LABORATORY STUDY OF FATIGUE IN WATER CONVEYING HDPE AND PVC PIPES SUBJECT TO EXTREME HYDRAULIC TRANSIENT PRESSURES

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Abstract: Fatigue curves (S – N curves) are presented for high density polyethylene pipes (HDPE, PPI 4710 resin) and for PVC pipes, obtained experimentally in a 100 mm diameter and 300 m long water pipeline with pipe samples of different thicknesses subject to repeated cycles of extreme hydraulic transient pressures, which are continued until the failure of the pipe samples. The pipe samples were used either 1, without alterations, or 2, altered with triangular grooves of different depths machined in its external surface, in order to favor the formation of cracks in those grooved sections. From the experiments, it is confirmed that failures have their origin in the cracks developed in weakened regions of the pipes. It is also confirmed that high density polyethylene pipes have high resistance to fatigue or to the cyclic application of high internal pressures, given the fact that for this material the pipe failures: 1, are localized and limited in length, 2, they occur under pressures much higher than its nominal design resistance for normal operating conditions and 3, they occur under pressures which are also much higher than those allowed by the design standards for the case of maximum hydraulic transient events. On the other hand, the experiments confirmed that: 1, PVC pipes do not have the high resistance to fatigue shown by the polyethylene pipes, and 2, PVC pipe failures are brittle and catastrophic, as they propagate very rapidly until the destruction of the pipe. The two polymers tested, which exhibit such different behavior, have very different glass transition temperatures, 90 degrees Celsius for PVC and minus 90 degrees Celsius for HDPE. When compared with the normal range of ambient temperatures, PVC is always used well below the glass transition temperature, behaving therefore as a glass, and HDPE is always used well above the glass transition temperature, behaving as a rubber.

Keywords: Fatigue, S-N curves, high density polyethylene, HDPE pipes, 4710 resin, PVC pipes, transient pressures, crack propagation, glass transition temperature

1. Introduction

In previous papers [1, 2] the authors have proposed, for extruded pipes of high density polyethylene pipes (HDPE pipes), used in the transportation and distribution of potable water, S-N curves that can be representative of HDPE materials (PPI 3608 and PPI 4710 resins). In these curves, the applied loads or stresses, relative to its nominal or design values, are represented versus the number of times that the material resists the applied loads or the applied stresses. In these graphs, we can distinguish a crack initiation curve, a failure or rupture curve, and a crack development region between the curves.

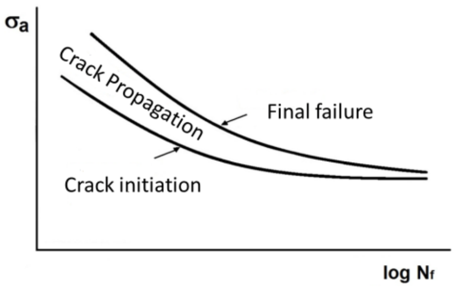


Fig 1. S – N curves, Ref [3].

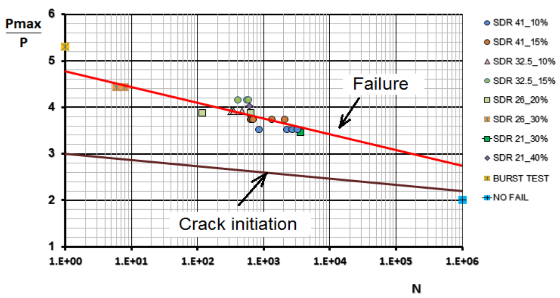
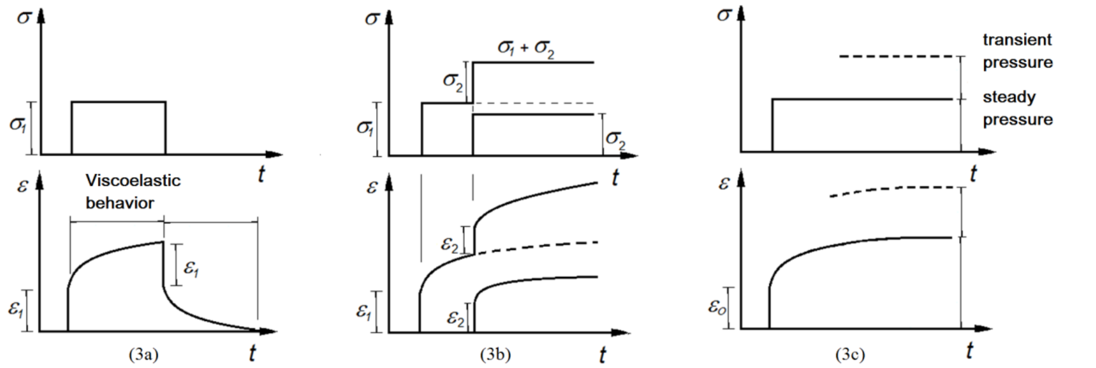


Fig 2. S – N curves for HDPE PPI 4710 [2].

The first experimental curve [1], which was obtained from a very long test (10^6 cycles) and two other short tests (10^0 and 10^3 cycles), was equivalent to the S-N fatigue curves obtained for typically elastic materials [3], such as steel and other metals. Further experiments [2], in which the pipe samples, altered with triangular grooves of different depths machined in its external surface were brought to failure through the application of repeated cycles of hydraulic transient overpressures, are shown in Fig 2.

2. Viscoelasticity

High density polyethylene (HDPE) and PVC are viscoelastic materials. These materials respond to the application of loads with an instantaneous elastic deformation, followed by a slow and continuous deformation, known as viscous flow or creep. When the load disappears, there is an instantaneous recovery of the elastic deformation, and an inverse viscous flow recovering gradually the viscous deformation (Fig 3a [4]).
According to the Boltzmann superposition principle [4], if two loads or stresses are superposed, its corresponding deformations are equally superposed (Fig 3b).



Figs. 3a and 3b: Viscoelastic material deformations under stresses and superposed stresses [4]. Fig 3c: Deformations under transient overpressures.

In our fatigue studies, the pipe samples are subject to an initial internal pressure that gives rise to an elastic deformation and to the viscous flow mentioned above. The application of cyclic overpressures caused by waterhammer will produce a new deformation curve, above the viscous flow curve. The deformations due to these transient loading and unloading cycles will be located between these two curves (Fig 3c).

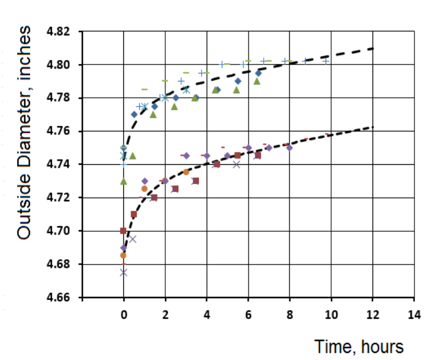


Fig. 4. Outside diameters measured during steady and transient flow.

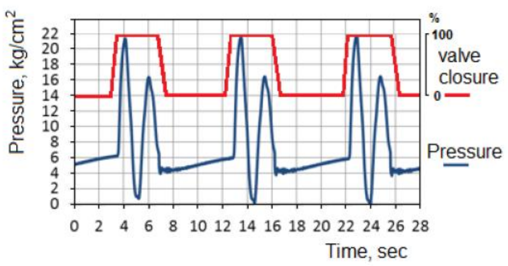


Fig. 5. Transient pressures and opening and closing cycle of the valve.

The theoretical curves shown in Fig 3c were obtained experimentally in an HDPE pipe sample and are shown in Fig 4. The lower curve corresponds to the measured outside pipe diameter and its growth due to the viscous flow or creep caused by the permanent internal pressure. The upper curve corresponds to the instantaneous deformation caused by the application of the transient pressures shown in Fig 5. The constant separation between the curves shows that the deformation and recovery are purely elastic.

3. Glass transition temperatures

Polymers, or plastics, go through different types of mechanical behavior, depending on its temperature and specifically, as solids, on its glass transition temperature, Tg, which is a transition temperature below which a plastic behaves as a glass, and above which it behaves as a rubber. This characteristic behavior is shown in Fig 6, where the Young modulus E is plotted versus the dimensionless absolute temperature T/Tg [5]. It can be seen that the modulus of elasticity, and correspondingly the design stress for internal pressure, are reduced drastically when the material goes from the glassy to the rubbery state.

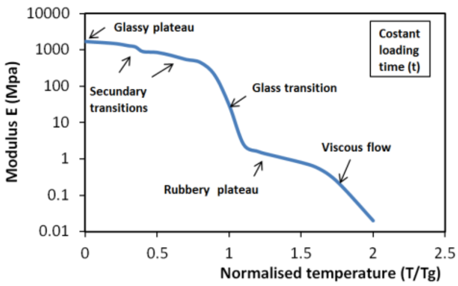


Fig. 6, Young modulus, linear polymer [5]

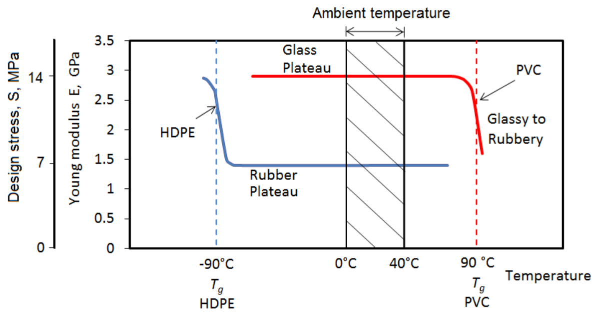


Fig. 7. Glass transition temperatures, PVC and HDPE

Glass transition temperature for PVC is 90° C, and -90° C for HDPE. Fig 7 shows the E-T and S-T curves for PVC and HDPE, showing that, for the typical ambient temperatures, 0° C to 40° C, PVC is clearly in the glass plateau, and HDPE is clearly in the rubber plateau, behaving accordingly. The Young modulus E and the design stresses S are shown in its real values, as they are used for the design of pipes that convey water under pressure.

4. Experimental installation

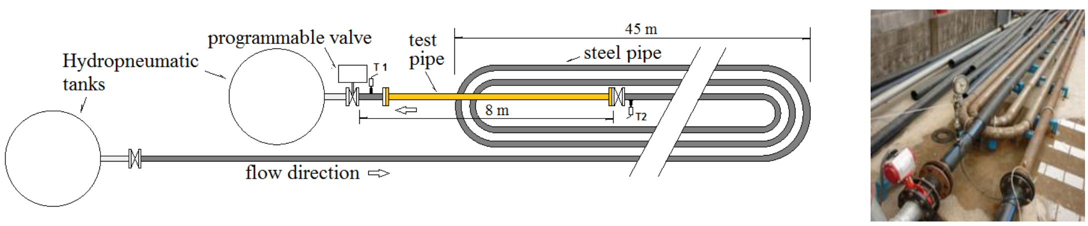


Fig. 8. Experimental set up

The experiments were conducted in the city of San Luis Potosí, in a model consisting of a 277 m long steel pipe, diameter of 100 mm and thickness of 1.5 mm, D/t ratio of 67, with two hydropneumatic tanks in the extremes, acting as constant head and as pressure wave reflecting bodies (Fig 8). Pressure wave celerity is 1120 m/s. In both ends of the steel pipe, upstream and downstream, 6 to 12 m of HDPE or PVC test pipes can be installed, and subject to extreme transient pressures, made possible by the high wave celerity of the steel pipe. Butterfly valves are installed at the upstream and downstream ends, with 0.2 s closure time. The valve has also a mechanical counter, which accumulates the number of valve cycles. This experimental installation is located in San Luis Potosí, Mexico, and was built under the technical advice of the Institute of Engineering of the Universidad Nacional Autónoma de México (UNAM), in the frame of an industry-university collaboration. The installation is available for research projects of universities and institutes.

5. Experimental results

The aim of the experiments reported in this paper is to obtain S-N curves for PVC and compare them with those obtained for HDPE in a previous paper [2]. Several PVC pipe samples, 6 m long, were subject to cycles of extreme transient pressures, which were higher than the internal design pressures of the pipes P (calculated as $P = 2\,S / (SDR - 1)$, where S is the design stress and SDR is the D/t ratio) and higher than the maximum pressures allowed by the codes during waterhammer events. For HDPE, the pipes are allowed pressures as high as 1.5 times its design pressure for recurring events, and 2 times its design pressure for occasional events [6]. The HDPE pipe final design thickness will be therefore the same as that calculated for steady state conditions. For PVC, the pipes must be calculated for the specific transient pressures that can occur during their lifetime [8], meaning that the pipe final design thickness will be generally greater than that calculated for steady state conditions.

The extreme pressure cycles, shown in Fig 11, were continued until the failure of the pipe. Different pipe samples were tested, for different values of the D/t ratio, also known as Standard Dimensional Ratio (SDR). For HDPE, SDR’s 41, 32.5, 26 and 21 had been tested [2]. For PVC, SDR’s 51, 41, and 32.5, were tested. A “sanitary” grade (SDR 51) was also tested. Outside diameter of the PVC pipes is 100 mm. The pipe samples were prepared with triangular grooves, machined in its external surface, 30 mm long, parallel to the pipe axis, with depths from 10 to 40% of the nominal thickness, with an angle of 60 degrees, similar to those cut in the round bar samples used in the standard fatigue tests (Fig 9), with the aim of provoking the development of cracks in those weakened pipe sections (Fig 10).

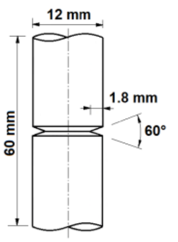


Fig. 9. Typical test specimen.

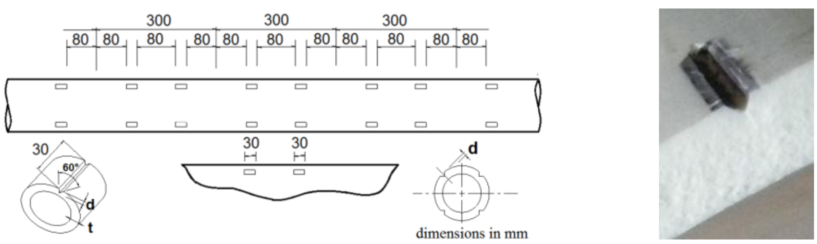


Fig. 10. Groove detail and pattern in pipe test samples

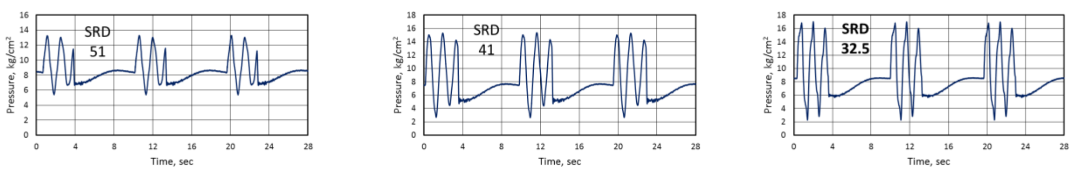


Fig. 11. Typical load cycles, PVC pipes, for different SDR’s.

The same type of experiments made with HDPE pipe samples [2] were repeated with PVC pipe samples. Initial pressures were between 0.7 and 1.7 times (1.3 to 1.9 times for HDPE) the design pressures of the pipes, and the average water hammer overpressures were between 2.1 and 2.7 times (3.5 to 4.4 times for HDPE) the design pressures of the pipes. The typical load cycles to which the pipes were subjected are shown in Fig 11. Peak frequency is 0.3 Hz.

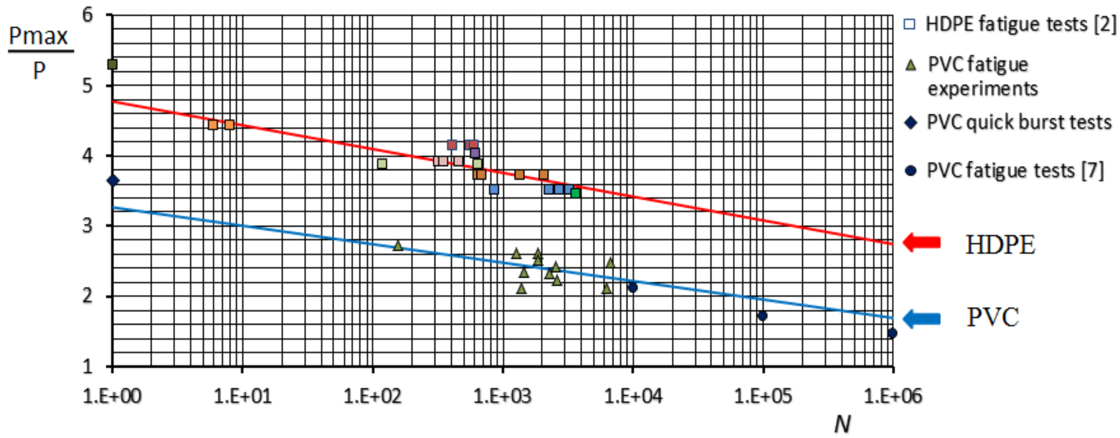


Fig. 12. Experimental results and S-N fatigue curves (logarithmic adjustment).

A total of 11 experiments were made, in which all pipe samples were brought to failure. In all cases, the failures occurred with a big burst and started in one of the grooves made with the purpose of provoking the failure. Contrarily to the case of HDPE pipes, where the failures were localized, fixed in length, and stable, that is, without propagation during the experiment, as shown in Photos 1 to 3 [2], the PVC pipe failures propagated very rapidly from the initial groove failure, destroying completely the pipe, as shown in Photos 4 to 9.

Photo1. HDPE SDR 41

Photo 2. HDPE SDR 32.5

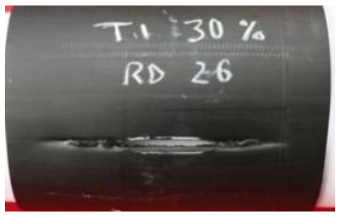


Photo 3. HDPE SDR 26

The results of the 11 experiments are shown in Fig 12, in which the logarithmically adjusted curves for HDPE and PVC are compared. The normalized maximum pressure applied, Pmax/P, was calculated with the average overpressures in each cycle and the design pressure of each pipe sample, according to its real average thickness and SDR. In Fig 12, three points in the PVC curve were added for N values of 10^4, 10^5 and 10^6, from Ref [7], which summarizes a number of conventional fatigue studies made with large numbers of load cycles, and which correspond very well with our smaller load cycles experiments with real pipes.
In addition, virgin PVC pipe samples, not previously subject to internal pressure, were also tested under the quick burst test (ASTM D 1599 99R05), in which the pipe samples are sealed with blind flanges and subject, inside a water tank, to an increasing internal pressure, until the moment in which the pipe fails, recording the maximum pressure reached. The average of these maximum pressures, normalized, is also plotted in Fig 12, as was for HDPE.


Photo 4. PVC


Photo 5. PVC


Photo 6. PVC


Photo 7. PVC


Photo 8. PVC


Photo 9. PVC

Conclusions

Curves S – N for HDPE pipes and PVC pipes were presented, resulting from experiments in which test pipes were subject to extreme transient pressures and where the transient cycles were maintained until the failure of the pipes.
The experiments confirmed that failures in pipes are caused by small cracks that appear in its weak sections, and develop gradually, under cyclic loads or transient overpressures, until the moment in which the failure happens.
It was shown that, contrarily to HDPE pipes, which have a very high resistance to fatigue and high pressures and whose failures are localized and do not propagate, PVC pipes do not have a high resistance to high pressures, and that its failures are brittle and propagate very rapidly, destroying completely the pipes.
The difference in the behavior of the two materials can be explained considering their respective glass transition temperatures, which show that for the normal ambient temperatures PVC behaves as a glass and HDPE behaves as a rubber.

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