PREDICTION OF DUCTILE FAILURE IN U-PVC PIPES FROM CREEP TESTS ON SPECIMENS

G.Castiglioni, D.Verzanini, A.Pavan
POLIlampol - Fondazione Laboratorio Prove Materie Plastiche
Politecnico di Milano

ABSTRACT

The possibility of predicting the resistance to creep and ductile failure in pressurized pipes from tensile creep tests on specimens taken from the same pipes, is explored. Experimental results obtained by the two testing methods are compared and discussed.

INTRODUCTION

Several phenomena can influence the durability of a pipe transporting a fluid under pressure, but in plastic pipes creep is particularly important. The test used to determine the resistance to creep and creep failure of pipes pressurized internally by water is the principal laboratory test in use to evaluate the lifetime of a plastic pipe. Performing this kind of test according to *ISO 9080* standard [1], is rather expensive, both because of the cost of the instrumentation and room required and of the duration of the test. Hence the interest for an easier creep test; for instance the uniaxial tensile creep test, provided it gives similarly significant information. The present work had two targets: first to set up a system for measuring the creep strain in a pressurized pipe, second to compare the results obtained on pressurized pipes with data obtained from tensile creep tests on specimens taken from the same pipes.

EXPERIMENTAL

Materials and Specimen Preparation

U-PVC pipes with a 75 mm OD were produced from U-PVC having a K value of 68 and stabilizated with a mixture of lead salts (2.1 phr), calcium carbonate (2.0 phr) and pigments (1.0 phr). The specimens, used for the tensile creep tests, were cut from the same pipes and mechanically worked after flattening the curved coupon between the plates of a press at a temperature of 100°C. The specimens were cut with their longitudinal axis in the pipe circumferential direction, so that the tensile stress in the specimens acted in the same direction as the hoop stress in the pipes. An equal aging treatment was applied to both types of test pieces, before testing: they were kept at 70°C for 5 hours and then slowly cooled to room temperature. All tests were performed at 20°C.

Creep Test on Pressurized Pipes

The creep tests on pipes were carried out on 850 mm long pipe segments according to the *EN 1452* standard [2]. The pipe lengths were closed with end metal cups mounted in such a way (type B in *EN 1452*) that no constraint is exerted in the axial direction of the test piece. The dry sealing is obtained by means of two O-rings placed between the end cups and the outer surface of the pipe. The two cups are maintained at a fixed distance from the free ends of the pipe segment by means of a rigid metal rod, as suggested in *EN 1452*. In this way the hydrostatic end thrust is not transmitted to the test piece: the only mechanical solicitation applied to the test piece is the internal pressure acting on the inner surface of the pipe and the axial stresses are nil. As the pipe wall thickness-to-pipe diameter ratio is of the order of 1/20 for the pipes used, the *thin-walled pipe* approximation can be applied: the radial stress can be neglected and the hoop stress can be taken as constant through the pipe wall thickness, i.e. a nearly uniaxial state of stress can be assumed to act in the pipe wall. This kind of test conditions is comparable to the conditions of the tensile creep test. The hoop stress σ_h in the pipe having an outer diameter d and a wall thickness e can be calculated as:

$$\sigma_h = p\frac{d-e}{2e} \qquad (1)$$

where p is the applied internal pressure which is maintained constant during the test.
Measurement of circumference length variations was obtained by means of a specially devised tool consisting of a thin, flexible steel wire wounded round the pipe. One end of the wire is fixed and the other end operates an LVDT transducer connected to a data logger.

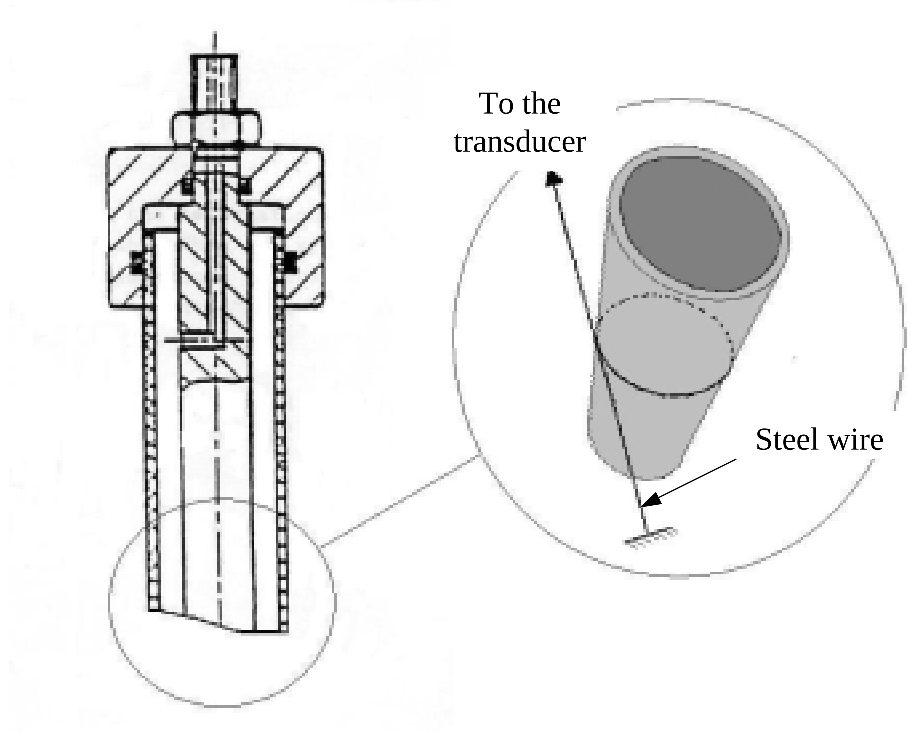

Fig. 1: Tool for performing the pressurized pipe creep tests (left) and method for measuring the hoop strain (right, schematic).

A light tension is applied to the wire so as to assure a perfect adhesion to the pipe surface. The displacement *Δl* read by the transducer is correlated to the pipe hoop strain ε_h by the equation:

$$\varepsilon_h = \frac{\Delta l}{\pi d_0} \qquad (2)$$

where d_0 is the original outer diameter of the pipe. Errors in the measuring system are estimated to be lower than 0.8%. The wire tool calibration was checked by measuring the hoop strain also directly by means of strain gauges glued onto the pipe surface near the wire. The results (Fig. 2) show that the two measuring systems are comparable. A non negligible difference can be observed for strains greater than 0.03, which are beyond the material yield strain.

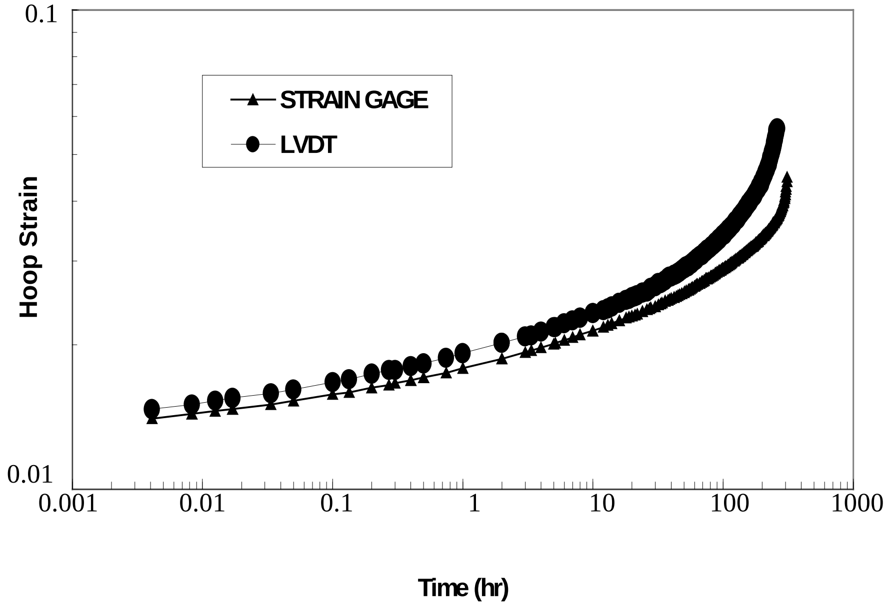

Fig. 2: Hoop strain: comparison between *LVDT* and strain gauge measurements at a hoop stress of 37 MPa. Temperature: 20°C.

Results obtained under three different hoop stress levels i.e. 37, 39 and 42 MPa are reported in Fig. 3 in terms of the anelastic creep compliance, i.e. the difference between the *total compliance D(t)* measured at the time *t* and the initial (elastic) *compliance* D_0, the *compliance D(t)* being defined as:

$$D(t) = \frac{\varepsilon_h(t)}{\sigma_h} \qquad (3)$$

The initial, nearly linear portion (in the double logarithmic plot) of each curve was fitted to the *Findley's* equation (3,4):

$$D(t) = D_O + mt^n \qquad (4)$$

The values of the fitting parameters D_0, *m* e *n* are reported in Table 1.

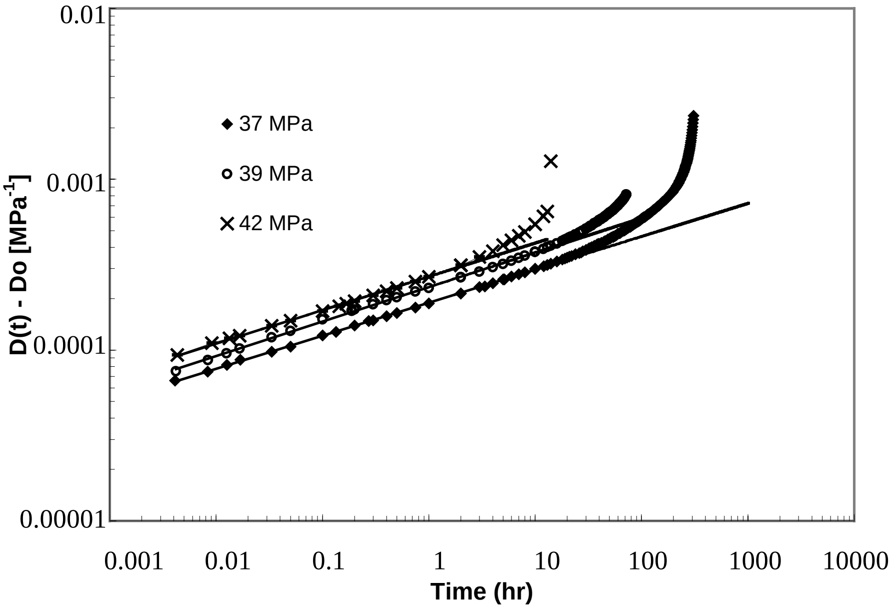

Fig. 3: Creep compliance data obtained on pressurized pipes under different hoop stress levels (see inset). Temperature: 20 °C. Points: experimental. Full lines: interpolated Findley's equation.

Table 1: *Findley's* model parameters from data in Fig. 3

σ_h[MPa]	D_0 [MPa^{-1}]	m	n
37	$2.94{\cdot}10^{-4}$	$1.89{\cdot}10^{-4}$	0.194
39	$2.86{\cdot}10^{-4}$	$2.34{\cdot}10^{-4}$	0.201
42	$2.94{\cdot}10^{-4}$	$2.69{\cdot}10^{-4}$	0.196
av. value	$2.91{\cdot}10^{-4}$	-	0.197
std. dev.	$\pm 5{\cdot}10^{-4}$	-	±0.004

Tensile Creep Test

The tensile tests were carried out on dumbbell type specimens having dimensions as shown in Fig.4. The displacement Δl_t between the two clamps was measured by means of two dial gauges and the axial strain ε_t was obtained by dividing Δl_t by the "equivalent gauge length" l_0^*,

$$\varepsilon_t = \frac{\Delta l_t}{l_0^*} \qquad (5)$$

l_0^* being computed by the following expression [5]:

$$l_0^* = l_0 + 2W_1 R\left\{-\frac{1}{R}\left[\frac{\alpha}{2} - \left(\frac{W_1 + 2R}{W_1}\right)\sqrt{\beta}\, arctg\left(\sqrt{\frac{1}{\beta}}\, tg\,\frac{\alpha}{2}\right)\right]\right\} \qquad (6)$$

in which $\alpha = arccos\left(1 - \frac{W_2 - W_1}{2R}\right)$

and $\beta = \frac{W_1}{W_1 + 4R}$

with the values of the specimen dimensions W_1, W_2, l_0 and R specified in Fig 4.

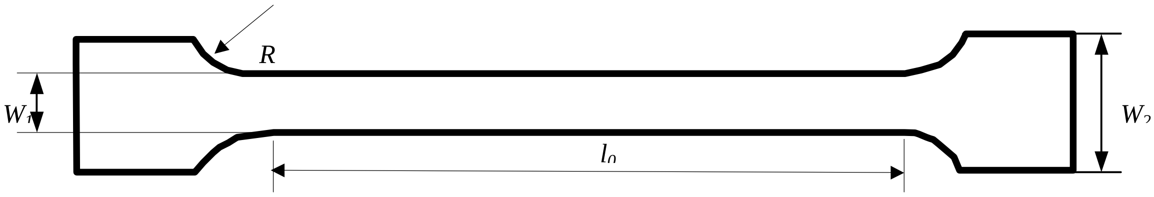

Fig. 4: Specimen geometry used for the tensile test.
W_1 = 7.61 mm, W_2 =20 mm, l_0 = 79.21 mm, R = 12.5 mm

The results obtained under different stress levels are reported in Fig. 5 together with Findley's model interpolations.

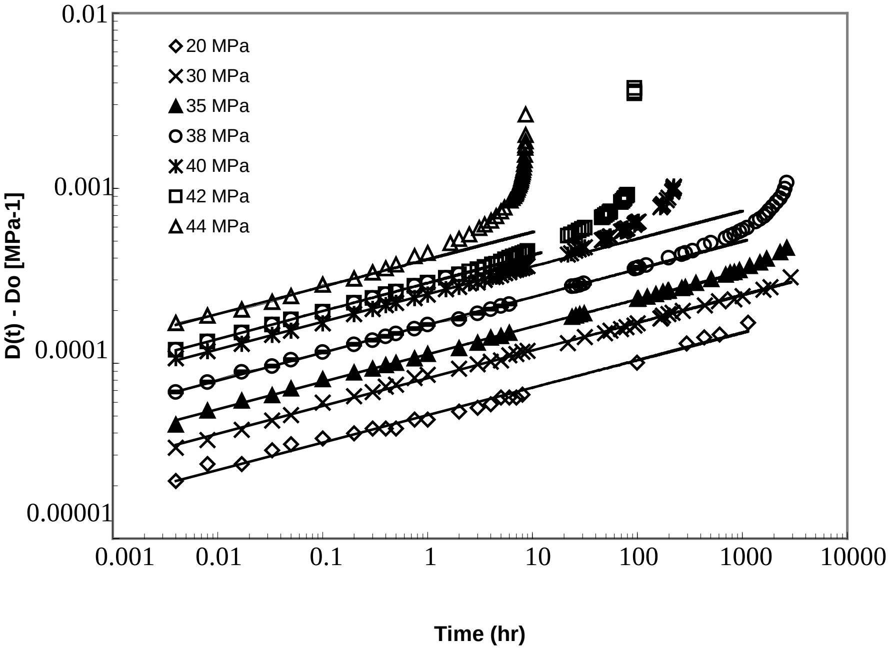

Fig. 5: Creep compliance data obtained from tensile tests creep under different stress levels (see inset). Temperature: 20 °C. Points: experimental. Full lines: interpolated Findley's equation.

Table 2: *Findley's* model parameters from data in Fig. 5

σ_t [MPa]	D_0 [MPa^{-1}]	m	n
20	$3.77{\cdot}10^{-4}$	$0.51{\cdot}10^{-4}$	0.157
30	$3.77{\cdot}10^{-4}$	$0.82{\cdot}10^{-4}$	0.159
35	$3.77{\cdot}10^{-4}$	$1.13{\cdot}10^{-4}$	0.157
38	$3.77{\cdot}10^{-4}$	$1.66{\cdot}10^{-4}$	0.160
40	$3.57{\cdot}10^{-4}$	$2.49{\cdot}10^{-4}$	0.158
42	$3.57{\cdot}10^{-4}$	$2.88{\cdot}10^{-4}$	0.160
44	$3.33{\cdot}10^{-4}$	$3.43{\cdot}10^{-4}$	0.156
av. value	$3.65{\cdot}10^{-4}$	-	0.158
std. dev.	$\pm\, 0.17{\cdot}10^{-4}$	-	± 0.002

DISCUSSION

Comparison of the experimental results obtained with the two tests, Fig. 3 and Fig. 5, shows a fairly good agreement. Findley's model appears to describe the data pretty well up to a viscoelastic strain (i.e. time-dependent component of the strain, equal to total strain minus initial elastic strain) of about 0.030~0.035 in both cases, although the average values of the two stress-indipendent parameters of the model, D_0 and n, are slightly different in the two cases (Table 1 and 2). The average value of the initial (elastic) compliance D_0 of the tensile specimen turns out to be somewhat larger than the homologous quantity determined in the hoop direction of the pipes. Viceversa, the creep rate of the *secondary* creep as represented by the exponent n of Findley's equation turns out to be somewhat larger in the pressurized pipe tests with respect to the tensile creep test.

Deviation from Findley's model at higher strains can be interpret as the onset of *tertiary* creep, corresponding to a different deformation mode [6]. A morphological investigation of the deformed material before and after that threshold was carried out by cutting the tensile test pieces lengthwise (i.e. in the applied stress direction) and observing the exposed section under the electron microscope. Figg. 6 and 7 show two characteristic micrographs taken on test pieces subjected to creep for the same period of time (3000 hr) up to a strain of less than and more of 0.03, respectively. In the former case deformation looks homogeneous whereas in the latter there appear to be microcavitated holes with the larger axis oriented in the applied stress direction.

In Figg. 8 and 9 the experimental data of Figg. 3 and 5 respectively are replotted according to a *Shelby-Dorn* type analysis [7], i.e. in the form of creep rates as a function of total creep strain for each constant stress level. On this kind of plot the *secondary* creep behaviour obeying *Findley's* law is represented by the negative slope portion of each curve, while the *tertiary* creep (accelerated total strain promoted by local material failure micromechanisms) corresponds to the rising portion of each curve. It appears that the onset of *tertiary* creep, corresponding to the minimum in the *Shelby-Dorn* curves, occurs at nearly the same value of the creep strain (i.e. 0.030~0.035) in both creep tests, irrespective of stress level.

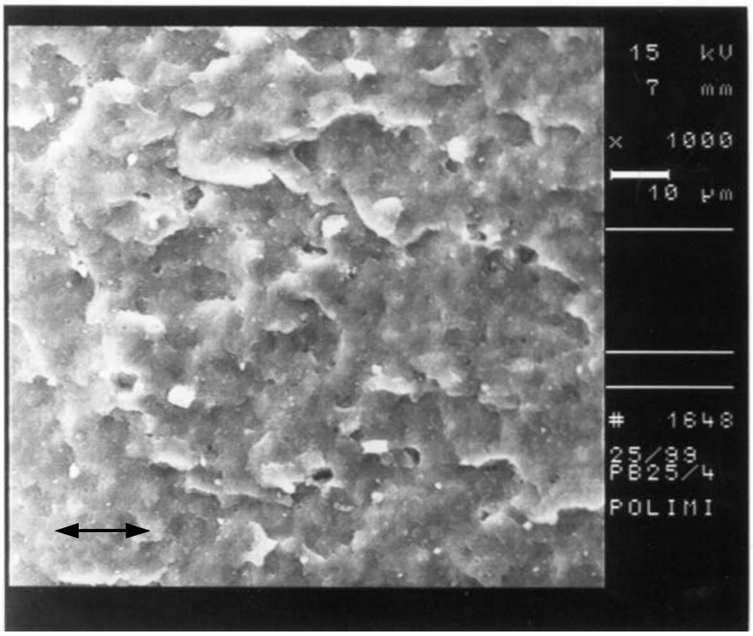

Fig. 6: Morphology of a lengthwise (direction shown by the arrow) section of a tensile test piece subjected to creep for 3000 hours under a stress of 30 MPa (total creep strain lower than 0.03).

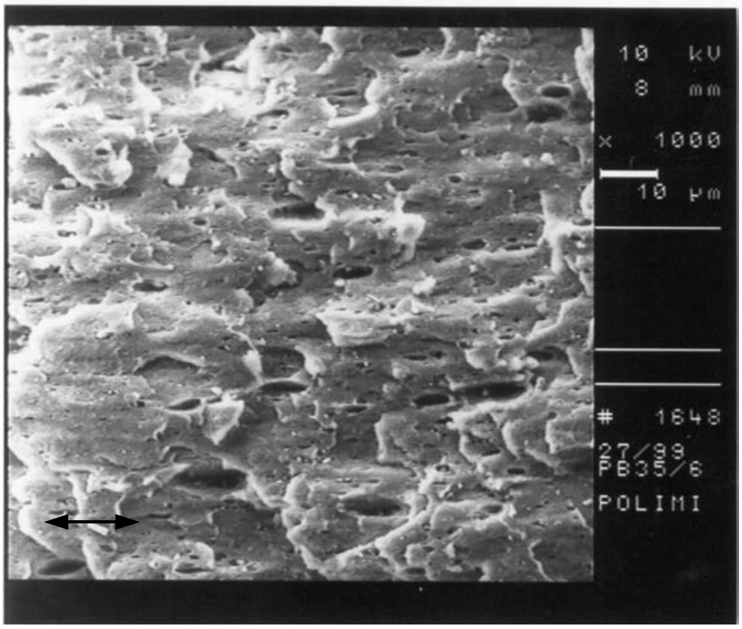

Fig. 7: Morphology of a lengthwise (direction shown by the arrow) section of a tensile test piece subjected to creep for 3000 hours under a stress of 37 MPa (total creep strain lower than 0.03).

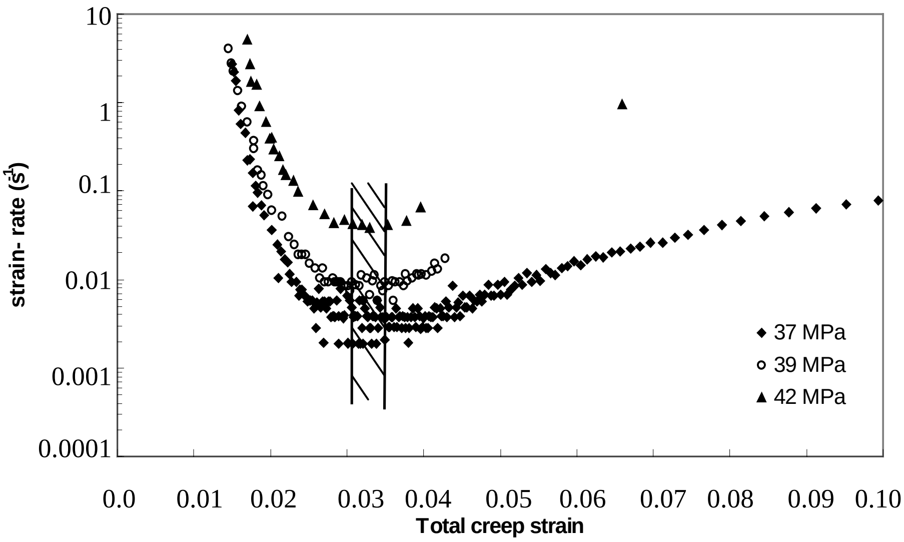

Fig. 8: *Findley's* model limit value for pressurized pipe test

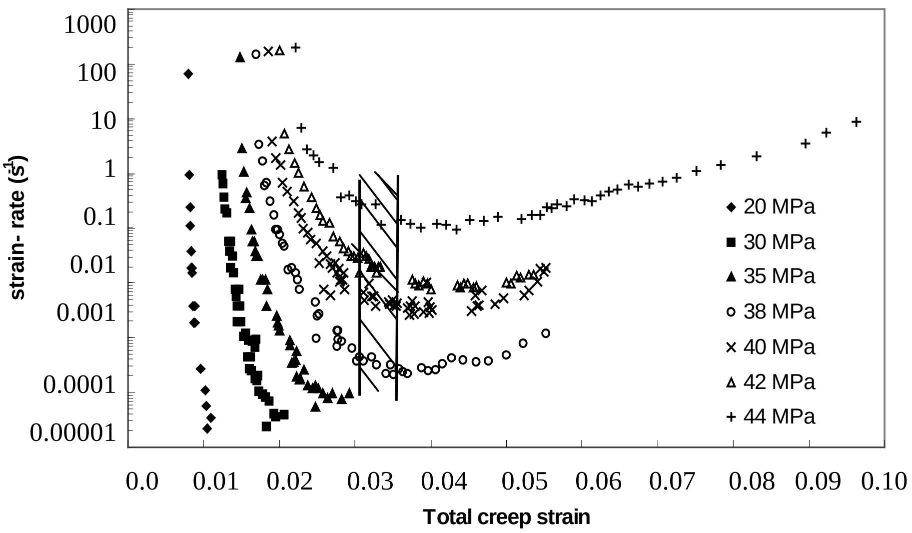

Fig. 9: *Findley's* model limit value for tensile creep test

The viscoelastic creep compliance curves, obtained under different stresses (Figg. 3 and 5), can be shifted up to full superposition so as to obtain a single *master curve* for a reference stress value. The *master curves* for the two test methods are shown in Fig. 10. The master curves for the two test methods are shown in Fig. 10 and the stress shift factors for the two cases are compared in Fig. 11.

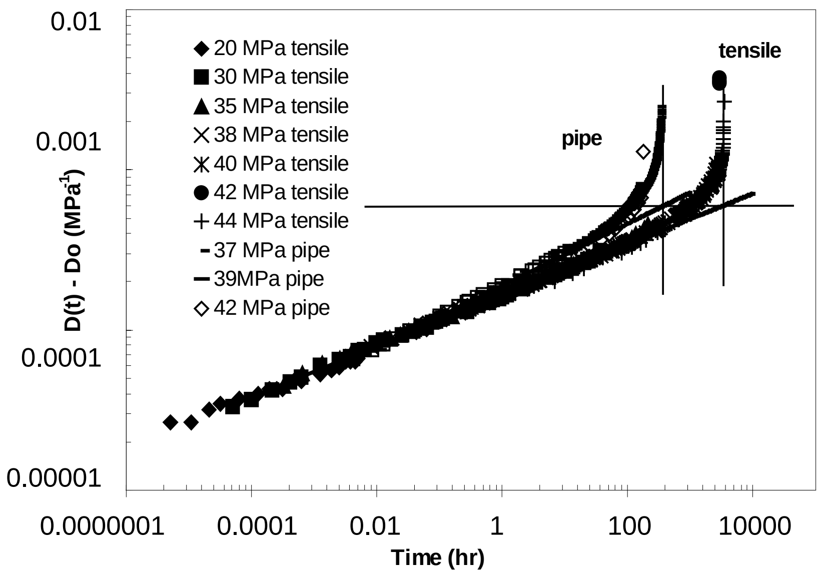

Fig. 10: Master curves of the anelastic compliance for pressurized pipe creep test at a reference hoop stress σ_h^o=37 MPa and for uniaxial tensile creep test at a reference tensile stress σ_t^o =38 MPa. Temperature 20°C.

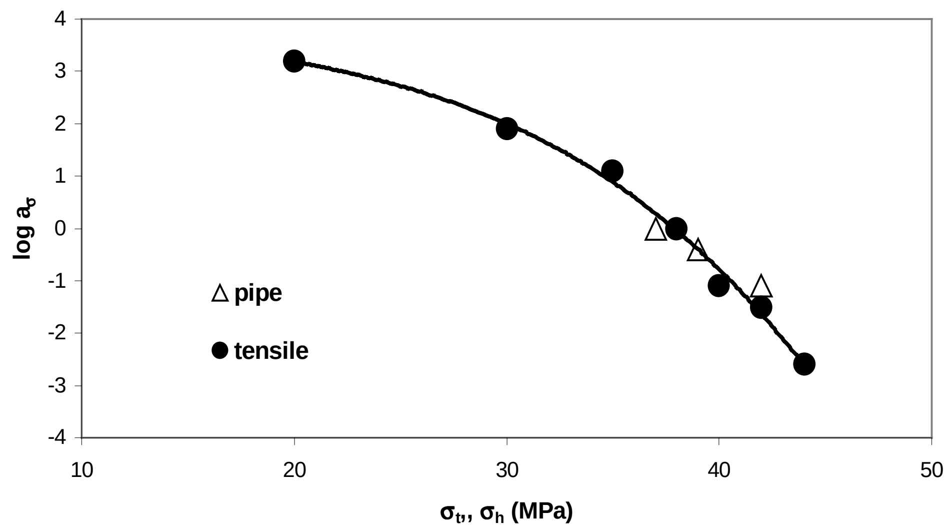

Fig. 11: Stress shift factor a_σ for pressurized pipe test, reference stress σ_h^0= 37MPa, and for tensile creep test, reference stress σ_t^0= 38MPa.

The superposition appears to be fairly good both in the *secondary* and in the *tertiary* creep regions for both test methods (Fig. 10) and the stress shift factors for the two cases compare quite well (Fig. 11) even after making allowance for the different reference stress used in the two cases.

The difference in creep rate between the two types of test already noted above brings about an increasing gap between the creep strain (or the viscoelastic compliance) in the two test: at the transition from *secondary* to *tertiary* creep at which plastic deformations onset the difference in time amounts to nearly one decade (Fig. 10).

This difference can be justified at least in part by the fact that both tests were carried out under constant nominal or engineering applied stress i.e. a value of stress defined with reference to the original dimensions of the test pieces. As creep progresses, however, the test piece dimensions change and both the *true* hoop stress in the pipe and the *true* tensile stress in the tensile specimen increase with time, but the former increases faster.

If the Poisson’s ratio of the material is known the *true* applied stresses can be estimated and a correction can be applied that would bring the creep curves and the times to failure of the two tests closer.

CONCLUSIONS

Creep tests carried out on pressurized U-PVC pipes and on uniaxial tensile specimens taken from the same pipes yield similar results, provided the true applied stresses are considered. The idea of using the simpler tensile test to predict the time for ductile failure in U-PVC pipes appears therefore promising.

ACKNOWLEDGEMENTS

Part of the experimental data presented in this work were taken from the diploma thesis submitted by P.E. Malacari and N. Gavioli to Politecnico di Milano (1999).

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