Economical and technical evaluation of PE100 pipes used in natural gas distribution systems

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Abstract

The use of PE100 resin pipes in natural gas distribution systems allows higher operational pressures than PE 80 resin pipe systems, therefore enable us to economically increase its flow capacity.

In spite of such elevated economy and effectiveness, PE100 pipes are not always selected. One of the reasons would be concerns about material deterioration and wall thickness thinning by squeeze-off operation, since these phenomena can affect long term integrity of the pipes.

Based on our experiences in Brazil and worldwide literature surveys about application of squeeze-off to PE100 pipes, we thought it is necessary to conduct reinforcement at any point where squeeze-off is applied to PE100 pipes.

To this end, it is necessary to establish efficient and trustful procedure of squeeze-off, re-rounding until reinforcement. In order to verify the operational procedure and long term integrity of the reinforcements, we conducted experiments on 1) relationships between deformations and squeeze-off time and re-rounding time, 2) effects of re-rounding tool geometry on final roundness, and 3) mechanical strength of two types of reinforcement.

Finally, we tried to quantify `How much is PE100 pipe system more economical and effective than PE80 system?` by making comparative studies in terms of flow capacity and installation costs based on actual PE pipe installation projects in Brazil. The results show 68% increase in flow capacity with only 0.5% increase in installation costs.

Key words: PE100, Squeeze-off, Re-rounding, Reinforce, Long term integrity, Comparison with PE80

1. Introduction

Note that, in this paper, `PE100 pipe` means PE pipes which is composed of PE100 resins and `PE80 pipe` means PE pipes which is composed of PE80 resins.

Petrobras Distribuidora and Mitsui Gas run natural gas distribution companies in Brazil.

Distribution of natural gas with pipes is fairly new in most of Brazilian states with at most 20 years' experiences, with the exception of São Paulo and Rio de Janeiro states where supply started more than 100 years ago.

In such a new distribution operation, supply was at first directed to the industrial market. Then, the distribution companies are gradually shifting to the residential market. Now it is a common practice to install PE pipes (PE80 pipes and PE100 pipes) in densely populated areas.

Under these situations, it has been our never changing philosophy to develop more efficient and economical gas network. Choosing most suitable pipe material would be one of the key factors to achieve it.

2. A business dilemma

Squeeze-off method, shown below in the Figure 1, making use of flexibility of PE pipe, is an effective flow-stopping measure in an emergency or even in ordinary operation. It allows the pipe to be squeezed together using specially designed tools thus preventing the flow of fluid and isolating the pipe section.

Figure 1 Squeeze-off of PE pipe

PE100 resin, developed in Europe in 1989, shows a bimodal molecular weight distribution, i.e., they consist of two different kinds of molecular chains (long and short), therefore combine a high tensile strength with a high resistance against slow and fast crack propagation.

The question is which should be used between PE80 and PE100. PE100 pipes allow higher operational pressures (thanks to higher tensile strength) if the pipe wall thickness is the same, therefore can increase its flow capacity. On the other hand, squeeze-off deformation can cause larger NEGATIVE impacts on PE100 pipes since the material is `harder`. There have been concerns and restrictions worldwide over the application of squeeze-off to PE 100 pipes as shown in Table 1 below, which are only examples.

Table 1 Examples of restrictions and concerns on the application of squeeze-off to PE 100 pipes

Restriction	Reference
"Equipment for squeeze-off of PE pipes is available on the market, but the effect of the squeezing on the long-term strength of PE 100 water pipes is still not fully studied"	NPG Nordiska Plaströgruppen, 2012 (Sweden) [1]
"There was concern over the internal cracks that can develop when squeeze off is released from large diameter, thick wall PE 100 pipes, and for this reason, it was mandatory to cut out and replace PE 100 pipe sections that had been subject to squeeze of within 6 months"	SAVIDIS, Y. and HILL, T [2] Advantica Technologies (UK), PE 100+ Association (USA)
"Reference should be made to the relevant pipe manufacture for specific advice regarding squeeze-off operations on PE 100 pipes (stress cracking could occur and mechanically-aided re-rounding would be required)"	Institute of Gas Engineers and Managers, 2014 (UK) [3]
"After the squeeze-off procedure is complete, the pipe must be • Inspected and re-rounded if necessary • Renewed if there are any signs that the pipe is damaged, i.e., splitting or cracking • Recorded and marked as having been squeezed-off"	GPS PE Pipe Systems, 2011 (USA) [4]
"After squeeze-off, the squeezed-off pipe (PE100) section should be reinforced with mechanical clamp" (Translation by the author)	Japan Polyethylene Pipes Association for Water Service [5]

3. Technical issues related to squeeze-off of PE100 pipes

Since the pipe is deformed severely by squeeze-off, there is a risk of damage and pipe wall thinning. The degree of damage and wall thinning depends on the velocity of operation (strain rate), level of squeeze (strain level), diameter of squeeze rods, pipe wall thickness, temperature, material properties, etc.

The ASTM F1041 [6] states, regarding the velocity of the operation, that it is appropriate to keep the maximum rate of squeeze equal to or less than 2 inches per minute and for release 0.5 inches per minute to avoid damage to inner surface of PE pipe.

However, this recommendation is not practical under emergency situation, since it is more important to squeeze to stop gas flow as rapidly as possible for safety reason (in Brazil, almost 100% of the application of squeeze-off is under emergency situation).

Another problem is that it is not possible to check if there exists any damage by squeeze-off INSIDE pipe wall, since NO inspection and evaluation method of such possible damages from outside is yet established (of course, it is not possible to cut and open the pipe).

Figure 2 shows a cut section of a PE100 pipe (SDR11, 63mm outer diameter) of squeezed-off point depicting two damages (pits) and pipe wall thinning. Compression ratio* of squeeze-off was 30% and temperature was 26-28^{o}C. The pits were elliptical-shaped (about 5mm x 2mm) with 1.0-1.5 mm in depth. The maximum ratio of pipe wall thinning was 15-20%.

* Compression ratio=1 - (minimum distance between two squeeze rods)/{2 x (original pipe wall thickness)}

It should be noted that it is not the end of the story, but the start: after the squeeze-off, internal gas pressure is imposed onto the squeezed-off part during its service life, thus enhancing the risk of SCG (Slow Crack Growth), since the crack can be initiated from the bottom of the damages.

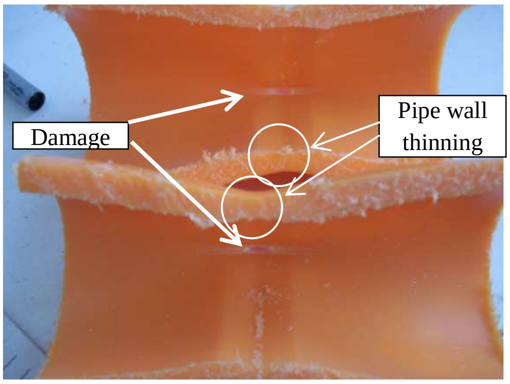


Figure 2 Damages and pipe wall thinning after squeeze-off

Considering the importance of the pipe integrity on which we rely during its remaining service life, it is recommended to do replacement or reinforcement at every squeeze-off point of PE100 pipes.

However, the replacement is often difficult in urban area because in usual there are lots of customers being supplied with the PE pipes. If we close valves in order to isolate the pipe section for the replacement, supply to such customers is suspended; it may cause much trouble. If another squeeze-off is applied for the replacement, instead of closing valves, it is necessary to do ADDITIONAL replacements of the new squeezed-off sections, therefore it does not solve the problem. In this sense, reinforcement will be the most realistic option.

Taking account of the situations above, we conducted studies on method and procedure of reinforcement which ensures long-term integrity of squeezed-off PE 100 pipes.

4. Procedure of squeeze-off and reinforcement

The reinforcement procedure is basically composed of three steps: 1) Squeeze-off, 2) Re-rounding of squeezed-off section and 3) Reinforcement by fittings. Since PE pipe material is a type of polymer which shows *viscoelastic characteristic*, the deformations are time dependent. At the same time, result of re-rounding may be affected by *elastic rebounding* of PE material when unloaded: it means a circular shape re-rounding tool cannot recover its original roundness because of the rebounding effect.

Based on the above thoughts, we prepared 10 test pipes to evaluate i) squeeze-off time effect, ii) re-rounding time effect, iii) re-rounding tool geometry effect and iv) effectiveness of coupler and saddle reinforcement fittings.

Table 2 Test parameters

No. Test	Squeeze-off time (min)	Re-rounding time (min)	Re-rounding tool	Type of Reinforce fitting
1	10	10	Circular	Coupler
2	10	10	Elliptical	Coupler
3	40	10	Circular	Coupler
4	40	10	Elliptical	Coupler
5	40	20	Circular	Coupler
6	40	20	Elliptical	Coupler
7	120	20	Circular	Coupler
8	120	20	Elliptical	Coupler
9	40	10	Elliptical	Saddle
10	120	10	Elliptical	Saddle

In the tests, pipes were squeezed-off vertically and measurements were done of vertical and horizontal diameters at two points. These points are apart by the distance equal to a length of reinforcement coupler, while the squeeze-off point is centered (See Figure 3 below). In other words, we measured deformations at points where electro-fusions of the reinforcement couplers will be realized. It is because the roundness after re-rounding is important to assure sound fusion and mechanical integrity of reinforcement.

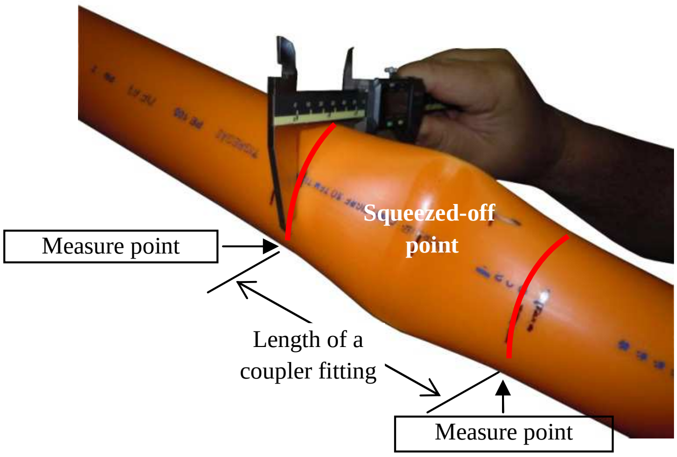


Figure 3 Measure points in the tests

In this paper, deformation is normalized by its original diameter, named '*Deformation ratio*', e.g., a deformation ratio of 0.9 means that a pipe diameter has changed (deformed) to 90% of its original diameter.

4.1. Squeeze-off time effect

We checked a relationship between squeeze-off duration and the resulting deformation. The ambient temperature was 26-28°C.

Results - As shown in the Figure 4 below, deformation by squeeze-off increases proportionally to the logarithm of Tsq (Duration of squeeze-off). It corresponds to viscoelasticity of polymer material.

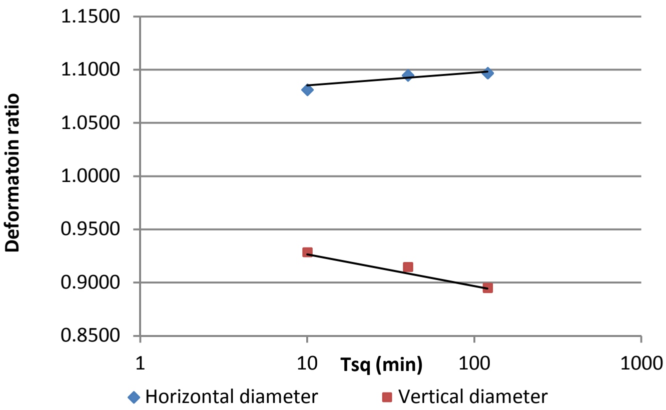


Figure 4 Time-dependency of deformation by squeeze-off

4.2. Re-rounding time effect

The objective is to find out the optimum duration of re-rounding in order to establish effective operations. The effect of re-rounding can be measured by 'How much does the re-rounding operation make the pipe recover its original shape?' It can be defined by the following formula (shown as (A/B) in Table 3):

$$\text{Re-rounding effect} = \frac{\text{Deformation ratio after squeeze-off}}{\text{Deformation ratio after re-rounding}}$$

Table 3 Deformation ratio and Re-rounding effect

	Circular	Trr = 20 min	Trr = 10 min	(a/b)
Dh	After Squeeze-off (A)	1.1024	1.0947	
	After Re-rounding (B)	1.0111	1.0143	
	Re-rounding effect (A/B)	1.0903 (a)	1.0793 (b)	**1.0102**
Dv	After Squeeze-off (A)	0.9146	0.9148	
	After Re-rounding (B)	0.9838	0.9810	
	Re-rounding effect(A/B)	0.9297 (a)	0.9325 (b)	**0.9970**
	Elliptical	**Trr = 20 min**	**Trr = 10 min**	**(a/b)**
Dh	After Squeeze-off (A)	1.0766	1.0905	
	After Re-rounding (B)	0.9905	0.9933	
	Re-rounding effect (A/B)	1.0869 (a)	1.0978 (b)	**0.9901**
Dv	After Squeeze-off (A)	0.9210	0.9103	
	After Re-rounding (B)	0.9996	0.9984	
	Re-rounding effect(A/B)	0.9213 (a)	0.9118 (b)	**1.0105**

By keeping duration of squeeze-off (Tsq) unchanged and by changing duration of re-rounding (Trr), it is possible to compare re-rounding effects on horizontal

(Dh) and vertical diameters (Dv). Trr were 10 min. and 20 min. whereas Tsq were 40 min. to all cases.

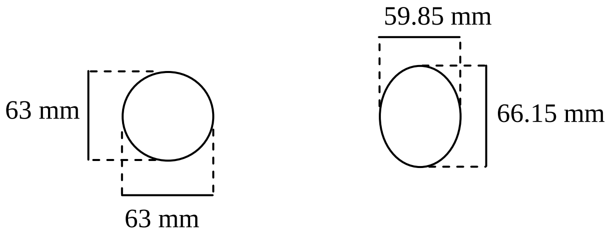
Results - The values of (a/b) in Table 3 imply the ratio of the re-rounding effects of 10 min. to 20 min. They are 1.0102 and 0.9970 for Circular re-rounding tool and 0.9901 and 1.0105 for Elliptical tool. Since these a/b values are very close to one (1) (actually they are all within 1±1.05%), there is little difference of the effect of the duration of re-rounding between 10 min. and 20 min. under temperature of 26-28°C.

Therefore, it can be said that most of the re-rounding deformation may complete within 10 min., and it is not necessary to keep re-rounding more than 10 min. under above said temperature condition. The finding can help realize effective operations at site.

4.3. Re-rounding tool geometry effect

Considering the work procedure of reinforcement (to be described later), it is important to obtain high degree of roundness by re-rounding so that 1) reinforce coupler can pass a squeezed-off/re-rounded section, 2) high degree of fusion of resin can be realized between reinforce coupler and pipe body to ensure mechanical integrity of the reinforced part.

Based on the above idea, we conducted experiments to compare the effect of re-rounding tool geometry on the degree of recovery of roundness after squeeze-off. Two types of tools were adopted, i.e., circular and elliptical as shown in Figure 5 below. Note that the ratio of length between long axis and short one of the elliptical type is around 0.90 (=59.85/66.15).



a) b)

Figure 5 Re-rounding tools: a) Circular and b) Elliptical

The results are summarized in Table 4 below in terms of *Oval ratio* (Dmin/Dmax):

Table 4 Average oval ratios in measuring points

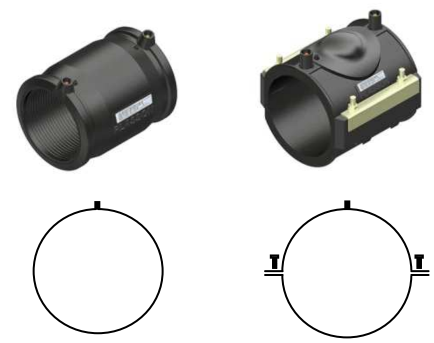
Re-rounding tool type	**Squeeze-off duration**	**After Re-rounding** (Re-rounding time 20 min)
Circular	40 minutes	0.973
Elliptical		1.009
Circular	120 minutes	0.969
Elliptical		0.998

From Table 4 above, it is clear that elliptical type is better than circular type as imagined; the oval ratios of elliptical type are both within 1% of 1.0, whereas the ratios scatter within 4% of 1.0 with circular type. It is, therefore, recommended to use an elliptical type for re-rounding.

4.4. Reinforcement fitting

Reinforcement couplers (Figure 6a) and reinforcement saddles (Figure 6b) have been evaluated by mechanical strength tests conducted at a laboratory of TIGRE S/A, in Joinville, Brazil from February 26th to April 18th and from September 5th to October 21st in 2013.

Note that two saddle fittings are used in pair (180 degrees apart) although only one saddle is shown in the Figure 6 (b).



a) b)

Figure 6 Reinforcement fittings: a) Coupler and b) Saddle

4.4.1. Hydrostatic tests

Short and long term accelerated hydrostatic tests were conducted on PE100 pipes (SDR11, 63mm outer diameter) under the conditions presented in Table 5 (ISO 1167) in the hot water bath shown in Figure 7.

8 test pipes, number 3 to 10 in Table 2, had undergone squeeze-off, re-rounding and reinforcement process before the tests. They are different one another in its squeeze-off duration Tsq (40 min, 2 hours), re-rounded duration Trr (10 min, 20 min), re-rounding tool (elliptical, circular) and reinforcement fitting type (coupler and saddle).

Table 5 Accelerated hydrostatic test conditions (ISO 1167)

Test type	**Circumferential stress σ_c**	**Required Min. Duration**
Short term resistance to pressure at 80ºC	5.5 MPa	165 hours
Long term resistance to pressure at 80ºC	5.0 MPa	1,000 hours

Before putting reinforcement fittings, all pipes have been *perforated* (see `Artificial hole` in Fig.8) to simulate a situation that Slow Crack Growth, initiated at damages at inner surface, reaches at the outer surface, so that the internal gas pressure is imposed on the inner surface of the reinforce fitting, especially on the fusion weld parts which seem to be critical.

Figure 7 Hot water baths (80°C)

Figure 8 below illustrates the reinforced pipe section with an artificial hole.

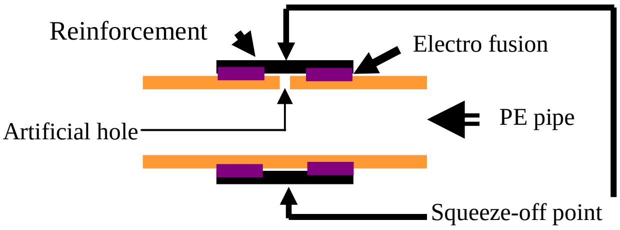


Figure 8 Reinforced pipe submitted to hydrostatic test

Results - All pipes cleared short term and long term tests in Table 5 without any leakage or any visible deformation. Figure 9 below shows one of the records of the evolution of internal pressure, which was constant for more than 1,000 hours.

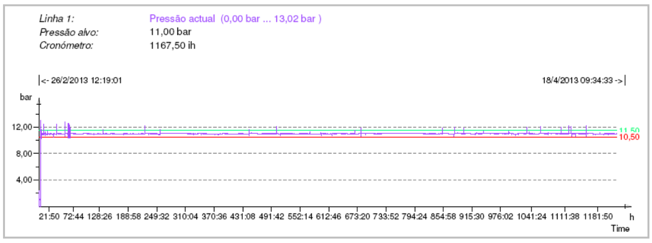


Figure 9 Pressure during hydrostatic test

4.4.2. Rupture tests

After the above hydrostatic tests, we conducted 4 rupture tests to compare mechanical strength of reinforced part and pipe body.

In the first two ruptures tests, Tsq (duration of squeeze-off) was 120 min. and Trr (duration of re-rounding) was 20 min. with coupler fitting in both test pipes. The difference was the re-rounding tool: one with elliptical and the other with circular.

Results - Both test pipes had ductile type ruptures in the pipe body as shown in Figure 10. It signifies that the reinforced part has more strength than pipe body after having endured 1,000 hours hydrostatic pressure under accelerated condition.

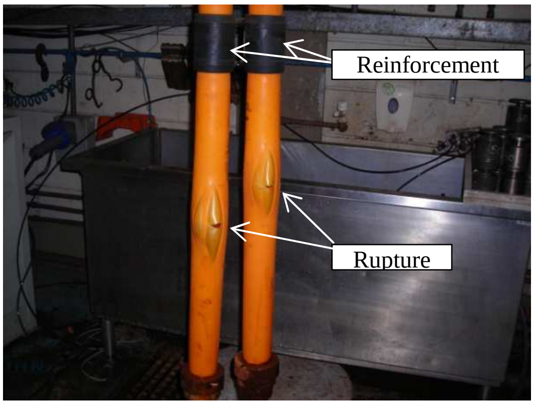


Figure 10 Results of rupture tests

Last two pipes were tested to verify the strength of saddle fittings. Pipes were re-rounded for 10 min. with elliptical type. The difference of the two pipes was Tsq = 40 min. and 120 min.

Results - Once again both pipes had ductile rupture in the pipe body at around 5 MPa of internal pressure.

4.5. Reinforcement method with coupler

The reinforcement method using EF coupler joint was invented by SEKISUI, a Japanese PE pipe manufacturer for water and gas industry, and used by the water industry. It is full encirclement type reinforcement and consists of the following steps:

1) A reinforcement coupler is introduced when a pipe section is cut off for the repair*;

2) After repair and re-rounding of the squeezed-off part, the EF joint coupler is slide to the squeezed point;

3) Electro-fusion of the reinforcement coupler is done and the reinforcement finishes.

* inside stoppers need to be removed beforehand

Figure 11 illustrates the reinforce method using couplers (EF joints).

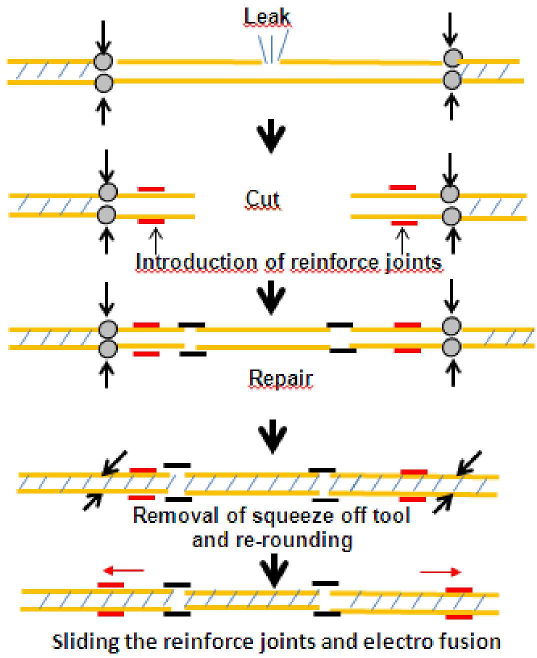


Figure 11 Reinforcement using EF couplers

4.6. Procedure of squeeze-off and reinforcement

Considering the results of tests mentioned above, the procedure of squeeze-off and reinforcement should be:

- Always do reinforcement when squeeze-off is applied to PE 100 pipes (unless effective inspection and evaluation method of internal damage is established);
- An elliptical type is preferable for re-rounding;
- Try to use a coupler EF joint reinforcement which is full encirclement type. A saddle type is acceptable only when it is difficult to slide the coupler joint;
- Register the squeezed-off point in GIS.

5. Comparisons between PE100 and PE 80

We made comparisons of PE100 and PE80 in two terms: 1) flow capacity and 2) installation costs.

For the purpose of the comparison of flow capacity, we conducted simulations using SynerGEE®Gas software of the modeled network in the city of Vitória, state of Espírito Santo.

In the simulations, original pipe diameters were kept unchanged to PE100 pipes and PE80 pipes, while the maximum operating pressure were defined as 0.4 MPa for PE80 and 0.7 MPa for PE100. Minimum acceptable delivery pressure was 0.1 MPa to all clients.

Result- Figure 12 bellow shows an example of the results of the flow simulations.

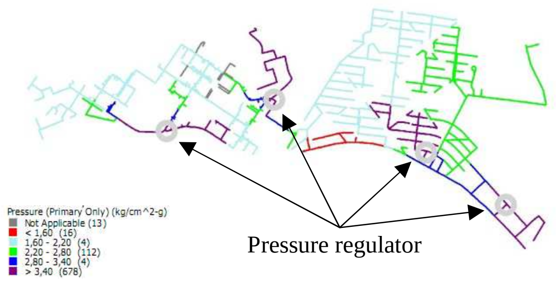


Figure 12 Example of the results of gas flow simulation

PE100 network with 0.7 MPa presented *1.68 times* higher flow capacity than PE80 networks.

To make comparisons of installation costs, we adopted, as a reference, installation bid price put forward by a contractor in 2013 to construct 66 km PE pipe networks in the neighboring cities of Vila Velha and Serra.

As for pipe costs, we referred a PE pipe manufacturer in Brazil and found that the prices of PE100 pipes are 10% higher than PE80 pipes on average.

Here, total costs are calculated as below:
Total costs = Installation costs + Pipe costs.

Result - Based on the premises above, the calculation of PE100 installation costs shows only *0.52%* higher than PE80. It would be because pipe material portion occupies very small part in the total installation cost components.

As a conclusion, PE100 pipe networks can increase its flow capacity by 68% while there is an increase in total installation costs by only 0.52%, compared with PE80 pipe networks.

Table 6 below summarizes the results of the comparisons mentioned above.

Table 6 Results of comparison <PE100 vs PE80>

Resin type	MOP (MPa)	External diameter	Relative cost	Relative flow capacity
PE80	0.4	63	100	100
PE100	0.7	63	100.52	168

6. Conclusions

- A PE100 pipe network with MOP 0.7 MPa has 1.68 times more flow capacity than PE 80 pipe network with MOP 0.4 MPa with less than 1% increase in total installation costs.
- One of the obstacles in the use of PE100 would be its vulnerability to squeeze-off. To overcome this problem, it is suggested to carry out reinforcement every time after applying squeezing-off.
- The Japanese water industry adopts a simple and effective method of reinforcement using EF coupler joint.
- It was shown through the mechanical strength tests that all the reinforced PE100 pipes using EF coupler and EF saddle types have passed accelerated 1,000 hours hydrostatic tests without any leakage. It was shown as well, after the above tests, that the reinforced part has more mechanical strength than the pipe body against internal pressure. Therefore, the reinforcements can assure long term integrity of squeezed-off PE100 pipes.
- The coupler fitting method, which is full encirclement type, is preferable because it covers the whole area affected by squeeze-off.
- The shape of roundness, which is obtained through re-rounding operation, is vital for secured reinforcement. Elliptical type re-rounding device has better re-rounding capacity than circular type and is recommendable.

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