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PHYSICAL AGING OF BURIED PVC SEWER PIPES AS AFFECTING THEIR LONG TERM BEHAVIOUR

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The investigation has indicated that deflected uPVC pipes are subjected to a physical aging process, which gives rise to a lower rate of decrease in the E-modulus than has previously been assumed. Based upon these findings the long term ring stiffness of PVC sewer pipes is determined. Concerning the bending strength of a deflected PVC pipe, the investigation has so far not indicated any upper limit for the allowable bending strain.

INTRODUCTION

In the design of buried PVC gravity sewer pipes, the ring stiffness of the pipe S_R plays an important role in the mechanical stability of the pipe. This applies both to the prediction of the deflection of the pipe as well as to the buckling criteria, which can easily be illustrated by the following two basic equations

$$\delta / D_m = f(q)/(S_R + c_1 S_S) \qquad (1)$$

and

$$p_{bs} = c_2 \sqrt{S_R S_S} \qquad (2)$$

Eq (1) is the modified Spangler formula giving the deflection of the pipe, where δ is the vertical decrease in the central pipe diameter D_m, q symbolizes the sum of the vertical soil and traffic load and S_S stands for the stiffness of the soil. Eq (2) gives the soil pressure acting against the pipe wall, causing the pipe to fail by buckling.

The ring stiffness S_R forms the basis for classification of sewer pipes and is then defined according to the following equation

$$S_R = EI/D_m^3(1-\nu^2) \qquad (3)$$

where E is the creep or relaxation modulus, I is the moment of inertia of the pipe wall and ν is the Poisson's number.

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As can be found from eq (3), the ring stiffness is directly proportional to the E modulus, which in turn is dependent on loading time, temperature and the stress or the strain in the pipe wall. When determining the ring stiffness both a creeping as well as a relaxation procedure can be applied. In both cases the standard loading time is mostly 3 minutes and the deflection 3 %. In this way the following relation exists between the former classification of PVC pipes based upon the relation D/s and that based upon ring stiffness:

D/s	51	41	34	26	21
S_R(kN/m²)	2	4	8	16	32

The ring stiffness defined according to the above is thus a short-term value, which does not take into consideration the creep or the relaxation phenomena during long term loading. Although the short term value is the most important one for the stability of pipes buried in sandy soils (where mainly only stress relaxation takes place), it is of great interest to find the ring stiffness value when the pipe is subjected to continuously increasing deflection due to creeping. This may particularly be the case in plastic soils such as silt and clay.

Previously it had been shown in reference (1) that the ring stiffness of PVC pipes seemed to decrease dramatically in the long term. It was of particular interest to try to find out the probability of that concept. The subject was stressed further in connection with the author's work on a recently published report called "How old can a plastic pipe be?" (2). The Swedish Council for Quality Control of Plastic Sewer Pipes (the "KP-Council") therefore sponsored a study of the relaxation phenomenon in deflected PVC pipes, the results of which are briefly presented in the following. The full report is in Swedish with an English summary (3).

THEORETICAL APPROACH

For viscoelastic materials, such as PVC, we can for each stress or strain level approximately describe the time dependent relation between stress σ and strain ε by applying the classical Hooke's law. Then we can use the common E-modulus for this relation despite the fact that in the case of plastics it is not an elastic modulus we are speaking about, but a creep or a relaxation modulus. Consequently, in the relation

$$E = \sigma/\varepsilon \tag{4}$$

Where E can be called a creep modulus, where the stress would be constant and the creeping free. If instead the strain was constant, we could refer to a relaxation modulus. In both cases the E-modulus will decrease in the course of the loading time due to an increase in the strain (creeping) or decrease in the stress (relaxation), respectively. The numerical values of the two E-moduluses are approximately equal.

For the purpose of further discussion, it is preferable to refer to the in-verted value of E or

$$1/E = \varepsilon/\sigma = C \tag{5}$$

Let us now assume that we will present the stress relaxation compliance (constant strain) in a lin C/log t diagram, where t is the loading time. Then, in principle, we can obtain at least three different curves according to Figure 1.

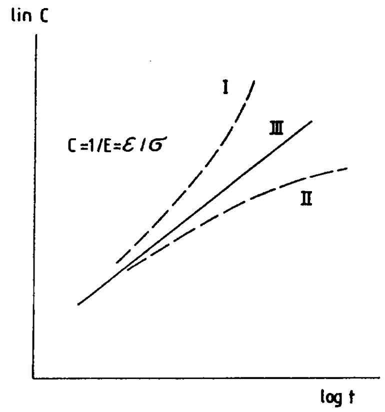

Figure 1 Principal curvatures for the lin C/log t relation.

Curve I means that C will reach infinity before the time does, or in other terms: the E-modulus may be zero within a practically limited time. If this occurred for PVC, it would be hardly possible to use the material for structural purposes, where long term strength is required. Curve II implies that C is approaching a constant value (and by that the E-modulus) within a reasonable time. This means also that the stress will not relax fully, but remain at a constant value in the long term. This would in turn imply that the visoelastic material had transformed into an elastic material after a certain time. This seems less probable. Finally, curve III, which is rectilinear, means that C will approach infinity when the loading time does. Consequently, the stress will not have relaxed to zero until after an infinitely long loading time. Also the E-modulus will then be zero.

Thus, could it be proved by long term tests that C is not following the curve I type, but rather the rectilinear curve III type, then the long term E-modulus (and consequently the ring stiffness) will be easily predicted based upon a rectilinear extrapolation of the C-curve. The intersection of the C-line with the vertical line representing, say 50 or 100 years, will then give a C-value, which, after inverting, gives the relaxation modulus at that time.

The same concept should theoretically be applicable in the case of constant stress and free creeping. Struik (4) has shown that amorphous materials, such as PVC, when subjected to constant tensile stress, will undergo a physical aging process demonstrated by the occurrence of a rectilinear C-curve after a certain loading time. This time, after which the rectilinear behaviour should occur, was assumed to be related to the age of the material at the time when stressing is commenced.

In several studies performed by the author it has been shown that a satisfactory rectilinear C-curve is achieved for crystalline HDPE and MDPE pipes subjected to constant tensile stress, but then mostly immediately after stressing commences and independent of the age of the material; references (5) and (6).

The aim of the present study was to try to find out whether a physical aging process is also present in the case of constantly deflected PVC pipes, in which the pipe wall is subjected to a constant bending strain and consequently the bending stress is relaxing in the course of time. In such a case it should be anticipated that the primary upwards bending of the C-curve in a lin C/log t diagram, will successively turn to a straight line.

TESTS

For testing, regular uPVC sewer and pressure pipes with a nominal external diameter of 315 mm were used. The length of each pipe sample was equal to the diameter. The samples were deflected permanently to a certain amount by applying opposing linear loads on the pipe. The force P needed for keeping the deflection constant was measured in an Instron loading machine at various time intervals of up to 10,000 hours (14 months).

The E-modulus was calculated according to eq (6)

$$\delta/D_m = 0.0186\ PD_m^2/EI \qquad (6)$$

The permanent bending strain ε prevailing in the pipe wall during the test was assumed to follow eq (7).

$$\varepsilon = \sigma/E = 4.28(\delta/D_m)(s/D_m) \qquad (7)$$

In this equation, s stands for the pipe wall thickness.

Eq (7) can be compared with the one found applicable for normal plastic sewer pipes buried in the ground and in which the factor 4.28 is increased to 6. (Had the loading implied a pure elliptical deflection shape, this factor would have been 3.)

The following table shows the bending strains (in %) in the pipe sample as a function of deflection and actual ring stiffness (in kN/m²).

Deflection	Ring stiffness (kN/m²)		
δ/D_m (%)	L 2(2.4)	T 8(9.5)	P 32(41.4)
5	0.43	0.67	-
15	1.3	2.05	3.46
25	2.2	-	5.76

(The values in brackets refer to the actual measured standardized ring stiffness for the various samples.)

Thus, a total of seven constant bending strains were studied with a doubling of the samples for each strain level. The samples were stored in an air-condioned chamber throughout the entire testing time at a temperature of +23°C±0.5°C.

The material for the pipes used was examined with regard to K-value, Vicat point, density and the amount of filler content. (All samples had K-values between 67 and 69, Vicat points in the range of 83°C and densities between 1,410 and 1,440/m³.) Furthermore, the frozen-in stresses were measured at the start and at the end of the test period. The ring stiffness for non-loaded samples was also measured at the start and at the end of the test period.

TEST RESULTS

Determined E-modulus according to eq (6) and corresponding C-value were graphically reproduced in diagrams of the type illustrated here as examples in Figure 2 and Figure 3. From these diagrams it can easily be proved that for all samples investigated the first part of the C-curve courses are in accordance with curve I in Figure 1. Should such a curvature continuously prevail in the long term, the PVC material could not be used easily as a structural material, as was already pointed out above. However, it is also shown that after a certain time the C-curve tends to be more or less rectilinear. This means, in such a case, that the material has successively increased its ability to function as a structural material.

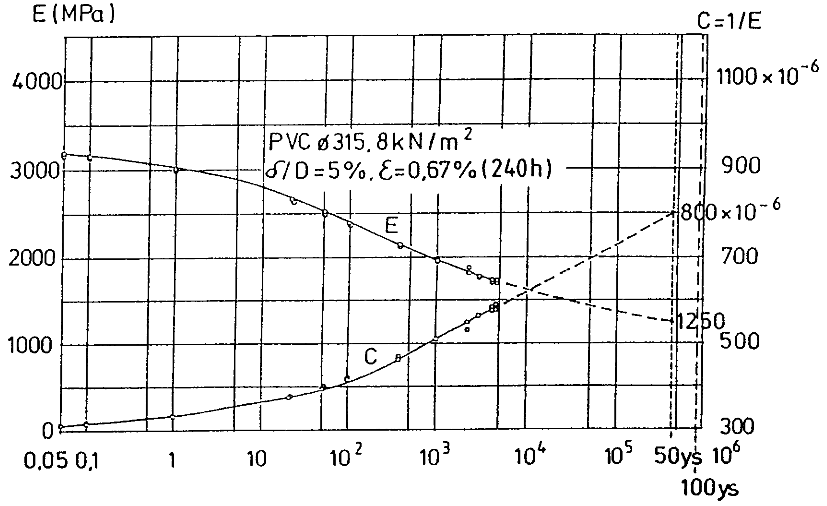

Figure 2 Relaxation modulus E and the compliance C for constantly deflected PVC pipe as a function of time. The pipe age was 240 h when the test was started.

In Figures 2 and 3, linear extrapolation of the C-curves has been made to 50 years. By inverting the C-values thus obtained, corresponding E-values are determined. A helpful support is consequently achieved for extrapolation of the E-curve over the last decades not invested. As predicted, the E-curves start to decrease in slope when the C-curve begins to be rectilinear. The E-values at 50 years are also larger than we have previously had reason to believe, which is obviously due to the physical aging process.

The E-values found from the tests have been plotted in Figure 5 as a function of the bending strain in the pipe wall and the loading time. On the x-axis the corresponding stress has been given according to Hooke's law. A correction scale has been inserted bearing in mind the deviation from the rectilinear relation between stress and strain in the viscoelastic material. As can be seen, the stress decreases in the course of time due to relaxation. In the diagram the origin point respresents infinity when the stress has fully relaxed.

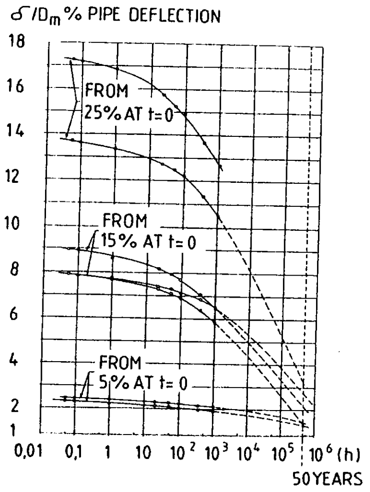

Figure 6 Pipe deflection recovery when releasing the pipe samples after 10,000 h loading.

In Figure 6 the recovery of the pipe deflection is illustrated when unloading some of the pipe samples after 10,000 hours. As can be seen, the pipe material has kept its original viscoelastic property, as the recovery is very rapid and tends to be almost complete in the long term. This also shows that despite the very high deflection of up to 25 % and strains up to 5.8 %, no pipe failure or cracks have occurred within the testing time of 10,000 hours. Today some samples have been kept deflected for a total of 2 years, still without cracks. A hypothesis could be that the reason why the pipe does not fail is the fact that the stress is not constant but decreases all the time due to relaxation. If this is true, there should be no reason to believe that the pipe will ever fail. However, preliminary tests seem to show that the condition in order for the hypothesis to be true is that the

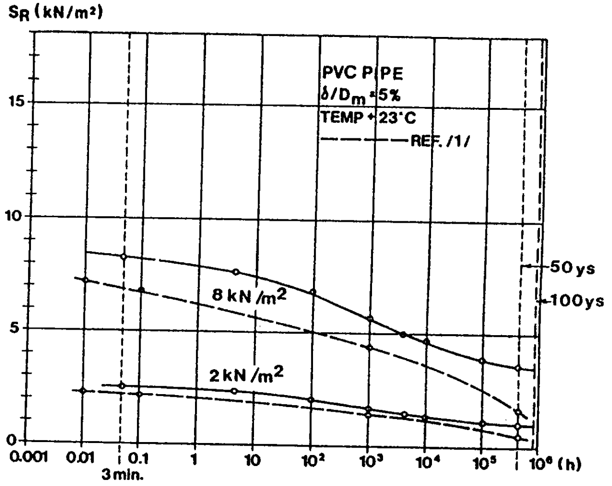

Figure 7 The ring stiffness according to eq (3) as a function of time for uPVC samples found in the present investigation (full lines), compared with the same given in ref (1) (dotted lines).

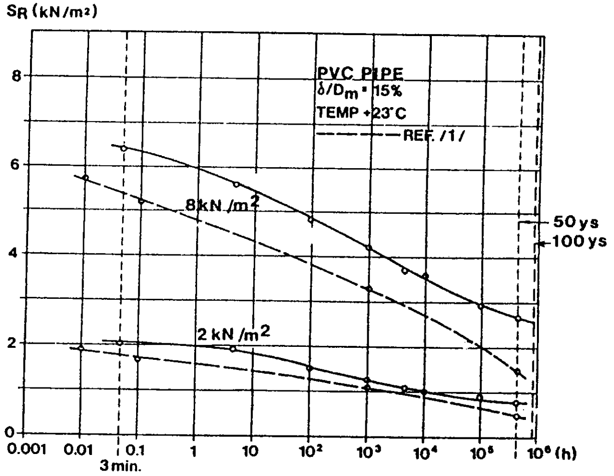

Figure 8 The ring stiffness according to eq (3) as a function of time for uPVC samples found in the present investigation (full lines), compared with the same given in ref (1) (dotted lines).

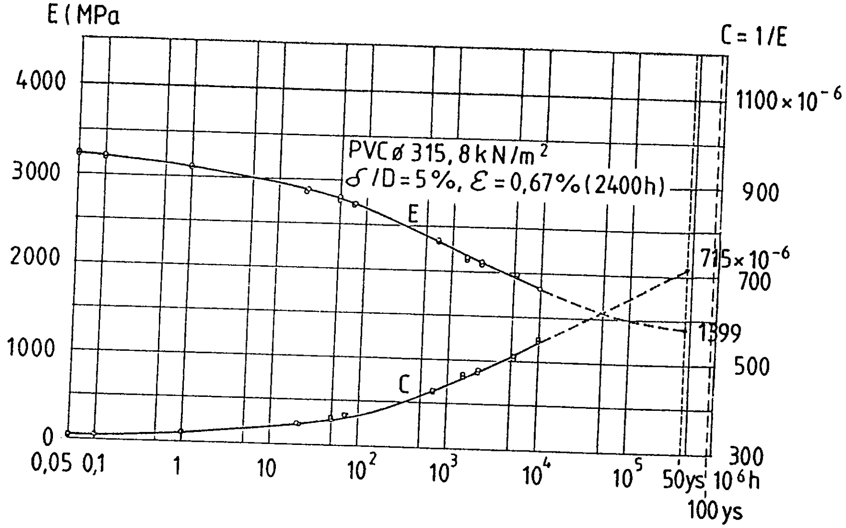

Figure 3 Relaxation modulus E and the compliance C for constantly deflected PVC pipe as a function of time. The pipe age was 2,400 h when the test was started.

Consequently, after a certain period of bending stressing the meaurements appear to show a successive move from an upward curvature of Type I to a rectilinear relation of Type III between C and the loading time (lin C/log t). The transmission from Curves I to III coincides simultaneously with an occurrence of an inflection point in the lin E/log t relation. This inflection point seems, however, to be more difficult to discover than the corresponding commencement of the linear course of the lin C/log t relation.

The occurrence in time of the transmission zone where the curve I turns to curve III dissimulates from case to case, as can be found from Figures 2 and 3. Consequently, it was natural to try to systematize the various observations based on the age of the samples when the testing commenced. The age of the pipe samples after extrusion varied between 24 hours and 10,000 hours. Thus, in Figures 2 and 3 the age of the pipe after extrusion is given at that time when the test stressing first started. (The time is indicated in hours within the brackets in the diagrams.)

The assumption formulated by Struik (4) did not appear to be contradicted in the present study. Thus, this means that after a primary stressing the pipe material will change from a stage of unpredictable behaviour (curve I) to a predictable one (curve III). The occurrence of this transmission zone indicates that the material has been subjected to a strengthening procedure, referred to as being due to a physical aging of the material.

Obviously some type of aging procedure occurs even if the material is not subjected to stress. Thus, in Figure 4 the change in the short term ring stiffness is plotted for unloaded pipes (nominal short term ring stiffness 8 kN/m²) of different ages after extrusion (ages from 7 hours to 14 months). It can easily be found that after storing for 50 years a ring stiffness measured for a pipe, say ten days after extrusion, will probably have increased its ring stiffness by approx 20 %.

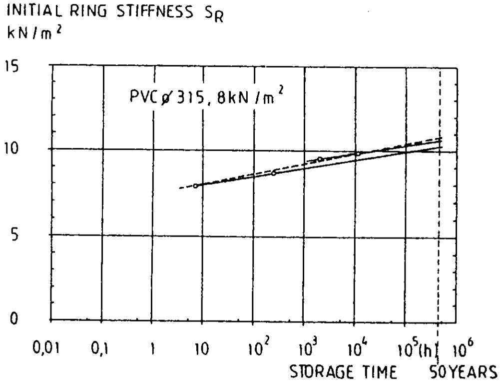

Figure 4 Increase in the initial ring stiffness as a function of time due to physical aging of the pipe material.

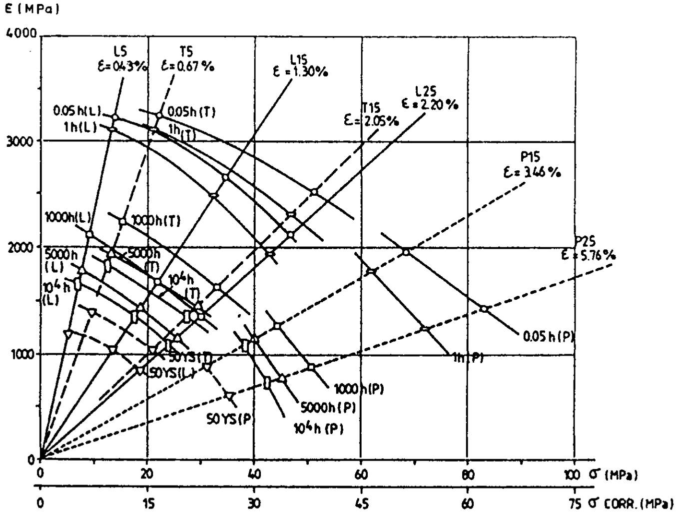

Figure 5 Measured relaxation modulus E=f(ε, σ) for constantly deflected uPVC pipes. Testing time 10,000 h at +23°C. L=2 kN/m², T=8 kN/m² and P=32 kN/m². The numbers after L, T and P stand for the pipe deflection in %.

PVC material is unplasticized and contains only a small amount of filler. In such a case, the present study (with strains up to 10 % in an extended part of the study) does not indicate any upper limit for the bending strain, which should not be accepted as far as the long term material strength is concerned. However, from a practical point of view, it is recommended not to exceed a bending strain of 2.5 %.

The E-values given in Figure 5 can now be used for determining the ring stiffness according to eq (3) as a function of the loading time. In Figure 7 and Figure 8, the full lines represent the result from the present study. The nominal stiffness class for the pipes is in this case 2 kN/m^2 and 8 kN/m^2, and the constant pipe deflection is 5 % and 15 % respectively. As can be seen, the ring stiffness curves now show a significantly lower rate of decrease than was previously assumed in reference (1). It is also of particular interest to see how the difference between the ring stiffness for 50 years and for 100 years is practically insignificant.

REFERENCES

1 Janson, L-E. Proc Int Conf Advances in Underground Pipeline Engineering. ASCE. Madison, USA.

2 Janson, L-E. "How old can a plastic pipe be?" The Swedish KP-Council. Stockholm. Report No 1 Oct 1987. In Swedish.

3 Janson, L-E. "Investigation of the relaxation Modulus for PVC pipes subjected to forced constant deflection". The Swedish KP-Council, Stockholm. Report No 2. Dec 1987. In Swedish with an English summary.

4 Struik, L C E. Physical aging in amorphous polymers and other materials. - Ph D Thesis, Technical University, Delft, 1977. Elsevier, Amsterdam (1987).

5 Bergström, G, Holmström, A and Janson, L-E. A study of the aging of a long term stressed submarine outfall pipe of HDPE. - VBB-Report Nov 1986. In Swedish with an English Summary.

6 Janson, L-E. Report on long term testing of MDPE pipe Ø1000 PN4 DGDS-0909 subjected to internal hydraulic pressure. - VBB-Report for Neste. Jan 1988. In Swedish.

RECENT DEVELOPMENTS IN THE DESIGN OF UNDERGROUND PLASTICS PIPES

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