Soft Matter Challenges in the Oil & Gas Industry

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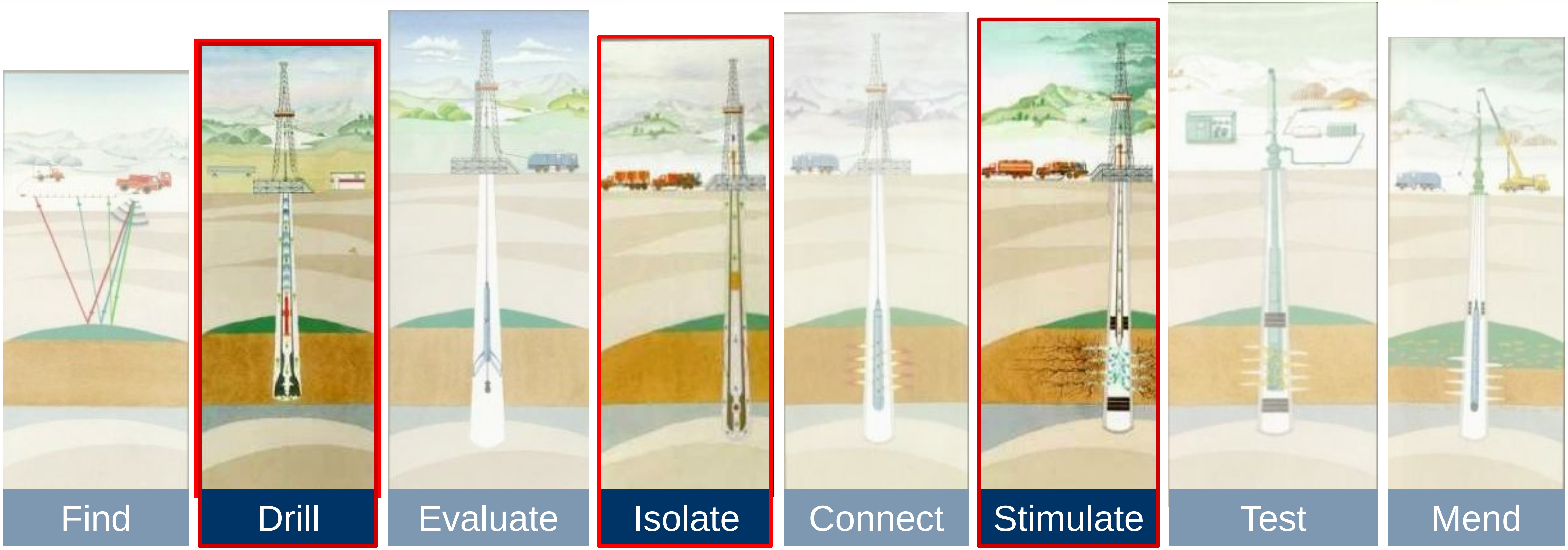
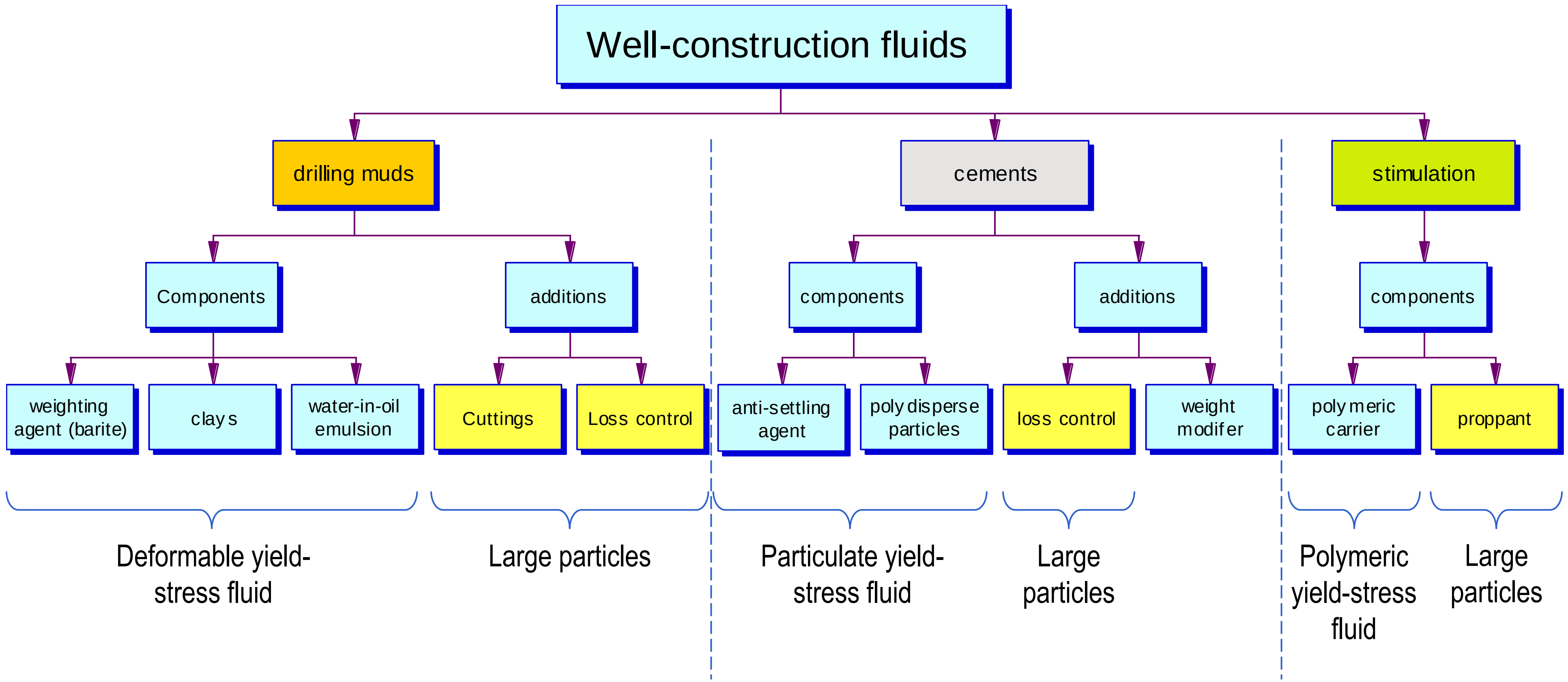
Drilling, Completing and Producing a Well



Well Construction involves pumping fluids which are complex colloidal systems. (Multi) particulate suspensions and liquid/gas emulsions in aqueous and non-aqueous continuous phases which contain electrolytes, polymers and surfactants.

In common: large particle (up to 1mm) transport in Non-Newtonian fluids.

Common fluid types



Size scales & Concentration Regimes

Colloidal nm - µm

Surfactants & Micelles
Polymers
Clays
Microfine Particles
} 0.1-~10 %v

Emulsion droplets - 5-50 %v

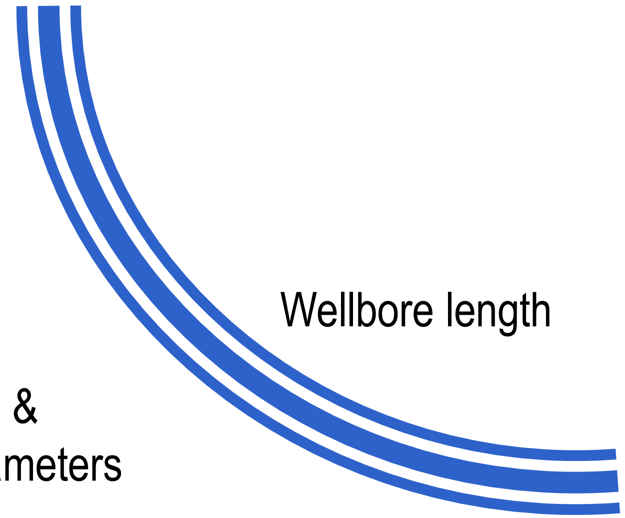
Fines 1 µm -100 µm

Barite
Cement
5-50 %v

Coarse& Intermediates 100 µm – 10 mm

Drill Cuttings & Cavings
Loss Circulation Materials
Proppant (Sand)
} 1-10 %v

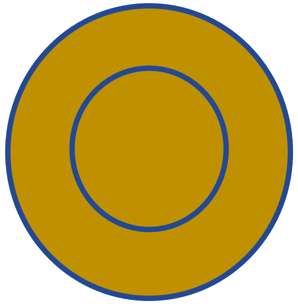
Semi-dilute to almost jammed



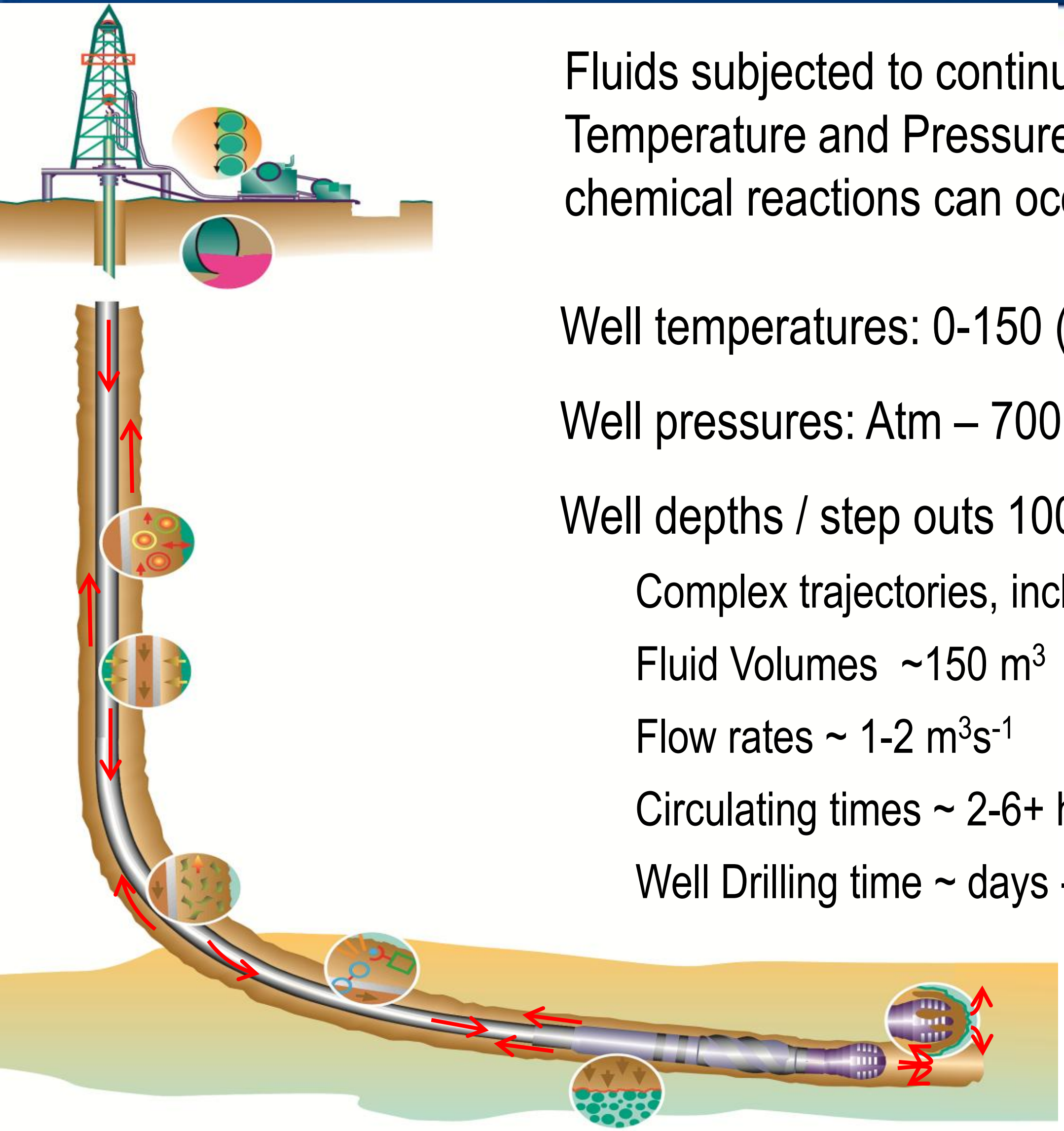
Wellbore length

Annulus &
Hole diameters

100 mm ... 1000 m -10 km



Operating Environment (Drilling Fluids)



Fluids subjected to continuous change in conditions during use:
Temperature and Pressure, Shear cycles, liquid & solids can be lost or added to the fluid, chemical reactions can occur …

Well temperatures: 0-150 (200) °C

Well pressures: Atm – 700 (1500) bar

Well depths / step outs 1000 -10,000 (12 000) m

- Complex trajectories, inclined and horizontal sections
- Fluid Volumes ~150 m^3
- Flow rates ~ 1-2 m^3s^{-1}
- Circulating times ~ 2-6+ hours
- Well Drilling time ~ days - months

Drilling Flow Regimes

	Shear rate / s^{-1}	Duration
Surface pits	< 1 - 5	~ hrs - days
Drill pipe	100 - 10,000 (t)	< 1 hr
Drill bit	10,000 -100,000 (t)	< 1 min
Annulus	(0) 1 – 1000	1-6 hrs
Surface Equipment	100-1000	< 2 hrs

Common Issues Across Well Construction

- Issues
- Large particle transport in NN fluids (especially yield stress)
  - Static and Dynamic
  - Stability, segregation, settling
- Fluidisation of particulate beds
  - Cuttings, barite, typical dense and cohesive
- Constitutive relations
  - Predictable rheology & effect on process
  - Length-scale separation issues – wall bounded flows

- Underlying physics
  - Appropriate constitutive relation
    - Ability to predict behaviour deep underground
    - Where no clear length-scale separation exists
  - Physical understanding
  - Effect of:
    - Particle shape (roughness, oblate, fibre)
    - Surface properties
    - Polydispersity
    - Pressure (and temperature)

Particle transport

- To transport particle out of the well in the horizontal or inclined section

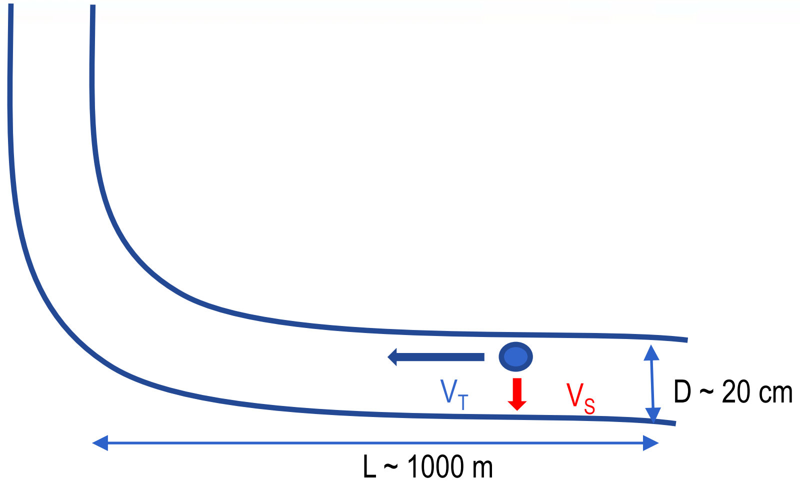
$$T_s \gg T_t \quad \text{or} \quad \frac{D}{V_s} \gg \frac{L}{V_t}$$

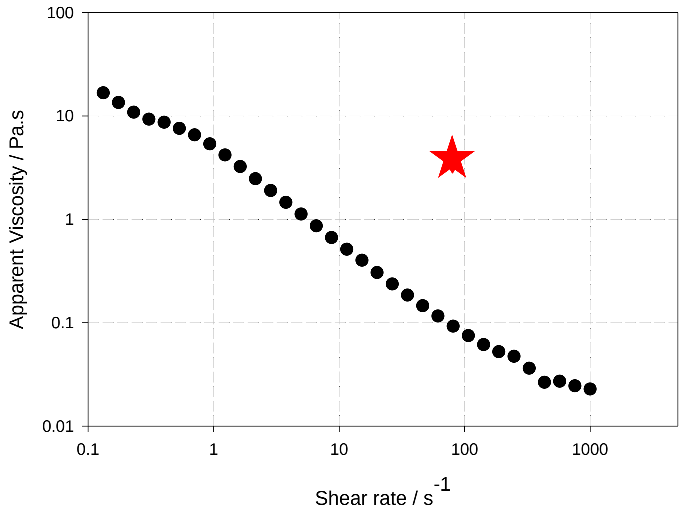
- For typical ~1 mm particles and typical flow velocities ~1 m/s Stokes settling velocity

$$V_S = \frac{\Delta\rho\, g\, d^2}{18\mu_m}$$

  suggests we would require a viscosity of >> 3 Pas to suspend these particles

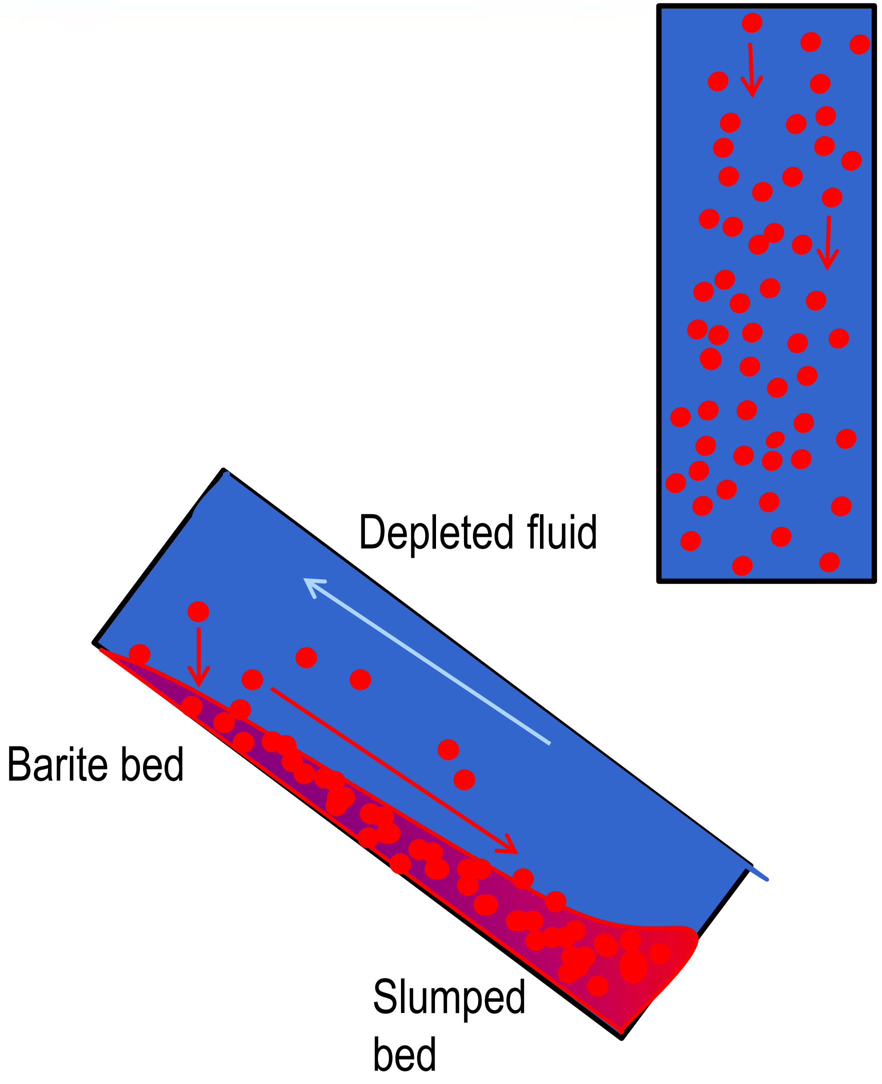
- Typical drilling fluid viscosity at these flow rates ~ 20 mPas leading to formation of dunes and beds in horizontal and inclined wellbores
- Additional effects of rotating inner pipe shear orthogonal to main flow
  - Enhanced migration in shear
  - Resuspension of settled beds





Barite sag

- The settling of weighting material under gravity can result in zones with variation in density of up to 0.5 s.g.
  - Current guideline specifications are for variations less than 0.05 sg (when we can only measure to an accuracy of 0.01)
- Can occur in static or dynamic conditions
  - Static sag controlled by yield stress
  - Low shear rates which just exceed yield stress more problematic
- Most problematic in deviated sections especially ~ 30-60°
  - Boycott effect accelerates sag
- Sagged beds dense and cohesive:
  - How to design systems so concentrated beds re-disperse?

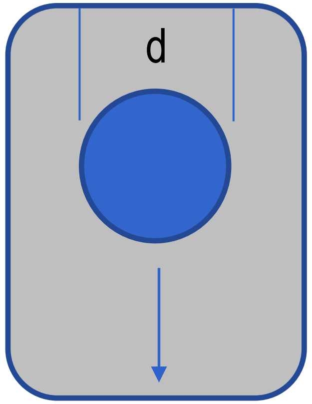


Particle suspension in static and low shear rate conditions

- Static: particle migration must be balanced by viscous drag, for a yield stress fluid:

$$\tau_y \times 4\pi\left(\frac{d}{2}\right)^2 = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 \Delta\rho\, g$$

  - 1 mm particles with $\Delta\rho \sim 1.2$ sg: $\tau_y \sim 2$ Pa – realistic value for drilling fluids



- Low shear rates: particles falling under own mass through NNF
- Understand development of yield stress locally to the particle on cessation of flow
- Modelling with concepts of localized shear in materials with embedded coarse particles will lead to some insights here

Oil Based Drilling Fluids

Brine-in-oil emulsion

- Base Oil phase (95-40 % v/v)
- Internal Aqueous phase (5-60 % v/v)
- Surfactant package - Emulsifiers + Wetting Agent for fluid stability

Dense particles

- Weighting agent (<25 wt%)
  - Barite - needs to be oil wetted
  - Up to 100µm; $D_{50} \approx 25$ µm

Colloidal additives

- Organoclay or oil-soluble polymer for rheology control
- Polymeric filtration additives

Other particles

- Cuttings and other large particles ~ 5%
  - Typically up to ≈ 1mm, can be up to ≈ 6mm, chips, tabular, soft, etc.

All contribute to rheology of fluid

↓

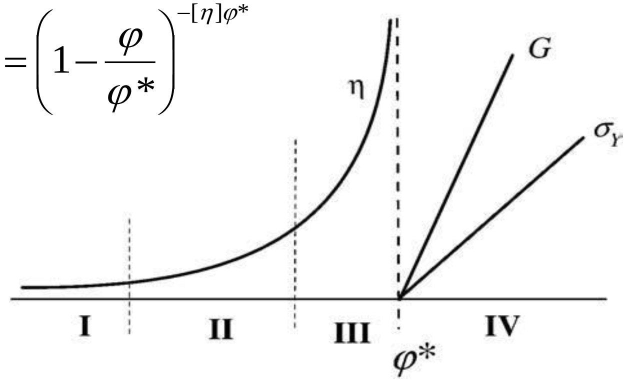
Formulation Challenge

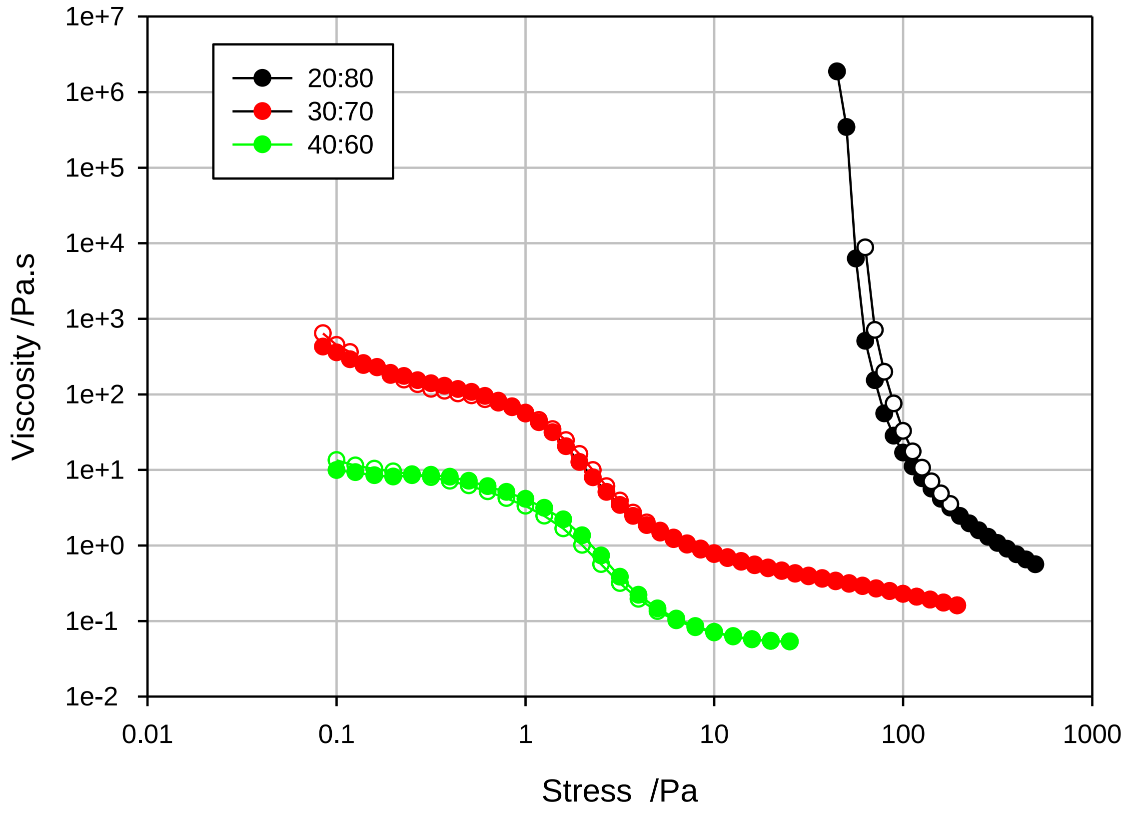
Emulsion Phase Rheology

Below ~ 50% vol droplets (and coarse particles) requires additional rheological additives such as organoclays or polymers to meet specifications for particle sedimentation

Rheological control becomes more difficult as we approach close packing

$$\frac{\eta}{\eta_o} = \left(1 - \frac{\varphi}{\varphi^*}\right)^{-[\eta]\varphi^*}$$



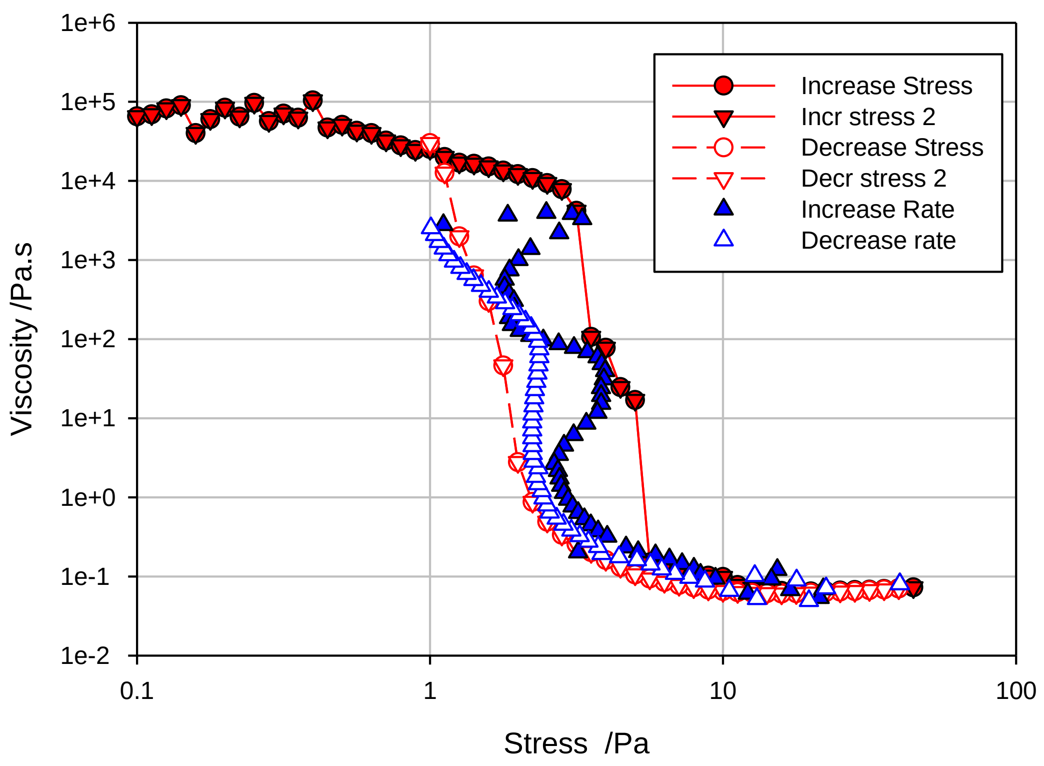


Clay-thickened emulsion systems

- At moderate brine volume fractions additional viscosifier is required
- In controlled-stress mode, low-shear viscosity *η(0)*, followed by collapse at ~ 3 Pa,
  - modelled by Mendes-Dutra model*:

$$\sigma = \left(1 - \exp\left(-\frac{\eta_0 \dot{\gamma}}{\sigma_y}\right)\right)(\sigma_y + K\dot{\gamma}^n)$$

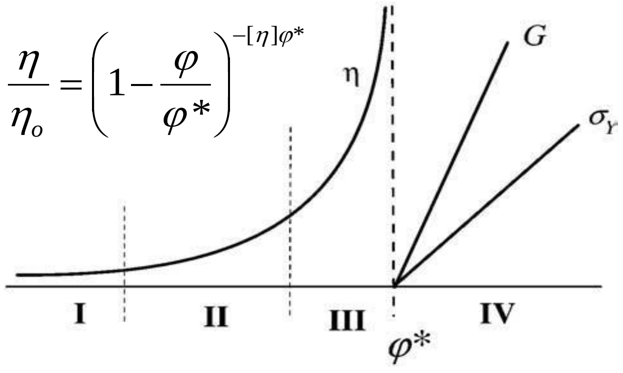
- Increasing *shear rate* behaviour is complex: structural rearrangements similar to aqueous clay gels
- Role of low shear rheological behaviour in controlling barite sag
- Additional complication of moderately strong thixotropy
- Both Herschel-Bulkley and Mendes-Dutra models limited utility in describing fluid behaviour – not all fluids fit well



OBM Moving into jammed systems

Combined Barite + Brine % vol in internal phase

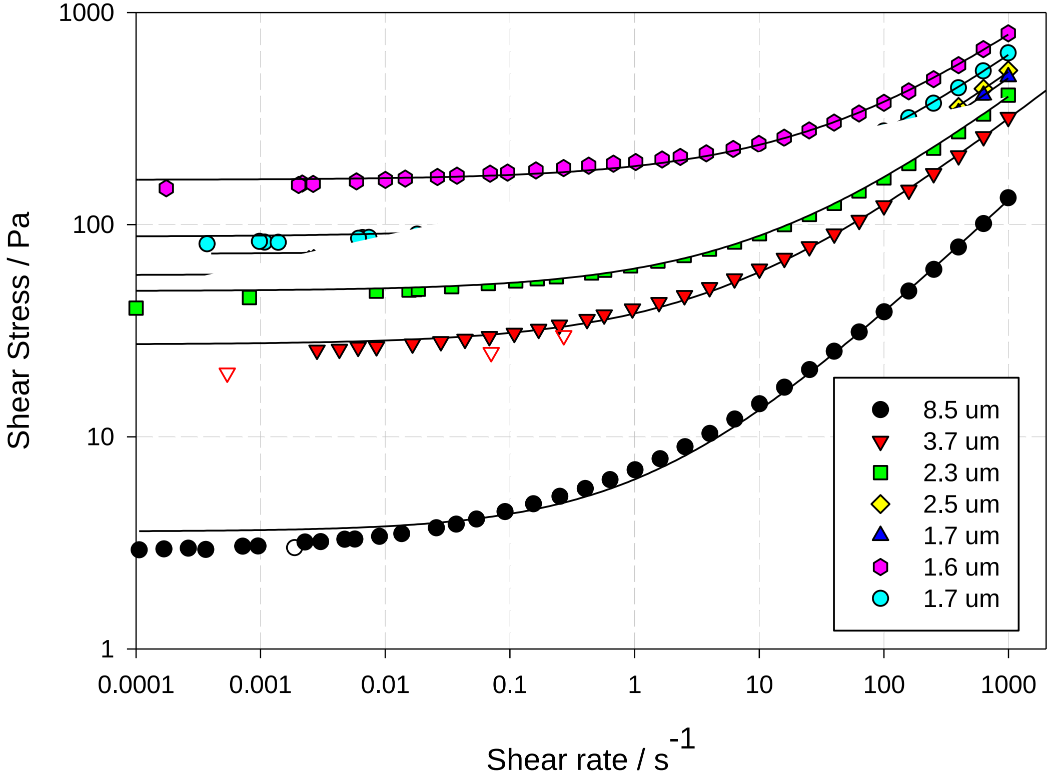
% vol emulsion	Mud Density S.G.							
	1.0	**1.1**	**1.2**	**1.3**	**1.5**	**1.6**	**1.7**	**1.8**
15	21	23	27	30	34	37	41	48
20	26	27	31	35	38	42	46	53
25	30	32	36	39	43	46	42	57
30	34	36	40	44	47	51	55	62
40	43	45	49	53	56	60	64	71
50	53	54	58	61	65	69	73	80
60	63	63	67	70	74	78	82	89
70	73	73	76	79	83	87	91	98



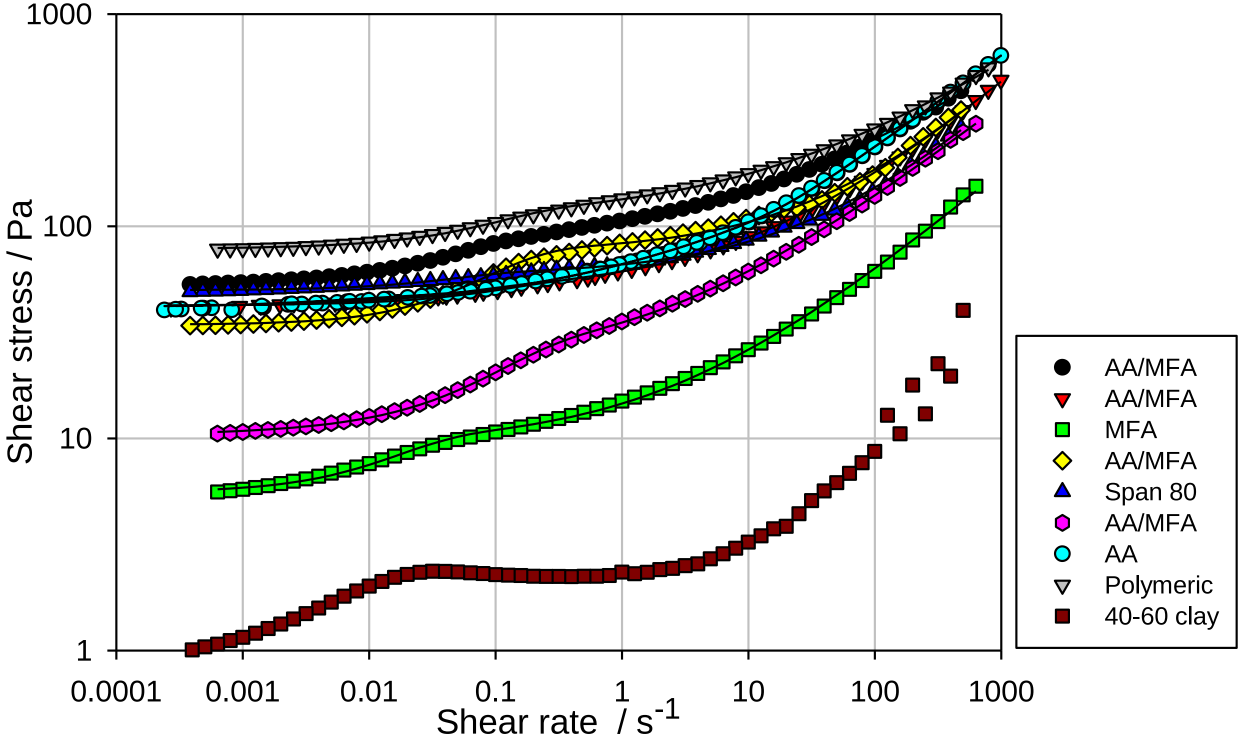
Rheological control becomes more difficult as we approach close packing

Simple High Internal phase emulsions (80% vol)

Rheology a strong function of droplet size (AA/MFA)



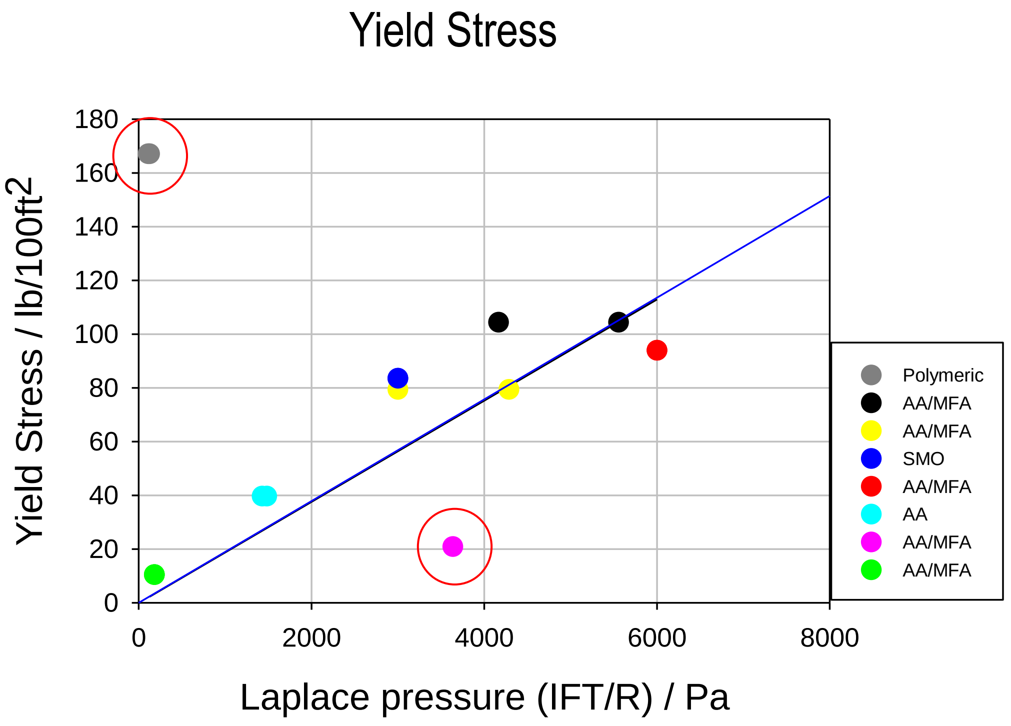
And emulsifier type

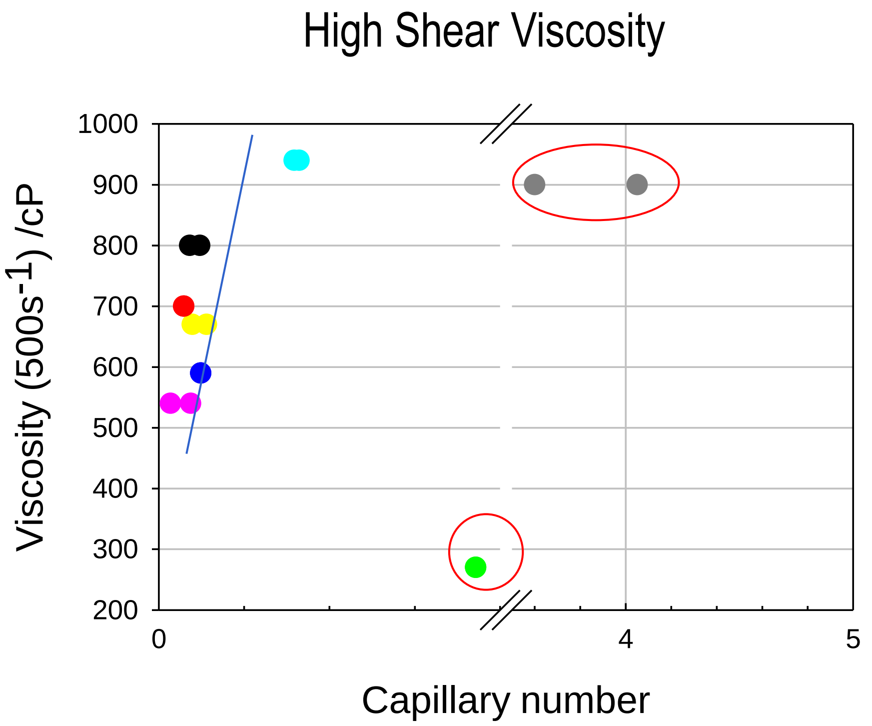


Fits to Windhab model*

$$\sigma = \sigma_{y1} + K\dot{\gamma}^n + (\sigma_{y2} - \sigma_{y1})\left(1 - \exp\left(-\frac{\dot{\gamma}}{\dot{\gamma}*}\right)\right)$$

Rheological Properties Scaling with Droplet Properties

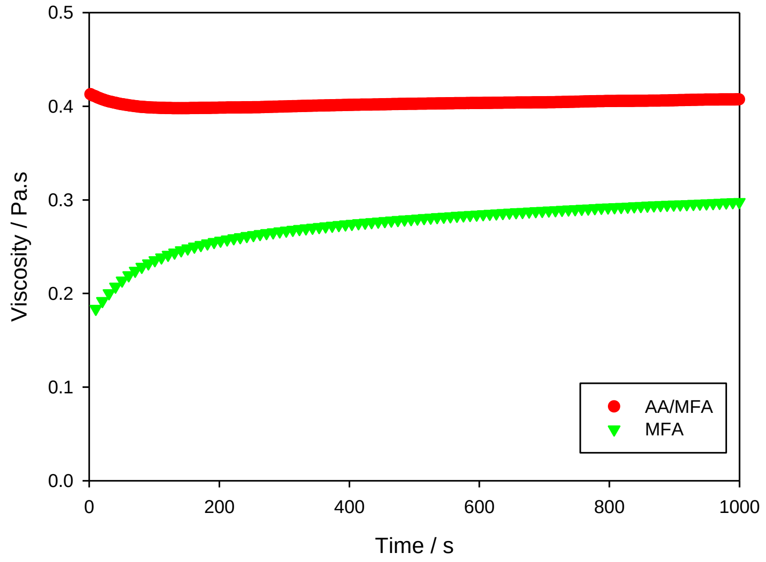




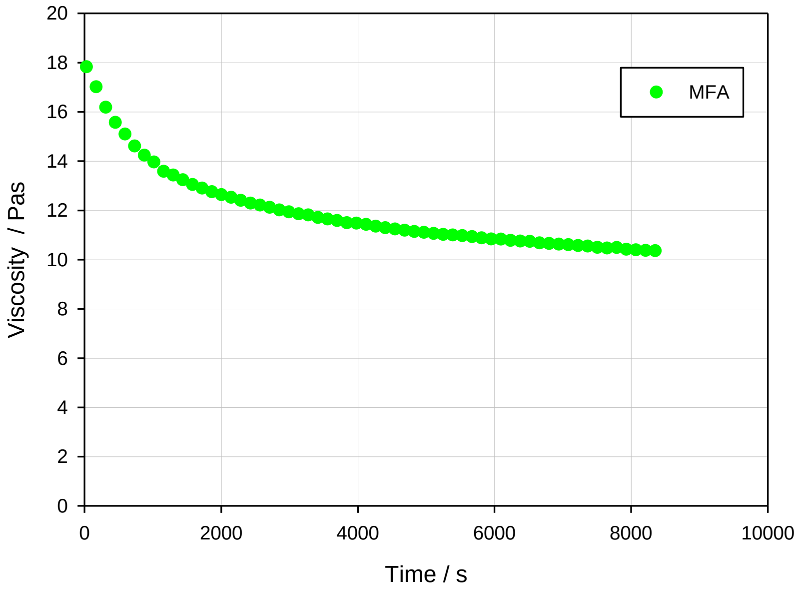
- Broadly agrees with theory, but there are some outliers

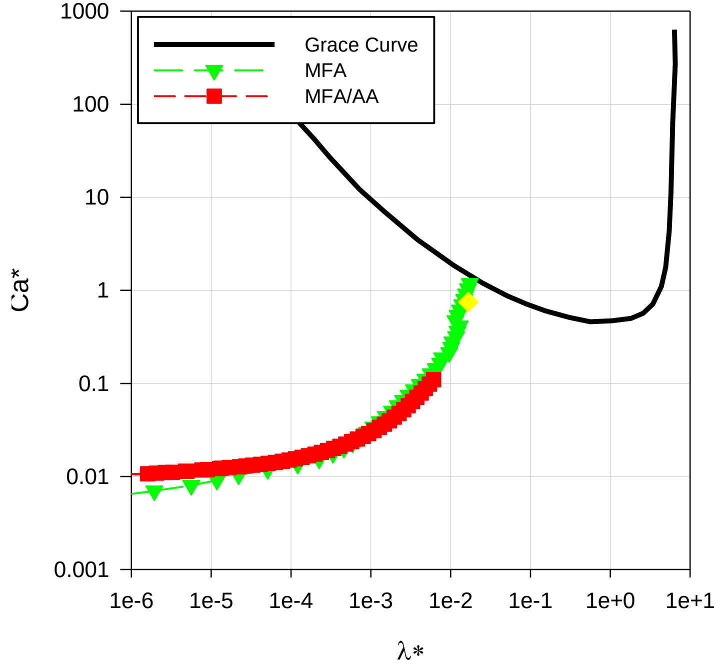
MFA emulsion behaviour under shear and at rest

Under prolonged Shear



At rest





- MFA emulsion – droplet break-up under prolonged shear? Coalescence at rest?

In Summary

- Well Construction involves pumping fluids which are complex colloidal systems which operate in the dilute to near-jammed regimes
- In common: large particle (up to 1mm) transport & suspension in Non-Newtonian fluids
- We need to predict and manage these fluids in various flow regimes downhole based on the underlying physics and appropriate constitutive relations

Acknowledgements

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