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ARTICLE

Ultimate Strength Evaluation of Urban Underground UPVC Pipelines Considering Effects of High-Temperatures

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ABSTRACT: The outstanding performance of unplasticized polyvinyl chloride (UPVC) has led to its widespread use in urban underground pipeline systems. However, understanding the effects of high-temperature industrial wastewater on the buried pipes is very complicated. To investigate the influence of industrial wastewater on the safety of pipes, the mechanical properties were tested using the material specimens. The changes in mechanical properties caused by the environmental temperature and heat cycles were experimentally analyzed. Empirical formulas to predict the mechanical parameters of UPVC pipe material were proposed. The ultimate strength of underground urban pipes was numerically studied by the parametric analysis. Results show that the maximum stress and ductility of UPVC pipe material decrease significantly as the ambient temperature and heat cycle increase. The ultimate strength of the underground pipe decreases exponentially with the increase in the ambient temperature. Both the temperature amplitude and the number of heat cycles have significant influences on the performance of the underground pipes.

KEYWORDS: Ultimate strength; polyvinyl chloride; urban pipes; high-temperature; industrial wastewater; mechanical-property

1 Introduction

Unplasticized polyvinyl chloride (UPVC) pipes are widely used in the urban underground pipeline networks due to many advantages, such as light weight, corrosion resistance, excellent mechanical performance, and economic efficiency [1–5]. However, in-service urban underground pipeline systems are continuously exposed to complex and extreme environmental conditions, resulting in a gradual decline in their safety and durability. Among all the disadvantageous environmental factors, high-temperature industrial wastewater is a significant threat to the safety and serviceability of the urban underground plastic pipelines [6–9]. For instance, the polyvinyl chloride (PVC) pipes are prone to thermal aging and become brittle under the effect of high temperature, which may lead to excessive plastic deformations, strength reduction, leakage risks, and even collapse of the underground pipe system.

The safety and mechanical behavior of urban underground pipe networks and PVC materials have attracted considerable attentions from many researchers. Recently, Amorim et al. [10] investigated the effect of ambient temperature on the tensile properties of UPVC materials. They reported that the elastic modulus, tensile strength and stiffness correlate with the environmental temperature. Darvishi et al. [11] studied the effect of methanesulfonic acid as a promoter in poly (vinyl chloride) suspension polymerization. They found that the thermal stability, microstructure, and processability of PVC are significantly enhanced. Olowookere et al. [12] proposed coarse-grained models to simulate the intrinsic thermal properties of PVC materials, and the effectiveness of this new model was demonstrated. Jemii et al. [13] conducted an investigation of the load-deflection response of the material used for polymeric pipes, and finite element (FE) models were established to predict pipe material response under the flexural load. It is reported that both the hydrothermal aging and the notching significantly affect the performance of the pipe material. Pyeon et al. [14] studied the mechanical properties of UPVC materials. It was revealed that the UPVC exhibits a rigid solid state at room temperature, and the ductility increases due to the glass transition at temperatures above 80°C. Miranda et al. [15] investigated the effects of aging treatments in urban environments on different polymers. They reported that the microplastic particles change due to environmental aging over time, which may affect material behavior. Deshmukh and Joshi [16] and Wang et al. [17] investigated the effects of additives on the mechanical properties of PVC materials, demonstrating significant improvements in both tensile modulus and strength. Most of the studies mentioned above focus on the mechanical behaviors of PVC materials undergoing different environmental treatments. However, research on the impact of the high-temperature wastewater inside the pipe remains scarce.

To investigate the ultimate strength and mechanical behavior of urban underground pipes and UPVC pipe columns, Musonda et al. [18] studied the performance of reinforced concrete-filled PVC pipe columns under repeated thermal cycles. The residual strength after thermal treatment and load-carrying capacity, ductility, and stress-strain behavior were analyzed. Woldemariam et al. [19] experimentally demonstrated the effectiveness of PVC tubes on the improvement of the structural performance. Nirmala et al. [20] studied the mechanical behavior of flexible UPVC pipes buried in both loose and dense sand backfill. They concluded that the backfill height leads to greater deflection of the buried pipes. Cassa and van Zyl [21] investigated the effect of pressure on the leakage exponent for circular holes in UPVC pipes. It was found that the area of the crack plays a critical role in the orifice equation and the effect of pressure on the leakage exponent is significant in pipes with cracks. Xu et al. [22] experimentally investigated the bearing capacities of UPVC pipes under axial compression. A formulation of the buckling curve was proposed to predict the ultimate strength. Matymish et al. [23] investigated the axial pullout response of a fusible polyvinyl chloride (PVC) main pipe with two service connections. The experiments showed that the service connections significantly increase the axial pullout resistance. These studies mentioned above have focused on the mechanical behaviors of PVC/UPVC underground pipes or columns without considering the effects of elevated temperature environments.

Based on temperature survey results, the high-temperature industrial wastewater is discharged periodically into the underground pipelines. For example, industrial chemical plants in most factories produce waste effluents, which are discharged almost daily after some special operations. The pipeline systems are typically heated rapidly and then gradually cool back to room temperature during discharge events. This study focuses on the effects of high temperatures and heat cycles on the mechanical behavior of pipe materials and structures. For this purpose, two series of tests were conducted to investigate the influences of environmental temperature and heat cycles. Finally, a numerical analysis was performed to evaluate the ultimate strength of underground pipe structures.

2 Mechanical-Property Tests

2.1 Test Material and Specimens

The pipe materials were tested to investigate the influence of high temperatures on their mechanical properties. Table 1 presents the basic properties of the tested material in this study. The pipe material was supplied by ERA Yonggao Co., Ltd. The reported density is 1494 kg/m^3, and the longitudinal reversion rate is 5.0% [24]. The round-clock method test demonstrates that the resistance of the sample material to external blows meets the requirements [25].

Table 1: Basic properties of urban underground UPVC pipes.

Density	Longitudinal Reversion	Thickness	True Impact Ratio (TIR)
1494 kg/m^3	5.0%	4.0 mm	≤10%

The underground pipe is round in shape, which is unsuitable for mechanical testing. In accordance with standard test methods, the pipe was machined into standard plate-shaped specimens [26]. Fig. 1 shows the dimensions of the specimen. The lengths of the grip part and the parallel part are 40 and 80 mm, respectively.

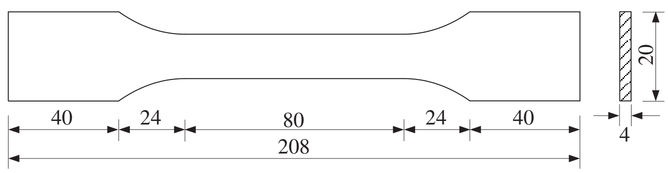


Figure 1: Dimension size of specimen (Unit: mm).

2.2 Test Equipment and Test Methods

The tests were conducted using a servo-hydraulic loading system (UTM-25). The maximum load capacity of this system is 25 kN, and the environmental chamber operates within a temperature range of −15°C to 80°C. Two test series were designed to evaluate the effects of thermal exposure: one under steady temperature conditions, and the other under repeated thermal cycling. In the first test series, different temperature environments were set, i.e., −10°C~80°C with an interval of 10°C. This range was selected based on the surveys, indicating that the highest temperature of the waste effluents in the industrial zone exceeds 75°C. In the second test series, thermal cycling was applied across four temperature ranges, i.e., 20°C~40°C, 20°C~60°C, 20°C~80°C, and 20°C~100°C. The number of cycles was set at 30, 60, 70, 80, and 90 for each case. Fig. 2 illustrates the loading system, a specimen inside the temperature chamber, and the specimens after fracture. The loading rate was set at 1 mm/min, and deformation was recorded using a strain gauge (TZT3827EN-16). The elastic modulus of the material was determined in the linear elastic stage, where the elastic deformation was measured using the strain gauge. The environmental temperature was controlled by the chamber during the first test series, while the preceding operation of temperature cycles in the second tests was carried out using an automatic electric water heater (NP100-10). Each heat cycle lasted about 2 h, including both heating and cooling phases.

Figure 2: Loading system and specimens. (**a**) Loading system; (**b**) Specimen inside temperature chamber; (**c**) Specimens after fracture.

3 Test Results and Discussions

Fig. 3 shows the stress-strain curves of the pipe specimens after being exposed to different temperature environments and temperature cycles, in which σ_0 and ε_0 represent the stress and strain during the monotonic load tests. The stress-strain curve of the pipe material undergoes the elastic stage, the pre-peak strain hardening stage before reaching the peak value. Subsequently, the stress enters a stable stage, where the load remains relatively constant until fracture occurs. The ultimate strength and ductility vary with changes in ambient temperature. Similarly, temperature cycles have a significant impact on the shapes of the stress-strain curves.

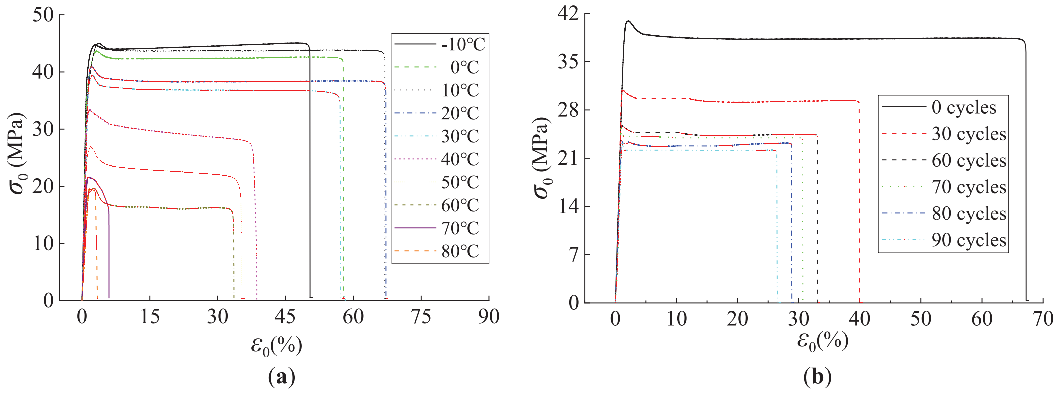


Figure 3: Stress-strain cures of pipe specimens. (**a**) Effects of temperature environment; (**b**) Effects of temperature cycles.

Fig. 4 shows the effects of temperature variations on the mechanical properties of pipe materials, where T and T_m represent the ambient temperature and maximum value during the heat cycles, and E, σ_u, and ε_f represent the elastic modulus, ultimate strength, and fracture strain, respectively. The results reveal that the elastic modulus decreases with increasing ambient temperature and as the number of thermal cycles increases. The fracture strain gets its peak value under the temperature range of 10°C~20°C, which indicates the ductility is better in this temperature range.

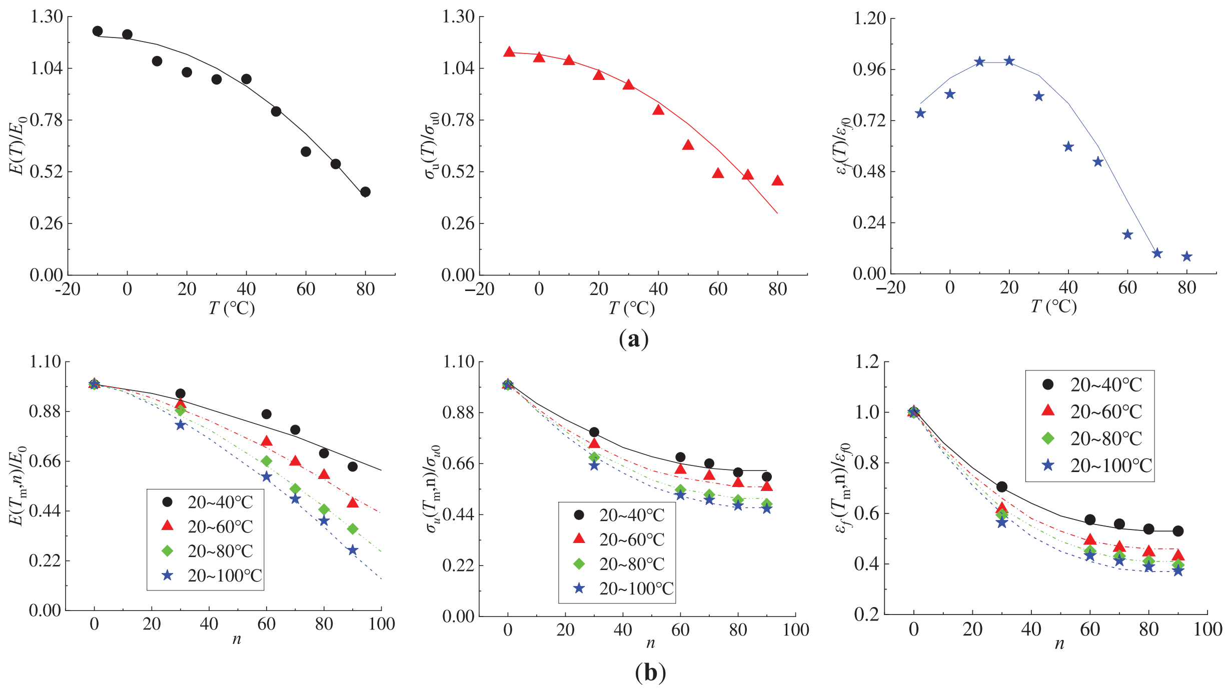


Figure 4: Relations between mechanical parameters and temperature actions. (**a**) Effects of temperature environment; (**b**) Effects of temperature cycles.

Based on the experiments, practical equations can be obtained to predict the constitutive parameters. For the effects of ambient temperature, these equations are proposed as follows.

$$\begin{cases} E\left(T\right)/E_0 = -1.0 \times 10^{-4} \cdot \left(T+10\right)^2 + 1.20 \\ \sigma_u\left(T\right)/\sigma_u = -1.0 \times 10^{-4} \cdot \left(T+10\right)^2 + 1.12 \\ \varepsilon_f\left(T\right)/\varepsilon_{f0} = -3.0 \times 10^{-4} \cdot \left(T-15\right)^2 + 1.00 \end{cases} \tag{1}$$

For the effects of temperature cycles, the mechanical properties are affected both by the maximum temperature (T_m) and the cycle number (n), and therefore, the predictive equations are expressed as follows.

$$\begin{cases} E\left(T_m, n\right)/E_0 = -a \cdot n^{1.4} + 1.00 \\ a = 2 \times 10^{-7}\left(100 - T_m\right)^2 - 1.28 \times 10^{-3} \end{cases} \tag{2}$$

$$\begin{cases} \sigma_u\left(T_m, n\right)/\sigma_{u0} = a \cdot \left(90 - n\right)^{2.2} + b \\ a = -1.1 \times 10^{-10}\left(100 - T_m\right)^{2.8} + 2.7 \times 10^{-5} \\ b = 7.5 \times 10^{-5}\left(100 - T_m\right)^2 + 0.47 \end{cases} \tag{3}$$

$$\begin{cases} \varepsilon_f\left(T_m, n\right)/\varepsilon_{f0} = a \cdot \left(90 - n\right)^{2.5} + b \\ a = -1.5 \times 10^{-11}\left(100 - T_m\right)^3 + 8.2 \times 10^{-6} \\ b = 1.4 \times 10^{-7}\left(100 - T_m\right)^{3.5} + 0.37 \end{cases} \tag{4}$$

In these equations, a and b are empirical coefficients used to fit the experimental data. The application scope of Eqs. (1)~(4) for the prediction of mechanical parameters is as follows: ambient temperature ranges from −10°C to 80°C, and the temperature cycles from an original temperature of 20°C to the highest temperature of 100°C within 90 cycles.

4 Ultimate Strength Evaluation of Underground Pipes

4.1 Numerical Model of Underground Pipes

The ultimate strength of underground pipes was investigated numerically using the experimentally obtained stress-strain relations. The analytical model of pipes was created using the software ABAQUS. Fig. 5 illustrates the FE model of the underground pipe structure. The numerical analysis was conducted using the plane-strain method. The element type of 4-noded plane strain quadrilateral elements with reduced integration (CPE4R) was selected for the simulation, and the size of the element mesh was less than 1.0 mm. The total number of elements was approximately 15,000. Based on a practical engineering project in Hangzhou, the buried depth was set at 4.0 m with silty soil. The aim of this study is to provide an insight to the effect of temperature-induced mechanical-property degradation on the structural behavior of underground pipes. Therefore, only the earth pressure caused by the silty soil and the self-weight of the pipe were considered. The soil pressure acting on the pipe was the product of the buried depth and the gravity density of the soil, and the pressure was applied radially inward. The lateral pressure coefficient of the silty soil was set at 0.34. The diameter (D) and thickness (t) of the underground pipe were 55 and 4 mm, respectively. Static Riks function in the software was adopted for the numerical analysis to predict the ultimate strength of the structure. In order to take all the temperature conditions into account, 10 cases of different temperature environments and 40 cases of thermal cycling scenarios were analyzed. Different constitutive parameters were assigned in each case to reflect the influence of temperature variations.

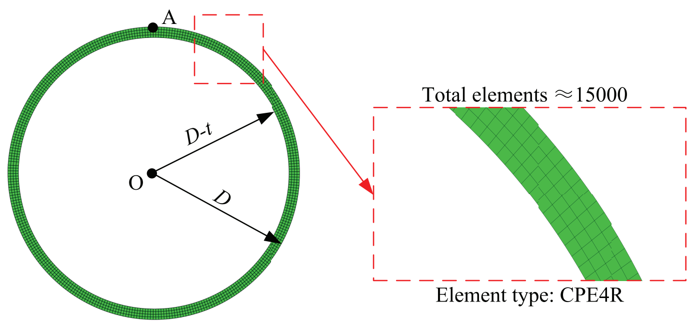


Figure 5: FE model of underground pipe structure.

4.2 Effects of Environment Temperature

Fig. 6 shows the load-displacement curves, ultimate strength, and the deformed configurations of the underground pipes under different temperature conditions. In the figure, p/p_0 is the ratio of the load acting on the pipe and the reference soil pressure, $p_{\max}$ is the ultimate strength of the pipe structure, and d is the vertical displacement of the top point A shown in Fig. 5. It can be seen that the load-displacement curves exhibit two distinct stages. In the ascending stage, the pipe material exhibits approximately linear behavior, transitioning from elastic to plastic deformation. In the descending stage, the strength reduces after its peak value, and in certain scenarios, buckling can be observed. The ultimate strength decreases almost exponentially with increasing ambient temperature. An empirical equation was developed to predict the ultimate strength of the underground pipes.

$$p_{\max}/p_0 = 3.97 - 0.88\exp\left(T/67.34\right) \tag{5}$$

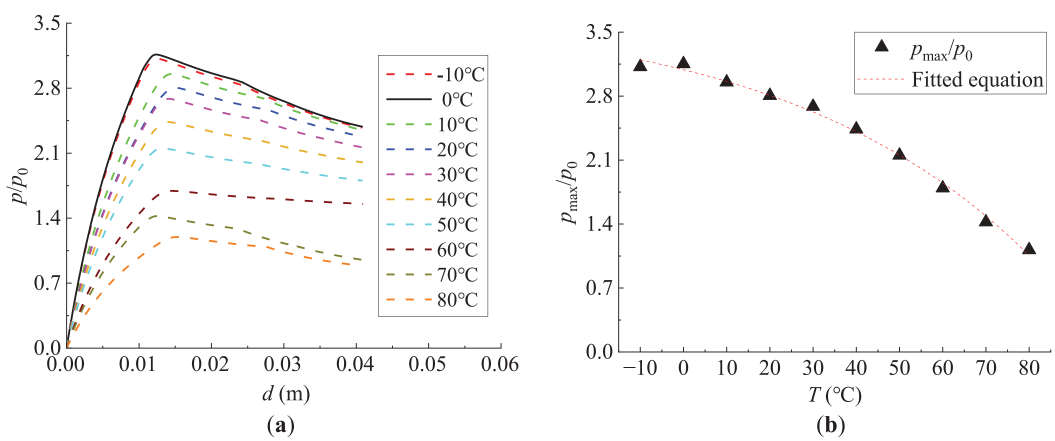
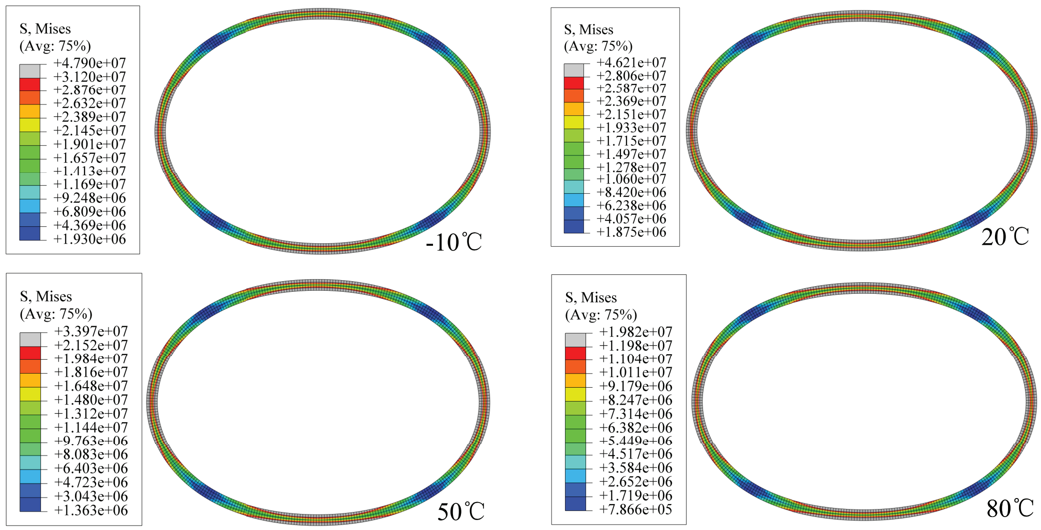


Figure 6: (Continued)

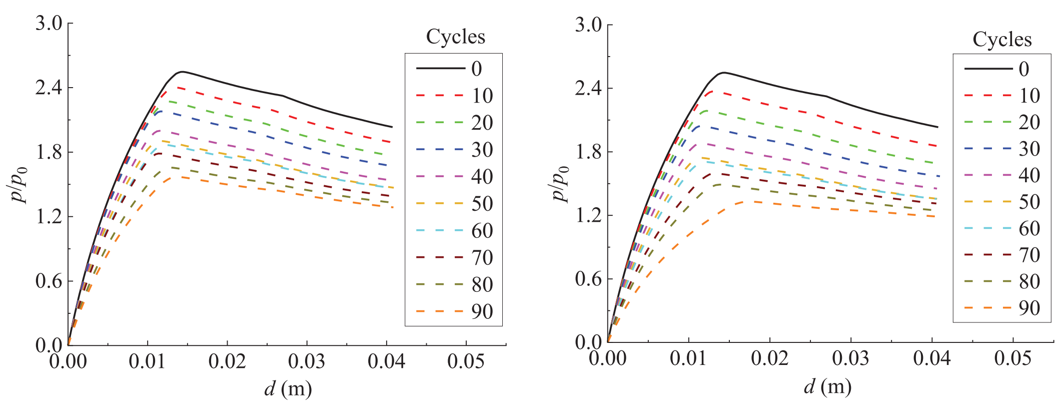


(**c**)

Figure 6: Effects of environmental temperature on underground pipe structure. (**a**) Load-displacement curves; (**b**) Ultimate strength; (**c**) Deformation and stress distribution.

4.3 Effects of Temperature Heat Cycles

Fig. 7 shows the load–displacement curves of underground pipes subjected to different temperature amplitudes and numbers of thermal cycles. The findings suggest that both the temperature amplitude and the number of heat cycles have significant influences on the performance of the underground pipes. Notably, as the maximum temperature in the thermal cycles increases, the reduction in strength becomes more pronounced, highlighting the significant influence of temperature amplitude.



(**a**) (**b**)

Figure 7: (Continued)

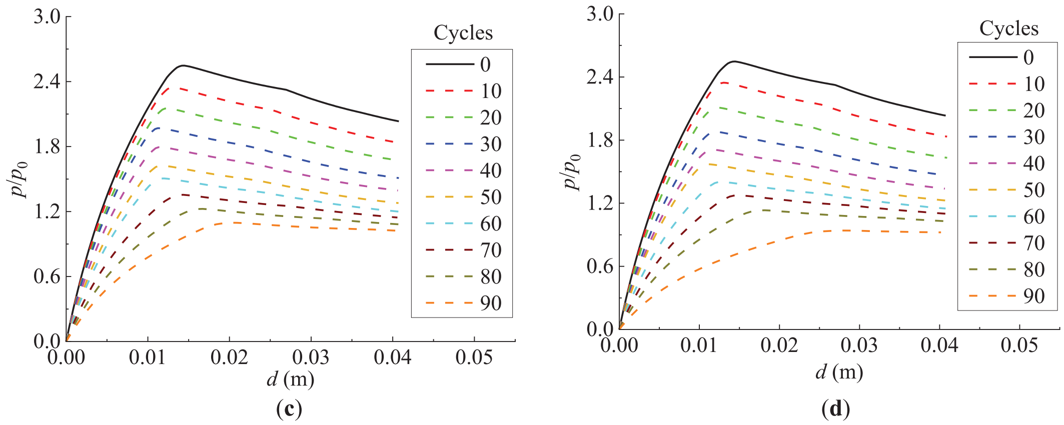


Figure 7: Effects of temperature heat cycles on load-displacement curves. (**a**) Temperature range of 20°C~40°C; (**b**) Temperature range of 20°C~60°C; (**c**) Temperature range of 20°C~80°C; (**d**) Temperature range of 20°C~100°C.

Fig. 8 exhibits the load-displacement curves of the underground pipes that experienced different numbers of temperature cycles. The results show that the maximum load (ultimate strength) decreases as the number of thermal cycles increases, with strength reductions reaching up to 25%.

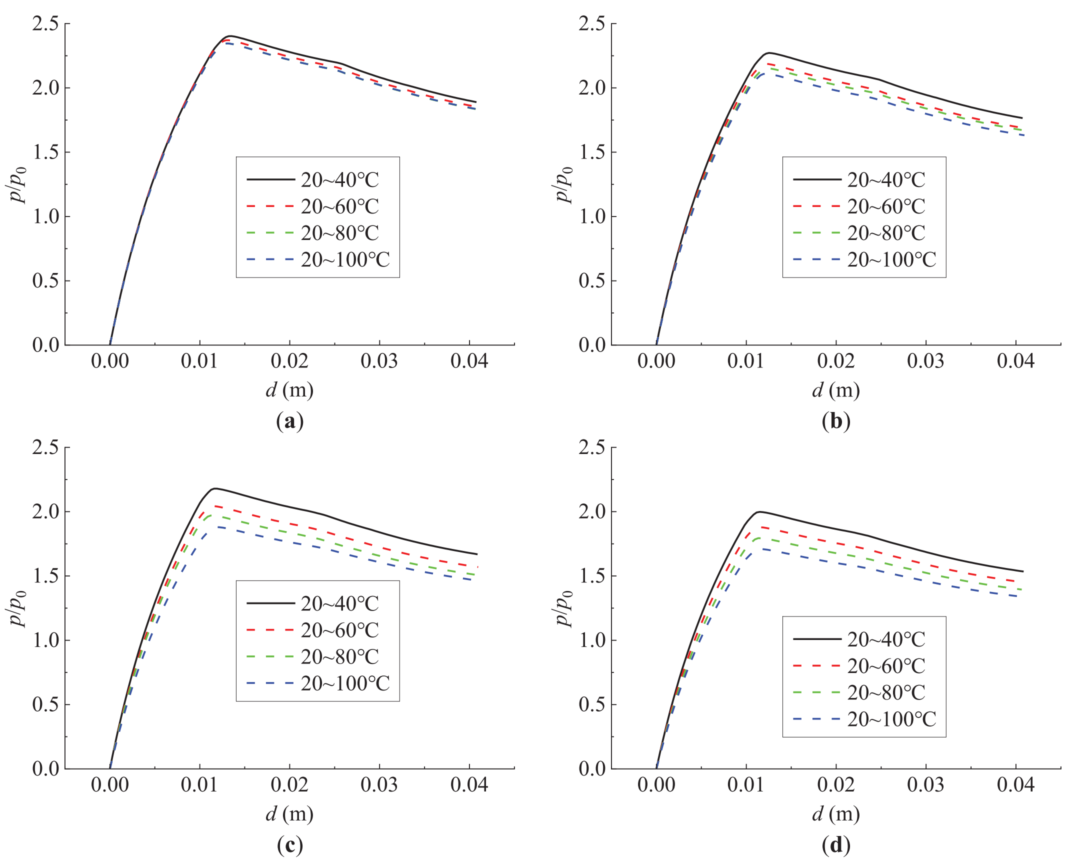


Figure 8: (Continued)

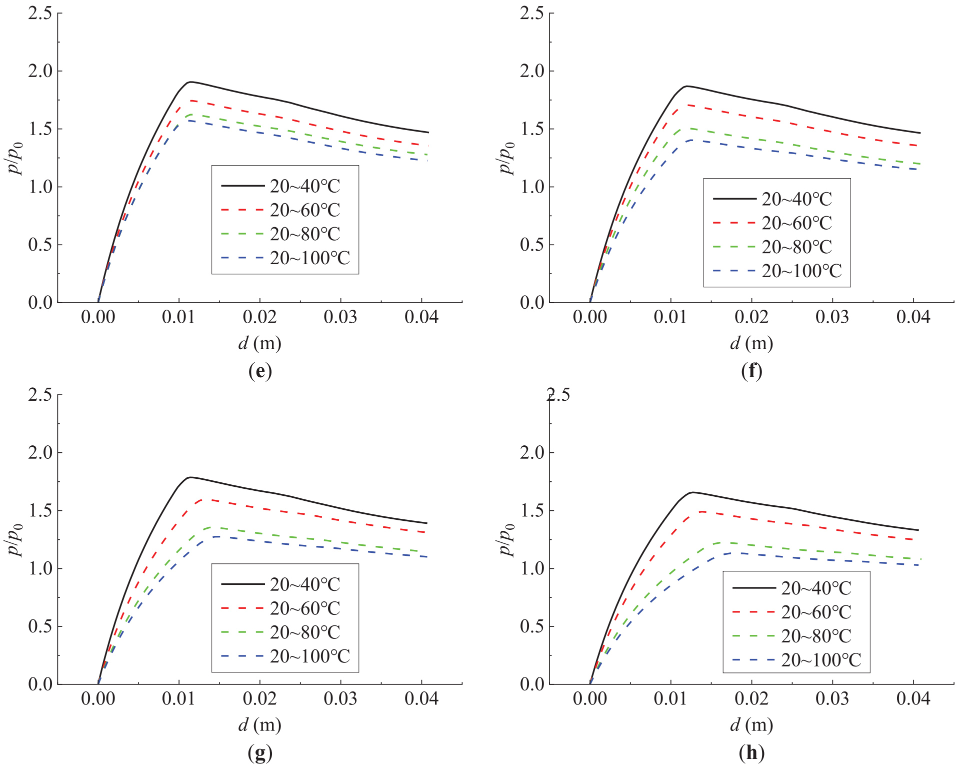


Figure 8: Effects of cycle numbers on load-displacement curves. (**a**) 10 cycles; (**b**) 20 cycles; (**c**) 30 cycles; (**d**) 40 cycles; (**e**) 50 cycles; (**f**) 60 cycles; (**g**) 70 cycles; (**h**) 80 cycles.

The ultimate strength of the underground pipes is further analyzed. Fig. 9 shows the ultimate strength of the underground pipes that underwent different heat cycles and the fitting curves. A linear descent relation is observed between the strength and the temperature range. Moreover, the strength decreases linearly with the number of heat cycles. Based on the parametric analysis, an empirical equation incorporating two independent variables (T_m and n) is proposed:

$$p_{max}\left(T_m, n\right)/p_0 = 2.547 - 1.218n\left(T_m + 55.42\right) \tag{6}$$

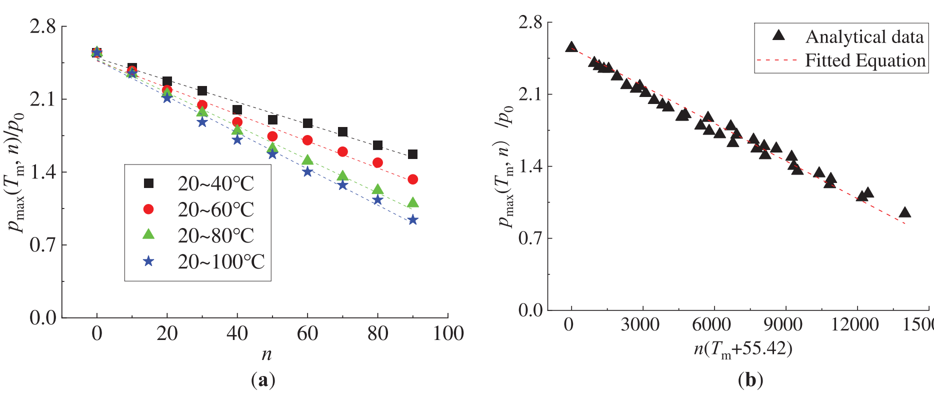


Figure 9: Fitting analysis of ultimate strength. (**a**) Initial fitting analysis; (**b**) Final fitting analysis.

5 Conclusions

In this study, tensile tests were conducted on buried UPVC pipe specimens to investigate the influence of thermal effects on their mechanical behavior. Numerical analysis was conducted to investigate the effect of temperature on the ultimate strength of pipe structures. Practical equations were proposed for predicting material properties and structural ultimate strength. The main conclusions are as follows:

(1) The stress of the pipe material undergoes the elastic stage, the pre-peak strain hardening stage, before reaching the peak value. Subsequently, the stress enters a stable stage, in which the strength remains constant until fracture.
(2) Ultimate strength and ductility vary with changes in ambient temperature. Temperature cycles significantly affect the shape of the stress-strain curves. The elastic modulus decreases with increasing ambient temperature and thermal cycling. Fracture strain reaches its maximum within the temperature range of 10°C to 20°C, indicating enhanced ductility in this range.
(3) In terms of the effect of environmental temperature, the ultimate strength of the underground pipe decreases exponentially with the increase in the ambient temperature. In terms of the effect of temperature heat cycles, both the temperature amplitude and the number of heat cycles significantly affect the performance of the underground pipes.
(4) Practical equations were derived for predicting the constitutive parameters of the pipe material, and empirical formulas were proposed for estimating the strength of the buried pipe structure. The results demonstrate that elevated temperatures considerably affect the safety of buried UPVC pipes. Therefore, it is recommended that factories discharge wastewater only after cooling it down.

This study provides insight into the effect of thermal impact on the safety of in-service buried UPVC pipes. For this purpose, only a simplified load case incorporating temperature effects was considered. Future studies could investigate more complex loading scenarios involving coupled effects of vibration cycles and thermal cycles on the long-term service life of urban buried UPVC pipelines.

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Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Peng G, Feng Y, Huan Y, Zhang T. Characterization of the viscoelastic-plastic properties of UPVC by instrumented sharp indentation. Polym Test. 2013;32(8):1358–67. doi:10.1016/j.polymertesting.2013.08.016.
2. Ran C, Yang B. Plastic deformation and mixed-mode I/II fracture behavior of un-plasticized polyvinyl chloride. Eng Fract Mech. 2020;230:106973. doi:10.1016/j.engfracmech.2020.106973.

3. Alotaibi E, Omar M, Shanableh A, Zeiada W, Fattah MY, Tahmaz A, et al. Geogrid bridging over existing shallow flexible PVC buried pipe—experimental study. Tunn Undergr Space Technol. 2021;113:103945. doi:10.1016/j.tust.2021.103945.
4. Xu S, Zeng Q, Zhao L, Jiang D, Han Y. Experimental and numerical investigation on the axial compressive behavior of UPVC square tubes. Results Eng. 2025;27:105651. doi:10.1016/j.rineng.2025.105651.
5. Kwon JA, Truss RW. The work of fracture in uniaxial and biaxial oriented unplasticised polyvinylchloride pipes. Eng Fract Mech. 2002;69(5):605–16. doi:10.1016/S0013-7944(01)00096-0.
6. Liu X, Zhao J, Ji Y, Yin X, Li Y, Yao F, et al. A novel risk assessment model of urban gas pipeline network in expansions by integrating the OPA method and GraphSAGE algorithm. Process Saf Environ Prot. 2025;195:106849. doi:10.1016/j.psep.2025.106849.
7. Hu Q, Che D, Zhang Q, Zhou J, Wang F, Zhang Z, et al. Improving underground pipeline resilience: prediction and interpretability analysis of urban water distribution network pipe failures during cold waves using machine learning. Tunn Undergr Space Technol. 2025;163:106717. doi:10.1016/j.tust.2025.106717.
8. Niaz F, Bicer Y, El-Sabek L, Amhamed AI. Thermodynamic analysis of pavement roads underground heat harvesting through water pipelines for effective management of urban heat island effect integrated to space cooling applications. Case Stud Therm Eng. 2024;58:104365. doi:10.1016/j.csite.2024.104365.
9. Liu P, Jin Z, Liang J, Liu Z, Chen Z, Chen F, et al. Lifetime prediction and aging mechanism of unplasticized polyvinyl chloride filled with calcium carbonate under long-term thermal and oxidative conditions. Eng Fail Anal. 2024;157:107869. doi:10.1016/j.engfailanal.2023.107869.
10. Amorim FC, Souza JFB, da Costa Mattos HS, Reis JML. Temperature effect on the tensile properties of unplasticized polyvinyl chloride. SPE Polym. 2022;3(2):99–104. doi:10.1002/pls2.10067.
11. Darvishi R, Rezaei SM, Hessari FA. Improving thermal stability and processability of poly(vinyl chloride) via methanesulfonic acid-promoted suspension polymerization. SPE Polym. 2025;6(2):e70008. doi:10.1002/pls2.70008.
12. Olowookere FV, Barbosa GD, Turner CH. Coarse-grained molecular dynamics modeling of polyvinyl chloride: solvent interactions, mechanical behavior, and dehydrochlorination effects. Macromolecules. 2023;56(24):10006–15.
13. Jemii H, Bahri A, Taktak R, Guermazi N, Lebon F. Mechanical behavior and fracture characteristics of polymeric pipes under curved three point bending tests: experimental and numerical approaches. Eng Fail Anal. 2022;138:106352. doi:10.1016/j.engfailanal.2022.106352.
14. Pyeon HB, Park JE, Suh DH. Non-phthalate plasticizer from camphor for flexible PVC with a wide range of available temperature. Polym Test. 2017;63:375–81. doi:10.1016/j.polymertesting.2017.08.029.
15. Miranda MN, Sampaio MJ, Tavares PB, Silva AMT, Pereira MFR. Aging assessment of microplastics (LDPE, PET and uPVC) under urban environment stressors. Sci Total Environ. 2021;796:148914. doi:10.1016/j.scitotenv.2021.148914.
16. Deshmukh K, Joshi GM. Thermo-mechanical properties of poly(vinyl chloride)/graphene oxide as high performance nanocomposites. Polym Test. 2014;34:211–9. doi:10.1016/j.polymertesting.2014.01.015.
17. Wang H, Xie G, Ying Z, Tong Y, Zeng Y. Enhanced mechanical properties of multi-layer graphene filled poly(vinyl chloride) composite films. J Mater Sci Technol. 2015;31(4):340–4. doi:10.1016/j.jmst.2014.09.009.
18. Musonda J, Mwero JN, Abongo K. Performance of uPVC RC-filled pipe columns exposed to thermal cyclic loading. Eng Technol Appl Sci Res. 2025;15(2):21232–42. doi:10.48084/etasr.9862.
19. Woldemariam AM, Oyawa WO, Nyomboi T. Structural performance of uPVC confined concrete equivalent cylinders under axial compression loads. Buildings. 2019;9(4):82. doi:10.3390/buildings9040082.
20. Nirmala R, Rajkumar R. Finite element analysis of buried UPVC pipe. Indian J Sci Technol. 2016;9(5):87225. doi:10.17485/ijst/2016/v9i5/87225.
21. Cassa AM, van Zyl JE. A numerical investigation into the behaviour of cracks in uPVC pipes under pressure. In: Proceedings of the Water Distribution Systems Analysis 2008; 2008 Aug 17; Kruger National Park, South Africa. doi:10.1061/41024(340)65.
22. Xu S, Wang Y, Han Y, Yu Y, Jiang D, Zeng Q. The bearing capacity performance of upvc pipe under axial compression. Case Stud Constr Mater. 2024;20:e03086. doi:10.1016/j.cscm.2024.e03086.

23. Matymish J, Moore ID, Woods JE, Hoult NA. Experimental response of a fusible PVC pipe with service connections to axial pullout. Tunn Undergr Space Technol. 2024;153:106018. doi:10.1016/j.tust.2024.106018.
24. GB/T 6671–2001/ISO 2505:1994. Thermoplastics pipes—determination of longitudinal reversion. Beijing, China: Standards Press of China; 2002.
25. GB/T 14152–200/ISO 3127:1994. Thermoplastics pipes—determination of resistance to external blows—round-the-clock method. Beijing, China: Standards Press of China; 2002.
26. GB/T 1040.0-2006/ISO 527-2:1993. Plastics—determination of tensile properties—part 2: test conditions for moulding and extrusion plastics. Beijing, China: Standards Press of China; 2007.