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Long-term behaviour of buried PVC sewer pipes

by Lars-Eric Janson, D.Sc., Professor, VBB Consulting Group,
Stockholm, Sweden

Presented by Ingemar Bjorklund.

Abstract

At the International Conference on Plastics Pipes VII in Bath 1988, a paper was presented by the Author called: "Physical ageing of buried PVC sewer pipes as affecting their long-term behaviour". The tests performed on constantly deflected pipes referred to at that time had been running for approximately one year. Today, main results are available after nine years of testing. As expected this long-term study has given a more safe basis for the assessment of the behaviour of buried PVC pipes than presented seven years ago. In particular, the ageing effect of the amorphous PVC material has been confirmed, implying that the short-term ring stiffness of the pipe will increase in the course of time.

1 Introduction

Seven years ago a paper was presented by the Author at the VII Conference on Plastics Pipes in Bath [1] dealing with the long-term behaviour of constantly strained PVC pipes (PVC-U 250). At that time "long-term" applied to a time period of one year. Today test data are available totally for almost nine years. Based on these additional data, the original theoretical approach is now scrutinized and evaluated. The laboratory tests have been performed at the Swedish National Testing and Research Institute (SP) in Gothenburg based on a programme made by the Author. The study was supported by the Swedish Independent Council for Quality Control of Plastics Pipes (the KP-Council).

The investigation has focused on the stress relaxation procedure in parallel-plate loaded constantly deflected PVC pipes, combined with the physical ageing effect recognized for amorphous polymer materials. As a result of the consolidation of the molecular structure (which is assumed to give rise to the physical ageing effect) it was anticipated that a linearity should appear between the inverted value of the relaxation modulus (or of the stress, as the strain is constant) and the loading time plotted in a lin (1/E)/log t graph. If so, it would be possible to make extrapolation to periods extensively exceeding the testing time and consequently describe the long-term stress relaxation procedure in full. The strain design criterion for constantly deflected PVC pipes could then also be subject to a theoretical prediction.

For description of the test procedure and basic pipe material data, etc. please see ref [1]. In ref [2] results obtained after approximately five years of testing are discussed for the full research programme. In the following, the further results are presented and discussed for some relevant parts of the investigation. - All tests (as well as storing of pipe samples during the nine years period) were performed at an air-conditioned controlled room temperature of 23° C.

2 Stress relaxation

Some of the constantly deflected PVC pipe samples, had a deflection of 5 % and a corresponding bending strain in the pipe wall of 0.67 %. All these pipes had a nominal short-term ring stiffness of 8 kN/m². In **Figure 1** the measured E-modulii (relaxation modulus) are plotted as a function of the logarithmic loading time. The inverted value of E, e.g. 1/E called C, is also plotted. (The pipe age was 2400 h in this case when the test started.) In [1] (see Figure 3 on p 28/6) test data were available up to 10,000 h (approx 1 year). Already at that time, the predicted rectilinear course of the lin C/log t relation was recognized and as such extrapolated to 50 years. The additional observations up to 78,000 h (approx 9 years) now plotted here in Figure 1 verify the rectilinear C-curve, although the direction of the line has been given a minor adjustment upwards. Thus, the former C_{50}-value was 715×10^{-6} giving an E_{50}-modulus of 1399 MPa. Now the C_{50}-value is more likely to be 750×10^{-6} (5 % increase) and the corresponding E_{50} equals 1333 MPa, which is 41 % of the short-term (3 min) E-modulus of 3237 MPa. Observe that it is the recognized rectilinear course of the C-curve, which makes it possible to (indirectly) extrapolate the E-modulus to 50 years and even 100 years or more. Thus a C_{100}-value of 783×10^{-6} deduced in the graph should give an E_{100}-modulus of 1277 MPa, etc. As can be found, the change during additional 50 years up to 100 years is insignificant from a practical point of view.

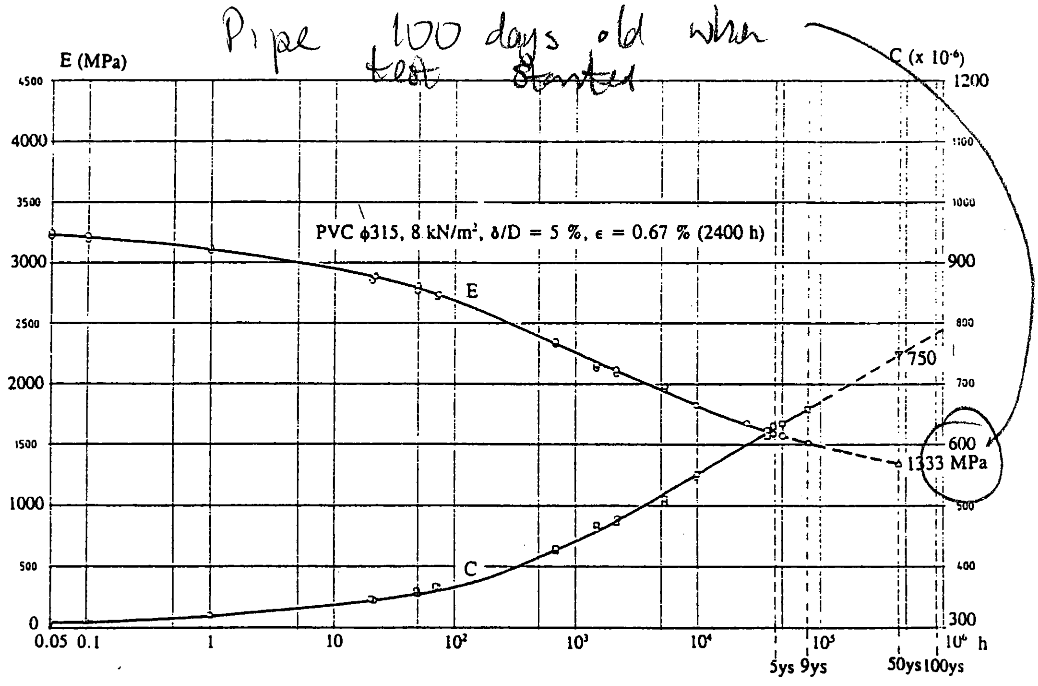

Pipe 100 days old when test started

Figure 1 Relaxation modulus measured during 9 years of constant pipe deflection. Temp + 23°C

It has furthermore to be understood that the decrease of the E-modulus in the course of time does not stand for a change of the physical strength property of the pipe material. Thus, the ring stiffness of the pipe is all the time the same corresponding to the short-term value. On the other hand, as the bending stress σ in the pipe wall is at each time directly proportional to E, e.g. $\sigma = \epsilon E$ and the bending strain ϵ is constant, the E-curve simulates the decrease or relaxation of the bending stress in the course of time. Consequently, by multiplying the plotted

E-values with $\epsilon = 0.67$ %, the corresponding bending stress is obtained as a function of the loading time. This type of analysis can also be used for predicting the further long-term stress relaxation. Hence, provided the C-curve continues to be rectilinear, C will successively reach infinity, but not until time does. As $C = \epsilon/\sigma$, this means that the stress relaxation procedure rests for ever, and that the stress, from a theoretical point of view, should approach zero, however, not until after infinitely long time.

This finding has been used in [2] as a basis for a hypothesis to the effect that, independent of the magnitude of the bending strain, no cracking or failure should ever occur as the molecular structure adjust itself to the continuously relaxation of the bending stress. However, the hypothesis is limited to be applicable only for the high quality materials tested, e.g. PVC-U resins based on K-values and Vicat points exceeding 65 and 80° C, respectively; and of course only as long as the chemical stabilisation system of the resin is intact. (It is of particular importance in this connection to state that the favourable behaviour recognized for these well specified high quality materials cannot be expected to be applicable for low molecular weight resins and particularly not for recyclable materials. Thus, extensive studies have to be performed until the long-term behaviour of such resins can be predicted.)

In **Figure 2** another test with the same deflection and bending stress is illustrated, which also was presented in [1] (see Figure 2 on p 28/5), but then after only 5000 h of investigation. (In this case, the pipe age was 240 h when the test started.) Today test results are available after 68,000 h (approx 8 years). Also in this case, the originally drawn rectilinear C-curve can be recognized, however, with a slight increase of C_{50} from 800×10^{-6} to 825×10^{-6} (3 % increase). The corresponding E_{50} will then consequently decrease from 1250 MPa to 1212 MPa. This latter E_{50} is 38 % of the short-term (3 min) E-modulus of 3167 MPa.

Pipe 10 days old when test started

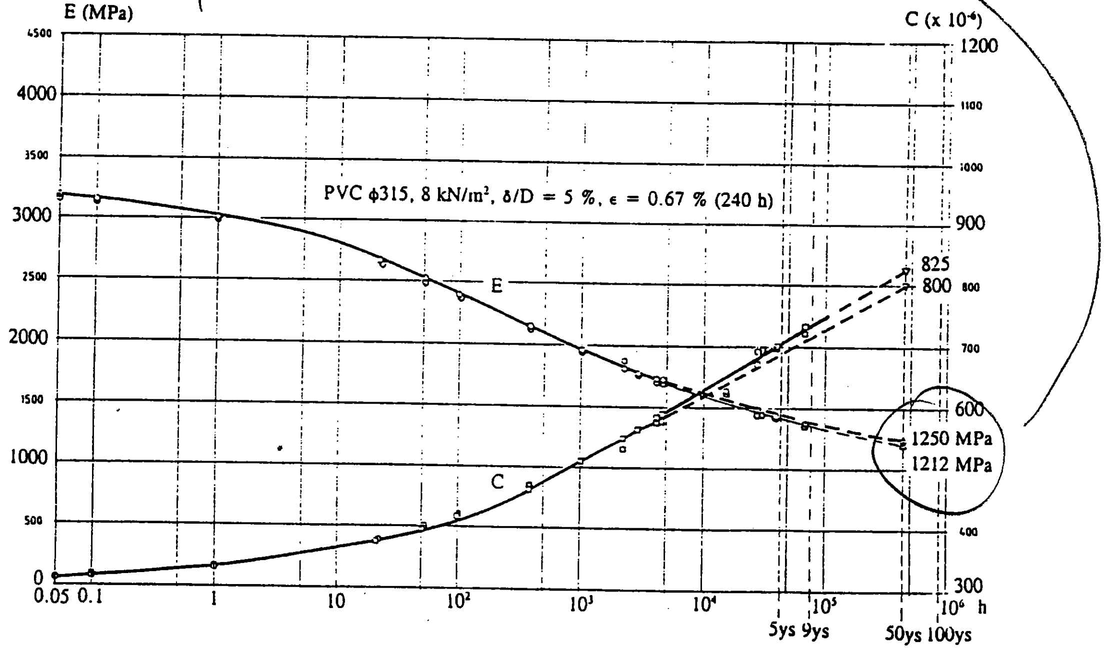


Figure 2 Relaxation modulus measured during 8 years of constant pipe deflection. Comparison is made of extrapolated values after 5000 h testing with the same after 8 years of testing. Temp +23°C

Finally in this series, **Figure 3** is illustrating a test, still with the same deflection and bending strain, but with samples taken from a newly manufactured pipe having an age of only 24 h when the test started. The first prediction of the long-term C- and E-values was in this case also performed after 5000 h, giving C_{50} = 853x10^{-6} and E_{50} = 1172 MPa. Now, after 8 years C_{50} has been deduced to 870x10^{-6} (2 % increase) corresponding to E_{50} = 1149 MPa. This latter value is 39 % of the short-term (3 min) E-modulus of 2937 MPa.

In **Table 1** a comparison is made for the three tests, the only difference between the samples being the age of the pipe when the tests started.

Table 1

Age of pipe (h)	$E_{3\,min}$ (MPa)	$E_{50\,ys}$ (MPa)	Correction of C_{50} after 8-9 years of testing as compared with earlier prediction
2400	3237 (100)	1333 (100)	+ 5 %
240	3167 (98)	1212 (91)	+ 3 %
24	2937 (91)	1149 (86)	+ 2 %

As can be seen, both short-term and long-term E-modulii decreases somewhat with decreased original age of the pipe sample. The need for correction of the predicted long-term C-value seems to increase with the age of the pipe. This does not contradict the theory of physical ageing of amorphous polymers, meaning that the rectilinear course of the lin C/log t-curve should commence first after a period of time exceeding the age of the pipe when starting the test.

Pipe 1day old when test started

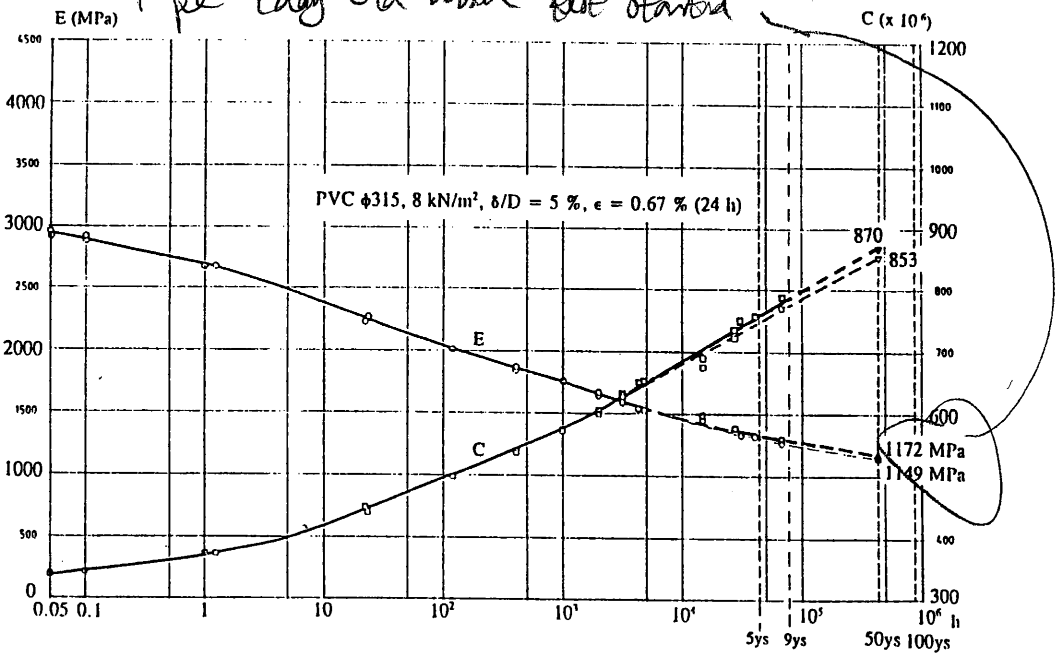


Figure 3 Relaxation modulus measured during 8 years of constant pipe deflection. Comparison is made of extrapolated values after 5000 h testing with the same after 8 years of testing

3 Stress/strain relations

Based on measured E-modulii as a function of loading time with the constant strain as parameters, it has been possible to deduce stress/strain graphs of the type illustrated in **Figure 4** valid for the PVC pipes discussed above, having a short-term ring stiffness of 8 kN/m^2. The ring stiffness S_R is a linear function of the E-modulus, here defined according to the formula

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

where I = moment of inertia of the pipe wall.

In this case, it is easy to recognized the relaxing bending stress values at $\epsilon = 0.67$ % (5 % deflection of the pipe) as deduced from Figure 1. Thus, it can be found that the initial (3 min) bending stress of 0.0067x3237 = 21.5 MPa will relax to 0.0067x1333 = 8.9 MPa after 50 years and to 0.0067x1277 = 8.5 MPa after 100 years. The similar type of deduction of the stress relaxation course can of course be performed for any constant bending strain. Consequently, what will happen in the long-term space is covered within the area of the graphs below the 100 years curve. This means that the horizontal strain axis simulates the infinite loading time as at that time the stress has relaxed to zero. (The statement provides that the so-called viscous part of the total strain is negligible).

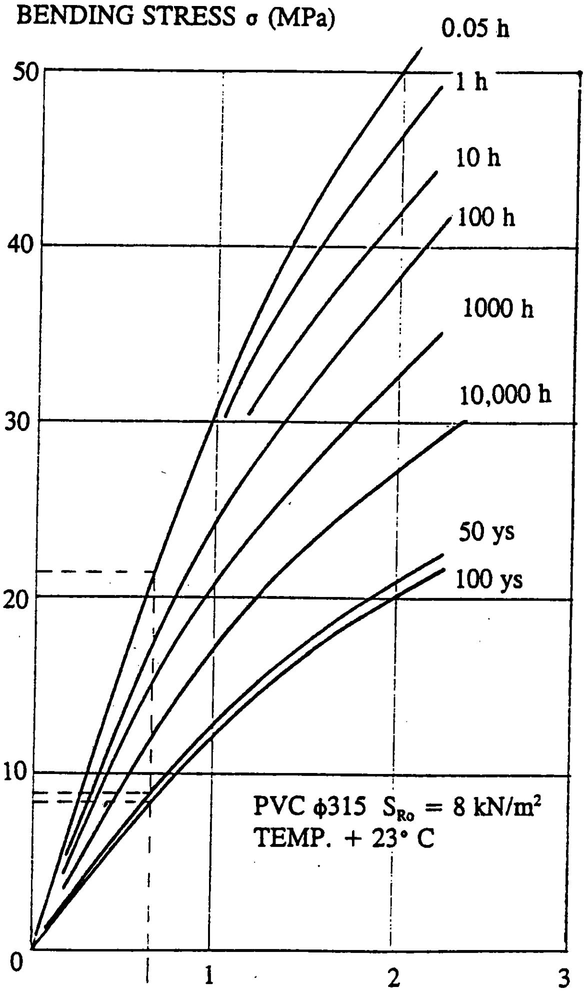


Figure 4 Stress/strain curves for constantly deflected pipes. The graph is deduced from measurements of samples with constant bending strains of 0.67 % and 2.05 %. Age of samples: 2400-4100 h when the tests started

Increased ring stiffness with time
for unloaded pipe

4 Physical ageing effects

In [1] it is shown that an increase of the initial short-term ring stiffness S_R is taking place in the course of time, even if the pipe is not subjected to stress. This increase of S_R is assumed to be due to the physical ageing process of the pipe material, which in turn is referred to as a consequence of a consolidation of the molecular structure of the polymer followed by a volume decrease [3] . Hence, it was found in [1] that the initial ring stiffness measured 10 hours after manufacturing of the pipe might increase by approx 20 % after 50 years. The measurements were performed on three samples of PVC sewer pipes with a nominal ring stiffness of 8 kN/m². One sample had an age of seven hours (TY) when the first measurement was made. The second and third had an age of 240 hours (TY) and 2400 hours (T), respectively. In [1] the ageing was followed up for approx 10,000 hours, while the ring stiffness has now been checked after additional 30,000 hours on pipe samples stored unloaded in the climate room at a temperature of +23° C. The result of the total measurement series is illustrated in **Figure 5**. As can be seen, the first and second samples (TY samples taken from the same manufacturing series) show an increase from approx 7.9 kN/m² to 9.3 kN/m² after approx 40,000 h and to 9.5 kN/m² as extrapolated to 50 years. Thus, the 20 % ring stiffness increase for a 10 hour old sample up to 50 years is not contradicted after this longer time of

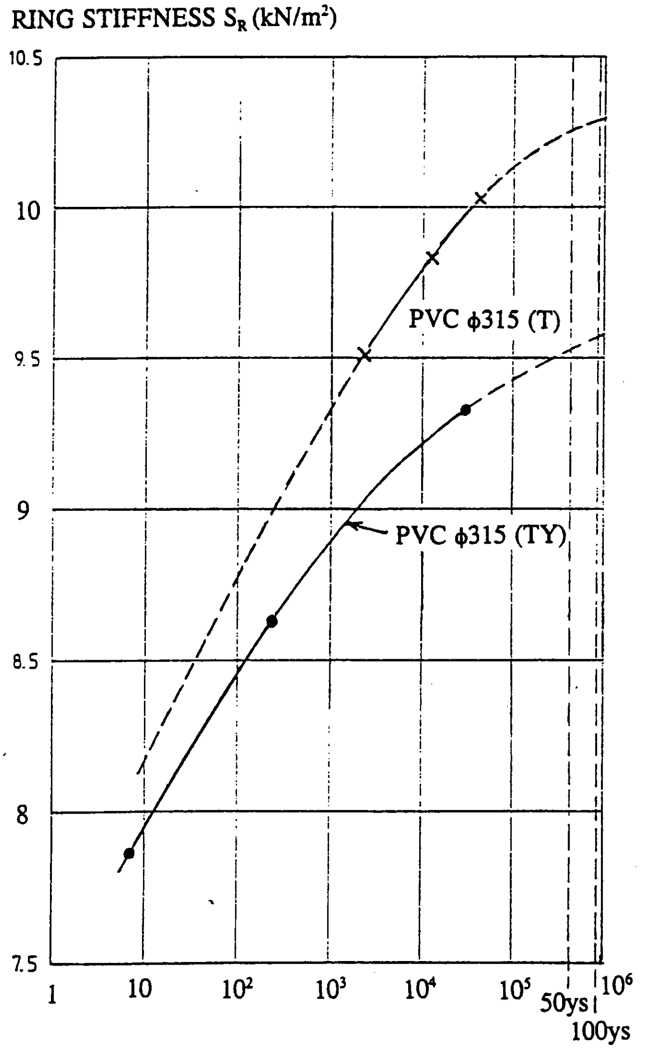


Figure 5 Increase of the initial ring stiffness as a function of time due to physical ageing of PVC pipes

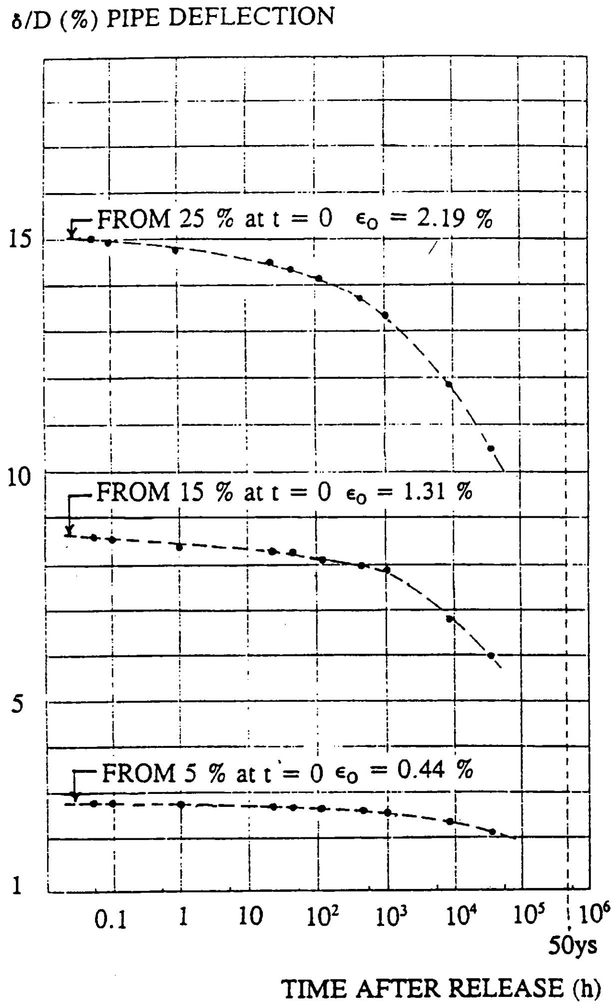
observation. The statement seems to be further confirmed by the study of the third sample belonging to another older series of pipe delivery and which had an age of 2400 hours (T) when the ring stiffness was first measured to 9.5 kN/m^2. After 10,000 h the ring stiffness was found to be 9.8 kN/m^2 and after 42,000 h approx 10 kN/m^2. In Figure 5 the assumed extrapolation forwards to 50 years gives 10.2 kN/m^2, while an assumed extrapolation backwards to 10 hours gives a ring stiffness of approx 8.2 kN/m^2, which means an increase in stiffness of 24 % between 10 hours and 50 years.

The study referred to in Figure 5 shows that the ring stiffness will increase in the course of time for unloaded pipes. In order to find out how the short-term ring stiffness may change in a constantly deflected pipe after long-term loading, the following investigation was performed. - A pipe sample with an initial short-term ring stiffness of 2.40 kN/m^2 and constantly deflected to 5 % during four years was released and the deflection recovery studied during one additional year. The deflection had at that time recovered to 2 %. Another regular measurement of the short-term ring stiffness was then performed. With correction for the fact that the pipe had a small initial more or less "stressless" deflection, the short-term ring stiffness was now found to be 2.61 kN/m^2. The result of the test shows that the short-term ring stiffness had increased with 8.8 % during the four years deflection of 5 %.

The studies referred to confirm that the short-term ring stiffness does not decline after long-term loading of the pipe. On the contrary, it will in fact increase, probably due to the physical ageing effect, as discussed. - It should be mentioned that the physical ageing effect has been recognized also for PE pipes, despite the polymer is semi-crystalline and not amorphous [4]. In [2] and [5] it has been shown by long-term testing that the increase of the short-term ring stiffness is in fact still more pronounced for PE than for PVC.

5 Pipe deflection recovery

A special study concerned the recovery of the deflection in course of the time after load release of the pipe samples. In [1] the deflection recovery of some samples was presented. These pipes had been kept constantly deflected to 5 %, 15 % and 25 %, respectively during 10,000 h, after which time they were released. The time dependent deflection recovery was recorded for 1000 h. A duplicate half of the sample series was kept deflected for totally 42,000 h (approx 5 years), after which time they were released. The deflection recovery of these samples has now been recorded during 37,000 h (approx 4 years). In **Figure 6** the recovery of one of the pipe series representing a ring stiffness of 2 kN/m^2 is illustrated. Thus, it can be seen that the pipe with an initial deflection of 25 % ($\epsilon = 2.19$ %) recovered immediately to 15 % upon release and after 4 years the deflection had been reduced to 10.5 %. In a similar way the 15 % deflected pipe ($\epsilon = 1.31$ %) recovered instantly to 8.5 % and after 4 years to 6 %. And the 5 % deflected pipe ($\epsilon = 0.44$ %) recovered immediately to 2.8 % and after 4 years of release to 2 %.



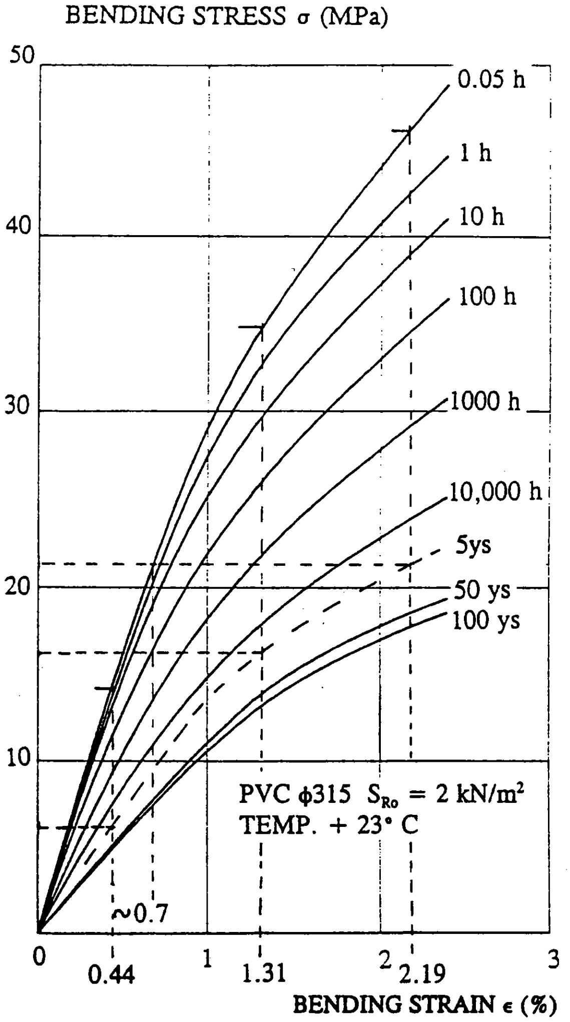


Figure 6 Pipe deflection recovery of PVC pipes constantly deflected during 5 years and now released during additional 4 years. Temp +23°C

Figure 7 Stress/strain curves for constantly deflected PVC pipes. The graph is deduced from measurements of samples with constant bending strains of 0.44 %, 1.31 % and 2.19 %. Age of the samples: 1700-3400 h when the tests started

In **Figure 7** the stress/strain graph is shown for the pipe series, for which this deflection recovery is recorded. The actual strain values 2.19 %, 1.31 % and 0.44 % for the initial pipe deflection of 25 %, 15 % and 5 %, respectively are marked in the graph. It is reason to assume that it is the bending stress still acting in the pipe wall at the moment of release, which will force the pipe deflection to recover. As can be seen the bending stress of the 25 % deflected pipe had decreased to approx 21 MPa after 5 years of constantly deflection. This stress should have a capability to cause a short-term (3 min) bending strain in the pipe wall of approx 0.7 %, corresponding to a deflection recovery of approx 8 %. E.g. the immediate recovery of the deflection should have been from 25 % to 17 % (measured 15 %). In the same way it can be found according to this theoretical approach that the 15 % deflected pipe should immediately recover to 9 % (measured 8.5 %) and the 5 % deflected pipe to 2.7 % (measured 2.8 %). The theoretical calculated and the measured values conform satisfactory with exception of the most deflected pipe. This is in agreement with the fact that the theoretical approach assumes a rectilinear stress distribution in the pipe wall. The actual deviation from this approach is most obvious in the heavily deflected and strained pipe sample.

The stress/strain graph may also be helpful in the prediction of the future deflection recovery of the pipe samples. However, in this case the bending stress is successively decreasing in the course of time and consequently the strain. Therefore the recovery process is taken place as a summary effect of all small instantaneous force impulses recognized by the stress/strain relaxation following the short-term curve down to the origin of the graph, e.g. to infinity, at which stage the stress/strain is zero and consequently the full deflection recovery has finally been reached giving back the original circular shape of the pipe.

6 Conclusion

The study presented helps to realize that thermoplastics pipes manufactured of high quality virgin resins (both PVC and PE), subjected to long-term constant deflection and strain, will keep their short-term vitality and are prepared to withstand additional new loads, whenever such occur, with the strength resistance originally valid for the pipe; or superior. This statement is of utmost significance for a proper understanding of the long-term behaviour of buried plastics pipes [6] and [7].

7 References

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