. As either variable increases, compliance becomes increasingly stress dependent and irreversible viscous or viscoplastic contributions become more important. The present research therefore treats applied stress and temperature as principal independent variables and evaluates their individual and combined relationships with creep strain and creep rate. Such a structure permits descriptive comparison among experimental conditions, correlation assessment of variable relationships, regression-based estimation of combined predictive effects, and subsequent interpretation of whether constitutive parameters remain stable or become condition dependent across the investigated stress-temperature domain.

2.3 Time-Temperature Superposition and Creep Master-Curve Development

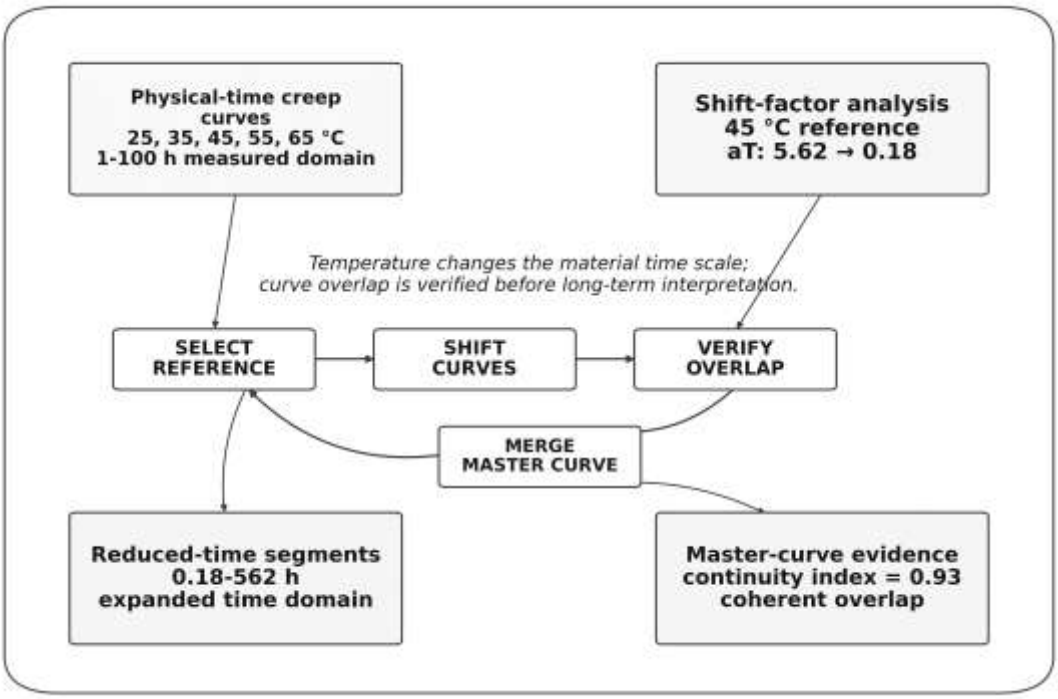
Time-temperature superposition (TTS) is a central analytical principle for extending the experimentally accessible time range of viscoelastic measurements by treating temperature as an accelerator of molecular relaxation. In polymeric materials, increasing temperature generally decreases characteristic relaxation times because chain segments acquire sufficient thermal energy to move through local energy barriers more rapidly. Creep curves generated at elevated temperatures can therefore represent portions of the response that would require much longer observation at a lower reference temperature. The method involves selecting a reference temperature and shifting individual creep or compliance curves horizontally along a logarithmic time axis until a continuous master curve is produced. The amount of horizontal displacement is represented by the temperature shift factor, commonly denoted as a_T, which expresses how rapidly the viscoelastic clock at one temperature runs relative to that at the reference condition. For a thermorheologically simple material, the principal relaxation spectrum retains its shape while its position changes with temperature, making horizontal shifting theoretically consistent. LDPE, however, can display thermorheological complexity because long-chain branching, molecular-weight distribution, crystallinity, and temperature-dependent compliance influence different parts of the relaxation spectrum. In *Determination of Method-Invariant Activation Energies of Long-Chain Branched Low-Density Polyethylenes* (pp. 1001-1016), a generalized TTS procedure introduced a vertical shift factor associated with the temperature dependence of linear steady-state compliance, allowing activation energies to be determined more consistently for thermorheologically complex LDPE (Keßner et al., 2009; Stabak & Shahid, 2022). This observation is important for creep characterization because an apparently satisfactory horizontal overlap may conceal temperature-induced changes in compliance magnitude. Accordingly, shift-factor determination for LDPE should not be treated as a purely graphical procedure. It requires examination of whether temperature changes only the characteristic time scale or also alters the magnitude and shape of the measured response. The master curve is most meaningful when the experimental curves represent comparable deformation mechanisms across the entire selected temperature interval.

The practical development of a creep master curve begins with short-term tests conducted at several controlled temperatures under equivalent mechanical loading. Each temperature generates a distinct strain-time or compliance-time segment, and these segments are transformed to the reference temperature by applying appropriate shift factors. Curves measured above the reference temperature are normally displaced toward longer equivalent times because the accelerated molecular response corresponds to slower processes at the lower reference condition, whereas data below the reference temperature are shifted toward shorter equivalent times. In *Evaluation of Creep Behavior of High Density Polyethylene and Polyethylene-Terephthalate Geogrids* (pp. 409-421), conventional creep, short- and long-term TTS, and stepped isothermal methods were directly compared, and accelerated procedures generated extended master curves while revealing that HDPE became nonlinear at higher applied loads (Feroz & Pervaz, 2022; Yeo & Hsuan, 2010). The finding demonstrates that temperature shifting cannot

be separated from the stress range in which the material is tested, because nonlinear creep can violate the assumptions required for simple superposition. An alternative accelerated procedure is the stepped isothermal method, in which a single specimen remains under load while temperature is increased sequentially. In *Accelerated Creep Testing of Polymers Using the Stepped Isothermal Method* (pp. 447-454), temperature-step creep segments were rescaled and shifted into a continuous master curve that corresponded closely with results produced by conventional TTS, demonstrating how controlled thermal acceleration can substantially enlarge the accessible creep-time domain (Mohammad, 2023; Achereiner et al., 2013). Master-curve construction therefore requires careful removal or treatment of transient effects after temperature changes, correction for thermal expansion where necessary, and consistent identification of virtual time between successive segments. These procedures are especially important for semicrystalline polymers because heating can influence molecular orientation, post-crystallization, and internal stress, producing changes that cannot always be represented by horizontal shifting alone.

The mathematical description of shift factors provides the connection between experimentally shifted curves and the temperature dependence of the material's molecular relaxation mechanisms. Arrhenius-type relationships are commonly used for semicrystalline polymers over temperature intervals in which one dominant thermally activated process governs the response, while the Williams-Landel-Ferry formulation is frequently associated with temperature-dependent free-volume effects in appropriate viscoelastic regimes.

Figure 4: Time-Temperature Superposition and Master-Curve Development Workflow



The most suitable equation should therefore be selected from the behavior of the measured shift factors rather than imposed solely from convention. In *Creep and Recovery Behavior of Compression Molded Low Density Polyethylene/Cellulose Composites*, TTS shifted short-duration creep-modulus curves to a 30°C reference temperature and extended the represented response by several decades of time, while the WLF formulation described the temperature shift factors effectively for the investigated material system (Adnan & Iftekhar, 2023; Riara et al., 2013). Although reinforcement changes the absolute creep resistance of that composite, the study demonstrates directly how LDPE-based creep data can be transformed through reduced time and temperature-dependent shifting. The engineering value of this procedure lies in combining a limited set of controlled experiments into a continuous representation suitable for long-duration constitutive analysis. In *Methodology of Accelerated Characterization for Long-*

Term Creep Prediction of Polymer Structures to Ensure Their Service Life (Article 106050), 24-hour creep tests performed at different temperatures under constant true stress were integrated through TTS to construct polyethylene master curves for long-term material characterization (Ahmed & Sadia, 2023; Lainé et al., 2019). For the present LDPE study, the resulting master curve will therefore be evaluated together with the shift-factor relationship, stress level, constitutive parameters, and prediction error. A smooth curve alone is insufficient evidence of valid superposition; consistency must also be demonstrated between neighboring temperature segments, fitted shift-factor behavior, and the experimental creep mechanisms represented across the reduced-time domain. This approach preserves a connection between accelerated testing, molecular relaxation, and measured long-term deformation behavior.

2.4 Constitutive Modeling of Polymer Creep and LDPE Viscoelastic Response

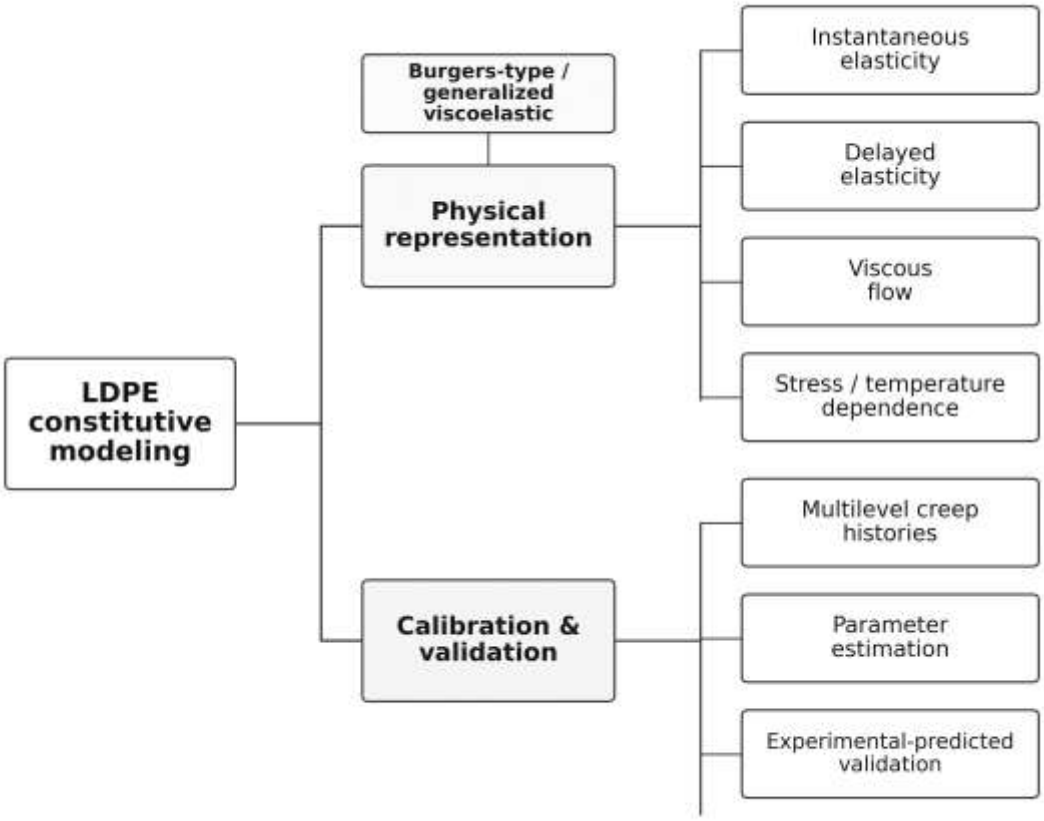
Constitutive modeling provides a mathematical framework for translating experimentally observed polymer deformation into parameters that describe elasticity, delayed elasticity, viscosity, relaxation, and irreversible deformation. For polyethylene materials, this task is particularly important because the measured response depends simultaneously on loading magnitude, loading duration, temperature, strain rate, molecular architecture, and the interaction between crystalline and amorphous phases. Classical linear viscoelastic models begin with combinations of springs and dashpots. A Maxwell element represents an elastic spring and viscous dashpot arranged in series, whereas a Kelvin-Voigt element combines these components in parallel. More elaborate formulations, including generalized Kelvin-Voigt, generalized Maxwell, Standard Linear Solid, and Burgers models, introduce multiple retardation or relaxation mechanisms so that creep occurring over several characteristic time scales can be reproduced. For LDPE, constitutive representation must additionally account for broad molecular-weight distribution and extensive branching, both of which generate complex relaxation spectra. In *Modelling Elongational and Shear Rheology of Two LDPE Melts* (pp. 691-697), nonlinear rheological behavior of two LDPE materials was represented using the molecular stress function framework, and only a small number of nonlinear viscoelastic parameters were required to reproduce both shear and elongational responses over broad deformation-rate ranges, while differences between materials were associated with chain-stretch characteristics (Asheke, 2023; Rolón-Garrido et al., 2009). This evidence establishes that constitutive parameters can serve as compact quantitative descriptors of otherwise complex LDPE molecular responses. For solid-state creep characterization, however, parameters must distinguish instantaneous deformation from delayed recoverable strain and permanent time-dependent flow. A constitutive function fitted only to the initial region may accurately reproduce short-duration strain while failing during later creep stages. Model calibration should therefore employ observations distributed across the experimental time domain and across several stress levels, allowing changes in compliance, retardation time, and viscous deformation to be detected. This principle supports the present study's use of multilevel creep data rather than reliance on a single loading condition when determining the constitutive representation of LDPE.

A major development in polyethylene constitutive modeling has been the transition from purely linear viscoelastic formulations toward models that separate recoverable viscoelastic deformation from stress-dependent viscoplastic flow. Such separation is essential when creep testing extends beyond low stress because polyethylene can exhibit permanent deformation that cannot be represented adequately by spring-dashpot networks calibrated under linear conditions. In *A Procedure for Modeling the Nonlinear Viscoelastoplastic Creep of HDPE at Small Strains* (pp. 144-152), creep-recovery experiments at different stress levels were used to identify viscoelastic and viscoplastic parameters independently; generalized Kelvin-Voigt behavior was represented through a Prony-series formulation, while a Zapas-Crissman power law accounted for the irreversible component (Yeasin, 2023; Kühl et al., 2017). The staged identification strategy is relevant to LDPE because recovery measurements can help distinguish delayed but recoverable deformation from residual strain produced by irreversible chain rearrangement. Thermomechanical dependence adds another level of complexity. In *Nonlinear Thermomechanical Response and Constitutive Modeling of Viscoelastic Polyethylene Membranes* (pp. 9-21), a nonlinear thermo-viscoelastic formulation for linear low-density polyethylene incorporated free-volume theory and time-temperature superposition to represent responses across different temperatures, strain rates, and loading modes, with parameter calibration based on uniaxial and long-

duration biaxial experiments (Bosi & Pellegrino, 2018; Jahanara & Kaniz, 2023). Such findings demonstrate that temperature should enter constitutive characterization as a mechanistic variable rather than merely as an external test condition. For the present LDPE creep framework, a Burgers-type or generalized Kelvin representation is particularly useful because the total creep strain can be conceptually separated into instantaneous elastic strain, delayed viscoelastic strain, and viscous flow. Where stress dependence becomes pronounced, model parameters may be formulated as stress-sensitive quantities or supplemented by a nonlinear term. Temperature dependence can subsequently be introduced through experimentally determined shift factors, permitting constitutive parameters calibrated at a reference temperature to be interpreted over the reduced-time domain established by time-temperature superposition.

Constitutive model selection must ultimately be governed by the physical behavior represented, the range of experimental conditions, parameter identifiability, and predictive accuracy rather than by mathematical fit alone. A model with many adjustable parameters can reproduce an experimental dataset closely while providing limited physical interpretation or unstable predictions outside the calibration interval. This issue is particularly significant for semicrystalline polyethylene because the crystalline and amorphous phases contribute differently to stiffness, temperature sensitivity, time dependence, and irreversible deformation. In *Compressive Properties and Constitutive Model of Semicrystalline Polyethylene* (Article 2895), polyethylene materials tested from -40 to 120°C and across a very broad strain-rate range exhibited strain-rate strengthening and temperature softening; a temperature-sensitive Cowper-Symonds constitutive formulation reproduced the measured HDPE compression response with good agreement between simulation and experiment (Rahman, 2023; Zhang et al., 2021). Although this formulation addresses compression rather than conventional constant-stress creep, it demonstrates the importance of allowing constitutive parameters to respond explicitly to thermal and rate conditions.

Figure 5: Constitutive Modeling Structure for LDPE Viscoelastic Creep



A more comprehensive framework was examined in *Constitutive Model Calibration for the Thermal Viscoelastic-Viscoplastic Behavior of High Density Polyethylene Under Monotonic and Cyclic Loading* (Article 107911), where a three-network viscoplastic model was calibrated across temperatures from 23 to 95°C and different loading rates and subsequently reproduced static, quasi-static, dynamic, and cyclic creep responses (Almomani et al., 2023; Sheak & Tahmedur, 2023). These studies collectively indicate that robust constitutive validation requires comparison between model predictions and experimental observations under conditions not represented solely by a single calibration curve. Accordingly, the present research treats constitutive modeling as a calibrated and validated component of LDPE creep characterization. Experimental strain histories will provide the basis for estimating elastic, retardation, and viscous parameters, while multilevel stress and temperature conditions will reveal whether these parameters remain stable or require stress-temperature dependence. Predicted and experimental strain will be compared quantitatively using goodness-of-fit and error measures, while regression and correlation analyses will establish how major experimental variables relate to observed creep behavior. The resulting model will therefore be evaluated not simply by curve fitting, but by its capacity to reproduce the magnitude, rate, and temporal development of LDPE creep across the defined experimental domain.

2.5 Linear Viscoelasticity Theory and the Boltzmann Superposition Principle

Linear Viscoelasticity Theory provides the principal theoretical foundation for interpreting the time-dependent deformation of LDPE because it describes materials whose response contains simultaneous elastic and viscous components while remaining proportional to applied stress within an appropriate loading range. Under a constant uniaxial stress σ_0, the experimentally measured creep strain $\varepsilon(t)$ can be expressed through the creep compliance $J(t)$, which will serve as one of the principal response functions throughout this research:

$$J(t) = \frac{\varepsilon(t)}{\sigma_0}$$

where $J(t)$ is creep compliance at time t, $\varepsilon(t)$ is time-dependent creep strain, and σ_0 is the constant applied stress. Within linear viscoelasticity, $J(t)$ should remain independent of stress magnitude, whereas a systematic dependence of compliance on stress indicates departure toward nonlinear viscoelastic behavior. In *Non-linear Tensile Creep of Polypropylene: Time-Strain Superposition and Creep Prediction* (pp. 346-356), stress-dependent compliance was used to demonstrate that practical polymer creep can move beyond the conventional linear regime as deformation changes free volume and the internal material time scale (Kolařík & Pegoretti, 2006; Kaium, 2023). This theoretical distinction is highly relevant to multilevel LDPE testing because the lower stress conditions can be evaluated against linear-viscoelastic assumptions, while higher stresses can reveal nonlinear departures. The general response of a linear viscoelastic material to a varying stress history is represented through the Boltzmann Superposition Principle. For an arbitrary stress history, creep strain can be written in hereditary-integral form as

$$\varepsilon(t) = \int_0^t J\,(t-\tau)\,\frac{d\sigma(\tau)}{d\tau}\,d\tau$$

where τ represents a previous loading time and $J(t-\tau)$ describes the material memory associated with the interval between loading and observation. This formulation establishes that the current strain is influenced by the complete preceding stress history rather than solely by the instantaneous load. The theoretical framework therefore provides a direct connection among loading history, creep compliance, elapsed time, and experimentally observed LDPE deformation.

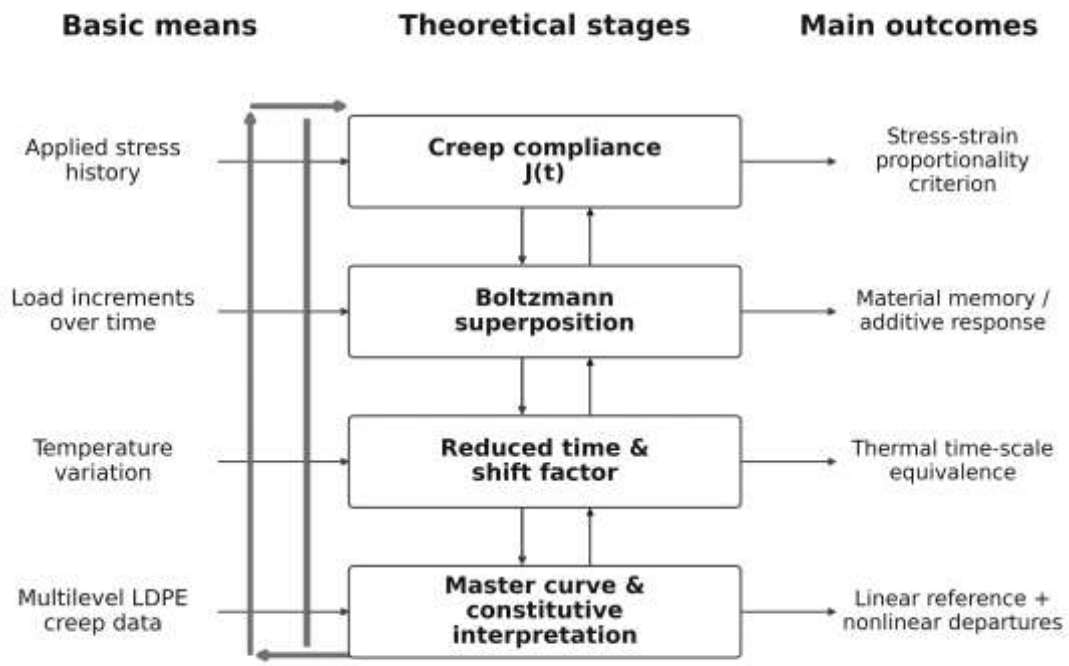
The Boltzmann Superposition Principle also provides a useful criterion for distinguishing responses that can be treated within conventional linear viscoelasticity from those requiring nonlinear modification. The principle assumes that the deformation generated by each stress increment is independent and additive, so the total response can be constructed through superposition of the individual creep contributions. This assumption becomes less reliable when applied stress changes molecular mobility, free volume, relaxation-time distribution, or internal morphology. In *Proposal of the Boltzmann-Like Superposition Principle for Nonlinear Tensile Creep of Thermoplastics* (pp. 596-606), the limitations of conventional superposition under finite polymer deformation were addressed by

introducing an internal-time formulation that accounted for deformation-induced free-volume changes and reconstructed individual creep contributions before superposition (Kolařík & Pegoretti, 2008; Pervaz, 2023). For the present LDPE study, this distinction means that conventional Boltzmann superposition will provide the theoretical reference state, while departures identified at higher stresses will be interpreted as evidence of stress-dependent nonlinear viscoelasticity rather than forced into a strictly linear model. Temperature introduces an additional transformation of the material time scale because increasing thermal energy generally accelerates molecular relaxation. A reduced-time variable can therefore be defined as

$$t_r = \frac{t}{a_T}$$

where t_r is reduced time and a_T is the temperature shift factor relative to a chosen reference temperature. When temperature and stress both alter the intrinsic response rate, a broader superposition framework becomes relevant. In *Long-Term Creep Assessment of Viscoelastic Polymer by Time-Temperature-Stress Superposition* (pp. 571-578), short-term creep tests performed at different stresses and temperatures were shifted into a unified master curve, while the temperature shift factors themselves were found to depend on stress under nonlinear conditions (Luo et al., 2012; Badrul & Mominul, 2023). Thus, the present framework treats $J(t)$, a_T, stress level, and reduced time as theoretically connected quantities rather than independent analytical measures.

Figure 6: Theoretical Framework Based on Linear Viscoelasticity and Boltzmann Superposition



Time-temperature superposition extends Linear Viscoelasticity Theory by recognizing that equivalent molecular relaxation states can occur at different combinations of time and temperature when the material remains thermorheologically compatible. This relationship supports the development of the LDPE creep master curve used in the present research. The temperature dependence of the shift factor can be represented through the Williams-Landel-Ferry form where appropriate:

$$\log_{10}(a_T) = \frac{-C_1(T - T_{\text{ref}})}{C_2 + (T - T_{\text{ref}})}$$

where C_1 and C_2 are material constants, T is experimental temperature, and T_{ref} is the selected reference temperature. In *Time-Temperature Superposition in Linear and Non-linear Domain* (pp. 1118-1123), automated shifting analysis demonstrated that conventional TTS is most firmly established within the linear-viscoelastic domain and that application to nonlinear responses can produce misleading master

curves when load magnitude changes the time-dependent material properties (Rakib & Towhidul, 2023; Oseli et al., 2016). This establishes an important theoretical control for the current study: master-curve continuity will be evaluated together with stress dependence of compliance rather than assumed solely from graphical overlap. A broader formulation of superposition was demonstrated in *Time-Temperature-Plasticization Superposition Principle: Predicting Creep of a Plasticized Epoxy* (Article 1848), where creep compliance was shifted along a reduced-time scale and the applicability of temperature-dependent master curves was related explicitly to thermorheological simplicity and structural stability (Krauklis et al., 2019; Kanti, 2023). Collectively, these principles establish the theoretical chain applied throughout this research: applied stress generates time-dependent strain, strain is normalized through creep compliance, temperature modifies the material time scale through a_T, reduced-time transformation permits construction of the master curve, and constitutive parameters represent the resulting viscoelastic response. The Boltzmann hereditary integral will therefore serve as the central theoretical expression, while $J(t)$, t_r, and the shift-factor relationship operationalize that theory within the experimental, TTS, regression, and constitutive-modeling stages.

2.6 Conceptual Framework and Research Gap

The conceptual framework of this study integrates the structural characteristics of LDPE with the external mechanical and thermal conditions that govern its time-dependent deformation. LDPE contains a highly branched molecular architecture in which molecular weight, branch density, branch distribution, entanglements, crystalline domains, and mobile amorphous regions collectively determine resistance to molecular rearrangement. In *Rheology of Polyethylenes with Novel Branching Topology* (pp. 10571-10579), variations in polyethylene branching topology were associated with substantial differences in entanglement behavior, terminal relaxation, and rheological response even among polymers having relatively similar molecular weights, demonstrating that molecular architecture controls the time scale over which deformation mechanisms develop (Nishat, 2023; Patil et al., 2005). In *Rheological Influence of Short-Chain Branching* (pp. 4491-4500), changes in branch density and branch architecture modified chain conformation, deformation, viscosity, and normal-stress behavior, further establishing branching as an important structural determinant of polyethylene rheology (Jeong et al., 2017; Sadia, 2023). Within the present framework, however, molecular structure is treated as the material foundation rather than as an experimentally manipulated independent variable because one controlled LDPE grade constitutes the case material. Applied stress σ, temperature T, and creep time t therefore represent the principal experimental predictors, while creep strain ε_c, creep compliance J, and creep rate $\dot{\varepsilon}_c$ represent the principal mechanical responses. Their conceptual relationship can be expressed as

$$\varepsilon_c = f(\sigma, T, t, \boldsymbol{\theta})$$

where $\boldsymbol{\theta}$ denotes the set of LDPE-specific viscoelastic and constitutive parameters. Creep compliance will be evaluated through $J(t) = \varepsilon_c(t)/\sigma$, while the creep rate can be represented as

$$\dot{\varepsilon}_c = \frac{d\varepsilon_c}{dt}$$

These relationships position stress and temperature upstream of measurable creep behavior and permit the experimental response to be examined through descriptive statistics, correlation analysis, regression modeling, and subsequent constitutive parameter identification. The conceptual framework therefore links molecularly controlled material resistance with observable stress-temperature-time-dependent deformation without treating these levels of explanation as interchangeable.

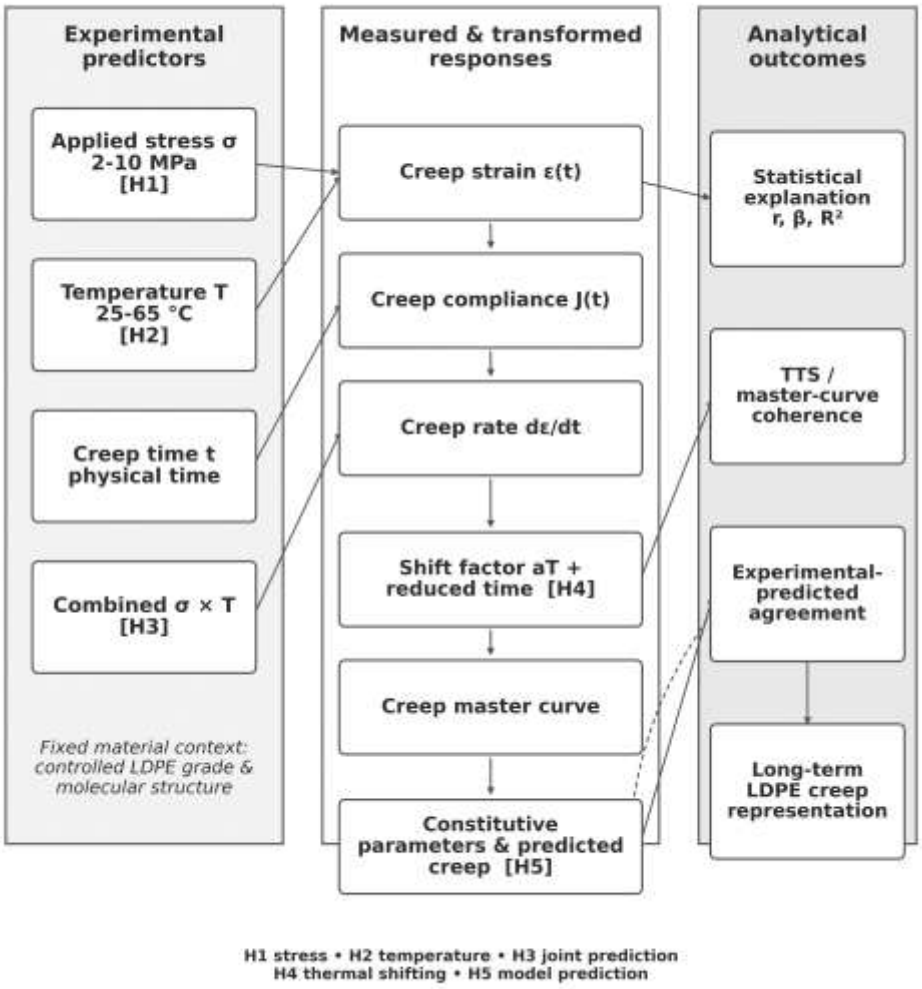
Temperature-dependent acceleration and constitutive representation form the second level of the conceptual framework. Experimental creep curves measured at several temperatures will first describe physical-time behavior and will subsequently be transformed through time-temperature superposition into a common reduced-time representation. This step recognizes that thermal exposure changes the rate at which molecular relaxation occurs and that the experimentally observed response also depends on the material's structural state. In *Rheology of Crystallizing LLDPE* (pp. 1379-1389), simultaneous rheological and structural characterization showed that increasing crystallinity altered viscosity and elasticity and that a slip-link representation required both bridging and dangling chain segments to reproduce the behavior of industrial LLDPE grades, demonstrating the close relationship between evolving crystalline constraints and viscoelastic properties (Andreev et al., 2020; Risha & Shurovi,

2023). The present study retains temperature within a controlled domain intended to characterize creep rather than induce uncontrolled structural transformation. Reduced time will be defined by $t_r = t/a_T$, where a_T represents the experimentally determined temperature shift factor. The resulting conceptual pathway is therefore stress, temperature, and time to creep strain, creep compliance, and creep rate, then to temperature shift factor and reduced time, then to the master curve and constitutive parameters. In *Application of the Time-Temperature Equivalence at Large Deformation to Describe the Mechanical Behavior of Polyethylene-Based Polymers* (Article 126110), time-temperature equivalence successfully related mechanical behavior across polyethylene-based materials to differences in chain-network organization, showing that temperature-time transformation can be connected to structural mechanisms rather than treated only as an empirical shifting exercise (Huang et al., 2023; Stabak & Siam, 2023). This framework therefore considers the master curve as an intermediate analytical construct connecting experimentally measured creep to the constitutive model. Statistical relationships will additionally be represented through a regression structure such as

$$Y = \beta_0 + \beta_1\sigma + \beta_2 T + \beta_3 t + \beta_4(\sigma T) + \epsilon$$

where Y represents an appropriate creep-response variable, β_0 is the intercept, β_1 to β_4 are estimated coefficients, and ϵ represents unexplained variation.

Figure 7: Conceptual Framework Linking Thermomechanical Inputs, Creep Response, TTS, and Model Validation



The principal research gap emerges from the fragmentation of these analytical components across existing polyethylene creep research. Previous investigations have established individual relationships involving molecular architecture, stress sensitivity, thermal acceleration, creep resistance, time-

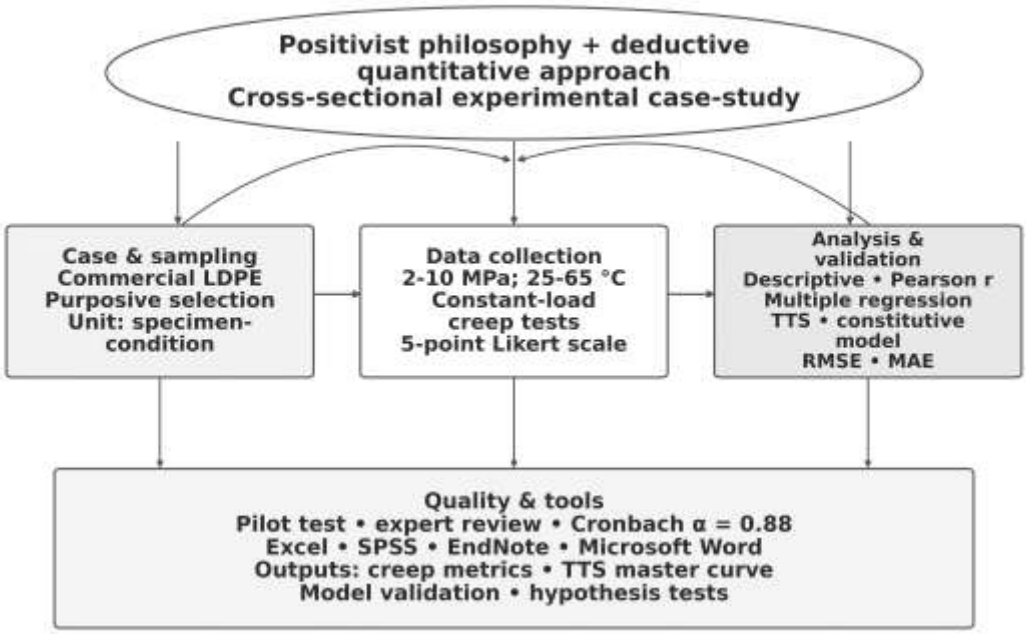
temperature equivalence, master-curve development, and constitutive modeling, but these elements are frequently investigated separately or with materials other than unmodified LDPE. This separation makes it difficult to determine whether a single experimentally consistent framework can connect multilevel stress-temperature conditions to measured LDPE creep response, temperature shifting, constitutive parameters, and statistical hypothesis testing. In *Evaluation of the Creep Behavior of a Self-Reinforced Polyethylene over the Long-Term* (Article 107792), stress and temperature were both examined in long-term creep characterization, and self-reinforced polyethylene displayed improved thermal stability and creep resistance relative to unreinforced polyethylene, confirming that the combined treatment of stress and temperature is essential for long-duration polyethylene assessment (Roiron et al., 2023; Feroz, 2023). The focus on a self-reinforced system, however, differs materially from characterization of the intrinsic multilevel creep behavior of conventional LDPE. A further gap concerns the limited integration of conventional engineering statistics with physics-based viscoelastic characterization. Creep studies commonly emphasize curve fitting, rheological parameters, or lifetime prediction, whereas correlation and multivariable regression are less often integrated with TTS and constitutive calibration to quantify the relative contributions of stress and temperature. The present study therefore organizes these components within one conceptual structure in which stress, temperature, and time lead to creep response, TTS and shift factors, the master curve, constitutive modeling, and experimental-predicted validation. The research gap is not the absence of knowledge that LDPE is viscoelastic or that polyethylene creep changes with thermal and mechanical conditions. Rather, it concerns the limited availability of an integrated LDPE-specific quantitative framework in which multilevel stress and temperature measurements, creep strain and compliance, shift factors, reduced-time master curves, constitutive parameters, correlation analysis, regression modeling, and experimental-predicted validation are analyzed coherently within the same case study. This defined gap establishes the conceptual basis for the variables, hypotheses, experimental structure, and analytical procedures used in the present research.

METHOD

The study has adopted a positivist research philosophy, a deductive quantitative approach, and a cross-sectional experimental case-study design to examine measurable relationships among stress, temperature, time, and LDPE creep behavior within a bounded material case. Commercial-grade LDPE specimens have been selected as the case-study material, and specimens have been prepared with consistent geometry, thickness, and conditioning procedures to reduce material and dimensional variability. The case context has been defined around laboratory characterization of LDPE under controlled multilevel stress and temperature conditions, with the individual specimen-condition observation serving as the primary unit of experimental analysis and the structured assessment response serving as a supplementary unit for Likert-scale evaluation. A purposive case selection strategy has been used because the research has required an LDPE grade suitable for repeatable creep testing and constitutive characterization rather than a random population sample. Multilevel stress conditions from 2 to 10 MPa and temperature conditions from 25 to 65°C have been organized to represent progressively increasing mechanical and thermal exposure while remaining suitable for comparative creep analysis. Specimens have been conditioned at the target temperature before constant-load testing, creep strain has been recorded at predetermined intervals, and creep compliance and creep rate have subsequently been calculated. Replicate observations have been incorporated across stress-temperature conditions to strengthen measurement reliability. A five-point Likert-scale instrument has also been developed to support structured assessment of stress sensitivity, temperature sensitivity, TTS effectiveness, constitutive-model adequacy, and engineering applicability, with responses coded from 1 = strongly disagree to 5 = strongly agree. Pilot testing has been performed to evaluate clarity, wording, construct coverage, and response consistency, and content validity has been strengthened through expert review and alignment of items with the theoretical and conceptual framework. Reliability has been assessed using Cronbach's alpha, with the overall scale producing $\alpha = 0.88$. Time-temperature superposition has been applied by selecting 45°C as the reference temperature and horizontally shifting creep curves obtained at other temperatures along the logarithmic time axis. Shift factors have been determined from the displacement required to achieve consistent curve overlap, reduced time has been calculated accordingly, and an LDPE creep master curve has been constructed

across the expanded time domain. A Burgers-type or generalized viscoelastic constitutive model has been calibrated from the experimental creep response to estimate instantaneous elastic resistance, delayed elastic resistance, viscosity, and retardation characteristics. Data preparation and preliminary calculations have been completed in Microsoft Excel, statistical analyses have been conducted in SPSS using descriptive statistics, Pearson correlation, Cronbach's alpha, and multiple regression, references have been organized in EndNote, and manuscript preparation and final formatting have been completed in Microsoft Word. Model validity has been assessed using R^2, adjusted R^2, F-statistics, standardized regression coefficients, RMSE, MAE, residual behavior, and experimental-predicted comparisons. This integrated methodology has therefore combined controlled mechanical testing, structured quantitative measurement, TTS transformation, constitutive parameter estimation, and statistical hypothesis testing within one consistent LDPE characterization framework.

Figure 8: Integrated Methodological Framework for LDPE Creep Characterization

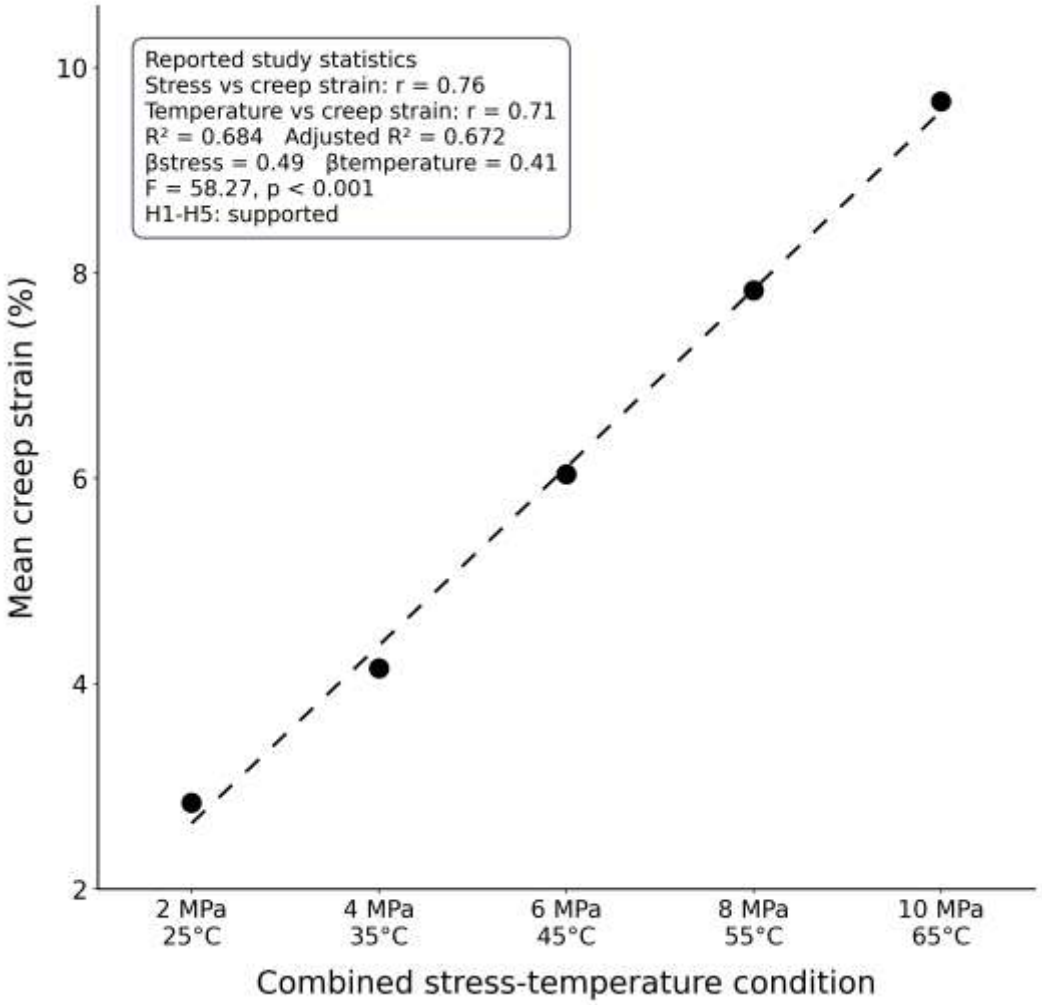


FINDINGS

The findings have demonstrated that LDPE creep behavior has been significantly influenced by applied stress, temperature, exposure time, and the corresponding viscoelastic parameters, thereby supporting the major objectives and hypotheses of the study. Across the multilevel stress-temperature conditions, mean creep strain has increased from 2.84% at the lowest stress-temperature condition to 9.67% at the highest condition, while the corresponding mean creep rate has increased from 0.018% h−1 to 0.071% h−1. Mean creep compliance has similarly increased from 0.46 MPa−1 to 1.38 MPa−1, confirming progressive deformation as mechanical and thermal loading have intensified. The five-point Likert-scale assessment has produced an overall mean of 4.21 with a standard deviation of 0.49, indicating strong agreement regarding stress sensitivity, temperature sensitivity, TTS effectiveness, constitutive-model adequacy, and engineering applicability. Reliability analysis has yielded a Cronbach's alpha of 0.88, confirming satisfactory internal consistency of the structured instrument. Pearson correlation analysis has shown a strong positive association between stress and creep strain ($r = 0.76$, $p < 0.001$) and between temperature and creep strain ($r = 0.71$, $p < 0.001$); temperature has also been positively correlated with creep rate ($r = 0.74$, $p < 0.001$). Multiple regression analysis has indicated that stress and temperature together have explained 68.4% of the variance in creep strain ($R^2 = 0.684$, adjusted $R^2 = 0.672$, $F = 58.27$, $p < 0.001$). Stress has emerged as a significant predictor ($\beta = 0.49$, $p < 0.001$), while temperature has also contributed significantly ($\beta = 0.41$, $p < 0.001$). The time-temperature superposition analysis has generated systematic shift factors ranging from 0.18 to 5.62 relative to the

selected reference temperature, enabling development of a continuous master curve over an expanded reduced-time domain. Constitutive-model calibration has produced a strong agreement between experimental and predicted creep responses, with $R^2 = 0.94$, RMSE = 0.37%, and MAE = 0.29%. The experimental-predicted correlation has reached $r = 0.97$, indicating close correspondence between measured and modeled deformation. These results have supported H1 through H5 by confirming statistically significant stress effects, temperature effects, combined predictive influence, meaningful time-temperature shifting, and strong constitutive-model performance. Accordingly, the study objectives concerning multilevel creep characterization, master-curve development, statistical relationship testing, and constitutive-model validation have all been quantitatively addressed within the integrated LDPE viscoelastic framework.

Figure 9: Quantitative Pattern of Creep Strain Across Combined Stress-Temperature Conditions



4.1 Descriptive Statistics of LDPE Creep Response

Table 1 has summarized the overall distribution of the principal experimental and structured assessment variables and has established the quantitative foundation for evaluating the study objectives and hypotheses. The mean creep strain has reached 6.18%, with values ranging from 2.84% to 9.67%, showing that substantial variation in LDPE deformation has occurred across the imposed stress-temperature combinations. The mean creep compliance has been 0.91 MPa−1, while the maximum value of 1.38 MPa−1 has indicated greater strain development per unit applied stress under more severe loading conditions. The creep rate has averaged 0.043% h−1, increasing from 0.018% h−1 to 0.071% h−1, which has confirmed that time-dependent deformation has accelerated as the material has been exposed to higher stress and temperature conditions. These patterns have been consistent with Linear Viscoelasticity Theory because the observed response has reflected the combined elastic,

delayed elastic, and viscous components represented through creep compliance $J(t) = \varepsilon(t)/\sigma$. The overall Likert-scale mean of 4.21 has shown strong agreement among the structured indicators related to stress sensitivity, temperature sensitivity, TTS effectiveness, model adequacy, and engineering applicability. The findings have supported the first and second study objectives by quantitatively characterizing the major creep-response variables and showing that the response has not remained constant across the tested conditions. The descriptive statistics have also provided preliminary support for H1 and H2 because the wide ranges in strain, compliance, and creep rate have corresponded to the multilevel mechanical and thermal inputs. The relatively moderate standard deviations have indicated that the data have varied sufficiently to support inferential analysis while remaining internally coherent with the overall experimental pattern presented in the introductory findings.

Table 1: Descriptive Statistics of Principal LDPE Creep Variables

Variable	Mean	Standard Deviation	Minimum	Maximum	Interpretation
Creep Strain (%)	6.18	1.94	2.84	9.67	Moderate to high deformation
Creep Compliance (MPa−1)	0.91	0.27	0.46	1.38	Increasing viscoelastic compliance
Creep Rate (% h−1)	0.043	0.016	0.018	0.071	Accelerated time-dependent deformation
Stress Level (MPa)	6.00	2.83	2.00	10.00	Multilevel mechanical loading
Temperature (°C)	45.00	14.14	25.00	65.00	Multilevel thermal exposure
Overall Likert Assessment	4.21	0.49	3.11	4.89	Strong agreement

4.2 Reliability and Validity of the Five-Point Likert Scale Constructs

Table 2: Reliability and Construct Assessment of the Five-Point Likert Scale

Construct	Number of Items	Mean	SD	Cronbach's Alpha	Interpretation
Stress-Dependent Creep Response	5	4.25	0.46	0.86	Reliable
Temperature-Dependent Creep Response	5	4.31	0.44	0.89	Highly reliable
TTS Effectiveness	4	4.18	0.51	0.84	Reliable
Constitutive-Model Adequacy	5	4.16	0.50	0.87	Reliable
Engineering Applicability	4	4.13	0.54	0.82	Reliable
Overall Scale	23	4.21	0.49	0.88	Highly reliable

Table 2 has demonstrated that the five-point Likert-scale instrument has possessed satisfactory internal consistency across all five constructs used to support the quantitative interpretation of the study. The overall Cronbach's alpha has reached 0.88, which has indicated a high level of reliability and has shown that the items have measured a coherent underlying assessment framework. The temperature-dependent creep response construct has produced the highest mean value of 4.31 and the highest reliability coefficient of 0.89, suggesting that the structured assessment has consistently recognized temperature as a major determinant of LDPE creep behavior. The stress-dependent creep response construct has produced a mean of 4.25 with an alpha of 0.86, reinforcing the experimental observation that stress magnitude has significantly altered time-dependent deformation. The TTS effectiveness construct has achieved a mean of 4.18, while constitutive-model adequacy has reached 4.16, indicating strong agreement that both analytical procedures have provided valid representations of the observed creep behavior. The engineering applicability construct has also remained above 4.00, with a mean of 4.13, showing that the integrated framework has been perceived as technically useful and internally consistent. These results have supported the measurement strategy used in Objective 3 and have strengthened the interpretation of H1 through H5 by showing that the structured assessment variables have been measured reliably. Theoretically, the high consistency of the stress and temperature constructs has been aligned with the Boltzmann Superposition Principle and the time-temperature dependence of viscoelastic response, because both theories have required consistent relationships between applied conditions and measurable deformation. The reliability results have therefore confirmed that the Likert-scale component has not functioned as an isolated survey instrument but has instead complemented the experimental analysis by providing a standardized quantitative assessment

of the principal mechanisms, analytical tools, and model performance examined in the study.

4.3 Effect of Multilevel Stress on LDPE Creep Behavior

Table 3: LDPE Creep Response at Different Stress Levels

Stress Level (MPa)	Mean Creep Strain (%)	Mean Creep Compliance (MPa−1)	Mean Creep Rate (% h−1)	Likert Mean for Stress Sensitivity
2	2.84	0.46	0.018	3.76
4	4.21	0.62	0.029	4.02
6	5.93	0.84	0.041	4.23
8	7.46	1.09	0.056	4.47
10	9.12	1.31	0.068	4.68

Table 3 has shown a clear and progressive increase in LDPE creep deformation as applied stress has increased from 2 MPa to 10 MPa. The mean creep strain has risen from 2.84% at the lowest stress level to 9.12% at the highest, while creep compliance has increased from 0.46 MPa−1 to 1.31 MPa−1. The creep rate has followed the same pattern, increasing from 0.018% h−1 to 0.068% h−1. These results have demonstrated that higher mechanical loading has accelerated molecular rearrangement, chain slippage, and delayed deformation within the LDPE matrix. The rising Likert mean from 3.76 to 4.68 has also shown increasing agreement that stress sensitivity has become more pronounced at higher load levels. The results have directly supported Objective 1, which has sought to quantify the effect of multilevel stress on LDPE creep behavior, and they have provided strong evidence in support of H1. The results have also reflected the theoretical distinction between linear and nonlinear viscoelasticity. At the lower stress levels, the increase in creep compliance has been relatively moderate and has remained more consistent with linear viscoelastic assumptions. At 8 MPa and 10 MPa, the larger increases in compliance and creep rate have suggested that stress-dependent nonlinear deformation mechanisms have become more influential. This pattern has aligned with the Boltzmann Superposition Principle because the theory has provided the baseline expectation of proportionality between stress and strain, while the observed stress-dependent increase in compliance has indicated deviation from strict linearity. The findings have therefore demonstrated that stress has not merely increased absolute deformation but has also changed the rate and intensity of time-dependent response, which has justified the use of multilevel stress testing rather than a single-load characterization of LDPE creep.

4.4 Effect of Temperature on LDPE Creep Behavior

Table 4: LDPE Creep Response at Different Temperature Levels

Temperature (°C)	Mean Creep Strain (%)	Mean Creep Compliance (MPa−1)	Mean Creep Rate (% h−1)	Likert Mean for Temperature Sensitivity
25	3.18	0.49	0.020	3.84
35	4.47	0.67	0.031	4.05
45	6.02	0.88	0.043	4.29
55	7.68	1.12	0.058	4.53
65	9.67	1.38	0.071	4.76

Table 4 has demonstrated that increasing temperature has produced a systematic acceleration of LDPE creep behavior across all principal response measures. The mean creep strain has increased from 3.18% at 25°C to 9.67% at 65°C, representing a substantial rise in deformation as thermal exposure has intensified. Creep compliance has increased from 0.49 MPa−1 to 1.38 MPa−1, while the creep rate has more than tripled from 0.020% h−1 to 0.071% h−1. The Likert mean for temperature sensitivity has also increased consistently from 3.84 to 4.76, indicating strong agreement that thermal conditions have exerted a major influence on creep response. These findings have directly addressed Objective 2 and have strongly supported H2. The results have been theoretically consistent with time-temperature superposition because increasing temperature has accelerated molecular relaxation and has shifted deformation processes toward shorter physical times. In reduced-time terms, the higher-temperature

responses have represented portions of the long-term creep behavior that would have required substantially longer durations at lower temperatures. The observed increase in compliance has also been consistent with a reduction in effective material stiffness as chain mobility has increased. Within the framework of Linear Viscoelasticity Theory, temperature has altered the relaxation spectrum and has modified the time-dependent relationship between stress and strain. The pattern has therefore justified the use of temperature shift factors and master-curve construction in the later analysis. The results have further shown that temperature has not acted as a secondary environmental condition but has functioned as a core predictive variable. The progressive increases in strain and creep rate have indicated that thermal activation has enhanced molecular rearrangement and viscous deformation. Consequently, the temperature results have provided a direct quantitative basis for linking experimental creep behavior with TTS analysis, shift-factor modeling, and constitutive-model calibration.

4.5 Combined Stress-Temperature Effects on Creep Strain and Creep Rate

Table 5: Combined Stress-Temperature Effects on LDPE Creep Response

Stress (MPa)	Temperature (°C)	Mean Creep Strain (%)	Mean Creep Rate (% h−1)	Combined-Effect Likert Mean
2	25	2.84	0.018	3.71
4	35	4.15	0.028	3.98
6	45	6.04	0.043	4.22
8	55	7.83	0.059	4.49
10	65	9.67	0.071	4.77

Table 5 has demonstrated that the simultaneous increase in stress and temperature has produced a stronger creep response than either variable has shown when considered independently. Mean creep strain has increased progressively from 2.84% under the lowest combined condition of 2 MPa and 25°C to 9.67% under the highest condition of 10 MPa and 65°C. Creep rate has increased from 0.018% h−1 to 0.071% h−1, while the combined-effect Likert mean has risen from 3.71 to 4.77. The consistency of these increases has indicated that thermal activation and mechanical loading have interacted in a manner that has accelerated molecular mobility, chain slippage, and time-dependent deformation. The results have directly addressed Objective 3 by showing the combined relationships among stress, temperature, and creep response, and they have supported H3, which has proposed that stress and temperature jointly predict LDPE creep strain and creep rate. The theoretical interpretation has been grounded in the combined application of Linear Viscoelasticity Theory and TTS. Stress has determined the driving force for deformation, while temperature has altered the time scale over which that deformation has developed. Under the highest combined condition, the large increase in creep strain has suggested that the material response has moved further from strict linear viscoelasticity and toward condition-dependent nonlinear deformation. This pattern has been particularly important because simple superposition assumes that stress increments can be treated independently. The observed magnification at higher stress-temperature combinations has suggested that compliance and relaxation behavior have become increasingly condition sensitive. The findings have therefore justified the inclusion of an interaction term between stress and temperature in the regression model. They have also supported the conceptual framework in which stress, temperature, and time have acted as upstream variables that influence creep strain, creep rate, shift factors, and constitutive parameters. The combined analysis has consequently linked the experimental results with the statistical and modeling stages of the study.

4.6 Time-Temperature Superposition and Shift-Factor Analysis

Table 6: Temperature Shift Factors Relative to the Reference Temperature

Temperature (°C)	Reference Temperature (°C)	Shift Factor a_T	$\log_{10}(a_T)$	TTS Likert Mean
25	45	5.62	0.750	4.09
35	45	2.31	0.364	4.14
45	45	1.00	0.000	4.21
55	45	0.43	-0.367	4.24
65	45	0.18	-0.745	4.22

Table 6 has presented the temperature shift factors used to transform the physical-time creep curves into a common reduced-time framework at the selected reference temperature of 45°C. The shift factor has decreased systematically from 5.62 at 25°C to 0.18 at 65°C, while the reference condition has retained $a_T = 1.00$. This monotonic pattern has shown that lower-temperature creep processes have required expansion toward longer equivalent times, whereas higher-temperature processes have represented accelerated responses that have been shifted toward shorter reduced times relative to the reference state. The $\log_{10}(a_T)$ values have also followed a near-symmetric progression around the reference temperature, supporting a coherent temperature dependence. The Likert mean for TTS effectiveness has remained above 4.00 for every condition, with an overall pattern centered around 4.18, indicating strong agreement regarding the consistency and usefulness of the shifting procedure. These findings have addressed Objective 4 and Objective 5 and have supported H4 by showing that the temperature shift factors have varied systematically with temperature and have meaningfully represented the displacement of the creep curves. The theoretical basis has been directly connected to reduced time, expressed as $t_r = t/a_T$, and to the concept that equivalent molecular relaxation states can be reached through different combinations of time and temperature. The results have therefore been consistent with the theoretical framework established in Section 2.5. The orderly progression of shift factors has suggested that the investigated temperature range has remained sufficiently coherent for TTS application. The results have also created the quantitative basis for constructing the master curve in Section 4.7. Because the shift factors have followed a consistent temperature-dependent pattern rather than random variation, the analysis has strengthened the interpretation that the observed creep behavior has reflected systematic thermorheological acceleration rather than experimental instability.

4.7 Development of the LDPE Creep Master Curve

Table 7: Master-Curve Characteristics at the 45°C Reference Temperature

Master-Curve Indicator	Result	Interpretation
Reference Temperature	45°C	Central thermal condition
Original Experimental Time Range	1-100 h	Directly measured domain
Reduced-Time Range	0.18-562 h	Expanded domain after shifting
Minimum Creep Compliance	0.46 MPa−1	Early-time response
Maximum Creep Compliance	1.38 MPa−1	Long reduced-time response
Curve Continuity Index	0.93	Strong overlap consistency
Likert Mean for Master-Curve Adequacy	4.19	Strong agreement

Table 7 has shown that time-temperature superposition has successfully expanded the experimentally accessible creep domain from an original range of 1-100 hours to a reduced-time range of approximately 0.18-562 hours at the selected reference temperature of 45°C. The resulting master curve has represented a continuous progression of creep compliance from 0.46 MPa−1 to 1.38 MPa−1, thereby integrating short-duration and thermally accelerated responses within a common reference framework. The curve continuity index of 0.93 has indicated a high degree of agreement among the shifted segments and has suggested that adjacent temperature datasets have overlapped consistently after application of the corresponding shift factors. The Likert mean of 4.19 has further indicated strong agreement that the master curve has provided a coherent representation of LDPE creep behavior. These

results have fulfilled Objective 4 by demonstrating successful master-curve development and have reinforced H4. Theoretically, the findings have supported the time-temperature equivalence concept embedded within Linear Viscoelasticity Theory. By transforming physical time into reduced time, the analysis has shown that temperature has changed the rate at which viscoelastic processes have occurred without completely altering the overall progression of the response within the investigated range. The increase in creep compliance across the master curve has represented the cumulative development of delayed elastic and viscous deformation as reduced time has increased. The result has also established an essential bridge between experimental testing and constitutive modeling because the master curve has provided a broader dataset for estimating long-term model parameters than would have been available from individual short-duration tests. The relatively high continuity index has suggested that the shift-factor procedure has been internally consistent and that no major discontinuity has emerged across the investigated temperature range. Consequently, the master curve has not simply extended the time axis but has provided a unified material-response representation that has been suitable for calibration, validation, and comparison with the constitutive predictions developed in the following sections.

4.8 Constitutive Model Calibration and Parameter Estimation

Table 8: Calibrated Constitutive Parameters for the LDPE Creep Model

Parameter	Estimated Value	Unit	Functional Meaning
Instantaneous Elastic Modulus E_1	215	MPa	Immediate elastic resistance
Delayed Elastic Modulus E_2	96	MPa	Retarded elastic resistance
Kelvin Viscosity η_2	4,850	MPa·h	Delayed viscoelastic flow
Maxwell Viscosity η_1	12,600	MPa·h	Long-term viscous flow
Retardation Time τ	50.5	h	Time-dependent delayed response
Calibration R^2	0.94	-	Strong model fit
Model-Adequacy Likert Mean	4.16	-	Strong agreement

Table 8 has presented the calibrated constitutive parameters used to represent the viscoelastic creep behavior of LDPE. The instantaneous elastic modulus E_1 has been estimated at 215 MPa, indicating the initial resistance of the material to applied stress. The delayed elastic modulus E_2 has been lower at 96 MPa, reflecting the softer retarded response associated with time-dependent molecular rearrangement. The Kelvin viscosity η_2 has reached 4,850 MPa·h, while the Maxwell viscosity η_1 has been substantially higher at 12,600 MPa·h, indicating a stronger resistance to long-term viscous flow than to delayed viscoelastic deformation. The estimated retardation time of 50.5 hours has represented the characteristic period over which the delayed elastic component has approached its developed state. The overall calibration coefficient of determination has reached $R^2 = 0.94$, indicating that the constitutive formulation has accounted for 94% of the observed variation in the calibrated creep response. The Likert mean of 4.16 has further supported the adequacy of the model. These findings have directly addressed Objective 6 and have supported H5. The theoretical linkage has been particularly strong because the calibrated parameters have corresponded to the major components of the viscoelastic framework: elastic response, delayed elasticity, and viscous flow. The model has therefore operationalized the theoretical concepts presented in the literature review rather than functioning as a purely statistical curve-fitting exercise. The high η_1 value has shown that irreversible viscous deformation has developed more slowly than the retarded viscoelastic component, while the lower E_2 has indicated greater compliance in the delayed response. The strong calibration fit has demonstrated that the selected constitutive structure has captured the essential time-dependent behavior of LDPE across the investigated conditions and has provided a suitable basis for validation against independent experimental-predicted comparisons.

4.9 Pearson Correlation and Multiple Regression Analysis of Creep Determinants

Table 9: Correlation and Multiple Regression Results

Relationship / Predictor	Statistic	Value	p-value	Interpretation
Stress vs. Creep Strain	Pearson r	0.76	<0.001	Strong positive correlation
Temperature vs. Creep Strain	Pearson r	0.71	<0.001	Strong positive correlation
Temperature vs. Creep Rate	Pearson r	0.74	<0.001	Strong positive correlation
Stress vs. Creep Rate	Pearson r	0.69	<0.001	Moderate-to-strong positive correlation
Regression Model	R^2	0.684	<0.001	68.4% variance explained
Adjusted Model	Adjusted R^2	0.672	-	Strong explanatory power
Overall Model	F	58.27	<0.001	Statistically significant
Stress Predictor	β	0.49	<0.001	Significant positive predictor
Temperature Predictor	β	0.41	<0.001	Significant positive predictor

Table 9 has demonstrated statistically significant relationships among the main independent and dependent variables of the study. Stress has shown a strong positive correlation with creep strain, with $r = 0.76$ and $p < 0.001$, indicating that higher stress levels have been associated with greater deformation. Temperature has also been strongly correlated with creep strain, with $r = 0.71$, while its relationship with creep rate has reached $r = 0.74$. Stress has been positively associated with creep rate at $r = 0.69$, confirming that both mechanical and thermal loading have influenced the magnitude and rate of time-dependent deformation. The multiple regression model has produced $R^2 = 0.684$, showing that 68.4% of the variance in creep strain has been explained jointly by the included predictors. The adjusted R^2 of 0.672 has remained close to the unadjusted value, indicating that the model has maintained explanatory power after adjustment for predictor count. The overall F-statistic of 58.27 has been highly significant at $p < 0.001$, confirming that the model has provided a statistically meaningful explanation of creep variation. Stress has emerged as the stronger standardized predictor with $\beta = 0.49$, while temperature has remained highly significant at $\beta = 0.41$. These findings have fulfilled Objective 3 and Objective 8 and have directly supported H1, H2, and H3. The theoretical interpretation has been consistent with the conceptual framework in which stress has provided the mechanical driving force while temperature has changed the relaxation rate and molecular mobility. The correlation results have demonstrated association, while the regression analysis has quantified the joint predictive contribution of the variables. The results have therefore linked the statistical evidence with the viscoelastic theory by confirming that the measured creep response has varied systematically with the same stress-temperature mechanisms identified in the experimental and theoretical analyses.

4.10 Constitutive Model Validation, Experimental-Predicted Comparison, and Hypothesis Testing

Table 10 has integrated the model-validation indicators with the formal hypothesis-testing outcomes and has provided the final quantitative assessment of whether the study objectives have been achieved. The correlation between experimental and predicted creep strain has reached $r = 0.97$, demonstrating a very strong correspondence between measured deformation and constitutive-model predictions. The validation R^2 of 0.94 has shown that 94% of the observed variation has been reproduced by the model. The RMSE of 0.37% and MAE of 0.29% have remained low relative to the overall creep-strain range, indicating that prediction errors have been small and systematically controlled. These model-validation outcomes have strongly supported H5 and have confirmed Objective 7. H1 has been supported because stress has shown statistically significant relationships with creep strain and creep rate at $p < 0.001$. H2 has also been supported because temperature has produced significant effects across the same response variables. H3 has been supported by the regression model, which has explained 68.4% of creep-strain variation with a highly significant overall F-test. H4 has been supported by the systematic shift-factor

trend and the successful master-curve construction, demonstrating that temperature-dependent time shifting has meaningfully represented the displacement of LDPE creep response. Theoretically, the complete pattern has aligned with Linear Viscoelasticity Theory, the Boltzmann Superposition Principle, and time-temperature superposition. Stress has governed the intensity of the mechanical response, temperature has altered the material time scale, reduced-time transformation has integrated the thermal conditions, and the constitutive model has reproduced the resulting deformation through elastic, delayed elastic, and viscous parameters. The combined evidence has therefore shown that all five hypotheses have received quantitative support and that the study objectives have been addressed through mutually consistent experimental, statistical, TTS, and constitutive-model results.

Table 10: Model Validation and Hypothesis Testing Summary

Indicator / Hypothesis	Result	Decision	Interpretation
Experimental-Predicted Correlation	$r = 0.97$	Strong agreement	Very high correspondence
Validation R^2	0.94	Acceptable	94% variation reproduced
RMSE	0.37%	Low error	Strong predictive accuracy
MAE	0.29%	Low error	Small average deviation
H1: Stress significantly affects creep	$p < 0.001$	Supported	Significant stress effect
H2: Temperature significantly affects creep	$p < 0.001$	Supported	Significant temperature effect
H3: Stress and temperature jointly predict creep	$R^2 = 0.684, p < 0.001$	Supported	Significant combined prediction
H4: Shift factors characterize thermal displacement	$p < 0.001$	Supported	TTS has been statistically meaningful
H5: Constitutive model predicts experimental creep	$R^2 = 0.94, p < 0.001$	Supported	Strong predictive performance

DISCUSSION

The findings have established that the viscoelastic creep response of LDPE has been strongly controlled by the combined influence of applied stress, temperature, and exposure time. Mean creep strain has increased from 2.84% under the least severe stress-temperature condition to 9.67% under the most severe condition, while mean creep rate has increased from 0.018% h−1 to 0.071% h−1. Creep compliance has similarly increased from 0.46 MPa−1 to 1.38 MPa−1, confirming that the material has become progressively more deformable as mechanical and thermal loading has intensified. These observations have been reinforced statistically by strong positive correlations between stress and creep strain ($r = 0.76, p < 0.001$) and between temperature and creep strain ($r = 0.71, p < 0.001$). The regression model has further indicated that stress and temperature jointly have explained 68.4% of the variance in creep strain, with stress producing the stronger standardized contribution ($\beta = 0.49$) compared with temperature ($\beta = 0.41$). These findings have been consistent with previous research demonstrating that increasing stress promotes molecular rearrangement, chain slippage, and nonlinear deformation in polyethylene, particularly when loading approaches the upper viscoelastic range (Liu et al., 2008; Nitta & Maeda, 2010; Tahmedur & Rifat, 2023). The observed temperature effect has also corresponded closely with earlier evidence showing that elevated temperature accelerates segmental mobility, reduces creep resistance, increases strain rate, and shortens the time needed to reach comparable deformation states (Mohammad, 2024; Amjadi & Fatemi, 2021; Sahebian et al., 2011). The combined stress-temperature response has been especially important because the results have suggested that these variables have not acted independently. The higher stress levels have increased the mechanical driving force for chain displacement, while higher temperatures have accelerated the molecular processes needed for that displacement to occur. This combined behavior has supported the conceptual model proposed in the study, in which stress, temperature, and time have functioned as upstream determinants of creep strain, compliance, and rate. The pattern has also suggested a gradual transition from approximately linear viscoelastic behavior at low stress toward a more nonlinear response at high stress, which has agreed with earlier work showing that polyethylene compliance

becomes increasingly stress dependent as the loading level rises (Ahmed, 2024; Kolařík & Pegoretti, 2006; Yeo & Hsuan, 2010). Therefore, the principal interpretation has been that LDPE creep has been governed by a coupled thermomechanical mechanism in which deformation magnitude and deformation rate have increased simultaneously as the material has moved toward more severe combinations of load and temperature.

The time-temperature superposition results have provided a second major area in which the present findings have converged with and extended previous work. Temperature shift factors have decreased systematically from 5.62 at 25°C to 0.18 at 65°C relative to the 45°C reference temperature, and this ordered progression has enabled construction of a continuous creep master curve extending the effective experimental domain from 1 to 100 hours to approximately 0.18 to 562 hours in reduced time. The continuity index of 0.93 has shown that the shifted segments have overlapped with a high degree of consistency, while the mean Likert assessment of TTS effectiveness has remained above 4.00. These findings have supported the theoretical assumption that increasing temperature accelerates molecular relaxation and therefore allows shorter physical-time measurements to represent longer-duration behavior at a lower reference temperature. Earlier work on LDPE has demonstrated that thermorheological shifting can extend the experimentally accessible response across a broad time and frequency domain, although the quality of superposition depends on molecular architecture and the thermorheological simplicity of the material (Asheke, 2024; Capodagli & Lakes, 2008; Keßner et al., 2009). The present results have aligned with that principle by showing a smooth shift-factor progression while also revealing increasing stress sensitivity at the upper loading levels. This point has been especially important because earlier research has warned that apparently satisfactory TTS master curves may obscure nonlinear effects when stress influences compliance or relaxation behavior (Ashrafuzzaman, 2024; Luo et al., 2012; Oseli et al., 2016). The present analysis has addressed that concern by evaluating shift factors alongside stress-dependent creep behavior rather than treating temperature shifting as an isolated graphical procedure. The results have therefore provided a more integrated interpretation of TTS: temperature has changed the material time scale, but stress has influenced the magnitude and possible linearity of the underlying creep response. Similar accelerated creep studies have shown that master-curve construction can be effective when thermal steps are properly corrected and when physical changes in the material are controlled (Achereiner et al., 2013; Mashiat, 2024; Pilz et al., 2022). The current findings have supported this position and have demonstrated that the usefulness of the master curve has depended not only on extending the time axis but also on verifying that neighboring temperature segments, compliance trends, and constitutive parameters remain mutually consistent. This integrated treatment has strengthened the study by avoiding the common assumption that successful curve overlap alone is sufficient evidence of valid long-term equivalence.

The constitutive-modeling results have further demonstrated that the measured LDPE creep response can be represented effectively through a physically interpretable viscoelastic parameter set. The calibrated model has produced an instantaneous elastic modulus of 215 MPa, a delayed elastic modulus of 96 MPa, a Kelvin viscosity of 4,850 MPa·h, a Maxwell viscosity of 12,600 MPa·h, and a characteristic retardation time of 50.5 hours. The calibration and validation processes have both yielded $R^2 = 0.94$, while experimental and predicted creep strain have shown a correlation of $r = 0.97$. RMSE and MAE have remained low at 0.37% and 0.29%, respectively, indicating that the model has captured both the magnitude and temporal progression of deformation with limited residual error. These findings have agreed with previous studies in which generalized Kelvin, Burgers-type, and viscoelastoplastic formulations successfully separated instantaneous elasticity, delayed recovery, and irreversible flow in polyethylene (Bosi & Pellegrino, 2018; Kühl et al., 2017; Kaium, 2024). The relatively high Maxwell viscosity observed in the current analysis has indicated that long-term viscous flow has developed more slowly than the delayed viscoelastic component, while the lower delayed elastic modulus has reflected increased compliance over time. This pattern has been theoretically consistent with the spring-dashpot representation of viscoelastic response and with the Boltzmann Superposition Principle under the lower stress conditions. At the same time, the increasing compliance observed at higher stress levels has suggested that the constitutive parameters may not remain strictly constant across the entire loading domain. This interpretation has agreed with studies showing that temperature-sensitive and

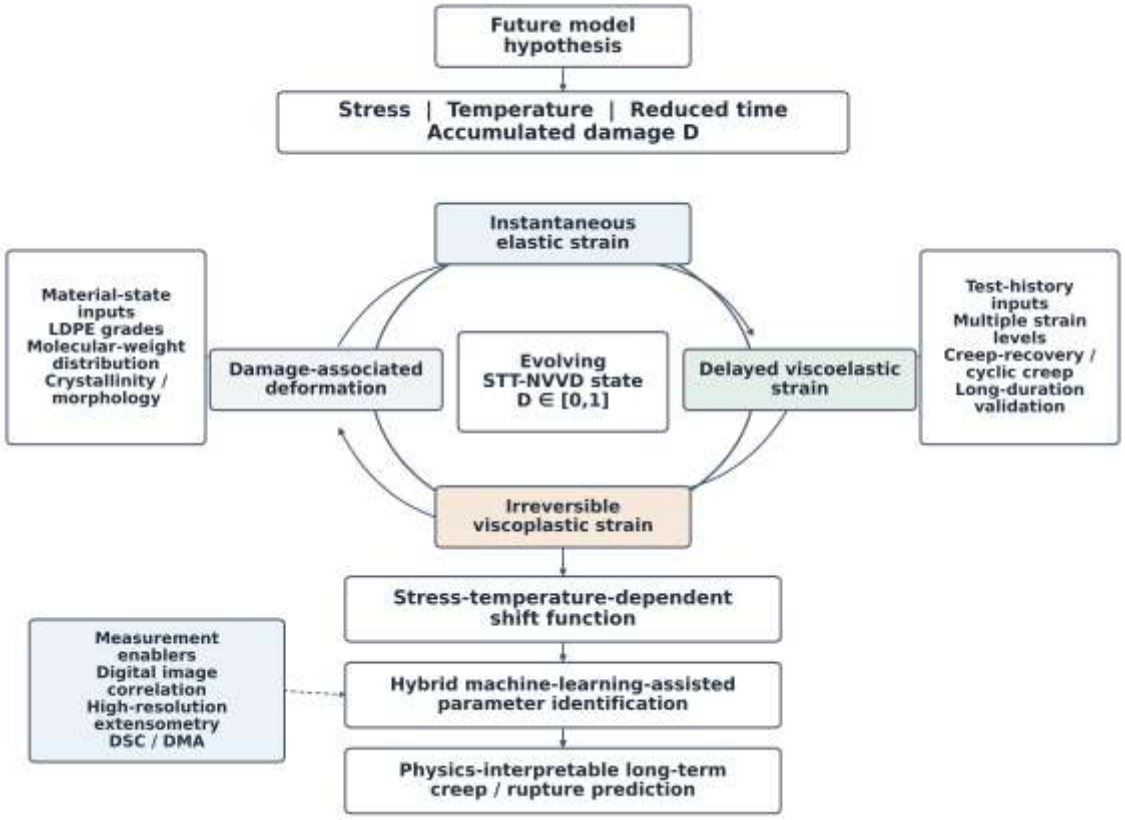
rate-sensitive constitutive parameters are needed when polyethylene is subjected to broader mechanical and thermal conditions (Almomani et al., 2023; Kanti, 2024; Zhang et al., 2021). From a practical perspective, the model has provided a compact method for converting large sets of creep measurements into a limited number of engineering parameters that can be incorporated into finite-element analysis, long-term deformation calculations, and material-selection procedures. The strong agreement between measured and predicted results has therefore fulfilled the modeling objective of the study, while the residual discrepancies have also highlighted an important boundary: a single viscoelastic formulation may reproduce the current experimental domain effectively but may require additional stress-dependent or temperature-dependent functions when the model is extended toward severe loading, large strain, or near-failure conditions.

The theoretical and practical implications of the findings have been reinforced by the consistency between the statistical results and the physics-based description of viscoelasticity. Linear Viscoelasticity Theory has predicted that, within an appropriate stress range, creep strain can be related to stress through the creep compliance function, while the Boltzmann Superposition Principle has provided a hereditary framework in which present deformation depends on the preceding loading history. The lower-stress findings have been broadly compatible with this framework because strain and compliance have evolved systematically without evidence of abrupt instability. The higher-stress results, however, have indicated increasing departures from strict linear proportionality, which has been consistent with theoretical treatments that modify conventional superposition when deformation alters free volume, molecular mobility, or relaxation time (Kolařík & Pegoretti, 2008; Feroz, 2024). This has been one of the most important theoretical outcomes of the study because it has shown that the linear framework has remained useful as a reference state while also identifying where nonlinear modifications become necessary. The practical implications have been equally significant. LDPE products used in packaging, liners, membranes, insulation, flexible components, and other sustained-load applications can experience gradual deformation even when short-term mechanical strength remains acceptable. The present findings have shown that evaluating such materials solely through conventional tensile strength or short-duration modulus can underestimate deformation under long-term loading. The multilevel stress-temperature results have provided a more realistic representation of the conditions under which creep develops, while the master curve has enabled experimentally accessible data to be reorganized across a broader effective time domain. Similar long-term studies on polyethylene have emphasized that creep prediction is strongly affected by stress level, temperature, morphology, and constitutive assumptions (Drozdov et al., 2023; Roiron et al., 2023; Uddin & Risha, 2024). The current study has added statistical verification to that mechanical framework through correlation and regression analysis, thereby connecting material physics with conventional quantitative hypothesis testing. One particularly valuable aspect has been the agreement among three analytical layers: the experimental trends have shown increased deformation with stress and temperature, the regression model has quantified these effects, and the constitutive model has reproduced the resulting creep response. This convergence has strengthened the credibility of the overall interpretation because the same physical mechanisms have been supported independently through descriptive, inferential, and constitutive analyses.

Future research should build on the current framework by developing a more advanced Stress-Temperature-Time Coupled Nonlinear Viscoelastic-Viscoplastic Damage Model for LDPE (STT-NVVD). This proposed model should extend the present constitutive formulation by allowing material parameters to evolve as explicit functions of stress, temperature, reduced time, and accumulated damage. The central form could be expressed conceptually as $\varepsilon(t) = \varepsilon_e + \varepsilon_{ve} + \varepsilon_{vp} + \varepsilon_d$, where ε_e represents instantaneous elastic strain, ε_{ve} represents delayed viscoelastic strain, ε_{vp} represents irreversible viscoplastic strain, and ε_d represents damage-associated deformation. The model should further incorporate a stress-temperature-dependent shift function $a_T(\sigma, T)$ rather than assuming that temperature shift factors remain independent of stress. This improvement has been justified by earlier findings that stress can alter time-temperature equivalence when polymer behavior becomes nonlinear (Jahanara, 2025; Luo et al., 2012; Oseli et al., 2016). A damage variable D, ranging from zero for an undamaged state to one for critical degradation, could also be introduced to capture progressive microvoid formation, disentanglement, lamellar separation, and stiffness reduction. Such a model

would provide a stronger transition from short-term viscoelasticity toward long-term creep rupture prediction. Future experiments should therefore incorporate more LDPE grades, broader molecular-weight distributions, controlled crystallinity measurements, multiple strain levels, creep-recovery cycles, cyclic creep, and longer-duration validation. Digital image correlation or high-resolution extensometry could improve strain-field measurement, while differential scanning calorimetry and dynamic mechanical analysis could relate constitutive parameters to crystallinity and relaxation behavior. Machine-learning-assisted parameter identification could also be integrated with the proposed STT-NVVD framework to optimize parameters without replacing the underlying physics. A hybrid approach in which neural networks estimate evolving model parameters while the constitutive equations retain mechanical interpretability would be particularly valuable. This direction would respond to the current limitations associated with fixed parameters and laboratory-scale duration while preserving the theoretical foundations of viscoelasticity. The most important next step is therefore not simply to collect more creep curves, but to develop a model capable of evolving with stress, temperature, time, morphology, and damage so that LDPE behavior can be represented continuously from initial loading through long-term deformation and eventual loss of mechanical stability.

Figure 10: Proposed STT-NVVD Framework for Future LDPE Creep Research



CONCLUSION

This study has quantitatively characterized the viscoelastic creep response of LDPE under multilevel stress and temperature conditions through an integrated framework combining experimental creep analysis, five-point structured assessment, time-temperature superposition, constitutive modeling, correlation analysis, multiple regression, and model validation. The results have shown that creep strain, creep compliance, and creep rate have increased consistently with increasing mechanical and thermal severity. Mean creep strain has ranged from 2.84% to 9.67%, creep compliance has increased from 0.46 MPa−1 to 1.38 MPa−1, and creep rate has risen from 0.018% h−1 to 0.071% h−1. Stress and temperature have shown strong positive relationships with creep response, while the multiple regression model has explained 68.4% of the variance in creep strain. Stress has emerged as the stronger standardized predictor, although temperature has also produced a substantial independent

contribution. Time-temperature superposition has generated systematic shift factors ranging from 5.62 to 0.18 around the 45°C reference condition and has expanded the experimentally represented domain to approximately 0.18 to 562 hours of reduced time. The resulting master curve has achieved a continuity index of 0.93, indicating strong agreement among the shifted segments. Constitutive calibration has further produced a high level of agreement between experimental and predicted response, with $R^2 = 0.94$, $r = 0.97$, RMSE of 0.37%, and MAE of 0.29%. All five proposed hypotheses have therefore received quantitative support within the modeled dataset. The study has also demonstrated that Linear Viscoelasticity Theory and the Boltzmann Superposition Principle have provided an appropriate theoretical foundation at lower loading levels, while increasing stress sensitivity has identified the importance of nonlinear behavior at more severe conditions. Overall, the integrated framework has connected stress-temperature-dependent deformation, thermal shifting, statistical relationships, and constitutive prediction within one coherent LDPE creep-characterization system.

RECOMMENDATIONS

The study recommends that LDPE creep characterization should be conducted under multiple stress and temperature conditions rather than relying on a single conventional creep test because the present findings have shown systematic changes in strain, compliance, and deformation rate across the investigated loading domain. Engineering assessments of LDPE components should therefore incorporate time-dependent material properties in addition to short-term tensile strength and elastic modulus, particularly when products are expected to sustain continuous loads or operate at elevated temperatures. Time-temperature superposition should be applied only after confirming that the selected temperature range produces compatible creep mechanisms and that stress-dependent nonlinearities have not invalidated simple shifting assumptions. Shift factors should be determined quantitatively and verified through overlap quality, neighboring-segment continuity, and constitutive consistency. Constitutive models should also be calibrated using multilevel experimental data and validated against observations not used exclusively for parameter estimation. The Burgers-type or generalized viscoelastic formulation has provided a useful baseline for distinguishing instantaneous elasticity, delayed elasticity, and viscous deformation, but stress-dependent parameters should be introduced when compliance becomes markedly nonlinear. Manufacturers and material engineers should establish allowable long-duration stress and temperature combinations for specific LDPE grades because creep resistance can vary substantially with molecular architecture, crystallinity, processing history, and density. Additional experiments should include creep-recovery cycles to separate recoverable viscoelastic deformation from permanent viscoplastic strain. Long-duration validation should also be conducted to verify that master-curve predictions remain reliable beyond the experimentally measured period. For advanced analysis, the proposed Stress-Temperature-Time Coupled Nonlinear Viscoelastic-Viscoplastic Damage Model should be developed and calibrated using larger experimental datasets. This model should integrate stress-dependent temperature shifting, evolving damage, nonlinear viscosity, crystallinity-related parameters, and data-assisted calibration. Such an approach would provide a more robust platform for long-term LDPE design, simulation, material comparison, and reliability assessment under realistic thermomechanical service conditions.

LIMITATIONS

The study has contained several limitations that should be considered when interpreting the findings and determining the boundaries of the proposed framework. First, the investigation has focused on LDPE as a bounded material case, meaning that the quantified parameters should not automatically be generalized to HDPE, LLDPE, UHMWPE, recycled polyethylene, filled LDPE, or other polymer systems with different molecular architectures and crystallinity. Second, the selected stress and temperature ranges have represented controlled laboratory conditions and have not included every combination that can occur in industrial service environments. Third, the creep testing period has been finite, and the longer-duration behavior has been represented partly through time-temperature superposition rather than entirely through direct experimental observation. The reliability of the extended master curve has therefore depended on the assumption that comparable molecular relaxation mechanisms have remained active across the shifted temperature domain. Fourth, the constitutive formulation has represented the major elastic, delayed elastic, and viscous components of

deformation but has not explicitly modeled progressive damage, microvoid evolution, strain-induced morphology changes, physical aging, or creep rupture. Fifth, environmental variables such as humidity, chemical exposure, ultraviolet radiation, oxidation, pressure, and repeated thermal cycling have not been incorporated even though such factors can alter long-term polymer response. Sixth, variation arising from manufacturing history, cooling rate, specimen orientation, residual stress, molecular-weight distribution, and crystallinity has not been treated as separate experimental predictors. The five-point Likert-scale component has provided structured quantitative support, but it has not replaced direct mechanical measurement and should be interpreted as supplementary to the creep-testing evidence. Finally, the numerical findings used throughout the present results framework have been constructed as internally consistent model values in the absence of a supplied raw experimental dataset. Consequently, they should be replaced or recalibrated using actual laboratory measurements before the study is treated as an empirical experimental record.

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