FLEXIBLE PIPES FOR NEW BURIED PIPELINES AND REHABILITATION OF EXISTING ONES

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1. INTRODUCTION

Healthy pipelines supplying clean water and disposing of dirty wastewater are essential for healthy living, especially in South Africa's high density urban areas. The demand for these essential services resulting from the rapid urban densification in South Africa has not been met. In addition to this the focus on supply, rather than ensuring that the wastewater disposal matches the fresh water supply to prevent an accumulation of wastewater within these high density urban areas has not been done, resulting in unhealthy living conditions.

In many established urban areas, this densification means that the water services installed to meet the requirements of stands with single dwellings, are not adequate when multiple dwellings or townhouse complexes are these stands. In addition, many of the informal and semiformal areas developing around the urban areas have inadequate water services, in particular for wastewater. Installing water services in trenches in both situations is a problem because there is not the space to do so. When trenches are dug it causes disruption and costs to residents and businesses, and implications are seldom considered. The alternative is to use trenchless techniques as these minimize disruption and can be done at lower cost when trenches are deeper that 1,0 to 1,5 m. These techniques can be used for installing new as well as rehabilitating existing services.

The are four basic technical factors to consider when designing new pipelines and the rehabilitation of existing pipelines. The primary function is always hydraulic performance. The secondary supporting requirements are structural integrity, water tightness and durability. Although these secondary requirements are closely linked the one that generally results in serious failures is structural integrity. There are similarities and differences in determining the structural requirements of new buried flexible pipelines and linings to rehabilitate existing pipelines. With buried pipelines there is interaction between the pipeline and the surrounding soil; when rehabilitating pipelines, it is interaction between the liner and the host pipe.

Although the focus of paper is on the structural factors, the others are addressed briefly as they influence each other. An additional fact to address is that many wastewater pipelines needing rehabilitation are made from rigid materials. Hence the need to understand the differences between the properties of rigid and flexible pipes.

In addition to pipes, pipelines consist of joints, fittings and appurtenant structures. The properties of these addition items must be considered when designing pipelines or linings. This is beyond the scope of this paper.

2. BASIC PRINCIPLES

The basic theory covered is applicable to both buried pipelines and pipeline linings. Both can be subjected to internal and external pressures. As far as internal pressure is concerned the same approach is used for all pipe materials and the way they are classified. However for external loads this is not the case, as the buried pipeline is supported by the surrounding soil, whereas the lining is supported by the host pipeline. Due to this difference there is the potential for confusion, hence this paper also addresses this issue as there are differences between the critical external loads on buried pipelines and pipeline linings.

Before a new pipeline is designed and installed the site conditions need to be established. When an existing pipeline needs rehabilitation, its condition first needs to be established before deciding on what needs to be done so that the liner is designed to meet these requirements. This assessment should include evaluating the hydraulic performance of the pipeline as well as the condition of the pipes.

2.1 Hydraulic requirements

There are differences between the hydraulics of pipelines flowing partly full under gravity and full under pressure. The energy level above the invert of a gravity pipeline has two components, the depth of flow and the velocity head, whereas this energy level for a pressure pipeline consists of three components, pipe diameter, velocity head and pressure head. Ideally a pipeline should be designed throughout its length to operate as either a gravity or pressure system, with no sections where the flow changes from being partly full to completely full as this can seriously affect the hydraulic performance. The implications of these differences also needs to be considered in the structural design of both pressure and gravity pipelines. For gravity pipelines, such as stormwater drains or sewers, which flow party full the pressure component falls away and there is an air/water interface within the conduit.

2.2 Structural requirements

At times, the term strength is loosely used. A clear distinction should be made between the structural property of a material, expressed as stress and the structural property of a product, expressed as strength. Stress is the load a material can handle per unit area, whereas strength is the load that a product made using this material can handle. The product strength is a combination of the material stress and the product's sectional properties.

By way of example the long term (50 yr.) tensile stress that the material polyethylene (PE100) can safely handle in direct tension is 8 MPa. A 630 mm outside diameter pipe with a 30 mm wall can handle 0.8 MPa (8 Bar) of internal pressure. By reducing wall to 15,4 mm the stress the material can safely handle is still 8 MPa, but the pipe strength is reduced so that it can handle only 0,4 MPa (4 Bar) of internal pressure.

Material properties, whether direct or flexural are determined by testing samples and then calculating the stress. The units usually used are MPa, kPa Pa or Bar. For pressure applications the unit of a Bar is frequently used as this for all practical applications is equivalent to the atmospheric pressure.

A structural product's strength to handle external load is usually expressed as the kN. For products, such as pipes, that are tested the strength is usually expressed as kN/m of length/m of diameter. This provides the means of classifying them, irrespective of size, in consistent terms, such as pipe stiffness (PS) pipe nominal stiffness (NS) or pipe ring stiffness (PRS) for flexible pipes or as diameter strength (D load) for rigid pipes.

2.3 Water-tightness

Older pipelines consisted of pipes that were jointed and installed in excavated trenches that were then backfilled, so their performance is dependent upon the pipes, the joints, the material through which the trench is dug, the bedding and the backfill material. Pipelines should be installed so that they are water-tight and will remain so, to ensure that the hydraulic performance and structural integrity are not compromised. As bedding material is generally cohesionless it is more permeable than the material through which excavations were made. This means that any groundwater in the vicinity will flow into and follow route of the backfilled excavations. Provided the pipeline is water tight this will not cause a problem as the flow through this material will be slow.

A serious problem arises if there are leaks and the associated infiltration carries solid material through the defective joints into the pipeline. This can be initiated when there are poor and variable founding conditions causing settlement and joints between pipes opening and no longer effectively being sealed. When an internal multisensory inspection indicates ponding due to sagging, a check should be done on the joints between pipes to determine the extent of problems and measures to effectively seal these joints before any rehabilitation.

This problem is progressive as the flow path developed either side of the pipeline results in the loss of bedding and backfill support, and the size of cavities that can form around the pipeline over time. Eventually the size of a cavity becomes so large that it can daylight as a sinkhole. In an urban area this has very serious consequences as it means that transportation routes have to be closed and buildings evacuated.

2.4 Durability

Although structural, leakage and hydraulic problems usually occur where caused, corrosion problems do not necessarily occur where expected. They are influenced by the effluent properties and on cementitious sewers are frequently due to upstream hydraulic conditions, where there are flat sections of sewer, siphons and rising mains fed by pump stations. The gas hydrogen sulphide (H_2S) gas is generated under these sections and then released downstream when the velocity increases. The rate at which H_2S gas is released increases with velocity and is biologically converted to suphuric acid (H_2SO_4) on the sewer walls. This reacts with the cementitious material that is alkaline, resulting in corrosion and material loss above the flow line, but not below the water line. Hence the corroded sewer no longer has a circular profile, but a 'mushroom' shape with a loss of strength.

3. STRUCTURAL REQUIREMENTS

With buried gravity pipelines when empty or flowing partly full the external imposed loading is from the earth and traffic. For flexible pipes this deflects the pipeline vertically resulting in it deforming horizontally and being pushing into the surrounding soil. Passive pressures are developed enabling the pipeline to carry loads greater than an unsupported pipeline could carry. The pipe must have sufficient stiffness to ensure that it will not deform excessively into a vertical ellipse during embedment compaction.

For rigid pipes this deflection is for all intents zero, so under installation conditions the pipeline will settle less than the surrounding bedding or soil, thus attracting more load than that from the material directly above. Rigid pipes are assisted in carrying the imposed loads by their bedding. When the assistance of the surrounding embedment or bedding support is taken into account the actual load on a rigid pipeline could be almost an order of magnitude greater than that on a flexible pipeline under the same fill height.

Structurally a flexible pipe, in combination with the surrounding embedment, needs the stiffness required to prevent excessive deformation under imposed load. A rigid pipe on the other hand, in combination with the bedding support, needs the strength required to carry this load. When a rigid pipe is reinforced, it has some flexibility and will deform slightly under load, but not sufficiently to change the structural requirements.

When a flexible pipe is used to rehabilitate a structurally sound gravity pipeline, the loading is the ground water pressure between the host pipe and the liner. The lateral deformation of the liner is constrained by the host pipe, which enhances the ability of the liner to withstand the buckling forces due to this pressure, but not in the same way as the embedment does when the pipeline is installed in the ground. The most serious buckling is that at the invert as the water pressure is greatest there. If the pipeline to be rehabilitated is no longer structurally sound and collapse imminent, the lining must be designed to handle external water pressure and earth loading.

With a pressure pipeline, not subject to dynamic effects, the two loading cases to consider are when the pipeline is empty and when it is in service operating under pressure. In the former the loading is the same as that for the empty gravity pipeline. In the latter, unless the operating pressure is very low, the internal pressure will be much greater than any ground water pressure and cancel out any potential buckling effects. The liner is designed to cope with bucking effects of ground water pressure when the pipeline is empty and internal pressure when the pipeline is operating under pressure.

A critical issue when a pipeline deforms under load is the impact of this could have on the hydraulic performance and the water tightness of the joints.

3.1 Differences between types of pipes

In broad terms pipes are classified as being rigid or flexible. When dealing with pipeline rehabilitation most pipelines requiring rehabilitation are rigid and the linings are flexible, so there needs to be an understanding of how the two interact structurally.

The structural properties of thermoplastic and thermoset pipes or pipe liners, irrespective of their ND or material properties can be expressed as their pipe stiffness (PS) where the test load applied increases in direct proportion to the nominal diameter (ND). The relation between test load and PS is covered in various standards based on the parallel plate testing of pipes given in SANS 791 as per equation (1). This is a physical model.

$$PS = \frac{F/L}{\Delta y} \times 1\,000 \qquad (1)$$

Where: PS is the pipe stiffness, in kN/m/m (or in kPa which is frequently used);
F is the force applied, in newtons;
Δy is the measured change in distance between plates at a specified % compression, in millimetres;
L is the length of specimen, in millimetres.

In principle this equation could be applied to both flexible and rigid pipes, as it does not consider the material properties. The difference is that in the case of pipes with some flexibility the load at a given deflection is measured, whereas with rigid pipes that are not reinforced the load when the pipe collapses is measured. When necessary to test a product the test load is needed this equation can be arranged as:

$$F = PS \times L \times \Delta y/1000 \qquad (2)$$

The units have been changed from those used in SANS 791 to those commonly used for structures. This formula can be used for any pipe material, bearing in mind that the value for Δy may change depending on the material. Lining materials are generally either flexible as with fold and form, or semi-rigid as with certain CIPP linings.

If these equations are applied to non-reinforced rigid pipes the Δy at collapse load will in effect be zero (probably less than 0,01%) making this an impractical to assess the performance of these pipes. These equations could be applied to reinforced rigid pipes where the procedure is to measure the load at a given crack width, taken as the serviceability limit, or at collapse load where there would be some deflection.

3.2 External loading on the pipes under installed conditions

Under installed conditions the total external load will be due to fill and traffic loads. The installed load will vary significantly depending on the installation conditions which could be under an embankment in a trench or in a tunnel. The installed load will deform the pipeline into a horizontal ellipse and this load is calculated based on the external diameter of the pipe. This load will be less than or equal to the test load multiplied by a bedding factor. This bedding factor for a well bedded flexible pipe depending on the bedding angle will be between 10 and 15. The corresponding bedding factor for a rigid pipe such as concrete will generally range from 1,5 to 2,0.

As flexible pipes will deform more than the compacted backfill either side of them the fill load on them will generally be less than the load directly above them, which is called the geostatic load. The geostatic load is calculated from the material mass directly on top of the pipe which is the pipe outside diameter x soil density x fill height. So the load per m^2 under 1 m of fill with a density of 20 kN/m^3 will be 20 kN/m^2.

Both rigid and flexible pipes when subjected to internal pressure will expand and hoop tensile stresses will develop in the pipe wall. Pressure pipelines need to be designed to handle this internal pressure when in operation, but will also need to be designed to handle the external loads when empty.

3.3 Deflection of pipes under installed external loading

The structural parameter used to evaluate flexible pipes under installed conditions is their stiffness to resist deflection. This is taken as the long term value that can be expected after a few years once the soil around the pipeline has consolidated. The pipe deflection due to the imposed load is countered by a combination of soil stiffness and pipe stiffness, so these three factors have to be considered as shown in principle by equation (3).

$$\text{Deflection} = \frac{\text{Imposed load}}{\text{Pipe stiffness} + \text{Soil stiffness}} \quad (3)$$

For a rigid, or reinforced rigid pipe the structural parameter used is strength which is its ability to resist the stress in the pipe wall due to internal pressures and external loads. The required pipe strength is given by equation (4). Where the soil strength is defined as the bedding factor.

$$\text{Pipe strength} = \frac{\text{Imposed load}}{\text{Soil strength}} \quad (4)$$

For a flexible pipe the calculation is usually done using the Modified Iowa Formula as given in equation (5).

$$\frac{\delta}{ND} = \frac{T_f\ B_f W}{8 \times PRS + 0{,}061 \times F_d \times E'} \quad (5)$$

Where : δ is deflection in mm

ND is nominal diameter in mm

T_f is time lag factor

Bf is bedding factor

W is total load in kN/m

PRS is pipe ring stiffness in kN/m/m

F_d is design factor

E´ is modulus of soil reaction in kPa (kN/m^2)

Both the pipe ring stiffness (PRS) and the soil stiffness (E') must be expressed in the same units even though their orders of magnitude are different. It is important to understand that units used must be compatible, even though the former applies to the pipe strength and the latter to the soil stiffness. A table of commonly used E' values is given in Appendix A. The PRS taking into account the pipe dimensions and material properties can be calculated theoretically using equation (6):

$$PRS = (E \times I) / (D^3 (1 - \upsilon^2)) \quad (6)$$

Where : PRS is the pipe ring stiffness in kN/m/m

E is the modulus of elasticity for pipe material in kPa (not MPa as usually given)

I is the moment of inertia for the pipe wall in mm^3

D is the outside diameter of the pipe in mm

υ is the Poison's ratio

The PRS is a theoretical value that can be approximated by converting the PS determined by testing. The latter is an easy way of doing this as the test gives an actual value that is not based on the material properties or the manufacturing process. It is a practical way of determining the PRS of a profiled wall pipe. These test results can be analysed statistically and thus take into account the variability of the pipe or liner strength due to the manufacturing process, actual dimensions and material properties. The conversion of PS to PRS given by equation (7) is a close approximation adequate for most applications.

$$PRS = \frac{PS}{53,69} \tag{7}$$

An accurate value can be obtained by adjusting the parallel plate test by including dimensional details as given in equation 14 under heading 4.1. With excessive deflections the value of EI changes as the radius of curvature changes. For accepted defections of 5 or 7,5 % this is not a problem. By applying equation (5) and the PRS the pipe deflection under the installed conditions can be obtained. The difficulty is making sure that the embedment support measured by E´ is adequate and this depends on the compaction of this material. The flexible pipe will probably carry less than 10% of the load and the embedment the balance. Probably the most commonly used E´ values are those published by Amster Howard and copied from the Handbook of PVC Pipe produced by the Uni-Bell PVC Pipe Association, converted to Metric units and reproduced in Appendix A. (Approximate value of 7 MPa equivalent to 1000 psi has been used)

As shown in this Appendix the E´ value is largely dependent both on the embedment material and the degree of compaction. It is important to note the negative effect of the fines content, and in particular the clay content. The higher the plasticity and fines content the greater the compactive effort required. In addition to this when there is little or no compaction the accuracy in predicting the deflection is compromised. Bearing these factors in mind it is advisable that the E´ value should be at least 7 MPa (7000 kPa) which is achievable with the free draining selected granular materials as specified in the SABS 1200 LB or the revised SANS 2001 series. This is provided the trench widths are as specified in SABS 1200 DB or the revised SANS 2001 series: earthworks for pipe trenches calls for a minimum allowance of 300 mm on either side of small pipes. The SANS standards refer to Mod AASHTO standards for bedding compaction whereas pipe standards generally refer to Standard Proctor densities. The reason for this is that the heavy compaction equipment used for road layers should not be used in close proximity (300 – 500 mm) to pipelines

3.4 External loading on linings

As explained above, the imposed loading on buried pipelines is due to the vertical soil pressures over the pipeline that causes it to deform into a horizontal ellipse. The deformed pipeline pushes into the surrounding soil that then resists this deformation. The resultant deformation is determined from equation (5).

On the other hand the imposed loading on liners inside pipelines that are empty or partly full is due to the ground water pressure that accumulates between the liner and the host pipeline that causes it to buckle into a deformed shape with one or more lobes as the liner is constrained by the host pipe when the pipeline is empty. This water pressure is determined from equation (8) given in ASTM F 1216.

$$P = \frac{2KE_L}{(1-\upsilon^2)} \times \frac{1}{(SDR-1)^3} \times \frac{C}{N} \tag{8}$$

Where : P is the groundwater pressure in MPa at the pipe invert level
K is the enhancement factor from the existing host pipe
E_L is the long term time corrected modulus of elasticity for liner in MPa
SDR is the standard dimension ratio for the liner which is the ratio of the OD to the wall thickness
υ is the Poisson's ratio for the liner material
C is the ovality correction factor
N is a factor of safety

The ovality correction factor, C is determined by equation (9) Where q is the percentage ovality of the pipe.

$$C = ([1 - q/100] / [1 + q/100]^2)^3 \tag{9}$$

The critical buckling formula (10), where P_{CR} is the critical buckling pressure before any factors are applied is:

$$P_{CR} = \frac{24E_l I}{D} = \frac{2E_l}{(1 - \upsilon^2) \times (SDR-1)^3} \tag{10}$$

This means that equation (10) with the additional factors added can be re written as equation (11):

$$P_{CR} = \frac{24E_L I}{D^3} \times K \times \frac{C}{N} = PRS \times K \times \frac{C}{N} \qquad (11)$$

Equations (5) and (11) show that for the external loading pipelines subjected to earth loads and linings subject to external water pressure the required structural properties are determined by using the PRS.

A lining installed in a pressure pipeline during operation will expand the same way as a pipeline installed in the soil, thus developing the same flexural hoop stresses in the wall and must be designed accordingly. This means that for low pressure pipelines that the combination of the stresses due to internal pressures and external loads needs to be checked.

3.5 Lining thickness for external loading

From a lining material supplier's perspective the important parameters to know are the external diameter (OD) and the thickness of the liner. The liner OD needs to match the internal diameter (ID) of the host pipe and the liner thickness determined by rearranging equation (8) as shown by equation (12).

$$t = OD / \left[\left(\frac{2 \times K \times E_L \times C}{(1-\upsilon^2) \times P \times N} \right)^{1/3} + 1 \right] \qquad (12)$$

Where: OD is outside diameter of liner in mm

The other factors are defined below equation (8)

3.6 Liner thickness for internal pressure on linings

When pressure pipelines are rehabilitated, the lining needs to be designed for two different loading cases, for internal pressure when the pipeline is flowing full under operating conditions and for external loads as described above for when the pipeline is empty. As most aging pipelines are rigid, they have been designed to carry load, not transfer it. This means that the linings for pressure pipelines have to be designed to handle internal pressure without any assistance from the host pipelines where the liner wall thickness is calculated from equation (13).

$$t = OD / \left(\frac{2 \times \sigma}{P \times N} + 1 \right) \qquad (13)$$

Where : OD is outside diameter of liner in mm

σ is the long term hoop tensile stress that the pipe wall material can handle in MPa

P is the internal pressure in pipeline in MPa

N is a factor of safety

The internal pressure to be considered may be the maximum allowable operating pressure or the burst pressure, whichever is specified by the client. If the pipeline is structurally unsound it is recommended that the liner is designed to handle the burst pressure as if the host pipeline made no contribution to its structural properties. To design pipes that need to handle internal pressure the direct tensile stress of the material is needed and this requires doing a direct tensile test on the material.

4. CONFIRMING STRUCTURAL PROPERTIES

4.1 Test methods to model external loads

There are two test used to model the structural properties required to handle the external loading on pipes or liners. The three point bending test as shown in Figure 1 and the parallel plate test as shown in Figure 2. There are pros and cons to both of these tests and these have to be considered. From an overall perspective the parallel plate test makes sense as it is the same test as is used for the different pipe materials ranging from the flexible plastic pipes to the rigid concrete pipes. It is a simple approach to take and test a section of the whole pipe as covered by ISO 9969 as distinct from a sample taken from the circumference of a pipe. It therefore models what the pipe or lining does under installed conditions and gives the PS from which the PRS can be calculated. On the other hand the three point bending test determines the flexural tensile stress and the flexural modulus of the material itself as covered in ASTM D 790. To obtain a complete understanding of the pipe or liner properties the output from both these tests is required.

The parallel plate equipment with minor modifications can also do the three point test loading. The combined output from these two tests will provide the short-term modulus of elasticity and short-term bending stress needed for liner design as well as the PRS proving that the finished liner meets site requirements. Although many laboratories prefer to use the three point bending test, the equipment needed to do this requires a curved section of liner as shown in Figure 1 is a more sophisticated operation. However if a flat, rather than a curved sample is made and tested as per ASTM D 790 the flexural properties of the material can be obtained.

Figure 1: Three point bending test (ASTM D 790)

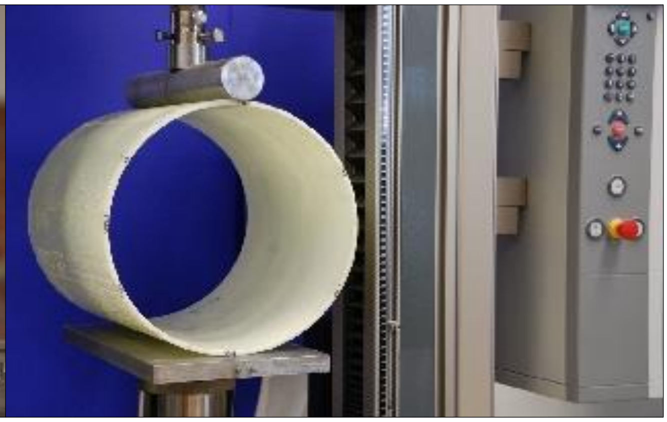

Figure 2: Parallel plate test (ISO 9969)

When pipes and liners are used in pressure applications it is necessary to determine the product performance subject to internal pressure and the direct tensile stresses of the materials used. Doing pressure tests on samples of pipes or liners needs additional equipment as described under section 4.2. The direct tensile stress of a material can obtained by adding a component to the parallel plate tester as described under section 4.3. By combining the output from these tests, all the actual material and pipe or liner properties can be confirmed, and used for the design of products for both external loads and internal pressures.

The parallel plate testing equipment can be operated in the manufacturer's own plant to do these tests and then these results periodically correlated with those done by an accredited authority.

An accurate determination of PRS is calculated by using equation (14) as given in ISO 9969, which includes the dimensional properties of the product and gives an accurate value as distinct from the approximate value as given by equation (7).

$$PRS = (0{,}0186 + 0{,}025 \times \Delta y/ID) \times (F/(L \times \Delta y)) \times 10^6 \qquad (14)$$

Where: PRS is pipe ring stiffness in kN/m/m (or kPa as used in some standards)
0,0186 is the inverse of 53,69 given in equation (7)
Δy is deflection in mm that corresponds to the specified deflection
ID is internal diameter of pipe or liner in mm
F is the force in kN that corresponds to the specified deflection
L is the length of the test piece in mm
10^6 is a conversion factor for mm/mm to m/m

The preference for the three point test is that it is easier to obtain the samples, however this is not testing the liner. The writer believes that a suitable way should be found for obtaining samples of the complete liners from site for doing the parallel plate tests. In addition, if the parallel plate tests facilities are available where the liners are manufactured, samples can be tested on the premises before being supplied to site. Statistical analysis can then show the actual structural properties and ways of reducing product costs without compromising the required product quality can be investigated.

The output from equation (14) will not be exactly the same as that from equation (6) as the former is a physical test using the actual material properties and the product dimensions whereas the latter is a mathematical model based on the theoretical material property and product dimensions. When several tests are done there will be a scatter of results which require statistical analysis, whereas with equation (6) there will be a single result.

4.2 Test method to model internal pressures

The factory test for internal pressure is just a duplication of what actually occurs under installed conditions. The only difference is that it is over a pipe length rather than the pipeline length. This means that there needs to be a means of restraining the ends to contain the pressure. Some standards do not allow restraining of the endcaps as it influences the way the pipe is behaving. So this can either be done by having thrust bocks or test heads that are tied together with bolts to contain the pressure as shown diagrammatically in Figure 3. The test heads must have a compressible material fitted to them that will act as an effective seal. The Pressure applied is obtained by rearranging equation (13) and excluding N is given in equation (15).

$$P = (2\sigma \times t) / (OD - t) \quad (15)$$

Where σ is the short term hoop tensile stress that the pipe wall material can handle in MPa

It is important to note that when dealing with external loads that the product strength is dependent upon the wall thickness to the power of three, as shown in equations (11) and (13) where the term $(SDR - 1)^3$ is used. But when dealing with internal pressure where the required product strength has a linear relationship to the wall thickness, as shown in equations (13) and (15). This means that even though thin walled pipes or linings may be quite capable of taking high internal pressures, due to the high direct tensile stress that the materials can handle, their ability to take external loads when empty must always be checked.

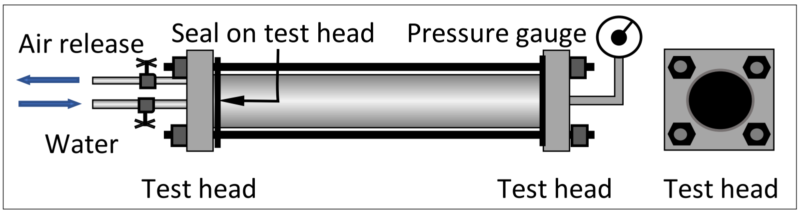

Figure 3: Hydrostatic pipe test between test heads

4.3 Direct tensile testing

Direct tensile tests of liner and plastic pipe materials are done on samples made in a “dog bone” shape. This testing is covered by ASTM D 638. The purpose of the dog bone shape is to help direct the stress/strain to the narrowest part of the specimen (the gauge section). The sample has a shoulder at each end and a gauge section in between. The shoulders are wider than the gauge section so that when the sample is loaded with a tensile force that the stress concentration occurs in the thin middle section. To avoid these problems standards such as ASTM D 638 specify different dimensions and shapes depending on the materials being tested.

Testing of plastics as per ASTM D 638 using “dog bone” specimens is used to obtain material properties by measuring the forces required to pull a test specimen to its specified strain value and then its breaking point. This output enables product designers and quality managers to predict the product performance for end-use applications. This information is critical for developing new products, ensuring compliance with standards, improving manufacturing efficiencies and reducing production costs.

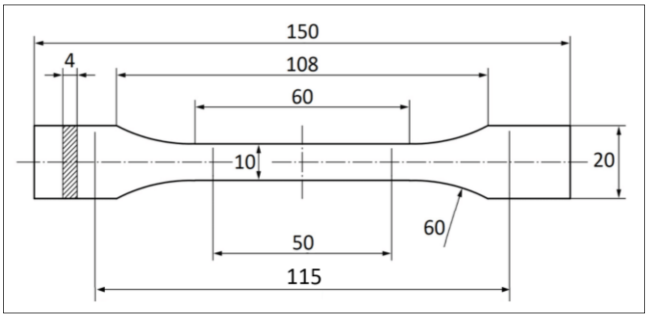

Figure 4: Typical dogbone sample

Test speed is specified and an extensometer is used to measure and record the amount by which the specimen stretches. The test data provides material properties such as ultimate tensile strength, yield strength, elongation and reduction in area, and the information to calculate the Young’s modulus and Poisson’s ratio for the material.

5. STATISTICAL ANALYSIS

By analysing test results using statistical techniques such as the Normal distribution or small sample distributions gives both the average values and the variability of the material or product property being measured. A typical distribution is shown in Figure 5. This can be used to show the effectiveness of the manufacturing process and whether the quality control measures taken are adequate. Accepting the average results gives a false impression as this does not give a true picture of the variability in the material or product properties and whether or not the minimum requirements are being met. From the end user’s perspective the minimum value is the critical value, as this shows that the product has the strength to meet the maximum in service requirements. From the manufacturer’s perspective in addition to obtaining the minimum value, the variability of the results is important as this shows how effective the controls are during the manufacturing process.

On construction projects it is usually acceptable when 95 % of the samples tested meet the specified value. In other words with the Normal distribution the 90 % confidence limits plus the 5 % tail that is greater than this.

For large samples (≥ 30) the Normal distribution is applicable, but this is impractical as the number of samples available are generally much smaller than this.

For the Normal distribution the values calculated are :

- Mean x which is the average value
- Standard deviation σ which is a measure of the scatter
- The variance υ which is a measure of control and equal to σ/x
- The 95 % confidence limits are x ± 1,96 σ

For the Normal distribution a 2,5 % tail means that 97,5 % of the samples are acceptable. So for 97,5 % of the PRS results at yield to be acceptable means that 1,96 x standard deviation less than the mean must be greater than or equal to the specified minimum value of the required PRS, or any other structural property as the flexural modulus, flexural stress or tensile stress.

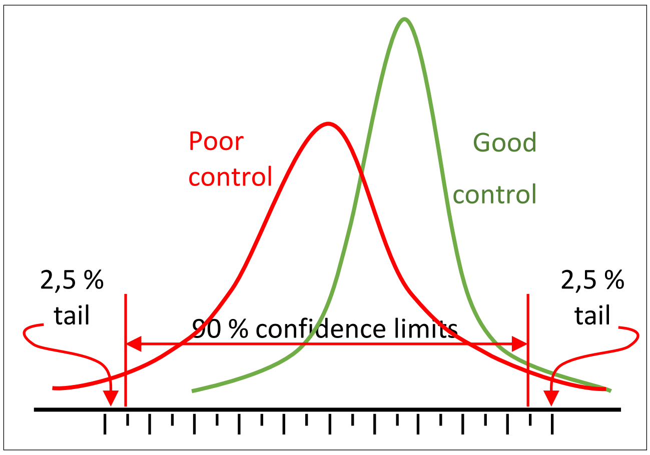

Figure 5: Statistical distributions

In practice, as the number of samples required to use the Normal distribution is impractical, the Student's 't' or another small sample distribution will be used. For smaller samples a 5 % tail, in other words a 95% pass rate is generally accepted. Instead of standard deviation the variability is now termed the standard error. For the Student's 't' distribution the values calculated are :

- Mean x which is the average value
- Standard error 's' which is a measure of the scatter
- The variance υ which is a measure of control and equal to s/x
- The 90 % confidence limits are determined by the number of degrees of freedom = sample size less 1.

So for a sample size of 7, there will be 6 degrees of freedom and the 90 % confidence limits will range from x – 1,943 s to x + 1,943 s. This is almost identical to the 95 % confidence limits for the normal distribution. When a limited number of samples are available for testing that there should be at least 7. As the number of samples decreases the measure of scatter for a given confidence limit increases giving a less reliable answer.

By plotting routine material or product test results on a graph showing the upper and lower confidence limits is an effective means of evaluating the variability of material or product quality over time. A typical control sheet using this approach is shown in Figure 6.

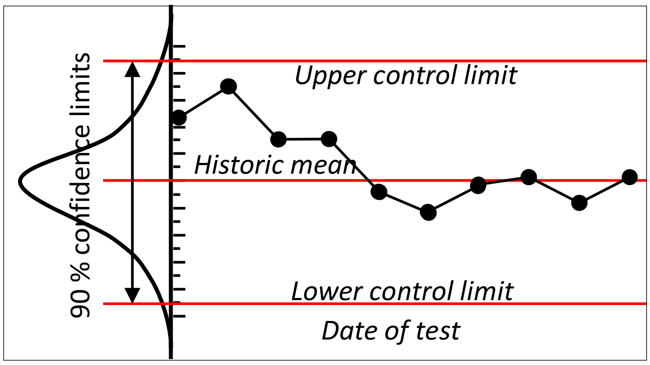

Figure 6: Control chart

The distribution to the left of the vertical axis would be the historic record. The actual results for a period are plotted and their values in relation to the historic mean and control limits evaluated. This will show whether or not the results are remaining within the control limits and by plotting a trend line it can be seen whether there is an upwards or downwards movement in the results. Although the plot on Figure 6 shows that the results are within the control limits, there appears to be a downward trend and this indicates a potential problem and that the reason for this needs to be investigated.

5. VALUE OF TESTING LINERS AND MATERIALS

The value of testing materials and the products made from them is that their actual structural properties and their variability can be determined. This also justifies the magnitude of safety factors. A clear distinction must be made between the material properties and product properties made from these materials as shown by the results of the different tests undertaken.

There must also be a clear distinction between doing routine testing ensuring that the specified product or material values are met and developmental testing where the actual product or material properties over their full performance levels to collapse are done so that realistic safety margins between specified and ultimate structural properties can be established.

Typical curves of the flexural stress strain relationships for non-rigid pipes are shown in Figure 7.

- Curve a: Specimen breaks before yielding
- Curve b: Specimen yields then breaks before 5% strain limit
- Curve c: Specimen neither yields nor breaks before 5% strain limit

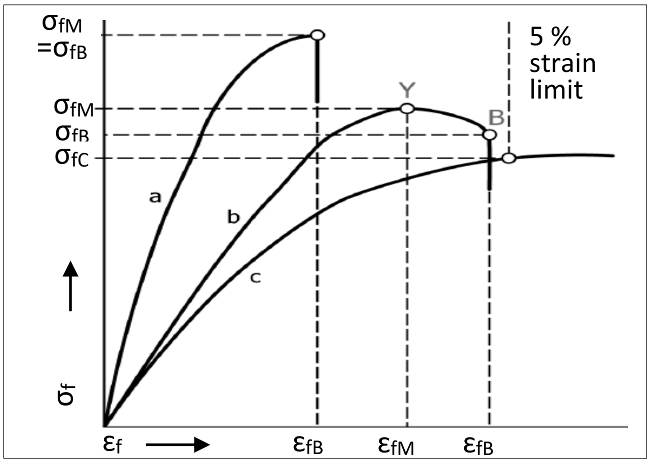

Figure 7: Flexural Stress (σ_f) Versus Flexural Strain (ε_f)

When choosing a lining material the potential for deformation after installation must be taken into account. This set of curves is also applicable to the stiffness performance of liners or pipes made from the various materials. If the rehabilitated host pipeline will be subject to movement once back in service if the original joints were inadequate or there are chances of relative settlement due to founding conditions, a more flexible lining should be used. Generally the allowable deflection under operating conditions is specified as 3% or 5% and this is quite adequate for doing routine tests.

When doing developmental testing the products should be tested to failure so that the margin of safety between working and ultimate conditions can be established. This is equally applicable to the lining materials and the linings made from them.

6. CONCLUSIONS

This report covers the differences between the structural properties of flexible pipes for new pipelines and flexible linings for rehabilitation of existing pipelines, the product testing required and the value of statistical analysis of test results in confirming the values and reliability of these products.

Lining suppliers and installers need a thorough understanding of the structural and other properties of the products they are supplying and installing with the proof that they meet the required project specifications.

The three point testing covered in ASTM D 790 and the "dog bone" tensile testing covered in ASTM D 638 describes how the material properties for lining designs are determined. The parallel plate testing covered in SANS 791 and ISO 9969 describes how the lining properties (PS and PRS) required for designing the rehabilitation of deteriorated pipelines are obtained.

In house parallel plate and the other tests provide the means of realistically evaluating the structural properties of the liners using various combinations of tube and resin materials. The structural properties of the liners will be in the same format as for pipes installed in open trenches, providing market place decision makers with the confidence they need to go trenchless. These results should be certified periodically by an accredited laboratory.

A clear distinction is needed between, the testing to determine the material properties used for manufacturing liners, and the testing to determine the properties of the manufactured liners to be used on site. A distinction must also be made between the routine testing of liners being manufactured for the market place and the developmental testing of liners to optimize their material quantities and costs.

The statistical analysis of test results is essential and this requires a standard procedure for choosing the sample size to be tested so that the same number is always taken and that the analytical parameters for evaluating the results do not have to be adjusted. These results should be monitored over time so that any deviations in properties can be identified, and where necessary remedial action taken.

It cannot be assumed that the properties of the joints and fabricated fittings used on pipelines will be the same as those of the pipes. Additional factors, such as dimensions and material properties may be significantly different and need to be considered. Their impact on the design of new pipelines or liners to rehabilitate existing pipelines are outside the scope of this paper.

APPLICABLE STANDARDS AND REFERENCES USED

The relevant standards covering the above tests are:

- SANS 791 for determining PS of PVC pipes (applicable to all materials)
- ASTM D 790 for determining flexural tensile stress and flexural modulus
- ISO 9969 for determining PRS
- ASTM F 1216 for determining wall thickness to take external water pressure on liners
- ASTM D 638 for determining direct tensile stress of all materials

The publications used when compiling this paper are:

SABS 0102: The Code of Practice for The selection of pipes for buried pipelines. Part I: General provisions
SABS 1200 DB Earthworks (pipe trenches) or revised SANS 2001 series
SABS 1200 LB Bedding (pipe) or revised SANS 2001 series
SAPPMA Technical Manual
Amster Howard: Pipeline Installation
Handbook of PVC pipe: Design and Construction: Uni-Bell PVC Pipe Association

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APPENDIX A: TYPICAL AVERAGE E´ VALUES FOR MODULUS OF SOIL REACTION

AVERAGE VALUES OF MODULUS OF SOIL REACTION, E'
(For Initial Flexible Pipe Deflection)

Soil type-pipe bedding material (Unified Classification System[a]) (1)	E' for Degree of Compaction of Pipe Zone Backfill, psi			
	Loose (2)	Slight <85% Proctor, <40% relative density (3)	Moderate 85%-95% Proctor, 40%-70% relative density (4)	High >95% Proctor, >70% relative density (5)
Fine-grained Soils (LL > 50)[b] Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; Otherwise use E' = 0			
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML ML-CL, with less than 25% coarse-grained particles	0,35 MPa 50	1,4 MPa 200	2,8 MPa 400	7 MPa 1,000
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles Coarse-grained Soils with Fines GM, GC, SM, SC[c] contains more than 12% fines	0,7 MPa 100	2,8 MPa 400	7 MPa 1,000	14 MPa 2,000
Coarse-grained Soils with Little or No Fines GW, GP, SW, SP[c] contains less than 12% fines	1,4 MPa 200	7 MPa 1,000	14 MPa 2,000	21 MPa 3,000
Crushed Rock	1,000	3,000	3,000	3,000
Accuracy in Terms of Percentage Deflection[d]	±2	±2	±1	±0.5

[a]ASTM Designation D 2487, USBR Designation E-3.
[b]LL = Liquid limit.
[c]Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
[d]For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate Deflection Lag Factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598,000 J/m^3) (ASTM D 698, AASHTO T-99, USBR Designation E-11). 1 psi = 6.9 kN/m^2.

SOURCE: "Soil Reaction for Buried Flexible Pipe," by Amster K. Howard, U.S. Bureau of Reclamation, Denver, Colorado. Reprinted with Permission from American Society of Civil Engineers Journal of Geotechnical Engineering Division, January 1977, pp. 33-43.