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CHARACTERISATION OF AGED HDPE PIPES FROM DRINKING WATER DISTRIBUTION: INVESTIGATION OF CRACK DEPTH BY NOL RING TESTS UNDER CREEP LOADING

C. Devilliers 1), 2), 3), L. Laiarinandrasana 1), B. Fayolle 2), E. Gaudichet-Maurin 3)

1) MINES ParisTech, MAT-Centre des Matériaux, UMR CNRS 7633, B.P. 87, 10 rue Henri Desbruères, 91000 Evry, France
2) ARTS ET METIERS ParisTech, Procédés et Ingénierie en Mécanique et Matériaux UMR CNRS 8006, 151 boulevard de l'Hôpital, 75013 Paris, France
3) Véolia Environnement, Centre de Recherche sur l'Eau, Chemin de la Digue, 78603 Maisons-Laffitte, France

ABSTRACT

HDPE pipes are used for the transport of drinking water. However, disinfectants in water seem to have a strong impact on their mechanical behaviour, limiting their lifetime in operation. Indeed, oxidation occurs when they are in contact with disinfectants leading to the formation of a thin oxidised layer coupled to the cracks initiation of cracks of different lengths from the inner wall surface. An original method is proposed here to characterise the ageing effect of the pipe mechanical behaviour. Inspired from the ASTM D 2290-04 standard, Nol Ring tests have been performed under tensile and creep loadings on smooth rings. A constitutive equation has been determined from these tests using a finite element (FE) modelling. FE simulations have been performed to study the influence of the thin oxidised PE layer. Precracked specimens with different crack depth ratio have also been modelled. The crack depth ratio is an important parameter to quantify pipe ageing.

KEYWORDS

HDPE pipes, Nol Ring creep test, ageing effects, fracture mechanism, crack depth ratio, aged layer thickness, finite element modelling.

INTRODUCTION

High Density Polyethylene (HDPE) is a widely used material for the distribution of drinking water. HDPE pipes are exposed to an internal pressure due to water flow. Furthermore, when they are in contact with disinfectants such as chlorine dioxide ClO_2 or chlorine Cl_2 (in severe conditions (T,P and concentration)), oxidation of HDPE occurs by a chain scission phenomenon. Oxidation turns out to be highly confined to the immediate surface of the inner wall in contact with disinfectants, leading to a decrease of HDPE molar mass and consequently, to a hardening as well as an embrittlement of the material [1]. The oxidised layer thickness seems to stabilize at 200 µm whatever the initial pipe thickness due to the diffusion of reactive species from the inner wall [2].

Moreover observations with a scanning electron microscope (SEM) were performed on pipes collected on site, after several years in service. A multicrack network on the internal surface in contact with disinfectants has been evidenced [2], [3]. The following scenario is assumed. Cracks initiation seems to be strongly linked to volume variations between substrate and coating: firstly, the increase of density, i.e. the shrinkage of the degraded inner surface layer constrained by the outer unchanged material generates internal stresses at the interface substrate / coating. The cracks which appear on degraded inner surface are due to an incompatibility between the initial material and the degraded layer. This step is supposed to be instantaneous. Secondly, the most noxious (deepest) longitudinal crack, will propagate under the internal pressure until the complete failure of the pipe.

To characterise the mechanical properties of pipes, the ASTM D2290-04 standard recommends carrying out tests on rings cut out from the studied pipe. It is called Nol Ring test. Initially, the standard requires carrying out tests on notched ring with a monotonic tensile loading. Laiarinandrasana *et al.* [4] showed that notches induced multiaxial stress state within the cross section of the ring. Furthermore pipes in service are submitted to an internal pressure, which is closer to a creep loading than a monotonic tensile loading. It is to be noticed that the Nol Ring test subjected to a creep loading is the simplest laboratory test that is representative of the pipe loading in service (between creep tests on dogbones specimens taken from the pipe and pipes under pressure).

In order to classify the degradation of HDPE pipes, Rozental-Evesque *et al.* [5] carried out Nol ring tensile tests and used the strain at failure as key parameter. In this study, the Nol Ring test with a creep loading will be used to characterise the pipe degradation from a mechanical viewpoint. The aim is to study the influence of the aged layer thickness and the crack depth ratio on the creep material characteristics.
To this end, creep tests were carried out at various stress levels on smooth rings and “precracked” rings with a longitudinal initial crack, with various crack depth ratios on the internal wall. Fracture mechanics concepts were used in order to quantify the influence of the crack depth ratio, compared with the effects of oxidized layer thickness.

SPECIMEN, MATERIAL AND TESTING

Material and specimens

HDPE pipes used for drinking water distribution were kindly supplied by Veolia Environnement. The main physico-chemical characteristics are summarised in Table 1. The crystallinity index X_c and the melting point T_f were determined by using Differential Spectroscopy Calorimetry (DSC) technique. Gel Permeation Chromatography (GPC) allowed measuring of the number average molar mass M_n, the weight average molar mass M_w and the Z average molar mass M_z. The Young’s modulus E was graphically estimated via stress-strain curve obtained at room temperature on small dog-bone specimens. The studied PE exhibits an initial semi-crystalline microstructure composed of spherulites. Typical spherulite diameter has been determined to be about 10 µm.

Parameters	X_c	T_f	M_n	M_w	M_z	E
Values	55%	127℃	10.2 kg/mol	206.5 kg/mol	2343.2 kg /mol	650 MPa

Table 1: Physico-chemical characteristics of HDPE pipes

Pipes dimensions are the following: length **L** = 500 mm, internal diameter $\mathbf{\Phi_0}$ = 31 mm, and thickness **T** = 4.5 mm. Rings of 12 mm in width **W** were cut from these pipes. They will be called "smooth rings" thereafter, in contrast with "precracked rings" as described below.
For precracked specimens, a crack is introduced by pushing a “cutter” blade onto the internal wall of the ring. The initial crack depth **a** is precisely measured after creep test by SEM. The crack depth ratio a/T is the parameter that be used in this study. It should be mentioned that

only one side of the ring is precracked, in order to avoid the gap between double diametrical edge cracks planes. Figure 1 shows a sketch of a precracked ring specimen.

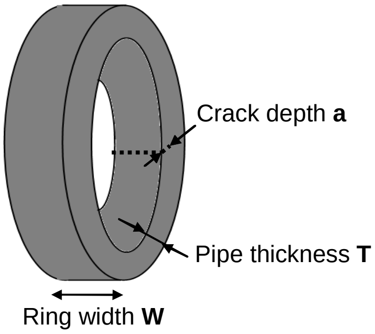

Figure 1: Precracked specimen dimensions

Testing

The specimen is loaded through two half disks, which apply tensile stress, perpendicular to the crack plane, to the ring. The system described in the standard method has been improved to prevent from disks rotation [4].

During the test, both displacement and applied tensile force as a function of time are recorded. The load cell capacity is 500daN, and displacement is measured using a LVDT (Linear Variable Differential Transformer) captor. Two kinds of loadings were studied:

- Monotonic loading: These tensile tests are conducted at three different crosshead speed of 10, 50 100 mm/min. They were devoted to study the loading step of the creep test.
- Creep loading: These creep tests are performed at different nominal stresses (between 9 and 12MPa). The loading step is carried out by controlling the load with an imposed time to loading around 1.5s. This is done in order to minimize viscoelastic effects during the loading step. The corresponding strain rate could be deduced from the experimental datafile.

EXPERIMENTAL RESULTS ON SMOOTH RING

Tensile tests

During a Nol Ring test, a bending effect occurs in the horizontal cross section, due to the loss of roundness of the ring during the loading [6]. Therefore displacement and stress fields are not homogeneous in the structure, and a multiaxial stress state can be observed in the cross section.

Nevertheless, attention is paid here on global parameters, such as engineering strain and stress. They can be defined as follow:

- Engineering strain is the LVDT displacement divided by the initial internal diameter $\mathbf{\Phi_0}$.
- Engineering stress (or nominal stress) $\boldsymbol{\sigma}_{\mathbf{nom}}$ is the measured load **F** divided by twice the initial section of the ring ($\boldsymbol{\sigma}_{\mathbf{nom}} = \mathbf{F} / (2 * \mathbf{S}_{\mathbf{nom}})$ with $\mathbf{S}_{\mathbf{nom}} = \mathbf{W} * \mathbf{T}$) to take both sides of the ring into account.

The obtained results show that global stress-strain curves are highly strain-rate dependent.

Creep tests

Four creep tests were conducted at 9.6, 10.1, 10.8 and 12.2 MPa as nominal stresses (cf. figure 2). For each test, strain due to the loading step is subtracted from the total strain, as well as loading time is deduced from the total time.

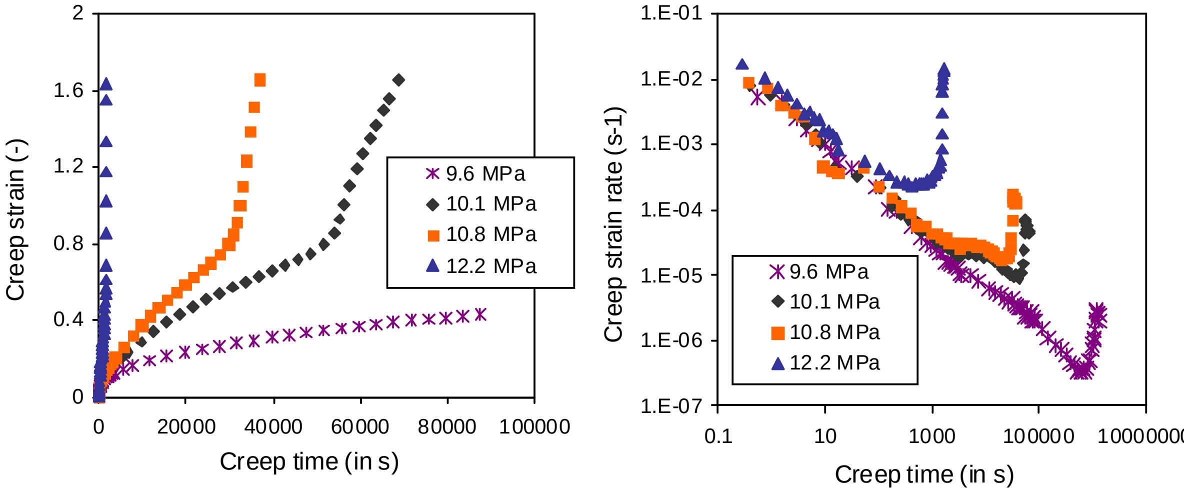

Figure 2: Global curves of creep tests: a) creep strain history and b) creep strain rate history for different nominal stresses

In this study, attention is focused on primary and secondary creep stages. Indeed, tertiary creep stage was evidenced as soon as necking appears within the ring.. Primary creep stage is characterized by a strain rate decrease until reaching a minimal value $\boldsymbol{\dot{\varepsilon}_{\min}}$, deducted from figure 2 b). The value remains constant during secondary creep stage. The complex response of the material requires a numerical modelling in order to quantify displacement and stress distributions in the ring.

NUMERICAL MODELLING OF SMOOTH RING

The in-house finite element software Z-set [7] was used to simulate all mechanical tests. Constitutive equations are integrated using an implicit scheme. As very high deformation occurs in the ring, all calculations were done using an updated Lagrangian formulation. The simulation has been performed under 2D plane strain conditions for time reduction purposes.

Mesh and boundary conditions

The mesh corresponding to the NoI ring test is presented in figure 3. For symmetry reasons, one quarter of the specimen is meshed. Metallic half disks are considered as rigid compared with HDPE rings. Then, one rank of elements is useful.

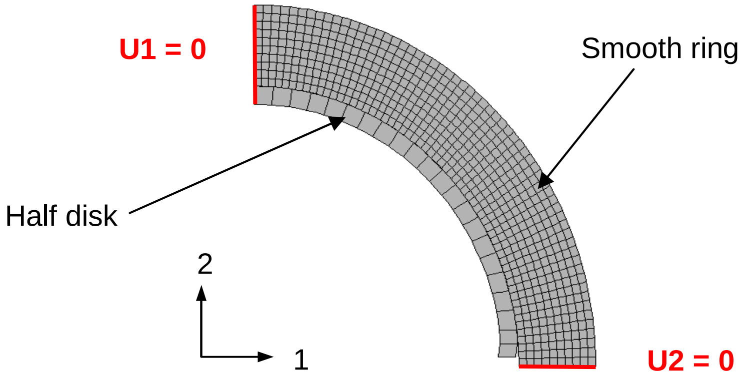

Figure 3: Mesh used for finite element analysis of smooth rings

The following boundary conditions are prescribed to ensure symmetry of the structure:

- Displacement is blocked in the 2 direction (U2) in the horizontal cross section,
- Displacement is also blocked in the 1 direction (U1) in the vertical cross section.

Contact between steel and HDPE is ensured using a Coulomb law with a friction coefficient equal to 0.6. Linear elastic law with a high Young's modulus (E = 2.1 GPa) is attributed to the half disk. Displacement for tensile test (resp. load for creep tests) is imposed on the rigid body, following the direction 2 and according to the investigated crosshead speed (resp. the nominal stress applied).

Determination of the HDPE constitutive equation

A constitutive equation for HDPE based on double nonlinear deformation model [8] has been chosen to be able to simulate creep tests as well as tensile tests. In the DID (double inelastic deformation) model, the inelastic strain $\boldsymbol{\varepsilon}_{\mathbf{inel}}$ is supposed to be split into two viscoplastic strains $\boldsymbol{\varepsilon}_{\mathbf{vpl1}}$ and $\boldsymbol{\varepsilon}_{\mathbf{vpl2}}$ with different sensitivities according to the applied stress (equation 1).

$$\varepsilon_{inel} = \varepsilon_{vpl1} + \varepsilon_{vpl2} \quad \text{Equation 1}$$

Each viscoplastic strain is modelled by a Norton flow. Details about DID model are published elsewhere [8]. Material coefficients accounting for both kinematic and isotropic hardening were successfully identified by using experimental data on monotonic tensile and creep tests (cf. table2).

Parameters	n_1	K_1	C_1	D_1	R_{01}	Q_1	b_1
Values	2.2	18	150	145.5	0.01	11.7	48.3
Parameters	n_2	K_2	C_2	D_2	R_{02}	Q_2	b_2
Values	5	44	201	145.5	0.01	5	60

Table 2: Parameters of the DID model used to simulate tensile and creep tests on smooth rings.

Figure 4 shows representative results of simulation compared with experimental data. It should be mentioned that the whole secondary creep stage was not simulated due to substantial distortion of elements located in the cross section.

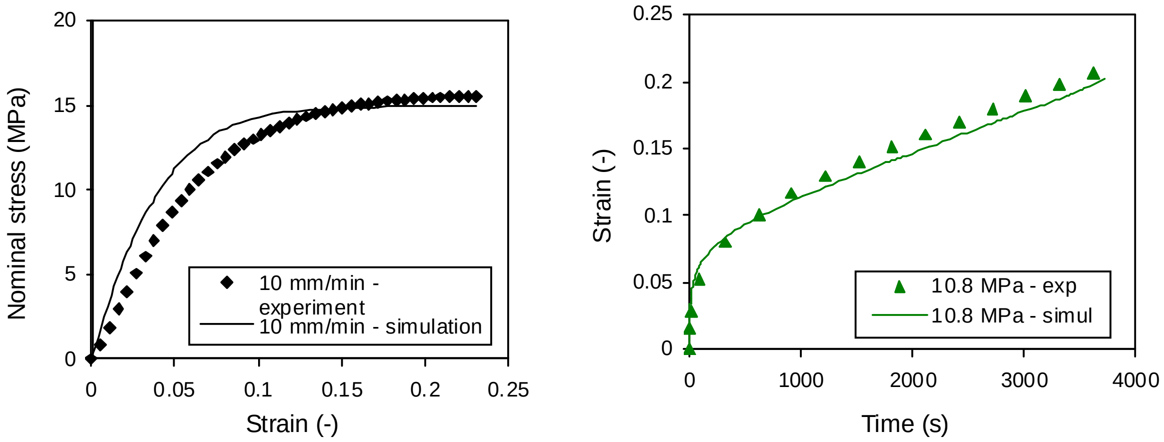

Figure 4: Comparison between experiment and simulation using a DDI model: a) tensile test at 10 mm/min, b) creep test à 10.8 MPa

Influence of oxidised layer thickness on global curves

Previous studies have shown that thin layer of oxidised brittle PE has no influence on the global response of the ring for monotonic tensile loadings. Here, the study is focused on creep loadings.

Consequently, numerical simulations of a ring with a 200 µm thick layer of brittle PE have been carried out for the same nominal stresses as for virgin PE. The constitutive equation of the oxidised layer is also a DDI model. The corresponding material parameters are determined from mechanical tests carried out on a model PE with a lower molar mass, which is supposed to be representative of a thick homogeneously aged sample of polyethylene. For each applied stress, minimum creep strain rate is determined from the creep strain history (see figure 4). Figure 5 presents the numerical results, and compares them with a ring of virgin PE in terms of creep strain rate versus applied nominal stress.

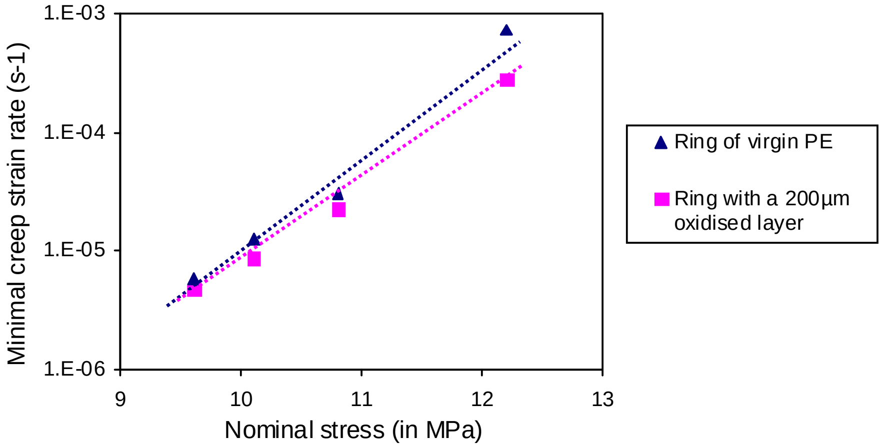

Figure 5: Influence of a 200 µm thick layer of oxidised and brittle PE on the minimal creep strain rate.

Figure 5 shows that a small influence is observed at low nominal stresses. But this difference becomes significant when the applied nominal stress is high. A lower minimal creep strain rate is an indication that the ring becomes stiffer during ageing. However, the ratio of aged layer thickness over the total thickness of the pipe (around 0.044 in our case) is too low to have a real impact on the global response of the ring. Furthermore, it was mentioned that oxidised wall exhibited crack network. Then, the following investigation attempts then to study the influence of the crack depth ratio on the creep strain rate of a virgin PE. To this end, experimental and numerical studies are combined.

FRACTURE MECHANICS APPLIED TO PRECRACKED RINGS

Geometry, mesh and boundary conditions

Experimentally, a crack is introduced on one side of the ring, so one half of the specimen must be meshed for symmetry reasons (cf. figure 6). Furthermore a refining mesh in the ligament is necessary. Concerning boundary conditions, displacement is blocked in the direction 2 for both horizontal cross sections.

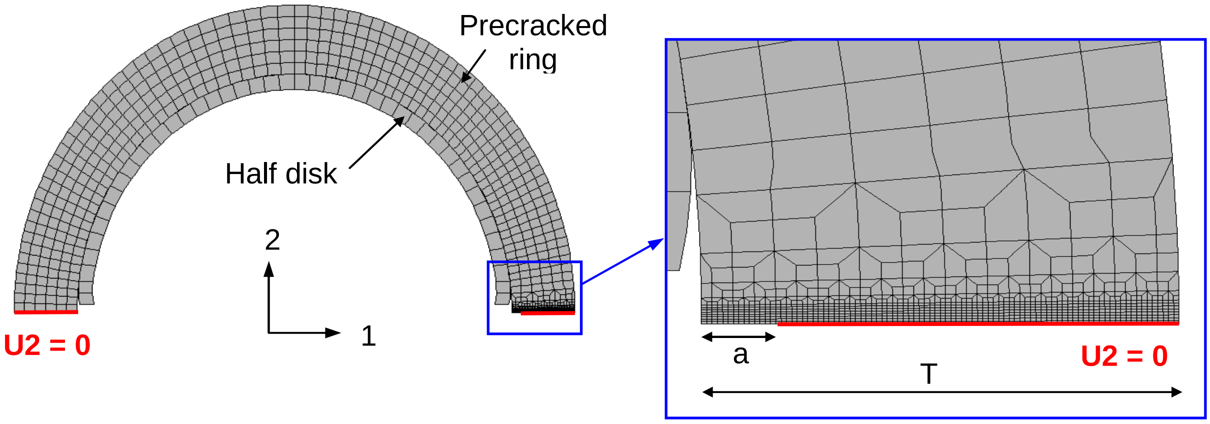

Figure 6: Mesh used for finite element analysis of precracked rings

Influence of the crack depth ratio on global curves

For precracked rings, the following terms will be used:

- Reference strain rate which is the LVDT displacement divided by the initial internal diameter $\mathbf{\Phi_0}$.
- Net stress which is the measured load **F** divided by the sum of nominal surface for the non-cracked side and the net surface for the cracked side ($\boldsymbol{\sigma}_{\mathbf{net}}$ = **F** / ($\mathbf{S_{nom}}$ + $\mathbf{S_{net}}$) with $\mathbf{S_{net}}$ = **W** * (**T**-**a**)).

Calculations were performed for different crack depth ration (a/T = 0.1, 0.2, 0.35, 0.5, 0.65) and different net stresses (9, 10, 11, 12 MPa). Figure 7 reports the minimal strain rate as a function of the a/T ratio parameterised by the applied net stress.

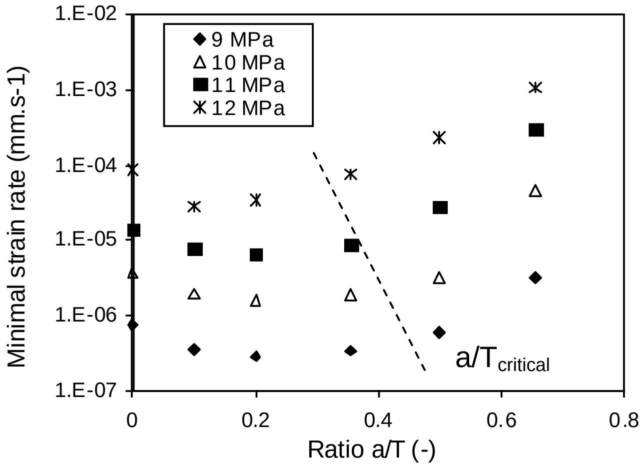

Figure 7: Influence of the a/T ratio on the reference strain rate for different net stresses

For a given net stress, an increase of the minimal strain rate is observed when crack is longer. Here a critical crack depth ratio $a/T_{critical}$ is attempted to be defined. Below $a/T_{critical}$ crack is supposed to be short and whatever the net stress value, crack blunting alleviates the stress singularity and the stress triaxiality near to the crack front. The net stress has no influence in the minimum strain rate. Conversely, for deep crack, crack blunting due to viscoplastic effect directly impacts the minimum strain rates in the sense that strain rate increases with crack depth ratio. According to figure 7, it seems that $a/T_{critical}$ depends on the net stress value: the higher the net stress, the lower critical crack depth ratio. The dashed line plotted in figure 7 represents this critical crack depth ratio.

CONCLUSION AND PERSPECTIVES

An attempt is made to characterise the ageing effect on HDPE pipes using Nol Ring tests. Tensile and creep tests on smooth rings allowed to assess parameters for the constitutive equation of the material. Finite element modelling showed that the thin layer of oxidised HDPE has very low influence on the global response of the ring. Another parameter is then investigated to characterise pipes degradation: the depth of cracks generated during oxidation. Precracked rings with various crack depth ratios are modelled. A critical value has been highlighted below which cracks have no influence on the minimal strain rate, and over which minimal strain rate increases with crack depth.

The constitutive equation used for this study does not take damage into account. First damage analyses have shown the presence of voids in the material, which are likely to grow under loading. A multimechanism model, which takes into account the initial crystallinity ratio, coupled to a damage model will be used for the next finite element simulations. Using an adapted failure criterion, the final aim is to simulate the failure of a pipe under pressure. Then, this methodology can be applied to quantify the degradation state of HDPE pipes under operational conditions (disinfectant concentration, water temperature and pressure).

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Corresponding author: clemence.devilliers@mines-paristech.fr