# PLASTIC PIPE LONG-TERM PIPE STIFFNESS BY CONVENTIONAL AND ACCELERATED TEST METHODS

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## ABSTRACT

Parallel-plate loading mechanism (ASTM D2412 standard test method) was used for investigating the long-term pipe stiffness values of HDPE, PE corrugated, PVC and ABS pipes by conventional and accelerated test procedures. The nominal inside diameters of the test pipes were 300 and 400 mm. Generally, long-term plastic pipe stiffness values decrease as increasing test duration and shown as an S-type long-term deflection curve for the test plastic pipes on a semi-log time scale. Long-term pipe deflection is a function of pipe material properties, pipe geometry, SDR value, and external loading conditions. The Rate Process Method (RPM) was used as the accelerated method for estimating the long-term pipe deflection and pipe stiffness value in conjunction with the parallel-plate loading mechanism. Long-term plastic pipe stiffness values were formulized based upon the test results.


*Key words:* Long-term pipe stiffness, rate process method (RPM), plastic pipe, geo-pipe.

## 1. INTRODUCTION

Many of today's plastics were developed during and just before World War II. Some were introduced into piping systems in the 1930's. Plastic piping systems obtained wide acceptance in the late 1950's and early 1960's. Since then plastic pipe usage has increased at an astounding rate. The primary benefits associated with all of these plastic piping products are the following: sustainability, corrosion resistance, chemical resistance, low thermal conductivity, flexibility, low friction loss, long term performance, light weight, variety of jointing methods, nontoxic, biological resistance, easy identification, and low maintenance. In general, thermoplastic piping is relatively flexible as compared to metal (rigid) piping. There are several types of thermoplastics, which are commonly used in the manufacture of pipe, such as Polyvinyl chloride (PVC), Acrylonitrile-butadiene-styrene (ABS), Polyethylene (PE), Polybutylene (PB), and Polypropylene (PP). Water mains, hot and cold water distribution, drain, waste, and vent (DWV), sewer, gas distribution, irrigation, conduit, fire sprinkler and process piping are the major markets for plastic piping systems throughout the world. Underground piping makes up the largest part of the market.

Three parameters are most essential in the design or the analysis of any flexible pipe installation. They are load (depth of burial), soil stiffness in pipe zone, and pipe stiffness. Among of them, external loads and surrounding soil stiffness are controlled by site conditions. However, pipe stiffness is closely related to material properties and is an important design parameter.

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## 2. FLEXIBLE PIPE DESIGN

In the late 1920's and 1930, Spangler developed a rational design procedure to predict the deflection of an installed flexible conduit. This design procedure calculated the horizontal deformation of the conduct as a function of the vertical load, the bedding support provided, and soil pressures acting laterally to resist the horizontal movement of the pipe. Based upon the assumption the pipe was sufficiently rigid, the deformed shape would be that of an ellipse, the vertical deflection assumed to be approximately equal to the horizontal. Therefore, the Spangler Equation is modified as follows:

$$\Delta x = \Delta y = D_e\, K\, W_c \,/\, (0.149\,\mathrm{PS} + 0.6\,\mathrm{E}') \tag{1}$$

where $\Delta x$ is horizontal deflection of pipe (mm), $\Delta y$ is vertical deflection of pipe (mm), $D_e$ is deflection lag factor, $K$ is bedding constant, dependent upon the support the pipe received from the bottom of the trench, $W_c$ is vertical load per unit of pipe length (N/m), PS is $F/\Delta y$ = pipe stiffness (kPa), E′ is modulus of soil reaction (kPa).

As shown in the equation, pipe approximate deflections under earth load are a function of pipe stiffness, soil modulus, and the handing and installation characteristics of a pipe during the very early stage of soil around the pipe.

The EI of a pipe is a function of the material's flexural modulus (E) and the wall thickness ($t$) of the pipe. Since I = $t^3/12$. As such it is a fixed value for any given set of material and dimensional parameters. However, the quantities pipe stiffness (PS) and stiffness factor (SF) are computed values determined from the test resistance at a particular deflection. These values are highly dependent on the degree of deflection, for as the pipe deflects the radius of curvature changes. The greater the deflection at which PS or SF is determined, the greater the magnitude of the deviation is from the true EI value. By application of the correction factor $C = [1 + (\Delta y/2d)]^3$, the measured PS or SF values can be related to the true EI of the pipe as long as the pipe remains elliptical. Therefore:

$$PS = F\ C\ /\ \Delta y = (F / \Delta y)\ (1 + \Delta y / 2d)^3 \quad (2)$$

$$SF = EI = 0.149\ r^3\ (PS) \quad (3)$$

where $d$ is initial inside diameter, $r$ is mean radius of the pipe.

Typically, pipe stiffness (PS) at 5 and 10% deflection, is determined for plastic pipe for each specimen. As specially request, stiffness factor (SF) also can be calculated at 5 or 10% deflection for each specimen. At present, the ASTM D2412 is the most common used test standard. However, PVC sanitary sewer lines found to continuously deflect 13 years installation (Rinker, 2004). The long-term deflection of plastic pipes installed deep in the ground is always a concern for sewerage engineers. According to Modified Spangler's equation, flexible pipe deflection is a function of pipe stiffness. Therefore, the long-term deflections of HDPE, PE corrugated, PVC and ABS jacking pipes under parallel-plate loading mechanism were investigated. Moreover, the change of pipe stiffness versus time for these pipes were also determined based upon the test results.

## 3. TEST PIPES AND EQUIPMENTS

HDPE smooth wall pipe are commonly used for water mains application. HDPE corrugated pipe is commonly used in drainage system. PVC and ABS jacking pipes are the most common used pipes in sewerage system in Japan and Taiwan. Due to the flexibility of these pipes, pipes with diameter of 200 to 450 mm are used in sewerage construction. Moreover, pipes with diameter of 300 and 400 mm are the most common used pipes used in jacking pipe construction. Therefore, 300 and 400 mm HDPE, PE corrugated, PVC and ABS plastic pipes were selected in the study. Two types 300 mm ABS pipes with different inner diameters were used in the study. The typical physical properties of these pipes are listed in the Table 1. Pipe stiffness (PS) values of these pipes were determined according to ASTM D2412 standard test method. The initial pipe stiffness (IPS) will be used as the reference data for further analyses. Typical material properties of these pipes are summarized in the Table 2. These data were the average values based upon 6 sets of tests.

In order to measure the long-term vertical deflection of the test pipe under constant load, a custom-made parallel-plate loading apparatus was designed and built. Dead load was used in the system. A double balance beam system was used to transfer the dead load to the parallel load plates. The transfer load ratios were 8 to 1 and 2.5 to 1, respectively. The total transfer ratio is 20 to 1. A load cell can be attached to the test apparatus to monitor the actual loading during the test as needed. Vertical deflection was measured using a LVDT with accuracy of 0.01 mm. The maximum allowable deflection is 40 mm. 12 units of this apparatus were built for conducting the standard long-term tests. These apparatuses were placed in a temperature and humility controlled room. A closer view of the setup of these test apparatuses is shown in the Fig. 1. A diesel electrical generator is connected to the electricity system to prevent any interruption of the test due to the electricity supply. HOBO U12 Temp/RH external data logger is used to trace the condition of the room. All the data were collected in a data acquisition system.

**Table 1 Typical physical properties of the test plastic pipes**

| Type | Nominal diameter (mm) | Diameter (mm) | | Thickness (mm) | Mass per length (kgf/m) |
|---|---|---|---|---|---|
| | | Outside | Inside | | |
| PVC | 300 | 317.70 | 285.30 | 16.03 | 21.30 |
| | 400 | 422.21 | 378.71 | 21.38 | 38.59 |
| ABS | 300 (I) | 316.34 | 290.61 | 12.84 | 12.57 |
| | 300 (II) | 327.25 | 299.67 | 13.92 | 14.23 |
| | 400 | 442.29 | 401.69 | 19.88 | 27.55 |
| HDPE | 300 | 317.03 | 275.83 | 19.62 | 26.72 |
| | 400 | 403.96 | 358.80 | 23.84 | 17.31 |
| PE corrugated | 300 | 367.50 | 306.21 | 27.73 | 4.27 |

**Table 2 Typical material properties of the test plastic pipes**

| Type | Nominal diameter (mm) | Tensile strength (MPa) | Ovality (%) | Initial pipe stiffness (kPa) |
|---|---|---|---|---|
| PVC | 300 | 52.31 | 0.27 | 2092.04 |
| | 400 | 50.88 | 0.89 | 2069.73 |
| ABS | 300 (I) | 42.77 | 0.17 | 858.43 |
| | 300 (II) | 43.33 | 0.30 | 1033.78 |
| | 400 | 45.11 | 0.48 | 1285.94 |
| HDPE | 300 | 28.91 | 0.19 | 1206.75 |
| | 400 | 27.91 | 2.06 | 970.78 |
| PE corrugated | 300 | 28.72 | 0.45 | 243.67 |

**Fig. 1 Setup of the long-term pipe stiffness test apparatuses**

Since conducting the standard long-term test is a very time consuming process to achieve the desired test results. A series of accelerated tests was also performed. The custom-made parallel-plate loading apparatus was placed in a temperature controlled chamber. The accelerated parallel-plate load tests were performed using different elevated temperatures up to 60°C. The setup of the accelerated test apparatus is showed in the Fig. 2. Based upon the test results, the relationships between pipe stiffness and test duration could be expressed in the form of one of the following equations for predicting the long-term pipe stiffness or test duration based upon the accelerated test results (Koerner *et al*. 1990):

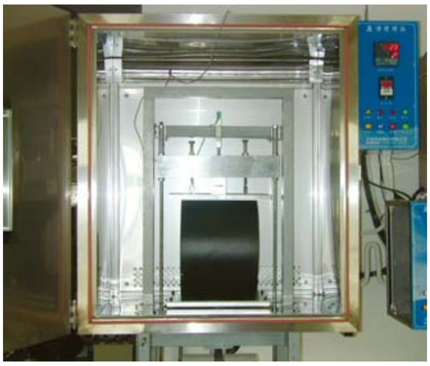


**Fig. 2 Setup of the accelerated pipe stiffness test apparatus**

$$\text{Log}\,(t_f) = A_0\ T^{-1} + A_1\ T^{-1}\ (PL) \tag{4}$$

$$\text{Log}\,(t_f) = A_0 + A_1\ T^{-1} + A_2\ T^{-1}\ (PL) \tag{5}$$

$$\text{Log}\,(t_f) = A_0 + A_1\ T^{-1} + A_2\ \log\,(PL) \tag{6}$$

$$\text{Log}\,(t_f) = A_0 + A_1\ T^{-1} + A_2\ T^{-1}\ \log\,(PL) \tag{7}$$

where $t_f$ is test duration, T is test temperature, PL is computed pipe stiffness base upon the test load, $A_0$, $A_1$, and $A_2$ is constants.

## 4. LONG-TERM PIPE DEFLECTION

Since the test materials included HDPE, PE corrugated, PVC and ABS pipes and the test pipe sizes consisted of 300 mm and 400 mm, deflection (non-dimension) and pipe stiffness (PS) calculated at 5.0% deflections were used for the presentation. Even the initials inside diameter and pipe stiffness are different for each type of pipe. However, the use of this term would make the presentation easier.

A series of tests were performed using different percentage of the average initial pipe stiffness (IPS) value determined according to the ASTM D2412 standard test method. The tests were started from higher pipe load associated with high percentage of IPS, such as 95%, 90%, 85%, and 80% IPS, *etc*. The vertical deformation of the pipes was monitored using a LVDT and the data was collected using an automatic data collection system. Each test was terminated as the vertical deformation reaching 5.0% deflection of the initial inside diameter of the pipe.

Typical pipe deflection curves for ABS (II) 300 mm pipe under various loadings were shown in the Fig. 3. Since the required time to reach 5.0% deflection was quite different for various percentage of IPS loading, the test data are presented on a semi-log coordinate system. The test duration (horizontal axis) is presented in log scale. The required time to let the pipe reaching 5.0% deflection increased rapidly as decreasing the applied loading. The test performed using 80% initial PS loading is reaching 5.0% deflection at the time near 10,000 hours. S-type deflection curves are shown in the figure on a semi-log coordinate system.

The deflection curves under 80% of initial PS loading for the test pipes are shown in the Fig. 4. In general, these curves are almost parallel to each other. For the test PVC pipes, the pipe stiffness values are about the same (around 2,000 kPa). However, the curve associated with PVC 400 mm pipe shown greater deflection than that for 300 mm PVC pipe. Therefore, it is concluded that pipe deflection would increase almost proportional to the diameter of test pipe with similar initial PS value for same pipe type under parallel-plate loading mechanism. Based upon the PS values shown on the Table 2, the PS value for the test 300 mm ABS(I) pipe (858 kPa) is about 2.43 times less than that for 300 mm PVC pipe (2,092 kPa). The data shown on the Fig. 4, the deflection associated with ABS pipe only shown slightly greater than that for PVC pipe. The difference of deflection is only about 20% between each other. The reason for causing this behavior is expected to be related to pipe materials and required further study.

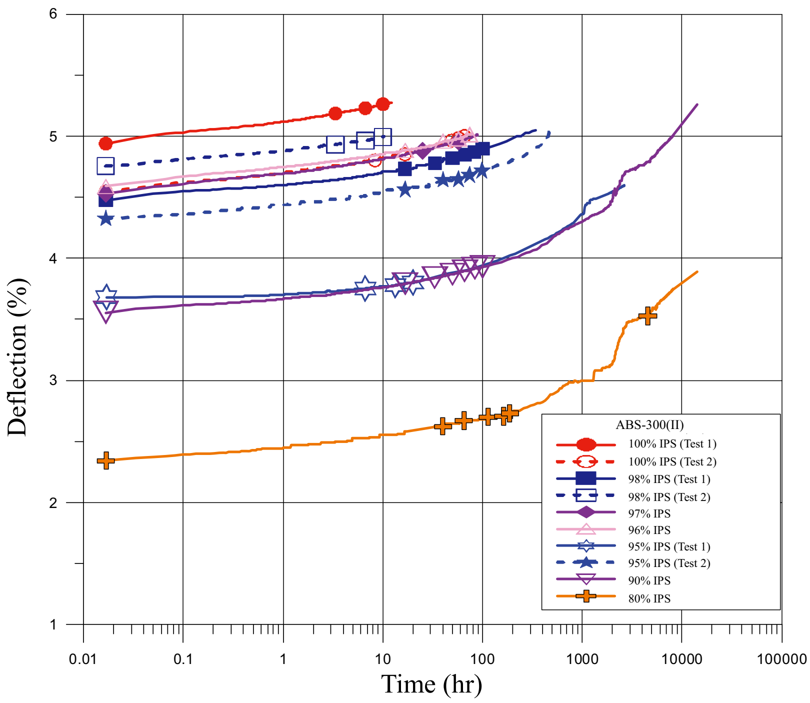



**Fig. 3 Long-term deflection curves for 300 mm ABS (II) plastic pipes**

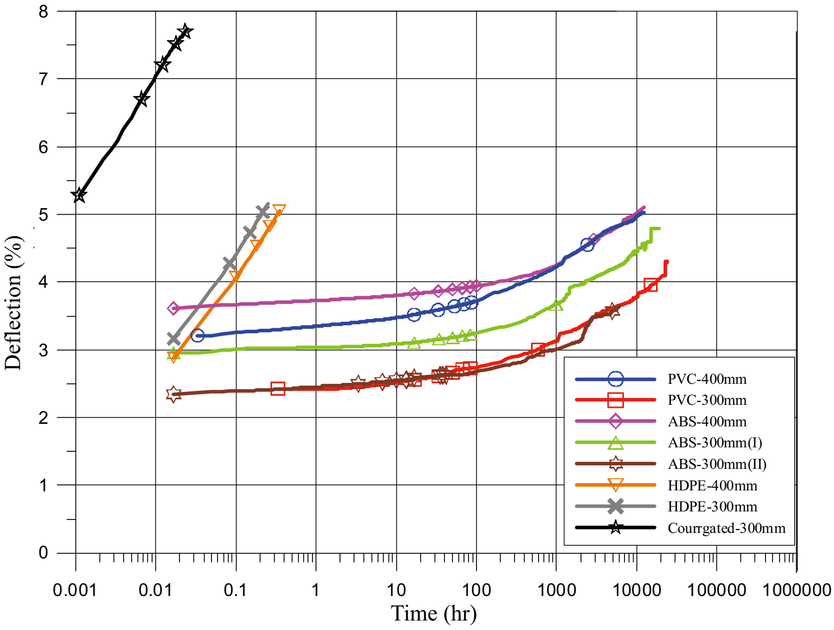



**Fig. 4 Long-term deflection curves for different types of plastic pipes under 80% initial PS (IPS) loading**

## 5. LONG TERM PIPE DEFLECTION PREDICTION FORMULATION

The compression pipe deflection measured at inner diameter $D_f(t_f)$ at any time during the service time for ABS and PVC pipes was formulated using an exponential function as follow:

$$D_f(t_f) = D_s + (D_f - D_s) \times (1 - e^{(a1/t^{-a2})}) \tag{8}$$

where $D_f$ is the anticipated ultimate pipe deflection (%), $D_s$ is the initial deflection (%), $a1$ and $a2$ are constants, and $t$ is duration (hour).

Based upon the results of data analysis, 12% ultimate pipe deflection, $D_f$, provides the best curve fitting with other data. $D_s$ is the initial pipe deflection which is a function of percentage of initial pipe stiffness, $a1$ is a variable and is a function of compression pipe load. Constant $a2$ of 0.35 fits the most pipe load conditions. The observed pipe deflection data and pipe deflection values calculated based upon the proposed formulation at 98%, $98\%^{-1}$, 90%, 80% IPS compression pipe loads for ABS-300 (II) pipe are plotted in Fig. 5 for comparison. Two sets data at 98% IPS with different initial deflections are presented in Fig. 5. An excellent agreement between these two sets data is shown in the figure. The prediction formulations for the corresponding loads are listed as follow.

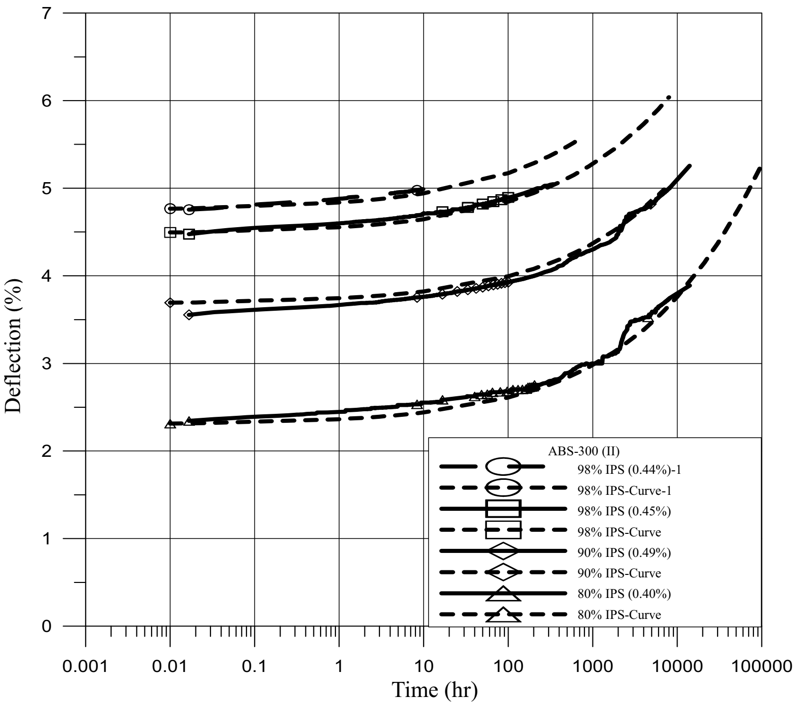



**Fig. 5 Comparison the ABS-300 (II) pipe deflection between the observed values and data calculated according to proposed pipe deflection formulation**

## 6. LONG-TERM PIPE STIFFNESS

Based upon the data shown above, plastic pipe would continue to deflect under parallel-plate loading mechanism. However, the required time to reach 5.0% deflection would increase as decreasing of applied loading. Based upon this observation, it can be concluded that pipe stiffness would decrease as increasing the duration time under parallel-plate loading. The results of a series of tests for different pipe materials and diameters, the decreasing trend of PS value can be calculated for different deflection values. For the data observed in the study, the Fig. 6 shown the PS values for the test pipes associated with 5.0% deflection. Due to 5.0% deflection PS data for 300 mm ABS (I) pipes are required a very long duration time, only a few data were obtained at the present and are not shown in the figure. Even 300 and 400 mm PVC pipes consisted of similar initial pipe stiffness values, however, 400 mm PVC pipe deflected much faster than that for 300 mm PVC pipe under similar load. It is implied that, for the test pipes, the deflection of 400 mm PVC pipe could be a safety concern in comparing with 300 mm PVC pipe during service life. As shown in the figure, the PS value decreases as increasing the duration time on a semi-log scale for 400 mm PVC and ABS pipes and 300 mm PVC pipe with 5.0% deflection.

By applying different percentage of initial pipe stiffness load into the proposed formulation (6) for PVC-300mm and ABS-300mm (II) pipes, the required time for PVC-300mm and ABS-300mm (II) pipes reaching 5% deflection can be calculated and plotted in the Fig. 7 as the dash lines. The test data obtained from long term tests are also plotted on the figure for comparison. Good agreement between these two sets data is observed.

## 7. ACCELERATED TEST RESULTS

The rate process method (RPM) was used to accelerate the load deflection creep behavior in the study. Elevated temperatures of 40°C, 60°C, and 70°C were used in the test. Typical time-deflection curves for 300 mm ABS (II) pipes tested under 70°C are plotted in a semi-log scale shown in Fig. 8. In addition, the pipe stiffness values can be computed based upon the accelerated test results. The compression pipe load presented in percentage of initial pipe stiffness (IPS) can be obtained by dividing the computed pipe stiffness value by the initial pipe stiffness. The compression pipe load presented in percentage of IPS versus duration plotted on a semi-log scale at different test temperatures for the 300 mm HDPE, PVC, ABS (II), and PE corrugated pipes are shown in Fig. 9 marking as the data points. The pipe load (PL), percentage of IPS, were further formulated on a log-log scale with parameters of duration time, test temperature, and pipe stiffness based upon current limited test data. The calculated percentage of initial pipe stiffness values (PL) based upon the developed Eqs. (9), (10), (11), and (12) shown as the solid lines in the Fig. 9.

$$\log(t_f) = -5.44 + 9388.75 \times T^{-1} - 9.08 \times \log(\mathrm{PL}) \quad (9)$$

$$\log(t_f) = -45.32 + 22925.70 \times \mathrm{T}^{-1} - 2559.22 \times \mathrm{T}^{-1} \times \log(\mathrm{PL}) \quad (10)$$

$$\log(t_f) = -26.95 + 14700.70 \times \mathrm{T}^{-1} - 1920.21 \times \mathrm{T}^{-1} \times \log(\mathrm{PL}) \quad (11)$$

$$\log(t_f) = -37.951 + 18765.69 \times \mathrm{T}^{-1} - 3420.20 \times \mathrm{T}^{-1} \times \log(\mathrm{PL}) \quad (12)$$

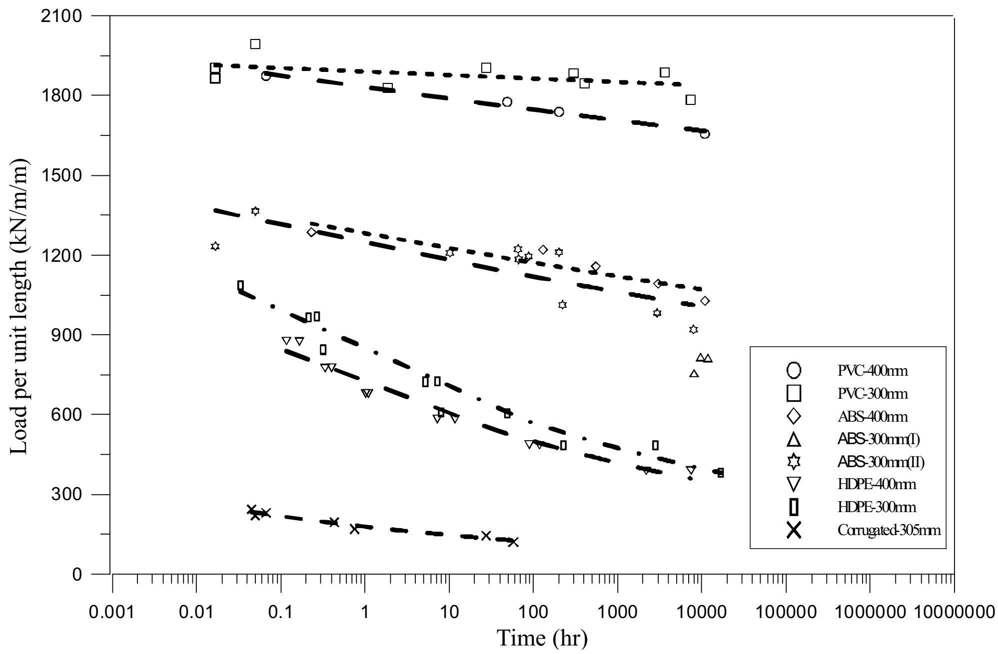



**Fig. 6 Long-term pipe stiffness values for different types of plastic pipes**

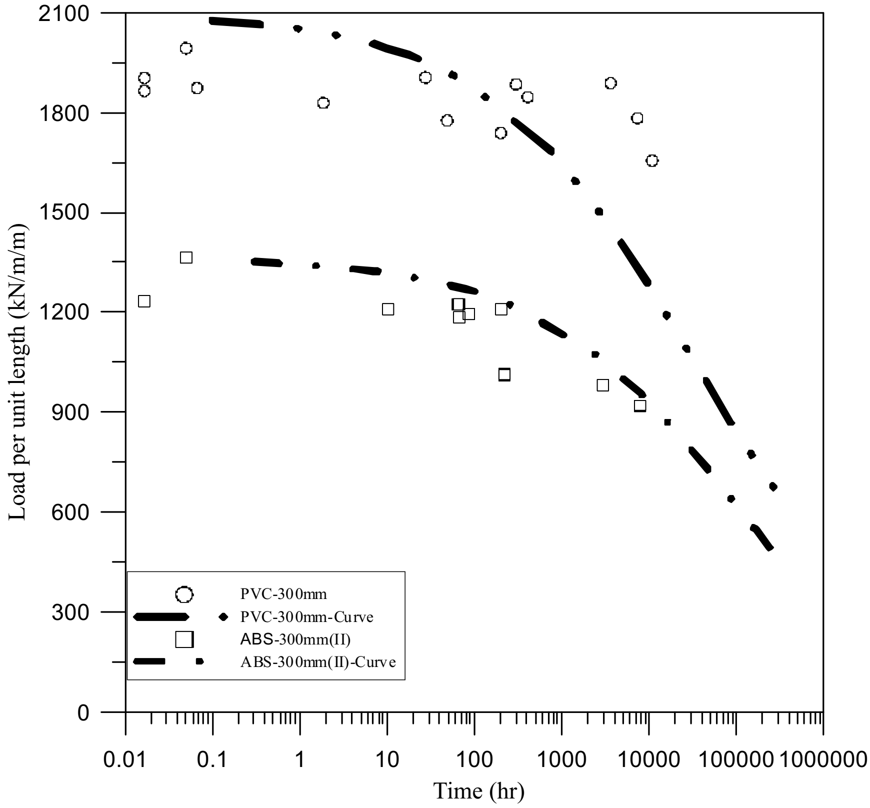



**Fig. 7 Comparison between the results calculated using proposed formula and observed compression pipe load versus required duration for reaching 5% pipe deflection for PVC-300mm and ABS-300mm (II)**

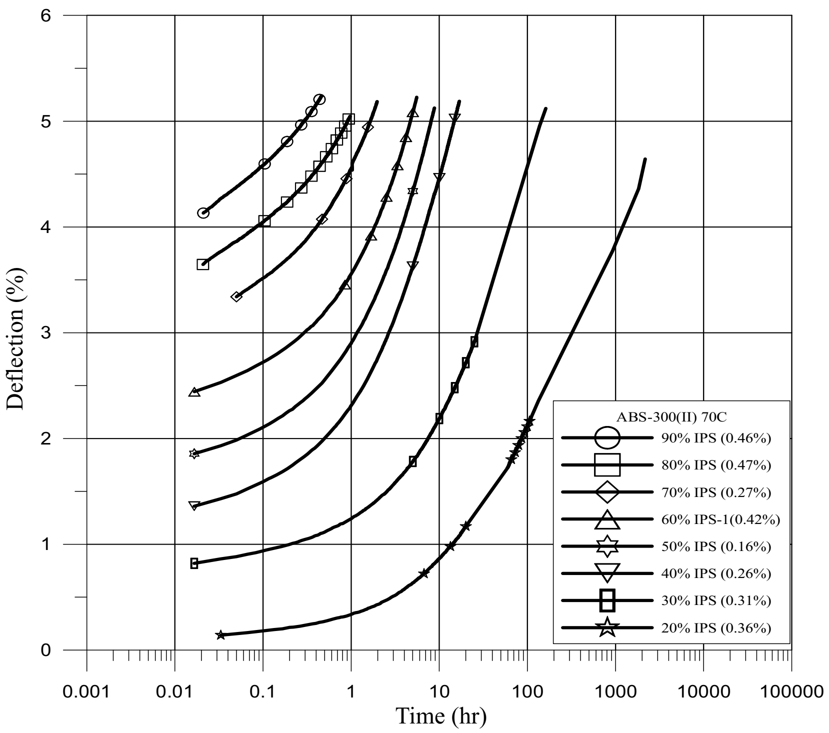
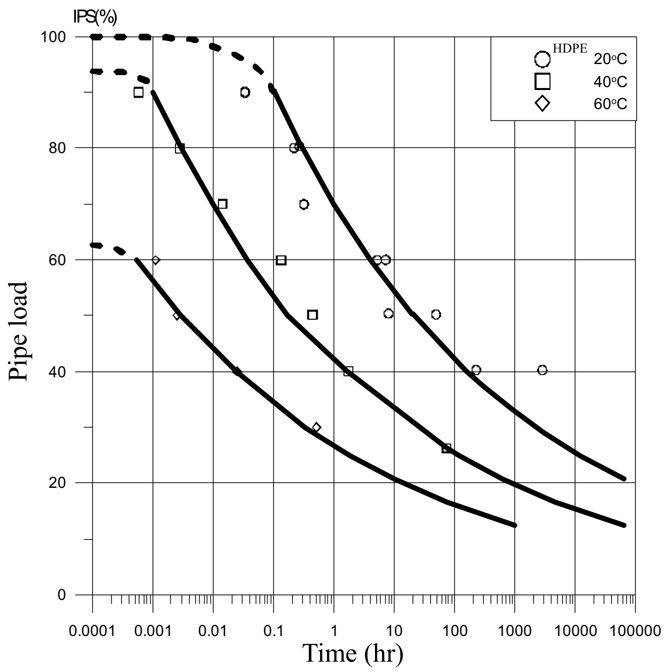
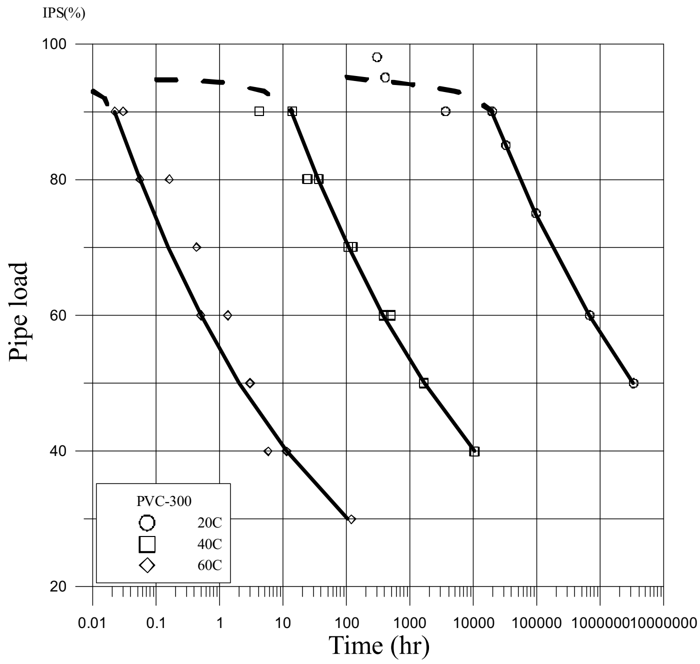


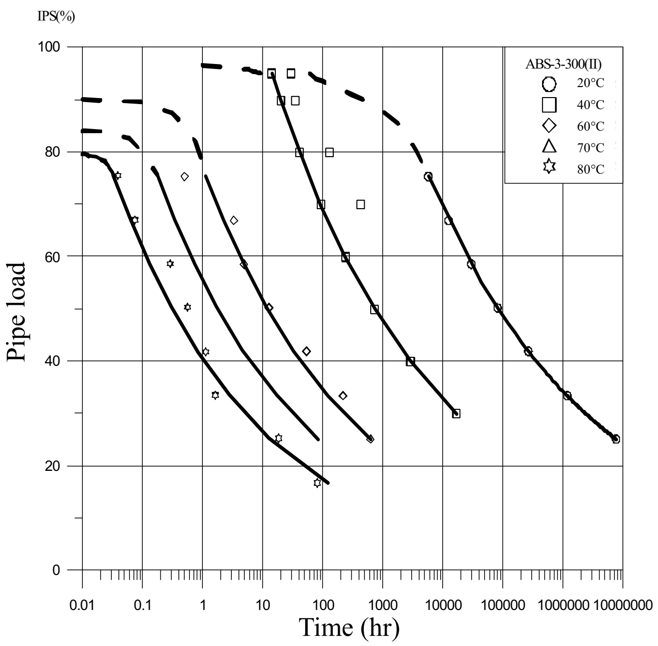

**Fig. 8 Accelerated parallel load plate test results for 300 mm ABS (II) pipe at 70°C elevated temperature**



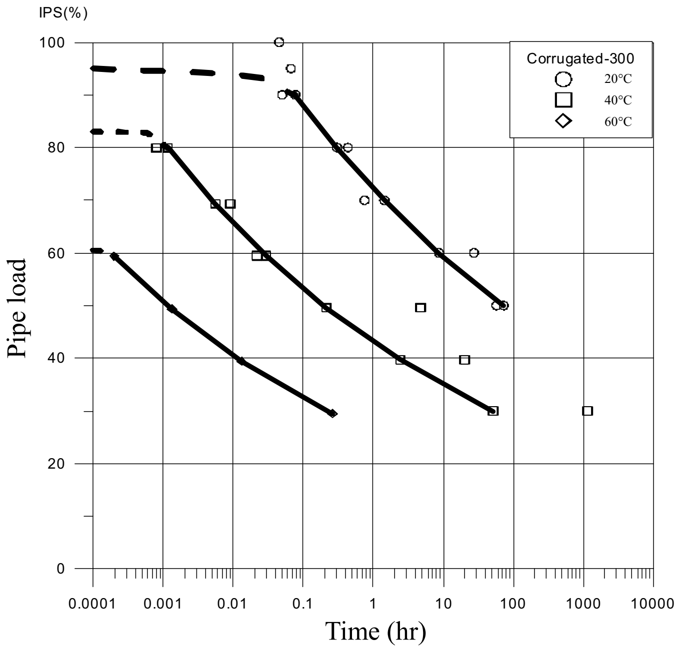

**(a) 300 mm HDPE pipe**




**(b) 300 mm PVC pipe**




**(c) 300 mm ABS (II) pipe**




**(d) 300 mm PE corrugated pipe**

**Fig. 9 Required durations for reaching 5% pipe deflection at different percentages of IPS pipe loads and elevated temperatures for various 300 mm pipes**

where $t_f$ is duration time (hour), T is test temperature, and PL is percentage of initial pipe stiffness.

Same procedure was also applied to 400 mm HDPE and PVC pipes. The results are not presented in the paper due to limited space.

## 8. SUMMARY AND CONCLUSIONS

The long-term deflection of HDPE, PE corrugated, PVC and ABS plastic pipes under parallel-plate loading mechanism was investigated using conventional and accelerated test procedures. The nominal inside diameters of the test pipes were 300 and 400mm. The ASTM D2412 standard test method was used in the study. The following conclusions are made based on the above discussions:

1. Generally, long-term plastic pipe stiffness values decrease as increasing test duration and shown as an S-type long-term deflection curve for the test plastic pipes on a semi-log time scale.
2. 300 mm and 400 mm PVC test pipes consisted of similar initial pipe stiffness values, however, 400 mm PVC pipe shown almost 35% greater deflection in comparing with 300 mm PVC pipe under similar loading conditions. The deflection rate approximately increases as increasing pipe diameter.
3. It would take around 10,000 hours to let 400 mm PVC and ABS plastic pipes reaching 5% deflection under conventional parallel-plate loading test, however, it seems that it would take very long time to let 300 mm PVC and ABS pipes reaching 5% deflection.
4. Long-term pipe deflection is a function of pipe material properties, pipe geometry, SDR value, and external loading conditions. However, the deflection lag factor of Spangler's formulation should not be a constant value for estimating the pipe deflection. A plastic pipe deflection prediction formula is proposed.
5. In comparison of the initial pipe stiffness values between 300 mm PVC and ABS pipes, the stiffness value of PVC pipe is about 2.43 times higher than that for ABS pipe. However, the deflection of ABS pipe is only about 20% higher than that for PVC pipe.
6. The use of rate process method with higher test temperature for conducting parallel-plate loading test is an effective procedure to accelerate the load-deflection response for plastic pipes and reduce the test duration time.
7. The formulation for estimating long-term pipe stiffness value can be developed based upon the accelerated test results at different elevated temperatures for the test plastic pipes.

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