Adhesion and Moisture Damage Characterisation of Asphalt Mixtures

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Seminar
University of Granada
21st December 2011

Outline

- Background and Motivation
- Adhesion Theories (Surface Free Energy)
- SFE Test Methods
- Intrinsic Adhesion and Energy Parameters
- Practical Adhesion Testing
- Adhesive Fracture Energy and Loci of Fracture
- Concluding Remarks

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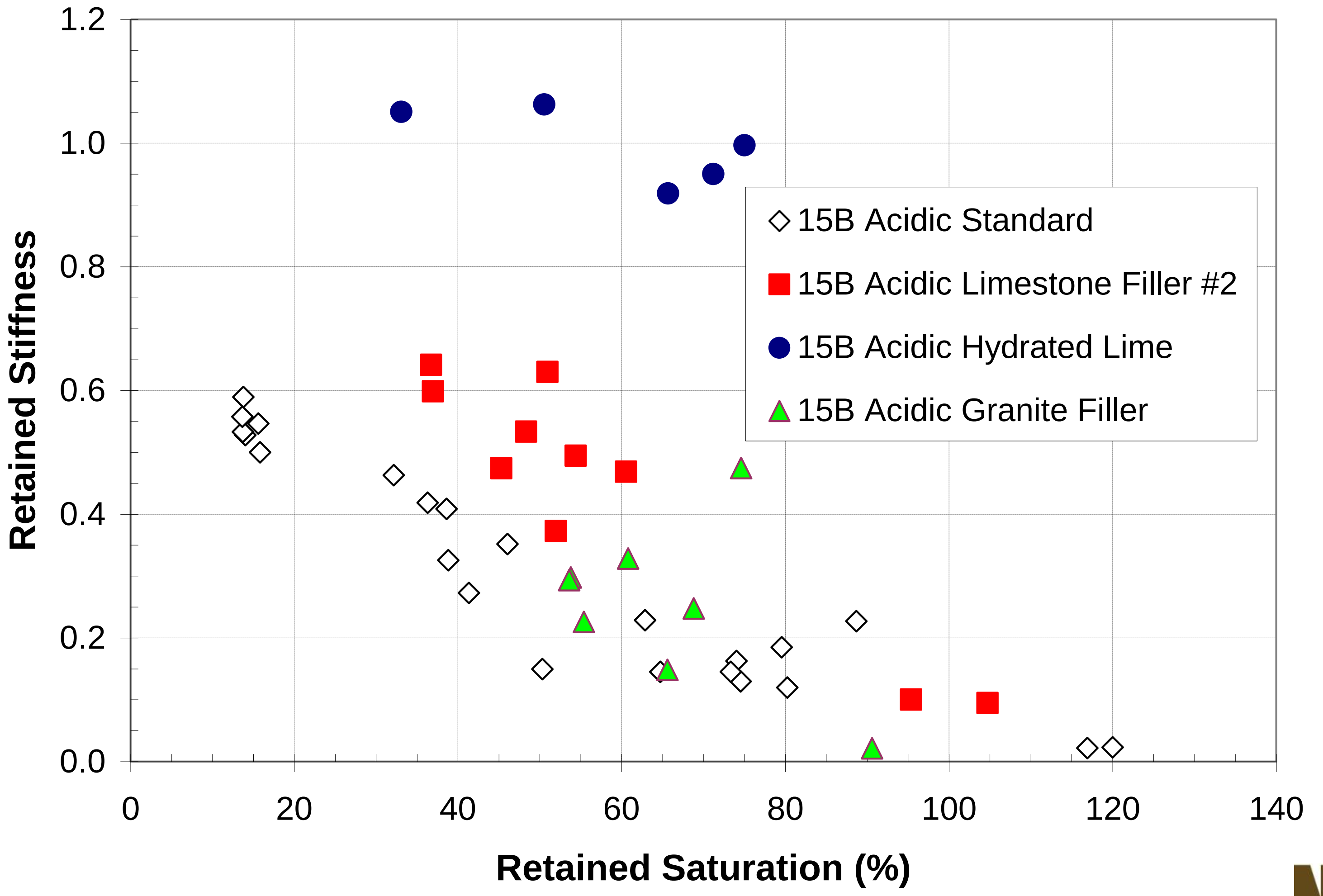
SATS – Aggregate Type



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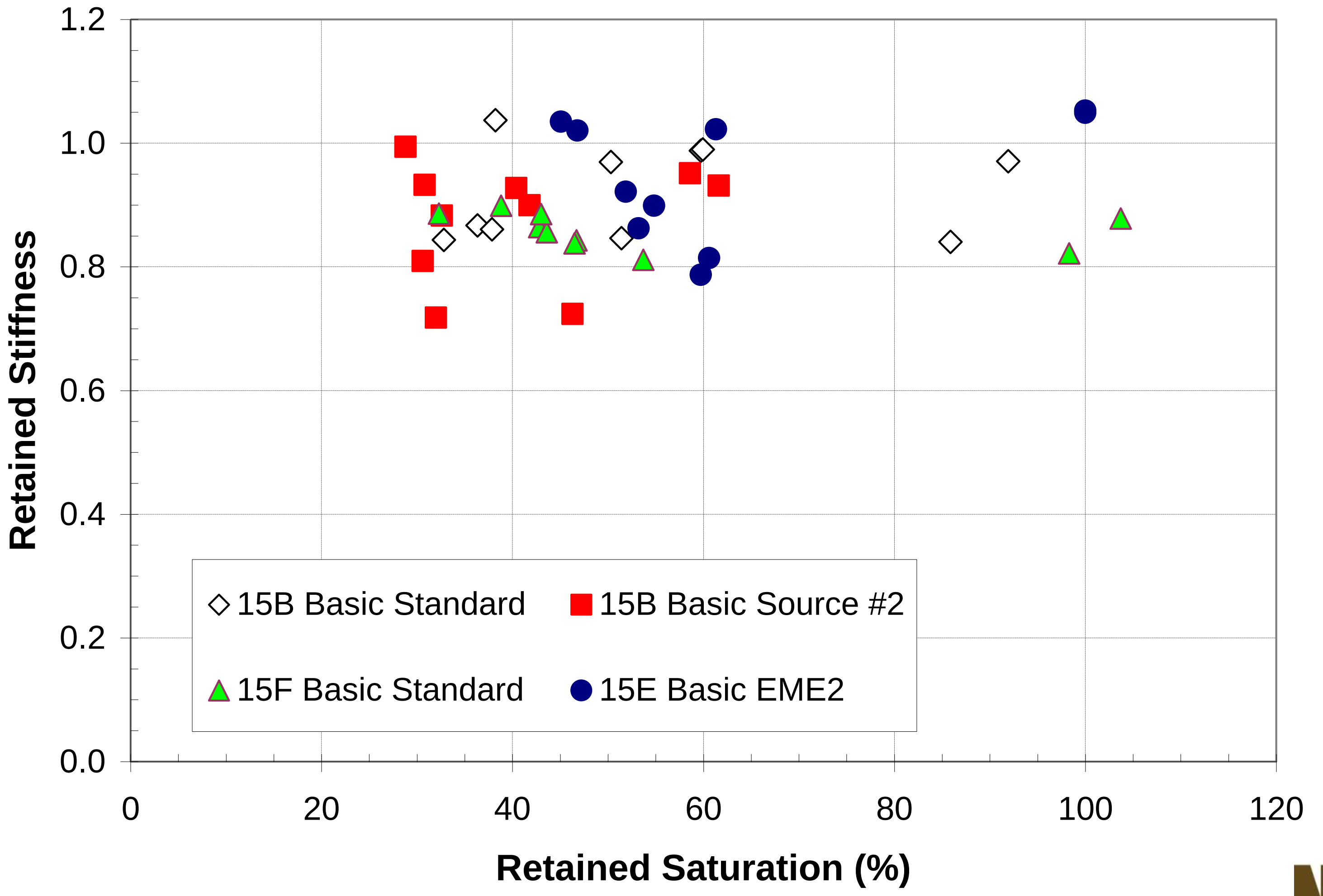
SATS - Bitumen Source



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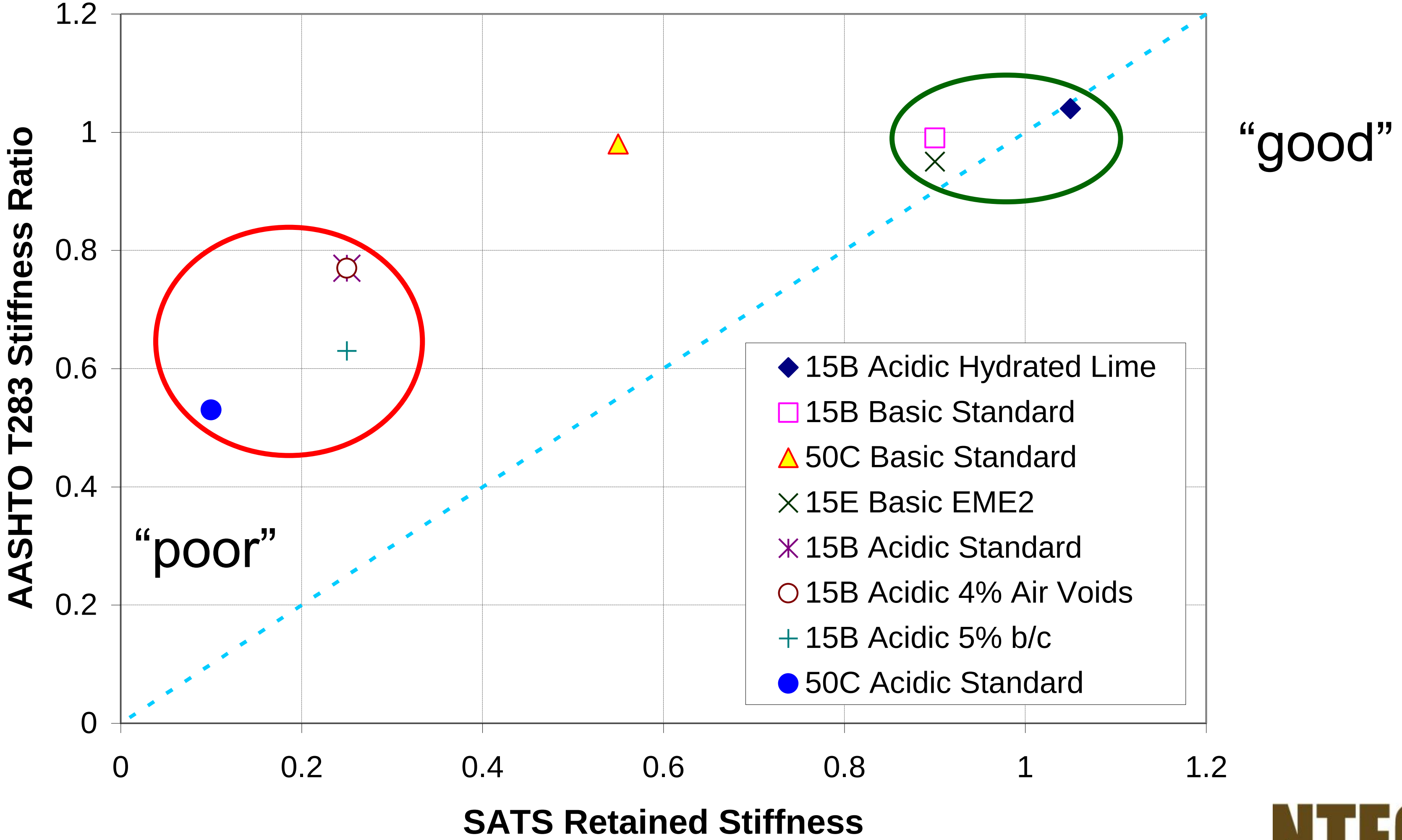
AASHTO T283 versus SATS conditioning



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Background and Motivation

Material Properties
(Bitumen and Aggregate)
- Physical properties
- Chemical properties

Mixture Properties
- Bitumen content and film thickness
- Air void structure

External Factors
- Construction
- Environment
- Traffic

Performance of asphalt in pavement

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Adhesion Theories

- Broad classification of mechanisms that explain adhesion and debonding:
  - Mechanical
  - Physio-chemical
  - Chemical

- Some other mechanisms / amplifiers of adhesion and debonding:
  - Weak boundary layers
  - Electrostatic and pH effect

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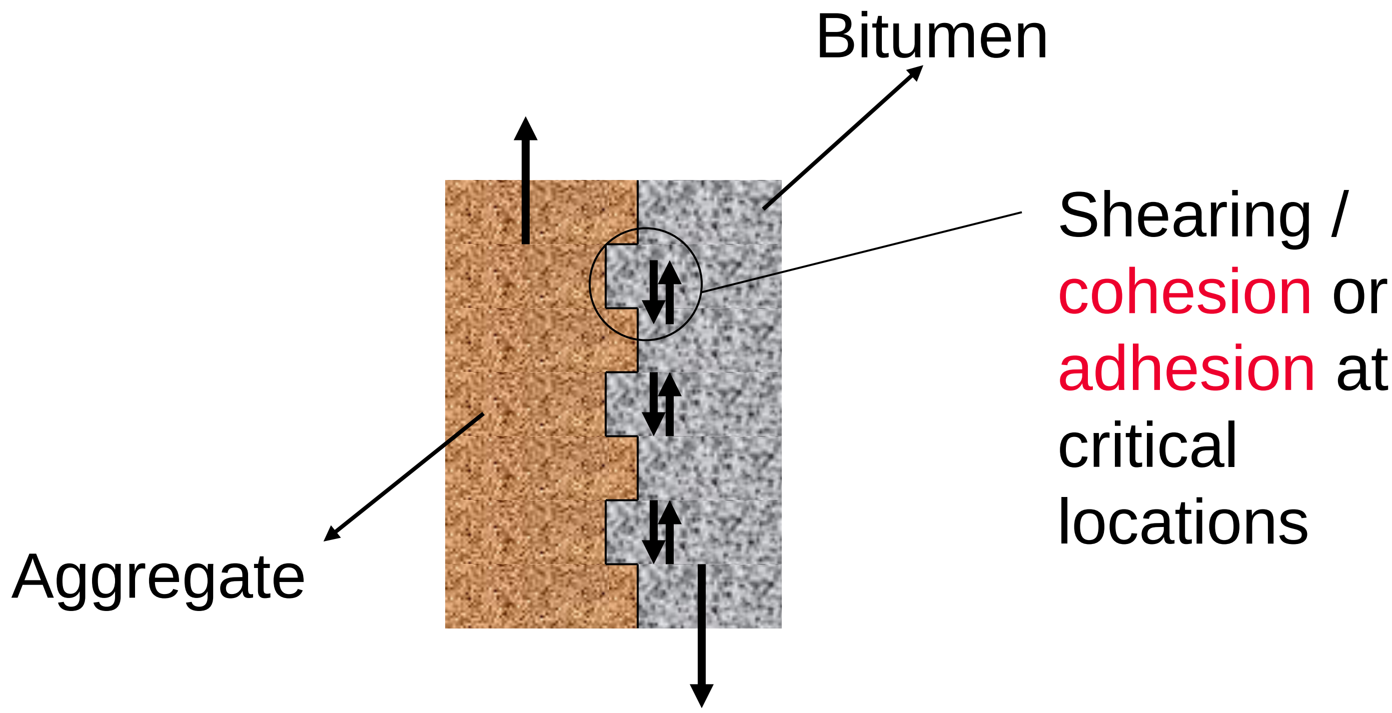
Adhesion Theories - Mechanical

- Lock and key



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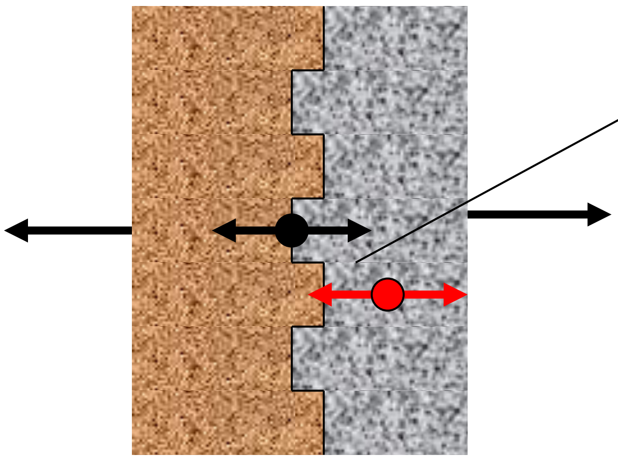
Adhesion Theories - Mechanical

- Greater area of bonding



- Adhesive or cohesive failure mode
- Increased surface will cause redistribution of stresses and improve adhesion

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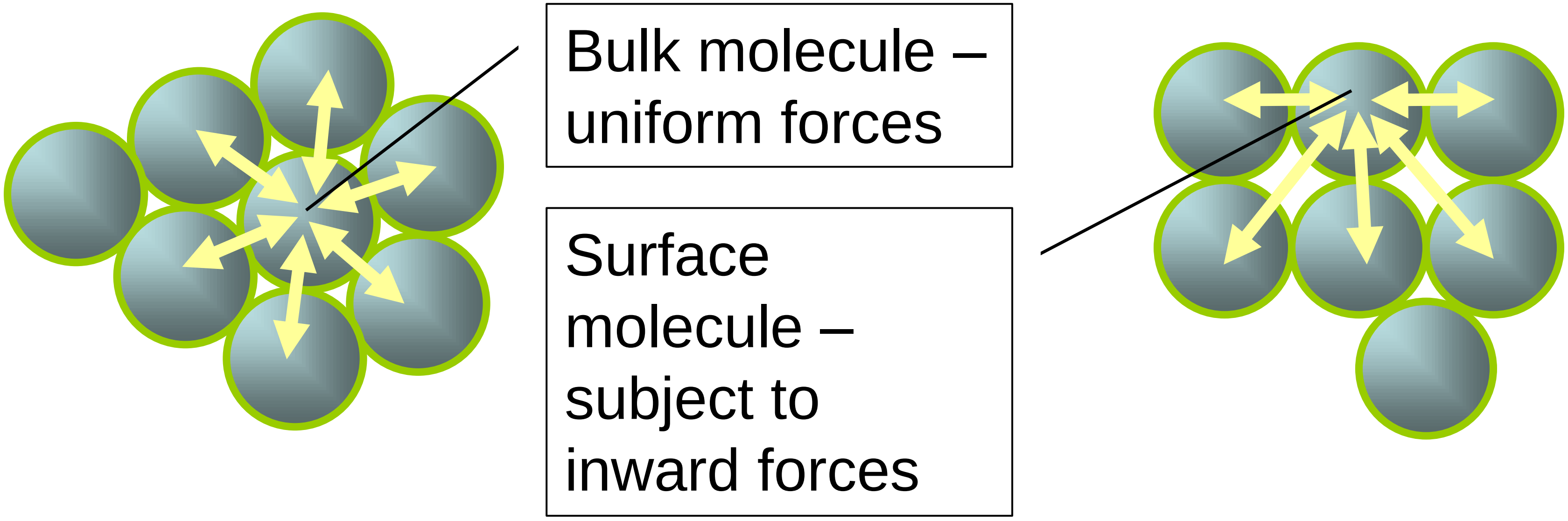
Adhesion Theories – Physio-Chemical

Surface Energy - Definition

Energy required to form a unit area of new surface



Physical Meaning

Work done to remove a molecule from bulk to surface

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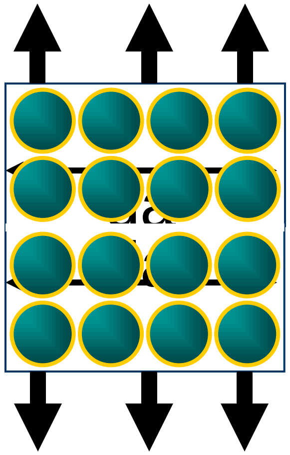
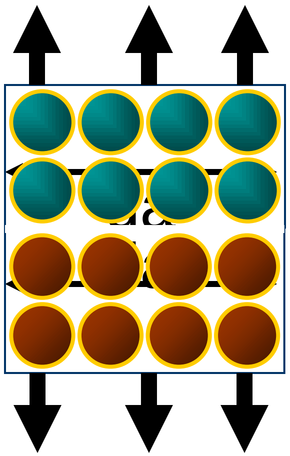
Adhesion Theories – Physio-Chemical





→ Cohesive Fracture Energy = $\mathbf{2}\gamma$

→ Adhesive Fracture Energy = $\gamma_1 + \gamma_2 - \gamma_{12}$

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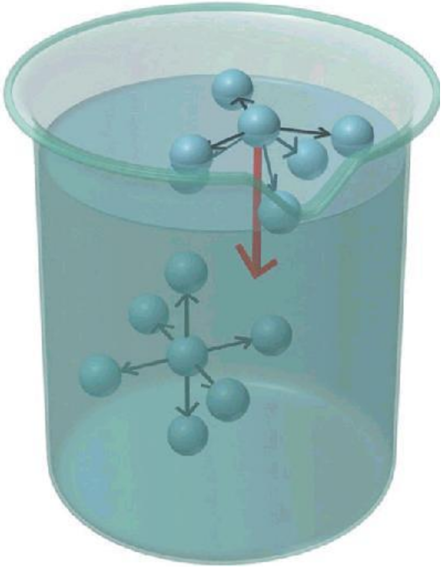
Surface Free Energy

- Surface free energy is defined as the energy/work required to create a new unit surface area of the material in vacuum
  - Surface energy of a bitumen-aggregate combination consist of two components
    - Non Polar (apolar) component
    - Acid-base component

$$\gamma^{Total} = \gamma^{LW} + \gamma^{AB}$$ (Unit; ergs/cm²)



Where:

γ^{LW} = Liftshitz-Van der Waals component

γ^{AB} = Acid-Base component

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Surface Free Energy

- Good and Van Oss postulated:

$$\gamma^{AB} = 2\sqrt{\gamma^{+}\gamma^{-}}$$

Where,

γ^{+} = Lewis acid component of surface interaction

γ^{-} = Lewis base component of surface interaction

- Three-component (acid-base) theory of SFE:

$$\gamma = \gamma^{LW} + 2\sqrt{\gamma^{+}\gamma^{-}}$$

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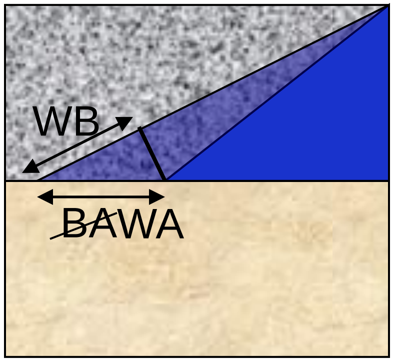
Adhesion Theories – Physio-Chemical

Three Phase System – Bitumen-Aggregate-Water



A = lost bitumen-aggregate interface ($-\gamma_{AB}$)
B = new water-asphalt interface (γ_{WB})
C = new water-aggregate interface (γ_{WA})

Total energy used

$$\Delta\gamma_{WAB} = \gamma_{WB} + \gamma_{WA} - \gamma_{AB}$$

≤ 0 !! (Almost always)

= fn (3 surface energy components of each material)

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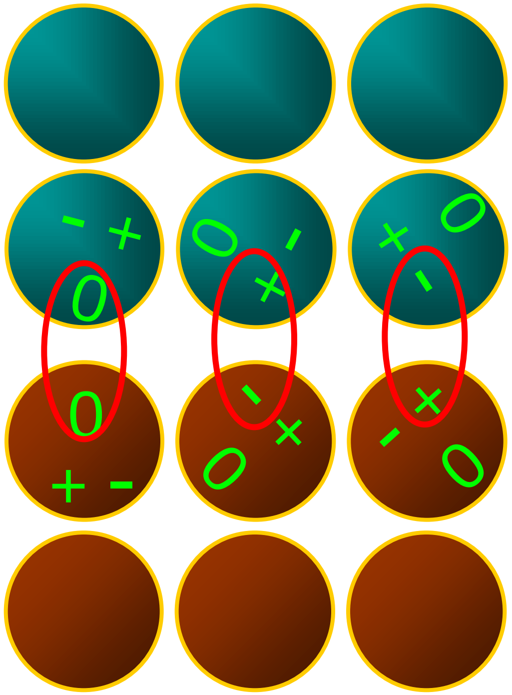
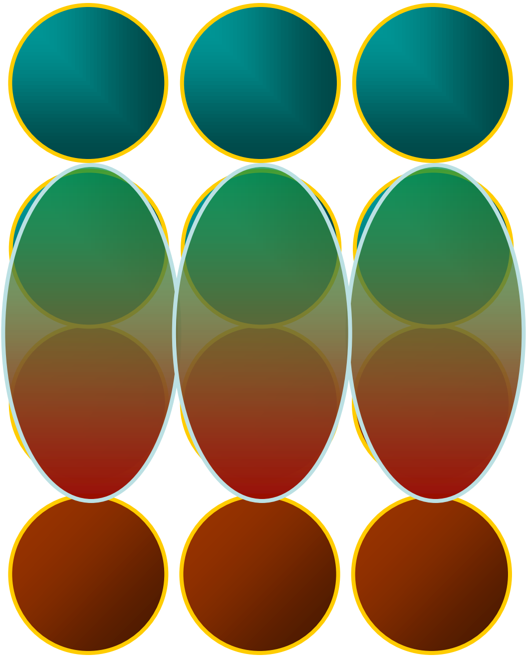
Adhesion Theories – Chemical





Physio-Chemical Adhesion due to Surface Energy

versus

Chemical Bonding

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Adhesion Theories – Chemical

- Typical examples in asphalt mixtures:

$$CaCO_3 + 2X\text{-}COOH \rightarrow Ca(XCOO)_2 + H_2O + CO_2$$

eg: carboxylic acids from bitumen

eg: from limestone aggregate

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Test Methods

- Specific surface area (Mechanical interlocking)
  - Nitrogen adsorption methods
  - Vapour sorption

- Surface Free Energy
  - Adsorption methods
  - Contact angle methods
  - Calorimetric methods
  - Chromatographic methods
  - Contact probe methods

- Chemical Reaction
  - Calorimetric methods

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Test Methods – Surface Energy

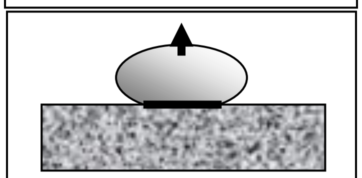
$$2\sqrt{\gamma_X^{LW}\gamma_P^{LW}} + 2\sqrt{\gamma_X^{+}\gamma_P^{-}} + 2\sqrt{\gamma_X^{-}\gamma_P^{+}}$$

Work of Adhesion

Spreading or Contact angles

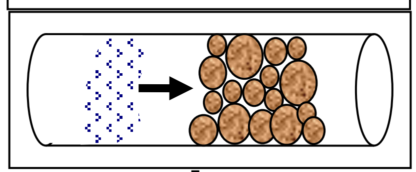
WP, SD, DVS

Elastic bodies in contact



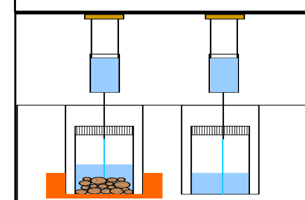
AFM

Retention time/ volume of vapors



IGC

Heat of Immersion



Microcalorimeter

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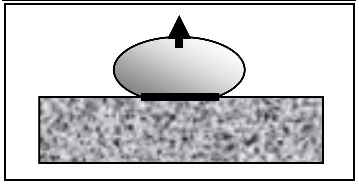
Test Methods – Surface Energy

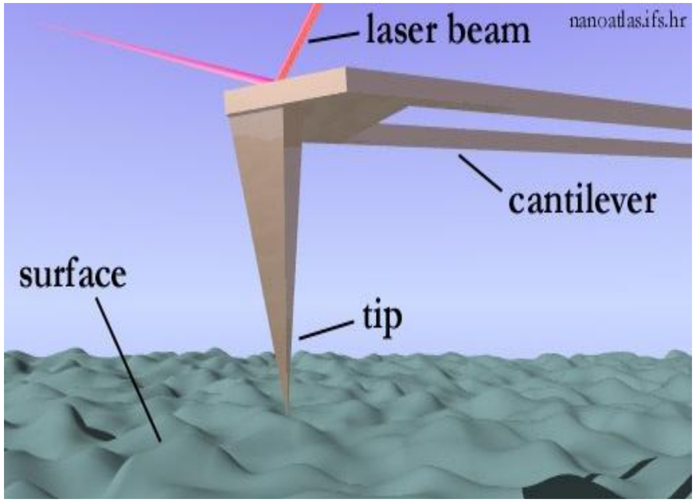
$$2\sqrt{\gamma_X^{LW}\gamma_P^{LW}} + 2\sqrt{\gamma_X^{+}\gamma_P^{-}} + 2\sqrt{\gamma_X^{-}\gamma_P^{+}}$$

Work of Adhesion

Elastic bodies in contact



Atomic Force Microscopy (AFM)



- Applicable for bitumen
- Aggregate surfaces are very rough to be used with AFM
- Measures properties at nano scale which are difficult to generalize
- Requires time and expertise
- Work with polar probes (modified cantilever tips) is under research
- Powerful tool to investigate properties at close to molecular scale

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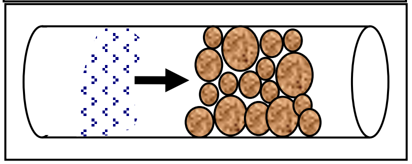
Test Methods – Surface Energy

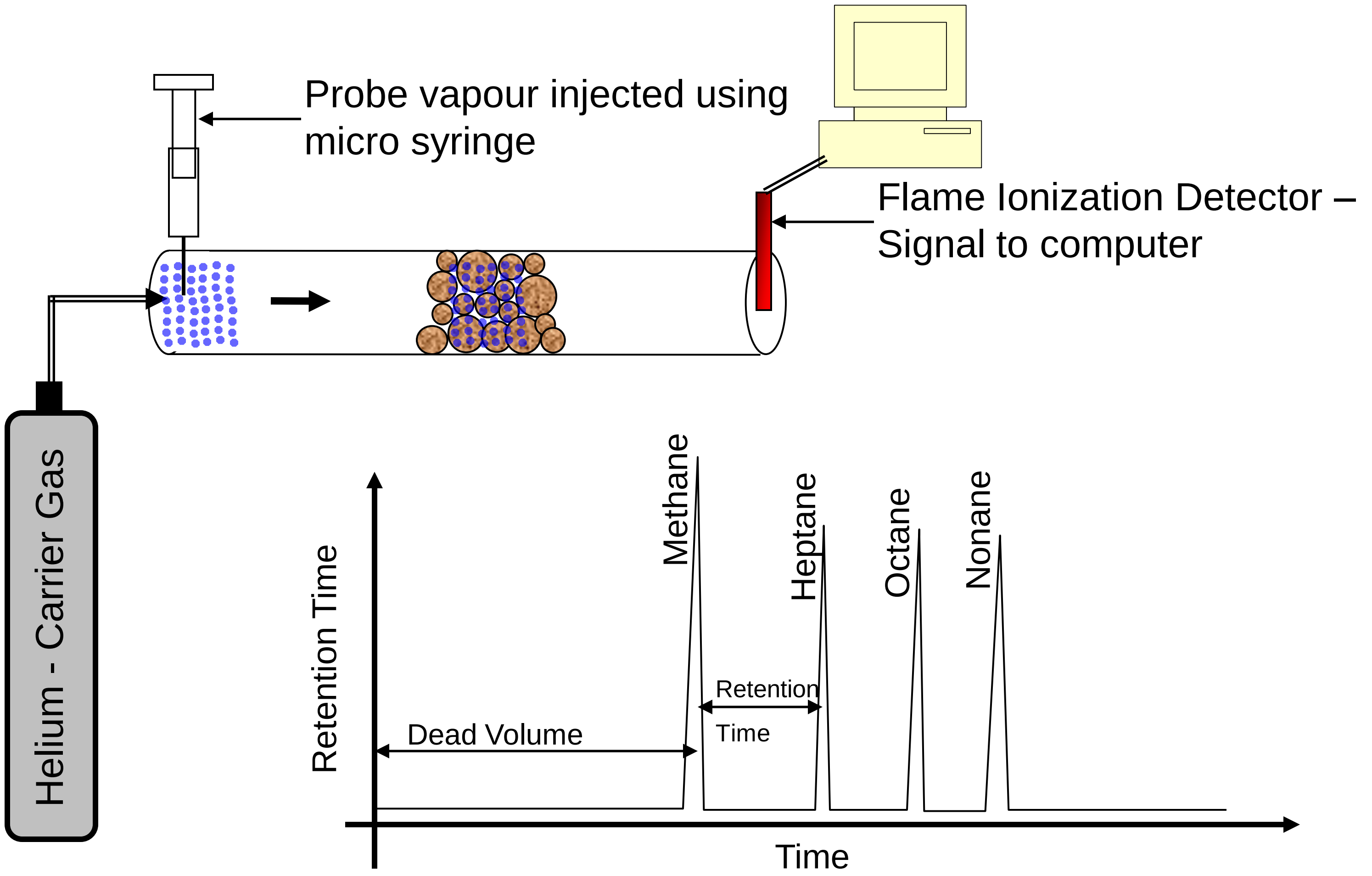
$$2\sqrt{\gamma_X^{LW}\gamma_P^{LW}} + 2\sqrt{\gamma_X^{+}\gamma_P^{-}} + 2\sqrt{\gamma_X^{-}\gamma_P^{+}}$$

Work of Adhesion

Retention time/
volume of vapors



Inverse Gas Chromatography (IGC)



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Inverse Gas Chromatography (IGC)

- Can be used for both bitumen and aggregate
- Relatively a very fast technique
- Sensitive to polar components

Drawbacks

- Infinitely diluted conditions - only high energy spots are characterized making it more suitable for homogenous materials
- Finite concentration technique can be used for heterogeneous materials but requires more time

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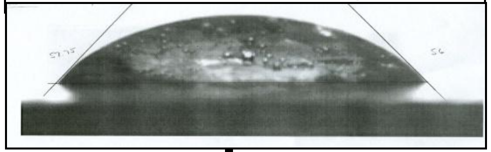
Dynamic Vapour Sorption (DVS)

$$2\sqrt{\gamma_X^{LW}\gamma_P^{LW}} + 2\sqrt{\gamma_X^{+}\gamma_P^{-}} + 2\sqrt{\gamma_X^{-}\gamma_P^{+}}$$

Work of Adhesion

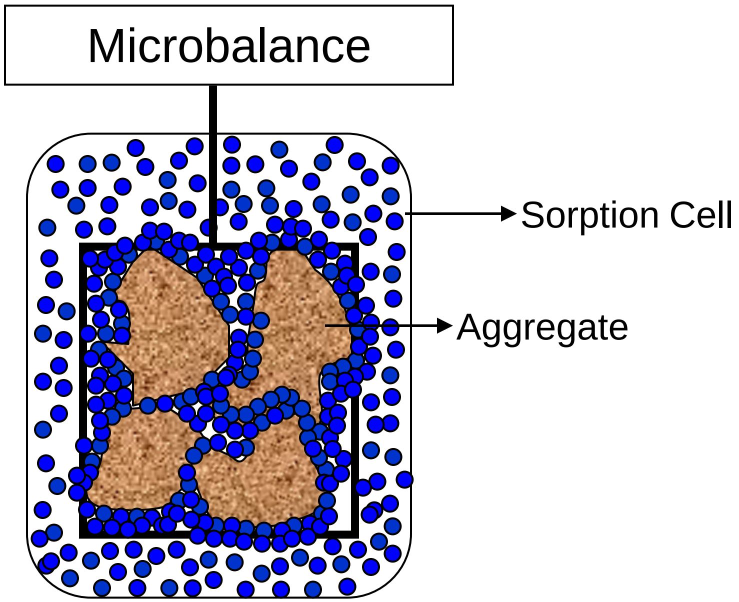
Spreading / Wetting or Contact angles

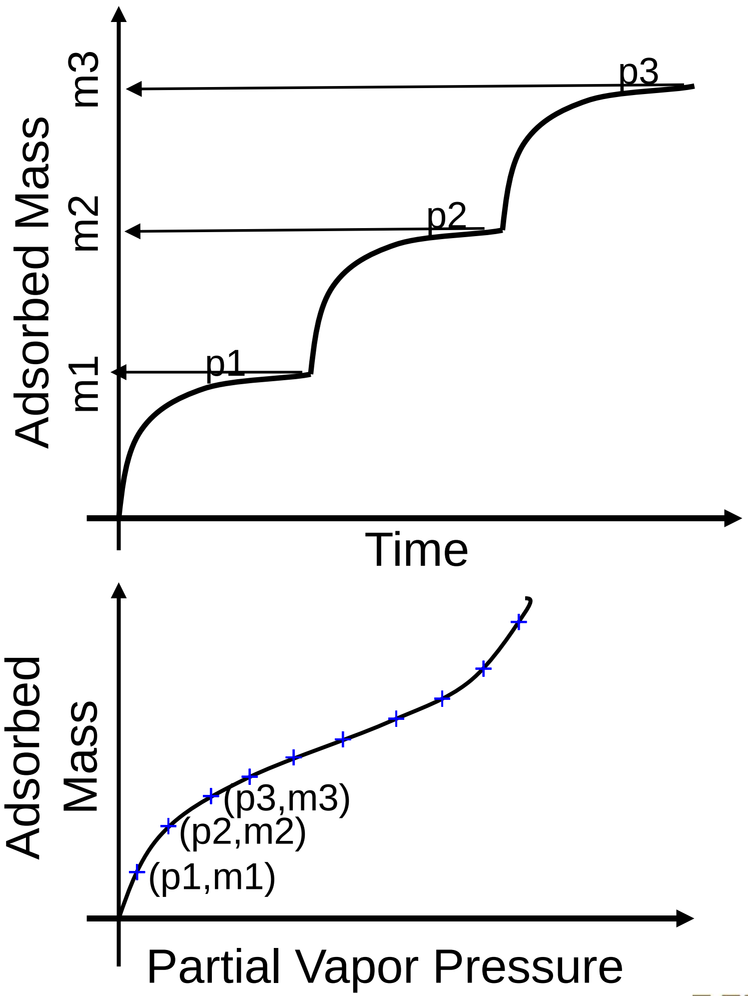


$$\pi_e + \gamma_P^{Total}(1+\cos\theta)$$

1

Dynamic Vapour Sorption (DVS)





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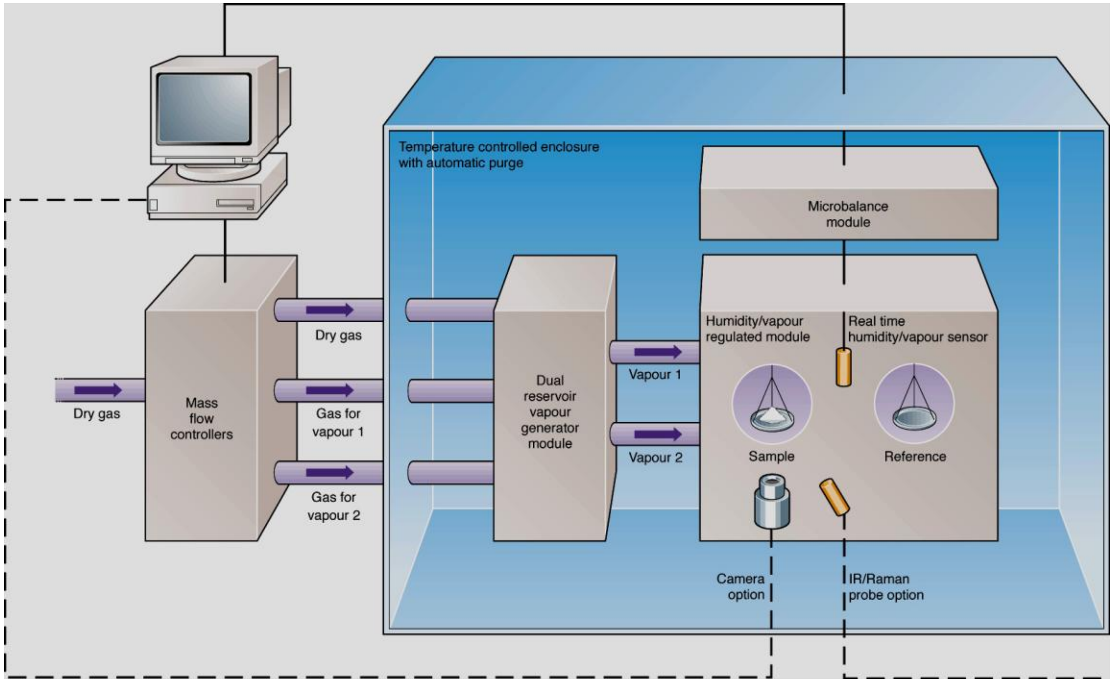
Dynamic Vapour Sorption (DVS)

- Specific surface area (SSA) - Brunauer-Emmett-Teller (BET) approach

$$A = \left(\frac{n_m N_o}{M} \right) \alpha$$

- Number of vapour molecules - Langmuir approach

$$\frac{P}{n(P_0 - P)} = \left(\frac{c-1}{n_m c} \right) \frac{P}{P_0} + \frac{1}{n_m c}$$



- Spreading pressure - Gibbs free energy equation

$$\Pi_e = \frac{RT}{A} \int_0^{Po} \frac{n}{P} dP$$

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Dynamic Vapour Sorption (DVS)

- Applicable for aggregate only
- Can accommodate large sample sizes

Drawbacks

- Inherently time consuming

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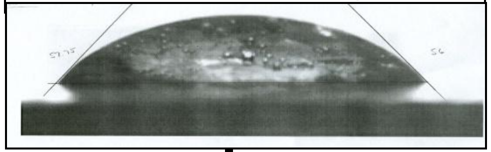
Wilhelmy Plate Method

$$2\sqrt{\underline{\gamma_X^{LW}}\,\gamma_P^{LW}} + 2\sqrt{\underline{\gamma_X^{+}}\,\gamma_P^{-}} + 2\sqrt{\underline{\gamma_X^{-}}\,\gamma_P^{+}}$$

Work of Adhesion

Spreading / Wetting or Contact angles

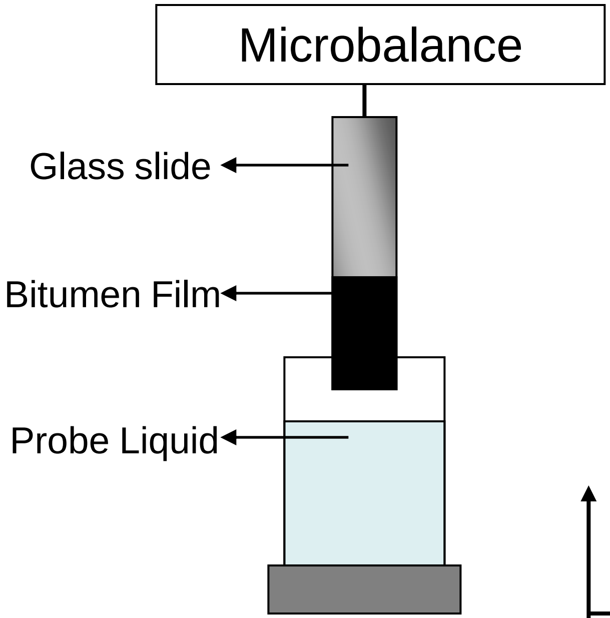


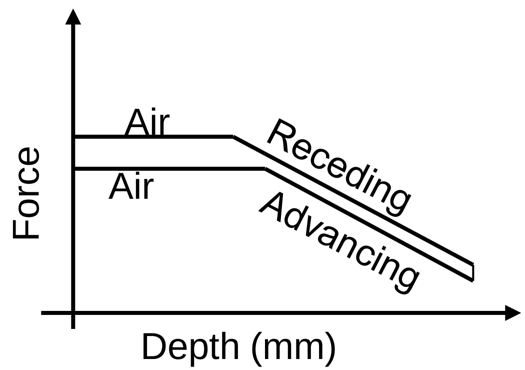
$$\cancel{\pi_e} + \gamma_P^{Total}\left(1+\cos\underline{\theta}\right)$$

0

Wilhelmy Plate Method

Wilhelmy Plate Method





In air:

Weight of Slide

In liquid:

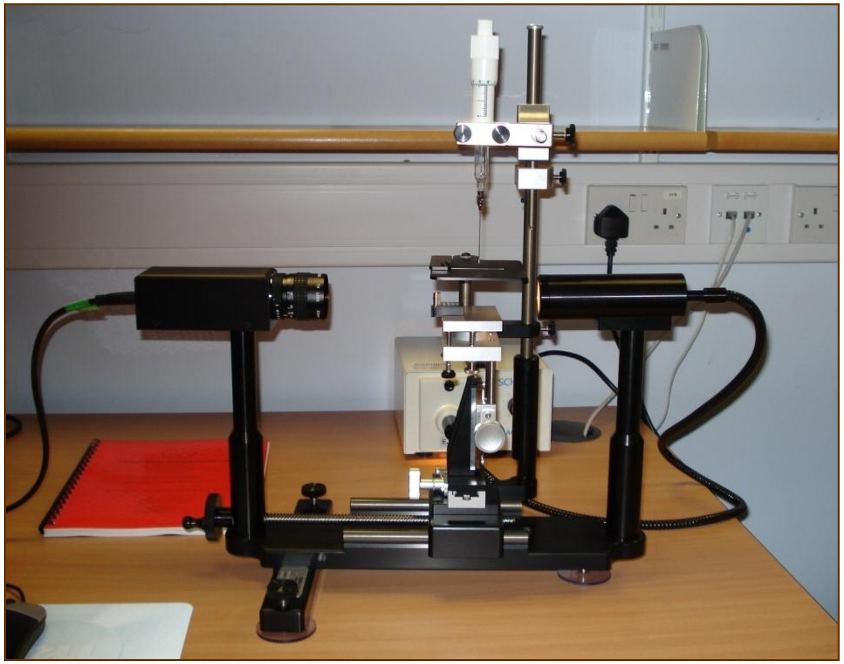
Weight of Slide – Buoyancy – Adhesion

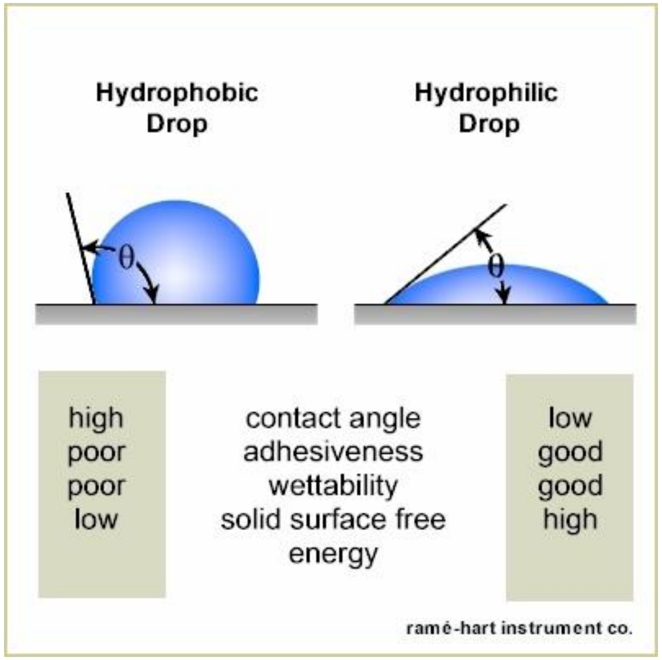
Buoyancy: Volume * liquid density * g

Adhesion: Perimeter * γ_{liquid} * Cos θ

SE Measurement Techniques

- Goniometer





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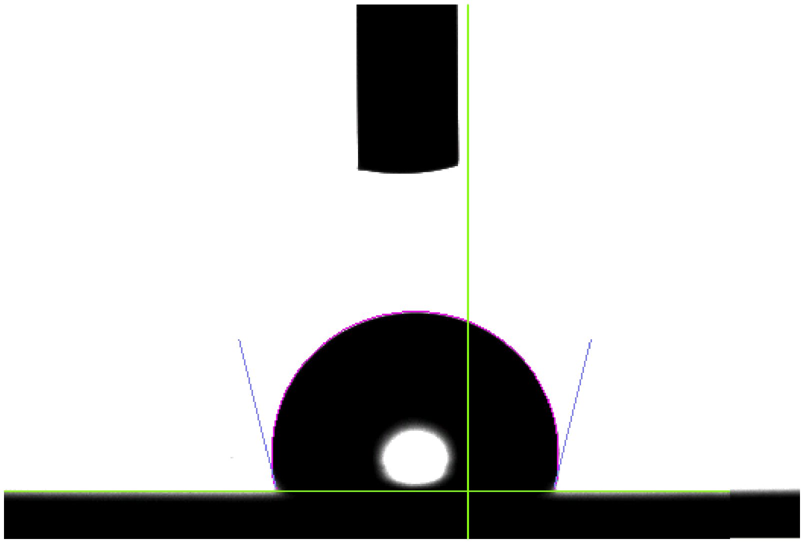
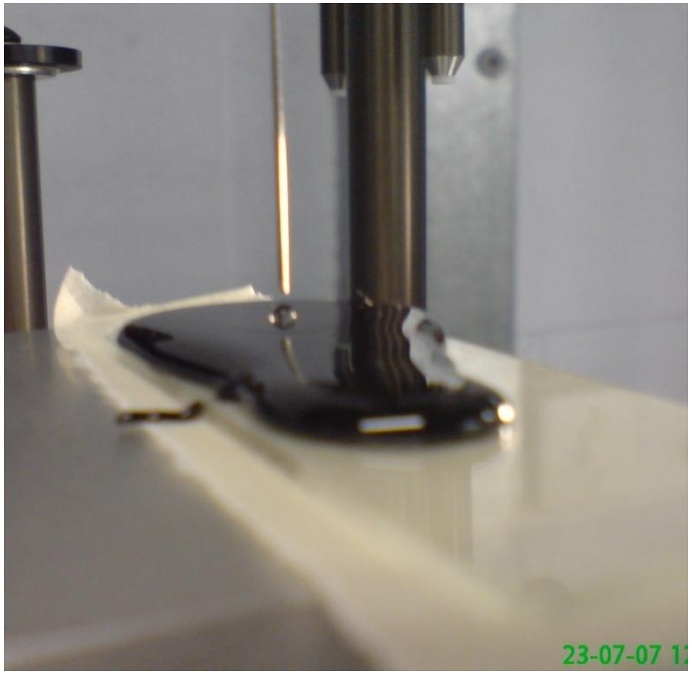
Goniometer Test Procedure



1) Level the stage

2) Produce a drop

3) Lower the syringe to dispense the drop on the bitumen



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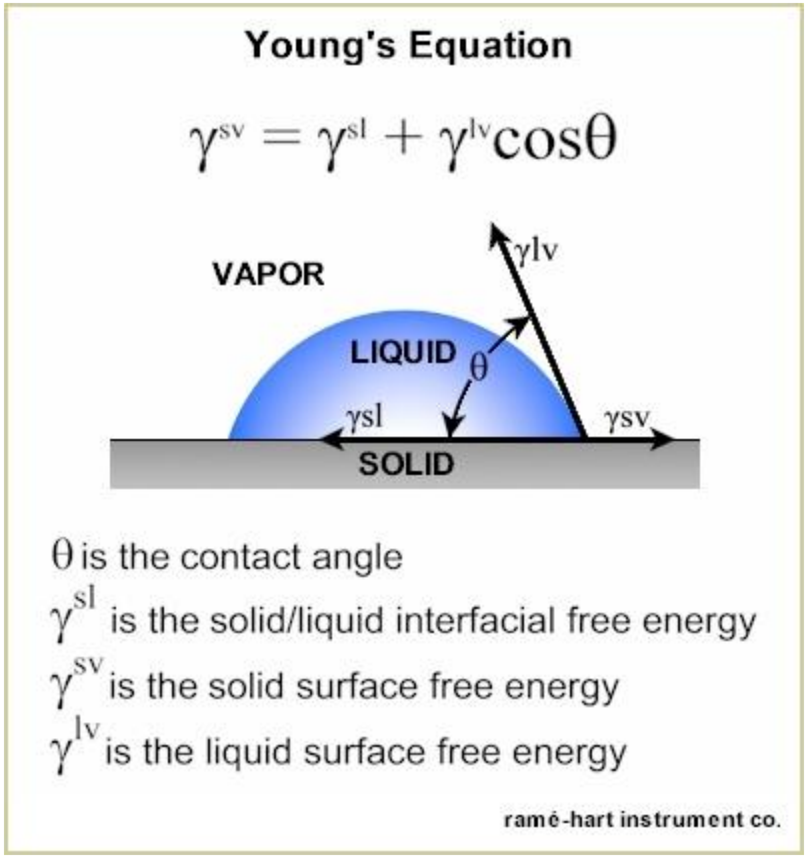
SE Measurement Techniques



$$\gamma_{LA}\cos\theta + \gamma_{SL} = \gamma_{SA}$$

Dupre's Equation

$$W_{SL} = \gamma_{SA} + \gamma_{LA} - \gamma_{SL}$$

$$W_{SL} = \gamma_{LA}(1+\cos\theta)$$

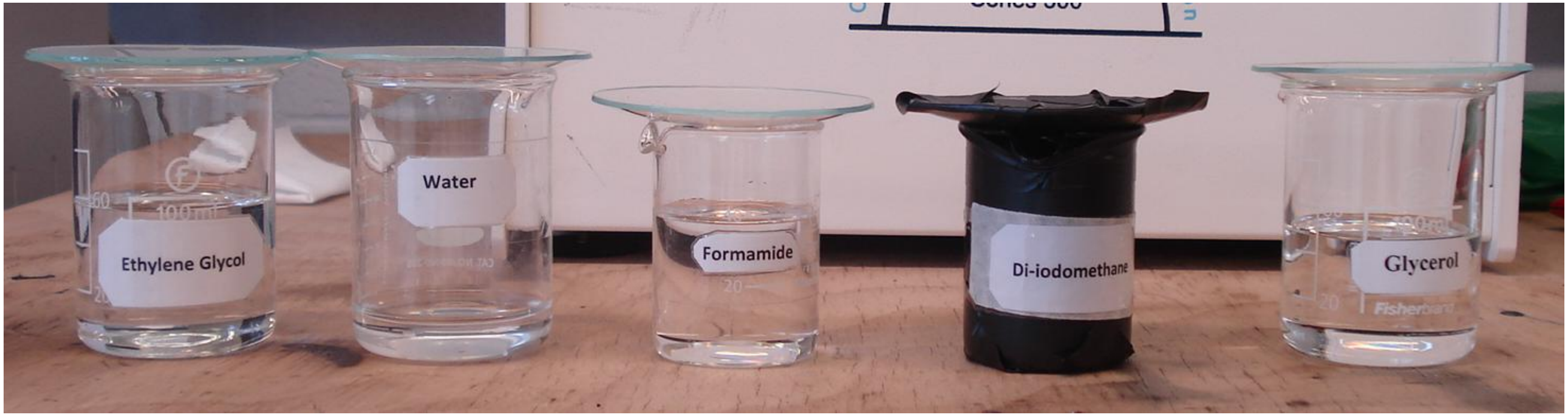
Dry adhesive bond strength

$$W_{SL} = 2\sqrt{\gamma_S^{LW}\gamma_L^{LW}} + 2\sqrt{\gamma_S^{+}\gamma_L^{-}} + 2\sqrt{\gamma_S^{-}\gamma_L^{+}}$$

$$\gamma_L(1+\cos\theta) = 2\sqrt{\gamma_S^{LW}\gamma_L^{LW}} + 2\sqrt{\gamma_S^{-}\gamma_L^{+}} + 2\sqrt{\gamma_S^{+}\gamma_L^{-}}$$

Probe Liquids

No.	Probe Liquid	γ^{LW}	γ^{+}	γ^{-}	γ^{TOTAL}	SQRT γ^{LW}	SQRT γ^{+}	SQRT γ^{-}
1	Water	21.8	25.5	25.5	72.8	4.67	5.05	5.05
2	Glycerol	34.0	3.92	57.4	64.0	5.83	1.98	7.57
3	Diiodomethane	50.8	0	0	50.8	7.13	0	0



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Contact Angle Approach

- Applicable for bitumen only
- Very fast and precise technique

Drawbacks

- Interpretation of contact angles must be made with caution

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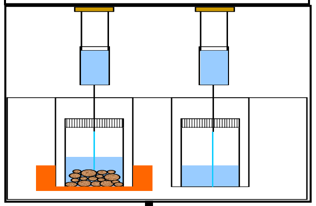
Test Methods – Surface Energy + Chemical

$$2\sqrt{\gamma_X^{LW}\gamma_P^{LW}} + 2\sqrt{\gamma_X^{+}\gamma_P^{-}} + 2\sqrt{\gamma_X^{-}\gamma_P^{+}}$$

Work of Adhesion

Heat of Immersion



$$\gamma_P - \Delta H_{imm} + T\Delta S_{imm}$$

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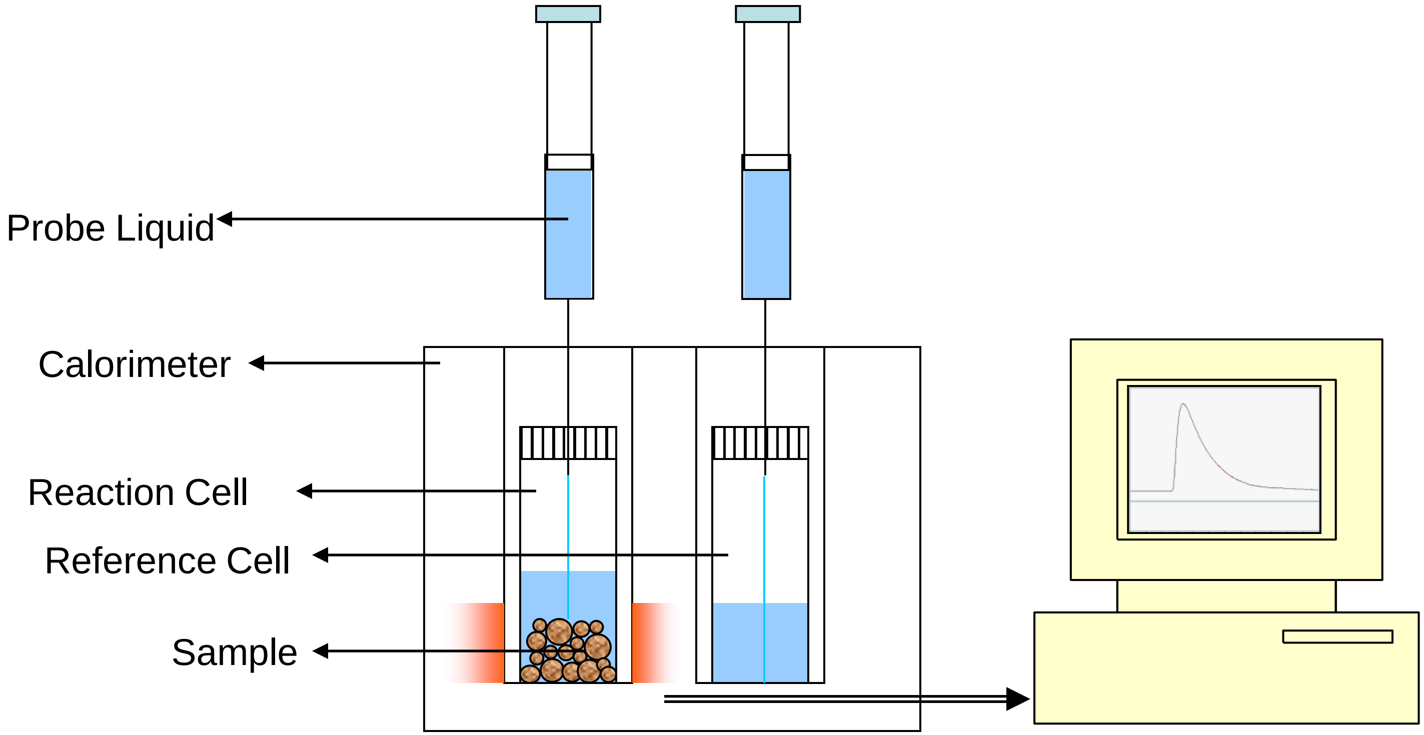
Microcalorimeter



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Microcalorimeter – Surface Energy + Chemical

Advantages and Applications

- Rapid estimate of surface free energy of aggregates (with any precondition)
- Quantify hydrophilic character of aggregates
- Measures total heat of adhesion between two phases

Drawbacks

- Measures total heat of adhesion between two phases
- Assumption for enthalpy needs to be made
- Specific surface area of aggregates must be known

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Application – Surface Energy

Wilhelmy Plate Test

- Output: Contact angles
- Analysis: Work of adhesion with probe liquids
- Result: Three surface energy components

Vapour Sorption Test

- Output: Adsorption isotherm
- Analysis: Work of adhesion with probe vapours
- Result: Three surface energy components

Performance related parameters based on surface energy

Intrinsic Adhesion Calculations

Adhesive bond energy (dry)

$$W_{BA}^{a} = 2\sqrt{\gamma_B^{LW}\gamma_A^{LW}} + 2\sqrt{\gamma_B^{+}\gamma_A^{-}} + 2\sqrt{\gamma_B^{-}\gamma_A^{+}}$$

Adhesive bond energy (wet)

$$\Delta G_{BWA}^{a} = 2\gamma_W^{LW} + 2\sqrt{\gamma_B^{LW}\gamma_A^{LW}} - 2\sqrt{\gamma_B^{LW}\gamma_W^{LW}} - 2\sqrt{\gamma_A^{LW}\gamma_W^{LW}}$$
$$+ 4\sqrt{\gamma_W^{+}\gamma_W^{-}} - 2\sqrt{\gamma_W^{+}}\left(\sqrt{\gamma_B^{-}} + \sqrt{\gamma_A^{-}}\right) - 2\sqrt{\gamma_W^{-}}\left(\sqrt{\gamma_B^{+}} + \sqrt{\gamma_A^{+}}\right)$$
$$+ 2\sqrt{\gamma_B^{+}\gamma_A^{-}} + 2\sqrt{\gamma_B^{-}\gamma_A^{+}}$$

Bond energy ratio

$$ER = \left|\frac{W_{BA}^{a}}{W_{BWA}^{a}}\right|$$

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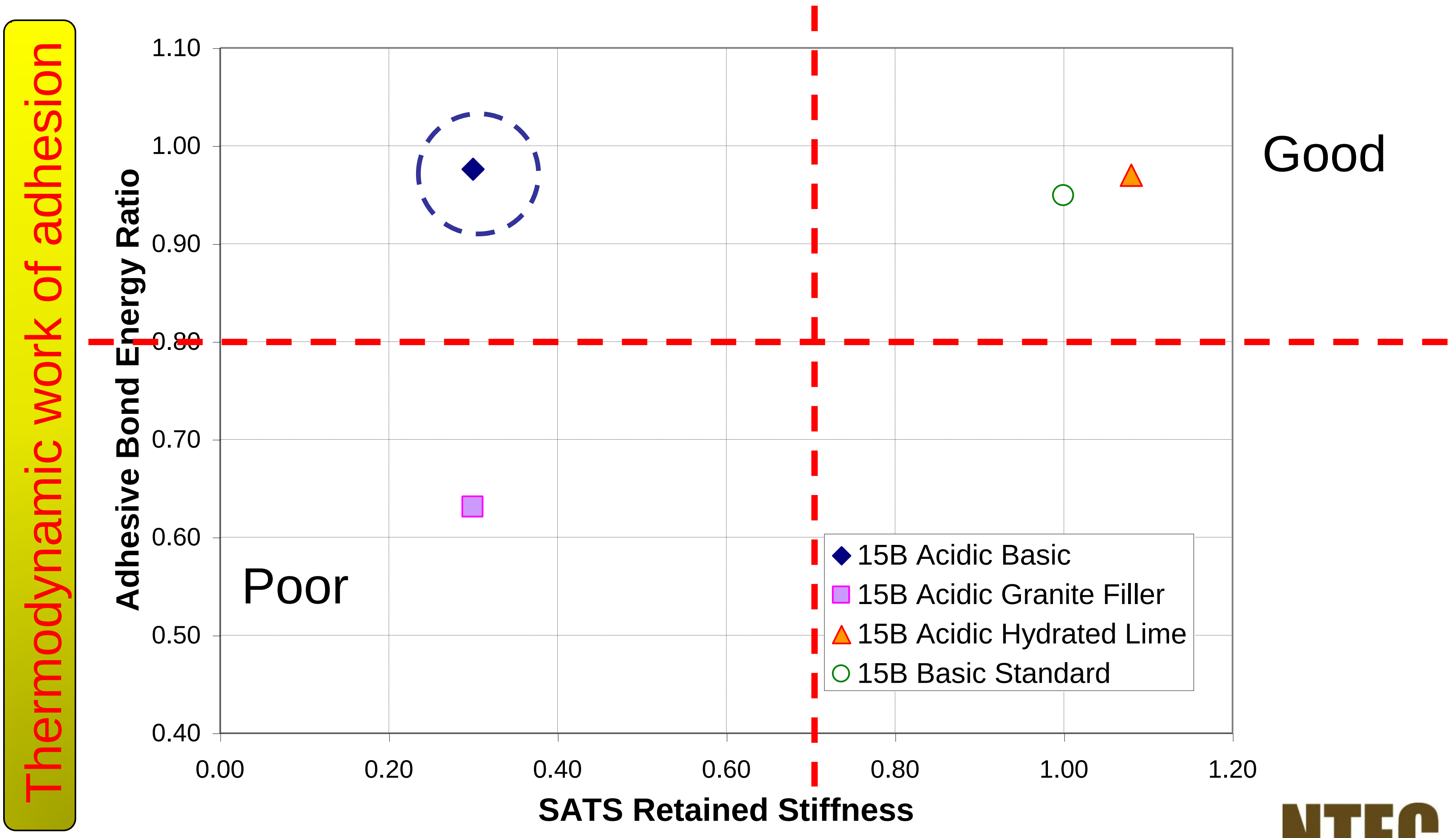
Application of Surface Energy

Moisture damage assessment:

$$\left|\frac{\Delta W_{AB}}{\Delta W_{ABW}}\right|$$

	Granite A	Gravel A	Gravel B	Limestone A	Limestone B	Quartzite A	Sandstone A	Sandstone B	KAG	NAG
PG 64-22 A	0.40	1.05	0.58	0.53	0.74	0.56	1.37	0.88	0.35	0.63
PG 64-22 B	0.65	1.98	1.00	0.86	1.38	0.97	2.54	1.41	0.71	1.08
PG 64-22 C	0.49	1.48	0.76	0.66	1.04	0.74	1.90	1.10	0.51	0.82
PG 64-22 D	0.58	1.38	0.80	0.72	1.03	0.78	1.69	1.10	0.58	0.86
PG 64-22 E	0.61	1.96	0.97	0.83	1.34	0.94	2.57	1.40	0.66	1.05
PG 64-22 F	0.74	2.47	1.18	1.00	1.66	1.14	3.29	1.71	0.81	1.27
PG 64-22 G	0.62	1.92	0.97	0.83	1.34	0.94	2.47	1.37	0.68	1.04
PG 64-22 H	0.47	1.26	0.69	0.62	0.90	0.67	1.63	1.02	0.45	0.75
PG 64-22 I	0.69	2.20	1.08	0.92	1.51	1.05	2.87	1.55	0.75	1.17
PG 64-28 B	0.46	0.93	0.59	0.56	0.70	0.58	1.16	0.83	0.40	0.64
PG 76-22 A	0.72	1.49	0.93	0.87	1.15	0.92	1.79	1.24	0.70	1.00
PG 76-22 B	0.45	1.07	0.62	0.57	0.78	0.61	1.37	0.91	0.40	0.68
PG 76-22 C	0.67	1.24	0.83	0.79	0.99	0.82	1.48	1.09	0.62	0.89
PG 76-22 D	0.60	1.50	0.85	0.77	1.10	0.83	1.88	1.19	0.60	0.92

SATS versus intrinsic adhesion ratio



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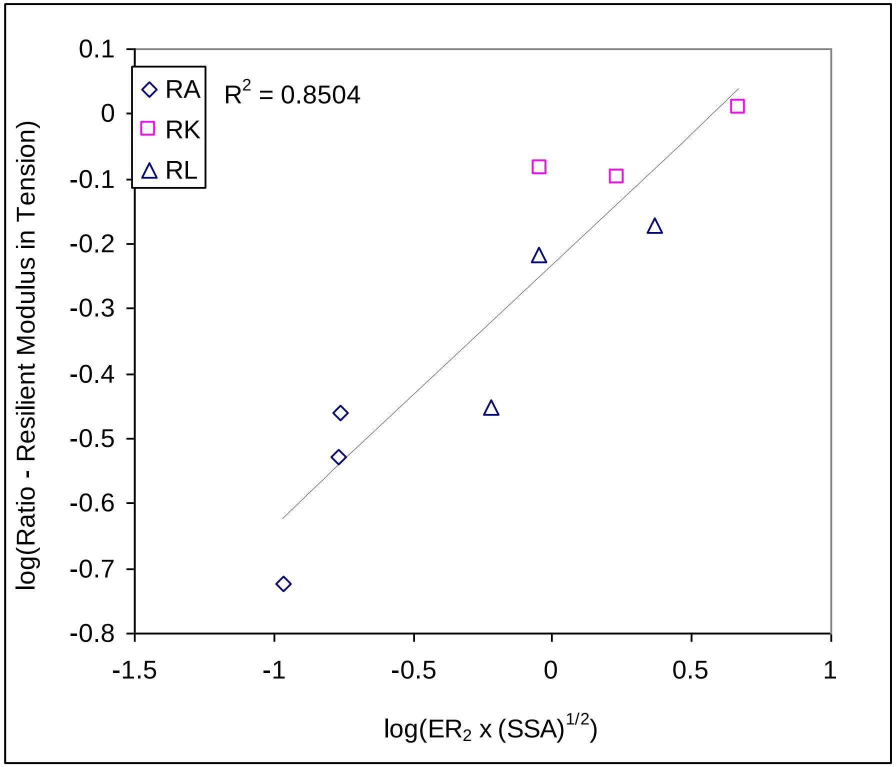
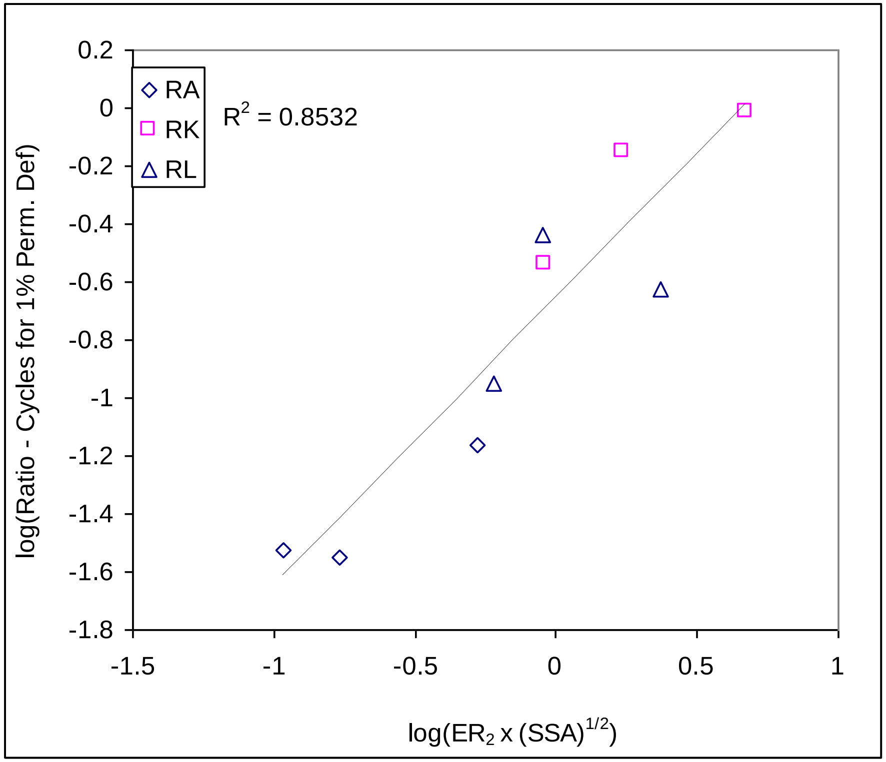
Energy Parameters

- ‘Good’ versus ‘poor’ moisture damage performance

$$\left|\frac{\Delta W_{AB} - \Delta W_{AA}}{\Delta W_{ABW}}\right| \times \sqrt{SSA}$$





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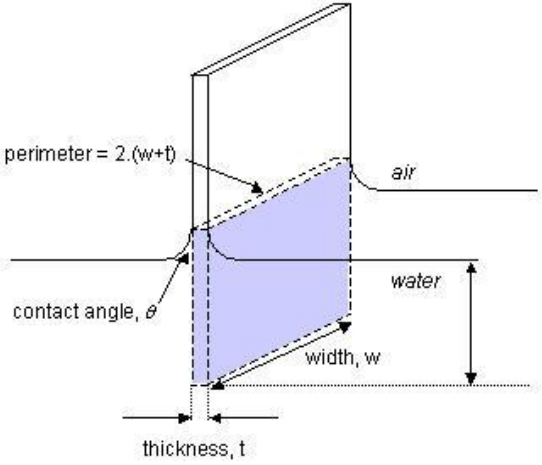
SFE Measurements

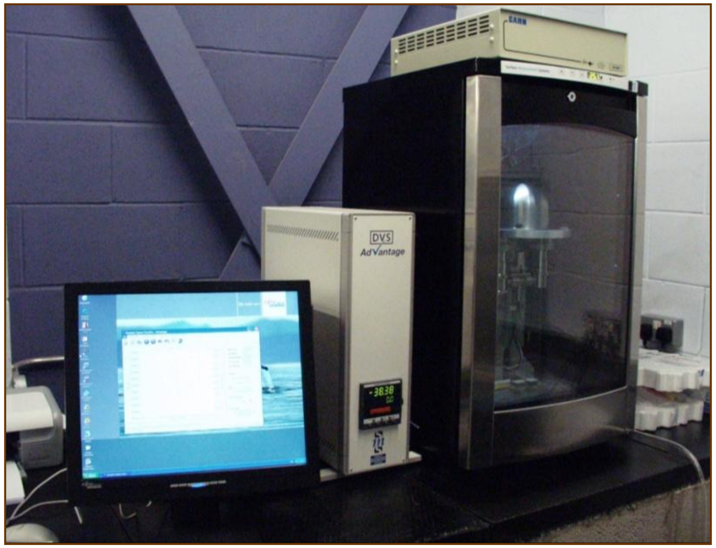
- **Dynamic Contact Angle Analyzer, DCA**

  Dynamic (advancing/receding) contact angle values of bitumen

- **Dynamic Vapour Sorption System, DVS**

  Surface energy components of the aggregates using the gas adsorption characteristics of selected solvents





Energy Parameters (Moisture Damage Indices)

$$ER_1 = \left| \frac{W_{12}}{W_{132}} \right|$$

$$ER_2 = \left| \frac{W_{12} - W_{11}}{W_{132}} \right|$$

$$ER_3 = \left| \frac{W_{12}}{W_{132}} \right| * SSA$$

$$ER_4 = \left| \frac{W_{12} - W_{11}}{W_{132}} \right| * SSA$$

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Bond energy ratios

Adhesive bond energy ratio, ER_4 for aggregate and bitumen

Bitumen	**Bond Energy Parameter ER_4**					
	Aggregates					
	UK-AA	**UK-AB**	**UK-AC**	**UK-AD**	**UK-AF**	**AR-AE**
UK-BA15	0.48	0.27	1.02	0.11	0.34	0.20
UK-BB50	0.46	0.22	0.84	0.10	0.28	0.16
UK-BC100	0.52	0.14	0.61	0.09	0.19	0.10
UK-BD15	0.48	0.21	0.89	0.14	0.29	0.15
UK-BE50	0.62	0.27	1.21	0.16	0.39	0.19
UK-BF85	0.68	0.29	1.28	0.15	0.41	0.21
UK-BG75	0.56	0.20	0.82	0.10	0.27	0.14
UK-BH115	0.50	0.16	0.64	0.09	0.21	0.11
UK-BI60	0.56	0.20	0.82	0.10	0.27	0.15
UK-BJ190	0.39	0.12	0.48	0.08	0.15	0.09
UK-BK37	0.44	0.16	0.62	0.08	0.20	0.12

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- Practical Adhesion Testing
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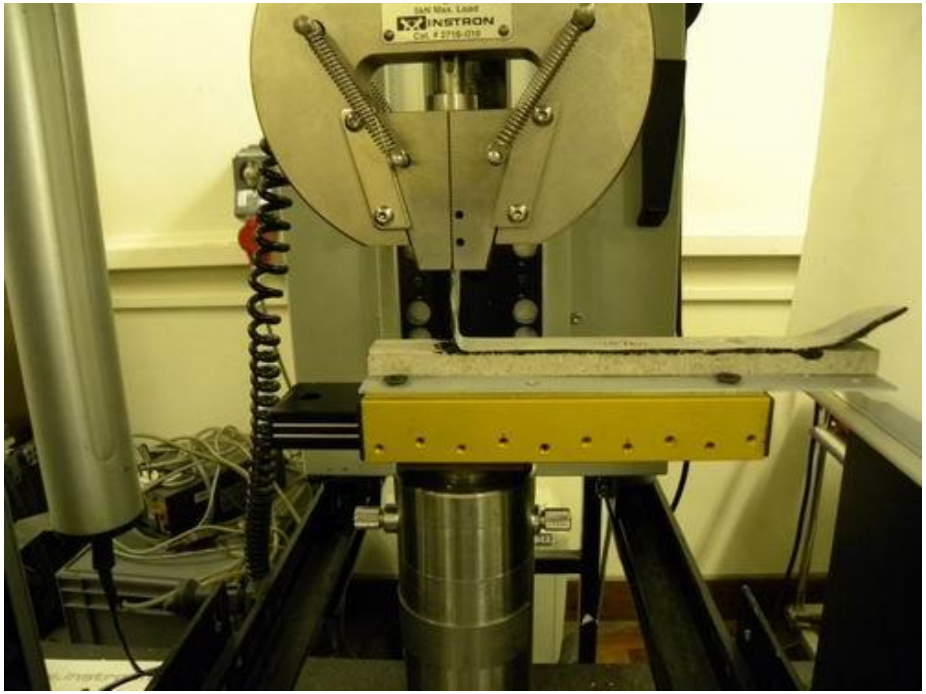
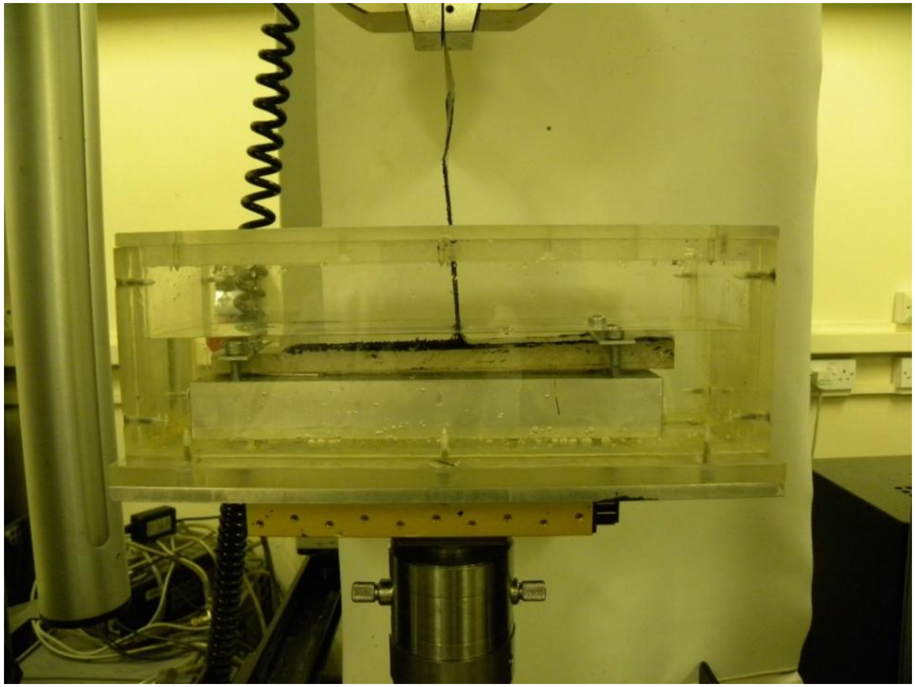
- Concluding Remarks

NTEC

PEEL Fracture Test

- Dry condition
- Wet condition





NTEC

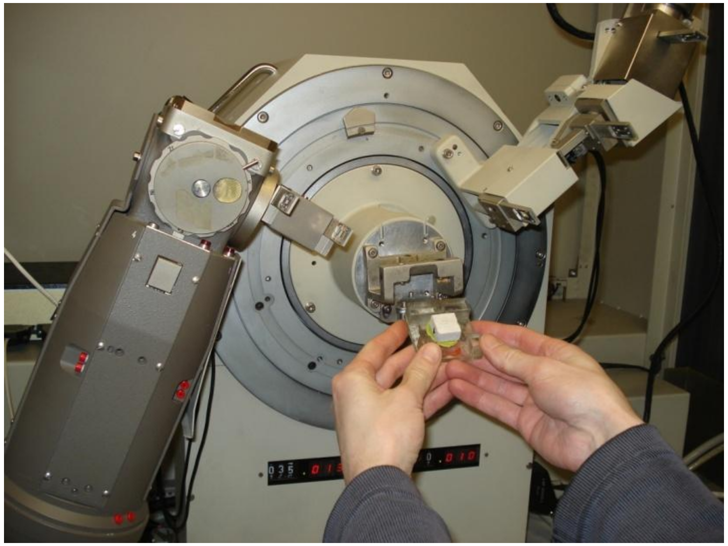
Aggregate Plates Fabrication

NTEC

Aggregate Surface Analysis

- Profilometry
  - Roughness of the crushed and cut aggregate surfaces

- X-ray Diffraction
  - Texture/crystal orientation of the crushed vs cut surface



NTEC

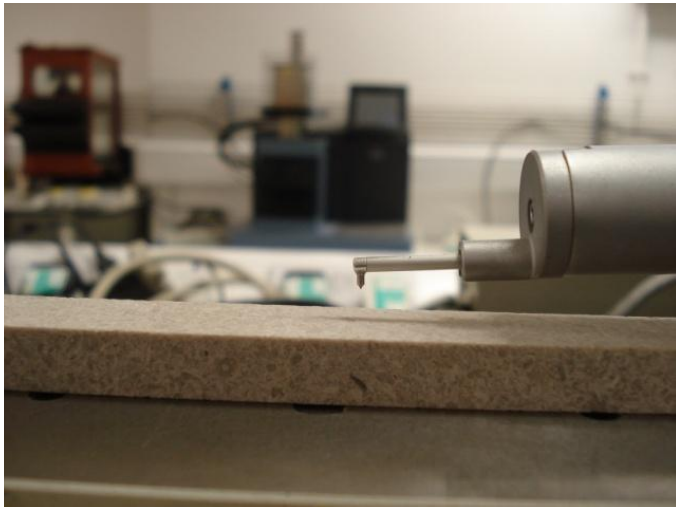
Profilometer

- Roughness Parameter; Ra (µm)

No	Crushed Aggregate		Saw Cut		Water Jet Cut	
	Piece 1	Piece 2	Longitudinal direction	Transverse direction	Longitudinal direction	Transverse direction
1	7.912	8.586	3.866	3.674	4.040	2.879
2	8.589	8.062	3.729	3.235	4.159	2.721

❑ Test Conditions

- Evaluation length = 10mm
- Cut-off/Filter point = 0.8mm & 2.5mm
- Sampling length = 2.5mm
- Pre and post travel = 0.4mm
- Noise filter = 0.008mm



Surface Roughness

- Roughness parameter Ra (µm) with 0.8mm cut-off

Crushed Aggregate	Saw Cut	Water Jet Cut		Sand Blasted	Polished
		Longitudinal direction	Transverse direction		
8.062	3.729	4.159	2.721	5.742	0.346

- Roughness parameter Ra (µm) with 2.5mm cut-off

Crushed Aggregate	Saw Cut	Sand Blasted	Polished
16.285	4.721	14.503	0.429

NTEC

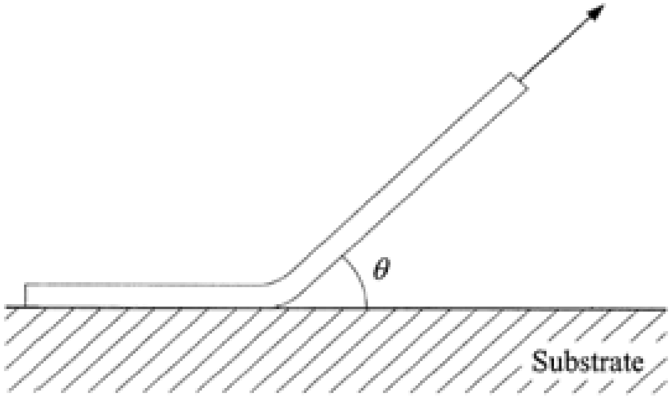
PEEL fracture test

Three components:

•Adhesive: bitumen (UK-BE50)

• Substrate: Stone

• Peel arm: Aluminium film and fabric



The Journal of Adhesion **79**, 2003, 239 – 265.

$$G_A = G_E - G_P$$

$$G_E = \frac{F}{b}(1 - \cos\theta) \qquad \theta = 90^{\circ}$$

- Fully-opened bondline
- Direct observation of the failure of the adhesive layer
- Plastic deformation is taken into account by analysis

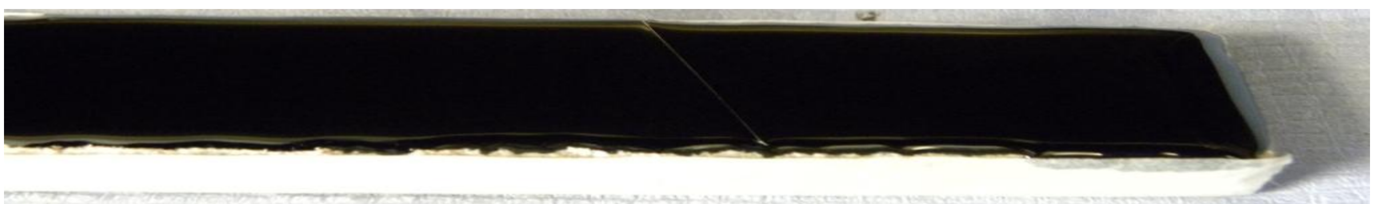
NTEC

Preparation of PEEL specimens

1

2

3



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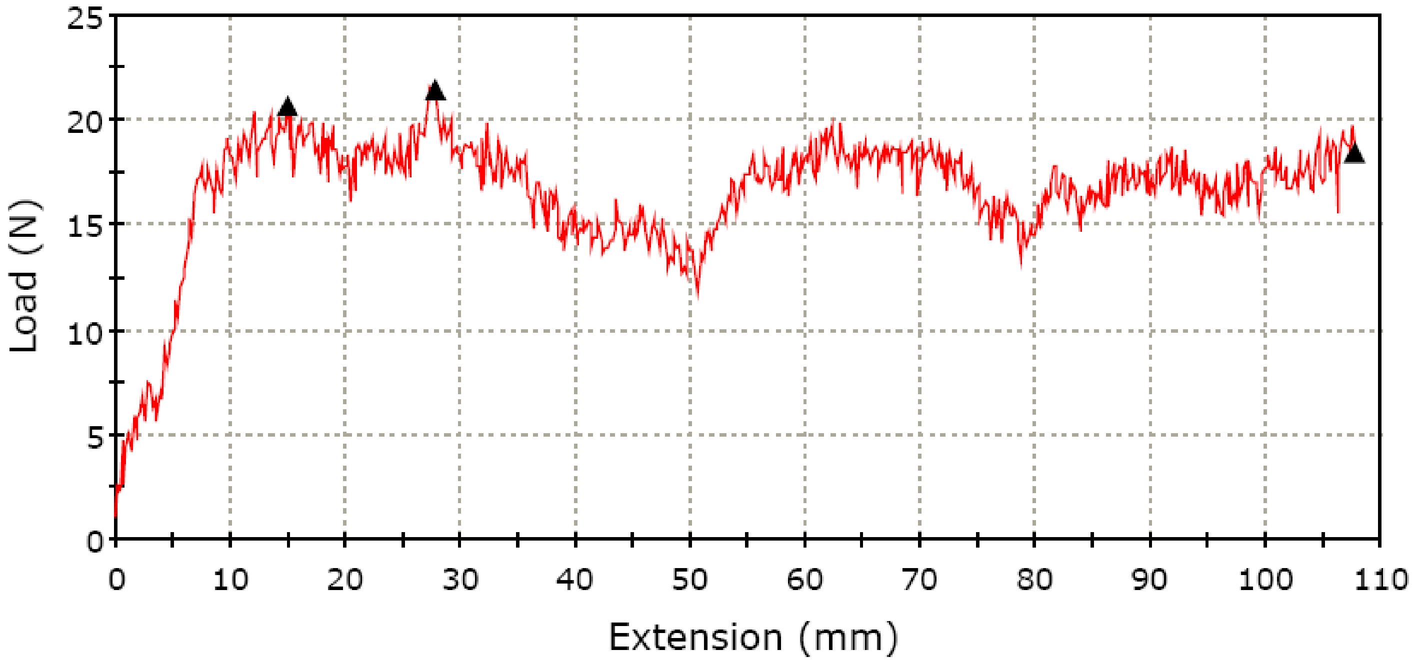
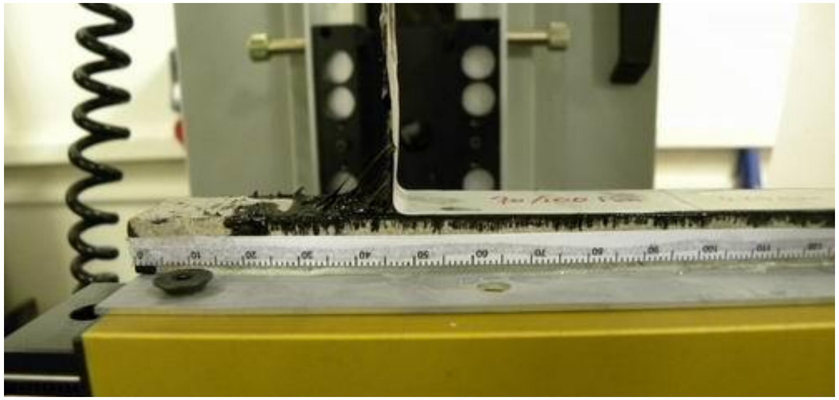
5

NTEC

UK-BF85

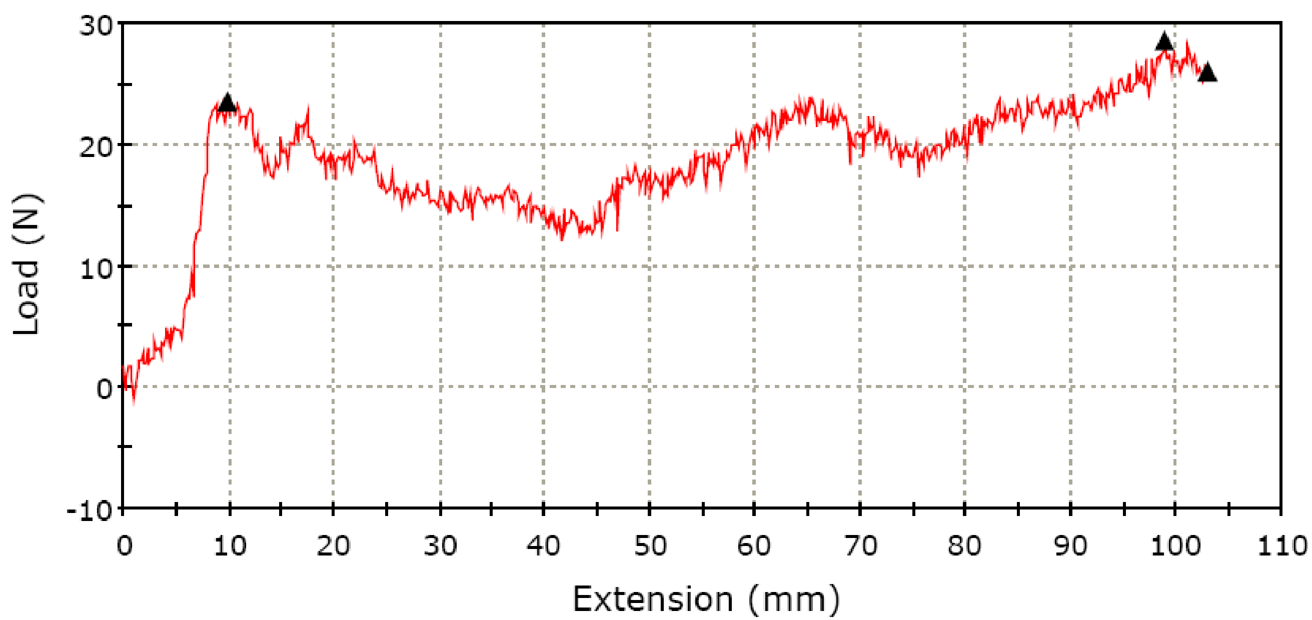


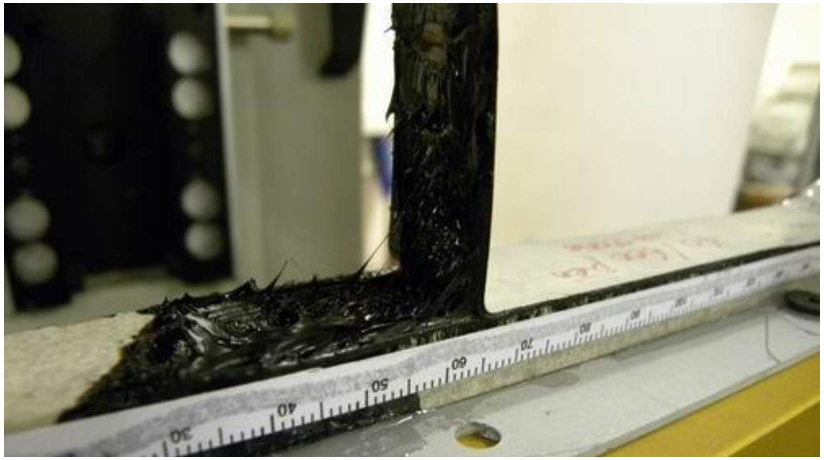


ha = 0.25 mm, h = 0.1 mm, R = 10 mm/min

NTEC

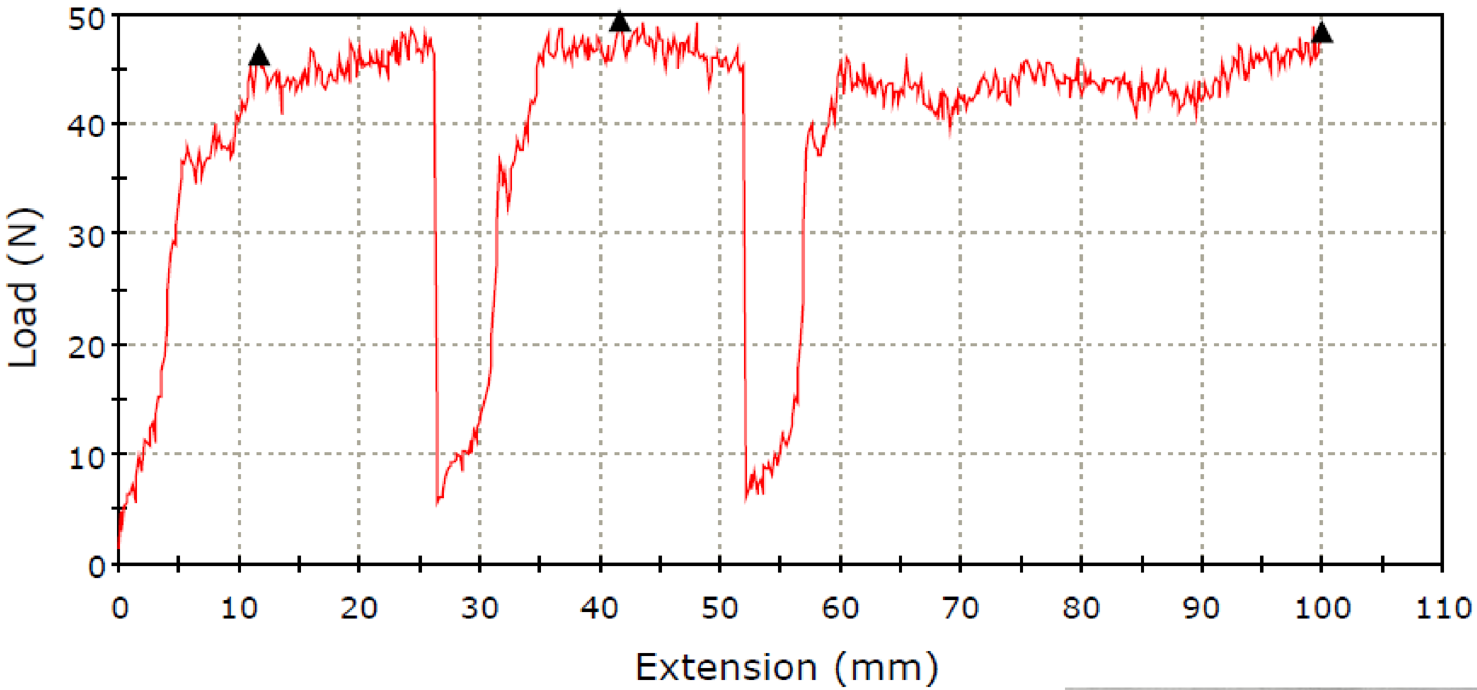
UK-BE50

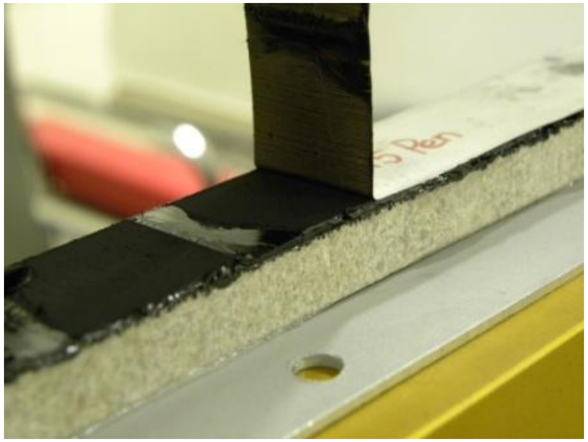


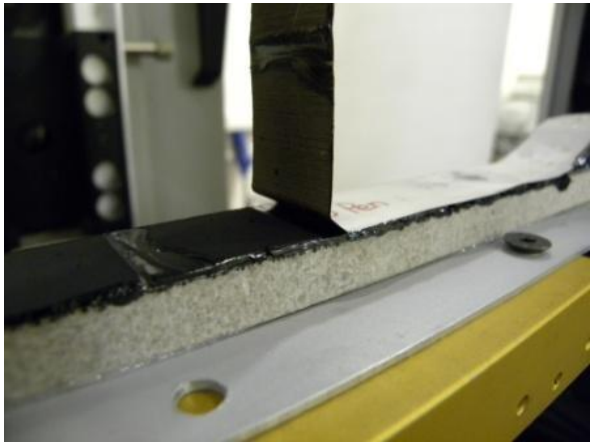


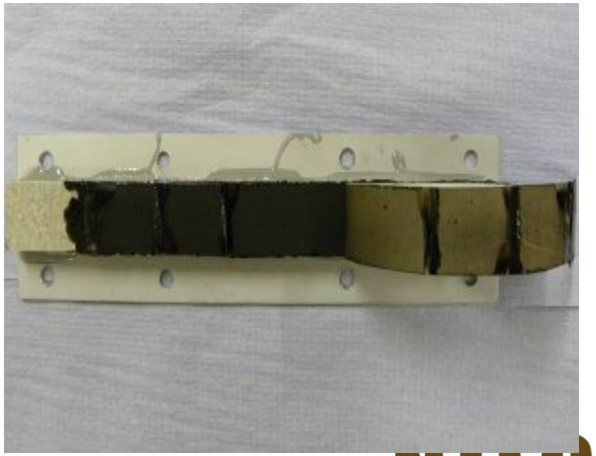
ha = 0.25 mm, h = 0.1 mm, R = 10 mm/min

UK-BD15





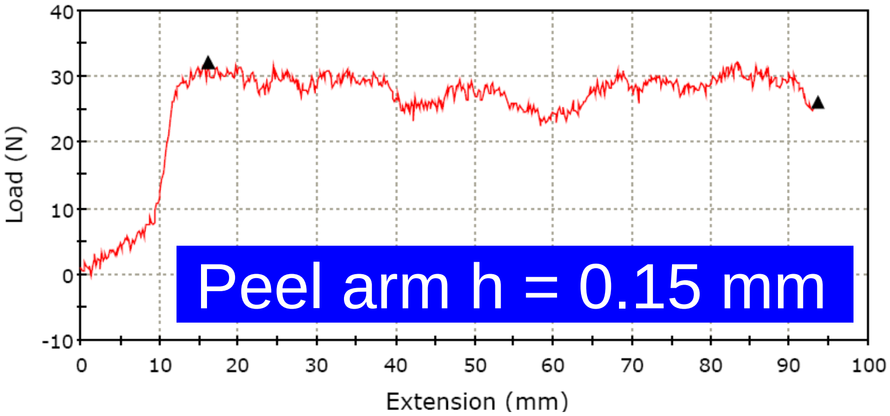


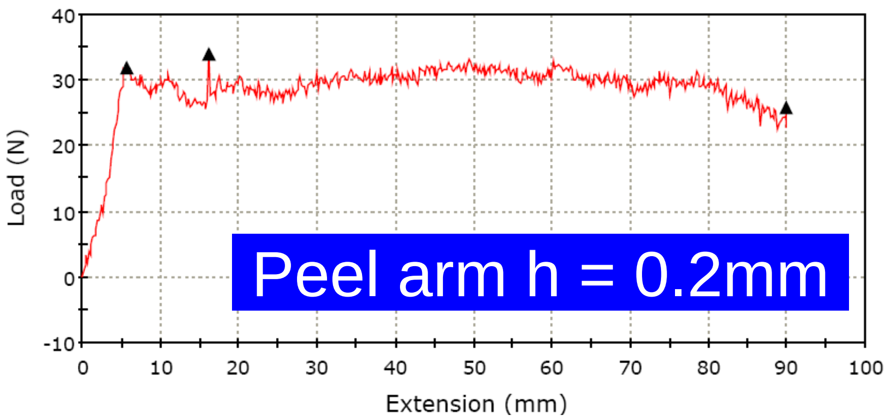


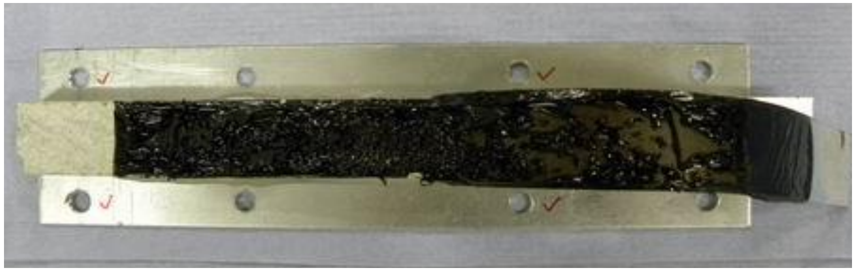
ha = 0.25 mm, h = 0.1 mm, R = 10 mm/min

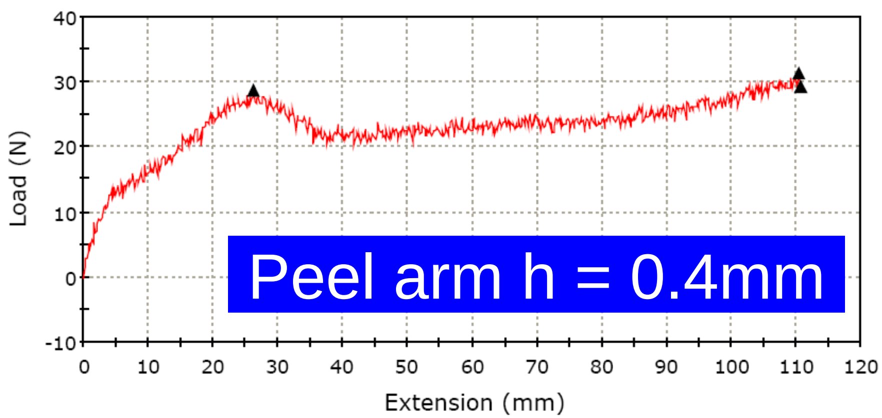
NTEC

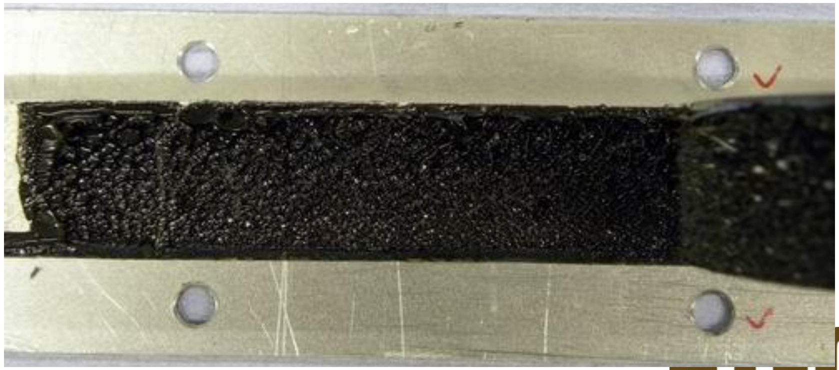
Peel arm thickness (UK-BE50)







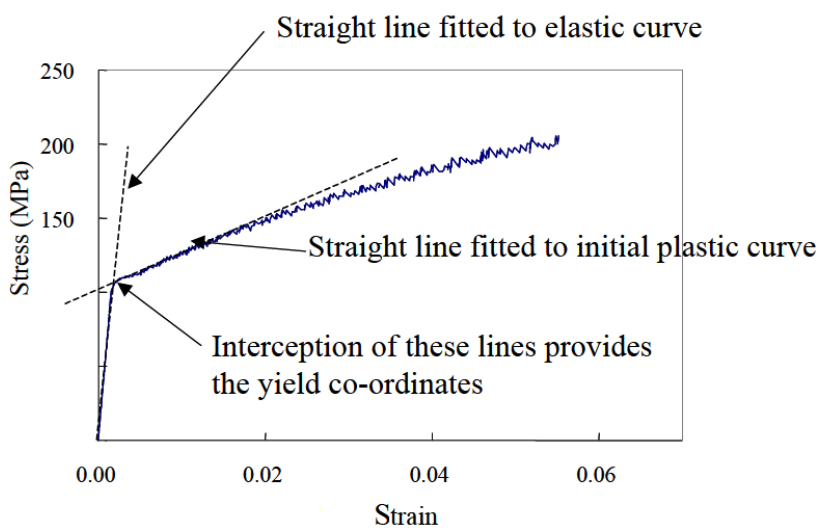




PEEL result analysis

Peel Arm Properties						
	(choose one)		(choose one)			
E GPa	σ_y MPa	ε_y %	n Power Law	α Bilinear	h mm	b mm
70	105			0.1	0.15	20

Adhesive Layer		Test Parameters		Maximum Stress (optional)
h_a mm	E_a GPa	P N	θ deg	σ_{max} MPa
0.25	0.000821	17	90	



$$G_c = G_{tot} - G_d$$

Results										
G_C J/m²	G_d J/m²	G_{tot} J/m²	G J/m²	Correction %	$\sigma_{max\,(o)}$ MPa	θ_0 deg	k_o	R_o mm	ε_{max} %	Loading / Unloading condition
516	334	850	850	39.35	1.84	31.54	12.43	4.02	1.87	3

NTEC

PEEL fracture tests

Fracture energy of different bitumen

Bitumen	Peel arm thickness h (mm)	Adhesive thickness h_a (mm)	G (J/m^2)	Comments
UK-BF85	0.15	0.25	516	Cohesive failure
UK-BE50	0.15	0.25	528	Cohesively failure
UK-BD15	0.15	0.25	1378	Adhesively failure

Effect of peel arm thickness

Bitumen	Peel arm thickness h (mm)	Adhesive thickness h_a (mm)	G (J/m^2)	Comments
UK-BE50	0.15	0.25	912	Cohesively failure
UK-BE50	0.20	0.25	904	Cohesively failure
UK-BE50	0.40	0.25	497	Cohesively failure

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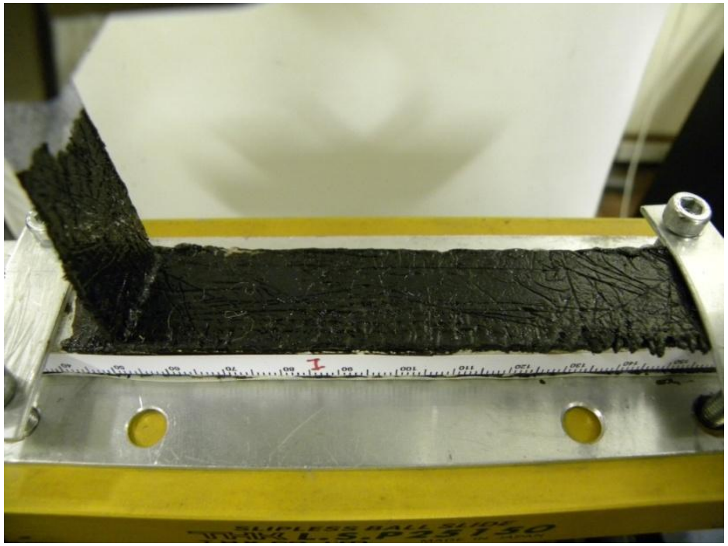
Fabric peel arm

1



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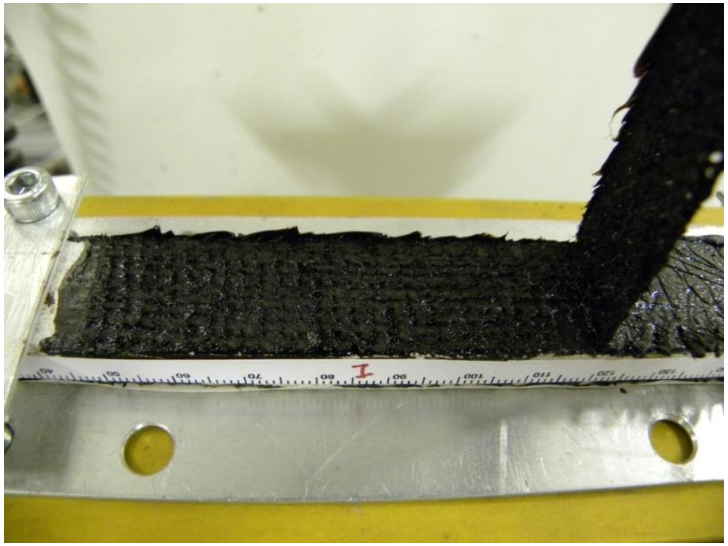
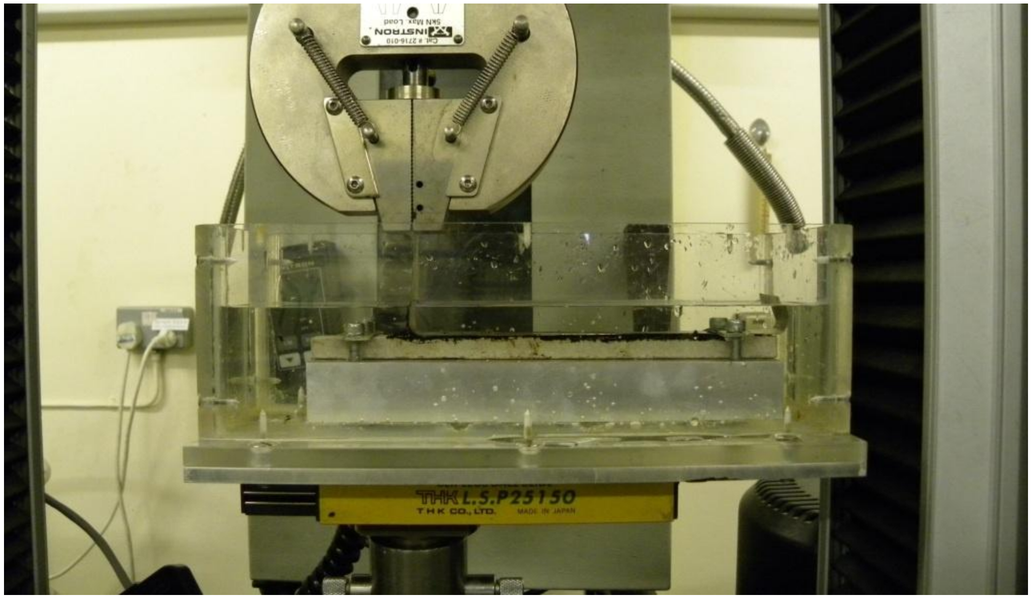
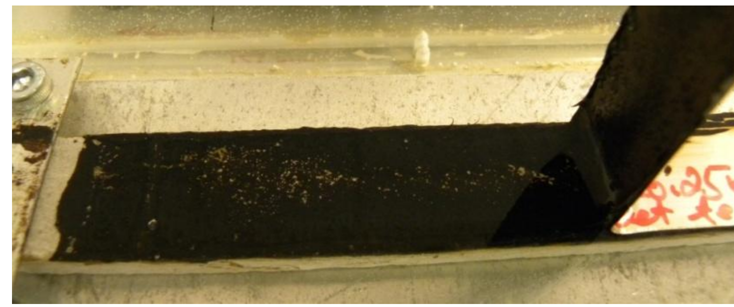
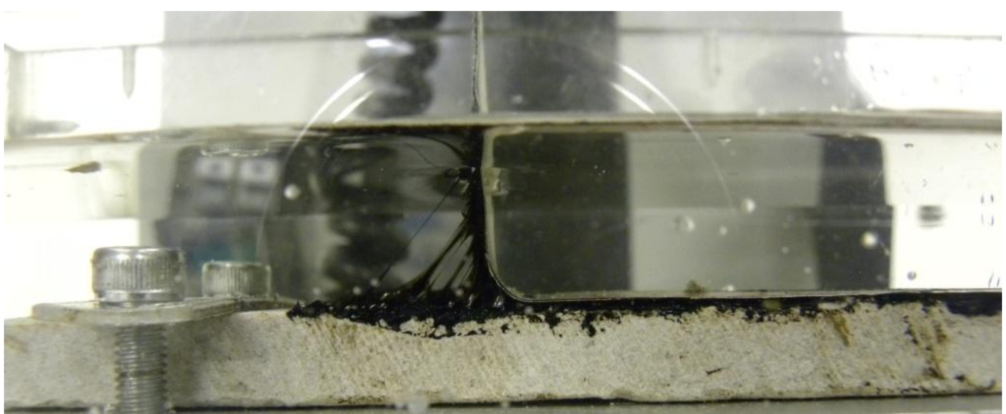


4

Submerged Peel Test

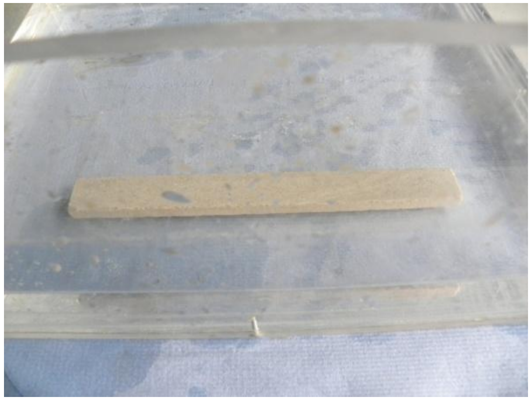


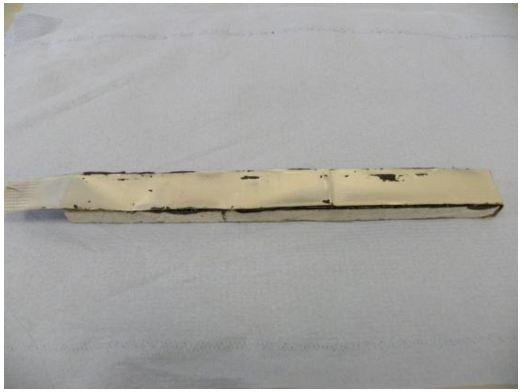




Methods to introduce water

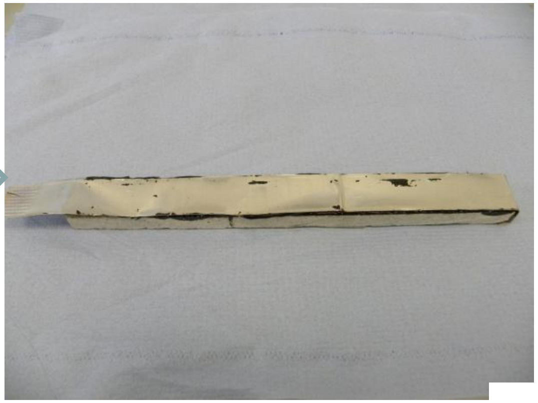
Pre-bonding treatment (1 – 14 days)





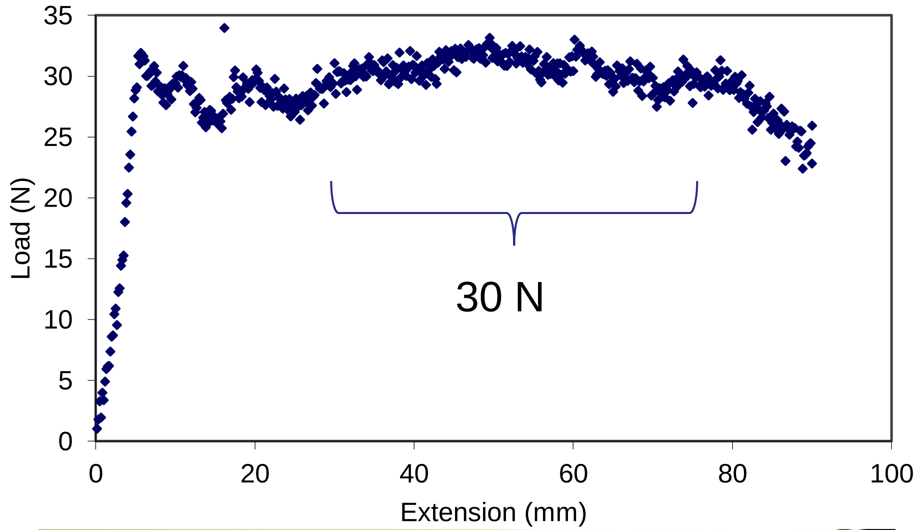
As-made substrate Submersed in a water bath Bonded joint

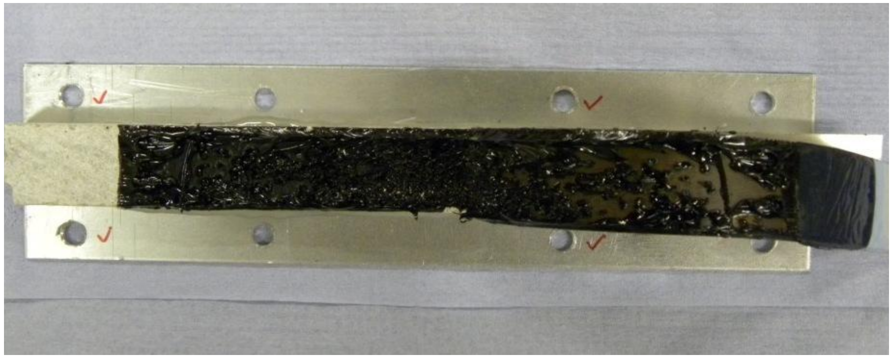
Post-bonding treatment (1 – 14 days)

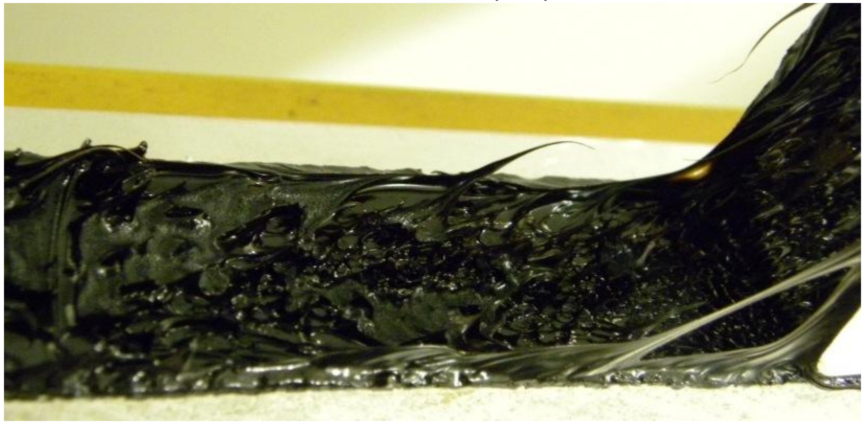


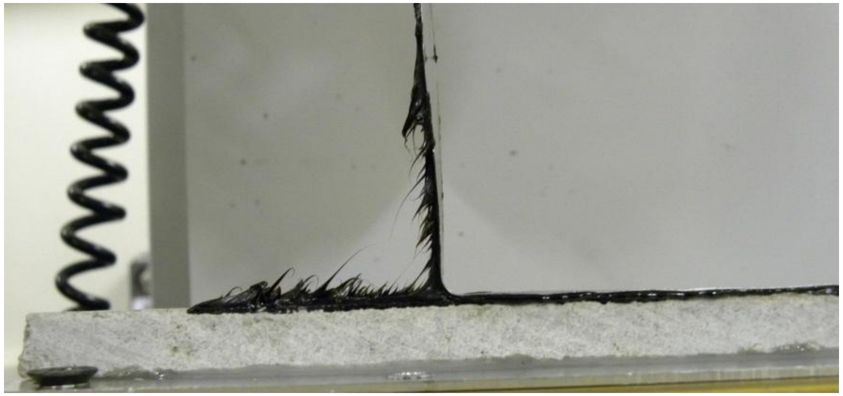
As-made substrate Bonded joint Submersed in water bath

Dry specimen





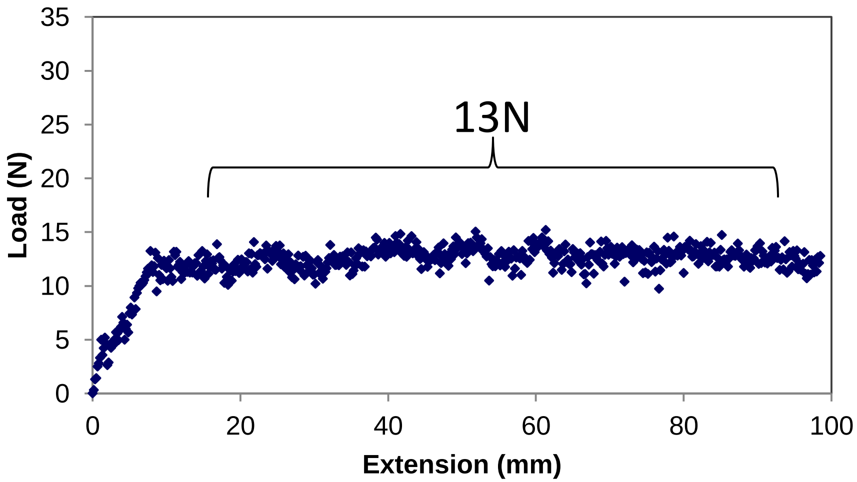


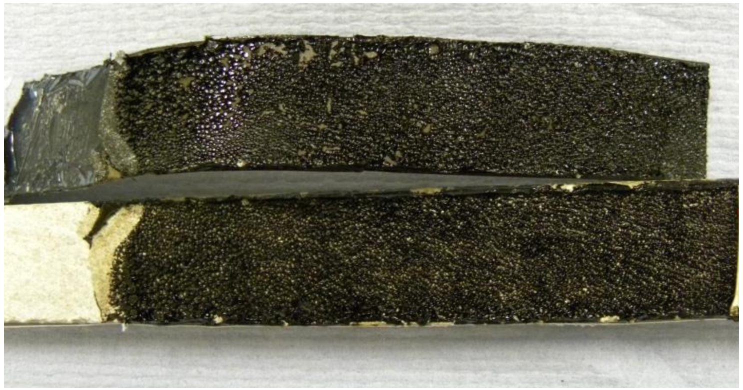


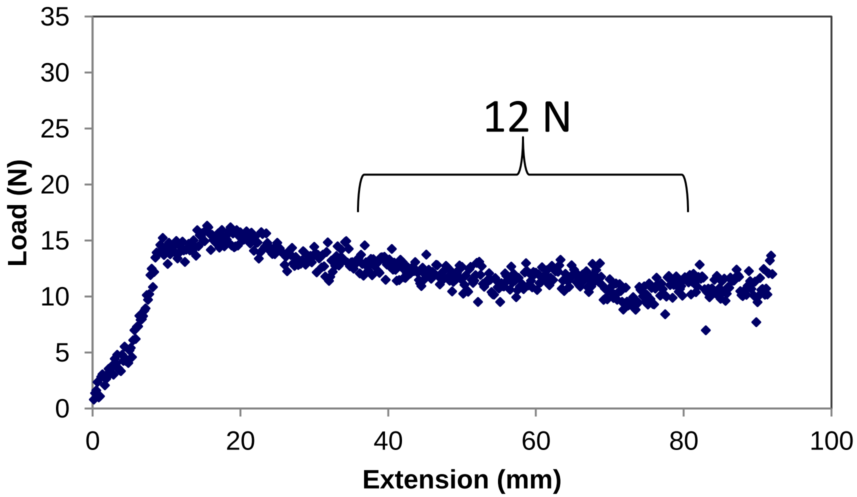
Peel arm thickness h = 0.2 mm

NTEC

Wet specimens (6 hours in water)



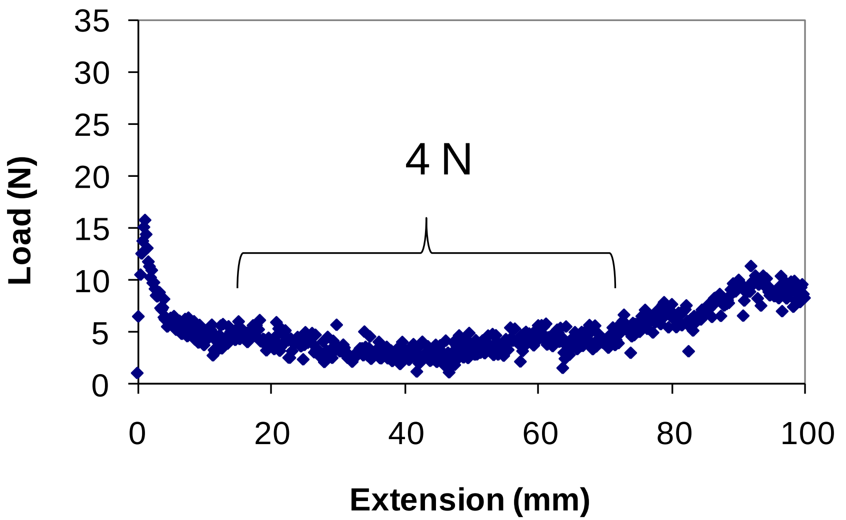


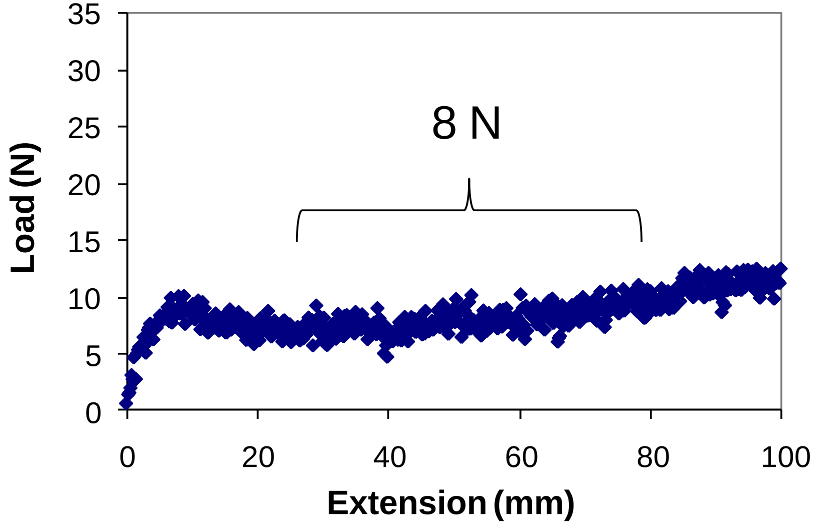


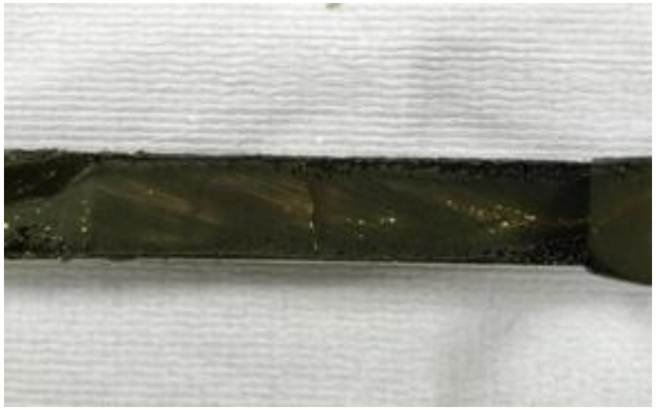
Peel arm thickness h = 0.2 mm

NTEC

Wet specimens (3 days in water)



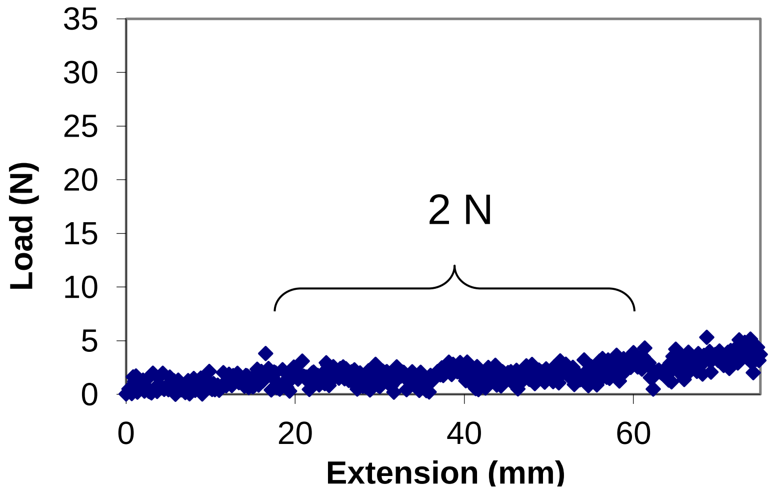


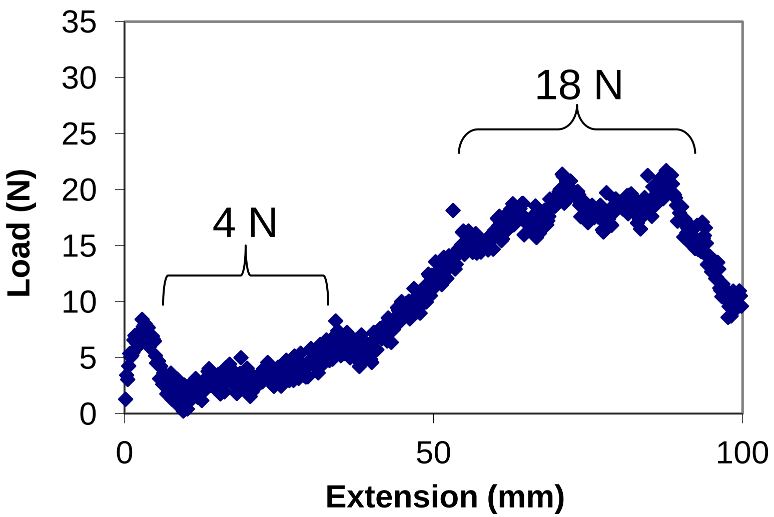


Peel arm thickness h = 0.2 mm

NTEC

Wet specimens (7 days in water)



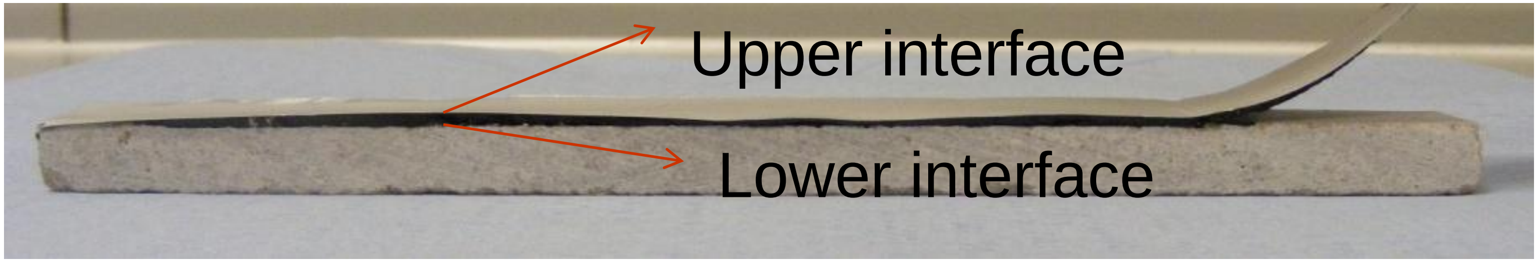


Peel arm thickness h = 0.2 mm

NTEC

Table of fracture energies

		P/b (N/m)	G_A (J/m^2)	Comments
Dry specimens	h = 0.15 mm	1400	326	Upper interface/ cohesive
	h = 0.2 mm	1500	336	Upper interface/ cohesive
	h = 0.4 mm	1150	226	Upper interface/ cohesive
Wet specimens h = 0.2 mm	0 day	1500	336	Upper interface/ cohesive
	0.25 day	625	126	Cohesive/ lower interface
	1 day	300	57	Lower interface
	3 days	300	57	Lower interface
	5 days	375	72	Lower interface
	7 days	80	32	Lower interface
	14 days	400	76	Lower interface



NTEC

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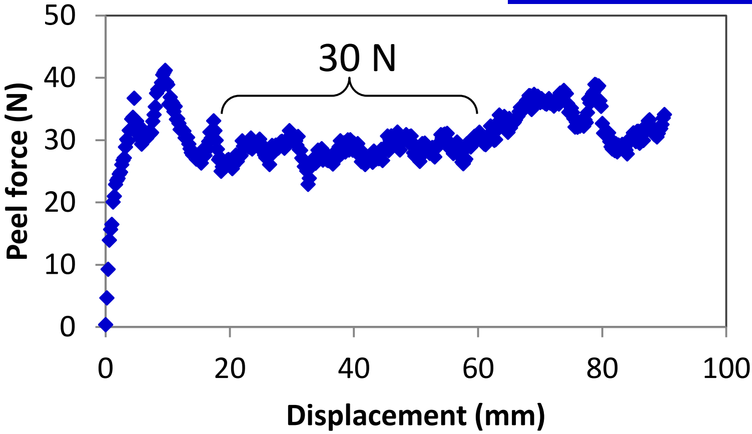
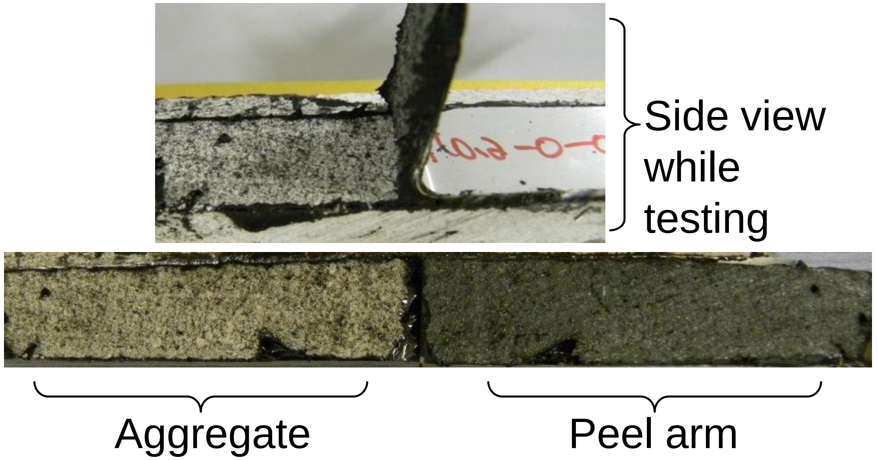
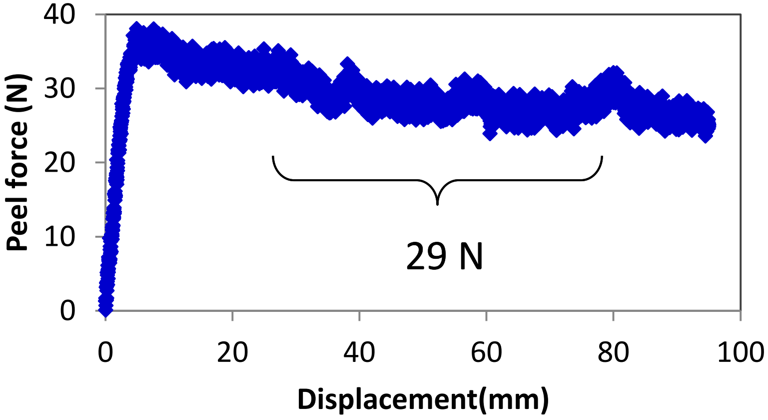
NTEC

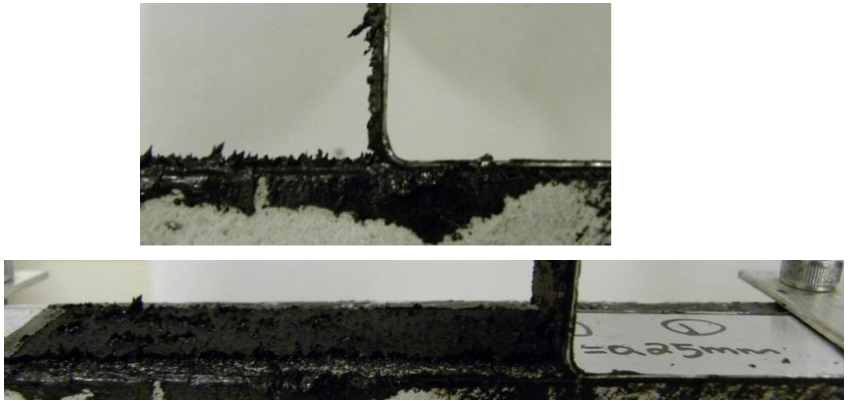
UK-BD15 Dry Conditions

A lower test speed: R = 2 mm/min









NTEC

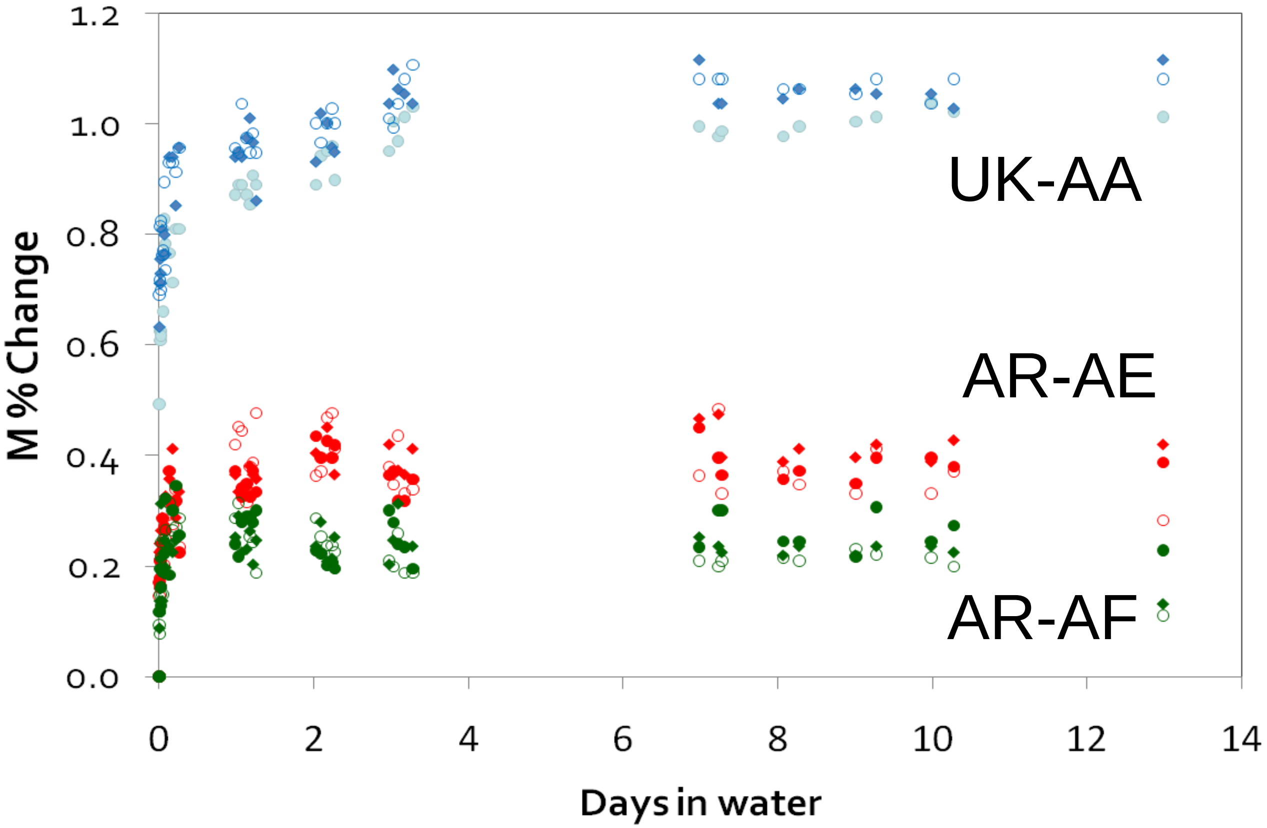
Different bitumens

UK-BF85		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	12	307	Cohesive failure
Pre-bond conditioning	1 day	11	253	Mainly cohesive failure, lower-interfacial failure
	7 days	7	160	Mainly cohesive failure, lower-interfacial failure
Post bond conditioning	1 day	-	-	More tests will be carried out
	7 days	8	188	Mainly Cohesive, lower-interfacial failure

UK-BE50		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	16	438	Cohesive failure
Pre-bond conditioning	1 day	6	134	Mainly lower-interfacial failure
	7 days	2	46	Mainly lower-interfacial failure
Post bond conditioning	1 day	9	216	Cohesive/ lower interfacial failure
	7 days	2	46	Cohesive/ lower interfacial failure

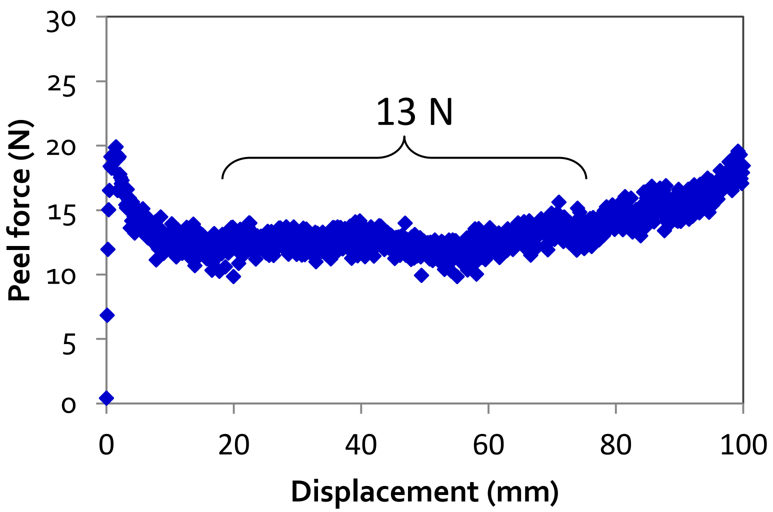
UK-BD15		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	30	953	Upper/lower-interfacial, cohesive failure
Pre-bond conditioning	1 day	14	378	Mainly lower-interfacial failure
	7 days	10	245	Mainly lower-interfacial failure
Post bond conditioning	1 day	5	405	Lower-interfacial failure
	7 days	9	216	Lower-interfacial failure

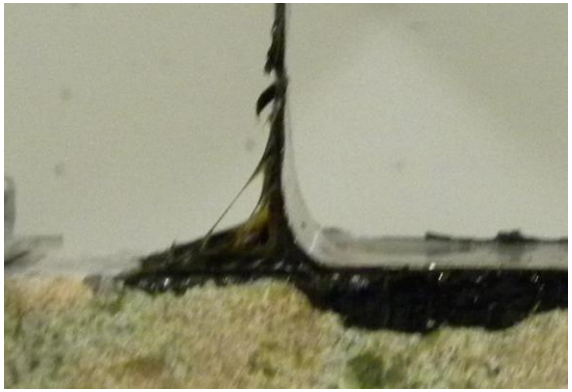
Different water-absorbent substrates

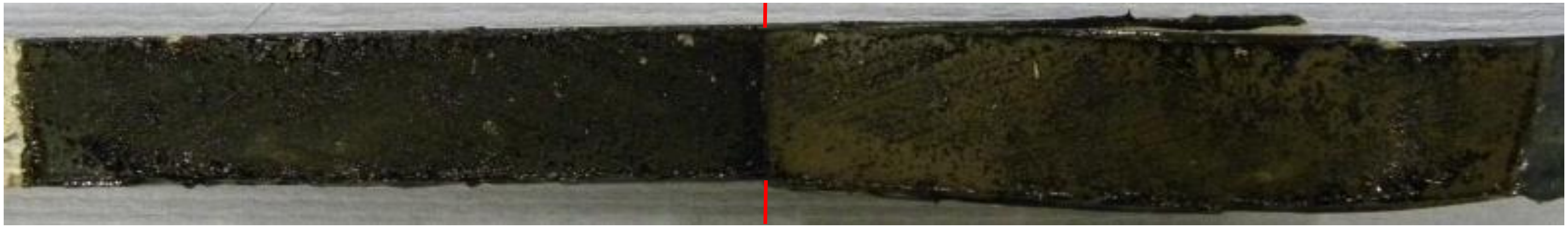


NTEC

AR-AE (Dry specimen)

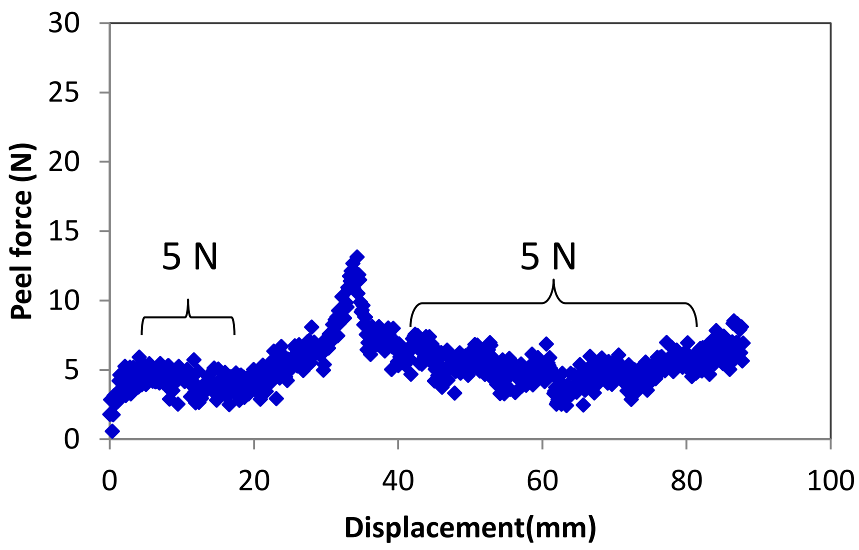


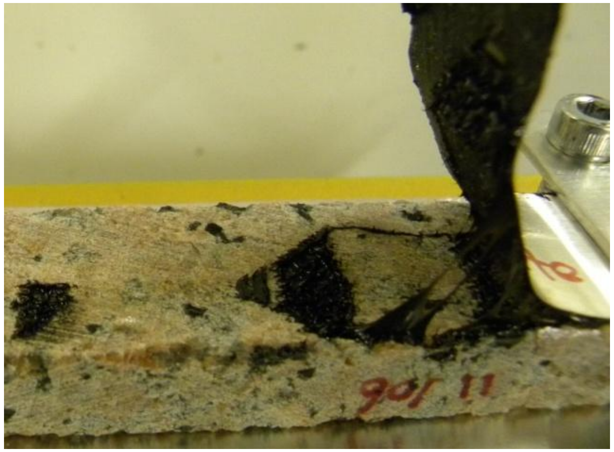


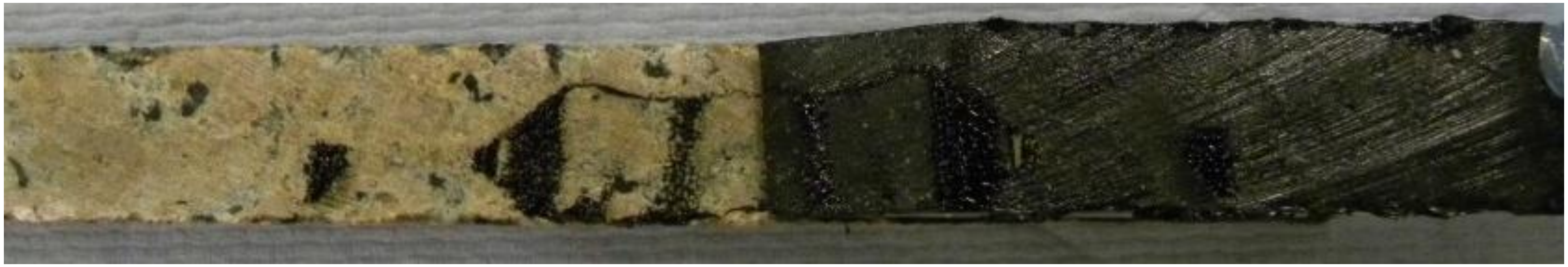


NTEC

AR-AE (3 days pre-bond conditioning)







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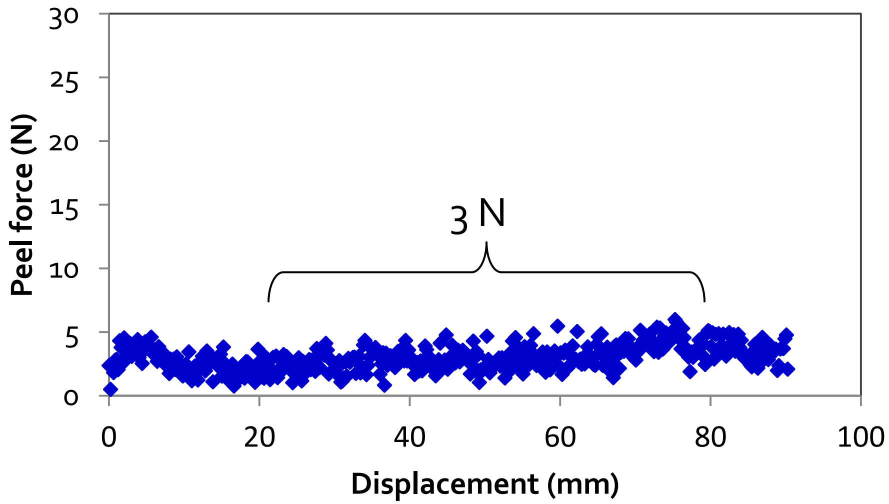
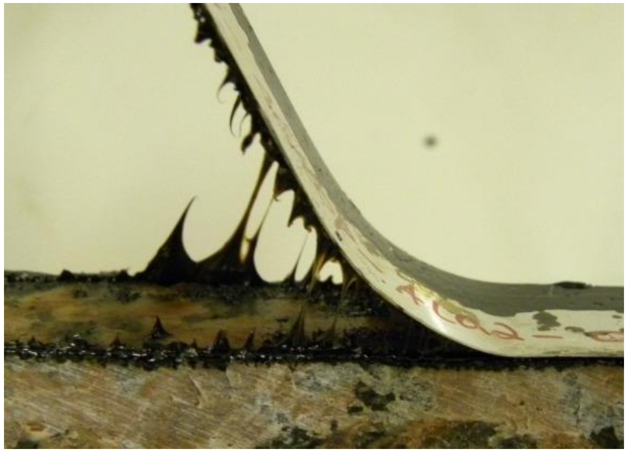
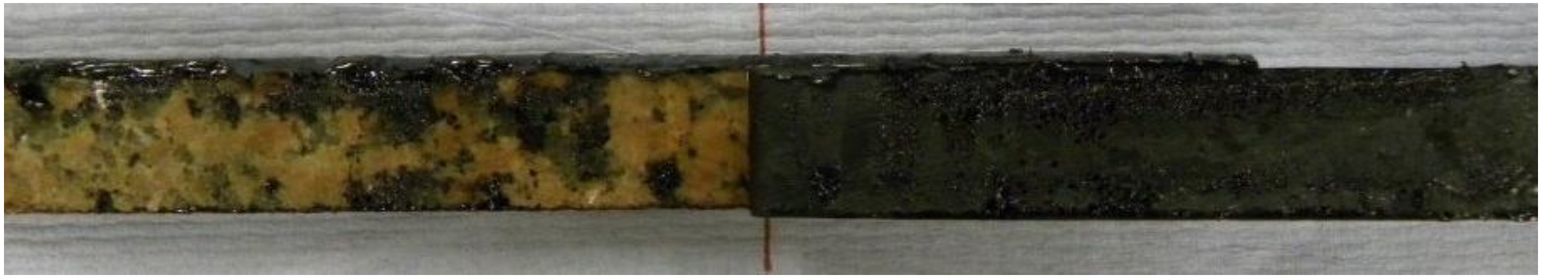
AR-AE (3 days post-bond conditioning)







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Different aggregates

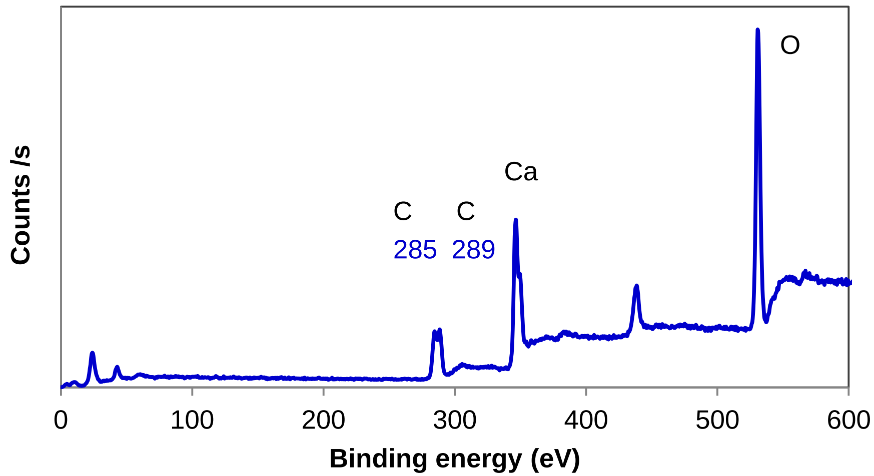
AR-AF		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	14	371	Cohesive failure
Pre-bond conditioning	1 day	12	318	Mainly Cohesive failure
	3 days	11	275	Mainly Cohesive failure
Post bond conditioning	1 day	6	127	Mainly Cohesive failure
	3 days	5	109	Mainly Cohesive failure

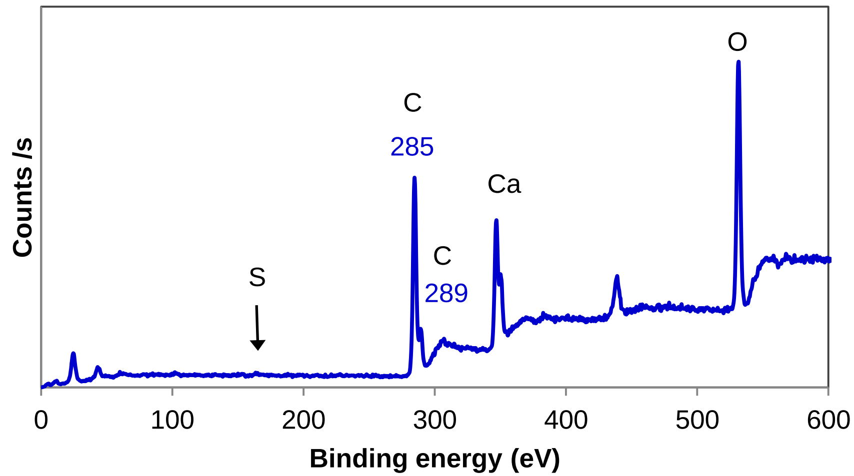
UK-AA		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	16	438	Cohesive failure
Pre-bond conditioning	1 day	6	134	Mainly lower-interfacial failure
	3 days	4	86	Mainly lower-interfacial failure
Post bond conditioning	1 day	9	216	Cohesive/ lower interfacial failure
	3 days	3	65	Cohesive/ lower interfacial failure

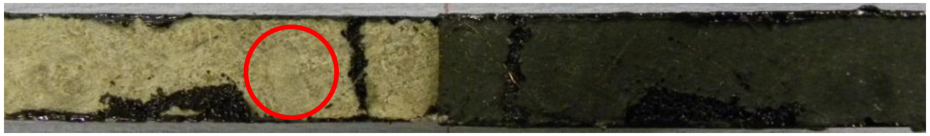
AR-AE		P (N)	G_A (J/m^2)	Comments
Dry specimens	0 day	13	338	Cohesive failure
Pre-bond conditioning	1 day	9	223	Cohesive, lower-interfacial failure
	3 days	5	109	Lower-interfacial failure
Post bond conditioning	1 day	6	136	Cohesive/ lower interfacial failure
	3 days	3	65	Mainly Lower-interfacial failure

XPS Spectrum (Loci of Fracture)

UK-AA with UK-BE50







- Pre-bond conditioned
- Post-bond conditioned

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Outline

- Background and Motivation
- Adhesion Theories (Surface Free Energy)
- SFE Test Methods
- Intrinsic Adhesion and Energy Parameters
- Practical Adhesion Testing
- Adhesive Fracture Energy and Loci of Fracture
- Concluding Remarks

Conclusions and Recommendations

- Fundamental concepts of surface free energy, thermodynamics, intrinsic adhesion and peel adhesion can be used to access dry and wet bitumen-aggregate systems
- Combination of vapour sorption and contact angle SFE approaches
- Energy ratios need to consider physical properties (SSA) as well as physico-chemical
- Modified peel test used to determine fracture energy for dry and moisture conditioned bitumen-aggregate combinations

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Conclusions and Recommendations

- Need to correlate intrinsic and practical adhesion (cohesion) results with both laboratory (SATS/AASHTO T283) as well as field performance of various asphalt mixtures

- Effect of moisture damage performance enhancers (anti-stripping additives/agents, modified binders, etc) need to assessed using screening tests

- Need to broaden database to include wider spectrum of UK road pavement (asphalt) materials

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Adhesion and Moisture Damage Characterisation of Asphalt Mixtures

Thank you

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