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KONTROLLRÅDET FÖR PLASTRÖR

REPORT NO. 3
FROM THE KP-COUNCIL
DECEMBER 1991

LONG-TERM STUDIES OF PVC AND PE PIPES SUBJECTED TO FORCED CONSTANT DEFLECTION

(Långtidsstudier av PVC- och PE-markavloppsrör utsatta för påtvingad konstant deformation)

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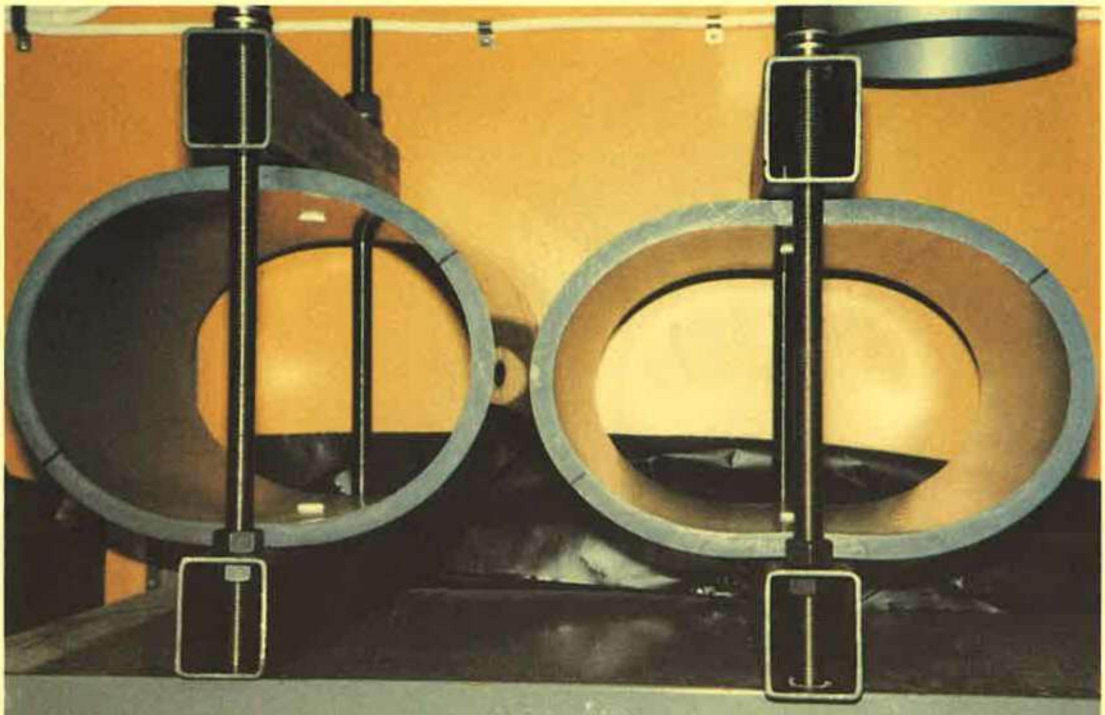

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FÖRORD

Kontrollrådet för plaströr, KP-rådet, bildades 1970. Rådet utför opartisk kontroll av ej SIS-märkta, i Sverige tillverkade eller införda rör, rördelar och brunnar av plast avsedda för markförlagda va-ledningar. Vidare har rådet till uppgift att informera om frågor som berör verksamhetsområdet och ta initiativ för att främja tillkomsten av ändamålsenliga bestämmelser och normer för plaströr.

Rådets huvudmän är Boverket, Byggentreprenörerna, Svenska Konsultföreningen, SKIF, Sveriges Plastförbund, SPF samt Svenska vatten- och avloppsverksföreningen, VAV. Statens provningsanstalt är representerad med en adjungerad ledamot.

KP-rådets verksamhet finansieras genom avgifter från anslutna tillverkare. Överskott som uppkommer i rådets verksamhet satsas på FoU-projekt inom plaströrsområdet.

Föreliggande rapport är den tredje i en serie från KP-rådet. Rapport nr 1 "Hur gammalt kan ett plaströr bli?", oktober 1987, innehåller en värdering av de olika faktorer som påverkar avloppsrör av PVC och polyeten lagda i mark. Sammanfattningsvis pekar allt mot att dessa ledningar har minst 100 års brukstid, förutsatt att dagens högkvalitativa rör används och att föreskrifterna för schaktning, läggning och återfyllning följs.

I rapport nr 2 "Undersökning av relaxationsmodulen hos PVC-rör som utsätts för påtvingad konstant ovalitet", december 1987, redovisas studier av PVC-rör som under drygt ett år utsatts för konstant deformation. Det påvisas att åldringsprocessen hos PVC-rör möjliggör en extrapolering av ringstyvheten från korttidsstudier till tider upp emot och sannolikt förbi dem som är av praktiskt intresse, d v s upp mot 100 år eller mer.

Nu föreliggande rapport nr 3 baseras på fortsatta studier under totalt ca fem år för PVC-rör och drygt åtta år för PE-rör. Det konstateras att rören, som hållits konstant deformerade under ovan angivna tider, trots stora deformationer och töjningar, inte i något fall uppvisar sprickor eller andra skador. Vidare påvisas att rören efter avlastning har kvar det ursprungliga korttidsvärdet för E-modulen och därmed också den ursprungliga ringstyvheten. Sammantaget ger resultaten ingen anledning till omprövning av de utsagor om rörens brukstid som görs i rapport nr 1 och 2.

I rapporten redovisas också bl a ett tilläggsstudium avseende amerikanska PVC-rör där rörmaterialet innehåller stor mängd filler i form av krita.

Laboratorieundersökningarna som bildar grunden för utvärderingarna har utförts hos Statens provningsanstalt i Göteborg. Vissa rörprover kvarligger hos provningsanstalten för att långsiktig kontroll skall kunna göras av de slutsatser som redovisas i denna rapport.

Stockholm i december 1991
Kontrollrådet för plaströr
Ulf Sahwenberg
Ordförande

Rådets sekretariat är förlagt till VAV. Som rådets sekreterare fungerar överingenjör Nils Lindblad, VAV.

THE SWEDISH COUNCIL FOR CONTROL OF PLASTICS PIPES (KP-Council)

Scope of Work

Quality control of plastics pipes, pipe fittings and manholes for water supply and sewerage is carried out in Sweden by an authority specially set up for the purpose, known as the Swedish Council for Control of Plastics Pipes.

The Council began its work in 1970. It was set up by and answers to the National Board of Housing, Building and Planning, the Associated General Contractors and House Builders of Sweden, the Swedish Association of Consulting Engineers, the Swedish Plastics Federation and the Swedish Water and Waste Water Works' Association. The National Testing Institute is a co-opted member. The Council's secretariat is situated at the Swedish Water and Waste Water Works' Association (VAV) in Stockholm.

The Council undertakes the control of products manufactured in accordance with standards associated with the industry or its companies, and which have been approved by the Council, or are in accordance with standards issued by the Council.

Swedish manufacturers or importers of plastics pipes produced in accordance with standards approved by the Council may apply to the Council for association. On receipt of the application, inspection of the applicant's manufacturing and laboratory equipment is carried out under the supervision of the Council and a record is kept at the factory in order to check that the technical and personnel resources are of an acceptable standard. In addition, samples are tested in order to check that the products fulfil the requirements laid down in the standards.

If the conditions for association are shown to be met after inspection and sampling, the applicant is given the right to mark its products with the Councils registered and legally protected KP marking. This shows that the products have been approved in tests in accordance with the regulations which apply for the work of the Council. Products bearing this marking are usually accepted by purchasers without special acceptance testing.

Thereafter, production control is carried out twice yearly under the supervision of the Council. The manufacturer's record of in-company production control stipulated in the standard procedure is examined on each control visit. In addition, samples are taken for laboratory testing to the extent and for the characteristics specified in the standards. The tests are carried out by the Gothenburg department of the Swedish National Testing and Research Institute, or under its supervision.

Some collected and evaluated experience of the KP-Council work is published in Special Reports. The present Report is No. 3 in the series.

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SAMMANFATTNING

I KPs Rapport 2 [1] beskrivs ett studium av PVC-rör, som under drygt ett år utsatts för konstant deformation. (Ref. [1] utgör basen för en engelskspråkig uppsats publicerad i Bath, UK, 1988, [2].) I rapporten påvisas hur den fysikaliska åldringsprocessen hos PVC-rör möjliggör en extrapolering av ringstyvhetsdata från korttidsstudier till tider upp mot och sannolikt förbi dem som är av praktiskt intresse, dvs upp mot 100 år eller mer. Det kan allmänt konstateras att riktigheten av de extrapoleringar av E-modulen som görs i [1] efter ca ett års mätningar i stort sett bekräftas i föreliggande rapport. Sålunda kan rätlinjighet påräknas hos kompliansen C (=1/E) i ett lin C/log tid-diagram, men först efter en tid överstigande rörets ålder vid provningens början. Det konstateras vidare att denna rätlinjighet hos kompliansen innebär, teoretiskt sett, att böjdragspänningen i rörväggen till följd av relaxation närmar sig noll först efter oändlig tid. Ett plastmaterial som skall utsättas för mekanisk belastning under lång tid bör uppvisa nämnda egenskap. Vidare påvisas i rapporten att böjspänningen som omedelbart byggs upp i rörväggen vid deformationens början reduceras till ca 40 % efter 50-100 års belastningstid.

Frågeställningar avseende livslängden hos markavloppsrör av termoplast behandlas även i KPs Rapport 1, oktober 1987, [3]. Förutsatt att preciserade rör- och jordbetingelser gäller, förutsägs i [3] en livslängd av minst 100 år för markförlagda självfallsledningar av termoplast. (Här avses i första hand dagens standardiserade rörkvaliteter av PVC, PE och PP.) De resultat som nu redovisas i föreliggande rapport, baserade på fortsatta studier under totalt ca fem år för PVC-rör och drygt åtta år för PE-rör, ger ingen orsak till omprövning av de utsagor om rörens livslängd som görs i [3].

Ett tilläggsstudium som också redovisas i rapporten avser de i [1] omnämnda provningarna av amerikanska PVC-rör innehållande stor mängd filler (26 %) i form av kalciumkarbonat (krita). Något överraskande konstateras att rör med en initiell ringstyvhet av ca 8 kPa och deformerade till 5 % medförande en böjtöjning i rörväggen av 0,6 % uppvisar ett rätlinjigt lin C/log tid-förhållande efter ca 10,000 h, likt normalt gällande för PVC, och utan antydan till utveckling av mikrosprickor eller liknande fel. Provningstiden är i skrivande stund ca 4 år. Inblandningen av filler av den typ som här använts synes således inte ge försämrade livslängdsbetingelser för PVC-rör som utsätts för måttlig rördeformation och töjning. (Fillersammansättning samt kornstorlek redovisas i rapporten). I stället ökar styvheten hos röret väsentligt genom inblandningen av filler. Sålunda uppgår E-modulens korttidsvärde vid rördeformationen 5 % till 4 200 MPa och långtidsvärdet (50 år) till ca 2 200 MPa. Detta skall jämföras med 3 200 MPa respektive ca 1 300 MPa för i mätningarna ingående standardiserade svenska PVC-markavloppsrör av klass T (ringstyvhet 8 kPa) med en fillerhalt av ca 8 %. Någon väsentlig skillnad i slaghållfasthet har heller inte kunnat noteras. - Att uttalandet ovan om rörets livslängdsbetingelser begränsas till rör med måttlig rördeformation sammanhänger med att studier av kraftigt deformerade rör (15 % samt med töjningen 1,8 %) visar ett anmärkningsvärt avsteg från den linjära lin C/log t-kurvan efter ca 2,5 år. Vidare visar prover med extrema töjningsvärden upp till 4 % ett kraftlöst tillstånd i provet efter en deformationstid av ca 3 år.

I ett särskilt avsnitt av rapporten redovisas resultatet av långtidsstudier av PE-rör tillverkade av Nestes råvaror NCPE 2467 (HDPE Typ 1), NCPE 2467-BL (modifierade HDPE Typ 2) och NCPE 2418 (MDPE) respektive. Dessa studier, som pågått under drygt åtta år, utgör i nuvarande redovisning ett slutresultat av de undersökningar, som interimistiskt publicerats i VBBs rapport till SPF 1983-09-26 [7] och till Neste 1987-11-04 [9]. (Ref. [7] har utgjort basen för en engelskspråkig uppsats som publicerades i Madison, USA, 1985, [8]). Även PE-rören uppvisar en vacker rätlinjighet i lin C/log tid-sambandet, dock betydligt tidigare än för PVC-rören, och dessutom oberoende av rörens ålder. Någon nämnvärd justering av tidigare gjorda extrapoleringar av E-modulerna till 50-100 år har inte behövt göras. - Liksom för de långtidsbelastade PVC-rören diskuteras böjspänningens relaxation under aktuell belastningstid. En extrapolering av provningsresultaten visar att den ögonblickliga böjspänningen reduceras till ca 30 % efter 50-100 års belastningstid.

Av speciellt intresse beträffande PE-studierna utgör avlastningsförsöken som utförts på de rörprover som varit konstant belastade under åtta år. Man finner därvid ett remarkabelt uppträdande hos PE-rörets förmåga att återta sin ursprungliga cirkulära form. Sålunda ger deformationsmätningarna efter avlastningen vid handen att ett nära linjärt samband synes råda mellan linjär återgående rördeformation och logaritmisk avlastningstid. (PE-rörens sätt att uppträda skiljer sig här markant från motsvarande PVC-rörs. De sistnämnda visar en deformationsåtergång som följer en parabolisk kurvform, vilken därför inte låter sig extrapoleras i ett semi-logaritmiskt diagram baserat på nuvarande observationsperiod.) Studierna av deformationsåtergången har i nuvarande värdering endast omfattat en tidsperiod av ca ett år, men skulle den iakttagna tendensen visa sig bestående, skulle det betyda att rörmaterialet äger förmåga att mer eller mindre fullständigt återta sin ursprungliga form inom en definierbar tidrymd. Detta i sin tur skulle betyda att den elastiska och den s k försenade elastiska deformationen dominerar och att den viskösa andelen av deformationen är obetydlig, (jfr [4] sektion 3.1). Ett troligt undantag från detta uttalande kan påräknas gälla de kraftigast deformerade rören bestående av MDPE.

För såväl PVC- som PE-rör gäller att ingen övre gräns kunnat bestämmas för böjtöjningen i konstant deformerade trycklösa markavloppsrör. Det är således praktiska hänsyn samt stabilitetsvillkoret för rör i jord (bucklig etc) som får utgöra dimensioneringskriteriet för dessa rör. Beträffande PVC-rör med hög fillerhalt kan inte samma generella uttalande göras om avsaknad av en övre dimensionerande töjningsgräns. För de fillerfyllda rör som här studerats finns indikationer på att böjtöjningen i rörväggen bör inte väsentligen överstiga 0,5 %.

I ett avslutande kapitel påvisas att PVC- och PE-rör som hållits konstant deformerade under lång tid (5 respektive 8 år) efter avlastning har kvar det ursprungliga korttidsvärdet för E-modulen och därmed också ringstyvheten.

Laboratorieundersökningarna, som bildar grunden för den utvärdering som presenteras i rapporten, har utförts hos Statens Provningsanstalt i Göteborg (SPG) under ledning av civilingenjör Gunnar Bergström. Utan hans sakkunniga medverkan och värdefulla rådgivning samt laboratoriepersonalens skolning och berömvärda noggrannhet skulle denna rapport knappast ha kommit till.

Det skall slutligen anmärkas att vissa rörprover kvarligger hos SPG. Avsikten är att långsiktigt kontroll skall kunna göras av de slutsatser som redovisats i föreliggande rapport. Dessa prover avser framför allt några PVC-rör med ursprunglig ålder 24 h, 240 h och 2 400 h respektive. Vidare studeras fortlöpande övriga PVC-rörs återgående deformation efter avlastning. De amerikanska fillerfyllda rörproven hålls likaså fortsättningsvis under konstant deformation. PE-rören som avlastats kommer likaså att kontrolleras beträffande deformationsåtergången åtminstone under ytterligare ett à två år.

1. SUMMARY

In the Swedish KP-Council Report No. 2 [1] an investigation is presented of uPVC pipes, which had been subjected to forced constant deflection for a period of one year. (Reference [1] forms the basis for a paper presented at the Int.Conf.Plastics Pipes in Bath, UK, 1988 [2]). In the reports it is shown how the physical aging process of PVC pipes opens up the possibility to extrapolate the ring stiffness from short-term data up to and probably passing periods of time which are of practical interest, i.e. up to 100 years or more. It can be stated generally that the accuracy of the extrapolations of E-modulus made after one year in [1] largely can be verified in the present report. Thus, rectilinearity can be expected for the compliance C (= 1/E) plotted in a linC/log t diagram, but not until after a loading time, which significantly exceeds the age of the pipe when the pipe deflection study is started. It is further stated that this rectilinearity of the compliance means, from a theoretical point of view, that due to relaxation the bending stress in the pipe wall does not approach zero until after an infinite time of deflection. A plastic material which will be subjected to long-term mechanical loading should have this property. Moreover, it is shown in the report that the bending stress which is initially built up in the pipe wall when the deflection starts, will be reduced to approximately 40 % after a loading time of 50-100 years.

Questions concerning the lifetime for buried gravity thermoplastic pipes is also treated in KP-Council Report No. 1 [3]. Provided specified pipe quality and soil conditions are prevailing, a lifetime of at least 100 years is predicted in [3]. (The statement concerns modern standardized gravity pipes of PVC, PE and PP). The results which are now given in the present report, based on continued studies for a total of 5 years for PVC pipes and 8 years for PE pipes, give no reason to reconsider the statements made in [3] concerning the lifetime of the pipes.

An additional study which is also presented in the report concerns testing of an American PVC pipe containing a large amount of filler (26 % calcium carbonate). Somewhat surprisingly, it was found that pipes with an initial ring stiffness of approximately 8 kPa and constantly deflected to 5 % (bending strain 0.6 %) show a rectilinear linC/log t relation after approximately 10,000 h, like normal PVC, and without any indication of commencing micro cracks or similar faults. The testing time is now 4 years. Thus, the adding of filler of the actual type does not seem to give deteriorated life length conditions for PVC pipes, subjected to moderate deflection and bending strain. Instead the ring stiffness of the pipe is significantly increased due to the high filler content. Hence, the short-term E-modulus at a pipe deflection of 5 % is 4,200 MPa and the long-term value (50 years) is 2,200 MPa. This can be compared with 3,200 MPa and 1,300 MPa respectively, which is found in the study to be valid for standardized Swedish PVC pipes of class T (ring stiffness 8 kPa) with a filler content of 8 %. Concerning the impact strength, no significant difference has been found when compared with normal PVC. The reason for the statement above to be limited to pipes with moderate deflection and strain is that strongly deflected pipes (15 % and 1.8 % strain) show a remarkable deviation from the rectilinear linC/log t curve after approximately 2.5 years. Moreover, samples with extreme bending strains of up to 4 % show a powerless state after a deflection time of approximately 3 years.

In one particular section of the report, the results are presented of long-term studies of PE pipes manufactured from the NESTE grades NCPE 2467 (HDPE, Type 1), NCPE 2467-BL (modified HDPE, Type 2) and NCPE 2418 (MDPE). These studies, which have been running for more than 8 years, now form the final result of investigations which were published in the VBB Interim Reports to the Swedish Plastics Federation (SPF) in 1983 [7] and to NESTE in 1987 [9]. (Reference [7] formed the basis for a paper published at an international ASCE conference in USA, 1985 [8].) Like the PVC pipes, the PE pipes show a beautiful rectilinear linC/log t relation, although much earlier than the PVC pipes, and in addition independent of the age of the pipes. It has not been necessary to make any significant adjustment to the previously made extrapolations of the E-modulus up to 50-100 years. As in the case of the long-term loaded PVC pipes, the relaxation of the bending stress is discussed. An extrapolation of the actual test results shows that the initial bending stress will be reduced to approximately 30 % after a loading time of 50-100 years.

Of particular interest are the studies of the deflection recovery of the PE pipe samples since they have been released after 8 years of constant deflection. A remarkable behaviour is found concerning the ability of the PE pipe to recover its original circular shape. Hence, the deflection measurements after releasing the pipe samples show a more or less rectilinear relation between linearly plotted deflection recovery and logarithmic time after start of the release. (The behaviour of the PE pipes differs significantly from that of the PVC pipe. The latter shows a deflection recovery following a parabolic curve shape. Consequently, the PVC curves cannot be long-term extrapolated based on the present time of

recovery measurement.) The deflection recovery has now only been studied for approximately one year, but if the observed trend proves to be stable, it would mean that the PE pipe has an ability to more or less fully revert to its original circular shape within a definable space of time. This in turn would mean that the elastic strain and the so-called retarded elastic strain dominate and that the viscous part of the strain is insignificant, (compare [4] Section 3.1). A possible exception from this statement seems to be valid for the most strongly deflected MDPE pipes.

It has been found in the case of both PVC and PE that no upper limit from a practical design point of view seems to exist for the bending strain in constantly deflected gravity sewer pipes. Consequently, the only criteria on which the design of these pipes have to be based are practical deflection considerations and the mechanical stability of buried pipes (buckling, etc.). For PVC pipes containing a large amount of filler, the same general statement implying a lack of an upper design bending strain limit cannot be made. Hence, for the filler-filled pipes studied, there are indications that the long-term bending strain in the pipe wall should not exceed 0.5 %.

In a closing section it is shown that PVC- and PE-pipes, which have been kept long-term constantly deflected (for 5 and 8 years respectively), after release have E-modulus and consequently also pipe ring stiffness values, which are equal to or larger than the original short-term values.

The laboratory tests, which form the basis of the evaluation presented in the report, have been performed at the Swedish National Testing and Research Institute in Gothenburg (SPG) under the supervision of the head of the Institute Mr Gunnar Bergström (M.Sc. Technical Physics). Without his competent co-operation and valuable advice, as well as the competence of his staff and remarkable accuracy of their laboratory work, this report would not have been written.

Finally, it shall be noted that some pipe samples are still stored at SPG, the reason being that it shall be possible to make a long-term check of the conclusions presented in the report. These samples are primarily PVC pipes with initial ages of 24 h, 240 h and 2,400 h respectively. Furthermore, the deflection recovery for all released PVC pipes will be successively measured. The American filler-filled PVC pipe samples will be kept under continuous constant deflection. The PE pipes which have been released will be successively checked with regard to the deflection recovery, at least for another year or two.

2. STRESS RELAXATION IN CONSTANTLY DEFLECTED PVC PIPES

PVC pipe samples with a diameter and length of 315 mm and with various nominal ring stiffness values from 2 to 32 kPa have been subjected to forced long-term constant deflection at an air-conditioned room temperature of +23°C, [1]. (Reference [1] formed the basis of a paper published at the International Conference Plastic Pipes VII in Bath, UK in 1988 [2]). The theoretical constant bending strains in the wall of the pipe samples caused by the deflection are from 0.43 to 5.76 %. Each sample in the original study was doubled, which made it possible to continue the measurements after the first reports [1] and [2] had been published. At that stage, half the series of samples were released from the forced deflection while the other half were saved in the loaded position in the laboratory. The first report [1] evaluated the tests after 14 months.

The general intention of this continued study was to try to verify the statements made in the first reports, in particular concerning the long-term relaxation behaviour of the thermoplastic polymers. Of particular interest in this connection is the influence of the physical ageing process on the long-term ring stiffness of PVC pipes. The investigation is also of interest when discussing the life span of buried thermoplastic sewer pipes. In [3] it was stated that, provided certain specified requirements are fulfilled concerning both pipe quality and soil mechanics, the life span can be estimated at not less than 100 years. The present study of the long-term pipe material behaviour will show that the life span prediction of 100 years is not contradicted.

The force needed to keep the pipe samples continuously deflected has been successively measured in an Instrone machine up to a loading time of approx. 5 years. Most samples have now been released and the rate of deflection recovery has been measured for approximately one year. However, five PVC samples are still being kept deflected and the longest loading time is currently approx. 49 700 h (5.7 years).

All PVC pipe samples were manufactured by UPONOR (Sweden) and were taken from normal commercial pipe production. The external diameter is 315 mm and the length of each sample is the same as the diameter, 315 mm. Various wall thickness have been used corresponding to pressure classes PN4 bar (L-class), PN6 bar (T-class) and PN10 bar (water pressure distribution class, P). The pressure classes are based on a long-term design tensile stress of 10 MPa. Concerning the T-class samples, two series were manufactured: one in 1985 and the other in 1987 (in the following the latter is identified as TY = T "Young"). The nominal short-term ring stiffness according to the formula:

$$S_R = EI/D^3 \tag{2.1}$$

is 2 kPa, 8 kPa and 32 kPa respectively.
(D is defined in this report as the diameter of the central line of the pipe wall).

The material properties of the various pipe classes are given in Table 2.1

Table 2.1

Pipe classes PN (bar)	4 (L)	6 (T)	6 (TY)	10 (P)
K-value	69.0	68.3	68.2	67.2
Vicat point °C	83.2	83.4	83.4	83.2
Density (inside wall) kg/m^3	1440	1440	1445	1420
Density (outside wall) kg/m^3	1440	1440	1445	1410
Filler (after burning) %	7.0	7.6	8.4	1.7

In the following, a comparison is made between the previous E/t-diagrams and the ones now achieved since additional loading time has elapsed. In this way, it is easy to see whether the previous extrapolation of the E-modulus up to 50 years has to be adjusted or not.

It should be emphasized that although we are here speaking of a long-term decrease in the E-modulus, this is only a fictive decrease. The real active E-modulus is almost constant and for each new load impulse the E-modulus is the same as the initial one represented by the short-term value. Consequently, the fictive decrease in the E-modulus only represents the decrease in the bending stress in the pipe wall caused by relaxation. This is easily understood as $E = \sigma/\epsilon$, and as long as the strain ϵ is constant, as in this case, a decrease of E means in reality only a decrease in the stress σ. Of particular interest is the fact that if the compliance $C = 1/E \doteq \epsilon/\sigma$ shows a rectilinear course in the lin C/log t-graph, this means theoretically that the stress will not relax to zero until the loading time has reached infinity, [2]. Behaviour of this type in a polymer material indicates a favourable property, which should also be an adequate requirement for a long-term loaded structural polymer material.

In Figs 2.1-2.9 the additional results of the measurements have been plotted in the lower graph. In the upper graph the result presented in [1] after 10,000 h is reproduced. (The figures in brackets give the age of the pipe samples when commencing the tests.) As can be seen no or only insignificant adjustments have to be performed when extrapolating the rectilinear part of the C-curves up to 50 years. The corresponding influence on the course of the E-curves is accordingly also insignificant.

Thus, in Fig. 2.1 the 50 year-E-value for Sample L52 has only decreased from 1185 MPa to 1159 MPa. The E-value for Sample T151 in Fig. 2.4 has decreased from 1399 MPa to 1370 MPa, for Sample P151 in Fig. 2.8 from 890 MPa to 866 MPa and for Sample P251 in Fig. 2.9 from 608 MPa to 601 MPa. No change at all has been made in Figs 2.2, 2.3, 2.5 and 2.7. However, a clear deviation from the rectilinear C-curves is indicated by the last spots for Sample L152 in Fig. 2.2 and for Samples T55 and T56 in Fig. 2.5 and for Samples T53 and T54 in Fig. 2.6. These deviations have not been considered in the extrapolation as it is quite probable that they are due to scattering of the measurement. This is particularly true of the last spots in Fig. 2.5 and 2.6. As both curves represent samples which are still under deflection, future measurement may show the truth of the statement. Concerning sample L152 in Fig.2.2, see also the assessment made in Section 6.

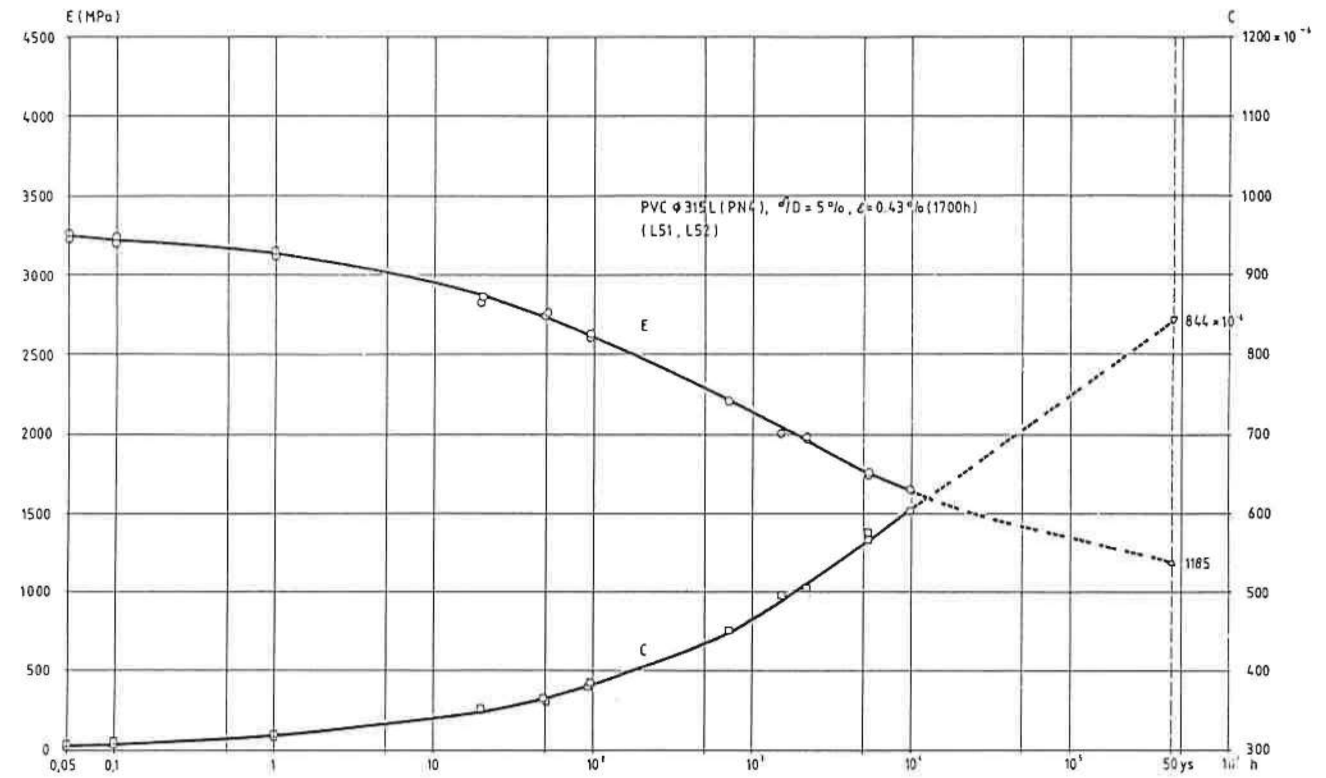
An obvious possibility which presents itself now, after this long-term investigation, where the rectilinear course of the C-curve has been rather well confirmed, means a further extrapolation of the C-curve to 100 years. An important condition for the extrapolation to be allowed is, of course, that the chemical stabilization system is still intact throughout this additional 50 year period. This question was discussed in [3] and further in [4], and it was concluded that for normal standard unplastized PVC pipes, the chemical stabilization will not form a practical design criterion within such a short time space as 100 years. Thus, in Figs 2.1-2.9 the result of a rectilinear extrapolation of the C-curve to 100 years has been illustrated. It can be seen that the corresponding E-modulus, given as the inverted value of C is more or less insignificantly influenced by the longer loading time up to 100 years.

Besides these findings, the main result from the study so far is that the fictive E-modulus after 50 or 100 years in constantly deflected PVC pipes cannot be found unless the testing time is sufficiently long to reach a rectilinear course of the lin C/log t-curve. This testing time is normally at least one year. Hence, the preliminary finding in [1] that the rectilinear course of the lin C/log t-curve would commence after a period of time equal to the age of the pipe when starting the test, has not been accurately verified in the present long-term investigation.

Based upon Figs 2.1-2.3, which concern pipes with a nominal short-term ring stiffness of 2 kPa, a σ/ϵ-graph has been deduced with the loading time from 0.05 h up to 100 years as parameter Fig. 2.10. From this graph it can be found that the short-term bending stresses (3 min. value) in the pipe wall will relax to approximately 40 % of the original value after 50-100 years of constant bending strain caused by pipe deflection. Thus, it can be expected that the ability of the pipe to revert to its original circular shape will decrease in terms of recovery velocity, the longer the pipe has been loaded (see also Section 5).

General comment

To facilitate presentation of this study no mathematical consideration has been given to the influence on the test results of the consequence of the second order theory on the true magnitude of the E-modulus. This second order theory involves consideration of the fact that the pipe ring stiffness as determined valid for a fully circular ring, will decrease when the pipe deflection increases. The influence of such a consideration begins to be of practical importance when the pipe deflection exceeds approximately 5 %. Consequently, by using the eq. (2.1) for describing the E-modulus as a function of measured ring stiffness, it is obvious that the initial E-modulus will decrease as a function of an increased pipe deflection. This means that all short-term E-moduli as presented in the report show a decrease with increased initial pipe deflection. This would not be true in the case of an elastic material, since the E-modulus of the material is then always the same irrespective of the loading case (as long as the linear relation between stress and strain is valid). However, for a viscoelastic material, the stress distribution in the pipe wall is not triangular as presumed according to the elastic theory, but will be more or less parabolic depending on the magnitude of the bending stress. This means that the stress at the pipe wall surface will be less in the case of a viscoelastic material than it would be in an elastic material. Thus the E-modulus will also decrease to a level that has been found to concur approximately with the E-modulus given in the report. Consequently, no reason has been found for trying to find a more sophisticated evaluation of this study by introducing the influence of a mathematically based second order theory.



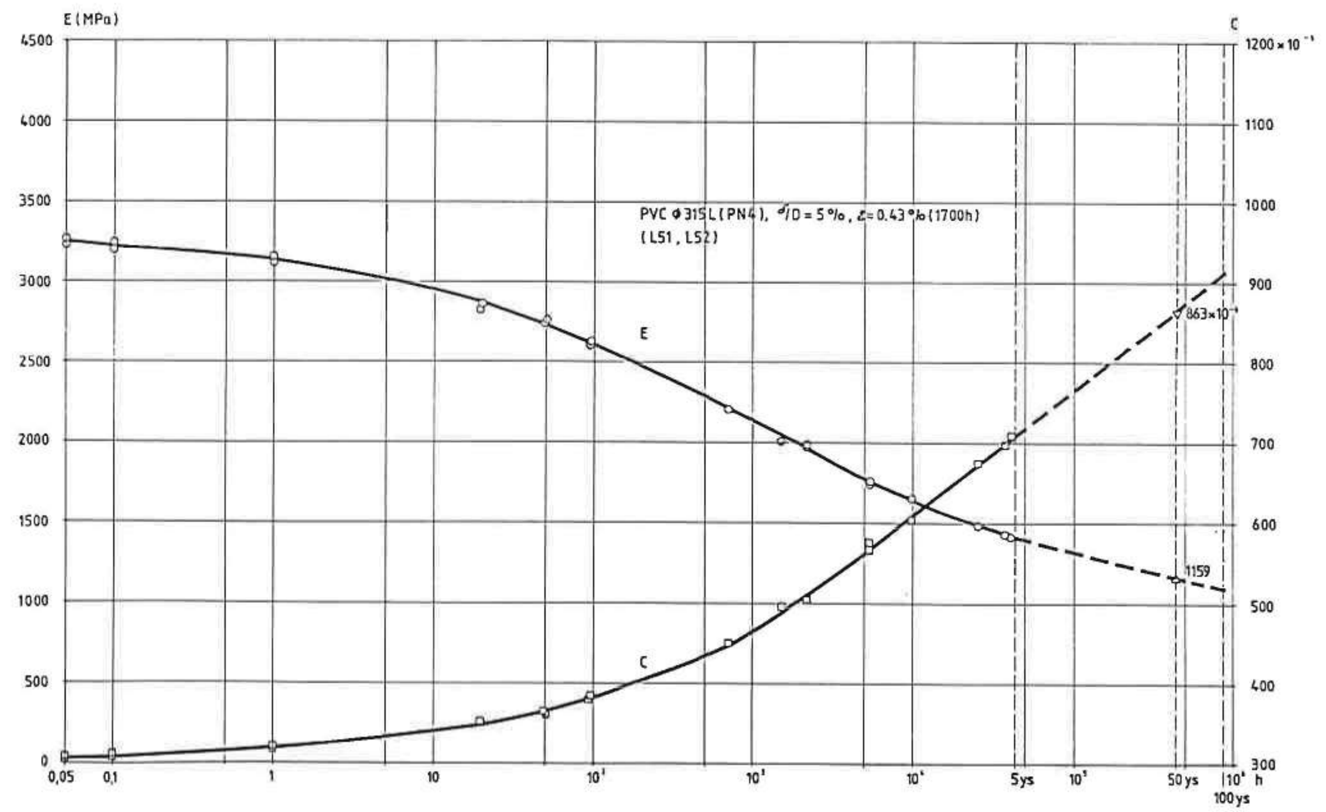
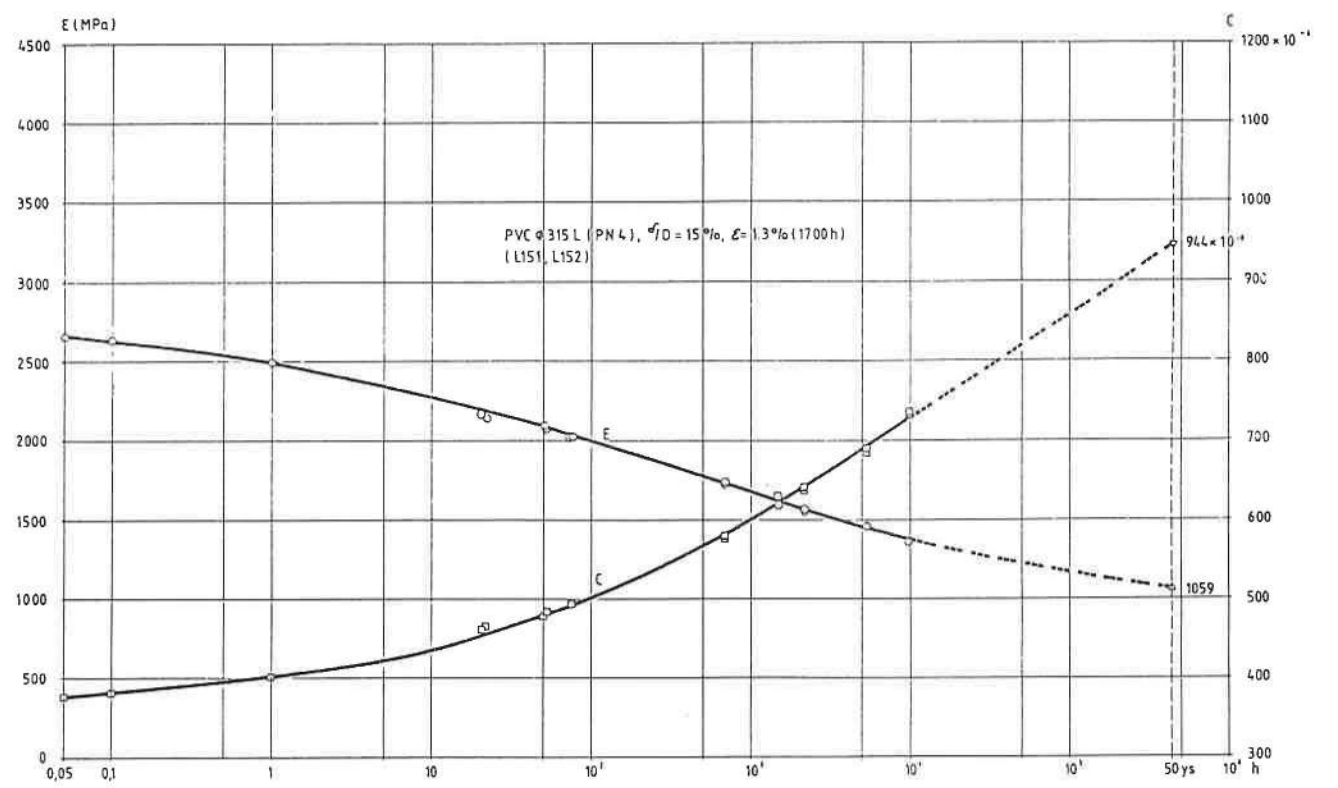


Fig. 2.1 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



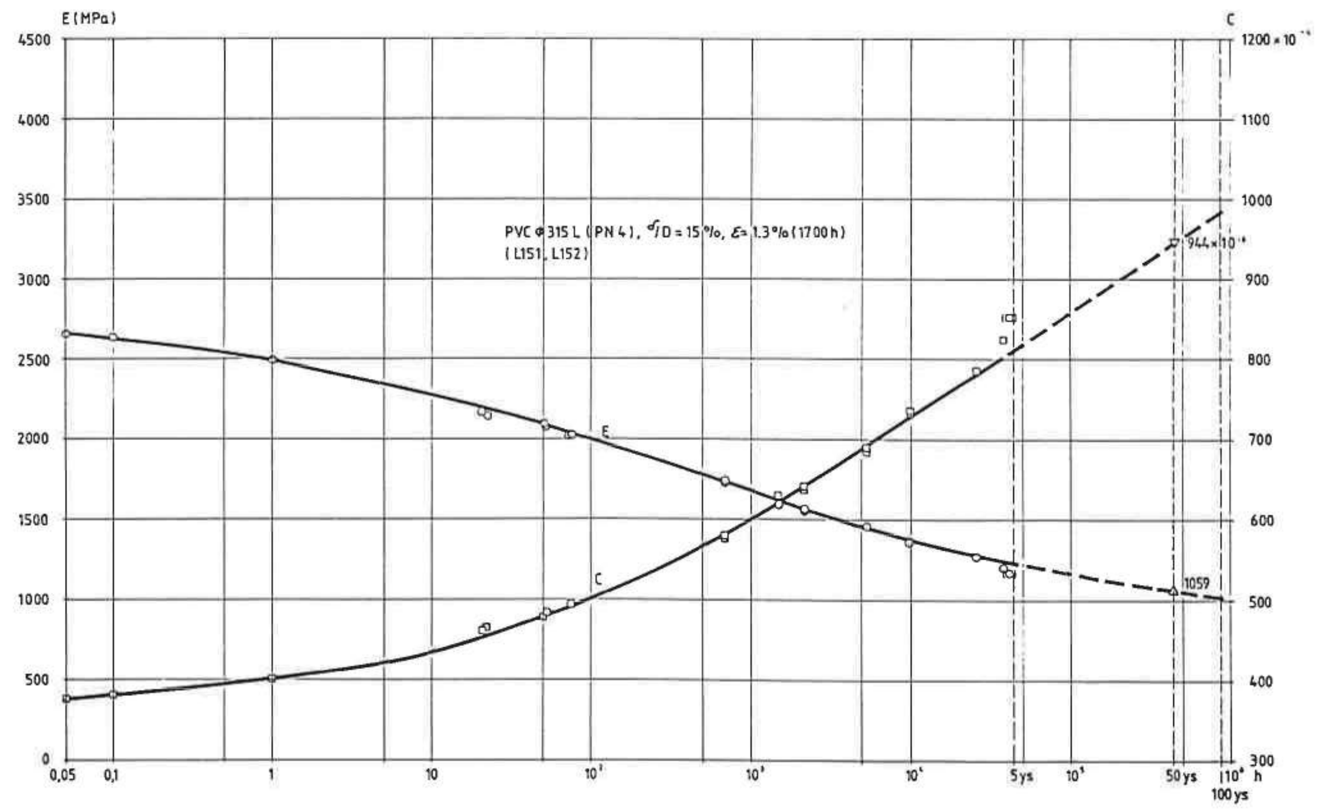
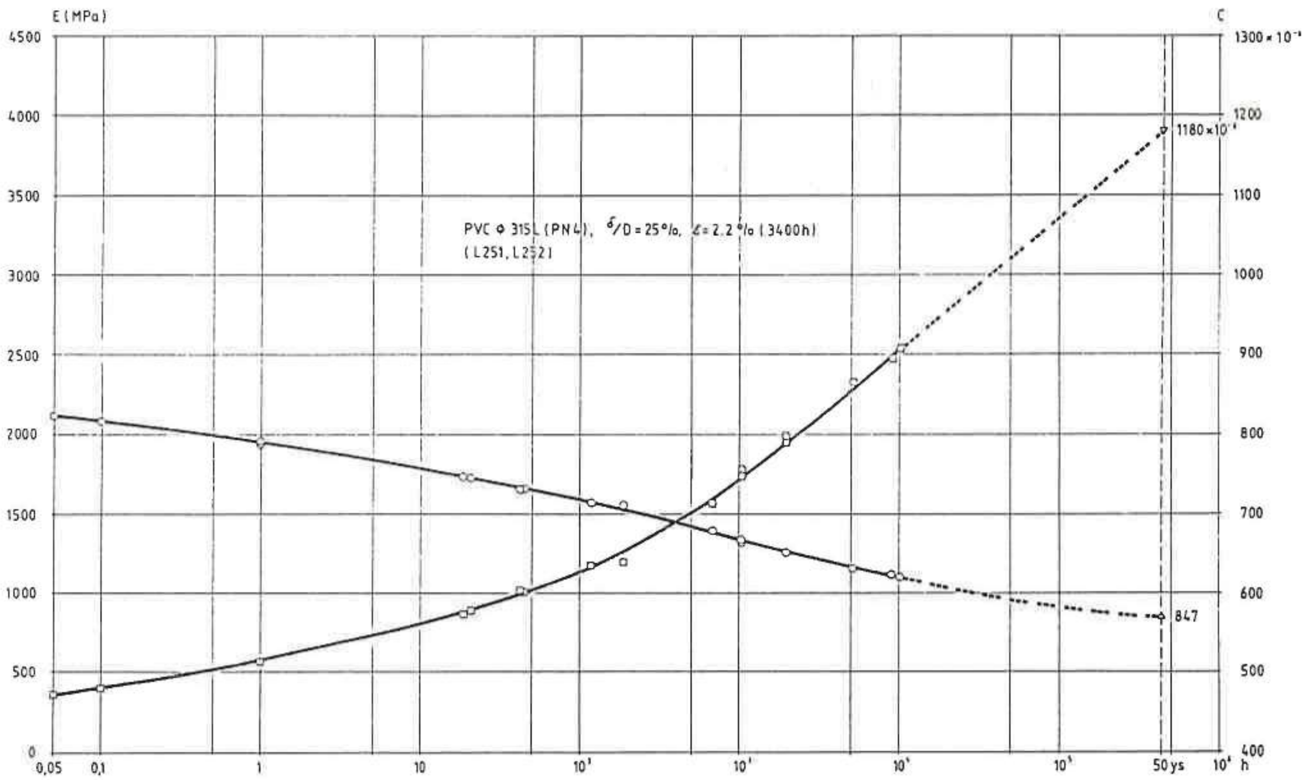


Fig.2.2 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



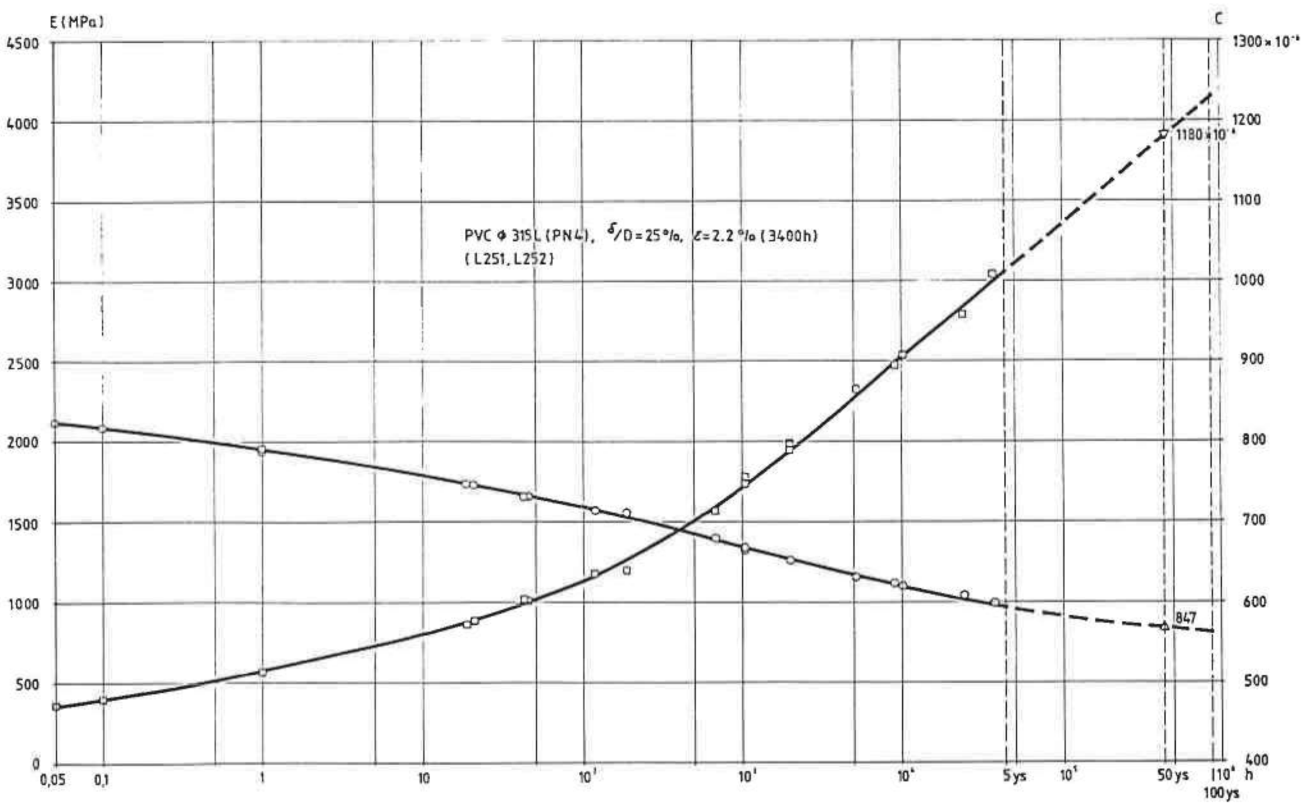


Fig.2.3 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.

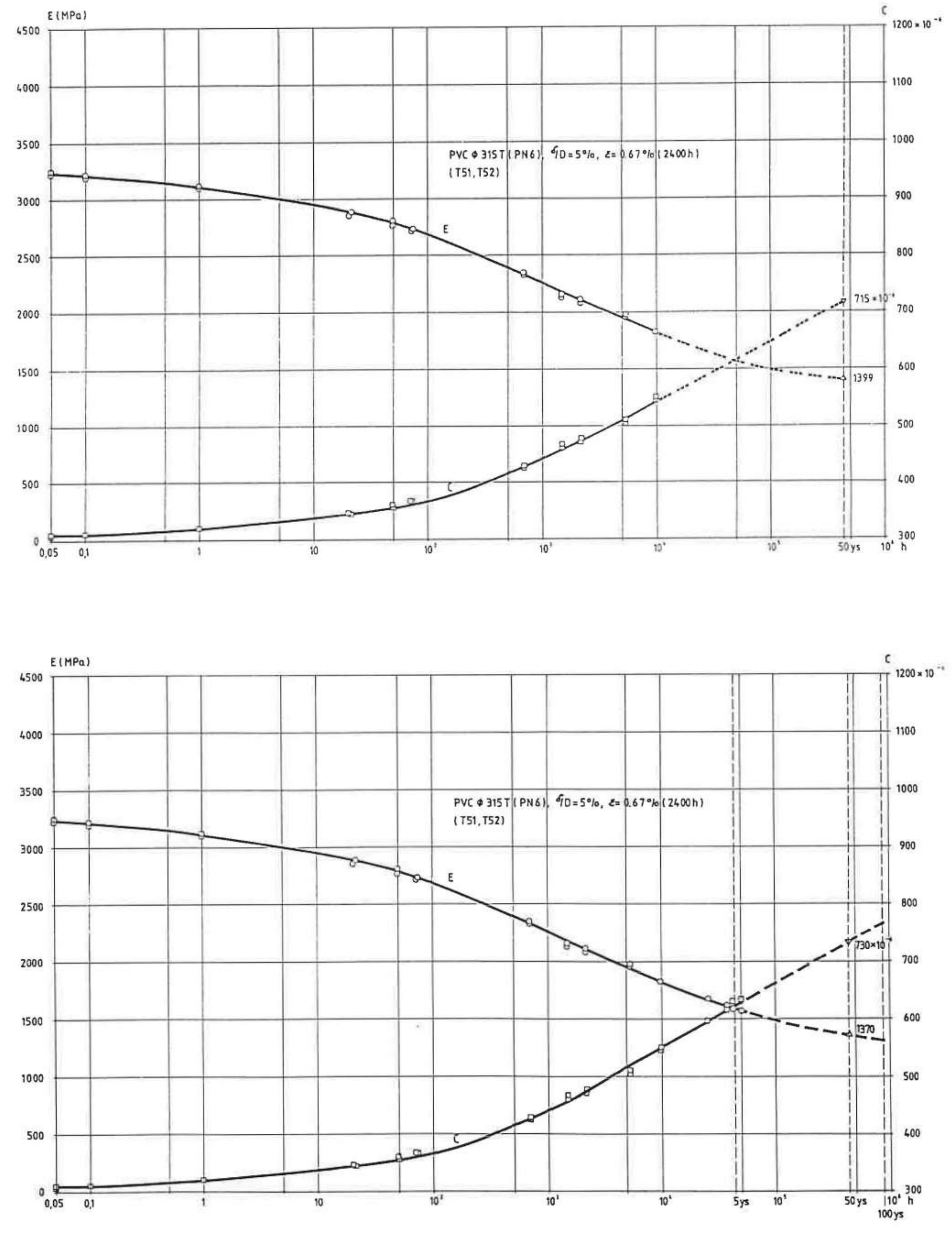


Fig.2.4 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.

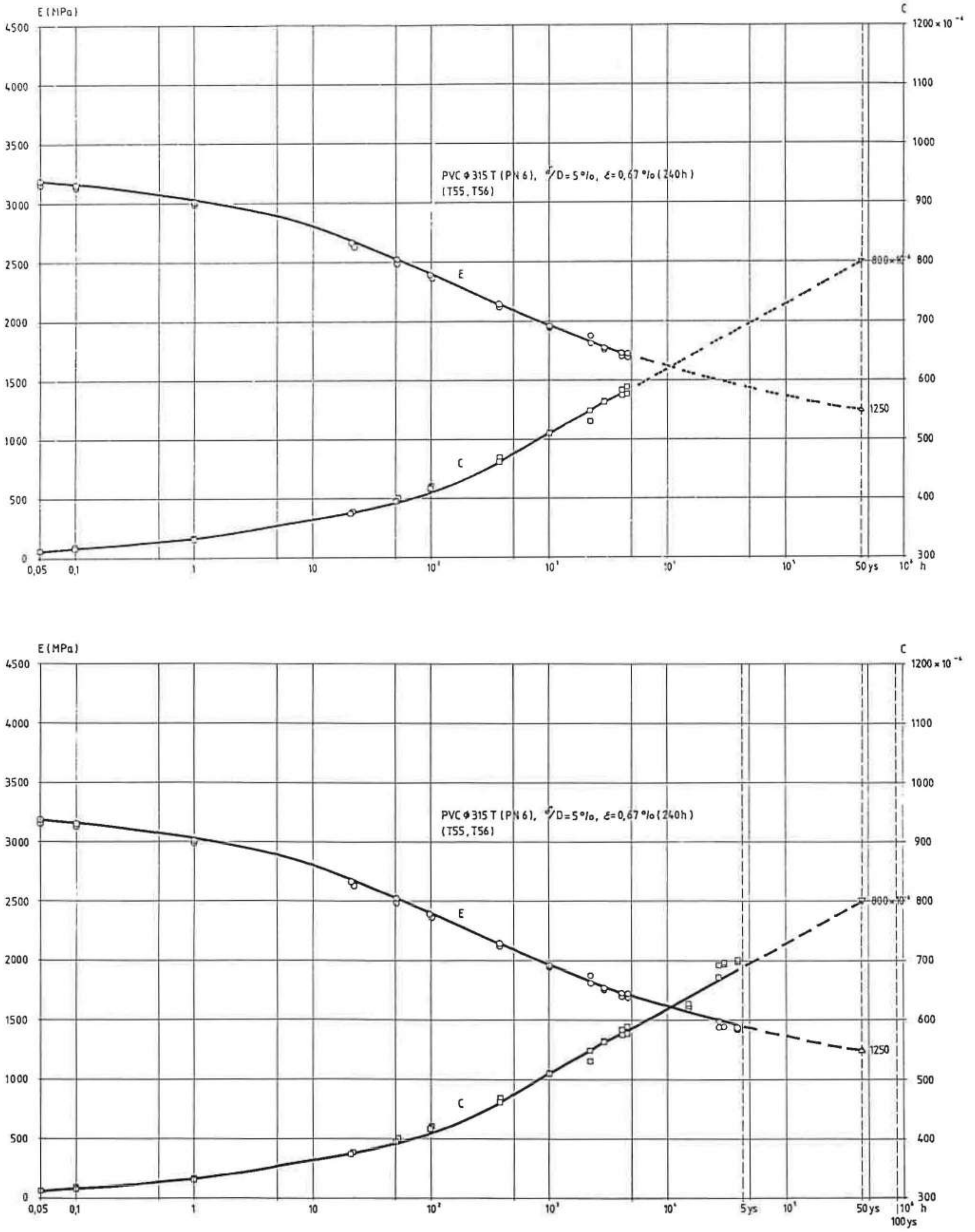
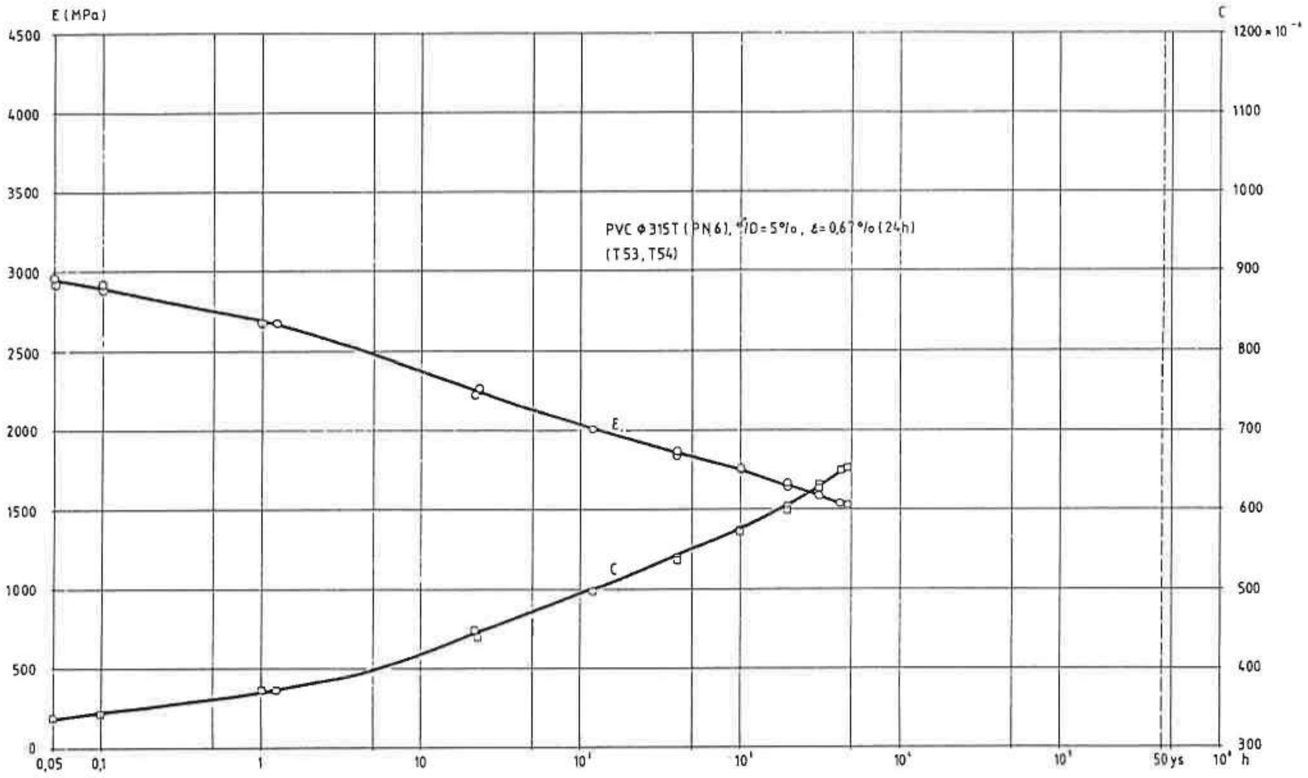


Fig.2.5 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



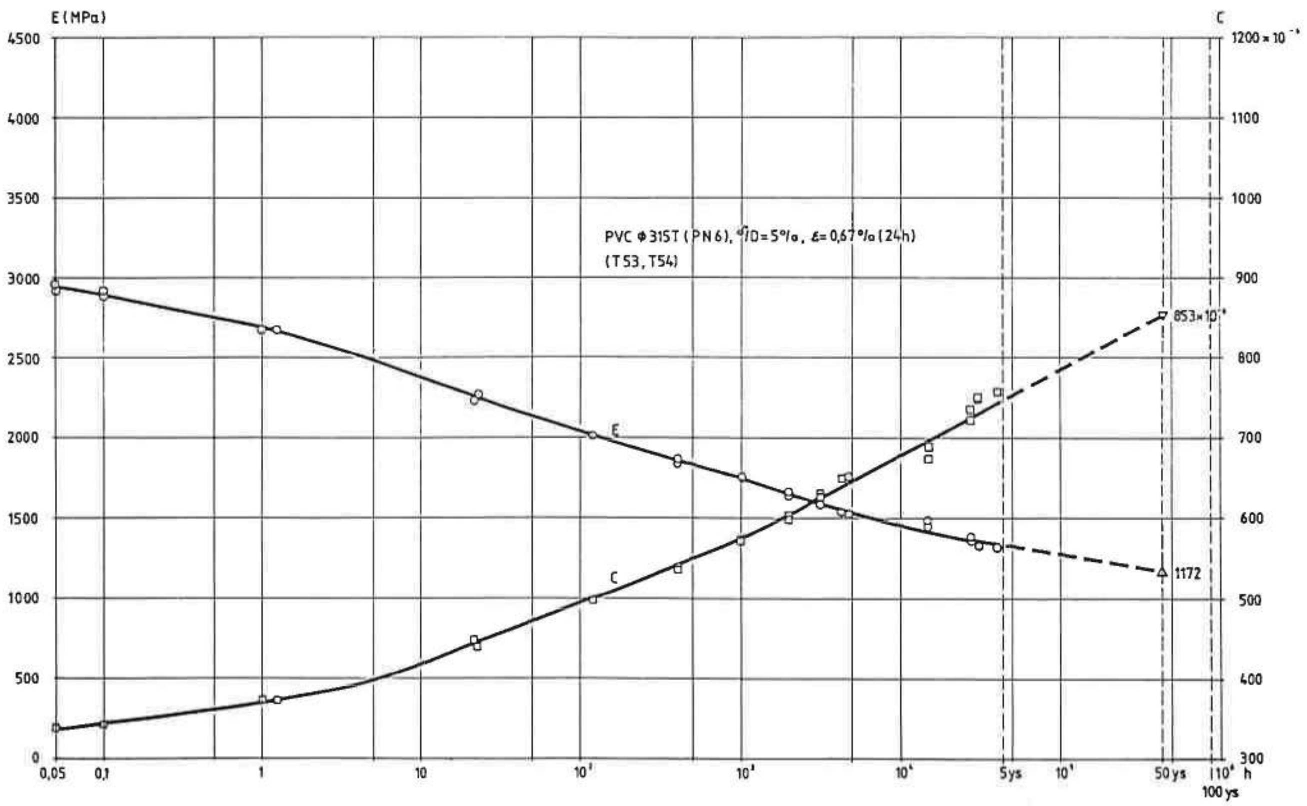
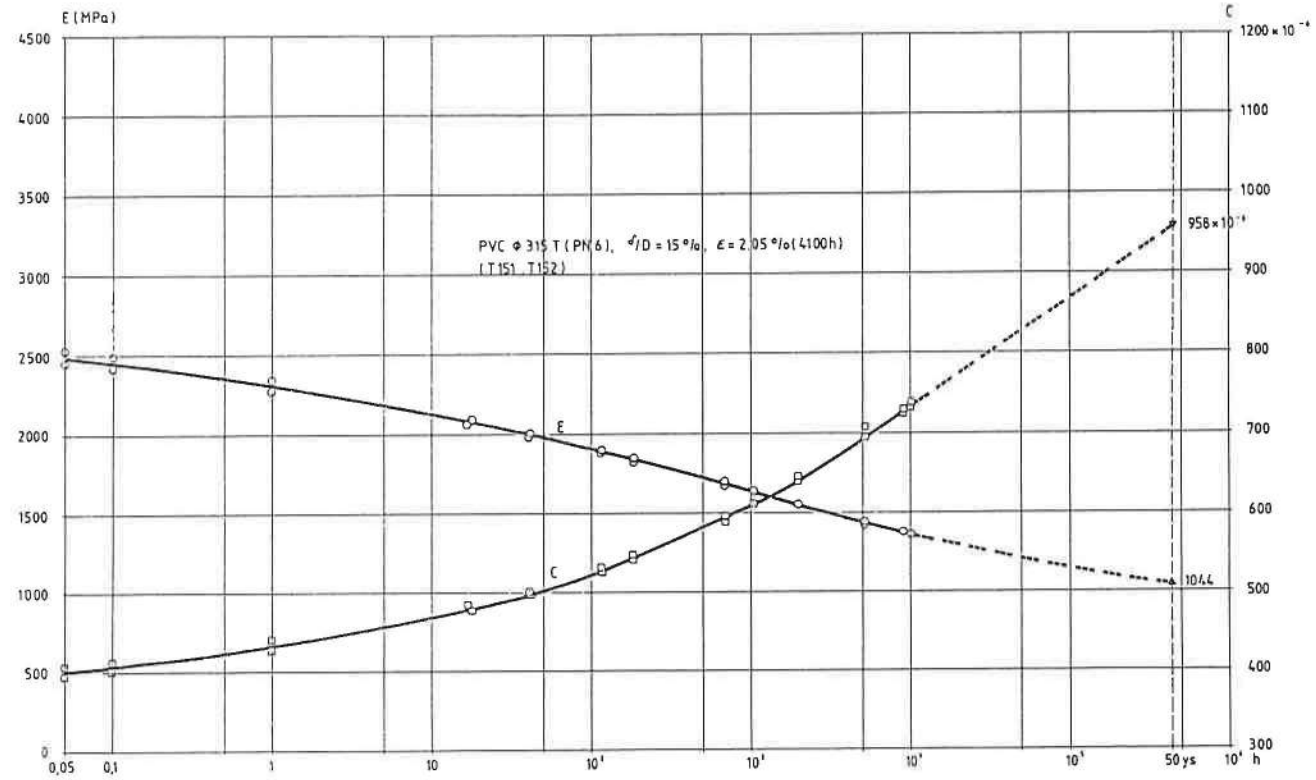


Fig.2.6 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



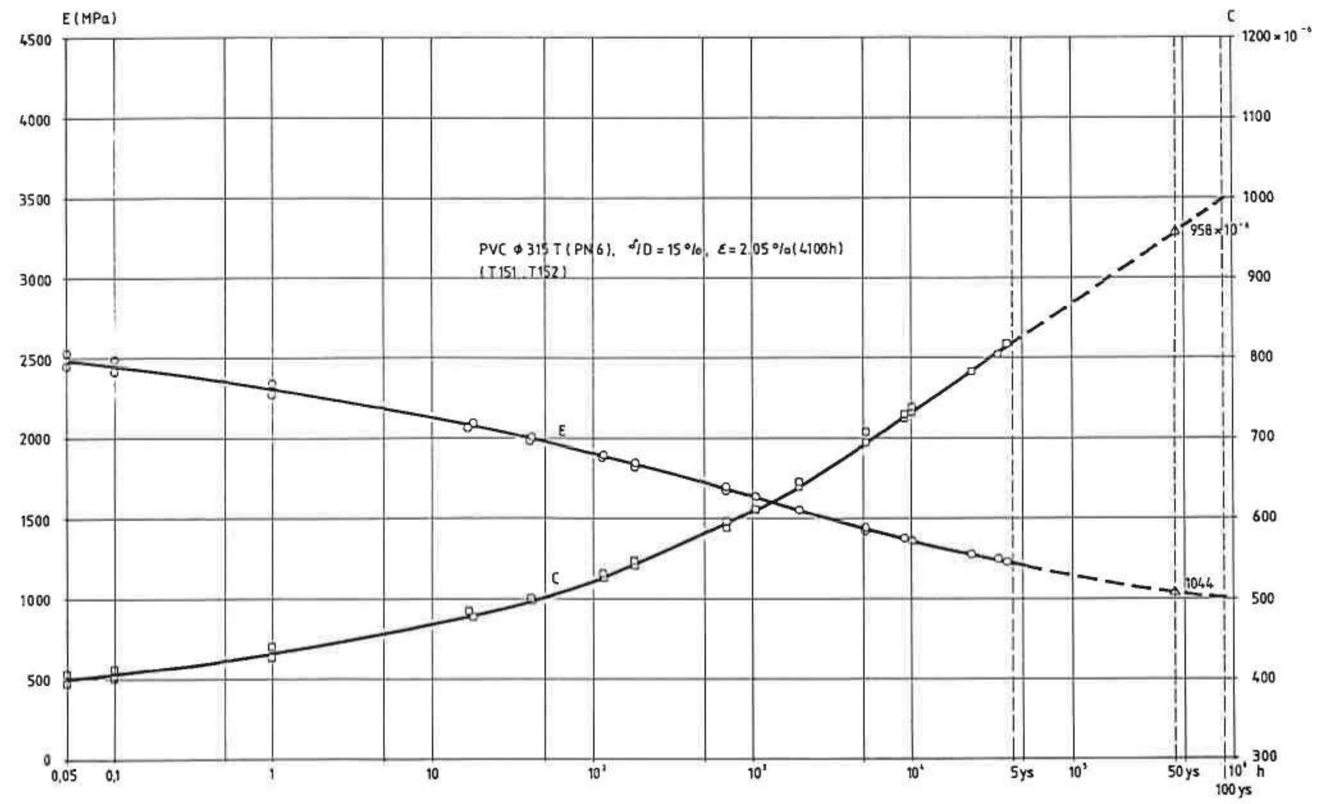
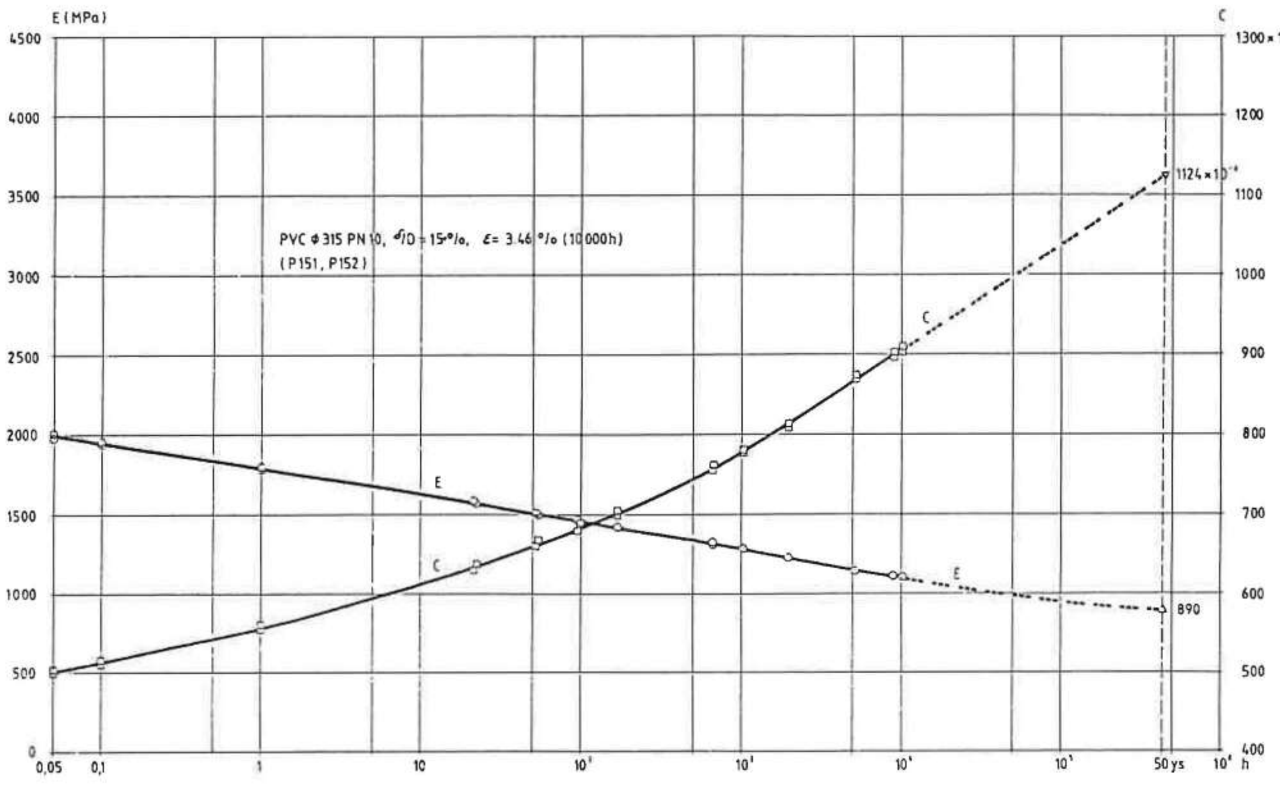


Fig.2.7 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



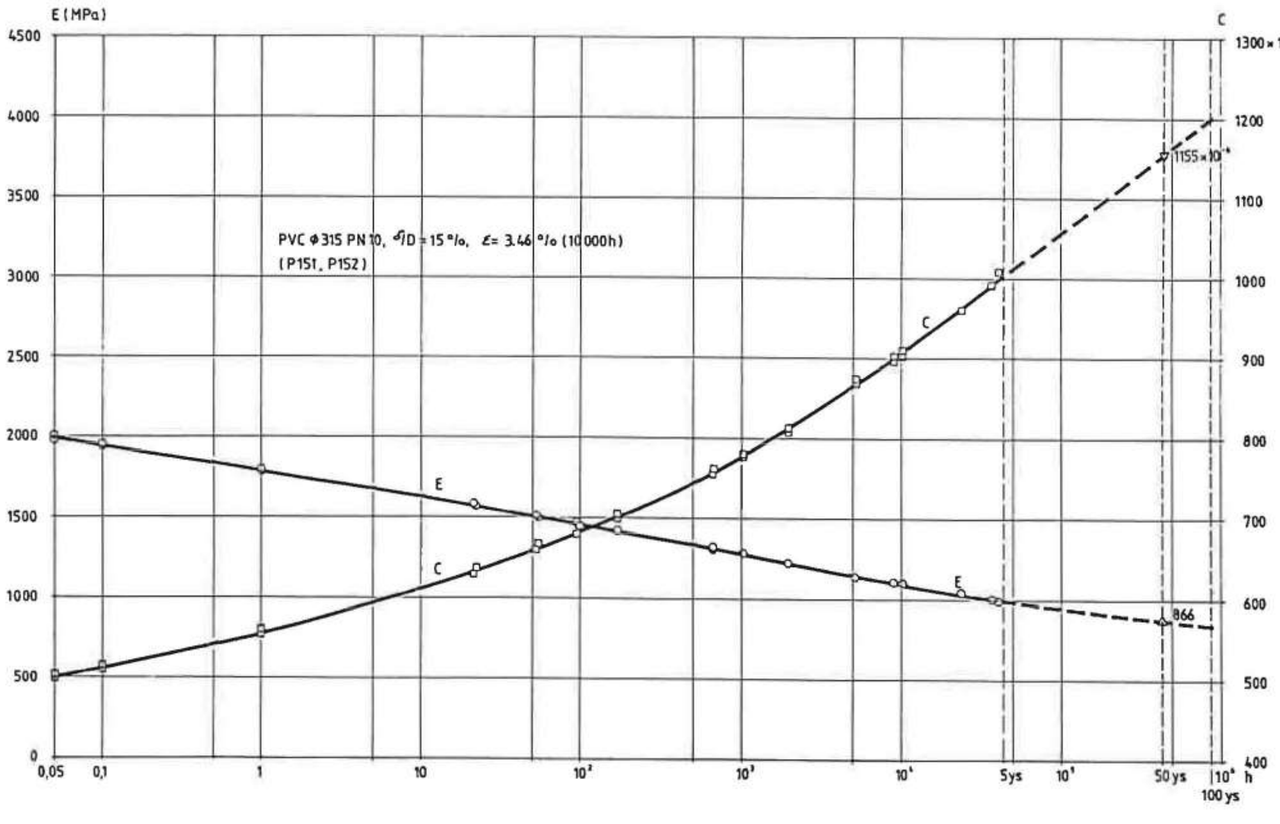
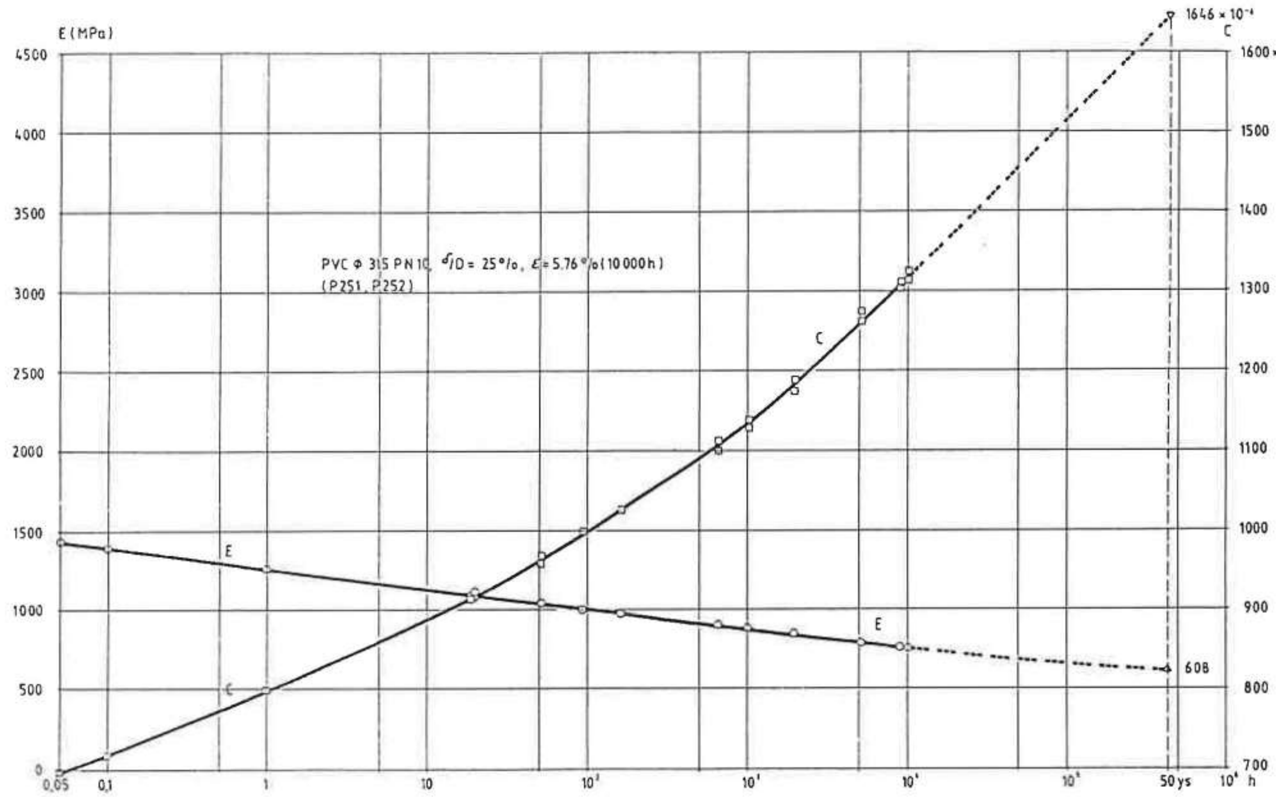


Fig.2.8 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.



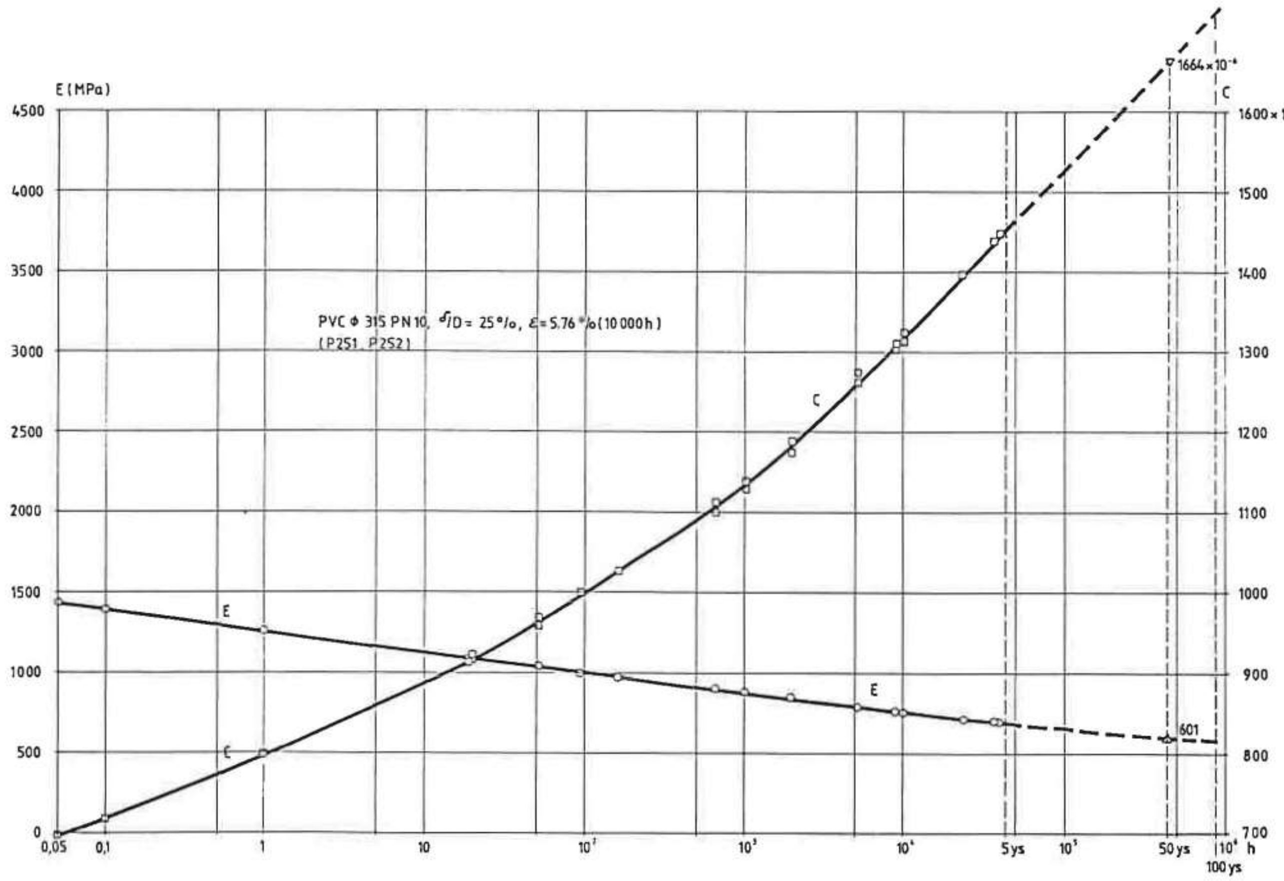


Fig.2.9 Relaxation E-modulus after 10,000 h of constant pipe deflection according to [1]: Upper diagram. - The same after 5 years: Lower diagram.

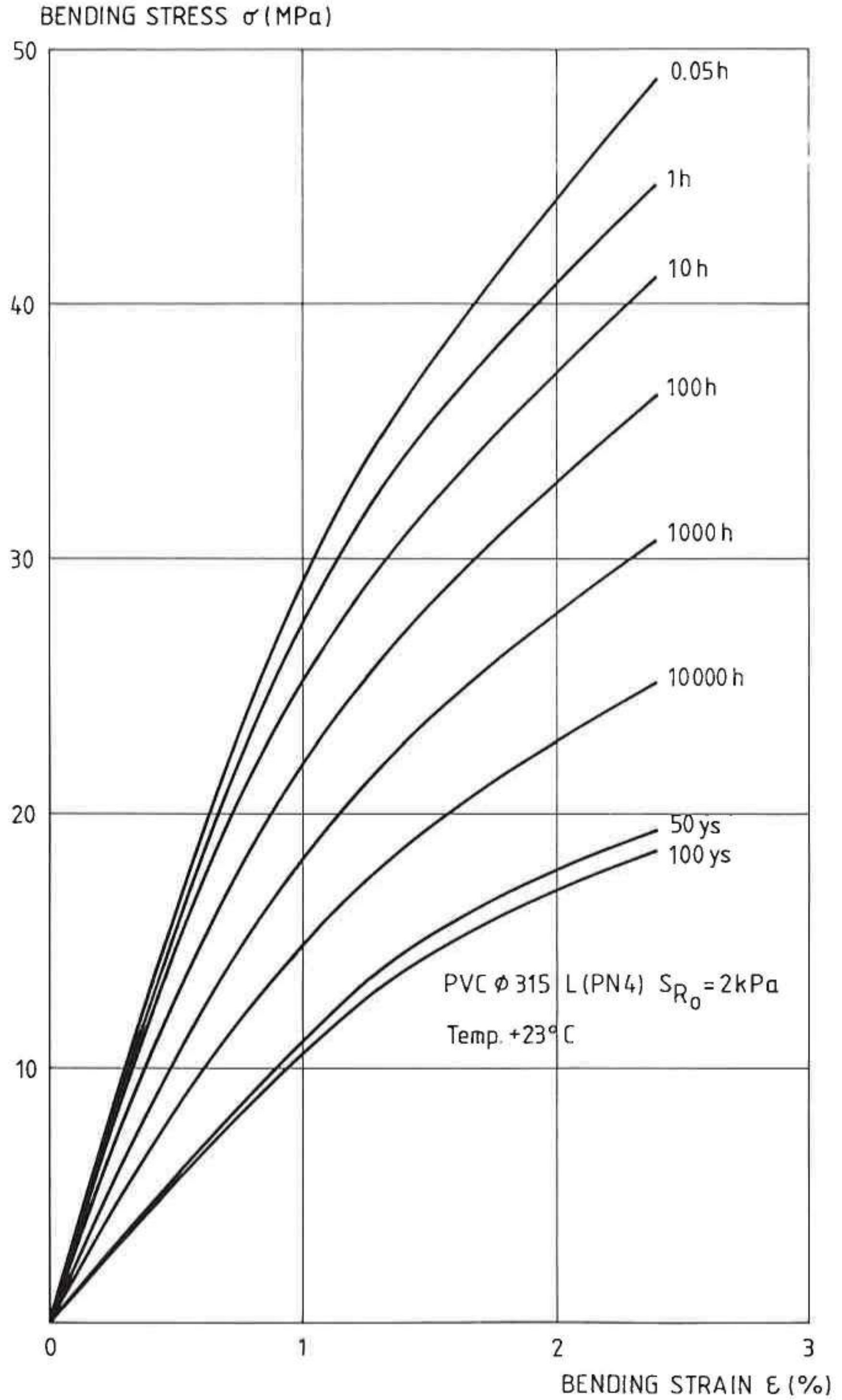


Fig. 2.10 Stress/strain curves deduced from Fig. 2.1-2.3

3. RING STIFFNESS CHANGE IN PVC PIPES IN THE COURSE OF TIME

Ref. [1] discusses the increase in the initial short-term ring stiffness as a function of time. This increase is assumed to be due to the physical ageing process taking place in the pipe material, which in turn is referred to as a consequence of a consolidation of the molecular structure of the amorphous PVC polymer followed by a volume decrease, [5]. Hence, it was found in [1] that the initial ring stiffness measured 10 hours after manufacturing of the pipe might increase by approximately 20 % after 50 years. The measurements were performed on three samples of PVC sewer pipes PN6 with a nominal ring stiffness of 8 kPa. One sample had an age of 7 hours (TY) when the first measurement was made. The second and third had an age of 240 hours (TY) and 2,400 hours (T) respectively. In [1], the ageing was followed up for approx. 10,000 hours, while the ring stiffness is currently being checked after an 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 Fig. 3.1. As can be seen, the first and second samples (TY samples taken from the same manufacturing series) show an increase from approximately 7.9 kPa to 9.5 kPa 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 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 2,400 hours (T) when the ring stiffness was first measured to 9.5 kPa. After 10,000 h, the ring stiffness was found to be 9.8 kPa and after 42,000 h approximately 10 kPa. In Fig. 3.1 the assumed extrapolation forwards to 50 years gives 10.2 kPa, while an assumed extrapolation backwards to 10 hours gives a ring stiffness of approximately 8.2 kPa, which means an increase in stiffness of 24 % between 10 hours and 50 years.

Another pipe sample, PN10, with a nominal ring stiffness of 32 kPa and an age of approximately one year when first measured had at that time an actual ring stiffness of 41.4 kPa. After an additional year, the stiffness was found to be 42.5 kPa and finally, after a total age of 5.6 years, the stiffness had increased to 42.8 kPa. As could be expected from Fig. 3.1, the addition increase in stiffness is very small after a pipe age of approximately one year. This can probably also be recognized by the rectilinear course of the linC/log t-curves after approximately one year of constant deflection (Figs 2.1-2.9).

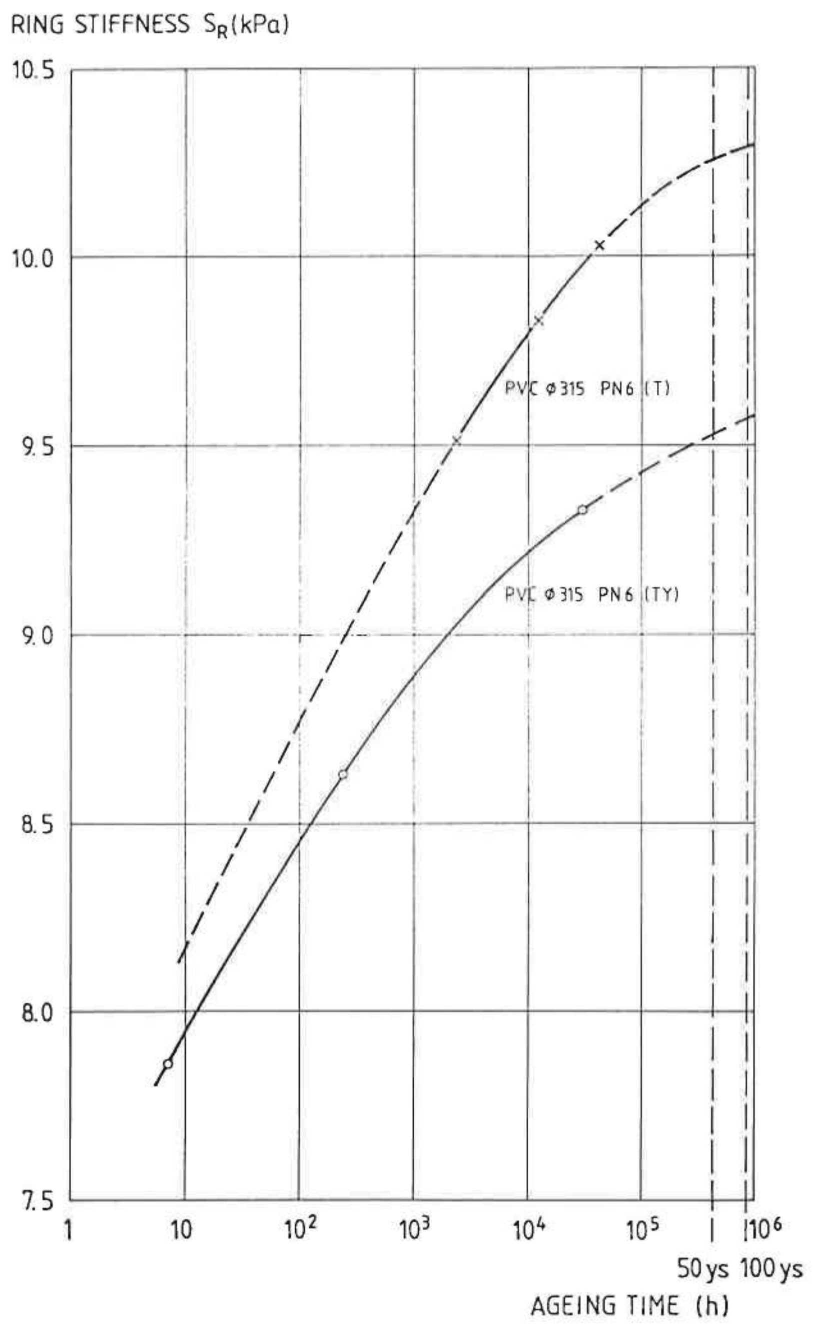


Fig. 3.1 Increase of the initial ring stiffness as a function of time due to physical aging of the pipe.

4. FROZEN-IN STRESSES IN PVC PIPES

In [1] the frozen-in stresses in the pipe samples were measured according to the "cut-up" method further described in [4]. Thus it was found that the stresses when originally measured were 6.2 MPa in the PN6 (TY) sample at an age of approx. 240 h, 4.9 MPa at an age of 2,400 h, and 6.3 MPa in the PN10 sample at an age of one year. Samples from the same pipe delivery had been stored in the laboratory and these samples were now cut up and the frozen-in stresses measured, Fig. 4.1. Table 4.1 gives the results of the new measurements. In the calculation, the increase in the E-modulus due to physical ageing has been considered as deduced from the ring stiffness values presented in Fig. 3.1. The figures in brackets show the values without consideration to the ageing effect.

Table 4.1 Frozen-in stresses (MPa) as a function of age of the samples after manufacture.

Age (years)	PN6 sample (TY)	PN6 sample (T)	PN10 sample (P)
0.03	6.2		
0.3		4.9	
1			6.3
2			6.0 (5.8)
3.7	5.2 (4.8)		
5		4.1 (3.9)	
5.7			5.4 (5.3)
50 ys (extrapolated)	4.5	3.5	4.8

One aspect of particular interest in Table 4.1 is that the relaxation of the frozen-in bending stress is rather slow, and furthermore that the relaxation process is slowed down by the physical ageing effect of the pipe material.

Contrary to what was assumed in [1], the relaxation of frozen-in stresses in PVC pipes seems to be a far slower process than predicted, now based upon the additional study presented. Thus, taking the physical ageing process into consideration, a frozen-in stress measured in a normal quality control test approximately 10-20 hours after pipe manufacture will decrease to only 85 % of that value after 1-2 years and to not more than 70 % after 50-100 years. This is an important new finding, the consequence of which should be that the relaxation of the frozen-in stresses can be neglected from a practical point of view, when designing a buried thermoplastic pipe. Thus the frozen-in stress will be more or less fully recognized in the pipe wall during most of the life span of the pipe. Simultaneously, it can be stated that this consideration does not play any significant role as far as gravity pipes are concerned, but that it certainly has an effect in the case of pressurized pipes where the total wall stress picture is a combination of both bending stress under relaxation and a tensile stress subjected to creep.

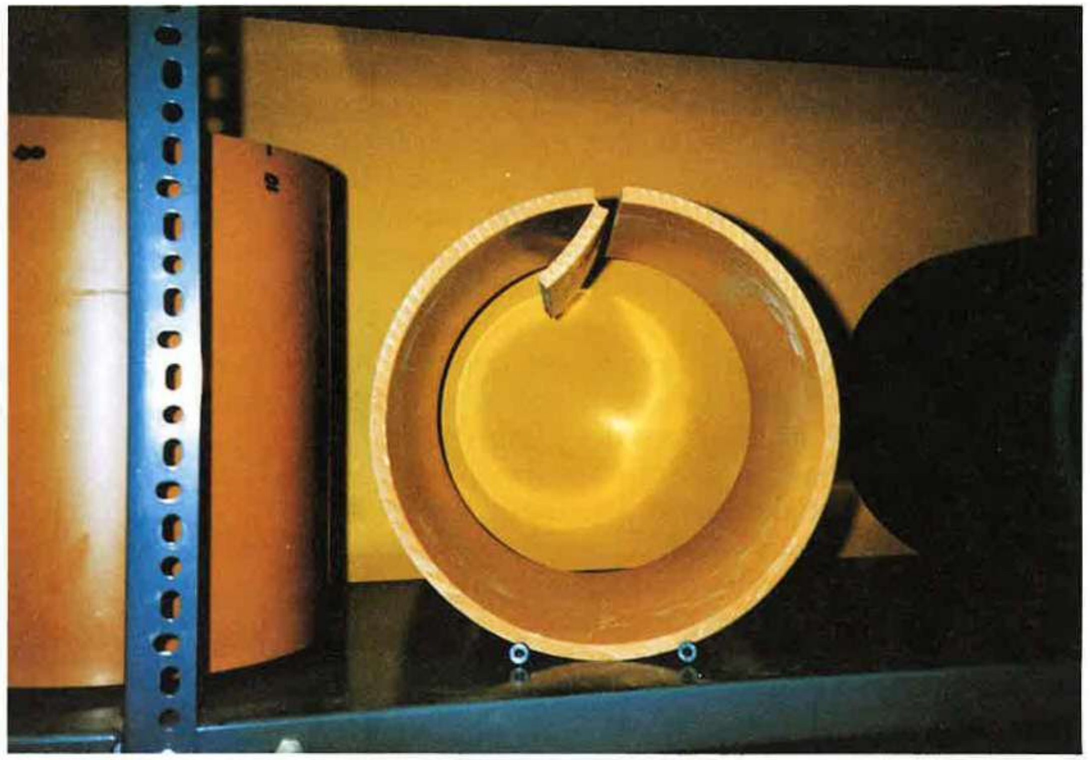


Fig.4.1 Measurement of frozen-in stress in PVC pipe ø 315 mm PN6 (T) by cutting up the sample. The decrease of the pipe periphery is shown as the difference between the width of the plate cut away and the open space where it originally was placed.

5. DEFLECTION RECOVERY WHEN RELEASING CONSTANTLY DEFLECTED PVC PIPE SAMPLES

The deflection recovery of the PVC pipe samples during 1,000 h load release was presented in [1], see Fig. 5.1. (Full lines). These samples had at that time been constantly deflected during 10,000 h. The duplicate half of the sample series were then kept deflected for totally 42,000 h (approx. 5 years) after which time they were released. The deflection recovery of these samples during approximately one year is illustrated in Fig. 5.1 (dotted lines). See also Fig. 5.2. As can be found when comparing the full and the dotted lines in Fig. 5.1 the immediate recovery is now less and the recovery process more slowly after 5 years of deflection than after 10,000 h of deflection. This is quite natural and verifies the statement in Section 2, saying that the recovery velocity will decrease as a consequence of the fact that the bending stress in the pipe wall, which forces the deflection to recover, decreases in the course of loading time due to relaxation; see Fig. 2.10 (or Figs 2.1-2.9). It has also been understood that the full recovery, independent of the pipe deflection and actual time period of constant deflection will take very long time (theoretically infinite time). As an example, after 50-100 years of deflection release it can be assumed (based upon a cautious extrapolation of the curves in Fig. 5.1) that the deflection recovery at that time may be 50 % of the original deflection, more or less independent upon the actual magnitude of the deflection.

However, as the deflection recovery follows a parabolic curve, the extrapolation must be taken with great care. Only continueing studies can show the real long term curve shape. Therefore the samples will be stored in the laboratory as long as possible for further investigation.

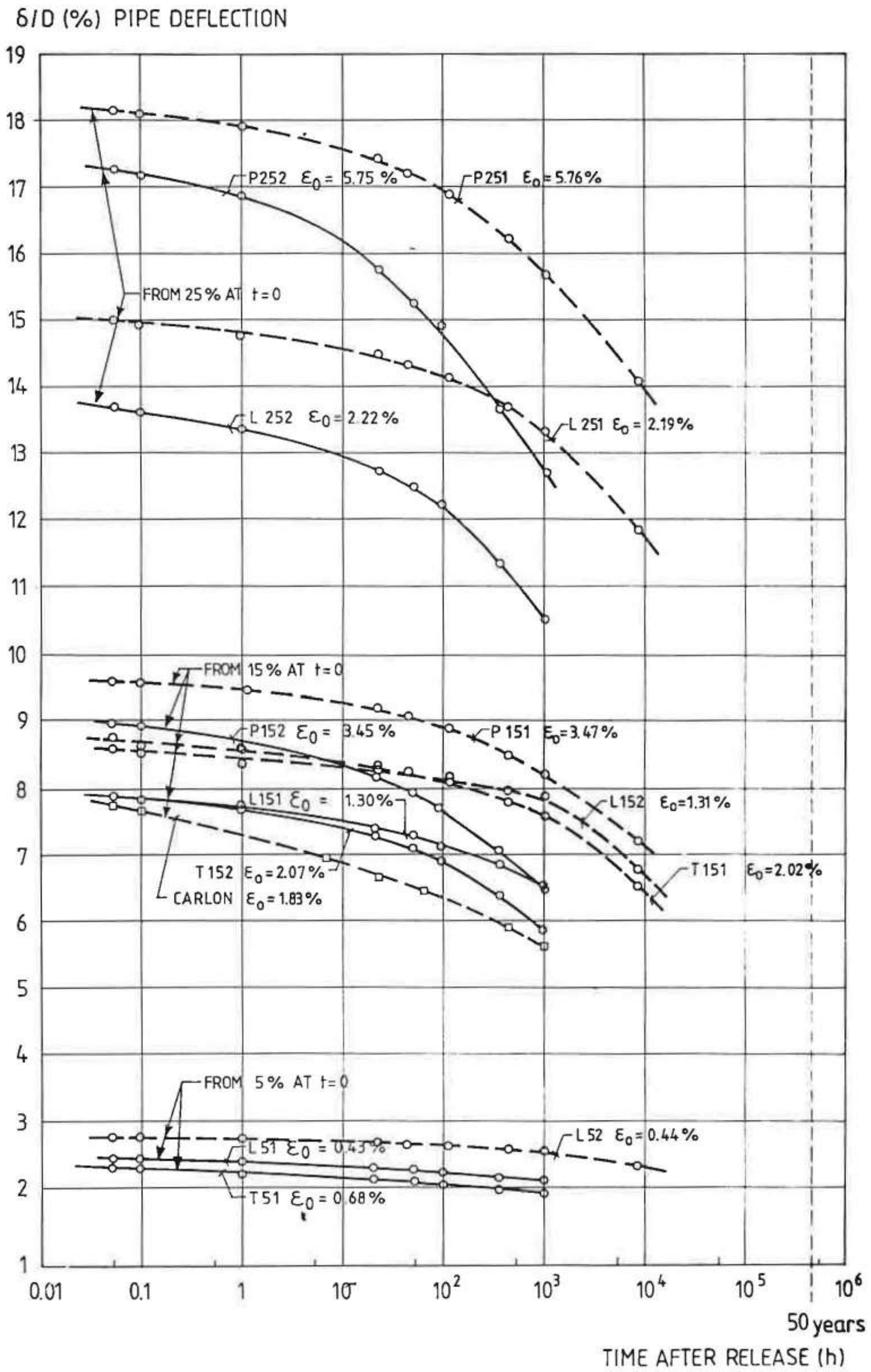


Fig. 5.1 Pipe deflection recovery when releasing PVC pipes after 10,000 h of constant deflection: Full lines. The same after 5 years of loading: Dotted lines.

Fig. 5.2 Pipe samples under deflection recovery. PVC pipe ø 315 PN4 (L) originally deflected to 15 %: To the right. - PVC pipe ø 315 PN10 (P) originally deflected to 25 %: To the left.

6. BENDING STRAIN LIMIT FOR LONG-TERM DEFLECTED PVC PIPES

One of the original purposes of this study was to try to find out whether or not there exists a practical upper bending strain limit for designing constantly deflected uPVC pipes. The question was originally discussed in [6] and further in [1] after 10,000 h of relaxation measurements. Based upon studies of deflected pipes with constant bending strains of up to 5.76 % and deflected plates with constant bending strains of up to 10.4 % it was concluded in [1] that no such practical upper strain limit seems to exist for designing buried PVC gravity sewer pipes. Instead it is only the mechanical stability of the pipe which should serve as the requirement basis for the structural design.

The present study gives no reason to change this previous statement. Hence the lin C/log t curves in Figs 2.1-2.9 continue to show a rectilinear course after 5 years of deflection. In one case (Sample L152, Fig. 2.2) there was reason to suspect that some form of failure had occurred after approx. 30,000 h as the lin C/log t curve suddenly shows a dramatic upward course. However, if this observation had been a consequence of some form of cracking in the pipe wall, it would also have been identified in the deflection recovery graph in Fig. 5.1. But there, the deflection recovery follows the same pattern as for the daughter Sample L151. It seems, therefore, that the discontinuity in Fig. 2.2 is merely a result of measurement errors. The same is probably the case with Samples T53-T56 in Figs 2.5-2.6. In these latter cases all samples are still under deflection, and hopefully the final confirmation will be given by the future studies. However, as the strain is very low (0.67 %) it is unlikely that the measurement results in Figs 2.5-2.6 are anything else other than scattering of the measurements.

[1] also presents the results of forced bending of plates taken out from half parts of PVC pipes (PN6 and PN10), which were bent upside down. The theoretical strains in these samples are 6.6 % (PN6) and 10.4 % (PN10). The samples have now been examined visually and no micro cracks have been found, Fig. 6.1. Furthermore, the forces needed to keep the plates deflected have been measured. In Table 6.1 these forces are compared with the original forces as well as with the same forces after 6380 h as presented in [1]. As can be seen, the forces measured after totally 33,300 h (approx. 4 years) are still significantly large. This

Table 6.1

Pipe class	ε %	t = 0	Forces (N) at t = 6380 h	t = 33,300 h
PN6	6.6	2330	1710	1527
PN10	10.4	6420	3725	3280

observation supports the previous statement that no micro cracks have occurred during the 4-year constant deflection of the pipe walls.

The hypothesis presented in [1], i.e. that the reason why no failure occurred is because bending stress relaxation is going on continuously, has not been contradicted by these additional long-term studies.

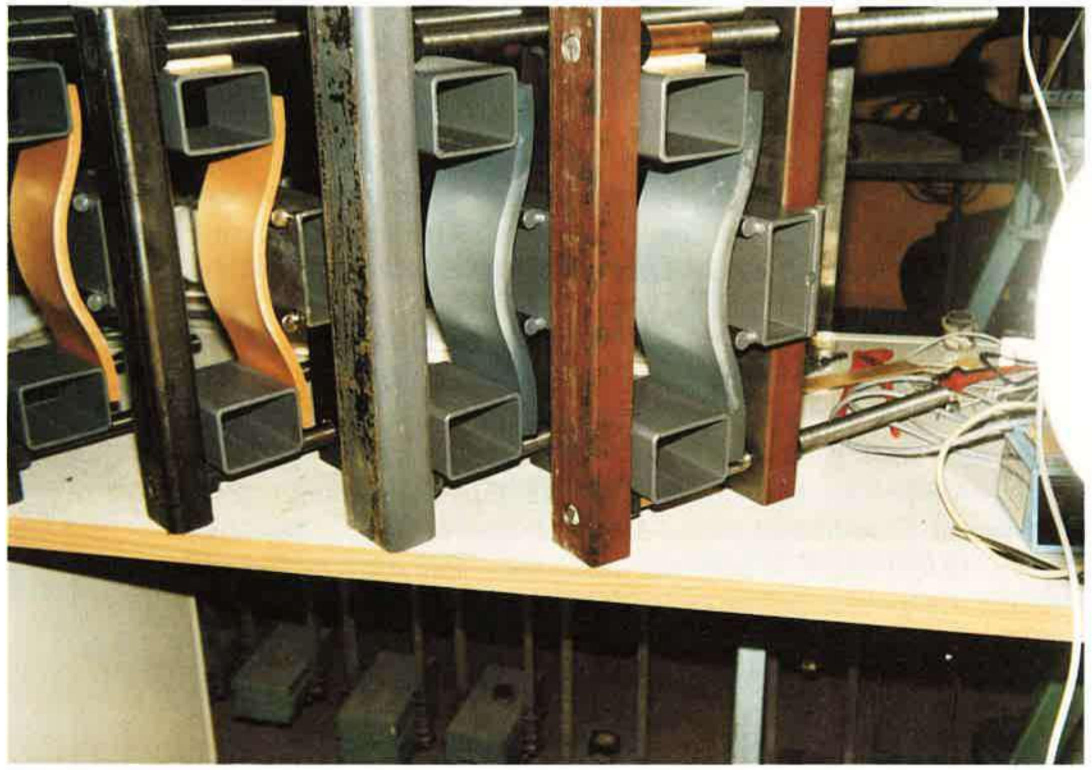


Fig. 6.1 Strongly deflected samples taken out as a part of the PVC pipe. The exposed side of the samples in the picture corresponds to the original inside surface of the pipe PN6: To the left. - PN10 to the right. - The samples have been kept deflected during approximately 4 years without showing any cracks.

7. PVC PIPES CONTAINING A LARGE AMOUNT OF FILLER

As indicated in [1], a relaxation study of a PVC pipe manufactured in the USA ("Carlon") with a filler content of 26 % had been started at that time, (1987). The external diameter D_{ex} is 213 mm and D_{ex}/s = 36, implying a nominal PN value of approximately 5.7 bar (provided the design tensile stress is 10 MPa). Three pipe samples were studied, one with a constant deflection of 5 % and two others with a constant deflection of 15 %, (Fig. 7.1). The corresponding bending strain values are 0.60 % and 1.83 % respectively. The K-value was determined to 68.1 and the Vicat point to 81.0°C. The density on the inside of the pipe wall was 1570 kg/m^3 and on the outside 1580 kg/m^3. The short-term ring stiffness was determined to 7.9 kPa. The frozen-in stress was exceptionally low, or 1.1 MPa.

The measurements have now been going on for 35,000 h (approx. 4 years) and the results are illustrated in Fig. 7.2 and Fig. 7.3. As can be seen in Fig. 7.2 the lin C/log t curve has about the same shape as those found for the normal PVC pipes according to Figs 2.1-2.9, and a rectilinear course seems to have been reached after approx. 10,000 h at 5 % constant deflection. The main difference in comparison with the normal PVC pipes concerns the E-values, which at 5 % deflection are 4200 MPa at 0.05 h (3 min.) and 2169 MPa at 50 years.

Hence, the filler content of 26 % has contributed to an increase in the short-term E-modulus at 5 % deflection from 3200 MPa (fig. 2.4) to 4200 MPa (31 % increase) and the long-term E-modulus (50 years) from 1320 MPa to 2170 MPa (65 % increase).

The study of the sample with a deflection of 15 % according to Fig. 7.3 shows a rather good rectilinear lin C/log t-curve up to about 25,000 h. Thereafter the last measurement at 34,000 h indicates a remarkable upward deviation in the C-value. It is possible that this change, which may have been initiated already after approximately 2.5 years of deflection, will reveal the onset of micro cracking in the pipe sample. Therefore, no extrapolation of the curves can be performed until further long-term measurements have been made (compare the discussion in Section 8, Fig. 8.2, Sample No. 20).

The relaxation studies have not yet been completed, but will continue as long as there is sufficient space available in the climate room. However, so far it can be stated that for pipes with moderate deflection (5 %), there is no indication to the effect that the pipe material is particularly crack-susceptible or that it has any other weakness making it unsuitable for use as a buried gravity sewer pipe.

In order to obtain further information on the remaining elastic behaviour of the pipe material, a separate pipe sample was released after three years of 15 % constant deflection. The deflection recovery over 1000 h is illustrated in Fig. 5.1. When compared with the recovery of the normal PVC pipes, it seems as though the filler-filled material has about the same capacity for deflection recovery. Hence, this single recovery study contradicts the statement made above based on the observation in Fig. 7.3.

Therefore, in order to find out whether a strain higher than those studied above would reveal any difference as regards strain characteristics between normal PVC pipes and filler-filled PVC pipes, half a pipe sample was bended upside down (compare Section 6) and stored in that position for three years, see Fig. 7.4. The theoretical bending strain was 4 % in this case. The initial force to keep the sample deflected was unfortunately not measured, but based upon the high short-term E-modulus for the filler-filled PVC pipe, it is assumed that the force may have been of the same order of magnitude as the one given in Table 6.1 for the PN6 sample. However, the same force after three years was only 320 N, which indicates that the heavily strained filler-filled PVC material has a limited capacity to recover the deflection. Again, we have here another indication that there obviously exists an upper bending strain limit for the filler-filled PVC pipe studied.

Finally, it was of interest to find out whether or not the filler-filled PVC pipe had the same impact strength as the normal PVC pipe. Thus, standardized impact strength tests according to Swedish Standard SS 16 13 51 were performed at +21°C and at -20°C respectively for the filler-filled pipe as compared with the normal PN6 class pipe. Notched bars according to Fig. 7.5 were taken out from the pipe walls. The results of the test are presented in Table 7.1.

Table 7.1

Impact strength according to Charpy (kJ/m^2)

Normal PVC pipe PN6

Temperature (°C)	Number of samples	Mean value	Standard deviation
+ 21	7	14.8	1.5
- 20	7	8.2	1.4

Filler filled PVC pipe

Temperature (°C)	Number of samples	Mean value	Standard deviation
+ 21	7	10.6	1.1
- 20	7	6.7	0.4

As can be found the impact strength of the filler filled pipe is somewhat, although not significantly, less than the same of the normal PVC pipe. Consequently, this particular filler filled PVC grade studied, has properties which certainly could be accepted as pipe material for buried gravity sewer pipes provided the pipe deflection is moderate.

However, it is certainly true that the result presented in this study, is not generally valid for all type of filler additives. The acceptable result in this case for moderately deflected pipes should therefore be discussed as a consequence of the particular filler property used. Hence, it can be assumed that the favourable influence of the filler on the strength properties of the PVC material is connected to both the grain size as well as to the grain size distribution of the filler (in this case pure calcium carbonate).

In order to study this question further a sample taken from the pipe wall was dissolved in THF. The dissolved material was separated by centrifugation and then washed, dried and photographed in a SEM microscope. The dissolved solid material was found to be pure calcium to an amount of 26.8 %. In Figs 7.6 and 7.7 photos with enlargement of 500 and 1000 respectively are reproduced. As can be seen the grain size of the filler material is between 5 and 10 microns. The grain size distribution can be looked upon as rather narrow as the amount of very small grains seems to be slight or none. The shape of the grains are more round than rugged or sharp. (The analysis of the filler material has friendly been performed by Norsk Hydro, Norway.)

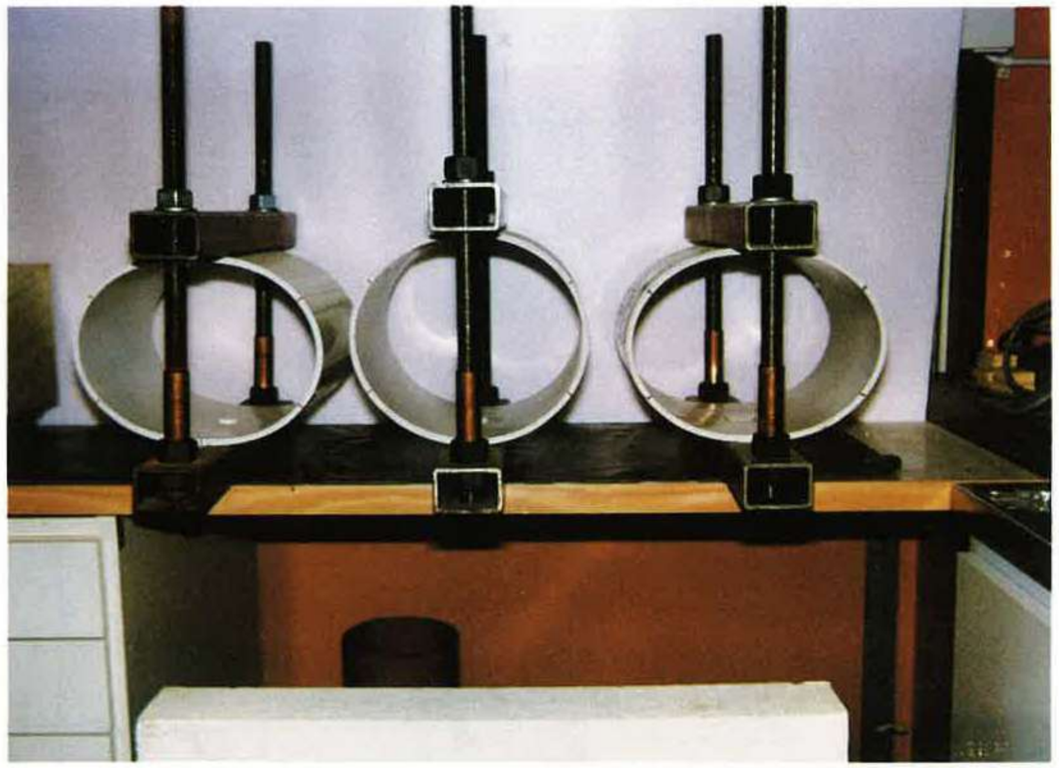


Fig. 7.1 Constantly deflected Carlon PVC pipes with large amount of filler.

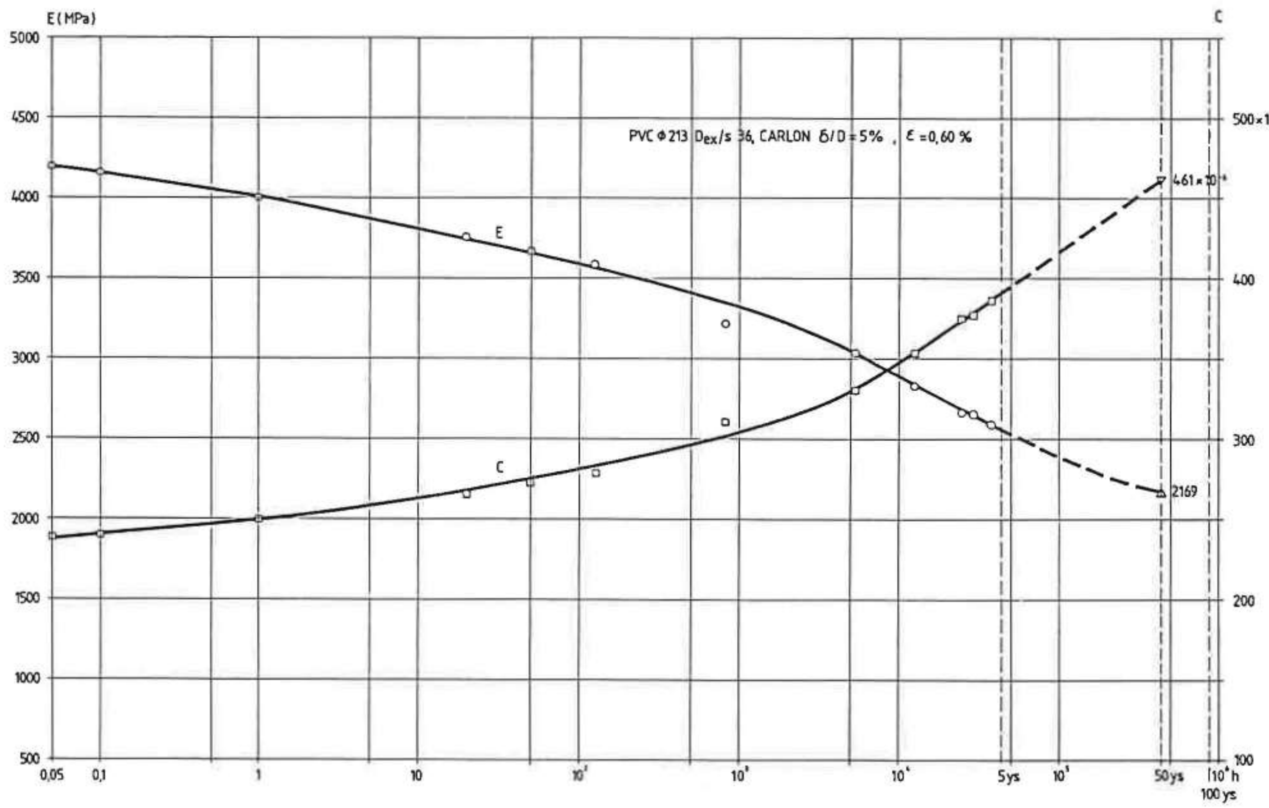


Fig. 7.2 Relaxation E-modulus for the filler filled Carlon PVC pipe, deflected to 5 %.

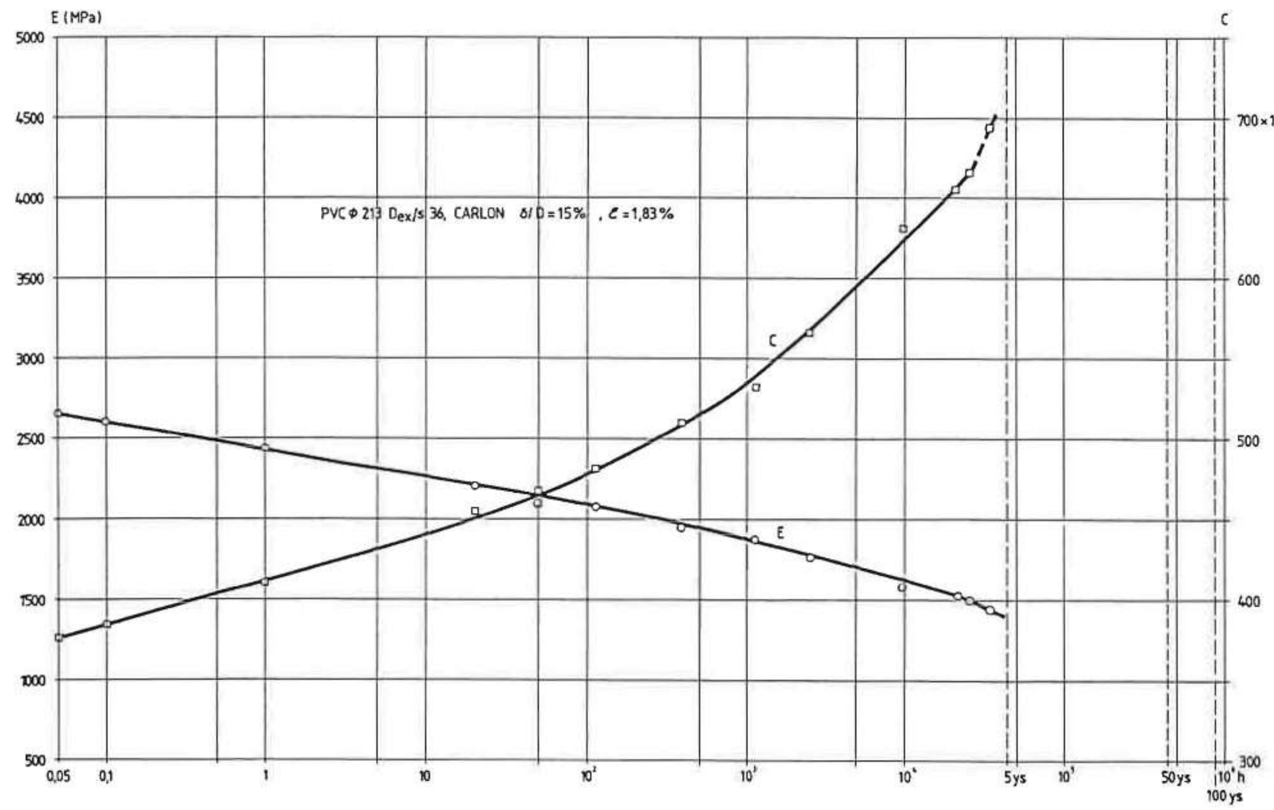


Fig. 7.3 Relaxation E-modulus for the filler filled Carlon PVC pipe, deflected to 15 %.

Fig. 7.4 Strongly deflected Carlon PVC pipe sample taken out as a part of the pipe. Compare Fig. 6.1.

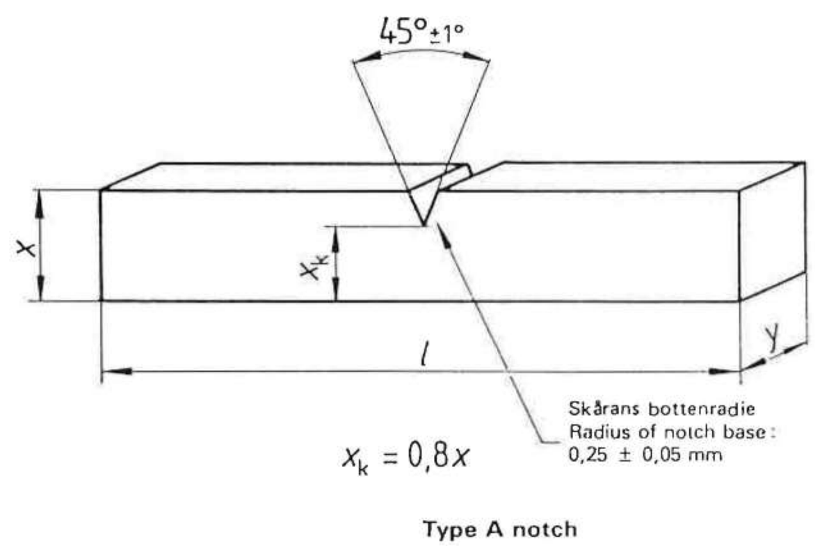


Fig. 7.5 Sample for impact strength testing according to Swedish Standard SS 16 13 51. The actual bar had x = 4 mm, y = 10 mm and l = 80 mm.

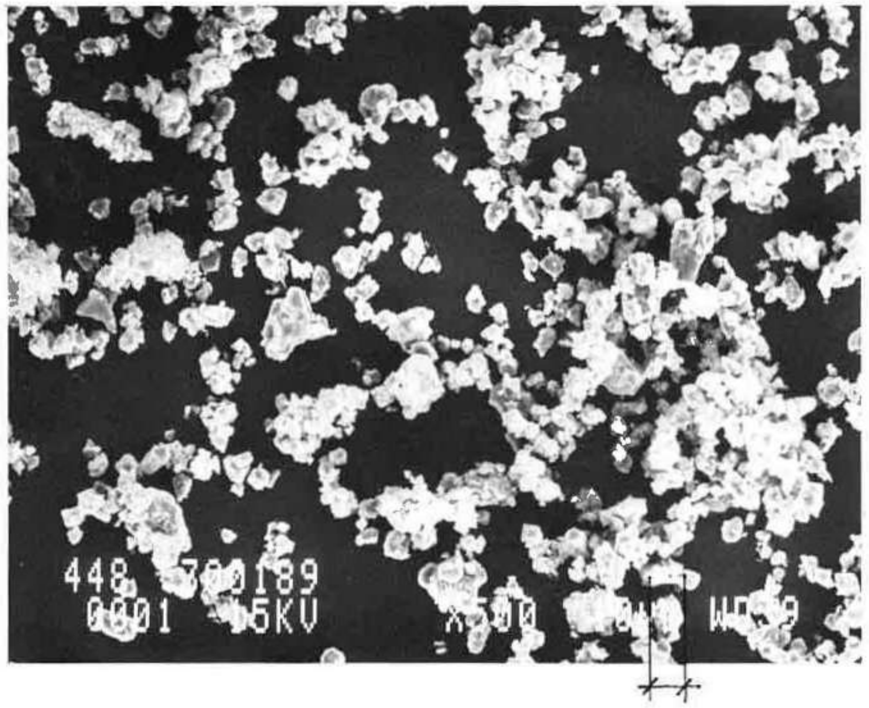


Fig. 7.6 Filler of calcium carbonate photographed in SEM microscope. Enlargement 500X. The scale shows the length of 10 microns.

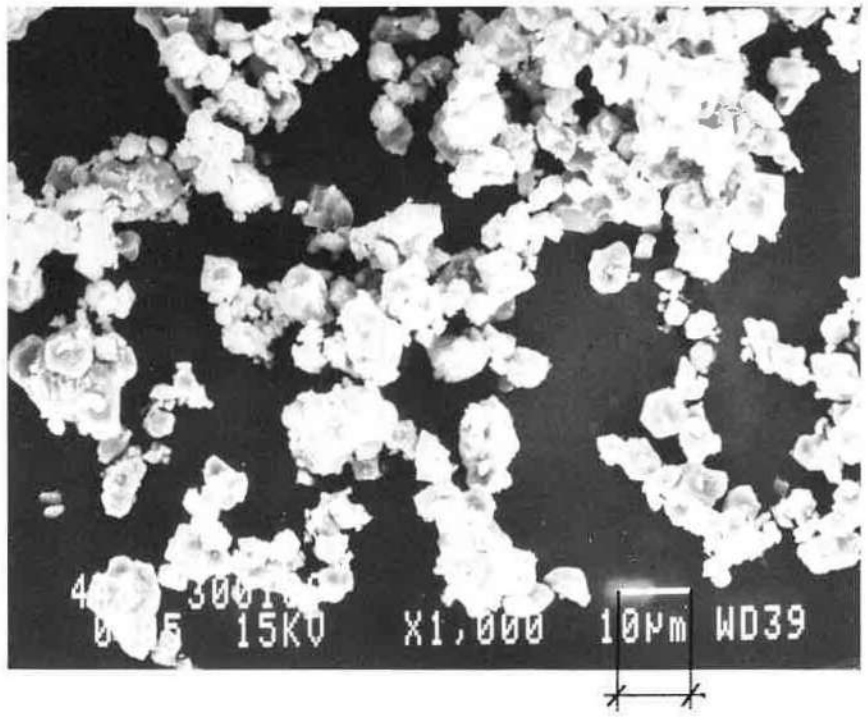


Fig. 7.7 Filler of calcium carbonate photographed in SEM microscope. Enlargement 1000X. The scale shows the length of 10 microns.

8. STRESS RELAXATION IN CONSTANTLY DEFLECTED PE PIPES

A long-term study of constantly deflected polyethylene pipes started in 1982 as a VBB commission for Neste Chemicals (at that time Unifos Kemi) and the Swedish KP-council. A first report was presented in 1983 [7] after one year of investigation. This report was used as a basis for a paper presented at an ASCE international conference in Madison, USA, [8].

Since then, the study has continued but has now been terminated after totally 72,000 h (8.2 years) of constant deflection. A supplementary report in Swedish [9] was presented after 41,200 h (4.7 years) of deflection. The following section provides complementary information on the findings presented in [8] and [9].

Three different PE grades have been studied, all from Neste Chemicals (Sweden). One is the HDPE grade DGDS 2467 (Type 1), another the modified HDPE grade DGDS 2467 BL (Type 2) and the third is the MDPE grade DGDS 2418. (The letters DGDS are today recognized as NCPE). As test samples extruded pipes have been used with an external diameter of 315 mm. The length of the sample is the same as the diameter. (Hence, the external size of the PE samples is the same as for the PVC samples dealt with in Section 2.) The wall thickness of the PE samples corresponds in one series to the pressure class PN4 (nominal wall thickness 12.1 mm) and in another series to the pressure class PN6 (nominal wall thickness 17.8 mm). Both classes are based on a long-term tensile design stress of 5 MPa. The corresponding nominal short-term ring stiffnesses for the two HDPE pressure classes are 4 kPa and 16 kPa respectively. The pipe samples are deflected, giving constant strains between 1.1 % and 3.5 %.

Figs 8.1-8.3 show the lin C/log t-curves and the corresponding E-modulus curves. As previously described, the compliance C stands for the inverted value of the E-modulus and that the rectilinear part of the lin C/log t-curve illustrates the relaxation behaviour of a physically aged amorphous polymer [5]. As polyethylene is not amorphous but semi-crystalline, the lin C/log t-curves do not have the same shape as those for the amorphous PVC material. Thus, it has been found in the present study that the rectilinear course of the curve occurs very early, which means more or less immediately for highly strained material and after 10 to 100 h for less strained material. Consequently, the long-term physical ageing process discussed for PVC cannot be recognized in a similar way by the actual course of the lin C/log t curve for PE. A practical positive effect of this observation is that the long-term (50-100 years) E-value can be found for most PE materials after a testing time of less than 1000 h, while for PVC the testing time has to be up to one year or more.

From Figs 8.1-8.3 it can be seen that the measurements after 10,000 h concur well with the rectilinear lin C/log t curves drawn up at a testing time of only 1000 h. Thus, the more than eight years of constant pipe deflection have given no reason from a practical point of view to change the long-term E-values that could be determined after only approximately six weeks of testing.

A particular observation for sample No. 20 in Fig. 8.2 needs to be commented on. The sudden increase in the lin C/log t curve after 5000 h was discussed in [9], and was found to be due to a micro cracking in the summit of the pipe sample. It could be proved that the reason for cracking was due to the fact that the sample belonged to a pipe delivery which had been accidently thermally oxidized during manufacture. It is very interesting to find out that the change in the E-curve after 5000 h is insignificant, while the C-curve shows more sensitivity in the graphic representation applied in this case. Consequently, a study of the E-curve on its own would not have given such an early indication of failure in progress 15,000 h (1.7 years) before the full open crack was a visible fact. The fully cracked sample is shown in Fig. 8.4.

Another observation which has to be commented on, concerns sample No. 24 in Fig. 8.3. Here, a sudden decrease in the C-value appears after 60,000 h (6.8 years), which must be the result of a measurement error. Otherwise the E-modulus would have stopped decreasing, which would in turn mean that the plastic material had suddenly started to behave as elastic. This is certainly not true.

One important finding from the long-term studies is that the E-modulus after 50 years is significantly higher than was previously assumed. Thus, for moderately deflected pipes (4-5 %) the 50-year E-modulus is approximately 200 MPa, while previously 100 MPa was often used. - An extrapolation of the C-curves to 100 years, and after inverting the C-values, corresponding E-values are given which are only slightly less than the 50-year value. This supports the statements made in [3], implying that the service period for standardized gravity thermoplastics sewer pipes can certainly be 100 years or more, provided properly installed so that buckling does not occur. The present long-term investigation also

supports the statement already made in [6] and again in [8], that there is no practical upper bending strain limit for the design of buried gravity polyethylene pipes to be used up to 100 years. The condition is, however, that the internal pipe wall has not been thermally oxidized during manufacture, and moreover that the stabilization system of the grade is chosen to resist the chemical ageing process. (Compare the so-called Stage III, in the stress/time-diagram for pressure pipes, [4]).

As in Section 2, the lin E/log t-diagrams have been transformed to σ/t-diagrams with the loading time as a parameter. Fig. 8.5 illustrates the relations for the HDPE Type 2 grade and Fig. 8.6 for the MDPE grade. The difference between the two grades is insignificant. Thus, it can be stated that the short-term bending stress (3 min value) will relax to approximately 30 % of the original value after 50-100 years of constant bending strain caused by pipe deflection.

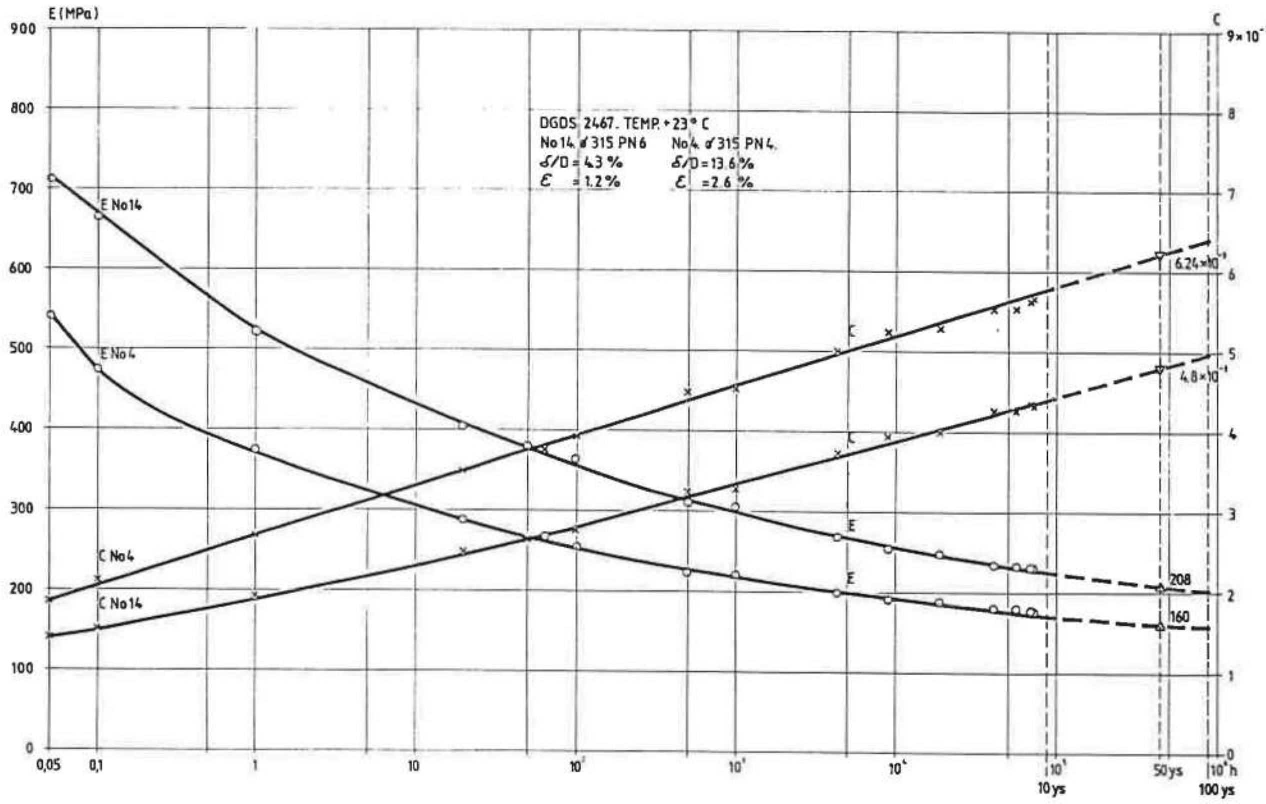


Fig. 8.1 Relaxation E-modulus for HDPE Type 1 pipe ø 315 mm.

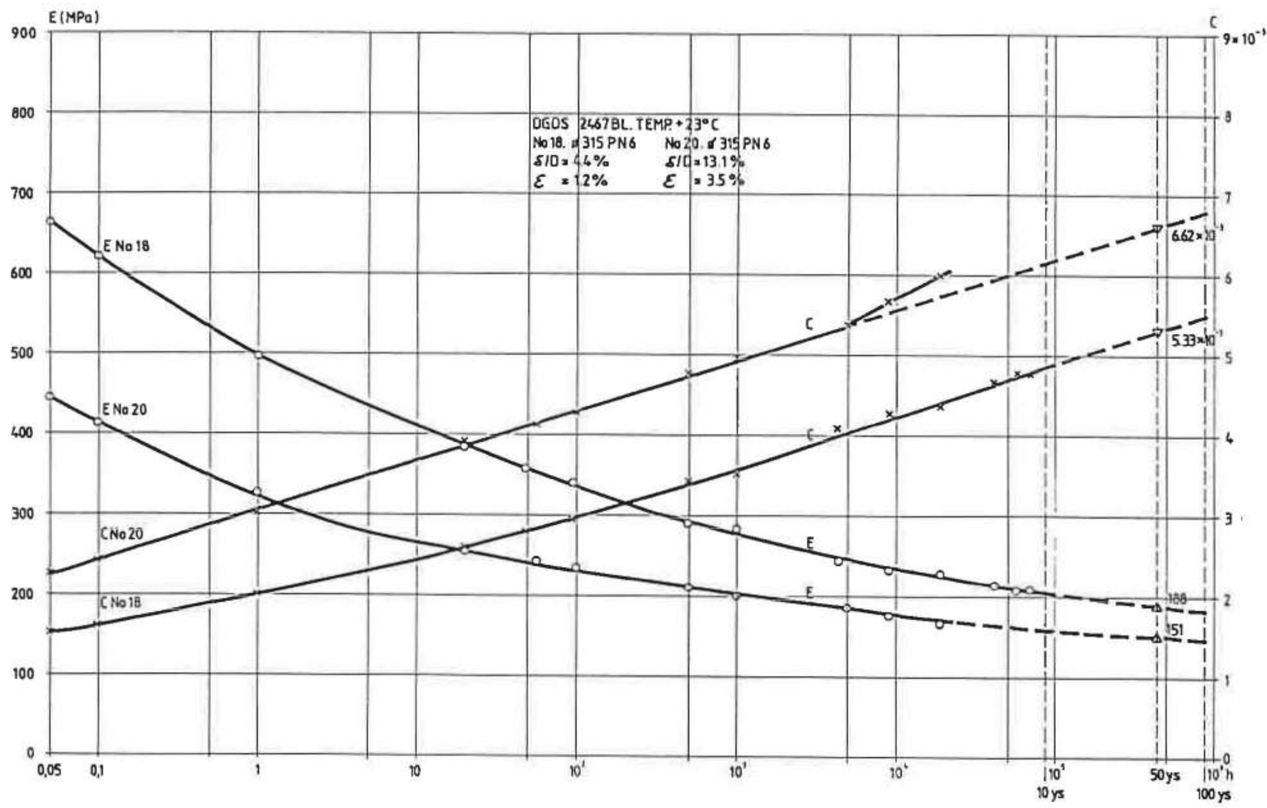


Fig. 8.2 Relaxation E-modulus for HDPE Type 2 pipe ø 315 mm.

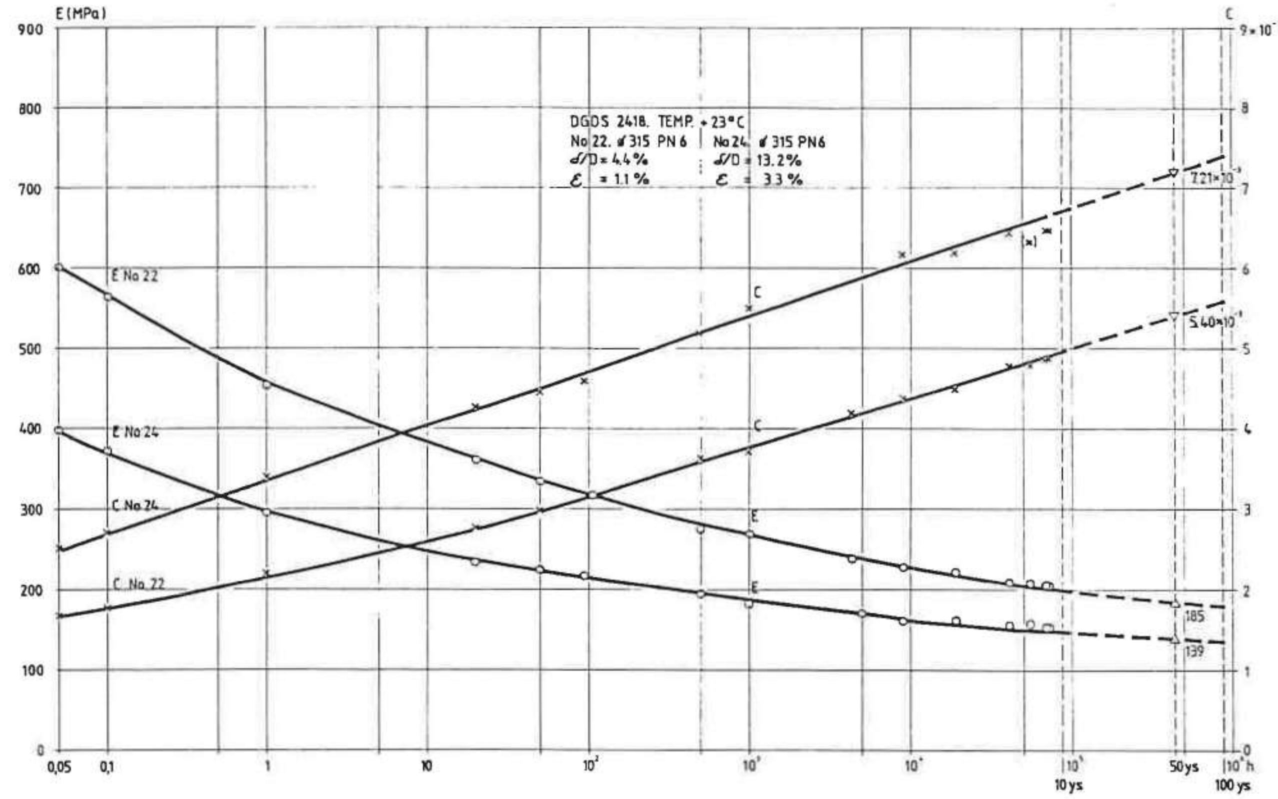


Fig. 8.3 Relaxation E-modulus for MDPE pipe ø 315 mm.

Fig. 8.4 HDPE pipe sample No. 20 (compare Fig. 8.2) after full cracking due to thermal oxidation of the internal pipe wall.

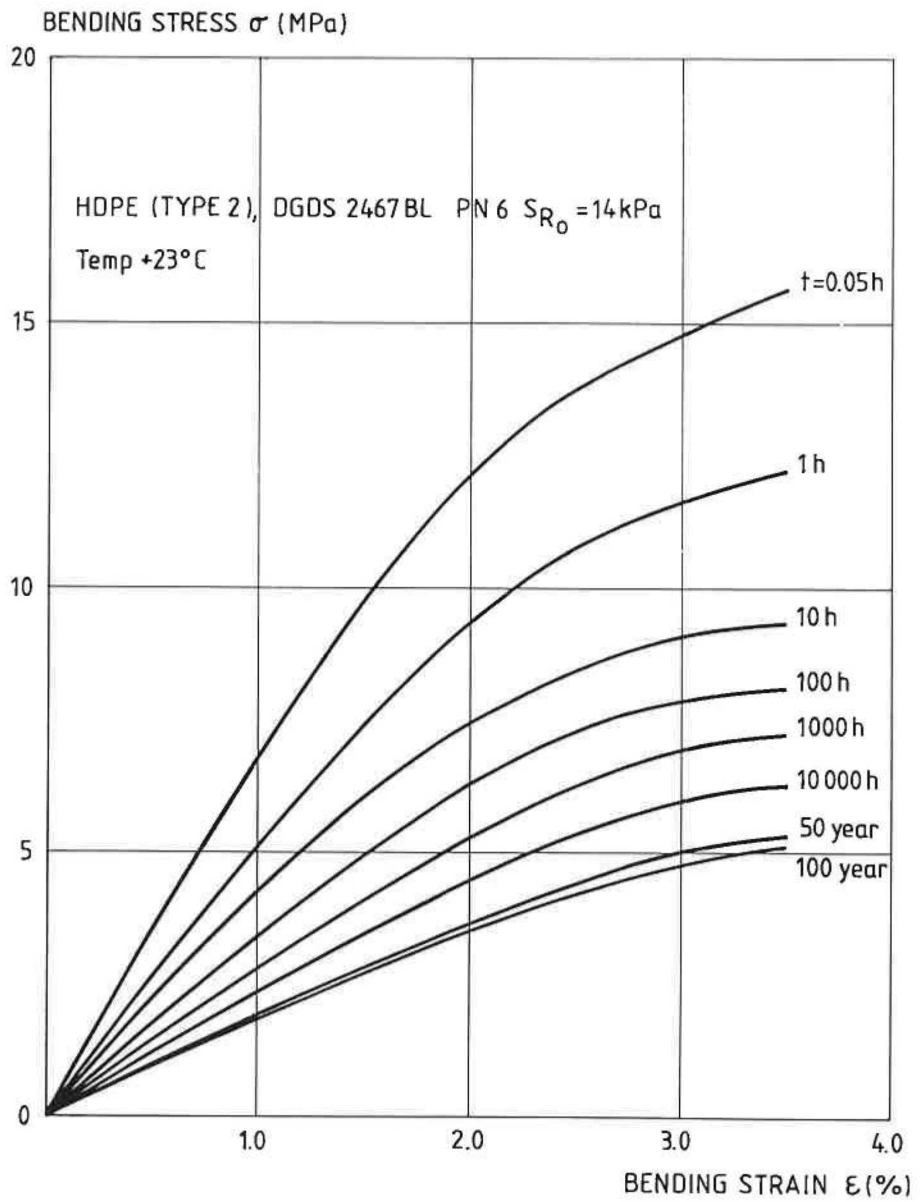


Fig. 8.5 Stress/strain diagram for HDPE pipe Type 2 as deduced from Fig. 8.2.

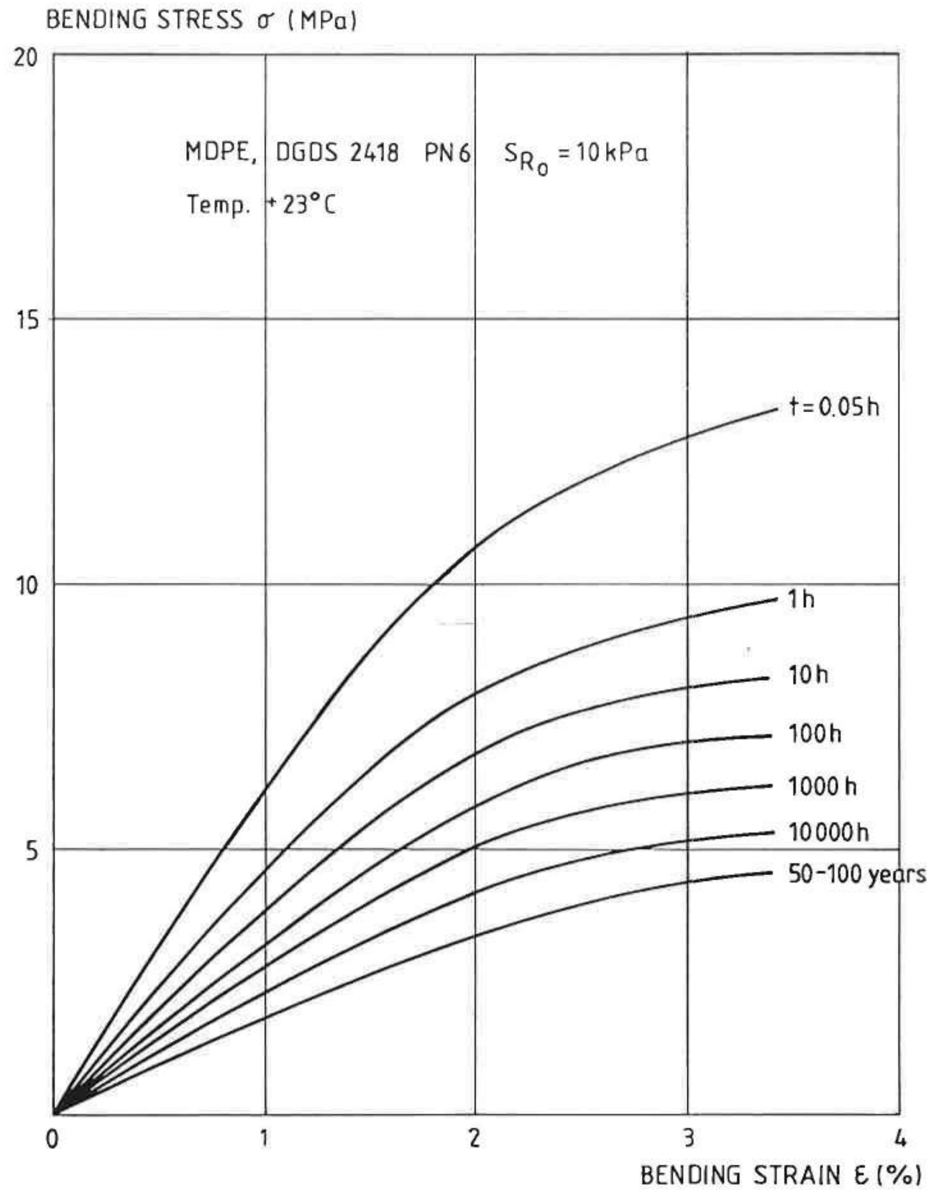


Fig. 8.6 Stress/strain diagram for MDPE pipe as deduced from Fig. 8.3.

9. DEFLECTION RECOVERY WHEN RELEASING CONSTANTLY DEFLECTED PE PIPE SAMPLES

All samples were also doubled in the PE investigation. The study of the first series was terminated in 1983 [7] and at that time these samples were released and the deflection recovery measured for 1000 h. Figs 9.1-9.3 present the results of the study for this first series of samples (full lines). As can be seen, a remarkable rectilinear course of the curves is recognizable for all samples kept deflected for one year. If a rectilinear extrapolation had been performed, the deflection would have recovered fully after some thousand years. However, a long-term curve configuration of this kind is certainly not true, as the viscous part of the strain would give a residual deflection even after an infinitively long time. But it is certainly true that the shorter the time of forced deflection, the faster the recovery process will take place after releasing the sample.

This is well illustrated in Figs 9.1-9.3 by the recovery curves (dotted lines) valid for the "daughter" samples now released after 8.2 years of deflection. The recovery measurements have here been made for approximately one year. Hence, it can be found that the immediate deflection recovery is somewhat less after many years of constant deflection than after only one year of deflection. This is to be expected, as the bending stress in the pipe wall, which has to force the pipe deflection to recover, has further decreased in the course of time due to relaxation.

A more unexpected finding is that the rectilinear course of the lin (δ/D)/log t-curves also takes place during the prolonged time of observation in question, i.e. up to one year. This is well illustrated for the two HDPE grades independent of the level of the initially forced deflection. For the highly deflected MDPE pipe (13.2 %), however, a bending of the C-curve appears after 50 h only. This behaviour could not be recognized for the MDPE pipe samples released after 10,000 hours of constant deflection as illustrated in Fig. 9.3. The continuing investigation will hopefully help to give an explanation of this particular observation.

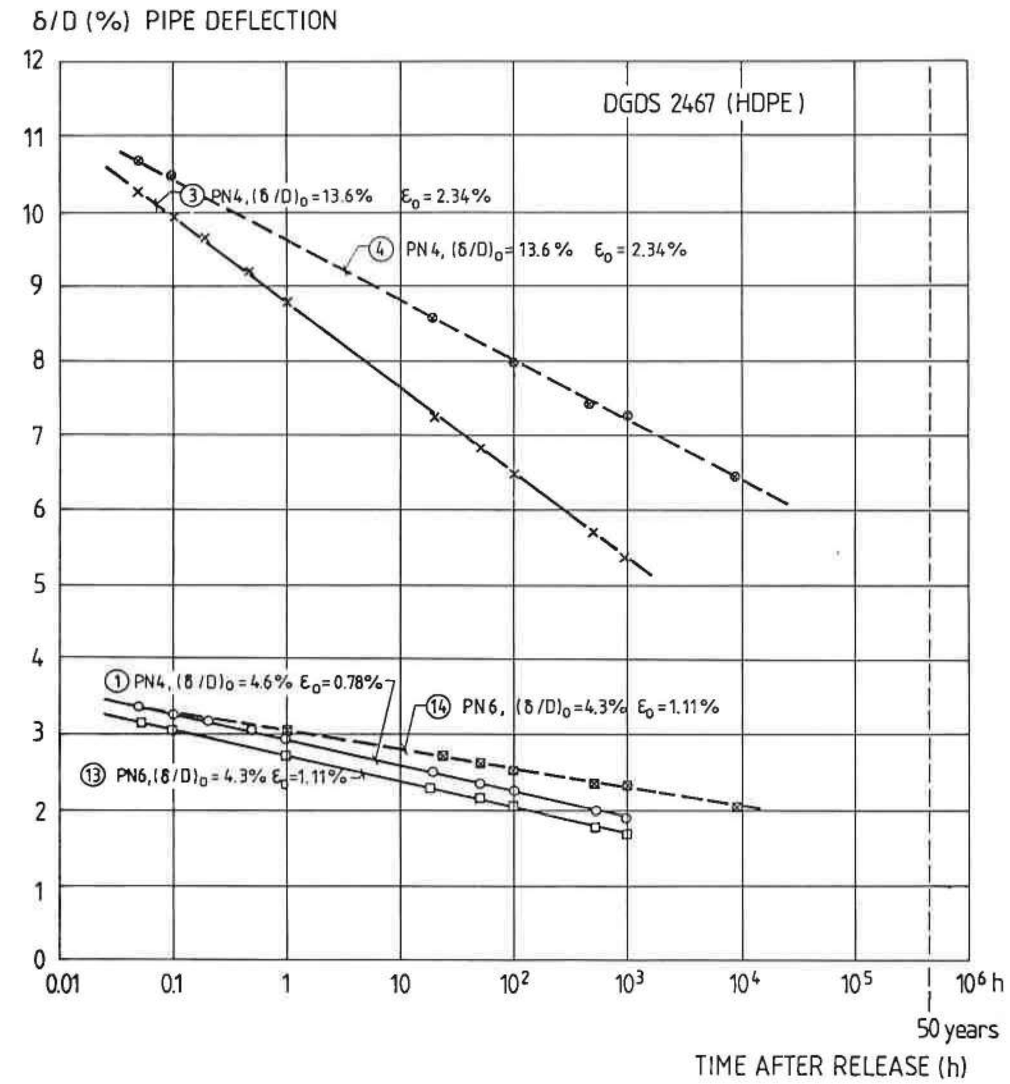


Fig. 9.1 Pipe deflection recovery when releasing HDPE Type 1 pipes after 10,000 h of constant deflection: Full lines. - The same after 8.2 years of deflection: Dotted lines.

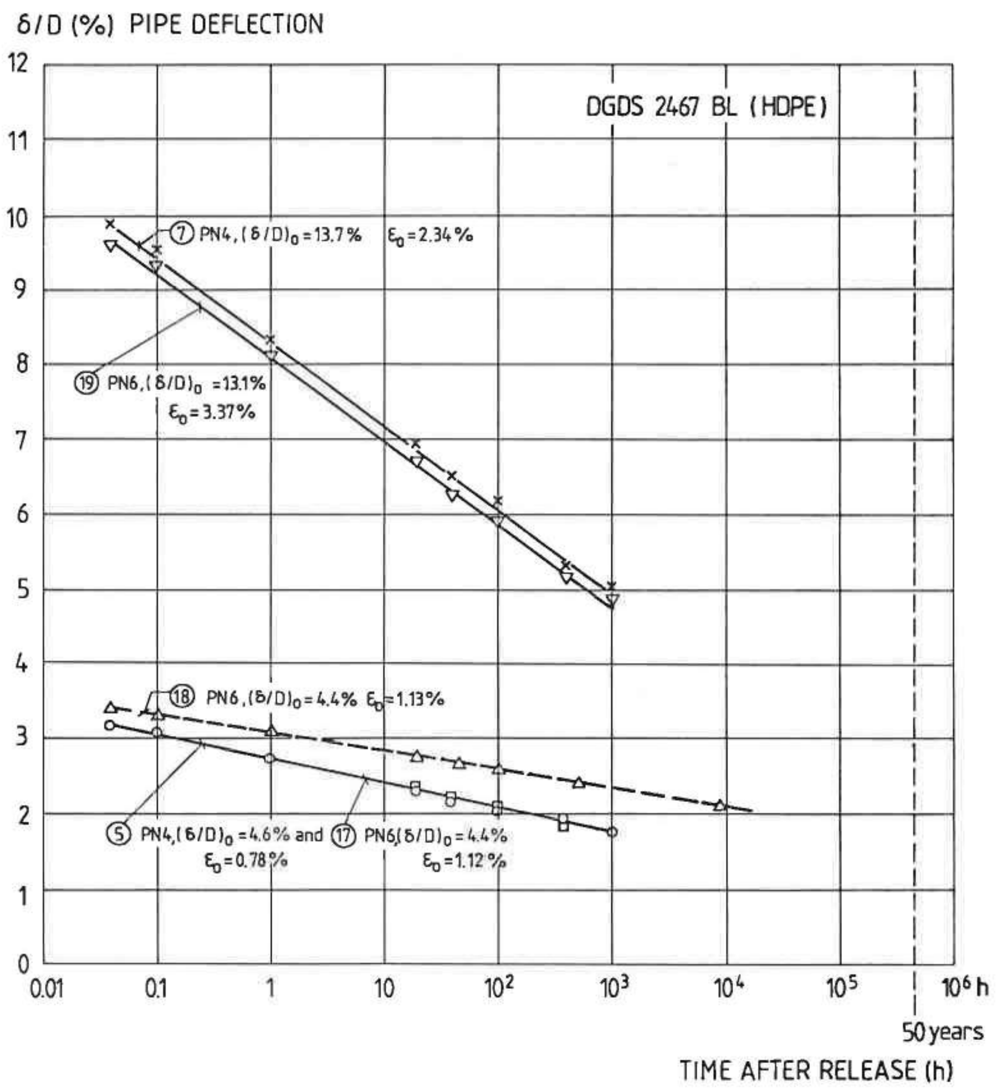


Fig. 9.2 Pipe deflection recovery when releasing HDPE Type 2 pipes after 10,000 h of constant deflection: Full lines. - The same after 8.2 years of deflection: Dotted lines.

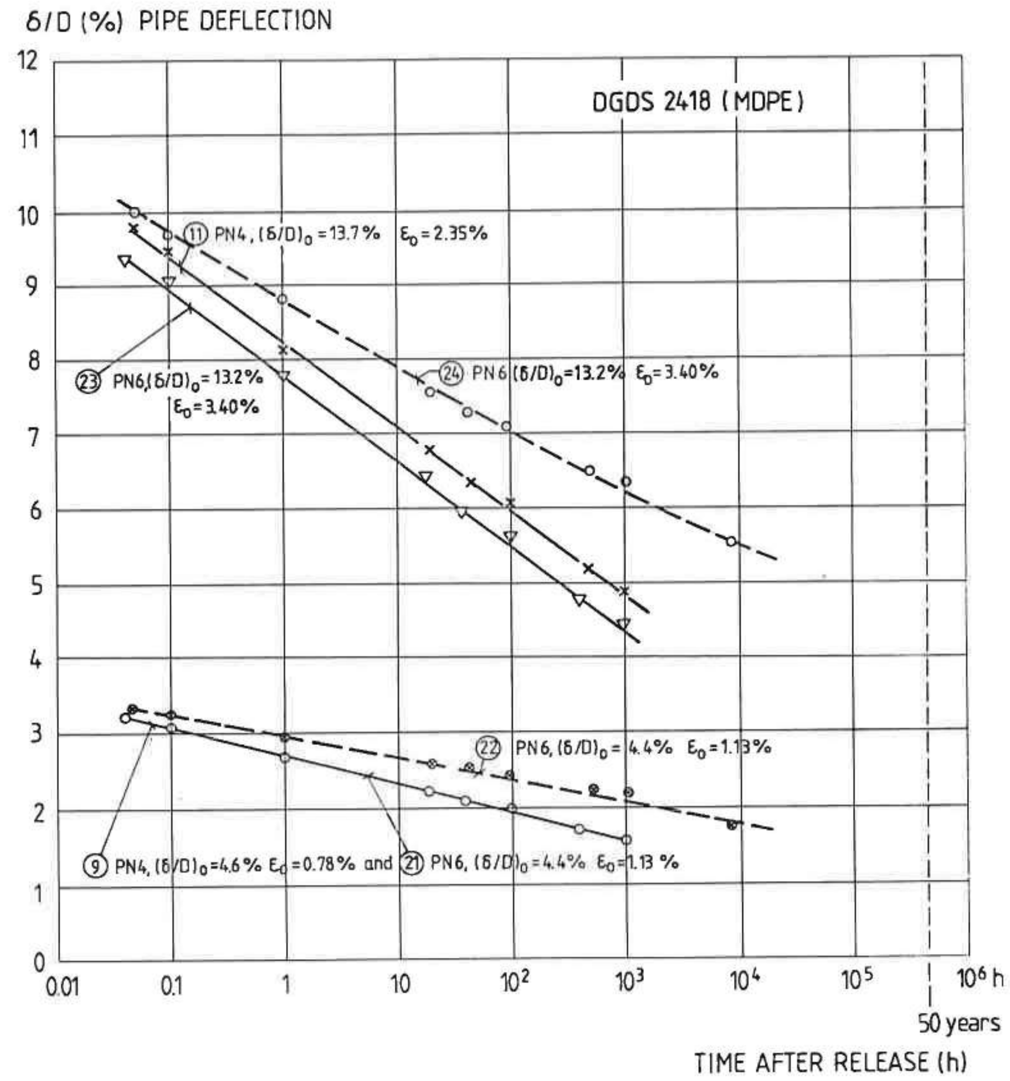


Fig. 9.3 Pipe deflection recovery when releasing MDPE pipes after 10,000 h of constant deflection: Full lines. - The same after 8.2 years of deflection: Dotted lines.

10. SHORT-TERM RING STIFFNESS AFTER LONG-TERM CONSTANT DEFLECTION OF THERMOPLASTIC PIPES

During the constant deflection of a plastic pipe the initial bending stress in the pipe wall will decrease in the course of time due to stress relaxation. As the deflection is constant, the bending strain in the pipe wall is also constant. The E-modulus according to Hooke has been defined as the ratio between stress and strain i.e. $E = \sigma/\epsilon$, and consequently it is obvious that E will decrease in the course of the loading time as σ does. The same situation concerning the E-modulus occurs if the deflection is free, i.e. the stress σ is constant and the strain ϵ increases in the course of time due to creeping. In both cases, it must be understood that the decrease of the E-modulus is only fictive and has nothing to do with the capacity of polymer materials to resist new initial forces after a long loading time, a capacity represented by the short-term relation between stress and strain. As the ring stiffness is a linear function of the E-modulus, it also means that after a long loading time, the ring stiffness continues to retain its short-term value for each new impulse of loading.

In order to demonstrate this theoretical fact practically, two long-term deflected pipe samples were subjected after release to further short-term loading. Consequently, PVC pipe sample L52 as illustrated in Fig.2.1 and Fig.5.1 was subjected to another short-term ring stiffness determination. The sample had been constantly deflected to 5 % for more than 4 years, and after one year of release the deflection had recovered to 2.1 % (see Fig.5.1).

Originally, the short-term ring stiffness was determined at 2.40 kPa using the 3 % deflection and 3 minutes relaxation procedure according to the following formula, where the ring stiffness S_R is given as

$$S_R = [0.0186 + 0.025\,(\delta_0/D + \delta_1/D)]\,\frac{P}{L\delta_1} \qquad (10.1)$$

The second term 0.025 $(\delta_0/D + \delta_1/D)$ in the outside brackets represents a correction for the case where the circular ring has a small initial "stressless" deflection. Here, δ_0 stands for this initial "stressless" deflection and δ_1 for the additional deflection caused by the linear load P. The length of the pipe sample is indicated by L.

Using the same formula and assuming that the pipe ring is now more or less "stressless" after one year of release the sample was subjected to a further 3 % deflection. Thus δ_0 = 2.1 % and δ_1 = 3 % in this case. The results of the test showed that the short-term ring stiffness was 2.61 kPa after the pipe had been constantly deflected and stressed for approximately four years. This means an increase in the ring stiffness of 8.8 %, an increase which could well be explained as being caused by a physical ageing process as discussed in Section 3.

The same testing was performed using the HDPE NCPE 2467 BL (Type 2) pipe sample No. 18 constantly deflected to 5 % for 8.2 years and illustrated in Fig.8.2 and Fig.9.2. The initial "stressless" deflection δ_0 was in this case 2.2 % and δ_1 = 3 %. The ring stiffness was then calculated according to the equation (10.1) to be 18.1 kPa, while the original ring stiffness eight years earlier was 15 kPa. Thus, it seems as though a physical ageing process takes place in HDPE as well, which is even more pronounced than for PVC but has so far not been studied. Although the calculation method is not quite adequate (see further "General comment" in Section 2) the results so far clearly confirm that the short-term ring stiffness and consequently the short-term E-modulus has not declined after long-term loading of the pipe (4-8 years). On the contrary, it has in fact increased, probably due to some type of physical ageing effect.

This fact is of great importance for an adequate understanding of the deflection process undergone by buried thermoplastic gravity pipes as discussed in [10] and further in [11].

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