COMBINED LOADING OF BURIED THERMOPLASTICS PRESSURE PIPES

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SUMMARY

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1: Example calculations for combined loading using option 1 and option 2 as under development in CEN TC164/165 JWG1

2: Wintergerst results on PE pipes

1. Introduction

The design of buried thermoplastics pipes for pressure applications is based on the situation of free creep under the action of internal pressure. For traditional materials, the stresses induced due to internal pressure and those induced by external loading are combined as far as a simple ring evaluation is considered. When at the same time axial bending takes place as well, one then calculates the equivalent stress, which stress is compared with the allowable stress.

Thermoplastic materials do not allow the combination of the bending and tensile stresses in the way suggested by most traditional design methods. The background to this is however not very well spread.
With the publication of EN805 *“Water supply-Requirements for systems and components outside buildings*” product standards are obligated to show how the relation is built between the product related pressure classification and the system related pressure classification, involving combined loading.

For the above reasons, TEPPFA has decided to initiate a technical report on the issue of ‘Combined Loading’. In this report, first an overview is given on how thermoplastic pipes are designed. Attention will be given to the safety factor and overall design factor approaches which are different. Reference will be made to previous work followed by results from additional tests to check / confirm previous findings. Finally an advice will be given on how to design thermoplastics pipes. Furthermore, the answer to the request of EN805-January 2000, to relate the product classification pressure (PN) to the allowable operating pressure (PFA), will be given.

In EN805, PFA – the allowable operating pressure- is defined as the maximum hydrostatic pressure a component is capable of withstanding continuously in service.

2. Traditional design of buried pipes

Pipes buried in soils are loaded by soil and traffic. Furthermore, prescribed displacements due to settlement and subsidence of the soil occur.
The traditional design of buried pipes is based on experience and knowledge gained with linear elastic materials. The verification against limit-state of pipes is done using the traditional material models. In most regions in Europe however, for thermoplastics pipes the PN rating on the products is used for determining the allowable operating pressure.

Linear elastic materials have a unique limit state stress or strain, whereas thermoplastics materials with their visco-elastic behaviour exhibit an endless range of failure strains / stresses. For the failure model it is of great importance to know if the material is loaded by constant load or if the load is not able to follow the deformation of the material. In the latter case, stress relaxation will occur. In traditional failure mechanics this means that the stress at a crack tip vanishes and crack growth is arrested. Failure mechanics tests also showed difficult to be carried out, because blunting of the crack tip quickly occurs. The ability to redistribute (peak) stresses in combination with a relative huge yield potential is a great feature of thermoplastics. Involving all these aspects in the definition of an analytical failure model would become a difficult job. For that reason, tests have been developed to verify the longevity of these materials for its application.

3. Structural design of buried thermoplastics pipes

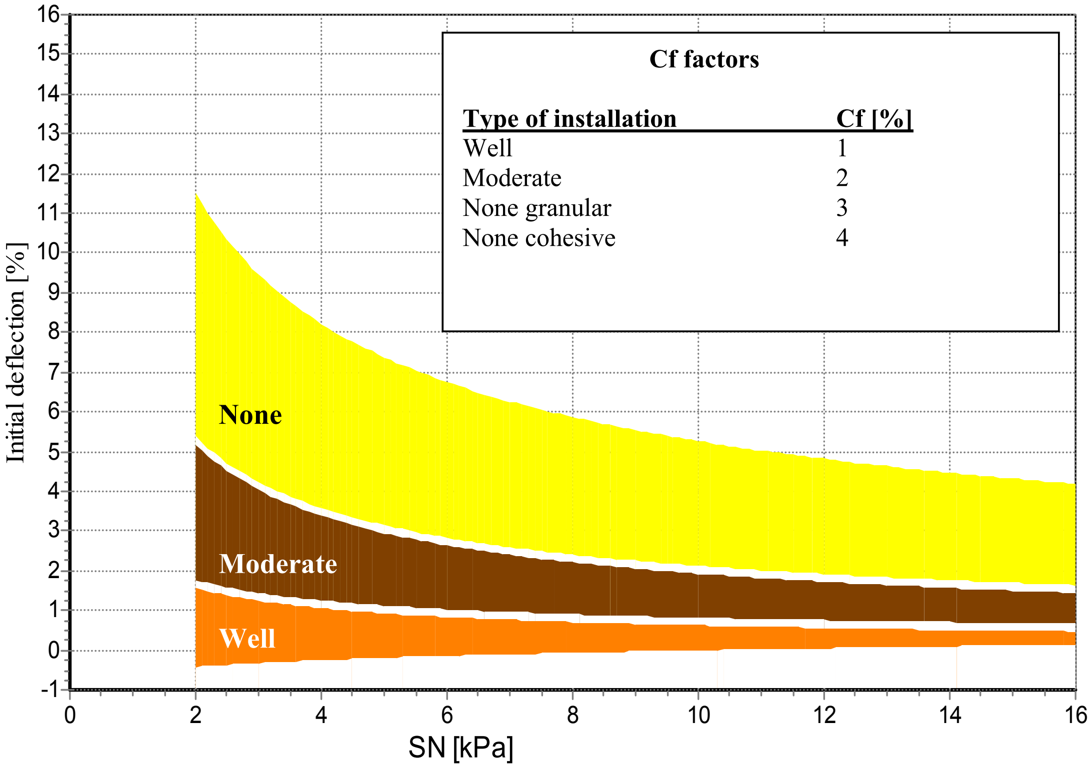
For buried thermoplastics pressure pipes the following design steps shall be considered:

- Pipe without internal hydrostatic pressure
- Pipe with only internal hydrostatic pressure

3.1 Pipe without internal hydrostatic pressure

Every pipe, including pressure pipes are buried while the pipe is not pressurised. This means that the pipe might deform slightly during and immediately after installation.
The pipe deformation can easily be predicted by using the TEPPFA design graph as shown in Figure 1. Details about the study performed to achieve this graph can be found in lit.1.

Figure 1: Deflections occurring immediately after installation as a function of pipe ring stiffness (SN) and type of installation



Cf factors

Type of installation	Cf [%]
Well	1
Moderate	2
None granular	3
None cohesive	4

Experimental work over a period of 40 years have shown that pipe deflection increases in the cause of time irrespective if the pipe is made out of visco-elastic material or linear elastic material. In the TEPPFA project it has been explained that this increase is not due to creep of the pipe material, but due to settlement of the soil.

In order to determine the final deflections occurring after complete settlement of the soil the values as listed in Table 1 shall be added.

Table 1: Cf factors to obtain the final deflection.

Type of installation	**Cf Settlement add-on value [%]**
Well	1
Moderate	2
None, granular	3
None, clay	4

The final deflection can be calculated as follows:

Final deflection = Initial deflection + Cf (1)

It is important to note that the C_f factor covers the effect of depth of cover, groundwater and traffic load, as these are all playing an important role in the settlement process.

SN is determined by ISO 9969 or can be calculated by

$$SN = E/[12(1-v^2)]*(s/d)^3 \qquad (2)$$

in which:

SN	Pipe ring stiffness	[kPa]
E	Young's modulus	[MPa]
v	Contraction coefficient	[-]
s	Wallthickness	[mm]
d	Mean pipe diameter	[mm]

Design of buried pipes involves finally a check against the limit state.
This check involves:

- Verification of serviceability limit-state
- Verification of structural integrity limit state.

3.1.1 Serviceability limit state: In order to avoid a significant decrease in discharge capacity and to allow cleaning and inspection equipment to have access to the pipe, the final pipe deflection shall be limited till 12%. This means that the pipe deflection immediately after installation should be limited to 8%. In case saddle joints might have to be mounted after installation it is recommended to limit the deflection to a reasonable level. However, also in case of severe deformation, saddles can still be mounted by using re-rounding tools.

3.1.2 Structural integrity limit-state: the final deflection shall be limited to 15%. This means that the deflection shall be less or equal to 10% immediately after installation. The value of 15% incorporates a safety factor of 2. This is a minimum factor because thermoplastics pipes show that up to a deflection of 30% still an increase in force is developed. For gravity sewer pipes for instance where it has become common practice to use structured wall pipes, a special test has been designed to safeguard that the condition of increasing load up to 30% deflection is fulfilled.

3.1.3 Limits determined by buckling: After the pipe has been buried and is still without internal pressure, or if surge occurs in water mains, then buckling is the second phenomena to be checked upon.
In lit.2 Janson has given the formulas to be used for such a check.
Below an overview is given.

The critical buckling pressure of a buried pipe can be calculated and verified against the sustained load at the outside of the pipe. For buried pipes, sustained load is the load exerted by groundwater and part of the soil load. The load to be taken into account is given by the relevant standards. The resistance against buckling can be calculated for flexible pipes using the following formulas (Lit.2).

Soft soils / mud: Condition $SN > 0.0275 * Et$

$q_{crit} = 24 * SN + 2/3 * Et$ ………………………………………. .. (3)

Other soils: Condition $SN \leq 0.0275 * Et$

$q_{crit} = 5.63 \sqrt{(E_t * SN)}$ …………..……………………… …(4)

In which:

q_{crit}	The critical buckling pressure	[kPa]
SN	Pipes ring stiffness	[kPa]
E_t	Tangent modulus (E_s) of the soil	[kPa]

When a pipe is deflected, it will result in a lower buckling resistance of the pipe.
The value found has then to be corrected with β :

$\beta = (1-3 * (\delta/d))$…………………………………… (5)

3.2 Pipe with internal pressure only

The pipe with pressure only is designed using the following formula:

$\sigma = P/2 * [D/s-1]$ …… (6)

in which :

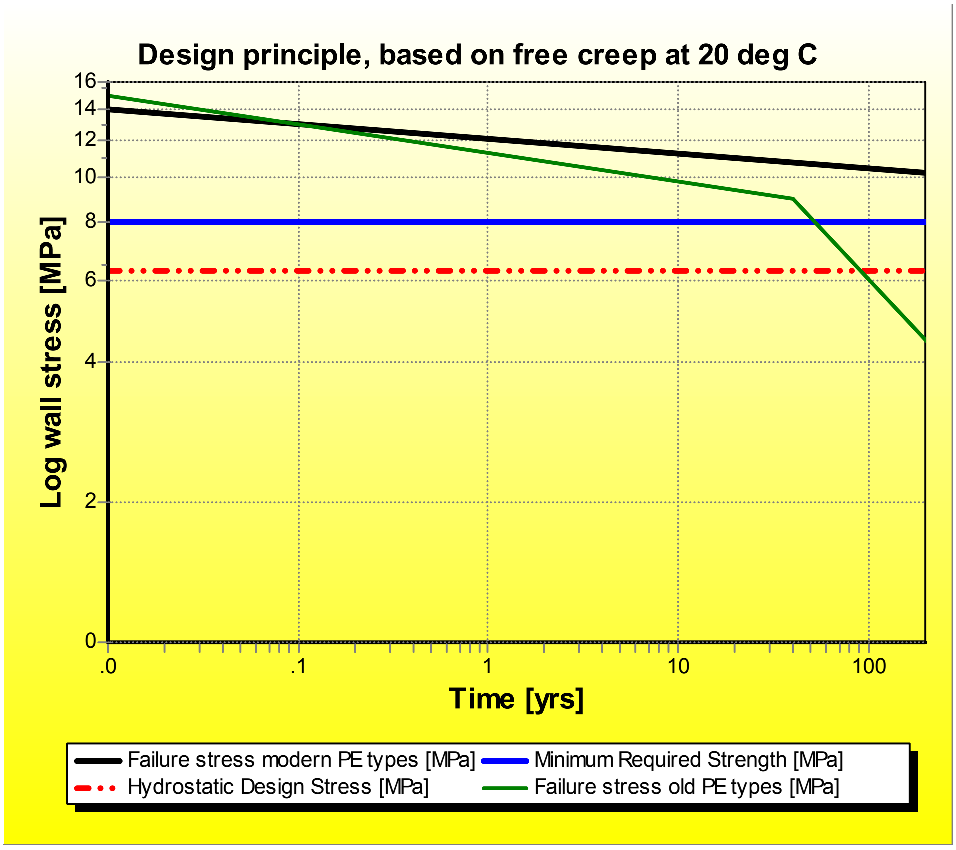
σ	Hoop stress…..	[MPa]
D	Outside pipe diameter….	[mm]
P	Internal pressure	[MPa]
s	Wallthickness	[mm]

The check against limit-state is performed by using the Hydrostatic design stress (HDS) of the material. This value is related to the Minimum Required Strength (MRS) of the material, via the overall design coefficient (C).
Thus :

$$HDS = MRS / C \quad (7)$$

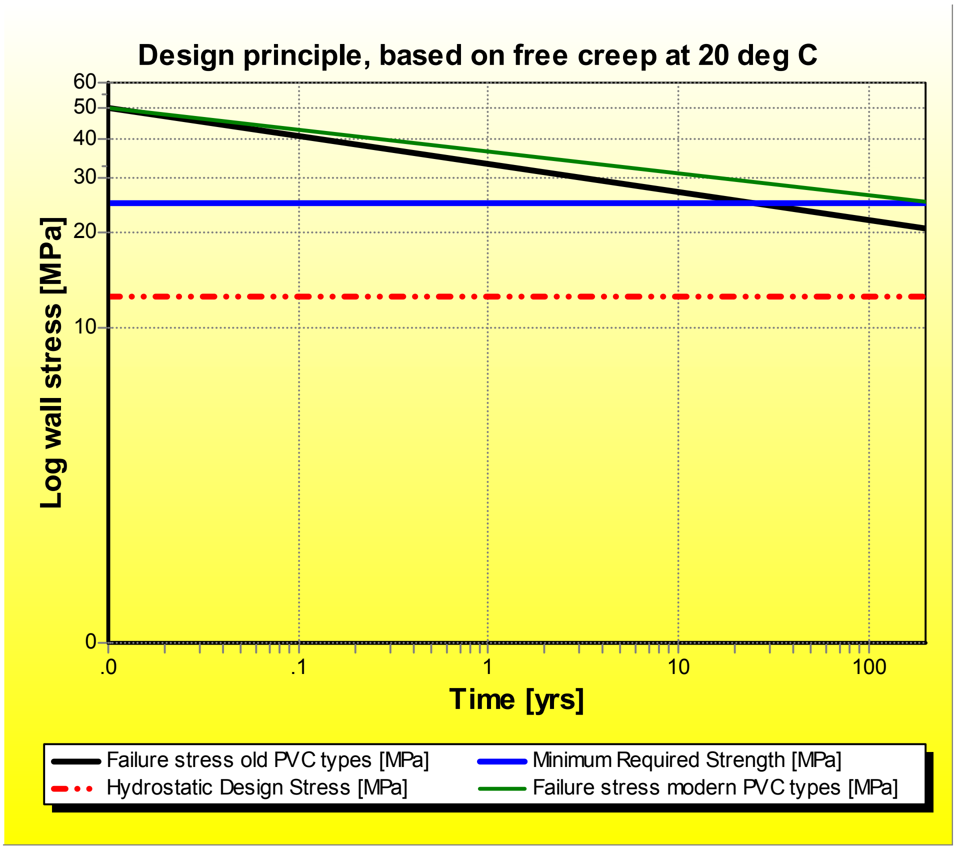
The relation is shown in figure 2 and figure 3 for PE and PVC respectively.

Figure 2: Schematic representation of the material classification and design procedure for PE.



In figure 2 a graph is shown with lifetime on the horizontal axis and the wall stress due to internal pressure on the vertical axis. Both axes are log scaled.
Two PE types are represented. The lines shown for these materials are the so-called Lower Confidence Lines. Most commercial available PE materials for pressure applications have their characteristic line somewhere in between the two shown. If the 50 years strength is 8 MPa or greater then the material is classified as a PE80 material and if its strength is 10 MPa or greater it is called a PE100.
The Hydrostatic Design Stress is also shown in the graph, which level is obtained by applying an Overall Design Coefficient C. The ‘C’ value is determined for 50 years free creep at 20 deg C. It is be noted that the C value can also be expressed as a time dependant factor.

Figure 3: Schematic representation of the material classification and design procedure for PVC.



The same type of graphs as for PE apply for PVC as shown in figure 3. The standard line is the line that has to be fulfilled in order to obtain a material classification PVC250. This line will best represent the first generation PVC. The upper line best represents the PVC types nowadays commercially available. The Overall design coefficient used to obtain HDS is 2.5 for pipes with diameters smaller or equal than 90 mm and the factor is 2 for pipes with diameters bigger than 90 mm. These values are inherited from the past. Modern production techniques have improved the quality of the pipes to such an extent that they are less vulnerable for handling and storage. Reason why lower values, even down to 1.4, are considered for certain types of PVC pipes.

Both in PVC and PE, developments are underway resulting in stronger materials. In order to avoid that each separate material has to be classified differently, it has been chosen to group the materials in different classes. Table 2 shows an overview of material classes as currently recognised. Extension of these classes might occur when new materials have been developed. The overview shows the classification for water supply applications. When gas or chemicals are considered higher values of the overall design coefficient might be required. For instance for PE gas pipes a minimum value of 2 is used as overall design coefficient.

Table 2: Material classes for PE and PVC for water supply.

Class	**MRS [MPa] water**
PE	
PE 63	6.3
PE 80	8.0
PE 100	10.0
PVC	
PVC 250	25.0
PVC 315	31.5
PVC 355	35.5
PVC 400	40.0
PVC 450	45.0
PVC 500	50.0

Note: PVC 315 up to PVC 500 are special types of PVC which have been oriented in production and inherit additional strength from that.

Safety factor versus Overall Design Coefficient

For traditional elastic materials safety factors related to maximum allowed stress or load can be defined. The value, however, is valid for the initial conditions. For traditional elastic materials it is considered that this initial condition does not change in the course of time and hence claimed to be independent of lifetime. For thermoplastics, safety factors can be defined, related to the stress and also to time. It means that safety factors are to be defined in relation with time. (For traditional materials usually the prediction of deterioration, like corrosion, of the material is not known and hence safety factors relating to these aspects are not given.)

Safety factors as traditionally anticipated has no meaning for thermoplastics materials. When the stress increases temporarily over the MRS value, then immediate failure will not be the result, this in contrary to traditional materials. Only when the stress is exceeding the MRS value for a long period of time, failure might be the result, but only then when the condition of sustained creep is fulfilled.

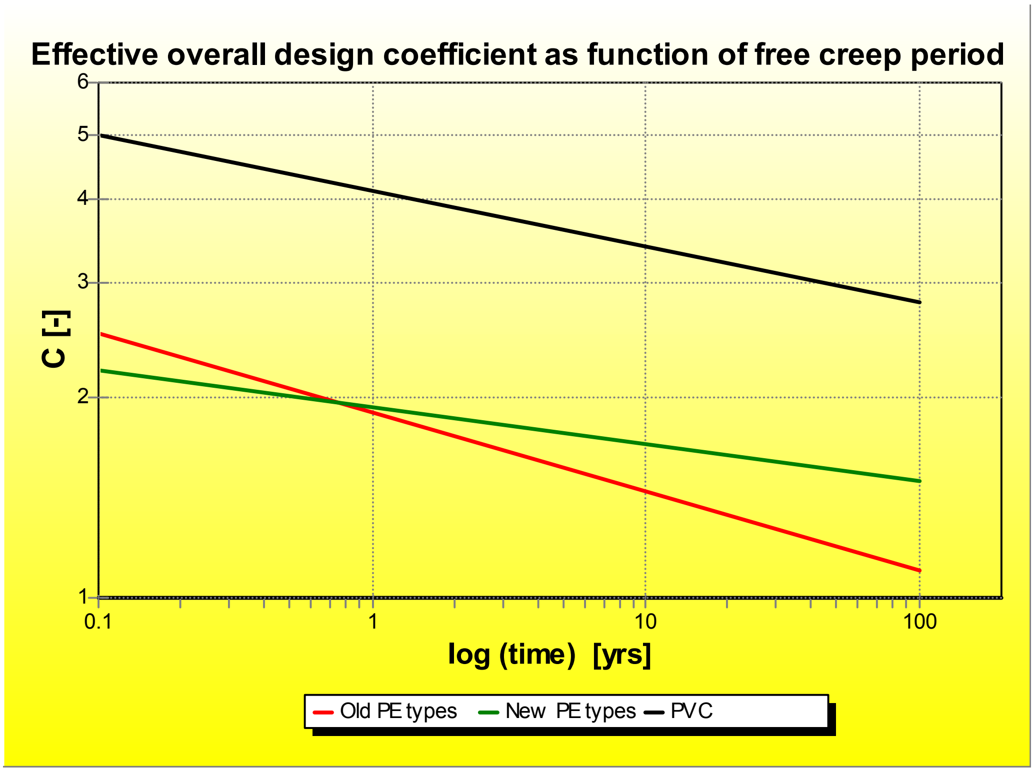
It has been explained that for thermoplastic materials, the traditional safety factor approach is not relevant. Therefore, the so-called Overall Design Coefficient (C) has been introduced. This factor covers the effects of handling, scoring, material variation etc.

The factor C is related to a 50 years lifetime for a condition of free creep at 20 ˚C.

The effective overall design coefficient can be plotted against the free creep period, which is the period at which the pipe is experiencing a constant internal pressure at a constant temperature of 20 deg C, without being hindered by outside soil pressures. This is shown in Figure 4.

In reality pipes in soil do not experience a free creep condition, except in very soft soils.

Figure 4: Effective overall design coeefficient C’



In design however, the factor C is related to a free creep period of 50 years at 20 deg C.
The graph shows also that the factor at 100 years is almost the same as the value for 50 years. Considering the fact that most commercially available materials have strength values far above the MRS value, it can be stated that the C factor for 50 years practically equals that of 100 years.
The lines have not been extended over 100 years for reasons that the traditional testing of plastics pipes does not cover this. In literature 2 however it has been indicated that at 20 ˚C PE materials will last for at least 500 years and PVC for 4000 years before they will have deteriorated. However there is no prove that the pressure capabilities are in tact after such a long period.

4. <u>Combined load tests</u>

In literature, information can be found where it was proven that combined loading of thermoplastic pipes has not the same effects as for traditional elastic materials. Wintergerst (lit.3) for instance performed a lot of tests to find evidence for de-rating of PVC and PE pipes when subjected to internal pressure and simultaneous bending of the pipe.
Alferink et al (lit.4) performed tests with deflected pipes which are loaded by internal pressure as well. The effect on time to failure showed to be positive in the sense that in the tests it could even take a longer time to burst than with the non-deflected pipe.
Two types of combined load tests have been performed so far, one with a deflected straight pipe, and one with a pipe that is bend to a certain radius.

4.1 Tests on deflected straight pipes combined with internal pressure.

Pipes have been deflected between two parallel plates, after which the pipes were pressurised.
The initial bending stress and strain can be calculated by:

$\varepsilon = df * (\delta/d) * (s/d)$ ………………………………… (8)

$\sigma\ (t)= [E /(1-v^2)]* \varepsilon * t^{(-m)}$ ………………………….. (9)

in which:

ε	Maximum tangential bending strain	[%]
σ	Maximum bending stress at a specific time	[MPa]
(δ/d)	Pipe deflection	[%]
v	Contraction coefficient of the material	[-]
s	Wallthickness of pipe	[mm]
d	Mean pipe diameter (d=D-s)	[mm]
t	Elapsed time	[-]
m	Relaxation coefficient	[-]
df	Strain factor	[-]
E	Young's modulus uni-axial stress	[MPa]

The strain factor is 3 when pipes deform elliptically. For pipes with a stiffness of 4 kPa and higher buried in ground, the deformation can be considered to be elliptical. For pipes deflected between two parallel plates, the strain factor is 4.28. This means that the parallel plate test provides a conservative situation compared to practice.

The strain at the position where the plates press the pipe (crown and sole) is calculated when using strain factor of 4.28. At the position at the springline, this is the position where the pipe shows the horizontal deformation, a strain factor of 2.44 is valid.

The initial stress can be calculated by applying Hook's law and plain strain conditions, as reflected in formula 9.
It shall be noted that the pipe is in a condition of constant strain, meaning that the strain induced stresses will relax in the course of time. The Young's modulus does not decrease. (Lit.2) On the contrary, the modulus increases due to molecular consolidation. The consolidation process is characterised by applying the factor m. For design however, one does not consider the marginal increase of the Young's modulus in the course of time.

The stresses and strains induced by internal pressure are calculated by formula 6, when the pipe is circular. When the pipe is deflected the stress due to internal pressure is not the same along the circumference.

At the sole and the crown of the pipe the tangential stress due to internal pressure can be calculated by:

$\sigma_{crown} = P\ (d-\delta-2s)/(2*s)$ ………………………….. (10)

$\sigma_{springline} = P\ (d+\delta-2s)/(2*s)$ …………………….. (11)

Results of the tests and calculations are shown in the following tables.
In table 3 the measured results as well as the calculated results are shown. At test ID 1, pipes are not deflected and the stress due to internal pressure is 12.5 MPa at the crown as well as at the springline. The bending stress is zero. For sample 2, the pipe is deflected up to 8% and hence the tensile stress caused by pressure is 11.5 MPa at the crown and sole, and 13.5 MPa at the springline. The bending stress is also shown in columns 2 and 4. Adding the stresses together gives the total stress at crown and springline.

Table 3 Tests on PE100 pipes (Wavin M&T laboratory)

ID	(δ/d) [%]	Stress [MPa]	Failure time [hrs]	T [C]	Remark	Stress [MPa]					
						1	2	3	4	Total crown	Total springline
1	0	12.5	199.6	20		12.5	0	12.5	0	12.5	12.5
2	8	12.5	365.5	20	Outside clamped section, ductile failure	11.5	13.2	13.5	7.5	24.7	21.0
3	8	3.5	>800	80	detergent in-and outside,stopped before failure	3.2	13.2	3.8	7.5	16.4	11.3
4	8	3.5	>800	80	detergent in-and outside,stopped before failure	3.2	13.2	3.8	7.5	16.4	11.3
5	0	10-12.5	537.6	20		*	0	*	0	*+	*+
6	8	10-12.5-15-17.5	1356.1	20		*	13.2	*	7.5	*+	*+
7	8	10-12.5-15-17.5	1362.1	20		*	13.2	*	7.5	*+	*+
Note to the stresses: 1: tensile at crown 2: bending (initial) at crown 3: tensile at springline 4:bending (initial) at crown * Tensile stresses in stepped stress test, sequence as indicated.											

The results in table 3 indicate that pipes, which are subjected to combined loading, perform better than those traditionally tested, with a free creeping condition under the same internal pressure. It shall be emphasised that the amount of test data is insufficient to establish a clear relationship between deflected and non-deflected pipes.

However the results are by far sufficient to show that tensile bending and tensile hoop stresses shall not be added together. ID numbers 1 and 2 show clearly that the time to failure is not affected in a negative way by the bending of the pipe. The samples 3 and 4 were chosen to force brittle failure to develop. After 800 hrs these tests were stopped, because no failure developed.
The samples 5,6 and 7 show what happens when the pressure is stepwise increased from 10 to 17.5 MPa. The step interval varied in time between 200 - 240 hours. Interesting is that pipes perform better when the pressure is stepwise increased. The samples 4, 5 and 6 where this is done prove this clearly.

The reason for this is probably, that when pipes are pre-loaded, consolidation of molecular structure (increase of density) is accelerated. So the materials physical ageing process is finalised quicker.

Table 4 - Tests on PE80 pipes. The PE80 is a representative sample of commonly used PE80's for pressure applications. (Wavin M&T laboratory)

ID	**(δ/d) [%]**	**Stress [MPa]**	**Failure time [hrs]**	**T [C]**	**Stress [MPa]**					
					1	**2**	**3**	**4**	**Total crown**	**Total springline**
1	0	5.9	17.60	80	5.9	0	5.9	0	5.9	5.9
2			16.16	80						
3			15.27	80						
4	5	5.9	4345.00	80	5.6	6.5	6.2	3.7	12.1	9.9
5			10250.00	80						
6			>15000.00	80						
7	10	5.9	5777.00	80	5.3	12.9	6.5	7.4	18.2	13.9
8			13143.00	80						
9			12182.00	80						

The difference between the results of the deflected pipe and those of the reference pipe is significant. In all samples ductile failure was found. The total stresses are again calculated using a traditional linear elastic approach and using the superposition principle. These as such calculated stresses are extremely high and if they were the stresses experienced under free creep condition, they would have resulted in premature failure.

So far the results showed mainly ductile failures. It was found of importance to check what would happen when brittle failure would develop. Therefore two materials were chosen, which are not meant for pressure applications. It is expected that this will deliver brittle failures within a reasonable time period. Table 5 and 6 show the results of the combined loading tests on these materials.
At 80 C the relaxation is much quicker and hence bending stresses should have even less effect on the total stress than in case of a 20 deg C test

Table 5. Tests on PE special grade (Wavin M&T laboratory)

ID	(δ/d) [%]	Stress [MPa]	Failure time [hrs]	T [C]	Stress [MPa]					
					1	**2**	**3**	**4**	**Total crown**	**Total springline**
1	0	4.5	293.30	80	4.5	0	4.5	0	4.5	4.5
2			1082.30	80						
3			1468.80	80						
4	5	4.5	717.10	80	4.3	6.5	4.7	1.6	10.8	6.3
5			1091.10	80						
6			1191.70	80						
7	10	4.5	924.50	80	4.5	12.9	5.0	7.4	17.4	12.4
8			984.50	80						
9			1160.60	80						

The materials used in tables 5 & 6 are materials that are not used for pressure applications. These materials were selected to investigate the effect of failure type on the performance in combined loading.

All failures were of the brittle type. Brittle failure requires less strain development. From the results in table 5 we get the first indication that pipes loaded in a combined manner, cannot develop the same (creep) strain as those that are tested in the standard internal pressure test. In literature 7 the same conclusion was drawn from FEM analysis.

Table 6. Test on PE80 pipes. The PE material is a non-pressure pipe material (BP and GPS UK laboratory)

ID	(δ/d) [%]	Stress [MPa]	Failure time [hrs]	T [C]	Stress [MPa]					
					1	**2**	**3**	**4**	**Total crown**	**Total springline**
1	0	4.0	143.08	80	4.0	0	4.0	0	4.0	4.0
2			271.40	80						
3			234.13	80						
4	12.5	4.0	143.11	80	3.5	16.2	4.6	9.2	19.7	13.8
5			315.73	80						
6			278.90	80						

All samples failed in a brittle way. The time to failure of the pipes loaded either by internal pressure only or by combined loading are about the same. For brittle failures less strain is developed. Materials that develop ductile failures (table 4) showed to profit from a deflected pipe. Materials that develop brittle failure (tables 5 & 6) do not profit nor suffer from a deflected pipe. It shall be emphasised that the materials used in table 5 and 6 are not used in pressure applications.

Comparison of the time to failure shows that combined loading does not shorten the time to failure. The calculated combined stress however shows that there is a big difference in stress between the combined loaded pipe and the pipe only internally pressurised.

Next to PE also PVC is used for pressure pipes. PVC pipes have been used since the 1950's.

Nowadays, modern PVC's can be produced in an advanced way, by orientation of the molecules. Therefore it was decided to check if combined loading would have an effect on the time to failure of these pipes.

Table 7 shows the results

Table 7: Results for bi-axial oriented PVC pipes. (Wavin M&T laboratory)

ID	(δ/d) [%]	Stress [MPa]	Failure time [hrs]	T [C]	Stress [MPa]					
					1	2	3	4	Total crown	Total springline
1	0	26	51.40	60	26	0	26	0	26	26
2			79.50	60						
3			91.70	60						
4	5	26	253.40	60	24.6	3.44	27.3	3.27	28.1	30.6
5			283.40	60						
6			383.10	60						
7	10	26	633.64	60	23.3	6.9	28.6	3.9	30.2	32.5
8			646.81	60						
9			659.00	60						

The results show that the higher the deformation is, the longer it takes before failure occurs. The type of failure for these pipes is ductile in a way that before final failure, huge strain is developed.

From the results shown for thermoplastics (PE and PVC), the following can be concluded:

- The traditional way of combining stresses from internal hydrostatic pressure and external load, is not valid for the prediction of the time to failure.
- For materials failing in a ductile manner, deflection improves the time to failure.
- For materials failing in a brittle way, deflection has no effect on time to failure.
- The most severe loading condition for a thermoplastic pipe, is the loading condition where the pipe is free to expand, like in internal hydrostatic pressure testing. Such a condition is only present in real practice when the pipe is installed in peat.
- The failure processes are not accelerated by deflection of the pipes.

4.2 Tests on bent pipes

When pipes are bent combined with internal pressure, axial stresses and strains are developed. Here the load is also a prescribed displacement. That means that the stresses again relax in the course of time.

Prof. Wintergerst has performed several tests in which internal pressure was combined with bending stresses and strains. (lit.3)
A pipe is bend over a pre-shape curvature. That means that the pipe is bend to that curvature (R). By bending the pipe also deflects to a value of (δ/d). The strain at the outer fibre is the distance from the neutral axis to the outer fibre divided by the curvature R.

The following formulas apply:

Pipe ring deflection as a result of axial bending of the pipe can be expressed by:

$(\delta/d) = 1/16 * (d/s)^2*(D/R)^2*(1-v^2)$ ……………………… (12)

This ring deflection results in a hoop bending strain described by:

$\varepsilon_o = 3 * (\delta/d) * (s/d)$ ……………………………………(13)

The axial bending over the radius results in an axial strain of

$\varepsilon_{ax} = (D-((\delta/d)*d)/2)) / (2*R)$ ………………………(14)

In which:

(δ/d)	Pipe ring deflection due to bending	[%]
d	Average pipe diameter	[mm]
R	Bending radius	[mm]
D	Outside pipe diameter	[mm]
v	contraction coefficient	[-]
ε_{ax}	Axial bending strain	[-]
ε_o	Hoop bending strain	[-]

Wintergerst tested several PVC and PE pipes of 63 mm and bend the pipes to 17*d and 25*d for the PVC pipes. For the PE pipes he used 10*d and 25*d. The results of the internal pressure tests on straight pipes were then compared with those from the bent pipes. His conclusion is:
"For the combination of internal pressure and bending radii of 17 and 25 times the pipe diameter, no significant effect on time to failure is found for PVC." "For the combination of internal hydrostatic pressure and bending radii of 10*d and 25*d, no significant effect is found for PE pipes."
An example is taken from his test results and analysed with respect to combined loading.

Example analysis of Wintergerst result:
The graph produced by Wintergerst is shown in Enclosure 1. (lit. 3)
The PE material used is a GM51010
Pipe sample : 63 x 5.7 mm
Mean diameter Dm = 63-5.7 = 57.3 mm
s/Dm = 5.7/57.3 = 0.1
The bending radius used is 630 mm.
The ovality due to bending (from equation 13) results in a pipe deflection of 5%.
The circumferential strain (from equation 14) becomes 1.5%.
The axial strain due to bending (from equation 12) becomes 4.8%.

The circumferential stress becomes with Hookes law:

$$\sigma_0 = E(t) * \varepsilon_o \qquad (15)$$

The stresses become now for:

time = 3 min , E(3)= 900 MPa σ (3) = 13.5 MPa
time = 1 h , E(3)= 500 MPa σ (3) = 7.5 MPa
time = 200 h , E(3)= 200 MPa σ (3) = 3.0 MPa

According to Enclosure 2, short-term failure comes up at a constant tensile stress of 21 MPa. Simultaneously the bending stress is 13.5 MPa, due to bending of the pipe over a radius of 630 mm. After 1 hour with a constant tensile stress of 18 MPa failure appears. During this first hour the bending stress has relaxed from 13.5 to 7.5 MPa.

After 200 hrs with constant tensile stress of 13 MPa failure occurs. During this 200 hrs the bending stress has relaxed from 13.5 MPa to 3 MPa, etc. The total stress after 200 hrs is thus 13+3 = 16 MPa. If the bending stress of 3 MPa had had any influence on the strength of the pipe, the failure should have occurred already after 4 hrs, according Enclosure 2.

Thus the combination of loading of internal hydrostatic pressure and ring ovality due to pipe bending gives the same time to burst, as loading of a straight pipe with internal pressure alone.

Wintergerst showed that for PVC the extrapolation of the results shows that the MRS values are still above 25 MPa. For PE pipes the tests on 10 and 25 times the pipe diameter did not show any effect on the time to failure. This work was carried out in 1973. During the last 30 years, great improvements both in the field of raw material development and processing have taken place. Additional tests were performed on PVC pipes with an even smaller bending radius than used by Wintergerst.

The following tables show the results. It shall be noted that it was difficult to get failures within 1000 hrs, reason why in a few cases the stress has been increased after passing the 1000 hrs value.

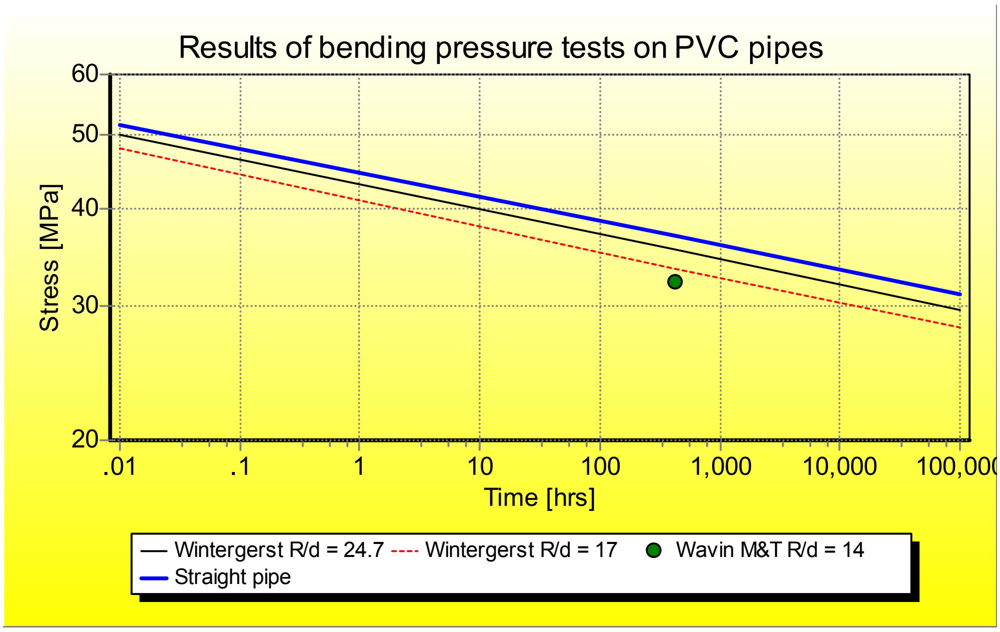
Table 8 Results hydrostatic pressure tests of 25 mm PVC pipes at 20°C. R/d = 14, (Laboratory Wavin M&T)

ID	Sample	Diam. [mm]	Wall thickn. [mm]	Test pressure [MPa]	Hoop stress [MPa]	Failure time [hours]	Failure type
1	Reference	25.2	1.99	5.522	32.2	>1674.68	*Pressure increased, ID 4
2	Reference	25.2	2.02	5.612	32.2	>1674.68	*Pressure increased, ID 5
3	Reference	25.2	1.98	5.491	32.2	>1674.68	*Pressure increased, ID 6
4	Reference*	25.2	1.99	6.800	39.1	123.85	Ductile
5	Reference*	25.2	2.02	6.800	39.1	164.35	Ductile
6	Reference*	25.2	1.98	6.800	39.1	166.91	Ductile
7	Cycle test	25.2	2.02	5.612	32.2	437.45	Ductile
8	Cycle test	25.2	1.98	5.491	32.2	>1674.68	*Pressure increased, ID 9
9	Cycle test*	25.2	1.98	6.700	39.1	11.88	Ductile

Note : Test ID 4,5,6 are the same samples as 1,2 and 3. Test Id 9 is the same as test ID 8. Test ID 7 is plotted in figure 5.

The table shows that the stresses had to be increased in order to get failure within a reasonable time. Only one result (ID=7) can be used in a straightforward comparison with the results of Wintergerst.
Figure 5 shows the results of Wintergerst to which a test result (ID=7) with a R/d =14 has been added.

Figure 5 Summary of Wintergerst test completed with characteristic result of M&T tests.



The results of the tests performed by Wintergerst are shown for two different R/d ratio's.

It is shown that ratios downto 24 do not affect the design stress significantly. R/d of 17 and 14 show to become more influential on design stress. Pipe bending radii in the field are limited to R/d = 100, which is far above the values shown before. That is why for design, combined loading does not play any role.

Wintergerst showed that PE is not affected at all by combined loading.
Table 9 and 10 shows the results of some extra tests, carried out in this work, with even smaller values of R/d with PE pipes performed at Wavin M&T.

Table 9: Results of hydrostatic pressure tests of 32 mm PE pipes at 20ºC, (Laboratory Wavin M&T)

ID	Sample	Diam. [mm]	Wall thickn. [mm]	Test press. [MPa]	Hoop stress [MPa]	Failure time [hours]	Failure type
1	Reference	32.3	3.08	1.982	9.4	>2349.65	*Pressure increased, ID 4
2	Reference	32.3	3.11	2.003	9.4	>2349.56	*Pressure increased, ID 5
3	Reference	32.3	3.12	2.010	9.4	>2349.56	*Pressure increased, ID 6
4	Reference *	32.3	3.08	1.982	10.6	*>556.00*	*Running*
5	Reference *	32.3	3.11	2.003	10.6	*>556.00*	*Running*
6	Reference *	32.3	3.12	2.010	10.6	*>556.00*	*Running*
7	Cycle test	32.4	3.12	2.003	9.4	>2633.90	*Pressure increased, ID 9
8	Cycle test	32.4	3.12	2.003	9.4	>2633.85	*Pressure increased, ID10
9	Cycle test*	32.4	3.12	2.259	10.6	*>556.00*	*Running*
10	Cycle test*	32.4	3.12	2.259	106	*>556.00*	*Running*
EN12201-2 : checkpoint 10 MPa at t=100 hrs *Note : Stress has been increased to obtain failure anyway*							

Table 10: Results of hydrostatic pressure tests of 32 mm PE pipes at 80ºC, (Wavin M&T laboratory)

ID	Sample	Diameter [mm]	Wall thickness [mm]	Test pressure [MPa]	Hoop stress [MPa]	Failure time [hours]	Failure type
1	Reference	32.4	3.06	0.822	3.94	>2322.03	*Pressure increased, ID 4
2	Reference	32.4	3.06	0.822	3.94	>2322.03	*Pressure increased, ID 5
3	Reference	32.4	3.06	0.822	3.94	>2322.03	*Pressure increased, ID 6
4	Reference *	32.4	3.06	0.960	4.6	*>556.00*	*Running*
5	Reference *	32.4	3.06	0.960	4.6	*>556.00*	*Running*
6	Reference *	32.4	3.06	0.960	4.6	*>556.00*	*Running*
7	Cycle test	32.3	3.08	0.831	3.94	>2561,44	*Pressure increased, ID 9
8	Cycle test	32.3	3.08	0.831	3.94	>2561,61	*Pressure increased, ID 10
9	Cycle test*	32,3	3.08	0.970	4.6	*>556.00*	*Running*
10	Cycle test*	32.3	3.08	0.970	4.6	154.86	Brittle
EN12201-2 Check point : 4.0 MPa and t=1000 hr *Note : Stress has been increased to obtain failure anyway*							

From the tests it is difficult to obtain firm conclusions yet. Only one failure has been found so far, the rest is running. When comparing the results with the checkpoints as declared in EN12201-2, then the conclusion seems to be valid that PE is not at all suffering from the combination of bending and internal hydrostatic pressure and hence earlier findings by Wintergerst are confirmed.

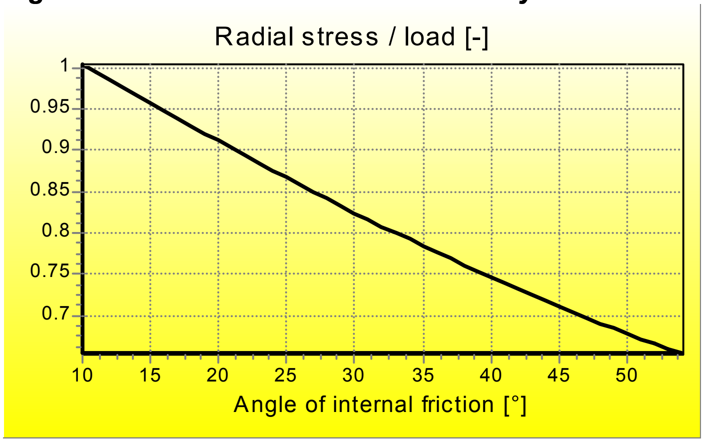
5. Pipes in soil

Thermoplastics pipes are buried in the soil. The performance of the pipes during and after installation has been extensively studied and discussed in the TEPPFA project (lit 1)
What will be discussed in this section is the performance of the pipe when pressurised after it has been buried.
Several design methods have been developed in the course of time and most of them start to calculate how a ring behaves when it is loaded by a certain external load distribution. In this section the aim is not to discuss the existing methods. In this section some understanding of what happens with the pipe in the ground will be discussed. For that purpose use will be made of a model proposed by Hoeg in 1968. (lit. 8)
It is a model where a cylinder is buried in a soil envelope. That soil envelope is loaded by the free field stresses and the response of the soil and the pipe can then be calculated. His model provides the opportunity to consider free slippage and non-slippage of the soil on the soil-pipe interface.
In this section the model will be used to calculate the external hydrostatic pressure on the pipe. The external hydrostatic pressure can be calculated and depends for a great deal on

the angle of internal friction of the soil. For peat soils this angle is about 10 ° and for gravel soils the angle can become close to 50 °.

In figure 6 the amount of external pressure as a function of soil friction angle is illustrated.

Figure 6 Relative amount of external hydrostatic soil pressure acting on the pipe.



What can be seen here is that for a friction angle of 40 ° the external hydrostatic pressure is about 75% of the external load. In case the pipe is buried at 2 meter depth, this load is 0.04 MPa. When a pipe is pressurised with a pressure of 0.8 MPa, then the effective internal pressure for the pipe design is 0.76 MPa or 7.6 bar instead of 8 bar.

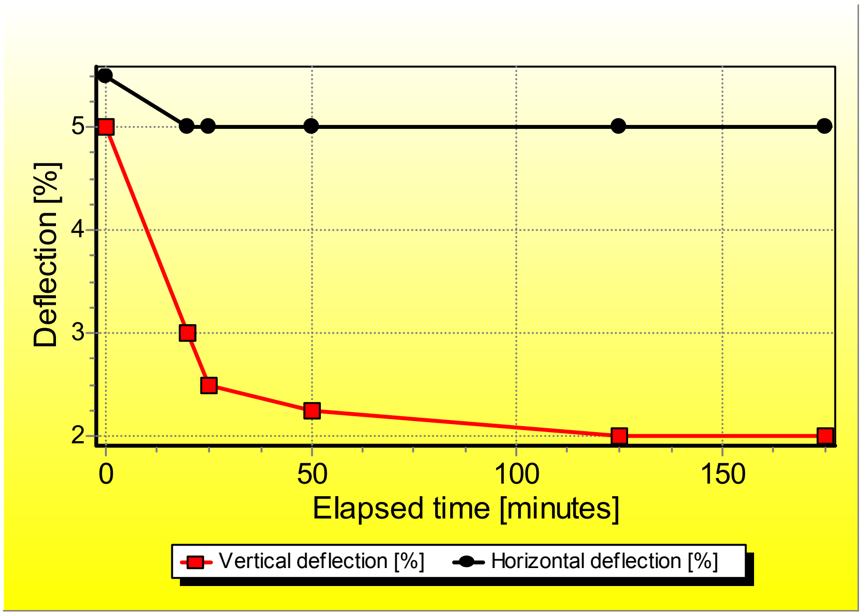
In peat, the hydraulic pressure equals more or less the external load.

Flexible pipes might deform slightly when buried in soils. In figure 1 one can easily read to what extent pipes are about to deflect.

When the pipe is pressurised, re-rounding likes to take place. The vertical diameter will increase by pressing into the soil and the horizontal diameter will decrease. The material however will also elongate. In order to elongate, the circumference of the hole in the soil has to become bigger. Doing so means, that the soil develops passive soil resistance. The pressures are so high, that it limits the complete re-rounding and also limits the full free extension of the pipe diameter. As a result, the pipe material cannot develop the full wall stress and hence will not become in a condition of full free creep. The above situation is valid for pipes buried in firm soil. When pipes are buried in soft soil however, full re-rounding will take place and the full free creep stress being developed. This is in accordance with the internal hydrostatic pressure testing.

In figure 7 results of a re-rounding test are given.

Figure 7: Re-rounding test on PE SDR26 pipes at the Wavin test site "Hammel" Denmark.



The internal hydrostatic pressure was 6 bar. The graph shows that the vertical deflection is much more affected by the pressure than the horizontal diameter. The vertical deflection decreases from 5 to 2 % deflection and the horizontal deflection only changes with 0.5 %. What happens is that the diameter of the pipe extends slightly. That extension is used to make up the vertical diameter increase. The horizontal diameter does hardly change, which is also logical. When the horizontal diameter has to become smaller, it has to act in the opposite direction as the internal pressure. If full re-rounding doesn't / cannot take place, such being the case in firm soil, full creep is excluded.

Currently, most design methods in Europe have not considered the combination of internal and external hydrostatic pressure. Recently, two options have been developed in CEN TC164/165 JWG1, called option 1 and option 2.
In Enclosure 1 example calculations are shown. Option 1 seems to consider the external hydrostatic pressure to some extent, whereas option 2 just seem to add the tensile bending to the tensile hoop stresses. The difference in result between both options is astonishing. Where option 2 shows a total stress of 12.6 MPa, option 1 shows a value of 6.6 MPa for the same case.

6. Discussion

Combined loading tests have been performed to find out to which extent the effect of external loading affects the time to failure. The tests performed can be considered as rigorous and present worse case conditions. The test chosen is a parallel plate loading, where the pipe is deformed up to high deflection levels by which bending strains and stresses are created. In real life, pipes will reround to some extent when pressurised. In the parallel plate loading test, the re-rounding cannot take place. In practice however the pipe is embedded in soil. Next to the fact that the pipe deflects due to the non-axisymmetric portion of the soil pressure, it also experiences radial soil pressure. The latter balances the stresses due to internal hydrostatic pressure to some extent. In the test this is not the case.

Some of the deflection levels used are significantly higher than in reality. Pipes having stiffness of 8 kPa and higher will not deflect to levels of 10%. In the test, these levels have been used as well.

It has been shown that stresses caused by internal hydrostatic pressure cannot be added to those induced by external load for the determination of the time to failure. A thermoplastic material does not follow the same rules as those of the traditional elastic materials. The features responsible for this, are the huge strainability of the thermoplastic materials and the stress relaxation phenomenon. An analysis showing the effect of stress relaxation is shown in literature 6.

The above means that for design one cannot use the traditional approaches as valid for elastic materials.
For thermoplastics one need to carry out a two step approach. The pipe shall be designed solely as a gravity pipe and as a pressure pipe. It shall be checked which of the two is the decisive one and dimensioning should be based on that.
The TEPPFA graph can be used as a simple way to design a pipe under gravity condition. However, in Europe several methods exist that claim to predict the pipe performance as well. Even if one of the European structural design methods is used, it is still good practise to check the result against the earlier mentioned TEPPFA graph.

In the thermoplastics industry, the use of a so-called overall design coefficient has become a common approach. These factors cover the traditional safety factor against overloading and the effects of handling and storage. The whole design of pressure pipes for the pressure component is based on test results from free creeping pipe samples under internal pressure. Considering the fact that pipes which are deformed show the same or a better performance under internal pressure than those without deformation, and the fact that pipes which stay deformed in the ground cannot fully expand, it can be concluded that the whole design is very conservative. Therefore in reality, the actual level of the factor of safety is much higher than assumed for the design of the pipe.

In literature 6, exercises with the cumulative damage theory have been performed, analysing the effects of point loading on different types of PE. There it was shown that the speed of relaxation is of significant importance for the lifetime of the pipe. A high relaxation speed favours a long lifetime. Limiting or preventing full creep is in that respect as important.

7. Conclusions

Thermoplastics pressure pipes, such as those made out of PE and PVC, shall be designed in the following way:

1. The pipe shall be considered without pressure and with a surge pressure of –0.8 bar, as required in EN805. The design shall be based on buckling resistance.
2. The pipe shall be designed as for a free creeping condition. The value to refer to is the Hydrostatic Design Stress (HDS). The HDS is the stress referring to the Minimum Required Strength (MRS) of the raw material using the Overall Design Coefficient C as given by the product standards.

In product standards of thermoplastics the relation between PFA and PN is given by:

$$PFA = ft*fa*PN \tag{14}$$

The values of ft (temperature rating factor) are very much material dependant, reason why they are mentioned in the product standard. The value for fa can be set to 1 when the following conditions are fulfilled:

- Deflections are limited to 12.5 %
- Bending radii are R/d > 50 * d for PVC as well as for PE in case of cold bend pipes
- Water, gas or sewage is transported. In case of chemicals advice shall be sought at the manufacturer, because certain chemicals might affect the strength of the material.

F.J.M. Alferink
2003-07-03

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Enclosure 1: Example calculations for combined loading using option 1 and option 2 as under development in CEN TC164/165 JWG1

An example is given for a PE80 material with a HDS of 6.3 MPa.
Further details:

- Depth of cover 1.2 meter
- Soil type group 4: fine grained soil, slightly cohesive.
- Diameter : 315 mm
- Wall thickness = 19 mm
- Internal pressure = 0.8 MPa

For reason of demonstration the options 1 and 2 as their current status is reflected in EN1295-3, are used.

Condition / method	**defl st [%]**	**defl lt [%]**	**Total stress short term [MPa]**	**Total stress long term [MPa]**
Product standard	2.5	5.0*	6.3	6.3
Option 1 – no traffic	1.6	2.1	6.4	6.4
Option 1 – traffic	5.4	5.1	6.7	6.6
Option 2 – no traffic	1.4	3.5	10.3	8.5
Option 2 traffic	4.1	9.9	17.9	12.6

* note : The long term deflection incorporates the effect of traffic load.

From the example it is clear that both options combine the stresses in a different way.
Option 2 seems to add just the stresses, whereas option 1 considers probably the external hydrostatic pressure as well. Traffic load has a considerable effect on deflection in both options. In option 2 also the stress is affected enormously by traffic load.

It is strongly recommended to avoid the use of option 2 and to a lesser extent the use of option 1 for the design of thermoplastics pressure pipes.

Enclosure 2. Wintergerst results on PE pipes

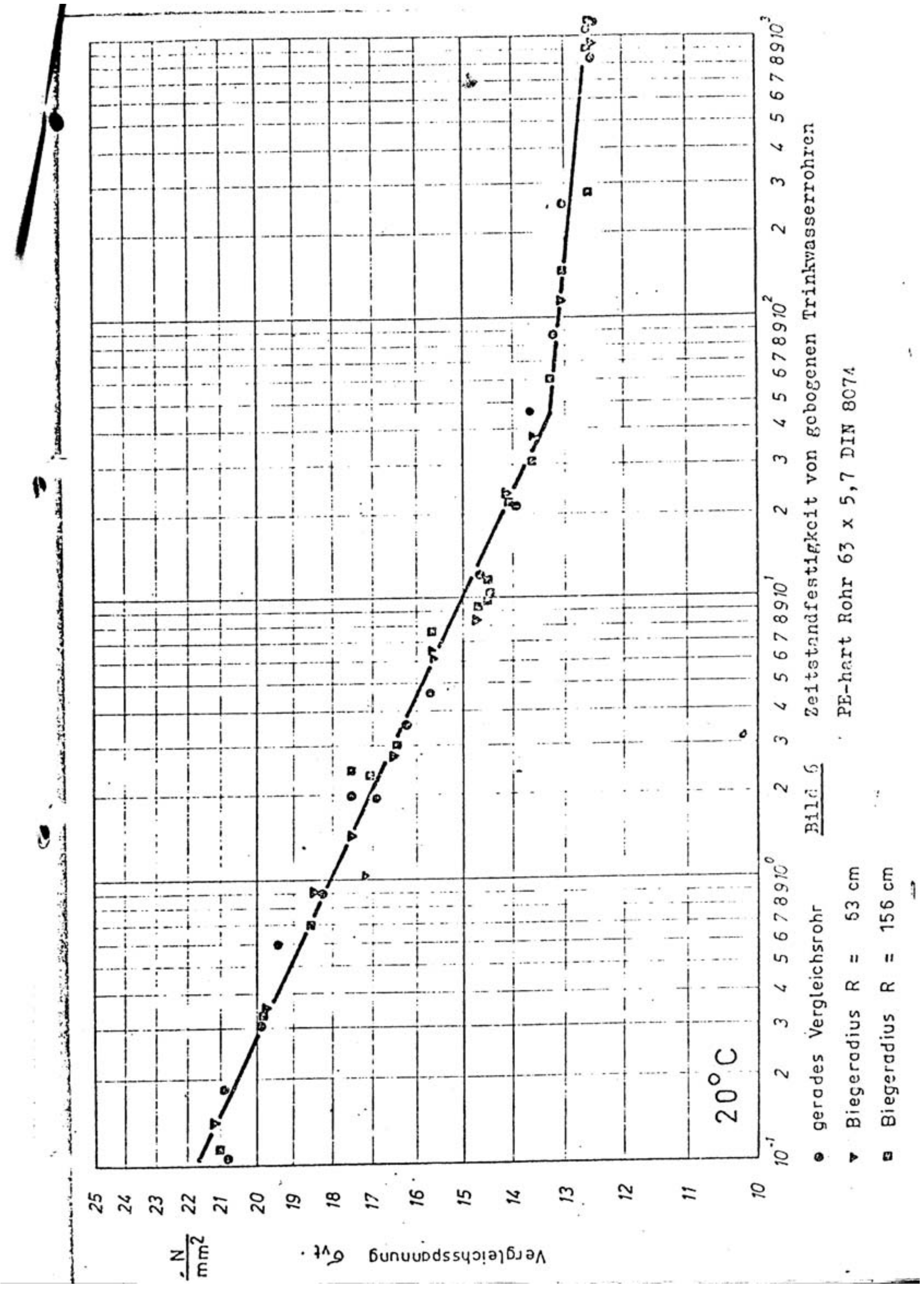

Bild 6 Zeitstandfestigkeit von gebogenen Trinkwasserrohren

PE-hart Rohr 63 x 5,7 DIN 8074