UNIVERSITY OF CAMBRIDGE

Surface Microstructure and Fracture Group:
Fracture & Shock

From static to dynamic (and in-between)

- the response of polymer bonded explosives

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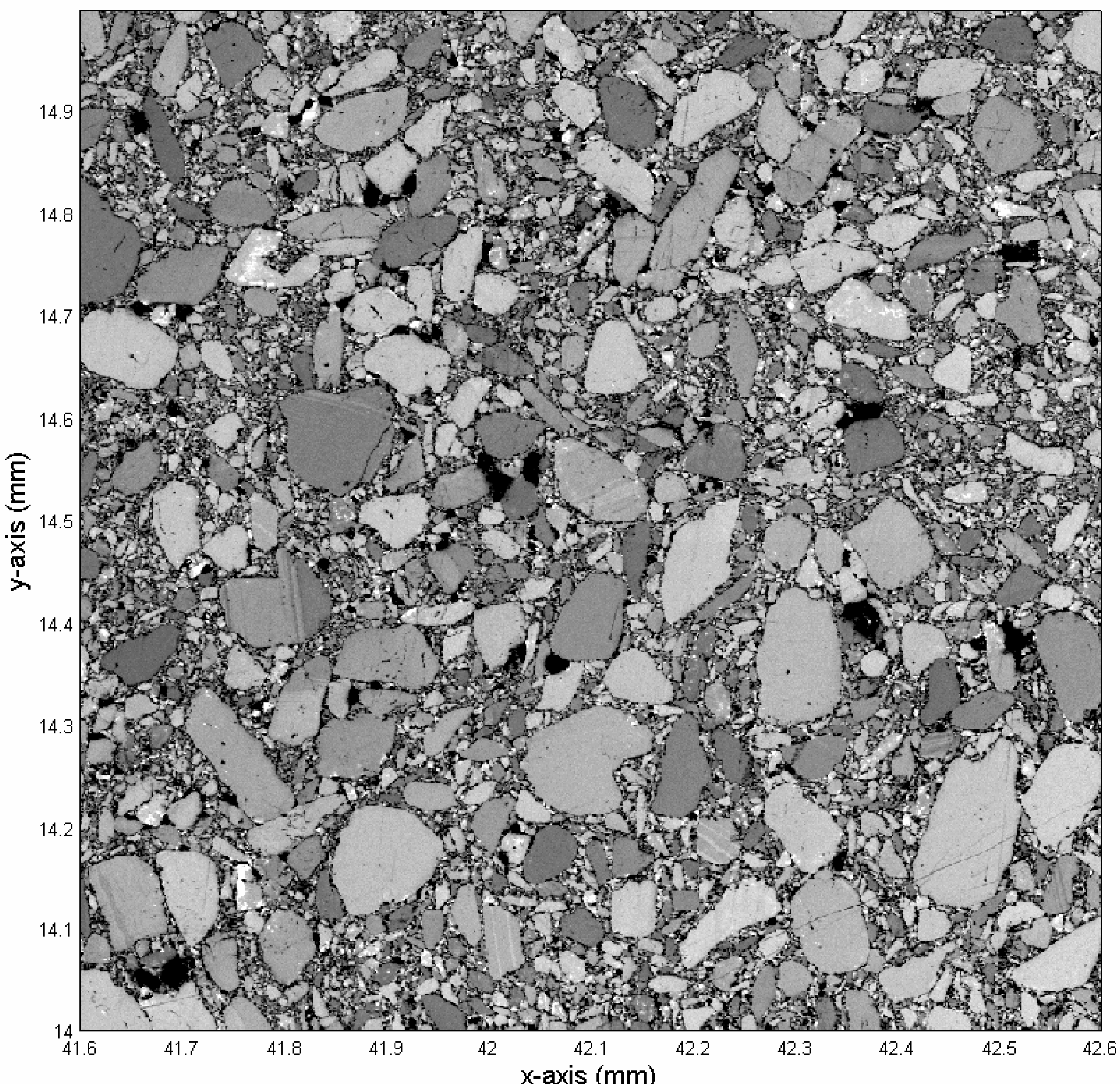
Introduction

- Short introduction to PBXs
- Methods for thermal characterisation
- Methods for mechanical characterisation
- Methods for introducing controlled damage
- Evaluation of damaged materials

Polymer Bonded Explosives



Thermal properties

Thermal properties

Thermal diffusivity D, Conductivity κ, and Specific Heat C_P are all related by:

$$D = \frac{\kappa}{\rho \; C_P} \;, \qquad (1)$$

We independently measured all three and used (1) to cross-check our result. Perform on PBXs and binder systems.

Introduction

- Thermal conductivity via Lee's disc method:

  Temperature gradient across a sample analysed using Fourier's 1D heat flow equation.

- Thermal diffusivity via Ångström's method:

  Measure phase and amplitude evolution of a thermal wave propagating in a sample rod.

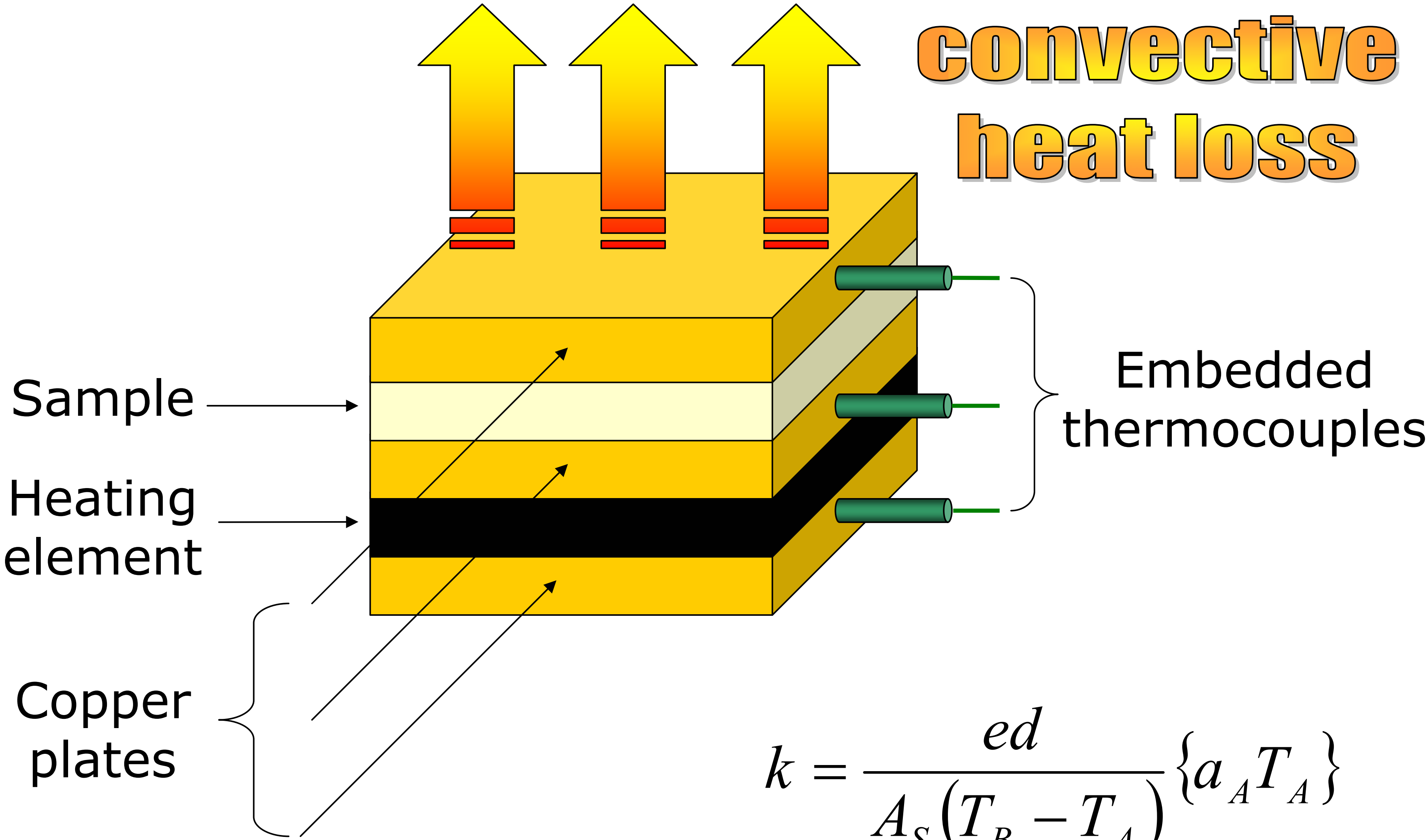
- Specific heat via DSC method:

  Power required to ramp temperature of sample a known amount is measured.

- Conductivity & diffusivity by transient hot-strip method:

  Due to Gustafsson *et al.* (1979) – solves heat equation for a heat source embedded in an 'infinite' body.

Thermal conductivity



$$k = \frac{ed}{A_S\left(T_B - T_A\right)}\left\{a_A T_A\right\}$$

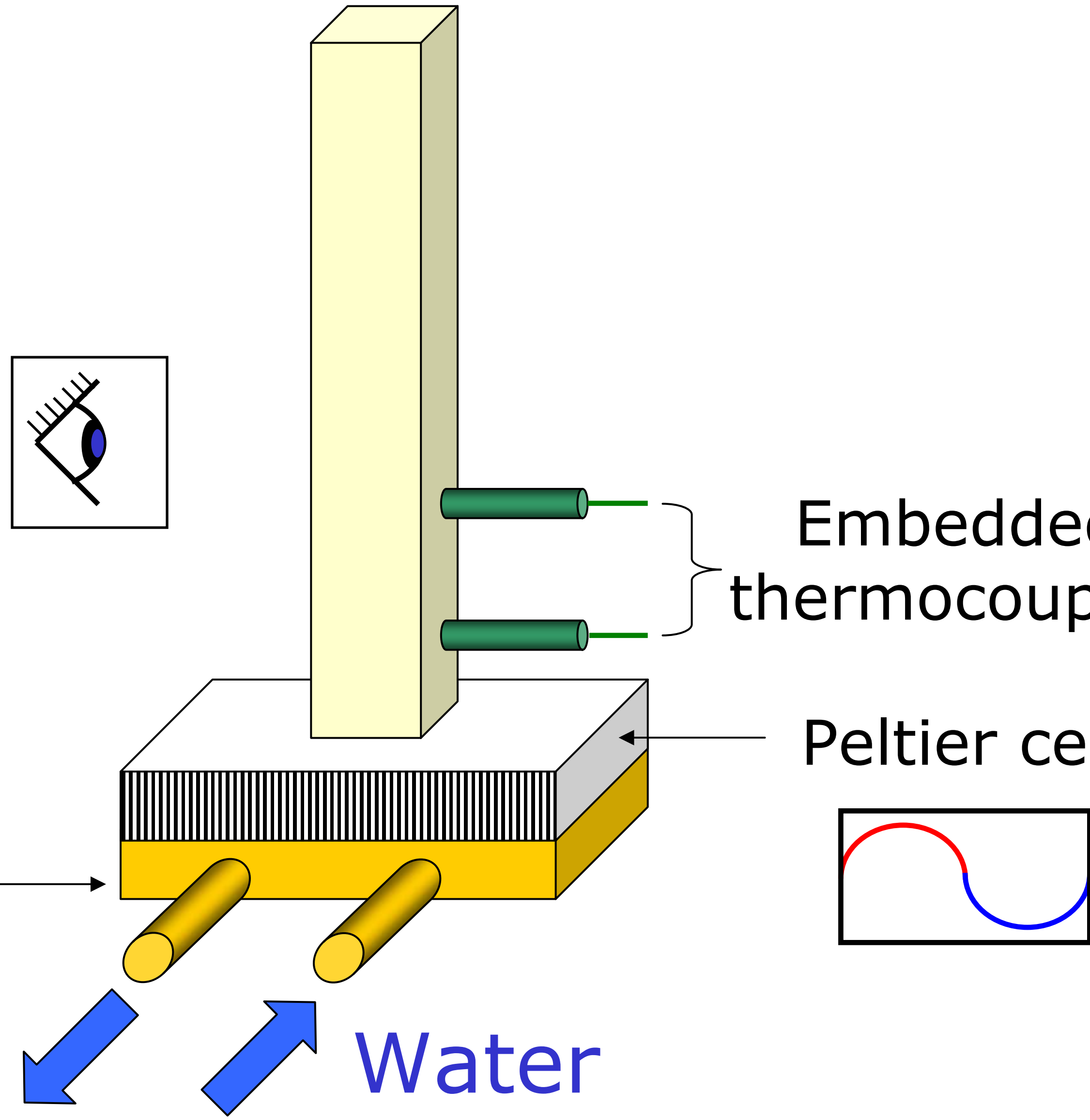
Ångström METHOD

Thermal diffusivity

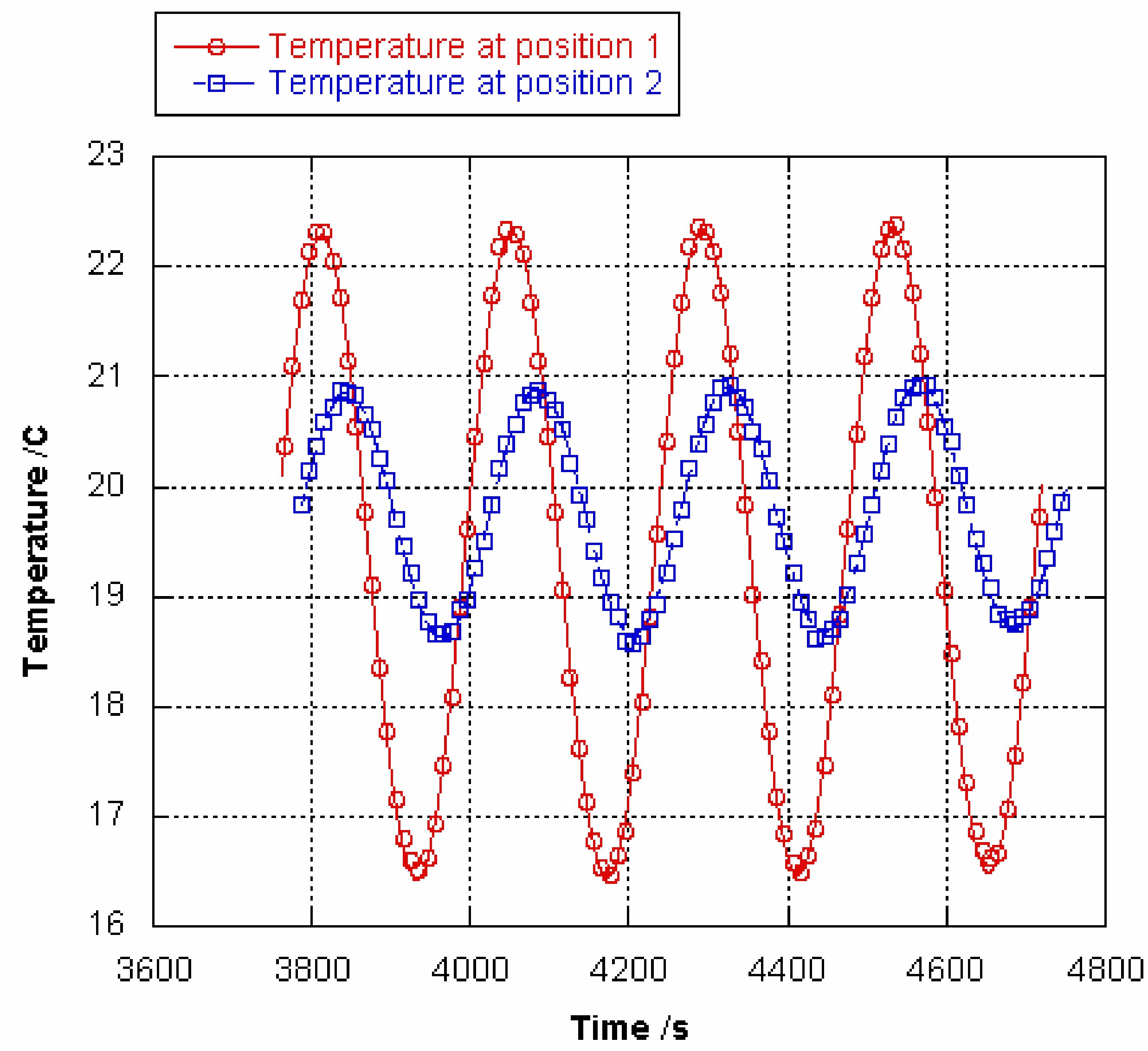
$$D = \frac{Lv}{2\ln(T_1 / T_2)}$$

Thermal imaging camera (FLIR SC300)

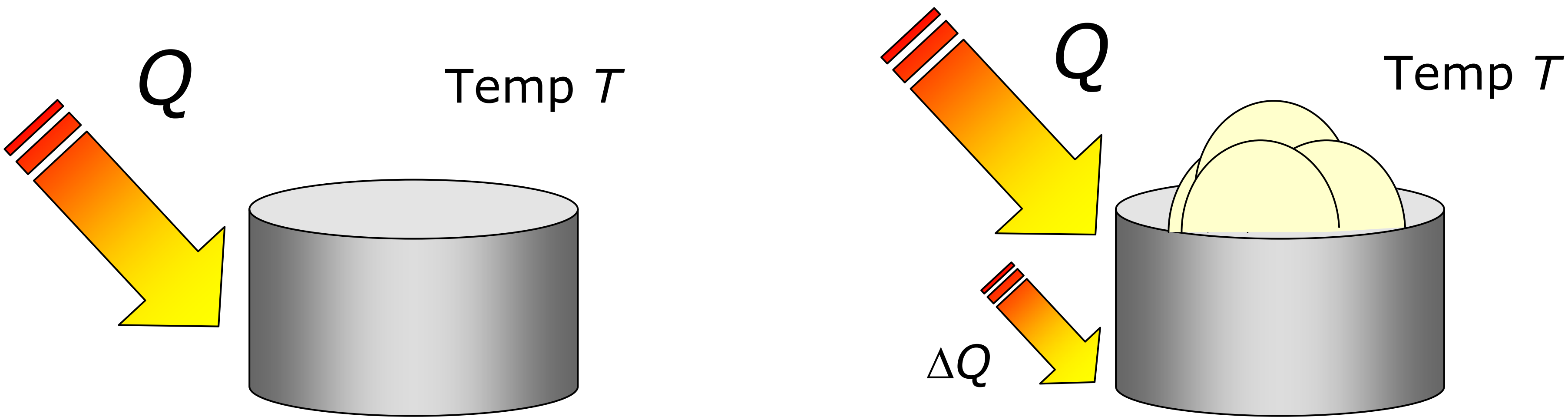
Water assisted copper heat exchanger



Thermal diffusivity



Specific heat



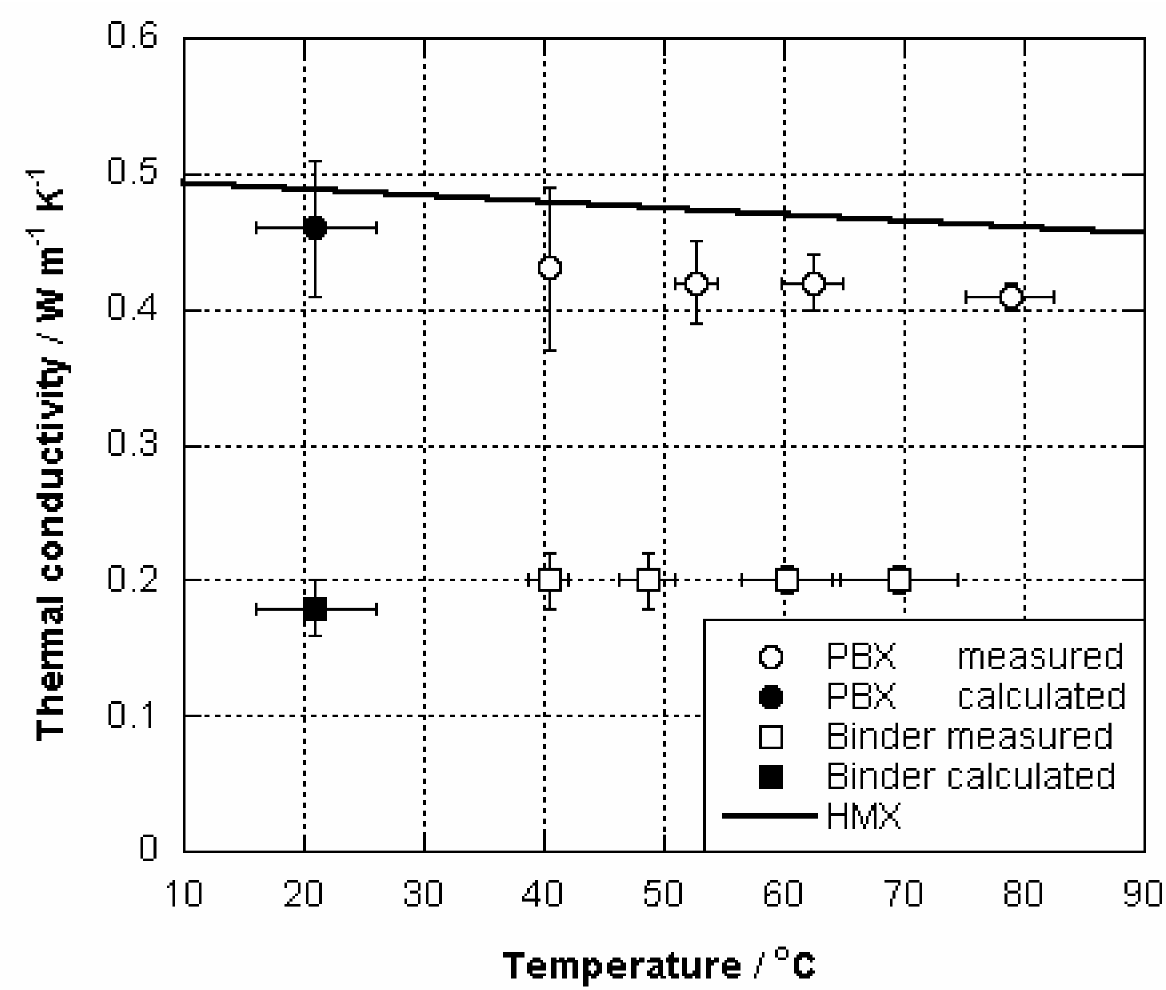
Empty reference pan

Sample pan

Measure additional power required to keep both pans at same temperature during a temperature ramp:

$$\frac{dQ}{dt} = mC_P \frac{dT}{dt}$$

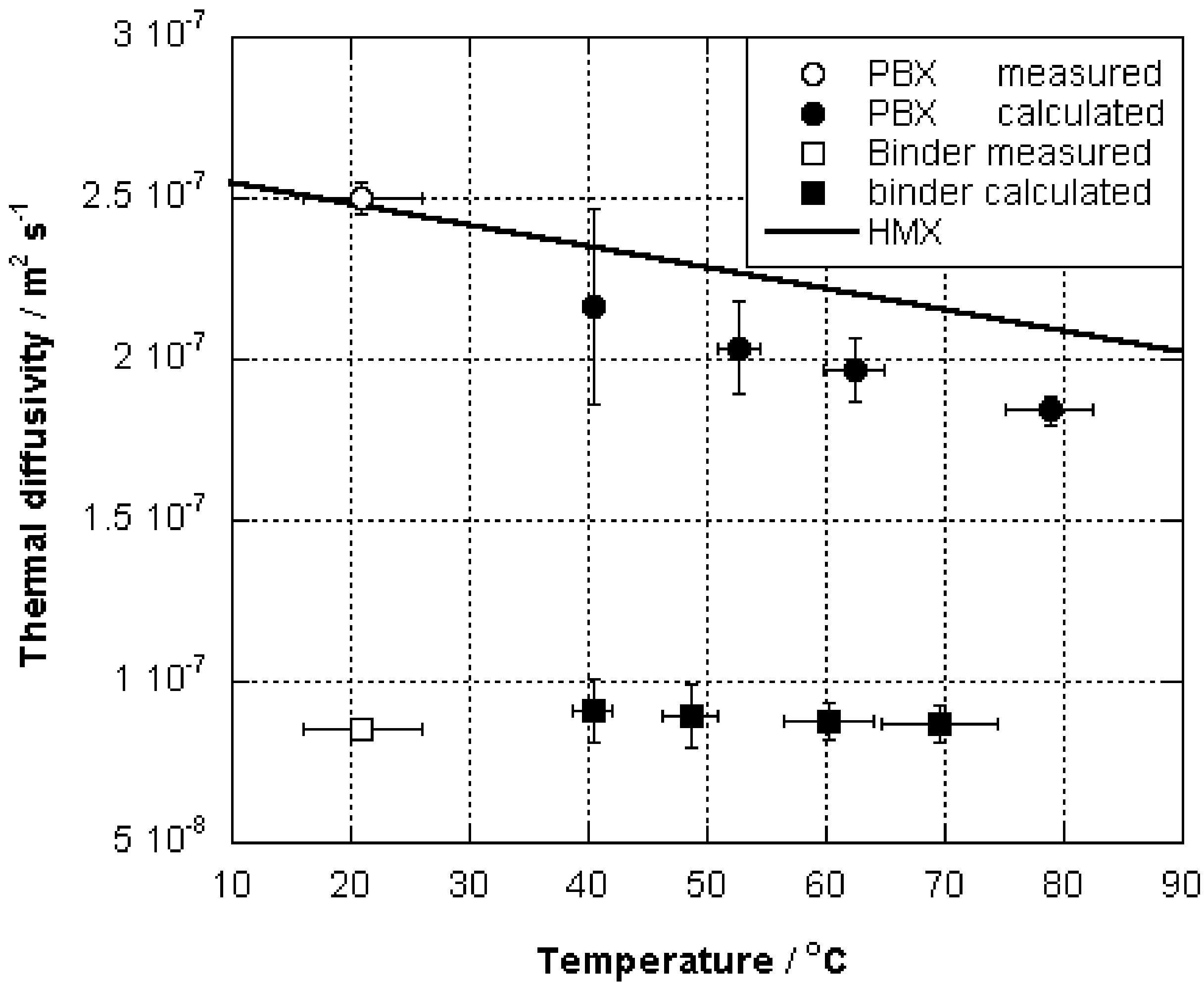
Thermal conductivity AWE PBX



HMX data from: Hanson-Parr D.M., and Parr T.P. (1999)

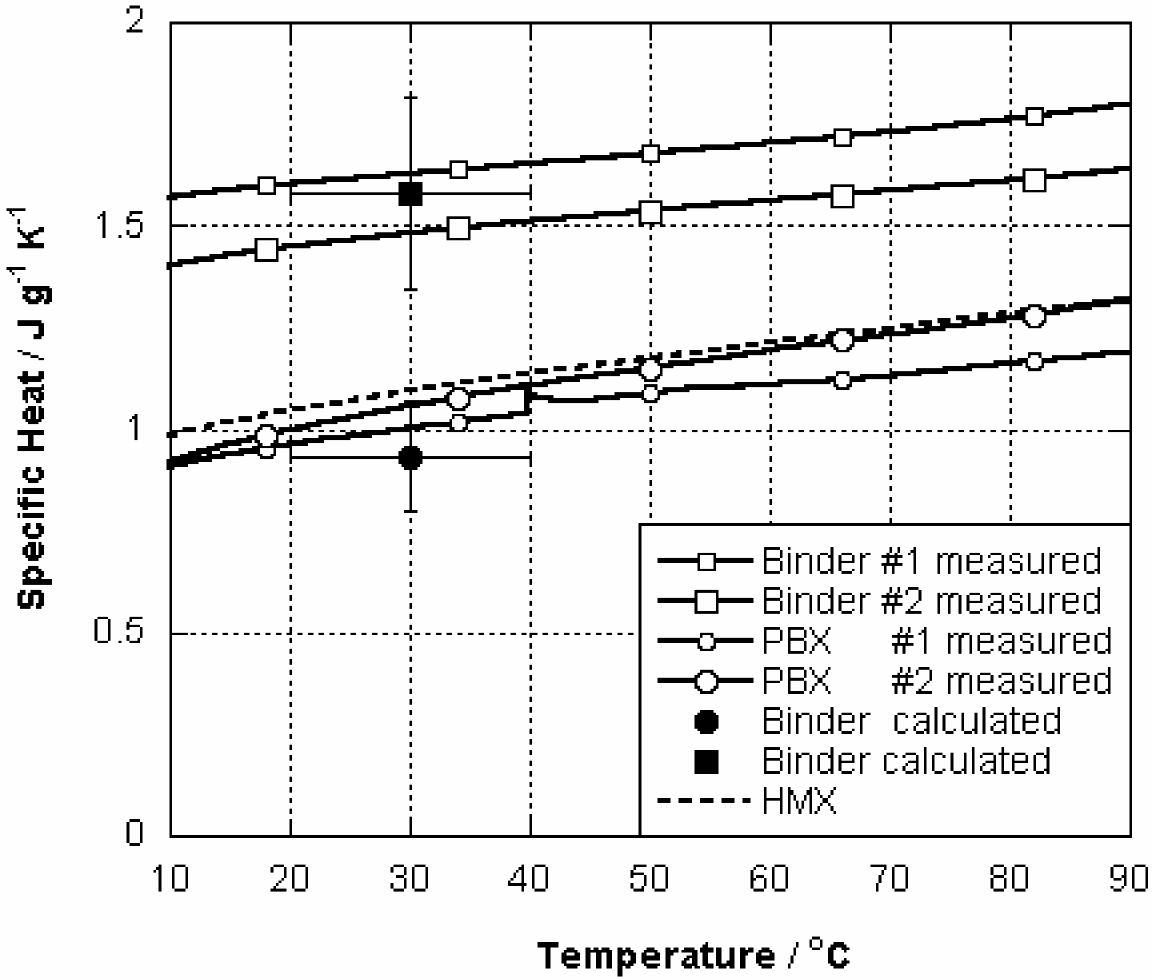
From Palmer *et al.* (2007)

Thermal diffusivity AWE PBX



From Palmer *et al.* (2007)

Specific heat capacity AWE PBX

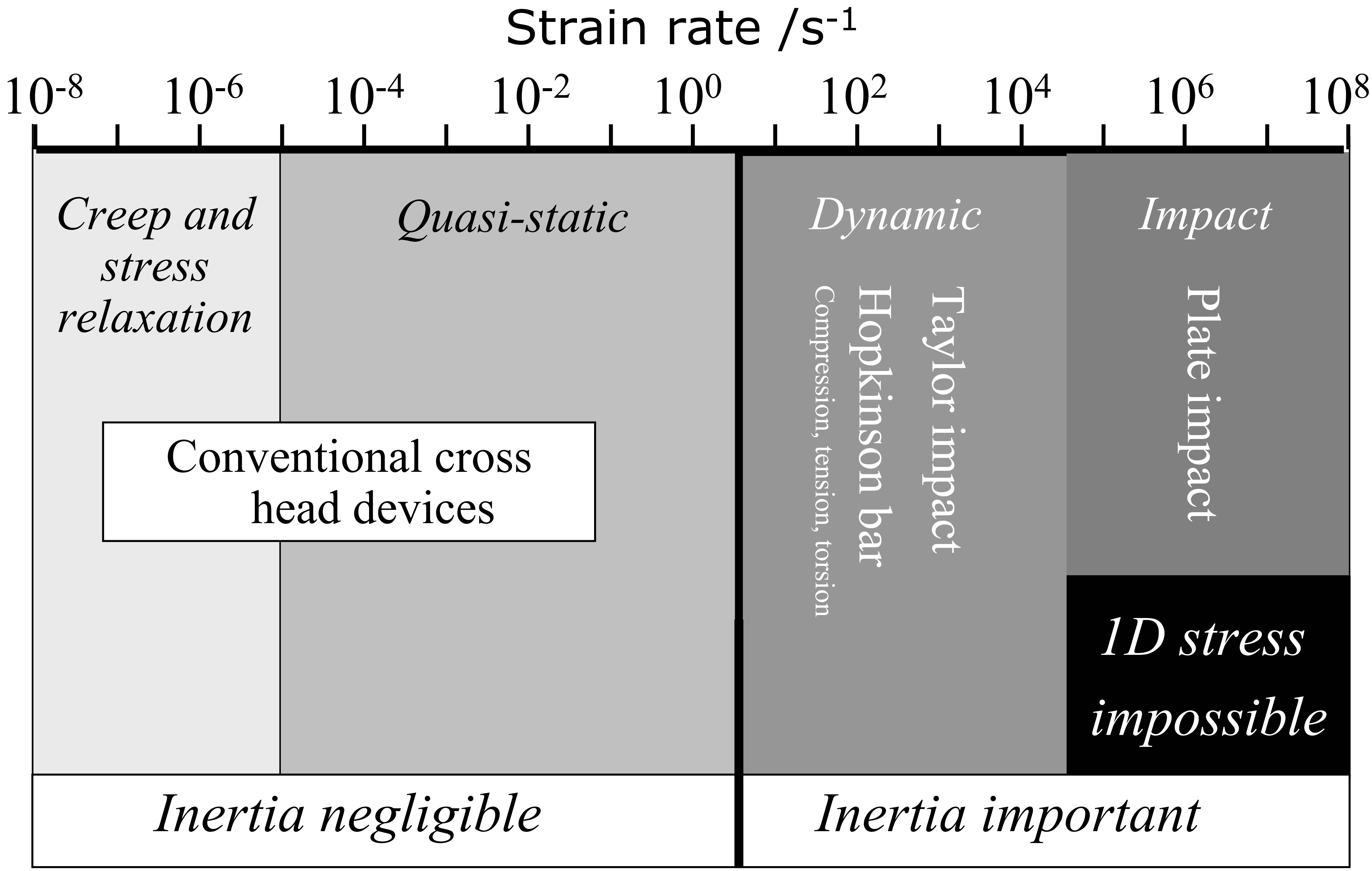


Large 'error' on temperature due to diffusivity data at 20°C and conductivity data at 40°C

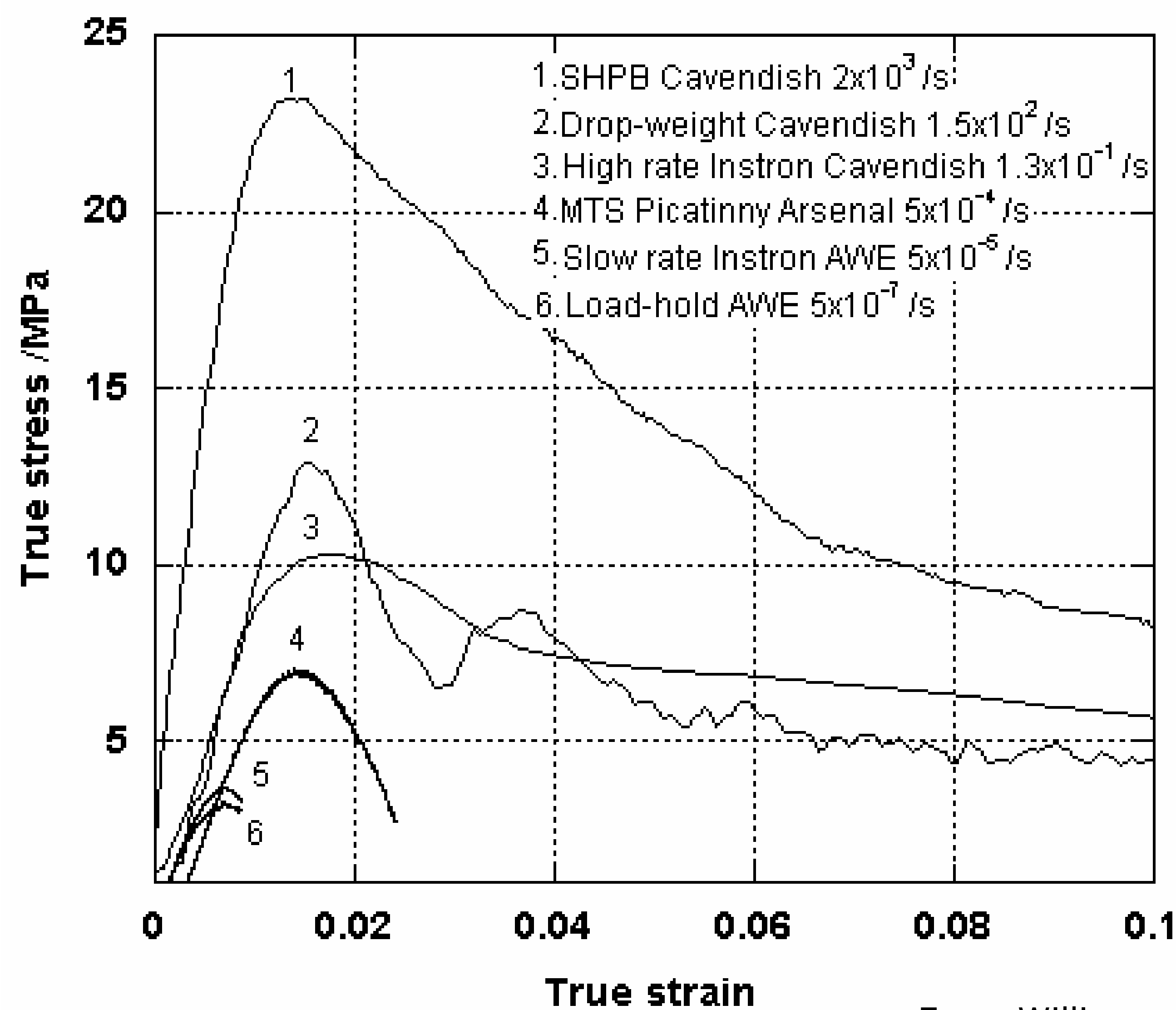
From Palmer *et al.* (2007)

Mechanical Properties

Strain rates of interest

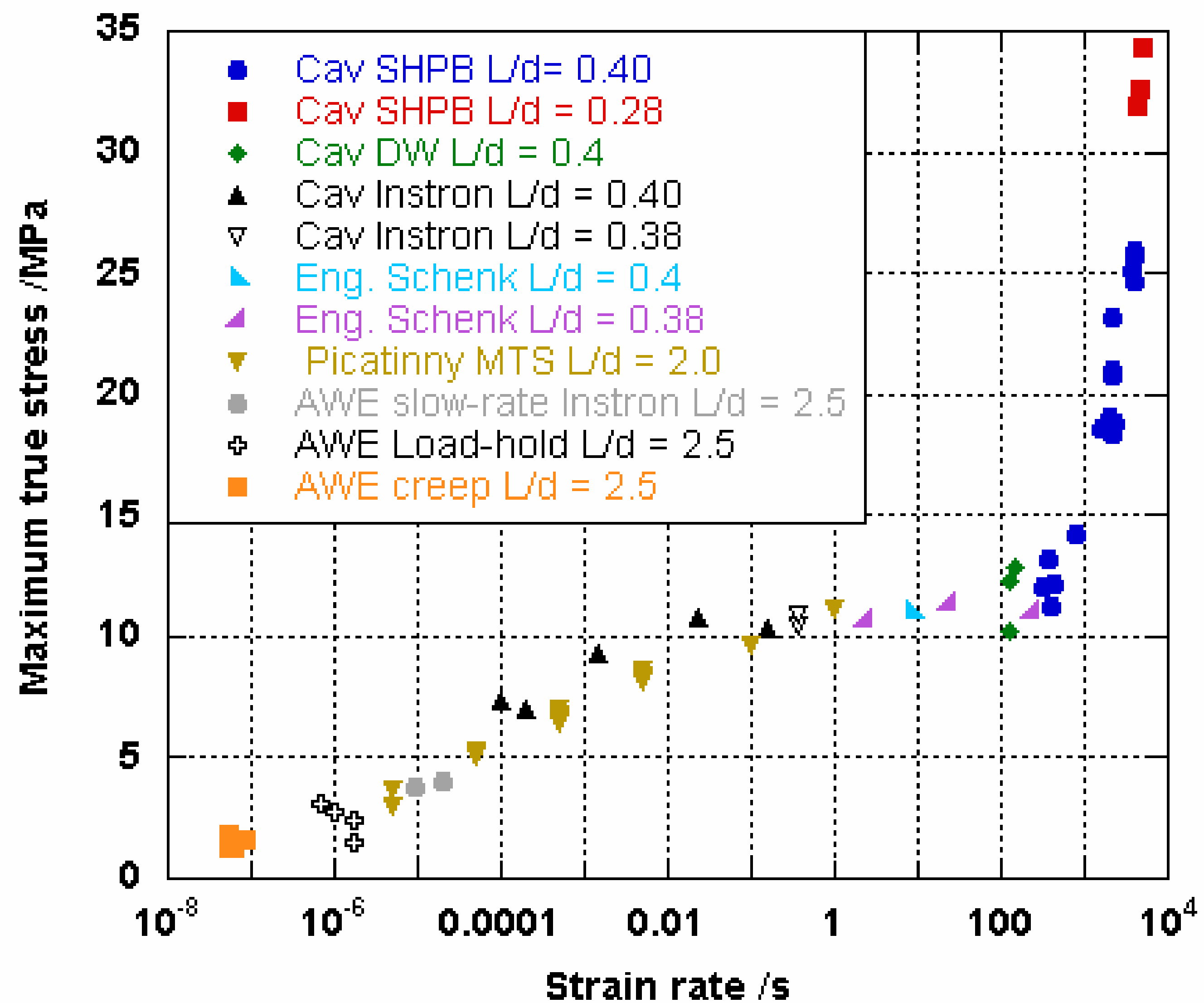


Rate dependence of AWE PBX



From Williamson *et al.* (2008)

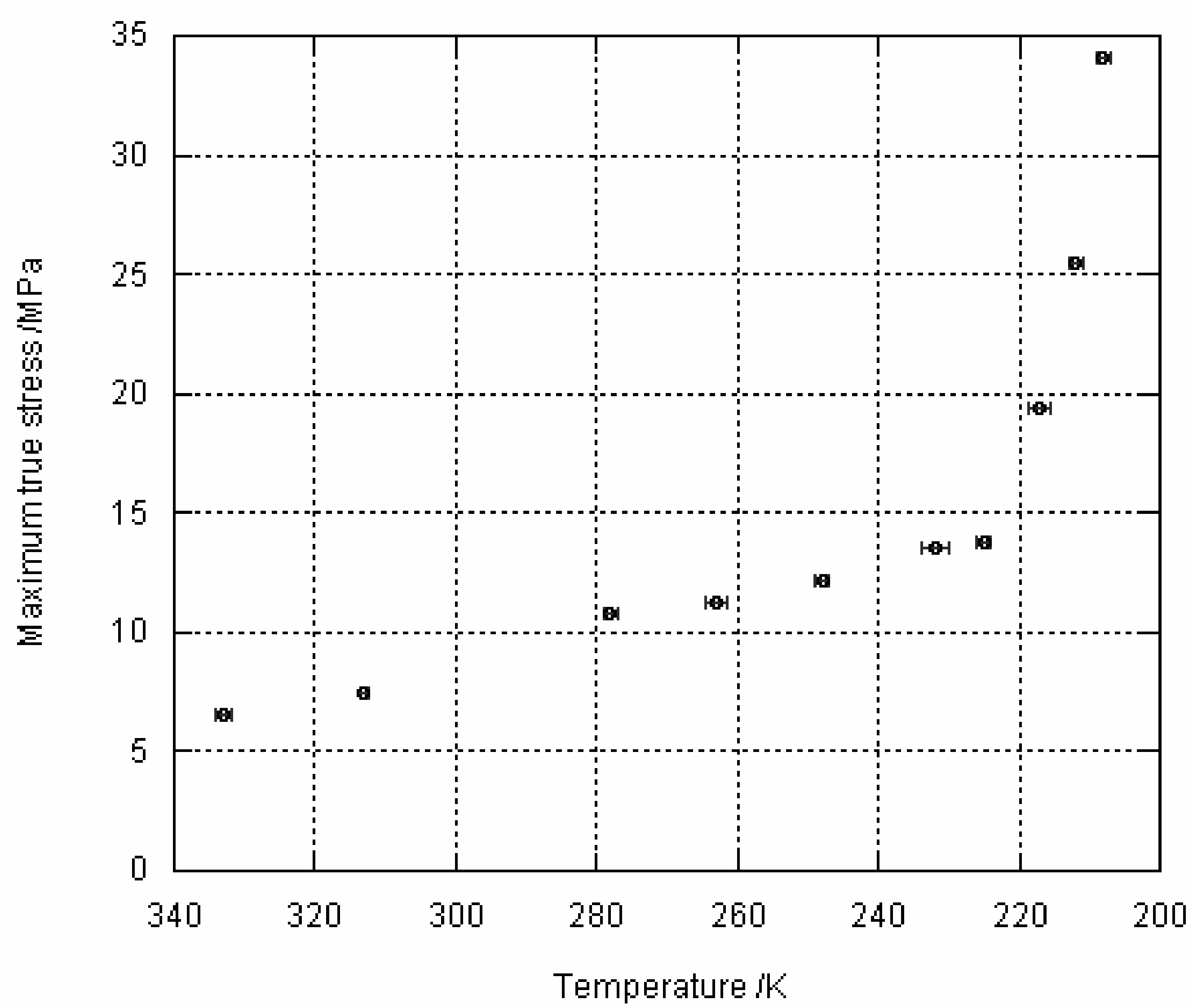
Rate dependence of AWE PBX



From Williamson *et al.* (2008)

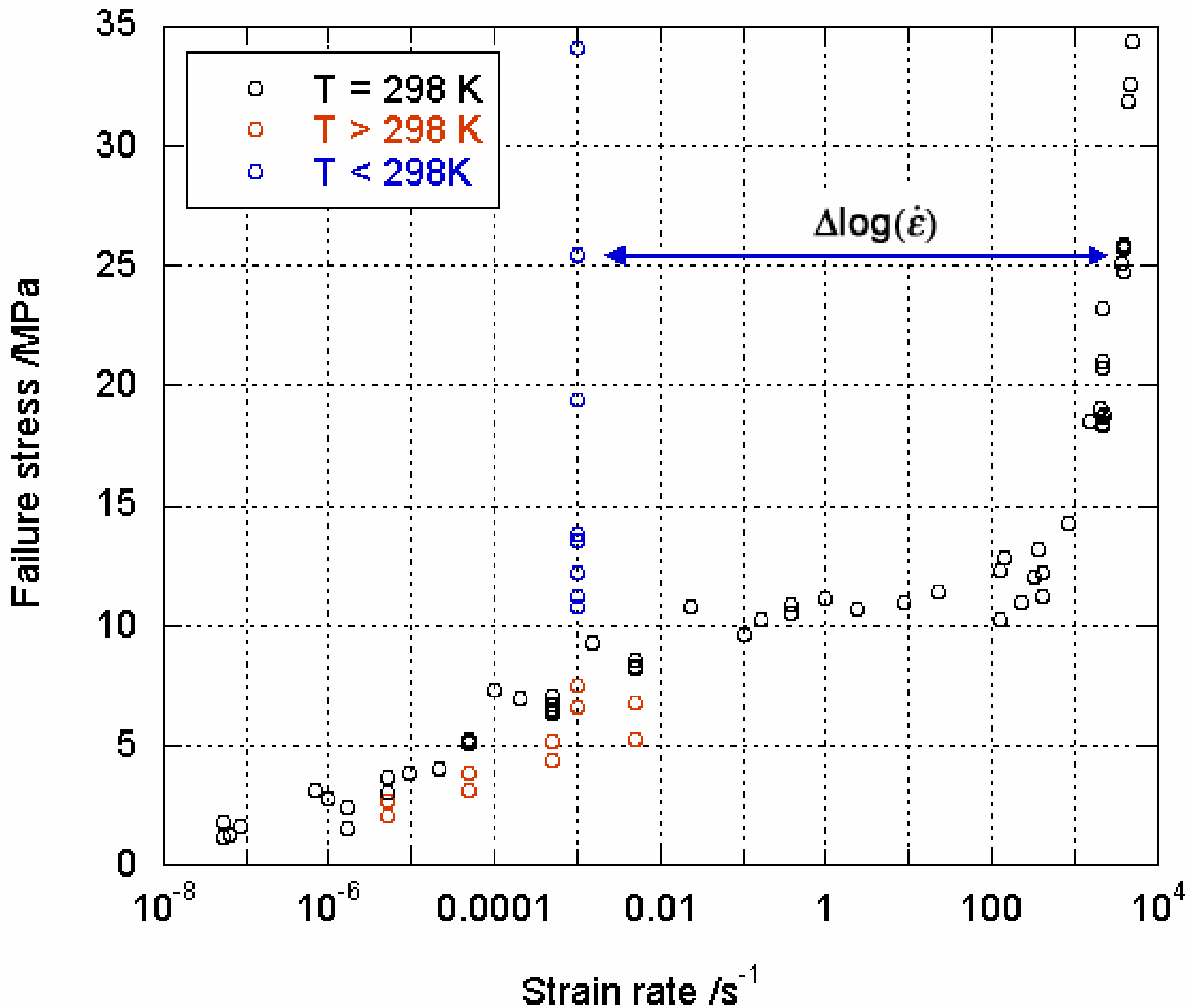
TEMP ENVELOPE

Temperature dependence of AWE PBX



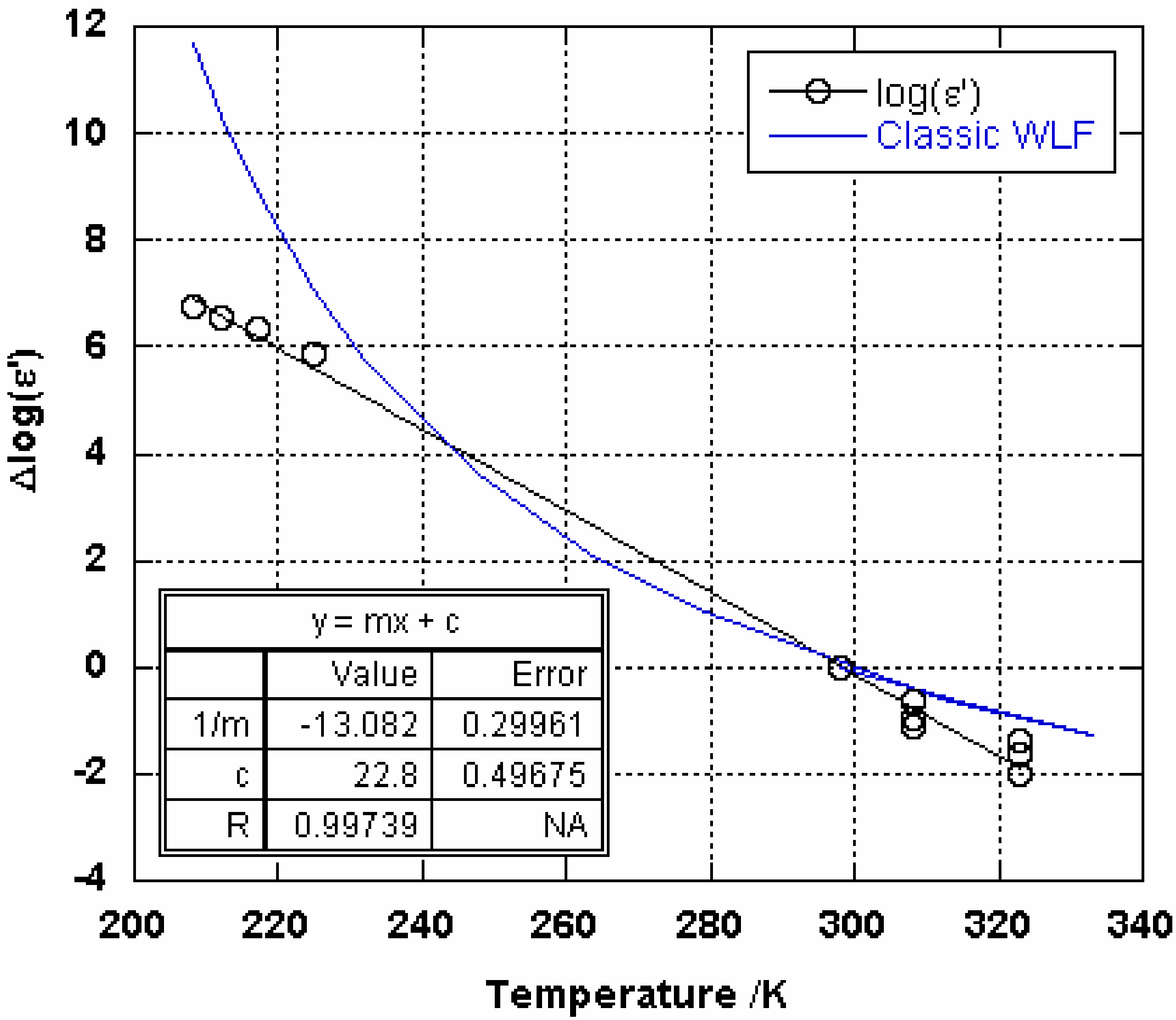
From Williamson *et al.* (2008)

Temperature-Rate dependence of AWE PBX



From Williamson *et al.* (2008)

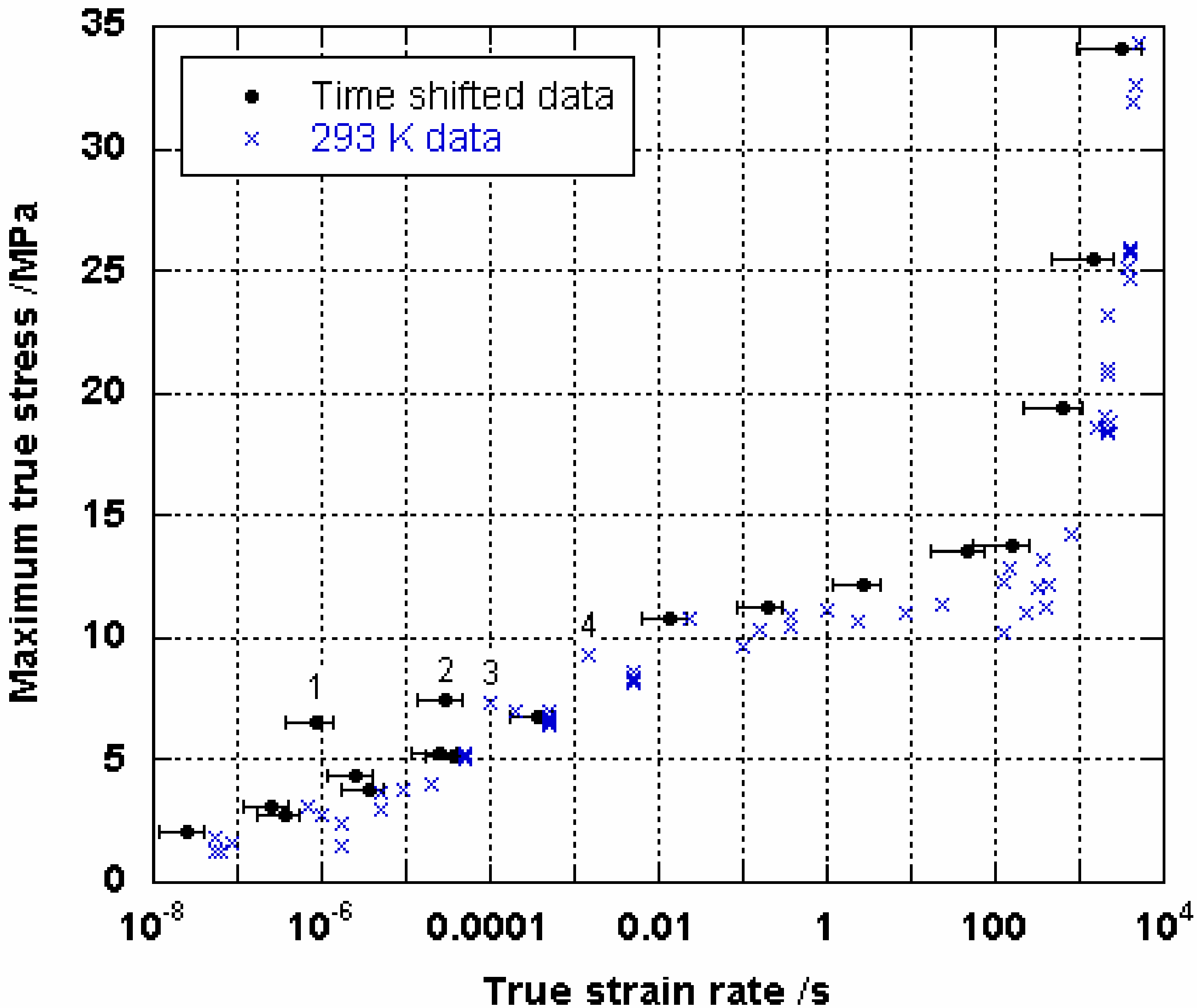
Temperature-Rate dependence of AWE PBX



REMAPPED DATA

From Williamson *et al.* (2008)

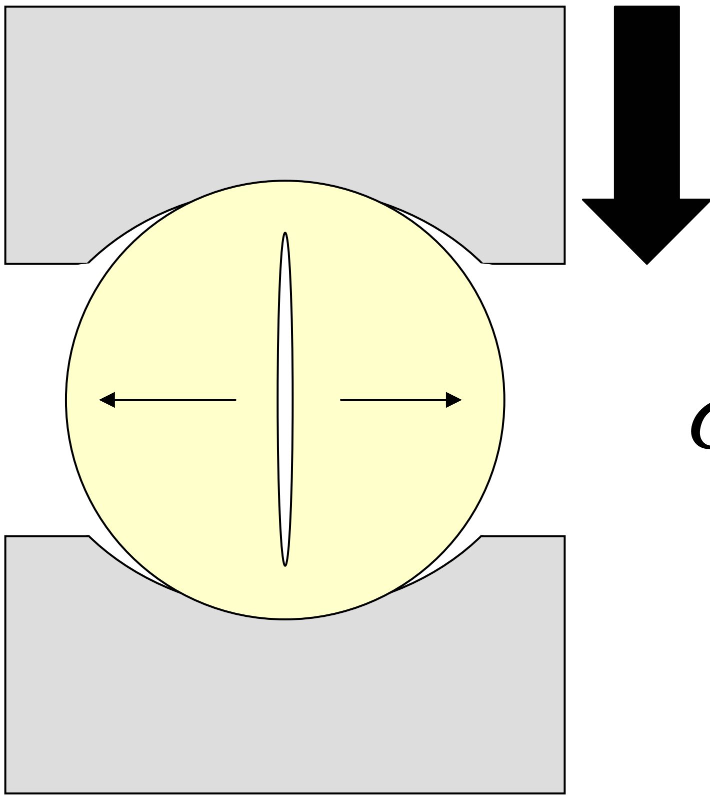
Temperature-Rate dependence of AWE PBX



From Williamson *et al.* (2008)

BRAZ TEST

Brazilian test

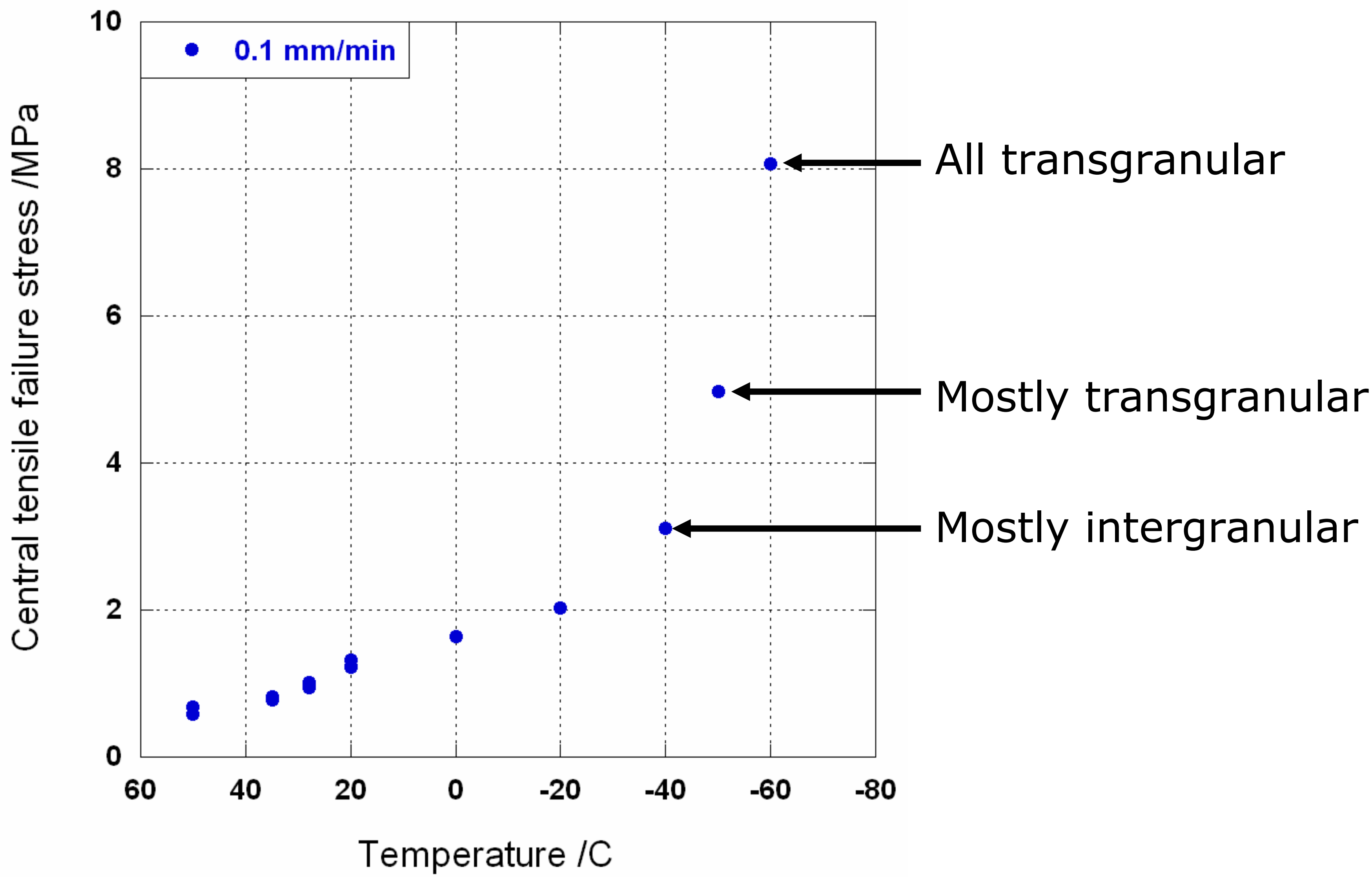


$$\sigma_F = \frac{2P}{\pi D T}\left(1 - \left(\frac{b}{R}\right)^2\right)$$

Brazilian test

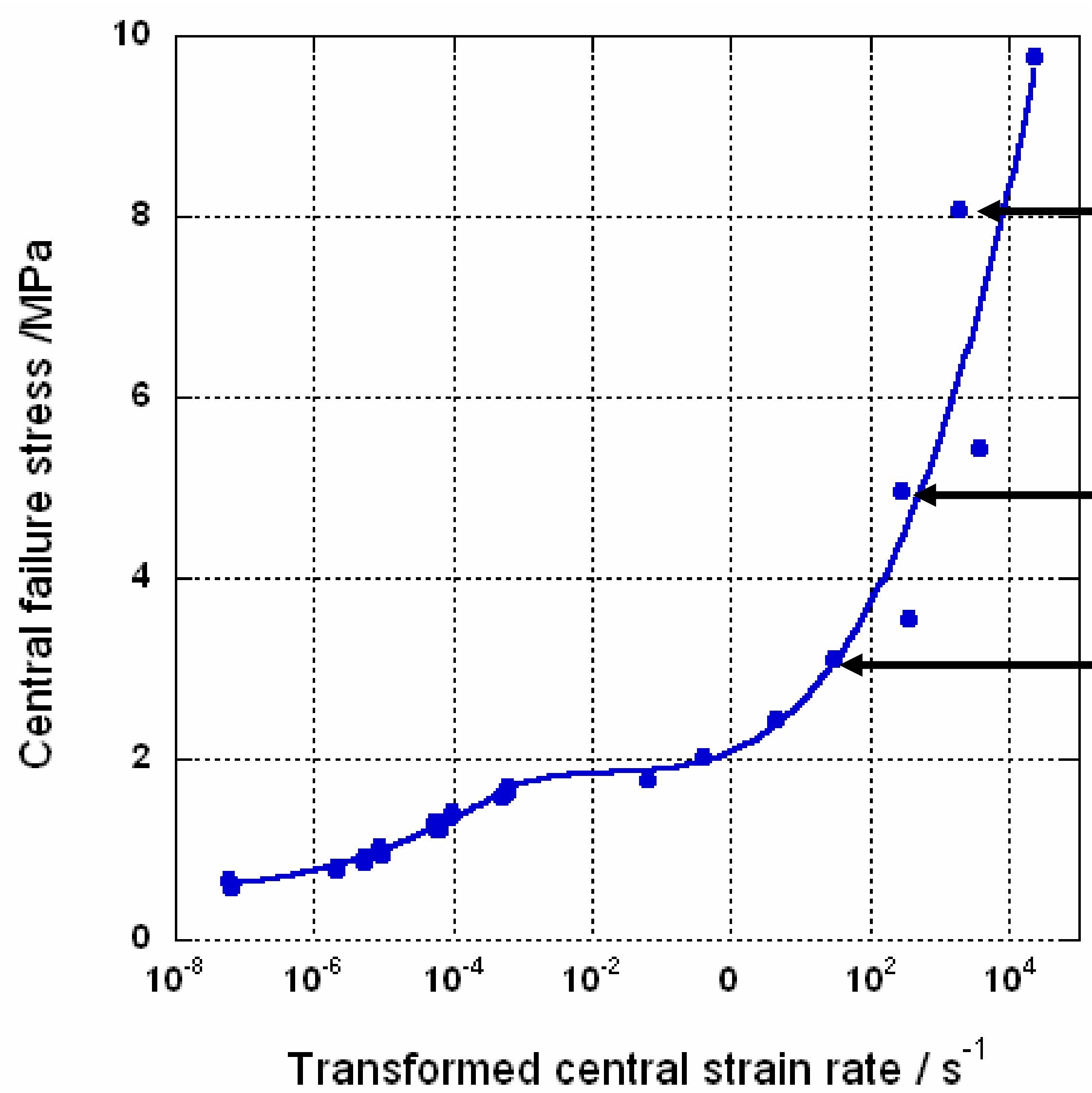
From Williamson *et al.* (2009a)

Failure mode AWE PBX



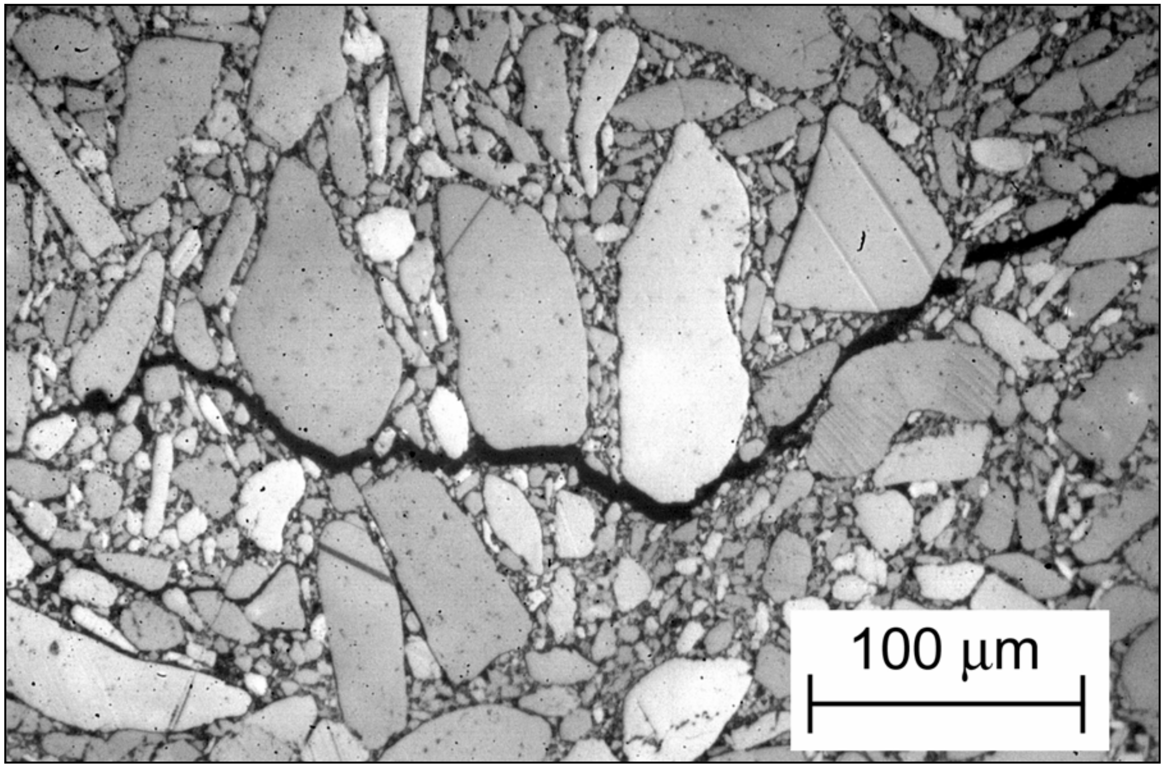
From Williamson *et al.* (2009a)

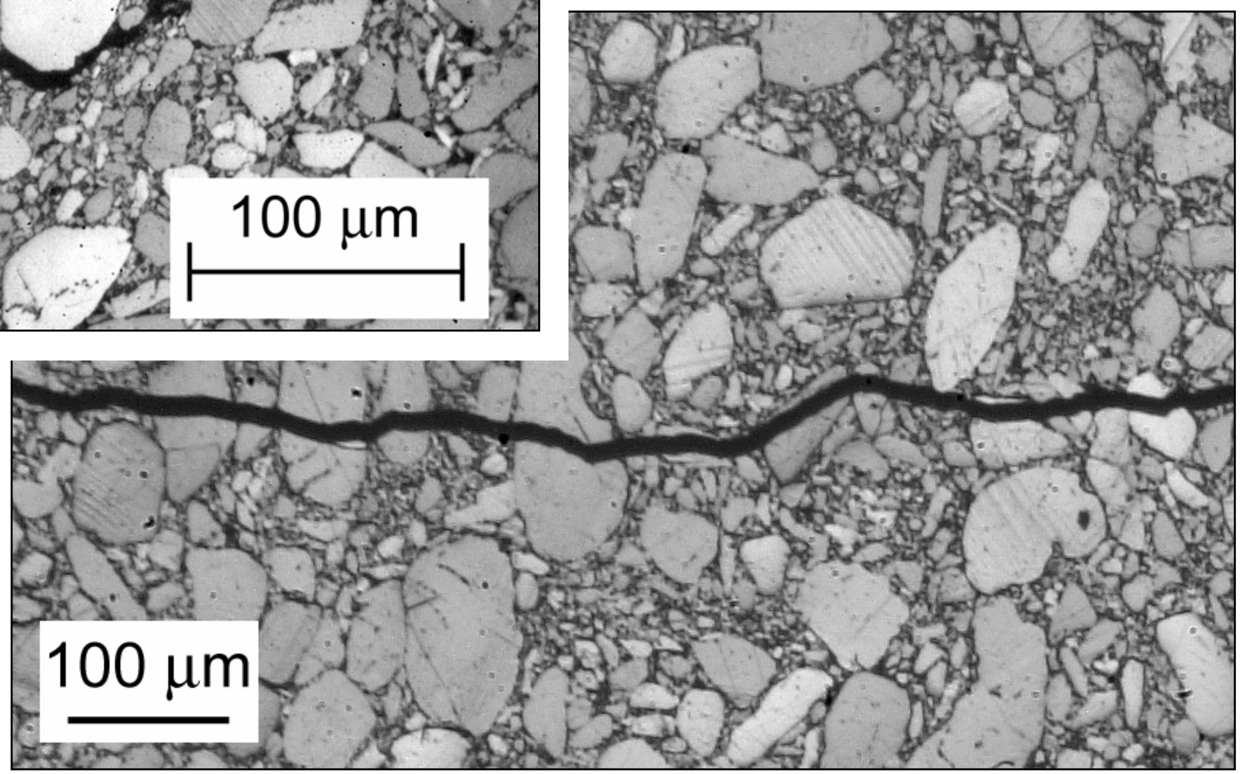
Failure mode AWE PBX



From Williamson *et al.* (2009a)

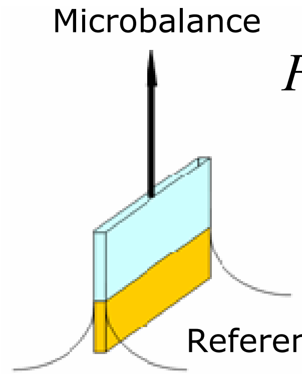
A different response?





From Williamson *et al.* (2009a)

Thermodynamic Work of Adhesion

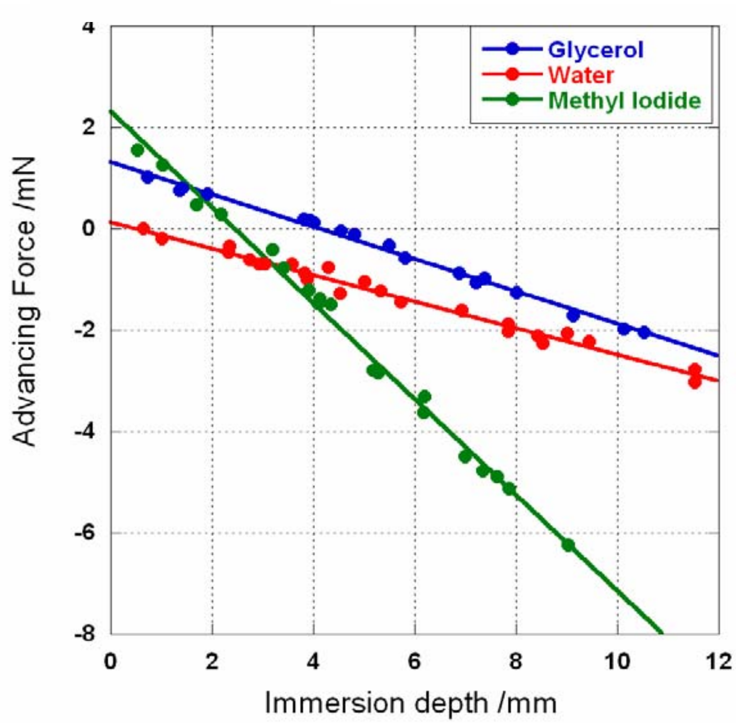


$$Force = p\gamma_L \cos\theta - (g\rho_L A)\Delta_I$$

Constant due to liquid tension

Buoyancy term dependant on immersion depth

The Wilhelmy plate method was used; Rosano *et al.* (1971). Binder coated microscope slides were immersed in reference liquids. The resultant push/pull due to surface buoyancy/tension was measured.



Work of adhesion W_a between liquid of surface tension γ_L which forms a perimeter p of contact angle θ against the binder is related to the measured force f by

$$W_a = \gamma_L + f/p = \gamma_L + \gamma_L \cos\theta$$

In analysis due to Kaelble (1970) the interactions of a non-fully-wetting liquid on a solid surface is described by:

$$W_a = 2\sqrt{\left(\gamma_L^d \gamma_S^d\right)} + 2\sqrt{\left(\gamma_L^P \gamma_S^P\right)}$$

Simultaneous equations using liquid pairs: solve for binder surface energy components

From Williamson *et al.* (2009b)

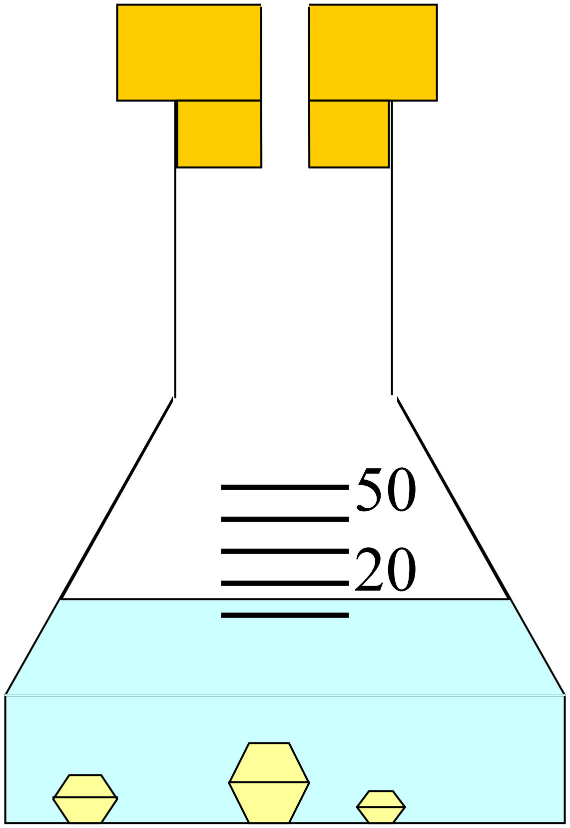
Thermodynamic Work of Adhesion

From these data and analyses the surface energy of the coating can be inferred (42.5 ± 2.8 mJ/m^2), and when combined with HMX data (Yee *et al.* 1980), the TWA calculated.

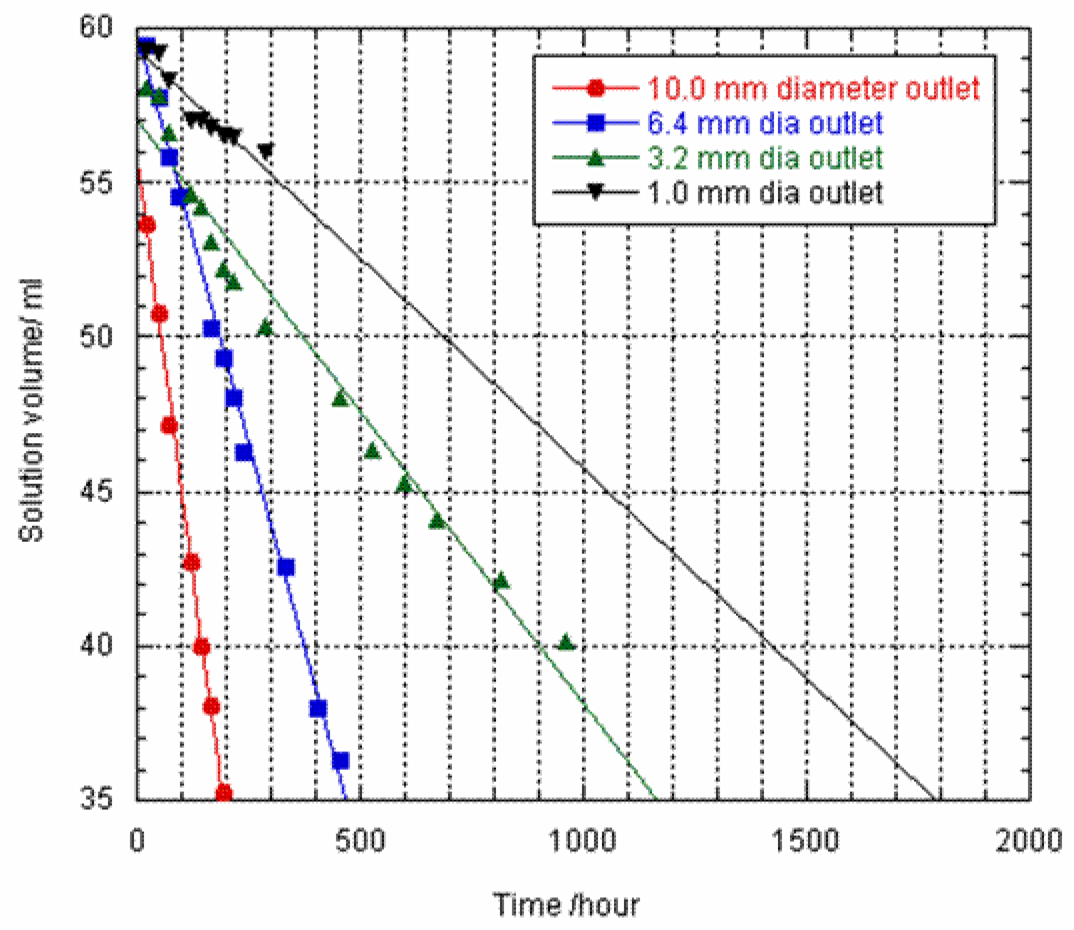
Crystal Face	HMX surface energy /mJ/m^2	HMX – binder TWA /mJ/m^2
{011}	45.0	81.5 ± 6.5
{010}	46.0	78.8 ± 7.9
{110}	48.0	79.7 ± 8.3

From Williamson *et al.* (2009b)

Measured Work of Adhesion: crystals



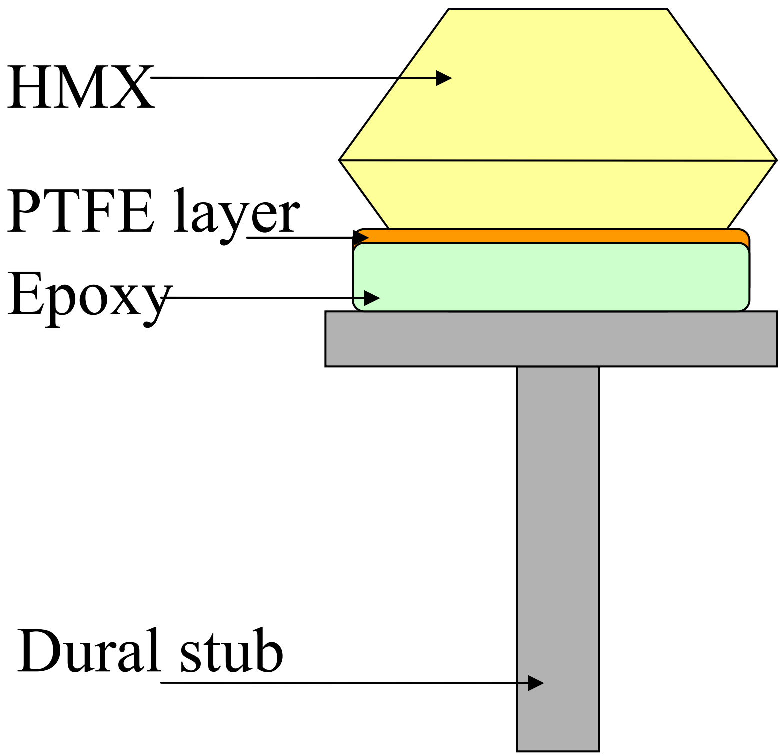
Growth by evaporation

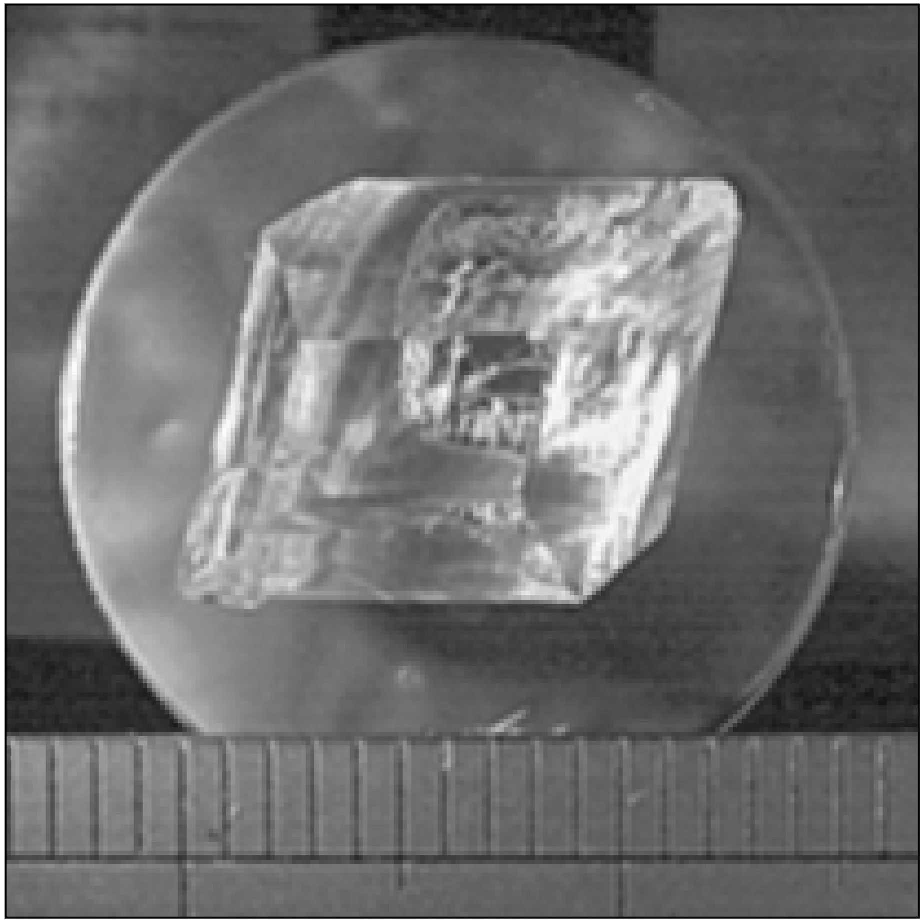


Controlled growth rate for 'best' crystals

From Palmer *et al.* (2005)

Experimental procedure: crystal



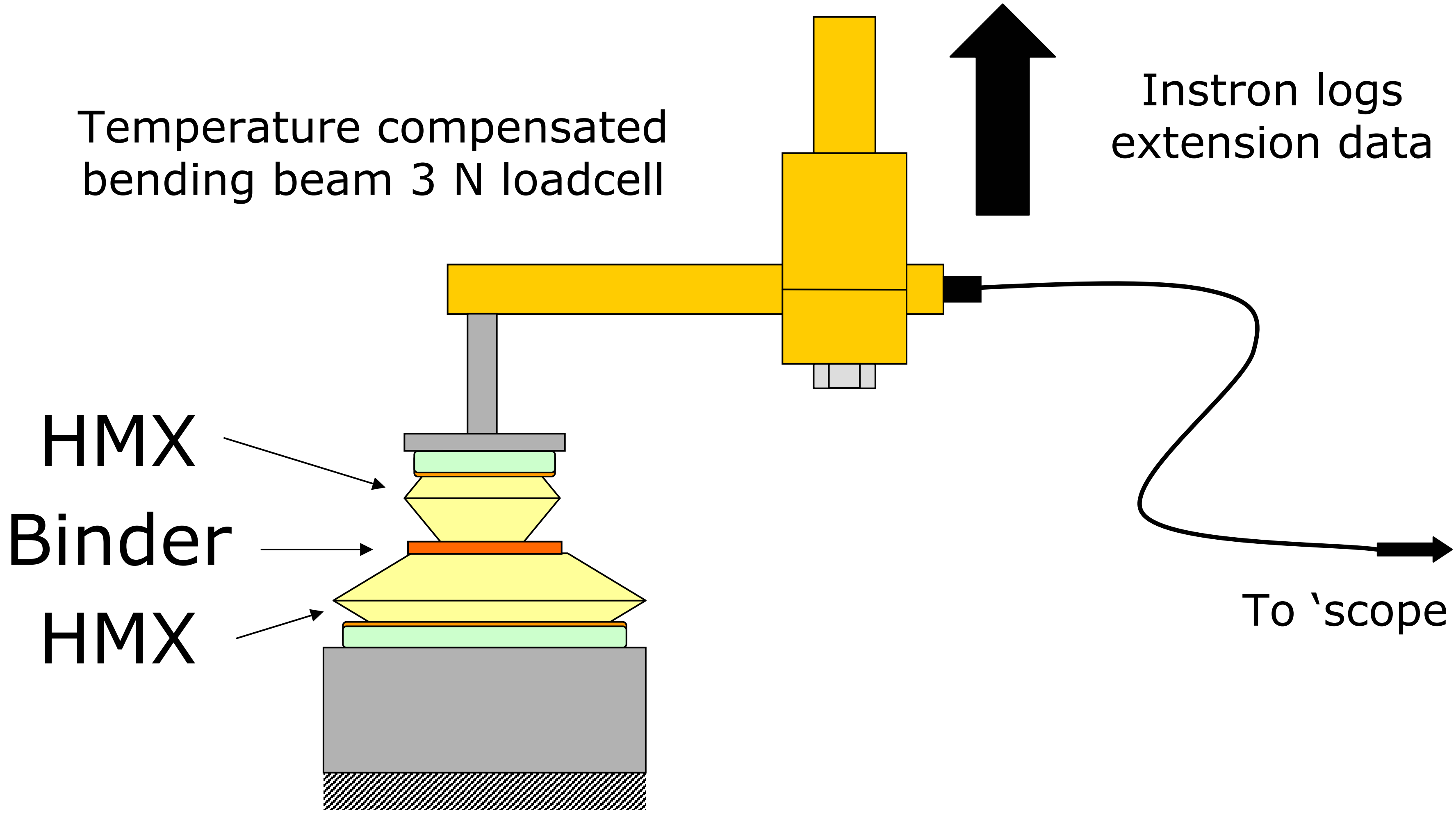


Single crystals ~ 1 cm^3

From Palmer *et al.* (2005)

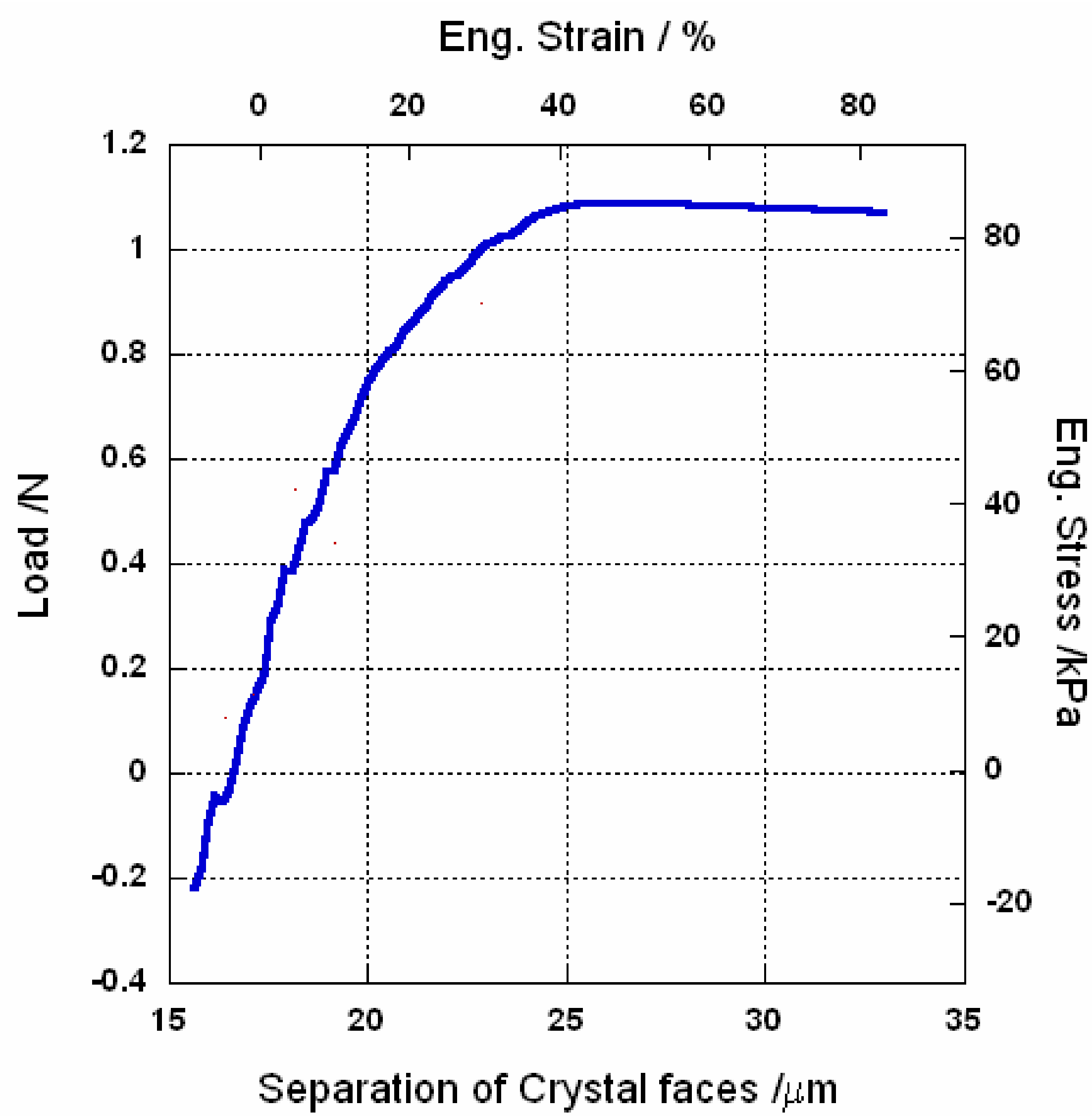
Schem. Pull-off

Measured Work of Adhesion : loadcell



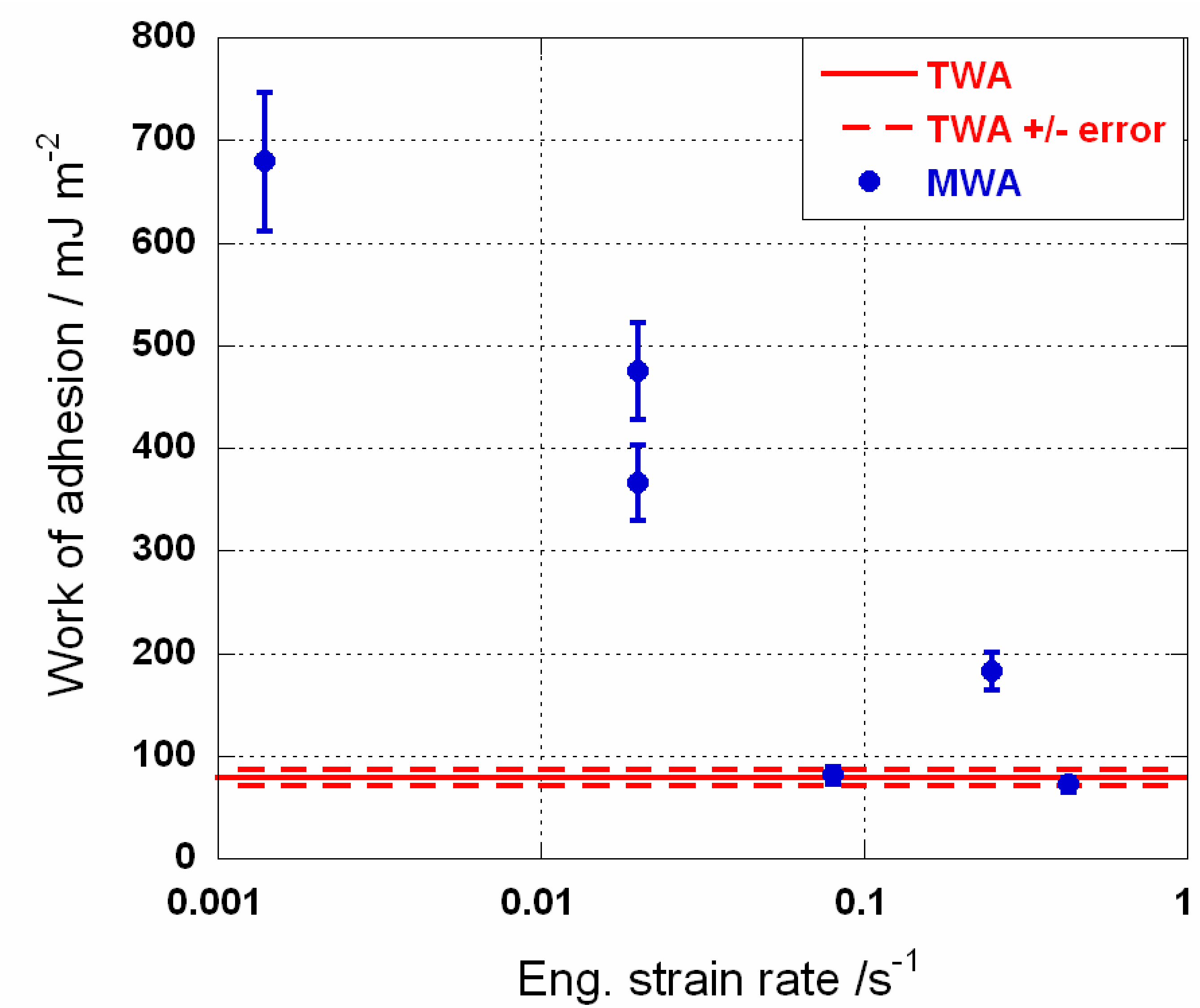
From Palmer *et al.* (2005)

Measured Work of Adhesion



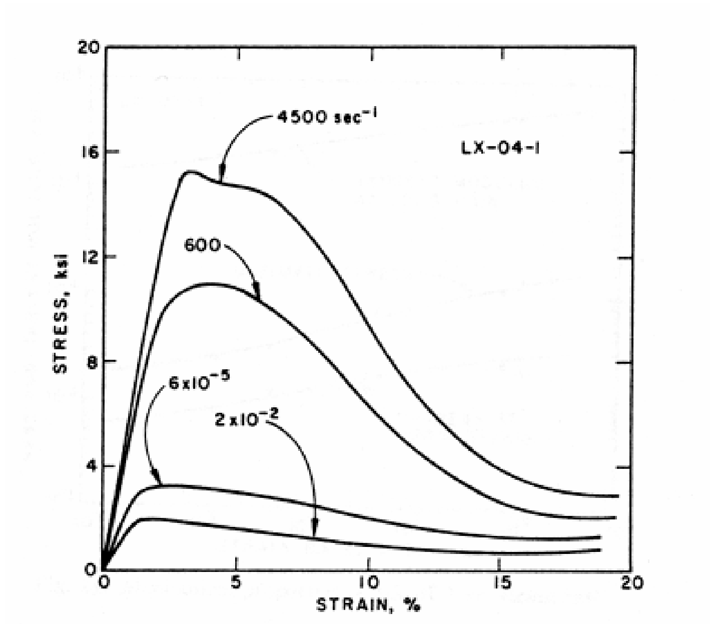
From Palmer *et al.* (2005)

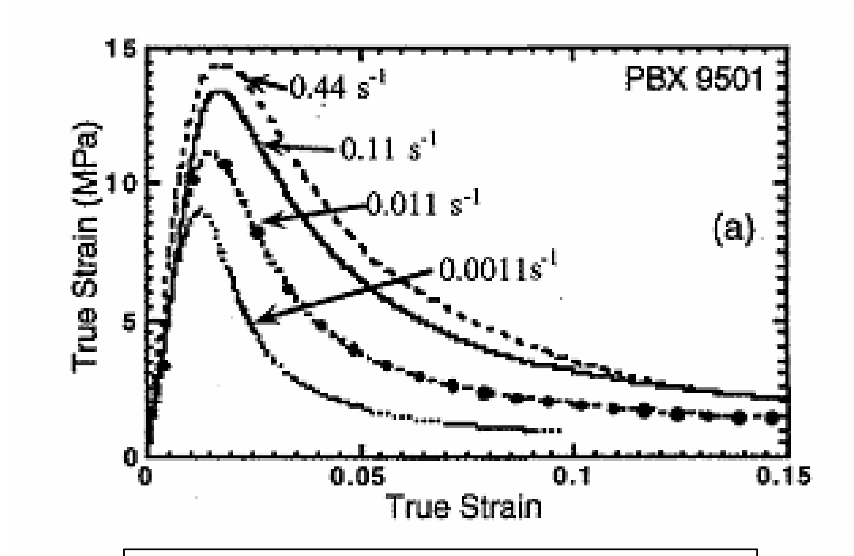
Work of Adhesion

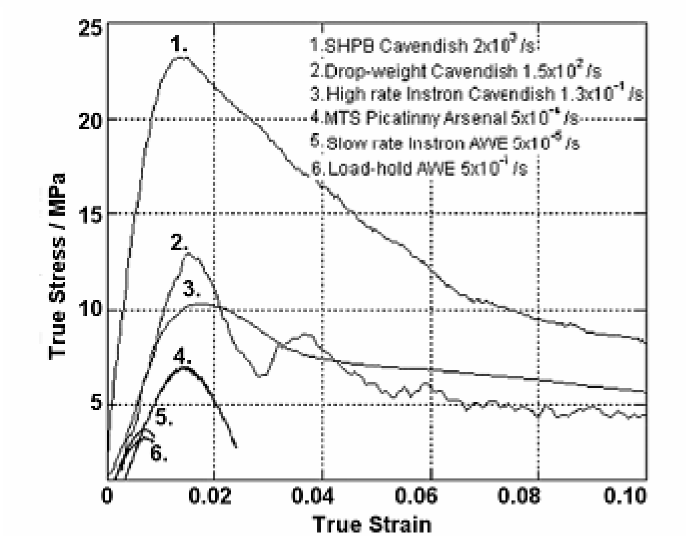


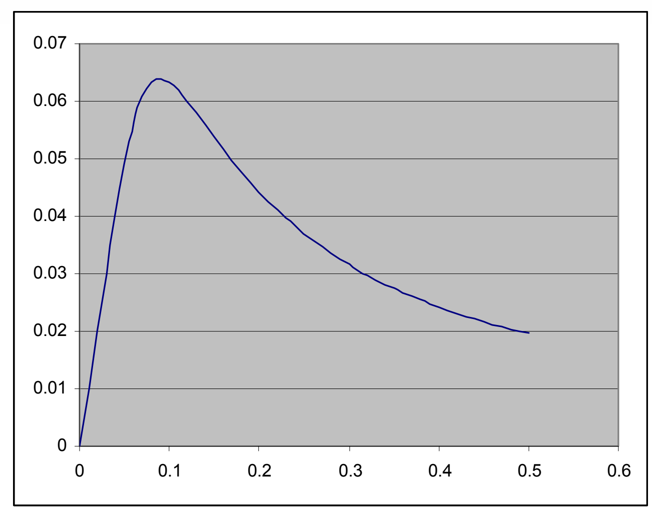
From Williamson *et al.* (2009b)

A description of failure





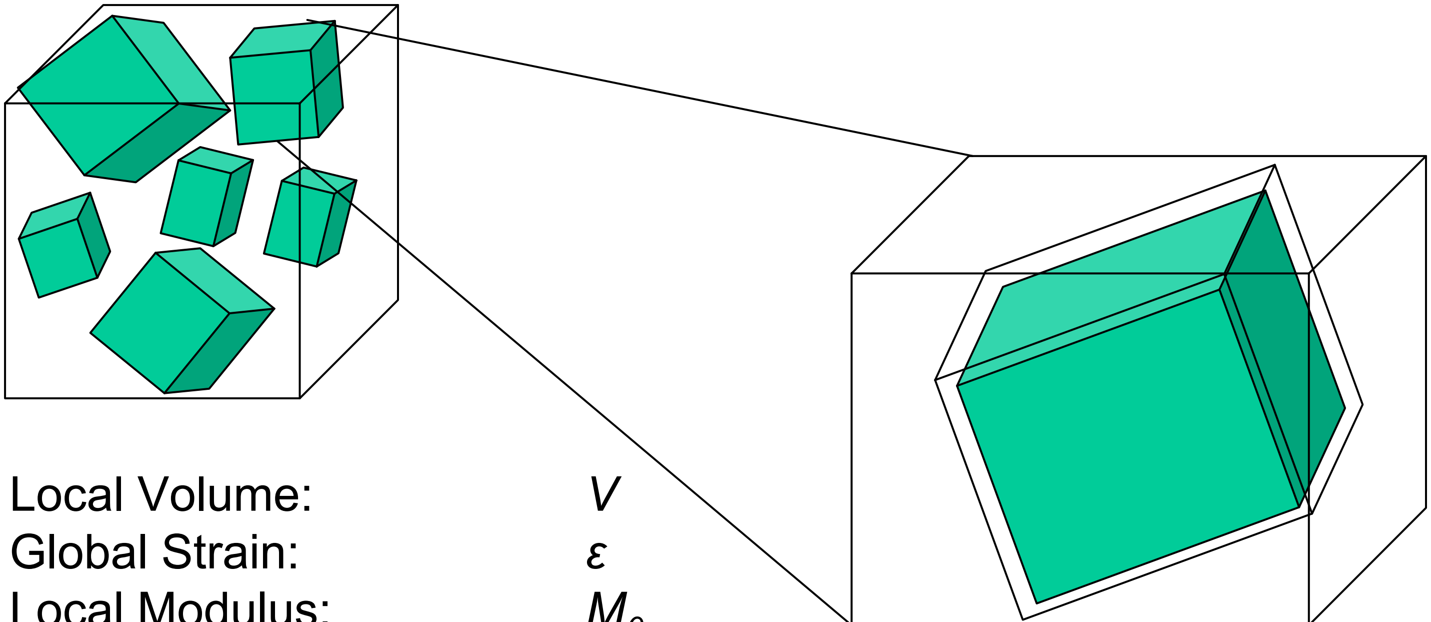




$$\sigma(\varepsilon) = M_0 \varepsilon \left(1 - \exp\left(-\varepsilon_a^2/\varepsilon^2\right)\right)$$

Simple model of adhesion

Based on a simple model



Local Volume: V
Global Strain: ε
Local Modulus: M_0
Particle Surface Area: A
Surface Energy: γ

Debond Energy = $A\gamma$

Strain Energy = $\frac{1}{2}M_0\varepsilon^2$

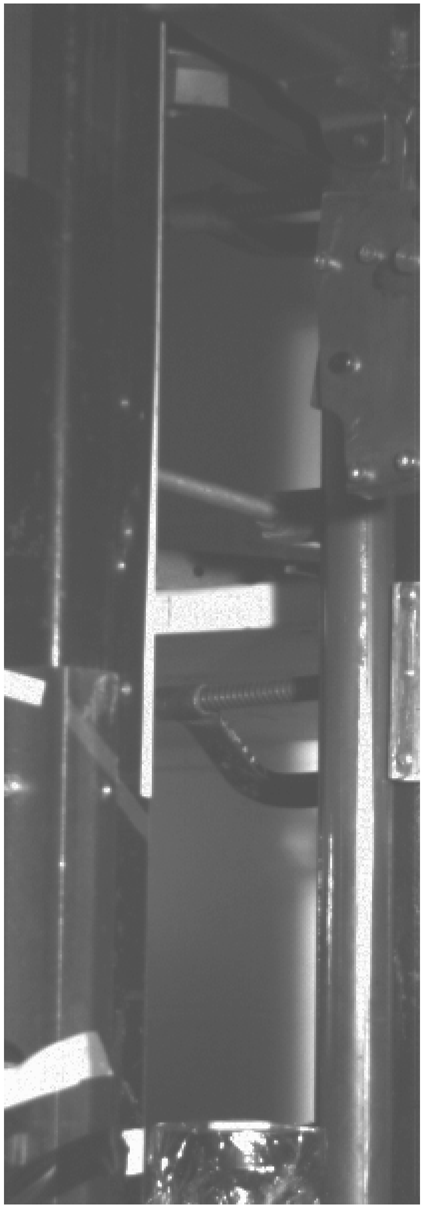
$\varepsilon_a^2 = 2A\gamma / M_0V$

Inducing controlled damage

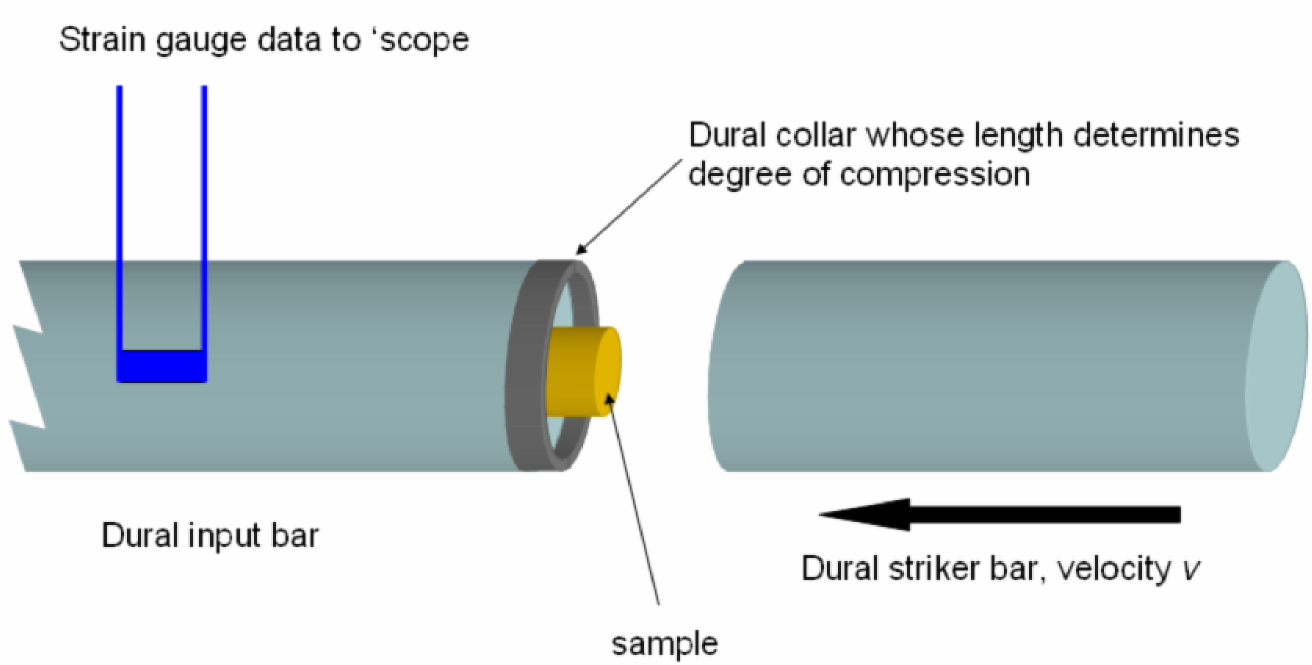
QRXs QinetiQ Research eXplosives

Constituent	Material and mass fractions		
	QRX 214	**QRX 221**	**QRX 217**
RDX	0.75	0.80	0.70
HTPB based binder	0.15	0.20	0.30
Density g/cm^3	1.455	1.517	1.426
Particle size distribution	Monomodal fine	Bimodal ↔	Monomodal coarse

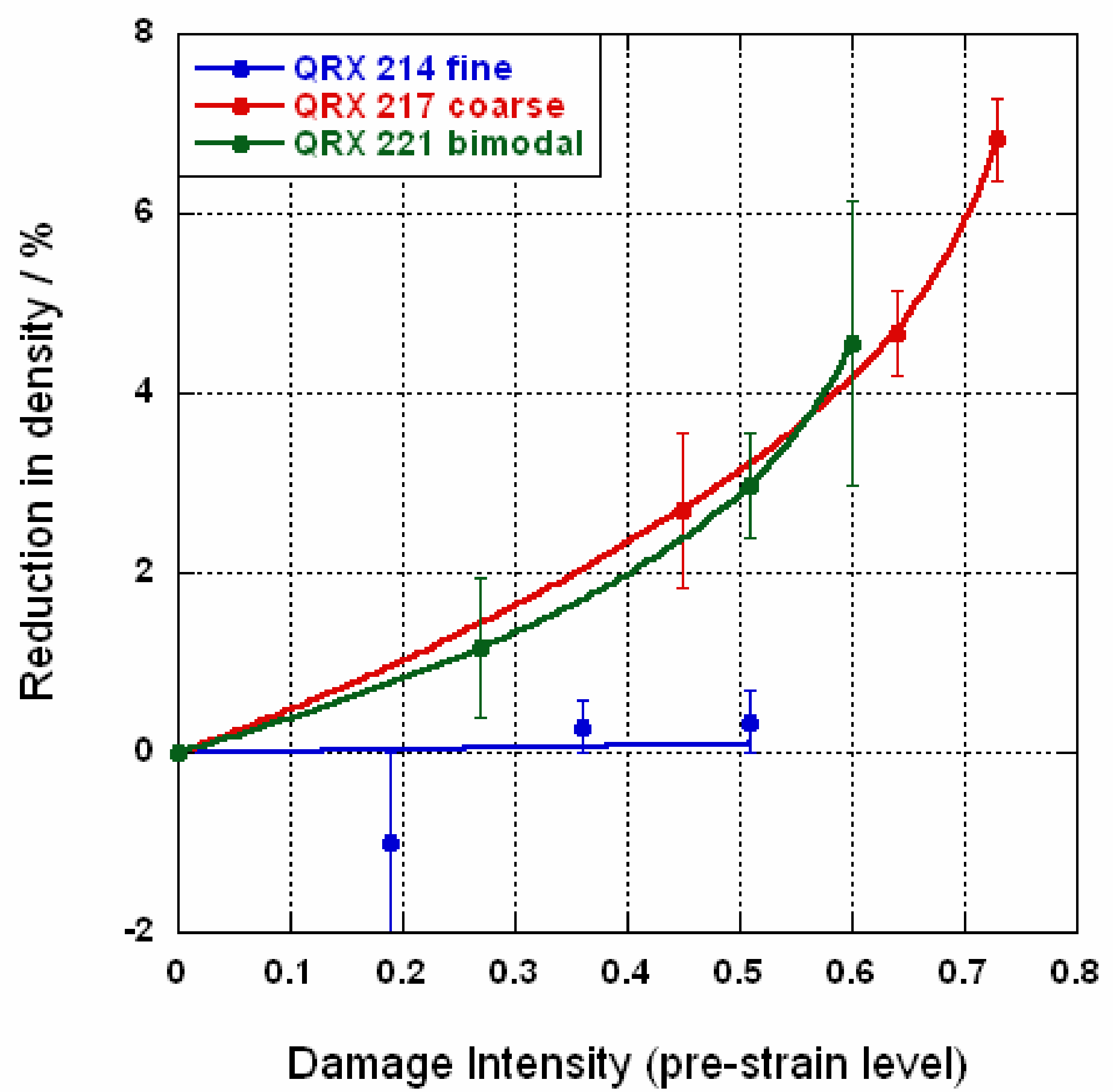
Inducing controlled damage



A restricted stroke SHPB or drop-weight is used to dynamically compress a pre-determined amount.

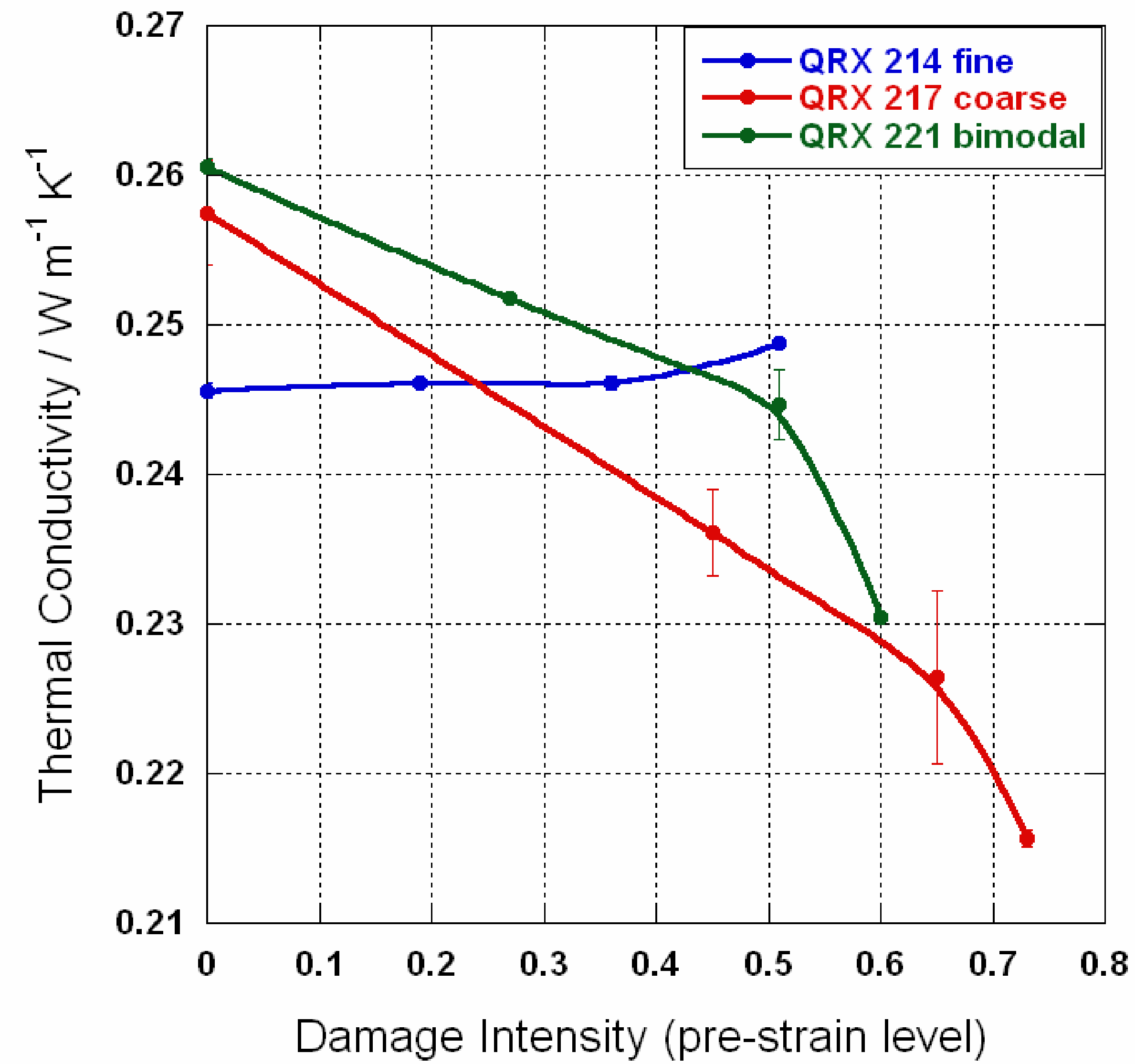


Evaluating damaged samples



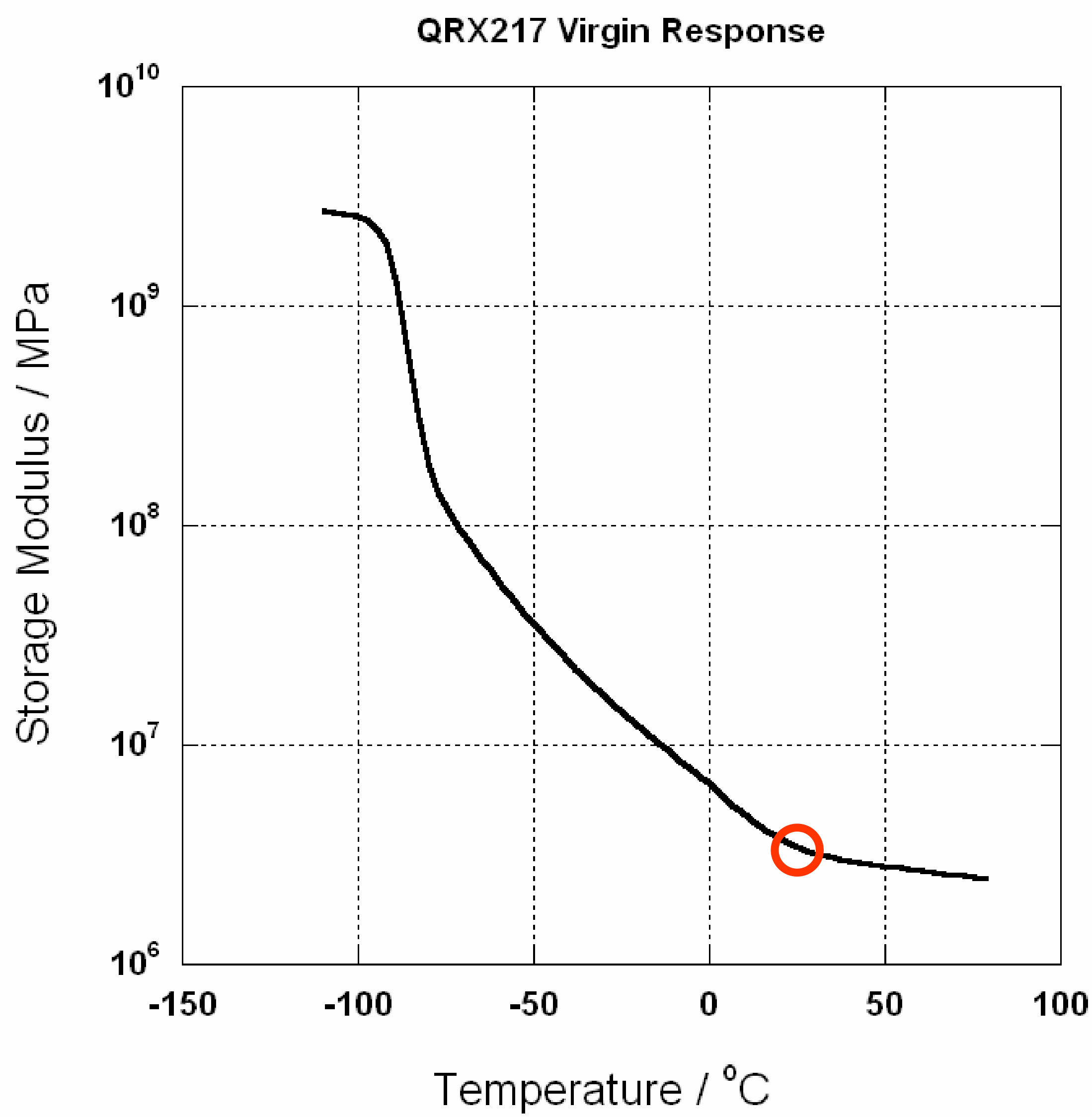
Degraded Thermal

Degradation of thermal conductivity



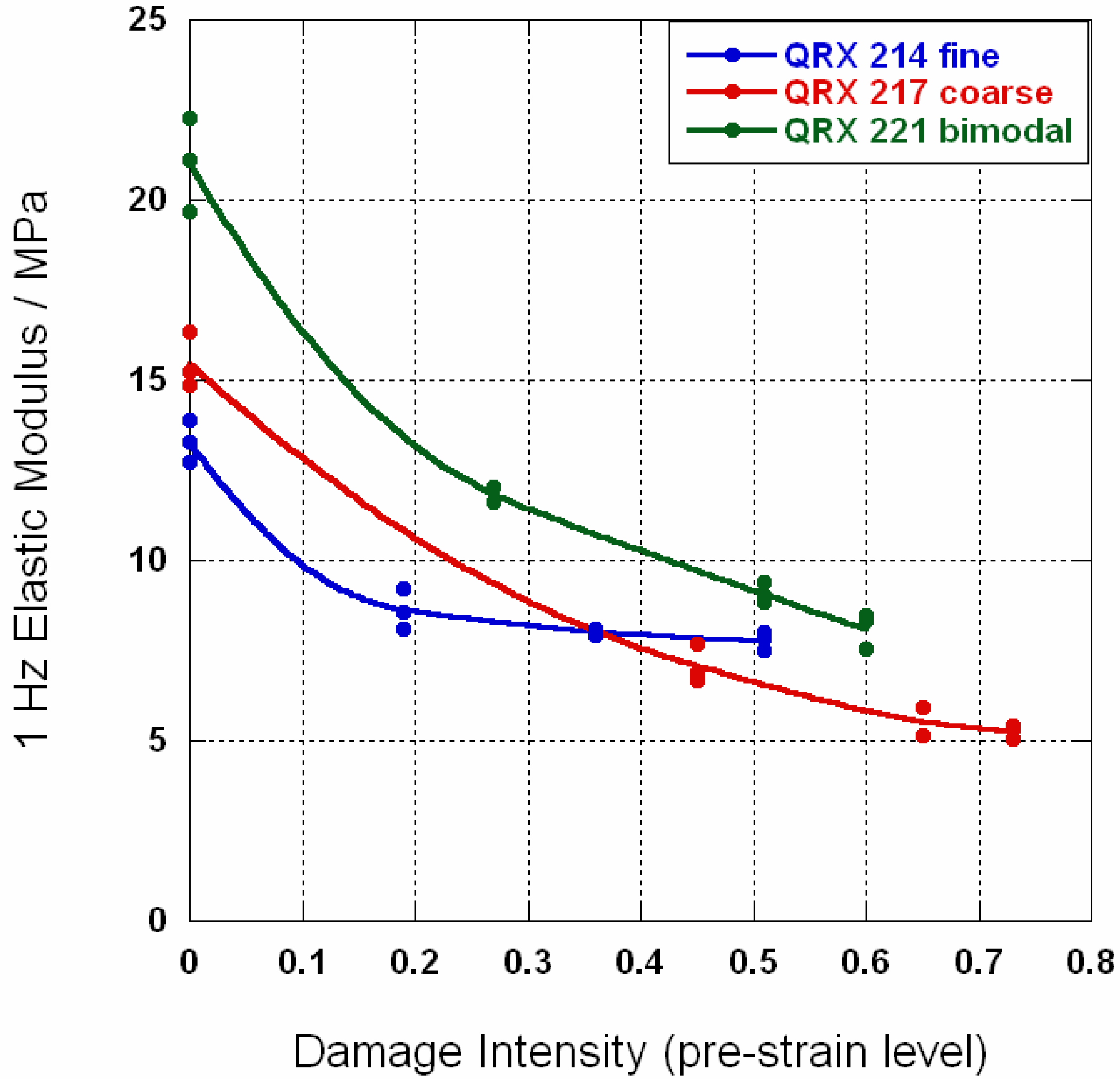
VIRGIN DMA

Virgin DMA Spectra



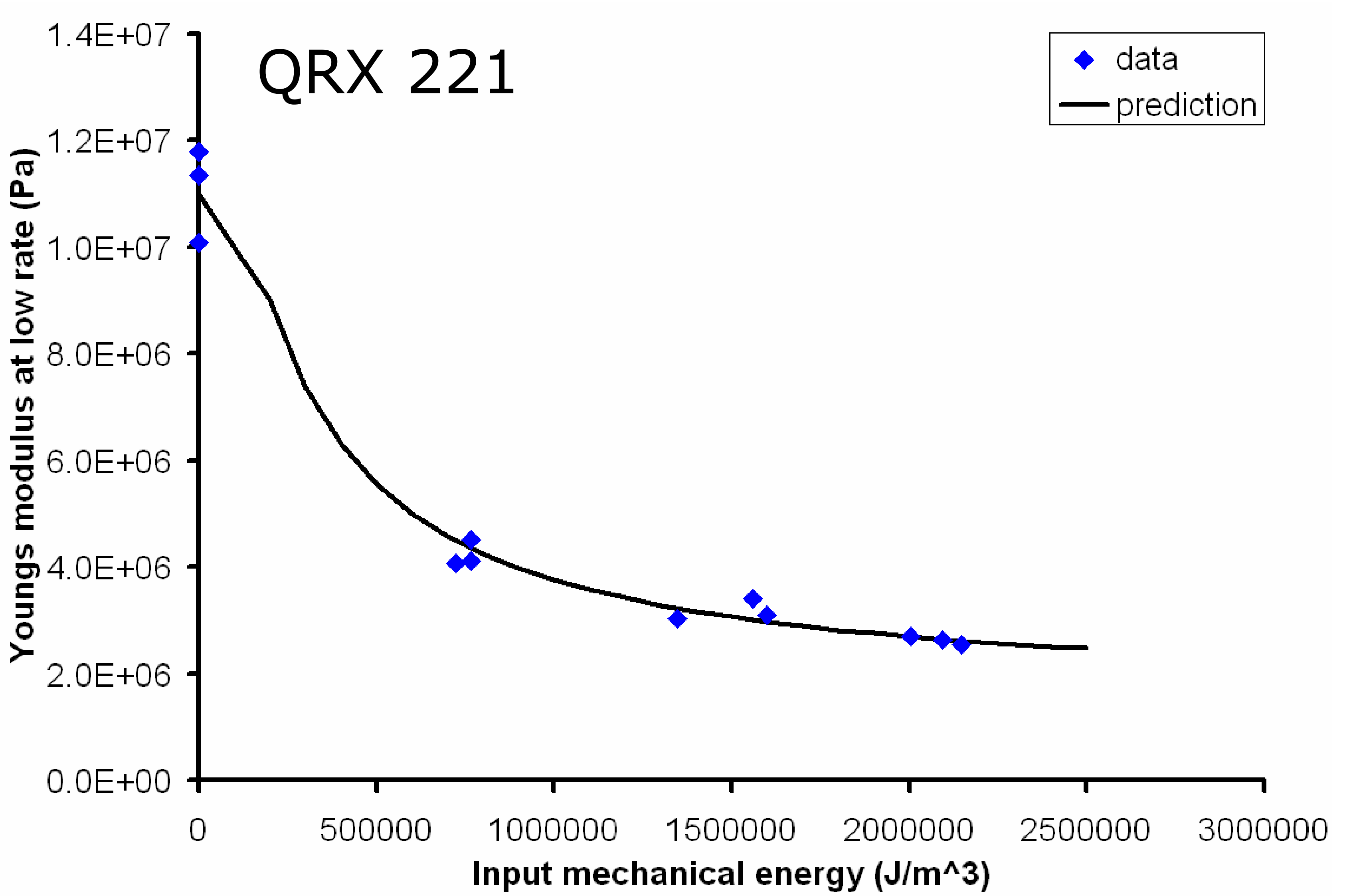
DAM FREQ SWEEP

Degradation of DMA Spectra



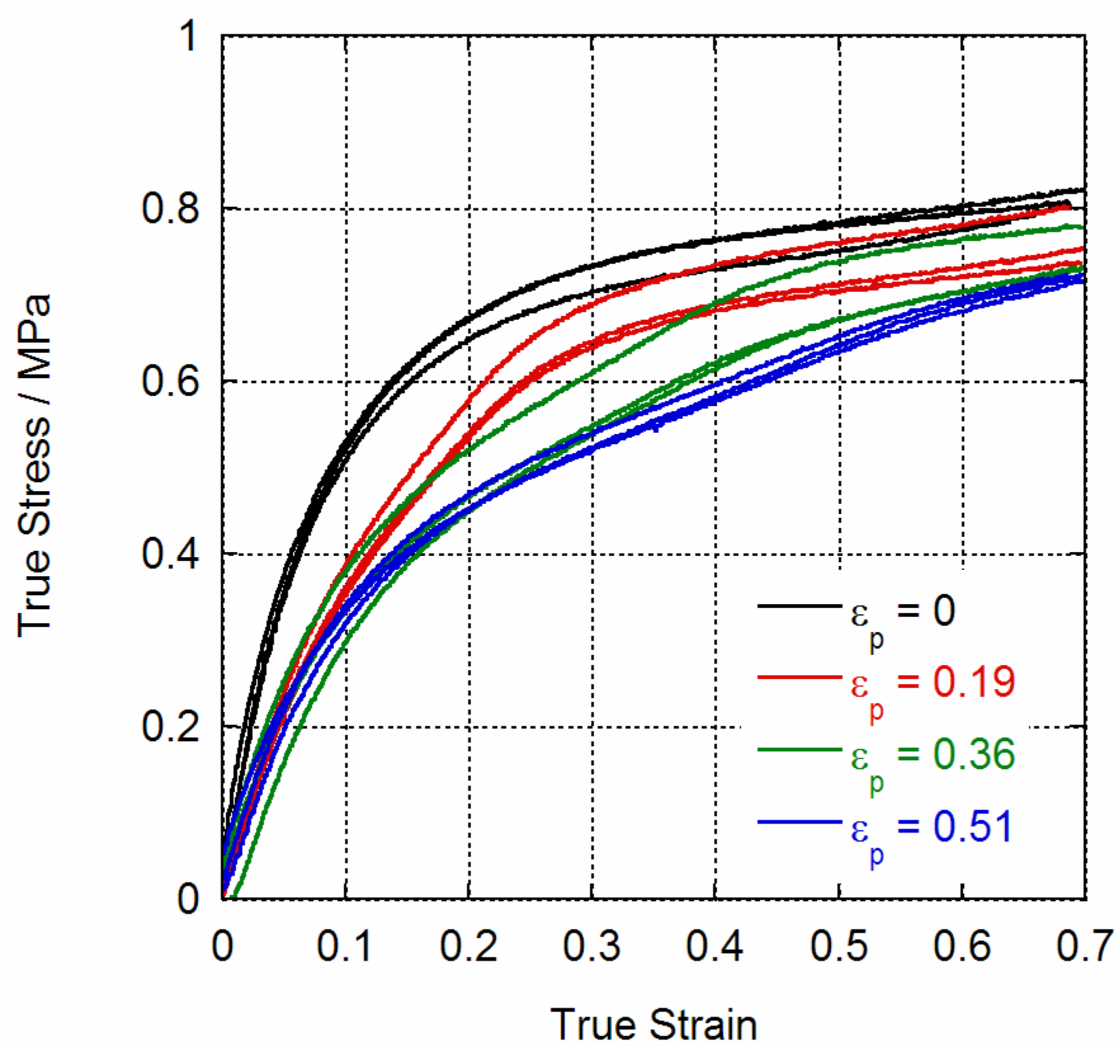
DEGRADED MODULUS PREDICTION

Predicted degradation of modulus



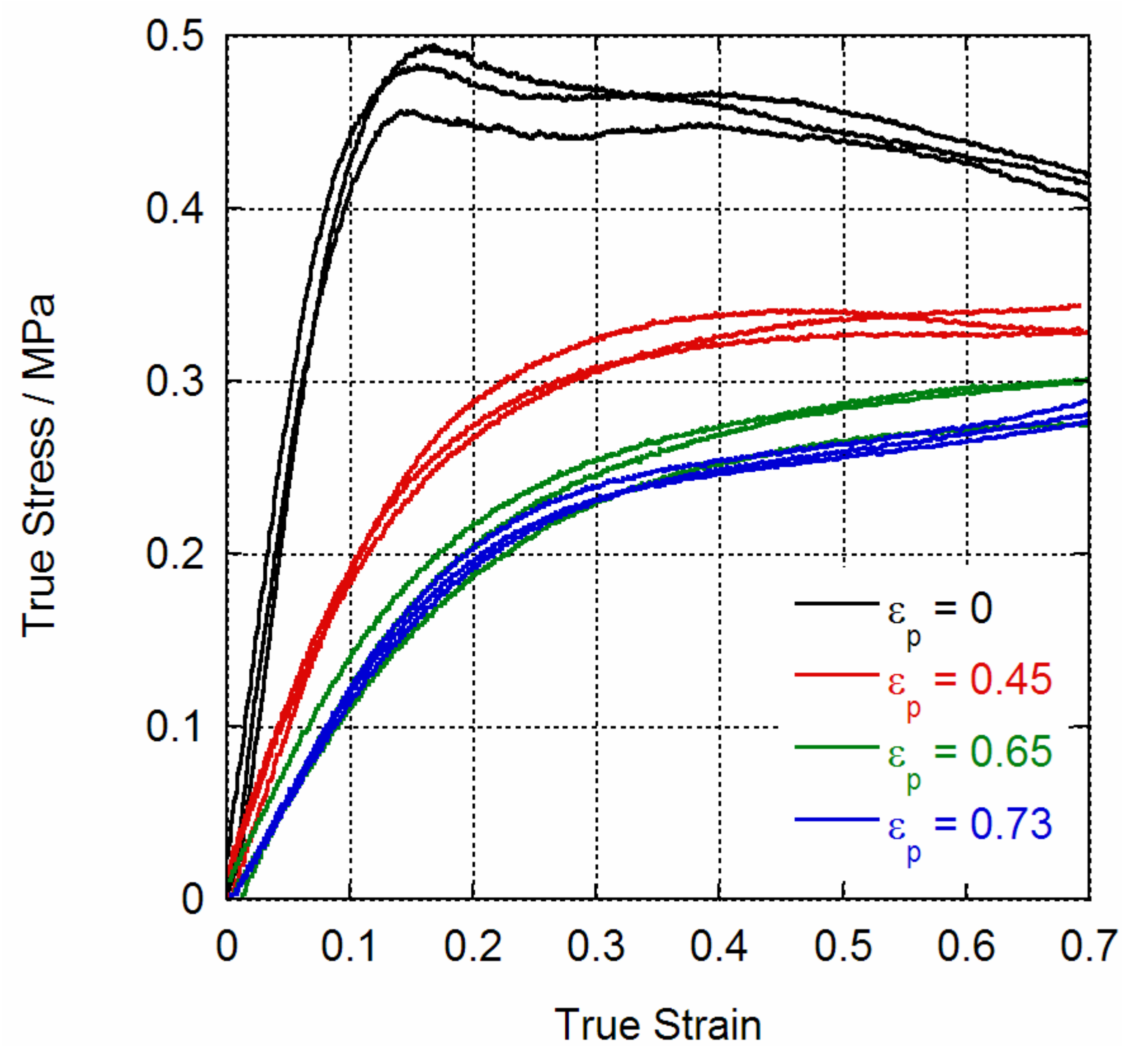
DEGRADED INSTRON

Degradation of strength



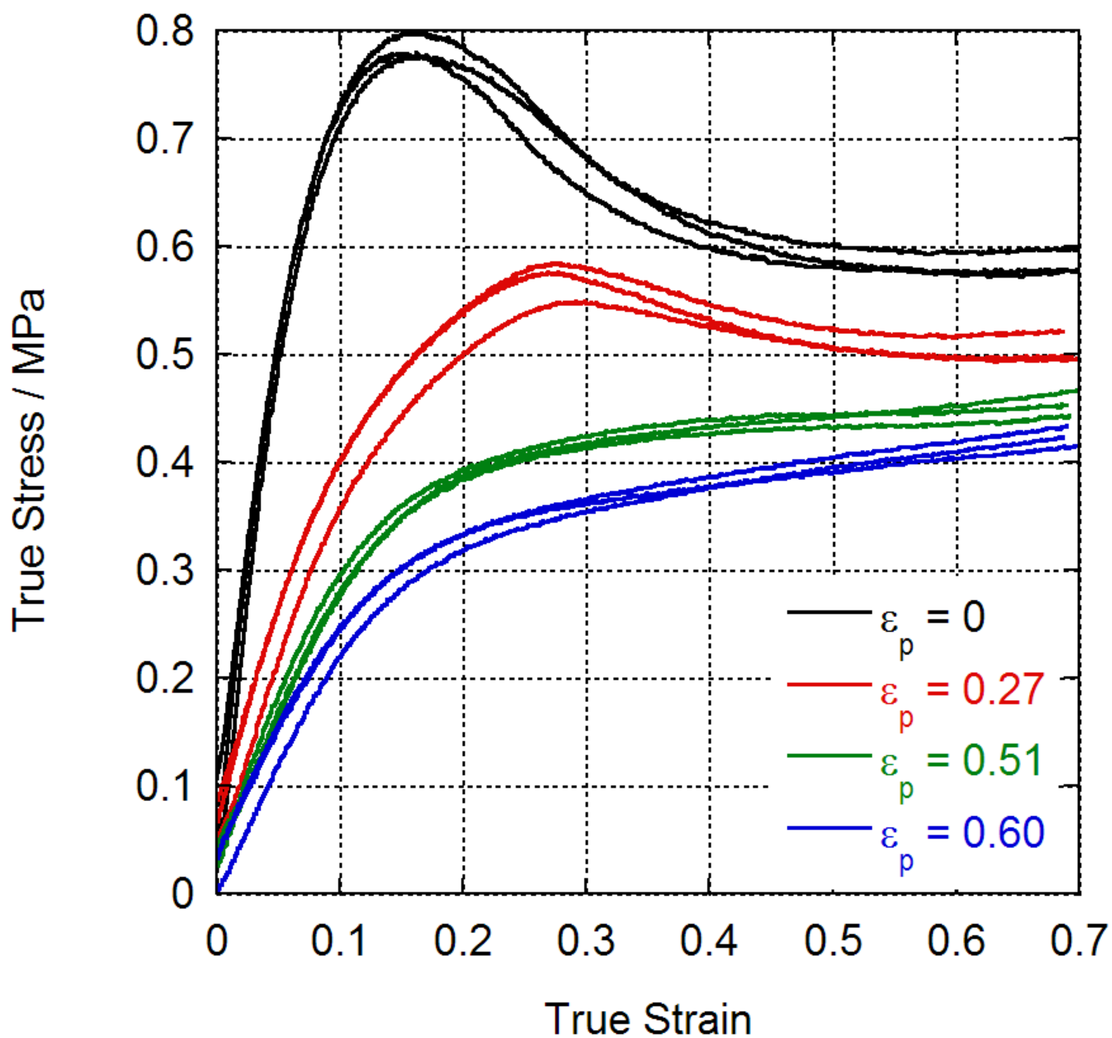
Low-rate response of QRX214 (monomodal fine)

Degradation of strength



Low-rate response of QRX217 (monomodal coarse)

Degradation of strength



Low-rate response of QRX221 (bimodal-fill)

Summary

Summary

Together with our sponsors, we at the Cavendish Laboratory are interested in understanding the full thermo-mechanical responses PBX and related materials, specifically by conducting insightful experiments.

The philosophy behind research is to get at the physical causes behind the experimental observations at the most fundamental level possible. Our colleagues in industry are approaching this from the direction of modeling.

Clearly understanding damage is very important, and here at the Cavendish, with the support of our sponsors, we feel we are making significant progress towards our goals.

A key attribute of the approach is the transferability of the techniques and understanding to be able to rapidly characterise new materials of all types.

Acknowledgements

- ISP for opportunity to present
- AWE for funding, samples and scientific input
  (*Steve Wortley & Rebecca Govier*)
- QinetiQ for funding, samples and scientific input†
  (*Ian Cullis, Peter Gould and Phillip Church*)
- EPSRC for funding and equipment
- PCS members past and present

† This research was carried out as part of the Defence Technology Innovation Centre Weapons Research Programme: UK-E: Hazard

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