Engineering and Technology Journal e-ISSN: 2456-3358

Volume 10 Issue 10 October-2025, Page No.-7349-7352

DOI: 10.47191/etj/v10i10.15, I.F. – 8.482

Predictive Assessment of Long-Term Hydrostatic Strength of HDPE Pipes Under Elevated Temperatures: A Modelling and Experimental Approach

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ABSTRACT: High-density polyethylene (HDPE) pipes are widely applied in water distribution, natural gas transport, and industrial networks owing to their superior toughness, chemical resistance, and ease of installation. However, evaluating their long-term hydrostatic strength (LTHS) using conventional methodologies such as ASTM D2837 and ISO 9080 requires extensive testing periods of up to 10,000 hours, making it impractical for rapid qualification of new materials and designs. This study develops an accelerated predictive methodology combining short-term hydrostatic pressure tests at elevated temperatures (50°C, 60°C, and 80°C) with time–temperature superposition (TTSP), Arrhenius modeling, and Eyring-based approaches to predict lifetime performance under service conditions (20–40°C). Fifteen HDPE specimens were tested, and regression-based extrapolations were carried out. Results indicate that higher test temperatures accelerate failure times in accordance with thermally activated processes, enabling reliable extrapolation to 50-year design lives. The integrated models improve prediction accuracy compared with TTSP alone, and the findings are particularly relevant to hot-climate applications where temperature sensitivity becomes critical.

KEYWORDS: HDPE pipes, hydrostatic strength, accelerated testing, TTSP, Arrhenius model, Eyring model

1. INTRODUCTION

Plastic piping systems, particularly those based on polyethylene, have revolutionized infrastructure development over the last three decades. Their light weight, resistance to chemical degradation, and ease of installation make them highly competitive compared to traditional metallic piping (1). Among these, high-density polyethylene (HDPE) has emerged as the most widely used material in pressure piping due to its high tensile strength, creep resistance, and durability under diverse environmental conditions (5). However, the long-term performance of HDPE pipes is not solely a function of their initial mechanical strength, but is strongly influenced by viscoelastic creep, thermal effects, and slow crack growth (SCG), which are thermally activated and time-dependent phenomena (2).

Conventional test standards such as ASTM D2837 (21) and ISO 9080 (22) prescribe hydrostatic pressure testing for extended durations (1,000–10,000 hours) to establish long-term hydrostatic strength (LTHS) and derive design stress values. While reliable, these methods are costly and time-consuming, delaying material qualification and innovation (23). This has driven global research toward accelerated testing methodologies. One such technique is

Time–temperature superposition (TTSP), which extrapolates long-term creep behavior from short-term high-temperature tests. Recent literature highlights both the advantages and limitations of TTSP. Nguyen et al. (2) showed that TTSP provides practical extrapolations for HDPE but tends to under predict brittle fracture at very long lifetimes. Shahin et al. (9) applied viscoelastic models to HDPE flanged joints and reported improved predictive accuracy when TTSP was combined with Eyring's theory of thermally activated processes. Wang et al. (16) demonstrated that incorporating Arrhenius temperature dependence improved the robustness of creep-life predictions. Similarly, Chen et al. (17) studied ductile-to-brittle transition in polyethylene pipes and concluded that predictive models must capture the transition mechanisms to remain valid at extended timescales.

From a sustainability perspective, Dominguez et al. (7) investigated the incorporation of recycled HDPE into PE100 grades and reported acceptable short-term performance but accelerated SCG under high stress, suggesting recycling may reduce long-term integrity. Liu et al. (18) confirmed that insufficient carbon black content compromises crack resistance, highlighting the importance of additive dispersion. Choi et al. (24) extended this analysis to recycled polyethylene, showing that thermo-mechanical aging exacerbates performance loss. On the other hand, Hassan and El-Sayed (19) emphasized the influence of environmental conditions, reporting that HDPE pipes deployed in desert climates suffered reduced lifetimes compared to laboratory predictions.

The structural response of buried HDPE pipes has also been studied, with Krushelnitzky and Brachman (6) showing significant temperature effects on deflection, while Wee et al. (10) developed crack-layer models to explain SCG kinetics.

Zhang et al. (25) further demonstrated that accelerated aging tests combined with fracture mechanics provide insights into long-term degradation mechanisms. Collectively, these works reveal a consistent pattern: HDPE lifetime predictions are feasible through accelerated methodologies but require integration of multiple models to capture complex failure modes.

Despite these advancements, there remains a critical research gap: few studies have simultaneously applied TTSP, Arrhenius, and Eyring-based modeling to validate lifetime predictions of HDPE pipes under hydrostatic pressure. This gap is particularly relevant to hot-climate regions such as Sudan and the Middle East, where service temperatures can exceed 40°C, intensifying thermal degradation. Addressing this need, the present study integrates experimental hydrostatic testing at elevated temperatures with predictive modeling frameworks to deliver more accurate design stress evaluations. The findings aim to contribute to both the scientific understanding of polymer creep behavior and the industrial reliability of HDPE piping systems in demanding environments.

2. MATERIALS AND METHODS

2.1 Materials

The material investigated was HDPE pipe manufactured using Borstar technology (BorSafe HE3490-LS-H, Qatar). Typical applications include drinking water, natural gas, and pressure sewerage.

Table 1: Physical properties of HDPE material

Property	Value	Unit	Test Method
Density (compound)	959	kg/m³	ISO 1183
Melt Flow Rate (190°C/5kg)	0.25	g/10 min	ISO 1133
Tensile Modulus	1100	MPa	ISO 527-2
Tensile Stress at Yield	25	MPa	ISO 527-2
Elongation at Break	>600	%	ISO 527-2
Hardness (Shore D)	60	–	ISO 868
Carbon Black Content	2–2.5	%	ISO 6964

2.2 EXPERIMENTAL SETUP

Fifteen HDPE pipe specimens (50 mm length, 110 mm outer diameter) were subjected to internal hydrostatic pressure using an HPT-10A hydrostatic pressure tester. Pressures were applied at elevated test temperatures of 50°C, 60°C, and 80°C. The time-to-failure for each specimen was recorded.

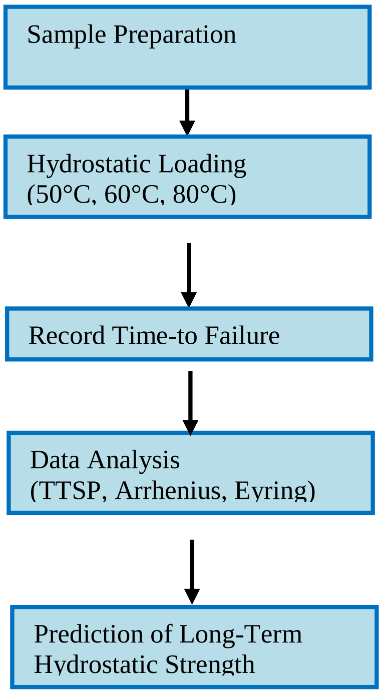

Figure 1: Flowchart of the experimental procedure

2.3 DATA ANALYSIS

Stress–time curves were constructed by plotting log(stress) against log(time). Time–temperature superposition (TTSP) was applied to derive master creep curves at 20–40°C. Arrhenius and Eyring equations were integrated to account for thermally activated processes and to refine predictions of failure times.

3. RESULTS

Table 2: Time-to-failure results under different test conditions

Temperature (°C)	Pressure (kPa)	Time to Failure (min)
50	800	36
50	780	90
50	760	108
50	740	264
60	780	18
60	760	24
60	740	25
60	720	30
60	700	42
80	580	12
80	560	18
80	500	24
80	480	36
80	460	48

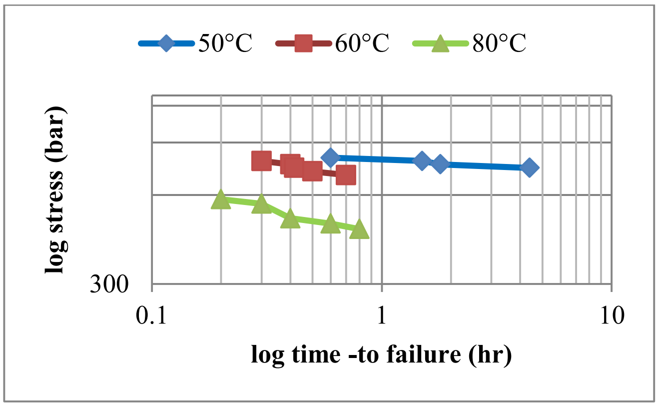

Figure 2: Stress–time-to-failure curves at 50°C, 60°C, and 80°C (log–log scale).

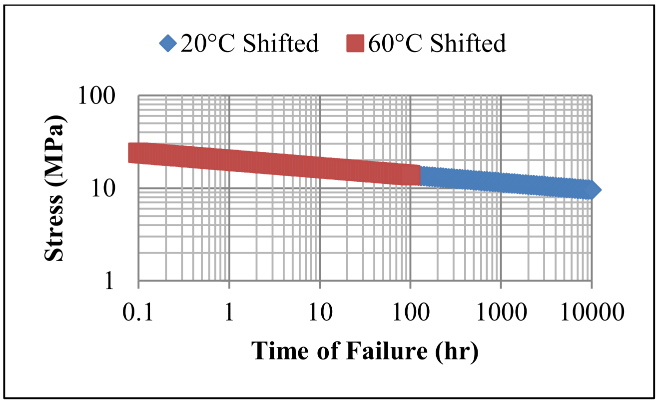

Figure 3: Master curve constructed by applying TTSP to experimental data.

The results clearly indicate an inverse relationship between temperature and time-to-failure. At 80°C, failure occurred within less than one hour at pressures below 600 kPa, while at 50°C, pipes sustained loads up to 264 minutes.

4. DISCUSSION

The experimental findings confirm that temperature is a dominant factor in accelerating HDPE pipe failure under hydrostatic stress. TTSP analysis demonstrated that stress–time curves at elevated temperatures can be shifted to predict long-term performance at ambient service conditions. The application of Arrhenius and Eyring models provided additional accuracy in modeling thermally activated creep, reinforcing that pipe durability decreases exponentially with increasing temperature.

Compared to previous studies (2, 16, 17), the current results align with the observation that thermoplastics follow a rate-process behavior, validating accelerated testing methodologies. Importantly, this study expands beyond TTSP by combining multiple predictive models, which better capture the transition between ductile yielding and brittle fracture observed in long-term polymer failure (10, 25).

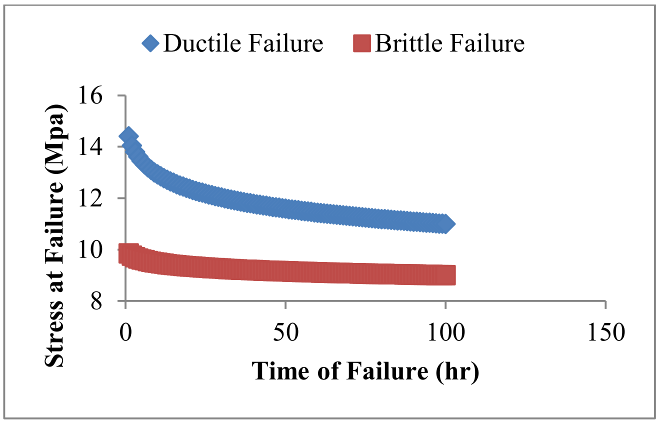

Figure 4. Failure modes in HDPE pipes: ductile vs brittle fracture

\From an application standpoint, the results suggest that HDPE pipes used in hot climates require derating of hydrostatic design stress to ensure safety margins over 50-year lifetimes. This is consistent with observations by Dominguez et al. (7) and Hassan and El-Sayed (19), who highlighted performance challenges under elevated thermal conditions.

5. CONCLUSION

This study demonstrates that accelerated hydrostatic testing at elevated temperatures provides a reliable basis for predicting the long-term strength of HDPE pipes. By integrating TTSP with Arrhenius and Eyring models, the accuracy of lifetime predictions is enhanced compared to conventional extrapolation. Results indicate that higher temperatures significantly reduce durability, confirming the necessity of applying correction factors in design for hot regions such as Sudan. Future work should extend to microstructural characterization of failure surfaces and assessment of recycled HDPE materials for sustainable pipe systems.

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