Fresh concrete: a multi-phase multi-scale rheology problem

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Heriot-Watt University - highlights

- Edinburgh - convenient for Festivals, Mountains, Whisky, Rugby
- Scottish University of the Year 2011 and 2012
- Strong international links
- School of the Built Environment hosts the Royal Academy of Engineering Centre of Excellence in Sustainable Building Design

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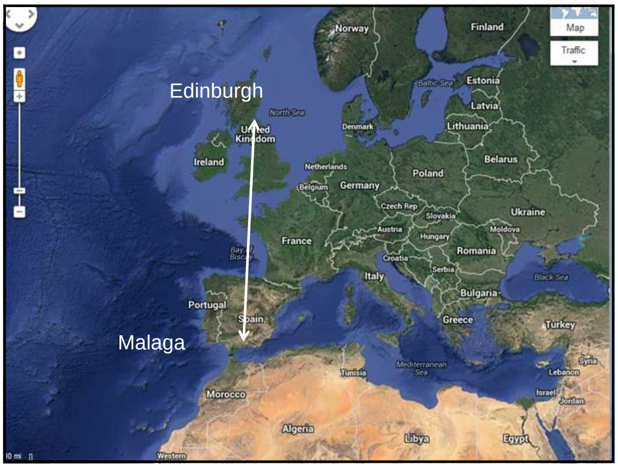

Talk overview

1. Fresh concrete
2. Cement paste
3. Mortar
4. Computer simulation

Part 1. Fresh concrete

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Reinforced concrete

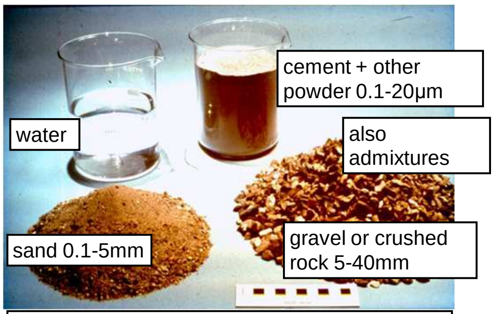
Universal construction material: 10^{12} tonnes/year.

The reinforcement may be very congested so the concrete has to be sufficiently fluid and cohesive to flow around it without segregating.

Flow of fresh concrete

Fresh concrete

Concrete ingredients



Multi-scale – nanometres to metres

Concrete is a suspension

Viscosity of suspensions of particles in water

Inert spheres at low concentration (Einstein):

$$\eta = \eta_s (1 + 2.5\phi)$$

Inert particles at high concentration (Krieger-Dougherty):

$$\eta = \eta_s \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m}$$

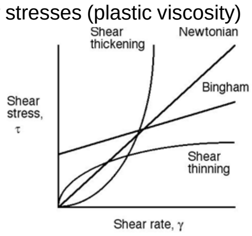
Cement is not inert

Particles attract each other in water

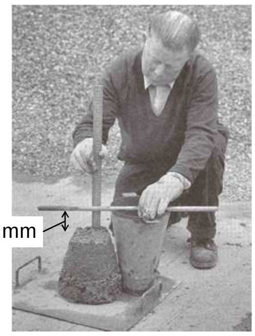
- Form a flocculated network
- Will support a stress (yield stress)
- Will flow at higher shear stresses (plastic viscosity)

Bingham model:

$$\tau = \tau_0 + \mu \dot{\gamma}$$



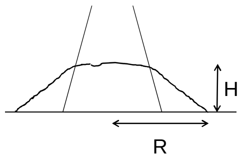
The slump test



The state-of-the-art in concrete testing (Abrams, 1922).

Fresh concrete will support its own weight – a characteristic of a Bingham

Analysis of slump test



Tattersall & Dimond 1977

110<H<240: $\tau_0 = 4.5H - 15$ (experimental)

Roussel & Coussot, 2005-6

H>>R: $\tau_0 = \frac{\rho g H}{\sqrt{3}}$ (analytical)

H~R: $\tau_0 = \rho\left(\frac{H-50}{175}\right)$ (numerical)

H<<R: $\tau_0 = \frac{225 \rho g V^2}{128 \pi^2 R^5}$ (analytical)

An instrument challenge

Rheometer size for granular materials

- Gap size must be 10x max particle size
- Surface roughness must be same as max particle size
- For cylinders outer/inner radius must be <1.1

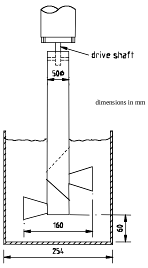
For coaxial cylinders, 20mm aggregate concrete needs a $5m^3$ sample.

$5m^3$ of concrete?

Clearly impracticable as a test sample!!

Rheometers - concrete

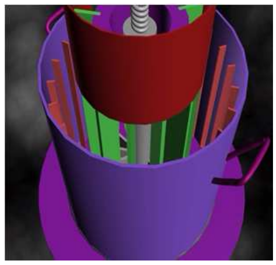
Two-point rheometer (Tattersall and Banfill, 1983 - 2002)



www.aptifirst.com (2013)

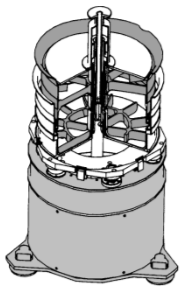
Rheometers - concrete

BML rheometer (Wallevik, 1992)

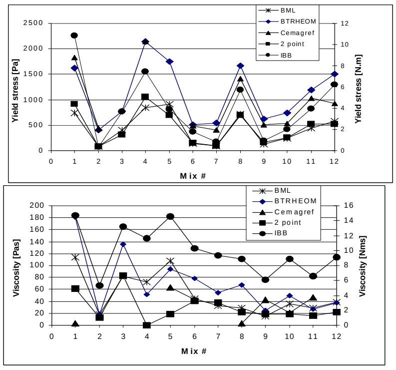


Rheometers - concrete

BTRHEOM (Ho et al, 1996)

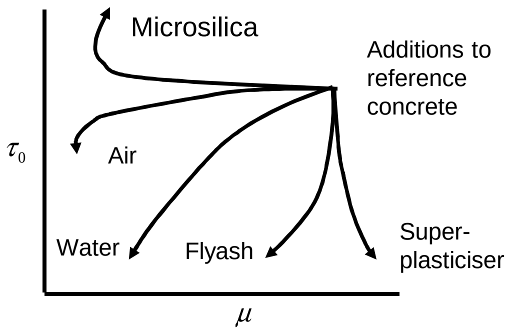


Do the concrete rheometers agree?



Ferraris et al 2001

Effects of concrete mix composition

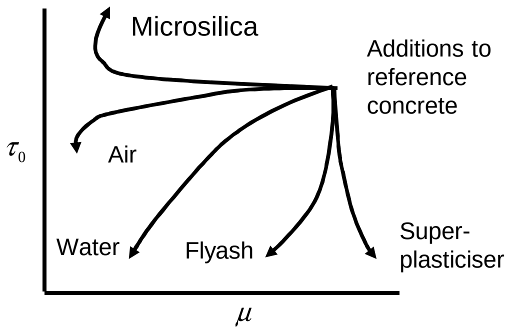


Practical applications

Rheology has been used to gain understanding of:

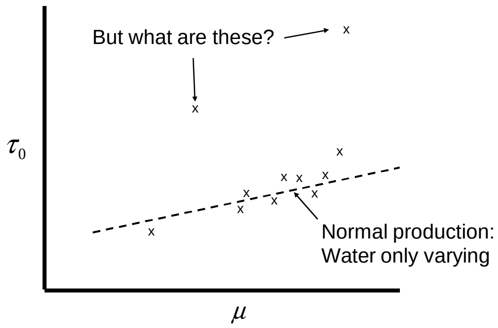
- Quality control
  Tattersall 1991
- Pumping of concrete
  Kaplan 2001
- Friction and pressure against formwork surfaces
  Djelal, Vanhove 2000, Billberg 2006, Roussel et al 2008
- Vibrational compaction of concrete
  Teixeira, Craik and Banfill 2000, 2012
- Self-compacting concrete
  Jin 2002, Wallevik 2000-2009

Effects of concrete mix composition



An application to quality control

11 batches of site produced concrete



Pumping

Long distances, high buildings, convenience on site

Formwork

Formwork must resist the stress of the concrete

Stress at foot: $\tau = \rho g h$

e.g. 120 kN/m^2

Yield stress and stiffening of concrete can help

e.g. 3 kN/m^2 initially.

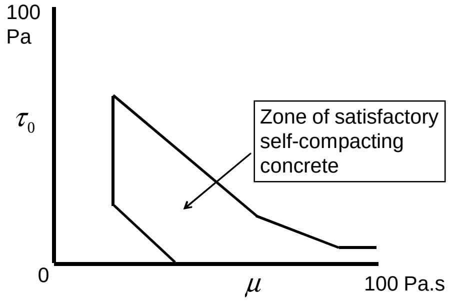
Also friction between concrete and the walls.

Vibrational compaction

Concrete is fluidised, yield stress is overcome.
Voids are eliminated.

Self-compacting concrete needs no vibration – less noise, safer for workers

Design of self-compacting concrete (Wallevik, 2000)



Review of concrete

Rheology of concrete has progressed empirically – a “top-down” approach.

But what about the “bottom-up” approach – from cement paste as a constituent?

In principle, it’s easier because of fewer variables and much easier experimentally. But…

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Part 2. Cement paste

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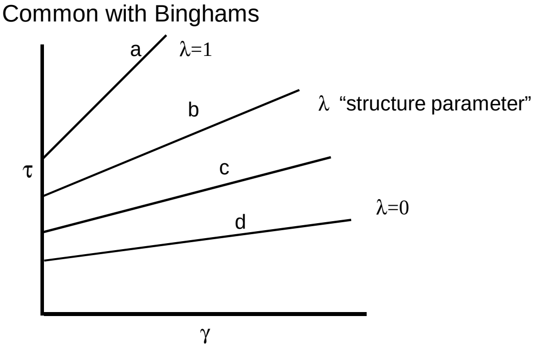
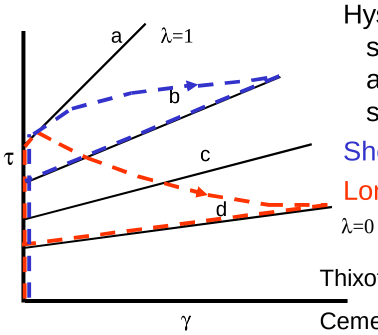
Structural breakdown

Common with Binghams



Structural breakdown



Hysteresis loop shape, τ_o and μ all depend on shear history.

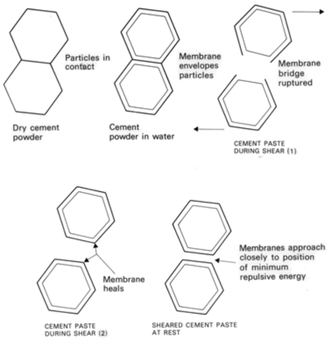
Short test time

Long test time

Thixotropy = reversible

Cement = irreversible

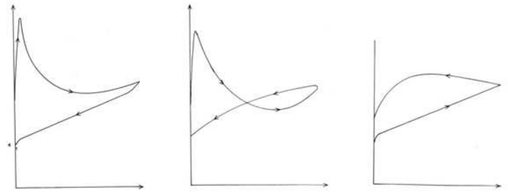
A structural breakdown model



(Tattersall and Banfill, 1983)

Hysteresis loops in cement paste

Banfill and Saunders 1981



Short - cycle times - Long

But cycle times for each loop shape depend on the cement

Hattori-Izumi approach (1984)

Based on colloid science

$$\eta_{app} = B\left[n\frac{U_0(\gamma Ht^2+1)+Ht}{(Ht+1)(\gamma t+1)}\right]^{2/3}$$

apparent viscosity

interparticle friction coefficient

no of particles

initial degree of dispersion

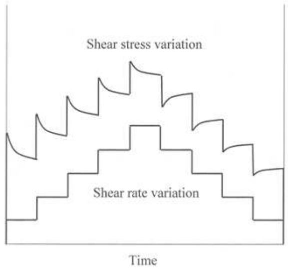
coagulation rate constant

Equation reproduces the various observed loop shapes.

Extended Hattori-Izumi

Refinement of some terms to include memory enables time dependency to be explored, modelling breakdown and rebuilding (Wallevik, 2003)

Time dependence is important for self-compacting concrete – issues of hydrostatic pressure on formwork.



Experimental challenges – cement paste

- The material changes as you measure it
- More intense mixing makes it thinner
- So you need to be careful in choosing test conditions
- Also look out for slippage and sedimentation in the test
- Some unexpected plug flow reported

All this held up progress with cement paste, but now we know why concrete seems to be a simple Bingham – all the structure in the paste has been destroyed before we test it.

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Part 3. Mortar

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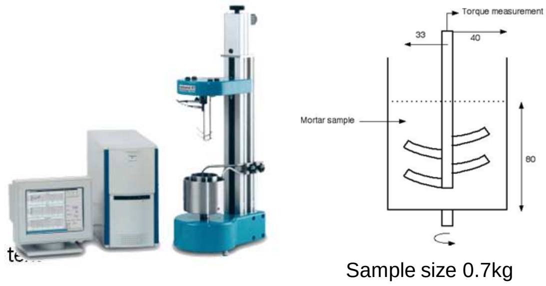
Issues for mortar

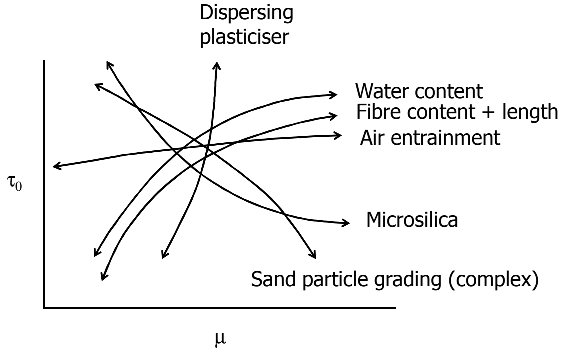
- Mortar = Cement+sand+water (+admixtures)
- Used alone in masonry
- Smaller particles make reliable rheometry easier, with smaller samples
- Coarse gravel/rock particles are inert, so we can omit them.
- Jin 2002: “Concrete Equivalent Mortar”
- Extensively used for studies of admixtures for concrete

Testing mortar – Viskomat NT

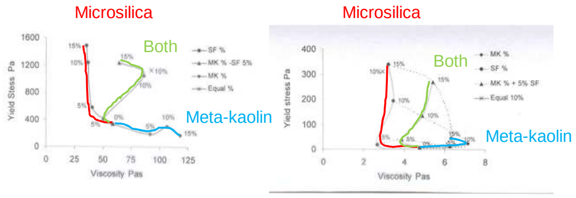


Sample size 0.7kg

Effect of mix variables



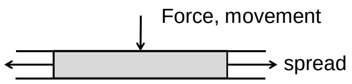
Concrete Equivalent Mortar?



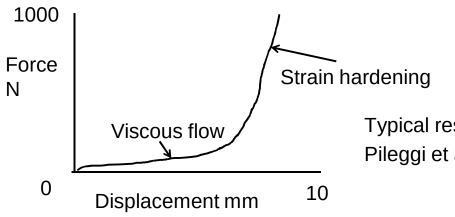
Concrete Mortar

The agreement is encouraging (Amin 2001)

Testing mortar – Squeeze flow

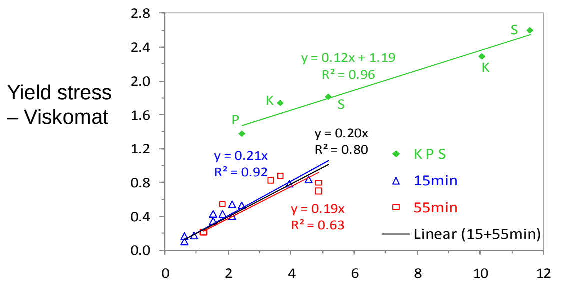


Cylindrical sample



Typical results
Pileggi et al 2000-2009

Comparison of methods



Extensional viscosity ≈ 20-40 x shear (plastic) viscosity
(Cardoso et al, in press 2013)

Conclusions for mortar

1. Test methods are available and results can be used with confidence for mix formulation.
2. Mortar can be used as equivalent to concrete.
3. Rotational and squeeze-flow rheometry give consistent results.
4. The Trouton ratio (20-40) suggests that mortar is a granular material with a relatively low elasticity.

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Part 4. Prediction and simulation

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Can we predict rheology from first principles?

Yield stress prediction (Flatt, 2002):

Two types of particles j, k with size a_j and a_k

volume concentrations φ_j and φ_k

$$\tau_0 = \frac{36}{\pi^6}\frac{\phi^2}{\phi_m(\phi_m-\phi)} G \sum_{j=1}^{j_{max}} \frac{\phi_j}{a_j^2} \sum_{k=1}^{k_{max}} c_{j,k}{}^{max} h_{j,k} \Delta V_{j,k}$$

volume fraction
max attractive force
coordination number
probability that particles will stick on impact
dead volume between two particles

Can we predict rheology from first principles?

Yield stress in cement paste (Flatt & Bowen, 2006):

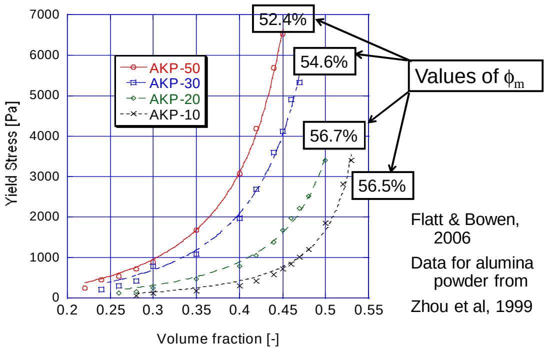
Particle size distribution with median size $a_{v,50}$

particle volume concentration ϕ

$$\tau_0 = K \frac{\phi^2 F_{\sigma,\Delta V}}{\phi_m(\phi_m-\phi)} \frac{G}{a_{v,50}}$$

dead volume between 2 particles
attractive force
constant
max volume fraction at close packing

Yield stress prediction

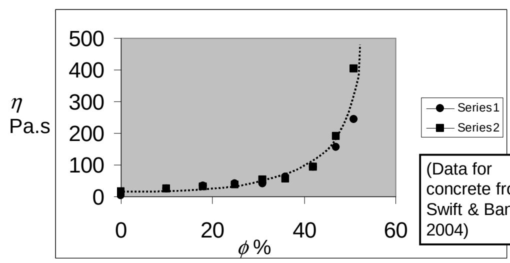


Flatt & Bowen, 2006

Data for alumina powder from Zhou et al, 1999

Plastic viscosity prediction

Krieger-Dougherty again $\eta = \eta_s \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m}$



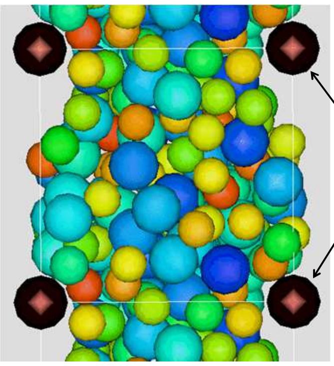
(Data for concrete from Swift & Banfill, 2004)

Numerical simulation of flow

Potentially useful to analyse:

- Filling of formwork – segregation, blocking, voids
- Mixing processes – (re)-design of mixers
- Empirical test methods – how do they relate to rheology?
- Distribution and orientation of fibres in composite materials

Flow through reinforcement



Stationary reinforcing bars

Martys et al 2003

Conclusions

1. Fresh concrete is a multi-phase, multi-scale material.
2. Rheology affects many site processes.
3. Test methods are now well established and can be used with confidence for quality control, mix formulation and process modelling.
4. It will soon be possible to predict rheology from the properties of ingredients and model flow behaviour in real situations.

Further reading

1. Tattersall and Banfill, Rheology of Fresh Concrete, 1983 (out of print but available from Banfill as a CD)
2. Banfill, Rheology of fresh cement and concrete, Rheology Reviews, 2006, p61-131
3. Roussel (editor), Understanding the rheology of concrete, 2012

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Thank you for listening

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