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INAIL

Ageing of high density polyethylene piping

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Pipes in high-density polyethylene piping: Just to begin

The drain tube of my shower

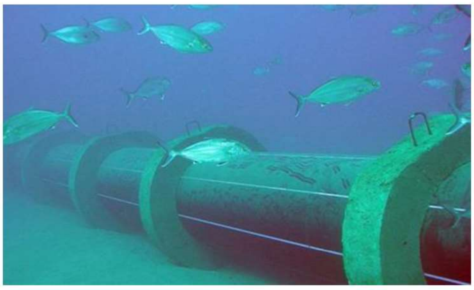
The brittle fracture occurred after no more than 20 years of use

A very little piece
but I had to spend 500 euros to replace it and to paint the ceiling of the apartment below

Pipes in high-density polyethylene piping: Applications

Pipes in high-density polyethylene piping: Under ground

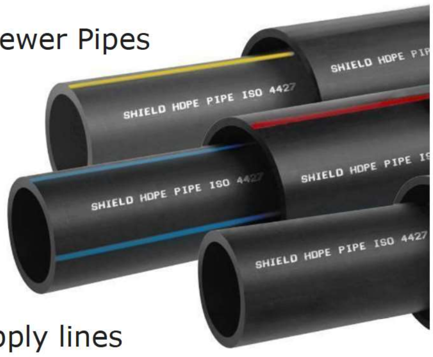
Pipes in high-density polyethylene piping: Under sea



Pipes in high-density polyethylene piping: Types

Black no Stripes – For all applications except for fuel gasses

Black with Cream Stripes – Sewer Pipes



Black with Yellow Stripes or Full Yellow Jacket –
Fuel gases, process gases, liquefied gases under pressure

Black with Blue Stripes – Drinking/potable water

Black with Lilac o Purple Stripes – Recycled or reclaimed water

Black with Red Stripes – Water dedicated for fire extinguishing supply lines

Pipes in high-density polyethylene piping: Sizes and Characteristics

Mechanical characteristics	Value	Thermic characteristics	Value
Density	0.95 g/cm^3	Melting point	130 °C
Yield stress	25 MPa	Max service temperature for short time	90 °C
Elongation at yield	10 %	Max service temperature for long time	75 °C
Elongation at break	> 600 %	Minimum service temperature	-200 °C
Young's modulus	1000 MPa	Softening temperature	80 °C
Bending resistance	24 MPa	Linear thermal expansion coefficient	1.8×10^{-4} K^{-1}
Impact resistance	No breakage	**General characteristics**	**Value**
Hardness (Rockwell ball)	46	Weather resistance	Medium
Compression permissible load	22 MPa	Flammability	Flammable

Mechanical and Thermic Characteristics

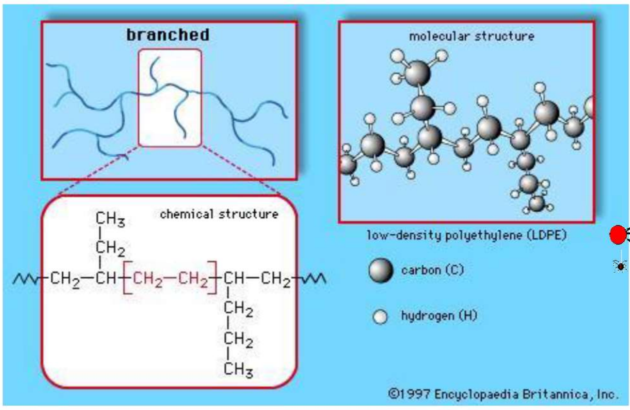
In yellow, the gas pipe under periodic requalification referred to the Italian DM 329/04

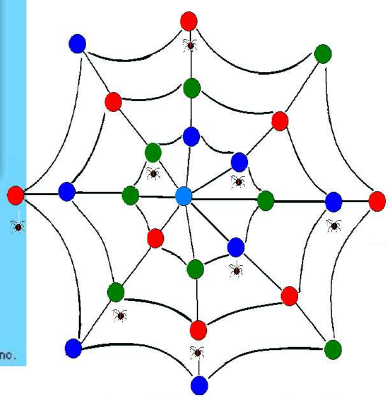
Model number: Gas pipe
Material: HDPE

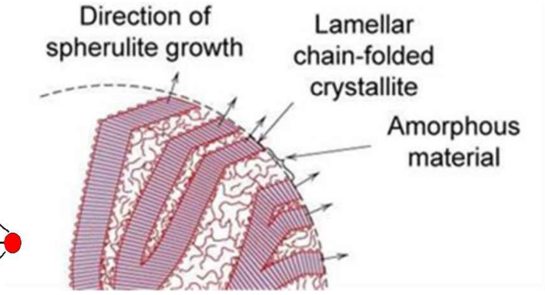
Specification:

Nominal External Diameter dn, mm	PE80		PE100	
	SDR 17,6	SDR 11	SDR 17,6	SDR 11
	Pressure Nominal PN ≤ 0,2 MPa	Pressure Nominal PN ≤ 0,4 MPa	Pressure Nominal PN ≤ 0,6 MPa	Pressure Nominal PN ≤ 1,0 MPa
	Nominal Thickness en, mm	Nominal Thickness en, mm	Nominal Thickness en, mm	Nominal Thickness en, mm
20	2,3	3	2,3	3
25	2,3	3	2,3	3
32	2,3	3	2,3	3
40	2,3	3,7	2,3	3,7
50	2,9	4,6	2,9	4,6
63	3,6	5,8	3,6	5,8
75	4,3	6,8	4,3	6,8
90	5,2	8,2	5,2	8,2
110	6,3	10	6,3	10
160	9,1	14,6	9,1	14,6
200	11,4	18,2	11,4	18,2
250	14,2	22,7	14,2	22,7
280	15,9	25,4	15,9	25,4
315	17,9	28,6	17,9	28,6
355	20,2	32,3	20,2	32,3
400	22,8	36,4	22,8	36,4
450	25,6	40,9	25,6	40,9
500	28,4	45,5	28,4	45,5
560	31,9	50,9	31,9	50,9
630	35,8	57,3	35,8	57,3

The high-density polyethylene: morphology and chemical structure

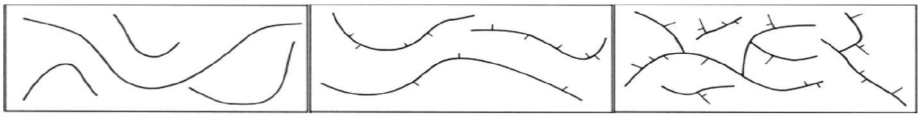






HDPE

Additives to prevent oxidation mechanisms



High-Density PolyEthylene
Low degree of short-chain branching

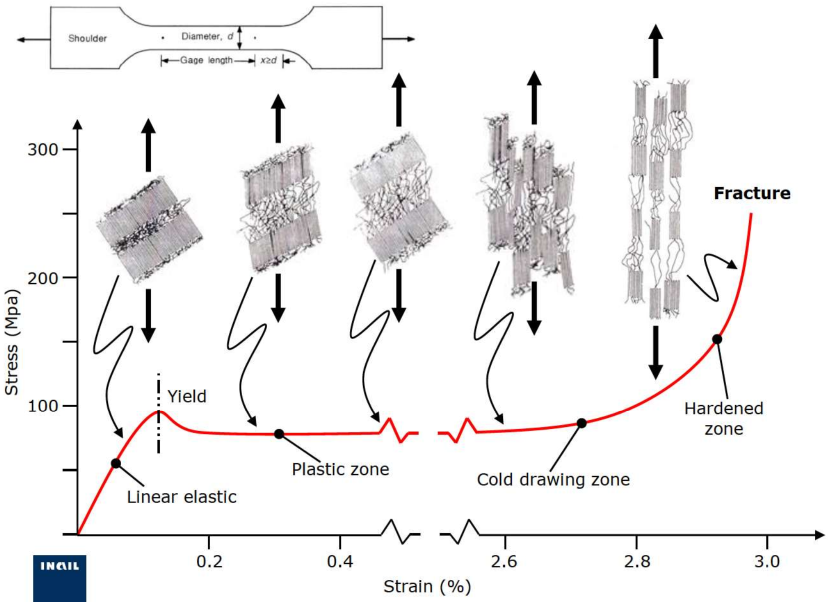
Linear-Low-Density PolyEthylene
High density of short-chain branching

Low-Density PolyEthylene
High degree of short-chain branching + long-chain branching

The high-density polyethylene: mechanical characteristics

Due to the semicrystalline structure, the HDPE is a viscoelastic polymer

ASTM D638 '*Standard test method for tensile properties of plastics*'



In addition to the elastic zone that is really short

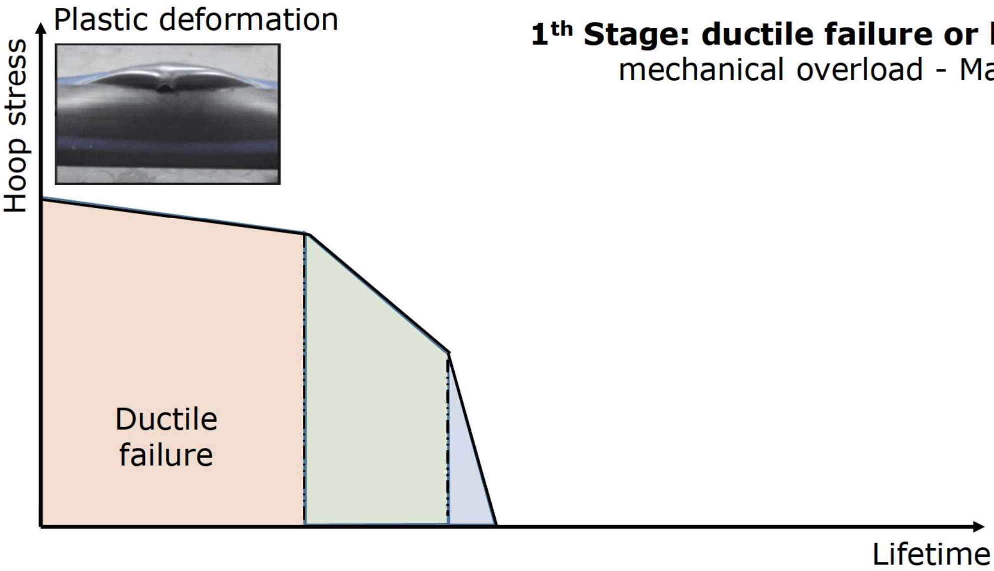
three main zones in the stress-strain curve:

1) **The plastic zone**: an increase in deformation does not correspond to an increase in tension. In this area the load is supported by the crystalline phase

2) **The cold drawing zone**: the lamellae of the crystalline phase flow and the amorphous phase settles accordingly. In this area the load is supported both by the amorphous and by the crystalline phase

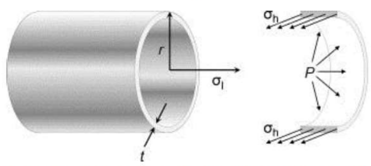
3) **The hardened zone**: for further deformations the amorphous phase has reached its maximum extension. Further deformation causes the crystalline phase to break

The high-density polyethylene piping: mechanical characteristics during the lifetime



1th Stage: ductile failure or ballooning - Pipe is subjected to mechanical overload - Material fails due to ductile yielding

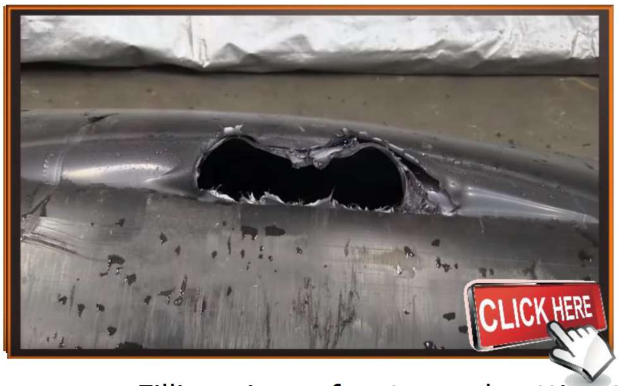
$\sigma_h = P\,r\,t$

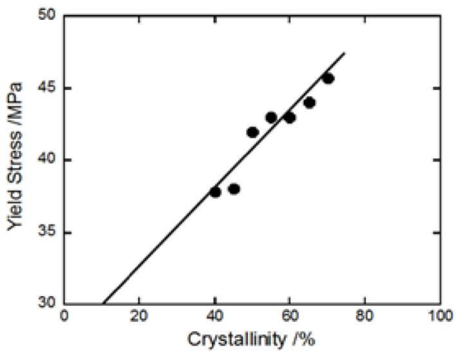


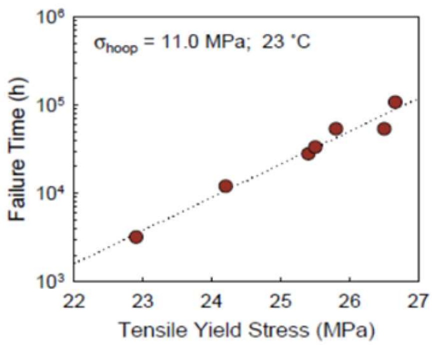
ASTM D1598-15a '*Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*'

Mechanical characteristics during the time: ductile failure

In the 1th stage if the pipe is subjected to mechanical overload, the material fails due to ductile yielding







Filling pipes of water and putting them in pressure till they break, it can be seen that:
the higher is the crystallinity percentage of the HDPE used ->
-> the higher is the value of the Yield stress of the pipe

Fixing the pressure inside the pipes at values that overload the material, it can be seen that:
the higher is the Yield stress of the HDPE used ->
-> the higher is the time to fail of the pipe

Mechanical characteristics during the time: ductile failure

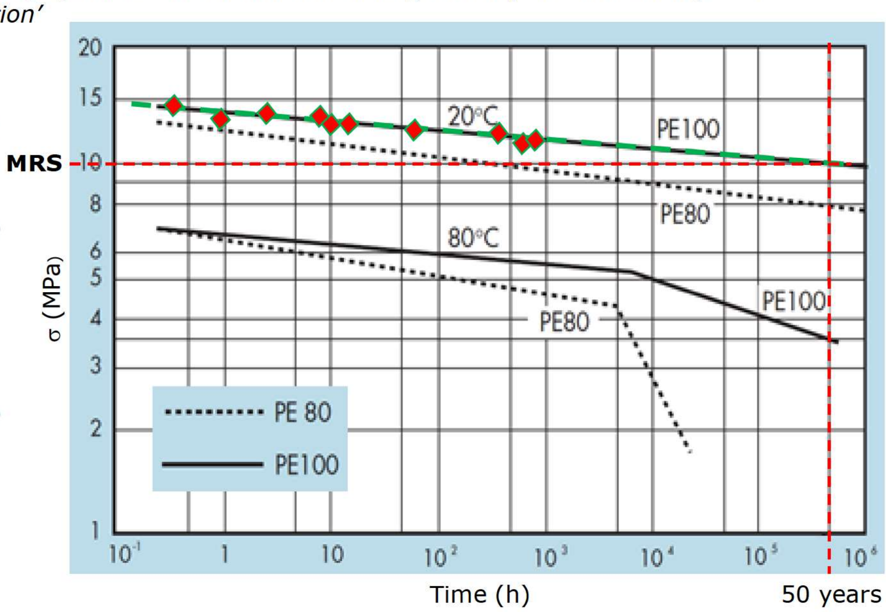
Performing hydrostatic tests until failure or not less then 9000 hr

in accordance with ISO 9080 *'Plastic pipe and ducting systems - Determination of long term hydrostatic strength of thermoplastic materials in pipe form by extrapolation'*

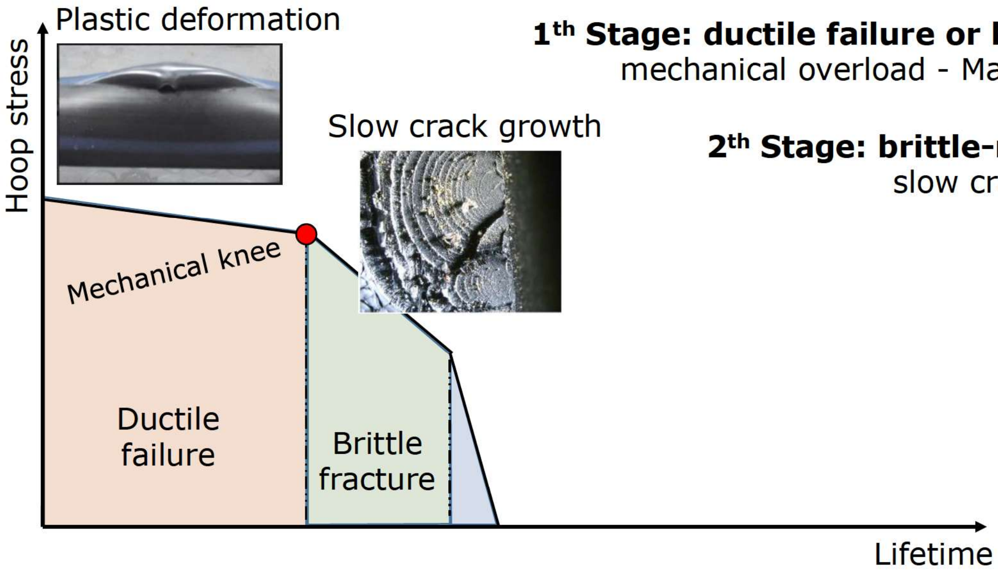
and extrapolating the measured curve it can be determined the <u>Minimum Required Strength</u> (**MRS**) that can be thought as the load – due to pure internal pressure – that would cause the pipe ductile failure after 50 years of service at 20 °C

If the tests are performed <u>at temperatures higher</u> than 20 °C <u>the curves are lower</u> and show a knee followed by a faster descent long before than the 50 years of service:

this is the so called 'mechanical knee' and indicates that <u>the HDPE begins to mechanically react to the load in a different way</u>



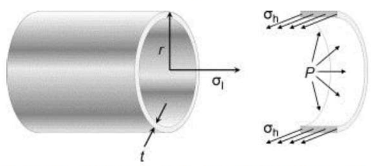
The high-density polyethylene piping: mechanical characteristics during the lifetime



1th Stage: ductile failure or ballooning - Pipe is subjected to mechanical overload - Material fails due to ductile yielding

2th Stage: brittle-mechanical failure - Caused by slow crack growth through the pipe wall in a brittle manner

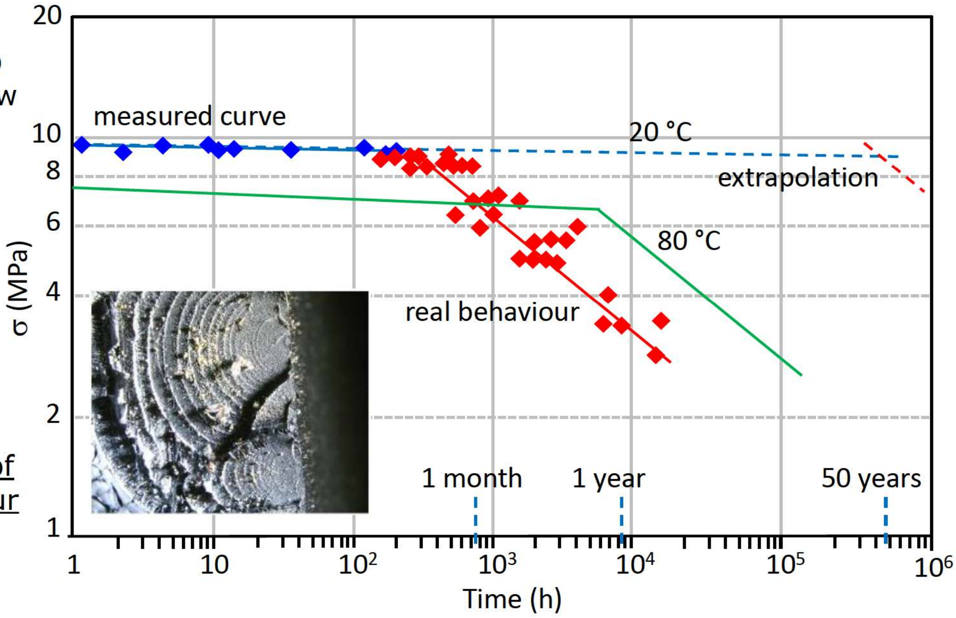
$\sigma_h = P\,r\,t$



ASTM D1598-15a '*Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*'

Mechanical characteristics during the time: brittle failure

For loads lower than the MRS and times longer that the one corresponding to the mechanical knee – ideally far beyond the 50 years lifetime at 20 °C and earlier only for higher temperatures – fractures that occur are of brittle type



Brittle failure is associated with creep and creep rupture due to the slow grow of those damages that occur at microscopic level when the HDPE is exposed to a constant tensile stress

Creep is a plastics time dependant non-reversible deformation that can be accelerated by temperature (as seen before), stress concentrations, fatigue and chemical environment

The real practice reveals that mostly of the failures are of brittle type and occur – even at ambient temperature – in time very lower than 50 years

Mechanical characteristics during the time: brittle failure

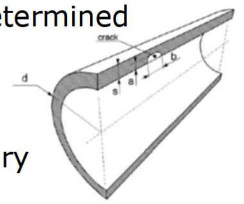
As **in the 2th stage** the failure is determined by the slow growth of a crack caused by a defect or stress concentrated in a point

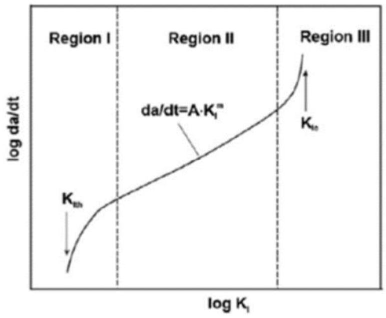
a HDPE pipe is characterized by the <u>Slow Crack Growth resistance</u> (**SCG**) that is <u>the time to fail in the brittle-mechanical way</u> and is determined

- ❑ or calculating it as

$$t_f = \int_{a_0}^{a_f} \frac{da}{A[K_I(p_{int},d,s,a)^m]}$$

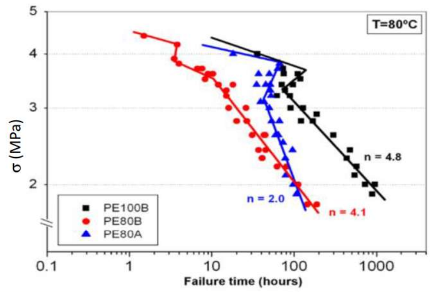
with the laws of the linear elastic fracture mechanics theory



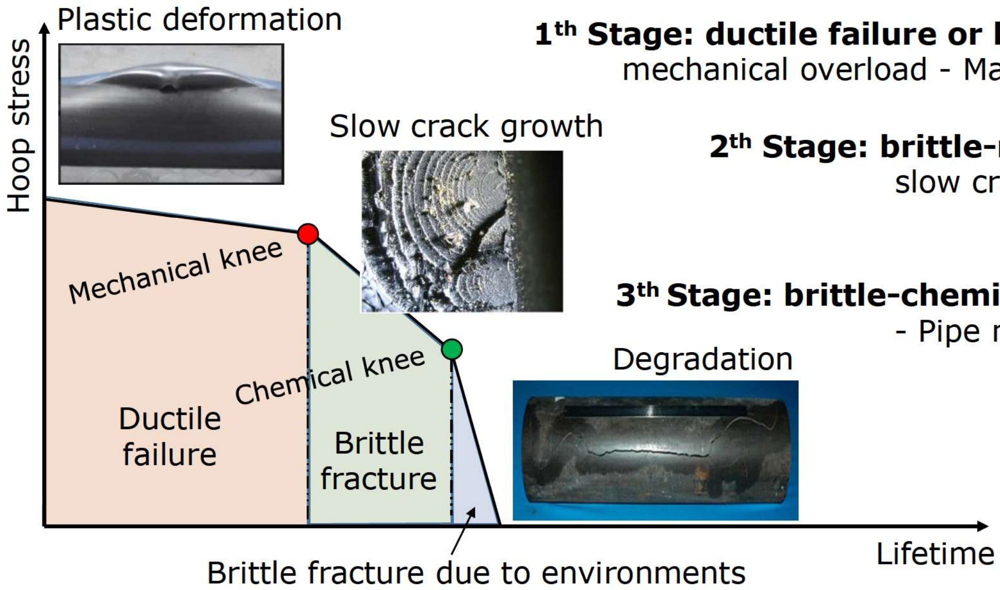


- ❑ extrapolating the knee position between the stage I and the stage II in accordance with the:
  - ISO 9080 *'Plastic pipe and ducting systems - Determination of long term hydrostatic strength of thermoplastic materials…'*

- ❑ or performing traction tests on samples with notches of different shape in accordance with the:
  - ASTM F1473 *'Standard test method for notch tensile test to measure the resistance to slow crack growth …'* – traction tests at 2,5 Mpa, 80 °C
  - ISO 16770 *'Determination of environmental stress cracking of polyethylene'* - traction tests at 4 Mpa, 80 °C in 2% acid solution



The high-density polyethylene piping: mechanical characteristics during the lifetime

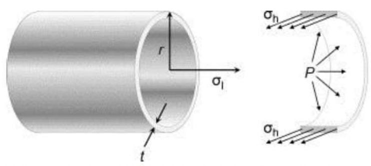


1th Stage: ductile failure or ballooning - Pipe is subjected to mechanical overload - Material fails due to ductile yielding

2th Stage: brittle-mechanical failure - Caused by slow crack growth through the pipe wall in a brittle manner

3th Stage: brittle-chemical or brittle-oxidative failure - Pipe materials are physically degraded due to oxidation

$\sigma_h = P\ r\ t$



ASTM D1598-15a '*Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*'

Mechanical characteristics during the time: brittle fracture due to environments

If the load is too low to determine both ductile failure and brittle fractures, a pipe without defects or cracks will break at a theoretical life of well over 50 years

In the 3th stage the time to fail is no longer dependent by the pressure inside the pipe and the failure is determined by the degradation of the material

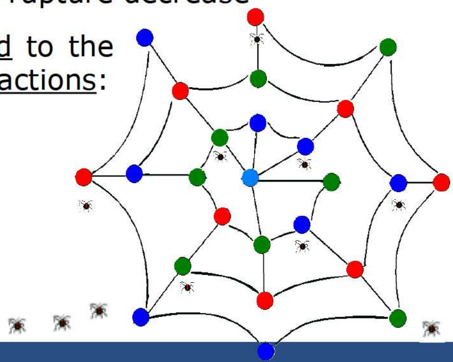
Due to the action of oxygen, light (UV ray), heat, moisture, chemical agents and shear stresses, HDPE undergoes to thermo-oxidative degradation phenomena that cause the rupture of the polymer chains

The processes predominantly affect the amorphous part of the HDPE, with a gradual increase of the brittleness of the polymer accompanied by a deterioration of its mechanical properties: the hardness increases while the resilience, the elongation and resistance to rupture decrease

Stabilizing additives – such as pigments and/or chemicals – are added to the HDPE in small amounts (1-2%) to stop or slow down the degradation reactions:

pigments (such as carbon black) capture the UV rays

chemicals react with free radicals or intermediates reagents preventing them from resumption in ripple effect



The consumption of additives is a key process for the HDPE stability and lifetime

Where do problems arise? Degradation due to additives consumption

The consumption of additives is a key process in the HDPE stability and lifetime:

it occurs by washing away, by evaporation and by chemical reaction
and leads to the HDPE degradation that is a very complex physic-chemical phenomena

It is very difficult to correlate artificially obtained ageing
and what actually happens during the years of service

For problems of encumbrance
the pipes are left outdoor, exposed to the sun,
to the rain, to thermal changes

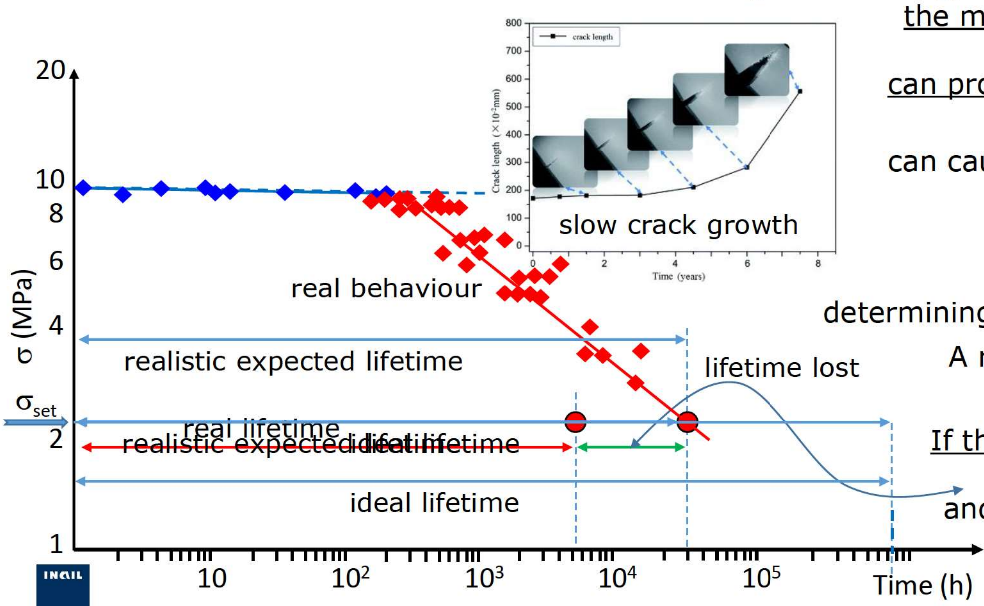
all inappropriate weather conditions that may result in leaching or consumption of additives

and the leaching or the consumption of additives may result in pipes with an ageing already in place and in an ageing resistance in the years of service other than the presumed ones

Where do problems arise? Aging due to degradation phenomena

Let’s suppose to bury a new pipe: on the basis of its MRS and its SCG resistance we set the pressure inside to have a long lifetime

During the handling, the transport and the undergrounding, <u>the machines</u> with which the pipe is seized, moved, loaded, unloaded, buried <u>can provide carvings or cracks on its surface</u>



Also landslides of the ground can cause cracks and/or tensions in the pipe

In correspondence of the cracks tensions can concentrate until the critical stress is exceeded, determining the growth of the cracks themselves

A realistic lifetime shorter than 50 years is to be expected

<u>If the degradation phenomena has begun the new pipe has already lost lifetime</u> and its real lifetime will be even shorter:

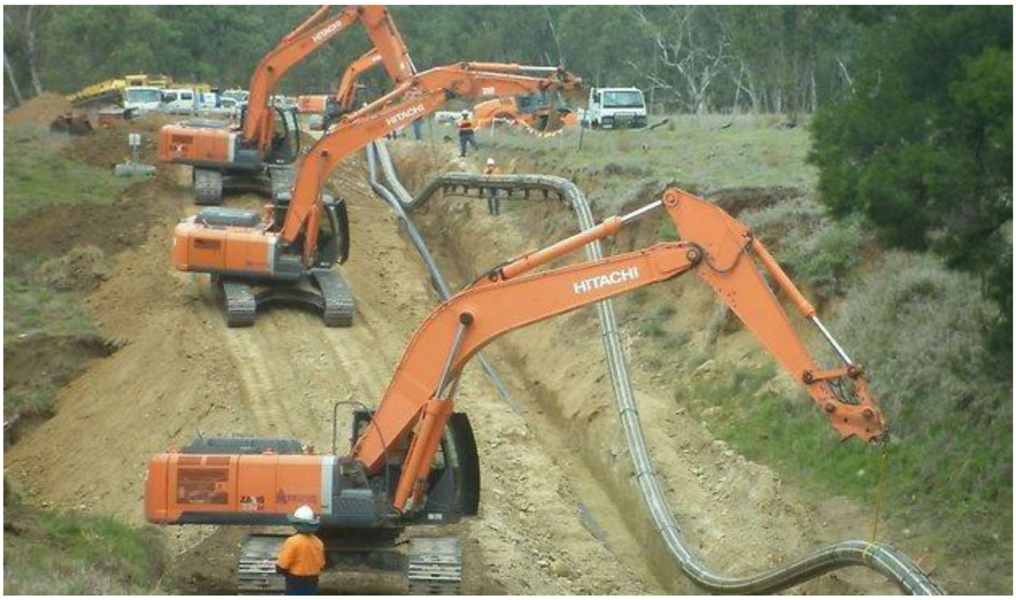
it is like saying that at the time of its burying the pipe is already old

Where do problems arise? Cracks and tension in hardened material

Pipe rolls stored for a long time in the open air can undergo to phenomena of hardening that stiffens the pipes curved

At the time they are buried (months or years later) they are grasped and straight by stretching deforming them possibly beyond their actual limit and determining cracks

In the undergrounding the stretched pipes are blocked by metal staples or boulders so that the material remains subjected to residual tensions



Cracks and residual tensions can lead the pipes to sudden breakage in times rather short and certainly minor than the 50 years at least expected

Where do problems arise? Thermoweld joints aging

Further critical issues are the thermoweld joints: however well standardized at international level, joints can be the seat of

- particles in the molten material - due to contaminations with the surrounding environment – that compromise the fusion integrity and can act as stress concentration sites, the precursors to SCG
- residual tensions – bending and torsion – when the welds join the extremes of tubes products in rolls

But even when they involve ends of tubes produced in bars, little or nothing is known of the mechanical characteristics and resistance to the ageing of HDPE in the molten area

Therefore, whilst the undergrounding of tubes produced in bars simplifies the positioning, it requires a greater number of thermoweld joints

Nor it is thinkable - for purely economic considerations - that a manhole of inspection is carried out for each of the many thermoweld joints

Therefore, **the thermoweld joints are often covered directly by the ground and forgotten**

Where do problems arise? Inspections and controls

The 'Achilles heel' of HDPE pipeline systems is at the point of installation and it is clear that the 50 years for which HDPE pipes are designed and guaranteed are not an attainable lifetime

Inspections and controls that can monitor the actual aging of the material are essential

They are moreover necessary to perform the decennial integrity inspection on those HDPE pipelines that are within the limits of the Italian D.M. 329/04 i.e. the pipelines

	Liquids	Gas
Group 1	Subject to verification if DN > 80	Subject to verification if DN > 80
Group 2	Not subject (I e II category	Subject to verification if DN x P > 5000 (III category)

Of course it is possible to perform hydraulic tests – e.g. during 24 hours, recording the pressure values – to detect breakages or cracks that already exist;
but the hydraulic test does not say anything about the aging or the integrity of the material

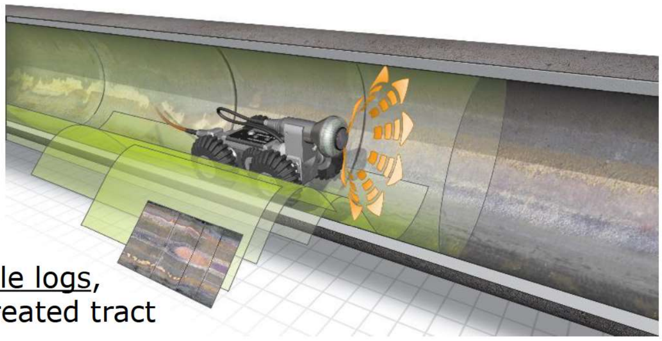
As an HDPE pipe is used - where the pressures and temperatures and the characteristics of the conveyed fluid allow - mainly thanks to the possibility of undergrounding it for hundreds of meter, it would be ideal an ND control method that allow to check the integrity of the piping 'in situ' and 'on long range',
as to limit excavations and inspection manholes

Where do problems arise? Inspections and controls

The elastoplastic structure of HDPE absorbs the acoustic waves and attenuates the signal to completely dampen in the first decimetres, thus ND control methods largely used for undergrounded metal piping - such as Acoustic emissions or Guided waves – are not suitable for HDPE ones

Ultrasonic phased array and other ultrasonic ND control methods are useful but locally and on unburied zones, as for instance a excavated thermoweld joint or a thermoweld joint in a manhole

The use of Microwaves is in the experimental phase, but till now the power of the signals to be injected into the piping to obtain reliable indications on their structural integrity are such as to be dangerous for the health of the operators



Possible method of inspection could be represented by robots - able to record/transmit signals or images – to be inserted and radio-control inside the pipes; but even such systems need excavations and manholes and are still in the experimental phase

Currently, to have indications on the real ageing of a pipeline in HDPE, it is only possible to withdraw sample logs, in numbers or from points considered significant for the treated tract

But to detach the sample logs, then it is necessary to perform thermoweld joints to restore the continuity of the pipe, thus going to insert or multiply critical points

Conclusions

Where the pressures and temperatures and the characteristics of the conveyed fluid allow HDPE pipes are a viable alternative to the classic metal piping

The elasticity and plasticity of HDPE are the characteristics that make it versatile and attractive

but **HDPE pipes are durable only if they are preserved, treated, armed and installed with appropriate concerns**

In order to have indications on the real ageing of a pipeline in HDPE
- whether it is a water pipe, more so if it is a gas pipe and the inspection is needed by the law -
NDT are currently not suitable to perform inspection 'in situ' and 'on long range'
and it is only possible to withdraw sample logs
in numbers or from points considered significant for the treated tract

It is urgent to **study methods and to define procedures that allow reliable indications of the effective state of integrity of HDPE piping** especially when they are buried, since the risk they get damaged and broken for times far below those expected is actual

Thank you for your attention. Good lunch!

…and be careful with the ~~additives~~ spider