Effects of loading rate and saturating fluid on chalk mechanical behavior

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NGI

Motivation

Many oil and gas fields in the North Sea are found in very porous over-pressured chalk formations which compact significantly during the lifetime of the field

→ contributes significantly to the recovery mechanism, in some areas of the Valhall field up to 50-60 %

→ sea bed settlement (ref Valhall and Ekofisk)

→ Implications for foundation, and well casing failure

Reservoir compaction: 1) result of changes in effective stresses, 2) water weakening of the chalk during massive seawater injection.

Chalk mechanical behavior is susceptible to changes in several parameters: Pore fluid composition, porosity, strain/load rate

Chalk exhibit pronounced creep deformations under constant load at high stresses or near the strain rate dependent elastic-plastic limit

Background for current tests

In situ conditions

Stress / Pore pressure	(MPa)
Total vertical stress σ_V	22.5
Initial total horizontal stress σ_H	18.0
Initial octahedral stress σ_{oct}	19.5
Initial Reservoir Pressure P_o	13.5
Initial Effective vertical stress σ'_V	9.0
Initial Effective horizontal stress σ'_H	4.5
Initial Effective octahedral stress σ'_{oct}	6.0

Pore fluid

Salt	Concentration (g/l)
NaCl	58
KCl	-
$CaCl_2$, 6 H_2O	55.6
$MgCl_2$, 6 H_2O	8.5

Gas and brine (~30%) saturated

Conducted tests

Uniaxial strain, depletion (CAUST) -vertically drilled plugs

Depth (m)	Porosity (%)	Fluid type
1131.45	39.9	brine
1133.55	34.6	brine
1309.56	30.6	dry
1309.56	31	brine
1309.56	31	brine

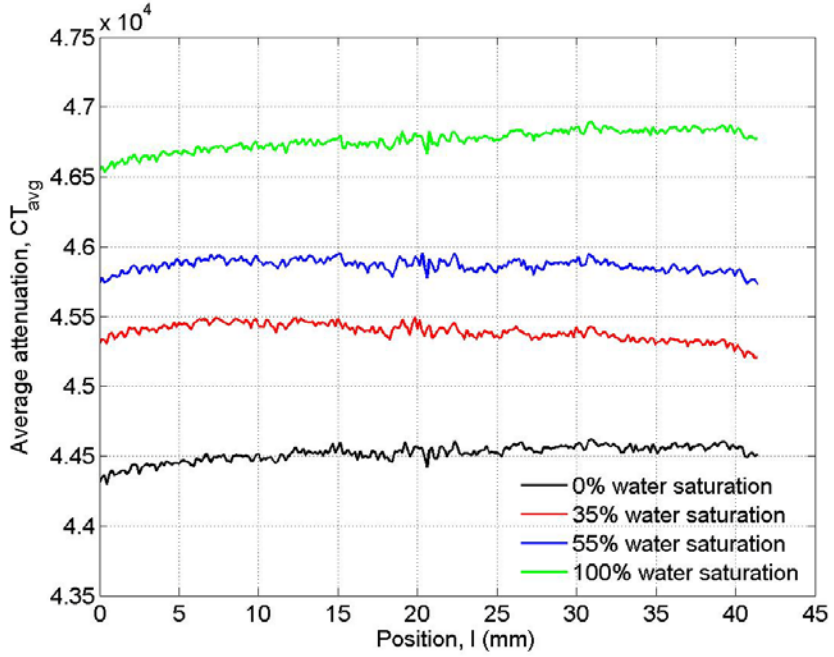
Isotropic, drained -horizontally drilled plugs

Depth (m)	Porosity (%)	Fluid type
1128.55	36.85	30% brine
1131.00	30.6	brine
1132.90	37.83	30% brine
1134.10	36.3	brine
1134.20	36.2	brine
1134.20	33.8	brine

Experimental approach

0% brine saturation → directly built into triax for test
100% brine saturated → built directly into triax and saturated in the cell
30% brine saturation → saturated in vacuum chamber w/diluted solution, evaporation to target weight/saturation level,

Homogeneous fluid distribution along the core axis verified with X-ray CT



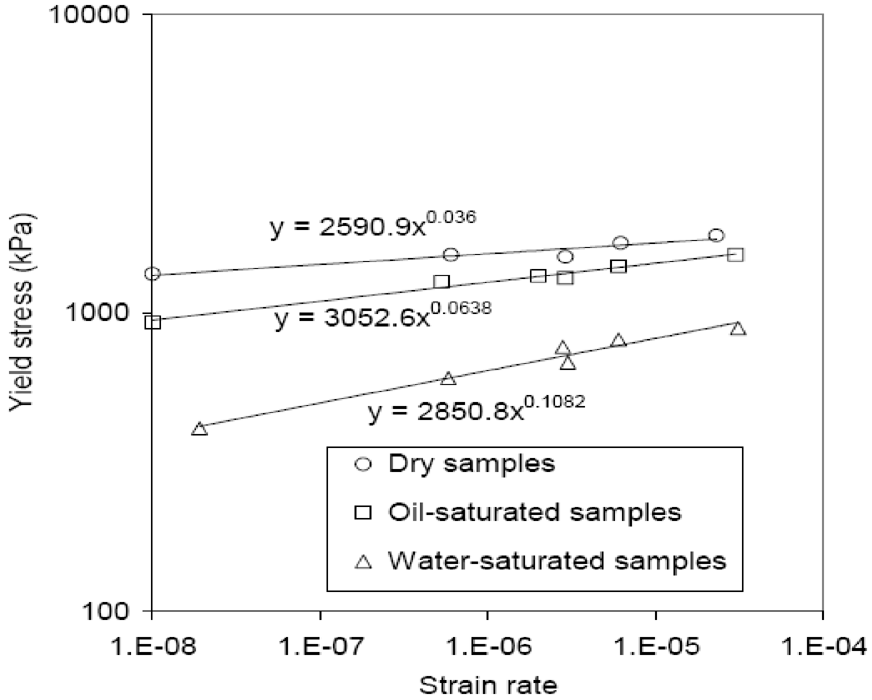
Results – fluid and porosity effects

Pore fluid composition has a pronounced effect on the behavior of chalk:

- Alters stiffness, elastic-plastic transition (pore collapse), creep rate.

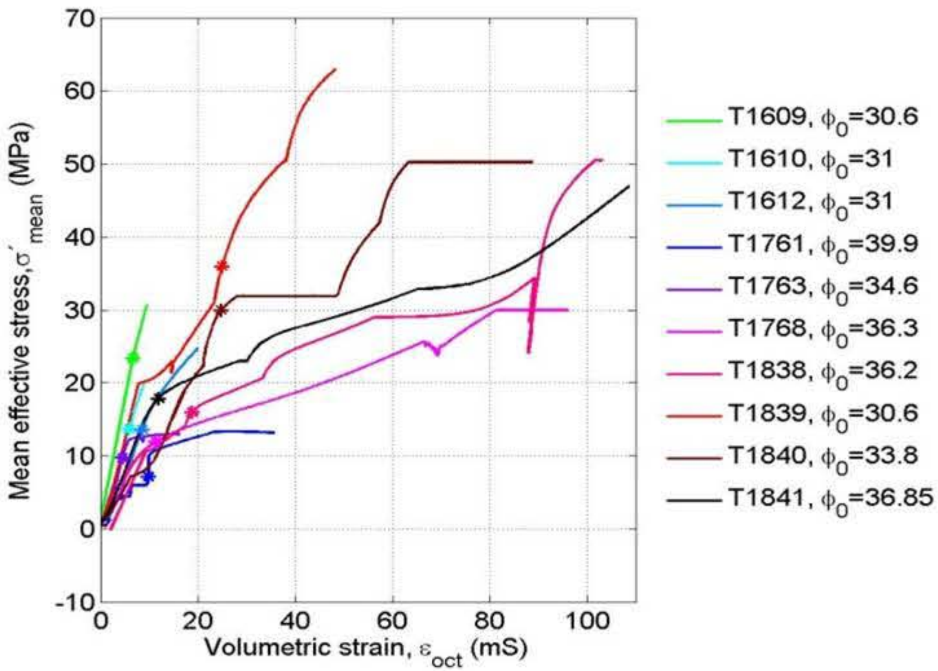
Water weakening effect upon flooding:

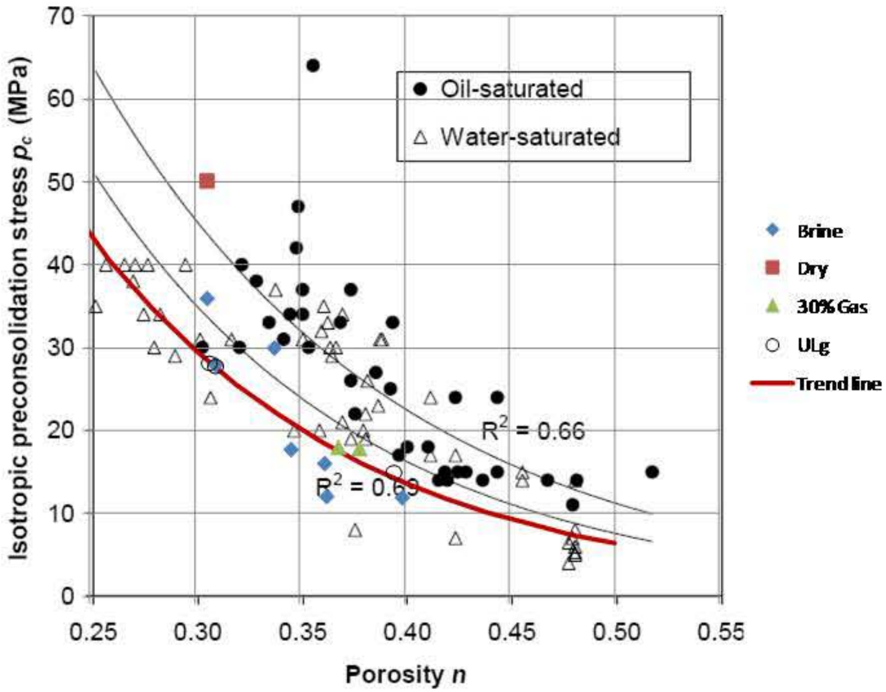
- Instantaneous permanent deformation and increase of creep rate
- Radical increase up to 15% water saturation in initially oil saturated chalk
- Not as well documented for water flooding in initially gas saturated samples



Hickmann 2004

Results – fluid and porosity effects

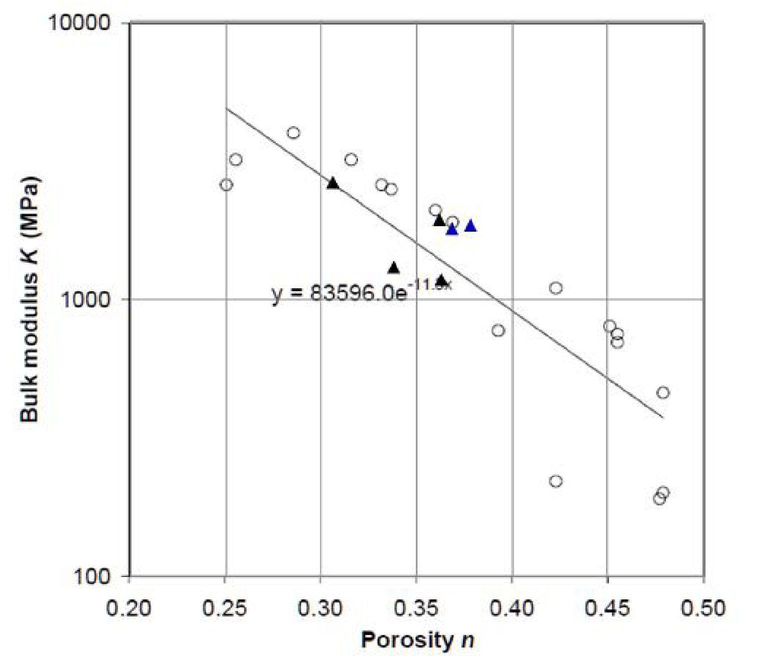




Joint Chalk Research (JCR) database

Results – fluid and porosity effects

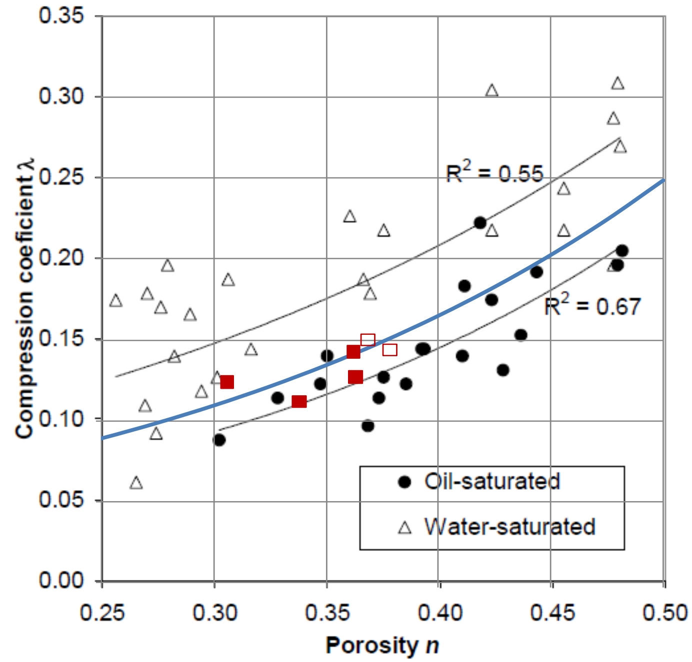
Before Pc



$$C_{pe} = 1/(K\,n)$$

Trend line $K = 83596 e^{-11.3n}$

After Pc



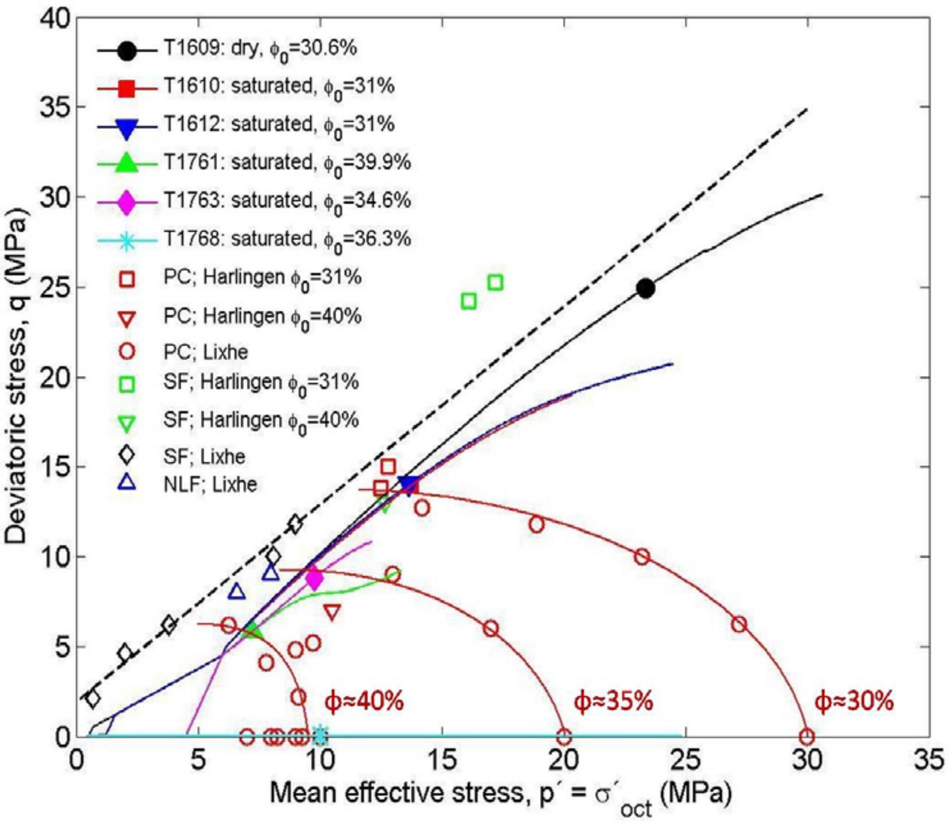
$$C_{bp} = \frac{d\varepsilon_v}{dp} = \frac{\lambda}{(1+e_0)p}$$

Trend line $\lambda = 0.032 e^{4.1n}$

(after JCR database and Hickman 2004)

Results – fluid and porosity effects

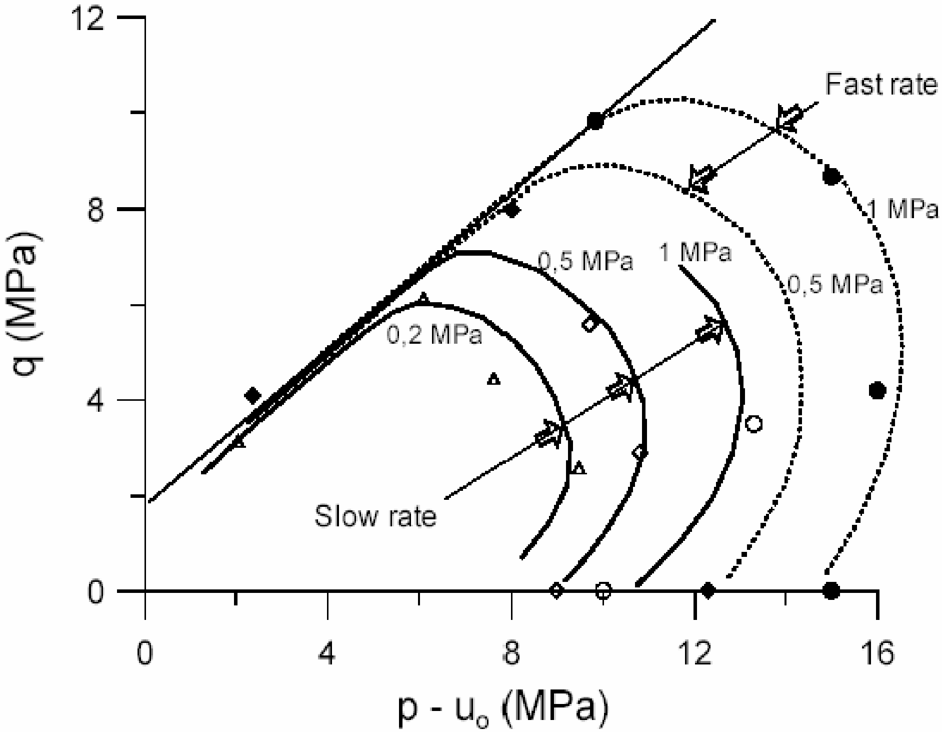
Failure envelope largely depend on saturating fluid and porosity

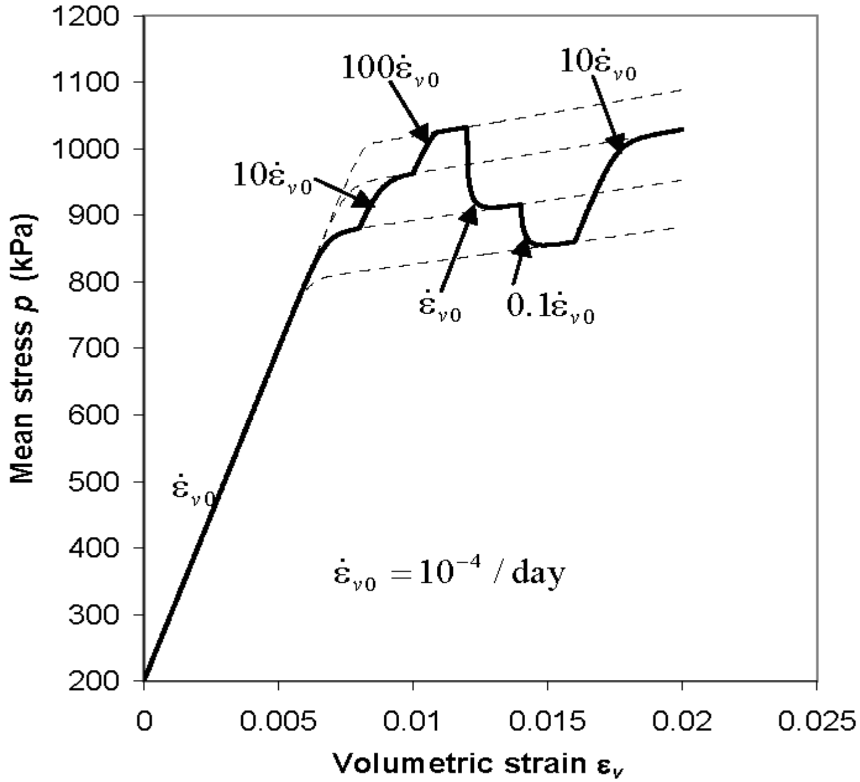


ULG (Collin 2002, Schroeder 2009) and NGI 2010 data

Results – rate sensitivity

... but also on load rate!

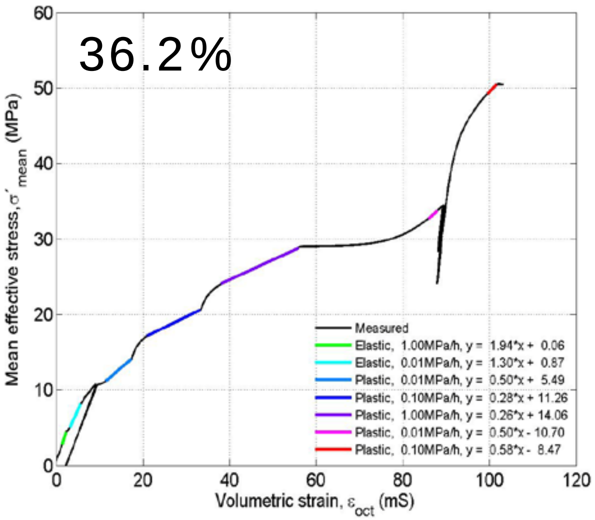


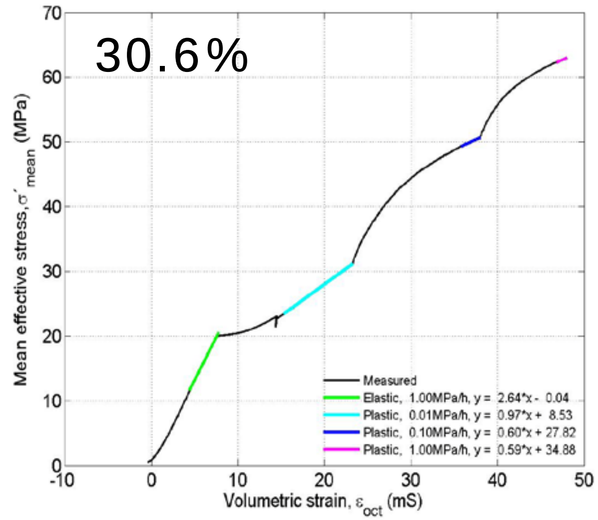


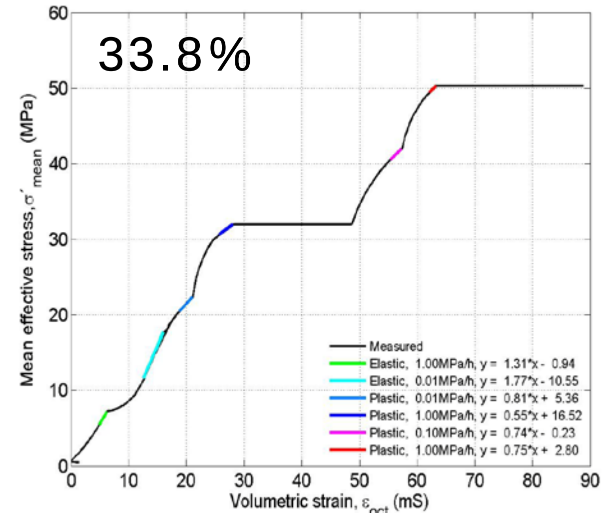
PASACHALK 2004

Hickmann 2004

Results – rate sensitivity (load phase)

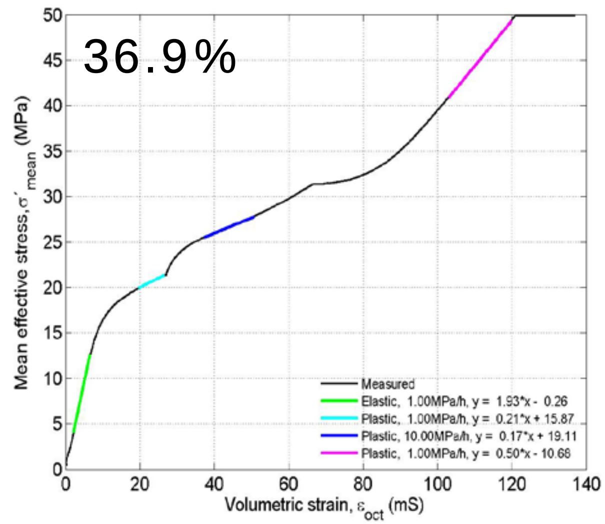


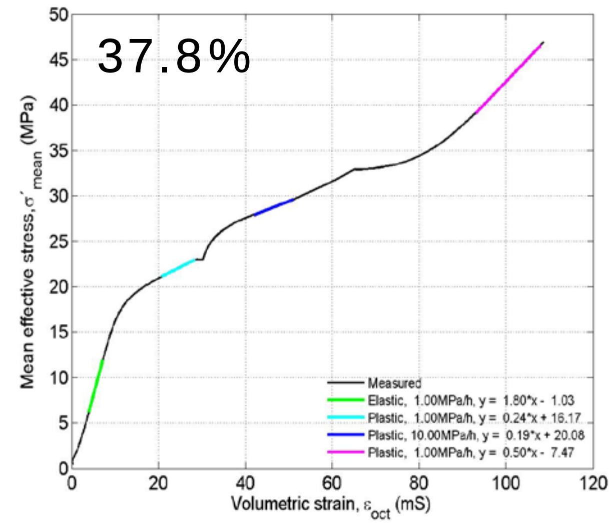




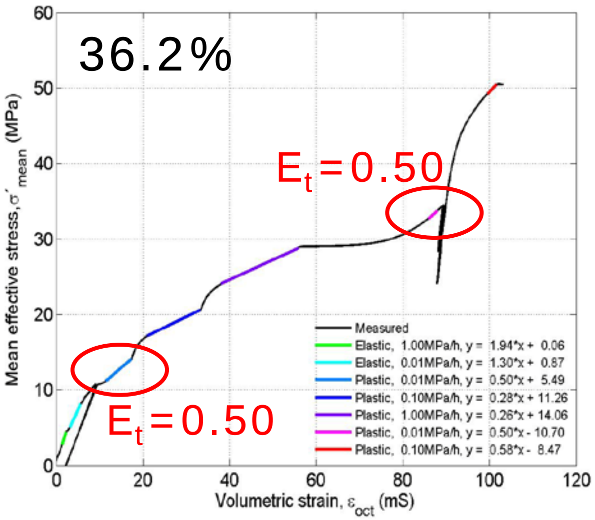
$$Et = \Delta\sigma'_{oct} / \Delta\varepsilon'_{oct}$$

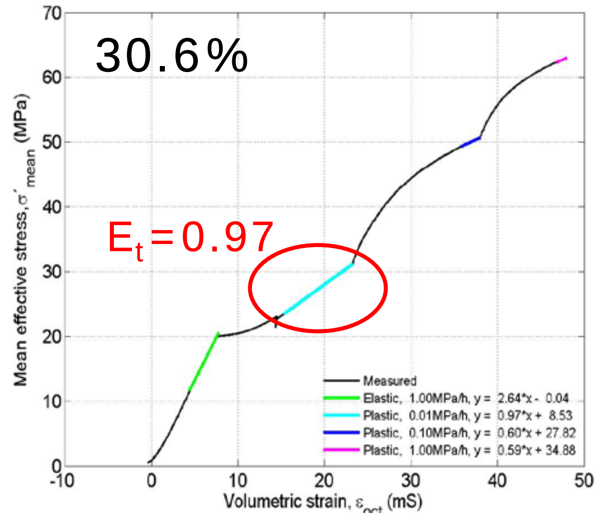
$$\sigma'_{mean} = \sigma'_{oct}$$

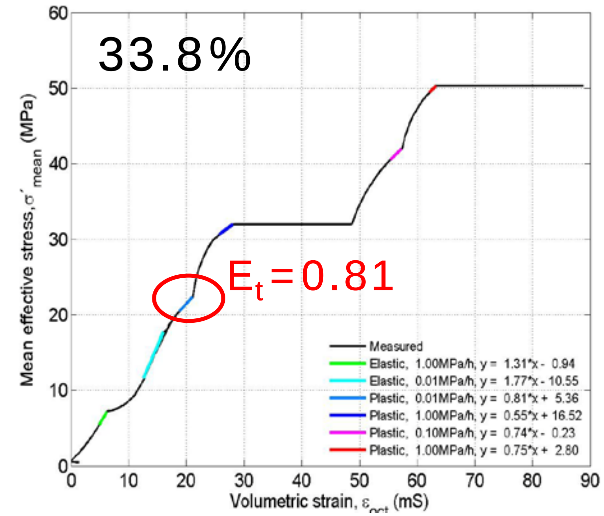




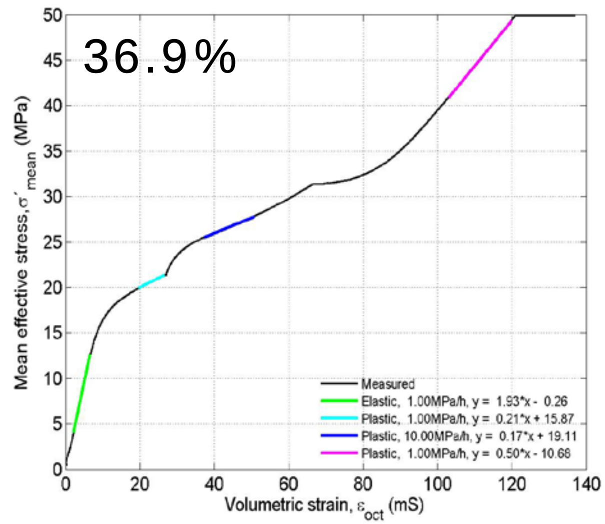
Results – rate sensitivity (0.01MPa/h)

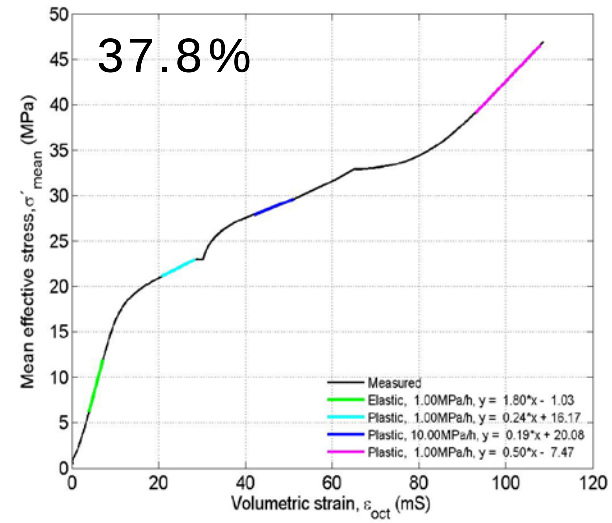




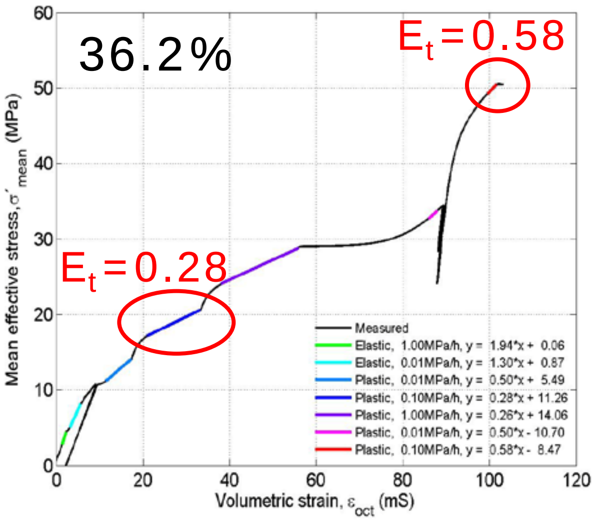


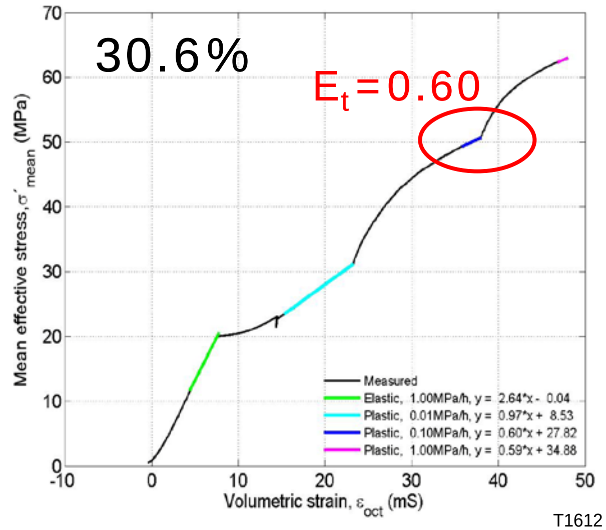
Porosity ↑ = E_t ↓

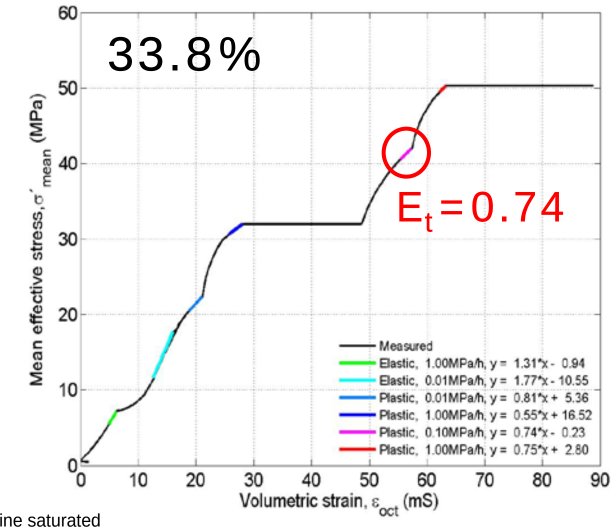




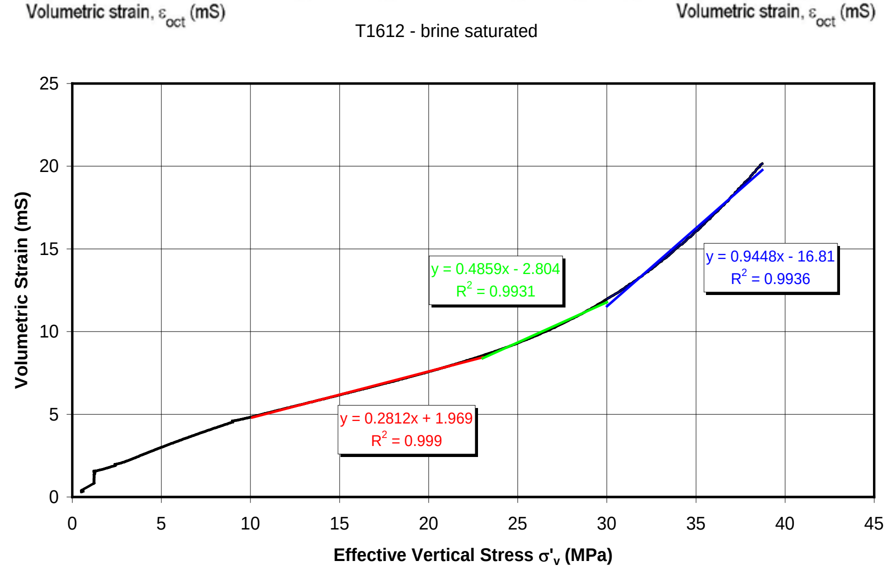
Results – rate sensitivity (0.10MPa/h)



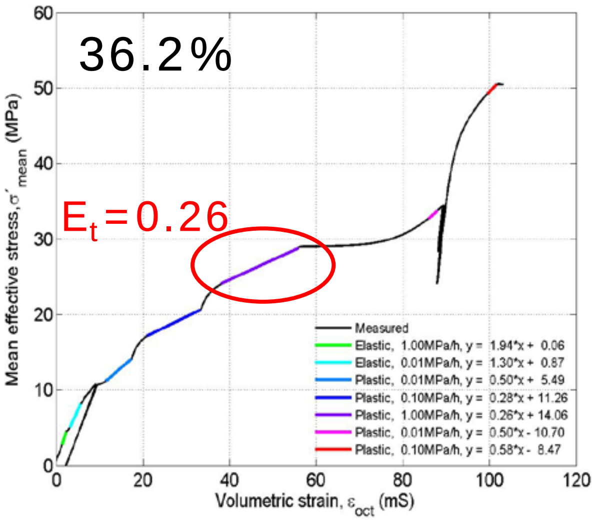


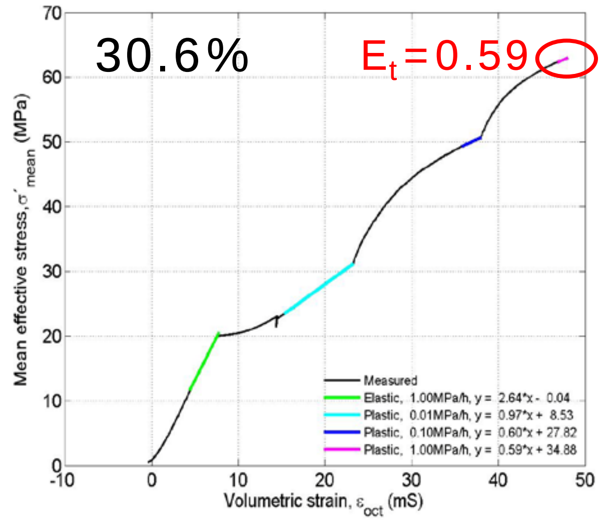


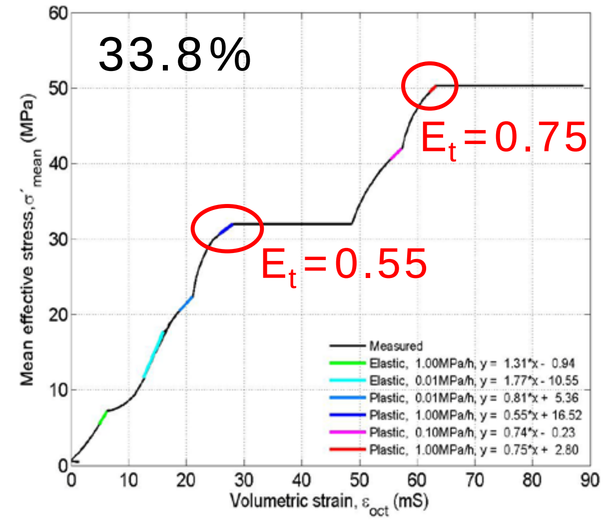
Strain hardening



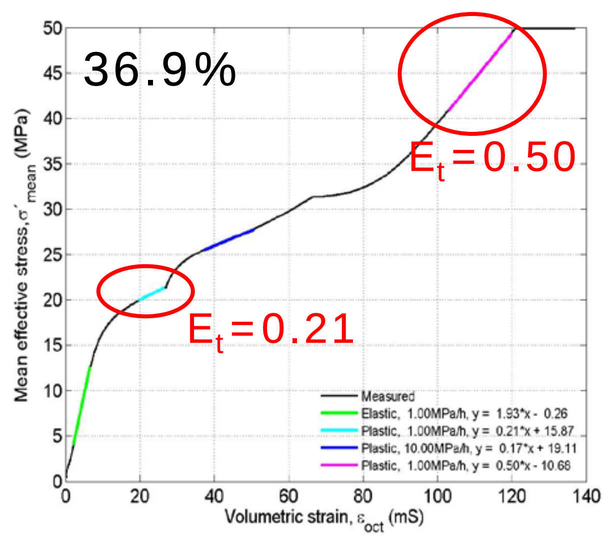
Results – rate sensitivity (1.0MPa/h)

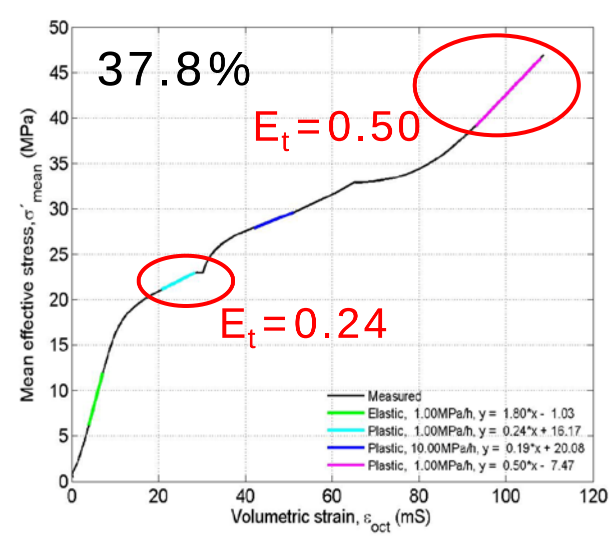




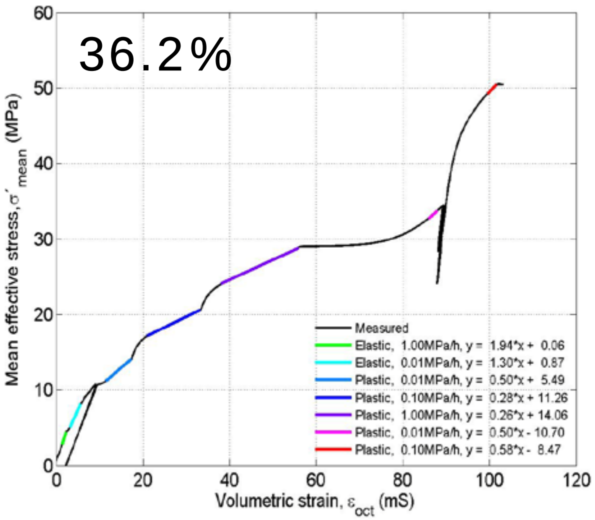


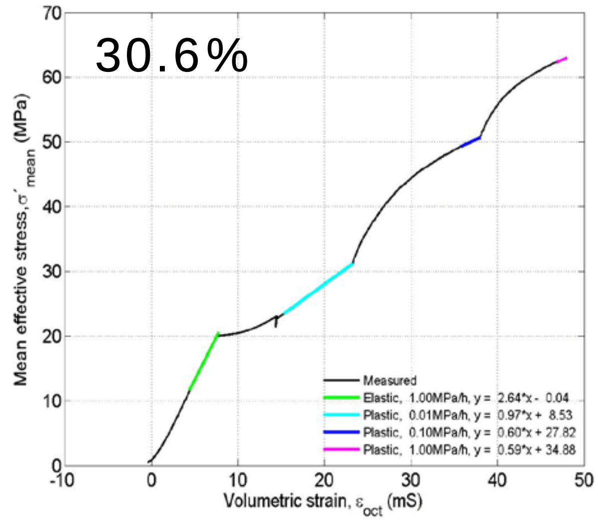
Strain hardening

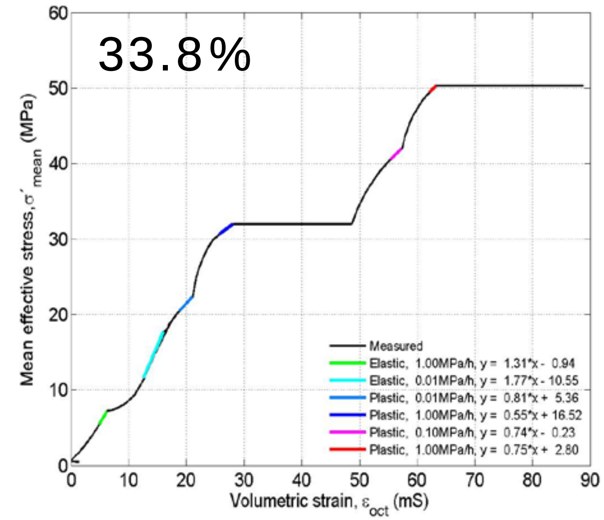




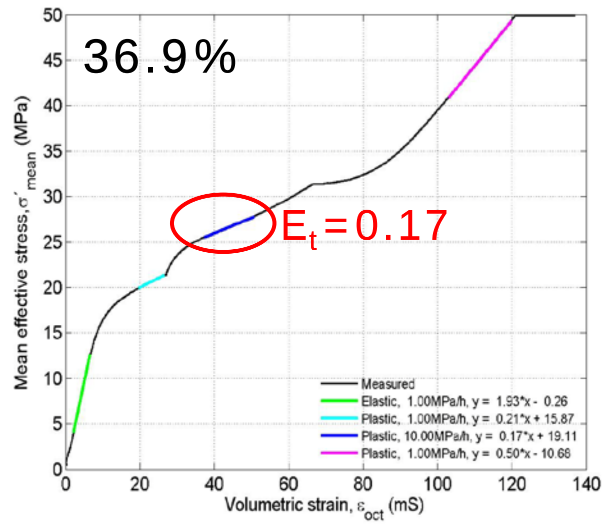
Results – rate sensitivity (10.0MPa/h)

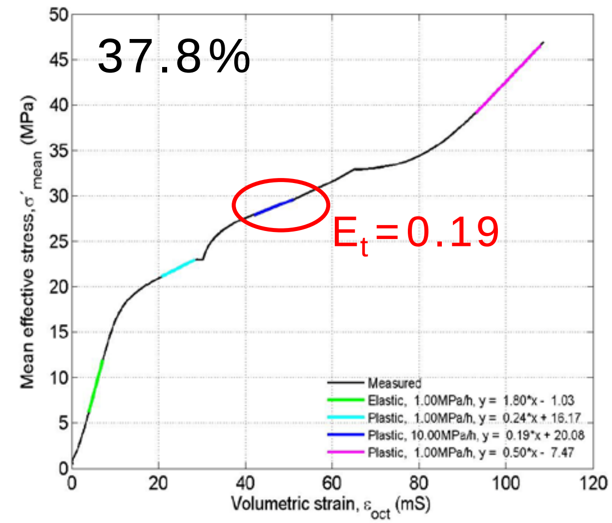






Load rate ↑ = E_t ↓





Results – rate sensitivity (load phase)

Test type	Fluid type	Porosity (%)	Mean stress (MPa) p_1	p_2	Mean stress rate (MPa/h) $\dot{p}_1$	$\dot{p}_2$	b
Isotropic	brine	36.2	14.1	16.1	0.01	0.1	0.057
			20.61	24.18	0.1	1	0.069
			34.6	43.7	0.01	1	0.050
Isotropic	brine	30.6	31.1	41.77	0.01	0.1	0.12
			50.64	57.27	0.1	1	0.053
Isotropic	brine	33.8	22	28	0.01	1	0.052
			42	45.77	0.1	1	0.037
Isotropic	30% brine	36.9	23.5	25.9	1	10	0.042
Isotropic	30% brine	37.83	21.37	23.66	1	10	0.044

Visco-plastic rate dependent compaction model (de Waal)

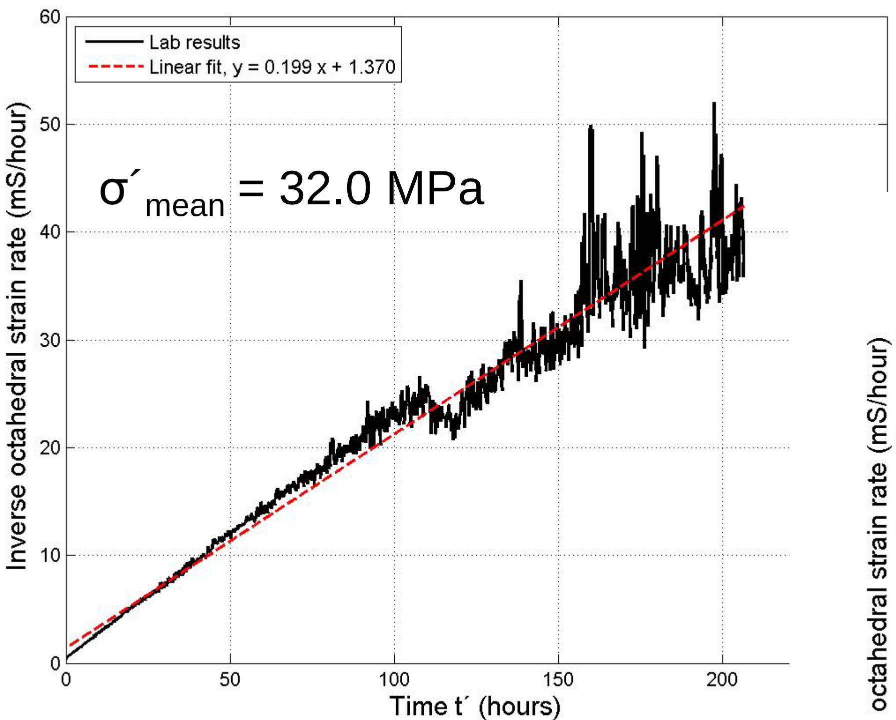
$$\dot{p} = \frac{\dot{\varepsilon}_v}{c_{b,o}} + bp\frac{\ddot{\varepsilon}_v}{\dot{\varepsilon}_v}$$

$$\frac{p_2}{p_1} = \left(\frac{\dot{\varepsilon}_{v2}}{\dot{\varepsilon}_{v1}}\right)^b$$

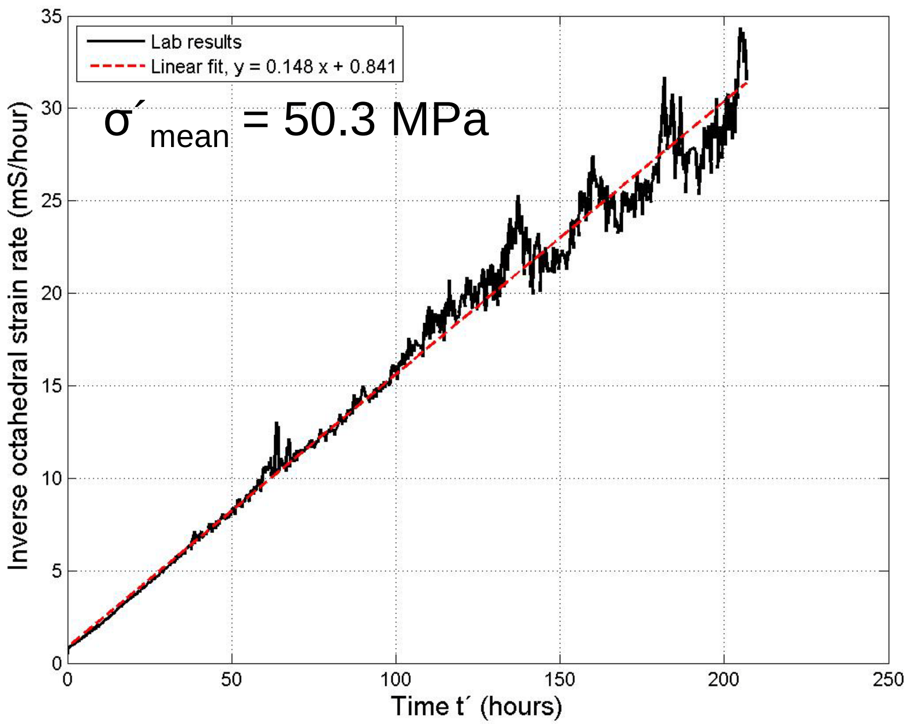
$$b = \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{\dot{p}_2}{\dot{p}_1}\right)}$$

Results – rate sensitivity (creep phase)

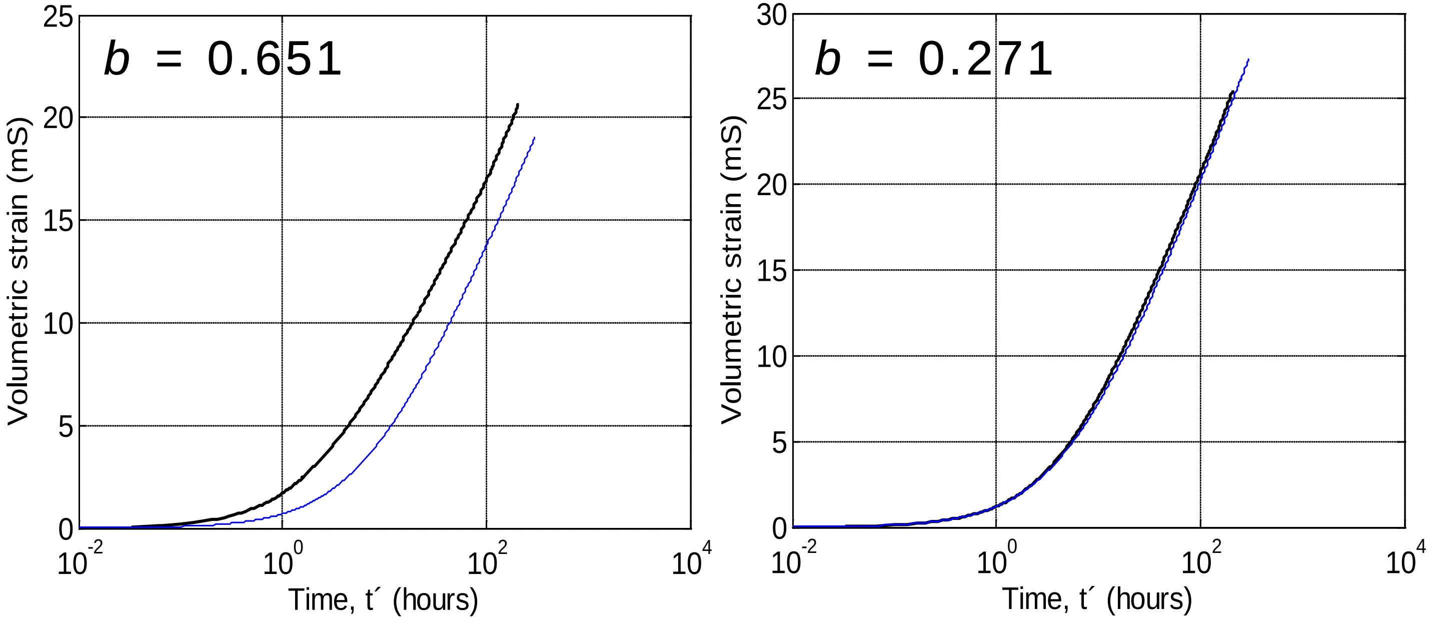
$$\left.\begin{array}{l}\varepsilon_v^t = bc_{b,o}\,p\ln\left[1+\dfrac{\dot{\varepsilon}_{vo}t}{bc_{b,o}\,p}\right] \\ C_c = bc_{b,o}\,p\ ,\ \tau = bc_{b,o}\,p/\dot{\varepsilon}_{vo}\end{array}\right\}\ \dot{\varepsilon}_v^t = \frac{C_c}{t+\tau}$$



Mean Stress p (MPa)	Slope inverse strain rate vs time $1/C_c$	Offset τ/C_c	$\dot{\varepsilon}_{vo}$ (mS)	$c_{b,0}$ (/MPa)	b
31.86	0.1986	1.3701	0.7299	0.0024	0.0651
50.22	0.1496	0.7708	1.2973	0.0049	0.0271



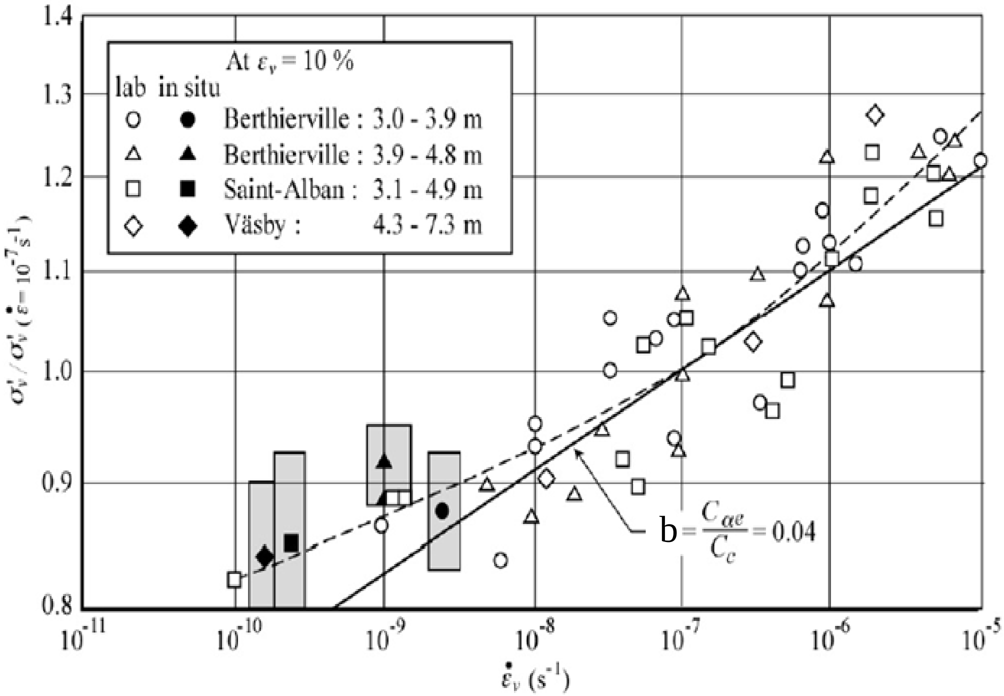
Results – rate sensitivity (creep phase)



0.045 (dry) to 0.108 (fully water-saturated) — Priol (2006), Lixhe outcrop chalk

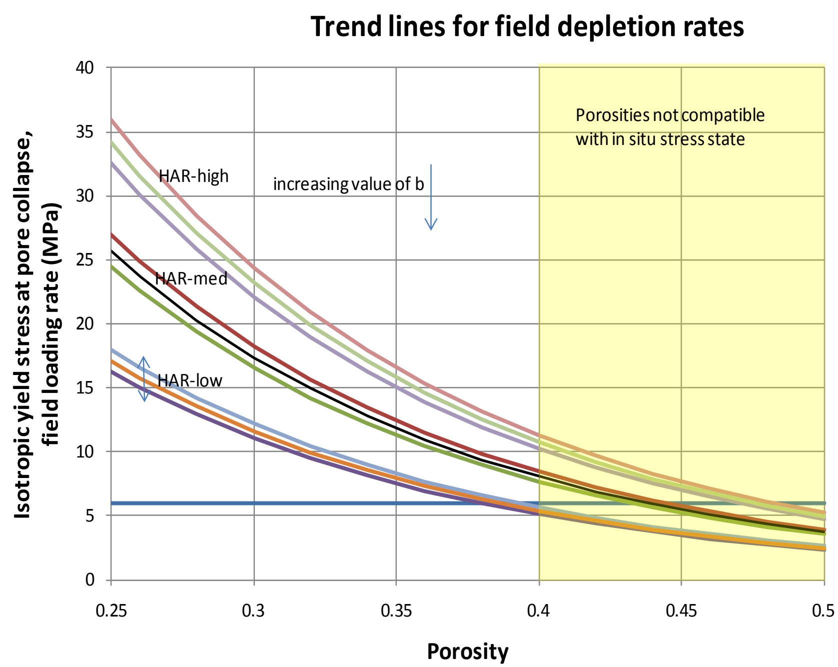
$b = 0.17e^{-3.1n}$ → 0.054-0.065 — Kristiansen & Plischke (2010), Valhall field

Relating laboratory data to field

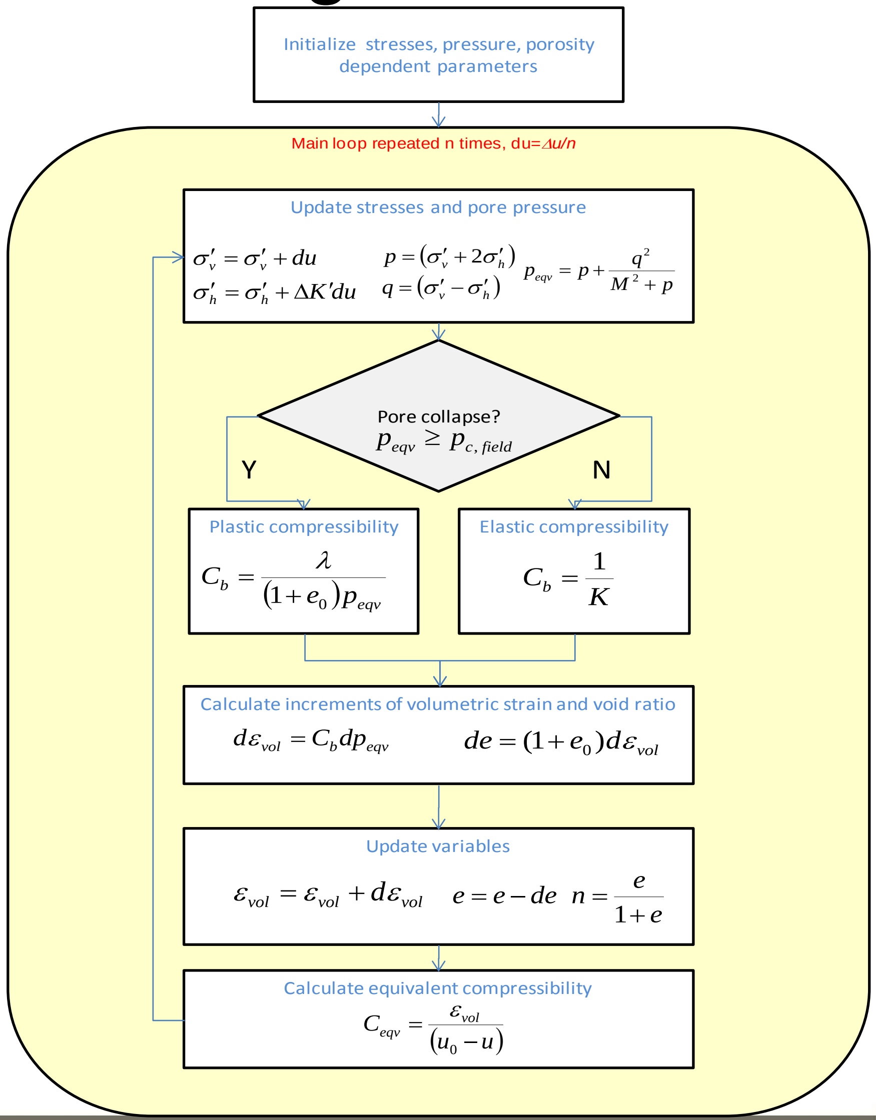


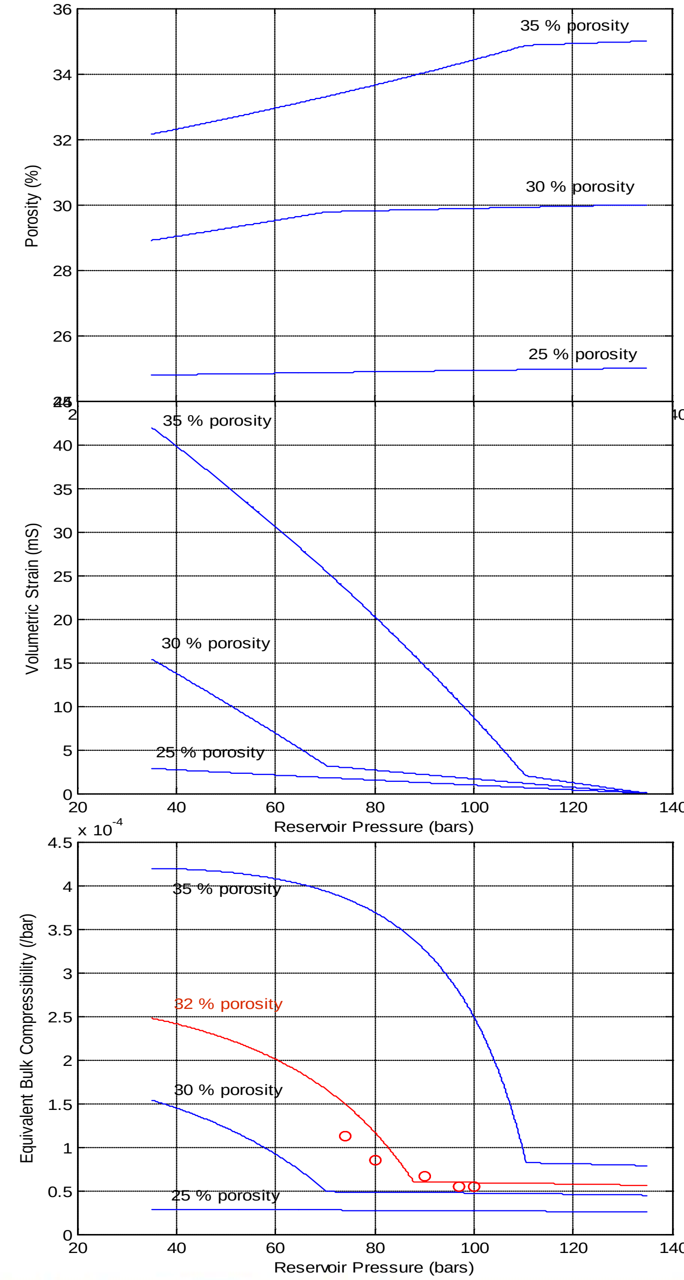
Leroueil 2006

$$\left(\frac{\sigma^{yield}_{field}}{\sigma^{yield}_{lab}}\right) = \left(\frac{\dot\varepsilon_{field}}{\dot\varepsilon_{lab}}\right)^{b}$$



Modelling field deformation





Summary

Demonstrated porosity, rate and saturating fluid effects on mechanical behavior:

Chalk exhibit rate dependent stiffness: 0.01MPa/h > 0.10 MPa/h > 1.00 MPa/h >10.00 MPa/h

Only subtle difference between mech. response at 30% brine saturation as vs100% saturation (*Pc* and *Et* slightly higher, *b* slightly lower)

The elastic and plastic compression properties of the chalk have been compared to available data from open literature: fit within the general scatter observed for chalk and proposed porosity-dependent correlations.

Laboratory experiments have been analyzed within the frame work proposed by de Waal (1986) to characterize the time and rate dependent behavior: agreement with other chalk data from the open literature.

A simple model is developed, and based on the defined material correlations it estimates the volumetric strain due to depletion.