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
Thermal properties
Thermal properties

Thermal diffusivity $D$, Conductivity $\kappa$, and Specific Heat $C_P$ are all related by:

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

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

**convective heat loss**

Sample

Heating element

Copper plates

Embedded thermocouples

\[
k = \frac{ed}{A_S(T_B - T_A)} \{a_A T_A \}
\]

Ångström METHOD
Thermal diffusivity

\[ D = \frac{L_v}{2 \ln(T_1/T_2)} \]

Thermal imaging camera (FLIR SC300)

Water assisted copper heat exchanger

Embedded thermocouples

Peltier cell

Water
Thermal diffusivity

- ○ Temperature at position 1
- ■ Temperature at position 2

Time /s

Temperature /°C

[Graph showing temperature fluctuations over time for two positions]
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


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

- Creep and stress relaxation
- Quasi-static
- Dynamic
  - Hopkinson bar
  - Taylor impact
  - Plate impact

- Conventional cross head devices
- Inertia negligible
- Inertia important

PBX COMPRESSION CURVES
Rate dependence of AWE PBX

From Williamson et al. (2008)
Rate dependence of AWE PBX

From Williamson et al. (2008)
Temperature dependence of AWE PBX

From Williamson et al. (2008)
Temperature-Rate dependence of AWE PBX

From Williamson et al. (2008)

REMAPPED DATA
Temperature-Rate dependence of AWE PBX

From Williamson et al. (2008)
Brazilian test

\[ \sigma_F = \frac{2P}{\pi DT} \left( 1 - \left( \frac{b}{R} \right)^2 \right) \]

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)

THERMO ADHESION
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 $\gamma_L$ which forms a perimeter $p$ of contact angle $\theta$ against the binder is related to the measured force $f$ by

$$W_a = \gamma_L + \frac{f}{p} = \gamma_L + \gamma_L \cos \theta$$

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

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

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

From Williamson et al. (2009b)
From these data and analyses the surface energy of the coating can be inferred (42.5 ± 2.8 mJ/m²), and when combined with HMX data (Yee et al. 1980), the TWA calculated.

<table>
<thead>
<tr>
<th>Crystal Face</th>
<th>HMX surface energy /mJ/m²</th>
<th>HMX – binder TWA /mJ/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>{011}</td>
<td>45.0</td>
<td>81.5 ± 6.5</td>
</tr>
<tr>
<td>{010}</td>
<td>46.0</td>
<td>78.8 ± 7.9</td>
</tr>
<tr>
<td>{110}</td>
<td>48.0</td>
<td>79.7 ± 8.3</td>
</tr>
</tbody>
</table>

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 cm³

From Palmer et al. (2005)
Measured Work of Adhesion: loadcell

Temperature compensated bending beam 3 N loadcell

Instron logs extension data

To 'scope

From Palmer et al. (2005)
Measured Work of Adhesion

From Palmer et al. (2005)
Work of Adhesion

From Williamson et al. (2009b) Gen. PBX stress-strain

Graph showing the work of adhesion in mJ m$^{-2}$ against engineering strain rate in s$^{-1}$. The graph includes data points for TWA and MWA, with error bars indicating variability. The data is from Williamson et al. (2009b).
A description of failure

\[ \sigma(\varepsilon) = M_0 \varepsilon \left(1 - \exp\left(-\varepsilon_0^2/\varepsilon^2\right)\right) \]
Based on a simple model

Debond Energy = \( A \gamma \)

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

\[ \varepsilon_a^2 = \frac{2A\gamma}{M_0 V} \]

Local Volume: \( V \)
Global Strain: \( \varepsilon \)
Local Modulus: \( M_0 \)
Particle Surface Area: \( A \)
Surface Energy: \( \gamma \)
Inducing controlled damage
<table>
<thead>
<tr>
<th>Constituent</th>
<th>Material and mass fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QRX 214</td>
</tr>
<tr>
<td>RDX</td>
<td>0.75</td>
</tr>
<tr>
<td>HTPB based binder</td>
<td>0.15</td>
</tr>
<tr>
<td>Density g/cm$^3$</td>
<td>1.455</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>Monomodal fine</td>
</tr>
</tbody>
</table>

Restricted stroke
Inducing controlled damage

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

![Graph showing the relationship between Reduction in density and Damage Intensity (pre-strain level). The graph compares QRX 214 fine, QRX 217 coarse, and QRX 221 bimodal samples.](image-url)
Degradation of thermal conductivity
Virgin DMA Spectra

QRX217 Virgin Response

Storage Modulus / MPa

Temperature / °C

10^10

10^9

10^8

10^7

10^6

-150 -100 -50 0 50 100
Degradation of DMA Spectra

![Graph showing the degradation of DMA spectra with different markers and lines representing various materials and conditions. The x-axis represents Damage Intensity (pre-strain level), and the y-axis represents 1 Hz Elastic Modulus (MPa). The graph includes data points and trend lines for different materials, such as QRX 214 fine, QRX 217 coarse, and QRX 221 bimodal. This helps predict degraded modulus.](image)
Predicted degradation of modulus

QRX 221

Youngs modulus at low rate (Pa)

Input mechanical energy (J/m³)

data
prediction
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)
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.
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References


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