Bentonite mechanical testing – constitutive and regression model fitting

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Objective

- Provide experimental data for elastoplastic model fitting in various conditions and various bentonite types
- Fit elastoplastic constitutive models to the experimental data
- Fit experimentally based surrogate models to the constitutive model parameter data

Procedure

Bentonite raw material
Wyoming Na, Georgian, …
powder, GraFi,…

Wetting option 1
Equilibrium with controlled RH in desiccator cabinet

Wetting option 2
mixing with water or salt solution

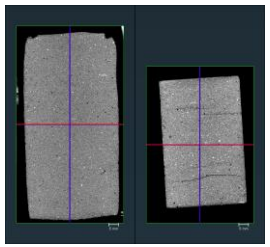
Volumetric compaction
cyclically with isotropic pressure

Calibration

Data on volumetric elastoplastic behaviour

Machining
of pre-samples

QA + additional tests
Electric resistivity / X-ray tomography



Calibration

Shearing
cyclically at constant volume

Data on isochoric elastoplastic behaviour

2

Design of Experiments

- Need to cover various conditions and bentonite types
  - Wyoming, Georgian and Bulgarian bentonite powders
  - 5 water contents
  - 3 dry densities
  - 3 wetting water salinities (constant Na/Ca ratio according to Posiva #2 reference water)
  - 5 triaxial test pressures

- Design of Experiments (DoE) statistical scheme
  - Maximal information from minimum number of samples
  - 31 samples in DoE

Bentonite type	Ben		Qualitative	Controlled	Wy; Ge; Bu
Water content	Kos	w%	Multilevel	Controlled	11; 14; 17; 20; 23
Dry density	Kui	g/cm^3	Multilevel	Controlled	1,4; 1,65; 1,8
Pressure componennt of stress	Jän	MPa	Multilevel	Controlled	0; 3; 6; 9; 12
Wetting water sodium	KasNa	mmol/l	Multilevel	Controlled	1,95; 110; 271
Wetting water calsium	KasCa		Quantitative	Uncontrolled	

A set of 31 samples in varying material/condition combinations

Exp No	B	Water %	ρ_dry	salt (mmol/l)	Init w %	ρ_dry	P (Mpa)	Exp No	B	Water %	ρ_dry	salt (mmol/l)	Init w %	ρ_dry	P (Mpa)	Exp No	B	Water %	ρ_dry	salt (mmol/l)	Init w %	ρ_dry	P (Mpa)
8	Na	11	1,40	1,95	11,48			1	GB	11	1,40	1,95	10,82			25	Ca	11	1,40	110	11,14		
13	Na	11	1,40	271	11,37			20	GB	11	1,40	271				12	Ca	11	1,65	1,95	11,19		
4	Na	11	1,80	1,95	10,95			10	GB	11	1,80	1,95	10,82			19	Ca	11	1,80	271	11,33		
22	Na	11	1,80	271	11,37			15	GB	11	1,80	271	10,86			27	Ca	14	1,40	110	14,20		
28	Na	20	1,65	110	19,70			29	GB	17	1,65	110	17,44			17	Ca	14	1,65	271	14,35		
3	Na	23	1,40	1,95	23,00			30	GB	17	1,65	110	17,44			6	Ca	14	1,80	1,95	14,26		
21	Na	23	1,40	271	23,05			31	GB	17	1,65	110	17,44			2	Ca	20	1,40	1,95	20,06		
11	Na	23	1,80	1,95	23,00			9	GB	23	1,40	1,95				23	Ca	20	1,80	271	20,10		
16	Na	23	1,80	271				14	GB	23	1,40	271	23,01			18	Ca	23	1,40	271	22,85		
								5	GB	23	1,80	1,95	23,18			7	Ca	23	1,65	1,95	23,38		
								24	GB	23	1,80	271	23,01			26	Ca	23	1,80	110	22,75		

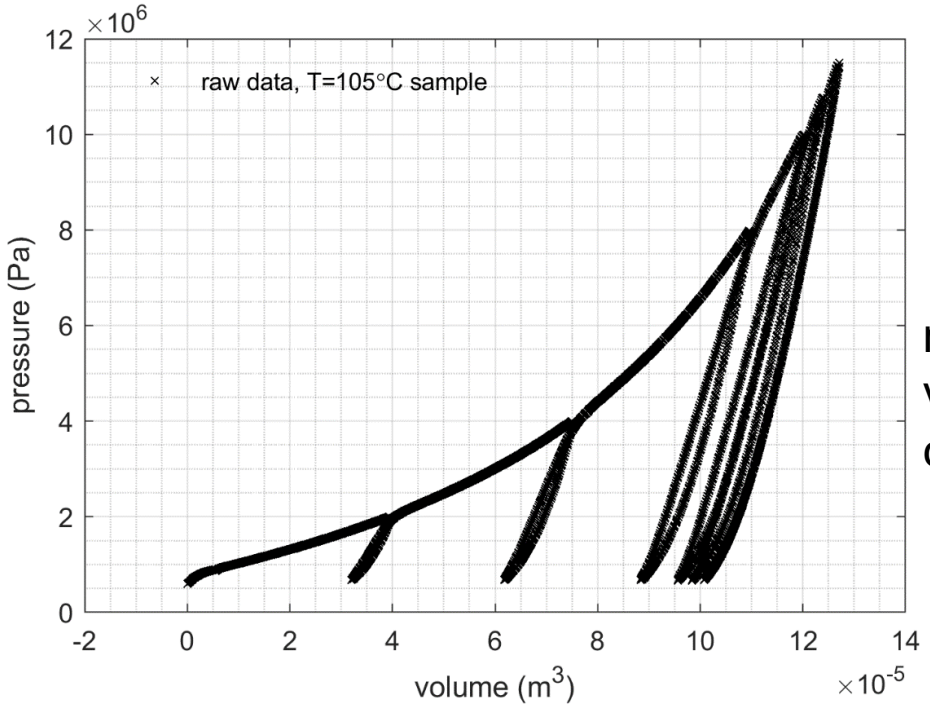
Reality

- Aim to produce samples for triaxial tests
  - Varying maximum compaction pressure
    - Difficult to compare data from different samples
- 31 samples in DoE
  - 48 compacted (+ test samples) volumetrically
    - Duplicates
    - Not all could be machined to triaxial shear test samples
      - Condition combination adjustment
  - Water content vs max dry density
    - Impossible combinations

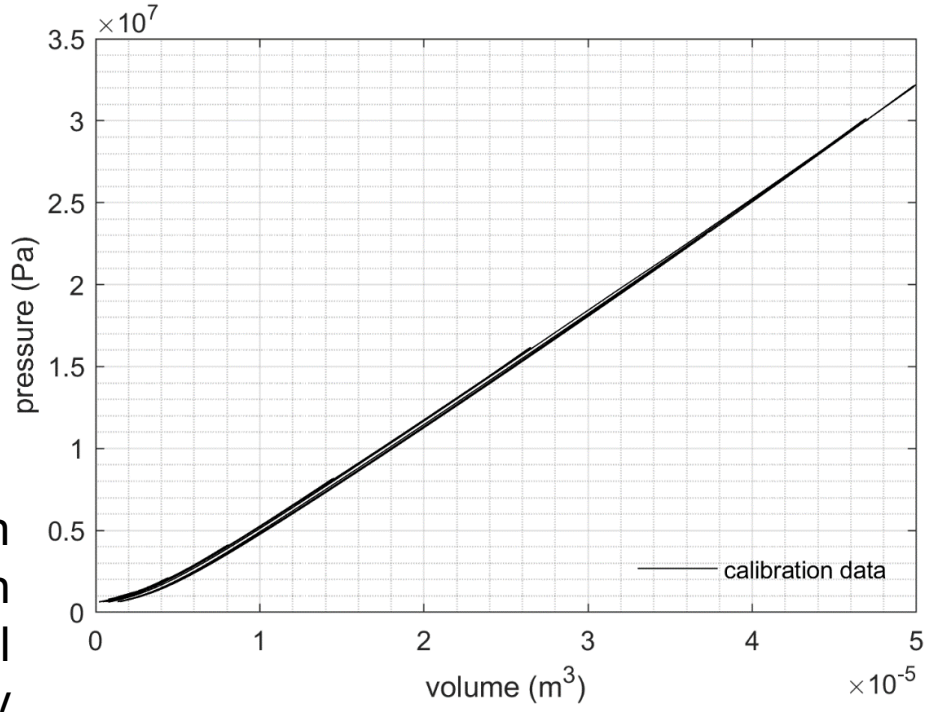
Volumetric compaction device

No	Equipment	Model	Total
1	Syringe Pump	Floxlab BTSP 175-15	1
2	Water De-Aerator	GDS Nold DeAerator	1
3	Storage Tank	GDS Instruments	1
4	Pressure Vessel	Dustec Pressure Vessel 100MPa with quick lock	1
5	Vacuum Pump	Edwards XDS 10	1
6	Hose Pump	Verderflex EV1500	2
7	Electric Chain Hoist	Yale Vego 0,5t	1
8	High Pressure Valves	Parker Autoclave Engineers 1034Bar	4
9	High-Pressure Piping	Parker Autoclave Engineers 1034Bar	3m
10	Low-Pressure Valves	Various Models	9
11	Low-Pressure Piping	Verderflex Tubes	5m
12	Desktop Computer	HP Desktop Computer	1

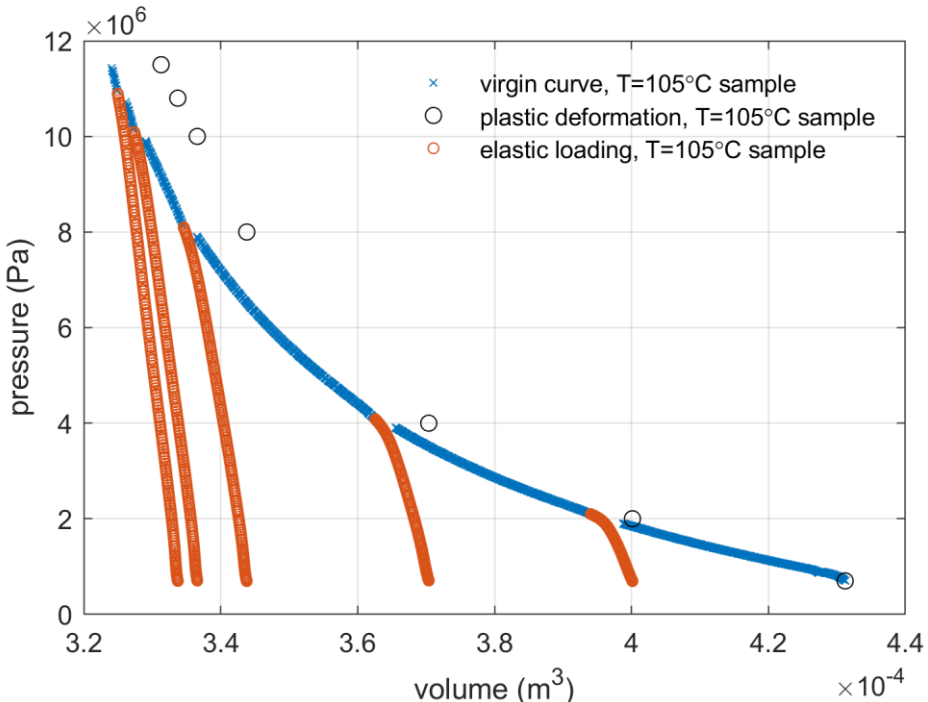
Calibration



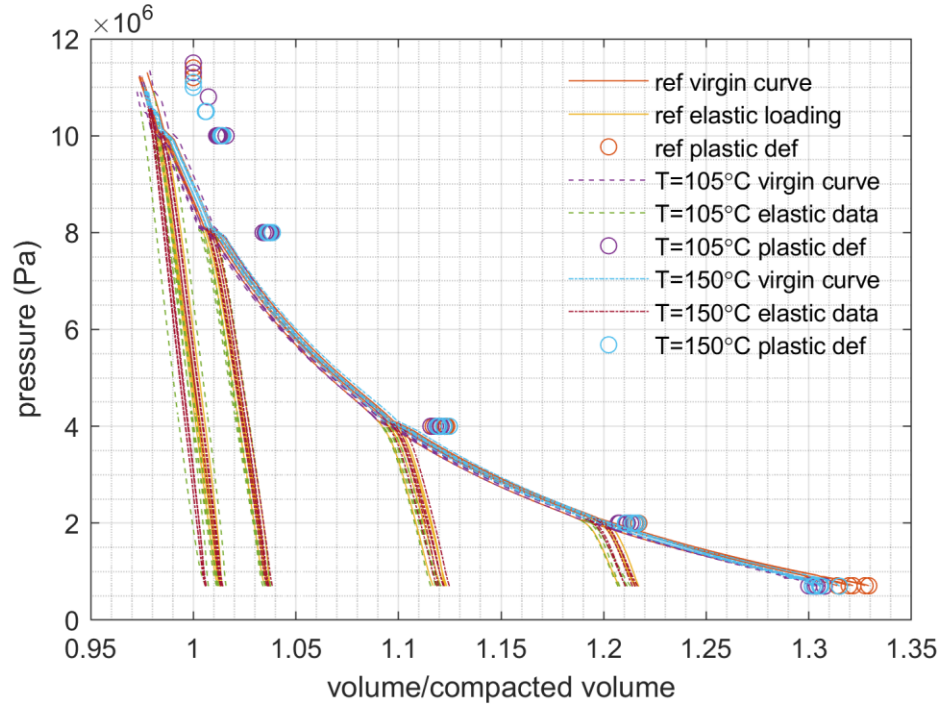
raw data of volumetric compaction



calibration with PVC/metal dummy



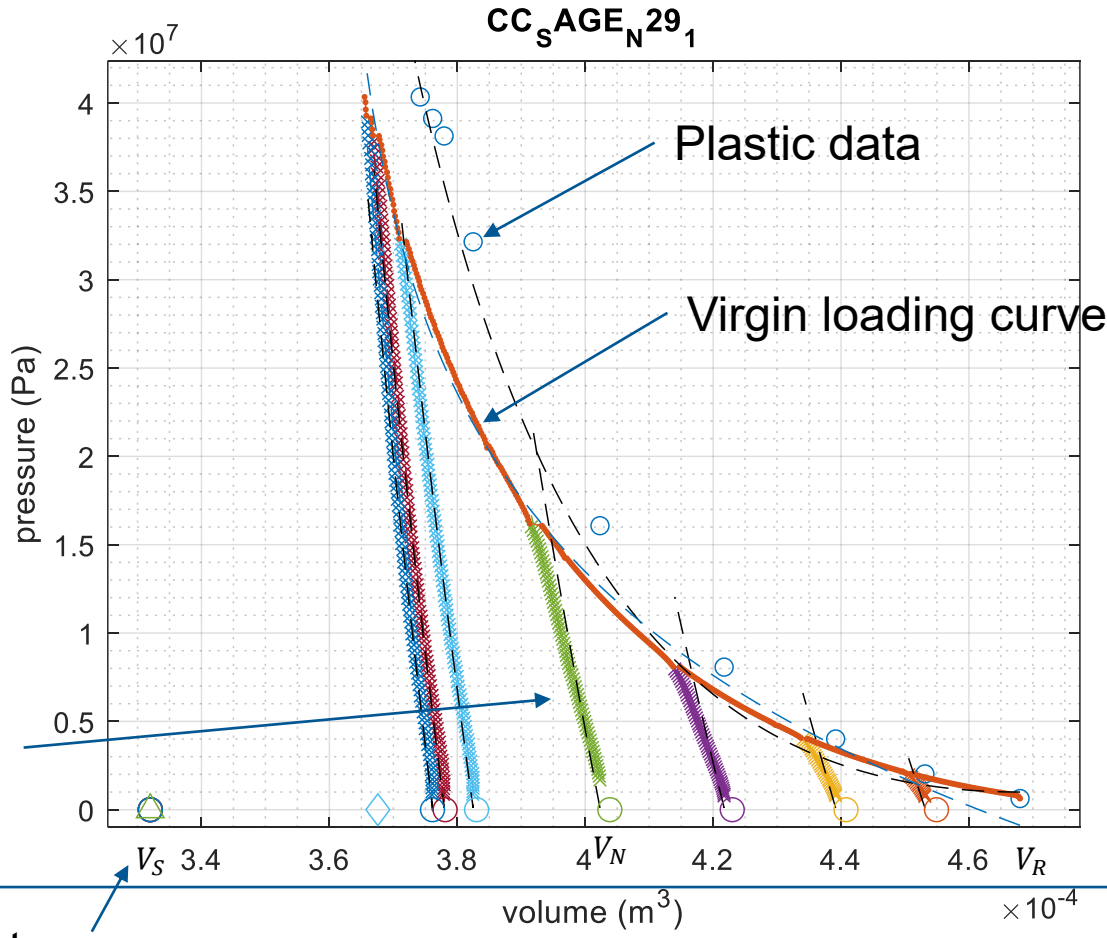
measured volume change reduced from the sample initial volume: separated elastic loading and plastic deformation



combined data

Constitutive model fitting principles

- p ⟶ ∞ when gas filled porosity ⟶ 0
- Elastic model example $$p = -\kappa \ln\left(\frac{V - V_s}{V_N - V_s}\right)$$
- Plastic model example $$p_c = p_{c0} - \lambda \left(\ln\left(\frac{V_P - V_s}{V_R - V_s}\right)\right)^2$$

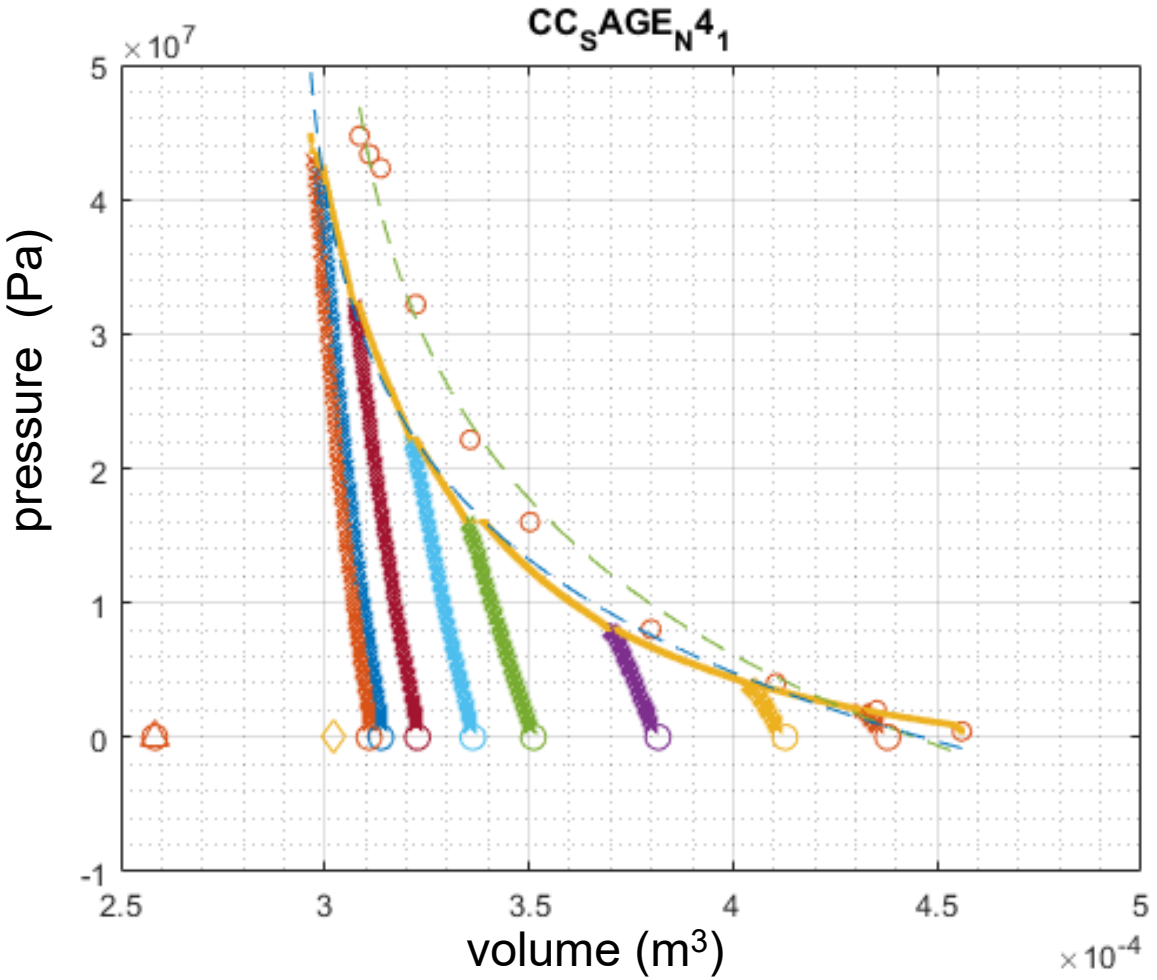


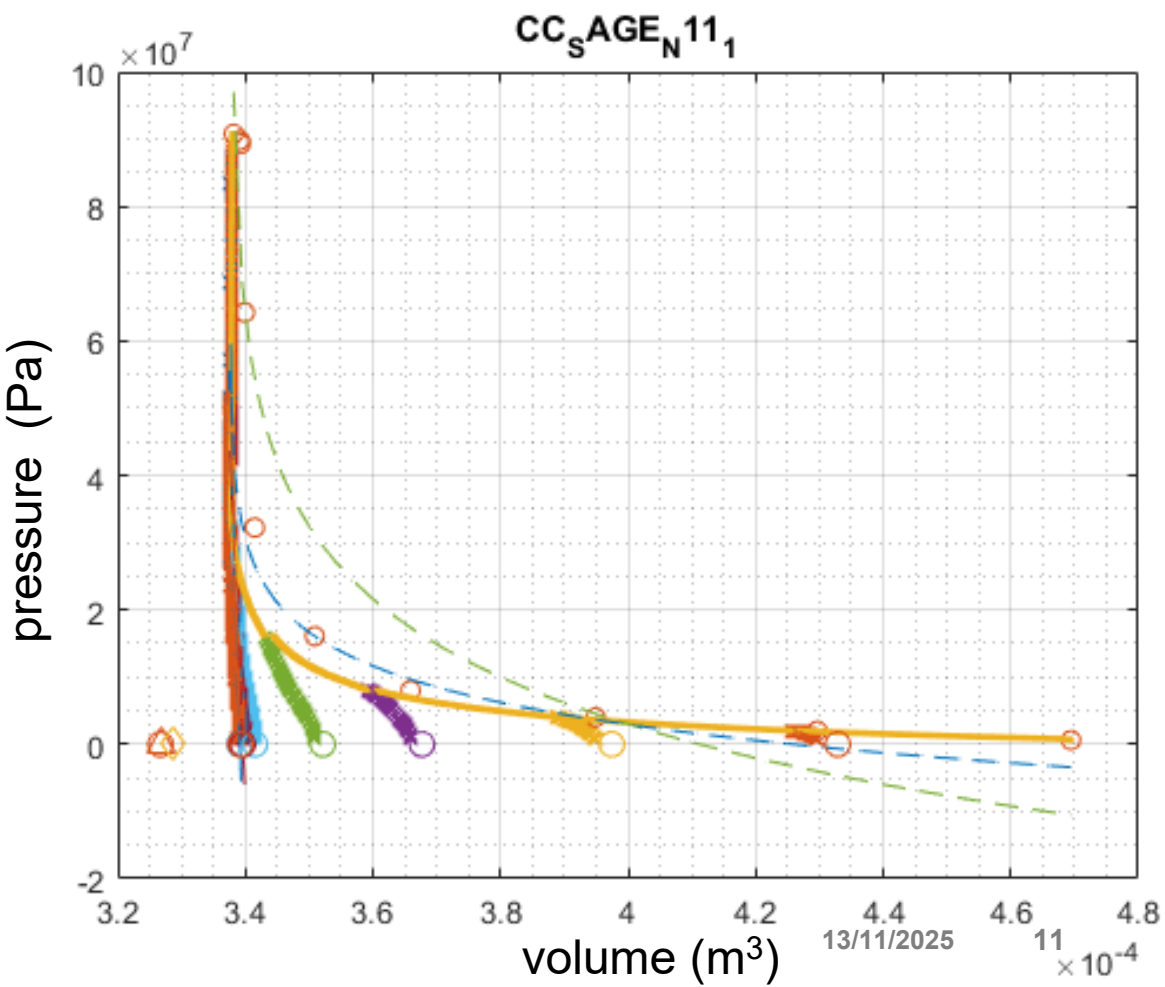
The first constitutive model fitting questions

- Measured Vs or fitted Vs? Vs = when $p \rightarrow \infty$
  - If fitted,
    - better fit to all elastic loading stages but one more model parameter

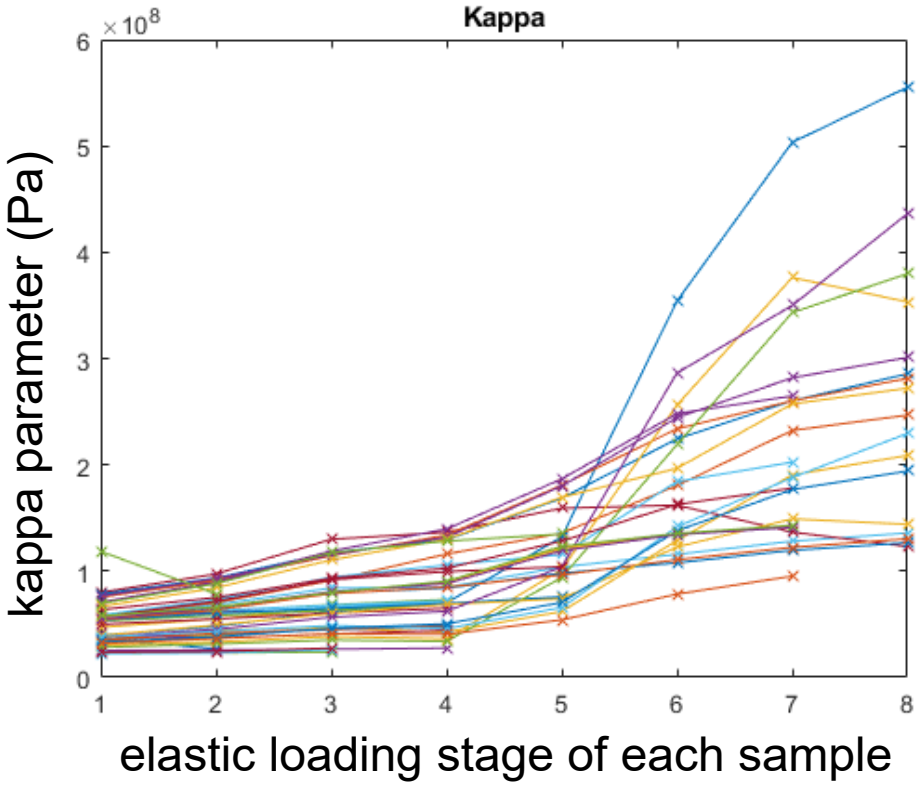
    → measured
- Elastic model dependency of plastic deformation
  - Fit to each elastic loading stage separately or fit to all elastic loading stage data?

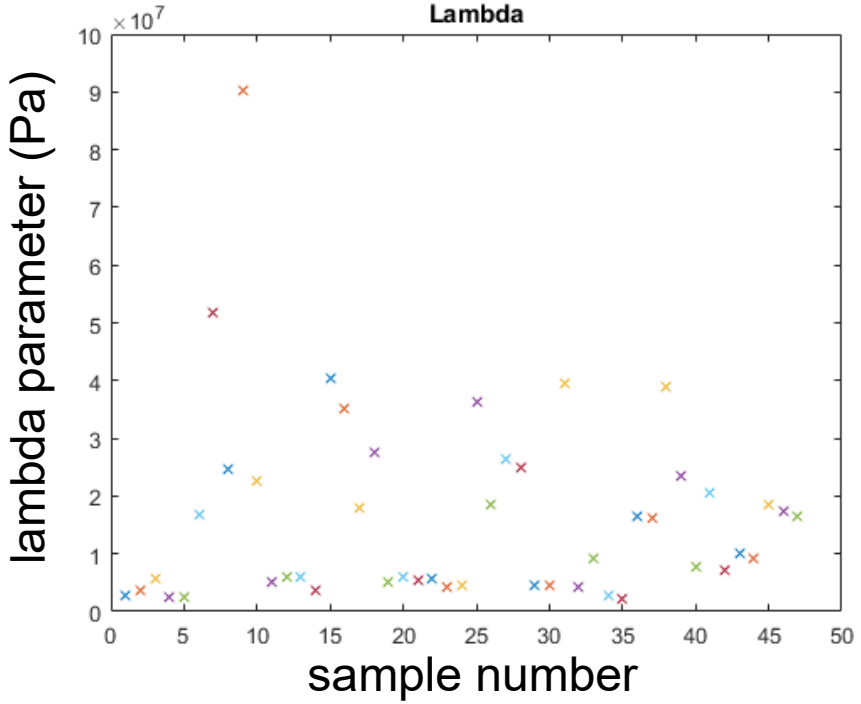
Fitting to each elastic loading stage: examples

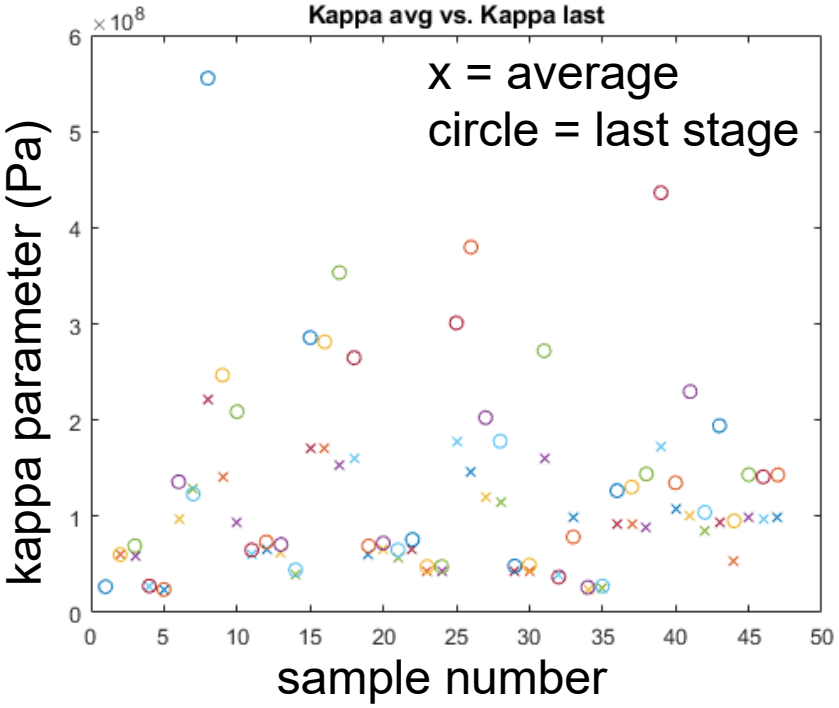




Fitting to each elastic loading stage: fit analysis



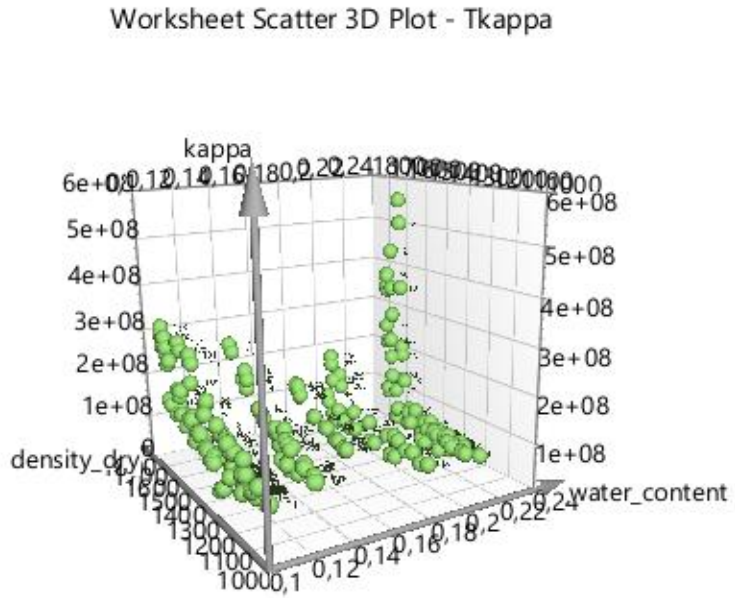


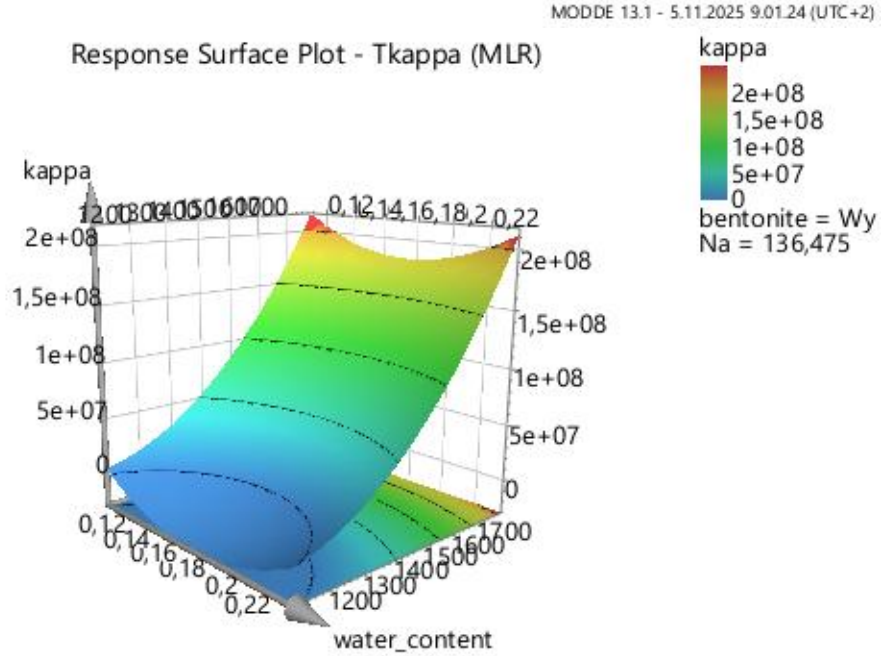


Fitting to each elastic loading stage: regression model results

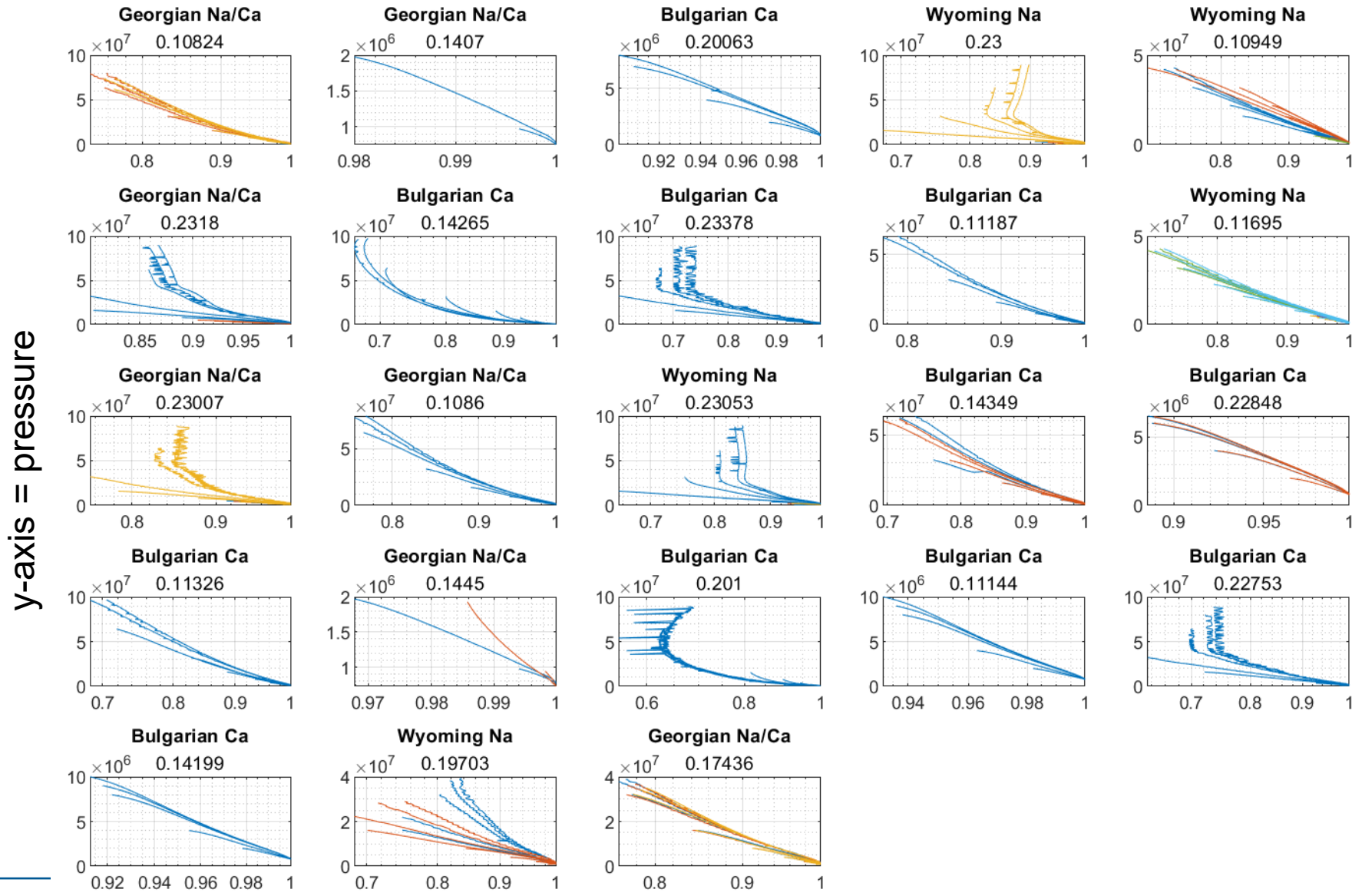
kappa	DF	SS	MS (variance)	F	p	SI
Total	267	4,8577e+18	1,81936e+16			
Constant	1	2,964e+18	2,964e+18			
Total corrected	266	1,89369e+18	7,11914e+15			8,4375e+07
Regression	8	9,03411e+17	1,12926e+17	29,4209	**0,000**	3,36045e+08
Residual	258	9,90282e+17	3,8383e+15			6,1954e+07
Lack of Fit (Model error)	120	6,894e+17	5,745e+15	2,63495	**0,000**	7,57958e+07
Pure error (Replicate error)	138	3,00882e+17	2,1803e+15			4,66937e+07

N = 267 Q2 = 0,443 Cond. no. = 8,048
DF = 258 R2 = 0,477 RSD = 6,195e+07
R2 adj. = 0,461





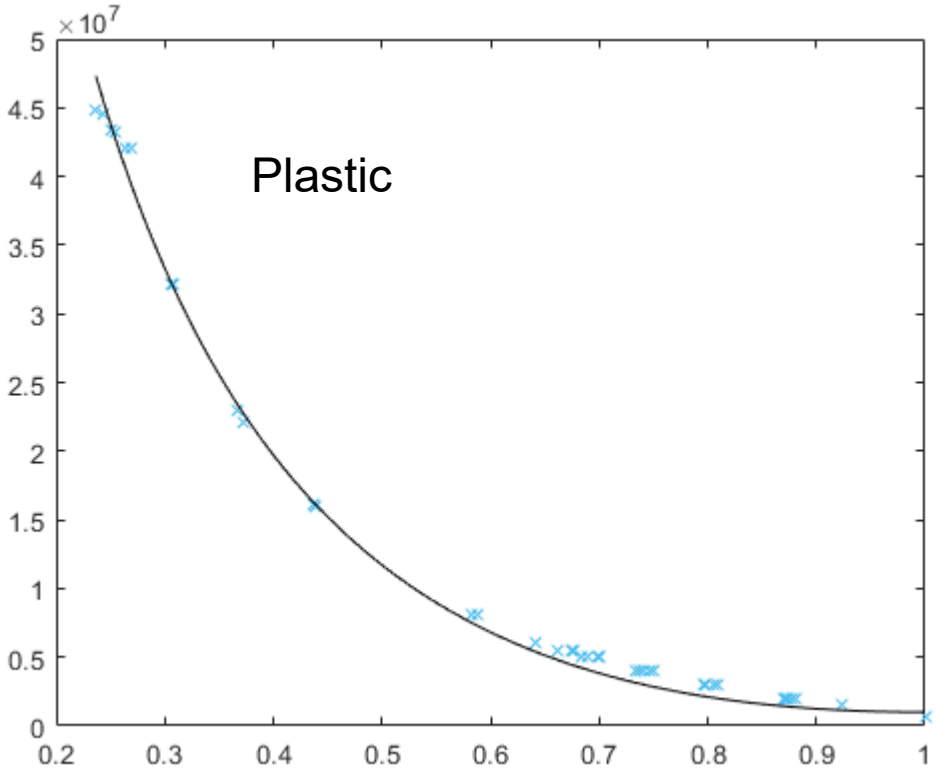
Data grouped for each bentonite type, water content and salinity combinations

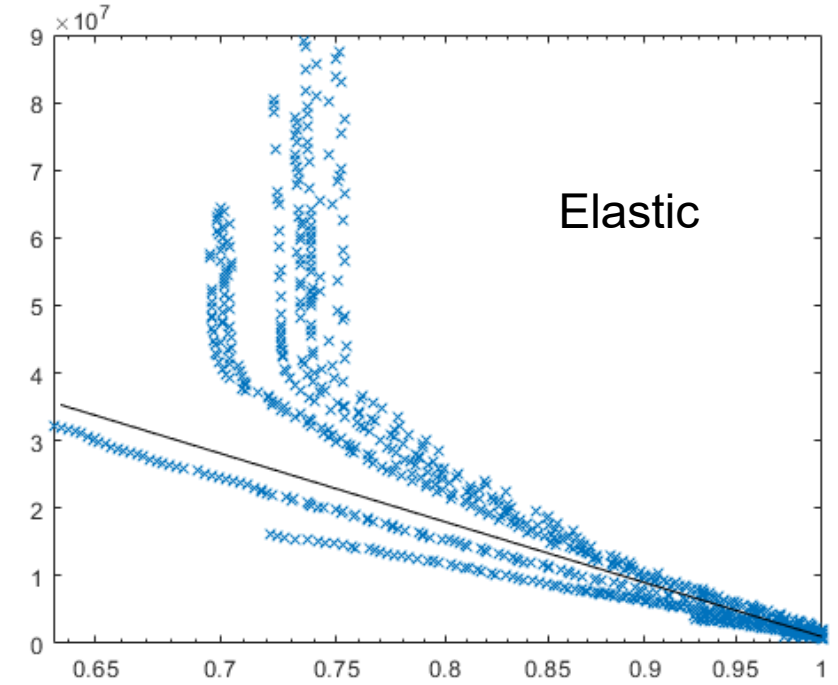


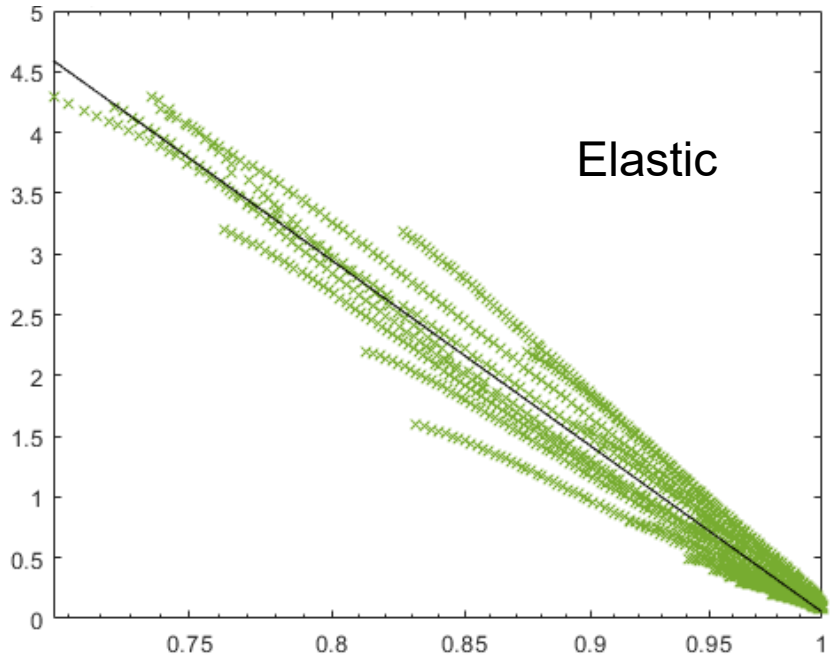
y-axis = pressure

x-axis = relative gas fille pore volume change

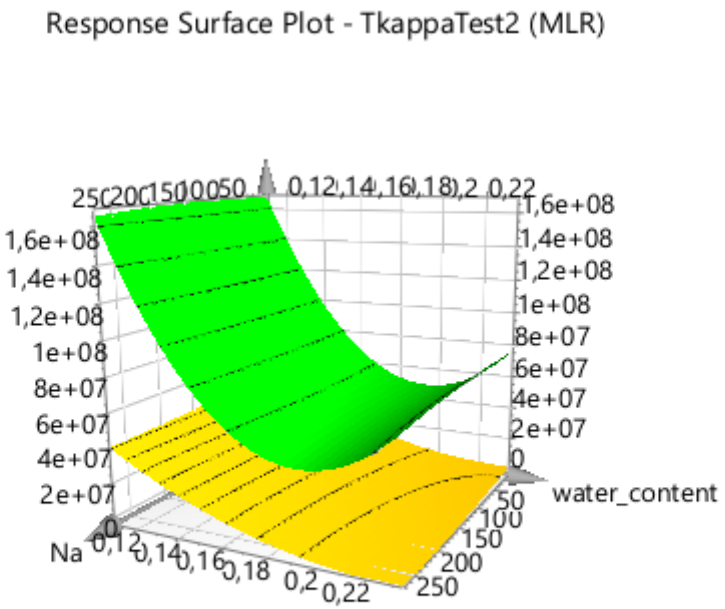
Fitting examples

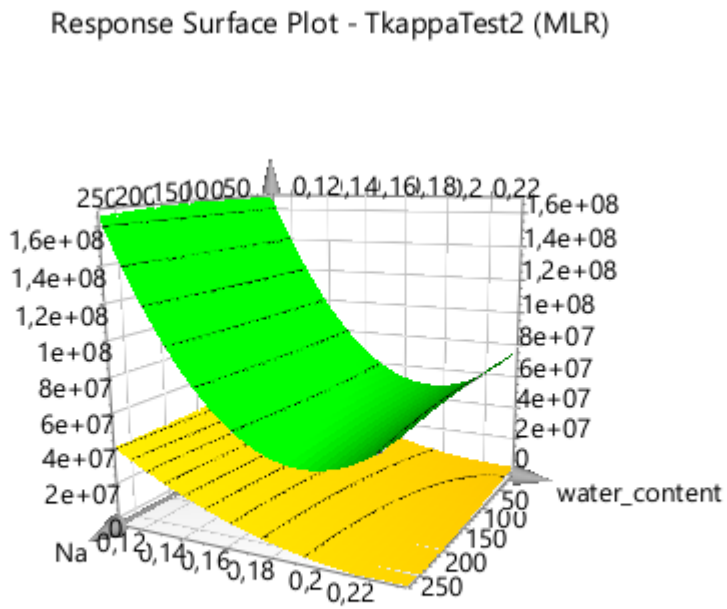


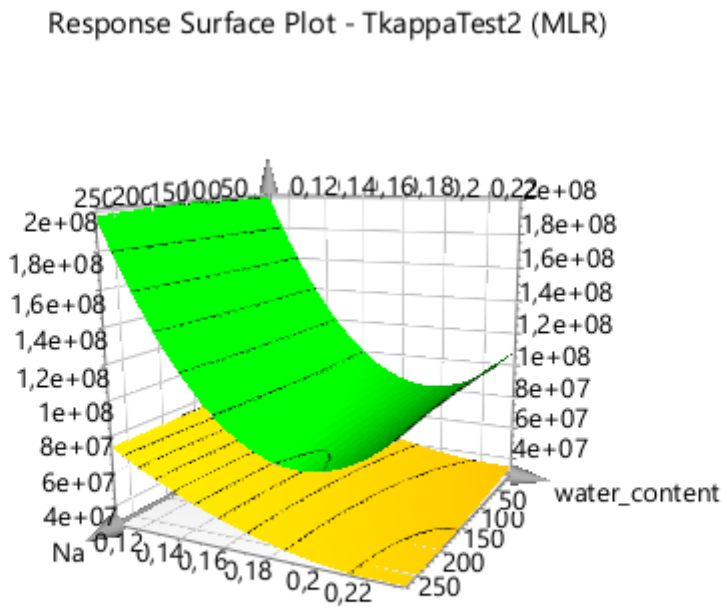




Regression model fitting to grouped data



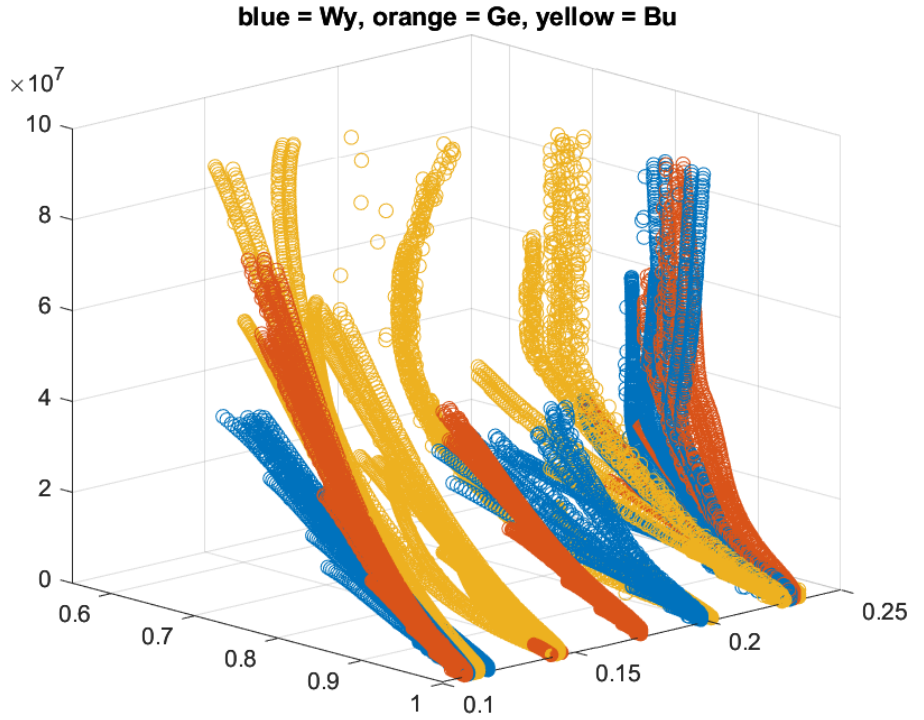




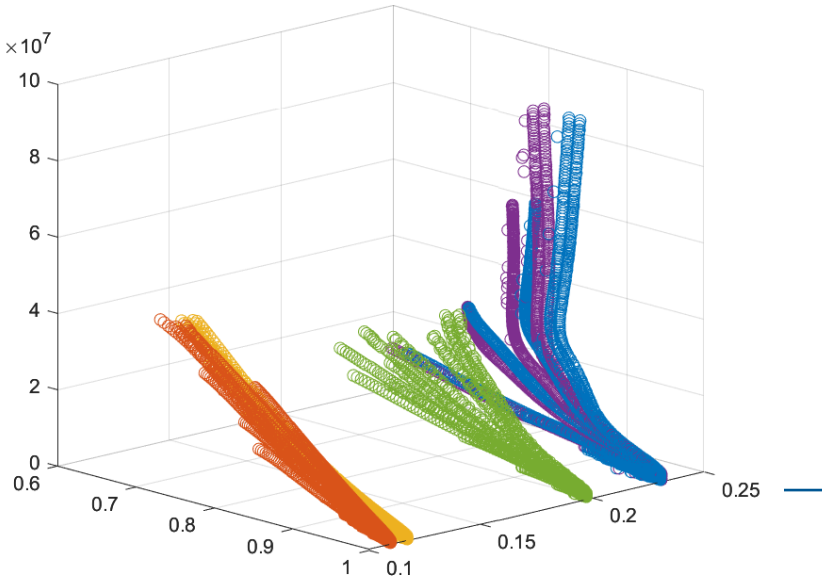
Regression model fitting to grouped data

- Something but not that good
- Wetting water salinity seems to have only small effect
- Next approach
  - Fit to (strainMeasure, waterContent) grouped data instead of polynomial multivariable regression model fitting to (strainMeasure, waterContent, bentoniteType, salinity) data
  - On-going

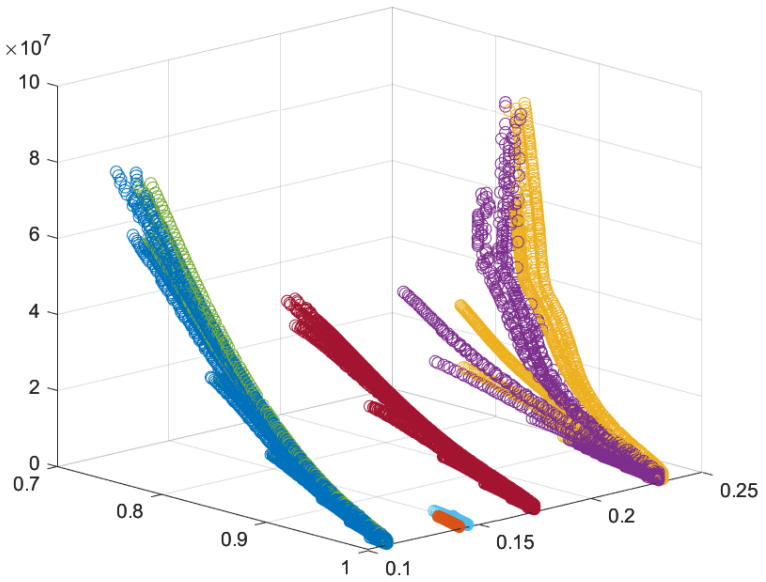
Elastic re-grouped data



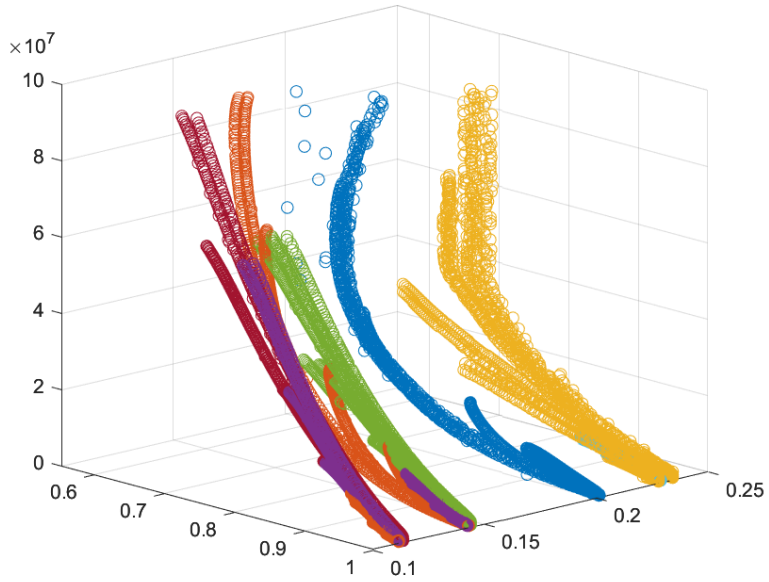
Wyoming bentonite



Georgian bentonite

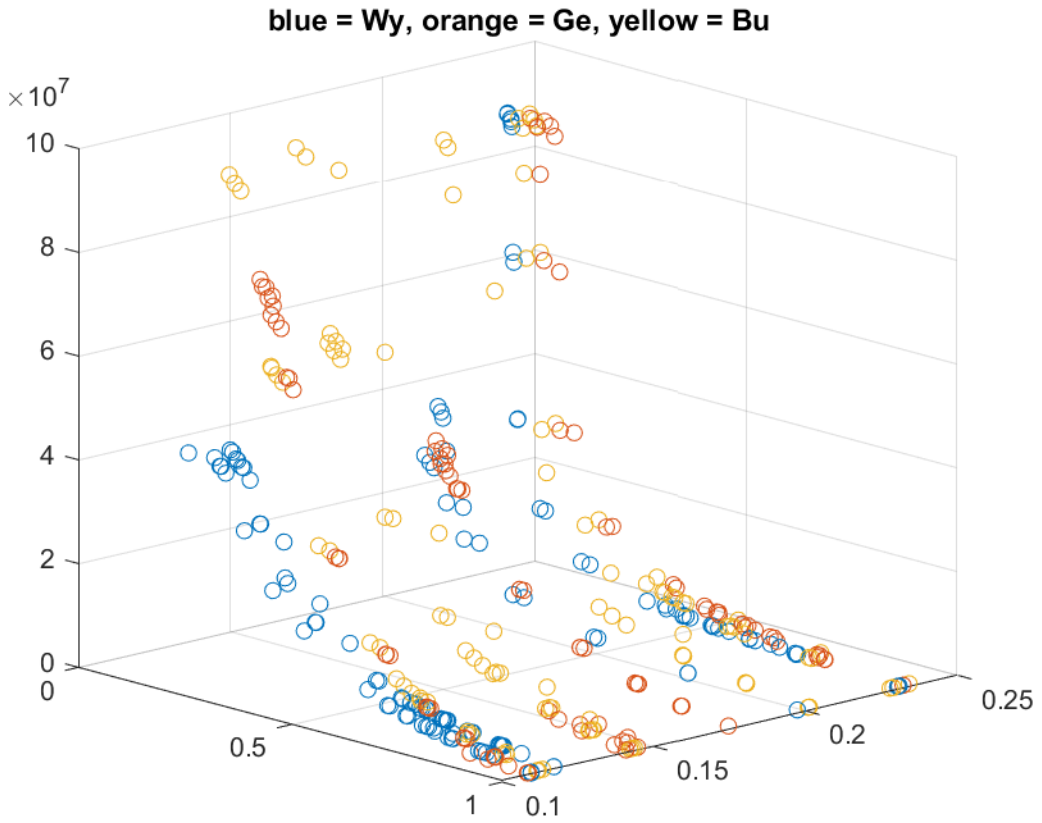


Bulgarian bentonite

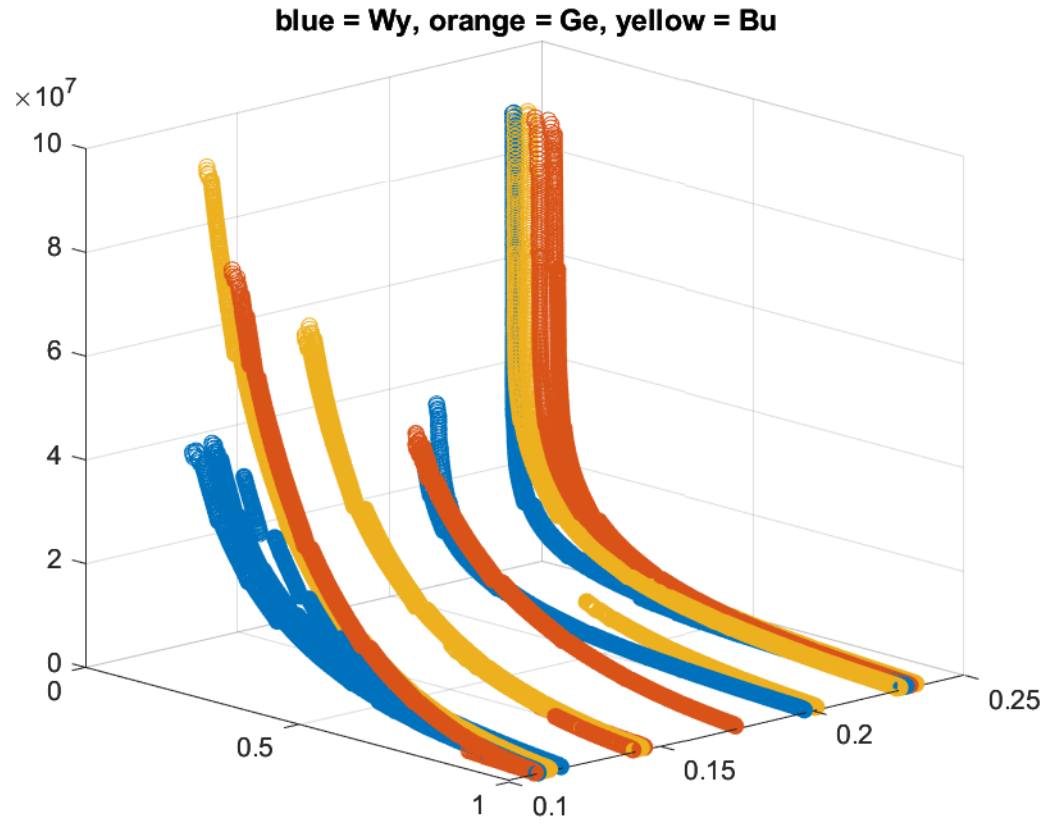


Plastic and virgin loading re-grouped data

Plastic



Virgin loading



Summary

- Volumetric compaction of planned samples + extra ones performed
- Shear tests?
- Constitutive and regression modelling performed
  - Need to continue the work for better experimentally based surrogate models
  - New compacted samples would make the fit quality better
  - Possible to add data from other samples (e.g. SAGE RH controlled bentonites, EURAD HITEC non-heat treated bentonite data)
- It is not a good idea to have qualitative variable (bentonite type) in DoE for quantitative analysis

Thanks!