Temperature and Time-Dependent Mechanical Behavior and Optimized Bolt Preload Management in HDPE Piping Systems with Steel Flanged Connections

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Abstract

High-density polyethylene (HDPE) is a widely used material in industrial piping systems, known for its cost-effectiveness and versatility. However, HDPE's mechanical properties are highly sensitive to temperature, which impacts its tensile, compressive, and relaxation behavior over both short- and long-term applications. This study investigates the effects of temperature on HDPE's mechanical performance and its influence on flanged connections with steel backing rings, commonly used in large-diameter HDPE pipelines.
Experimental analysis of HDPE at temperatures between 23◦C and 80◦C demonstrates that both tensile and compressive moduli, as well as yield strength, decrease linearly with rising temperatures, underscoring the need for temperature consideration in HDPE component design. Long-term stress relaxation tests reveal that HDPE's relaxation modulus is also significantly temperature-dependent. A nonlinear viscoelastic plastic model, the three-network model (TNM), was calibrated with these findings and implemented in finite element analysis (FEA) simulations, where it accurately predicts HDPE's time- and temperature-dependent mechanical response. Validated by three-point bending tests, this model provides a reliable basis for predicting HDPE's performance in various loading scenarios and environmental conditions.

Further, the TNM was applied to assess the performance of HDPE flanged connections under different temperature conditions over a simulated service life of one year. Results reveal that these connections are prone to leakage due to stress relaxation and bolt preload loss, which are exacerbated at higher temperatures. A realistic annual temperature profile was applied to evaluate leakage progression, leading to recommendations for periodic bolt re-torqueing to mitigate leakage. These findings highlight practical guidelines for enhancing the long-term durability of HDPE flanged connections under variable temperature conditions.
In addition to temperature effects, this study explores the elastic interaction between HDPE pipes and steel flanges, focusing on the impact of stiffness contrast on bolt preload and flange tightness. Through FEA simulations, two bolt-tightening methods were compared to optimize load distribution and contact pressure. The Tetra-Parametric Assembly Method (TAM) achieved superior results, particularly in configurations with high bolt counts and significant stiffness contrast. Applying a 30-30-40 tightening sequence proved effective for HDPE-to-steel connections, promoting uniform preload retention and contact pressure distribution

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across the assembly. These insights support improved design and maintenance practices for HDPE piping systems, enabling more reliable performance in demanding environmental and operational conditions.