Long term performance prediction of existing PVC water distribution systems

TNO Science and Industry

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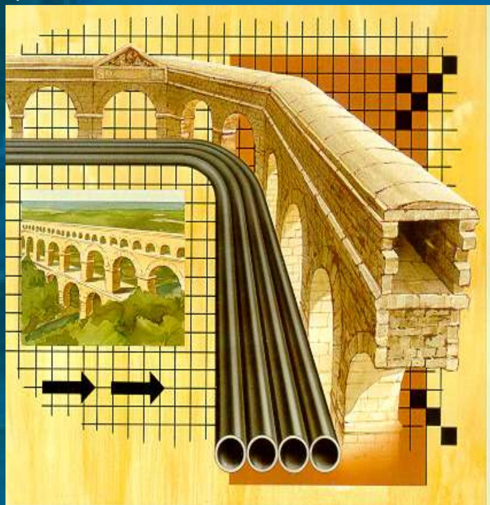

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Introduction

- PVC water pipes have been in service since 1950’s
- It was assumed that these pipes have a lifetime of approx. 50 year
- Question: “Do PVC pipes have to be replaced after 50 years or can they last longer?”

Objective:

development of reliable methods for prediction of residual lifetime of PVC water distribution systems based on a thorough understanding of underlying degradation processes which is accepted within PVC pipe industry and PVC water pipe users

Introduction

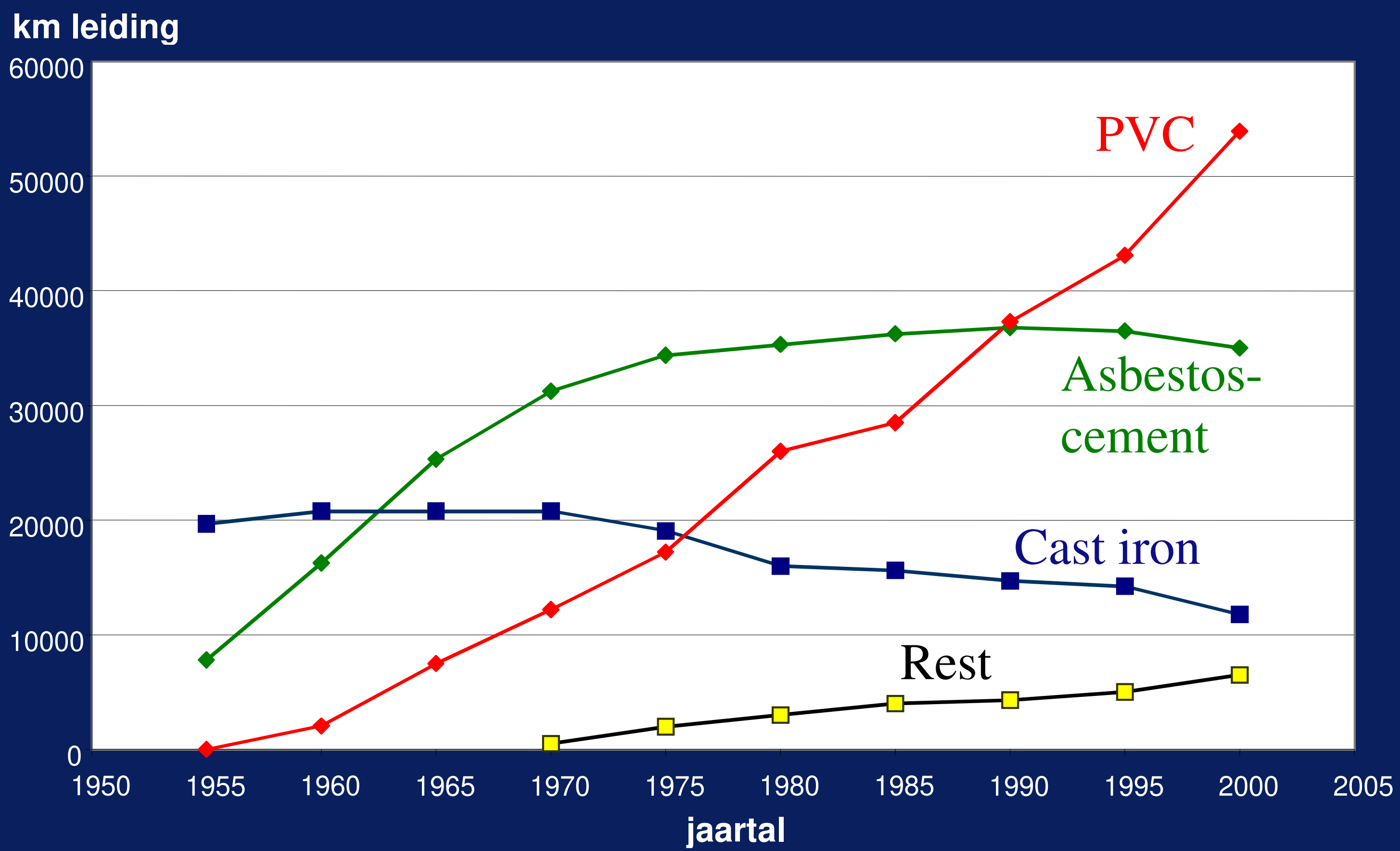
Sponsors

- water distribution companies by Kiwa
- PVC pipe manufacturers (Dyka, Pipelife, Wavin)
- PVC raw material producers (LVM, Shin-Etsu, Solvay)

- TNO (Netherlands organisation for applied scientific research)
- TNO Science and Industry (1 of 5 TNO institutes)
  - Materials Technology (1 of 8 departments)
    - Product assessment, durability and stabilisation

Introduction

Development of water distribution systems



Degradation and failure processes in PVC

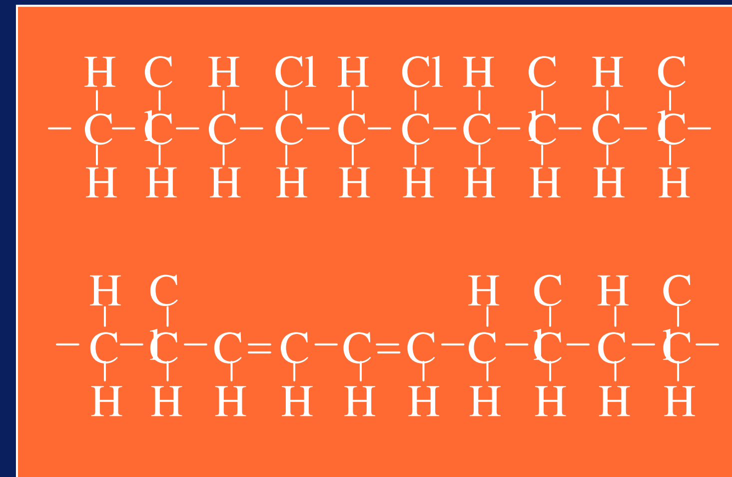
- Chemical degradation:
  - Change in chemical structure of the polymer

- Physical ageing
  - Change in physical structure of the polymer

- Mechanical damage:
  - Craze initiation and crack growth as a result of internal and external stresses may lead to ultimate pipe failure

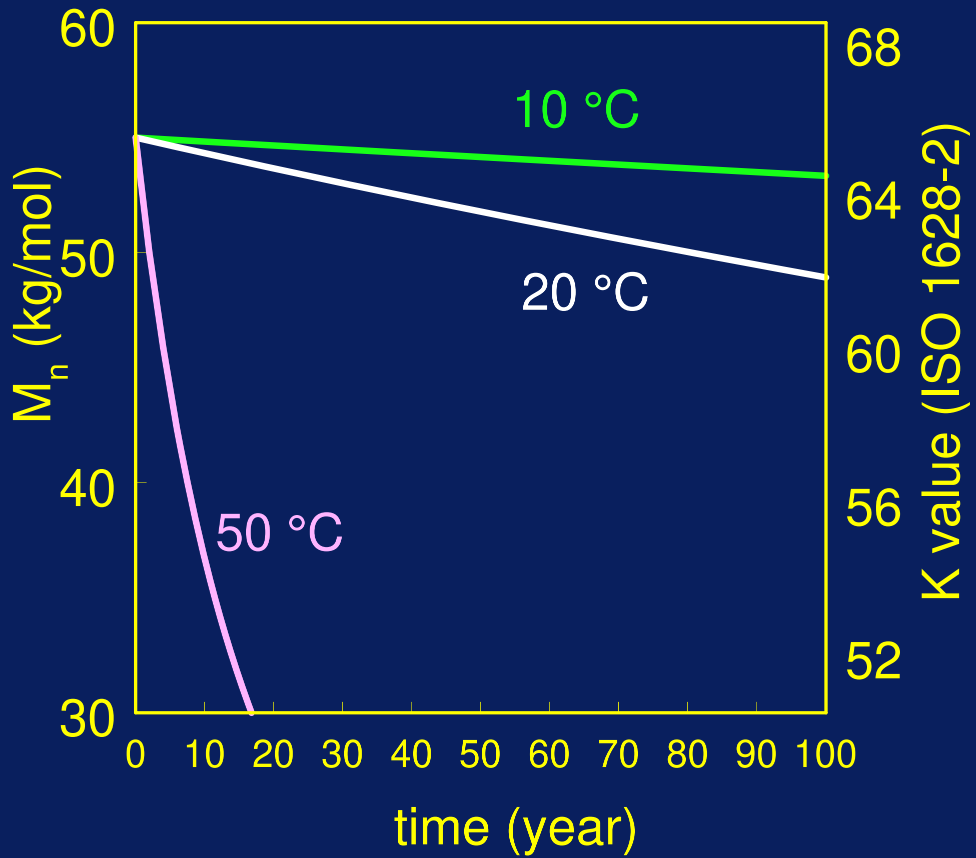
Chemical ageing

- Degradation mechanism:
  - Dehydrochlorination and thermo-oxidation
  - HCl is released influenced by thermal energy
    - Slow in service at 15 °C
    - Fast during processing at 200 °C
- Consequence:
  - Embrittlement
  - Discoloration
- Chemical physical checks:
  - K-value
  - residual amount of stabiliser
  - concentration of vinyl group



Chemical ageing

- Degradation kinetics from DHC experiments at elevated temperatures
- Most negative scenario indicates that at 10 °C the K-value decreases from 66 to 65
- Higher temperatures causes an accelerated degradation rate



Chemical ageing

- Modelling of chemical degradation indicates that the increase of the degree of degradation after 100 years at 15 °C is significantly smaller than is caused by processing

- *Conclusion:*
- *Chemical ageing at 15 °C seems not to have a significant influence the quality of PVC water distribution pipes*

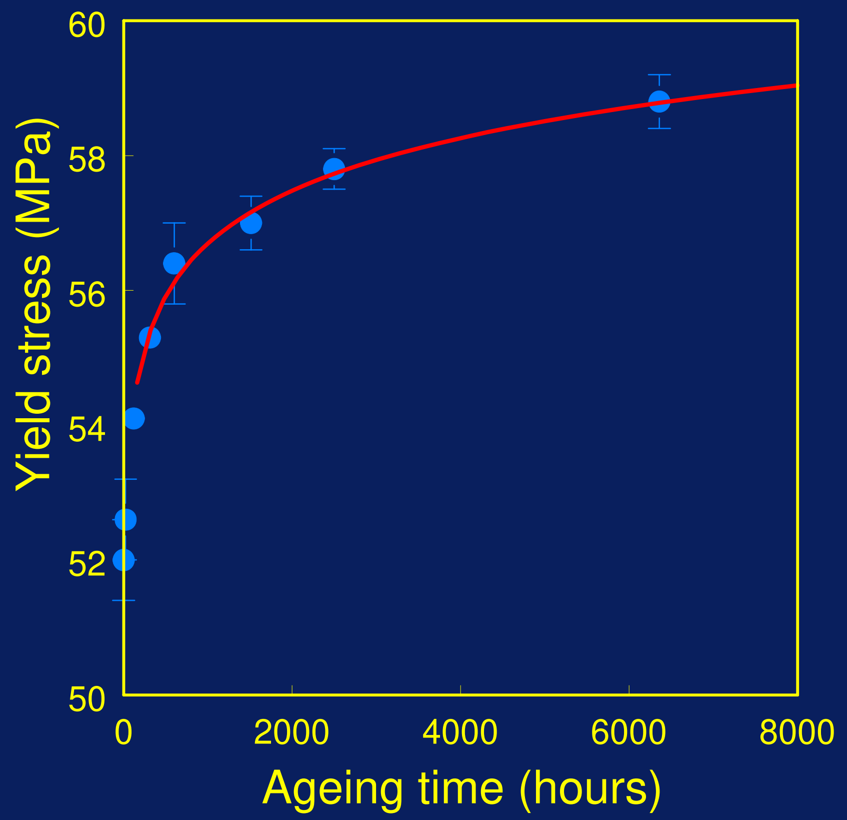
Physical ageing

- Ageing mechanism
  - Free volume relaxation (compacting of polymer)
  - Temperature dependent
    - Slow in service at 15 °C
    - Fast during cooling after extrusion of the pipes
- Consequences
  - Increase in craze initiation stress
  - Increase probability for crack growth after initiation
  - Increase in burst strength
  - Lower elongation at break
- Physical check:
  - Measurement of yield stress in stress-strain experiment

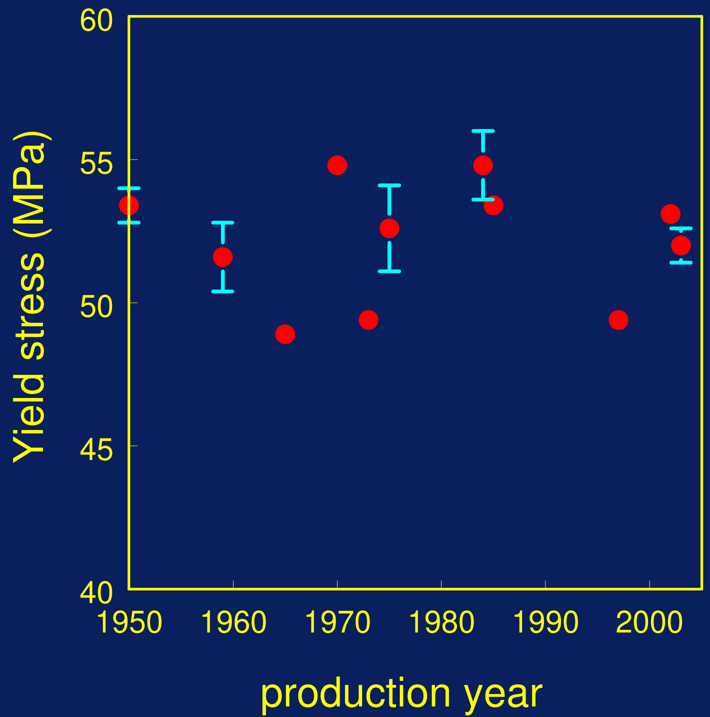
Physical ageing

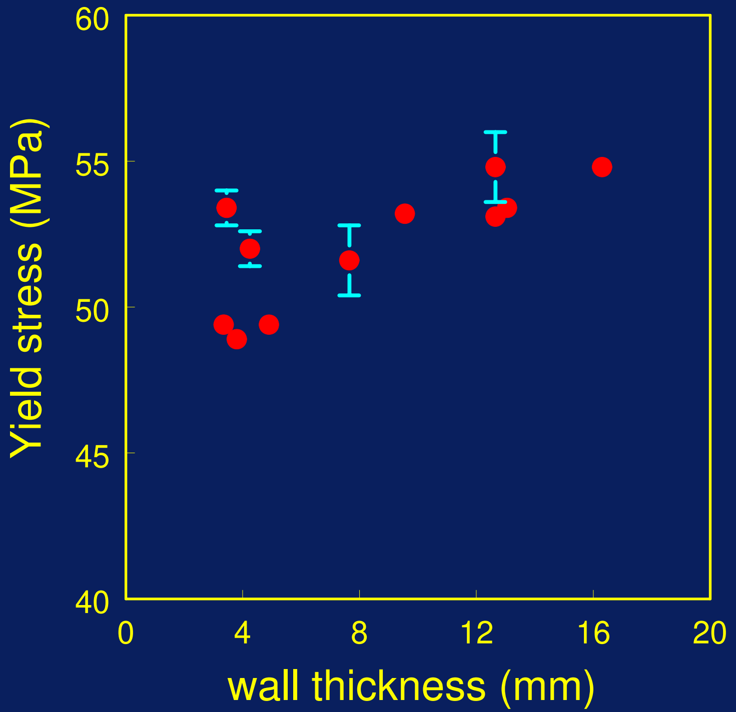
- Accelerated ageing of new PVC pipe at 60 °C leads to an increase in yield stress

- Expectation:
  The yield stress is an indication for the age of the excavated pipe



Physical ageing





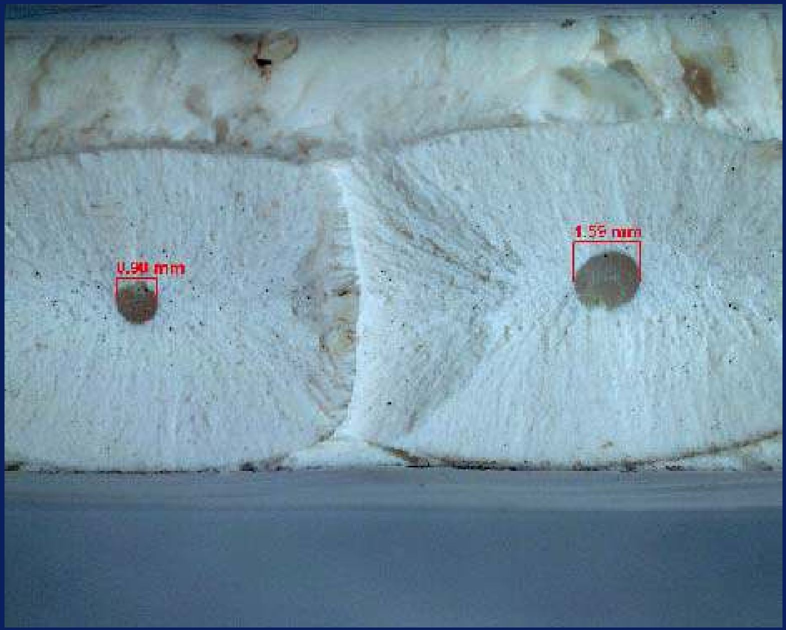
Physical ageing

- Yield stress depends on wall thickness and not on age
- Thicker wall cools more slowly and generates more physical ageing
- The state of physical ageing is determined immediately after production and hardly changes in service

- *Conclusion:*
- *Physical ageing at 15 °C seems not to have a significant influence on the quality of water distribution pipes*

Mechanical failure

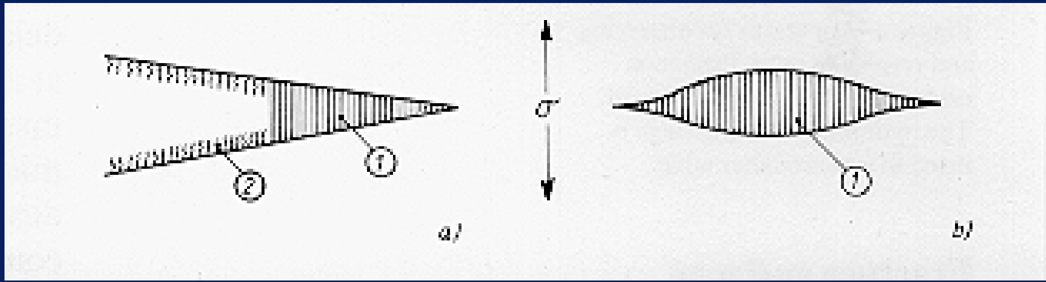
- Initiation of crazes and cracks under the influence of external stresses
- Presence of damage and particles accelerates failure
- Deformation of the surrounding soil
- Internal water pressure
- Water hammer
- Traffic load

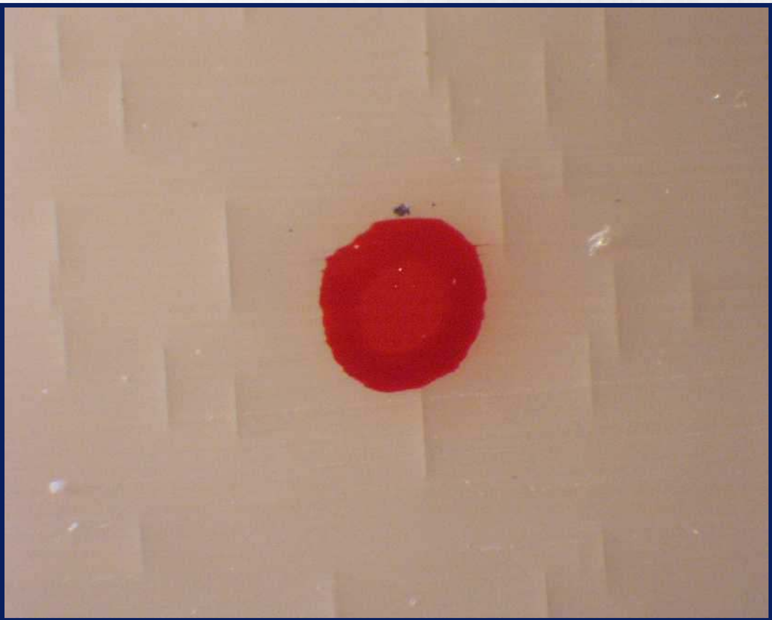


Failure mechanism

- Constant or peak load can lead to:
  - Craze initiation
  - Craze growth
  - Crack formation
  - Crack growth

- And ultimately to:
  - Pipe failure





External conditions

- PVC raw material
- Additives (stabilisers; pigments;…)
- Processing conditions (temperature, residence time in extruder; degree gelation; cooling rate; …)
- Internal stresses (size; relaxation; ...)
- Damages (scratches; “spider lines”; inhomogeneities; …)
- Mechanical loads (installation; water pressure; water hammer; soil; …)
- Effect of environmental conditions (temperature; UV; chemicals, …)

Experimental validation

- Constant loading
  - Craze initiation on tapered samples
  - Slow crack growth on small ting samples
  - Burst pressure on whole pipe segments

- Occasional loading
  - Fatigue loading of rings

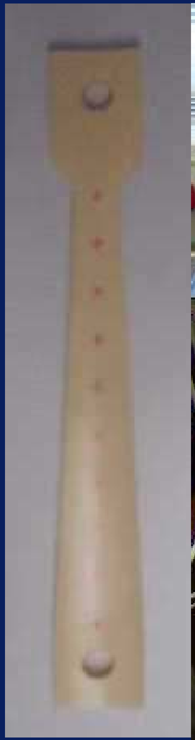
Experimental validation

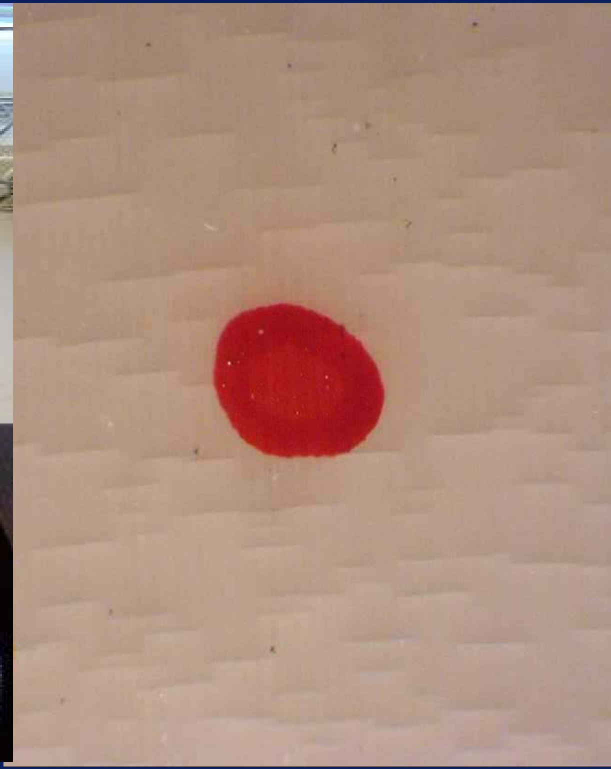
- Excavated pipes

Production year	Diameter (mm)	Wall thickness (mm)	*K*-value	Degree of gelation (%)
1959	200	7.6	71	58
1970	500	15.6	67	39
1975	315	9.7	64	38
1984	400	12.7	66	55
1997	160	4.8	67	80
2003	160	4.3	68	70

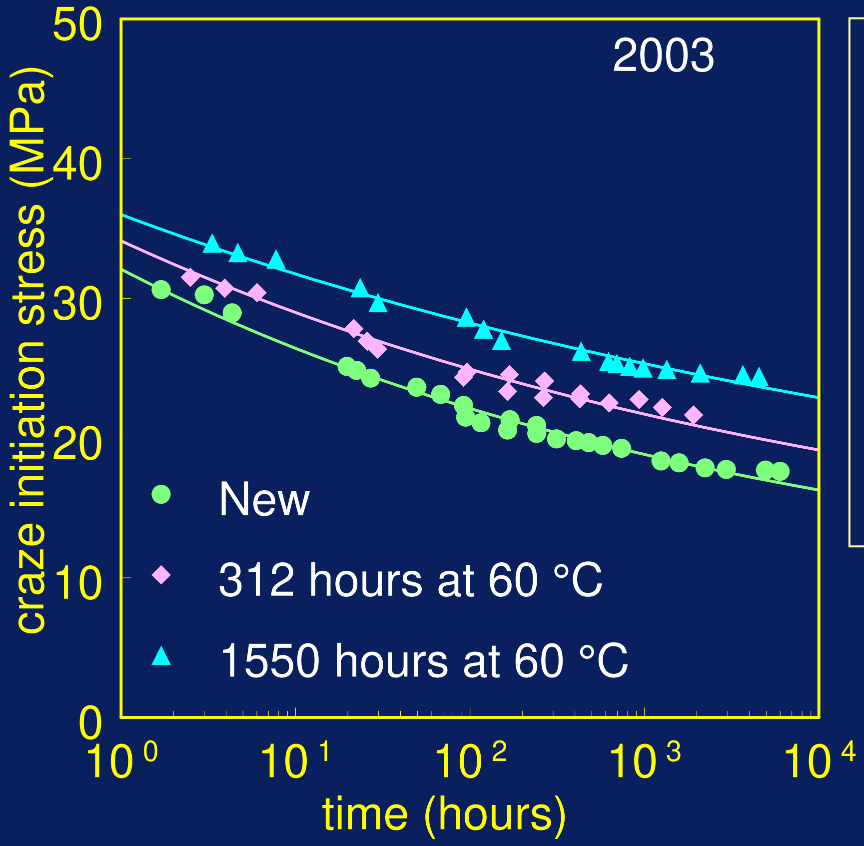
Craze initiation

- Tapered samples are stressed and the time until the formation of crazes is monitored





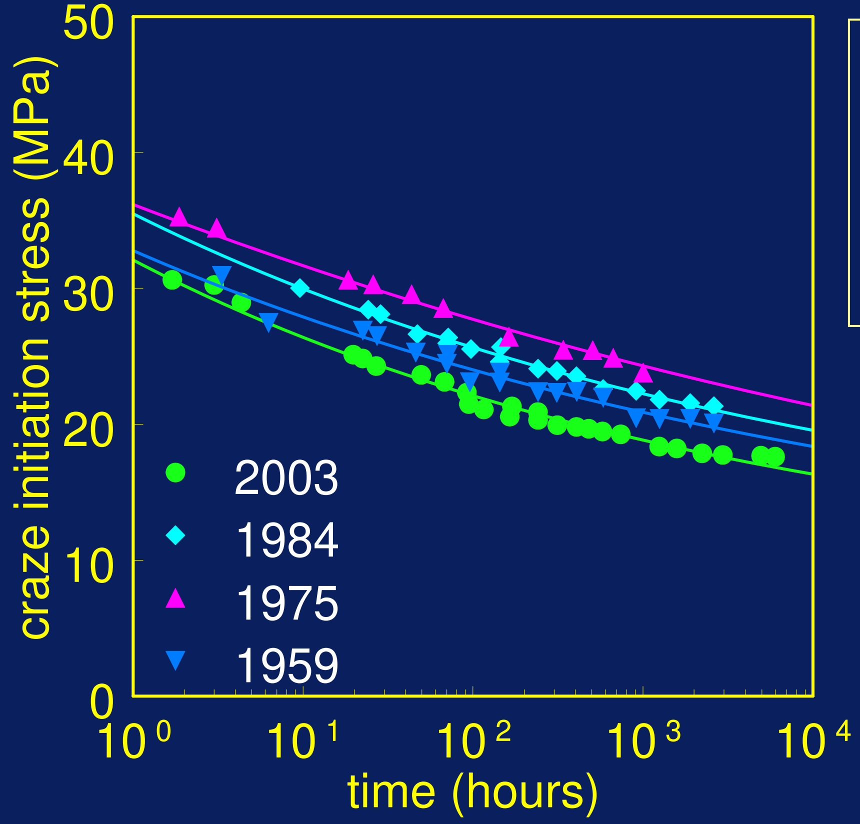
Craze initiation



Annealing of pipes at 60 °C increases physical ageing

Physically aged pipes have a higher resistance against the formation of crazes

Craze initiation



Craze initiation stress does not depend on the age of the pipe

Craze initiation

- Craze initiation stress level after 100 year service life at 20 °C

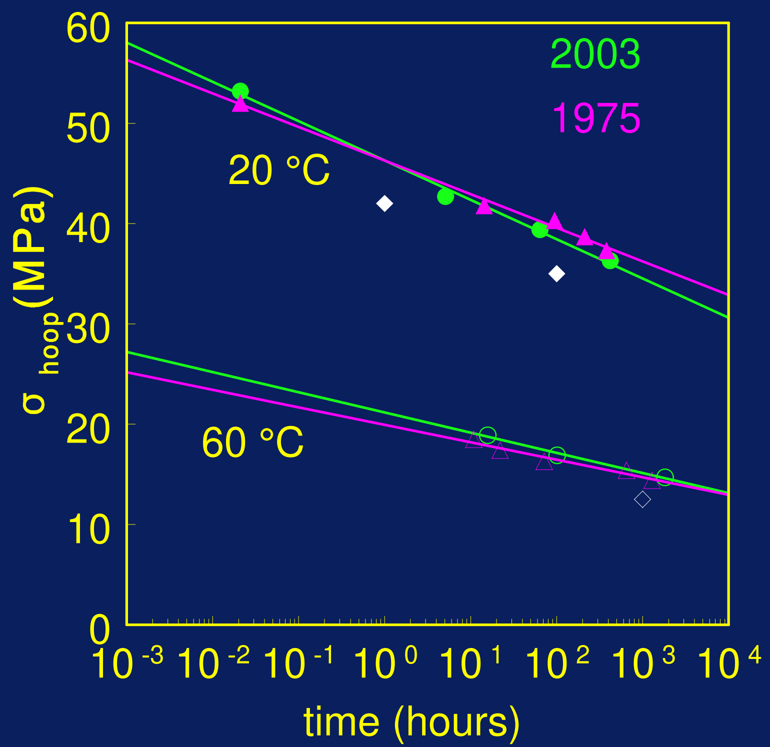
Production year	Stress level (MPa)	Uncertainty (MPa)
1959	14.3	2.1
1970	17.4	2.0
1975	16.9	0.9
1984	15.7	0.9
1997	21.4	2.7
2003	12.8	0.5

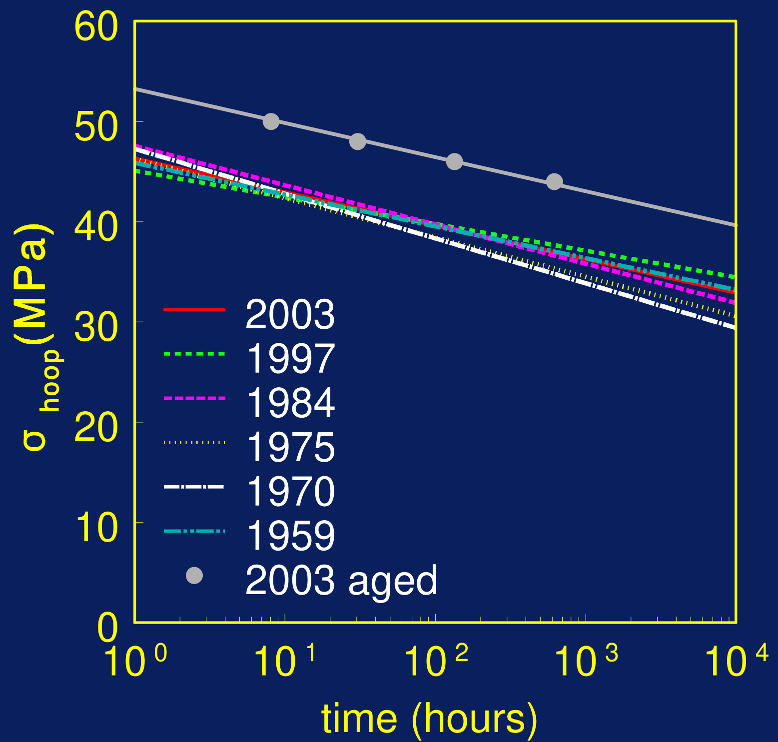
Critical values in view of the design pressure of 12.5 MPa

Burst pressure

- Pipes are hydrostatically pressurised and the time until failure is monitored

Burst pressure





All (excavated) pipes show a similar burst pressure behaviour

Ageing at 60 °C increases the resistance against internal water pressure

Burst pressure

- Burst pressure stress level after 100 year service life at 20 °C

Production year	Stress level (MPa)	Uncertainty (MPa)
1959	27.0	0.5
1970	20.7	0.5
1975	23.0	0.9
1984	24.3	1.4
1997	26.3	0.6
2003	28.4	0.6

Critical values in view of the design pressure of 12.5 MPa

Slow crack growth

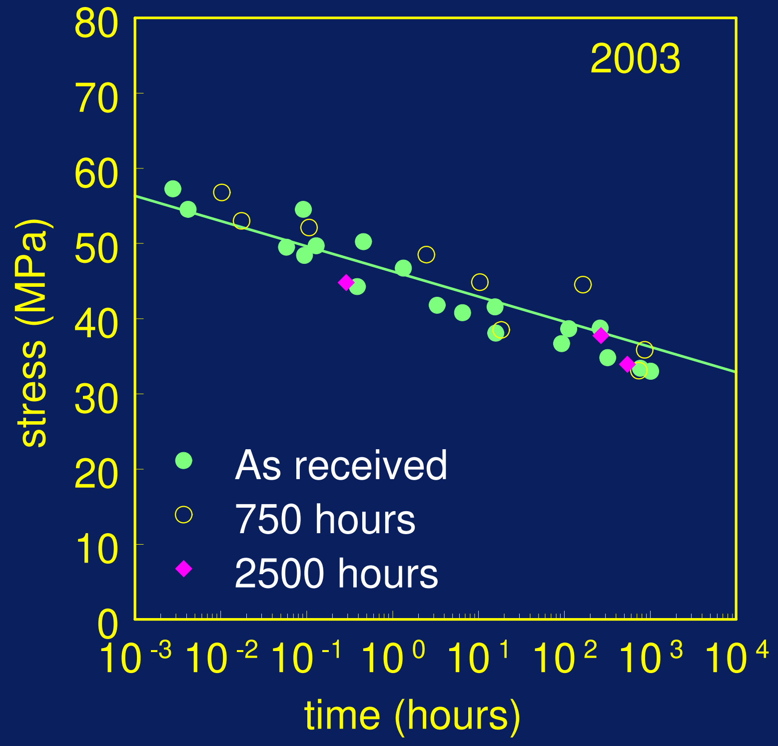
- Ring segment is notched and subjected to three point bending
- The time until failure is monitored versus applied stress

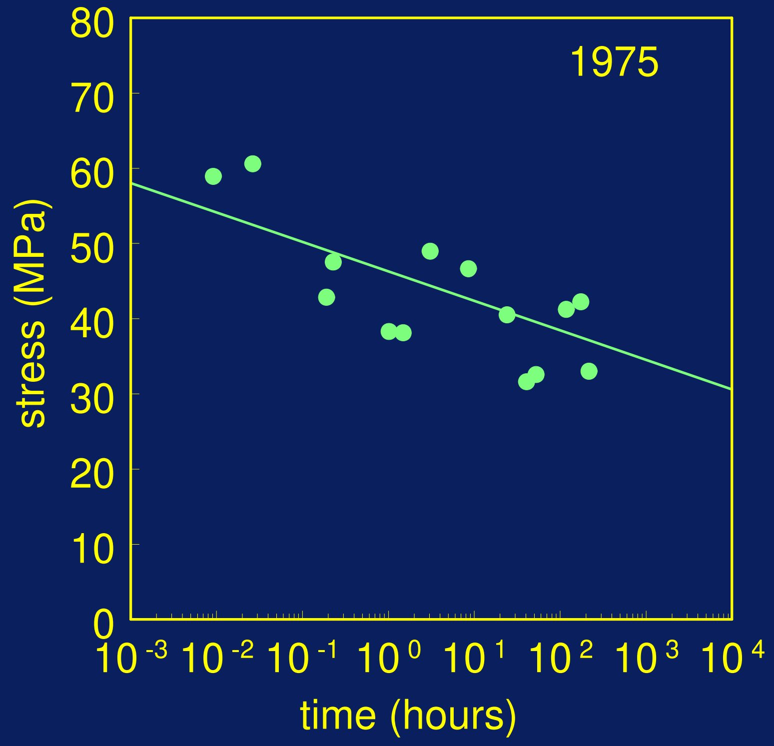
Slow crack growth

Ductile failure

Brittle failure

Slow crack growth





Slow crack growth

- All excavated pipes fail in a ductile manner
- Failure behaviour is comparable to burst pressure behaviour
- However, pipes of 1970, 1975 and 1984 show significant scatter in results
  - Low degree of gelation
  - Larger particles
- Extrapolation to 12.5 MPa for these pipes gives large uncertainty

Slow crack growth

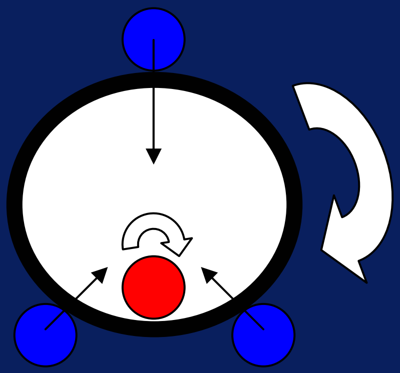
- Slow crack stress level after 100 year service life at 20 °C

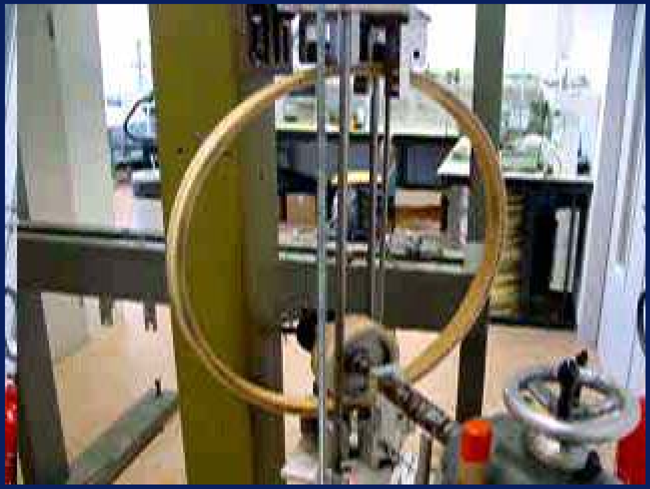
Production year	Stress level (MPa)	Uncertainty (MPa)
1959	26.7	1.9
1970	17.3	5.0
1975	19.7	6.3
1984	24.4	7.1
1997	22.1	4.7
2003	21.1	2.2

Critical values in view of the design pressure of 12.5 MPa

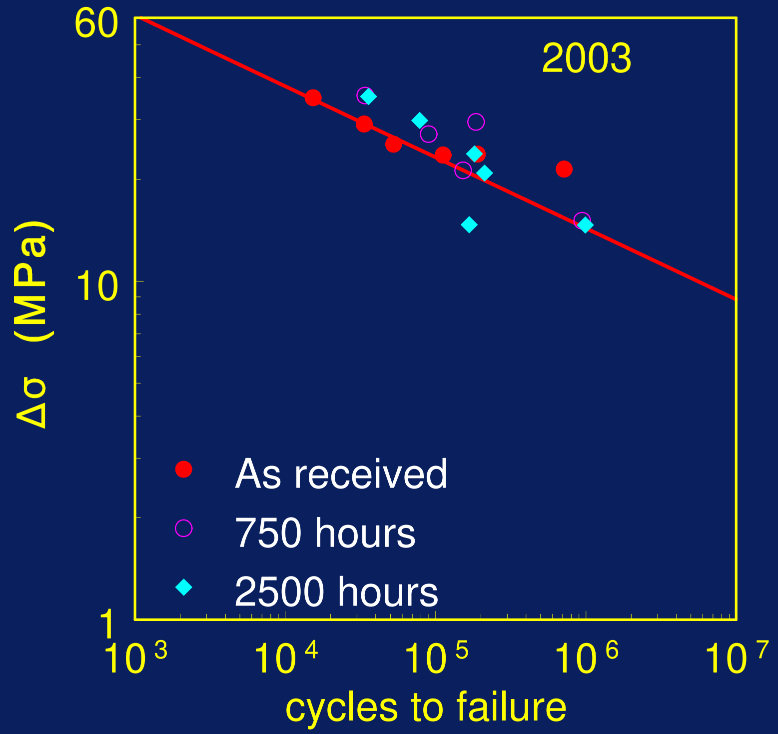
Fatigue

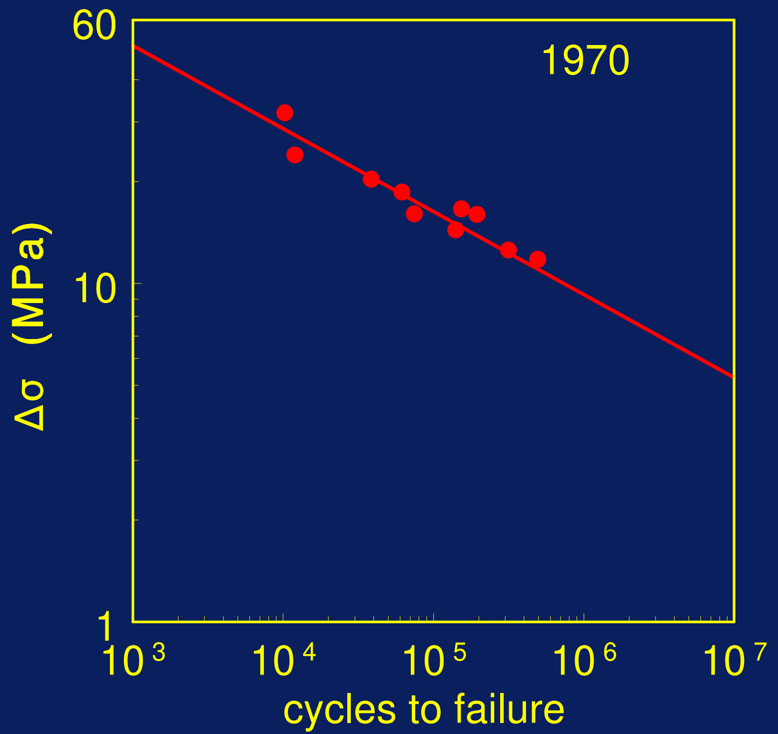
- Loaded ring is rotated
- Number of cycles until failure is monitored versus stress level applied





Fatigue


60
10
1
Δσ (MPa)
2003
As received
750 hours
2500 hours
10^3
10^4
10^5
10^6
10^7
cycles to failure


60
10
1
Δσ (MPa)
1970
10^3
10^4
10^5
10^6
10^7
cycles to failure

Fatigue

- Fatigue stress level that can be withstand for 10^7 cycles in 100 years at 20 °C (=10/hour)

Production year	Stress level (MPa)	Uncertainty (MPa)
1959	8.0	1.7
1970	4.1	1.7
1975	4.0	1.0
1984	5.5	1.7
1997	13.6	4.4
2003	8.9	1.4

- This means a deflection < 2% for the 1970, 1975 and 1984 pipes

Critical values in view of traffic load

Conclusions

- *Prediction service life of currently produced PVC water distribution pipes with the high quality control procedures on material, processing and stabilisation applied by Dyka, Pipelife and Wavin*

  > 100 years

- *Provided: good control during construction activities and service e.g.*
  - *Back fill of soil*
  - *Soil settlements*
  - *Water pressure*
  - *Magnitude and occurrence of water hammer*
  - *Ground works*

Conclusions

- *Residual service life of PVC water distribution pipes in service not restricted to 50 years*

- *Residual service time determined by:*
    - *Material properties*
    - *Stabiliser package*
    - *External load of soil and traffic*
    - *Water pressure (water hammer)*
    - *Ground works*
    - *New connections*
- *Unforeseen conditions*

Unforeseen conditions