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Procedia Engineering 119 (2015) 91 – 100

Procedia Engineering

www.elsevier.com/locate/procedia

13th International Conference on Computing and Control for the Water Industry, CCWI2015

Laboratory investigation of the leakage characteristics of unburied HDPE pipes

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Abstract

In this research work, the leakage characteristics of the viscoelastic material HDPE is investigated and compared to other materials like uPVC which is elastic and galvanised steel which is rigid in nature. Under no axial loading, the deformation in HDPE pipe wall causes the leak aperture to close up under increasing pressure head. As a consequence, the leakage exponent decreases from around 1 to 0.5 with increase in both longitudinal and circumferential crack lengths whereas for uPVC and steel, the leakage exponent increases under similar conditions. Consequently, the increase in discharge rate for increasing pressure in HDPE gets smaller.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Viscoelasticity, High Density Polyethylene (HDPE), Fixed and Variable Area Discharges (FAVAD)

1. Introduction

The need for finding new piping materials for our water distribution network is more than ever urgent with regard to the amount of water lost through leakage in various countries around the world. In addition, the water demand of our increasing population and the emergence of new industries are simply exacerbating the situation by putting much stress on the old existing infrastructure for water distribution. Moreover, current water management practices may fail to cope with the situation if the piping infrastructure is not properly maintained since the problem of leakage is persistent in any distribution network. In the light of the above problem, it is imperative that more

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Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.858

robust and sustainable materials be used for piping in water networks. High Density Polyethylene offers many interesting characteristics at that end and this explains its widespread use for water distributions. The main disadvantage of HDPE however, is that it has a high roughness coefficient compared to other commonly used pipes and this gives rise to much pressure drop downstream. As far as leakage in HDPE is concerned, many researchers have come to the conclusion that it exhibits viscoelastic behaviour with increase in pressure head meaning that the leak flow rate increases with dynamic change in leakage area. However, few researchers have investigated the behaviour of leaks in HDPE under different soil beddings or layout. The present work focusses on the leakage characteristics of unloaded HDPE pipes laid rough a surface. This paper provides an insight for using unburied HDPE pipe for leak detection and reduction not only for water but for gas distributions as well.

2. Background

According to Torricelli's theorem, the rate of leakage Q_l is proportional to the square root of the static head H in a pipe.

$$Q_l = C_l A_l \sqrt{2gH} \tag{1}$$

where
C_l= the discharge coefficient
A_l= leak area
g=acceleration due to gravity
H= total head at the point of leak

Several researchers have conducted tests on orifice in pipes and the hydraulics is now very well understood. The rate of leakage is in fact proportional to the square root of the head at that particular leak point according to Hikki [14], Greveinstein and Van Zyl [6] irrespective of the pipe material and size of hole, thereby confirming the relationship:

$$Q_l \; \alpha \; H^{0.5} \tag{2}$$

However, leaks are not always of orifice type and therefore other shapes like circumferential and longitudinal cracks were investigated. A more general form of the leak equation which is proposed by Lambert [15] is:

$$Q_l = C\,H^N \tag{3}$$

where
C is the leakage coefficient
N is the leakage exponent

In contrast to the general equation where *N* is 0.5 for orifices, the leak exponent for longitudinal, circumferential and spiral cracks were found to vary between 0.5 and 2.79 (Lambert [15]). Extensive research works have been performed with leaks of different shapes in pipes. For example Van Zyl and Clayton [1] investigated four factors that may explain the high values of *N* in pipes, namely leak hydraulics, soil hydraulics, pipe material behaviour and water demand. The third factor was considered the most important one suggesting that the leak area increases with increase in pressure. For flexible pipes like PVC, the relationship is complicated by plastic deformation and hysteresis as investigated by Ferrante et al [4] and Massari et al [7]. Cassa and Van Zyl [10] used finite element analysis to show that all types of leak vary linearly under pressure through elastic deformation under the FAVAD concept:

$$A(h) = mh + A_0 \tag{4}$$

where
A = the new leak area
h=head at leak point

m=slope of the head area curve
A_o= initial leak area

Rewriting the leak flow equation 1 according to FAVAD:

$$Q_l = C_d\sqrt{2g}\,(A_0 H^{0.5} + m\,H^{1.5}) \tag{5}$$

where
A_0 is the initial leak area
m is the slope of the head-area curve

This relationship, however as it is, can only be applied if we know the leak characteristics (A_0 and m) of the network beforehand and one leak is unlikely to be similar to another. Therefore, the use of this equation is limited and cannot be readily applied to a distribution network. Furthermore, the equation above predicts a maximum value of N of 1.5 and therefore does not explain the higher values of 2.79 for example found in field tests.

According to Van Zyl et al [2], for laminar flow N varies between 0.5 and 1 whereas for turbulent flow, N is less than 0.5. Greyvenstein [6] found that N may vary between 1.38 and 1.8 in uPVC pipes with longitudinal cracks and between 0.41 and 0.53 for circumferential cracks. The highest exponents were found in corrosion clusters of steel pipes. According to Cassa et al. [10], the area of the crack played a vital role in the orifice equation than previously believed.

With regard to the viscoelastic nature of HDPE, Ferrante et al. [5] and Massari et al. [7] concluded that the latter exhibits hysteresis and therefore is very complex to analyse under static conditions. Therefore the head-area slope m of equation 5 cannot be applied as such for a particular leak type for this material. On the other hand, M. Franchini and L,Lanza [13] showed that the leakage through pipes of different elastic materials can be represented by the classical Torricelli's equation by using a correction factor to cater for the variable leak area and hydraulic factors affecting the coefficient of discharge. He stated that the overwhelmingly high values of N obtained in laboratory can be attributed to the improper quantification of the leakage coefficient.

3. Experimental study

In an attempt to compare the leakage characteristics of unloaded HDPE with 2 other pipe materials namely uPVC and galavanised steel, rectangular slits of width 2mm and width varying up to a maximum of 20 mm were produced in the pipes. The pressure head in the pipes was restricted to a maximum of 3.5 bars which is typically the average pressure in a distribution network. Preliminary tests carried out on samples of uPVC and steel showed that the variation in discharge area for a slit of length below 24 mm was negligible.

3.1 Laboratory setup

The setup comprises of a booster pump P2 providing a mechanical head of 50 m connected to the sample test pipe of 3.5 m length as depicted in figure 1 below. The pump is connected to a frequency inverter such that the flow and thence the pressure in the pipe can be controlled. The maximum flow from the pump is 45 L/h. All specimen of uPVC, galvanized steel and HDPE used, are of diameter 40 mm and thickness 2 mm, laid on the surface of a rough table. The slit was directed sideways and the pipe was secured at both extremities. A pressure sensor and an ultrasonic flowmeter sensor were connected to the pipe network and measurements were logged on a PLC.

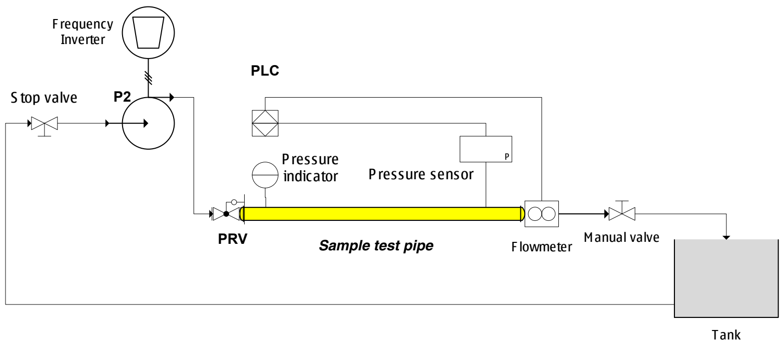

Figure 1: Laboratory setup

Strain gauge SG1 shown in figure 2 below, is used to monitor the longitudinal contraction whereas SG2 measures the lateral expansion of the pipe in case of a longitudinal crack. The hysteresis property of HDPE is not taken into consideration here; the pipe is assumed to behave elastically. The slit is positioned laterally so that a maximum deflection of the pipe is obtained. With the same disposition of strain gauges, circumferential slits are again restricted to a maximum length of 20mm so that SG1 experiences sufficient strain. The pipe rests on a rough table which inevitably restrains the radius of curvature. Undoubtedly, the roughness of the surface is going to have a significant influence on the variation of the cross-sectional area of the slit and hence on the leakage rate.

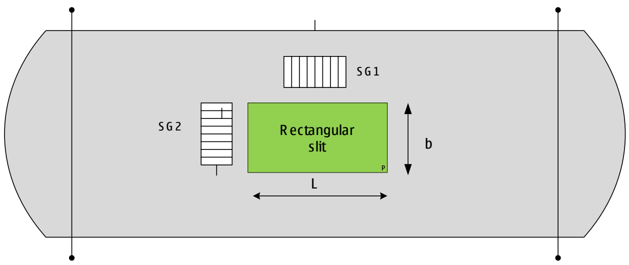

Figure 2: Placement of strain gauges longitudinally and laterally along the slit on the side of the pipe

3.2 Leakage model used

As such, equation 5 is not appropriate for analysis of HDPE because it applies mainly to elastic material and the value of the area-head slope *m* is different for different size of opening. To be able to compare the results of the three different pipe materials, equation 3 which is used in most water leakage modelling, has been solicited. The reason behind, as stated previously, is that the measured variation in the discharge area for uPVC and steel pipes were negligible. Although this is not the case for HDPE, an approximate value of its leakage exponent *N* can be obtained and compared to the other two pipes for the same pressure head. Moreover, the increase between successive pressure heads has been limited to 0.2 bars so that the corresponding variation in the leakage coefficient C_d and the discharge area *A* is small.
Using the model developed by Hikki [14] from equation 3 above, we have:

$$\frac{Q_2}{Q_1} = \left(\frac{H_2}{H_1}\right)^N \tag{6}$$

where

Q_1= the initial flow
H_1= the corresponding pressure head
Q_2= the final flow
H_2=the corresponding pressure head
N= the leakage exponent

Taking the natural logarithm on both sides:

$$\ln\left(\frac{Q_2}{Q_1}\right) = N\ln\left(\frac{H_2}{H_1}\right)$$

$$N = \ln\left(\frac{Q_2}{Q_1}\right)/\ln\left(\frac{H_2}{H_1}\right) \quad (7)$$

In order to cater for measurement errors in the pressure and flow and the fact that the relation between the variation of the pressure to the variation of flow is not perfect and that it contains several uncertainties related to the regime of flow, the type and form of the slits, the relation has been rewritten as:

$$\ln\left(\frac{Q_j}{Q_i}\right) = N\ln\left(\frac{H_j}{H_i}\right) + \mathcal{E}_{10} \quad (8)$$

Where i=1…k and j= 1….k
$\mathcal{E}_{10}$ represents the sum of measurement errors and modelling.
Equation 8 is that of a straight line with gradient N and intercept $\mathcal{E}_{ij}$

4. Results and findings

Without any lateral or longitudinal loading, the HDPE pipe was expected to undergo a deflection in the opposite direction of the leak due to the thrust provided by the water jet (Newton's third law of motion). This is illustrated in the top view of the pipe through figure 3 where the contraction of the wall containing the discharge is apparent. The deflection is here hindered by two factors mainly namely the roughness of the surface and the clamp at both ends of the pipe. However, since the pipe is sufficiently long (3.5 m) and the slit is positioned in the middle, the extent of deformation in the pipe wall was visible.

Figure 4 on page 6 shows the longitudinal contraction in microns around a 2x20 mm slit of the HDPE pipe through strain gauge SG1 whereas figure 5 clearly indicates that there is an expansion in the breadth of the same slit upon increasing the pressure head from 0 to 35 m. The deformation is not linear about the two axes as suggested by Cassa et al [9]. The corresponding approximate decrease in discharge area of the slit is then calculated from the two strain gauges as depicted in figure 6. For the maximum pressure of 35 m, a ΔA of 0.0307 mm^2 is obtained.

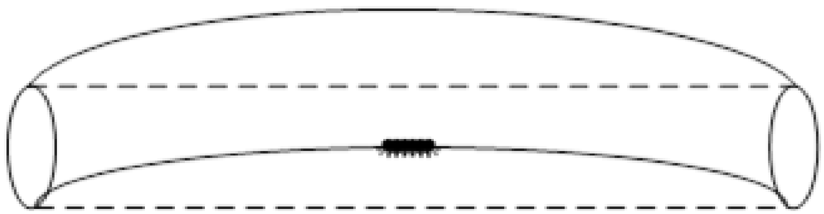

Figure 3: Deflection of HDPE pipe with longitudinal slit

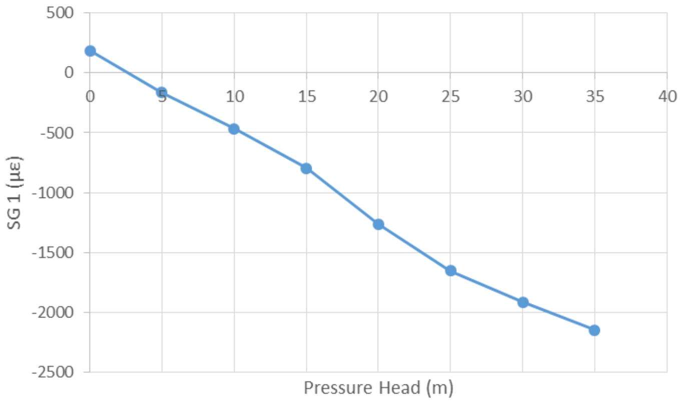

Figure 4: Variation of strain gauge SG1 with increase in pressure head for a 2x20 mm slit

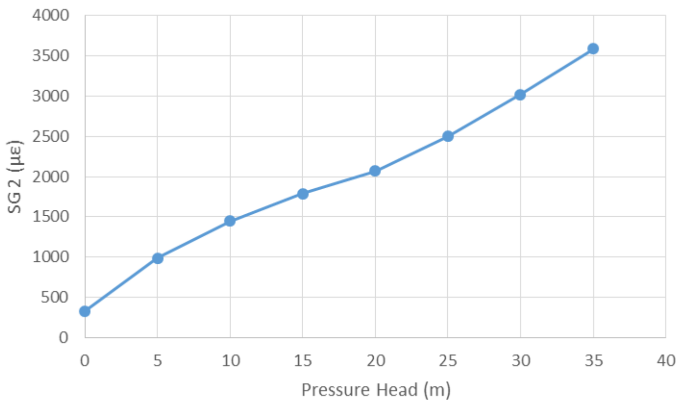

Figure 5: Variation of strain gauge SG2 with increase in pressure head for a 2x20 mm slit

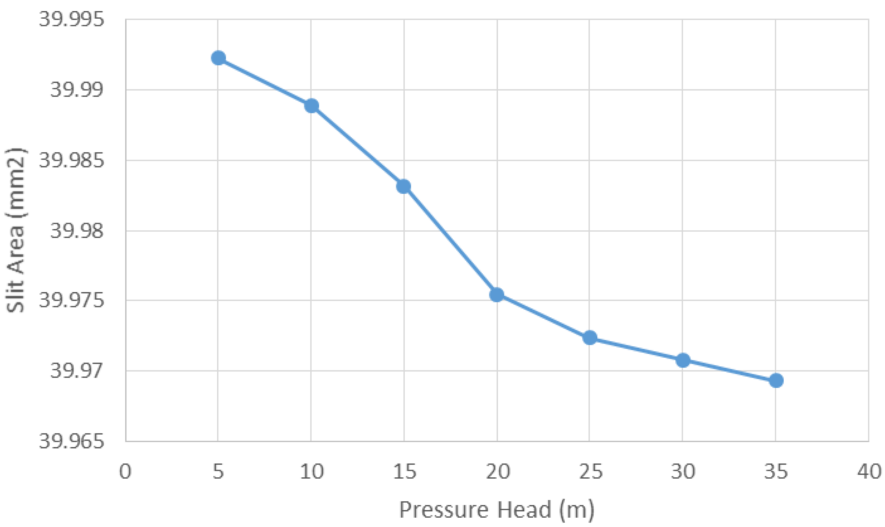

Figure 6: Approximate change in Area with increase in pressure for a 2x20 mm^2 slit

The same procedure was adopted for circumferential slits with a maximum breadth of 20 mm again so that the pipe gets sufficient thrust to curb under the action of the burst. Figure 7 below shows that the change in discharge area at a pressure head of 35 m for the circumferential slit is smaller than for the longitudinal one. This is can probably be explained by the fact that the expansion in SG2 is not much noticeable since it is found transversal to the direction of flow of water in the pipe.

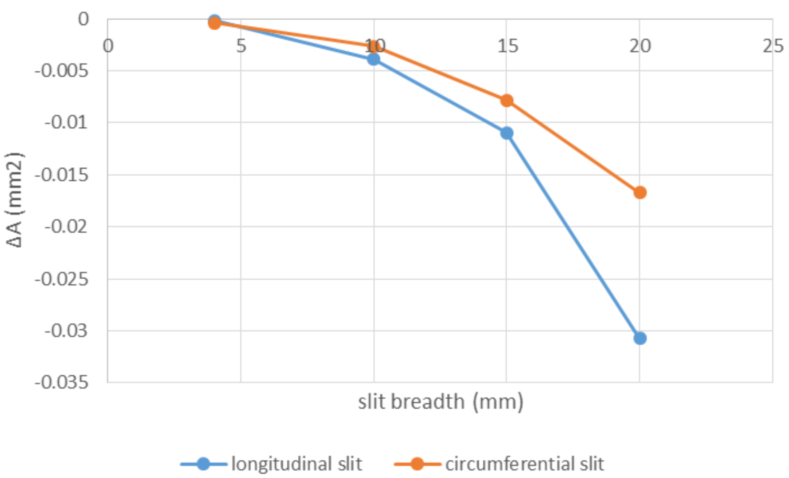

Figure 7: Variation of ΔA for different crack lengths at pressure H=35 m

Using equation 8 on page 5, the leakage exponential *N* was obtained from the gradient of plot of ln (Q2/Q1) versus ln (H2/H1) for each value of slit length as depicted in figure 8 below. The procedure was repeated for 10 mm, 15 mm and 20 mm longitudinal slits and 4 mm, 10 mm, 15 mm and 26 mm circumferential slits. Figure 9 shows the tendency of *N* for different crack lengths. The interesting thing to note here is the unexpected decrease of N with increasing slit breadth whereas several researchers like Cassa [9] and Massari [7] have previously found an opposite trend but under axial loading conditions. This may be explained by the decreasing discharge area with increase in slit width of figure 7. Another interesting thing is that for both curves of figures 9 (a) and (b), *N* tends towards 0.5. This suggests that discharge through both longitudinal and circumferential cracks in pipes can also be described by the classical Torricelli's equation and therefore what Franchini and Lanza [13] concluded about the leak equation 3 may not be unrealistic.

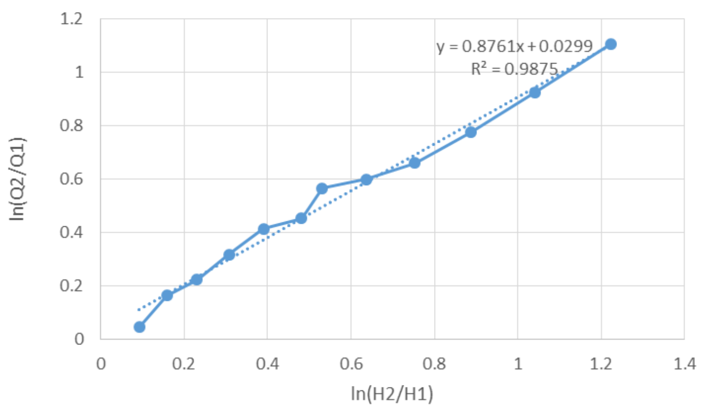

Figure 8: Finding the leakage exponent of longitudinal slit 2x4 mm in HDPE

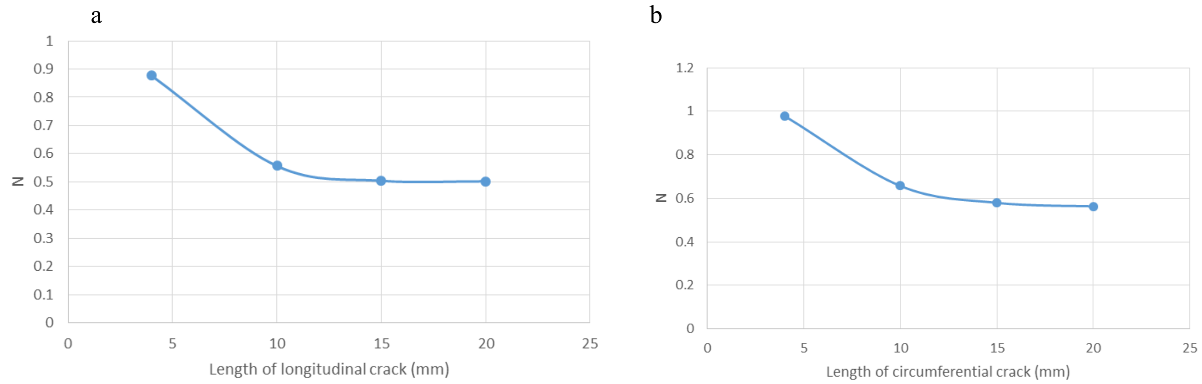

Figure 9: Variation of leakage exponential N with increase in breadth of (a) longitudinal crack; (b) circumferential crack of HDPE

Finally, the trend of increasing leakage exponent *N* for both longitudinal and circumferential cracks with increase in crack length is confirmed for both uPVC and galvanised steel by the experimental study in figures 10 and 11 below. However, for the same unloaded conditions in HDPE, a decreasing profile is registered in either case under the deformation of the pipe wall. From figure 10, for the same crack length of 15 mm longitudinally, the leakage exponents *N* in uPVC is 0.726; for steel it is 0.881 and HDPE 0.504, that is the smallest.

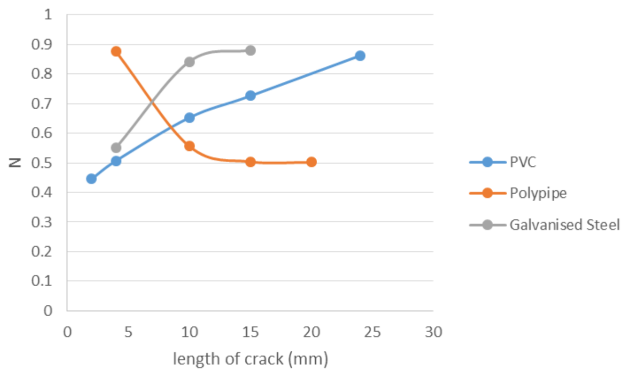

Figure 10: Comparing N for different pipe materials under identical conditions for longitudinal cracks

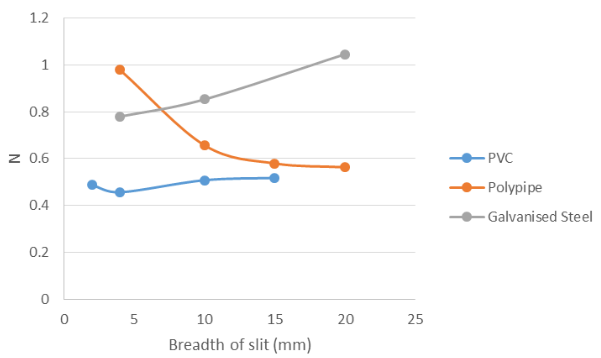

Figure 11: Comparing N for different pipe materials under identical conditions for circumferential cracks

4. Discussion

By comparing the results of leakage exponent *N* obtained for a longitudinal slit of 15 mm in the three pipe materials i.e. uPVC, galvanised steel and HDPE under the same experimental conditions, it can be deduced that for an increase of 50% in pressure head, there will be a 42.93% increase in leakage rate for galvanised steel, 34.23% for uPVC and only 22.67% for HDPE. This is summarised in table 1 below.

Table 1: Percentage increase in the leakage rate as a function of the increase in pressure for different values of *N*

	ΔP%	5%	10%	15%	25%	30%	50%
ΔQ %	N_{uPVC}=0.726	3.61	7.17	10.68	14.15	20.98	34.23
	N_{steel}=0.881	4.39	8.76	13.1	21.72	26	42.93
	N_{HDPE}=0.504	2.49	4.92	7.3	11.9	14.14	22.67

For circumferential cracks, the convergence of *N* to 0.5 for HDPE is again apparent from the graph of figure 11, meaning that the increase in rate of leakage will be at its lowest regime. Using FAVAD's theorem, the closing down of the aperture as a result of the wall contraction under increasing pressure head, is the main accountable reason for this. Undoubtedly, the coefficient of discharge is also altered when the area of discharge changes under the viscoelastic behaviour of HDPE. Therefore, limiting the value of *N* means reducing the leakage rate under an increasing pressure head. In this perspective, HDPE offers promising avenues for use at ground surface without any axial loading. However, the main problem remains that of larceny and when it comes to water, no compromise whatsoever can be made. New ways of laying the HDPE pipes have to be devised to reap the benefit showed in this present work. A pilot project, as shown in figure 12, is currently under way in Mauritius to investigate the behaviour of buried and unburied HPDE in terms of burst frequency and background leakage over a distance of about 2 km.

Figure 12: Pilot project for surface pipe laying of HDPE

References

[1] Van Zyl, J.E. and Clayton, C.R.I. (2005) "The Effect of Pressure on Leakage in Water Distribution Systems", *proceedings of CCWI2005 Water Management for the 21st Century*, University of Exeter, UK.

[2] Van Zyl J.E., and A. Cassa, Linking the power and FAVAD equation for modelling the effect of pressure on leakage. *Eleventh International Conference on Computing and Control for Water Industry (CCWI)*, University of Exeter, United Kingdom, 2011.

[3] Thornton, J., and Lambert, A. (2005). "Progress in practical prediction of pressure: Leakage, pressure: Burst frequency and pressure: Consumption relationships." *Proceedings of IWA Special Conference 'Leakage 2005'*, Halifax, Nova Scotia, Canada.

[4] Ferrante M., C. Massari, E. Todini, B. Brunone, and S. Meniconi, Experimental investigation of leak hydraulics, *J. of Hydroinformatics* 15(3) (2012) 666–675.

[5] Ferrante M., Experimental investigation of the effects of pipe material on the leak head-discharge relationship. *J. of Hydraulic Engineering*, 138(8) (2012) 736-743

[6] Greyvenstein B., and J. Van Zyl, An experimental investigation into the pressure- leakage relationship of some failed water pipes. *Aqua-Journal of Water Supply: Research and Technology*, 56(2) (2007) 117-124.

[7] Massari, C., Ferrante, M., Brunone, B., and Meniconi, S. (2012). "Is the leak head–discharge relationship in polyethylene pipes a bijective function?" *Journal of Hydraulic Research, IAHR*, 50(4), 409–417.

[8] Cassa, A. M. & Van Zyl, J. E., 2011. Predicting the head-area slopes and leakage exponents of cracks in pipes. Exeter, *Centre of Water Systems,* University of Exeter, College of Engineering Mathematics and Physical Science, pp. 485-490.

[9] Cassa, A. M. & Van Zyl, J. E., In press. Predicting the head-leakage slope of cracks in pipes subjects to elastic deformations. *Journal of Water Supply: Research and Technology - Aqua*.

[10] Cassa A., J. Van Zyl, and R. Laubscher, A numerical investigation into the effect of pressure on holes and cracks in water supply pipes. *Urban Water J*., 7(2) (2010) 109-120.

[11] Coetzer AJ, JE van Zyl and CRI Clayton: Experimental study of the hydraulics of small circular holes in water pipes. *Proceedings of the 8th annual symposium on water distribution Systems Analysis Symposium*, Cincinnati, Ohio, 27-30 August 2006.

[12] De Paola F., E. Galdiero, M. Guigni, R. Papa, G. Urciuoli, 'Experimental Investigation on a buried Leaking Pipe', *16th international Conference on Computer and Control in the Water Industry*. 1877-7058 © 2014

[13] Franchini M., L. Lanza: Use of Torricelli's Equation for Describing Leakages in Pipes of Different Elastic Materials, Diameters and Orifice
Shape and Dimensions. *Proceedings of the 16th Conference on Water Distribution Systems Analysis, WADSA 2014*.

[14] Hikki S.: Rlationship betwewn leakage and Water. Journal of Japanese Waterworks Assn.,1981, 5:50

[15] Lambert, A. (2000). "What do we know about pressure:Leakage relationships in distribution systems?" System Approach to Leakage Control
and Water Distribution Systems Management, IWA, Brno, Czech Republic.