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PLASTICS PIPES - HOW LONG CAN THEY LAST?

By Lars-Eric Janson*

* Dr. Sc. (Civ.Eng.)
VBB/SWECO Consulting group
P.O. Box 34044
S-100 26 Stockholm, Sweden
Fax +46-8-695 61 10

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FOREWORD

This Report constitutes a revised and enlarged edition in English of the First Report issued by the Swedish Council for Quality Control of Plastics Pipes (KP-Council) in October 1987. At that time the Report was written in Swedish and was titled "Hur gammalt kan ett plaströr bli?" A free translation into English of the Swedish title could be: "Plastics pipes - How long can they last?" The answer given in 1987 was: "At least 100 years". The new edition considers in particular additional research work reported during the last 10 years, and it has been clearly found that nothing has emerged, which contradicts the statement made in 1987. On the contrary, particularly the soil and pipe mechanics stability conditions now dealt with in Section 3 and the pipe material strength conditions dealt with in Section 4 have been possible to describe and verify in a more distinct way than previously. A new Section 7 has been added dealing with the actual sustainability conditions, a concept which was not very much discussed 10 years ago. In addition the list of References has been revised and extended.

The systematic study presented in this Report refers mainly to the thermoplastic pipes PVC-U (unplasticized polyvinyl chloride) and PE (polyethylene) used as buried gravity sewer pipes. However, the conclusions drawn can in most cases also be applied for these thermoplastic resins when used for tap water pressure pipes application.

Stockholm, November 1996

Lars-Eric Janson

Addendum
THE SWEDISH COUNCIL FOR QUALITY 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 and Physical Planning, the Swedish Federation of Architects and Consulting Engineers, the Swedish Plastics and Chemicals Federation and the Swedish Water and Waste Water Works' Association. The National Testing Institute in Gothenburg 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 which are in accordance with standards issued by the Council.

Swedish manufactures 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 examinated 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. 4 in the series.

The address of the KP-Council is:

c/o VAV
Regeringsgatan 86
S-111 39 STOCKHOLM
Sweden
Tel. +46-8-23 29 35
Fax +46-8-21 37 51

1. BACKGROUND

Thermoplastic pipes began to be used for municipal water supply and sewage disposal approximately 50 years ago in Sweden. At that time pipes were used mainly in smaller diameters for the distribution of water in rural and resort areas. The predominant pipe material used was low - density polyethylene (LDPE) in dimensions less than 100 mm diameter, later supplemented by high-density polyethylene (HDPE) for industrial purposes in the diameter range of up to 1000 mm. At the same time, the use of unplasticized polyvinyl chloride (PVC-U) pressure pipes in the diameter range 40-400 mm was developed. Development was very rapid and by the mid-60's PVC pipes had already taken half the market for pressurised water distribution from commonly used ductile iron pipes. Buried sewer pipes, mainly PVC, did not enter the market until the end of the 60's, but have since then had strong growth and are now the main alternative to concrete and clay pipes up to a diameter of 630 mm. Today, HDPE and MDPE (medium-density polyethylene) are also used as buried sewer pipes up to a diameter of 1600 mm.

The common new thing in using plastics pipes was, above all, the necessary understanding of the new design criterion, which meant that mechanical strength had to be put in relation, not only to the acting forces and the stress, as had always been the case, but also to the loading time and the temperature. The phenomenon of creep in viscoelastic materials, to which group plastics belong, means that failure eventually occurs after some time if the stress is kept constant and the possibility of deformation (creep) is kept free. Time until failure, however, is very dependent on the magnitude of the stress, which means that it is always possible to find a stress level that is so low that time until failure becomes very long and of absolutely no interest from a practical point of view.

However, in order to achieve international coordination in this matter, the 50 years' design service life in accordance with ISO and now also with CEN was chosen as the minimum requirement for plastics pipes for pressurised applications. It should be noted that the design stress selected was calculated with a safety factor which, if not utilized, means that the theoretical time until failure becomes more than 200 years for HDPE and more than 1000 years for PVC.

What limits the length of service life in practical terms, however, is not as a rule the design stress in the very long perspective, but the plastics stabilizing system in a materials technology sense. Every structural plastics's capability of meeting the expected strength requirements stands and falls on its own stabilizing system, which is designed to prevent a time - conditional chemical degradation of the material. One therefore speaks of an ageing limit, which restricts the validity field for the commonly accepted stress-time relations that are based on short-term measurements and long-term extrapolations. It should be pointed out that the ageing limit is highly dependent on the temperature, but that only temperatures above the usual design temperature of +20 °C can manifestly change the service life concepts that, according to the above, are to be theoretically expected for the best qualities of HDPE/MDPE and PVC-U pipes being used today. However, the phenomenon requires attention in discussions pertaining to the question about the real service life of plastics, when it comes to time spans that significantly exceed 50 years.

2. PROBLEM IDENTIFICATION

The problem areas for buried sewer pipes include consideration of the following four conditions:

A. Soil mechanics and pipe mechanics stability conditions
B. Pipe material strength conditions
C. Chemical and biological stability conditions
D. Functional stability conditions.

Relating to conditions A is the question about the relation between ring stability on one hand and pipe deflection increase on the other as a function of time, conditioned by geotechnical changes coupled with the changes of the ring stiffness by time. Also relating to this is the concept of "physical ageing" for plastics exposed to mechanical stress over long periods of time.

Relating to conditions B is the question of the size of the actual stress or strain, set in relation to those conditions that are critical in the long term.

Relating to conditions C is, among other things, the question about the environment's impact on the pipe material. (Example: Generating of hydrosulphuric acid in the waste water, ground water acidification etc). In this context, it must also be discussed whether biological (especially bacteriological) impact over time can become critical to the pipe's persistence or function (compare conditions D). Also relating to C is the question about the design of the stabilizing system relative to the compound of the raw material as well as how a time dependent stabilizer loss may affect the material decomposition.

Relating to conditons D are questions that are connected to the pipe's ability to, after a long period of time, still contribute to an acceptable "piping capability". Even if the material quality is sufficient, the service life is ended from a practical point of view when important functional conditions can no longer be met. These concern, above all, the tightness of the pipeline and its water discharge capacity. Relating to the latter matter is knowledge of the pipe material's wearing down through cleansing and abrasion as well as how possible pipe wall bio-fouling growth increases the surface roughness and reduces the active hydraulic performance area and consequently the flow capacity.

3. SOIL MECHANICS AND PIPE MECHANICS STABILITY CONDITIONS

The most essential load that a buried sewer pipe is exposed to is that arising from the soil pressure and from the traffic load on the ground surface. If the pipe is made of plastics, whose strain at break is so large that significant deflection of the circular ring cross section can be allowed, the deflection itself may contribute to a mechanically stable state. For every vertical load that the pipe is exposed to, a deflection of the pipe takes place. For each new load impulse, the pipe tries to counteract the ovalization forced by its short-term ring stiffness. Simultaneously the horizontal soil pressure acting on the pipe's sides increases with increasing vertical load, which in turn contributes to limiting the deflection. This interaction between active vertical soil pressure and passive counteractive horizontal soil pressure forms the concept according to which buried plastics sewer pipes are designed. Thin-walled plastics pipe thus has no possibility of bearing the vertical load by itself, but has to have horizontal support from surrounding soil in order to meet the stability criterion.

The prerequisite for achieving a long-term mechanically stable state is thus that the soil has such properties as to enable transmission of forces without causing too much deformation. The soil shall thus have elastic or almost elastic properties. If this is not the case, the pipe must be given such ring stiffness that it is able to bear the vertical load by itself. Regular plastics gravity sewer pipes are not designed for this type of loading. However, it should be pointed out that thermoplastic pipes designed for internal hydrostatic pressure (10 bars) are usually able to bear the soil load by themselves.

The design concept briefly described above for buried gravity sewer pipes has been thoroughly analyzed and discussed in a large number of reports and theses over the last 25 years. It would take too long to reproduce the documented knowledge here - it is sufficient to refer to some international conferences held during the 80's and 90's [1], [2] and [3], which have dealt with and presented the current level of knowledge concerning plastics sewer pipes. A general survey of current knowledge of both pressure pipes and sewer pipes is given in [4] and of buried sewer pipes in particular in [5]. An especially important contribution is the investigations that report the results of measured changes in deflection of plastics pipes over a long period of time. Particular mention should be made of [6], [7] and [8], which report up to 30 years of systematic measurement of changes of the deflection of buried gravity sewer pipes in different types of soils in Holland, as well as [9] and [10], which represent Nordic experiences.

When designing buried sewer pipes, two main conditions must be fulfilled. One is the pipe's deflection, which is not allowed to exceed a certain fairly low limit (5-8 %) when the pipe is new. In addition, it holds that after long-term use (defined as at least 50 years), the pipe's estimated deflection is not allowed to exceed 15 % according to Swedish practice. The other condition concerns the pipe's ability to resist buckling, which becomes critical particularly for pipes with low ring stiffness.

The predominant part of the plastics sewer pipe market in Sweden and in the rest of Europe concerns pipes with fairly high ring stiffness ($S_R \geq 4$ kN/m²). The deflection shape of the pipe when buried in the ground will thereby closely adjust itself to the elliptical one. The pipe deflection can then be calculated according to the well-known Spangler model (see [4]), which in principle follows the expression:

$$\delta / D_m = f(q) / (S_R + c_1 S_S) \tag{1}$$

where δ stands for the reduction of the vertical pipe diameter as a result of the ovalization, and D_m is the mean diameter of the pipe (D_m = D-s, where D is the external pipe diameter and s is wall thickness). In eq (1), q stands for the vertical soil pressure plus pressure caused by traffic load, S_R is the pipe ring stiffness and S_S is the stiffness of the side fill of the soil. (S_S is here expressed as a linear function of the secant modulus E' of the side fill).

As can be found from eq (1), the deflection increases with increased vertical load but is counteracted by increased pipe ring stiffness and/or increased stiffness of the side fill.

The pipe ring stiffness S_R introduced in eq (1) implies the following definition, (in some analogy with the definition for bending stiffness of plates and shells):

$$S_R = EI / [D_m^3 (1-\nu^2)] \tag{2}$$

where E is the pipe material's E-modulus (creep or relaxation modulus) ν is the Poisson's number and I is the moment of inertia for a unit length of the pipe wall. (For a solid pipe wall of uniform thickness $I = s^3/12$).

The ring stiffness according to eq (2), expressed in the unit kN/m² (kPa), constitutes the current basis for the classification of plastics gravity sewer pipes. Earlier classification according to traditional models was based solely on the relation s/D_m (in %) or D/s (in an absolute number). The change has come about due to the fact that (as eqs (1) and (2) show) the buried sewer pipe's ability to resist deformation not only depends on the pipe's geometrical quantities but also on the pipe material's E-modulus.

Classification is carried out according to a series of numbers for S_R consisting of 2, 4, 8, 16 and 32 kN/m² (kPa), respectively. In **Table 1**, the relations between the previously-used classification for PVC and HDPE pipes (PE 63) and the current one are shown.

Table 1

Designation	L (light)	M (medium)	T (heavy)	E (extra)	Pressure Pipe
PVC (s/D_m %)	2	2.5	3	4	5 (PN 10 bars)
PVC (D/s)	51	41	34	26	21
HDPE (s/D_m %)	3	4	5	6.3	8 (PN 8 bars)
S_R (kN/m^2)	2	4	8	16	32

Since according to eq (2), the expression for S_R contains the pipe material's E-modulus, which is both time, stress, strain, and temperature dependent, the ring stiffness in classification contexts must apply to a certain pipe deflection and a certain loading time at a given temperature. A distinction must therefore also be made between short-term load and long-term load. As the basis for the ring stiffness number given in Table 1 lies a short-term value, which is determined by keeping the pipe constantly deflected with two diametrically opposed linear loads for three minutes and with a 3 % deflection at a temperature of +23 °C.

The common way to determine the actual pipe ring stiffness is to measure the load P, that is required to maintain the pipe, with a length of L, at a constant deflection δ. A theoretical calculation gives the following expression:

$$\delta = (\pi/4 - 2/\pi)\, PD_m^3 (1 - \nu^2)/8\, EIL \qquad (3)$$

Combining eqs (2) and (3) and eliminating E gives:

$$S_R = 0.0186\, P/\delta L \qquad (4)$$

Let us now discuss the pipe ring stiffness change (equivalent to the E-modulus change) which at constant pipe deflection and linear viscoelastic appearance in the material, solely depends on loading time and temperature. Firstly, it should be pointed out that the E-modulus does not really represent any material property but only stands for a relative number which describes the relation between the stress and the relative strain that exists in a plastics material under load at a certain time after application of the load. The E-modulus (creep modulus) of plastics materials thus only shows that the material undergoes a time-dependent change in deformation at a constant load, not that the material softens. This in turn implies that a plastics material that has been exposed to a long-term load retains its short-term strength properties on the removal of the load as well as upon renewed loading or on a continuously recurrent short-term impulse load. The matter can also be stated like this: The plastics material always retains its original mechanical vitality and strength regardless of after how long time a new load is added. Examples that confirm the above are reported in [11] - [15].

An application of the statement above on the conditions for a buried plastics pipe gives the following results. The deflection process that the pipe undergoes as a function of time can on a sound basis be presumed to be the result of a long series of small short-term interacting load equalizations between vertical and horizontal soil pressure. On each such new short-term load impulse, caused by a settling movement or by a short-term additional load on the ground surface (caused by traffic for example) the plastics pipe resists the deflection supported by a force that is determined by the short-term ring stiffness. This is independent of after how long a time the addition of the new loading impulses take place. The final deflection of the pipe after a long time is thus not determined by a long-term E-modulus of the plastics material but becomes a result of the sum of a series of small short-term load impulses, each of which gives an additional deflection that is determined by the pipe material's short-term E-modulus. It is probable that the time factor for the creep modulus that applies to the determining of the real active ring stiffness is very short, or just a few seconds. Nevertheless, the three minutes value has been chosen in classification contexts in order to obtain measurable and reproducible results that are practical when testing. The real active ring stiffness that counteracts the pipe deflection process is, in other words, probably greater than the one indicated by the classification. (A theoretical analysis of the interaction process between pipe and soil is given in [16]. See also [4] Section 5.2a). The discussion so far is applicable mainly to pipes in non-cohesive soils but probably also to pipes in compact cohesive soils, where the backfill consists of non-cohesive soils. The question about the plastics pipes performance in loose clay and peat will be further discussed below.

If we now look at eq (1) again, we can, on the basis of the above, conclude that the increase of the pipe deflection over time in non-cohesive soils obviously mainly depends on the factor S_S which stands for the resistibility and stability of the side fill. If S_S thus approaches a constant value over time, implying that the soil is not further deformed or undergoing reconditioning, S_R also becomes constant over time and has then to be determined by the short-term ring stiffness. The pipe deflection, therefore, also becomes constant and solely determined more or less by the initial loading stage that prevailed when the pipe was installed. It should be observed that this somewhat simplified reasoning concerns regular sewer pipes in non-cohesive soils, in which case S_S is large in relation to S_R.

However, experience shows that the stiffness of the side fill is not constant, but neither that it is continuosly changing (from a practical point of view). The conditions vary greatly of course, depending on the soil type and laying depth but, above all, on the care taken when installing the pipe and refilling. It is a well-documented fact that loose soils and/or careless backfilling result in large pipe deflections initially and that these deflections will increase in the course of time. However, it is also documented that the deflection increase is most extensive during the first two years after the pipe has been installed. Thereafter the increase is mostly insignificant.

This is explained by the fact that during the first years, the soil undergoes the reconditioning and settling that the backfilling technique has not succeeded in achieving, but which Nature, with the help of traffic loading, groundwater movement, soil creep, soil frost action etc., finally takes care of. It can be generally said that S_S successively reaches a constant value after some time, which is mainly dependent on the backfilling technique, the laying depth and the type of traffic load. During this time, the pipe impulsively fights against additional deflection by virtue of its short-term ring stiffness. Thereafter, i.e. when the surrounding filling has found its shape and this shape fits the pipe's deflected shape, no further change in the pipe shape of any practical importance takes place. This is best demonstrated by the Dutch study previously referred to [6] and also by the investigations according to [7] and [8].

Figures 3.1-3.3 have been taken from [6]. (Classification relates to the one previously used according to Table 1). The study concerns deflection measurements over approximately 15 years in 630 different buried sewer pipes of PVC belonging to classes L, M and T, corresponding to S_R = 2, 4 and 8 kN/m², respectively. Figure 3.1 shows the deflection of pipes that are in non-cohesive soils and where good installation and refilling conditions exist (installation class A). Figure 3.2 shows pipe deflection in non-cohesive soils as well, but under average installation conditions (installation class B). Figure 3.3 shows pipe deflection under poor uncontrolled installation conditions (installation class C). If one disregards class L pipes, whose ring stiffness is just 2 kN/m² and which are used to a very small

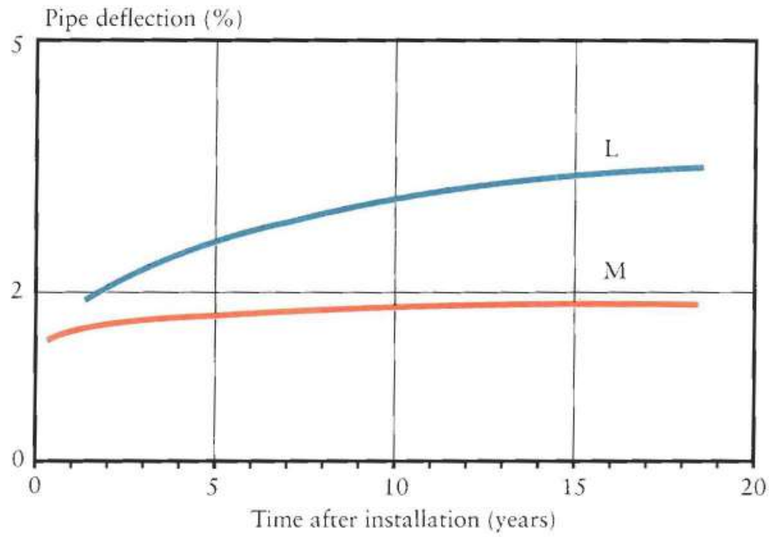

Figure 3.1 [6] Average deflection of pipes in installation class A

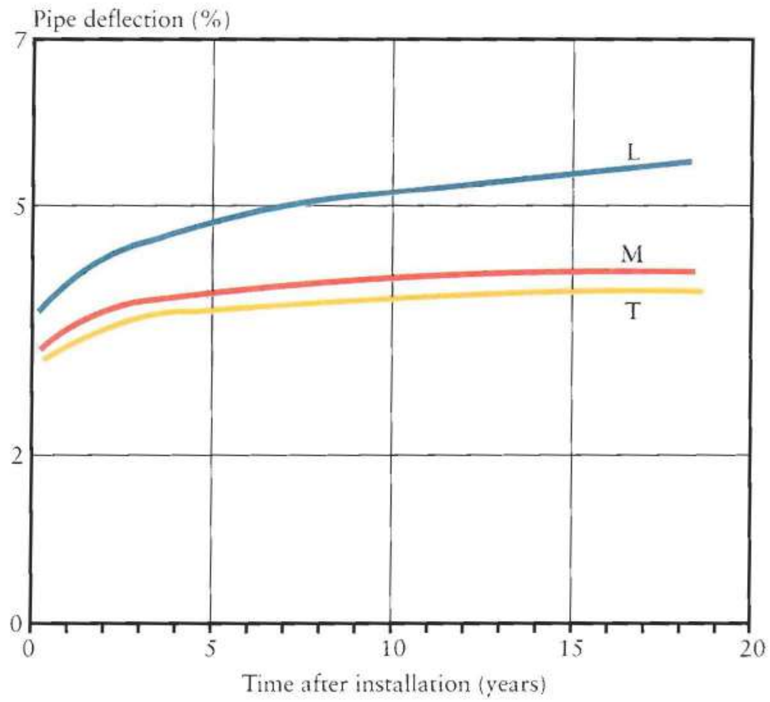

Figure 3.2 [6] Average deflection of pipes in installation class B

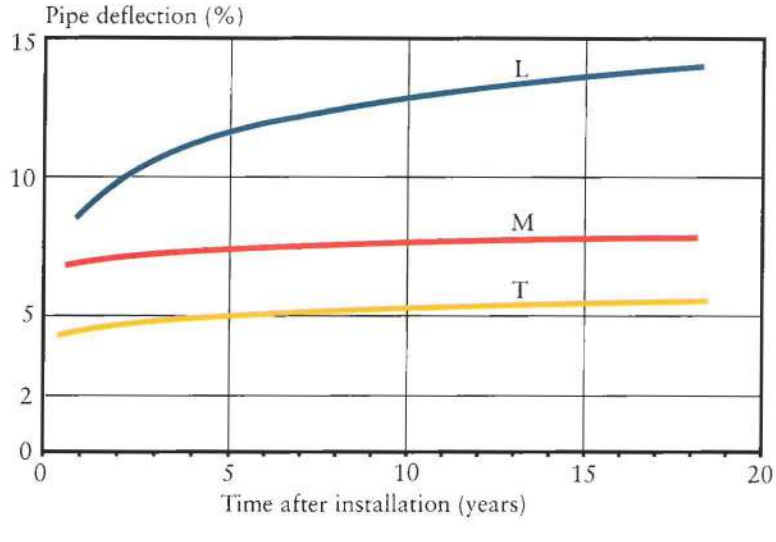

Figure 3.3 [6] Average deflection of pipes in installation class C

extent nowadays in the community network, one can, from all three diagrams, see that the increase in the pipe deflection after the first years after installation is very small. It thus seems that an extrapolation of the curves up to 50 years could hardly be regarded as risky and neither, in that case, an extrapolation up to 100 years. Such a linear extrapolation would under average installation conditions give a pipe deflection of at the most 6 % after 100 years for class M pipes; insignificantly less for class T pipes. Also for pipes in installation class C the pipe deflection after 100 years can be accepted for class M and T pipes, i.e. less than 10 %. However, it should be pointed out that the diagrams show the average values of measured deformations on a certain pipe length and that the occasional maximum pipe deformations can be up to 100 % greater. (See **Figures 3.4-3.6** which also show occasional measurement test results from the Dutch investigation of different pipe classes in installation class B). This has mostly to do with the imperfections that the pipe bedding creates for the pipe, acting as a beam in the longitudinal direction. The problem has been thoroughly described in [10], from which it is evident that these maximally appearing pipe deformations have a considerably smaller long-term growth rate than the reported average values. They are, in other words less inclined to increase over time in spite of their size.

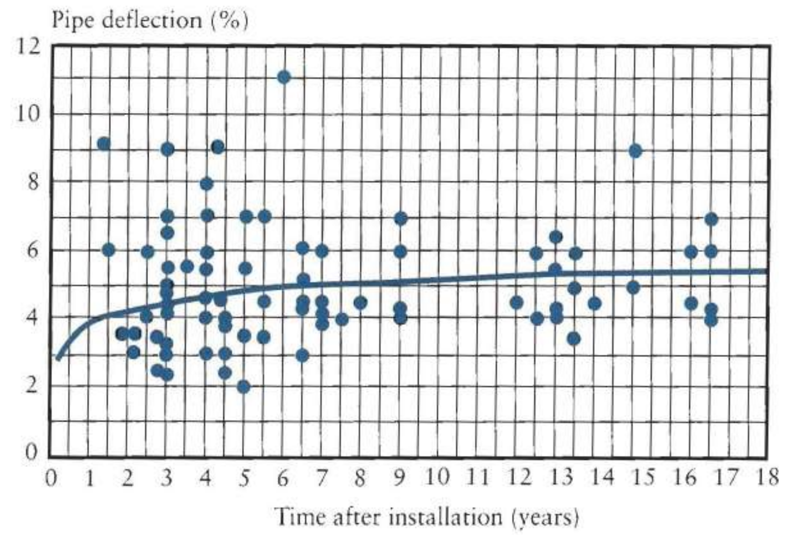

Figure 3.4 [6] Absolute deflection in installation class B. Pipe class L

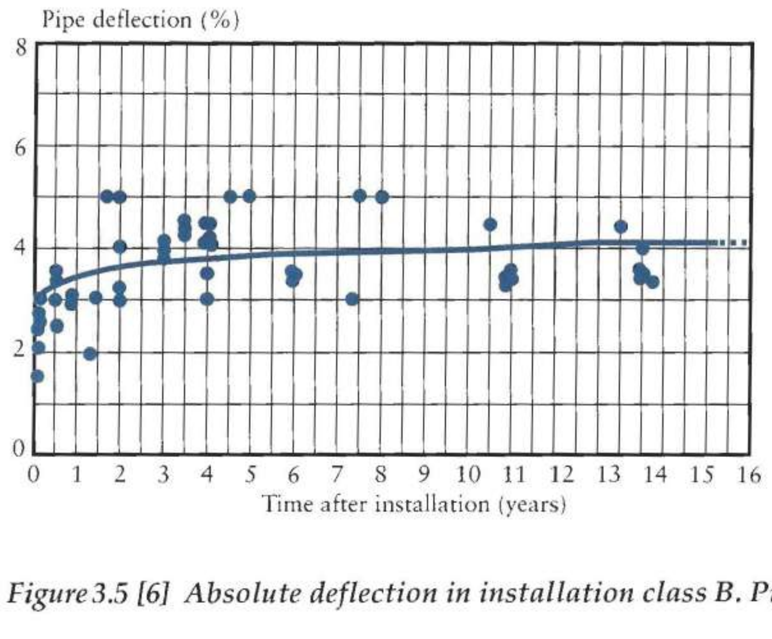

Figure 3.5 [6] Absolute deflection in installation class B. Pipe class M

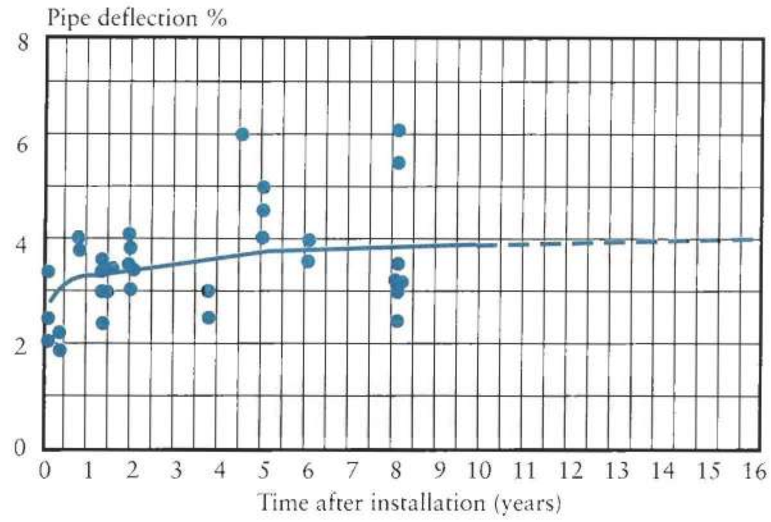

Figure 3.6 [6] Absolute deflection in installation class B. Pipe class T

In **Figure 3.7,** a diagram is shown which schematically describes the increase in deflection as a function of time [17], both with and without traffic load. As can be seen, the first period's events after installation are the most dramatic ones when it comes to the increase in deflection. In the report, it is emphasized that time until the decline in the increase in deflection, as expected, is considerably shortened if the ground surface is exposed to heavy traffic from the beginning. The reported practical studies can, in a satisfactory way, be said to confirm the theoretical discussion above [16].

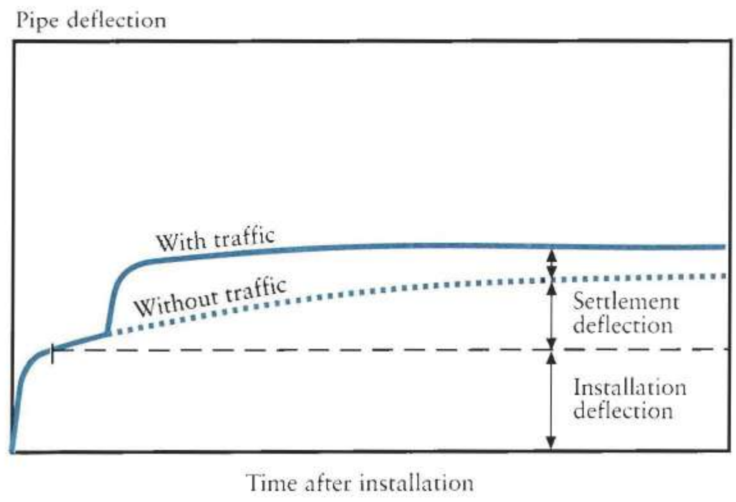

Figure3.7 [17] Fundamental relationship between pipe deflection and time with and without traffic load on the ground surface

If we now turn the discussion towards sewer pipes installed in soils of very loose clay or embedded in inhomogenous filling of non-compacted clay, one can count on creeping effects in the horizontally supporting soil even if the side fill closest to the pipe is made of non-cohesive material. We therefore have a more viscoelastic behaviour of the horizontal soil support. In this case, the pipe's increase in deflection probably takes places continuously and the previously described impulse-guided power transfer is no longer applicable. The pipe's creep behaviour is then significant, since in the long run, it is the long-term ring stiffness concept that becomes of interest. The final pipe deformation after say 50 or 100 years will probably be reached as a continuously ongoing creep in pipes and the surrounding soil. It may then be the pipe ring stiffness after 50 or 100 years that will be guiding for evaluating the pipe's ability to resist final deformation, in combination with the evaluation of the surrounding soil's ability to absorb forces. What is immediately clear in the case of these types of loose soil is that one must rely more on the pipe's ring stiffness than on the soil's stiffness. Pipes that are stiffer than regular ones should therefore be used, preferably of stiffness class 8 or 16 kN/m^2. This is of particular importance if there is a future risk of heavy traffic load.

In these loose soils, it is especially important to assess the risk of buckling, which means a sudden total collapse of the pipe. In this case the creep behaviour of the pipe material, as described by the long-term E-modulus, determines the deflection increase of the pipe until that stage when the buckling phenomenon becomes critical. It is, however, important to remember that at the moment when this stage occurs, the pipe nevertheless offers a resistance that is determined by the pipe material's short-term E-modulus. The phenomenon can be described approximately, either by application of buckling formulas that consider the deflection (and then by use of the short-term E-modulus) or formulas that do not consider this but instead use the long-term E-modulus in the calculation. Both methods have been proved to give almost identical results. Supporting this statement are also the results of a closer analysis of the former experiments carried out by Hochest, reported in [4], amongst others. One can find here that the soil pressure which after a certain amount of time causes buckling can be calculated with the help of the long-term E-modulus for the corresponding load period according to **Figure 3.8.** It is, however, completely possible to achieve the same result by using the short-term E-modulus but then, at the same time taking into account, when calculating, that the pipe in the initial buckling phase has obtained the deflection that immediately precedes the buckling. (**See Figure 3.9**).

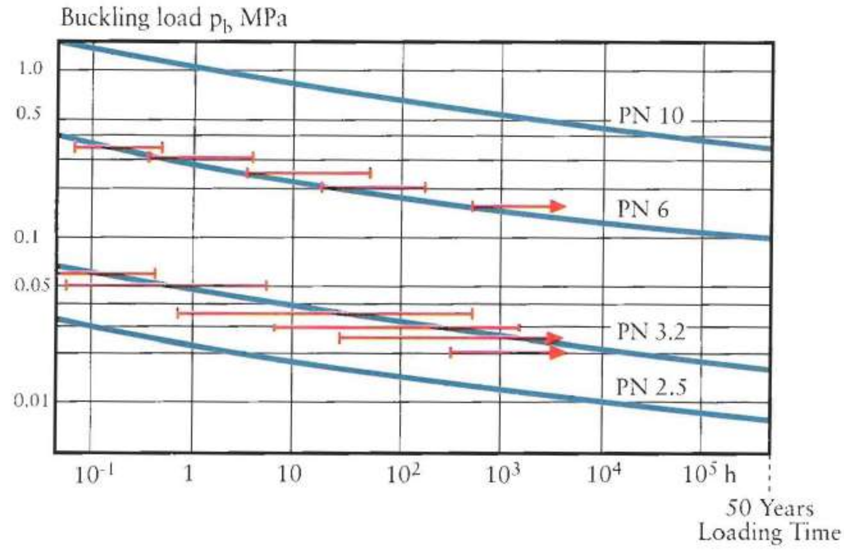

Figure 3.8 [4] Relationship between buckling load and loading time for HDPE 63 pipes of different pressure classes (PN bar) exposed to external hydrostatic pressure

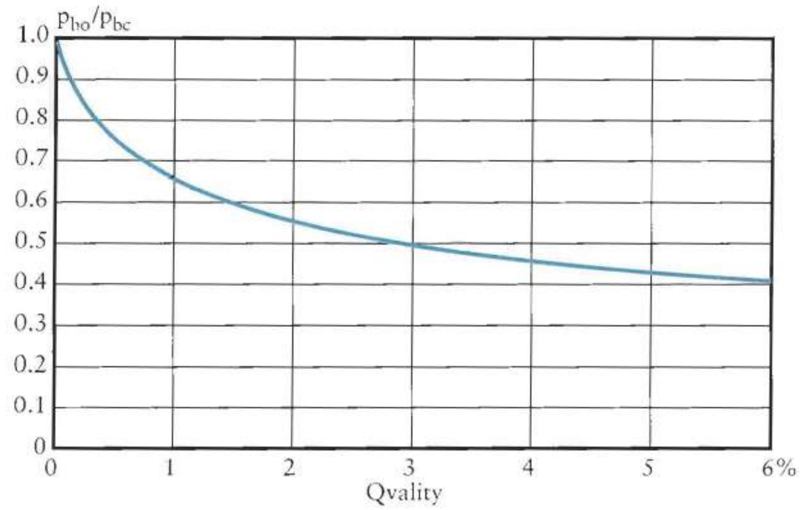

Figure 3.9 [4] The deflected pipe's buckling load in relation to the circular pipe's buckling load as a function of the deflection

A phenomenon that has great importance generally when discussing the long-term strength of thermoplastics is the material's ability to suffer a special type of physically ageing as a function of the loading time [18].

The phenomenon is explained by the molecular structure undergoing a successive consolidation over time, accompanied by a volume decrease. The physical ageing has been shown to have particularly great importance when it comes to determining the long-term E-modulus. Such investigations have been recorded in [13] and also in [4], where up to nine years constantly- loaded PE and PVC pipes have been studied. It is shown here that it is possible to make pretty safe extrapolations up to 50 years or more of the E-modulus based on laboratory investigations during not more than 100 hours for PE and during approx. 1000 hours for PVC.

This discovery is based on a study of the inverted value of E (1/E called the Compliance C). The method has been stated in [18] for PVC-U and receives a satisfactory verification in [13] (also for PE), further referred to in [14] and [15]. A deeper study of the knowledge on relaxation processes in polymers in general [19] does not contradict the conclusions drawn for PE and PVC in the references [13] - [15]. Thus, one concludes that the Compliance C after a fairly short period of time starts assuming a linear course, if plotted in a lin C/logt-graph. **Figure 3.10** ([13] and [15]) shows the results from a relaxation study that concerns a PVC sewer pipe (S_R = 8 kN/m²), that has been kept constantly deflected at 5 % during a total of nine years. The age of the pipe was 2 400 hours at the start of the study.

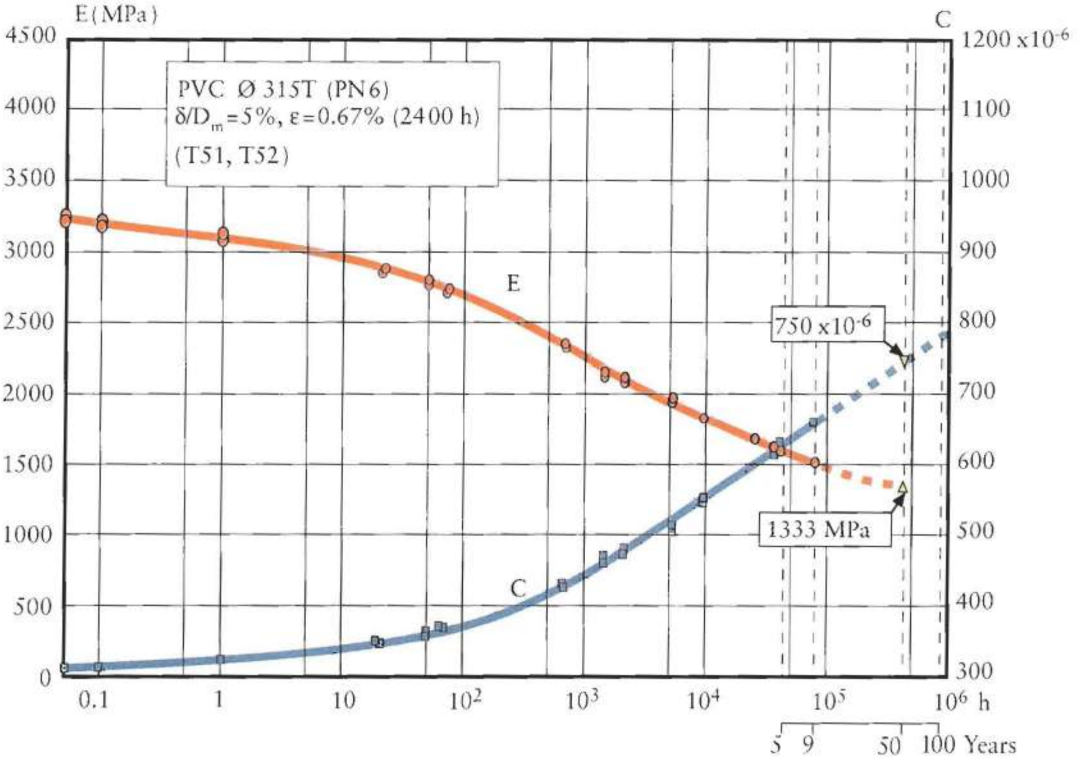

Figure 3.10 [15] Relaxation modulus E for ϕ 315 mm PVC pipe subjected to 5 % constant deflection during 9 years at 23 °C. The Compliance C = 1/E is extrapolated linearly already after 2400 hours. This linearity is well confirmed during the additional 9 years of measuring

A reactilinear extrapolation of the Compliance C after 2 400 hours gives $C = 750 \cdot 10^{-6}$ after 50 years and thus $E = 1/C = 1333$ MPa at that time. As can be seen in Figure 3.10, this E-modulus is considerably larger than that which would have been obtained if relying only on the E-curve up to, say 2000 hours, and then extrapolating this rectilinearly up to 50 years. Thus, it can be seen from the graph how the E-curve passes by a point of inflection, which lies in the time span of 2000-3000 hours, i.e. at the time when simultaneously the C-curve starts to find a rectilinear course.

From Figure 3.10 it can also be found that a further extrapolation of the C-curve up to 100 years gives $C = 780 \cdot 10^{-6}$ and consequently $E = 1/C = 1282$ MPa, i.e. an insignificant reduction from a practical point of view from the 50 years value of 1333 MPa. The short-term E-value (3 minutes) is as can be found 3 200 MPa, giving a long-term creep factor of approximately 0.4.

Even permanently deflected PE pipes show a constant lin C/logt-relation, but far earlier than PVC. This can be seen in **Figure 3.11** ([13] and [14]), which shows sewer pipes made of the classical Type 1 PE 63 resin (HE 2467), deflected to 4.3 % and 13.6 %, respectively. The rectilinear course of the C-curve is found already after 1 to 100 hours of loading.The deflection has been kept constant during eight years, and for the least deflected pipe the Compliance will reach $C = 4.8 \cdot 10^{-3}$ after 50 years and consequently $E = 1/C = 208$ MPa. A continuous extrapolation to 100 years will increase the C-value to $4.95 \cdot 10^{-3}$ and decrease the E-value insignificantly to 202 MPa. It is of interest to compare these E-values with the classical measurements referred to in the literature, that gives E-modulus of not more than 100 MPa for PE 63 pipes.

Thus, a general effect of the physical ageing of thermoplastic materials is that the E-modulus, measured as a short-term value, will increase in the course of time. This means that for each new additional stress of a certain magnitude applied after long time to a loaded pipe, the corresponding strain increase will be less than what it was when the pipe was originally loaded with such a stress. The consequence of the increased E-modulus is also that the pipe's capability to resist additional deflection, for instance caused by increased soil pressure, will increase in the course of time. This capability of the pipe to resist external forces can be expressed by the pipe ring stiffness S_R according to eq (2). In order to demonstrate the physical ageing effect, unloaded pipe samples have been stored in climate room for several years. After certain periods of time the actual short-term (three minutes) ring stiffness has been measured and compared with its original value. **Figure 3.12** illustrates the results of such measurements performed on PVC pipes with $S_R = 8$ kN/m^2 (kPa) [13], [15] and [20]. As can be found, the ring stiffness will increase from originally 8 kN/m^2 (kPa) up to about 10 kN/m^2 (kPa) after 50 years (extrapolated), corresponding to at least 20 % increase. The same type of study performed on 8-year old deflected PE 63 pipes shows, after release of the deflection, a 20 % increase of the ring stiffness within this 8-year period of time ([13] and [14]).

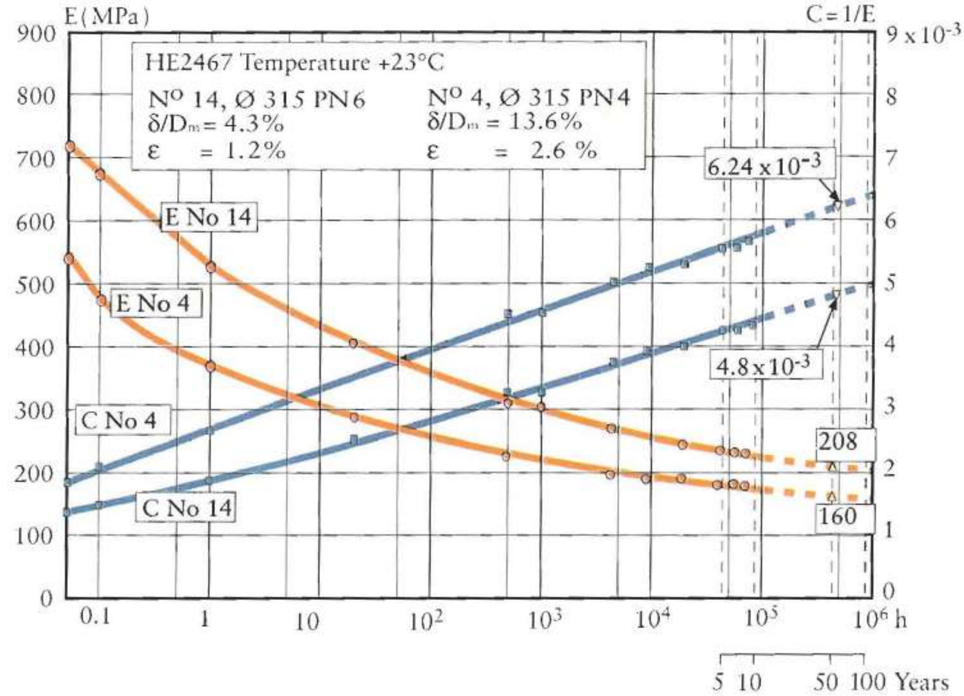

Figure 3.11 [14] *Relaxation E-modulus for ϕ 315 mm HDPE (type 1) pipe subjected to 4.3 % and 13.6 % constant deflection, respectively during 8 years at 23 °C*

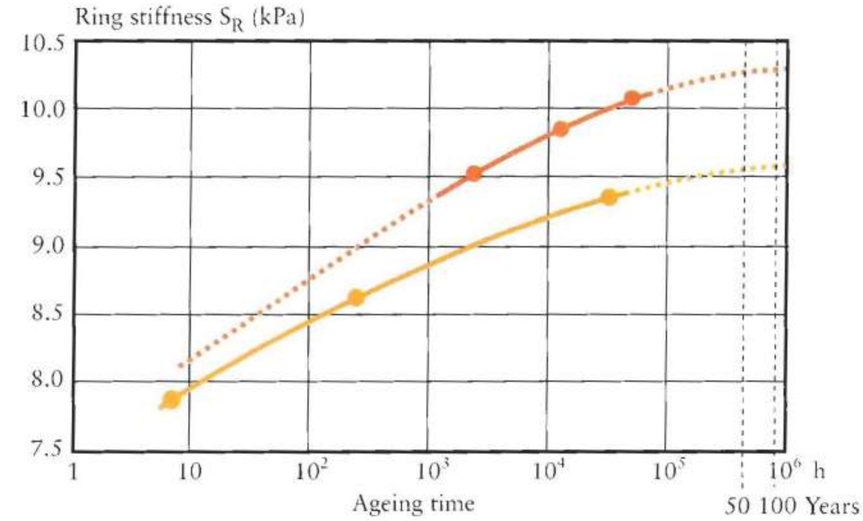

Figure 3.12 [15] *Increase of the initially measured short-term ring stiffness for ϕ 315 mm PVC pipes as a function of time due to physical ageing*

Thus, the consequence of the physical ageing of the polymer material is that the short-term E-modulus does not decline after long-term loading. On the contrary, it will in fact increase. As the ring stiffness is a linear function of the E-modulus, it also means that after a long loading time, the ring stiffness will retain or improve its short-term value for each future new impulse of loading. This fact is of great importance for an adequate understanding of the deflection process taking place in buried thermoplastic gravity sewer pipes.

To sum up this section, it can be said that the mechanical stability of the buried sewer pipe, as achieved after the first years of soil consolidation and soil creep, is not affected by the time thereafter in any practical way. This means that if the stability condition is met after say the first 5 years, the condition will be valid for 100 years and more, as well as for 50 years.

4. PIPE MATERIAL STRENGTH CONDITIONS

This section mainly discusses the pipe material's long-term strength. It should be first established that the load that causes strains in the material is mainly made up of vertical and horizontal soil pressure, which has been discussed previously. This gives bending stresses in the pipe wall that successively relax, as the pipe deflection after a certain period of time is practically constant. The result of this is that during most of its operating time, the pipe material is exposed to a constant strain, which for one and the same pipe deflection increases with the thickness of the wall or with the structural height of the wall (the latter applies especially to so-called lightweight pipes or "structured wall" pipes). Added to this load is also that which is caused by an uneven distribution of temperature and by frozen-in stresses in the pipe wall. The latter stress/strain conditions are, however, as a rule marginal in relation to those caused by pipe deflection. In axial direction, there is also a stress condition which arises from the beam effect in the pipe if the underlying pipe bedding is uneven. This stress condition is also clearly subordinate to the one that deflection of the circular ring cross section causes. In consequence with the above, the further discussion concentrates on what the effect could be when exposing the ring cross section to a constant bending strain for a long period of time.

This bending strain becomes rather moderate as long as the pipe's deflection is kept within 3-8 % and the pipe wall thickness is small relative to the pipe diameter (i.e. applying to pipe classes with a stiffness of, at the most, 8 kN/m^2). The strain in the pipe wall will then never exceed 1 %. For stiffer pipes or for pipes with larger pipe deflection (up to 15 %), the strain values are significantly higher and may well exceed 2 % and more. The question now is if these strain values (implying very large momentary bending stresses) can have a limiting effect on the material's long-term strength. This question has, especially during recent years, been made the object of studies, even though the problem has already been discussed 20 years ago when buried plastics sewer pipes began to be introduced on the market [9].

First, it should be made clear that the often very large bending stresses that the constant strain causes when the pipe cross section is undergoing a deflection process, decrease with time as a result of relaxation. The phenomenon was thoroughly discussed for PVC already in [20] and for PE in [21]. In both investigations, pipes have been studied that have been kept constantly deflected during a long time and for which the fictive decrease in the E-modulus has been determined as a function of time. Despite very large strains that are applied by deflection of thick-walled pipes, it was proved to be very difficult to simulate a material failure within a test period with continuous load of up to 10 years.

Thus for PVC, it has been completely impossible for the high-valued PVC qualities studied (pipes corresponding to international pressure pipe standards) while for PE, it has been possible to cause failure, but only in those cases where the pipe material has been thermally oxidized. (This latter stage was not unusual in certain thick-walled PE 63 pipes manufactured before 1975. The knowledge of the risks and consequences of thermal oxidation can be regarded as rudimentary in most plastics pipe factories [22] at that time. Today, as a rule, all large polyethylene pipes are manufactured by using an inert gas as pressure medium in the pipe, thus ruling out any risk of thermal oxidation during manufacturing of the pipe.) The study reported in [21] has recently been supplemented with further measurements of the E-modulus in PE pipes that have been kept constantly deflected during almost eight years at a temperature of +23° C. Strains of up to 2.5 % have not yet given any indication of failure [13].

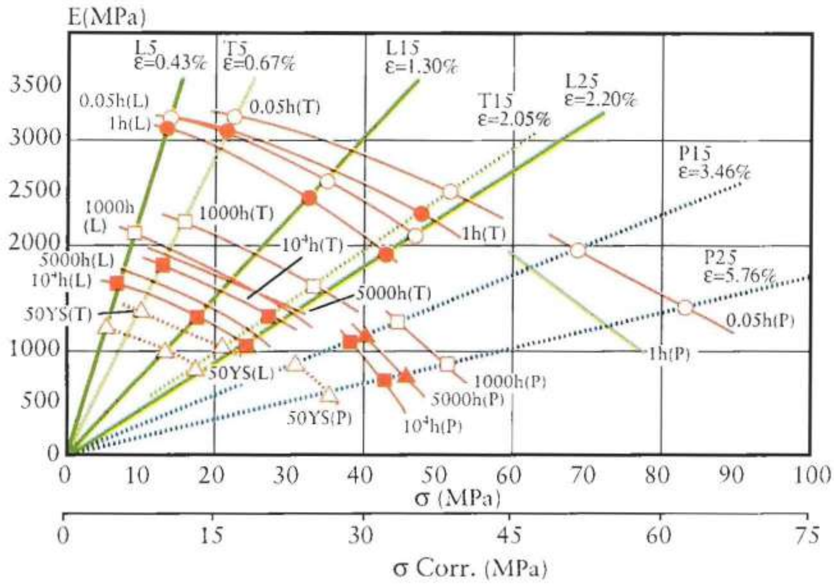

Figure 4.1 [4] The relaxation modulus E for PVC-U pipes as a function of fictive bending stress with the relative strain and the loading time as parameters. Temperature +23 °C

A special study that can be referred to is the above-mentioned ref. [13], the purpose of which was to try to create a material failure in PVC through exceptionally high strain values. Despite strains of up to nearly 6 %, it has not been possible so far to simulate a failure during nine years of load. In **Figure 4.1** [4] the course is illustrated, where the measured E-modulus has been plotted against the theoretical bending stress for PVC pipes deflected in such a way that the indicated constant strain values have been obtained.

One can see how the E-modulus and stress decrease due to relaxation when the loading time increases. In **Figure 4.2** the stress relaxation as a function of time has been plotted for the largest strain of 5.76 % stated in Figure 4.1. The stress has also been given after correction with regard to the non-linear distribution of stress in the pipe wall. (The lower abscissa line in Figure 4.1). As can be seen, the curves are concave with the abscissa (i.e. the stress = 0) as asymptote. Even if one made the assumption of a linear extrapolation after 10^5 hours, one finds that the curve does not reach the abscissa until 10^{10} hours have passed. The bending stress that in the initial phase amounted to approximately 50 MPa has thus relaxed to 17 MPa after 50 years. During the period of time up to 100 years, further stress reduction is evidently small and it does not seem probable that any dramatic change in the pipe's strength would occur before 100 years.

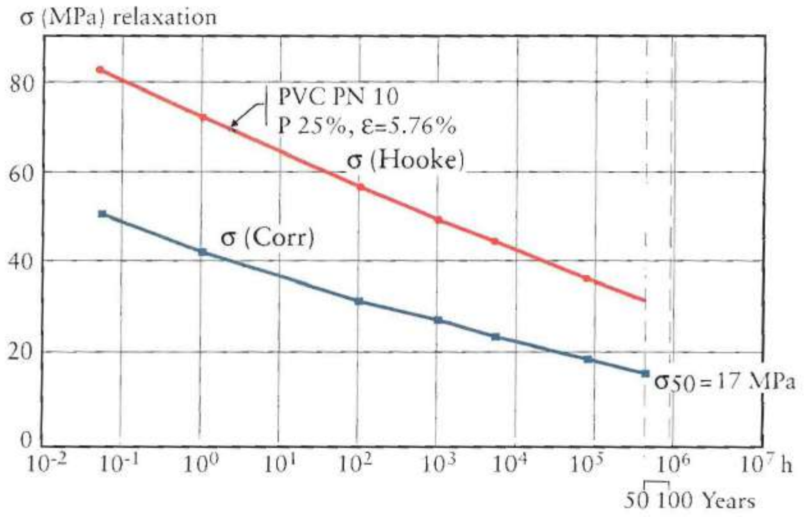

Figure 4.2 ***The bending stress relaxation as a function of the loading time in a PVC pipe of pressure class 10 bars that is kept constantly deflected to 25 %. Temperature +23 °C. Cf. Figure 4.1***

From all the studies that have been carried out until now, some of which have been going on for over 10 years, it is evident that material failure has not been possible to achieve in a PVC-U or PE pipe that has been exposed to a relaxing bending stress. (The condition is, however, that the material is pure and virgin and meets the strength requirements according to normal pressure pipe standard). A work hypothesis has thereby been developed in [13] with the implication that it is the stress relaxation procedure that contributes to preventing failure. The bending stress which is initiated when the pipe is deflected, thus decreases through relaxation as a function of time and approaches zero as times goes towards infinity. In consequence, the hypothesis has the implication that if a failure does not occur immediately in the initial phase, it will never occur; and this is independent of the size of the strain.

Again, it should be emphasized that the hypothesis for the time being is only applicable to well-processed thermoplastic pipes, manufactured from virgin raw materials with a minimum of additives of the type used when producing pressure pipes. For example, large amounts of unspecified additives (filler) or reprocessed materials can thus not be permitted. This is logical as long as the long-term experience that the hypothesis is based on only concerns pipes made of well specified virgin resins. The problem is discussed more thoroughly in [13] and in [4].

To sum up this section, it can be said that the constant bending strain that the pipe wall is exposed to will not cause failure as long as the pipe material retains its original properties, i.e. as long as the material's stabilization system is intact. Should the stabilization system be intact for ever, a material failure will thus never occur. This question will be further discussed in the next section.

5. CHEMICAL AND BIOLOGICAL STABILITY CONDITIONS

The statements made in Section 4 concerning the pipe material's strength are based on many years of experience of exposing constantly deflected pipes to air, water and water mixed with detergents [9]. In these various mediums, the time of exposure has obviously not shown to have any significance relative to the medium in question. An especially important observation in this context is of course that water containing detergents (which is normally the case for waste water) has not affected the pipe material any more than ordinary water has. This is somewhat unexpected since investigations of the strength of PE pipes exposed to a high concentration of detergents and, at the same time, exposed to constant stress, and thus free creeping (pressure pipes), have for one and the same stress shown times to failure that are approximately one quarter of those measured when testing in pure water [23] and [4]. (See **Figure 5.1**).

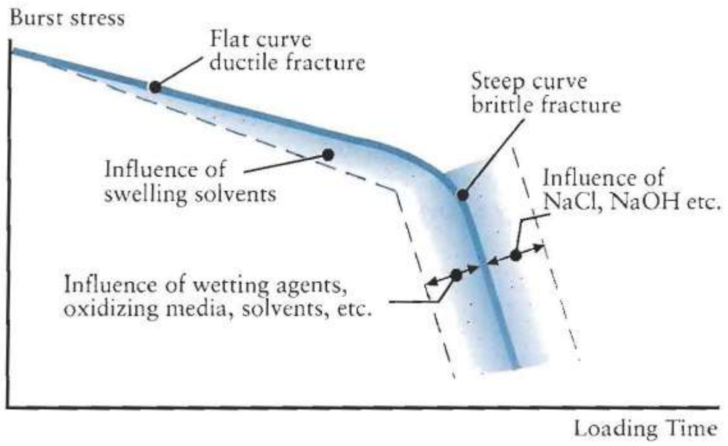

*Figure 5.1 [4] **The influence of different mediums on the stress/time curve's position for PE pipes subjected to internal hydrostatic pressure***

Naturally one arrives at the question as to whether the hypothesis presented in Section 4 (implying that the absence of failure in pipes subjected to constant deflection could be explained as being a result of the stress relaxation process) could also apply to the case when the plastics material is exposed to other mediums than pure water. As far as known, there is presently no knowledge that is able to answer this question. The consequence of this is of course that, for the time being, one has to rely on practical experiences, which in fact suggest that material failure in constantly deflected PE and PVC sewer pipes exposed to water containing detergents does not occur, not even during a very long (approximately 25 years) time period, in spite of the fact that, from a practical point of view, the strain values applied were in many cases strongly exaggerated. [7] and [8].

If, against this background, one looks at other common mediums that can attack a sewer pipe, namely hydrogen sulphide/sulphuric acid (internally) and acid groundwater (externally), it can only be stated that pressure pipes exposed to these substances show a longer length of life than do the same pipes exposed to pure water. (Similar influence as demonstrated in Figure 5.1 for NaCl and NaOH). Thus, it seems reasonable to say that the safety against material failure in buried sewer pipes made of plastics is greater in acid and saline environments than that which has been concluded to be the case for pure water; a relationship that is totally opposite to that which applies to ordinary cement- and iron-based pipe materials.

Against the background of the above, it is now logical to return to the question of what sets the limit for the plastics pipe's practical service life in reality. As has been indicated earlier, plastics seems to be a perfect construction material for sewer pipes as long as the material retains its original properties. This, in turn, is a matter that relates to the chemically based, built-up stability of the material and whether this stability changes over time. It is well-known that all plastics, as all organic materials, deteriorate with time, mainly as a result of chemical effects. In order to prevent or delay this effect, different types of stabilizers are added to the plastics in order to counteract the breakdown procedure that would otherwise occur as a result of thermal oxidation, ultraviolet radiation, etc.

Since the deterioration process is accelerated with increasing temperature, it is natural that the problem has not been given practical attention until connected to the development of pressure pipes for hot tap water distribution indoors. Extensive studies of ageing in polyethylene, polybutylene and polypropylene pipes [24], [25], [26] and [27] have therefore been carried out in recent years. All investigations on the relation between mechanical stress and time until failure in the temperature range of 80-120° C show, after some time, a burst mechanic phenomenon, where the time until failure is no longer dependent on the stress. Thus, apart from obtaining the customary curve course I (ductile failure) and II (brittle failure), a third phase III is obtained illustrated in **Figure 5.2** after which the material is no longer able to take up any forces, no matter whether these are small or large. The plastics has simply ceased to function as a structural material in this phase.

The problem was observed for ordinary polyethylene already in [28], where the concept "ageing limit" was introduced in order to indicate that beyond that limit, a commencement of ageing from a practical point of view took place. See **Figure 5.3.** As a criterion for this commencement of ageing, a minimum strain value of 200 % on short-term tensile loaded bars was used. If this value was below 200 %, one could ascertain that the stabilization system had been seriously consumed. Later comparative studies based

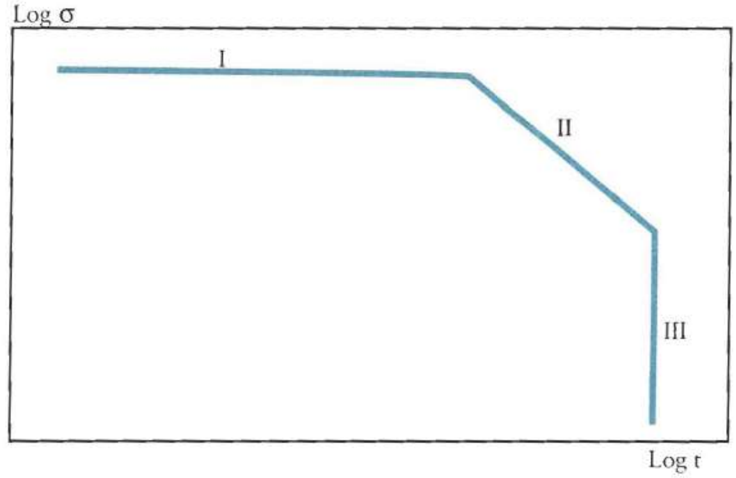

Figure 5.2 [25] Relation between stress and time to burst, principally referred to in three different stages, I (ductile type of fracture), II (brittle type of fracture) and III (fracture due to deterioration of the plastics material)

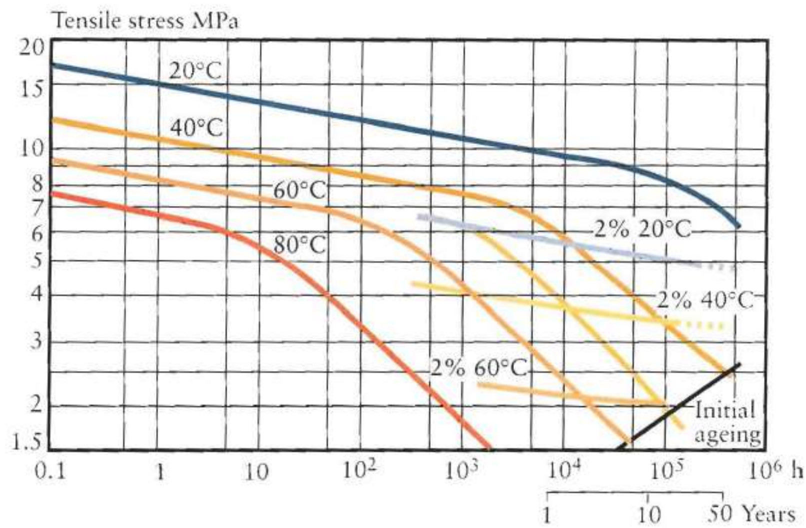

Figure 5.3 [28] Stress/time relationship for HDPE Type 1 with marked limit for "initial ageing"

on measuring the material's thermostability [29] confirmed the correctness of the original simplified criterion. In [29], is also made a valuation of when phase III could occur depending on the temperature. From **Figure 5.4** it is thus evident that if the temperature, on average, is kept at +20 °C, the commencement of ageing does not start until after $5 \cdot 10^6$ hours

(570 years). In order to prevent the commencement of ageing until 100 years have passed, one can from Figure 5.4 see that the average temperature during this time is not allowed to exceed +35 °C. For 50 years, the temperature +40 °C applies etc. It should be observed that in Figure 5.4 the ageing in air is shown to be slower than the ageing in water, which, however, is contradicted by results reported in [26]. Nevertheless, in [26], one arrives at the conclusion that a newly-developed quality of a medium-density PE 80 quality (MDPE of the type Borealis ME 0909) should be able to survive for 50 years in water/air at a tensile stress of 5 MPa, even if the average temperature is + 45 to + 50 °C.

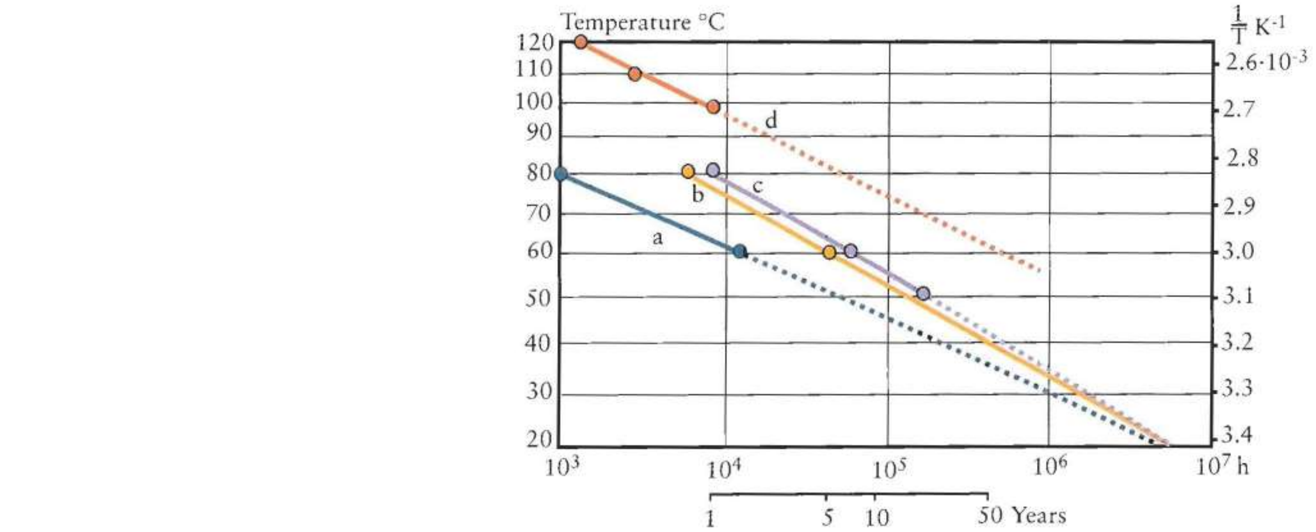

Figure 5.4 [29] Linear Arrhenius-proportion, where line a stands for the first knee point; line b for the second knee point; line c for "initial ageing" in water; line d for initial ageing in air

So far as known, investigations of the type reported above for polyolefins have not been presented for PVC. However, with support from studies at the Royal Institute of Technology in Stockholm it can be shown, amongst other things, that the stabilization systems for high quality PVC pipes are at least as well developed as stabilization systems for polyethylene [30]. As long as the annual average temperature is below +20° C, which is almost always the case when it comes to common sewer pipes, one can thus count on the fact that the stabilization system will remain intact for several hundred years in PVC pipes as well. It should be observed that the statement does not of course apply to house connections that are serving, for example, laundries and similarly large users of hot water. In such cases, however, it can be the mechanical stability as well as the thermal stability that sets the limit for the pipe's length of life.

Concerning the biological stability, it can be concluded that municipal waste water of course creates favourable conditions for bacterial cultures that easily establish themselves on the pipe walls and then cause more or less heavy sludge deposits. An important question in this context is whether the pipe material's properties could be such that they stimulate the bacterial growth more than what is normal in a sewer pipe. Such a critical property could be if the material was favourable to the bacterium's nutritional requirements and thus to some extent functions as fertilizer for a bio-culture. The question is of general interest and has been dealt with in connection with, amongst other things, attempts to create plastics that are readily broken down rapidly by Nature instead of lying around as litter for a long time. The attempts have so far, for different practical reasons, been abandoned. What has been discovered, however, is that plastics containing a nutrient salt component (for example nitrogen) have a greater ability to create their own bio-culture than do plastics based on simple hydrocarbons. It has thus not been possible to bacteriologically break down pure PE or rigid PVC-U. Nor have the most common additives that are required for the processing and thermostability of these plastics shown to be interesting enough for the bacteria, for replacing the more accessable substances already available in the waste water. It should be added then in the cases where material-dependent biological growth has been observed in plastics pipes, this has been in plasticized soft PVC, in which the plasticizing additive has proven to be growth-stimulating [31]. In PVC-U pipes used for municipal water supply and sewers, the PVC material is unplasticized.

During recent years, inspections have been carried out in old plastics pipe sewer systems [8]. Furthermore, supported by the Swedish Plastics Federation, approximately 20-year old PVC pipes have been taken up for examination. Any biological breakdown of the plastics material has not been apparent. The extent of the biological growth (sludge deposits) has not been concluded to be more extensive than what normally appears in municipal sewer pipes. Whether these observations can be used as a basis for a general statement about what could happen after a very long time is of course uncertain. However, it can be assessed as being a reasonable hypothesis to assume that as long as the plastics material only consists of compounds which are biologically inert, no biologically conditioned breakdown of the pipe material will take place, either in the short- or long-term.

6. FUNCTIONAL STABILITY CONDITIONS

In the above, the service life of plastics pipes has been discussed with a startingpoint from the pipe material's mechanical, chemical and biological stability. As has been suggested in the introduction, a product's service life concept also includes its ability to satisfactorily maintain the function for which it was originally intended. The concept "piping capability" has been introduced earlier [32] in order to describe a water supply and sewer system pipe's capacity to maintain its function, i.e. contain a certain degree of functional stability. Thus, also included in the general functional demand for a buried sewer pipe, with a starting-point from the user's needs, are demands on the pipe's tightness over time, its ability to transport water, its reliability in operation as well as its possibilities of maintaining its original functional demands through simple maintenance measures.

One can against this background let the concept of functional stability refer to the **time** during which a certain requirement is kept unchanged. The concept can thereby be said to include a time factor of X years during which the original function is upheld and during which a "maintenance-free period" thus exists. After X years, one can thus assess that a certain maintenance must be carried out in order to keep the original functional requirement continuously. If the sewer pipe is designed in such a way that it can take a number of n maintenance operations, its service life will be L = (n+1) X years. After the time L, one should thus count on a complete replacement of the pipeline.

Different functional requirements on the sewer pipe have different values for n and X, but the product (n+1) X must be constant for every function and equal to the one that applies to the pipe as a whole. If, for example, one would like to show that the pipe has a service life L = 100 years, the function that cannot be renewed without at least causing a replacement (or relining) of the whole pipe, i.e. n = 0, must be able to take a maintenance-free period of X = 100 years. The demand for tightness, which in turn depends on the material stability of the sealing rings of the joints and thereby the tightening capability, is thus an example of a demand for which, in such case, X must be 100 years since the sealing rings cannot be easily changed without relining the whole pipe. During this time, the demand on the pipe's ability to transport water must also be kept, which can be assumed to require cleansing, say every 10 years. One must then make sure that the pipe material can taken n = 9 such cleansings without being damaged in order to achieve L = 100 years, etc.

When it comes to tightness of ring sealed buried sewer pipes, this is not only dependent on the quality of the sealing rings for the joints but also on the deflection process caused by the pipe's earth and traffic load. As emphasized in Section 3, one can count on that a buried sewer pipe installed in a usual way goes through its final oval process already after a couple of years and that the pipe deflection thereafter will not change practically with time. Usually, this final deflection is less than 6 to 8 % on average. However, in order to be sure that the joint system is designed so well that it can even take an occasional extreme deflection, KP-marked plastics sewer pipes are type tested during internal and external overpressure at a deflection of 15 % and, at the same time, a two-degree vertical deviation from the straight pipeline alignment. A correctly installed buried plastics sewer pipe that through testing in conjunction with the final inspection has proven to fulfill the tightness demand will thus with great probability remain tight as long as the quality of the rubber ring does not change practically. It is a common opinion amongst professionals that the qualities of the synthetic rubber rings that are used today and whose performance has been adopted to the contact process with the plastics material will give the joint a sealing function for at least 100 years. (See also [5]). In recent years it has been common to use buried sewer pipes of PE with welded joints. For smaller pipe diameters electrofusion coupler jointing has often been introduced and for larger diameters the classical butt welding process is applied. In both cases a strength resistant and tight joint is achieved, which is independent of the deflection of the pipe. Furthermore it has been shown that the long-term strength for well-performed butt welded joints are the same as for the pipe itself [4].

If we now look closer at the question about the pipe's ability to transport water and the need for cleansing, the following can be said. Plastics pipes are characterized by the fact that they have an unusually smooth inner surface, which means that the friction losses on water flows are very low, at least as long as the pipe is new. However, the sludge deposit that is always formed with time on the sewer pipe's inner surface of course gives rise to a certain increase in the surface roughness. Even if the surface character of the sludge deposit is rather flat and is not different from deposits in pipes made of other materials, it can in certain cases become necessary to cleanse the pipe from sludge. For this purpose, high-pressure water jetting is used. Alternatively cleansing with mechanical tools is carried out. The pipe material must thus be able to resist this treatment without the surface roughness increasing, so that the pipe's capability to transport water will decrease with time. It is common knowledge that plastics are less sensitive to abrasion than other materials as long as the abrasive medium is sand or suchlike mixed with water since, in such case, the friction heat is unimportant. The plastics are easily scratched by tools, which is why, over time, a maintained smooth inner surface requires certain care when choosing cleansing tools. If this is kept in mind, both laboratory experiments and practical experiences have shown that abrasion and scratching will be insignificant [33] and [34]. Under all circumstances, one can count on pipes with maintained flow capability being able to take more cleansing operations than what, according to the above, are reasonably needed during a practical service life of, say, 100 years.

7. SUSTAINABILITY CONDITIONS

After having arrived at a conclusion implying that the thermoplastic PE and PVC sewer pipes may reach a service life of 100 years or more, it must be of particular interest to find out how these pipes can fulfil modern society's demand for "sustainable products". These products have to be non-toxic and renewable and in this way meet current demands according to the philosphy of recycling governing all products used today.

Firstly it may be stated that a professionally designed buried sewer pipe network system according to the above will have such a long service life that the renewable process will not be a frequent phenomenon. However, the problem of course, has to be solved the day when it shows up. Thus already today, technical development has been achieved for the reuse of PE and PVC pipes by grinding and re-extruding. As has been stated, this procedure requires that the stabilization system of the polymer is still active, and that the production control is focused towards those material properties which have importance for the long-term strength of the re-generated pipes. If not there will be an obvious risk for the very long-term strength discussed above not being fulfilled, implying that the piping capability will successively be reduced. In such cases when these requirements cannot be fulfilled, the most cost-effective and environmentally-friendly option should be to utilize the huge energy content of the plastics for heating. (Note that the regenerating of plastics products also demands energy). The high energy content in the plastics is valid particularly for PE, which is totally composed of hydrocarbons, which when burned gives only water and carbon dioxide. PVC which contains fewer hydrocarbons (in favour of chlorine) will produce a smaller amount of heat from a relative point of view, but can still favourably be burned. The hydrochloric acid which is generated during the burning can easily be neutralized by adding lime to the process. No toxic gases are produced. With regard to dioxines, it has been proved by frequent investigations in Sweden that the amount of these substances is less than when burning wood. The very small amount of the stabilizing additives lead or tin will be accommodated in the ashes and can easily be taken advantage of and be reused.

Certainly it is true that combustion of PE and PVC implies a consumption of petroleum, which in turn constitutes a non-renewable resource in the long-term. However, today it has to be remembered that out of the world's use of petroleum, 96 % is used for combustion in order to heat houses or drive vehicles. Only 4 % is used for producing the world's total amount of plastics [4]. The minor part of this which is used for production of PE and PVC-U pipes is in this context highly unimportant. As long as petroleum is used for producing energy worldwide, it may not be a fault to let a slight part, represented by used platics pipes, contribute to this energy demand. The contrary would in several cases imply a suboptimizing, which of course could be accepted temporarily in order to fulfil a certain short-term ideology, but could not be accepted if those requirements have to be fulfilled which in the long-term are needed for attaining a sustainable society from a practical point of view.

8. SYNTHESIS

In this study, attempts have been made to identify the particular topics that must be discussed if the question in the title of this Report has to be answered. The question primarily concerns the buried sewer pipes made of PVC-U and PE that are produced today and which comply with the quality requirements specified in [35] and which are the basis for KP-marking carried out by the Swedish Independent Council for Quality Control of Plastics Pipes. (Today Swedish Standards for buried sewer pipes made of PVC-U and PE are also available which in principle follow the quality requirements recommended by the KP-Council.) In all cases, it is assumed that the pipes have been installed under experienced supervision according to the directions in the officially-accepted national codes of practice.

With these conditions in mind, the ambition in this work has nevertheless not been higher than to try to analyse the probability of the answer to the question in the title being "at least 100 years". The synthesis of the work can therefore be provided in the form of summarizing assessment of what has appeared to be supporting and not supporting of the assumption that buried sewer pipes made of thermoplastics can function satisfactorily for at least 100 years.

If we begin with the geotechnical and mechanical stability conditions that have been discussed in Section 3, the main question concerns whether the ring cross section's deflection stagnates after a certain time and, in any case occasionally, never exceeds 15 % within 100 years. There should not be any doubt concerning this; a 100-year period of load can probably be easily achieved for pipes of at least ring stiffness class 4 kN/m^2 that have been installed in a regular way. In loose clay or when the pipes are surrounded by inhomogeneous clay that is not well-packed, the statement could have the same meaning as the above, if pipes of class 8 or 16 kN/m^2 are used. The fact that creep in the pipe material in the latter case does not become critical within the 100- year period is connected to the pipe material's physical ageing, which makes the fictive creep modulus decrease only insignificantly during the last half of the time span between 50 and 100 years.

The next question concerns the pipe material's long-term strength, which is dealt with in Section 4. The hypothesis presented there implies that bending strain in the pipe wall, which is the consequence of the pipe's deflection process, cannot cause failure. This is assumed to be valid as long as the bending strain is constant, and thereby stress relaxation exists, and as long as the pipe material's stabilization system is intact. Concerning the risk of failure in a thermoplastic material exposed to constant strain caused by constantly keeping the structural element in a bent shape, this risk, on a sound basis, seems to be unimportant. In the temperature range in which municipal sewer pipes normally operate (i.e. an average that never exceeds +20 °C), it cannot seem, based on the presented studies, hazardous to assume that the stabilizing systems applied today will function for at least 100 years. The consequence of this will be that buried sewer pipes in non-cohesive soils will function, without any material failure for at least 100 years.

When it comes to the pipe material's resistance against chemical breakdown, which has been discussed in Section 5, one can with a fair degree of certainty say that the mediums in a waste water system that are limiting for the service life for most other pipe material are totally harmless for plastics pipes. Not even high percentages of detergents seem to affect this statement concerning plastics pipes, as long as it relates to time concepts of 100 years. The pipe material's stabilization system that has been designed to secure the chemical and thermal stability can, as has been pointed out before, soundly be assessed as functioning satisfactorily for at least 100 years.

In Section 5, the resistance against biological breakdown was also discussed. In this field, the knowledge is without doubt more rudimentary than in other fields, and statements about the biological stability can only be stated with reference to the experiences gathered up until now. Thus it can be concluded that plastics pipes have been used for approximately 50 years in favourable environments for bacteriological growth without development of cultures that break down plastics. Whether new conditions for such cultures can suddenly appear is of course difficult to assess. With regard to the molecular structure of the plastics in question which consists mainly of inert components, it does, however, seem surprising if a biologically-conditioned breakdown could begin within an imagined period of 100 years.

If we look finally at the conditions for functional stability that are discussed in Section 6, the following summary can be made. With the construction that the sewer pipes system have today, there is no reason to believe that they would not be able to maintain their original water-tightness for at least 100 years. Also the maintenance measures that have been found to be necessary from experience in order to keep the pipes in a satisfactory operative condition, can neither be assessed as damaging to the pipes nor be regarded as technically/economically disadvantageous.

In Section 7 the sustainability concept is discussed, showing that the PVC-U and PE pipes used today should be considered as fulfilling society's demand of sustainable technology.

To sum up the synthesis, one can thus conclude that everything is pointing towards at least 100 years practical service life for today's buried sewer pipes made of highquality virgin PVC-U and PE resins, on condition that the pipes are used in accordance with the prevalent national standard installation instructions.

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