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Influence of Service Life on Physical and Mechanical Characteristics of Polyethylene Pipes

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Abstract—An experimental evaluation of the decrease in actual physical and mechanical characteristics of low pressure polyethylene (HDPE) pipes depending on the duration and conditions of their operation has been conducted. To assess the impact of operational factors on the pipe characteristics, the following parameters were determined: tensile elongation and tensile strength, thermal stability (induction period of oxidation (IPO) of the material), and degree of crystallinity. It was found that, after prolonged operation of HDPE pipes compared to the initial normative values, the most significantly affected parameters are the tensile elongation and the induction period of oxidation. Moreover, the changes in tensile elongation and IPO parameters have a similar nature in terms of the loss of properties, indicating a correlation between them. The most sensitive indicators for predicting the service life of HDPE pipes are the tensile elongation and the induction period of oxidation. On the basis of the data obtained, it seems promising to monitor the IPO value when determining the technical condition of polyethylene pipes. A calculated forecast of the service life of polyethylene pipes based on reaching their ultimate state has been performed.

Keywords: pipes, polyethylene, properties, service life
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INTRODUCTION

Over the past 30 years, polyethylene pipes have found wide application in various industries. This type of pipes is particularly actively used in the construction of low-pressure gas distribution networks and cold water supply systems, fire extinguishing systems, and other pipeline systems with a long service life [1].

The active implementation of polyethylene pipes in construction is facilitated by their low gas permeability, inertness to corrosive media, high elasticity and impact resistance at both low and high operating temperatures, ease of installation, and the absence of the need for additional protection [2].

The resistance of high-density polyethylene (HDPE) to the impacts of both external and transported media allows manufacturers of this type of pipes to specify a sufficiently long service life of 50 years or more [3, 4]. However, the question of the justification of the specified service life remains open at the moment. The existing regulatory documents do not contain requirements that would allow regulating the durability indicators of polyethylene pipes and pipelines, which makes it difficult to justify the actual duration of their operation. The question of what indicator of HDPE properties is most sensitive to operational impacts and can serve as a criterion for assessing the service life and regulating durability indicators also remains unclear.

Some promising methods for assessing the properties of polymer materials, which are currently not standardized, have been proposed [5, 6].

The aim of this study is to experimentally evaluate the reduction of actual physical and mechanical characteristics of HDPE pipes depending on the duration and conditions of operation.

EXPERIMENTAL

Two groups of HDPE pipe fragments from pipeline systems with approximately the same service life of 20–22 years were taken as objects of study.

The first group included fragments cut from gas distribution pipes of category 2 with operating pressures ranging from 0.3 to 0.6 MPa (Table 1).

The second group of pipe fragments was cut from a fire protection system and also had a service life of 20–21 years (Table 1).

With similar operating pressures and service life, the aforementioned groups of fragments were operated

Table 1. Service life and geometric characteristics of HDPE pipe fragments from gas distribution pipelines and HDPE pipe fragments from fire extinguishing systems

Sample no.	Service life, years	Outer diameter of pipes, *D*, mm	Ratio of pipe outer diameter to pipe wall thickness	Wall thickness, *t*, mm
Gas line pipes				
1.1	21	110	11	–
1.2	20	160	11	–
1.3	20	160	11	–
1.4	19	110	11	–
Pressure pipes of fire extinguishing systems				
2.1	21	250.6	–	24.8
2.2	21	316	–	31.6

Table 2. Regulatory requirements for physical and mechanical characteristics of HDPE pipes

Characteristic	Standard value of the indicator	Actual value according to the data sheet in the original state	Regulatory document
Gas line pipes			
Minimum long-term strength, MPa	≥8.0	–	GOST R 50838-95
Relative tensile elongation, %	≥350	–	
Thermal stability of pipes at 200°C, min	≥20	–	
Resistance to internal hydrostatic pressure at initial stress in the pipe wall of 10.0 MPa at 20°C, h	100	–	
Pressure pipes of fire extinguishing systems			
Relative tensile elongation, %	≥200	≥400	GOST 18599-2001
Ultimate tensile strength, MPa	–	20.0–25.0	–

underground and differed only in terms of working media.

The external surface of almost all samples was in satisfactory condition. The main defects were minor abrasions and scratches. No signs of degradation or interaction with chemicals were observed on any of the samples. The internal surface was smooth, without visually distinguishable mechanical damage.

The physical and mechanical properties of the gas pipes were determined according to GOST R 50838-95 "Polyethylene Pipes for the Supply of Gaseous Fuel. Specifications" and the pipes for the fire protection system were determined according to GOST 18599-2001 "Polyethylene Pressure Pipes. Specifications."

The normative requirements selected to evaluate the influence of service life on the properties of HDPE pipes, according to the specified standards, are presented in Table 2.

The regulated mechanical characteristics assess the strength and plastic properties of the pipe material.

To assess the impact of operational factors on the pipe characteristics, the following types of mechanical and physical properties were determined: tensile elongation and tensile strength, thermal stability (oxidative induction time), and degree of crystallinity.

It should be mentioned that the operating conditions of pipes in gas distribution and fire extinguishing systems differ in terms of the minimum operating temperature and the presence of seasonal thermal cycling. Fire extinguishing systems are operated at above-zero temperatures, while underground gas distribution pipelines are operated at below-zero temperatures during the winter period and transition to above-zero temperatures only after the ground is heated in the spring–summer period.

Tensile tests and the obtained values of tensile strength allow for assessing its change during long-term operation. The obtained values of tensile strength for pipes with a long service life can be related to long-term durability. The long-term durability of polyethylene is determined by resistance to internal hydrostatic pressure, as well as resistance to crack propagation. Tensile tests do not replace tests for resistance to

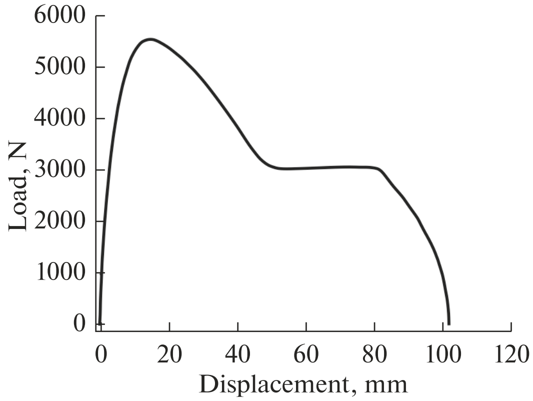

Fig. 1. Typical "displacement–load" diagram under tension of samples cut from HDPE pipes.

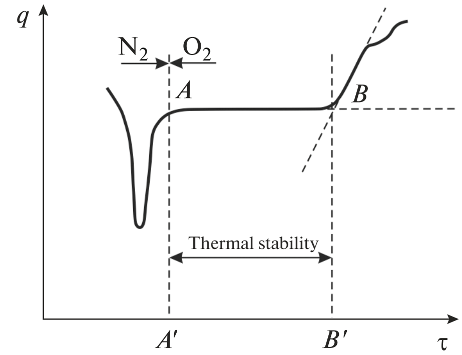

Fig. 2. Typical curve of differential scanning calorimetry in determining thermal oxidative stability of polyethylene.

internal pressure and resistance to crack propagation, but they can serve as a primary accelerated assessment of the quality of material.

The determination of properties under tension was carried out according to GOST 11262 on samples in the form of type 2 blades according to GOST R53652.3-2009 with a thickness of 10 mm and a calculated length of 50 mm. The samples were conditioned before testing. The tests were conducted on a SHIMADZU AGS-X universal testing machine at a tensile speed of 25 mm/min. The relative elongation was calculated on the basis of the equivalent initial length of 60 mm.

The following indicators were determined according to the test results: relative elongation and tensile strength, which were calculated according to GOST 11262. An example of the "load–deformation" curve characteristic of the tensile testing of HDPE pipe samples is shown in Fig. 1.

One of the standardized (GOST 58121.2-2018) physical characteristics of HDPE pipe material is thermal stability.

The determination of thermal stability is carried out by the method of differential scanning calorimetry (DSC) according to GOST R 50838, which involves determining the induction period of oxidation of the material (IPO). For the tests, samples with a thickness of 0.65 ± 0.1 mm and a weight of 12 to 17 mg were used. The sample was heated in a DSC 214 Polyma differential scanning calorimeter in a flow of inert gas (nitrogen) with a constant flow rate, and when the desired temperature was reached, the nitrogen flow was switched to oxygen flow at the same rate until an exothermic effect appeared on the thermogram, which corresponds to the thermo-oxidation reaction of the material. The time from the start of oxygen supply to the start of the exothermic effect was measured: the induction period of oxidation (or thermal stability). The thermal stability value in minutes, from point A' to point B', was considered as an indicator of thermal stability, as shown in Fig. 2.

The degree of crystallinity is also an important factor affecting the properties of polyethylene. According to modern concepts, HDPE, from which gas pipes are made, is a partially crystalline material with a crystallinity fraction of about 70%. The polyethylene crystals are folded, and since the length of the molecular chains is large, they can form regions (tie molecules) that do not enter the crystals but form an amorphous phase, occupying about 30% of the total volume of the material.

The degree of crystallinity of the samples was assessed using the DSC method according to GOST R 551354-2012 (ISO 11357-21). The degree of crystallinity of the material of the samples, *X*%, was calculated as follows:

$$X = \frac{\Delta H}{\Delta H^{100\%}} \times 100\%,$$

where ΔH is the enthalpy of melting of the PE sample material determined by the DSC method, J/g; and $\Delta H^{100\%}$ is the enthalpy of melting of 100% crystalline material (293 J/g) [5].

RESULTS AND DISCUSSION

The results of testing the physical and mechanical properties of the first group of samples cut from fragments of gas pipeline pipes are presented in Table 3.

It can be seen in Table 3 that the most significant changes compared to the normative values are observed in the indicators of tensile elongation and the induction period of oxidation (IPO). The values of elongation at break have decreased to 73% compared to the normative values.

The values of IPO also vary significantly among different pipe fragments. In the absence of initial factual values of this indicator, it is difficult to judge the degree of decrease, but the difference between the obtained values for the examined pipe fragments

Table 3. Physical and mechanical parameters of samples cut from fragments of gas line pipes and pressure pipes of fire extinguishing systems

Sample no.	Ultimate tensile strength, MPa	Relative tensile elongation, ε, %	Induction period of oxidation IPO (200°C), min	Degree of crystallinity, %
Gas line pipes				
1.1	24.46	358	>60	60
1.2	21.86	127.5	48	57
1.3	21.76	82.5	16	60
1.4	22.41	102.5	9.7	65
Standard (initial) values				
–	20–25	400	at least 20	–
Pressure pipes of fire extinguishing systems				
2.1	24.0 ± 0.333	121.8 ± 34.6	37	–
2.2	24.4 ± 0.3	228.6 ± 61.4	47.3	–
–	8.0	350	20	–

ranges from 20 to 84% compared to the highest value. It should be noted that fragments 1.3 and 1.4 are characterized by lower values in comparison with the normative requirements specified in GOST R 50838-95 for pressure pipelines.

Summary data on the test results of pipe fragments from fire extinguishing systems are presented in Table 3.

The analysis of the test results of the second group of pipe fragments shows that the greatest decrease in values is observed in tensile elongation, which amounted to 35% and 65% compared to the normative requirements. The values of IPO remained above the normative level, but it can be noted that sample 2.1, which has a greater decrease in plastic properties, also has a lower value of the IPO indicator.

Comparing the data obtained from gas distribution systems and fire extinguishing systems, one can see that more significant decreases in both elongation at break and IPO values are observed in samples of pipes from gas pipelines. Thus, the average decrease in elongation at break for gas pipeline pipes was 58%, while for fire extinguishing system pipes it was 50%.

The comparison of the trend in the obtained data of physical and mechanical properties shows that the indicators of elongation at break and IPO have a similar character of loss of properties, indicating a correlation between the change in their values (Fig. 3).

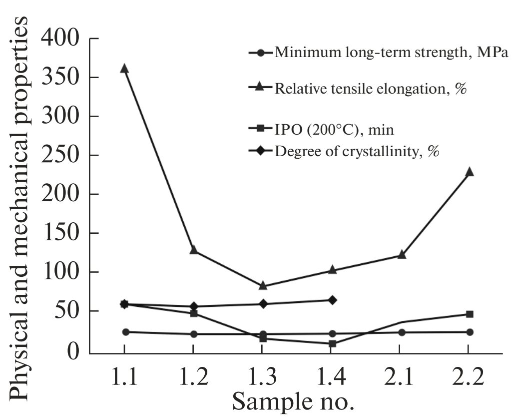

Fig. 3. Experimental results of material characteristics of samples of polyethylene pipes after long-term operation.

The ultimate strength and degree of crystallinity showed low sensitivity to operational impacts and remained at approximately the same level for all examined fragments.

It should be noted that the decrease in tensile elongation indicates an increase in the polyethylene brittleness and can lead to the appearance of cracks under cyclic and dynamic (impact) loads. The decrease in tensile elongation may be caused by changes in the amount of stabilizers in the polyethylene composition during operation.

The change in the induction period of oxidation for polyethylene can indicate either complete depletion of antioxidants or their absence. Analyzing the obtained experimental results, it can be assumed that fragments with an IPO value above 20 min have antioxidants present in sufficient quantities. However, if the IPO value is less than 20 min, then the antioxidants are sig-

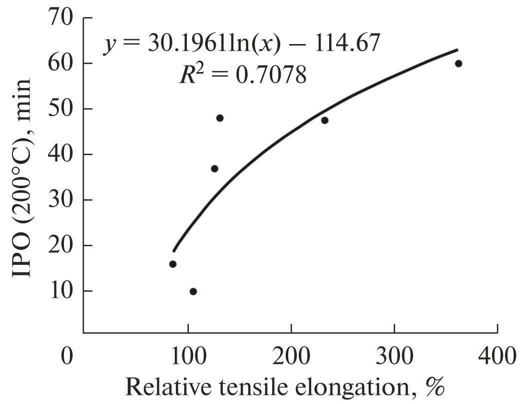

Fig. 4. Relationship of induction period of oxidation and plasticity of polyethylene pipes.

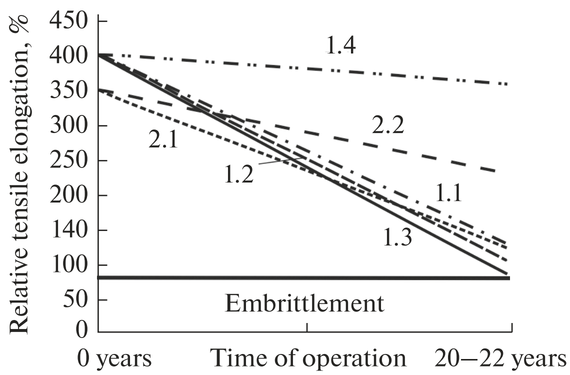

Fig. 5. Calculated relative elongation as a function of duration of operation of HDPE pipes.

nificantly depleted. There are documented data in the publications that oxidative degradation of polyethylene pipes can lead to premature failure [1]. HDPE pipes used for transport of water or aqueous solutions are susceptible to oxidative degradation in such environments [7]. The analysis of the obtained data also shows that gas distribution network pipes, which transport purified natural gas, demonstrate a decrease in IPO values and an increasing susceptibility to oxidative degradation.

To prevent oxidative degradation of HDPE materials, various chemical stabilizers and antioxidants are added to HDPE resin. Extensive oxidative degradation of HDPE leads to a decrease in the molecular weight of the polymer and subsequent loss of mechanical properties. Oxidized HDPE becomes very brittle and significantly reduces elongation under tensile stress.

On the basis of the research conducted, it can be concluded that the most sensitive indicators for predicting the service life of HDPE pipes are tensile elongation and the induction period of oxidation.

The correlation between these indicators on the basis of the generalization of the obtained data can be expressed by the trend equation presented in Fig. 4.

Using this equation, it is possible to determine the maximum decrease in tensile elongation at which the IPO value will fall below the normative level for pressure pipes (20 min). With a reliability of approximation of 0.71, the minimum permissible value of elongation at break was determined to be 86.5%. Since the presence of a stabilizer is one of the determining factors affecting the properties of HDPE, it seems promising to control the IPO value when determining the technical condition of polyethylene pipes.

Using the obtained values and the minimum permissible value of elongation at break, Fig. 5 shows the dependences of the decrease in operational parameters of the examined HDPE pipes over time and a forecast for reaching their ultimate state.

CONCLUSIONS

It has been shown that the most sensitive indicators for predicting the service life of HDPE pipes are the tensile elongation and the magnitude of the induction period of oxidation. The decrease in these parameters is significantly influenced by the operating conditions of HDPE pipes.

For gas line pipes, the values of tensile elongation have decreased to 73% compared to the normative level. For fragments of pipes in fire extinguishing systems, the reduction in tensile elongation ranges from 35 to 65%.

The decrease in the values of the induction period of oxidation for the examined fragments of gas line pipes ranges from 20 to 84%, with some fragments falling below the minimum normative value. A correlation has been found between the decrease in plastic properties and the decline in the values of the IPO indicator for fragments from systems where the IPO values are above the normative level.

Monitoring the degree of embrittlement of HDPE pipes by controlling the IPO value seems promising, using the achievement of a minimum value of elongation at break of 86–87% as an indicator of the technical condition of pipelines.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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