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D. V. Boger Research Interests

- Viscoelastic Fluid Mechanics
- Particulate Fluids
- Environmental Rheology
- Hydrocolloids

D.V. Boger

Particulate Fluids Processing Centre
Department of Chemical & Biomolecular Engineering
The University of Melbourne
Victoria Australia

Uhvhdufk
Uhvhdufk
Uhvhdufk#0

11Frqyhuvlrq#ri#Prqh|#lqwr#Nqrzohgjh

Lqqrydwlrq
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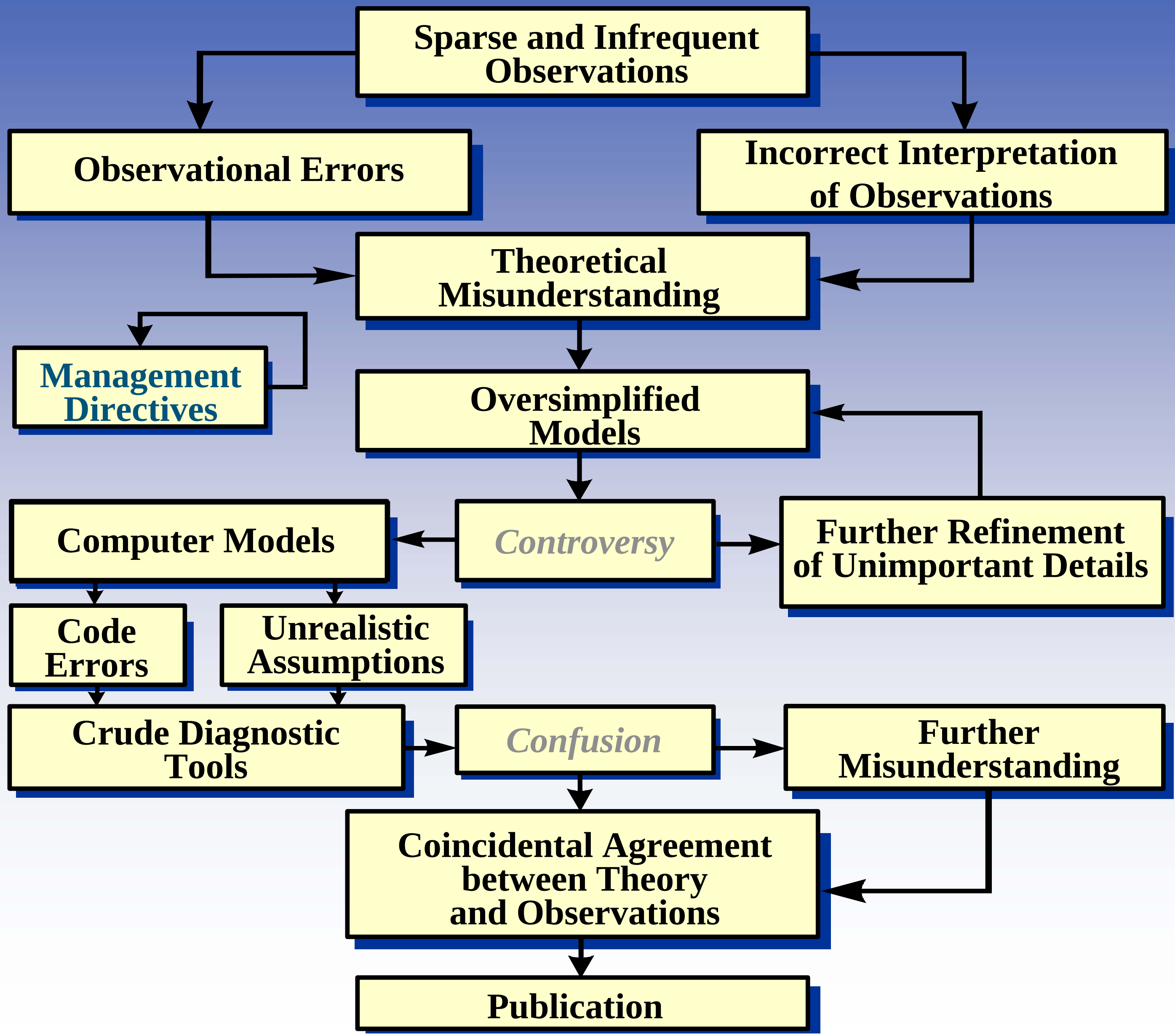
Lqqrydwlrq#0

11Frqyhuvlrq#ri#Nqrzohgjh#lqwr#Prqh|

The Course of Science



The Rheology and Surface Chemistry of Slurries

David V Boger
Laureate Professor
The University of Melbourne
Australia

Particulate Fluids – Suspensions

- Settling Suspensions
- Non-Settling Suspensions

Ratio of Time Scales = N_{Se}

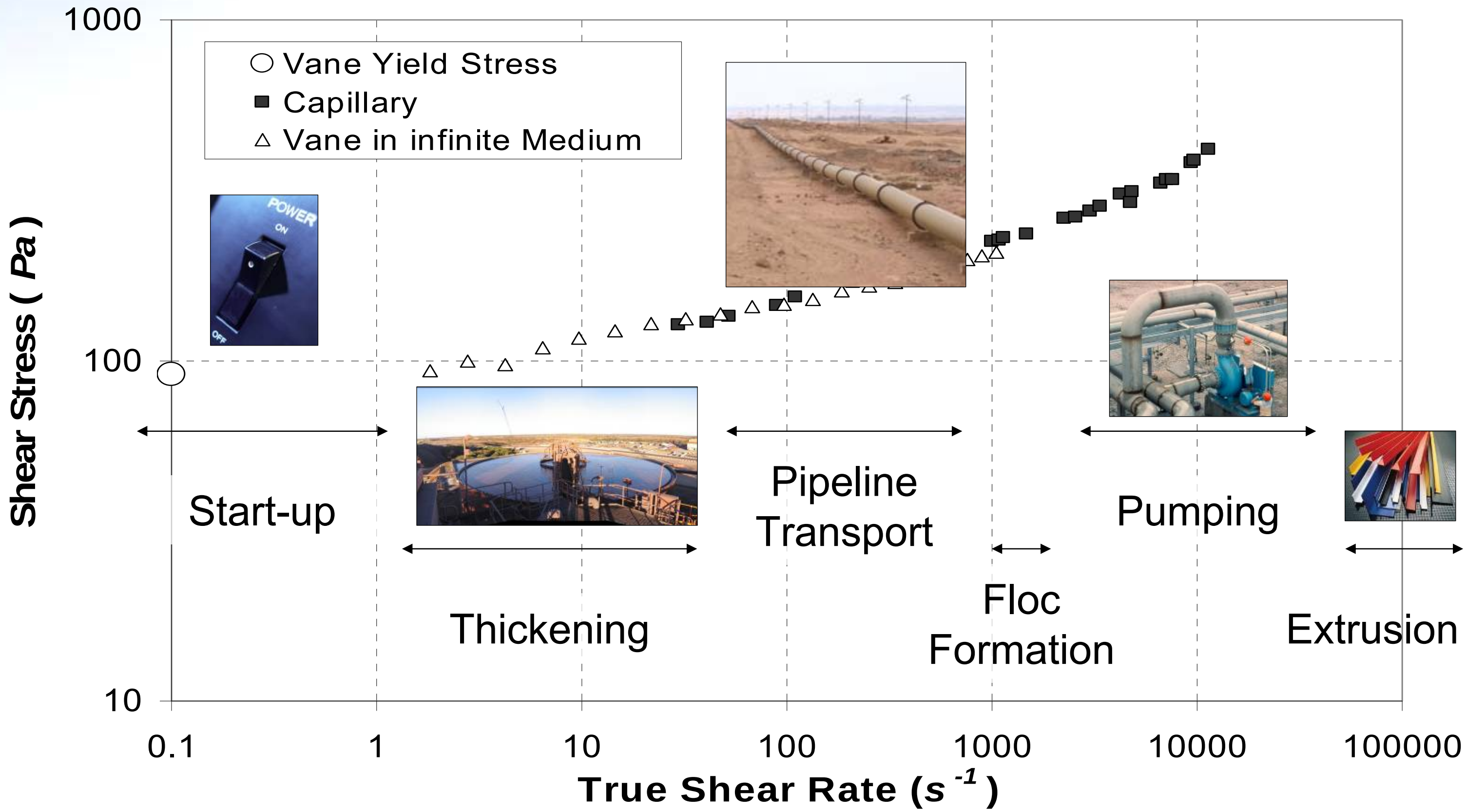
$$N_{Se} = \frac{\tau}{t_S}$$

τ = Characteristic time of the process

t_S = Characteristic time of settling

N_{se} <<1 Non-Settling (Rheology)

Why do we want to Characterise Rheology?



Bauxite Residue Disposal

1974 - Alcoa of Australia (Consulting)
1978 - G. Sarmiento (Ph.D)
1983 - Q.D. Nguyen (Ph.D - Alcoa)
1986 - N.J. De Guingand (M.Eng.Sc - Alcoa)
1992 - PROBLEM SOLVED ?
1993 - N. Pashias (Ph.D - Alcoa)
2000 - F. Sofra (Ph.D - Alcoa)
2005 - D. Cooling (Ph.D - Alcoa)

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Exploiting the Rheology of Mineral Tailings

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Environmental Rheology

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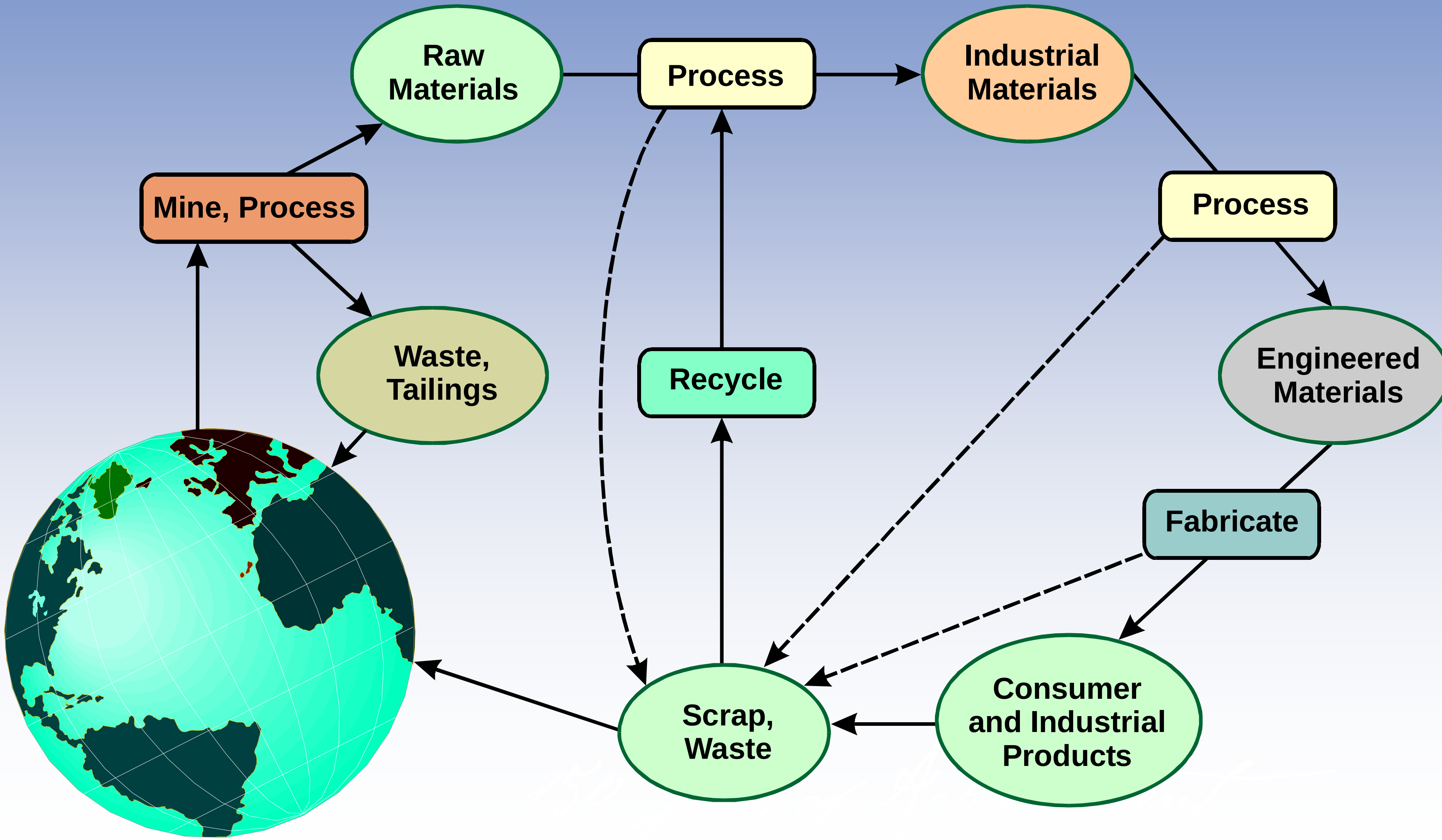
Department of Chemical & Biomolecular Engineering
The University of Melbourne
Victoria Australia

Sustainability, Recycling and Environmental Modelling



Escondida

D. V. Boger

BHP Billiton Fellow


'94 3 3

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The Canadian Oil Sands Industry

"By 2010 the oil sands industry will be producing about one million barrels of oil per day from surface mined oil sands. This equates to about one million cubic metres of coarse tailings deposit per day and 0.2 to 0.3 million cubic metres of fine tailings per day.
To date the industry has produced 400 million cubic metres of fine tailings."

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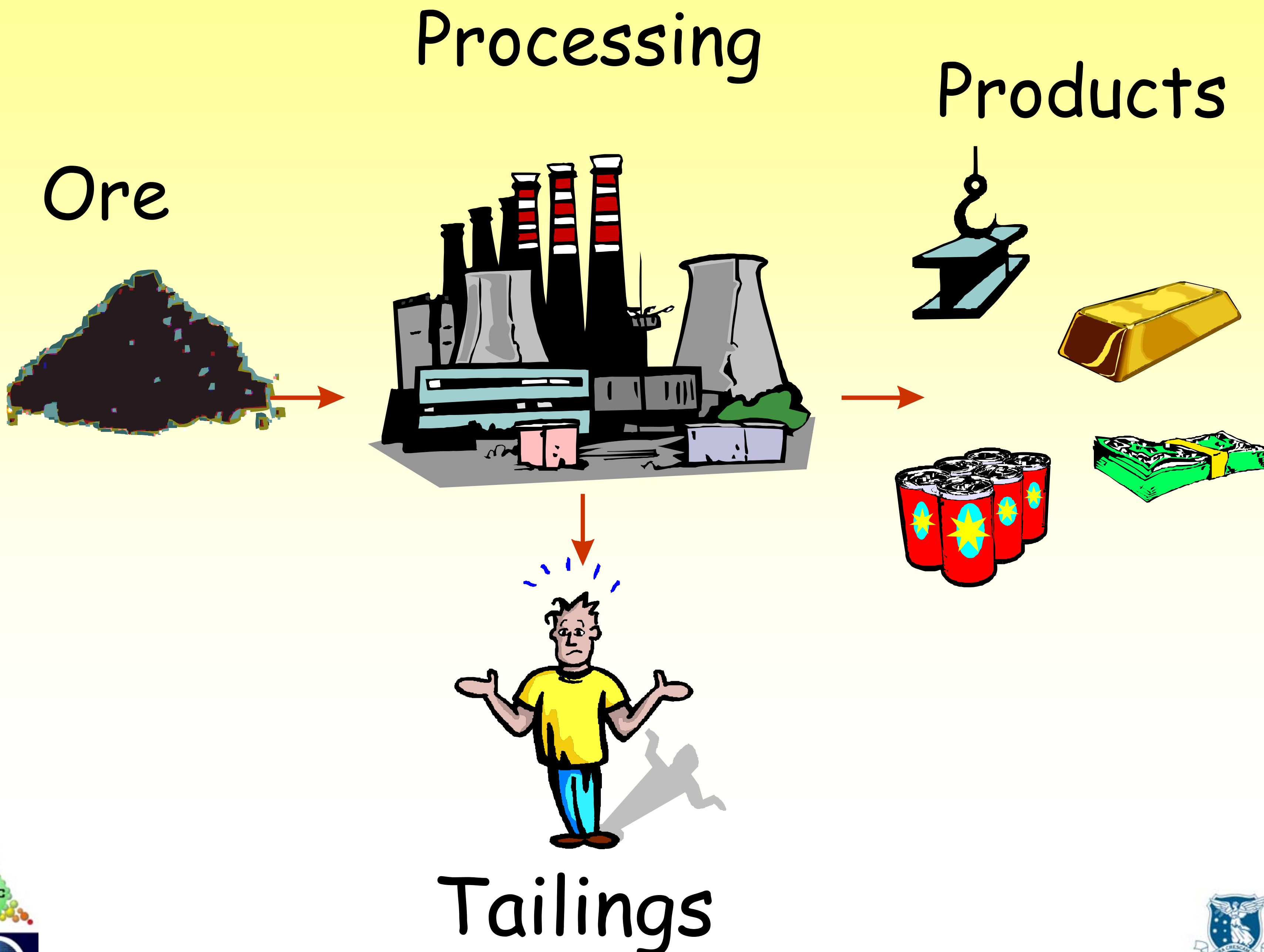
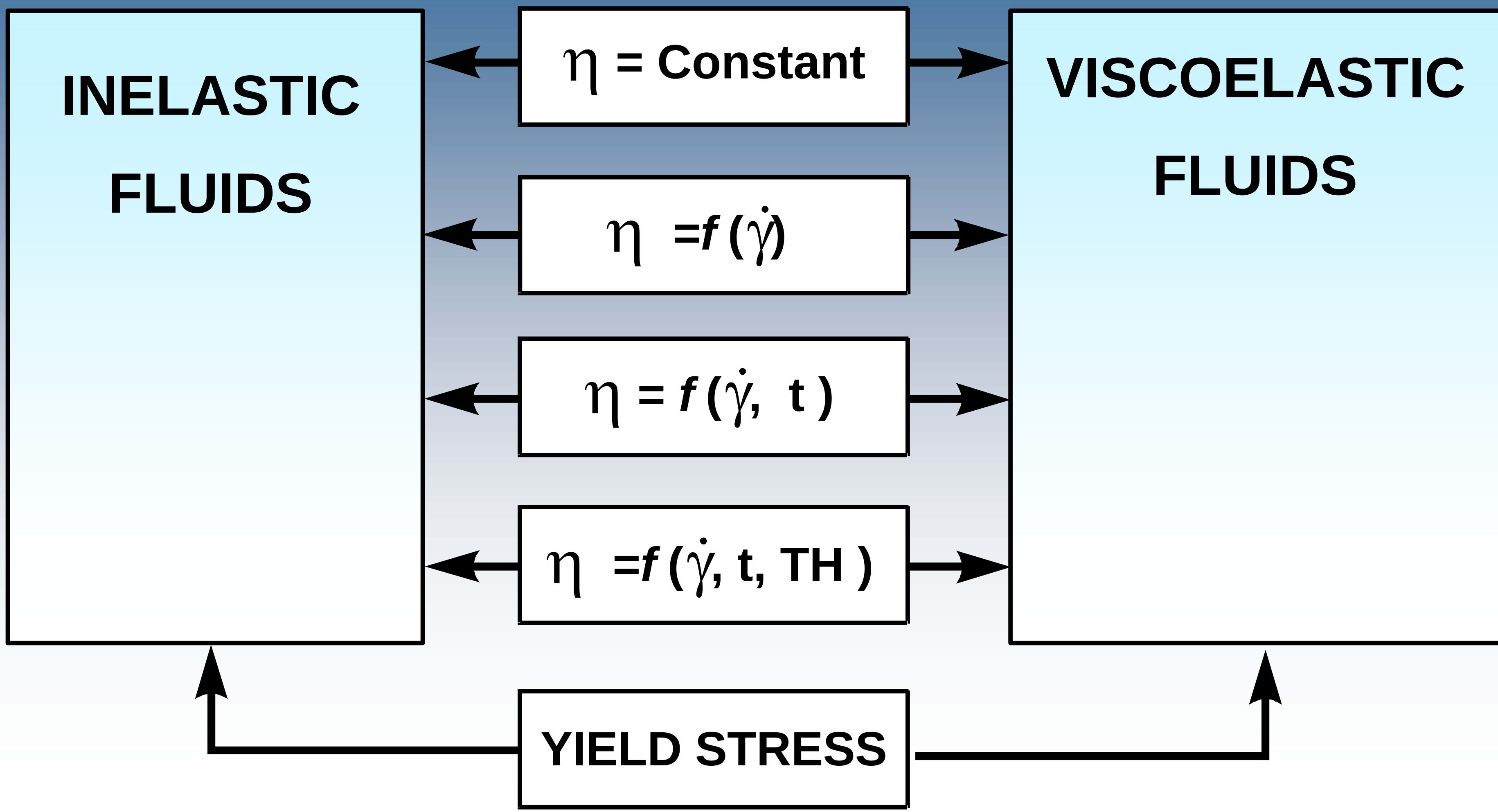
Oil Sands Tailings Deposition


Processing
Products
Ore
Tailings


INELASTIC FLUIDS
η = Constant
$\eta = f(\dot{\gamma})$
$\eta = f(\dot{\gamma}, t)$
$\eta = f(\dot{\gamma}, t, TH)$
VISCOELASTIC FLUIDS
YIELD STRESS

Rheometry

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Developments motivated by applications in minerals industry

- The Vane Yield Stress Rheometer
  (J. Rheol., 27, 321, 1983; and 29, 335, 1985)

- The Conical Slump Test for Yield Stress Measurement (50 cent Rheometer)
  (J. Rheol., 40, 1119, 1996)

- The Bucket Rheometer
  (J. Rheol. *In press*, 2007)

Yield Stress Measurement

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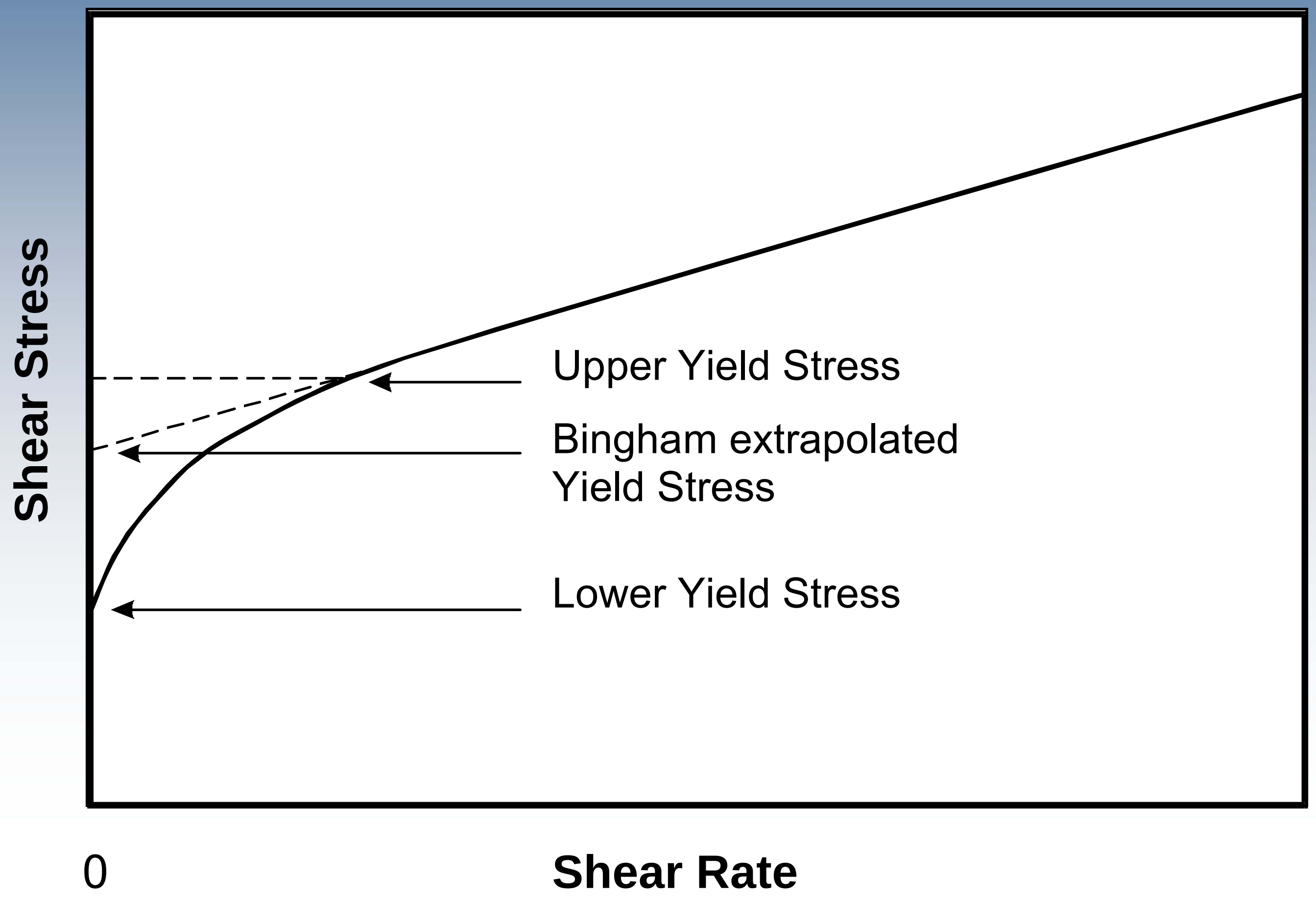
Typical Yield Stress Values

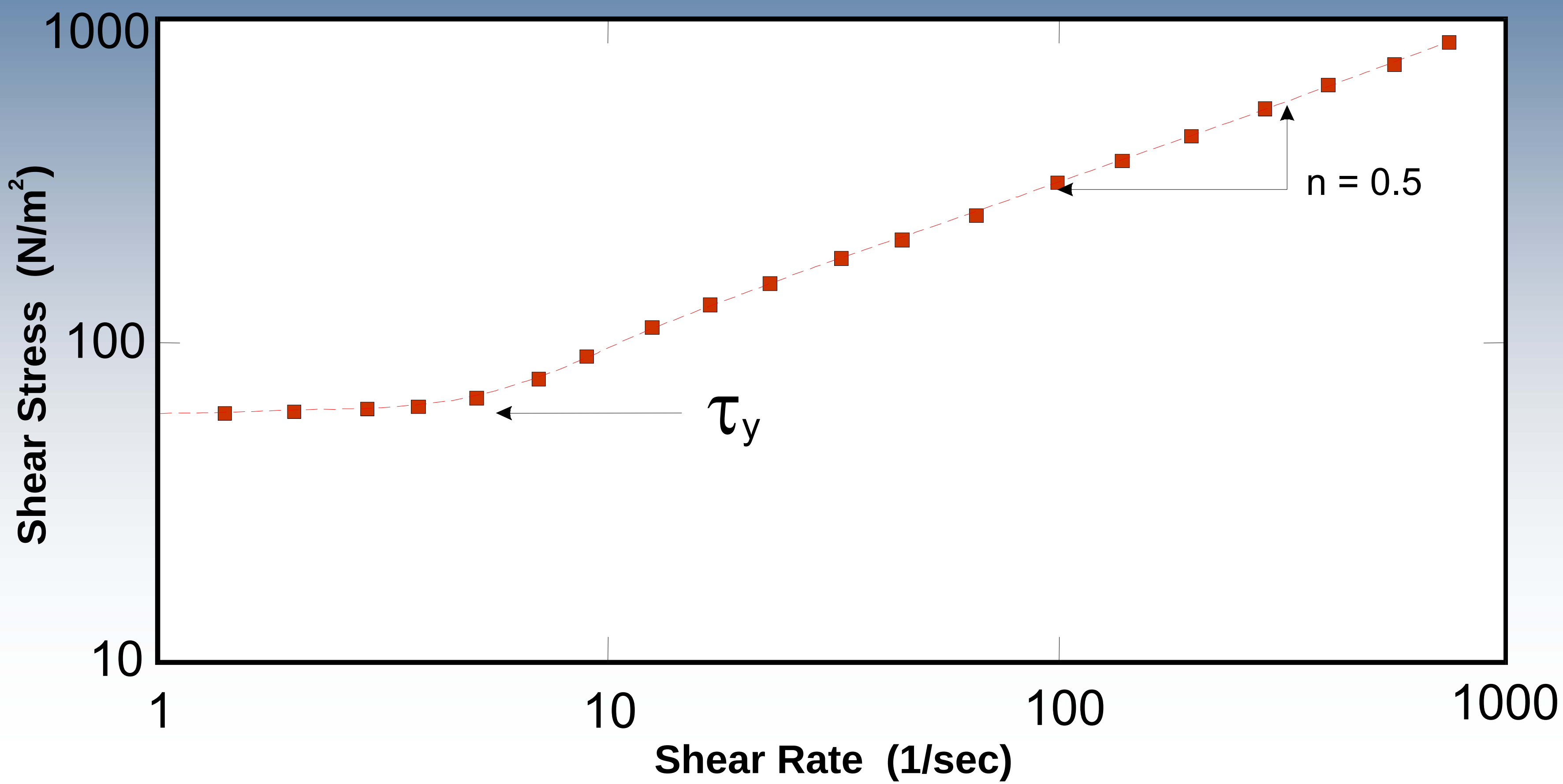
Tomato Sauce (Rosella)	15 Pa
Yoghurt	80 Pa
Toothpaste	110 Pa
Peanut Butter	1900 Pa
Thickened Tailing Disposal	30-100 Pa
Mine Stope Fill	250-800 Pa

The Yield Stress

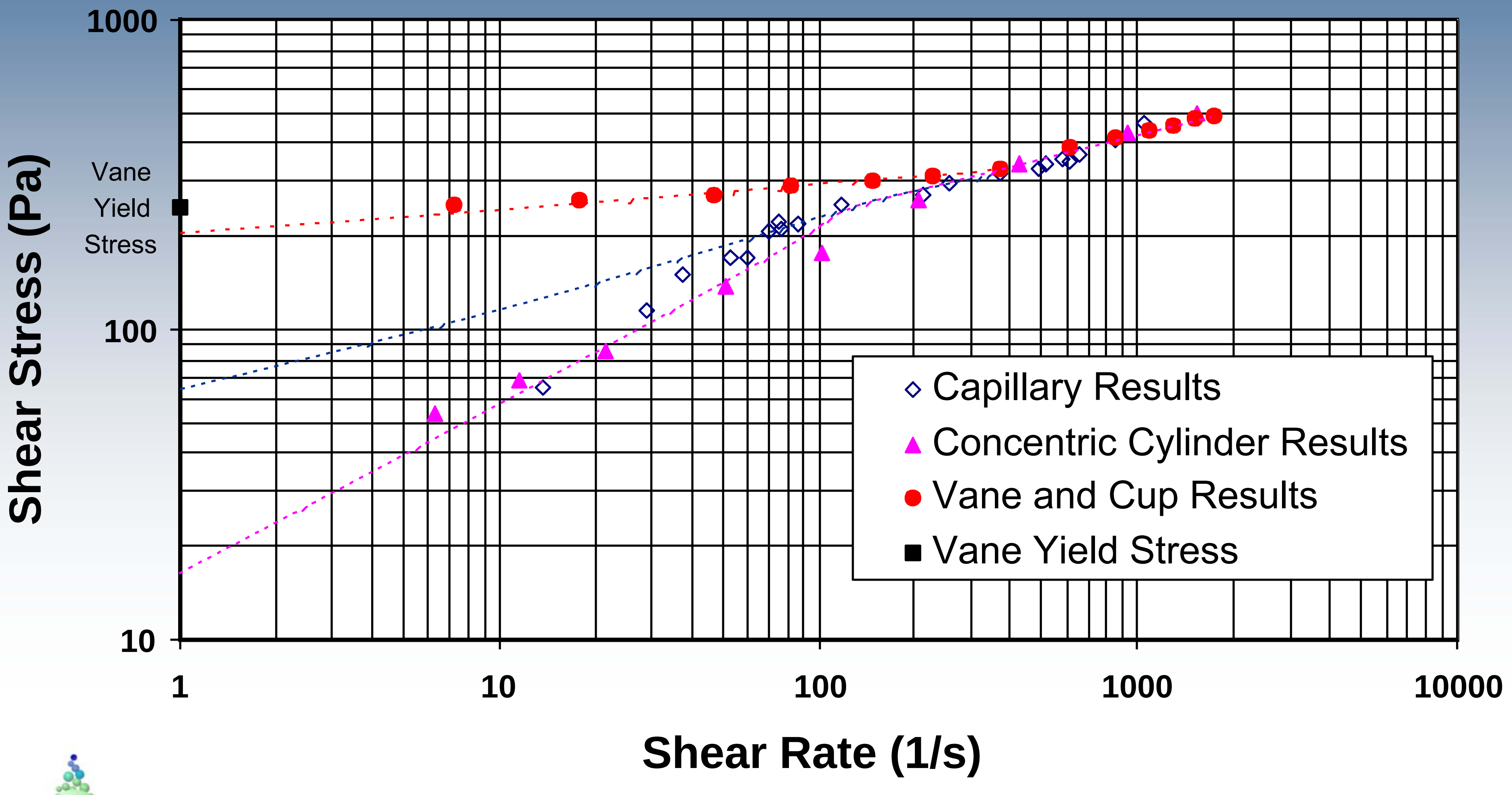


Tomato Soup Concentrate

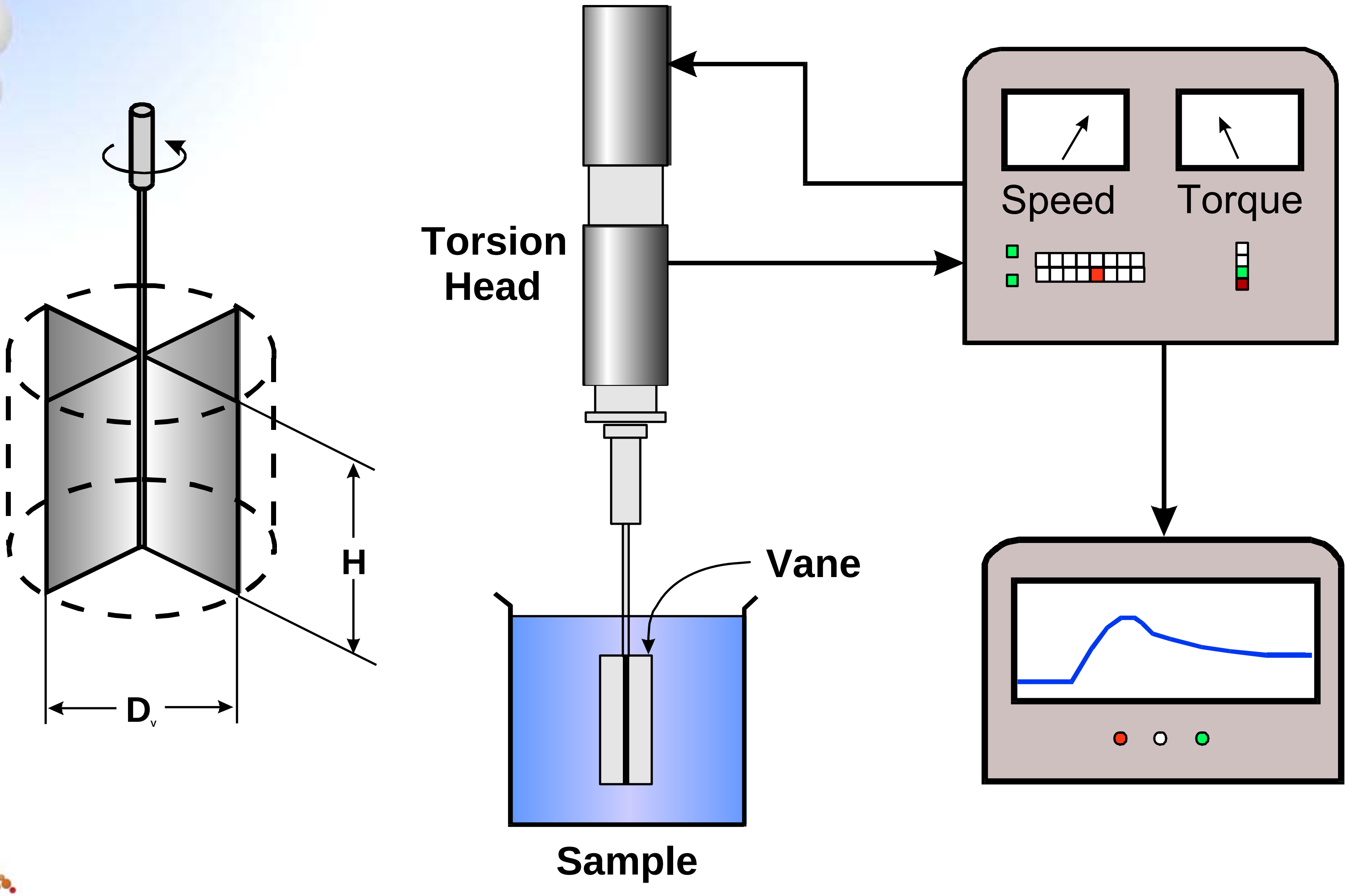
Temperature 20 °C



Flow Curves for Paste Sample - Yield Stress = 250 Pa



Vane Technique



The Vane Method

$$T_m = (\pi\, d l)\frac{d}{2}\,\tau_y + 4\pi\int_0^{d/2} \tau_e(r)\, r^2\, dr$$

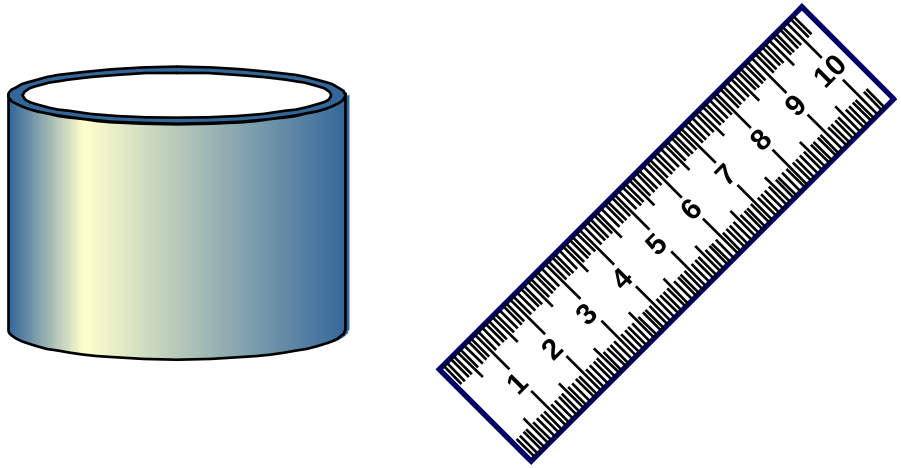
If $\tau_e = \tau_y$ then

$$T_m = \frac{\pi}{2} d^3 \left(\frac{1}{d} + \frac{1}{3}\right)\tau_y$$

"Yield Stress Measurement for Concentrated Suspensions" (with Q.D. Nguyen), J. of Rheology, 27, 321 (1983)"

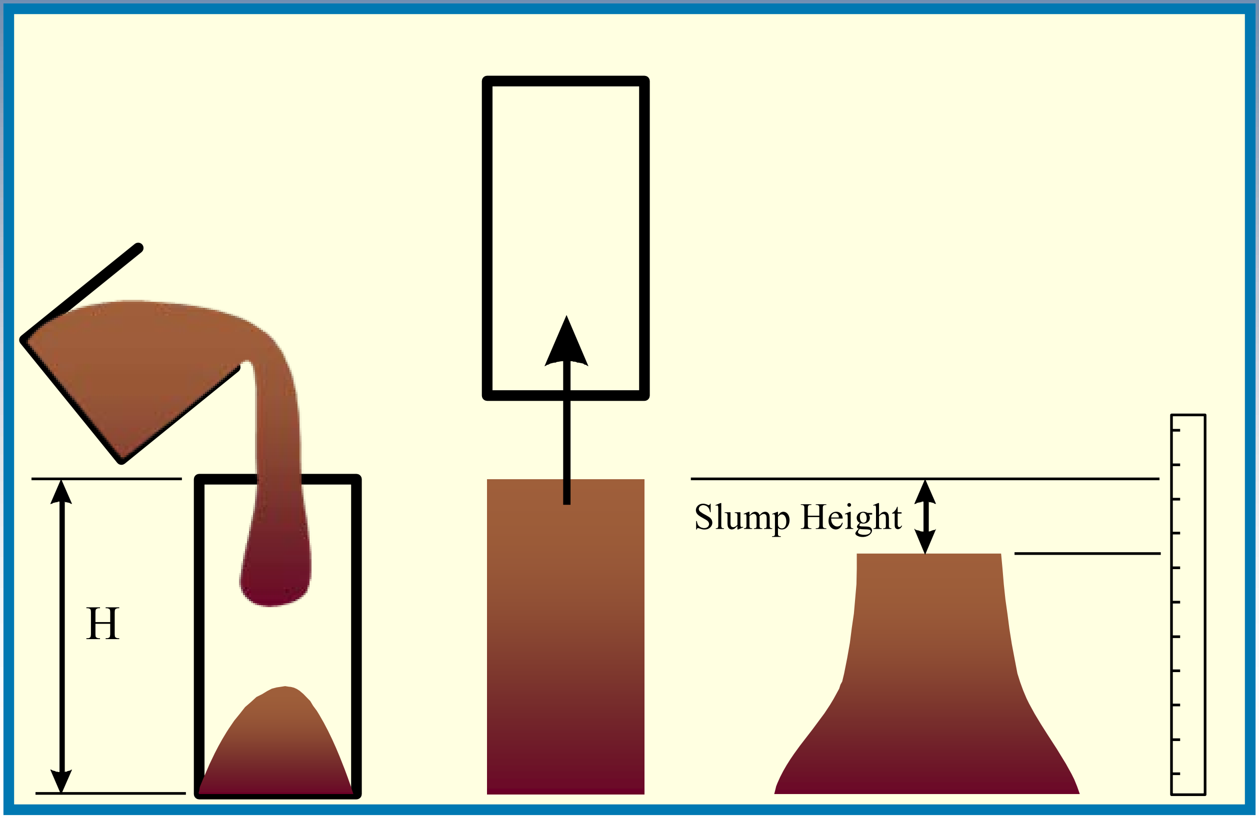
"Direct Yield Stress Measurement with the Vane Method" (with Q.D. Nguyen), J. of Rheology, 29, 335 (1985)"

“D#Fliw|#Fhoo#Wkhrphwhu#iru \hog#Vwuhvv#Phdvxuhphqw“



M1#Ukhro1/#73+9,/#44:<#4<9

The Slump Test



1. Fill slump mould
2. Remove mould vertically
3. Measure distance between mould and top of sample

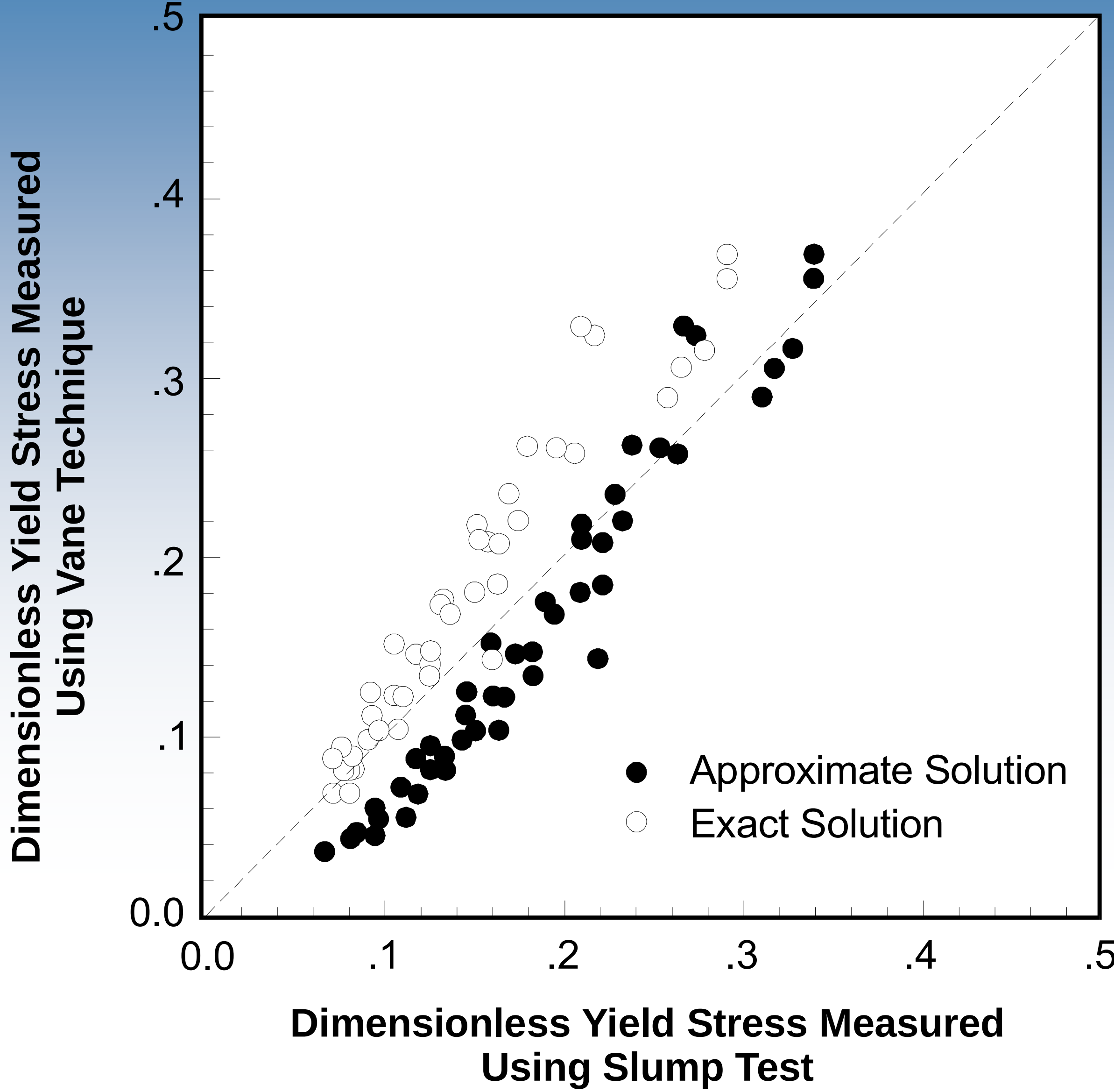
Slump Test

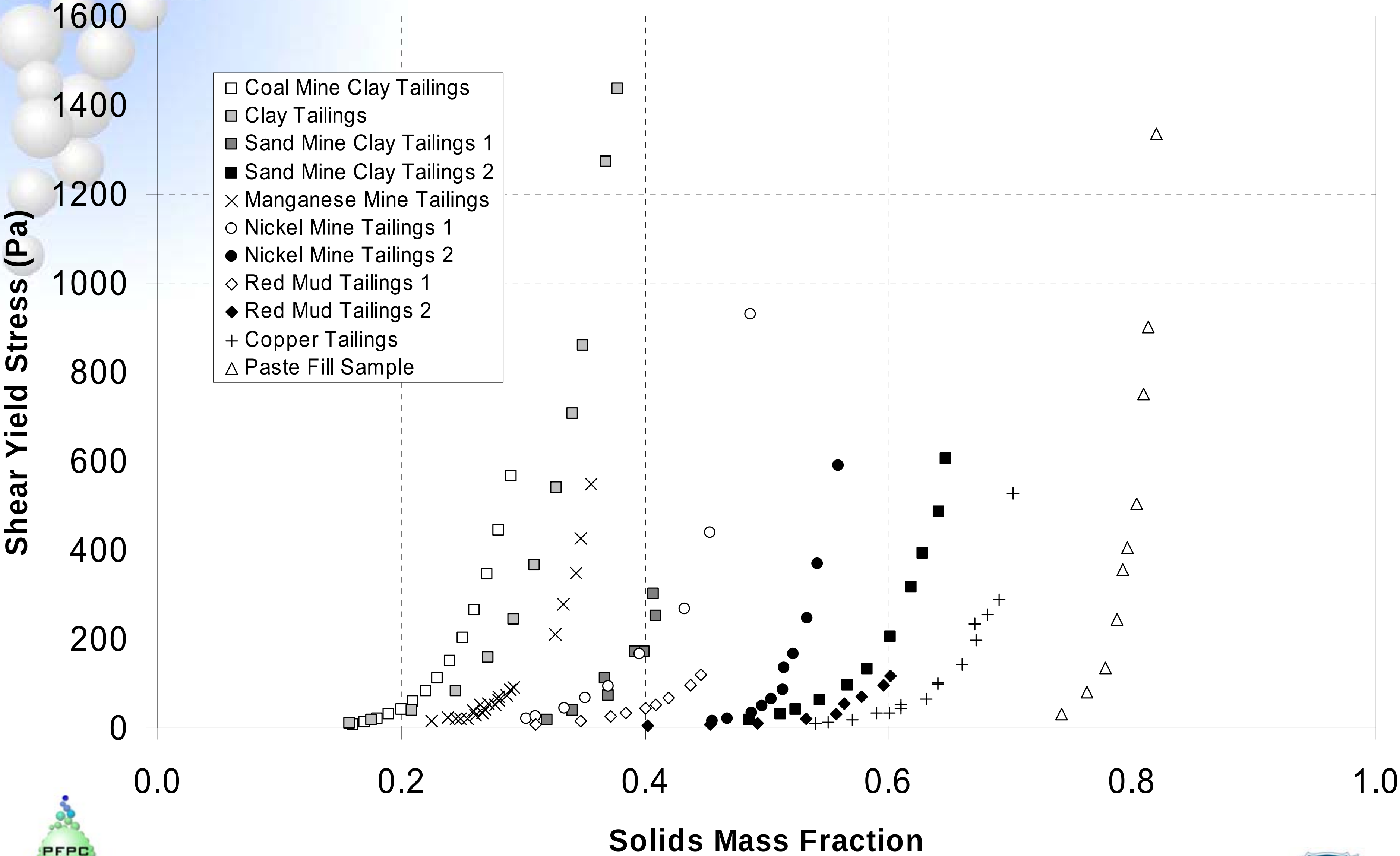
Approximate Result:

$$\tau_{y}^{'} = \frac{1}{2} + \frac{1}{2}\sqrt{S^{'}}$$


The Fifty Cent Rheometer
D.V. Boger
D.J. Glenister
N. Pashais
J. Summers

Comparison of Yield Stress Measuring Techniques





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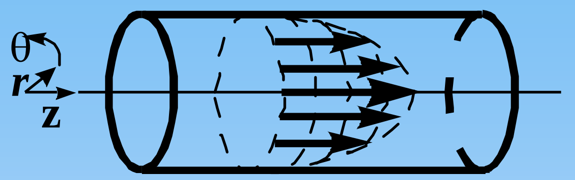
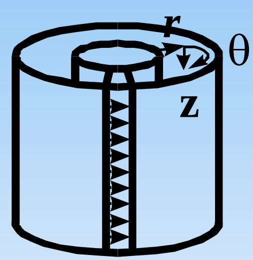
Viscometric flows used for viscosity measurement

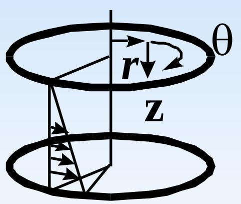
Poiseuille Flow



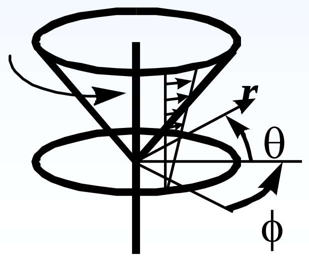
Couette Flow



Parallel Plate Torsion



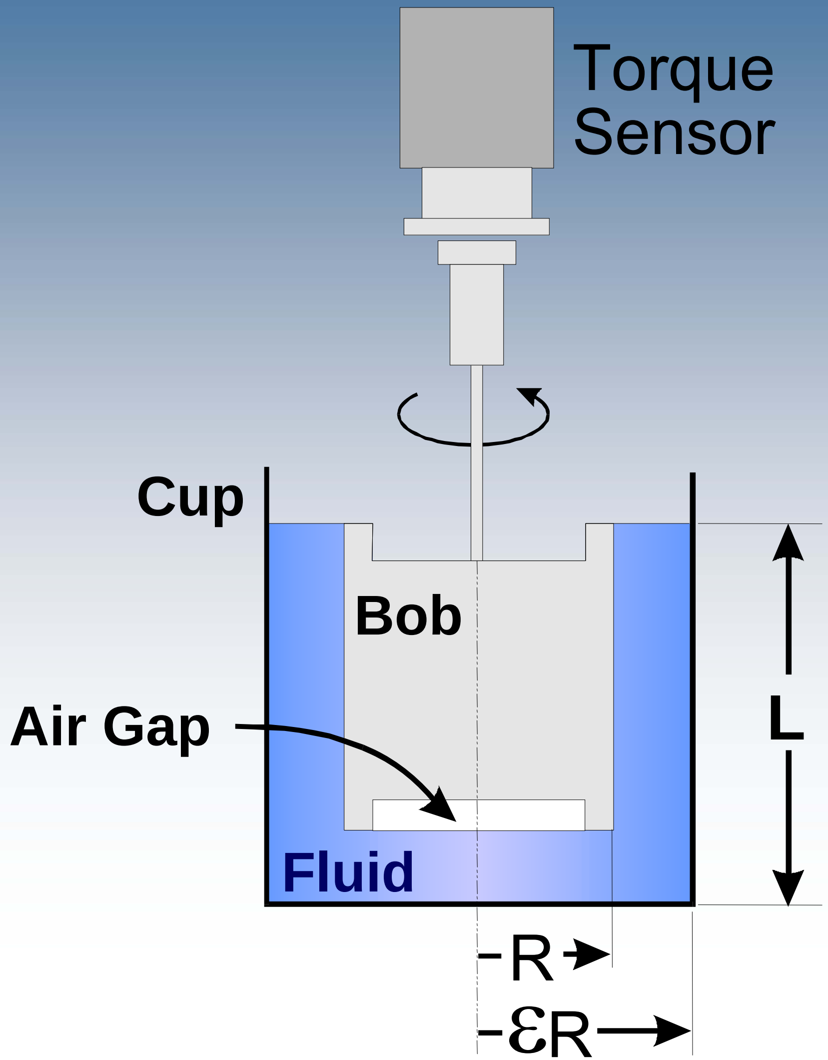
Cone and Plate Torsion



Current Methods of Characterisation

Capillary Rheometry

Rotational Rheometry


Torque
Sensor
Cup
Bob
Air Gap
L
Fluid
R
εR

Couette Viscometry

Basic Equations:

$$\dot{\gamma} = f(\tau) = -r\,d\omega / dr$$

$$\tau = T / 2\pi L r^2$$

$$\tau_1 = T / 2\pi L R^2 = \varepsilon^2 \tau_2$$

$$\Omega = \int_{\tau_2}^{\tau_1} \frac{f(\tau)}{2\tau}\, d\tau$$

where τ_1 and τ_2 are the shear stress at the surfaces of the bob (r=R) and the cup (r=εR), respectively.

Newtonian Fluid:

$$\dot{\gamma}_1 = f(\tau_1) = 2\Omega / (1-\varepsilon^{-2})$$

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Overview of the Problem

- Samples are not stable over time.
- Some testing methods are susceptible to particle size effects.
- Slip between the sample and the shearing interface can occur.
- Some instrumentation is very large and not portable.

THE BUCKET RHEOMETER FOR THE VISCOSITY CHARACTERISATION OF YIELD STRESS SUSPENSIONS

Daniel T. Fisher

Professor Peter J. Scales

Laureate Professor David V. Boger

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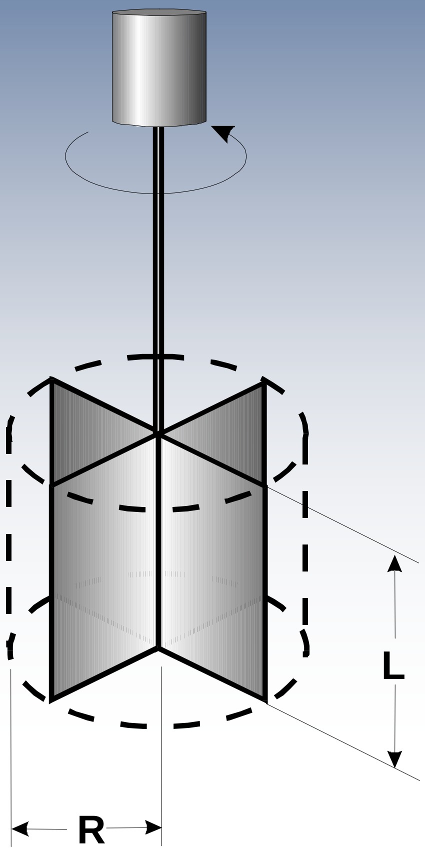
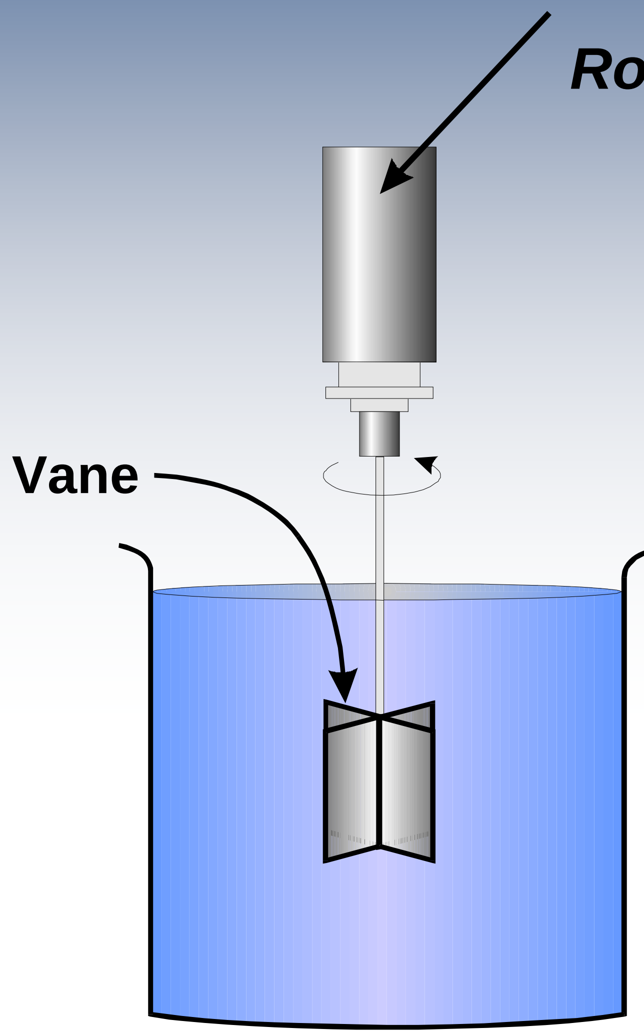
The Bucket Rheometer





Torque **(T)**

Rotational Speed **(Ω)**

Shear Stress:

$$\tau = \frac{T}{2\pi LR}$$

where **R = vane radius**

L = vane height

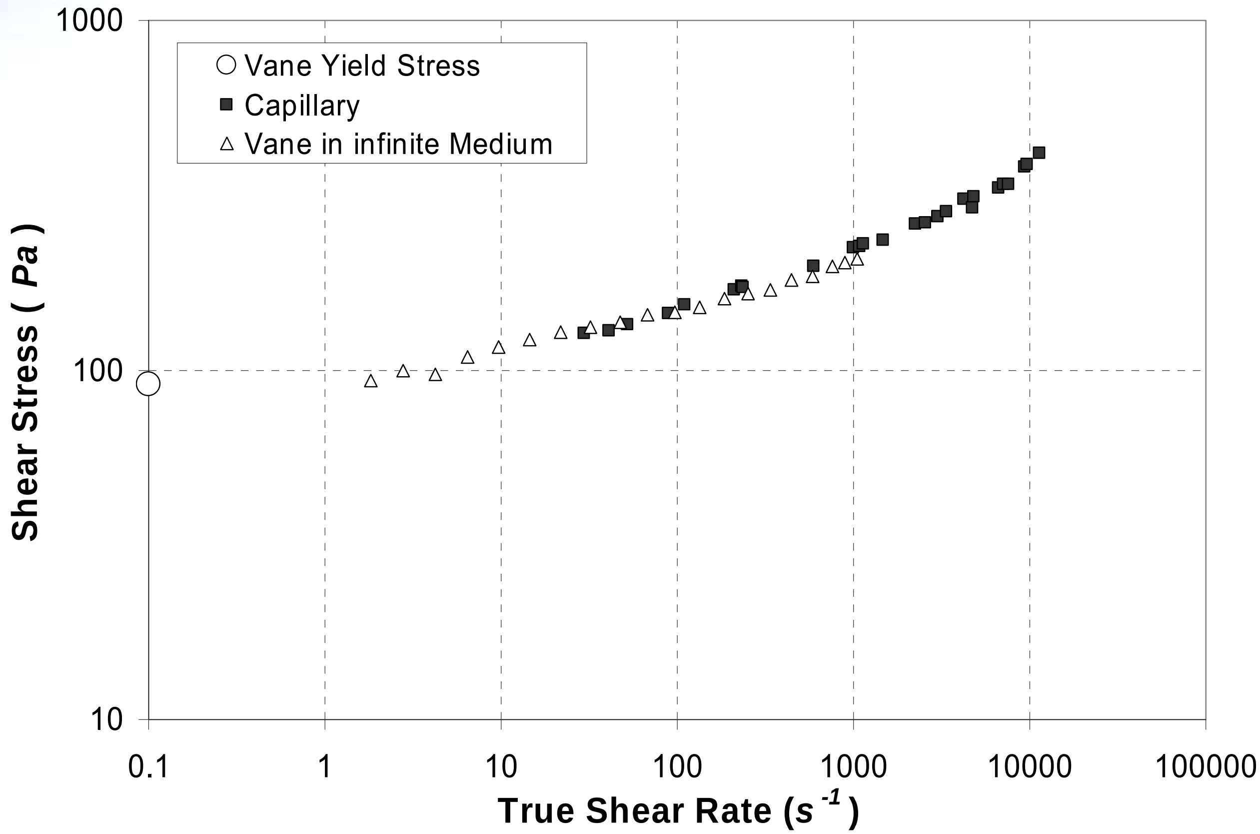
Shear Rate:

$$\dot{\gamma} = \frac{2\Omega}{S}$$

where $$S = \frac{d\ln T}{d\ln \Omega}$$

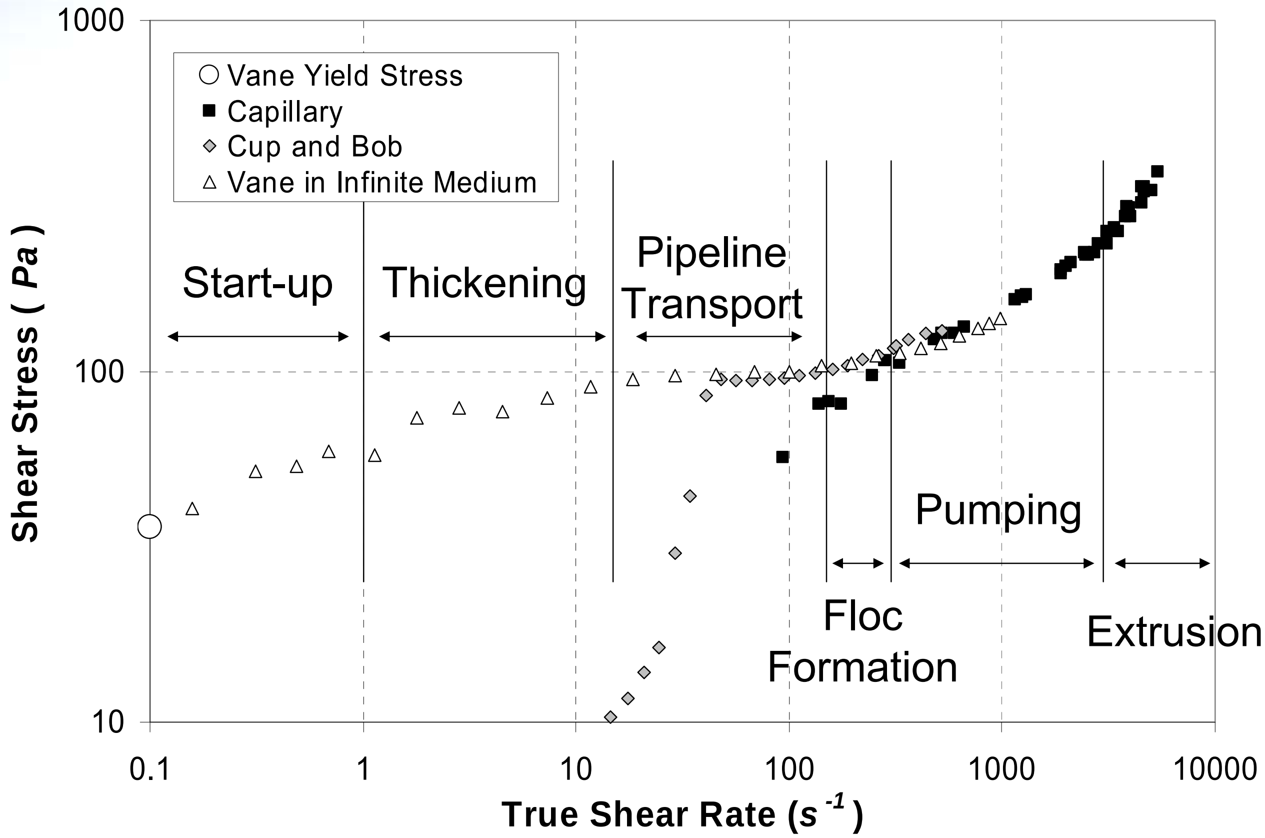
Alumina Paste (AKP50)

50.2%w/w and pH 7.60



Transitional Limonite Slurry

45.1%w/w and pH 6.34



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Ideal Particulate Fluids

D.V. Boger

Particulate Fluids Processing Centre
Department of Chemical & Biomolecular Engineering
The University of Melbourne
Victoria Australia

Rheology of Suspensions

DEFINITIONS:

Relative Viscosity

Einstein

$$\eta_r = \frac{\eta}{\eta_0} = 1 + 2.5\phi + 6.2\,\phi^2 + 0(\phi^3)$$

Bachelor

Specific Viscosity

$$\eta_{sp} = \eta_r - 1 = \frac{\eta - \eta_0}{\eta_0}$$

Instrinsic Viscosity

$$[\eta] = \lim_{\phi \to} \frac{\eta_{sp}}{\phi}$$

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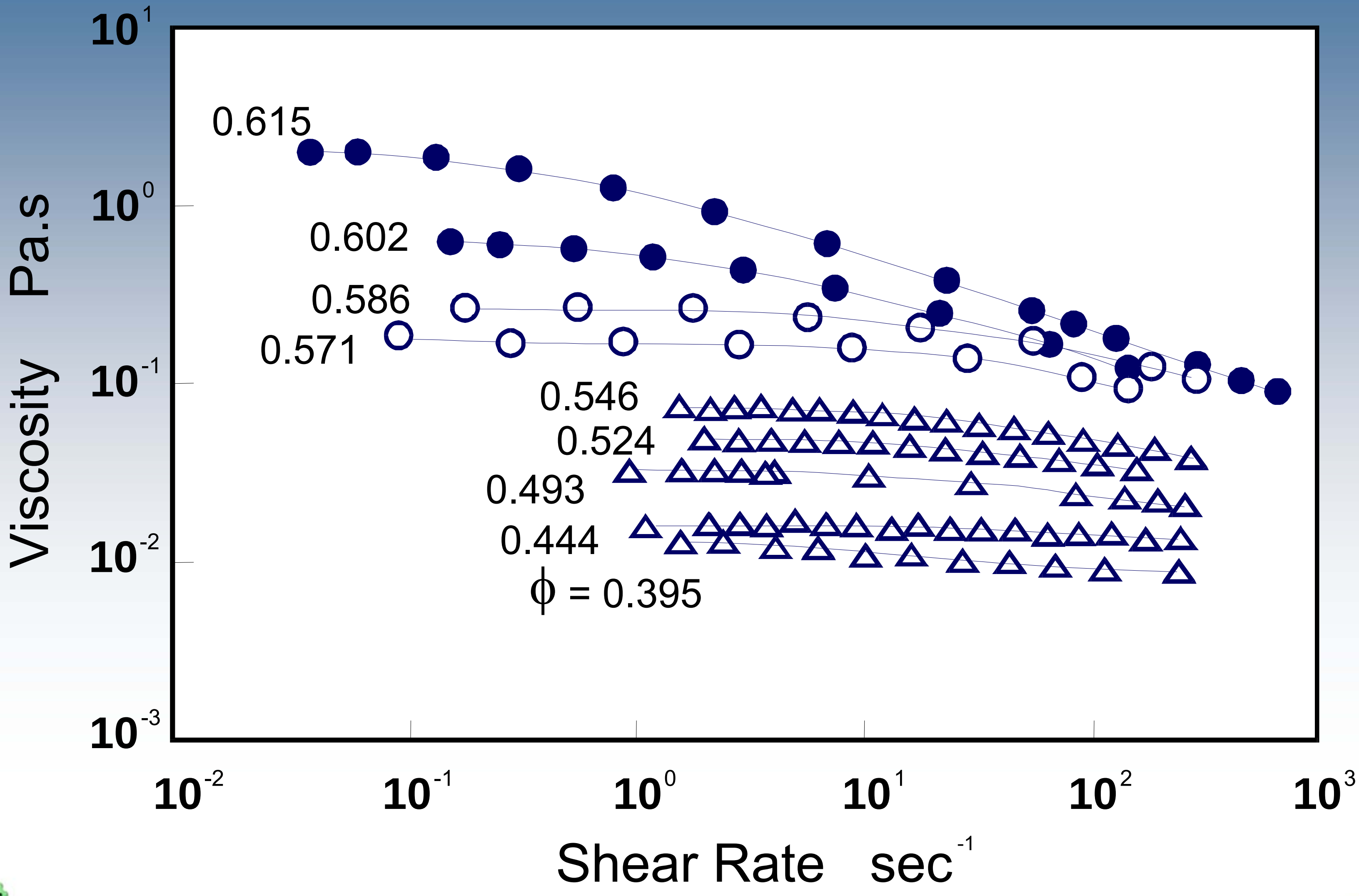
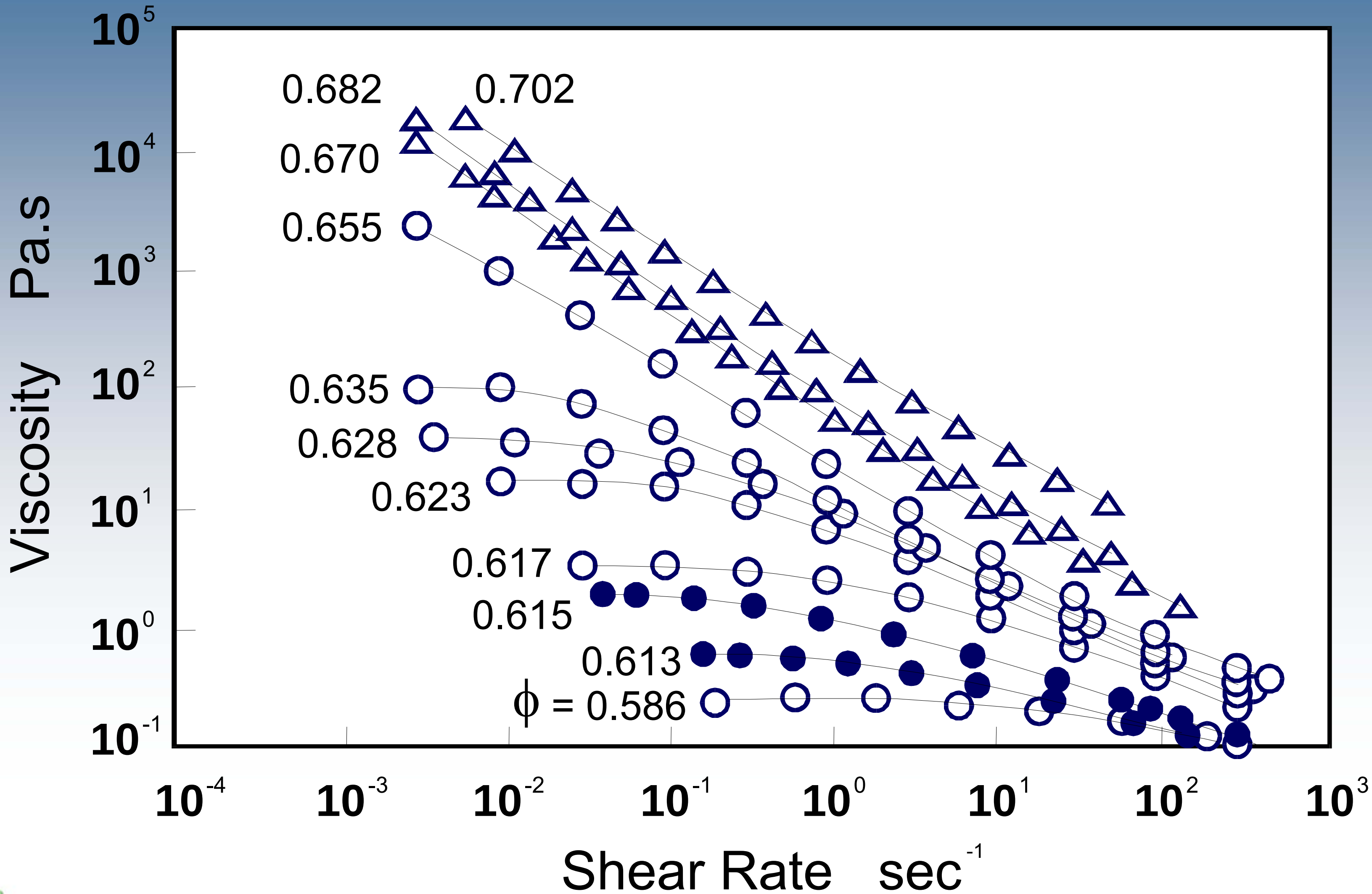


Viscosity Pa.s
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.615
0.602
0.586
0.571
0.546
0.524
0.493
0.444
$\phi = 0.395$
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
Shear Rate sec^{-1}



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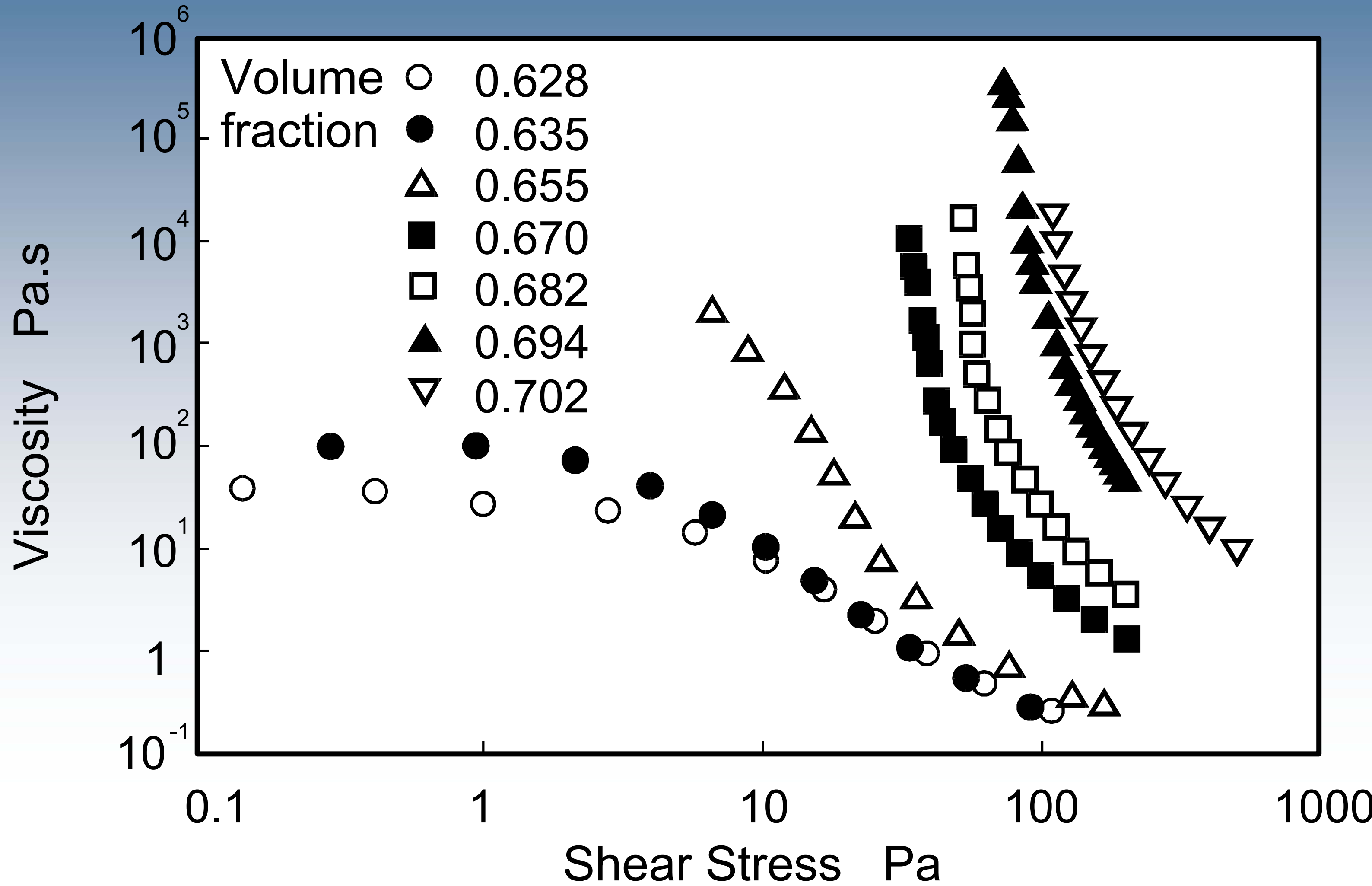


Volume fraction
0.628
0.635
0.655
0.670
0.682
0.694
0.702
Viscosity Pa.s
10^6
10^5
10^4
10^3
10^2
10^1
1
10^{-1}
0.1
1
10
100
1000
Shear Stress Pa

Yield Stress for Hard Sphere Suspensions

ϕ (Volume Fraction)	τ_y (Yield Stress, Pa)		
	Vane	Steady Shear	Creep
0.670	----	30 +/- 5	25 +/- 5
0.682	22 +/- 5	50 +/- 5	45 +/- 5
0.694	67 +/- 6	80 +/- 8	90 +/- 5
0.708	108 +/- 2	100 +/- 10	90 +/- 10

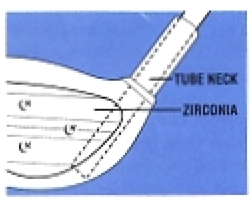
J. Coll. and Interfacial Sci., Vol 147, number 2, 479-495 (1991)

Our Ceramic Will Test Your Metal

Introducing The New Z-Driver From Coors CeraSports

Superior Performance. A well-hit ball with the Coors CeraSports Ceramic Z-Driver is an experience unlike any other in golf. The way it looks. The way it sounds. The way it feels. A confident feeling that translates into superior performance.

Precision Advantage. The secret is in the clubface. Computer-designed with optimum roll and bulge characteristic that maximize distance and accuracy. The Coors CeraSports Ceramic Z-Driver features the Zirconia (Z) clubface–a diamond-hard surface, precision-machined to the most exacting tolerances. So its accuracy and clean look are permanent. And in a game of unending variables, you'll welcome the consistency.



Consistent Accuracy. That's only the beginning. To give you every advantage, the Coors CeraSports Ceramic Z-Driver has an aerodynamically sleek tube neck design that maximizes clubhead speed. And because accurate distance is the real test, the tube neck design and deep penetrating shaft virtually eliminate twist and torque.

Drive after drive, your efforts translate into perfection off the tee.

Test Drive The Z-Driver. Playing the Z-Driver is exhilarating. Visit your pro shop and ask for a test drive. Or call 1-800-252-PUTT. The ceramic difference will change the way you feel about golf. Forever.

Coors CeraSports Ceramic Z-Drivers

Model	Head Size	Shaft Type	Head Color
Men's Z	Standard	Graphite R,S,X	Gray gloss
Men's Z	Standard	Steel	Gray gloss
Men's ZX	Expanded	Graphite R,S,X	Black gloss
Men's ZX	Expanded	Steel	Black gloss
Seniors' ZS	Expanded	Custom Graphite	Black gloss
Ladies' ZL	Standard	Custom Graphite	Gray gloss

Only right-handed Z-Drivers are offered at this time.

Ceramicon Designs, Ltd.
A Division of Coors Ceramics Company
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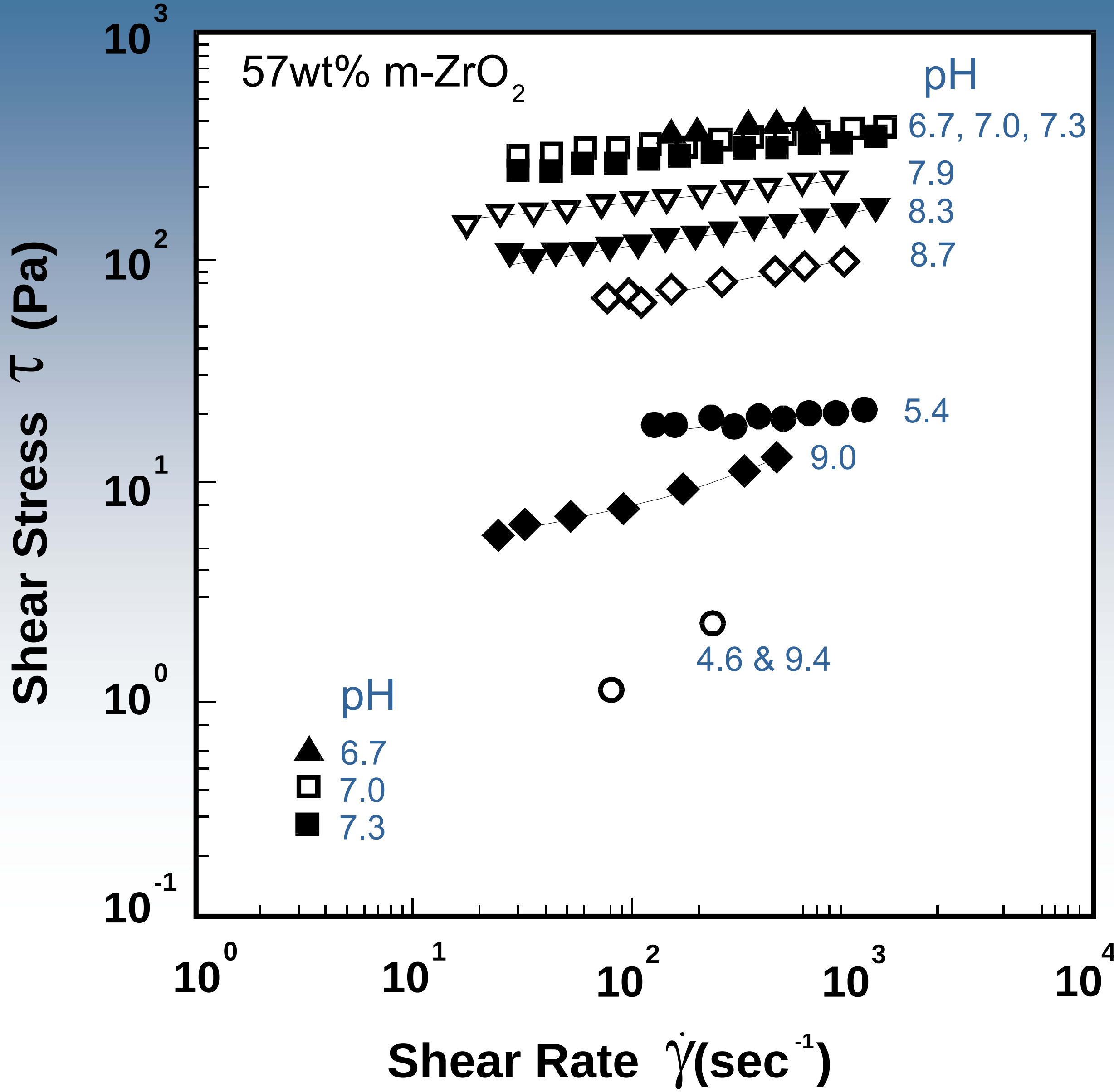
Discover The Ceramic Difference

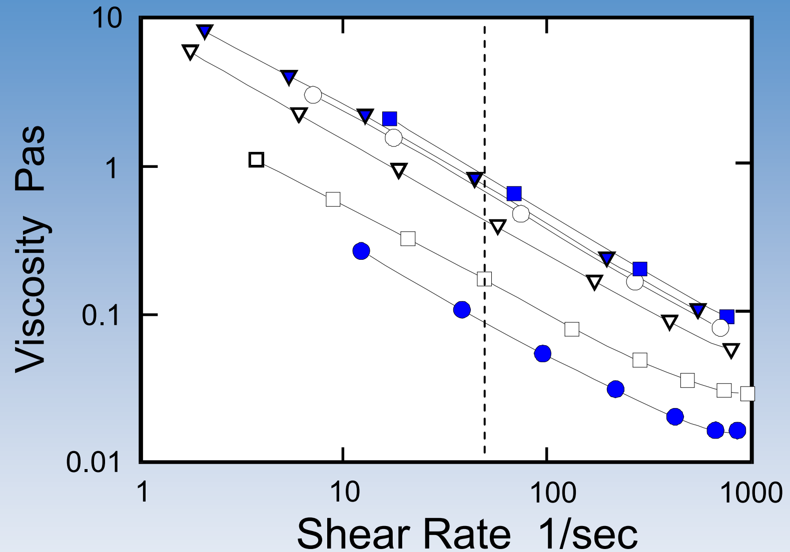

57wt% m-ZrO2
pH
6.7, 7.0, 7.3
7.9
8.3
8.7
5.4
9.0
4.6 & 9.4
pH
6.7
7.0
7.3
Shear Stress τ (Pa)
Shear Rate γ̇ (sec-1)
10^3
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3
10^4


...SNAKE SCALES, FROG FEET, BAT EARS ...
B.Parker, J.Hart & R.Binnington

The Rheology of TiO_2 Pigment Suspensions

50wt% solids CR62

Viscosity Profiles as a function of pH

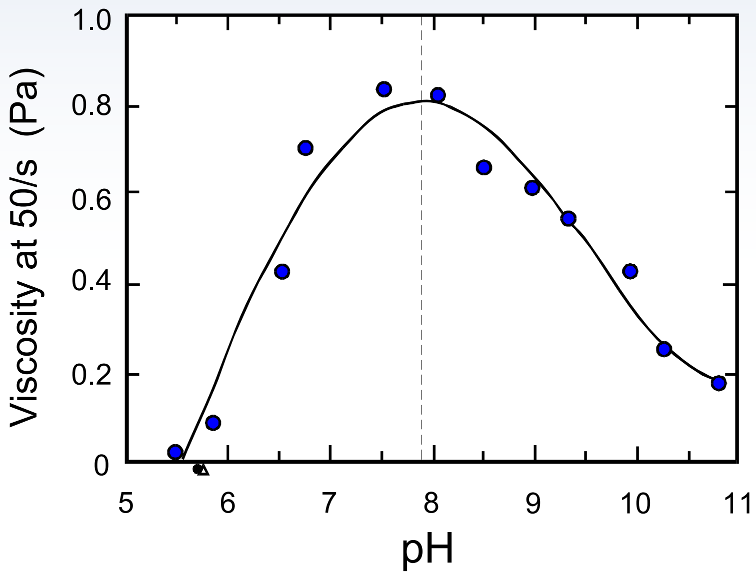


Power Law Behaviour

n = 0.2

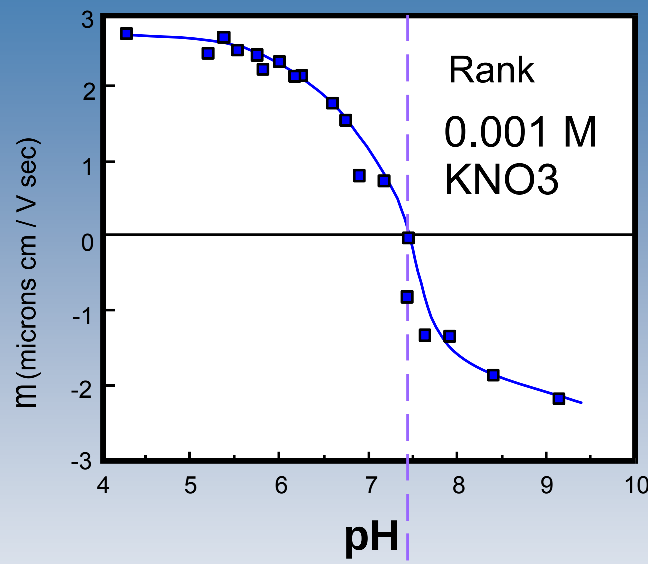
2<K<20

Viscosity Curve

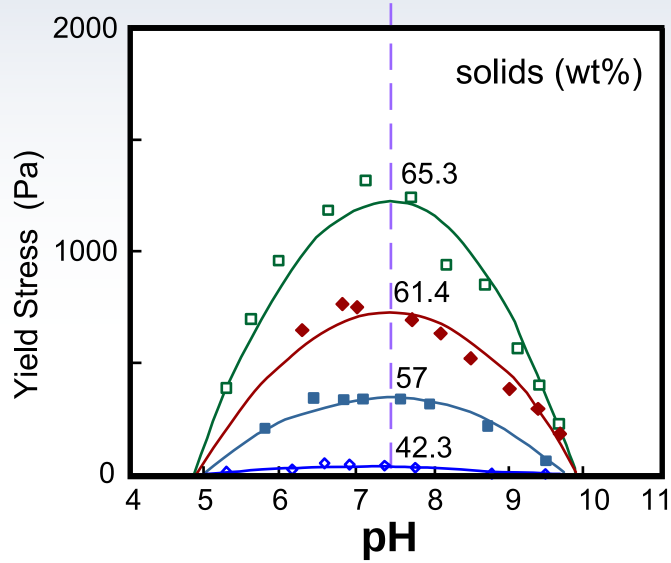


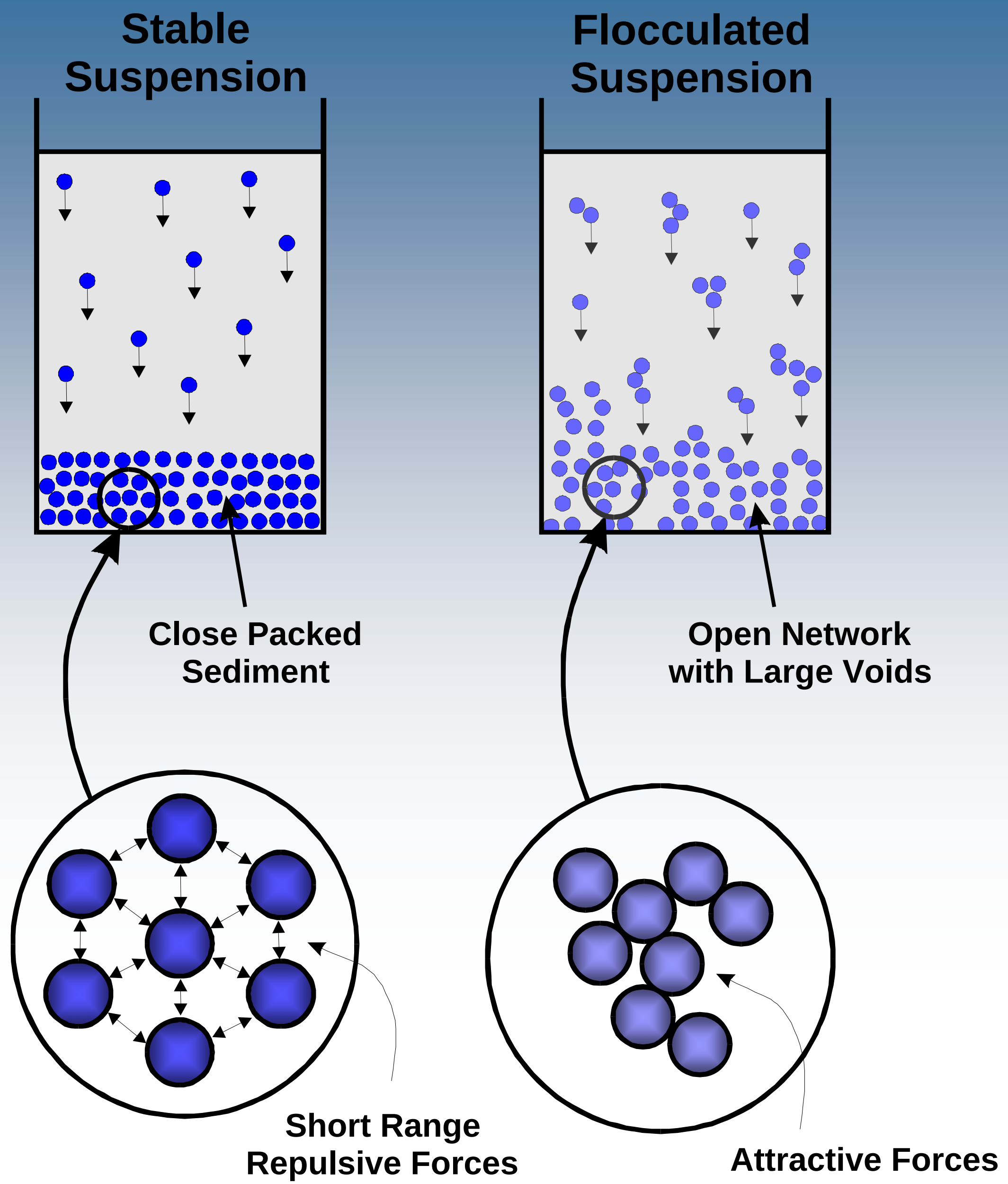
η_{max} occurs at pH = 7.9

1. Electrokinetics



2. Rheology





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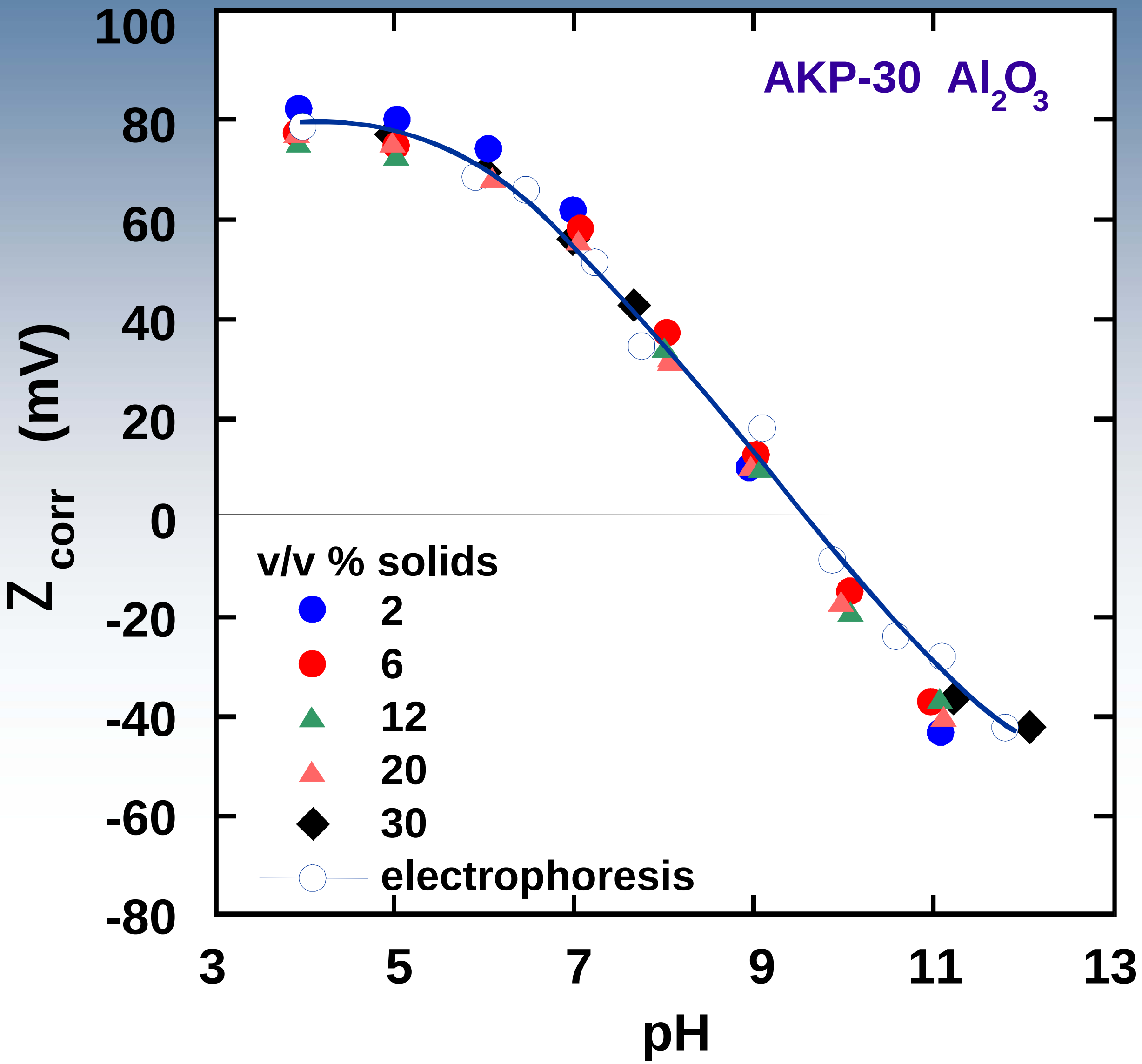
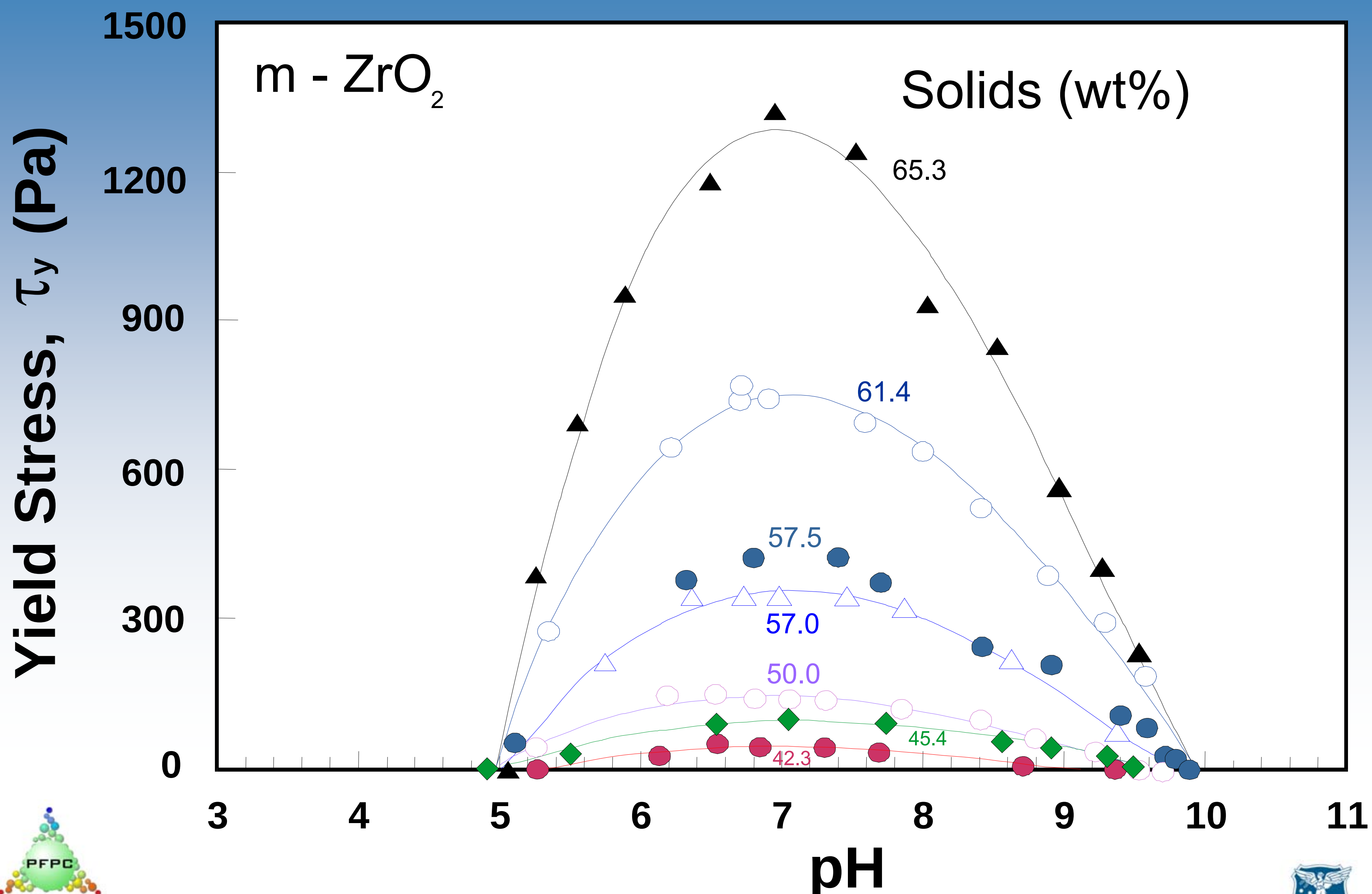
Alumina Electrokinetics

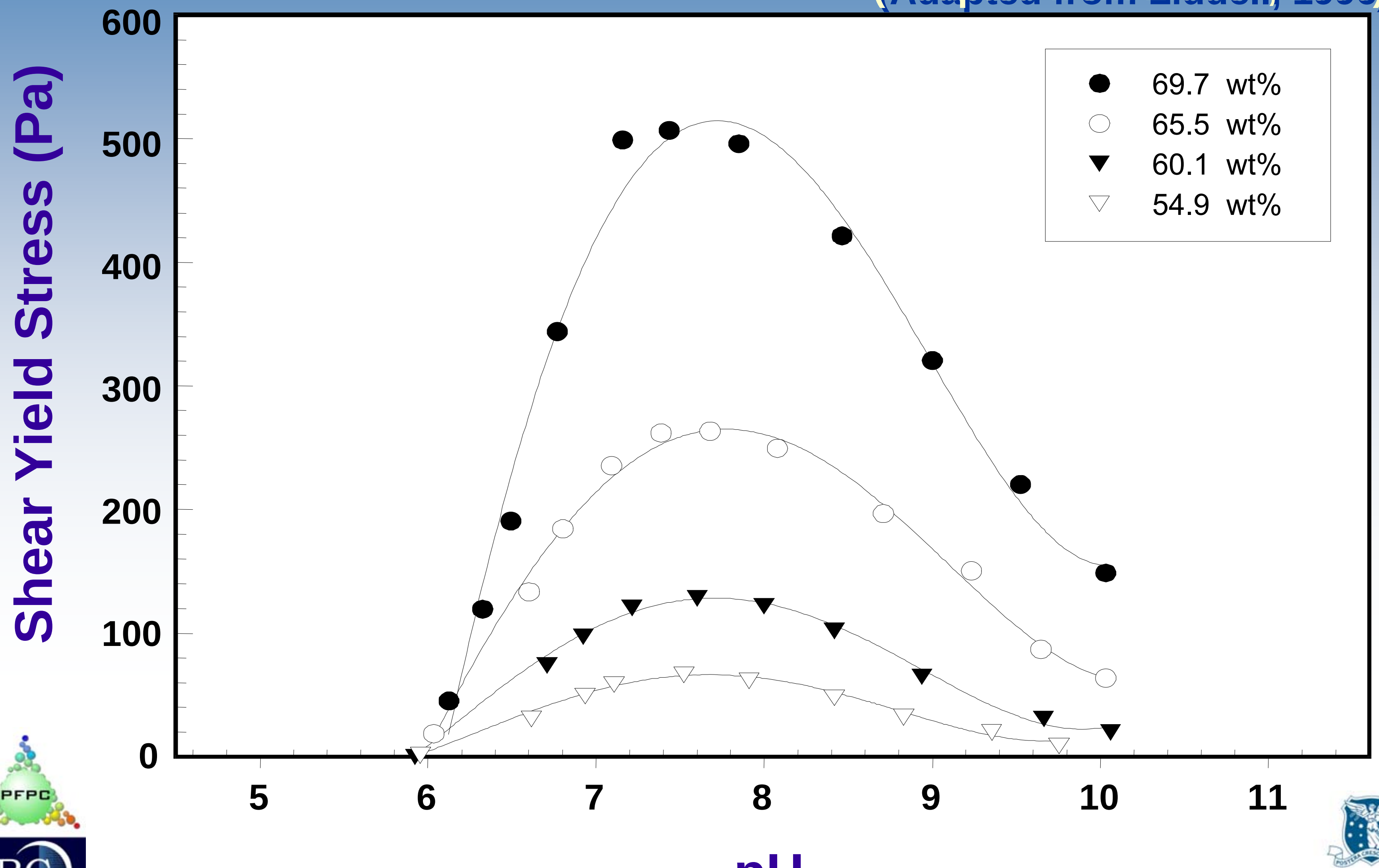




m - ZrO_2
Solids (wt%)
65.3
61.4
57.5
57.0
50.0
45.4
42.3
Yield Stress, τ_y (Pa)
1500
1200
900
600
300
0
3
4
5
6
7
8
9
10
11
pH

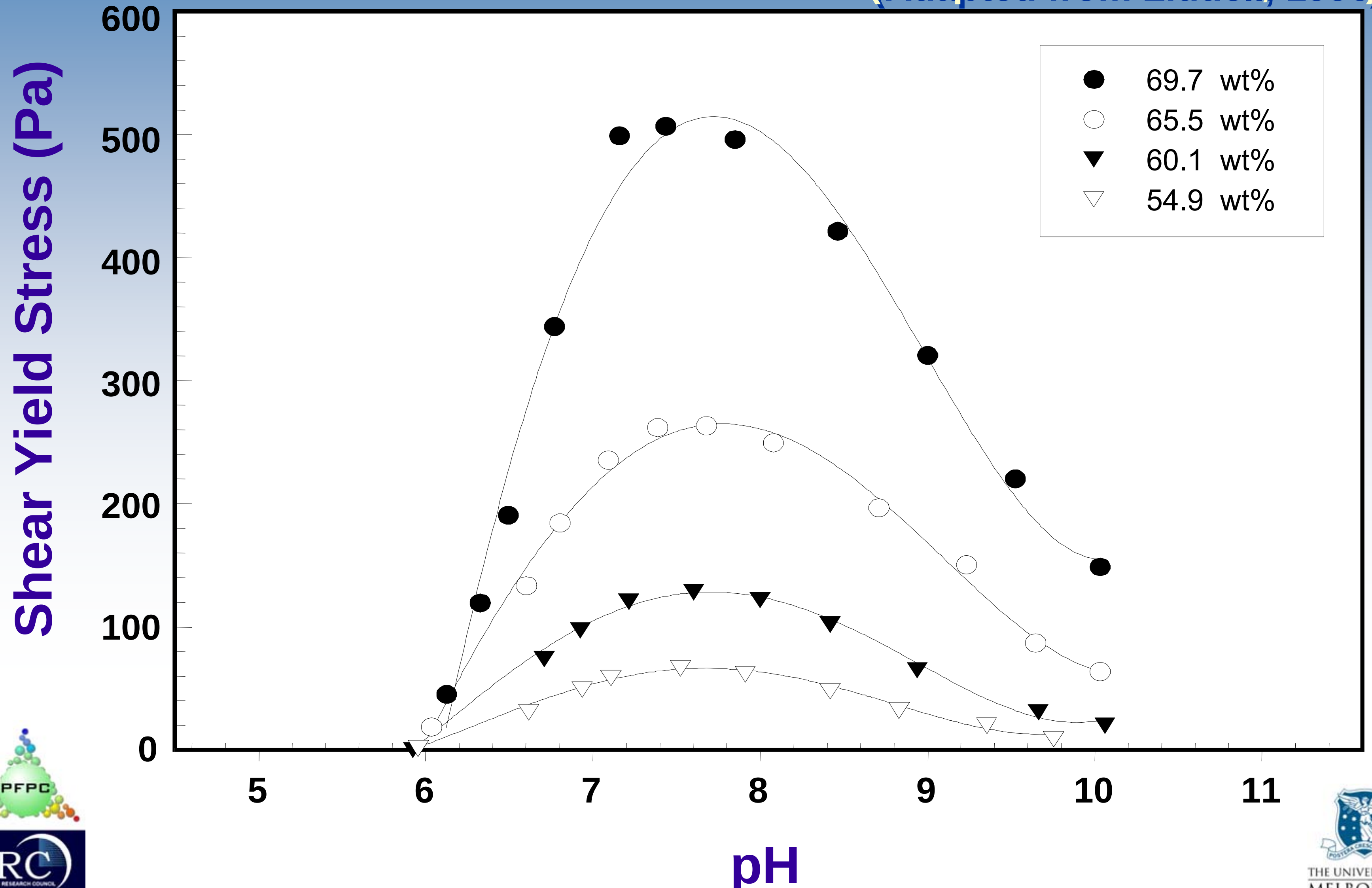
Yield Stress of Titania Suspensions as a Function of pH and Solids Concentration

(Adapted from Liddell, 1996)



Yield Stress of Titania Suspensions as a Function of pH and Solids Concentration

(Adapted from Liddell, 1996)



Additive Effects -Type of Interaction

a) STERIC INTERACTION

i) illustrated by small additive molecules
ii) modelling to show the importance of additive molecular size

b) BRIDGING FLOCCULATION

i) high molecular weight polyelectrolyte

c) HYDROPHOBIC INTERACTION

i) additive with a charge head group and a long hydrophobic tail, eg. dodecyl sulphate

Note that most analyses were conducted at the IEP so as to eliminate complication arising from electrostatic interaction

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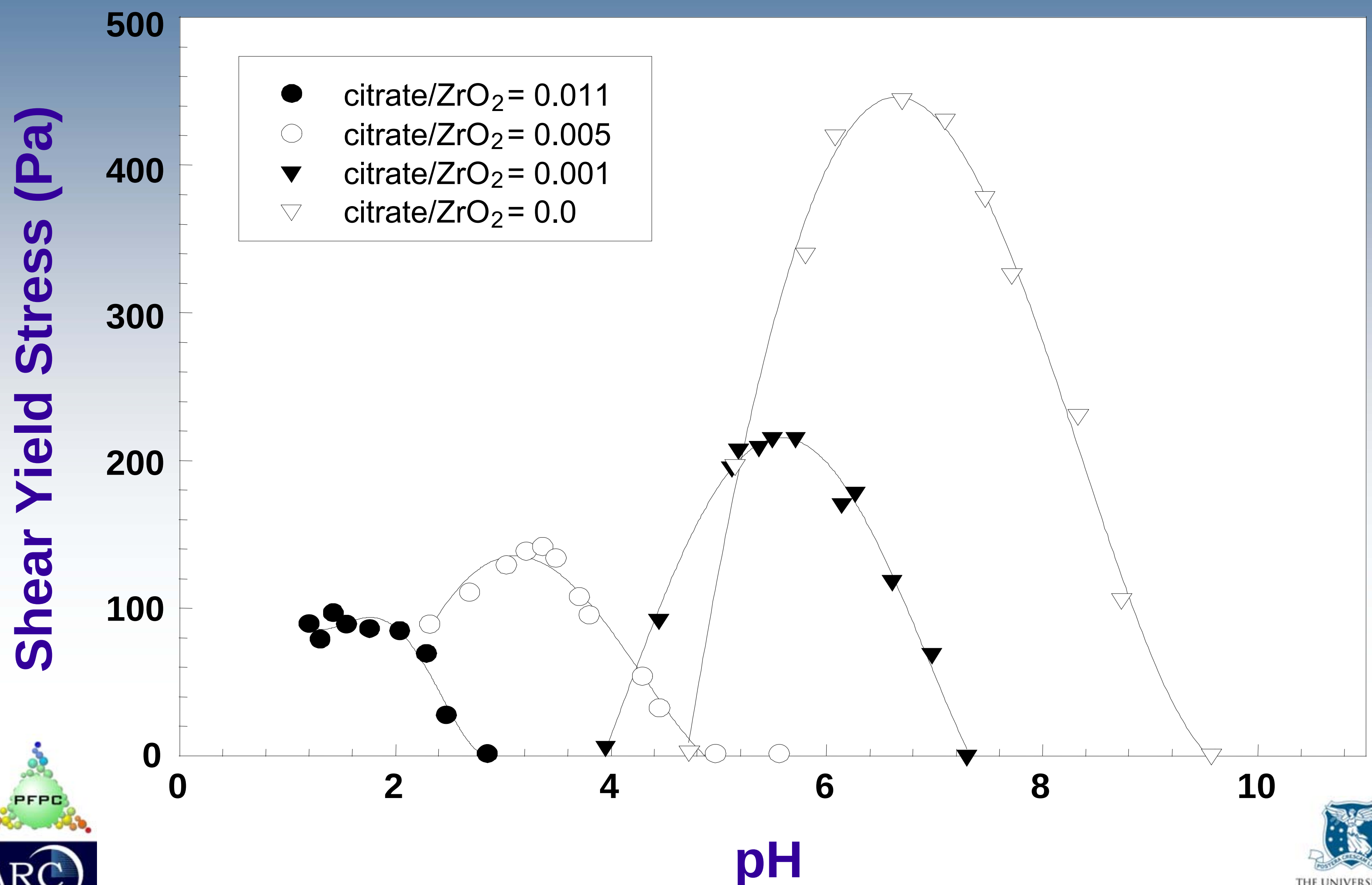
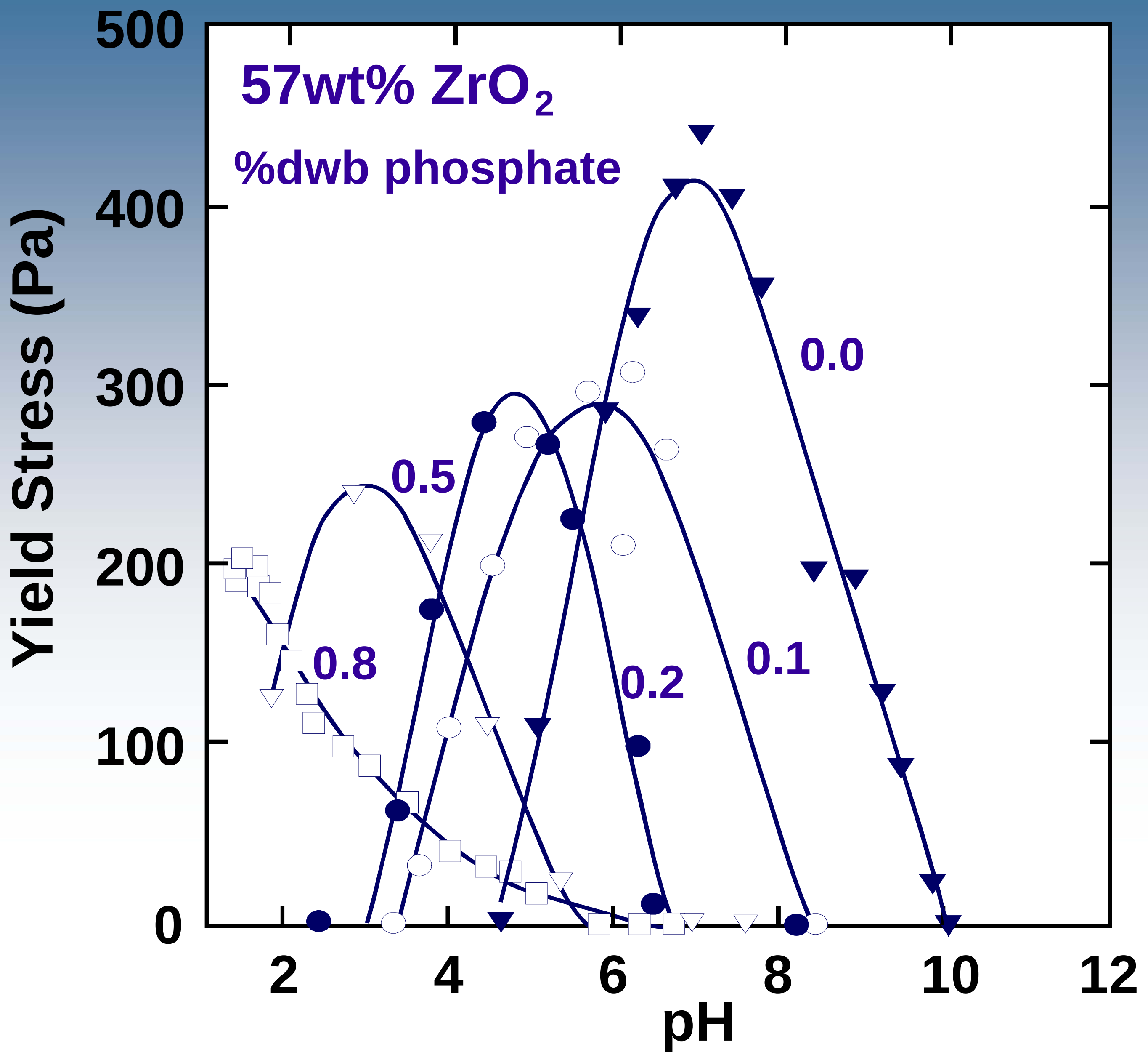
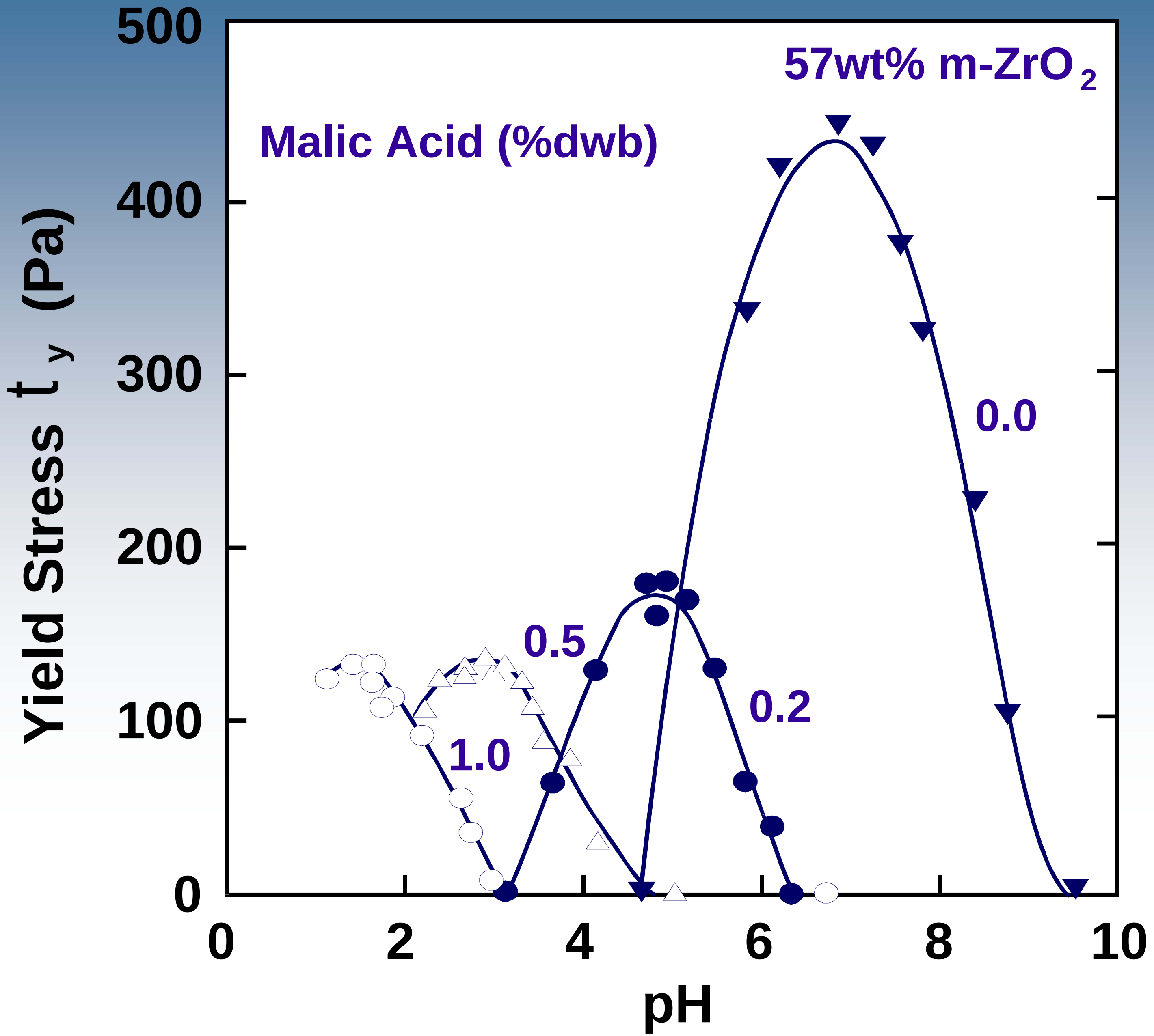
Yield Stress versus pH behaviour of 57% Zirconia Suspension as a Function of Citrate Concentration



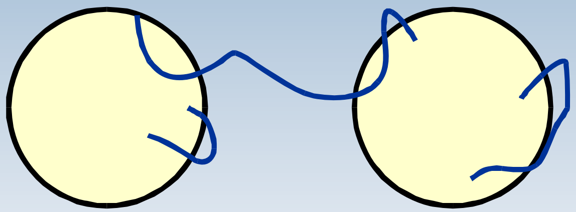

57wt% ZrO_2
%dwb phosphate
Yield Stress (Pa)
500
400
300
200
100
0
2
4
6
8
10
12
pH
0.0
0.1
0.2
0.5
0.8



57wt% m-ZrO2
Malic Acid (%dwb)
Yield Stress τy (Pa)
500
400
300
200
100
0
0
2
4
6
8
10
pH
0.0
0.5
0.2
1.0

Bridging Flocculation

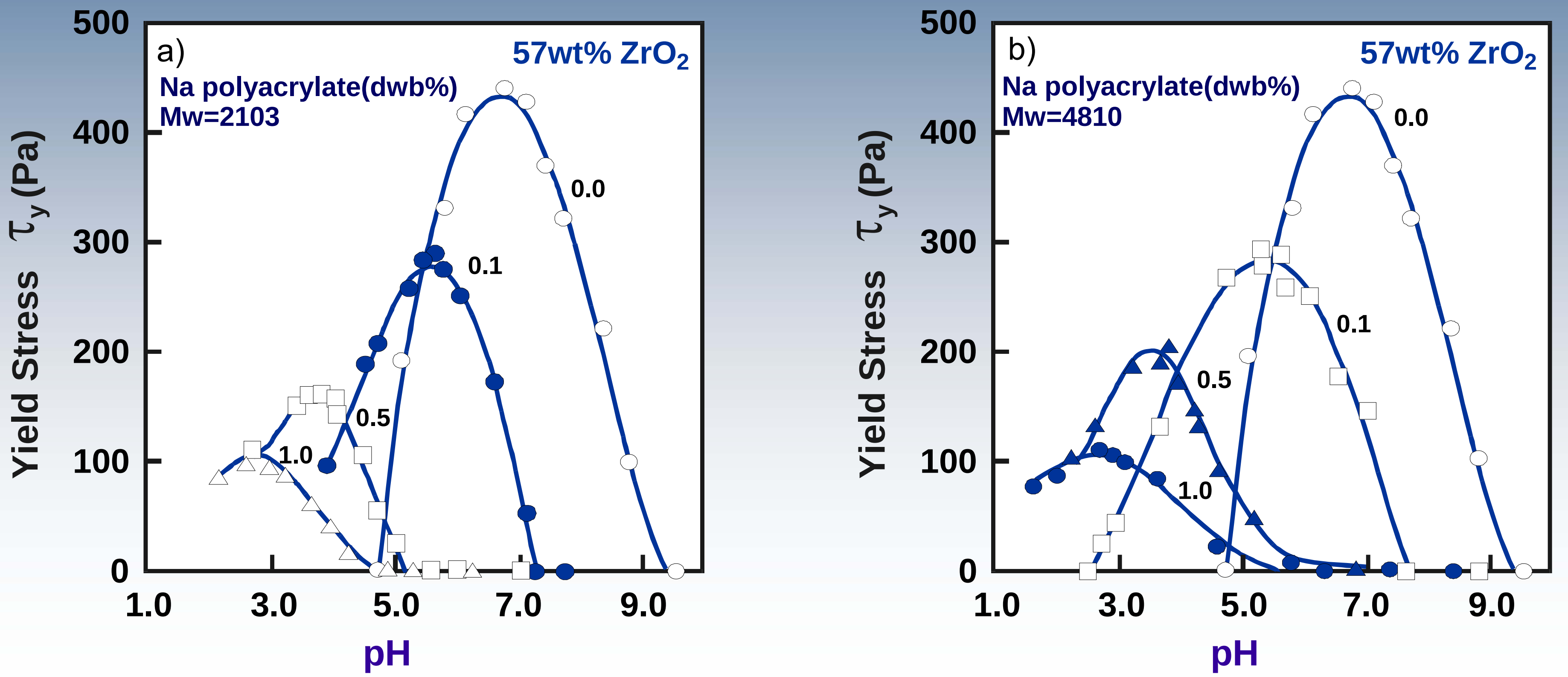
When a high Mw polymer is adsorbed onto 2 or more particles at the same time.



Bridging flocculation is an additional attractive force and is only important for high Mw polymer and at low additive concentration.

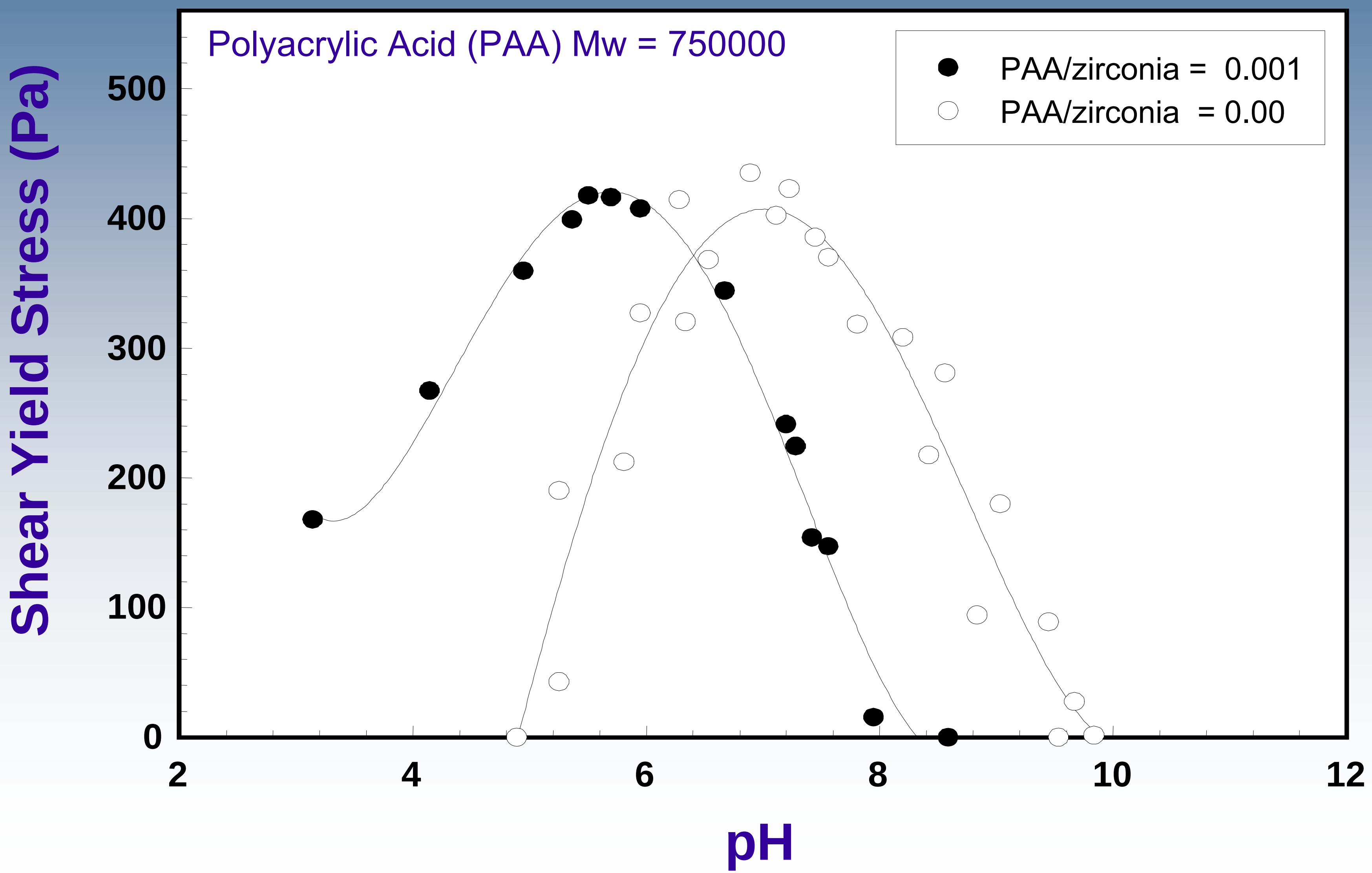
Z-Tech ZrO_2, S.A. = 15 m^2/g

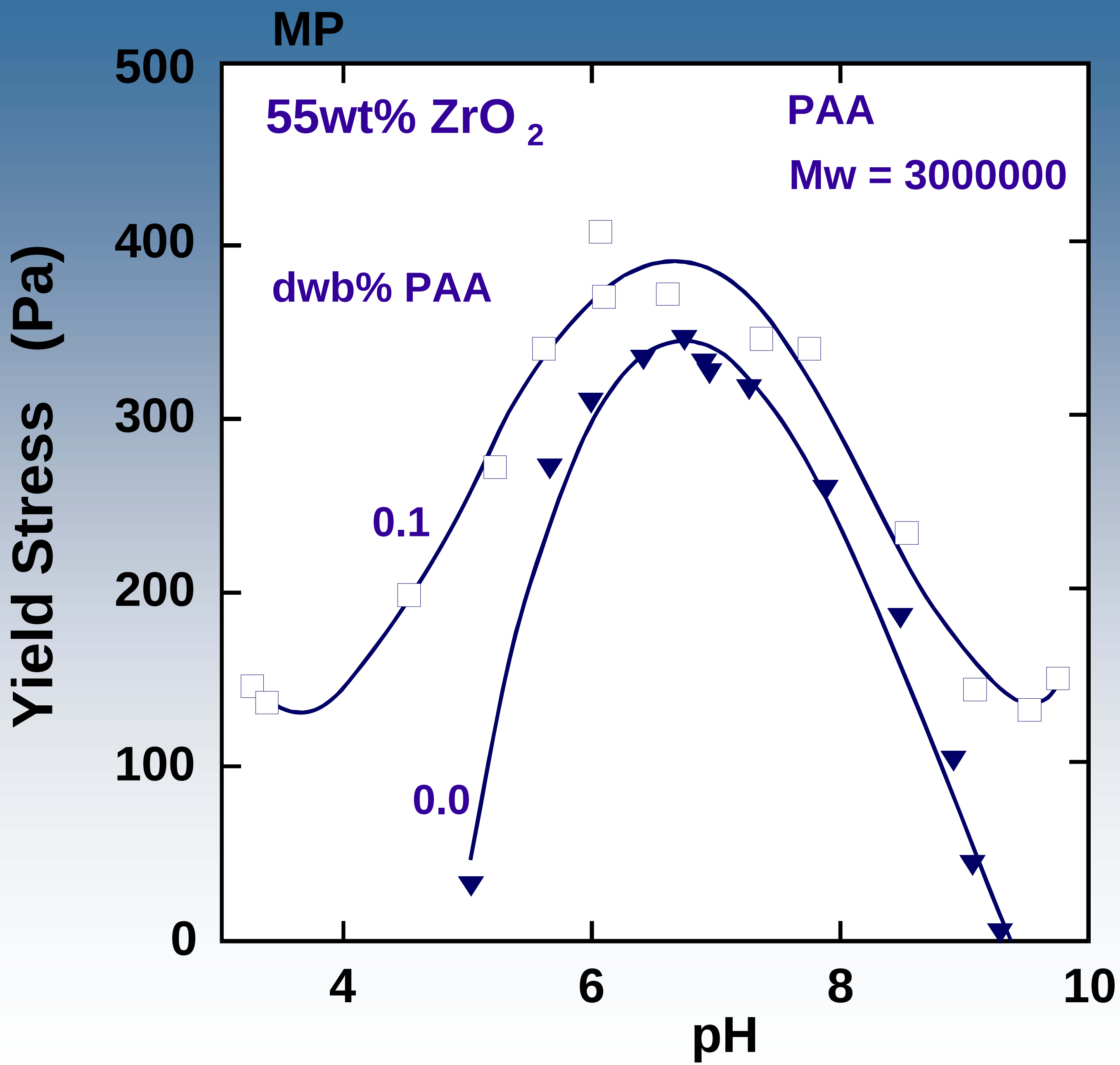
Yield stress-pH behaviour of 57wt% ZrO_2 suspensions treated with sodium polyacrylate of molecular weight: a)2103, b)4810



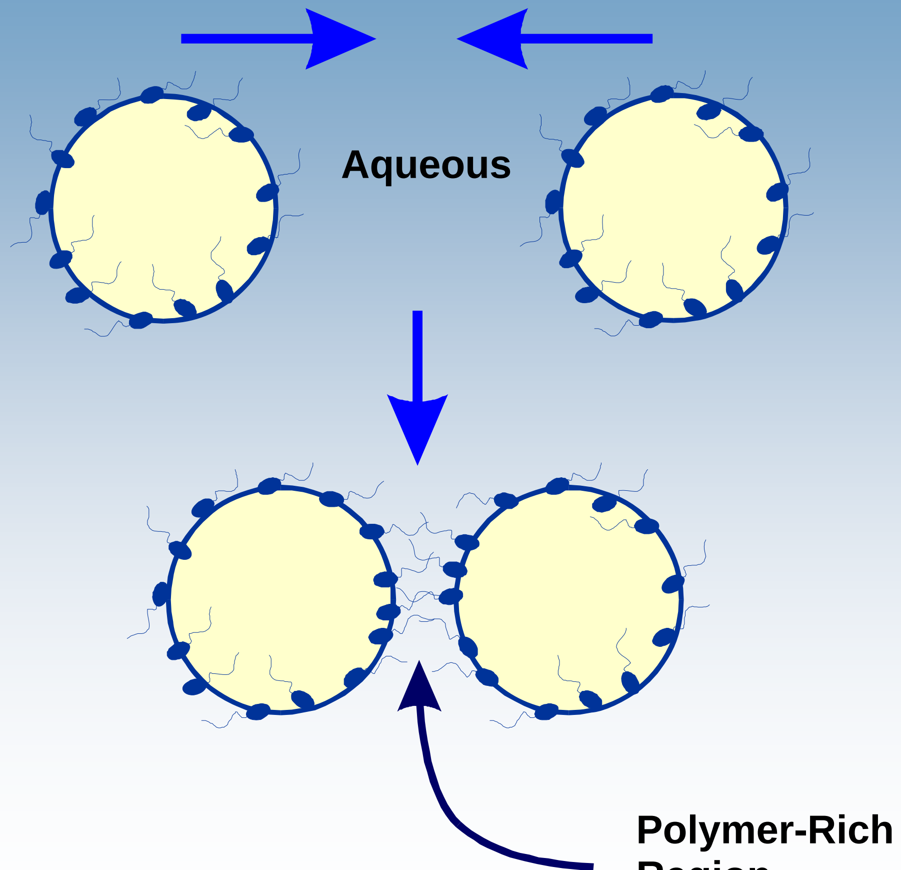
Leong, Y.K., Scales, P.J., Healy T.W. and Boger, D.V.,
94th Annual Meeting, American Ceramic Society, Minneapolis (1992)

Shear Yield Stress of Zirconia Suspension at 57wt% as a Function of pH and the Concentration of High Molecular Weight PAA




MP
55wt% ZrO 2
PAA
Mw = 3000000
dwb% PAA
0.1
0.0
500
400
300
200
100
0
4
6
8
10
pH
Yield Stress (Pa)

Hydrophobic Interaction



At IEP: $V_T = V_{VdW} + V_{hydrophobic}$

Hydrophobic interaction occurs when the adsorbed polymer chains have greater affinity for each other than for the aqueous medium

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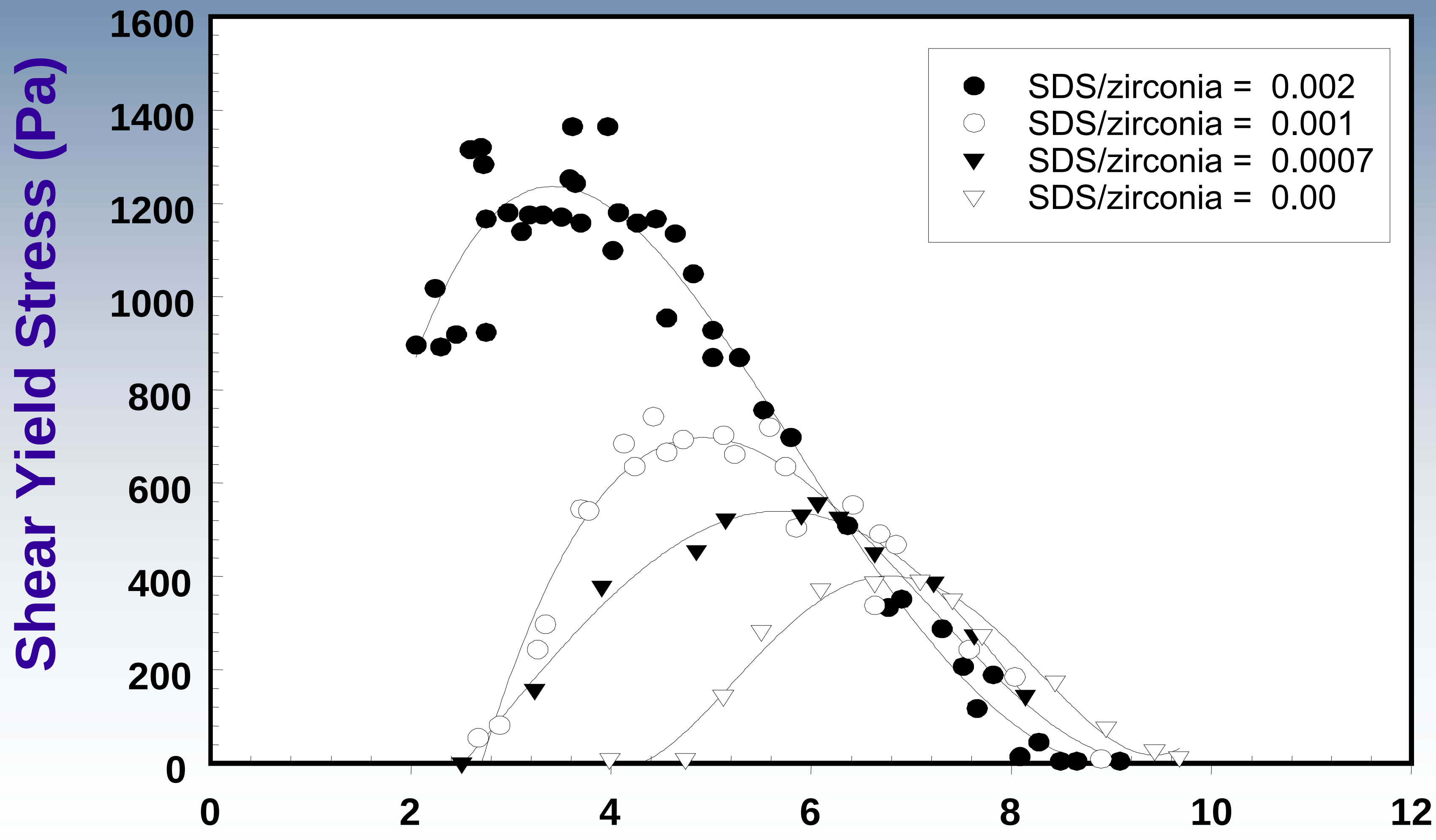
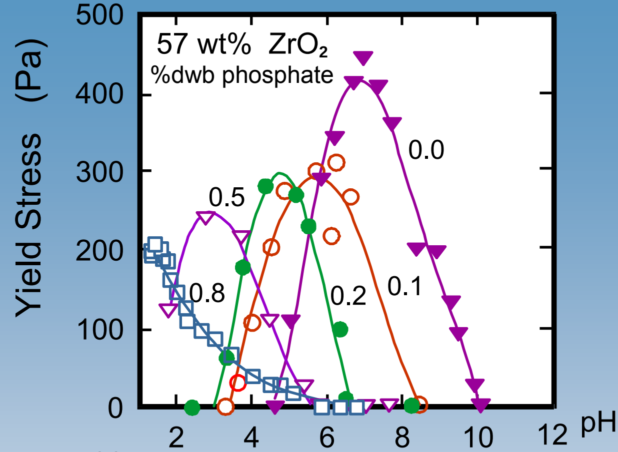
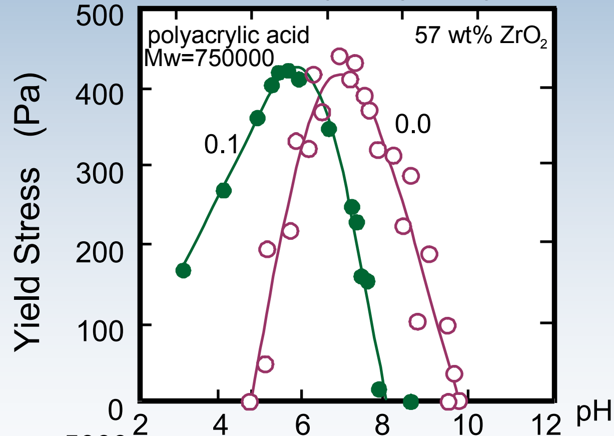
Shear Yield Stress of Zirconia Suspensions at 57% as a function of pH and Concentration of Sodium Dodecyl Sulfate (SDS)



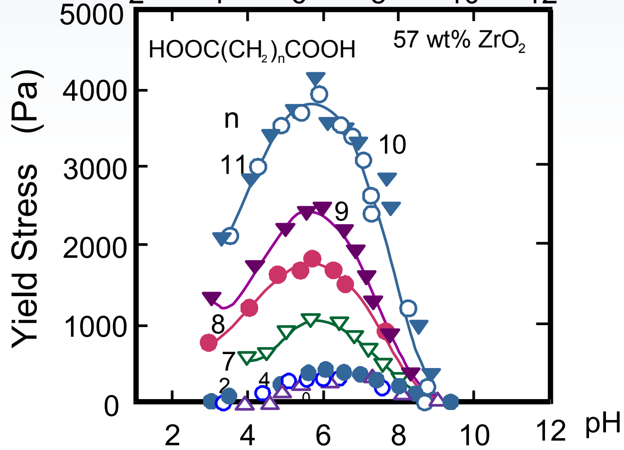
STERIC

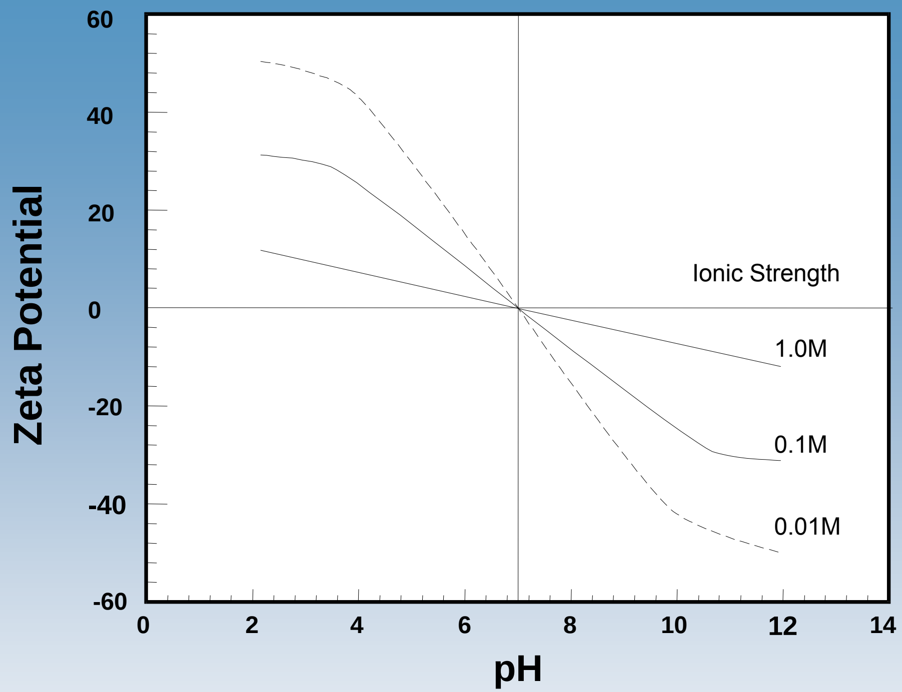


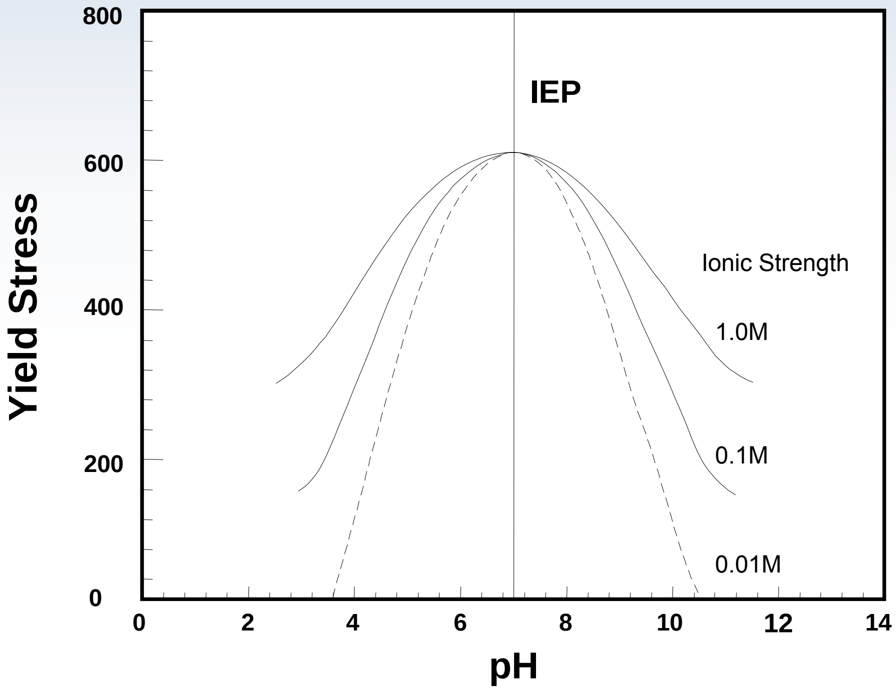
BRIDGING



HYDROPHOBIC



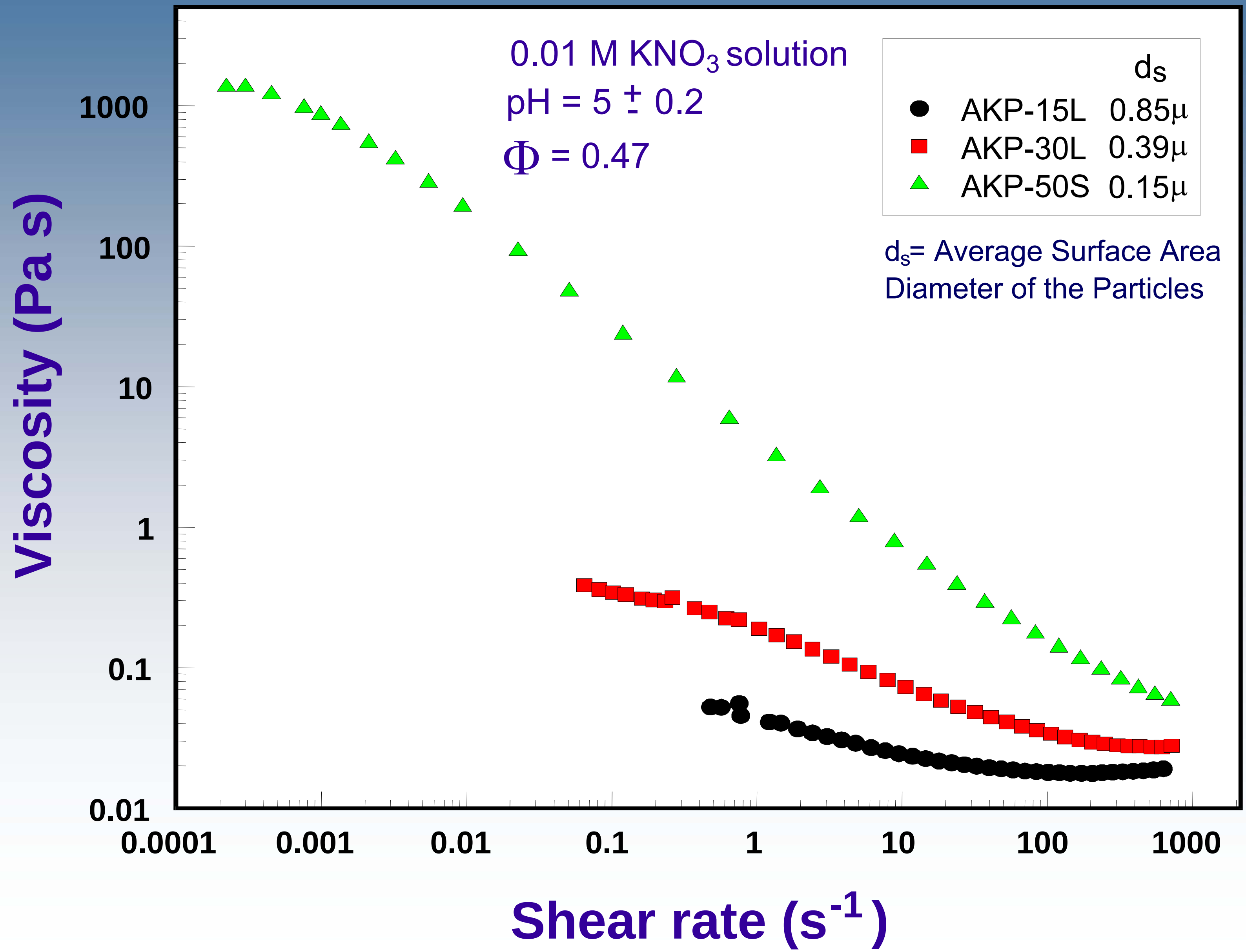

Zeta Potential
60
40
20
0
-20
-40
-60
0
2
4
6
8
10
12
14
pH
Ionic Strength
1.0M
0.1M
0.01M


Yield Stress
800
600
400
200
0
0
2
4
6
8
10
12
14
pH
IEP
Ionic Strength
1.0M
0.1M
0.01M

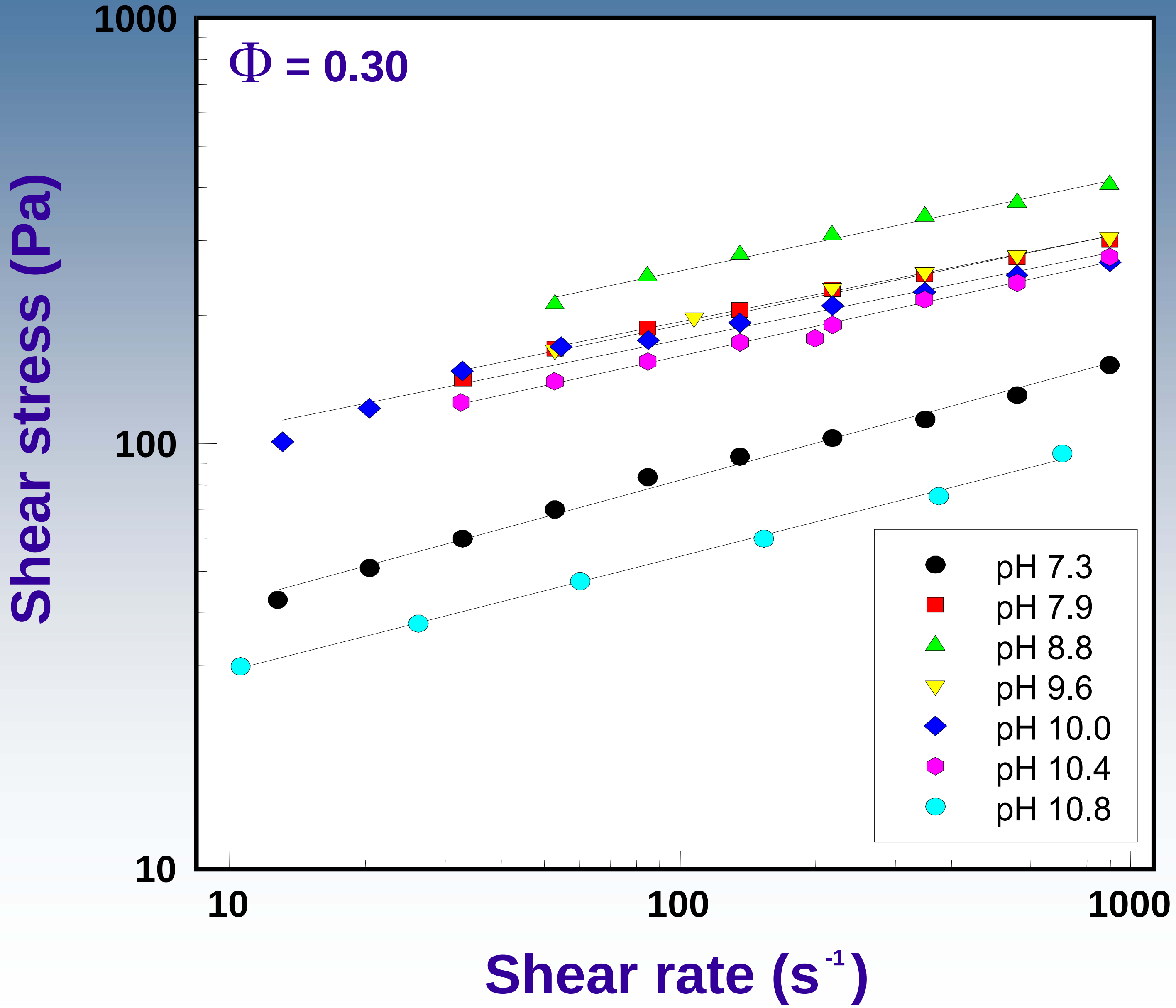
Properties of Alumina Particles

Samples	Density (g/cm^3)	BET Surface Area (m^2/g)	Mean Diameter (mm)
AKP-15	3.99	3.8	0.7
AKP-20	3.98	4.3	0.54
AKP-30	3.96	6.8	0.36
AKP-50	3.95	10.5	0.18

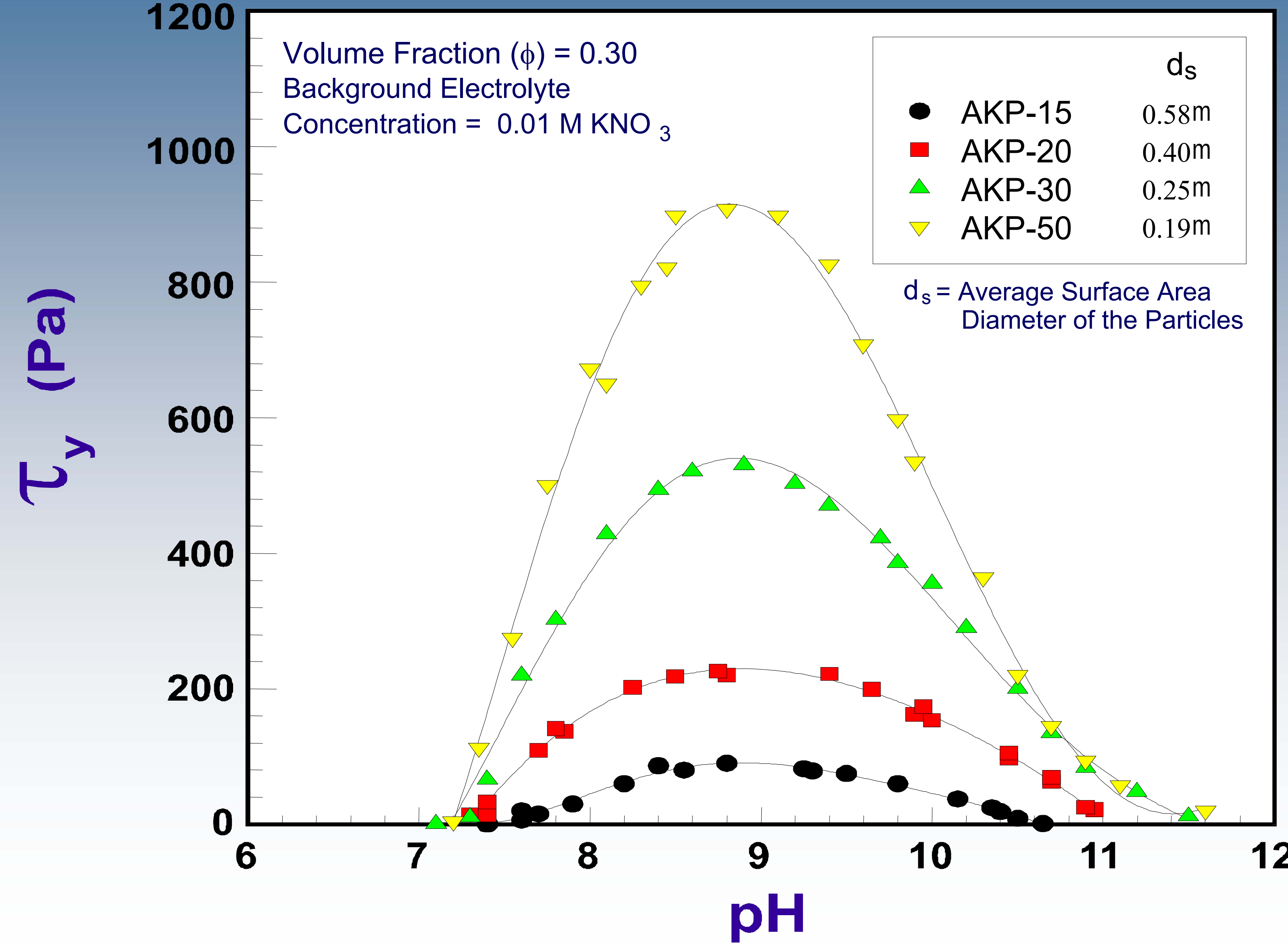
The Effect of Particle Size on the Viscosity of Alumina Suspensions



Flow Curves for AKP-20 Suspensions at various pH



Yield Stress as a Function of pH for Alumina Suspensions of Different Particle Sizes



For Monodisperse Particle Systems

At the iep

$$\tau_y = \frac{0.011\phi K(\phi,d)}{\pi}\left(\frac{A}{h_0^2}\right)\frac{1}{d}$$

where A is the Hamaker constant

h_0 is the interparticle spacing at contact

d is the particle diameter

Away from the iep

$$\tau_y = \frac{0.011\phi K(\phi,d)}{\pi}\left(\frac{A}{h_0^2} - \frac{24\pi\varepsilon\kappa\zeta^2}{(1+e^{\kappa h_0})}\right)\frac{1}{d}$$

Normalised Yield Stress

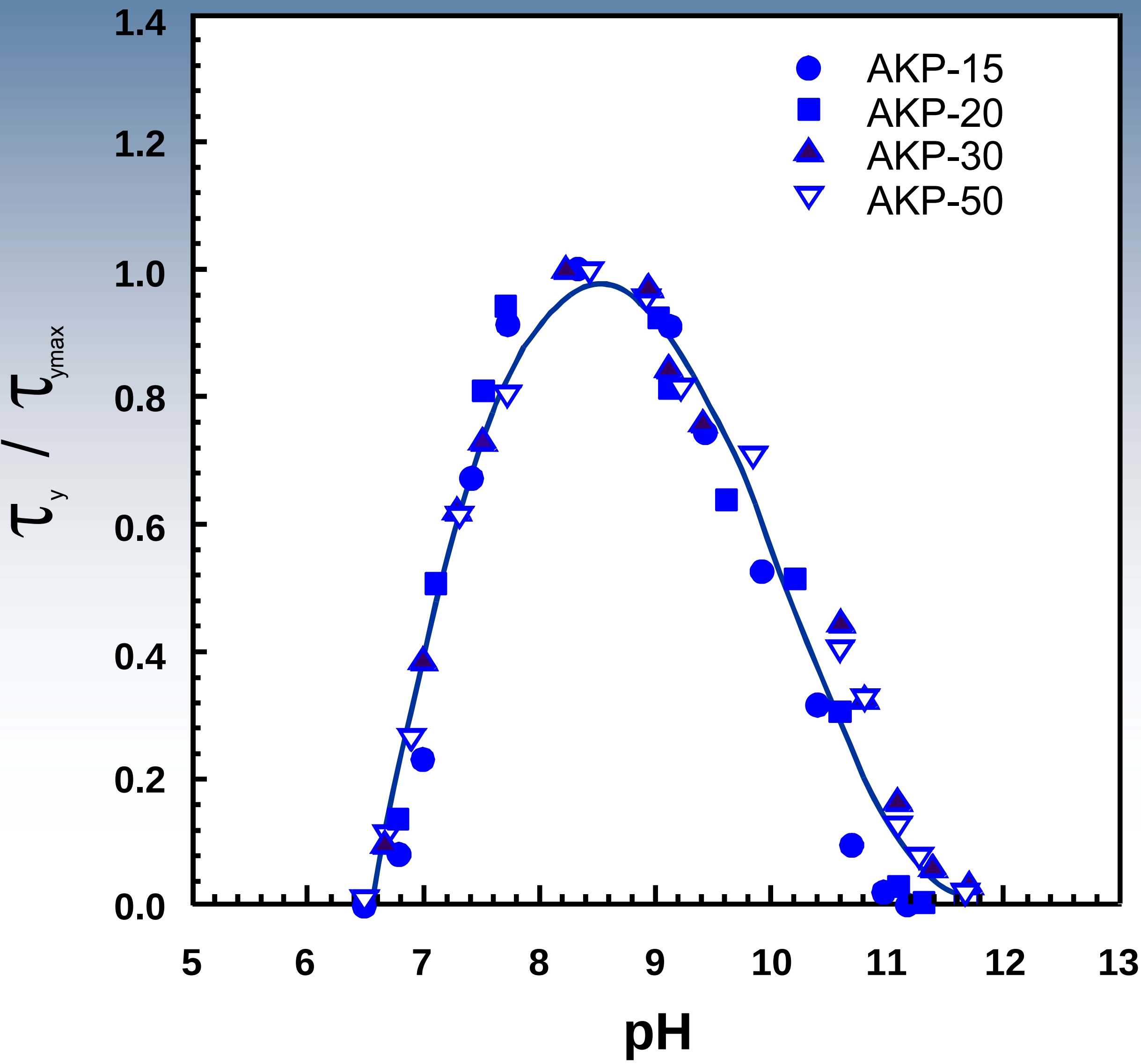
$$\frac{\tau_y}{\tau_{ymax}} = 1 - \frac{24\pi\varepsilon\kappa\zeta^2 h_0^2}{A(1+e^{\kappa h_0})}$$

No Volume Fraction Dependence

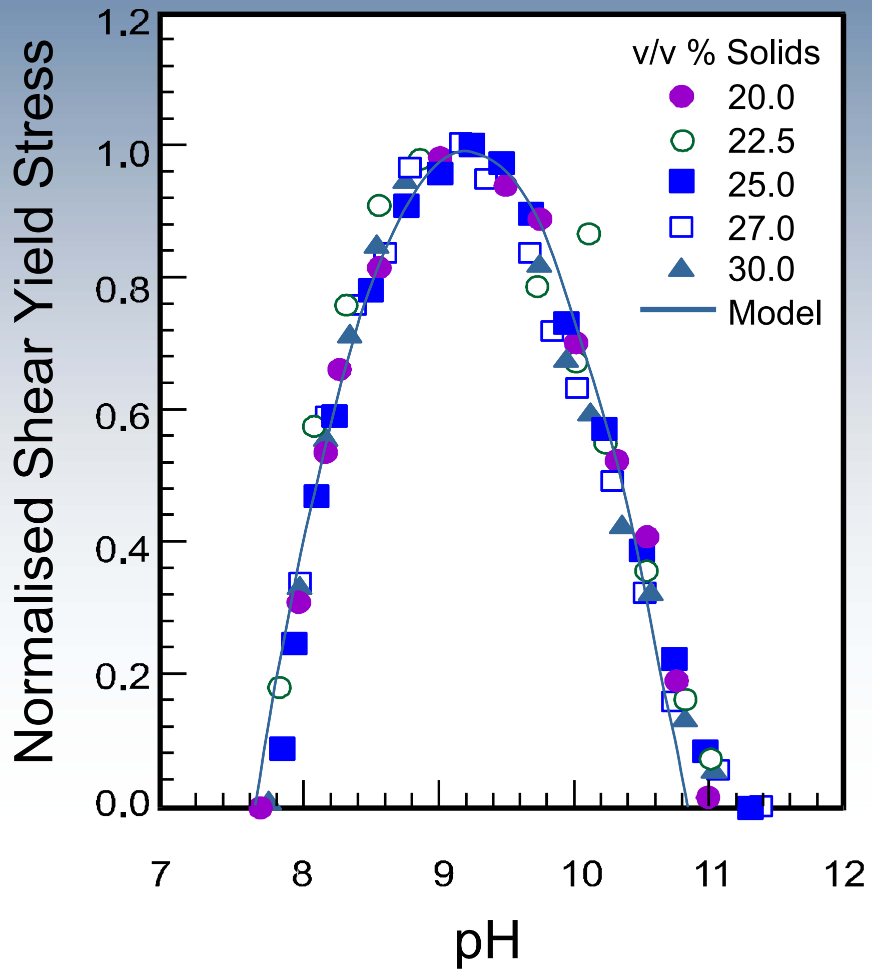
No Size Dependence

h_0 is the only Fitting Parameter

Force Comparison



Effect of Volume Fraction on Yield Stress

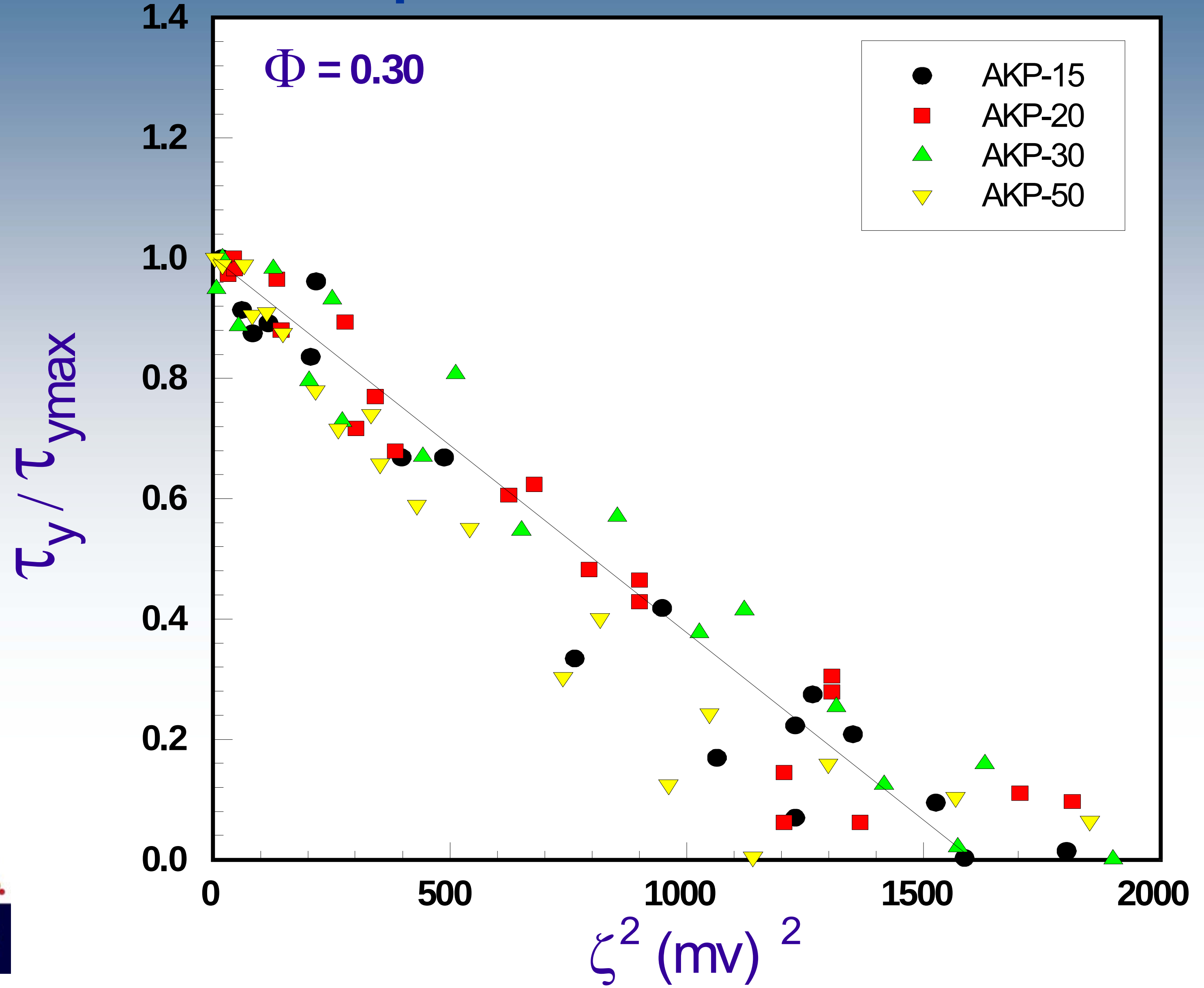


Normalised Yield Stress

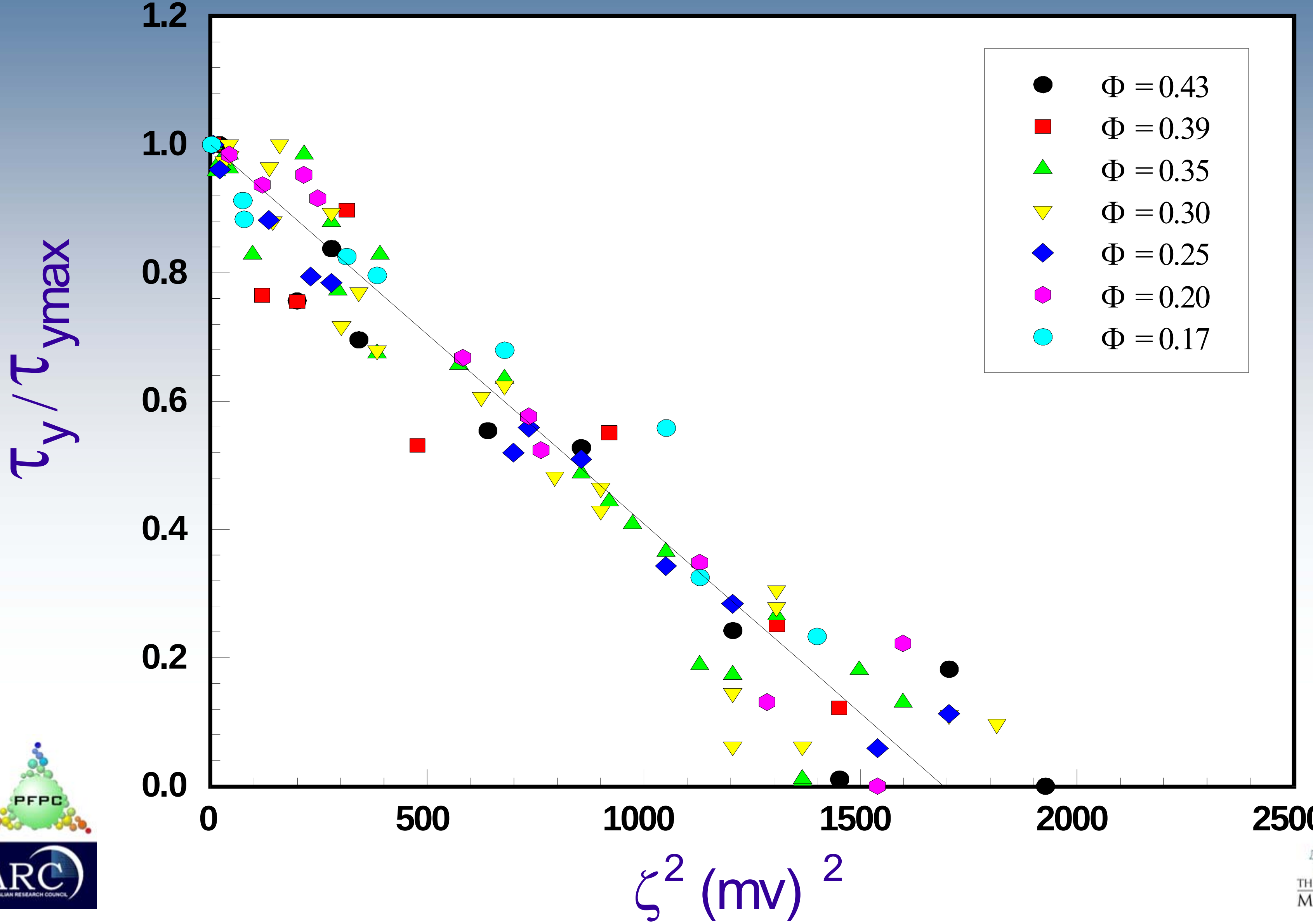
$$\frac{\tau_y}{\tau_{ymax}} = 1 - \frac{24\pi\varepsilon\kappa\zeta^2 h_0^2}{A(1+e^{\kappa h_0})}$$

- No Volume Fraction Dependence
- No Size Dependence
- h_0 is the only Fitting Parameter

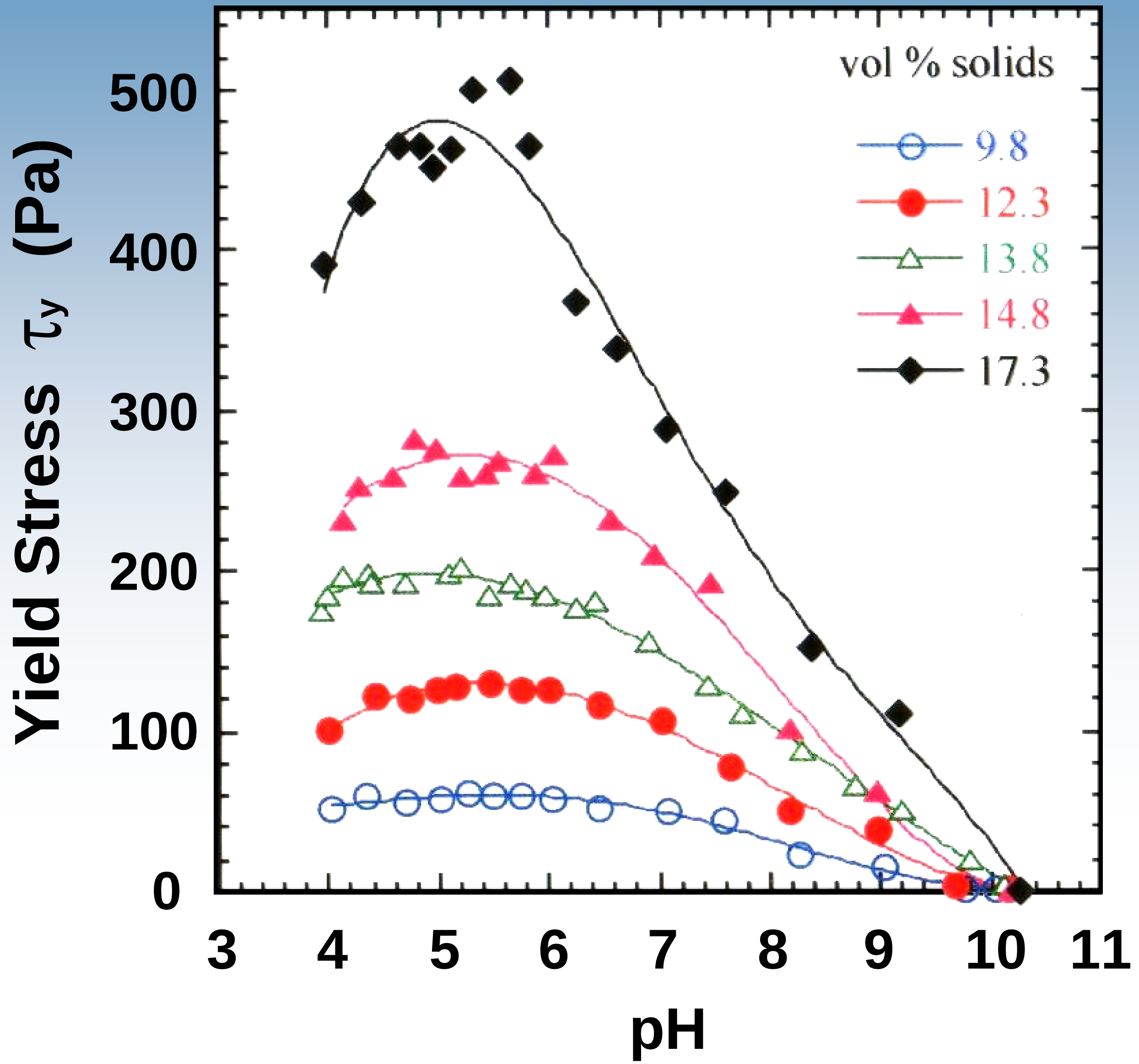
The Normalised Yield Stress as a Function of ζ^2 for Alumina Suspensions of Different Particle Sizes



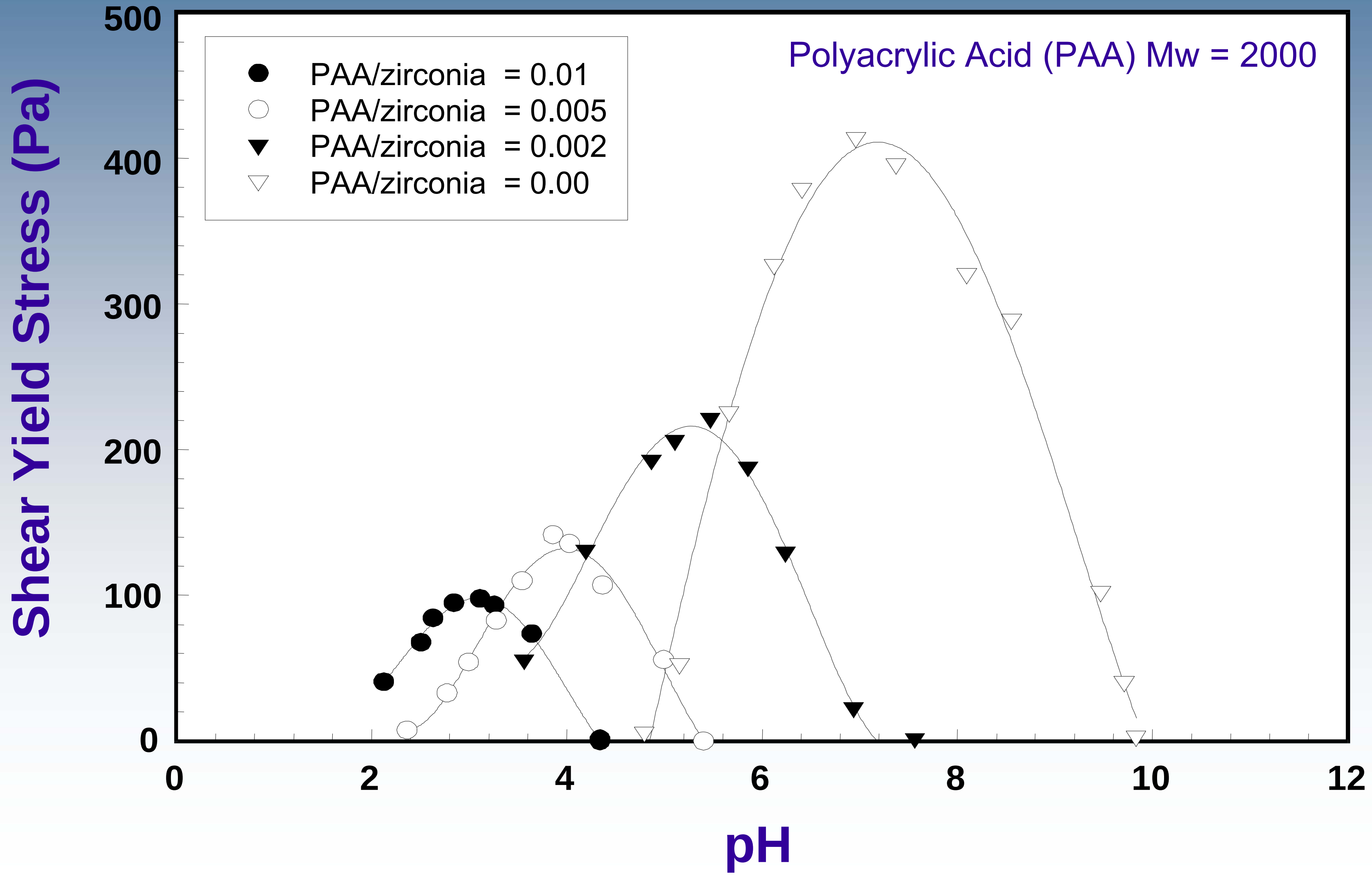
Normalised Yield Stress of Alumina Suspensions as a Function of ζ^2 for AKP-20.



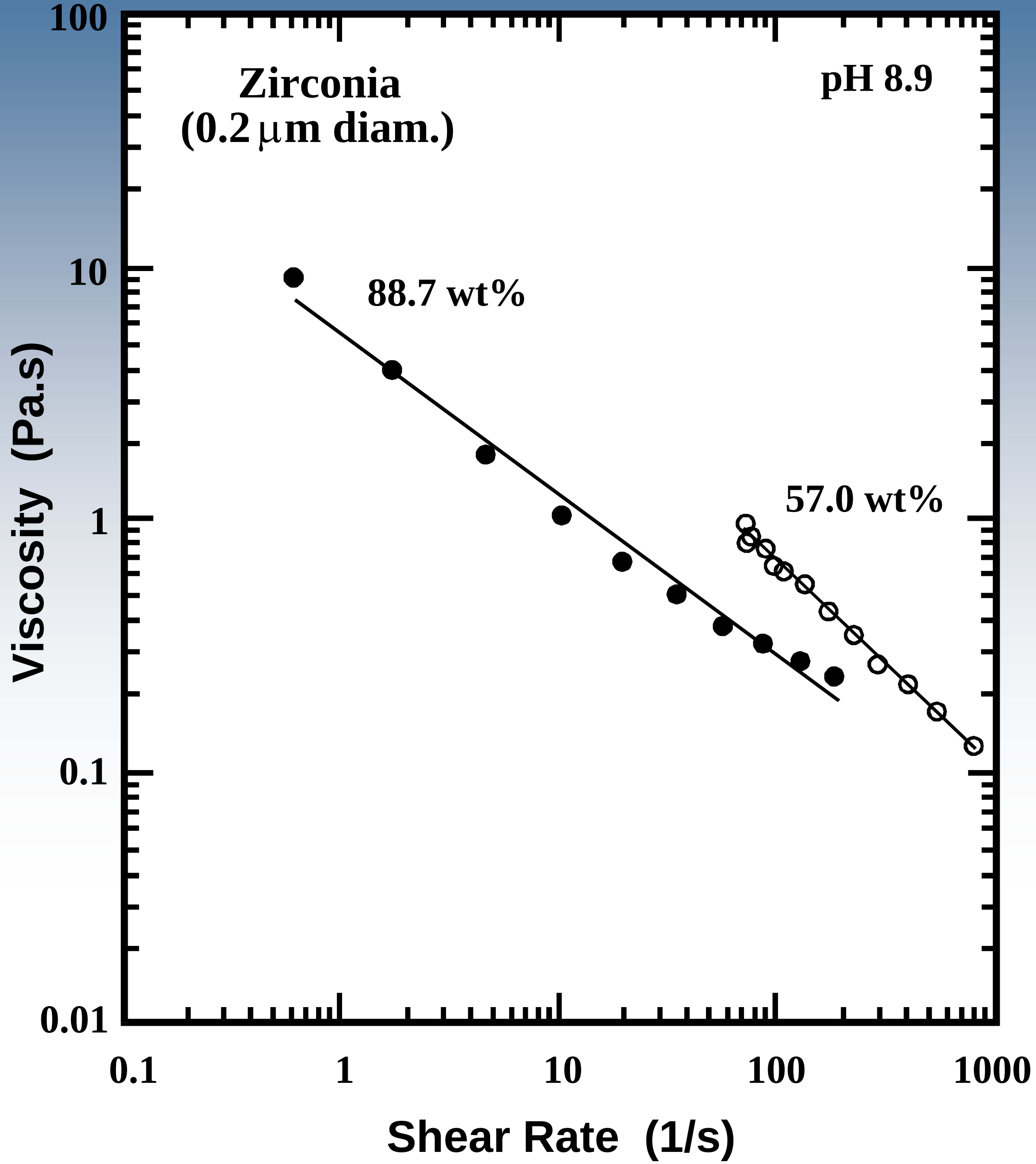
Kaolin Rheology



Effect of Low Molecular Weight Polyacrylic Acid on the Shear Yield Stress - pH behaviour for a Zirconia Suspension at 57wt%

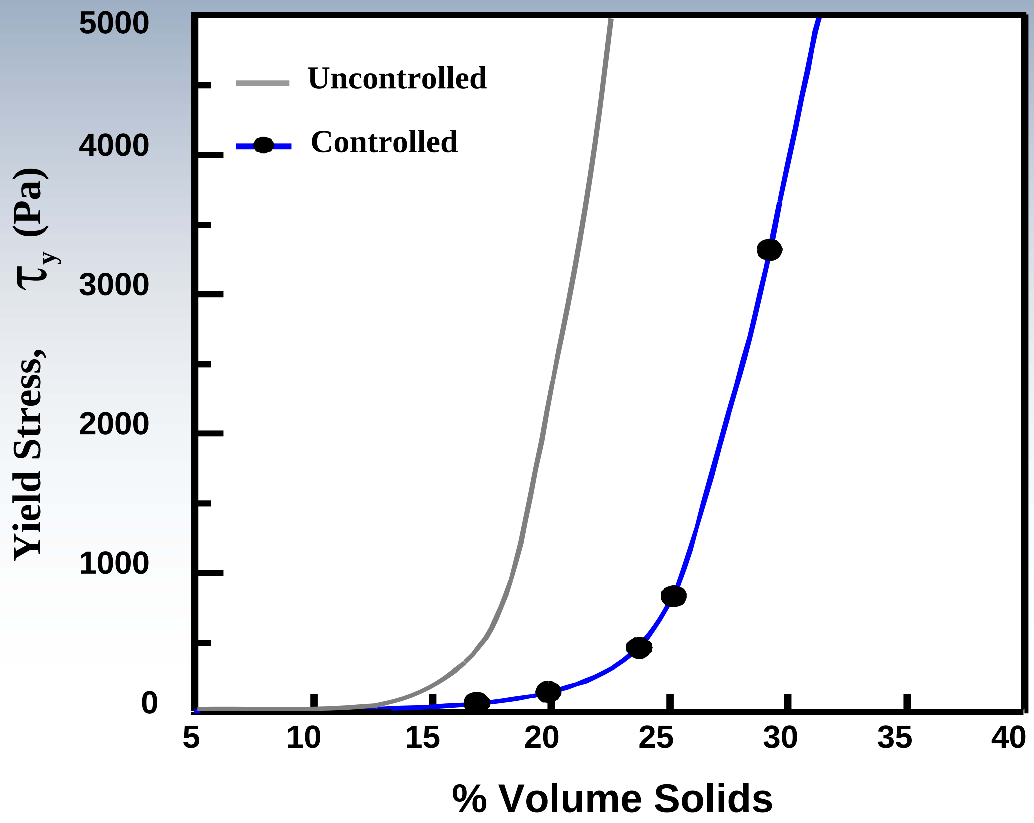


Manipulating the Flow Characteristics of Particulate Fluids



20g clay in 60g H_20 25% solids	Uncontrolled Dispersion 25% solids in 1 M $CaCl_2$	Controlled Dispersion 25% solids in 1 M $CaCl_2$

Effect on Yield Stress vs Volume Fraction Behaviour for Clay Dispersed in $CaCl_2$ *and* Clay Dispersed in Water with $CaCl_2$ added later.



Sustainability, Recycling and Environmental Modelling

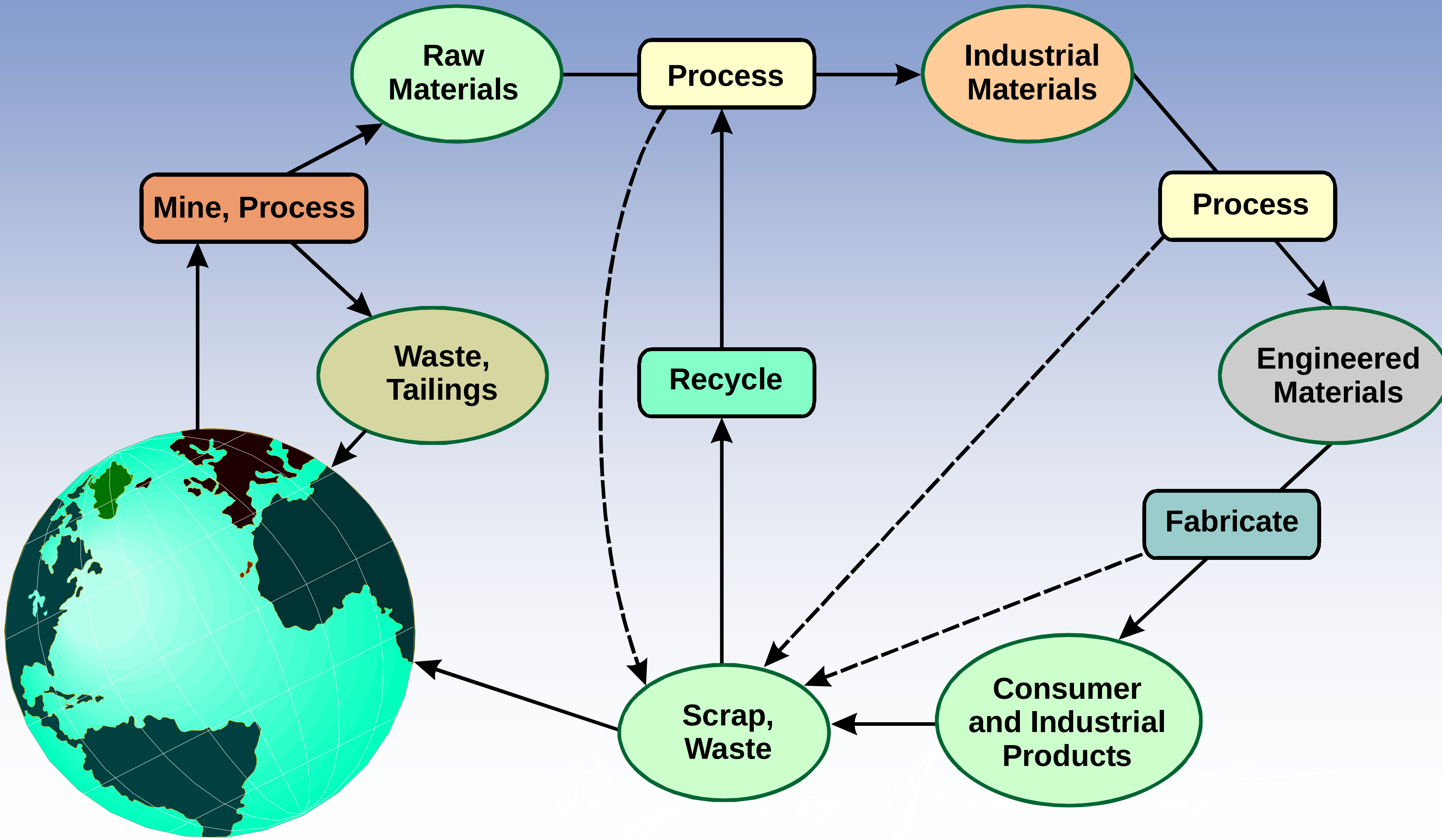


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Photo by Stuart Kirsch, 1996.

This forest was killed by dieback after being smothered with mine waste. It is on the lower Ok Tedi River near Dome Village.

*I*n-pit Fill

Environmental Policy and Tailings Disposal

Bob Watts

Chief Scientist and Vice President Technology

BHP Billiton

bhpbilliton

Main Menu

Ok Tedi Copper Mine in PNG

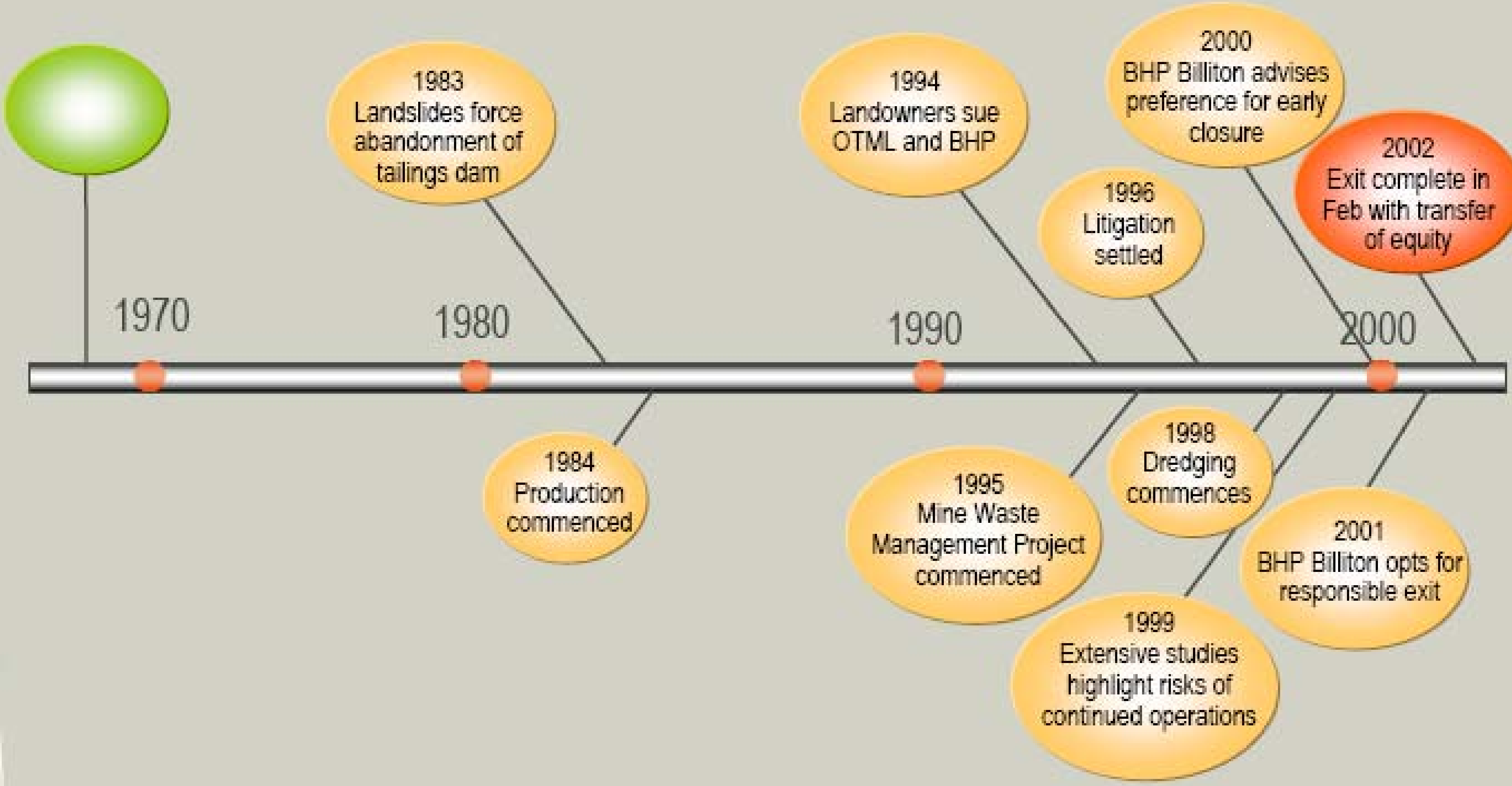

Photo by Stuart Kirsch, 1996.

This forest was killed by dieback after being smothered with mine waste. It is on the lower Ok Tedi River near Dome Village.

OK TEDI UPDATE

- Record profit – US$318.8 million – a 23% increase on previous year

- "…we are concerned that OTML's environmental monitoring indicated that the environmental impact of the mine may prove to be greater than previously understood."

  (Managing Director, Keith Faulkner)

- "In February 2005, areas of acid rock drainage were appearing on the levees of the Fly River….."

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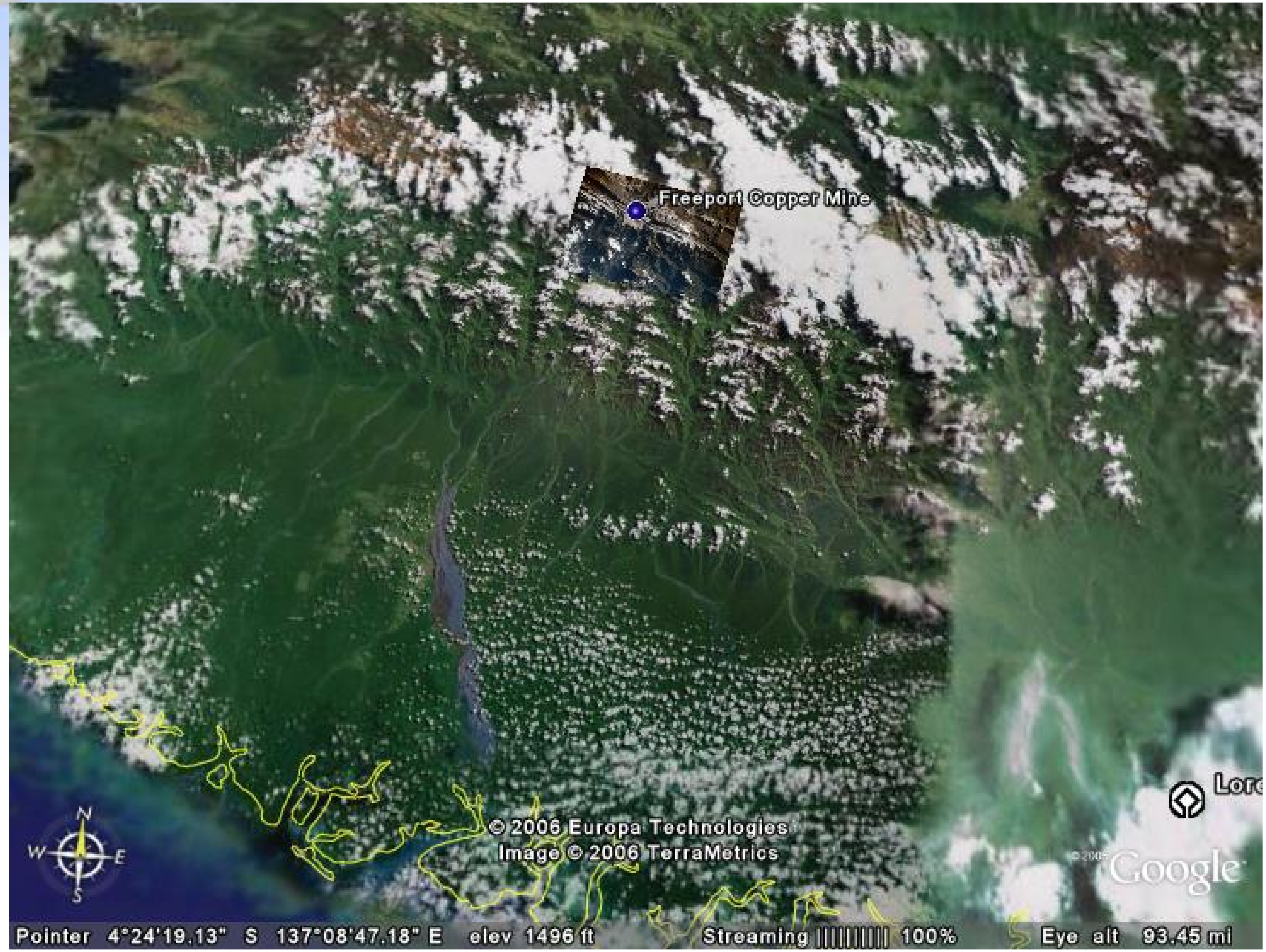
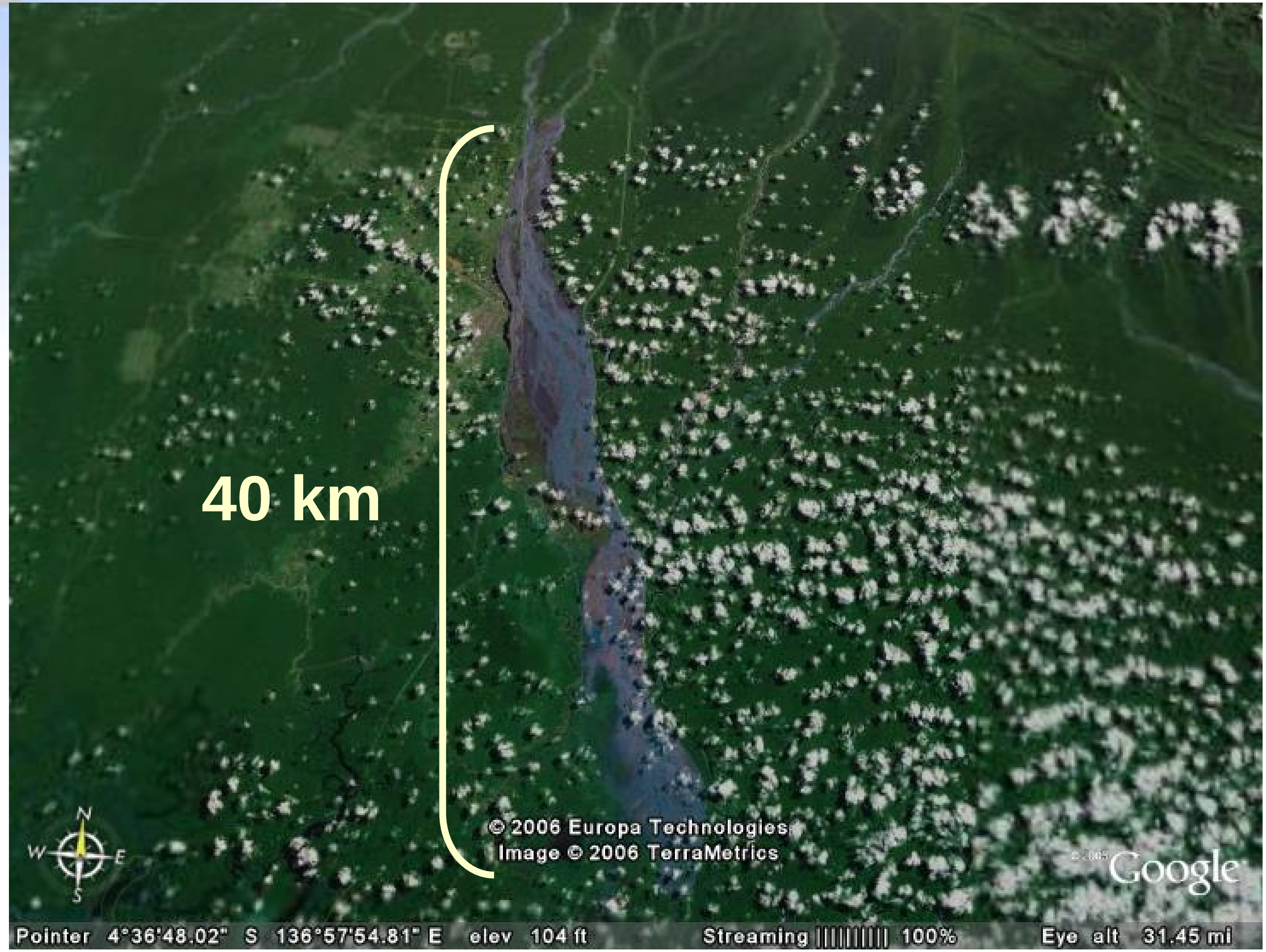
Freeport Copper Mine
Papua
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
Google
N
W
E
S
Pointer 4°24'19.62" S 137°08'47.22" E elev 1669 ft
Streaming |||||||||| 100%
Eye alt 776.00 mi


Freeport Copper Mine
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Google
Pointer 4°24'19.13" S 137°08'47.18" E elev 1496 ft
Streaming |||||||||| 100%
Eye alt 93.45 mi



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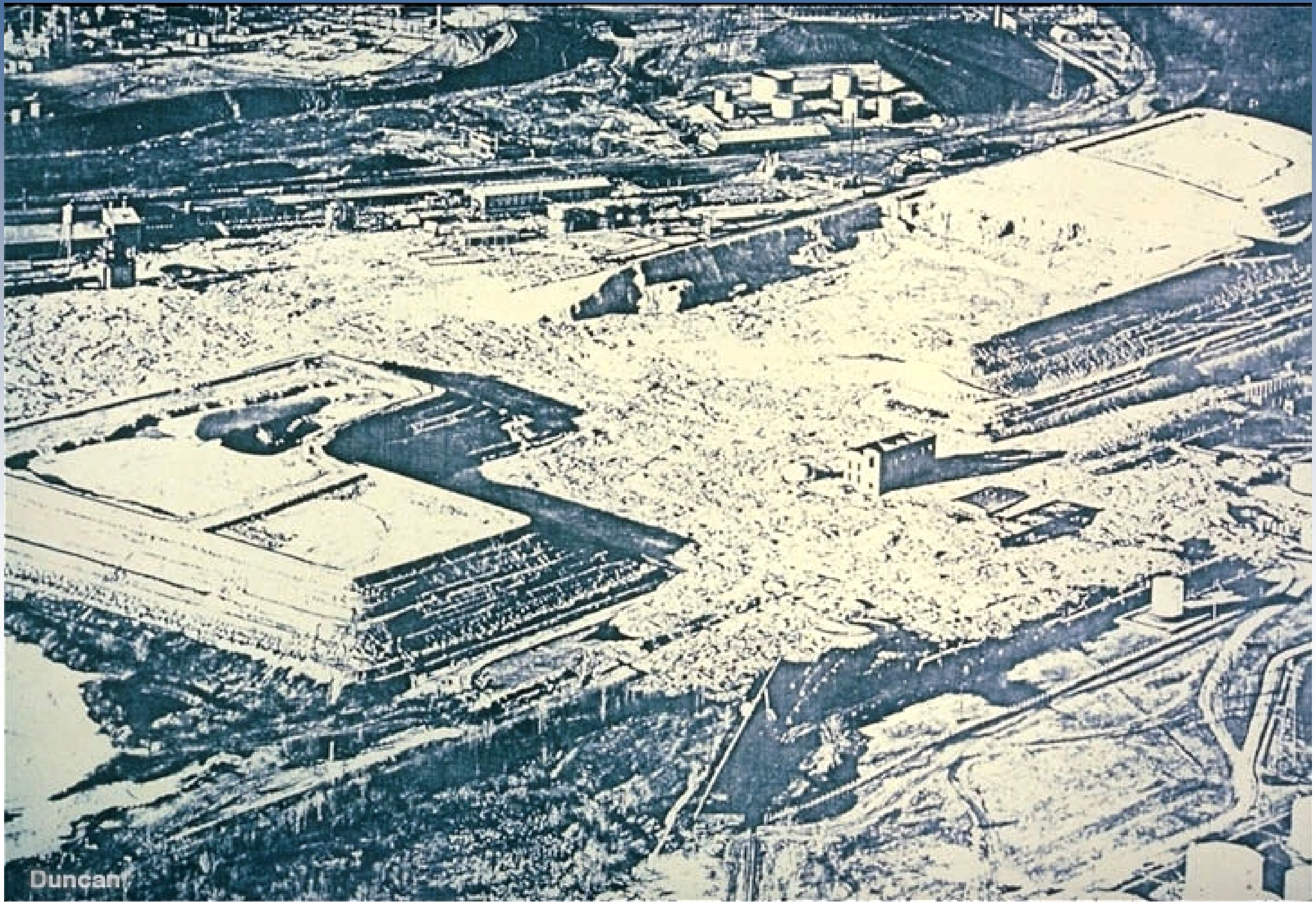
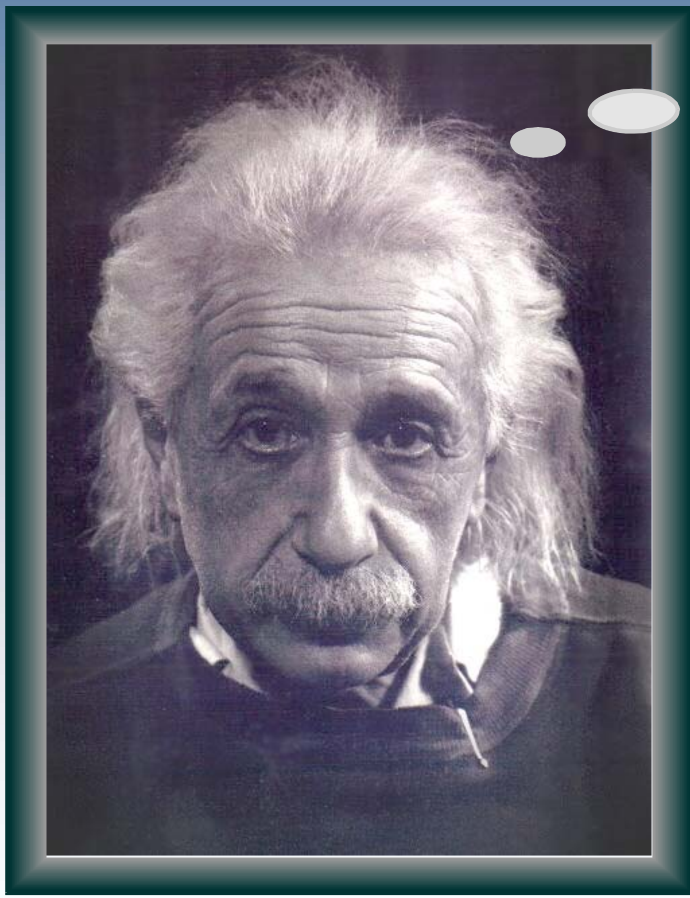
Failure of dam holding platinum tailings in South Africa



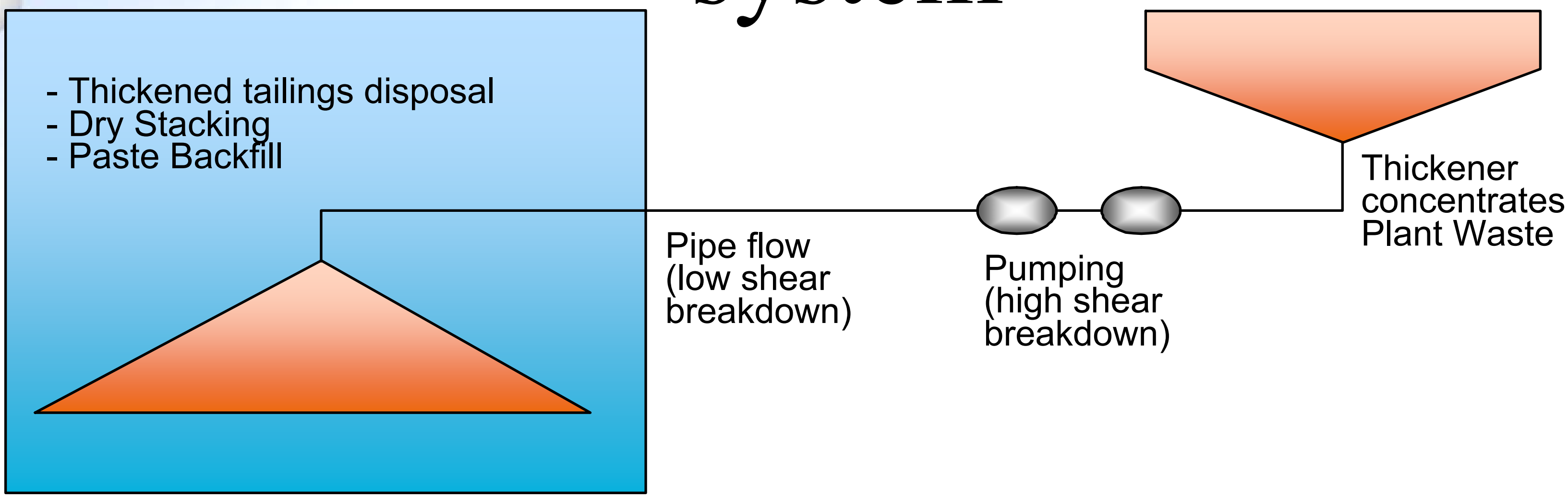
Failure of a carbide tailings pond near Louisville, Kentucky.

Failure of dam retaining gypsum tailings in Florida



A problem cannot be solved with the same kind of thinking that created it...

Suggested approach for determination of tailings disposal system



DESIGN SEQUENCE

1. Choice of disposal method, Depositional requirements.
2. Rheology requirements for pipeline transport.
3. Thickener design.

New Developments

- **Compression Rheology**

  - Compressive Yield Stress

  - Permeability

See: BSR Annual Rheology Review 2002: Compressive Rheology: An Overview, Ross G. de Kretser, David V. Boger and Peter J. Scales

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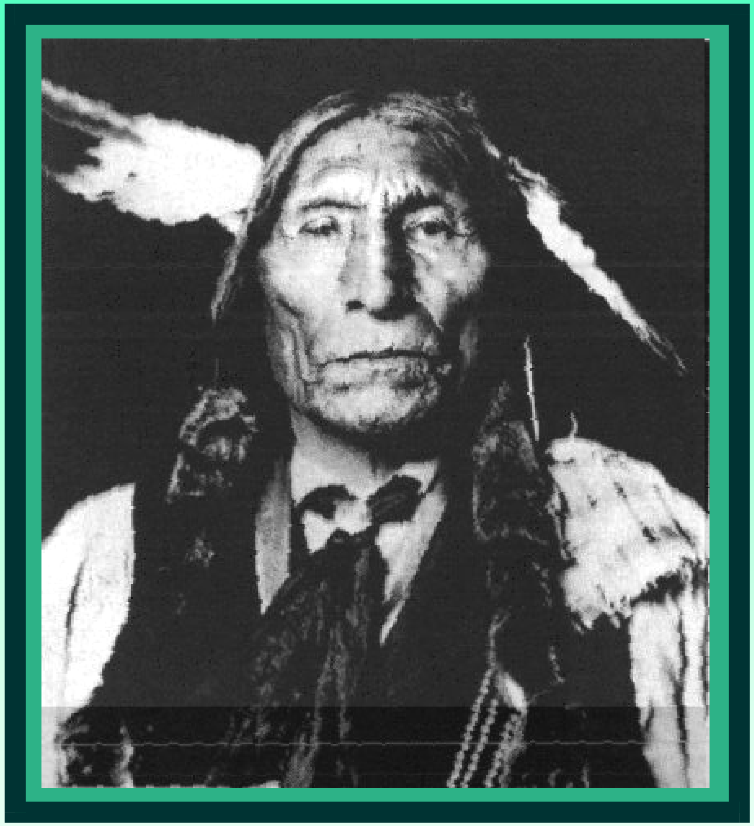
Rheology – Changing thinking in the minerals industry

D V Boger
Laureate Professor
The University of Melbourne
Victoria, Australia

Paste and Thickened Tailings Seminars

- Edmonton, Canada, November 1999 hosted by the University of Alberta
- Perth, Australia, April 2000 hosted by the Australian Centre for Geomechanics
- Edmonton, Canada, October 2000 hosted by the University of Alberta
- Pilanesberg, South Africa, May 2001 hosted by the University of the Witwatersrand
- Santiago, Chile, April 2002 hosted by the Instituto de Ingenieros de Minas de Chile and Gecamin Ltda
- Melbourne, Australia, May 2003 hosted by the Australian Centre for Geomechanics and the University of Melbourne
- Cape Town, South Africa, March 2004 hosted by the University of the Witwatersrand and Paterson and Cooke Consulting Engineers Pty Ltd
- Santiago, Chile, April 2005 hosted by the University of Chile
- Limerick, Ireland, April 2006 hosted by Leeds University, Dorr-Oliver EIMCO and Golder Associates (UK) Ltd
- Perth, Australia, March 2007 hosted by the Australian Centre for Geomechanics
- **Rheology discovered!**



Wolf Robe (June 1909)

"Only when the last tree has died
and the last river has been poisoned
and the last fish been caught
will we realise
we cannot eat money."

Cree Indian saying

Sustainable Development is the Simultaneous Striving for Economic Prosperity, Environmental Health and Social Well-being.

"Environmental considerations dictate that we must manipulate tailings to fit a particular environment rather than manipulating the environment to contain the tailings."

Understanding and exploiting the rheology of tailings helps us do this.

The Regulatory Trend

"It is interesting to observe that many times more technical effort is devoted to ground water and toxicological studies for abandoned deposits than was ever allocated for their original design and generation.

Unfortunately much of the cost has been borne by government; should we then be surprised that responsible government is therefore imposing much greater regulatory security?"

S.G. Virk, 1990

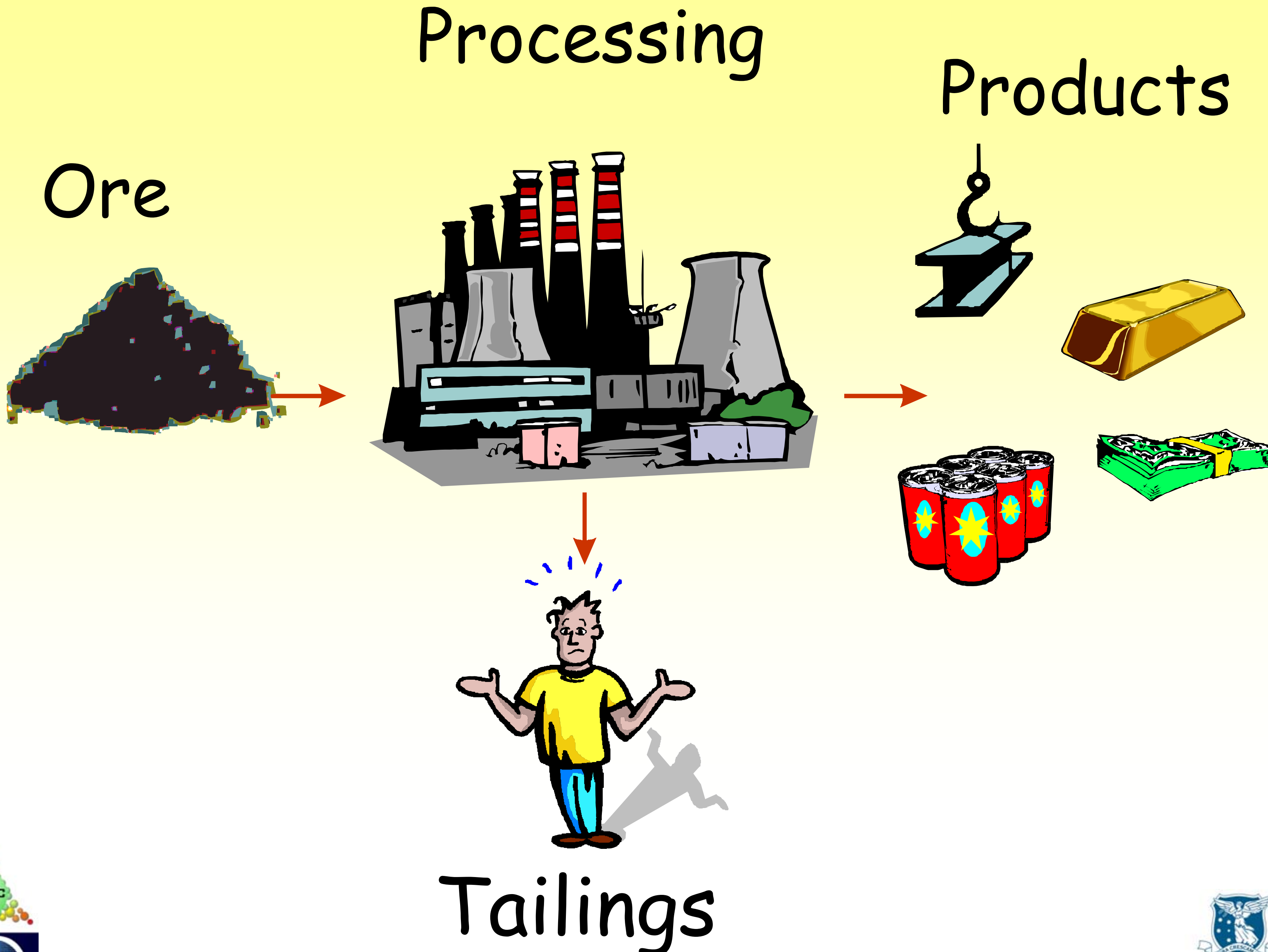
Rheological Consulting Services

Rheological Consulting Services Pty. Ltd.

- Australia
- Canada
- Chile
- Jamaica
- New Guinea
- South Africa
- USA
- New Caledonia
- Indonesia

The evidence is getting stronger that what is good for sustainable development can also be good for business, in sometimes surprising ways.

Business, society and the environment can "succeed" simultaneously.



Processing
Products
Ore
Tailings