Forced-flow exposure of sealants to CO_2, and indentation mapping of carbonation extent

CEMENTEGRITY WP 1 Additional Deliverable, v. 1
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Summary:
This report contains the slide deck presented at the CEMENTEGRITY Concluding *Ceminar*, held online on 2024-11-27, presenting the results of CEMENTEGRITY WP 1 for all 5 sealants tested. For further explanation, recordings of the full *Ceminar* are available on www.cementegrity.eu.

ACT3-CCUS Project

Cementegrity - Development and testing of novel cement designs for enhanced CCUS well integrity

Work Package 1

Gunnar Lende, Halliburton EESSA technology laboratory

10-01-2025

Released for publication

WP1 exposure mode – high ΔP axial dynamic – limited by permeability

Axial only exposure conditions:

Cement confined by pipe, by impermeable formation (clay) or both

→ Assuming axial only exposure

→ Small contact area

→ Damage progression can be very slow

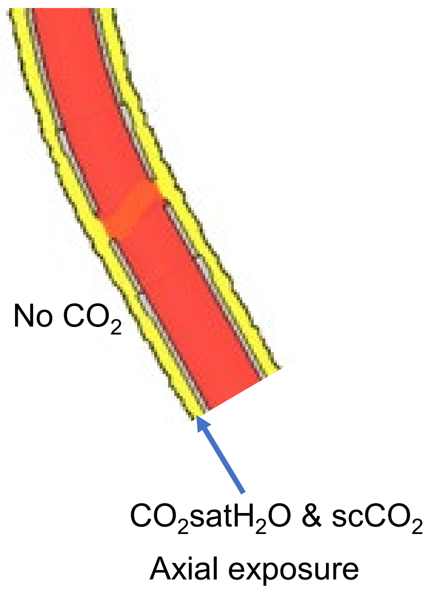
→ May mitigate with longer barrier

Five sealants studied in this project:

1. Standard OPC-silica blend with no attempts to reduce permeability (reference for old wells)
2. OPC-silica blend system with reduced permeability and typical field chemicals
3. OPC-silica blend system with reduced permeability, modified mechanical properties, and a CO2 sequestering agent
4. Non-Portland, Calcium-aluminate cement-based system considered highly acid resistant
5. Rock-based geopolymer developed for CCUS (by UiS)

All samples for all work packages molded and cured by Halliburton

Curing done at 150°C and 310 bar for 28 days for full hydration, no further reactions during storage, equal starting materials for all partners



Cementegrity WP1

Expectations:

1. Guidance on progression rate of CO_2 affected (carbonated) zone vs. detrimentally damaged (bi-carbonated) zone
2. Comparison of super critical ($scCO_2$) vs. CO_2 saturated freshwater (CO_2satH_2O) impact
3. Establish flow potential through matrix for both $scCO_2$ and CO_2satH_2O
4. Test method to identify zones for materials not responding to phenolphthalein, and where zones not visible
5. Test method to estimate mechanical properties of affected zone
6. System comparison

Physical properties

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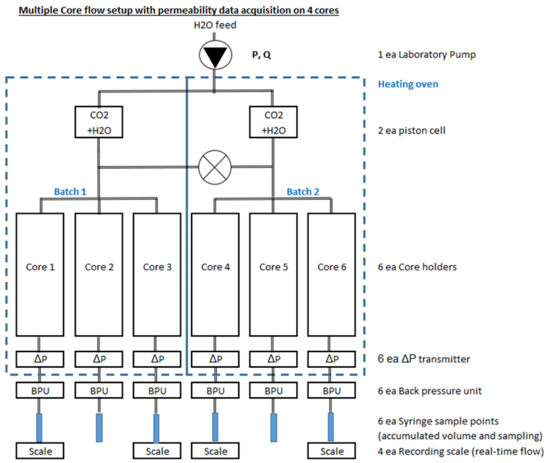
WP1 forced flow exposure tests

B setup - 2 x 3 channel, 3 and 6 months, CO_2satH_2O, 80°C



Axial ΔP adjusted to obtain suitable flow rate, varied with design

S1, S2, S3, S5: Pi = 62 bar, Po = 14 bar, ΔP = 48 bar → 603 bar/m

S4: Pi = 55 bar, Po = 48 bar, ΔP = 7 bar → 86 bar/m

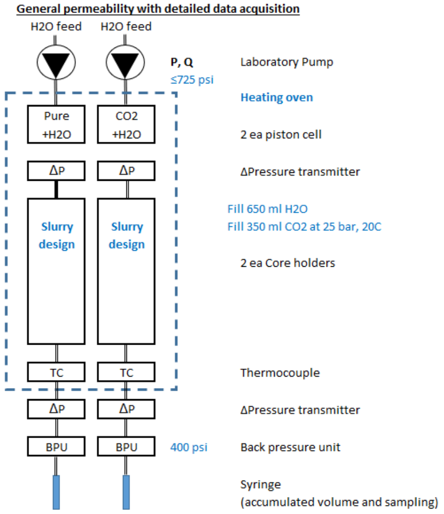
Over-saturation occurs when heating from 20 to 80 °C → multi-phase flow through sample

Determine Bi-carbonate leach and transportation potential

Tests:

1. Reference, 3 months flow, 6 months flow
2. Indentation map to determine carbonation front / map exposure/time effects
3. Young's Modulus, compressive strength, Poisson's ratio, 4x Brazilian tensile strength
4. Sample exhaust fluid for possible analysis

C setup – 2 x 1 channel 3 months, $scCO_2$ and CO_2satH_2O , 80°C



Axial ΔP adjusted to obtain suitable flow rate, varied with design

CO_2satH_2O: Pi = 62 bar, Po = 14 bar, ΔP = 48 bar → 603 bar/m (S4 259 bar/m)

$scCO_2$: Pi = 117 bar, Po = 83 bar, ΔP = 34 bar → 431 bar/m (S4 345 bar/m)

Over-saturation occurs when heating from 20 to 80 °C → multi-phase flow through sample

Determine Bi-carbonate leach and transportation potential (CO_2satH_2O)

Tests:

1. Flow rate underway, with permeability estimate
2. Water permeability before and after
3. Indentation map to determine carbonation front / map exposure/time effects
4. Sample exhaust fluid for possible analysis

Ø38 x L 80 mm cylinders

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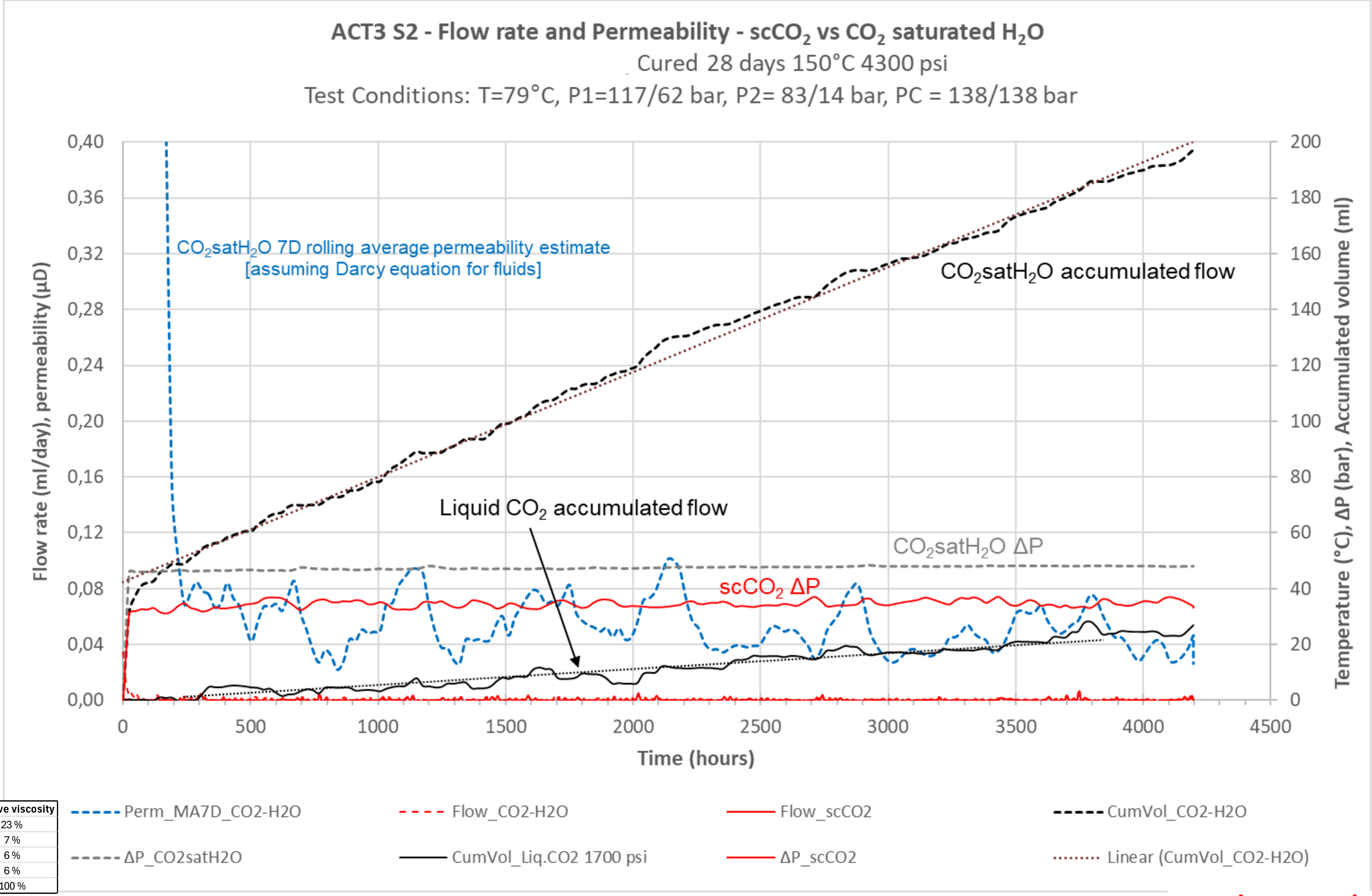
WP1 forced flow exposure tests – example chart

Typical OPC behavior is:

1. Rapid initial drop of flow rate with CO_2 and H_2O combination exposure, then slowly declining flow
2. Fairly constant flow of supercritical CO_2

Notes:

Actual flow rate inside sample differ from injection rate due to CO_2 expansion and phase change



Media	T (°C)	p (bar)	Density (kg/m3)	Relative density	Dyn viscosity (Pa s)	Relative viscosity
CO2	23	117	850	100 %	8,30E-05	23 %
CO2	80	117	291	34 %	2,55E-05	7 %
CO2	80	100	222	26 %	2,19E-05	6 %
CO2	80	83	169	20 %	2,02E-05	6 %
H2O	80	100			3,56E-04	100 %

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WP1 forced flow exposure tests – indentation test

Available tests:

1 x $scCO_2$ 6 months

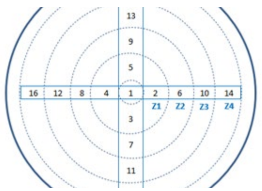
3 x CO_2satH_2O 6 months

In & out end – 13 measurements each

A and B side – 3 rows x 14 measurements

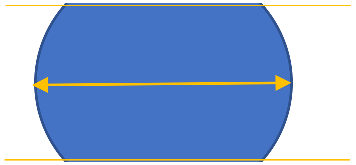
a) Test ends

Lost area



Lost area

b) Cut axially

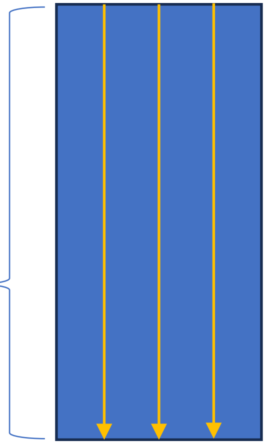


Cut (5 mm)

Cut (5 mm)

5 mm spacing

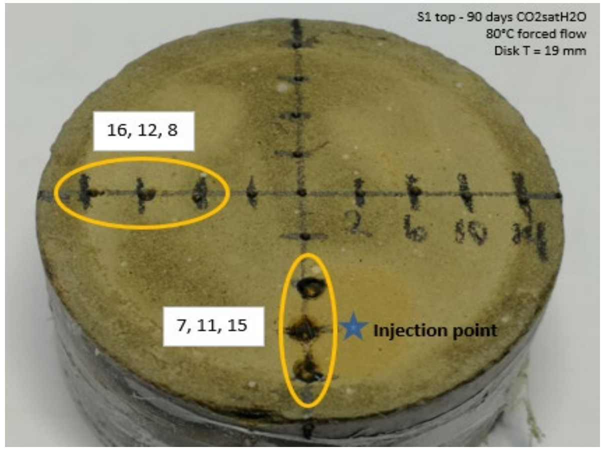
c) Test sideways



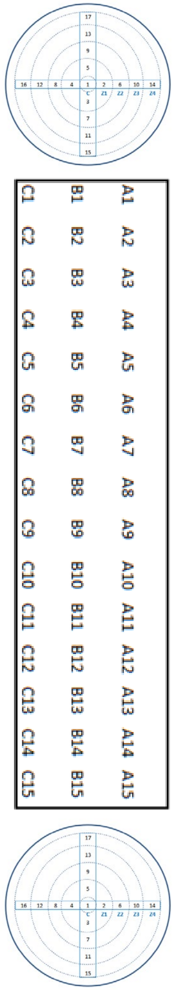
Zone 1 – 15
A1:C15

Sample height 79,5 mm

Zone 0 and 16



d) Map



$scCO_2$

Side A

Side B

CO_2satH_20

Side A

Side B

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WP1 forced flow exposure tests – indentation test S1

e) Chart

Observations:

Unaffected matrix found 10 / 15 mm below top at 90 / 180 days

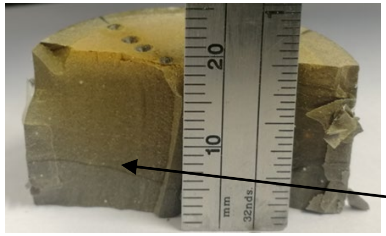
Change 90 → 180 days 5 mm

Softening by inlet area only

Notes:

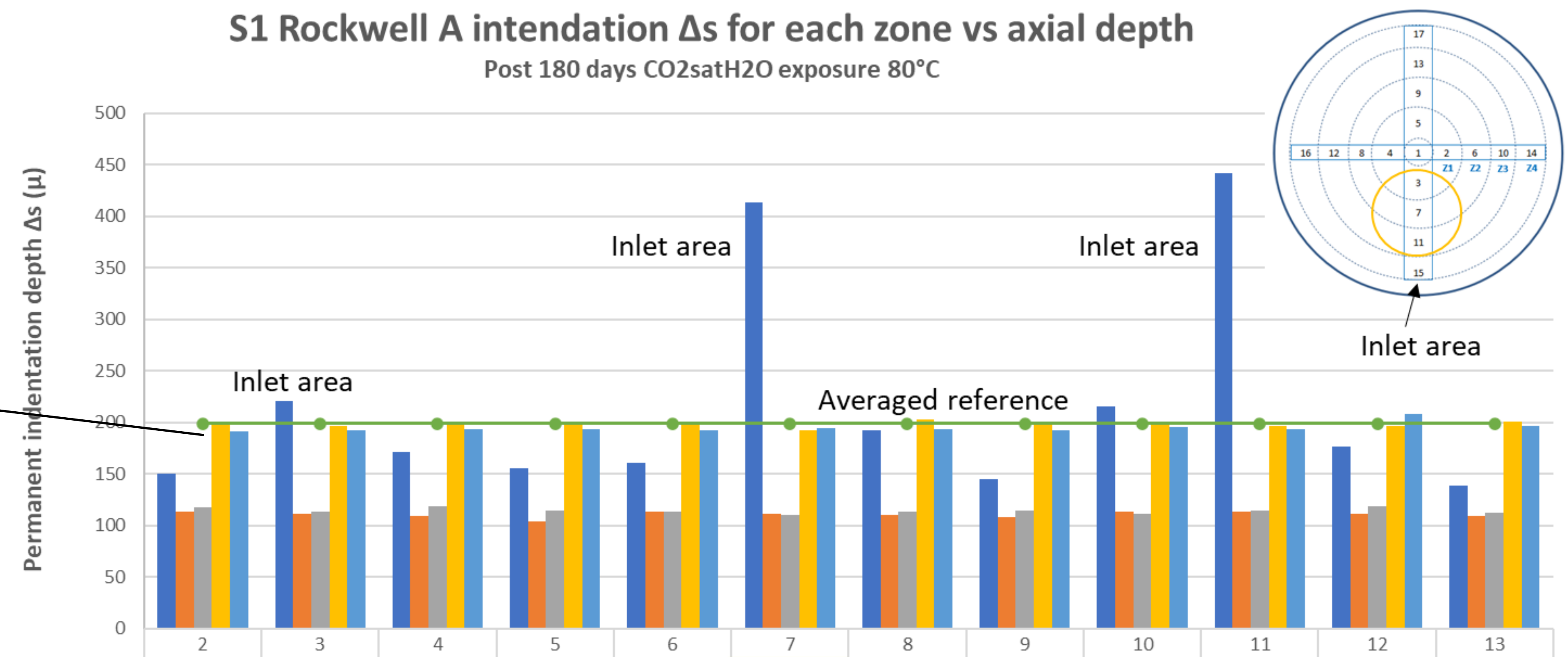
Progression front appears flat

First test → less data



Penetration depth

Inlet area



	2	3	4	5	6	7	8	9	10	11	12	13
0 mm	150	221	171	156	161	413	192	145	216	442	177	138
5mm	113	111	109	104	113	111	110	108	113	113	111	109
10mm	118	113	119	114	114	111	114	114	111	115	119	112
15mm	200	197	200	200	199	192	203	201	198	197	196	200
20mm	192	192	194	193	192	194	193	192	195	194	208	196
Reference Data Average	199	199	199	199	199	199	199	199	199	199	199	199

WP1 forced flow exposure tests – indentation test S2

e) Chart

Observations:

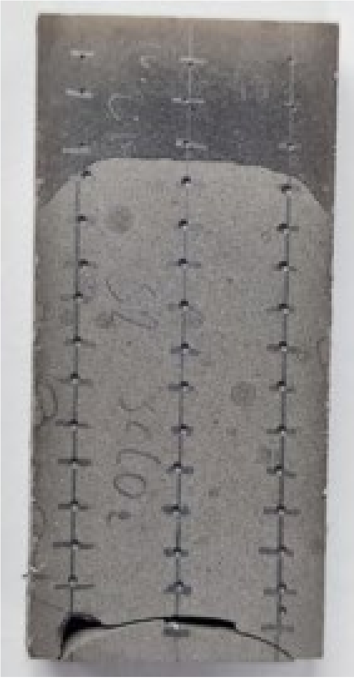
Both hardening and softening at 0 mm level (soft by inlet)

Increasing hardening 90 → 180 days at level 5 mm

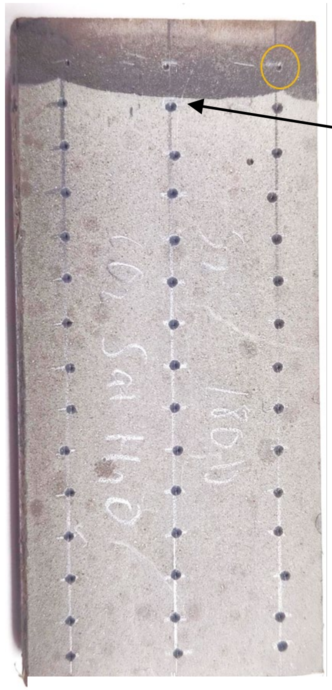
Unaffected at level 10/14 mm

Notes:

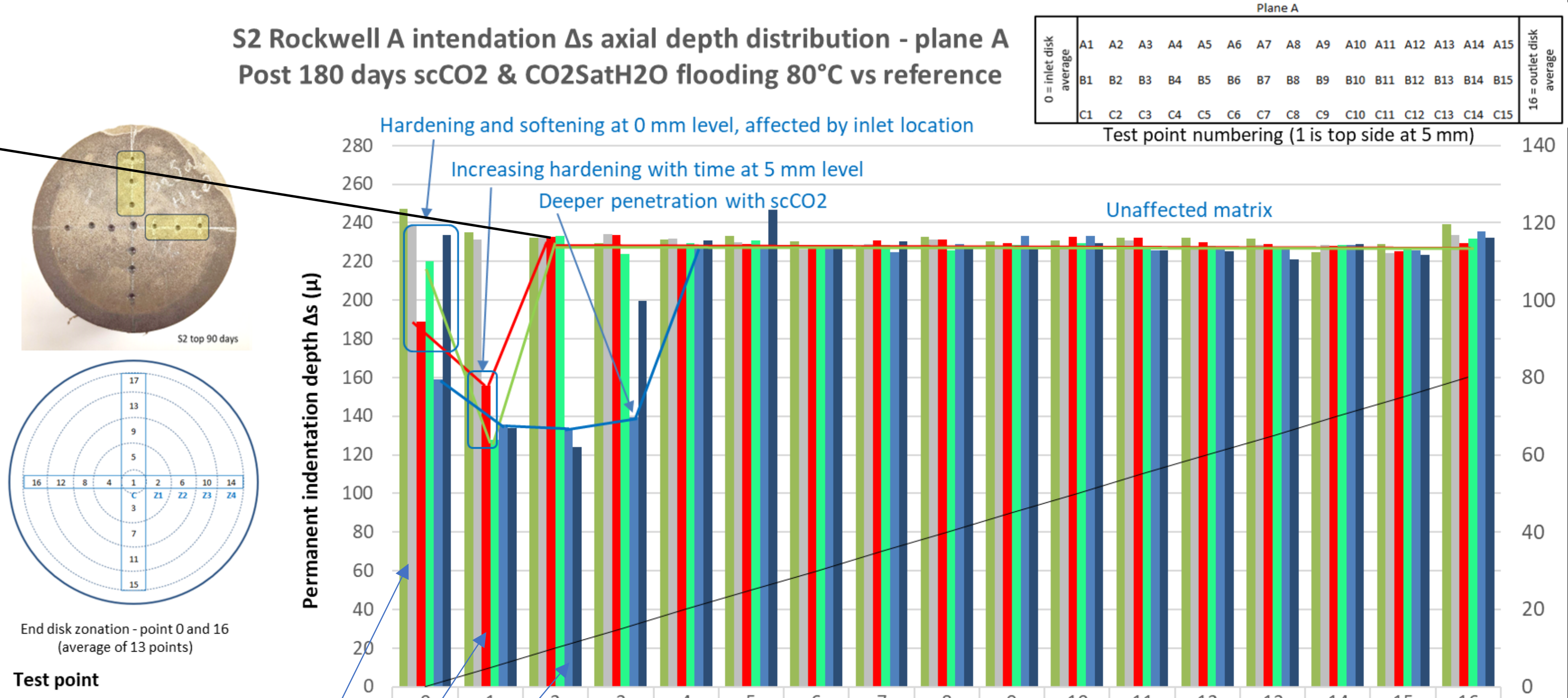
Twin cell setup exposure more less penetration depth than the six cell setup, suggesting variations can occur.



scCO2 180 days



CO2sH2O 180 days



Test point	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Reference - Plane A 90D unconfined	247	235	232	230	231	233	230	228	233	231	231	232	233	232	225	229	239
Reference - Plane A 180D unconfined	239	232	232	234	232	230	226	229	231	228	228	231	227	229	229	224	234
CO2satH2O P1 average 90D - Plane A	189	156	233	234	227	229	228	231	231	229	233	232	230	229	228	225	229
CO2satH2O P1 average 180D - Plane A	220	128	233	224	229	231	228	228	226	228	229	227	228	226	229	227	232
scCO2 average 180D - Plane A	159	136	133	140	229	227	227	225	229	233	233	226	226	227	228	226	236
CO2satH2O P2K average 180D - Plane A	234	134	124	200	231	247	228	230	227	227	229	226	225	221	229	223	232
Depth from top (mm)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80

WP1 forced flow exposure tests – indentation test S3

e) Chart

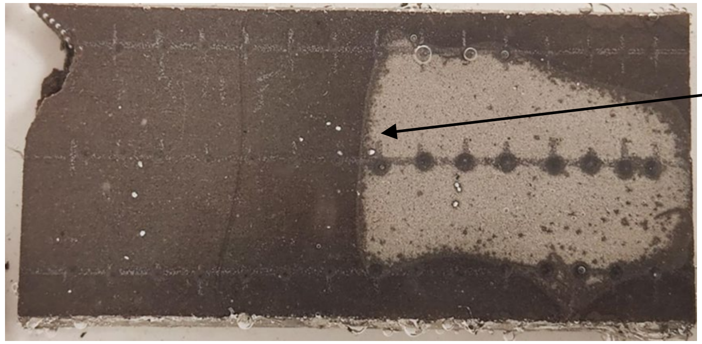
Observations:

$scCO_2$ hardening throughout sample, CO_2satH_2O hardening to 40mm

Large change 90 → 180 days

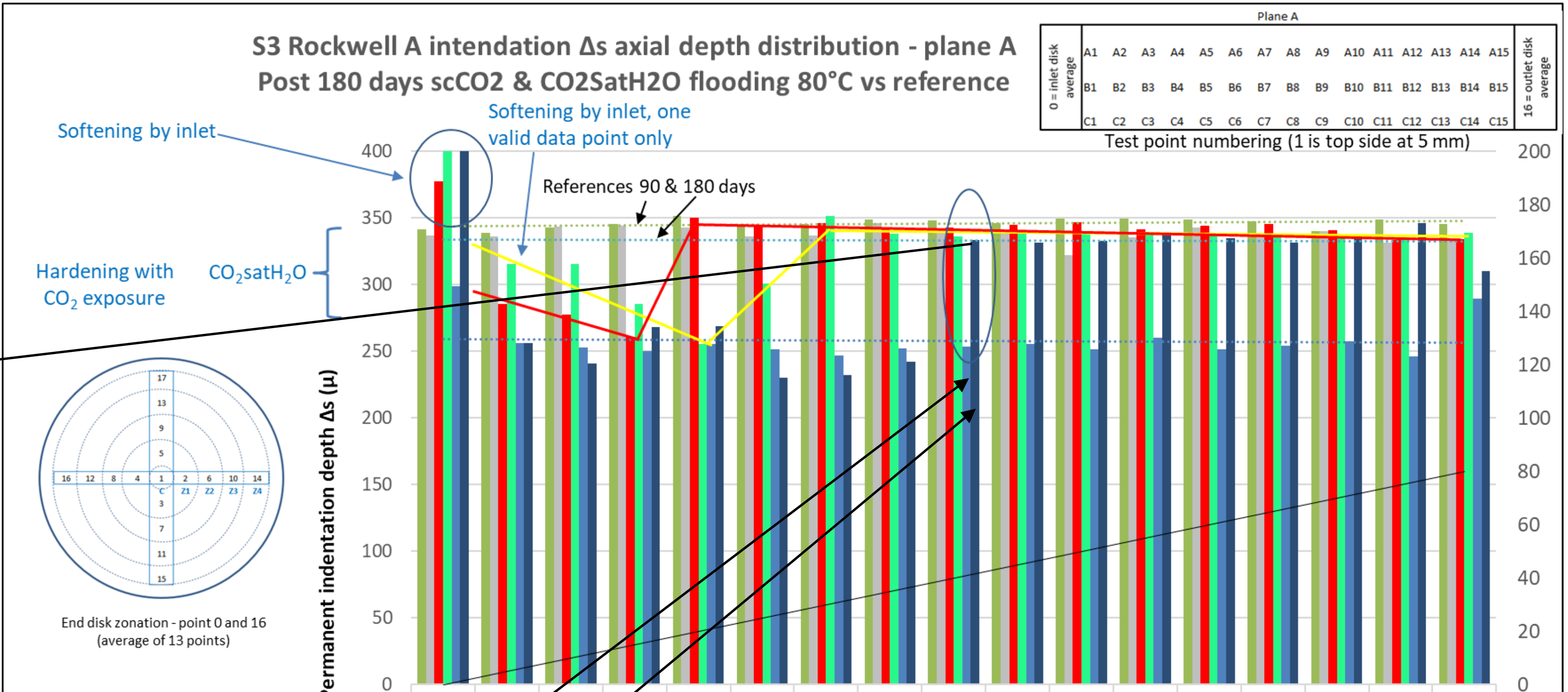
Softening by inlet

Notes:

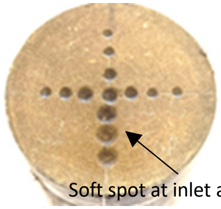


CO2satH2O 180D P2 (wet)

Test points along plane A - 1 through 15



Test point	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Reference - Plane A 90D unconfined	341	339	343	345	352	344	345	349	348	346	349	349	349	347	340	349	346
Reference - Plane A 180D unconfined	337	336	343	344	343	336	337	346	339	341	322	336	343	339	340	332	334
CO2satH2O P1 average 90D - Plane A	377	285	277	261	350	345	346	342	343	345	347	342	344	345	341	333	334
CO2satH2O P1 average 180D - Plane A	463	315	315	286	256	301	351	338	336	339	340	339	337	336	337	335	339
scCO2 average 180D - Plane A	299	256	253	250	256	251	247	252	254	256	252	260	252	254	258	246	290
CO2satH2O P2K average 180D - Plane A	449	256	241	268	269	230	232	242	333	332	333	339	335	331	337	346	310
Depth from top (mm)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80



Top disk post 180D CO2satH2O P1

Bottom disk post 180D CO2satH2O P1
No soft spots at exit

WP1 forced flow exposure tests – indentation test for S4

e) Chart

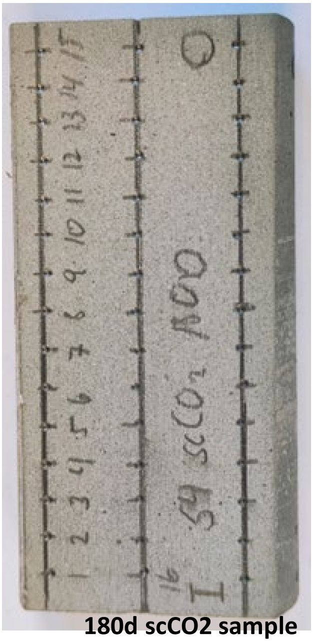
Observations:

Consistent hardening throughout sample, no soft spots

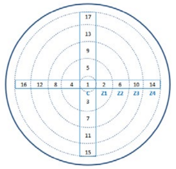
More hardening with $scCO_2$ than CO_2satH_2O

Notes:

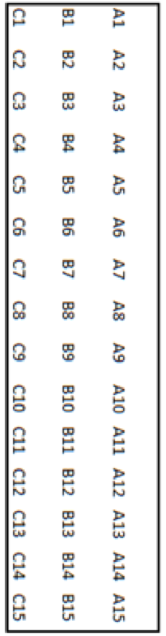
No response to phenolphthalein



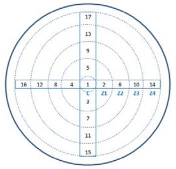
Point 0



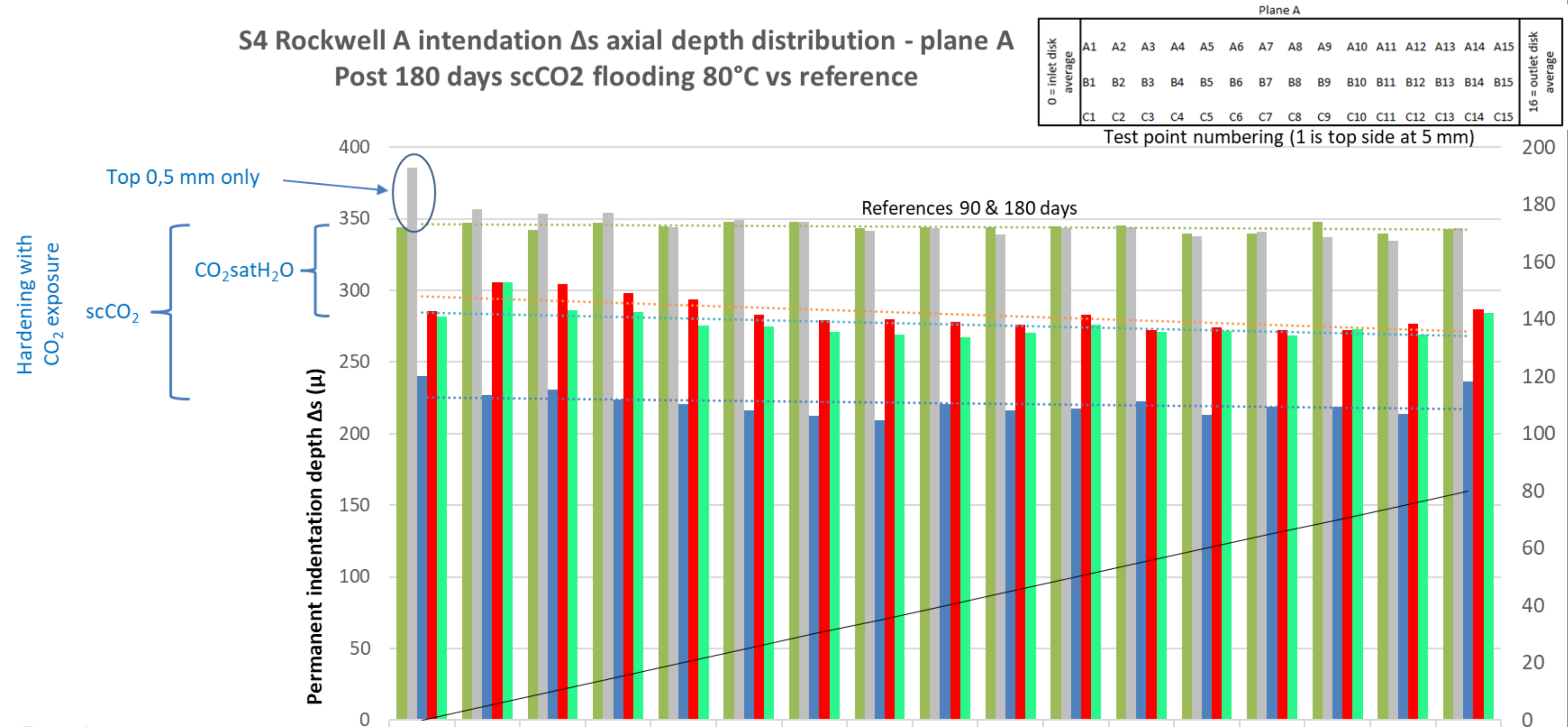
Points 1 - 15



Point 16



Average comparison including end disks



Test point	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Reference - Plane A 90D unconfined	344	348	342	347	345	348	348	343	344	344	345	345	340	340	348	340	343
Reference - Plane A 180D unconfined	385	357	354	354	344	349	348	342	343	339	344	344	338	341	338	335	344
scCO2 average 180D - Plane A	240	227	230	224	221	216	212	209	221	216	217	223	213	218	219	213	237
CO2satH2O P1 average 90D - Plane A	285	306	305	298	294	283	279	280	278	276	283	272	274	273	272	277	287
CO2satH2O P1 average 180D - Plane A	282	306	286	285	275	275	271	269	267	270	276	271	272	269	273	269	284
Depth from top (mm)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80

WP1 forced flow exposure tests – indentation test for S5

e) Chart

Observations:

General reference hardening with depth (segregation?)

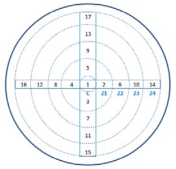
$scCO_2$ follows same hardening trend

Top level softening with CO_2satH_2O, then substantial hardening at 90 days, following trend at 180 days

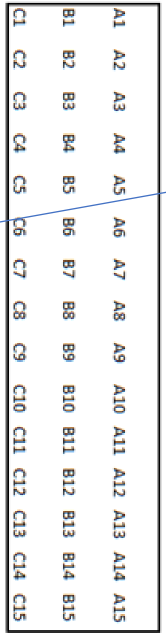
Notes:

post 180D CO2satH2O

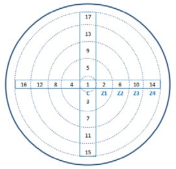
Point 0



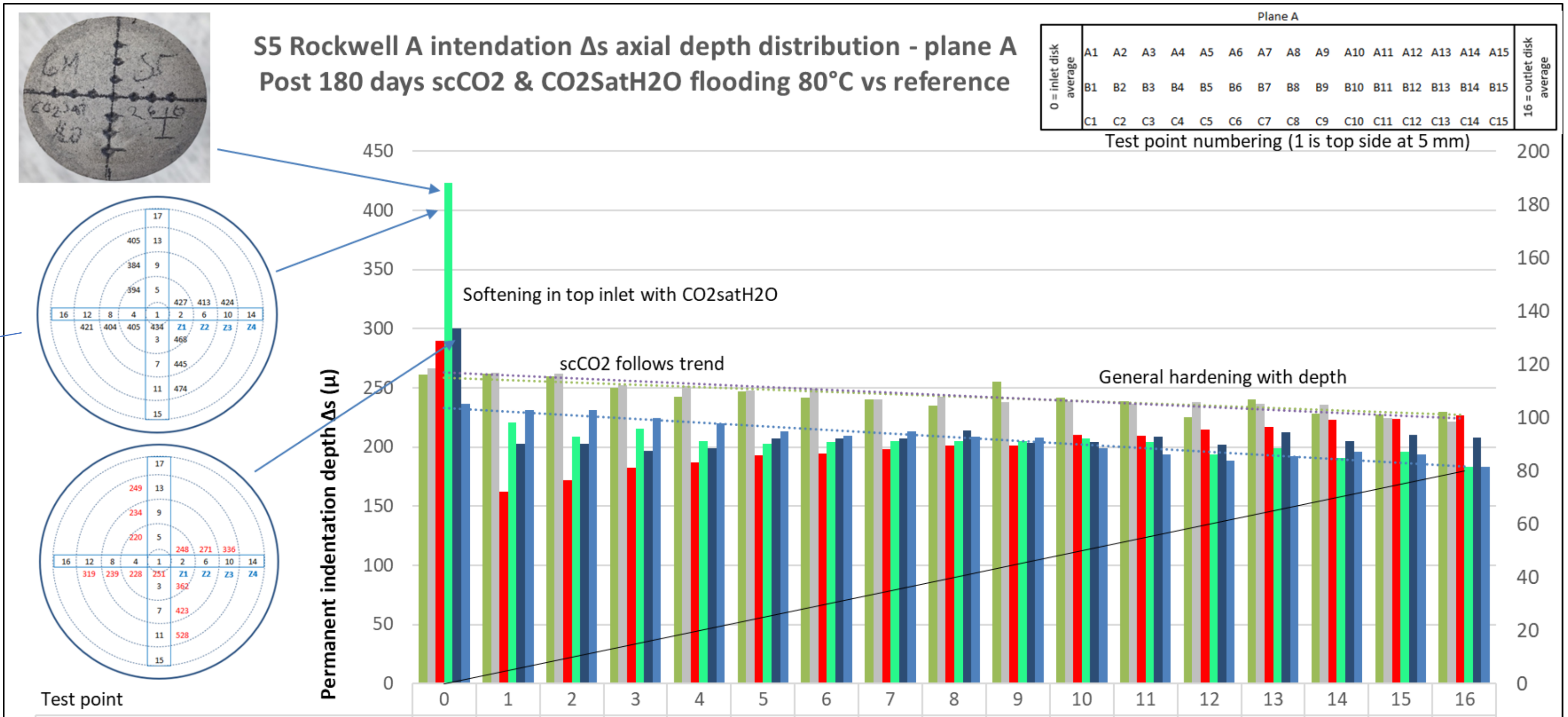
Points 1 - 15



Point 16



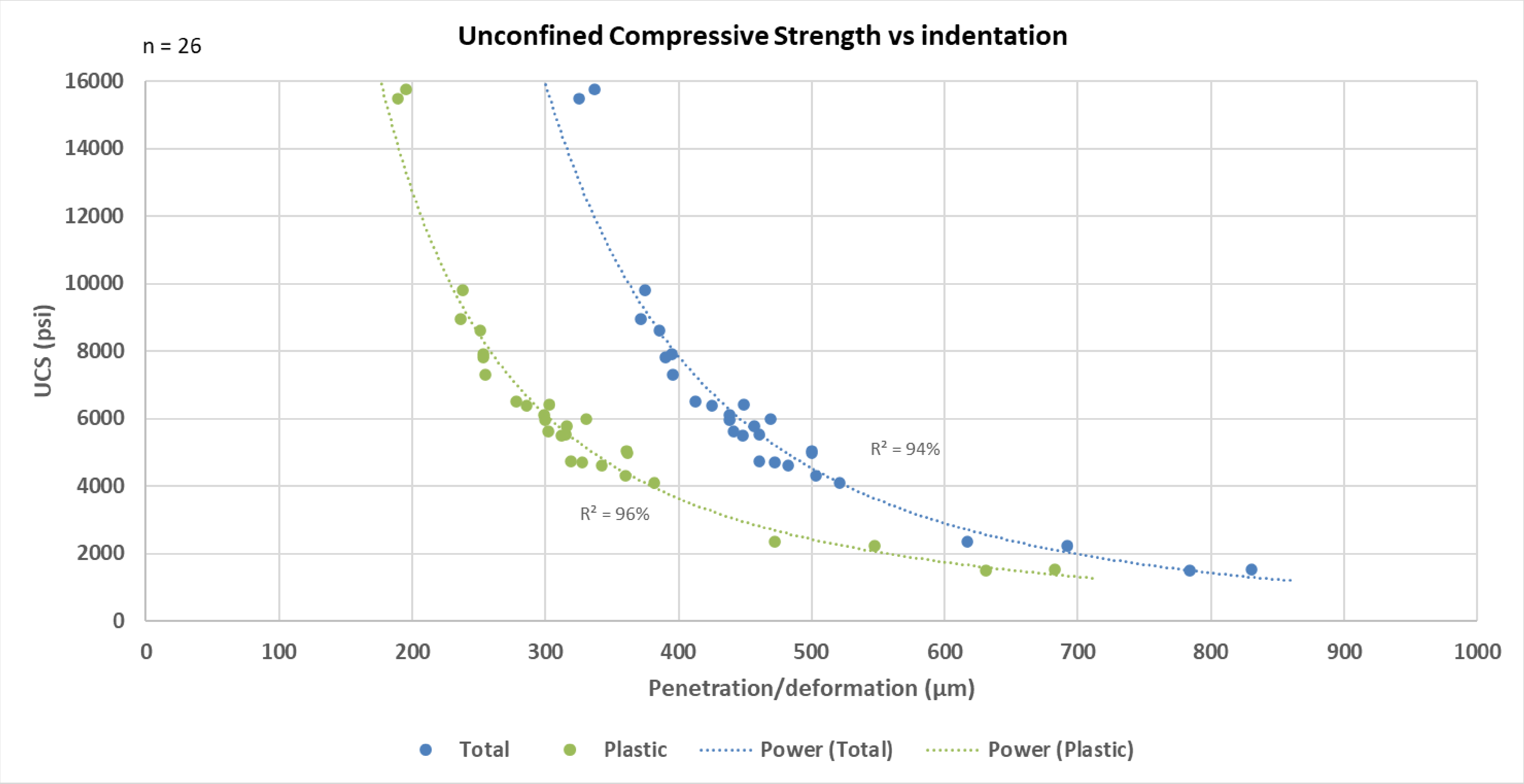
Average comparison including end disks



Test point	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Reference - Plane A 90D unconfined	262	262	260	250	243	247	242	240	235	255	242	238	225	240	228	228	230
Reference - Plane A 180D unconfined	266	263	262	252	251	248	249	240	242	238	239	236	238	236	235	224	221
CO2satH2O P1 average 90D - Plane A	290	162	172	183	187	193	194	198	201	201	210	210	215	217	223	224	227
CO2satH2O P1 average 180D - Plane A	423	221	209	216	205	203	204	205	205	205	207	204	193	199	191	196	184
CO2satH2O P2K average 180D - Plane A	301	203	203	197	199	207	207	207	214	204	204	208	202	212	205	210	208
scCO2 average 180D - Plane A	236	231	231	224	220	213	210	213	209	208	199	194	188	192	196	194	183
Depth from top (mm)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80

WP1 forced flow exposure tests – indentation test

f) Relate to mechanical properties



WP1 forced flow exposure tests – indentation test

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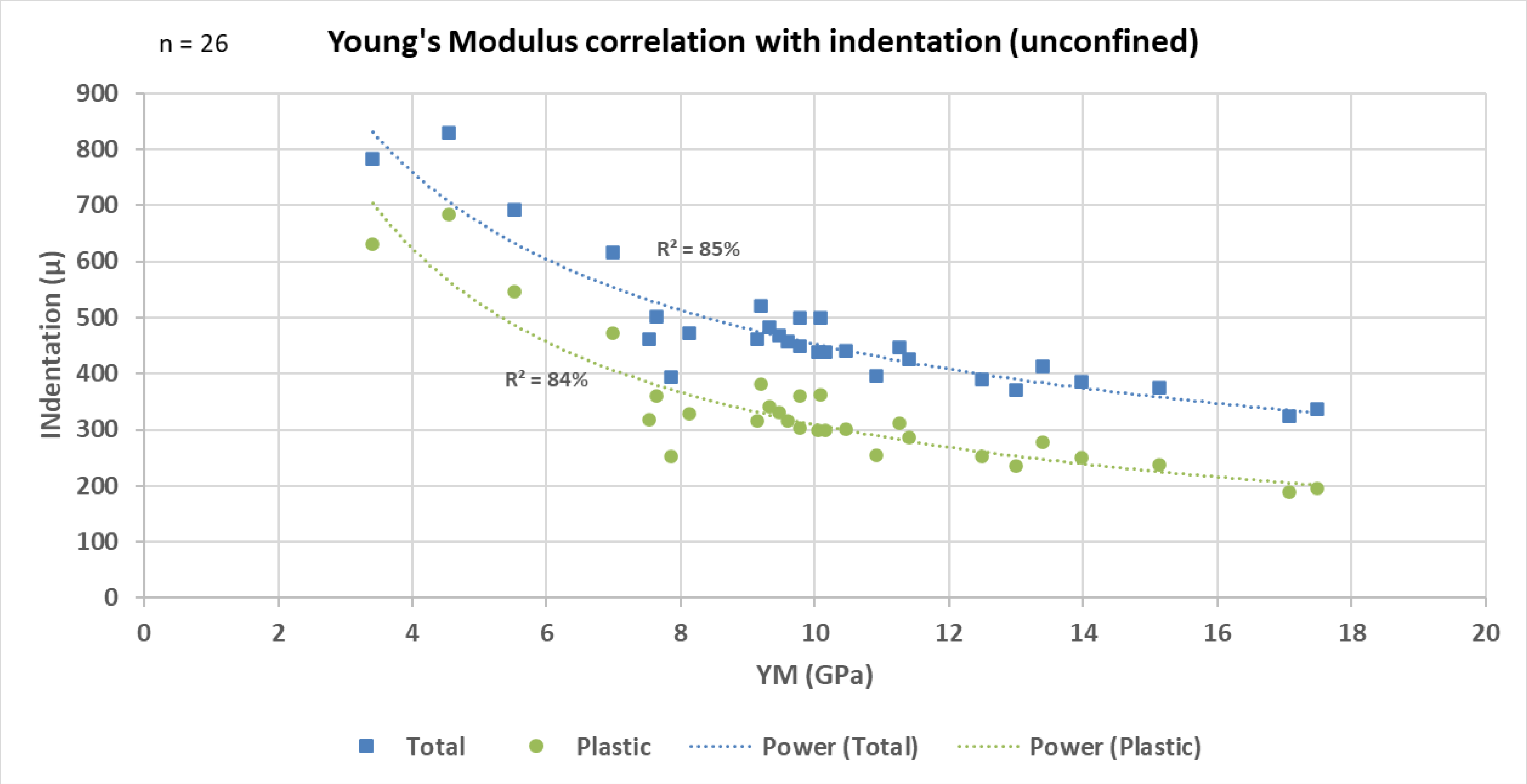


WP1 comparison data – flow of super critical CO_2

Observations:

High early phase flow that attains steadier level after some time

Can be attributed to CO_2 displacing pore water in combination with CO_2 response

For S5 marked change ±1300 hrs

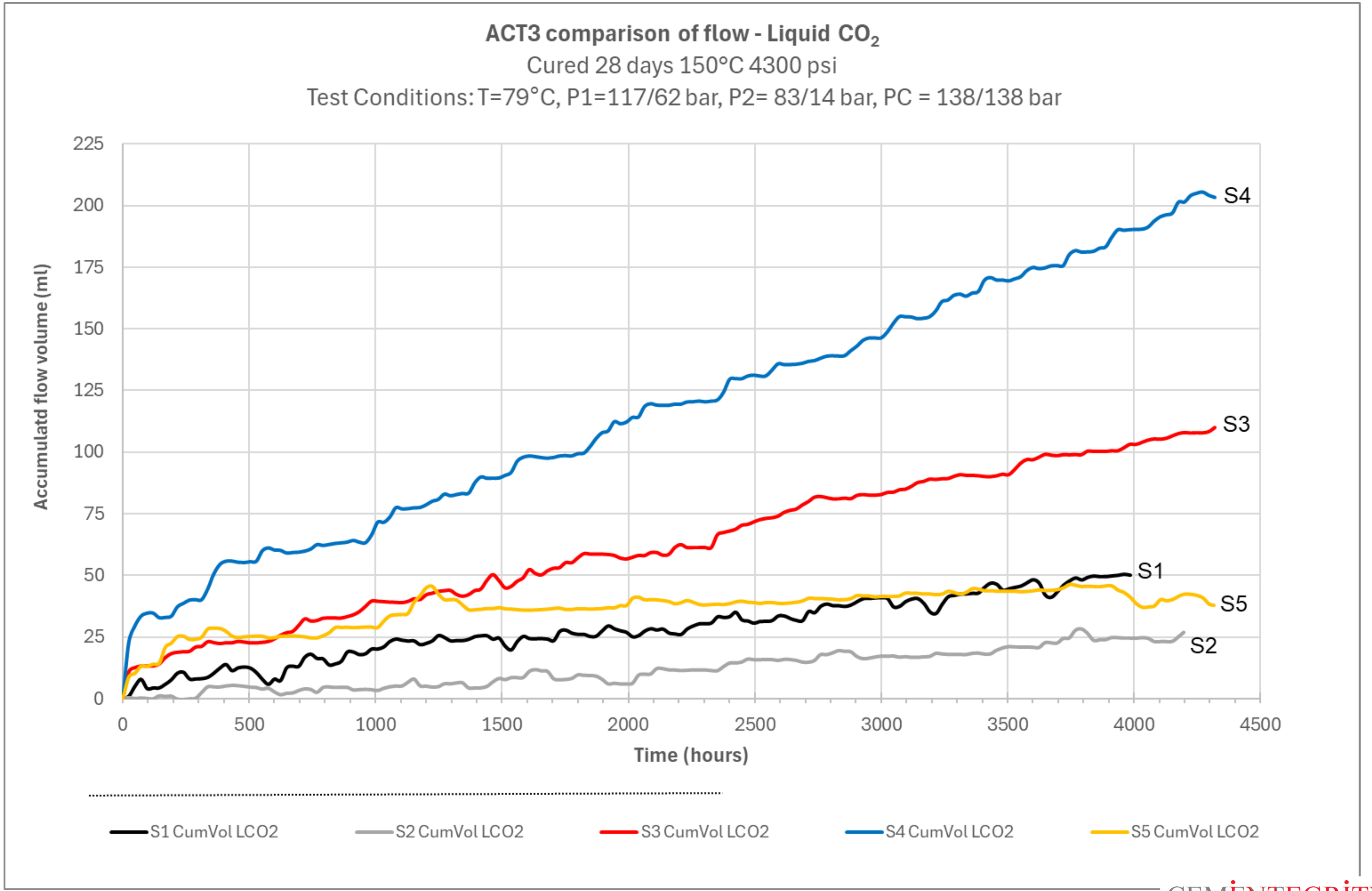
Notes:

Flow measurements are affected by changes in room temperature

CO2 expands while progressing through sample

→unsteady flow observed

S2 still flowing



WP1 comparison data – flow of CO_2 saturated fresh water

Observations:

High early phase flow that attains steadier level after some time

Can be attributed to CO_2 displacing pore water in combination with CO_2 response

Less fluctuations than with pure CO_2

S1 plugs very quickly, low flow

S2 shows dropping trend

S3 no dropping trend

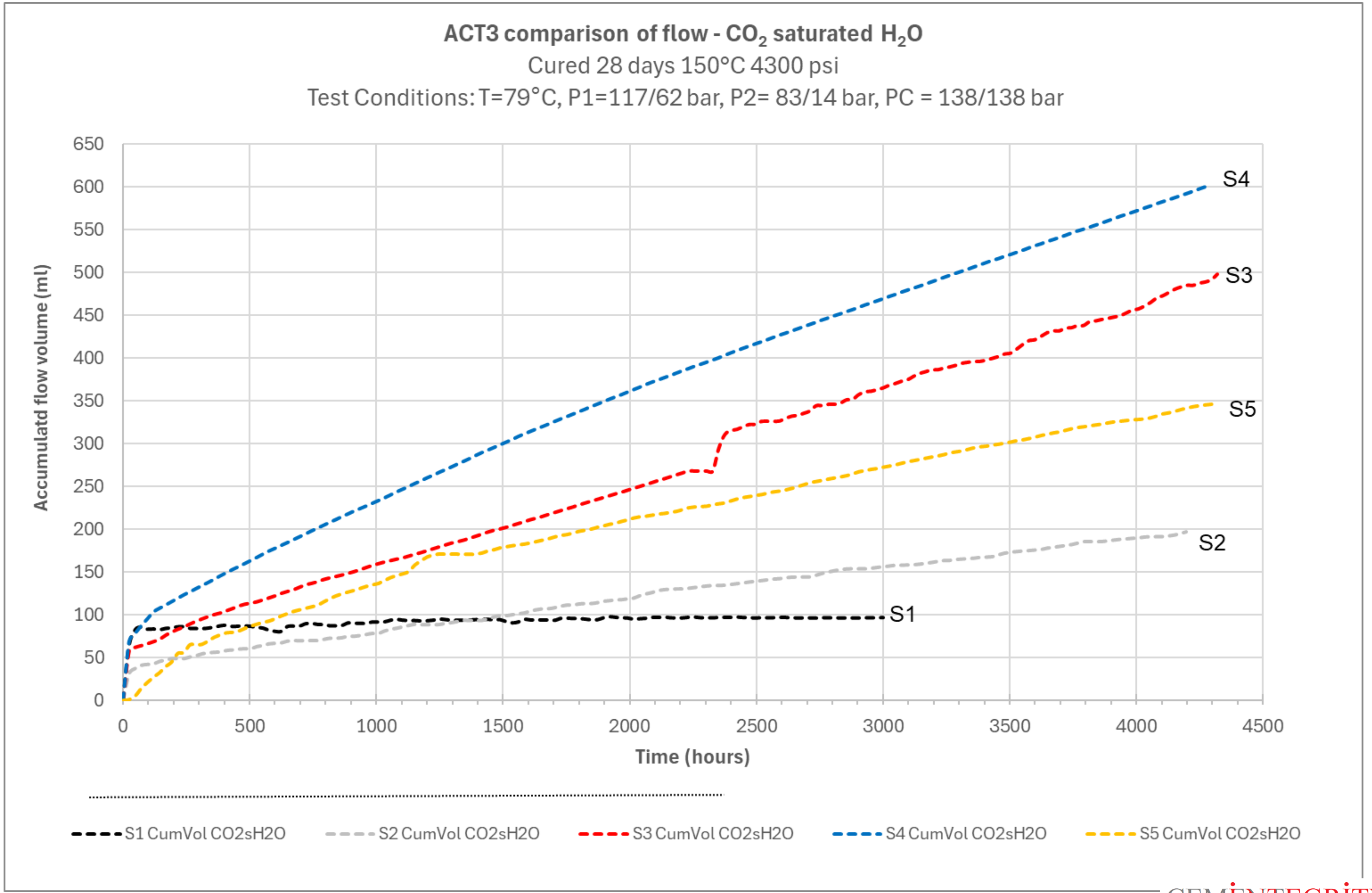
S4 clearly dropping trend

For S5 marked change ±1300 hrs

Notes:

S1 recording aborted early due to equipment problem

S3 flow temporarily interrupted at 2300 hours due to equipment problem



WP1 comparison data – flow of CO_2 saturated fresh water

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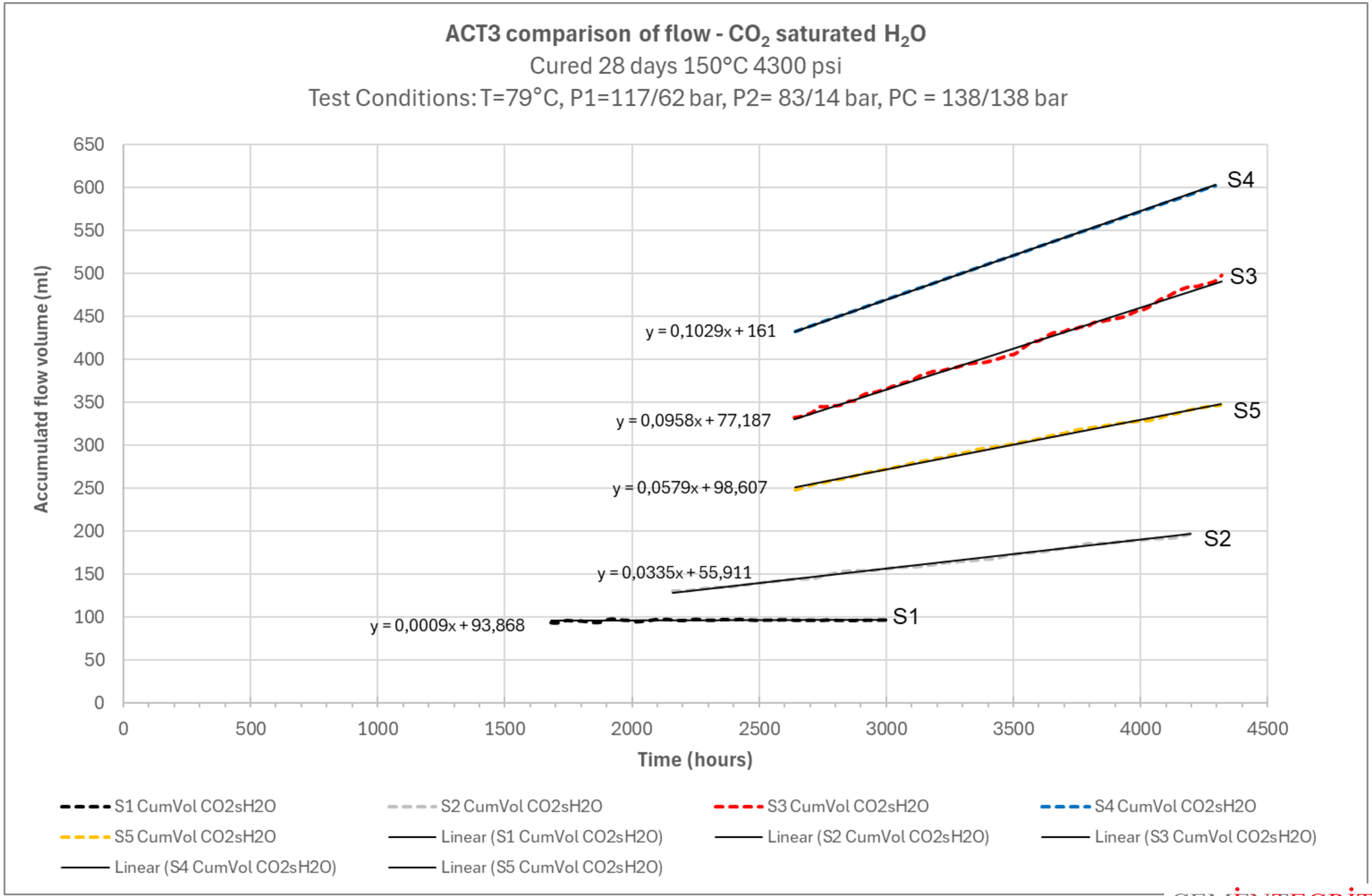

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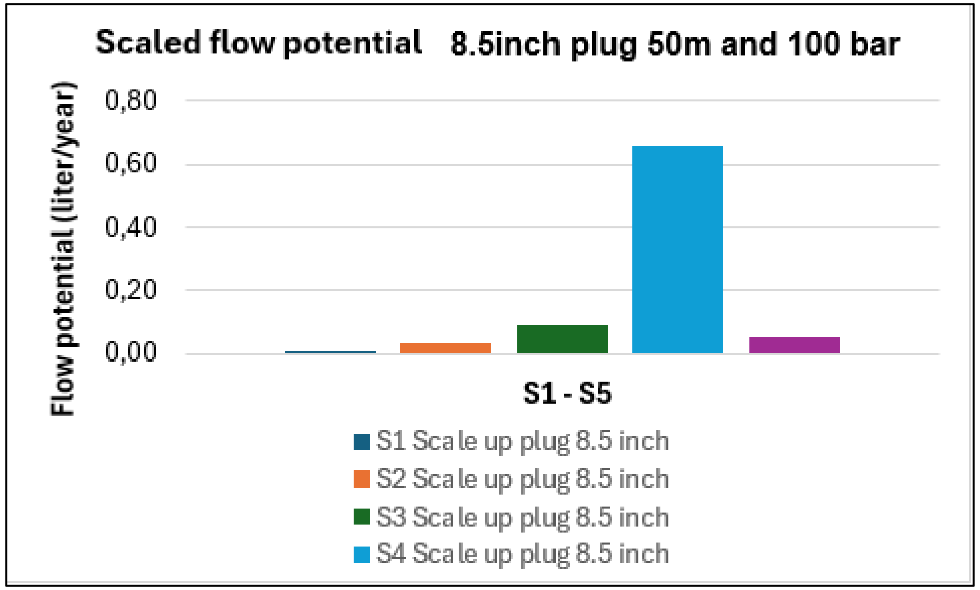
WP1 comparison data – flow of CO_2 saturated fresh water

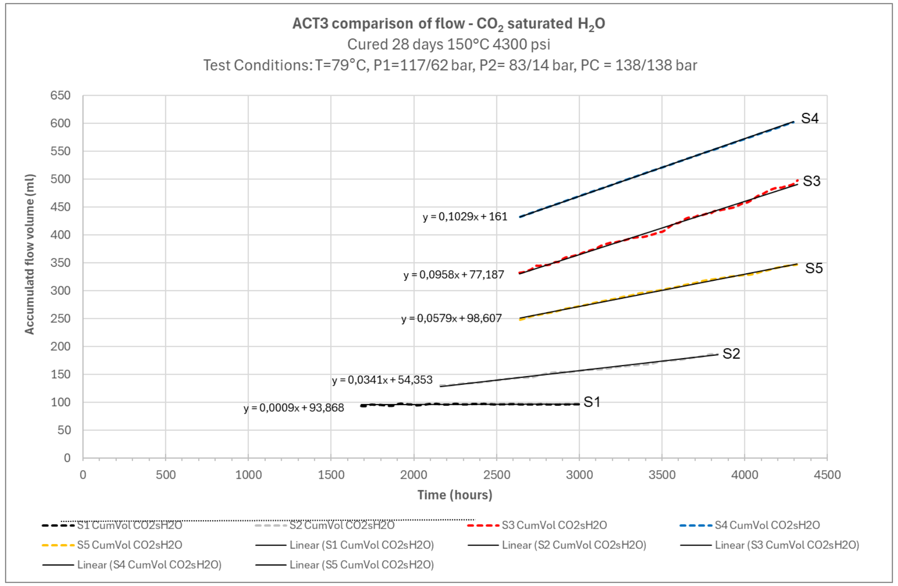
Assumptions:

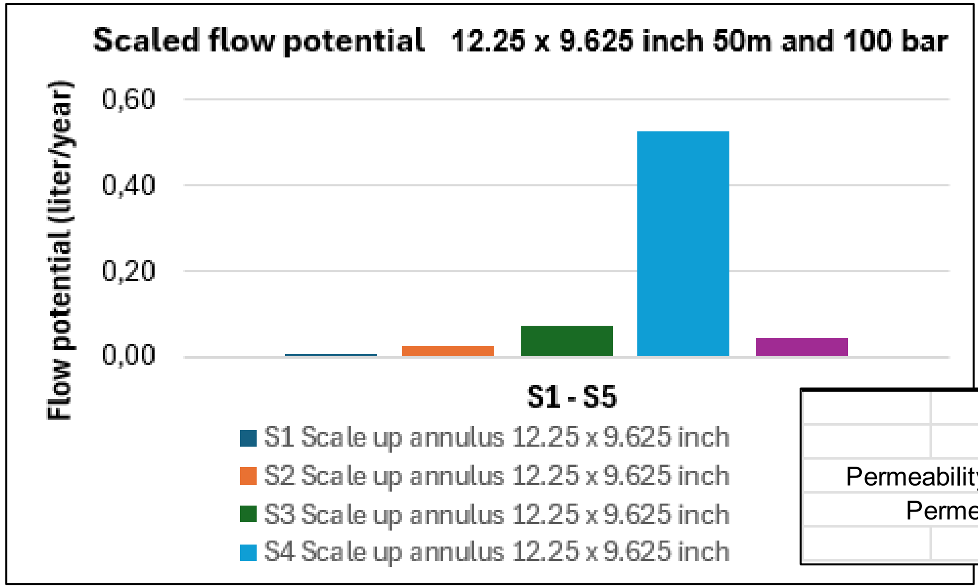
- Flow rate through sample = injection rate
- Last 1500 hour typical for long term flow
- Flow proportional to A_{flow} and ΔP/L

Notes:

- Neglectible flow potential
- Highly uncertain
- Highly dependent on inherent permeability
- Leak rate will be dominated by micro annulus or cracks







S1 CO2satH2O 80°C

Length	80	mm	3.1496	inch
Flow rate	0.0009	ml/hour		
Diameter	38.1	mm	1.5	inch
Flow area	1140.09	mm2	1.7671	inch2
Differential pressure	48.0	bar	696	psi
Pressure gradient	600.0	bar/m	2652	psi/ft
Flow rate	0.000015	ml/min	0.008	l/year
Flow scale factor	62	14	1.0	

S1 Scale up plug 8.5 inch

Length	50	m	164	ft
Diameter	215.9	mm	8.5	inch
Flow area	36610	mm2	56.7	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000002	ml/min	0.001	l/year
Flow scale factor			9.3	

S1 Scale up annulus 12.25 x 9.625 inch

Length	50	m	164	ft
Inner diameter	244.475	mm	9.625	inch
Outer diameter	311.15	mm	12.25	inch
Flow area	29096	mm2	45.1	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000001	ml/min	0.0007	l/year
Flow scale factor			11.8	

S2 CO2satH2O 80°C

Length	80	mm	3.1496	inch
Flow rate	0.0341	ml/hour		
Diameter	38.1	mm	1.5	inch
Flow area	1140.09	mm2	1.7671	inch2
Differential pressure	48.0	bar	696	psi
Pressure gradient	600.0	bar/m	2652	psi/ft
Flow rate	0.000568	ml/min	0.299	l/year
Flow scale factor	62	14	1.0	

S2 Scale up plug 8.5 inch

Length	50	m	164	ft
Diameter	215.9	mm	8.5	inch
Flow area	36610	mm2	56.7	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000061	ml/min	0.0320	l/year
Flow scale factor			9.3	

S2 Scale up annulus 12.25 x 9.625 inch

Length	50	m	164	ft
Inner diameter	244.475	mm	9.625	inch
Outer diameter	311.15	mm	12.25	inch
Flow area	29096	mm2	45.1	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000048	ml/min	0.0254	l/year
Flow scale factor			11.8	

S3 CO2satH2O 80°C

Length	80	mm	3.1496	inch
Flow rate	0.0958	ml/hour		
Diameter	38.1	mm	1.5	inch
Flow area	1140.09	mm2	1.7671	inch2
Differential pressure	48.0	bar	696	psi
Pressure gradient	600.0	bar/m	2652	psi/ft
Flow rate	0.001597	ml/min	0.839	l/year
Flow scale factor	62	14	1.0	

S3 Scale up plug 8.5 inch

Length	50	m	164	ft
Diameter	215.9	mm	8.5	inch
Flow area	36610	mm2	56.7	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000171	ml/min	0.0898	l/year
Flow scale factor			9.3	

S3 Scale up annulus 12.25 x 9.625 inch

Length	50	m	164	ft
Inner diameter	244.475	mm	9.625	inch
Outer diameter	311.15	mm	12.25	inch
Flow area	29096	mm2	45.1	inch2
Differential pressure	100	bar	1450	psi
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000136	ml/min	0.0714	l/year
Flow scale factor			11.8	

S4 CO2satH2O 80°C

Length	80	mm	3.1496	inch
Pressure gradient	600.0	bar/m	2652	psi/ft
Flow rate	0.000965	ml/min	0.507	l/year
Flow scale factor	62	14	1.0	

S4 Scale up plug 8.5 inch

Length	50	m	164	ft
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000103	ml/min	0.0543	l/year
Flow scale factor			9.3	

S4 Scale up annulus 12.25 x 9.625 inch

Length	50	m	164	ft
Pressure gradient	2.0	bar/m	106.1	psi/ft
Flow rate	0.000082	ml/min	0.0431	l/year
Flow scale factor			11.8	

Permeability	S1	S2	S3	S4	S5
Permeability reference	0,10		0,22	2,10	0,23
Permeability post exposure CO2satH2O	0,01		0,16	0,55	0,25
Permeability post exposure scCO2	0,04		0,30	0,37	0,21
Permebility pre-exposure	0,13	0,04	0,19	0,95	0,52

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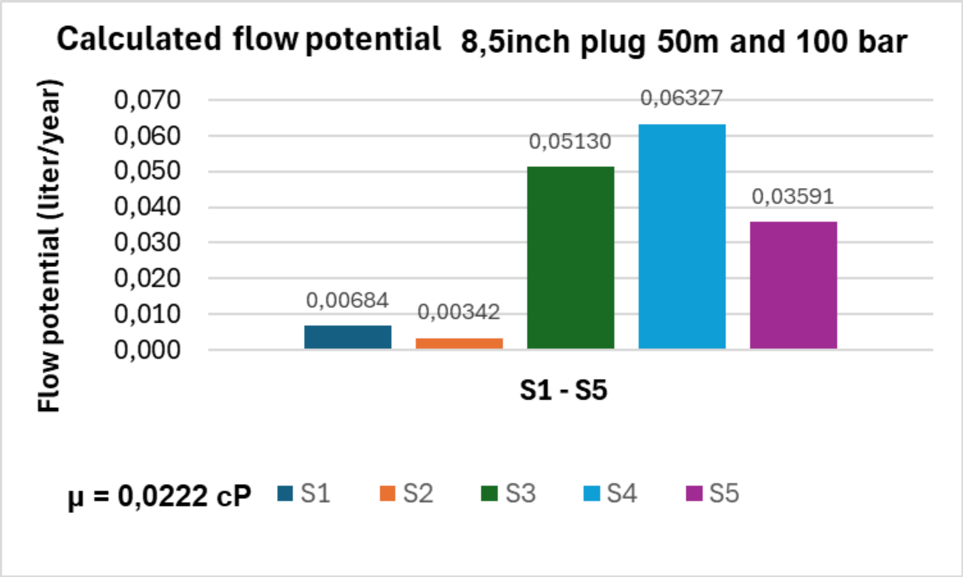
WP1 comparison data – estimated flow of super critical CO_2

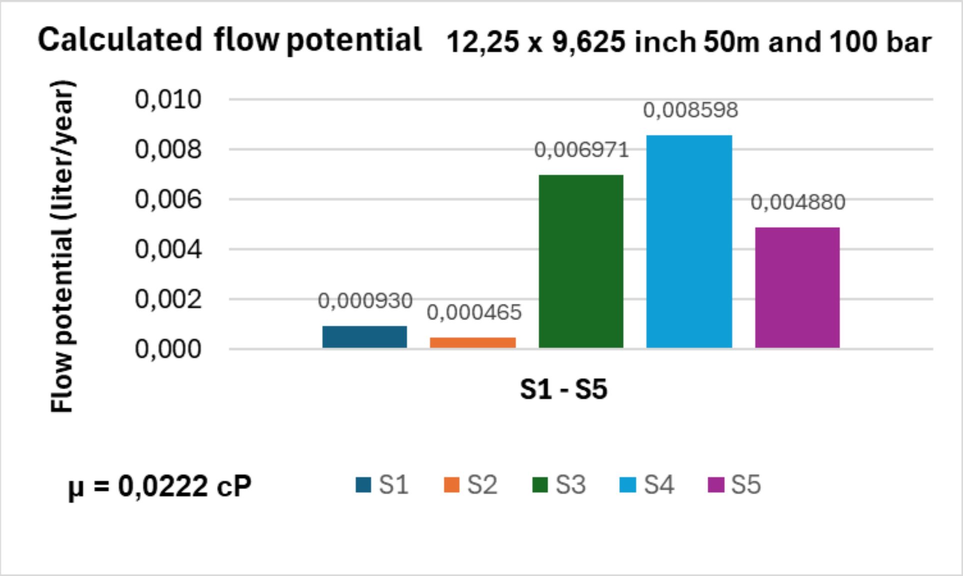
Assumptions:

- Calculated flow rate through sample
- μ = 0,0222 cP ($scCO_2$ at 80°C)
- Water permeability post $scCO_2$ exposure
- Barrier length 50 m
- ΔP = 100 bar

Notes:

- Neglectible flow potential
- Highly uncertain
- Highly dependent on permeability
- Leak rate will be dominated by micro annulus or cracks
- S2 data estimated
- Testing permeability with H_2O may affect result due to bicarbonation





Permeability	S1	S2	S3	S4	S5
Permeability reference	0,10	0,02	0,22	2,10	0,23
Permeability post exposure CO2satH2O	0,01	0,02	0,16	0,55	0,25
Permeability post exposure scCO2	0,04	0,05	0,30	0,37	0,21
Permebility pre-exposure	0,13	0,06	0,19	0,95	0,52
Highest permeability:	0,13	0,06	0,30	2,10	0,52

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WP1 comparison data

Observations:

S3 and S4 can be considered “elastic”

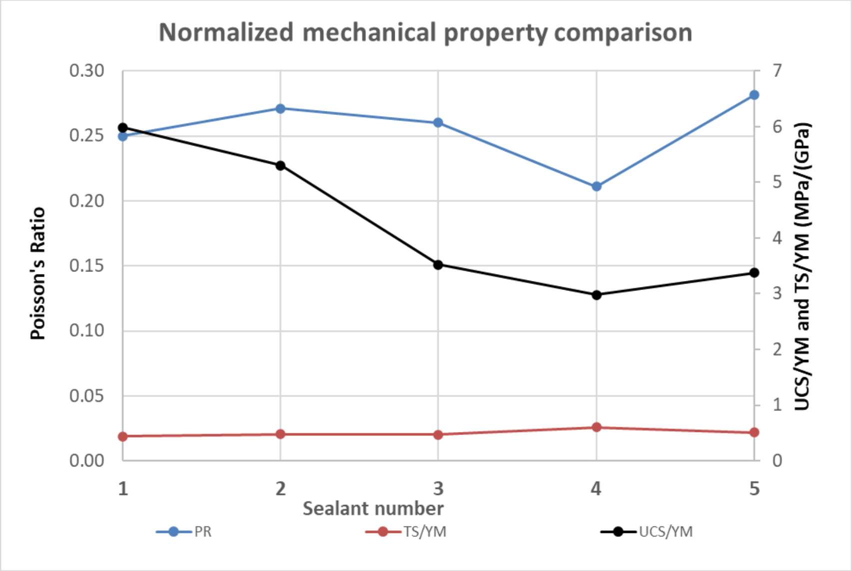
Others have quite high YM

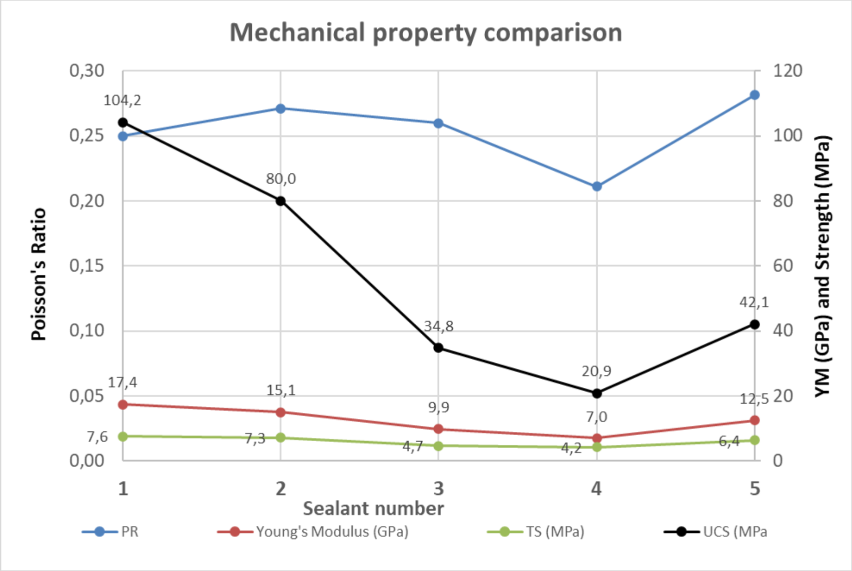
Normalized BzTS very similar throughout

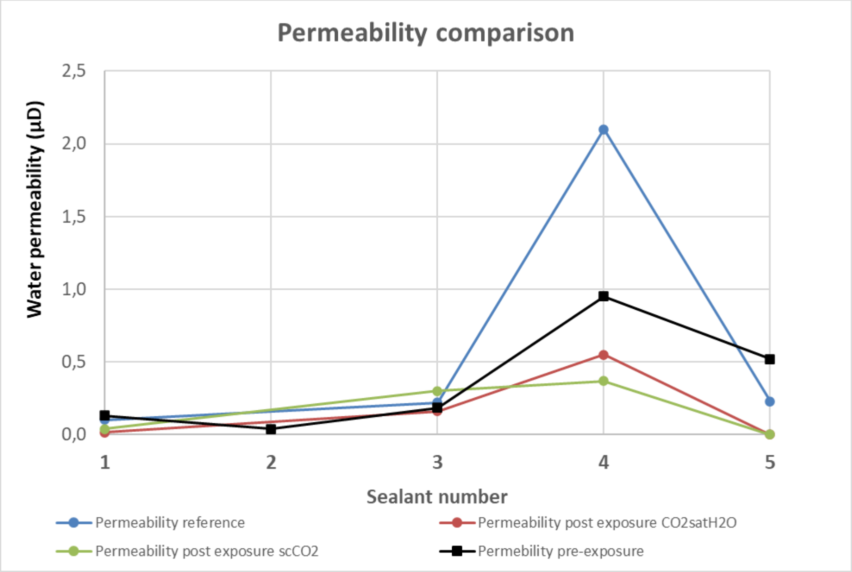
Normalized UCS favors OPC

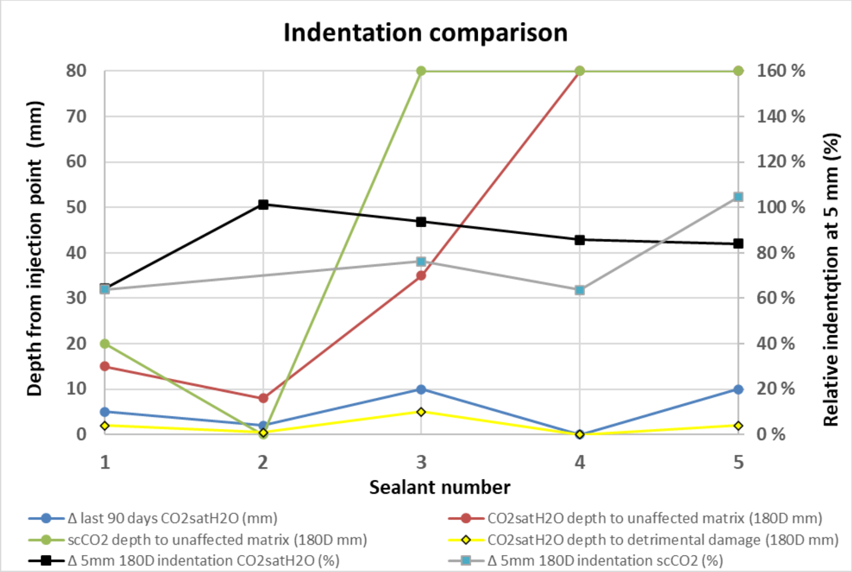
Notes:

Normalized strength obtained by taking ratio Strength/YM, where highest number is preferable









WP1 comparison data - indentation

Observations:

All S's show short distance to healthy matrix (no detrimental damage)

All S's show short damage progression last 90 days (90→180)

S3, S4, S5 all have change of indentation through entire sample for $scCO_2$

S1 has no change at 20 mm

S4 and S5 have change of indentation through entire sample for CO_2sH_2O

S1 has no change at 15 mm

S2 has no change at 8 mm

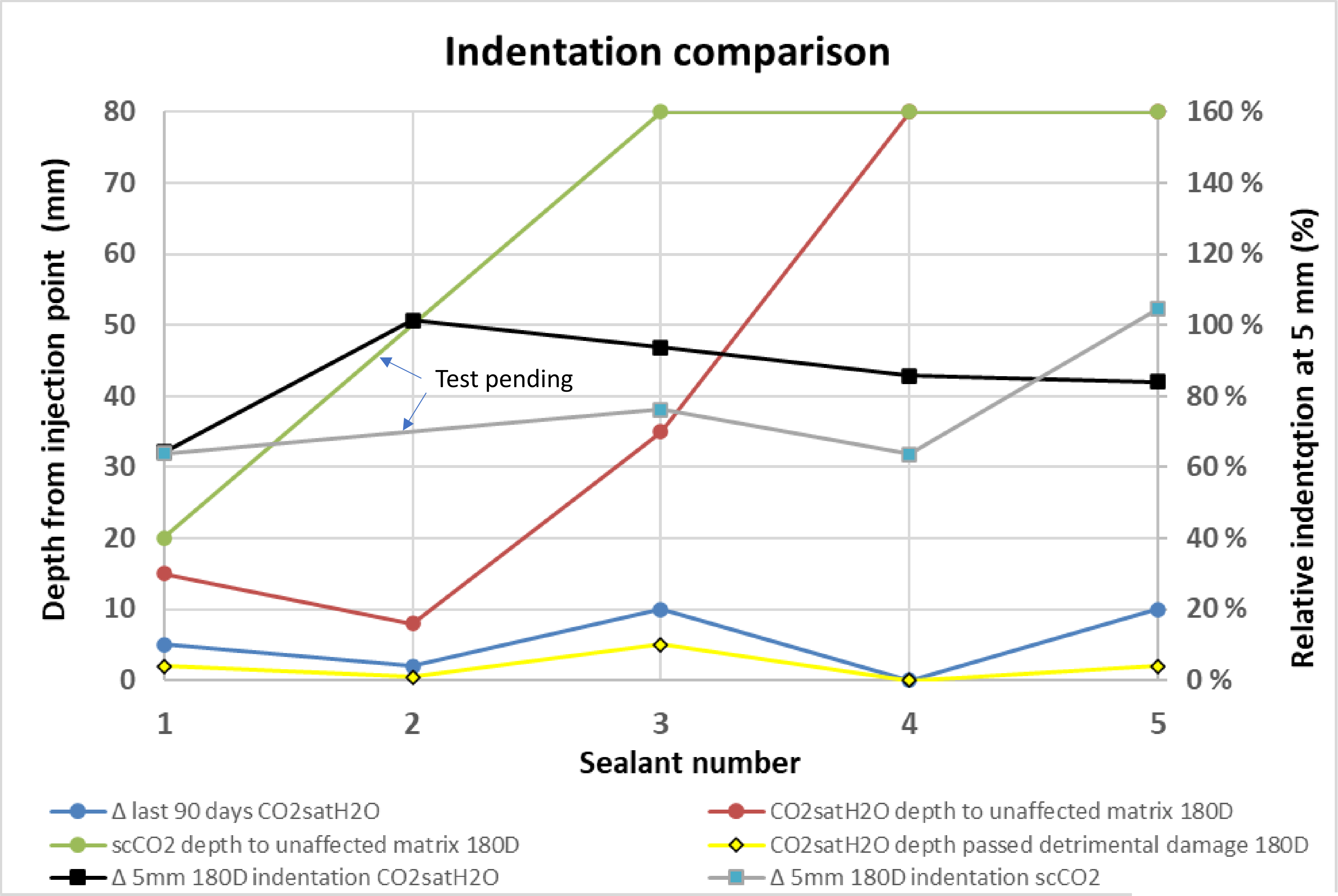
S3 has no change at 35 mm

S2 shows no sign of hardening at 5mm depth (100%) for CO_2sH_2O

All designs show hardening at 5 mm level for $scCO_2$

Notes:

S2 data not available for $scCO_2$



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WP1 comparison data – indentation – scaling Δs carbonation/bicarbonation progression

Carbonation

Assumptions all:

Time dependency = t^0,5

Assumption 1:

Controlled by diffusion only

Neglecting ΔP/L

Using 90 - 180 days Δ

Assumption 2:

NOT controlled by diffusion only

Applying ΔP/L correction

Using 90 - 180 days Δ

					Sealant	S1	S2 *	S3	S4	S5	
					Carbonation Δ mm per year CO_2satH_2O	0,03	0,01	0,06	0,00	0,06	
1E+03					Δ m per 1000 years CO_2satH_2O	0,03	0,01	0,06	0,00	0,06	
				P (bar)	L (m)	48	48	48	7	48	ΔP/L
				100	50	2	2	2	2	2	ΔP/L
					Correction	24	24	24	3,5	24	
1E+03					Carbonation Δ m per 1000 years CO_2satH_2O	0,001	0,000	0,002	0,000	0,002	

Bicarbonation

Assumption 1:

Controlled by diffusion only

Neglecting ΔP/L

Using 180 days Δ

Assumption 2:

NOT controlled by diffusion only

Applying ΔP/L correction

Using 180 days Δ

					Sealant	S1	S2 *	S3	S4	S5	
					Detrimental Δ mm per year CO_2satH_2O	0,01	0,00	0,02	0,00	0,01	
1E+03					Δ m per 1000 years CO_2satH_2O	0,01	0,00	0,02	0,00	0,01	
				P (bar)	L (m)	48	48	48	7	48	ΔP/L
				100	50	2	2	2	2	2	ΔP/L
					Correction	24	24	24	3,5	24	
1E+03					Detrimental Δ m per 1000 years CO_2satH_2O	0,0003	0,0001	0,0008	0,0000	0,0003	

Notes:

S2* preliminary result. Must consider uncertainty in testing and scaling versus geometry and time

WP1 comparison data – indentation – scaling Δs carbonation/bicarbonation progression

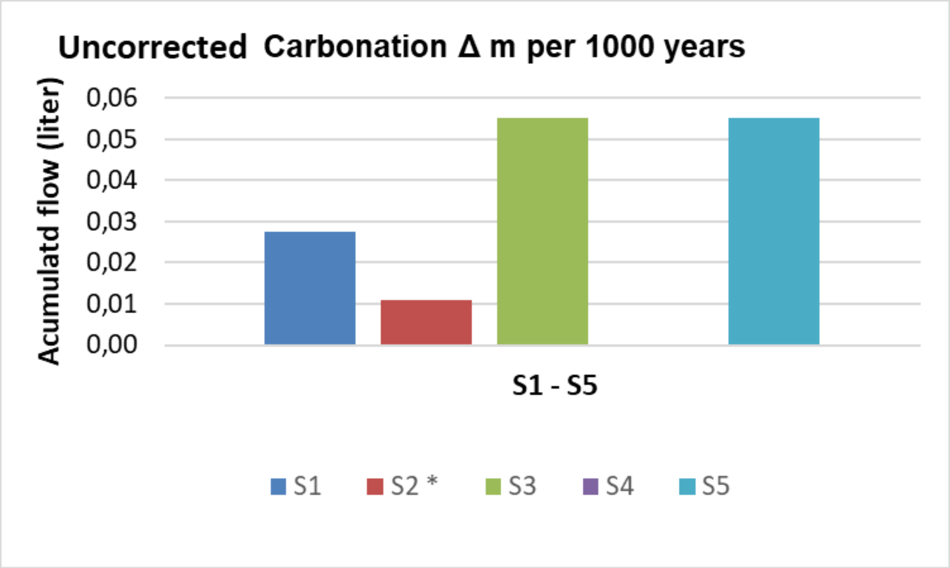
Assumptions all:
Time dependency = t^0,5
(square root of time, per Flick's law)

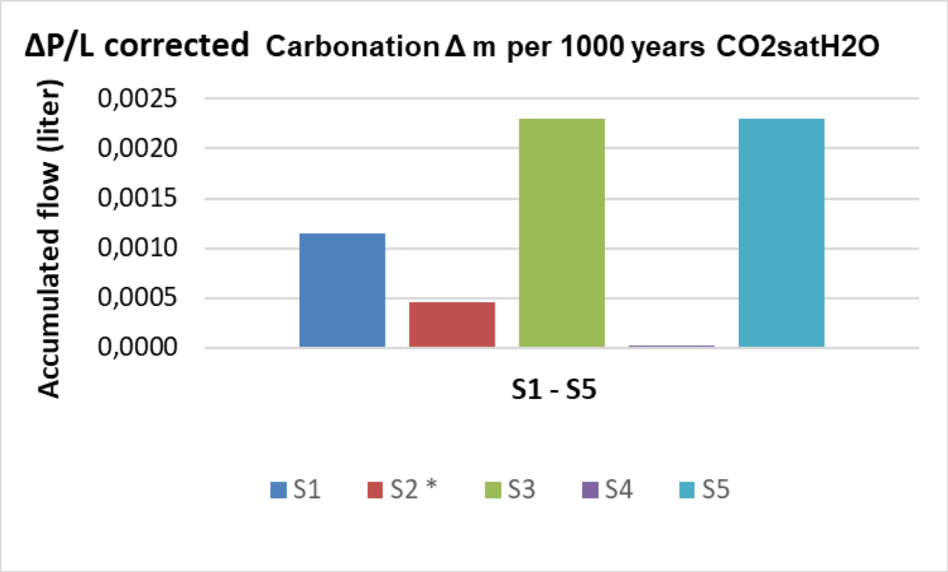
<u>Carbonation</u>
Assumption 1:
Controlled by diffusion only
Neglecting ΔP/L
Using 90 - 180 days Δ

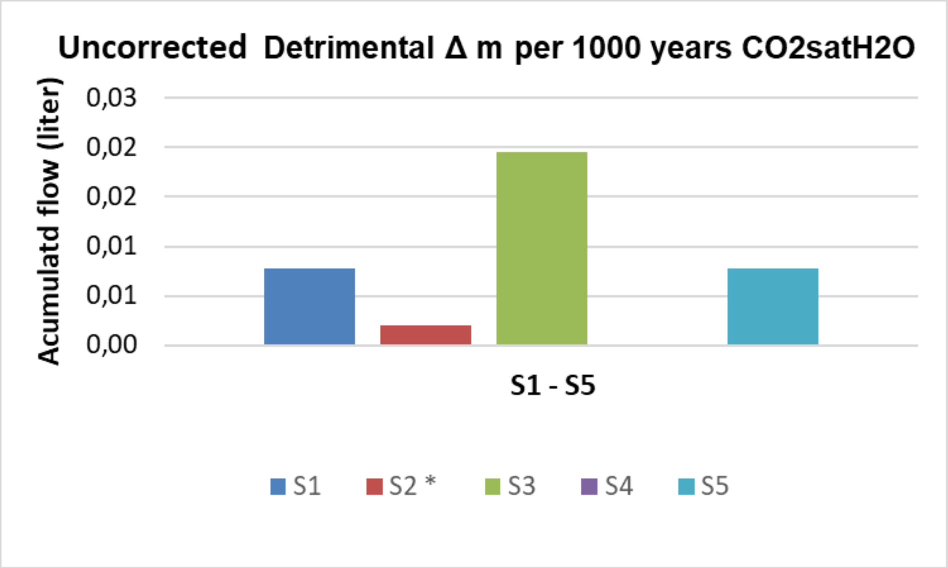
Assumption 2:
NOT controlled by diffusion only
Applying ΔP/L correction
Using 90 - 180 days Δ

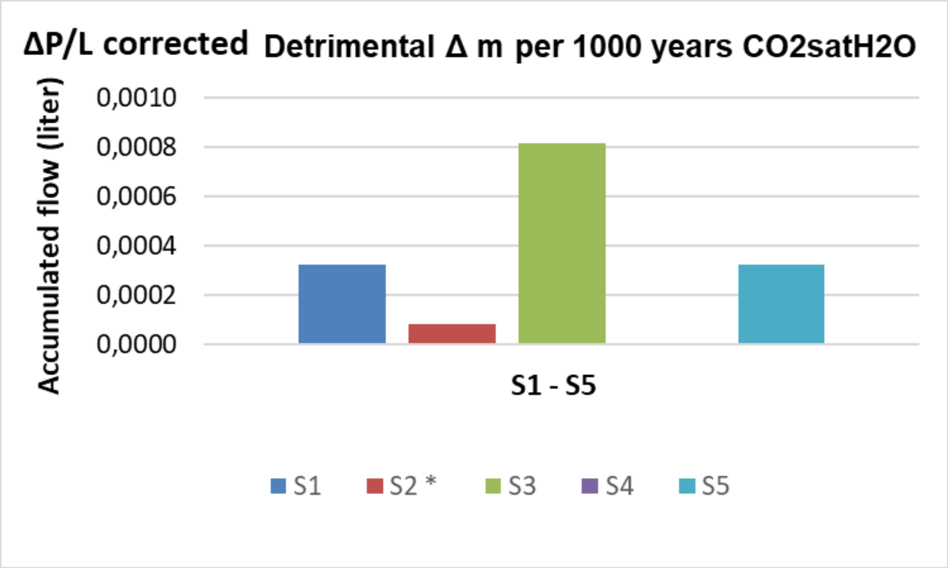
<u>Bicarbonation</u>
Assumption 1:
Controlled by diffusion only
Neglecting ΔP/L
Using 180 days Δ

Assumption 2:
NOT controlled by diffusion only
Applying ΔP/L correction
Using 180 days Δ









Notes:
S2* preliminary result. Must consider uncertainty in testing and scaling versus geometry and time

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WP1 comparison data - permeability

Observations:

S1 – S3 Δk change is within test uncertainty

Substantial variance for S4

Some variance for S5

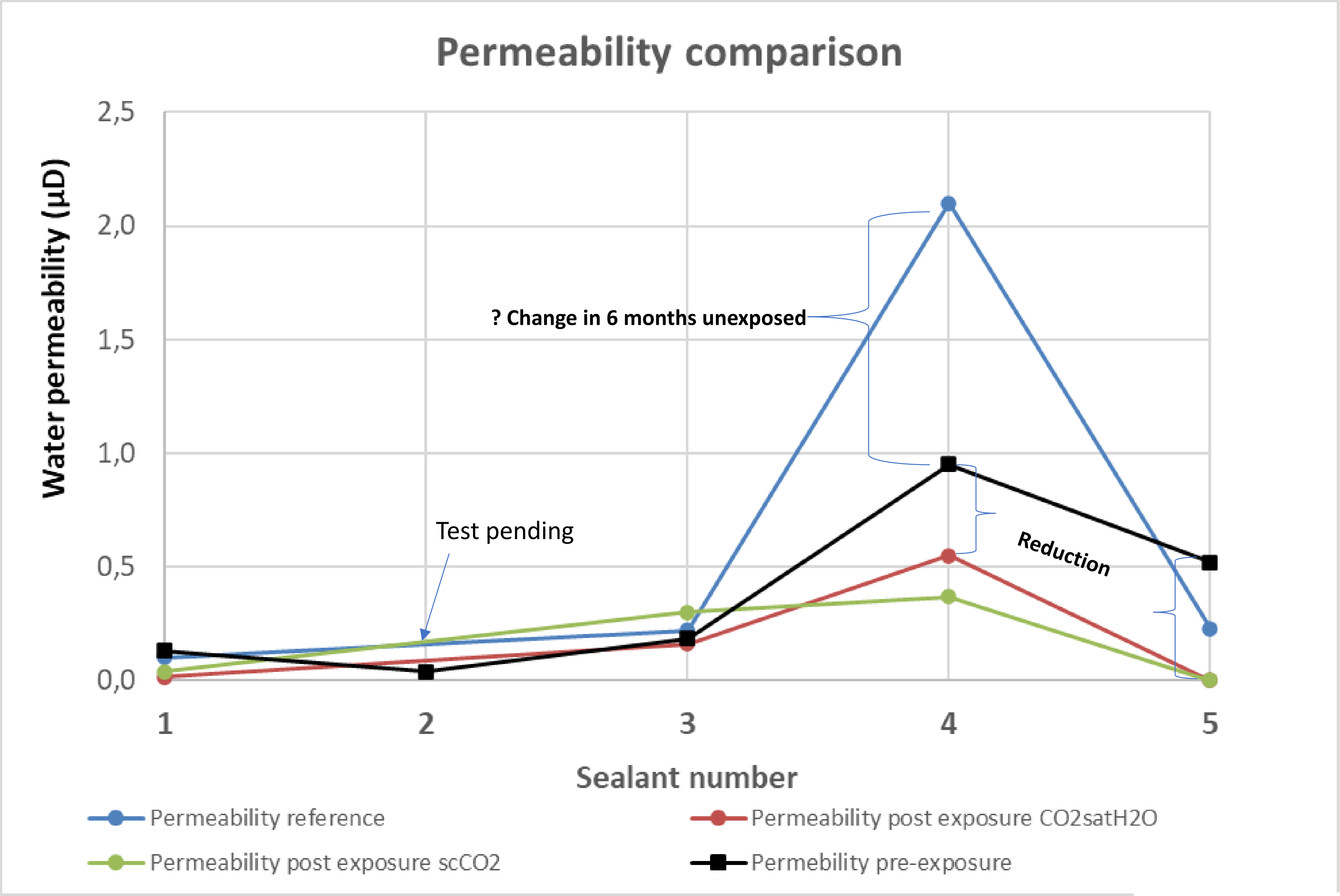
S4 and S5 reduction with exposure

S4 increase with time, no exposure

Notes:

S4 and S5 may still have ongoing structural changes after 6 months

S4 reference data may be artifact



WP1 S1 mechanical property change factor

Observations:

Dramatic permeability drop with CO_2 exposure

More for CO_2sH_2O than $scCO_2$

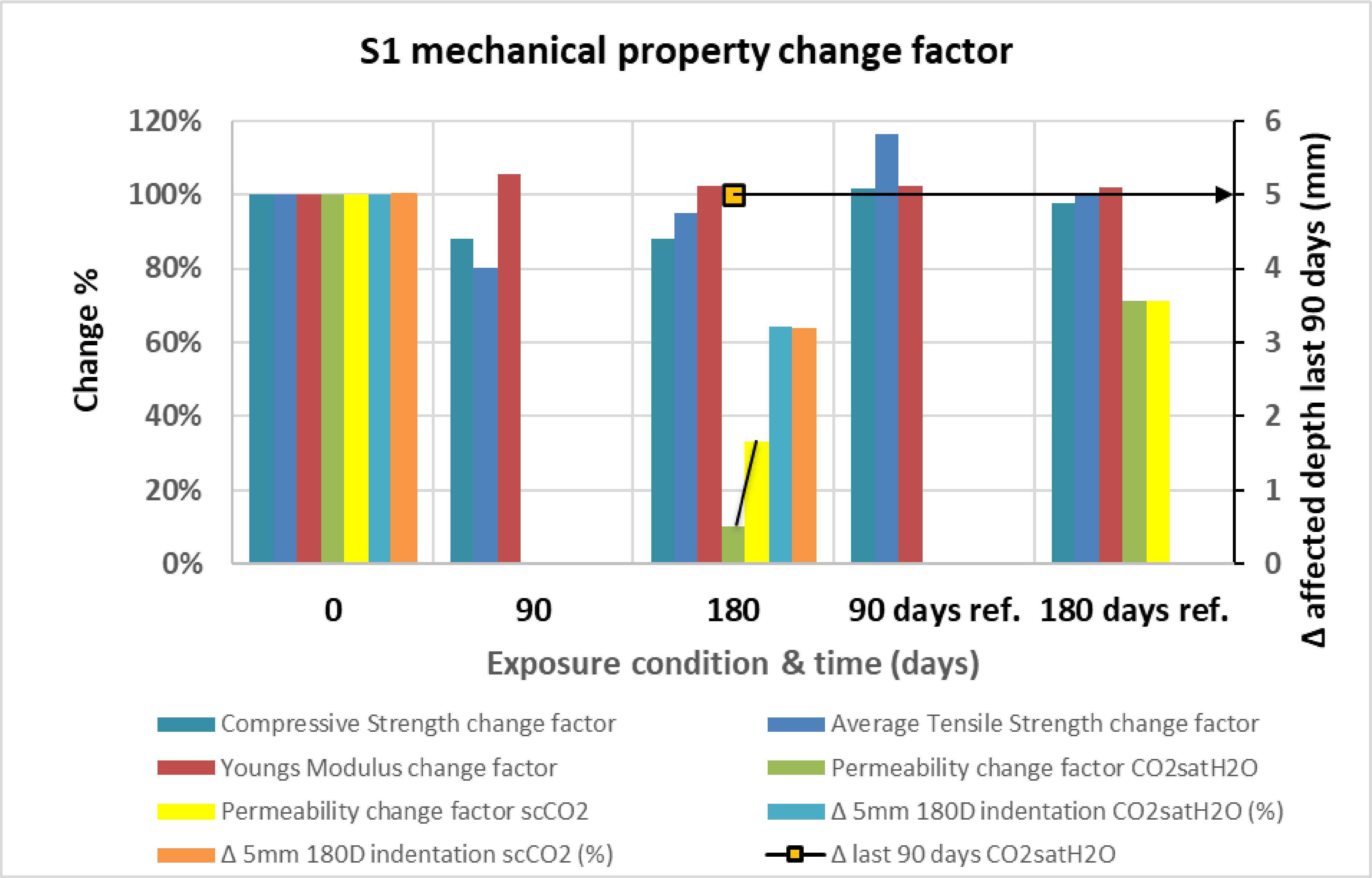
Permeability drop also for reference

General hardening at 5 mm level

Minor change in mechanical properties

5 mm progression last 90 days

Notes:



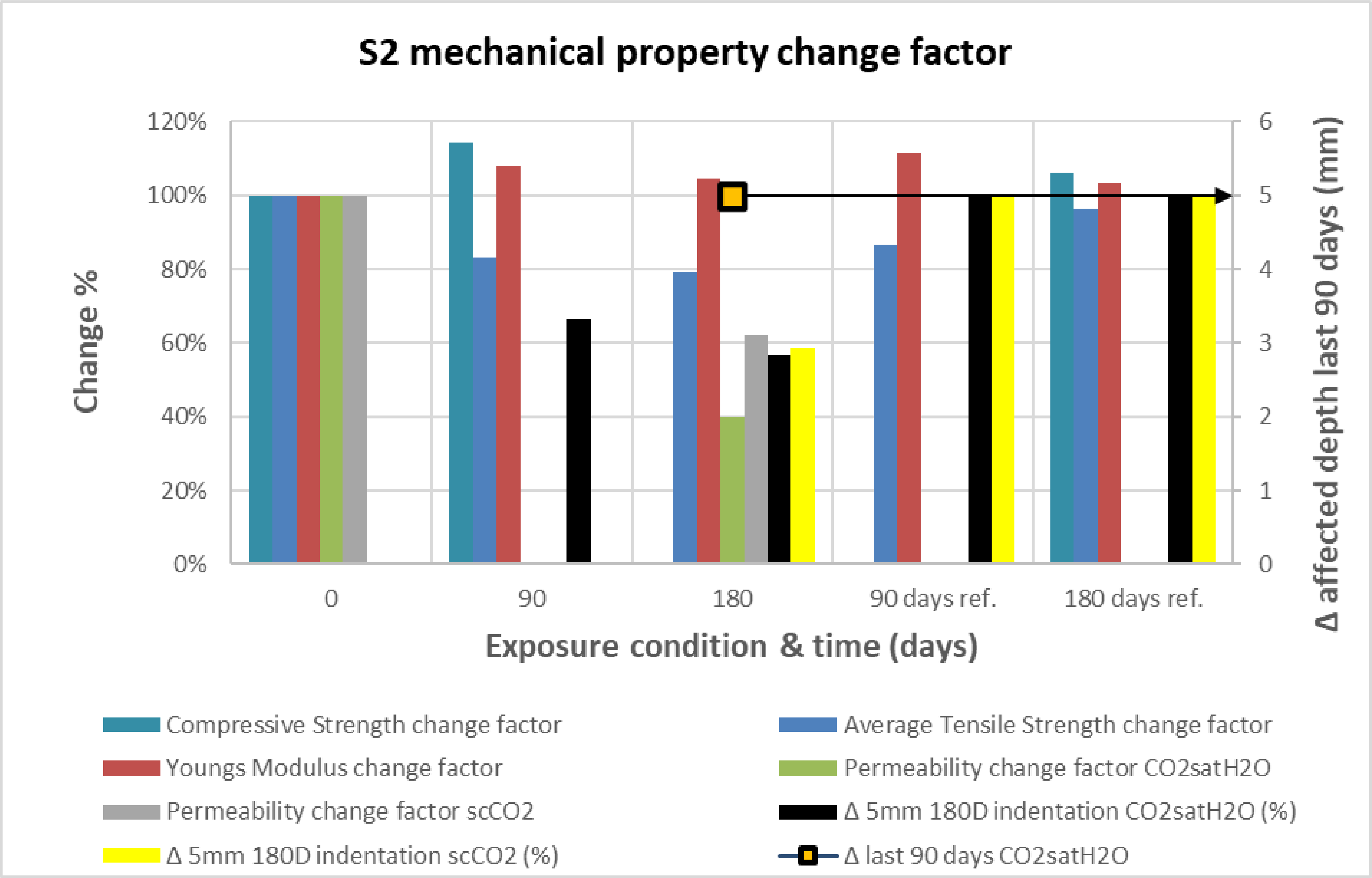
WP1 S2 mechanical property change factor

Observations:

Drop in BzTS

2 mm progression last 90 days

Notes:



WP1 S3 mechanical property change factor

Observations:

Large permeability increase with $scCO_2$ exposure

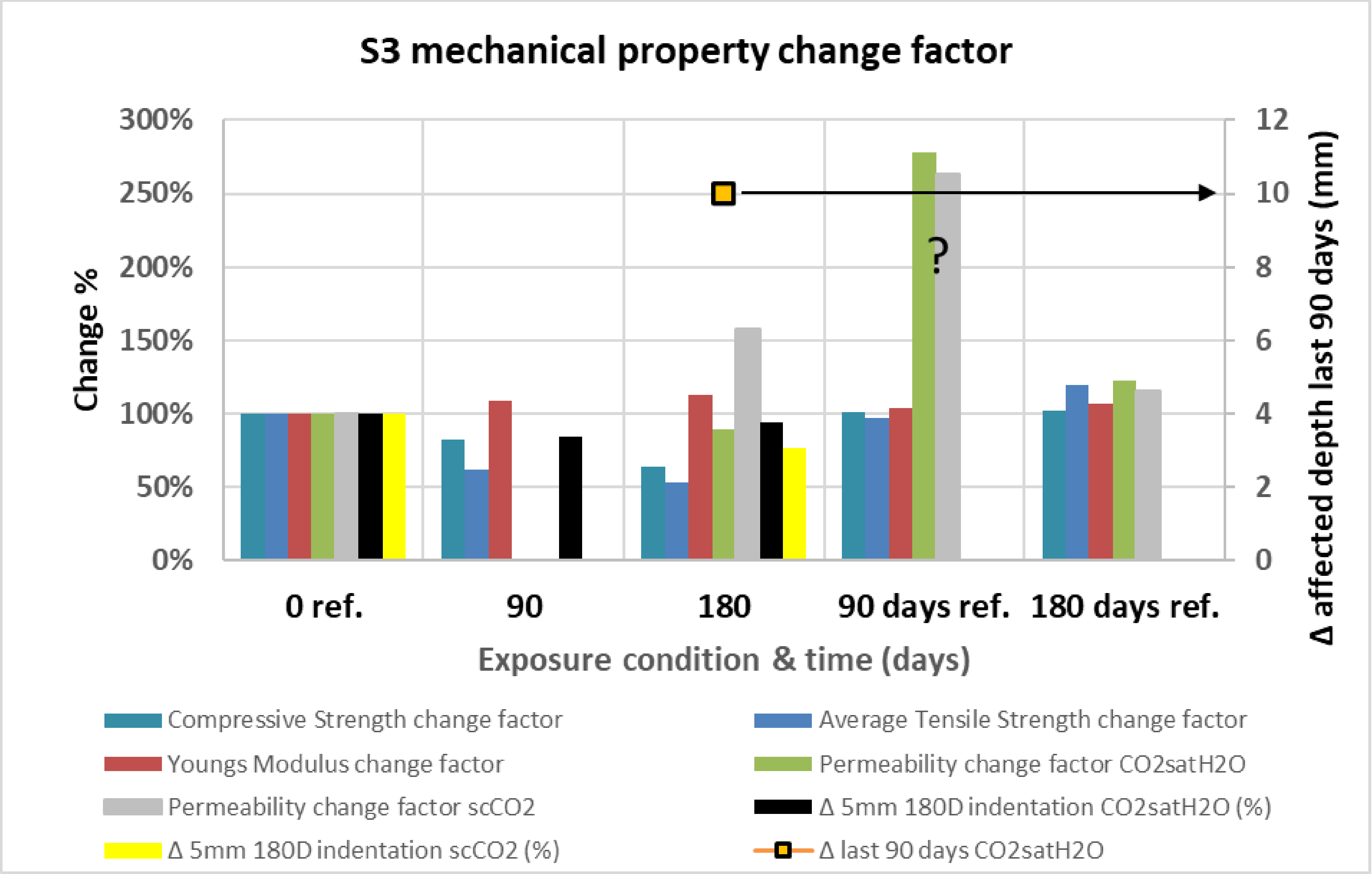
Minor change for CO_2satH_2O

Substantial drop in UCS and BZTS

10 mm progression last 90 days

Notes:

Dramatic change for reference 90 days (0,5µD), may be artifact measurement



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WP1 S3 mechanical property change factor

Observations:

Large permeability increase with $scCO_2$ exposure

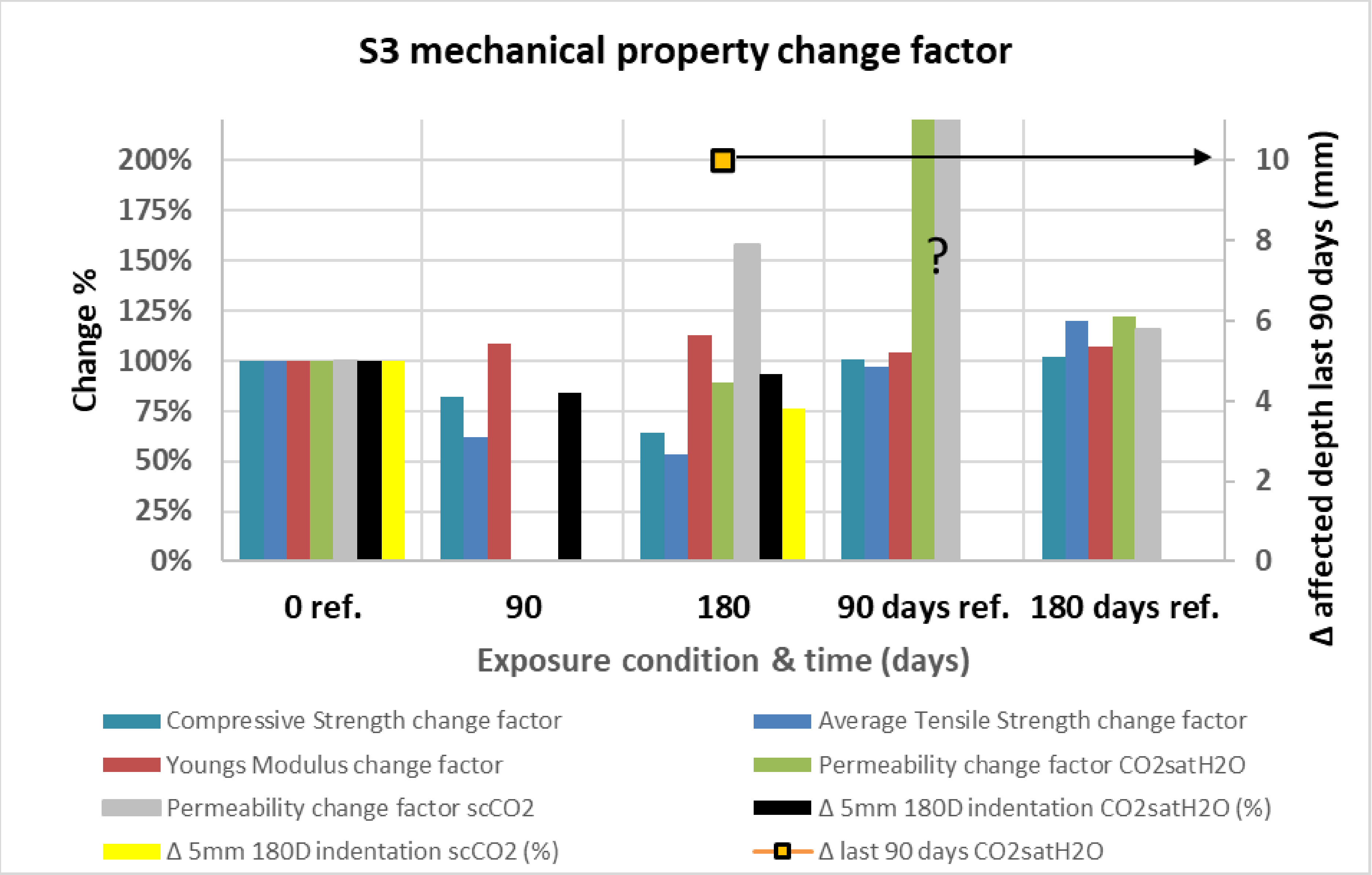
Minor change for CO_2satH_2O

Substantial drop in UCS and BZTS

10 mm progression last 90 days

Notes:

Dramatic change for reference 90 days (0,5µD), may be artifact measurement



WP1 S4 mechanical property change factor

Observations:

Substantial permeability decrease with CO_2 exposure, both types

Substantial increase in UCS, BzTS, YM

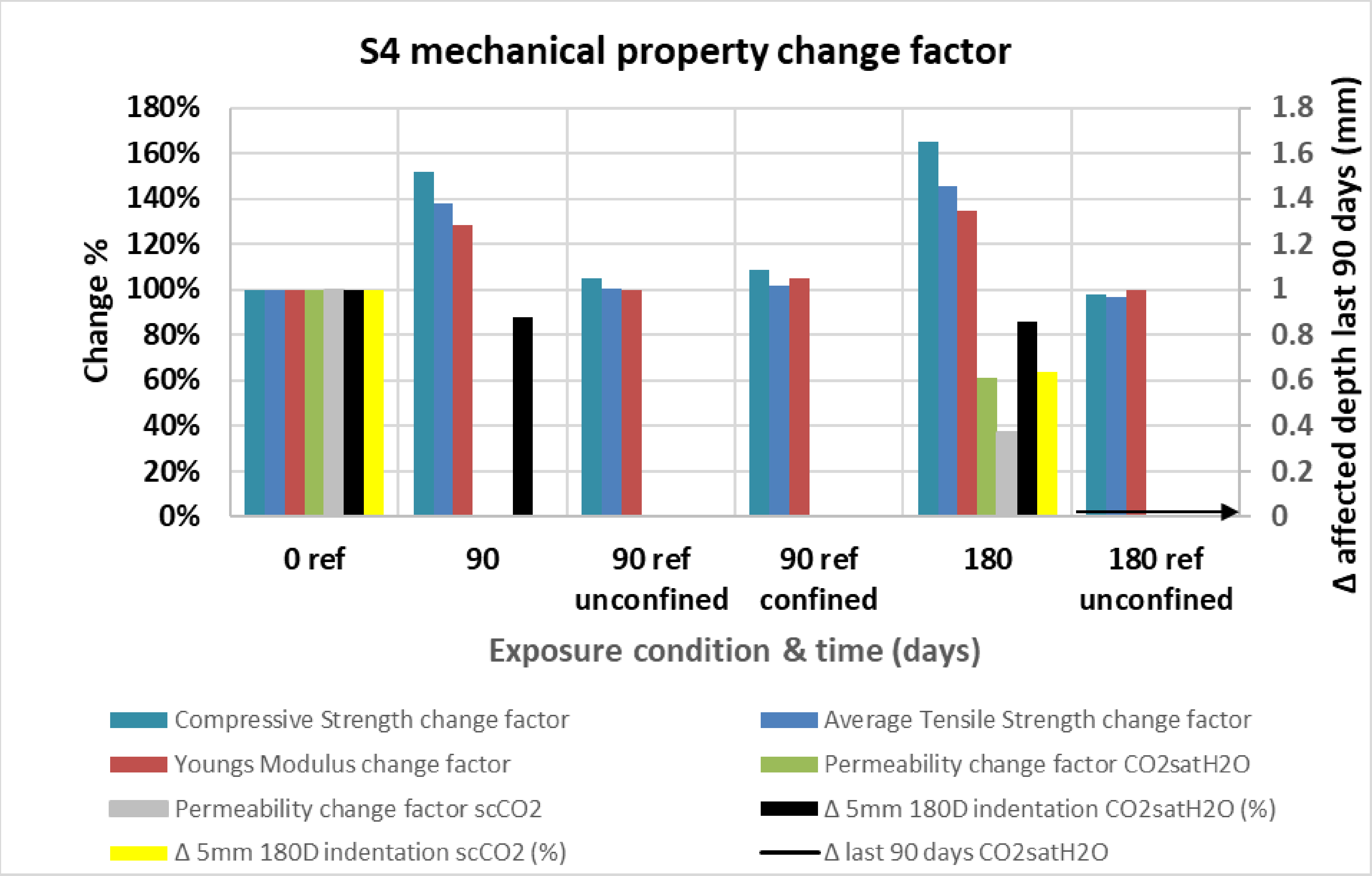
This not observed for reference

Reduction in indentation

Notes:

Sample appears homogeneous

Δ last 90D has 0 value (no change)



WP1 S5 mechanical property change factor

Observations:

Minor change in mechanical properties

Substantial permeability decrease with CO_2 exposure, both types

This is also observed for reference

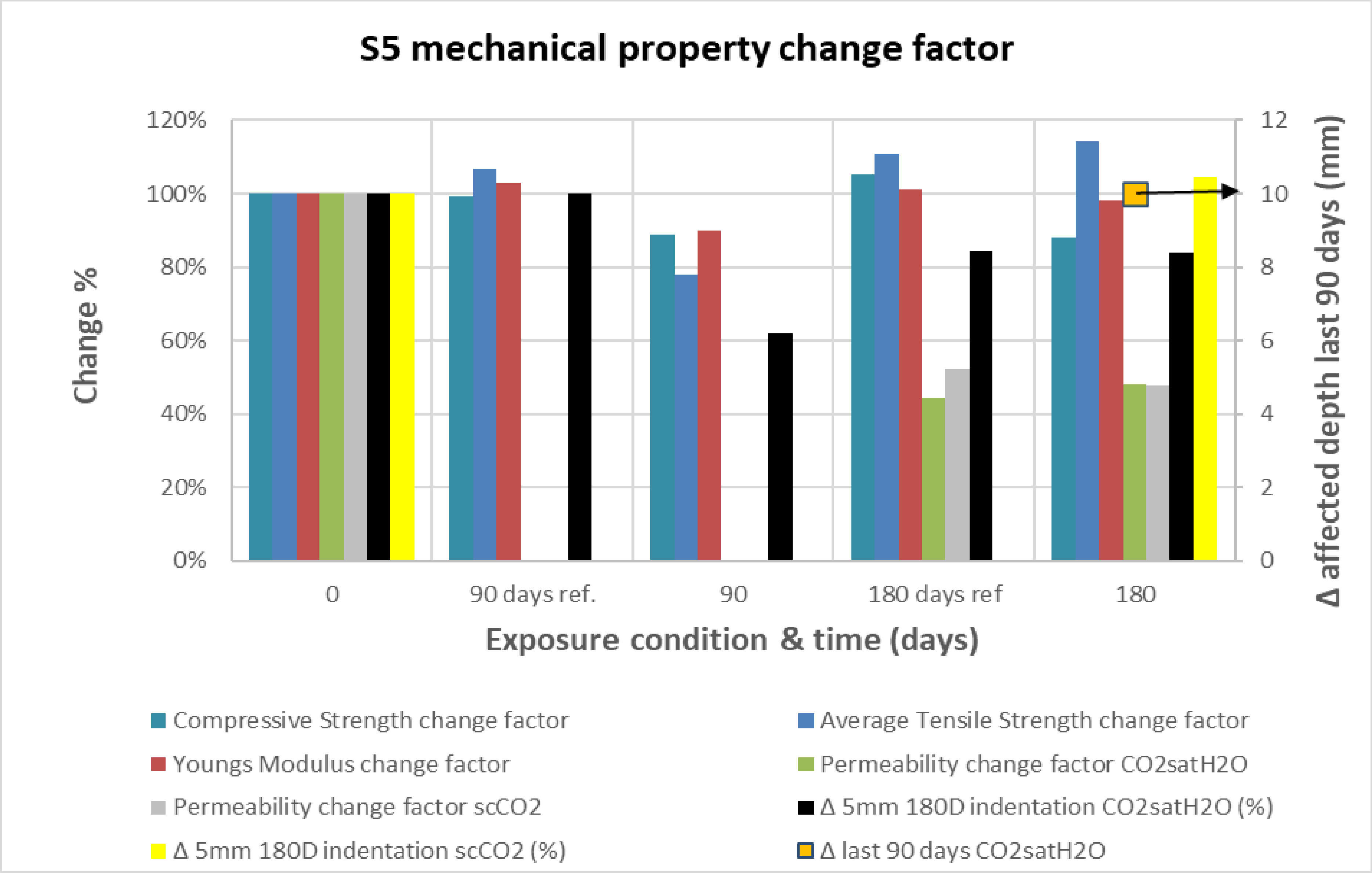
Small reduction in indentation

10 mm progression last 90 days

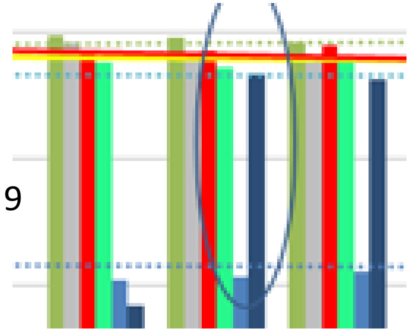
Notes:

Sample appears to segregate

Possibly still ongoing reactions at 6M



WP1 observations & conclusions – using the data in practice



Observations - flow:

1. Can we use permeability data for flow estimates?
   - There is little evidence supporting any increase with exposure
   - The highest value of pre-, post- and post-reference values should be used (water permeability)
2. Can we extrapolate flow data using the ΔP/L?

- Quite likely the near CO_2 entry area creates a high ΔP/L region with extra low permeability that is fairly thin

→ Any extrapolation of flow using ΔP/L across the entire barrier as input is most likely inaccurate and will underestimate flow potential

3. Can we use measured flow rate for flow estimates?

- What is observed (quick reduction in flow) is likely to also happen in the field given similar exposure mode

→ Extrapolation with barrier length should be used with caution as most likely inaccurate

→ It is preferred to base flow estimates on permeability input

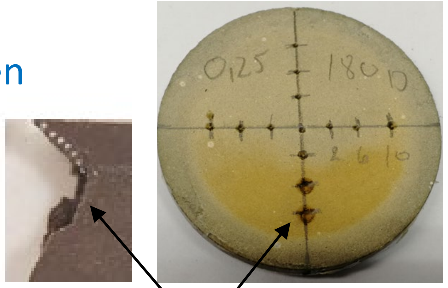
Observations – damage progression:

1. Can we extrapolate progression data using the ΔP/L?
2. Can we extrapolate progression data NOT using the ΔP/L (time only)?

- Tests outside of Cementegrity with no/minimal ΔP/L suggests that damage progression is primarily diffusion driven

→ Extrapolation to field using the ΔP/L as input cannot be justified

→ Extrapolation to field ignoring the ΔP/L as input may be justified, given uncertainty by scaling is accounted for



Observations – the importance of water:

1. Which case is worst – pure $scCO_2$ or CO_2 and water combination?

- Flow potential is higher with pure CO_2 due to lower viscosity, but bi-carbonation which is detrimental for OPC will not happen
- Therefore, the CO_2 and H_2O combination is worst case, especially if bi-carbonate leaching can happen

WP1 observations & conclusions – using the data in practice

Observations – sealant permeability:

1. Is permeability an important parameter for CO_2 resistance?
- If the design matrix responds negatively to CO_2 permeability / porosity is an important factor. This can be seen by comparing S1, S2 and S3 indentation depth to unaffected matrix and last 90 days change
- Low or no CO2 affected designs do not rely on very low permeability, an example is S4
1. Can the permeability for the highest flowing sealants be reduced by design optimization?
- Most likely they can be improved by tuning the design

Observations – mechanical properties:

1. Can the measured mechanical properties post exposure be assumed accurate?
- Not if the design shows impact by exposure, which is the case for S1- S3
- If the design can be considered homogenous throughout the data can be considered valid

Observations – use of indentation vs mechanical properties:

1. Can the measured mechanical properties post exposure be assumed accurate?
- Not if the design shows impact by exposure and is inhomogeneous, which is the case for S1- S3.
- The sample will then potentially fail at the weakest location
2. Can indentation data be used instead?
- Yes, to some extent. Good to reasonable correlation has been found with UCS and YM, not with PR and BzTS
- This allows for UCS and YM indirect estimates at specific locations my performing indentation tests there, if sample is sufficiently large

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