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ORIGINAL RESEARCH ARTICLE

Fatigue Failure in Polymeric Materials: Insights from Experimental Testing

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Abstract The investigation of fatigue failure in polymeric materials subjected to cyclic loading holds significant importance across diverse engineering applications. Numerous variables influence material behavior, encompassing material-related factors such as composition, molecular weight, orientation, and additives, as well as external factors like applied stress magnitude (stress amplitude, dynamic stress frequency and mean stress), and operating temperature. This paper presents an experimental exploration into the impact of loading parameters—mean stress, stress amplitude, and dynamic stress frequency—on the failure modes of two thermoplastic materials: high-density polyethylene (HDPE) and polyvinyl chloride (PVC). The study begins with an assessment of the mechanical and physical properties of the materials, followed by the design and manufacturing of a specialized uniaxial fatigue test rig. Tensile–tensile fatigue tests incorporating positive mean stress are conducted, evaluating the influence of altering stress amplitude and frequency on fatigue life and failure mode. The outcomes reveal that HDPE primarily experiences thermal and creep failure modes, with a lack of observed fatigue failure. Conversely, PVC specimens manifest three distinct failure modes: ductile, creep, and fatigue, with the type of failure contingent upon loading parameters. These findings offer significant insights into the various fatigue failure modes and contribute to an enhanced comprehension of the intricate interplay between loading dynamics and failure modes in polymeric materials.

Keywords High-density polyethylene (HDPE) · Polyvinyl chloride (PVC) · Failure modes · Experimental investigation · Fatigue life

Introduction

The development of polymeric materials has enabled their use in various structural and load-bearing applications such as gears, cams, mechanical couplings, bearing pads, etc. However, fatigue may occur in these components due to cyclic stress, leading to catastrophic failure at lower stress levels than those encountered during normal static mechanical loading. Understanding fatigue behavior and its damage mechanisms is essential for assessing the durability and long-term reliability of emerging materials in various applications, particularly in industries such as aviation and automotive where human safety is critical.

The fatigue failure of certain polymers exhibits diverse mechanisms depending on factors such as mean stress, stress amplitude, cyclic waveform, cyclic frequency of load application, and stress system (uniaxial or bending), see, for example, [1–8]. At higher stress amplitudes within a specific frequency range, thermal softening and yielding precede crack propagation, culminating in ultimate failure. Conversely, lower stress amplitudes predominantly invoke conventional fatigue crack propagation (FCP) mechanisms.

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Notably, at low frequencies, conventional crack propagation persists even under elevated stress amplitudes [9–11].

The study of fatigue in polymeric materials primarily encompasses two approaches: experimental investigations and modeling techniques. Experimental research involves conducting physical tests to evaluate the fatigue behavior of polymeric materials, while modeling work often complements experimental studies by providing theoretical frameworks and predictive tools. It is common for modeling efforts to incorporate experimental data to validate and refine the proposed models, ensuring a comprehensive understanding of the fatigue characteristics of polymeric materials.

Experimental Fatigue of Polymeric Materials

Polymeric materials and polymeric composites have gained significant attention as replacements for metallic materials, leading to extensive research aimed at evaluating and improving their properties. This research focus on fatigue properties has been prominent since the mid-20th century, reflecting the importance of understanding the fatigue behavior of polymeric materials.

Riddell et al. [12] investigated the fatigue behavior of thermoplastics. They concluded that increasing crystallinity in thermoplastics reduces damping and improves fatigue life, while also contributing to an increase in modulus and improved fatigue performance. They highlight the importance of considering temperature rise during fatigue testing of thermoplastics due to their relatively high damping compared with metals. Cessna et al. [13] investigated the flexural fatigue behavior of glass-reinforced thermoplastics (GRTPs) and compares the isothermal and nonisothermal fatigue life of different materials. They discussed the different mechanisms of fatigue failure observed in high-frequency and low-frequency cyclic loading. Broutman and Gaggar [14] conducted a comprehensive investigation into the bending fatigue behavior of epoxy and polyester resin. The study involved recording temperature variations during the tests using an infrared temperature detector. Furthermore, the influence of cyclic load frequency and moisture content on the fatigue behavior of the materials was also examined.

Crawford and Benham [15] conducted a study on the uniaxial fatigue behavior of injection-molded acetal copolymer specimens. Their investigation revealed the presence of two distinct failure modes, both associated with a gradual increase in specimen temperature. In the first mode, the temperature reached a stabilized value, initiating crack formation, and subsequent propagation over time. In the second mode, the polymer continued to heat up until thermal softening occurred. In another article [16], the same authors compared the results of uniaxial and rotating bending fatigue. They concluded that higher fatigue frequencies can be used with rotating bending fatigue without thermal softening. In yet another article [17], they investigated the uniaxial fatigue of different materials and showed that polypropylene and poly(tetramethylene terephthalate) are more prone to thermal failure in a wide range of loading. Crawford [6] underscores that practical scenarios often involve fluctuating stresses biased toward tension, creating an effective constant mean stress σ_m superimposed on a fluctuating stress σ_a. This complexity arises due to the polymers' creep response under steady mean stress. A substantial mean stress could precipitate creep rupture before fatigue failure transpires.

Hertzberg et al. [18] conducted a study to investigate the frequency sensitivity of polymeric materials under fatigue loading conditions within the range of 0.1–100 Hz. The research aimed to examine how the cyclic loading frequency influenced the fatigue behavior of the materials. Nielsen [19] conducted a study on the fatigue behavior exhibited by glass bead-reinforced nylon 6 through the utilization of the Maxwell rotating beam apparatus. The results of the investigation indicated that the presence of surface scratches can have a significant impact on the fatigue life of the material. Gotham et al. [20] ascertain that for polycarbonate, at a stress amplitude of $35\,MN/m^2$, failure results from thermal softening accompanied by necking, leading to gross ductile failure. As the applied stress reduces to $15\,MN/m^2$, craze/crack initiation occurs, resulting in failure at significantly lower strain levels and increased brittleness.

Mai [21] conducted a study on the fatigue behavior of polypropylene using a rotating bending machine. The investigation examined the effect of forced cooling on the failure mode of the material. Ali [22] investigated the low-frequency fatigue of three different polymers which are high-density polyethylene and polypropylene and polymethylmethacrylate. HDPE and PP exhibit fatigue strength and ductility within the range of ductile metals, while PMMA shows approximately no plastic strain and sensitivity to stress concentration. Takahara et al. [23] conducted a study on the fatigue behavior of high-density polyethylene by analyzing changes in dynamic viscoelasticity during the fatigue process. The investigation identified the conditions under which brittle and ductile failures occur and explored the influence of environmental factors such as temperature and heat transfer coefficient on fatigue behavior.

Shariati et al. [24] conducted an experimental and numerical investigation into the fatigue behavior of polyoxymethylene (POM) subjected to uniaxial fatigue loading. The findings of the study revealed that an increase in the mean stress level led to cyclic softening of the material.

Moore and Williams [25] conducted a thorough investigation into the fatigue characteristics and microstructural properties of a printed elastomer material. Their study focused on establishing a correlation between elongation and the anticipated fatigue life. Interestingly, their findings revealed that opting for a smoother surface finish, specifically the "glossy" option without support encasement, in PolyJet parts enhances the durability of the components. Mura et al. [26] conducted a study delving into the fatigue characteristics of polymers, namely ABS and PC-ABS, across a range of different temperatures. Their investigation centered on the impact of elevated and reduced temperatures on the material's fatigue behavior. The findings of their results revealed a substantial adverse influence imparted by elevated temperatures on fatigue performance. Conversely, a marginal positive impact might be realized under low temperatures.

Amjadi and Fatemi [27] undertook an extensive exploration into the multiaxial fatigue characteristics of diverse thermoplastics, encompassing high-density polyethylene (HDPE), polypropylene (PP), neat polyamide 66 (PA66), and PA66 augmented with short glass fibers. The investigation examined the effects of mean stress and stress concentration on the multiaxial fatigue behavior, concurrently offering analytical models to account for these effects. Shanmugam et al. [28] conducted an extensive examination of the fatigue performance exhibited by polymer-based materials manufactured using fused deposition modeling (FDM). Their study emphasized the significant impact of printing parameters and material properties on the fatigue properties of these materials. Wang et al. [29] conducted an analysis of the fatigue failure of thermoplastic polyurethane (TPU) under tension–tension load control tests and examined the change in hydrogen bond content. The S–N curve of TPU material exhibited a downward trend before reaching the fatigue limit, with fatigue fracture resulting from an increase in microphase separation and the aggregation of micropores on the material surface.

Additionally, numerous authors investigated the fatigue of thermoplastics composites, see, for example, [30–36]. Fotouh et al. [37] investigated the fatigue behavior of hemp-fiber-reinforced high-density polyethylene (HDPE) composites using fatigue life (S–N) curves at different fiber volume fractions. To anticipate the fatigue characteristics of natural fiber composites under varying fiber fractions, fatigue stress ratios, and moisture absorption conditions, a comprehensive model is formulated [38]. This model encompasses a generalized approach to capture the fatigue behavior exhibited by these composites. Jeannin et al. [38] address the ongoing gaps in understanding the high-cycle fatigue strength of plant fiber composites, as existing studies have been limited to 1–2 million cycles with linear stress-life trends. They investigate flax-epoxy laminated composites, employing high-frequency loading (30 Hz) to assess behavior over 10^6–10^8 cycles. Findings indicate a persistent fatigue damage progression and decreasing stress with cycles. Mejri et al. [39] developed a novel composite composed of high-density polyethylene (HDPE) matrix with short birch fibers (SBF) as a prospective substitute for high-performance polyamides in gear production. Through comprehensive mechanical evaluations involving 3-point flexural quasi-static tests, the HDPE composite containing 40 wt.% SBF demonstrated superior tensile and flexural properties compared to both PA11 and neat polyethylene. Moreover, fatigue tests revealed an elevated high-cycle fatigue strength (HCFS) for the HDPE-SBF composite compared to PA66 and ultra-high molecular weight polyethylene (UHMWPE), thus presenting a promising alternative for Nylon in the manufacturing of spur gears.

Fatigue Modeling of Polymers

Suresh [7] postulates that the rate of temperature rise $\mathrm{d}T/\mathrm{d}t$ during cyclic loading, influencing the mode of failure, is determined by the equation:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\mathrm{D}''\sigma_\mathrm{a}^2}{\rho c_p}\frac{f}{AV} + \frac{H}{\rho c_p}(T - T_0), \qquad \text{(Eq 1)}$$

where t represents time, f is the frequency, D'' is the loss compliance, σ_a is the stress amplitude, ρ is mass density, c_p is specific heat, A and V denote specimen surface area and volume, respectively, H represents the coefficient of heat transfer by convection, and T and T_0 signify the instantaneous specimen temperature and ambient temperature.

Constable et al. [40] conducted a study to investigate the fatigue failure mechanism of cyclic thermal softening in thermoplastics. They proposed a model that incorporates the influence of specimen compliance and the magnitude of cyclic load on thermal softening. The investigation specifically focused on studying the cyclic bending behavior of samples made of polymethylmethacrylate (P.M.M.A.) and polyvinylchloride (P.V.C.). Rittel [41] conducted an investigation into the conversion of mechanical energy to heat, denoted as β_int, during high strain rate deformation of glassy polymers, specifically focusing on polycarbonate (PC). The study revealed a dependence of the conversion factors, β_int and the rate of conversion, β_diff, on both strain and strain rate. The author concluded that while the overall ratio of converted energy (β_int) remained below 1, the rate ratio (β_diff) could exceed 1 at higher strain rates. This phenomenon was attributed to the reduction in stored energy from cold work and its subsequent transformation into heat.

Janssen et al. [42] presented a 3D constitutive model that accurately predicts the lifetime of polycarbonate under both constant and cyclic loading conditions, considering factors like molecular weight, thermal history, and physical aging. The model incorporates the influence of physical aging and proposes an extension for low cycle fatigue to properly describe energy dissipation. Chandran [43] demonstrated that a continuum-based approach can be used to characterize the mechanical fatigue fracture of polymers, with a specific focus on the macroscopic crack growth mechanism. The study found that the fractional remaining fatigue life of a polymer specimen is related to the fractional size of the remaining uncracked section, including the intact craze length. The constitutive equation was expanded to account for mean stress effects, enabling the prediction of stress-life behavior and endurance limit solely from the S–N behavior of fully reversed fatigue data. Hur et al. [44] investigated the physical and mechanical characteristics of pure polypropylene (PP) and glass fiber-reinforced PP composites (GF–PP) using activation energy and tensile experiments. They introduced three new models derived from the Zhurkov model calibration to enhance the precision of fatigue life predictions. Additionally, they developed a modified strain rate model that accounts for physical parameter dependencies, aligning well with projected fatigue life outcomes.

Spandan and Philippe [45] proposed the application of a bi-linear cohesive zone model for the simulation of fatigue crack propagation in polymers, considering a range of applied stress intensity factors. The cohesive model was incorporated into a cohesive-volumetric finite element framework, enabling the simulation of diverse fatigue fracture scenarios. Ding et al. [46] simulated Paris regime fatigue crack growth in polymers using a numerical procedure based on the assumption that crack extension is controlled by the plastically dissipated energy in the plastic zone around the crack tip. The approach was applied to generate numerical Paris regime curves, which were then contrasted with empirical findings for two categories of polymers: those demonstrating frequency-dependent fatigue crack propagation and those displaying frequency-independent fatigue crack propagation. Strong concurrence was observed between the computed and observed rates for both polymer classifications.

Akano et al. [47] proposed a continuum damage mechanics (CDM) model to assess the fatigue life of polymeric compliant mechanisms subjected to random varying stress cycles. The model considers the elastic strain energy based on a nearly incompressible hyperelastic constitution and uses a damage evolution equation to describe the fatigue life as a function of the nominal strain amplitude. Experimental and simulation results show a strong agreement with the predictions from the proposed model, validating its effectiveness in evaluating the fatigue life of compliant mechanisms.

The significance of investigating the fatigue behavior of materials has been established in previous literature, providing the impetus for the present research. In this study, a novel and simplified test rig was designed specifically for conducting uniaxial tensile fatigue tests on polymeric materials. Two different materials, namely polyvinyl chloride (PVC) and high-density polyethylene (HDPE), were selected for investigation. Fractography analysis was employed to analyze the fracture surfaces and identify fatigue failure mechanisms. Following this introduction, "Experimental Work" section of this paper provides a detailed account of the experimental procedures employed in this study. This includes a comprehensive description of the test rig design, as well as the selection and preparation of the PVC and HDPE samples utilized in the fatigue experiments. "Results and Discussion" section presents the obtained fatigue results and provides a thorough analysis and discussion of the observed trends and phenomena. Finally, the key findings derived from the experimental investigations and analysis are summarized in the Conclusion section.

Experimental Work

In this section, the details of the experimental work conducted in this study are described. This includes information about the materials used, the test samples, the design and construction of the test rig, and the testing parameters and conditions under which the experiments were performed. The materials and test samples are characterized in terms of their mechanical and physical properties, and the test rig is described in terms of its design and capabilities. The testing parameters and conditions are discussed in detail, including the stress amplitude, mean stress, and frequency of loading.

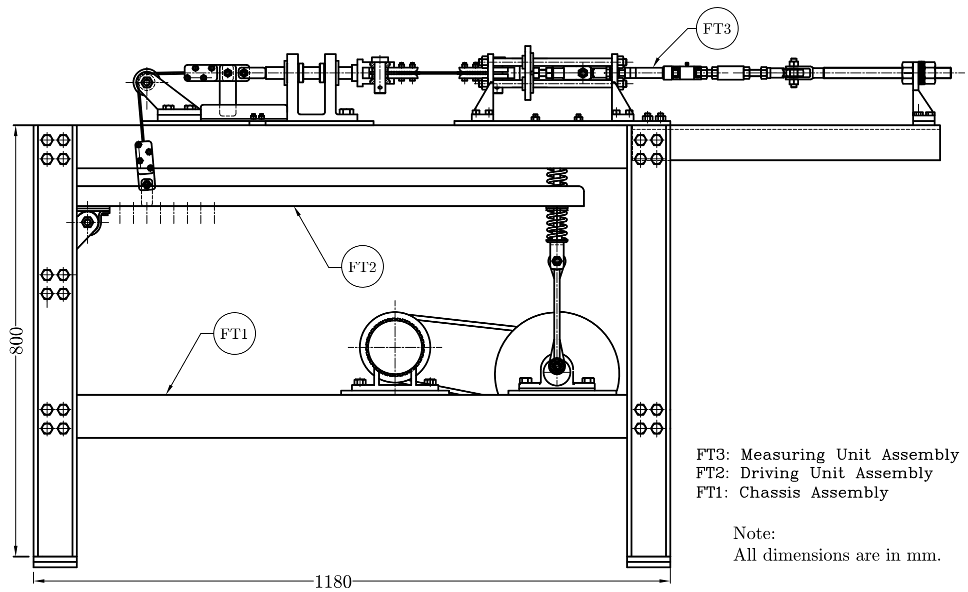
Fatigue Test Rig

A custom-designed apparatus was developed locally to conduct tension/tension fatigue tests, with the capability for simple modification to perform flexural fatigue tests. The apparatus was specifically designed for constant mean stress fatigue testing. It can be classified into four main modules: the chassis assembly, which accommodates the other modules of the fatigue tester; the driving module, responsible for generating the fundamental sinusoidal motion; the test module, allowing for the adaptation of loading and environmental conditions; and the data acquisition module, consisting of strain and force measuring units that feed data to a computer for stress calculation and plotting over time or number of cycles. The overall configuration of the fatigue tester is depicted in Fig. 1a and b.

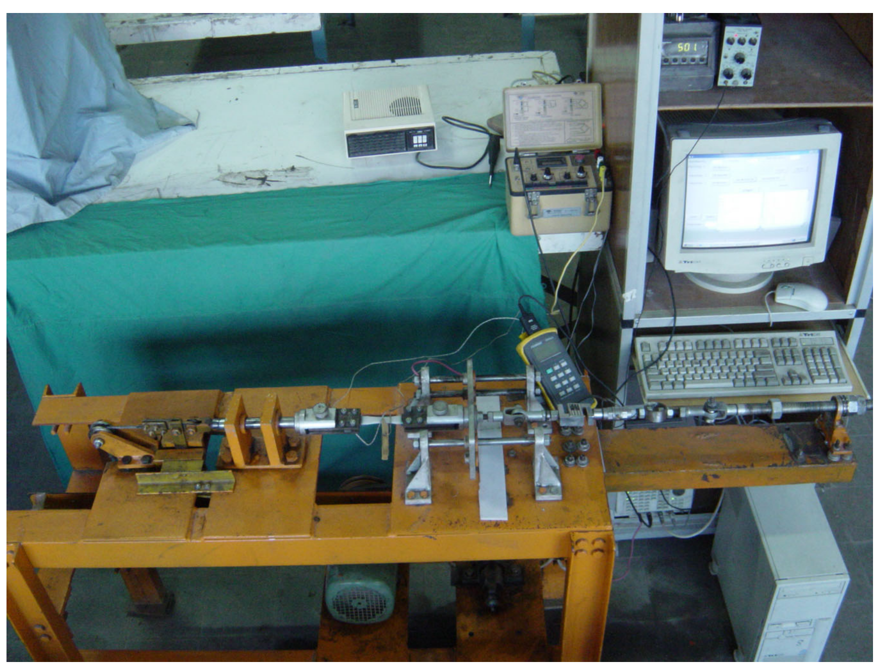
To investigate the fatigue behavior of the tested polymers, various parameters including force, number of cycles to failure, and temperature were measured. The measurement setup, as depicted in Fig. 2, encompassed the measurement of cyclic force parameters using two methods with three sensors. The average of the two methods was taken for analysis.

The first method involved the utilization of a KIAG SWISS 9301 B piezoelectric force transducer and an LFS-210 S beam load cell, as shown in Fig. 2. The piezoelectric force transducer was connected to a charge amplifier, and the analog output from the amplifier was directly monitored using a Yokogawa DL1200 digital oscilloscope. It

Fig. 1 Fatigue test rig (**a**) Schematic front view (**b**) Real photograph



(a)



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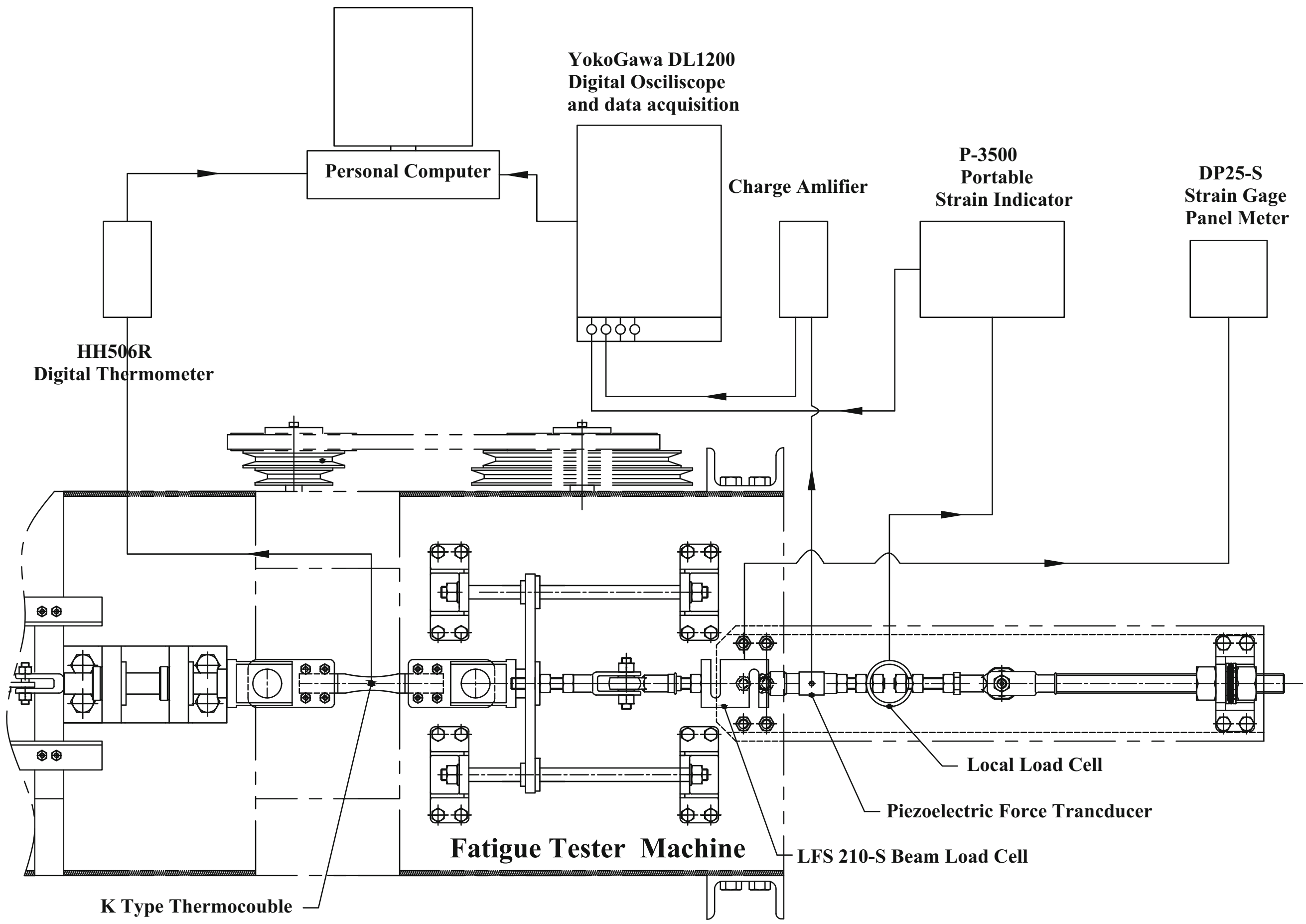

Fig. 2 Fatigue tester measurement setup

should be noted that the piezoelectric transducer solely measured load variations and was incapable of measuring mean stress. Therefore, the LFS-210 S beam load cell was employed specifically to measure the mean stress.

The second method involved a locally manufactured strain gauge load cell, as illustrated in Fig. 2. It consisted of an elastic thick cylindrical steel tube with two tightly fixed bolts. A Kyowa dynamic strain gauge was affixed to the surface of the tube and connected to a P-3500 portable strain meter. Through initial calibration, the strain readings obtained from the gauge were calibrated to the corresponding applied forces. The strain meter was connected to Yokogawa DL1200 digital oscilloscope to monitor the dynamic strain in the tube. The measurement of force was determined by calibrating the measured strain with known force values using a calibrated load cell. To ensure accurate load readings, the load cells were mounted in a manner that minimized the influence of side forces.

Fatigue Samples

In this investigation, unnotched specimens were employed to assess the endurance characteristics of the examined polymers, as depicted in Fig. 3 and referenced in [48]. The analysis considered fatigue failure, incorporating contributions from both crack initiation and crack propagation mechanisms. The chosen specimen geometry, as shown in Fig. 3, yields a stress concentration factor of 1.04, computed using the graphs outlined in Peterson [49]. This value aligns with recommendations from earlier studies, such as those by Owen [50] and Turner [51]. Furthermore, the specimen was statically modeled using the finite element method implemented in the ANSYS software package. A mesh consisting of 9060 elements was generated for the sample. Uniaxial loading of 1400 N was applied to the specimen. The stress distribution within the specimen was analyzed using the finite element method, and it was observed that the maximum stress occurred at the center, measuring 34.596 MPa, see Fig. 4. Comparatively, the theoretical stress was calculated based on the minimum

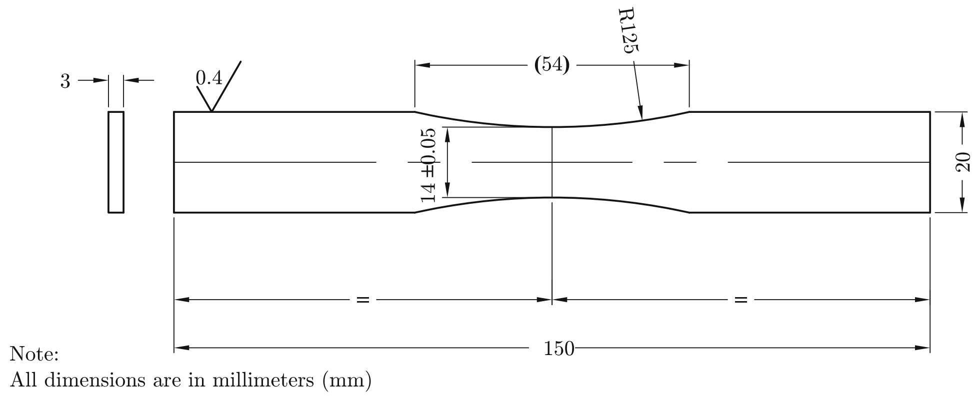

Fig. 3 Tensile fatigue test specimen considered in this work [48]

Table 1 Physical and mechanical properties of tested polymers

Material	Density (gm/cm$_3$)	Max. tensile strength σ_y (MPa)	Elastic modulus E (GPa)	Fracture strength σ_f (MPa)	Yield elongation ϵ_y (%)	Max. elongation ϵ_f (%)
HDPE	0.93	28.4	0.61	14.4	9	218*
PVC	1.33	52.5	2.8	30.4	4.7	15.7

*None of the HDPE specimens broke, and the maximum percentage elongation recorded does not represent the true value of maximum percent elongation. Instead, it represents the maximum elongation obtained until the universal testing machine automatically stopped

cross-section area and the applied load, yielding a value of $(1400/(3 \times 14) = 33.33$ MPa. This result indicates that a stress concentration of only 1.037 exists, which falls within an acceptable range as discussed previously.

The specimens were cut from a 3 mm sheet of each material in the longitudinal direction. Machining was accomplished using a sharp cutting tool and appropriate speed and feed to achieve a good finish with minimal heating of the specimen. The test specimens were polished with successively finer emery paper, finishing with emery paper Number 600 to remove all scratches and tool marks. Final polishing was performed lengthwise of the specimen to avoid transverse scratches that could lower the fatigue strength. All polishing was done by hand and with light pressure in accordance with references [52, 53], to prevent heating.

Sample Materials

The materials used in this investigation were an amorphous polymer PVC and a partly crystalline polymer HDPE with properties given in Table 1.

Experimental Parameters and Test Conditions for Fatigue Evaluation

Fatigue tests were conducted on two materials, namely PVC and HDPE, under various test conditions involving mean stress and cyclic frequency. HDPE samples were subjected to different mean stresses (11, 13, 15, and 17 MPa) and frequencies (8.33, 12.5, 15.5, and 20.5 Hz). Similarly, PVC fatigue samples were tested under different mean stresses (22, 27, 32, and 36 MPa) and frequencies (8.33, 12.5, 15.5, and 20.5 Hz). Following the fatigue tests, the failed specimens were carefully examined and subjected to detailed investigation.

Results and Discussion

Based on the previous work conducted on HDPE and PVC specimens [54, 55], it was observed that the fatigue lifetime of the polymers is significantly influenced by the mean stress and stress amplitude, while the frequency of load variation within the tested range had a negligible effect. Increasing the stress amplitude and/or mean stress resulted in a reduction in the fatigue lifetime of the polymers.

The present study's results indicated that the failure mode of the specimens depended on the polymer type, mean stress, stress amplitude, and frequency of the applied load. Visual examination of the failed HDPE specimens presented in Fig. 5 revealed that at high stress amplitudes, the failure mode exhibited typical thermal failure characteristics, such as softening. This behavior can be attributed to the rapid temperature rise, which is proportional to the square of the stress amplitude, as described by Eq 1. Thus, an increase in stress amplitude leads to a significant temperature rise in the specimen, resulting in thermal failure. Decreasing the stress amplitude while maintaining or increasing the mean stress promoted creep failure. It should

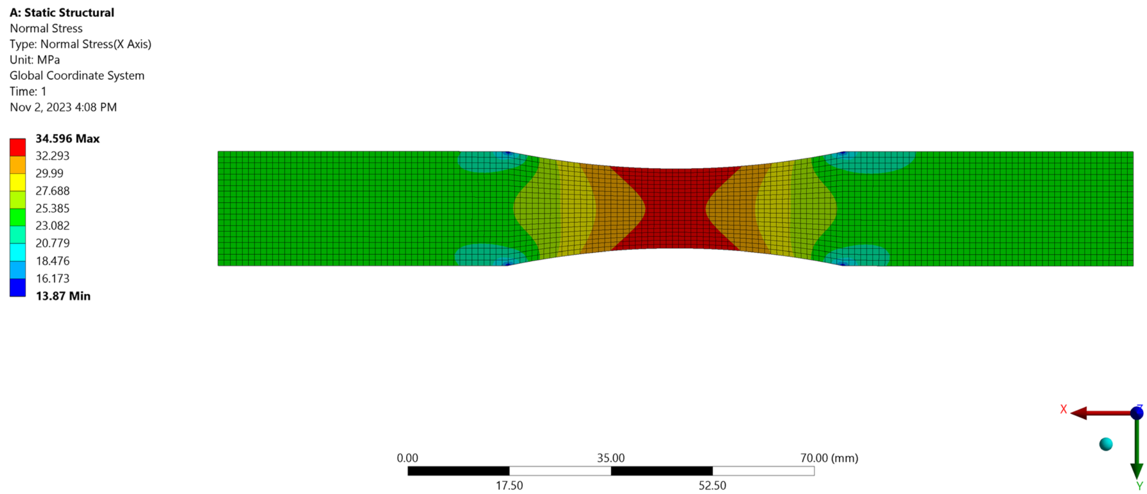

Fig. 4 Tensile fatigue test specimen stress distribution

Fig. 5 Effect of stress amplitude of HDPE, under mean stress σ_m = 15 MPa and frequency =12.5 Hz

be noted that fatigue failure was not observed in any of the tested HDPE specimens.

Figure 6 illustrates the failed PVC specimens tested under constant mean stress and variable stress amplitude. At high stress amplitudes, the failure mode tended to be ductile failure, characterized by softening, necking, and an increase in specimen temperature. As the stress amplitude decreased, the specimens exhibited fatigue failure, with crack initiation and propagation leading to failure accompanied by a slight change in the cross-sectional area. Further decreasing the stress amplitude resulted in creep failure, particularly at relatively high mean stress levels.

The present test apparatus is designed to maintain a constant stress amplitude in its loading configuration. Elevated stress amplitudes induce thermal softening failure, consistent with existing literature. The elevated damping and diminished thermal conductivity characteristics inherent to polymers amplify the susceptibility to thermal failure as temperature escalates over time [6, 7].

The contrast in thermal failure behavior between HDPE and PVC can be attributed to their distinct glass transition

Fig. 6 Effect of stress amplitude on PVC under mean stress = 36 MPa and frequency =12.5 Hz

temperatures and viscoelastic properties. The notably low glass transition temperature of HDPE, approximately −120 °C, renders it soft and viscous at room temperature, making it prone to thermal softening failure with increasing temperature. In contrast, PVC, with a higher glass transition temperature around 85°C, behaves in a brittle manner at room temperature. Elevated temperatures nearing or surpassing the glass transition temperature cause PVC to soften, displaying ductile behavior with necking prior to fracture—a phenomenon corroborated by prior studies on polycarbonate with a glass transition temperature of approximately 150 °C [20].

Creep failure in both HDPE and PVC can be attributed to mean stress under cyclic loads. Polymer failure due to creep under constant stresses is evident even at room temperature, making it likely for mean stress to significantly dictate creep failure under cyclic loads, particularly at low stress amplitudes and high mean stresses.

Thus, the combined influences of mean stress and stress amplitude dictate polymer failure mode and lifetime (cycles to failure). The stress amplitude-to-mean stress ratio plotted against the number of cycles to failure, with mean stress as a parameter, is depicted in Figs. 7 and 8 for HDPE and PVC, respectively. These graphs portray the general trend of decreased polymer lifespan with an increased stress amplitude-to-mean stress ratio. Detailed examination of the tested specimens reveals distinctive failure modes, as symbolically indicated in Figs. 7 and 8. HDPE specimens

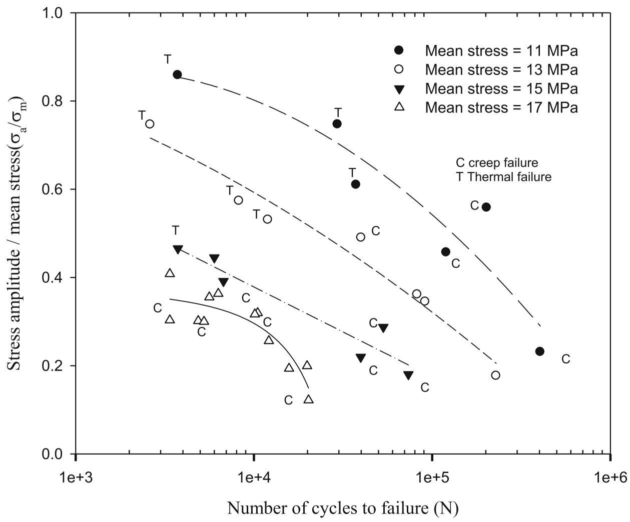

Fig. 7 (Stress amplitude/mean stress) vs. number of cycles to failure for HDPE specimens at different values of mean stresses and frequency =12.5 Hz

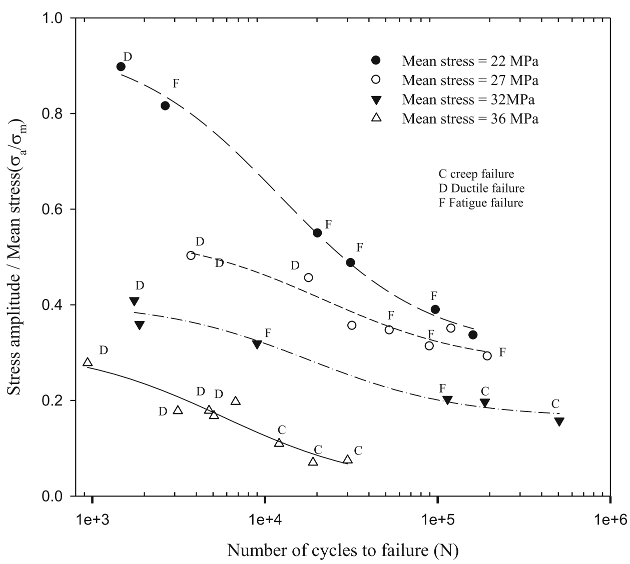

Fig. 8 (Stress amplitude/mean stress) vs. number of cycles to failure for PVC specimens at different values of mean stresses and frequency = 12.5 Hz

in Fig. 7 predominantly exhibit thermal failure at high stress amplitude-to-mean stress ratios. This is accompanied by significant increase in the specimen temperature which can reach up to 52 °C. A view of the failed section is shown in Fig. 11f. Figure 11 represents the optical microscopy of the samples fractured surface, see, for example, [56]. However, at lower ratios, mean stress plays a more influential role, leading to anticipated creep failure as shown in Fig. 5 top sample. In PVC specimens in Fig. 8, high stress amplitude-to-mean stress ratios induce ductile failure through softening and necking, see Fig. 6 lower sample and Fig. 11d. However at lower ratios, fatigue failure due to

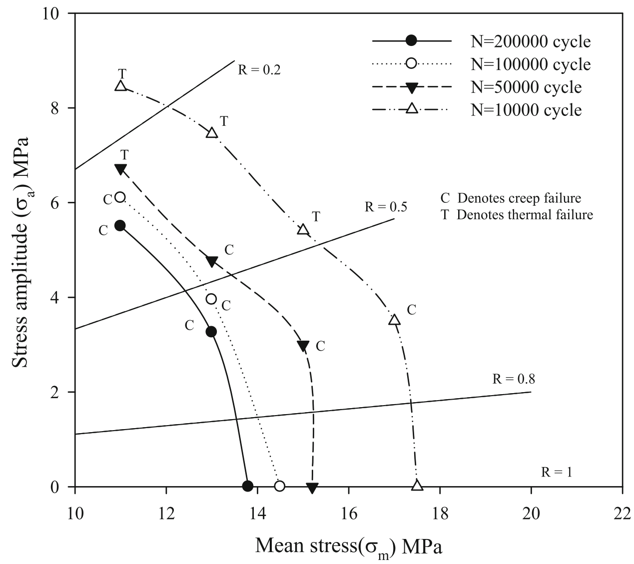

Fig. 9 Constant life diagram for HDPE at frequency = 12.5 Hz

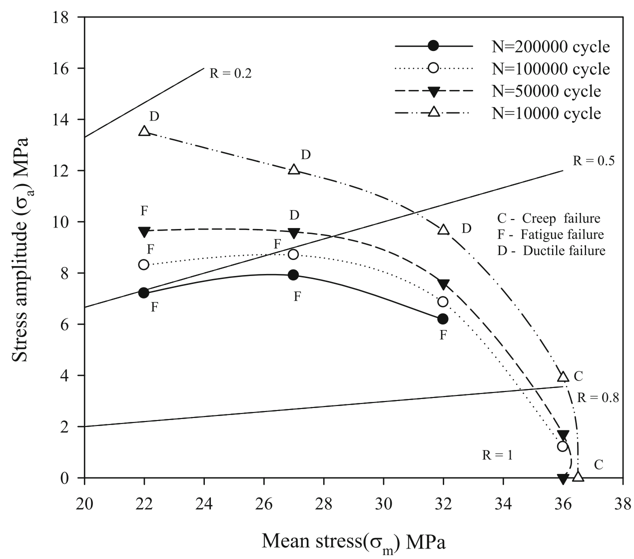

Fig. 10 Constant life diagram for PVC at frequency = 12.5 Hz

craze or crack initiation and propagation becomes the dominant mode, see Fig. 11a–c. Exceptionally low stress amplitude-to-mean stress ratios result in creep failure through significant plastic deformation, see Figs. 11e and 6 top sample.

The relationship between mean stress and stress amplitude is commonly represented by constant life diagrams, as shown in Figs. 9 and 10 for the tested HDPE and PVC specimens, respectively. These diagrams confirm that for a specified number of life cycles, the mean stress must be reduced as the stress amplitude increases to ensure that specimens do not fail within these life cycles. Beyond these life cycles, the specimens would fail by a mode dependent on the maximum to minimum stress ratio *R*. For HDPE specimens, thermal failure increases with increasing stress ratio R, while creep failure is the main failure mode at low R values. For PVC specimens, ductile failure is observed at low R values, while fatigue failure is the dominant mode at higher R values, see Fig. 11a, e respectively for the fractography of such failures. At high R values, creep failure dominates for both materials. It should be noted that the results at a stress ratio of unity (R=1) were obtained from experimental data carried out on a creep test rig at times equal to that necessary to give the same number of cycles as the test frequency.

Figures 12 and 13 elucidate the influence of load frequency on the failure modes of the examined HDPE and PVC materials, respectively. As evidenced in Fig. 12,

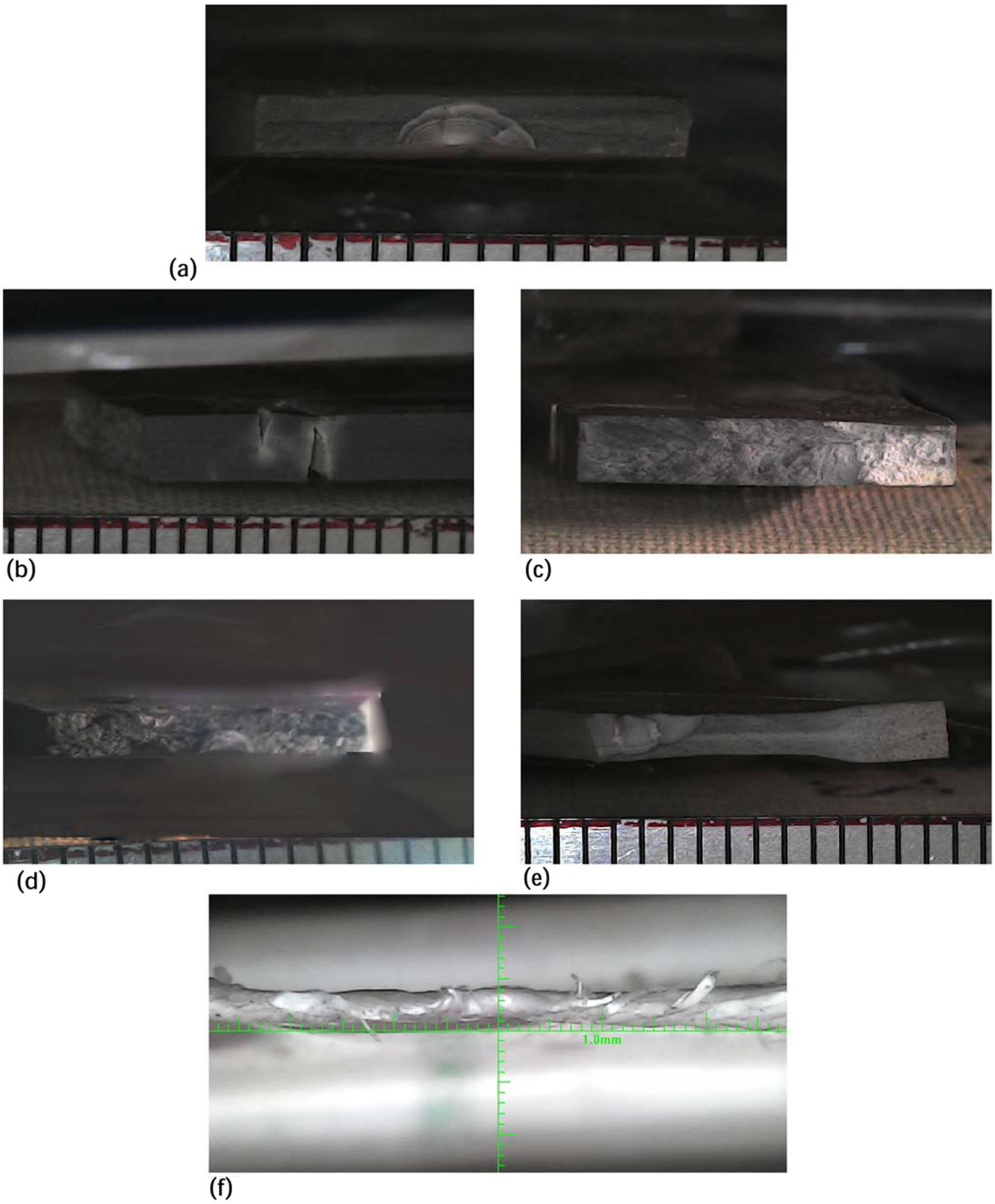

Fig. 11 Samples fractography of the failed specimens (**a**) PVC Fatigue central crack, (**b**) PVC side view of fatigue side crack, (**c**) PVC fracture surface sample in (**b**), (**d**) PVC ductile fracture, (**e**) PVC creep fracture, (**f**) HDPE thermal failure

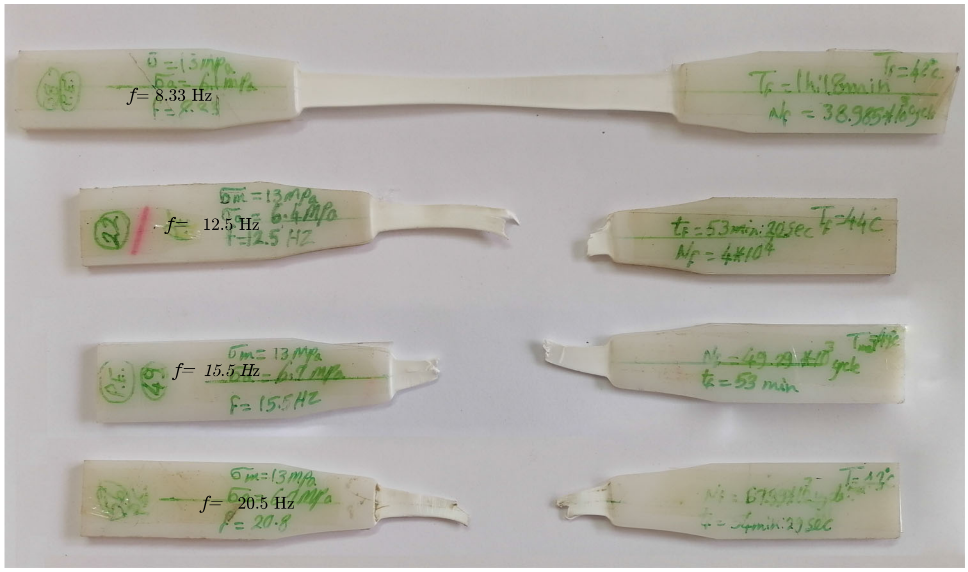

Fig. 12 Effect of load frequency on tested HDPE under $\sigma_m = 13$ MPa and $\sigma_a = 6$ MPa

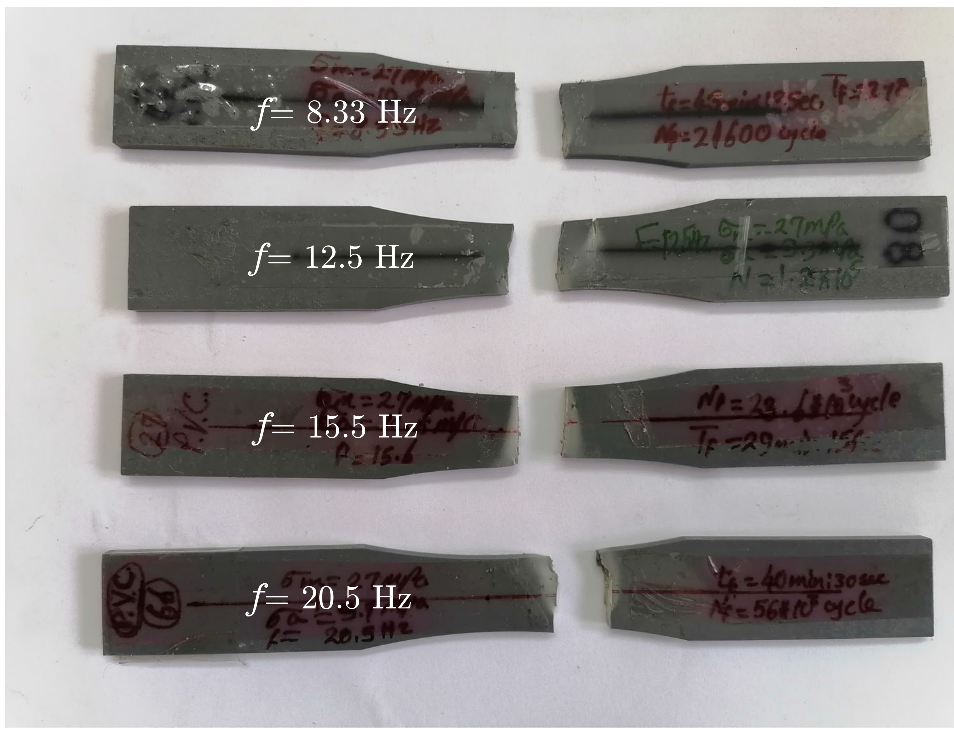

Fig. 13 Effect of load frequency on tested PVC under $\sigma_a = 27$ MPa and $\sigma_a = 10$ MPa

when σ_m is held at 13 MPa and σ_a at 6 MPa, HDPE specimens display thermal softening failure at high frequencies (20.5 and 15.5 Hz), attributable to temperature elevation caused by the pronounced damping and limited conductivity of polymers, as earlier mentioned. A reduction in frequency intensifies the inclination toward creep failure in HDPE specimens. On the other hand, as shown in Fig. 13 with σ_m set at 27 MPa and σ_a at 10 MPa, the failure mode for PVC alters with frequency variation. At high frequencies (20.5 and 15.5 Hz), PVC transitions from softening-induced ductile failure to fatigue failure at lower frequencies (12.5 and 8.3 Hz).

Conclusion

In this paper, the fatigue behavior of two polymeric materials, HDPE and PVC, was investigated using a simple, locally manufactured fatigue tester. The experimental tests conducted on these specimens under constant stress fatigue loading provided significant insights into the factors influencing failure mode. For polymeric materials subjected to cyclic loading, the primary factors influencing failure mode include stress parameters such as stress amplitude, mean stress, and frequency, as well as crucial material attributes such as the glass transition temperature.

Polymers with an exceedingly low glass transition temperature, such as polyethylene, predominantly succumb to thermal and creep failures depending on the specific stress conditions. Notably, fatigue failure in the form of craze initiation and propagation does not manifest in these instances. Conversely, glassy polymers with relatively elevated transition temperatures, such as polyvinyl chloride, exhibit a broader range of failure modes under cyclic loads, ranging from ductile to fatigue to creep failures, dictated by the specific stress conditions.

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Conflict of interest The authors declare that they have no conflict of interest.

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