A New Approach to Evaluation of Long-Term Performance of Plastic Pipe

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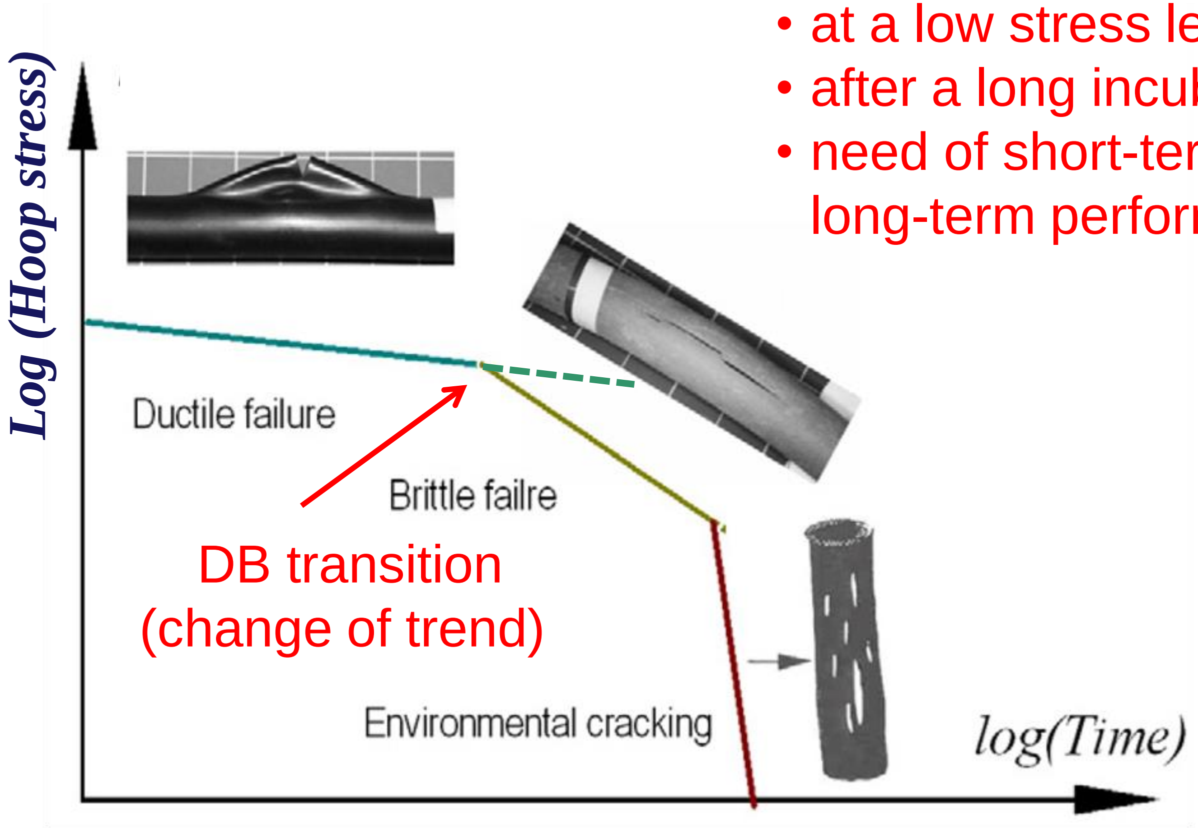
The challenges:
An unusual ductile-brittle (DB) transition

Creep test

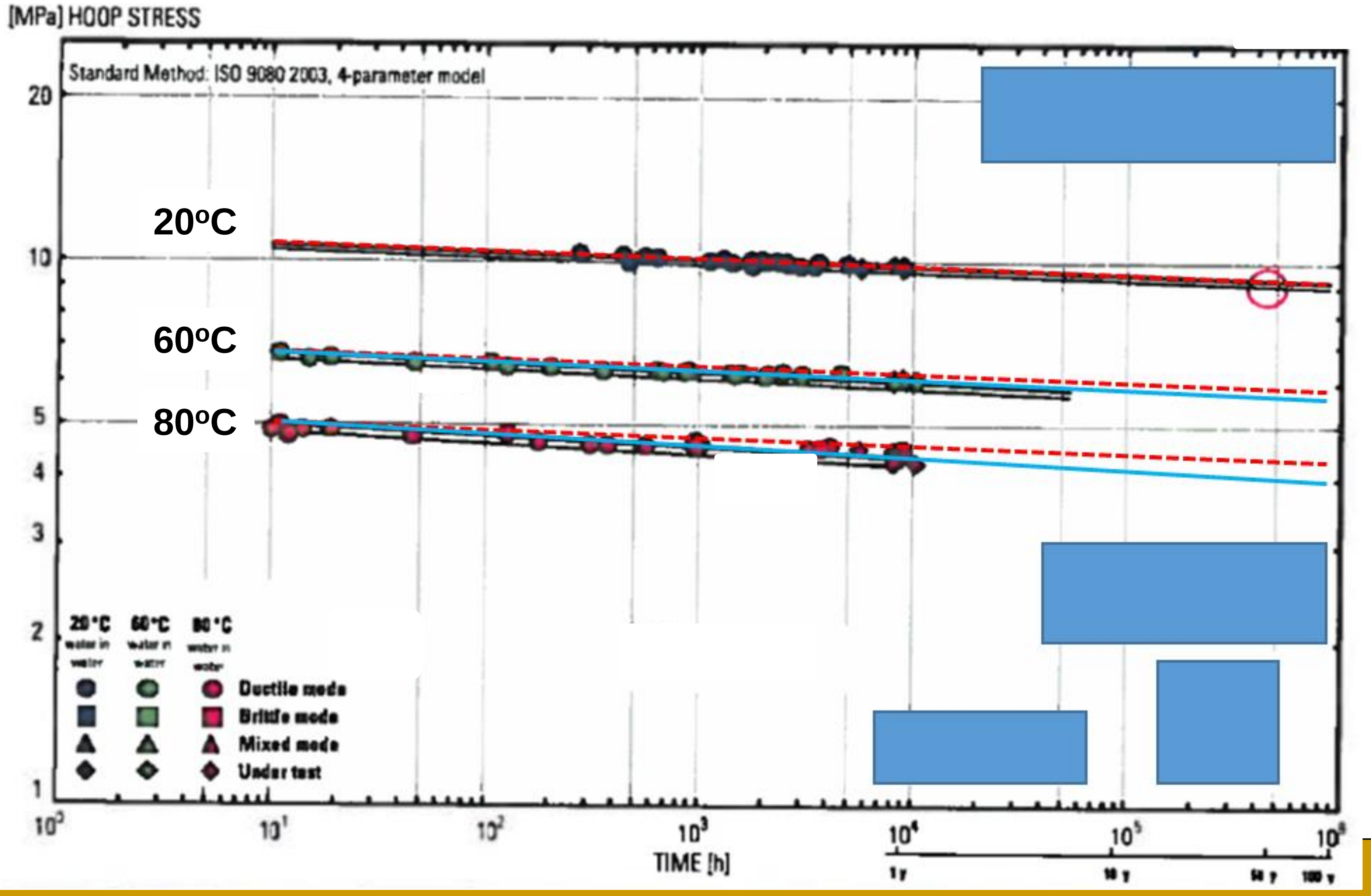
Brittle fracture:

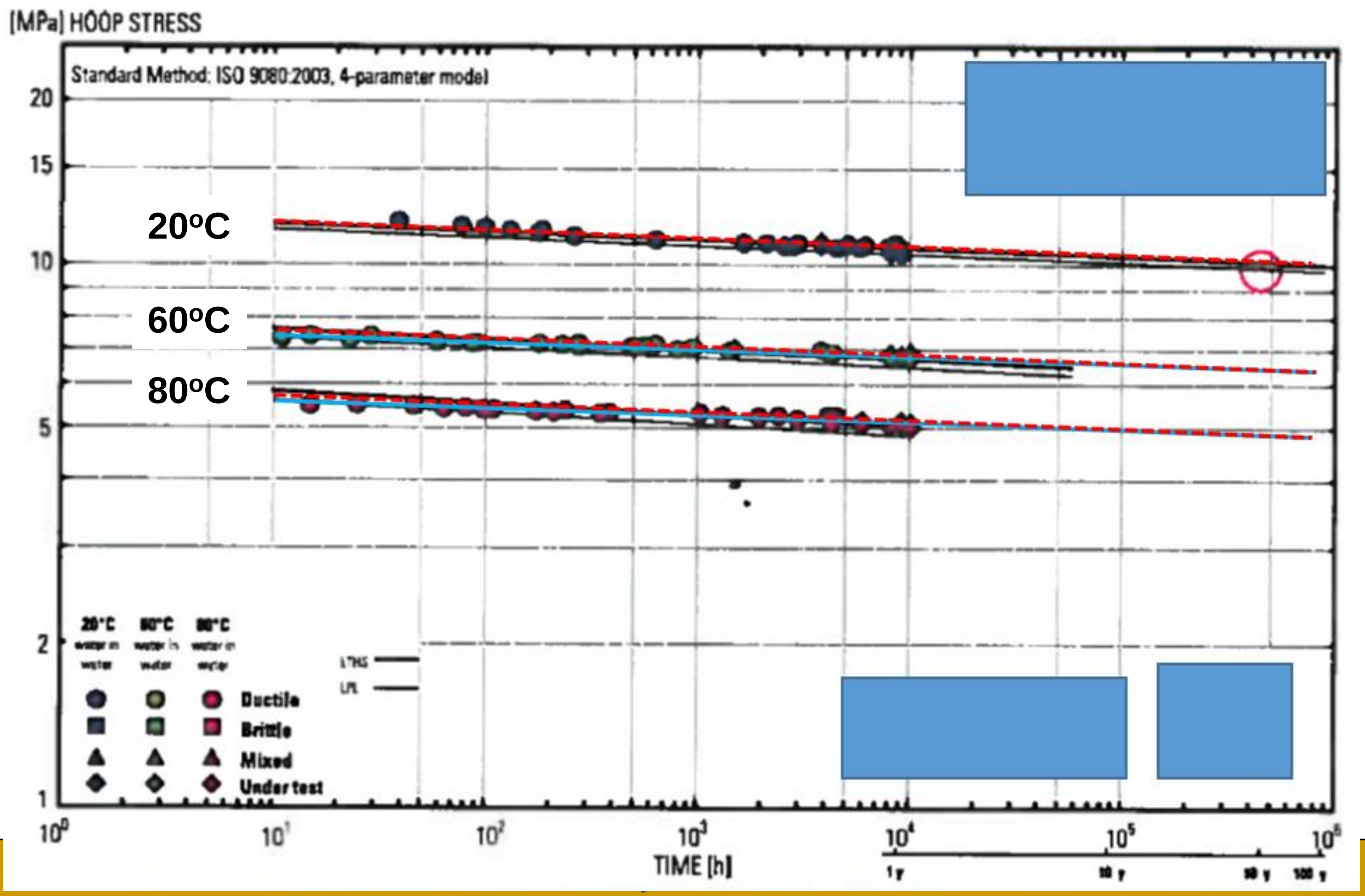
- at a low stress level
- after a long incubation period (in years)
- need of short-term tests to evaluate the long-term performance (>100yrs)



Y Zhao, B-H Choi, A Chudnovsky, Inter. J. Fatigue 51 (2013), 26-35

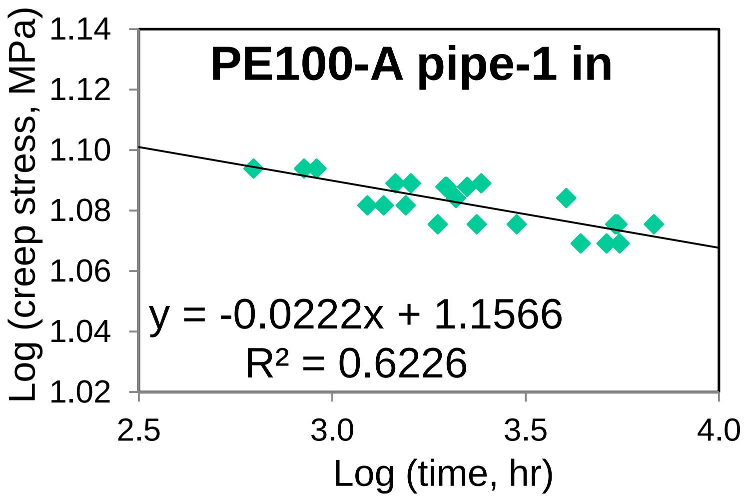
Some results based on ASTM D2837 and ISO9080 (long-term hydrostatic strength of plastic pipe)

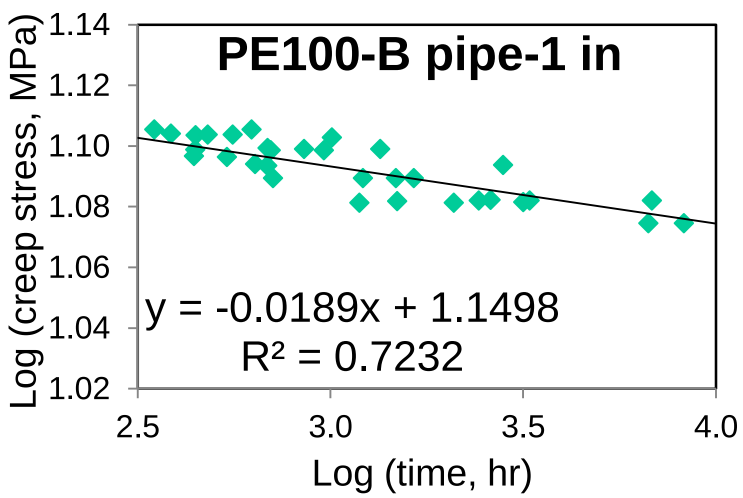



[MPa] HOOP STRESS
Standard Method: ISO 9080:2003, 4-parameter model
20
15
10
5
2
1
20ºC
60ºC
80ºC
20°C water in water
60°C water in water
80°C water in water
Ductile
Brittle
Mixed
Under test
LTHS
LPL
10^0
10^1
10^2
10^3
10^4
10^5
10^6
TIME [h]
1 y
10 y
50 y
100 y

Nature of long-term creep tests:

Hydrostatic test results - under constant loading





$$Log\ (\sigma) = a \times Log\ (t) + b$$

Uncertainty in time and stress: $\Delta t = [t^{(1\text{-}a)} / (10^b\ a)]\ \Delta\sigma$

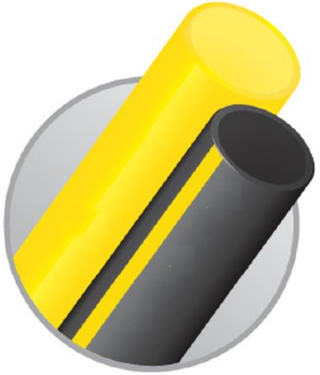
For t = 50 yrs:

Time uncertainty in terms of stress uncertainty: $\Delta t\ (\text{yr}) \approx -230\ \Delta\sigma\ (\text{MPa})$

Can we predict long-term performance of plastic pipe?

Outline

- Our idea for the cause of the DB transition (mechanism)
- Application of the idea to creep test results
- A new test method
- Evaluation of the new test method
- Recent research progress and results
- Conclusions
- Future work
- Acknowledgement



Idea for the cause of the DB transition

Different mechanisms for brittle and ductile fracture

(Low stress) (High stress)

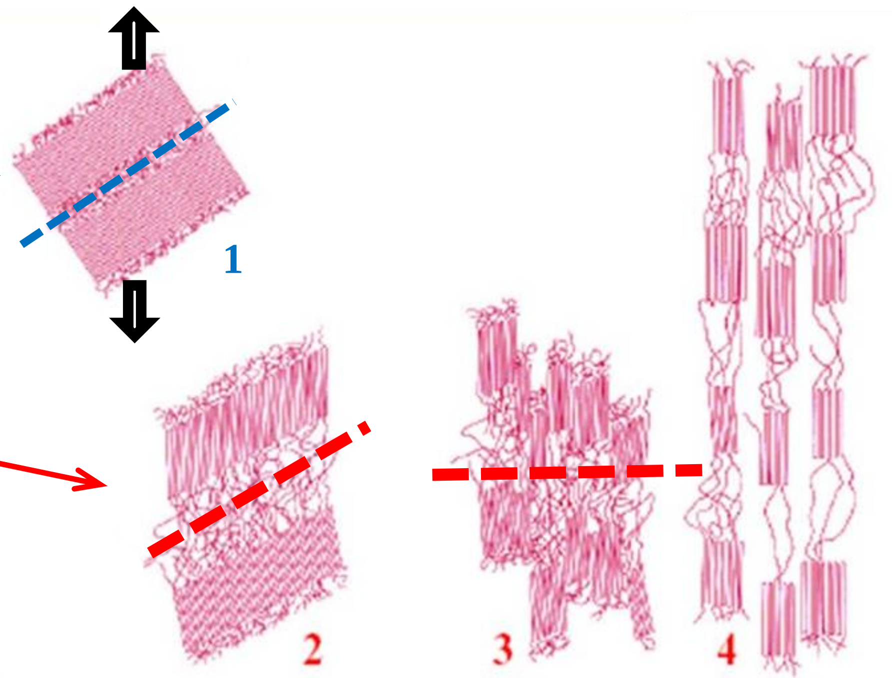
Fracture: a local phenomenon after deformation

- **Brittle fracture at a low stress** →

  (In the amorphous only)

- **Ductile fracture at a high stress** →

  (Including the crystalline phase)



- Below the critical stress level, deformation (fracture) occurs <u>only</u> in the amorphous phase, thus brittle

- Above the critical stress level, crystalline phase is involved in the deformation process, resulting in ductile fracture

- To determine the lowest stress level that allows the crystalline phase to be involved in the plastic deformation process

Detecting the DB transition:

(based on the three-coefficient method in ASTM D2837)

$$\log(t) = A + \frac{B}{T} + \frac{C}{T} log(S)$$

t: creep failure time
S: creep stress
T: Temperature (K)

⇩

$$\log(S) = \frac{T}{C}\log(t) - \frac{A}{C}\left(T + \frac{B}{A}\right)$$

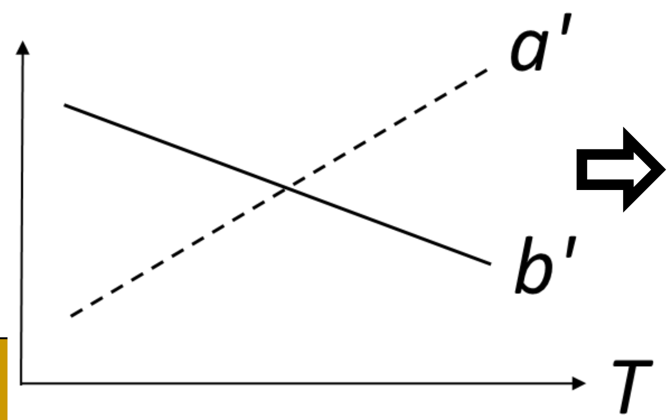
⇩

$$\log(S) = a' \log(t) + b'$$

$$a' = \frac{T}{C}$$

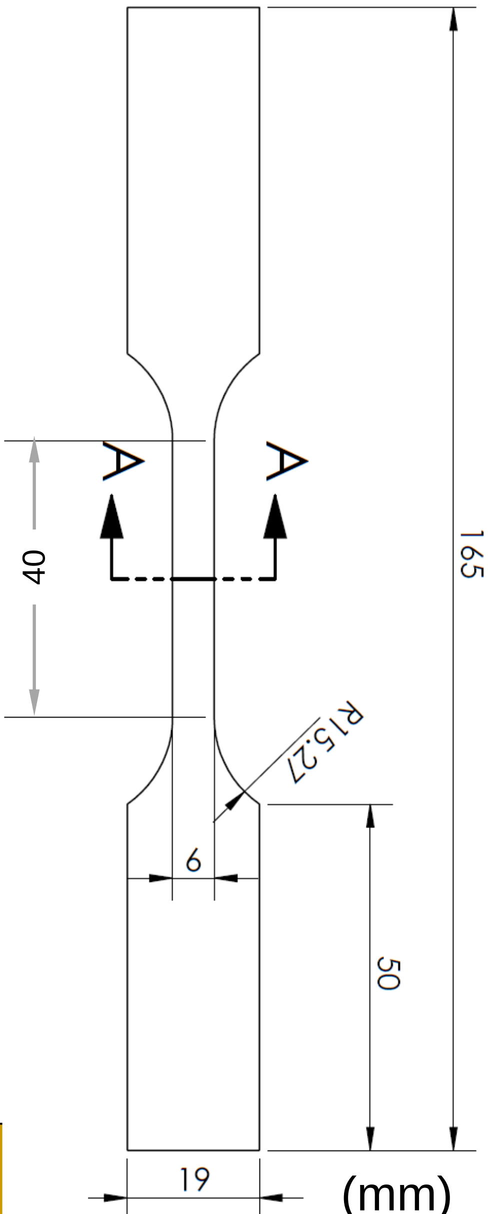
$$b' = -\frac{A}{C}\left(T + \frac{B}{A}\right) = -A\,a' - \frac{B}{C}$$

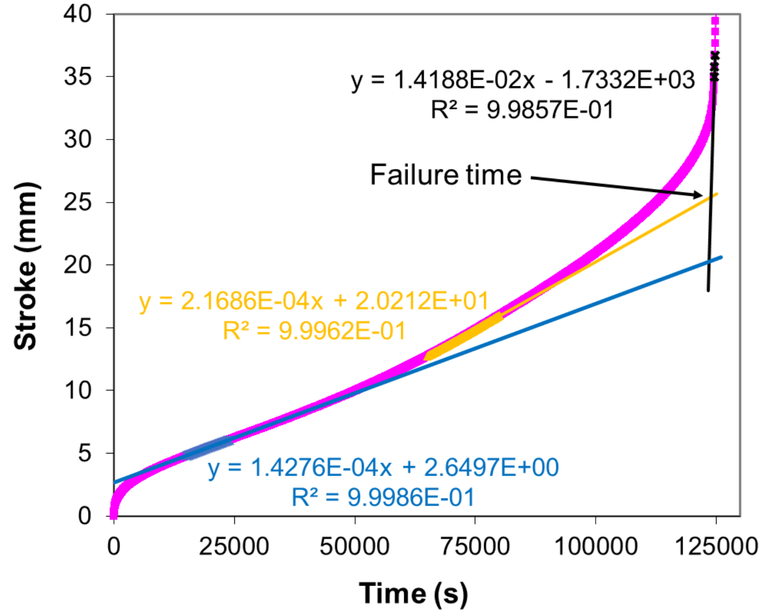
Creep tests at different temperatures

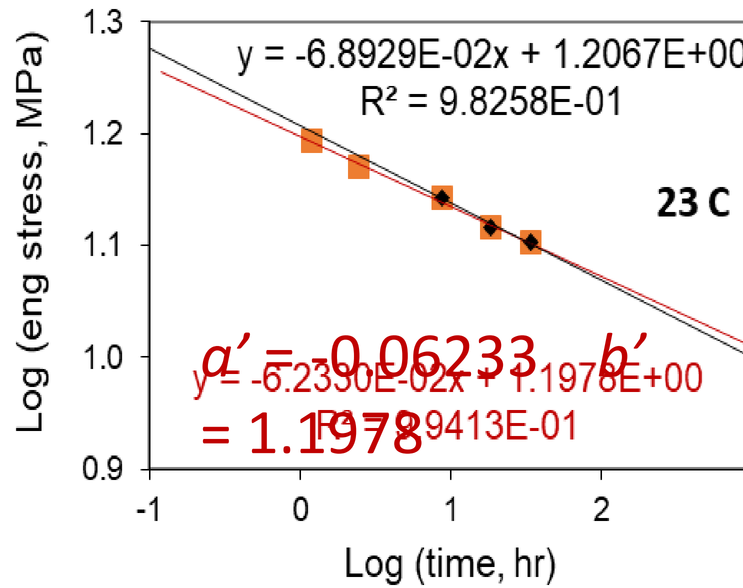


➡ **To detect the change of trend lines for *a′* and *b′***

Short-term creep test (HDPE plate with ρ = 0.941 g/cm³)

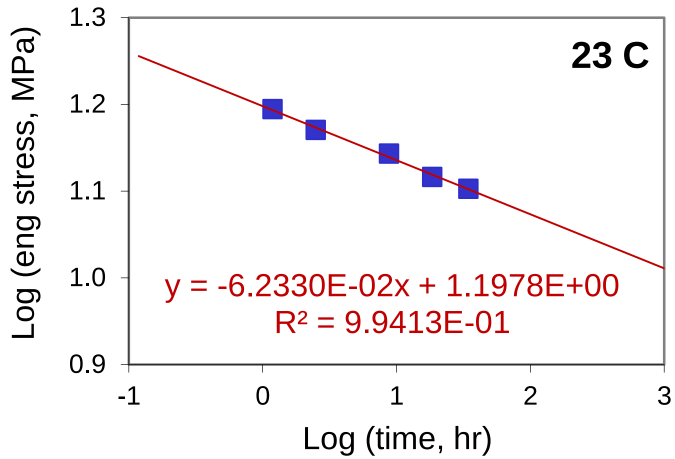


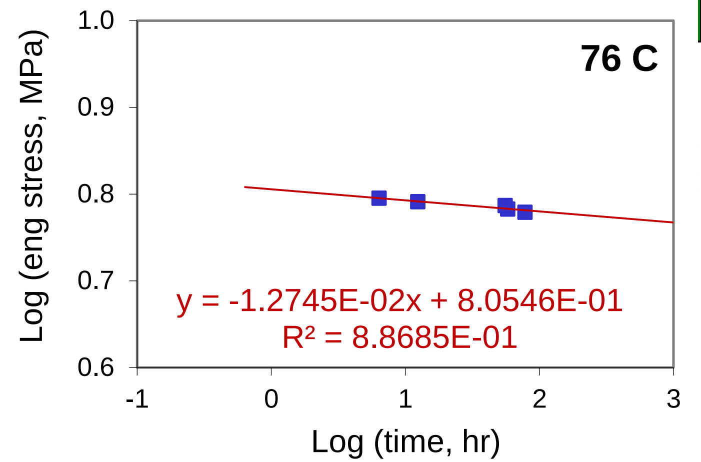


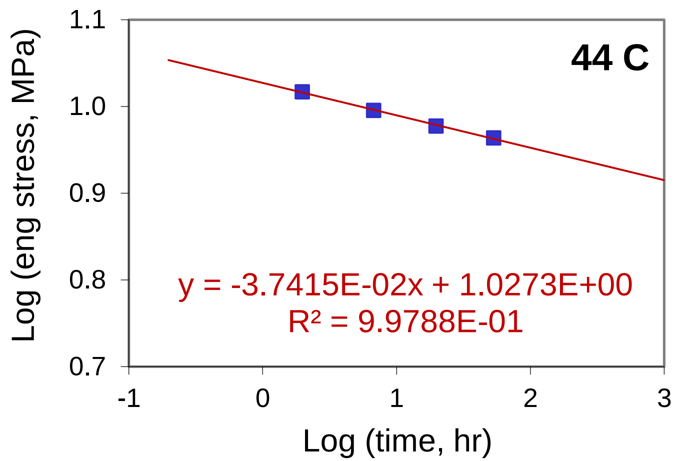


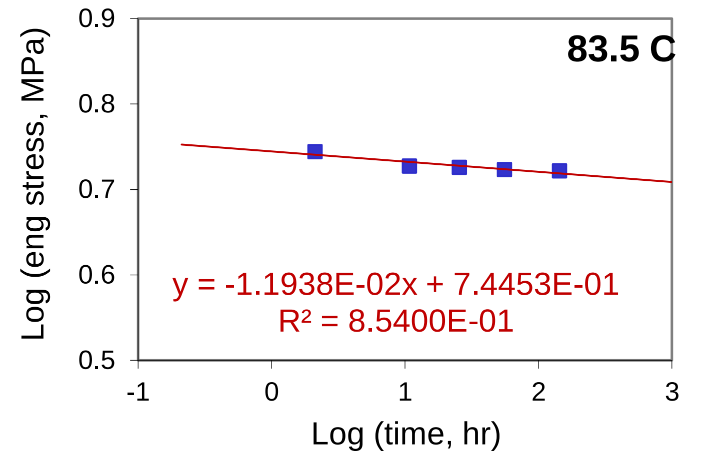
Summary of short-term creep tests (23 to 84°C)

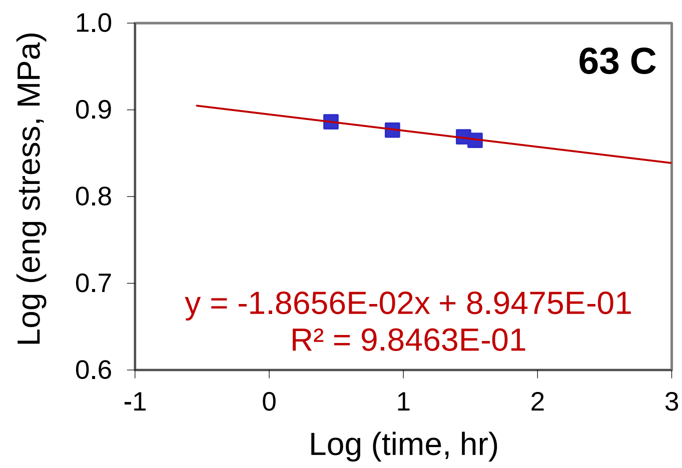
- Each took 2 to 60 hrs to complete, except one at 76°C and one at 83.5°C
- All failed though neck formation (ductile)

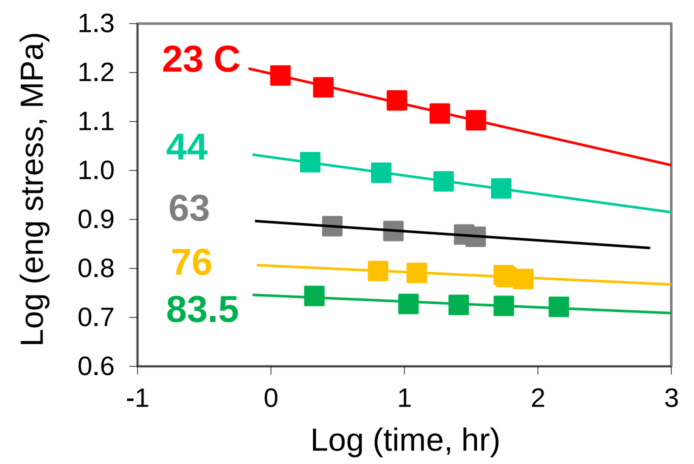






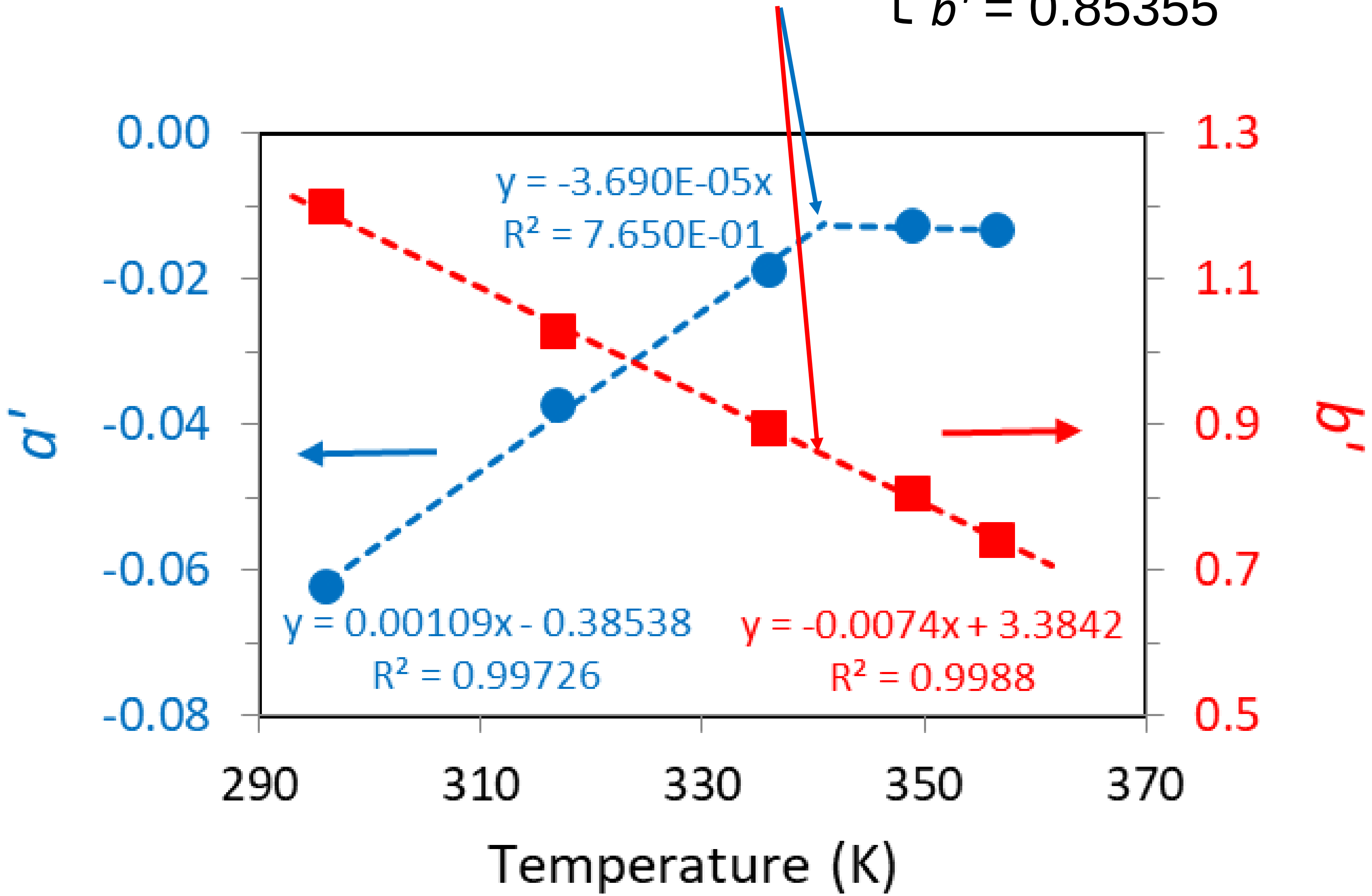






$$\log(S) = a' \log(t) + b'$$

342K $\begin{cases} a' = -0.01262 \\ b' = 0.85355 \end{cases}$



Time-temperature superposition

From ASTM D2837: $\log(S) = \frac{T}{C}\log(t) - \frac{A}{C}\left(T + \frac{B}{A}\right)$

Our version: $\log(S) = \underbrace{\left(\frac{T}{C} + D\right)}_{a'}\log(t) \underbrace{- \frac{A}{C}\left(T + \frac{B}{A}\right)}_{b'}$

For the PE plaque

T < 342 K:

a': $\frac{T}{C} + D = 0.00109\ \mathrm{T} - 0.38538 \Longrightarrow C = 917.4,\ D = -0.38538$

b': $-\frac{A}{C}\left(T + \frac{B}{A}\right) = -0.0074\ \mathrm{T} + 3.3842 \Longrightarrow A = 6.789,\ B = -3104.7$

T > 342 K:

a': $\frac{T}{C} + D = -3.69 \times 10^{-5}\ \mathrm{T} \Longrightarrow C = -27100,\ D = 0$

b': $-\frac{A}{C}\left(T + \frac{B}{A}\right) = -0.0074\ \mathrm{T} + 3.3842 \Longrightarrow A = -200.5,\ B = 91712$

T < 342 K:

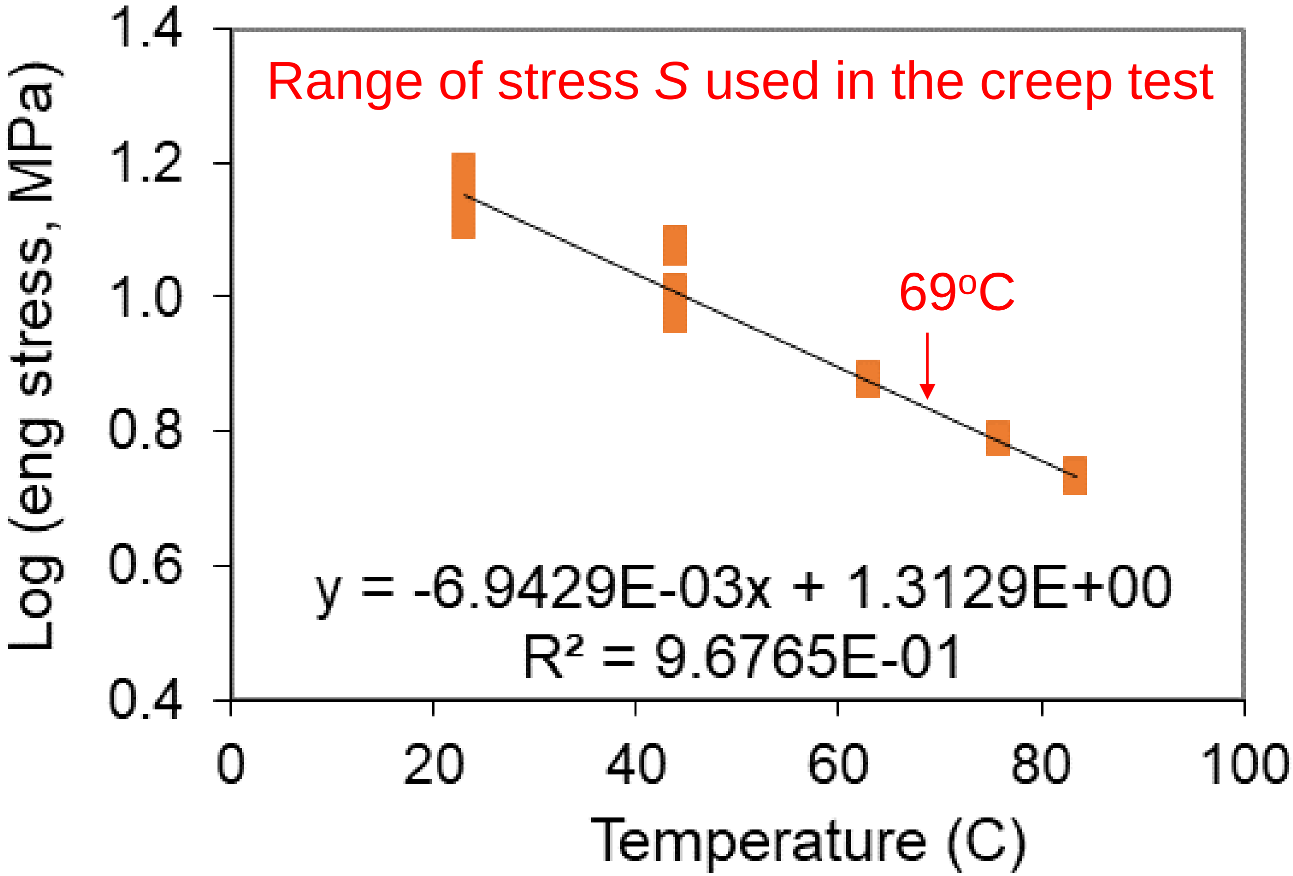
$$\log(S) = (0.00109\,T - 0.38538)\log(t) + 0.0074 \times (457.32 - T)$$

T > 342 K:

$$\log(S) = (-3.69 \times 10^{-5}\,T)\log(t) + 0.0074 \times (457.32 - T)$$

At transition, T = 342 K

Critical stress at the DB transition: $\log(S) = a' \log(t) + b'$



Critical stress of the transition, at 69°C (342K), S = 6.82 MPa

$$\log(S) = (0.00109\,T - 0.38538)\log(t) + 0.0074 \times (457.32 - T)$$

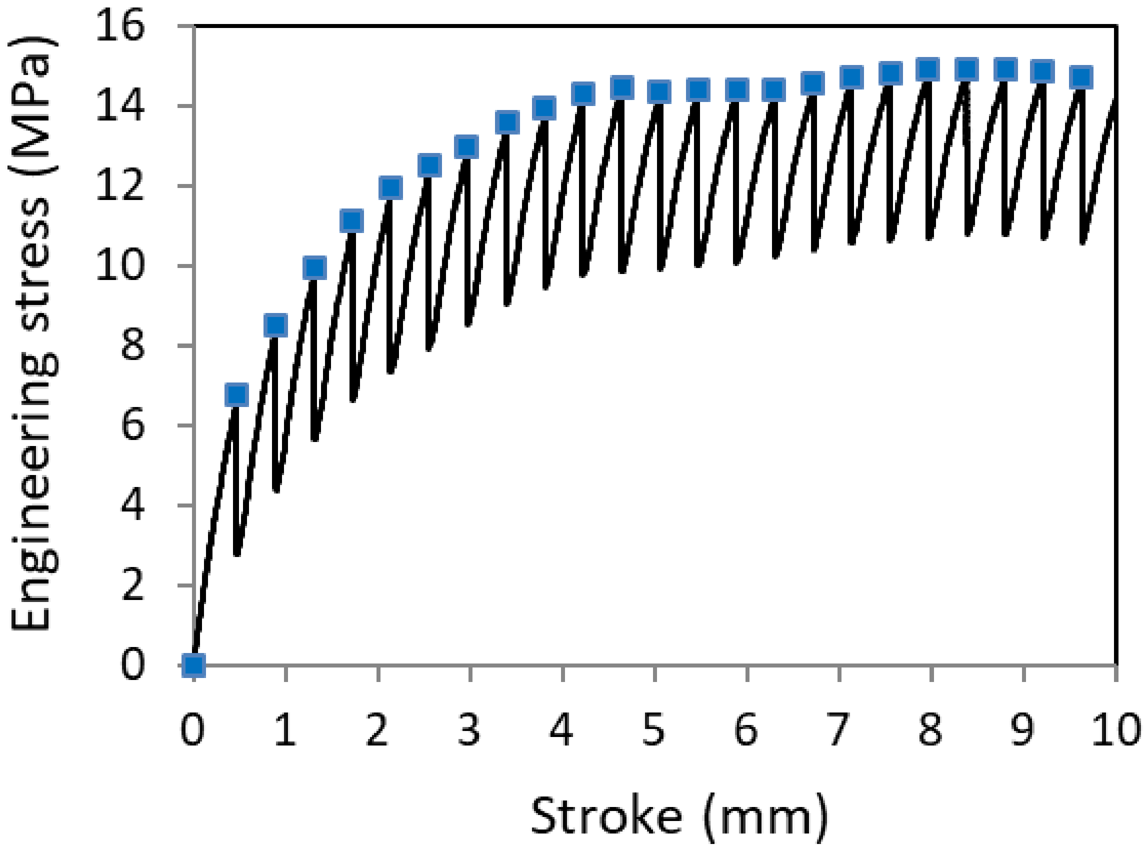
@23°C, with S = **6.82 MPa**, failure time t = 546,645 hrs (**62.4yrs**)

New test method to determine critical stress for DB transition

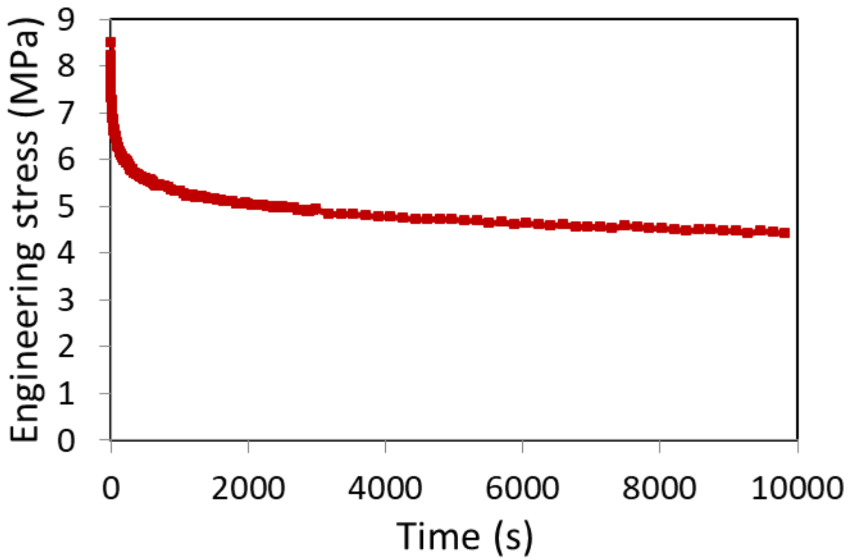
Idea: Change of the deformation mechanism ⇒ Change of relaxation behavior

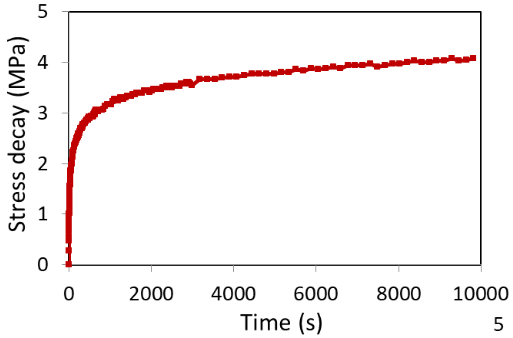
Change of the relaxation behavior → Critical point for transition

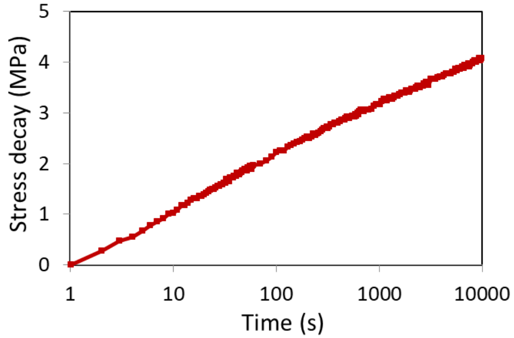
Multi-relaxation test on one specimen



Sample of analysis on data from the stress relaxation





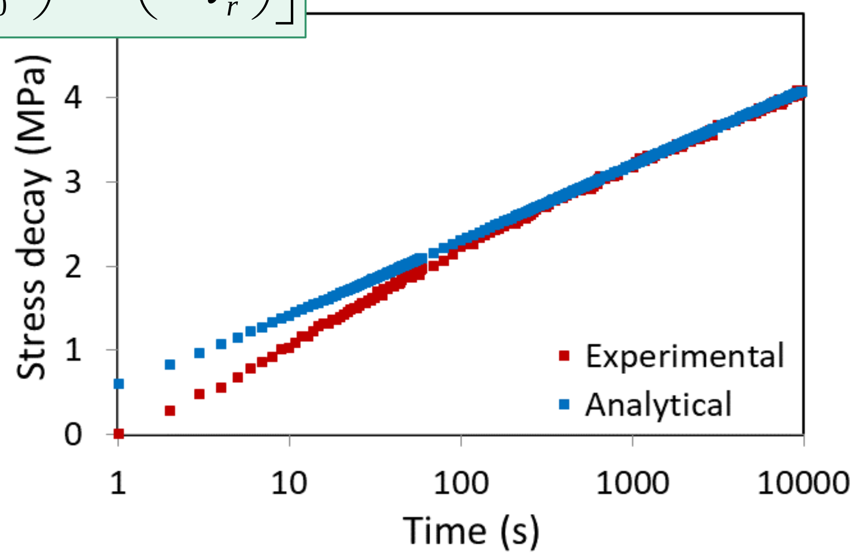


$$\Delta\sigma_r = \sigma_r(0) - \sigma_r(t) = \sigma_r(0) - 2\sigma_0 \tanh^{-1}\left[\tanh\left(\frac{\sigma_r(0)}{2\sigma_0}\right)\exp\left(-\frac{t}{\tau_r}\right)\right]$$

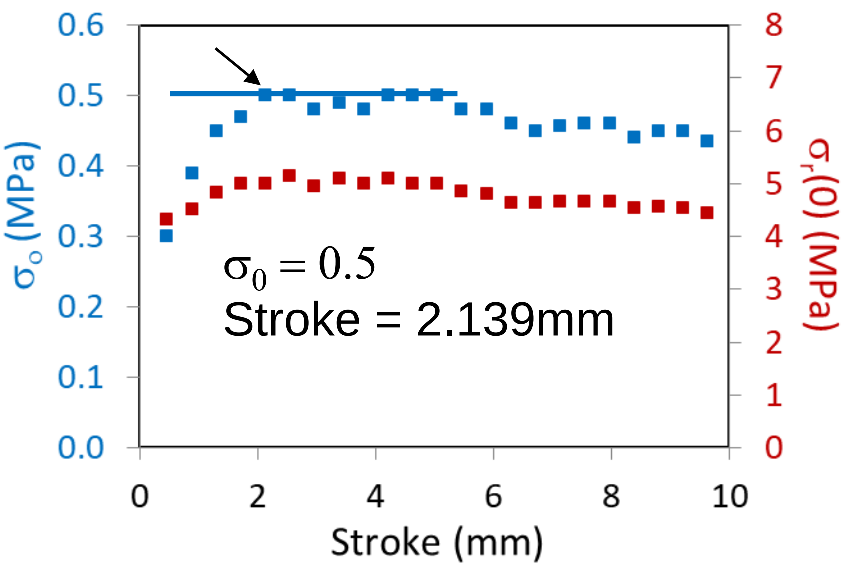
- K. Hong, A. Rastogi, G. Strobl. *Macromolecules 37* (2004) 10165-73

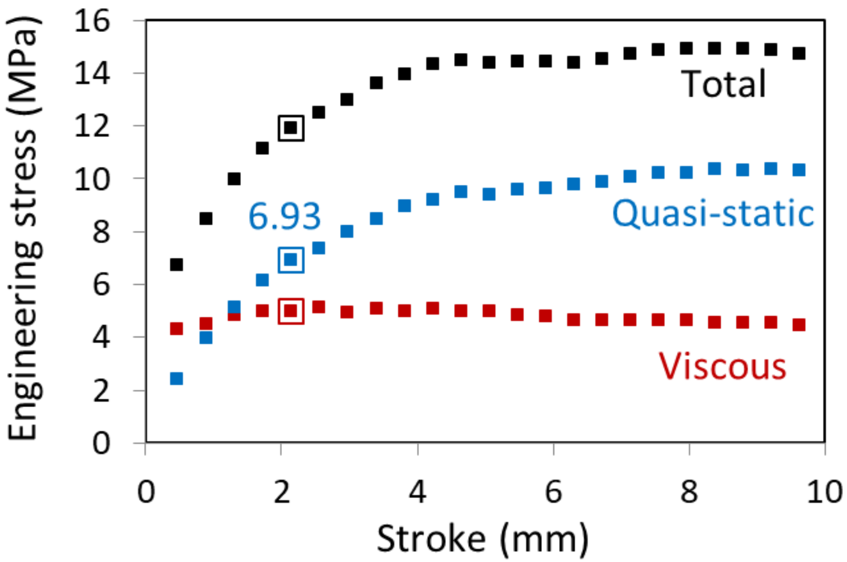
τ_r: fixed at 16,000 s

adjusting σ_0 and $\sigma_r(0)$

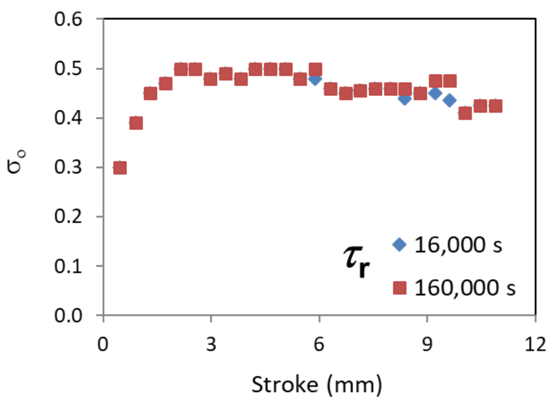


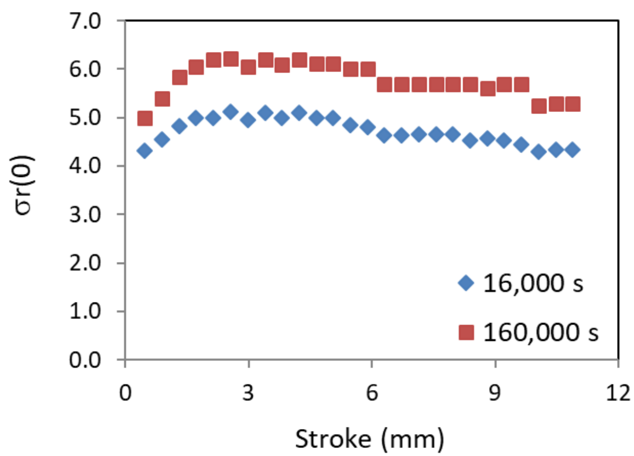
Critical stress for DB transition (with τ_r = 16,000 seconds)

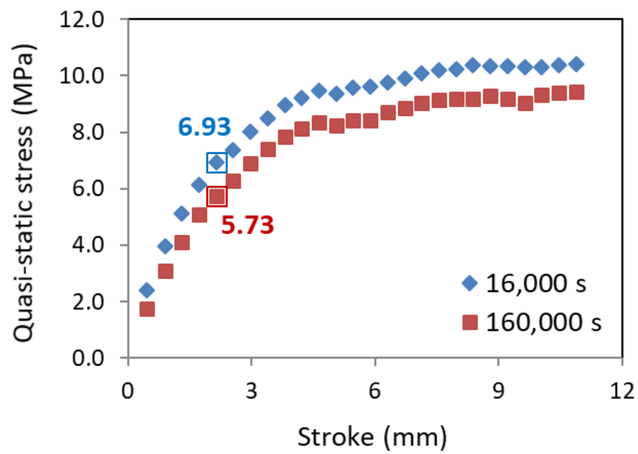




Critical stress from creep tests = 6.82 MPa

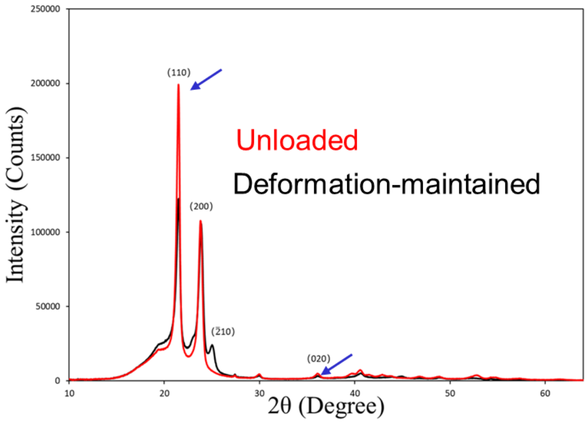


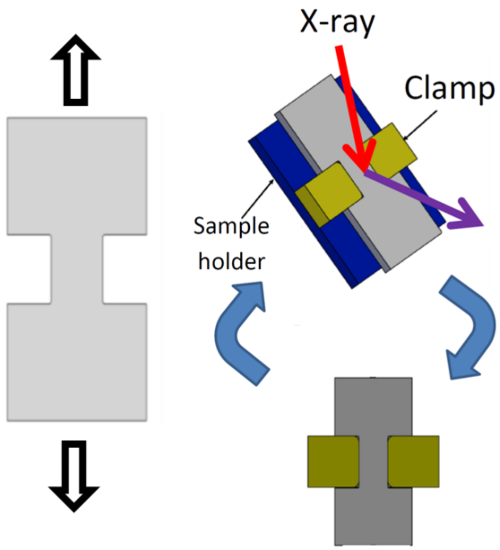




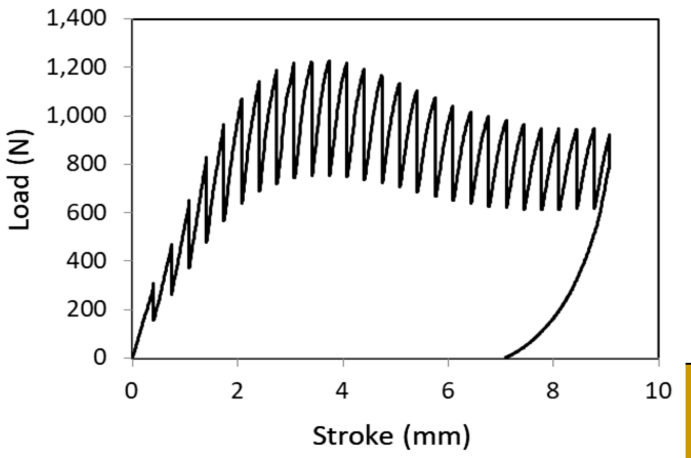
Evidence on the crystalline phase involved in the deformation

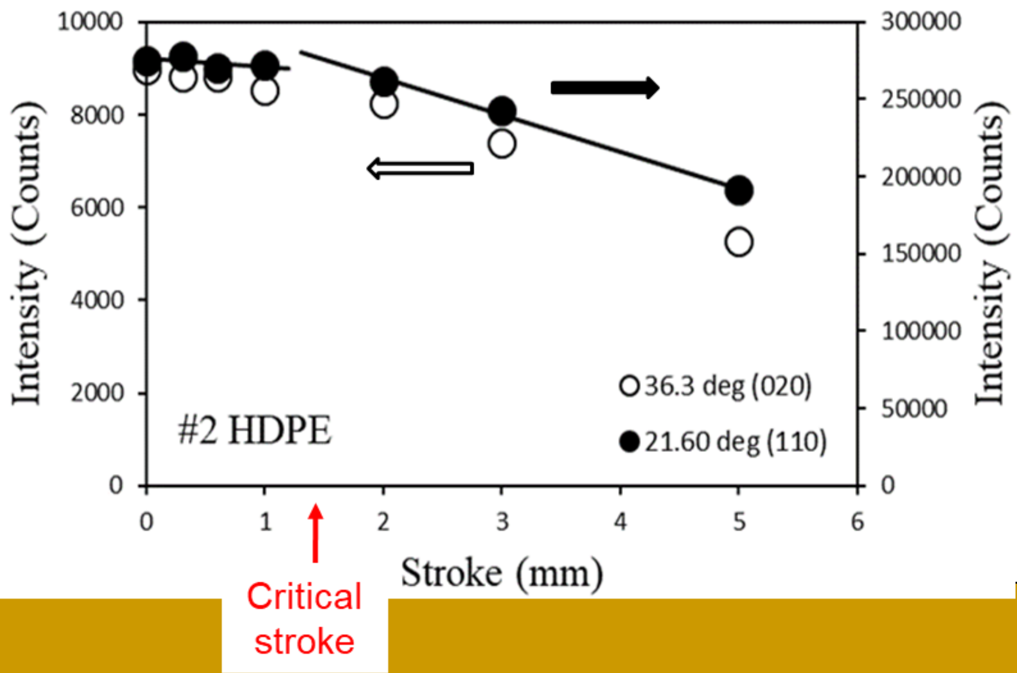
- **Wide-angle X-ray scattering (WAXS)**





Multiple relaxation test



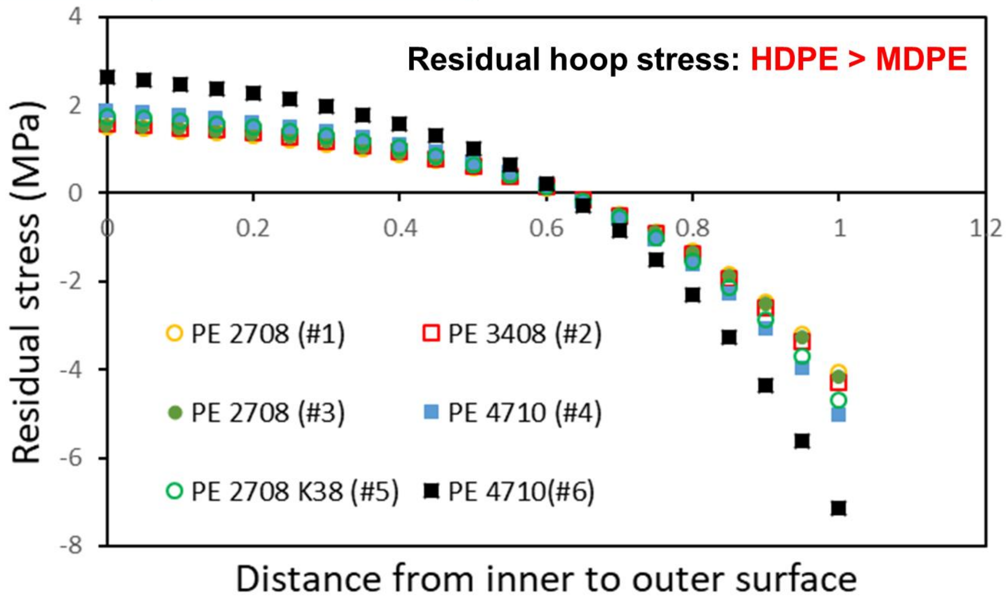


Apply the concept to 2-inch PE pipes

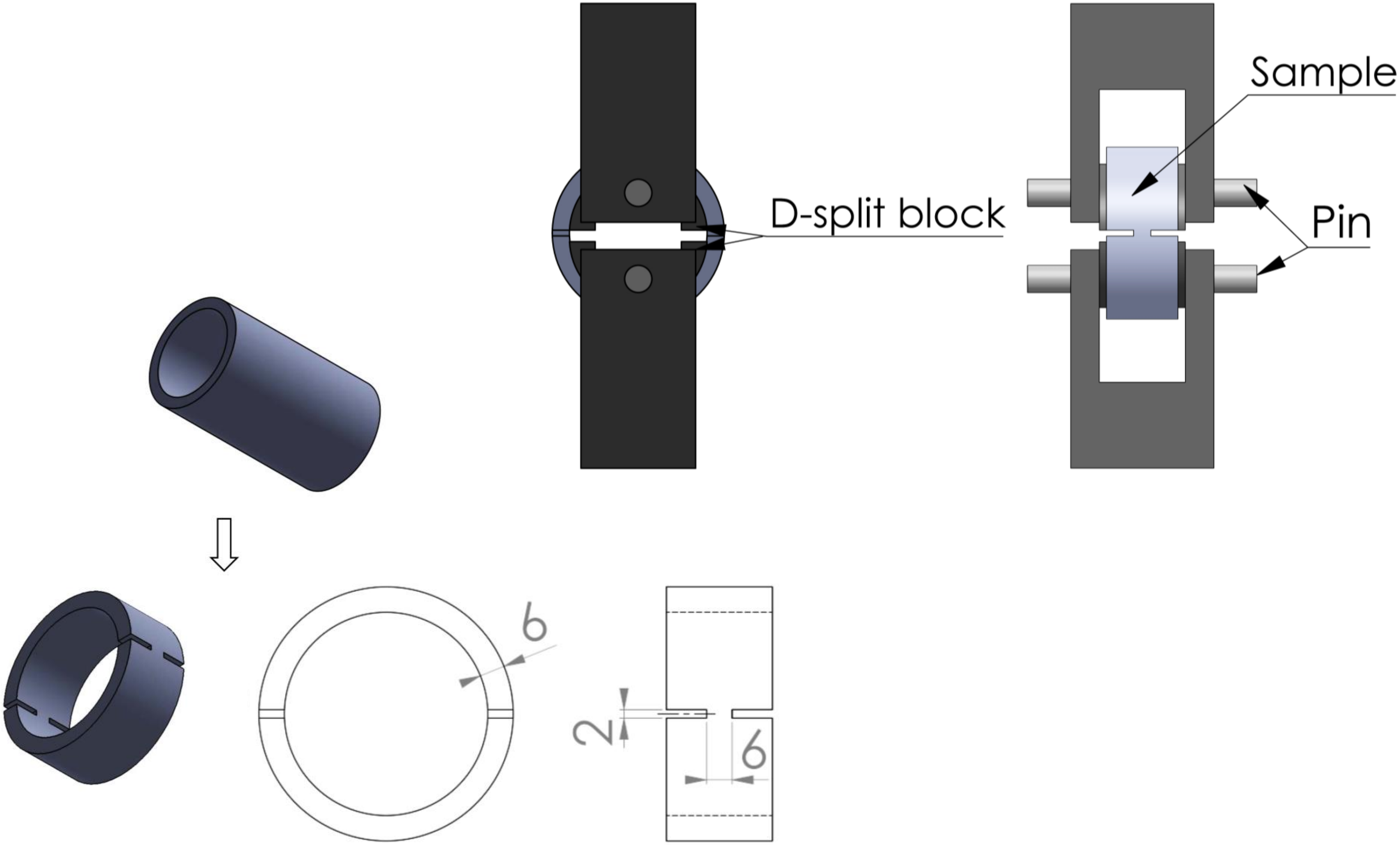
Residual hoop stress: based on one-slit-ring method

J. Poduška, P. Hutař, J. Kučera, J. S. Andreas Frank, G. Pinter, and L. Náhlík. *Polym. Test.*, **54**, 288 (2016)

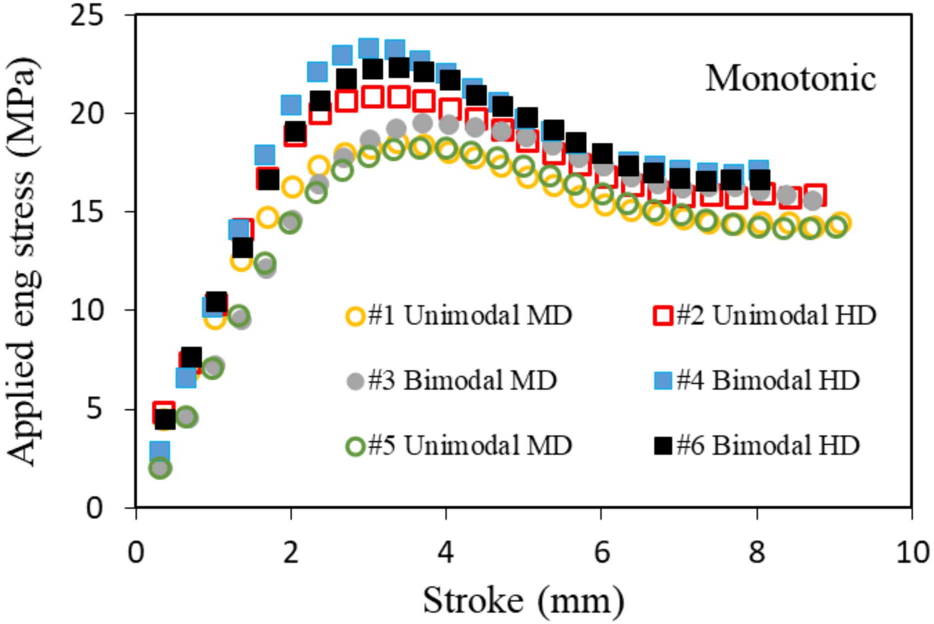
Material	Symbol	Density (g/cc)	Resin yield strength (MPa)
#1 Unimodal MDPE	PE2708-M-U1	0.940	19.3
#2 Unimodal HDPE	PE3408-H-U	0.944*	22.8*
#3 Bimodal MDPE	PE2708-M-B	0.940	19.3
#4 Bimodal HDPE	PE4710-H-B1	0.949	24.8
#5 Unimodal MDPE	PE2708-M-U2	0.940	19.3
#6 Bimodal HDPE	PE4710-H-B2	0.949	>24.1

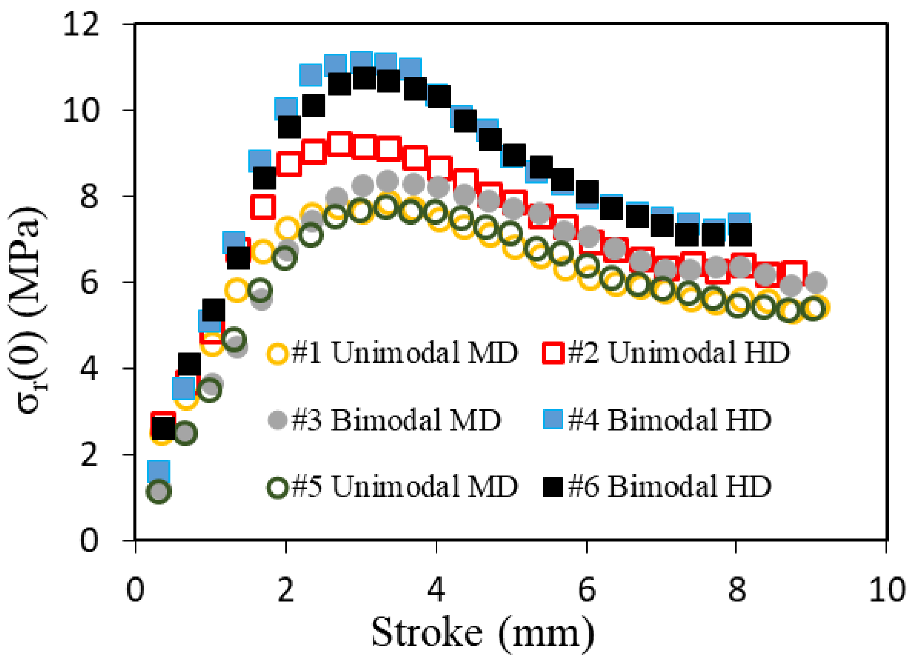


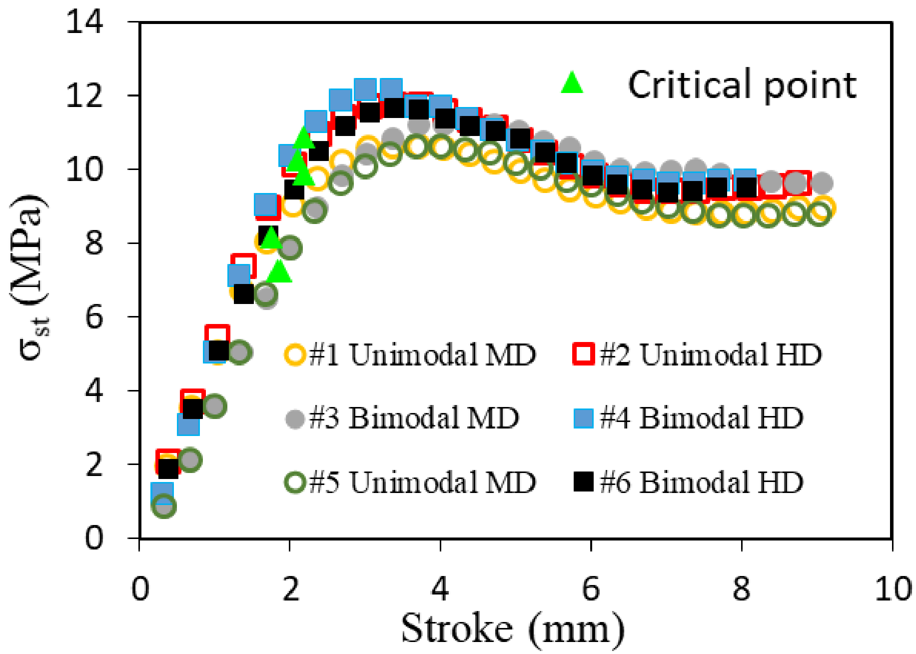
Multi-relaxation tests



Test results – 2-in pipe





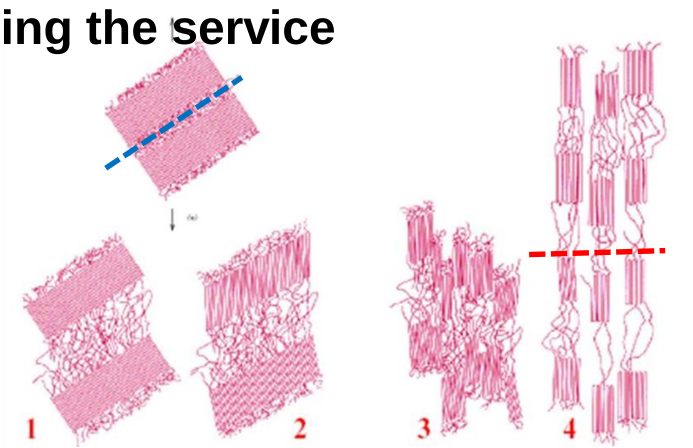


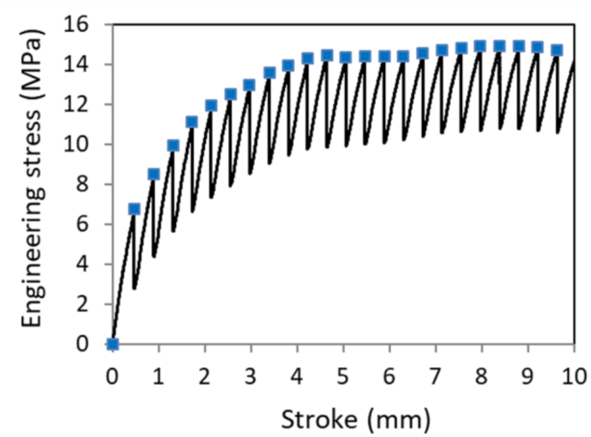
Pipe code	Critical area strain	Quasi-static stress at critical point (MPa)	Hydrostatic Design Basis at 23 ºC (MPa)
PE2708-M-U1	0.05	8.18	8.62
PE3408-H-U	0.09	10.25	11.03
PE2708-M-B	0.04	7.25	8.62
PE4710-H-B1	0.07	10.86	11.03
PE2708-M-U2	0.04	7.25	8.62
PE4710-H-B2	0.08	9.88	11.03

Conclusions

- Proposed and verified the transition for deformation mechanism in PE pipe when subjected to in-service loading conditions

- Developed a short-term, multi-relaxation test method to determine critical stress for the deformation transition and predict time for its occurrence during the service





Future Work

- To apply the research approach to PE pipe, taking into account residual hoop stress in the evaluation for their long-term performance

- To explore possibility of applying this test approach to evaluation of long-term performance of other plastics and FRP, and their load-carrying capability

Acknowledgement

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- **Wajdy Ateerah from Polytubes for supply of PE pipes**

Thank You!

PE4710-H-B-1in