Polyamide 12 for Gas Piping Systems with MOP 16/18 bar

Fitness for Alternative Installation Techniques demonstrated beyond PAS 1075

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For high pressure pipes this paper emphasizes PA-U12 as the easy to install alternative to steel. It underlines the superb performance of PA-U12 pipes for alternative installation techniques without need for a separate mechanical protection. An unplasticized polyamide 12 (PA-U12) pressure pipe compound was investigated by following PAS 1075 test principals and further modification of established and new small-scale accelerated reliable test (SMART) methodologies. The outstanding high combined resistance against external scratches from rocks after horizontal direct drilling (HDD) and against slow crack growth (SCG) as well as against penetration of shards (sharp fragment) of a cast iron pipe after burst lining is demonstrated. Results from a slightly modified Cyclic Cracked Round Bar (CRB) test allows the verification and ranking of the SCG resistance. It is concluded that PA-U12 pressure pipes are suitable for alternative installation techniques without an additional outside mechanical protection even in presence of rocks ‚n' shards.

Introduction

PA-U12 pressure piping systems are well known as a non-maintenance alternative versus steel pipes submitted to a maximum operating pressure (MOP) of up to 18 bar. Therefore, PA-U12 simply enlarges the operation pressure range of plastics in gas pressure piping systems from former 10 bar MOP for PE to currently 18 bar MOP, where it is competing with steel. Cost saving up to 60 % may be reached using non-conventional laying techniques in place of traditional laying techniques [1]. PA-U12 is benchmarked related to SCG methods and the historically in EU used PAS 1075 [2] test principals, to establish it as the easy to install thermoplastic alternative to steel.

Figure 1: PA-U12 pipe OD 160 after installation by HDD in Beckum (Westnetz, 2019)

Different publications have underlined the excellent resistance against third-party interventions [3, 4] and that related external surface damages are in general insignificant for the short or long-term performance of the PA-U12 pipes [5, 6, 7]. Slow crack growth (SCG) is regarded as a critical long-term failure mechanism for thermoplastic pipes. In the US notched pipe testing (notches 20 %, 30 %, and 50 % of wall thickness), and PENT testing have been carried out for PA-U12 using very aggressive test conditions. The lack of failures in all these tests demonstrate that the PA-U12 piping material has excellent resistance to the SCG mechanism [5].

As valid conclusions of SCG tests are based on brittle failures, the level of SCG resistance can only be demonstrated by modified SCG tests, as discussed in this paper [7, 8 ,9]. Already at PPXIX and 77th ANTEC it was published that the Cyclic Cracked Round Bar (CRB) test [11] is a suitable method to provoke real SCG in PA-U12 [10, 12]. Meanwhile the Strain Hardening (SH) test [13] and CRB test have been modified for PA U12 and results from both methods show a very strong and reproducible dependency to the molecular

Table 1: *Time to failure or to pipe removal of PA-U12 pipes under internal pressure and external point load [8].*

test 1219, run No.	test temperature [°C]	test pressure [bar]	equivalent test stress [N/mm²]	test duration [h]	remark
A5	40	36.85	17.01	14,440	removal without break; NM5
A6				14,440	
A3	60	31.63	14.75	22,582	
A4				22,582	
A7	80	28.14	13.00	4,528	tool tip penetration; water
A8				4,528	
A1				5,600	tool tip penetration; NM5
A2				4,871	
A9		21.66	Reduced to 10.00 ***)**	10,939	break at point load; NM5
A10				10,939	incipient crack at point load; NM5

*) with 0,3 mm axial notch at the inner pipe surface

weight (MW), which is expressed as viscosity number (VN) in case of polyamides. Moreover, for the tested PA-U12 grades both test methods correlated well to each other [13].

The public available standard (PAS) 1075 “Pipes made from Polyethylene for alternative installation techniques – Dimensions, technical requirements and testing” [2] is well established to provide requirements for polyethylene (PE) used in alternative installation techniques, as well as for the definition of PE with higher resistance to cracks (PE 100 RC). By referencing to PAS 1075 certification programs for PE and PE pipes with protection layers define thresholds for the suitability of pipe grades for alternative installation [14]. Within the current paper all aspects of the PAS 1075 test program will be covered by PA-U12 conform modifications or substitutions of tests with the target to verify that PA-U12 pipes can be laid by alternative installation methods without the need of any precaution, whether by ploughing or horizontal directional drilling (HDD) (***Figure 1***) in presence of rocks or by burst lining in presence of related shards.

Slow Crack Growth (SCG) and Brittle Failures for PA-U12

Surface damages a./o. loads potentially initiate and/or accelerate SCG as the most relevant failure mechanism during the operation of buried thermoplastic pressure pipes. Valid SCG test results are based on brittle failures, which for PA-U12 have not been observed by conventional test methods even after extreme long test durations. Finally, brittle SCG failures have been published first times for PA-U12 only after the modification of a full notch creep test (FNCT) [7] and a cyclic CRB test [10]. Results of notch pipe tests [6] at 90 °C test temperature are not representative as the increased temperature affected the crystallinity and caused hardening effects. This indicates that rising the test temperature over and including 90 °C is no option for the acceleration of SCG tests, as related recrystallization effects reduce the validity and/or comparability of test results.

Point Loading Test (PLT) and Acceleration Factor by Full-N Creep Test (FNCT)

Rocks, roots or other effects in the sand-less bed of a trench can lead to external point loads on pipes. Their resistance to SCG can be determined using the point loading test (PLT) acc. to Annex A3 of PAS 1075 [2].

At PPXIV results of FNCT and PLT were presented, where SCG was accelerated based on the non-standardized surfactant NM5 (2 % NM5 in deonized water, where NM5 is a mix of anionic and cationic tensides instead of lower accelerating Arkopal N-100). For FNCT, at σ = 14 MPa an acceleration factor of 34,2 has been determined for NM5 compared to water at T = 80 °C, and at σ = 8 MPa a brittle fracture surface of a FNCT-specimen extracted from a PA-U 12 pipe was shown. Until PPXIV the OD 110 SDR 11 pipe specimens did not fail in the PLT. Based on testing of 4500 hours at T = 80 °C the paper carefully concluded that “the installation of PA-U12 pipes for the transport of gas or water without sand embedding should be possible if the internal pressure is limited” [7].

After PPXIV this PLT test program has been continued with the target to create a brittle failure. Based on test temperature and test pressure combinations the equivalent test stresses have been calculated by using the modified Arrhenius concept (MAC) [15]. For 20 °C, the extrapolation according to MAC resulted in an equivalent stress of 20 N/mm² or in a MOP of 40 bar for SDR 11 pipes, respectively.

Table 1 shows the experimental PLT program and its results, where partially extreme long test durations are presented. Only the PLT run No. A9 with the reduced equivalent stress of 10 N/mm² and the axial notch at the inner pipe surface was able to initiate a brittle slow crack [8]. For comparison, clause O of DIN CERTCO‘s certification program specifies as minimum requirement for PLT of PE 100-RC pressure pipes

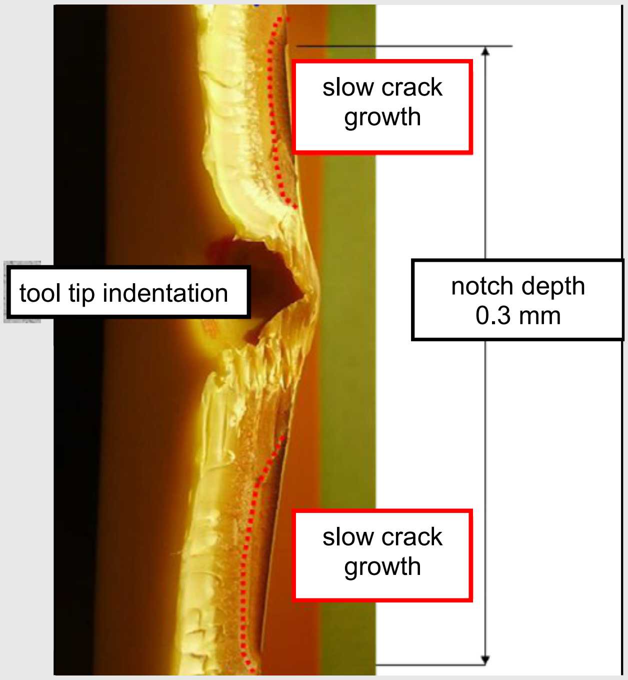


***Figure 2**: Brittle failure of notched PA-U12 pipe A9 after 10,939 h PLT (2 % NM5, 80 °C) [8]*

8,760 h at 80 °C and 4 N/mm² in 2 % Arkopal N-100 (note: a PE threshold in NM5 is only given for 90 °C) [14].
The results of the continuation of the PLT program have been discussed and interpreted based on Arrhenius principals. The PA-U12 pipe sample A9 had to be notched to provoke brittle failure as shown by ***Figure 2***. This brittle failure occurred at 2.5 times higher stress and approx. 25 % later then required in PAS 1075, although the acceleration factor of NM5 is by far higher than that of Arkopal N-100 [14]. Underlined by the fact that a brittle failure could only be generated by an additional notching of the inner pipe surface under the point load the report concludes that "PA-U12 pipes OD 110 SDR 11 are suitable for the transport of gas or water for laying methods without sand bedding" [8]. This statement includes no restriction for MOP 18 bar as specified by ISO 16486 series.

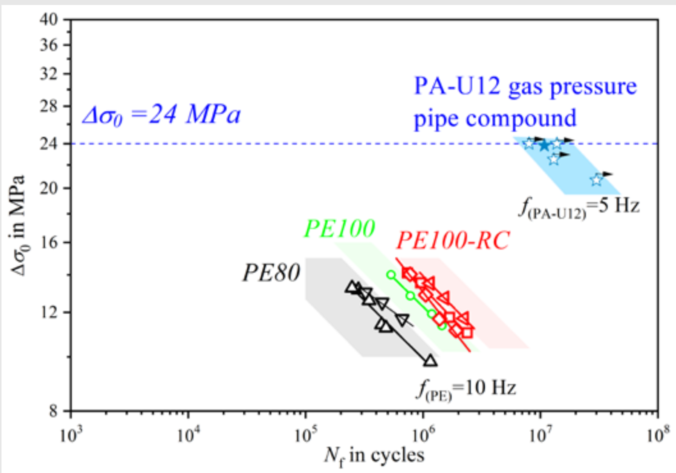


***Figure 3**: Failure cycle numbers Nf as a function of the applied stress ranges $\Delta\sigma_0$ in the Cyclic CRB tests of PA-U12 in direct correlation with typical failure regions of PE pipe grade classifications with representative test results [12]*

Cyclic Cracked Round Bar (CRB) Test

The cyclic CRB test is an established methodology for the determination of the SCG resistance of thermoplastic resins [24]. For testing PA-U12 the conditions as specified by ISO 18489 have been modified by lowering the loading frequency for the cyclic load from 10 Hz to 5 Hz for PA-U12 to prevent from effects of hysteretic heating. Moreover, higher loads were applied resulting in a stress range of $\Delta\sigma_0 > 20$ MPa [10]. The cyclic CRB as modified for PA-U12 has been investigated by a comprehensive research, where publications demonstrate the ability to characterize the SCG in correlation to SH [13], explain fracture modes [10,12] and compare results to PE [12].
For PE grades, brittle failures from cyclic CRB test have been published in 2015 and ***Figure 3*** shows the failure cycle numbers of PE [12] for comparison with those for a commercial PA-U12 high pressure pipe compound. Therefore, CRB specimens from PA-U12 with an OD of 13.8 mm have been tested by PCCL at $\Delta\sigma_0 = 24$ MPa as well as by Evonik at $\Delta\sigma_0 = 22{,}5$ and 20,5 MPa as shown by Figure 2. A filled asterisk as symbol represents a completed test including failure by SCG, while an unfilled symbol stands for an early stop of a test under already clear brittle failure mode [16] due to extreme testing duration.
Figure 3 shows that at minimum 1.8 times higher cyclic loads the level of failure cyclic numbers for PA-U12 is approx. one decade higher as for PE 100 grades. This extraordinary high SCG resistance underlines the findings of Hessel [7, 8] and it explains why with conventional SCG test methods also extreme test durations could not cause brittle failures. Previously discussed concerns on conventional methods have no meaning for CRB as its acceleration principal is based on a cyclic load and its "Wöhler" effect on a notched sample at room temperature. Furthermore, the potentially extraction of specimen from pipe walls may rise the future meaning of CRB for component testing.

Penetration Test

Shards (or sharp fragments) of a burst-lined cast iron pipe may penetrate through the wall of a pipe under internal service pressure. This is simulated by the penetration test acc. to Annex A.4 of PAS 1075 [2]. The penetration resistance of a PA-U12 pipe wall has been tested compared to a commercial OD 110 pipe concepts for alternative installation.
To simulate the penetration of a shard into the wall of a pressurized pipe, a die stamp (OD 6 mm) with blunted spike (OD 2 mm) displace the outside of the pipe before

Table 2*: Penetration Test on OD110 SDR11 pipes - test conditions (for water in water environment) and remaining wall thickness after 9000 h testing without failure [17].*

pipe	sample	wall thickness WT [mm]	displacement [%]	test temperature [°C]	hoop stress [MPa]	test pressure [bar]	remaining corrected WT 5) [%]
PA-U12	A2 1)	10.40	8.18	20 ±1	**13.46** 3)	27.9	**74.1**
	A3 1)			60 ±1	8.39 3)	17.4	64.7
	A4 1)			80 ±1	6.88 3)	14.3	57.1
PE/PP	B2 2)	**12.36** 4)		20 ±1	**7.48**	18.9	**74.0**

1) sample A: PA-U12 plain solid wall pipe
2) sample B: PE 100-RC pipe with an additional external PP protective layer
3) PA-U12 test pressure corresponds to 1,8 times of PE 100 (proportional to MOP)
4) Wall thickness of the pipe and the additional external protective layer.
5) The remaining WT was corrected with the result of the test without displacement.

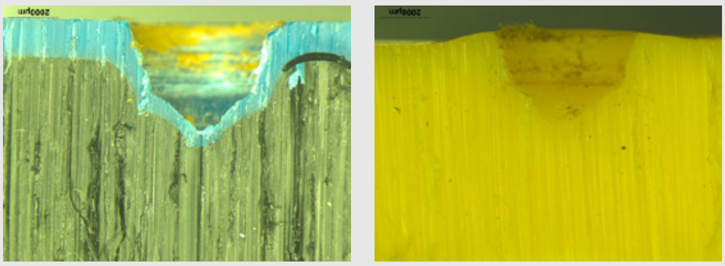
pressurizing it for starting the test. For the PA-U pipe this test has been carried out at different temperatures on 1.8 times higher stress level compared to PE. ***Table 2*** shows the test conditions and the results after 9000 h for a PA-U12 pipe and at 20 °C also for PE 100-RC pipe with an additional external PP protective layer. For room temperature the penetration depth into PA-U is 2.7 mm (= 25.9 % x 10.4 mm) under 1.8 times higher hoop stress compared to 3.2 mm (= 26 % x 12.36 mm) for the PP protected PE pipe, which is presented by photographs of the cross section in ***Figure 4***. According to PAS 1075 more than 50 % of the pipe wall thickness shall remain after 9000 h test duration, which for PA-U is fulfilled up to including 80 °C test temperature.

External Scratch Tests

Rocks with sharp edges can scratch pipe surfaces during horizontal direct drilling. The external protective layer scratch test acc. to Annex A.6 of PAS 1075 [2] or the gouge resistance test as defined by CSA Z 245.21-10 [19] are simulating this, where the scratch or penetration depth of a defined blade into the pipe or its protective layer surface is determined under constant load at constant speed.
The scratch resistance has been tested according to Annex A.6 of PAS 1075 [2], where under a load of 6 kg a 0.45 mm thin blade scratches the pipe surface with a speed of 100 mm/min over a length of min. 600 mm at 23 °C and on request at -10 °C [18]. For three commercially available OD 110 SDR 11 pipe solutions for alternative laying methodologies the scratch depths have been determined at

» a PA-U12 surface from PA-U12 plain solid wall pipe (no protective or outer layer)
» a PP surface from PE 100-RC pipe with external PP protective layer and
» a PE 100-RC surface from PE 100-RC pipe with integrated protective layer

The PP or PE 100-RC protective layers of both commercial PE pipe concept fulfilled the requirement for the scratch depth relative to the layer thickness. However, ***Figure 5*** shows only the values for the scratch depth as the relevant parameter for comparing PA-U12 with the outer protective layer materials PP and PE 100-RC. In principal, the scratch depth value is determined by dividing the line integral under the scratch depth curve by the length of the scratch. Within and between this scratch depth curves there is a wide scatter. Nevertheless, results like average scratch depth data are valuable indicators for scratch resistance of the thermoplastic surfaces. For PA-U12 the maximum scratch depth at room temperature is 0.53 mm only. And at same temperature the scratch depth values for PA-U12 are more than two times lower as for PP and more than six times lower as for PE 100-RC.
These results are in line with those from the gouge resistance test as defined by CSA Z 245.21-10 [19]. For a curved test tip (RT, 50 kg, 200 mm/min) a maximum penetration depth of 0.5 mm is determined for PA-U12, which is three times lower as for PP and approx. five times lower as for PE [20]. The relations between this gouge resistance test results are meaningful for thermoplastic pipes, allthough it is standardized for determining the quality of plant-applied external coatings for steel pipes..
Furthermore, the publications [20, 21, 22] present photos and REM images of pipe specimen surfaces from PA-U12 and PE after alternative installation. In line with both scratch test results, relatively low affected PA-U12 surfaces are in opposite of multiple and deep scratched PE after four times horizontal direct drilling (HDD) in rocks containing soil.
If pipe temperatures above room temperature may ask for



Sample A2
20 °C / 13.46 MPa / 8.18 % displacement

Sample B2
20 °C / 7.48 MPa / 8.18 % displacement

Figure 4*: Cut through the pipe wall / penetration point (close up) [17]*

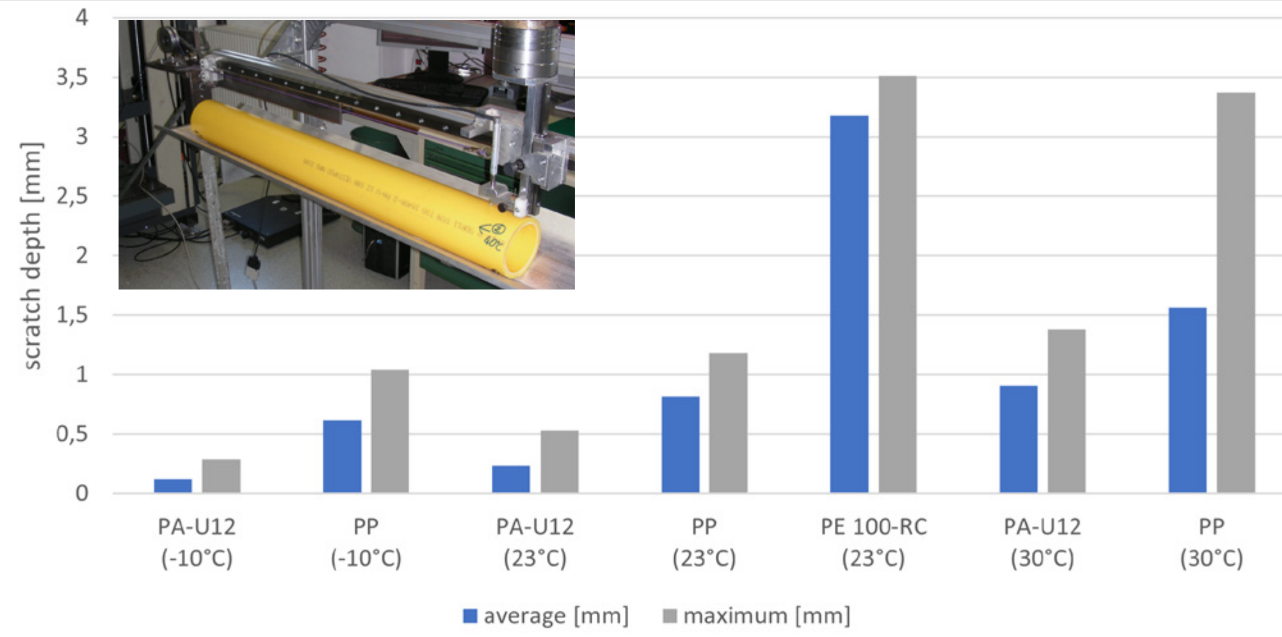


Figure 5*: Scratch test rack and scratch depth comparison of PA-U12 pipe surface to PP or PE 100-RC for –10 °C, room temperature and +30 °C [18]*

raising the wall thickness (WT) for covering potential scratch depth, existing WT reserves have to be considered like 11.1 % for PA-U180 pipes in CEN installations for MOP 16 bar.

Drag Force and Time Savings for Installation

For trenchless installation techniques such as HDD or burst lining, in general pipes from coils are installed by unwinding and pulling them into newly drilled holes or burst and enlarged holes from already existing pipes, respectively. The pipes shall not be overstressed by tensile forces during laying and therefore the maximum drag force F is defined by the following equations as specified by CEN TS 12007-6:2021 [23]:

$$F = \frac{\sigma \times \pi \times d_e^2}{SF \times SDR} \quad \text{with} \quad \sigma = \frac{\sigma yield}{1{,}25}$$

For comparing PA-U12 with PE pipes from same design the maximum drag force F correlates to the tensile stress at yield σ_{yield}, as external diameter d_e, standard dimension ratio SDR and safety factor SF are the same for both materials.
Considering the levels for tensile stress at yield as given by ***Table 3***, for PA-U12 the maximum drag force F allows to pull pipes of approx. double length compared to PE 100.

Table 3*: Level of tensile stress at yield* σ_{yield} *for PA-U12 180 and PE 100*

Tensile specimen from pipe	unit	PA-U12 180	PE 100
Tensile stress at yield acc. to ISO 527	[MPa]	~ 40	~ 20 - 23

That also reduces the number welds to the half resulting in additional relevant saving of corresponding time and costs for the installation of PA-U12 pipes by trenchless installation techniques.

Conclusions

The question why "Polyamide 12 is the easy trenchless to install alternative to steel" can be answered by the perfect combination of its product profile:

- high long-term hydrostatic strength allows MOP up to incl. 18 bar
- extreme impact resistance against damages during handling
- superior resistance against scratches from rocks during HDD
- very high resistance against penetration of shards from burst lining
- superlative slow crack growth resistance (5 to 10 times higher like for PE 100-RC)
- high drag force effects savings by installation of very long pipe segments from coils

The proven superlative SCG resistance is the key that PA-U12 high pressure pipes have not to care about rocks and shards, even in case of notches or scratches on the pipe surface. The superior results of all single tests discussed in this paper lead to the overall conclusion that high-pressure pipes made from this PA-U12 compound are suitable for alternative installation methodologies without any external protection layers. Hence, on top of approved PE concepts for alternative installation with MOP up to including 10 bar, this paper supports to establish "PA-U12 as the easy to install alternative to steel" for MOP at even higher pressure rates up to including 18 bar.

Acknowledgments

The research work of this paper was performed by the accredited test lab for plastics of the Technologische Gewerbemuseum (TGM, Austria), the Polymer Competence Center Leoben GmbH (PCCL, Austria) and the polymer testing lab of Evonik (Germany) supported by the German Plastics Center SKZ (Germany).

References

[1] Godon, P., Popa, A.; Non-conventional installation techniques' requirements, PPXIV, Budapest, Hungary:2008.

[2] Hessel, J., et al., PAS 1075 (Publicly Available Specification) Pipes made from Polyethylene for alternative installation techniques – Dimensions, technical requirements and testing, 2009

[3] Kempenich, S., et al., The resistance to impact of Unplasticized Polyamide 12 (PA-U12) pipes, PPXVII, Chicago, USA: 2014

[4] Taguchi, H. et al., Evaluation of the resistance to third party attacks of plastics pipes, PPXVIII, Berlin, Germany: 2016

[5] Patadia, H., Evaluation of Polyamide 12 (PA 12) for high pressure gas distribution applications, GTI: 2006 (public available by internet search)

[6] Taguchi, H., Numata, K., "Investigation of the creep failure behavior of polyamide pipes", PPXIX, Las Vegas, USA:2018

[7] Hessel, J., „Buried PA 12 pipes for then transport of gas & water; No sand embedding necessary?", Plastic Pipes XIV, Budapest, Hungary:2008.

[8] Hessel, J., Punktlastversuche an PA12-Rohren (110x10) im Hinblick auf die Anwendung nicht-konventioneller Verlegemethoden; Report R09 04 1219, 2009

[9] Messiha, M., Frank, A., PPT charts 12 and 26 of "Determination of the slow crack growth resistance of PA 12 pipe grades"; PPXIX, Las Vegas, USA; 2018

[10] Messiha, M., Frank, A., Determination of the slow crack growth resistance of PA 12 pipe grades; PPXIX, Las Vegas, USA; 2018

[11] ISO 18489 Polyethylene (PE) materials for piping systems — Determination of resistance to slow crack growth under cyclic loading — Cracked Round Bar test method

[12] Messiha, M. et al; Differences and similarities in fatigue failure mechanisms of PA 12 pipe grades compared to modern PE pipe grades; 77th ANTEC, Detroid, USA; March 2019

[13] Messiha, M., Gerets, B. et al; Investigating the applicability of the Strain Hardening Test and the Cyclic Cracked Round Bar Test to determine the Slow Crack Growth Resistance of modern PA-U12 grades; Journal of Polymer Testing, June 2020

[14] DIN CERTCO, Zertifizierungsprogramm Kunststoffrohrsysteme (Druckrohre und -formstücke) - Anhang OZP 14.23.39 - Druckrohre aus Polyethylen (PE) für alternative Verlegetechniken - PE 100-RC; www.dincertco.de; May 2017

[15] DVS 2203-4, Suppl. 3; Testing of welded joints – Tensile creep test – Checking the required tessile creep test weld strength reduction factor and the minimum service life of PE welded joints Messiha, M. et al; Investigating the influence of changes in molecular structure of PA 12 grades on the resistance against slow crack growth, PPXX, Amsterdam 2020

[16] TGM; Penetration test on pipes Dn 110 x 10 mm acc. to PAS 1075; test report VA KU 28345, Vienna (AU), 2020 May 27

[17] TGM; External protective layer scratch test on pipes OD 110 mm x WT 10 mm acc. to PAS 1075 (04.2009); test report VA KU 28345-2, Vienna (AU), 2020 July 2

[18] CSA Z 245.21-10 plant-applied external polyethylene coating for steel pipe – gauge resistance of PE coating.

[19] Stich, M.; et al; PA as reliable coating for steel pipe at Marl chemical park; 3R (p. 62 – 66), 2016

[20] Dowe, A.; et al.; Pipe made from PA12 – the right choice for trenchless installation, PPXV, Vancouver, Canada: 2010

[21] Stich, M.; et al; Innovativer Werkstoff schützt neue Fernleitung am Chemiepark Marl, bbr, 2015

[22] CEN TS 12007-6:2021; Gas infrastructure — Pipelines for maximum operating pressure up to and including 16 bar — Part 6: Specific functional recommendations for unplasticized polyamide (PA-U)

[23] Arbeiter, F., et al; Cyclic tests on Cracked Round Bars as a quick tool to assess the long-term behavior of thermoplastics and elastomers. Polymer Testing 45, 83–92. doi:10.1016/j.polymertesting. 2015.05.008

KEYWORDS: Polyamide 12, MOP 18 bar, gas piping systems, alternative installation, PAS 1075, cracked round bar test, strain hardening test

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