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ASSESSING CEMENT INTEGRITY IN CO_2 STORAGE: A PERFORMANCE ANALYSIS OF CONVENTIONAL AND CO_2-PROOF CEMENT BLEND.

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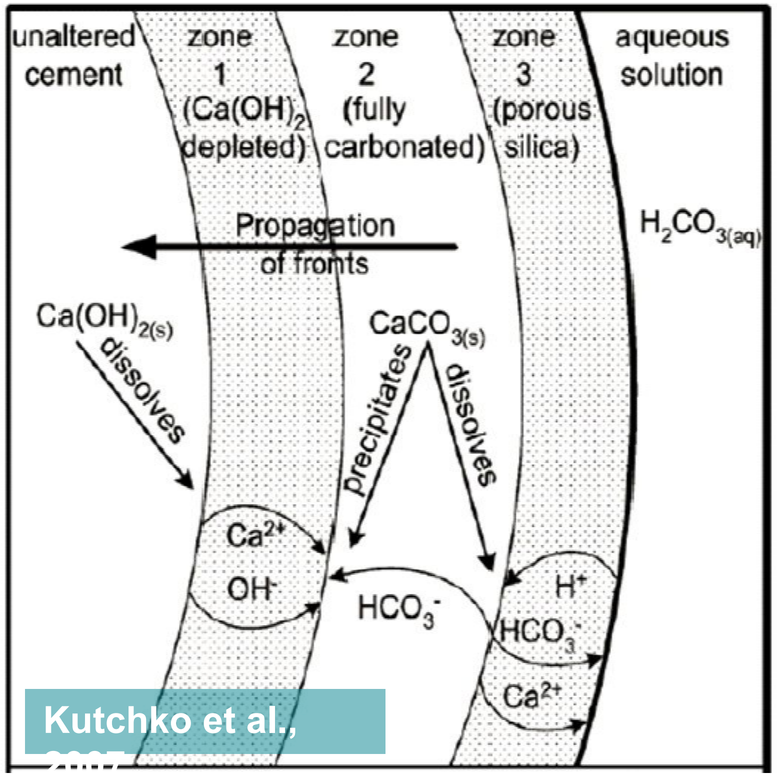
CEMENT CARBONATION

A barrier degradation from which there is no escape

- When CO_2 is injected into a well, it dissolves in the formation water forming carbonic acid (H_2CO_3).
- This reacts with cement's main components, portlandite $Ca(OH)_2$ and calcium silicate hydrate phases (C-S-H).
- The product are calcium carbonates ($CaCO_3$) which in turn can be dissolved further by the reaction with carbonic acid.
- Furthermore, as the water solubilizes CO_2, it continues to invade the set cement matrix, the equilibrium changes and insoluble $CaCO_3$ is converted into water-soluble calcium bicarbonate ($Ca(HCO_3)_2$) that brings new cycle of reactions.



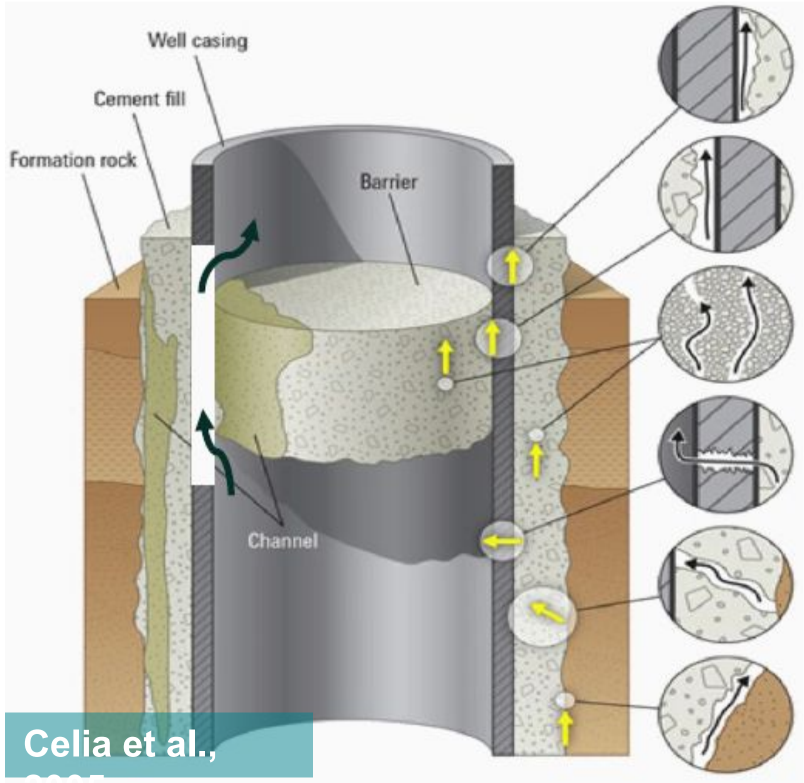
Kutchko et al.,

This occurs when a flow path for the CO_2 exists in the cement matrix and/or at the interfaces. Possible pathways are: micro-annuli along the interfaces, cement matrix permeability, and cracks.

TESTING CHALLENGES

The new purpose needs an innovative approach

- Cement integrity in wells related to CCS applications can be damaged by exposure to CO_2 and carbonated brines or as the result of physical processes during construction, operation, and abandonment.
- Cracks and permeability increasement due to carbonation are added to the cement barrier pathways already known.



Celia et al.,

- No dedicated standards on testing between cement and CO_2
- Many different test protocols reported in literature
- Common tests based on pre- and post- exposure sample analyses
- Time-consuming tests and lack of universal applicability

To face out these drawbacks, a comprehensive testing methodology was designed to provide input data for long-term stress analyses and improve the quality of the cement-CO_2 interaction research.

3-STAGE AUTOCLAVE TESTING

Performance comparison PRE- and POST-Ageing

Pre-Aging Tests

- Cement Slurry Characterization
- **Full Tx Mechanical Characterization**
- **Cyclic Stress Testing**
- Porosity and Permeabily Measurement with N_2/CO_2
- Mineralogical Analysis
- CT-Scan
- Phenolphthalein Test

Autoclave Aging

Cement Samples Immersion in CO_2/N_2 Environment @ Reservoir Conditions

Post-Aging Tests

- Aging Fluids Chemical Analysis
- **Full Tx Mechanical Characterization**
- **Cyclic Stress Testing**
- Porosity and Permeabily Measurement with N_2/CO_2
- Mineralogical Analysis
- CT-Scan
- Phenolphthalein Test

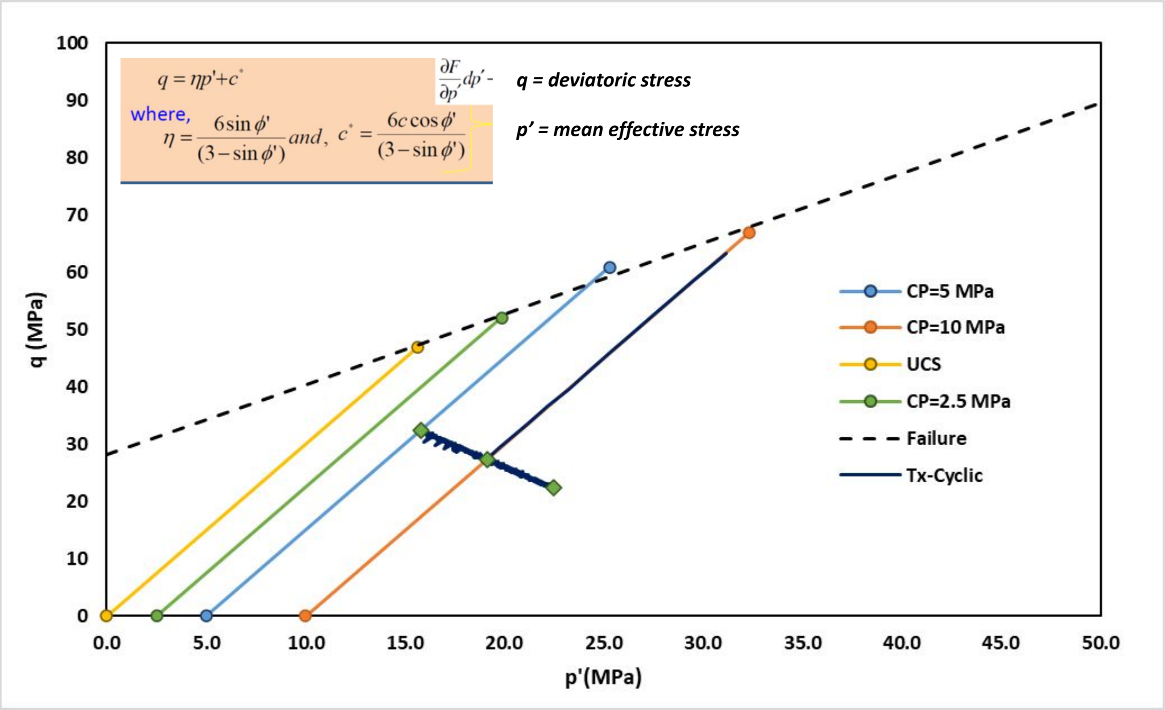
Test protocol mainly based on comparing performance and chemical-physical characteristics of the cement, before and after CO_2 exposure under the pressure and temperature conditions of the storage reservoir

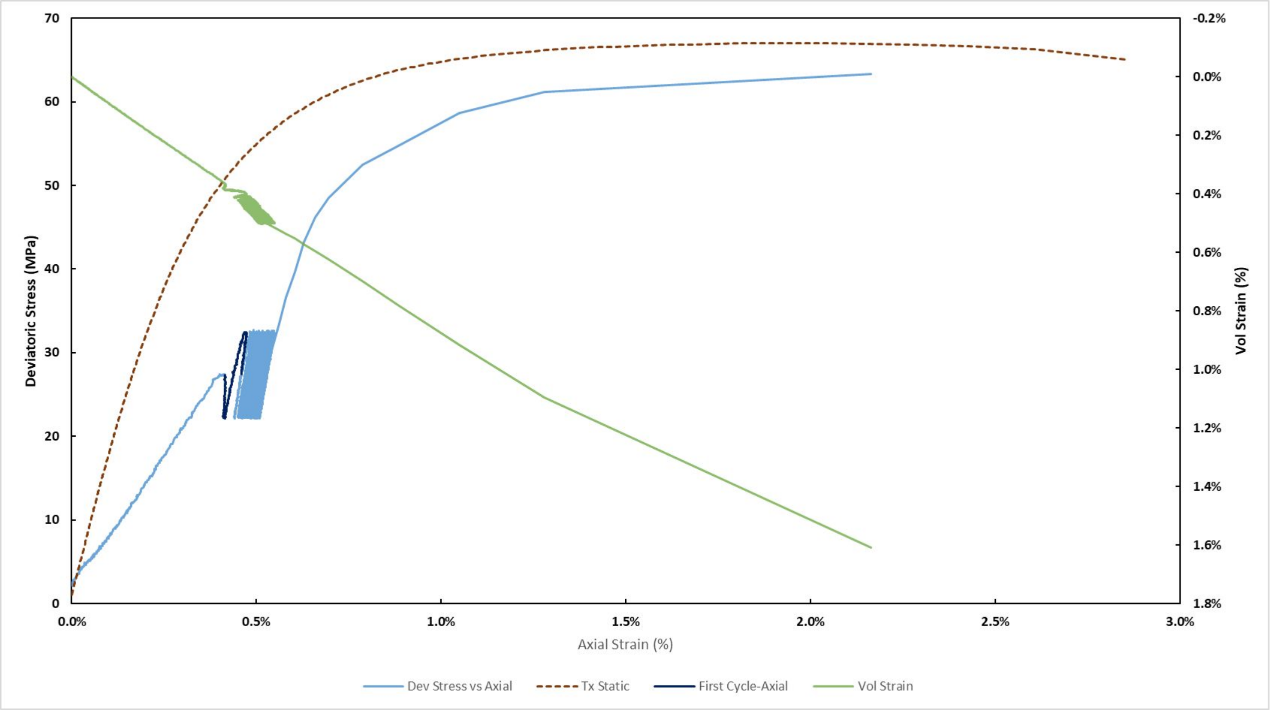
CYCLIC TESTING

Can cement withstands the injection induced stresses?

The testing procedure starts from anisotropic initial conditions in Tx cell:

- The conditions thus imposed allow the cyclic boundary test (10 MPa ± 5 MPa) to be performed with constant axial stress.
- If the specimen does not break at the end of the predetermined 96 cycles, rupture is forced by conventional triaxial testing at 10 MPa boundary pressure



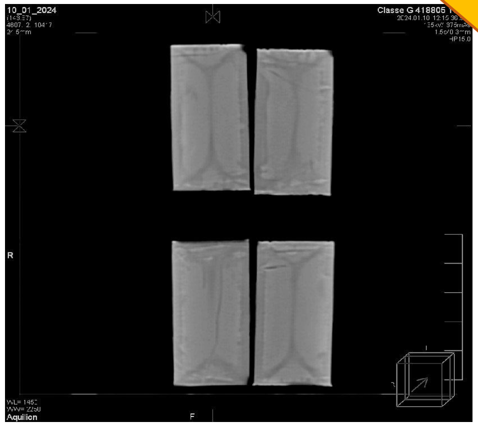


TESTING OUTCOMES

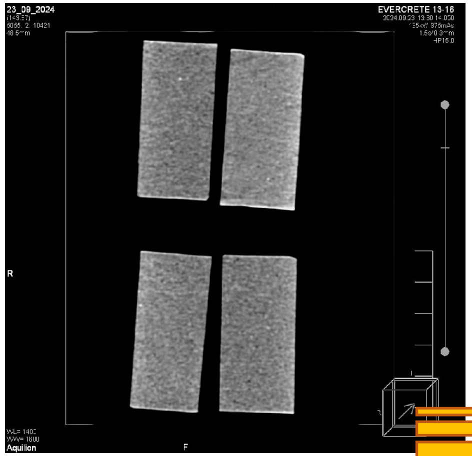
Class G cement VS CO_2-Proof cement: a visual check

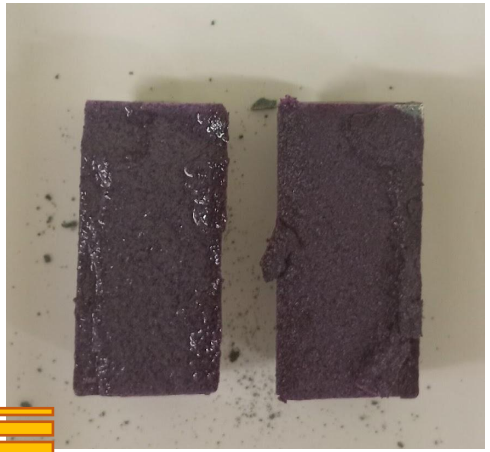
PRE-Exposure

POST-Exposure

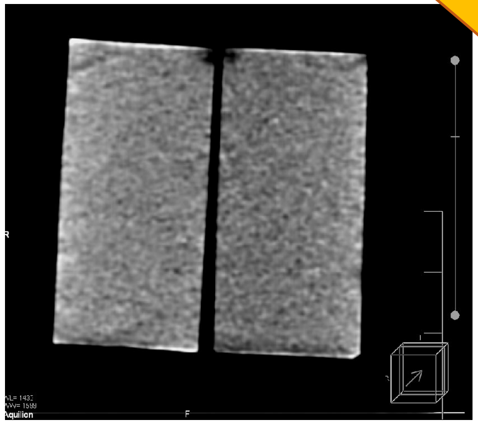


PRE-Exposure





POST-Exposure



TESTING OUTCOMES

Class G cement VS CO_2-Proof cement: resistance comparison

What happens Post-Exposure on Tri-Axial Conventional Testing?

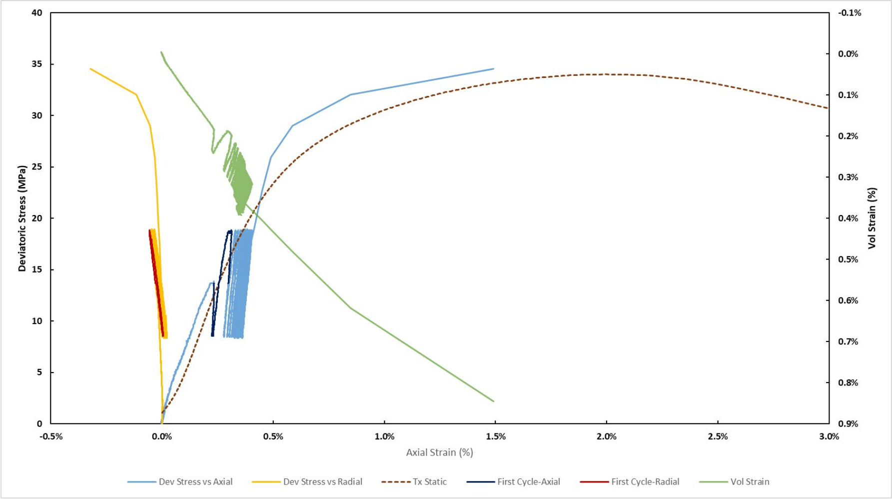
Class G cement:

- decrease slightly YM and increase PR
- lowering by less than half CS and TS
- loses its fragile behavior without confinement

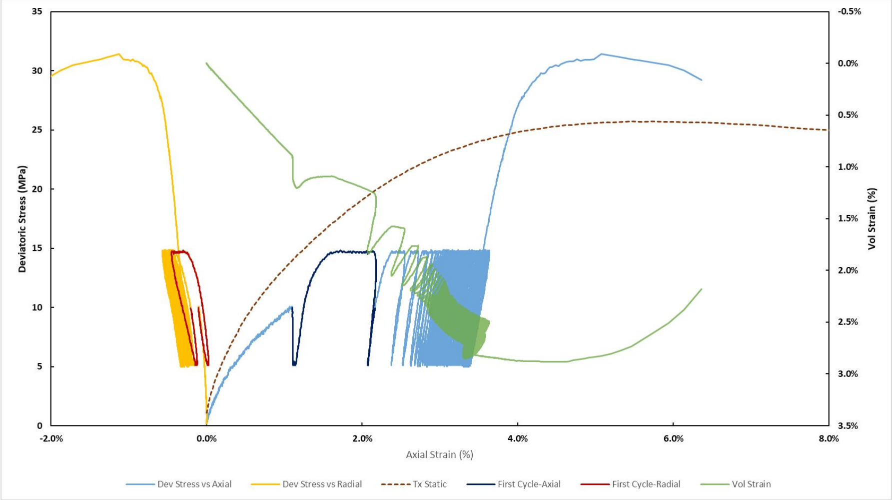
CO_2-Proof cement:

- decrease greatly YM and increase PR
- halve CS and TS

Cyclic Testing Sample		N° Cycles	CS [MPa]	Ref. Tx-CS [MPa]
Class G	PRE-	96	33,79	41,81
	POST-	0,5	36,9	N/A
CO_2-Proof	PRE-	96	34,52	34,01
	POST-	96	31,42	25,71



CO2-Proof Cement

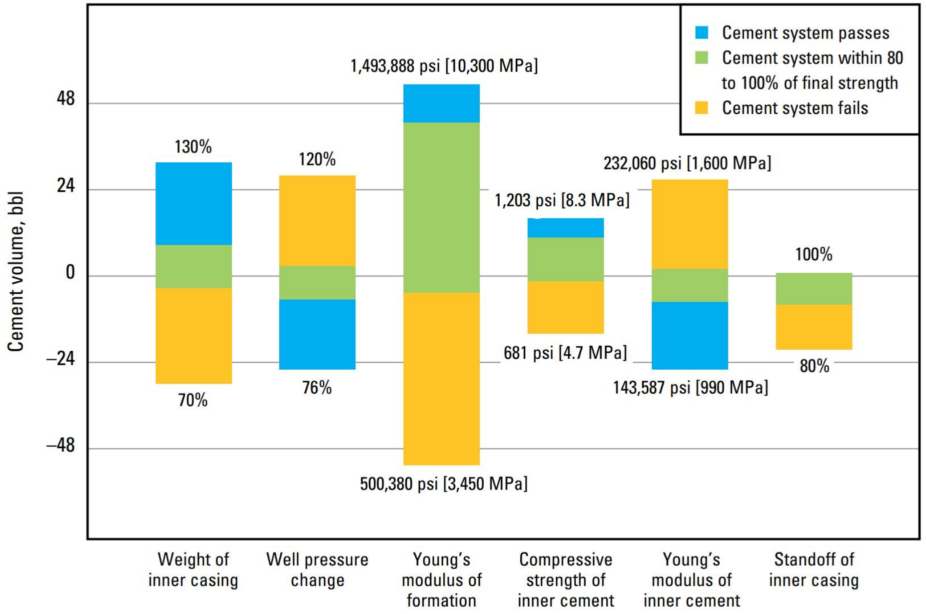


CO2-Proof Cement

COMPUTERISED STRESS ANALYSIS
Overview and input data

- 2-D mathematical model based on solid mechanics.
- Ability to model up to 10 casing strings simultaneously.
- Failure modes:
    - shear (compressive).
    - traction (tensile).
    - microannulus.
- Sensitisation function.
- Initial radial stress and pseudo-expansion prediction.

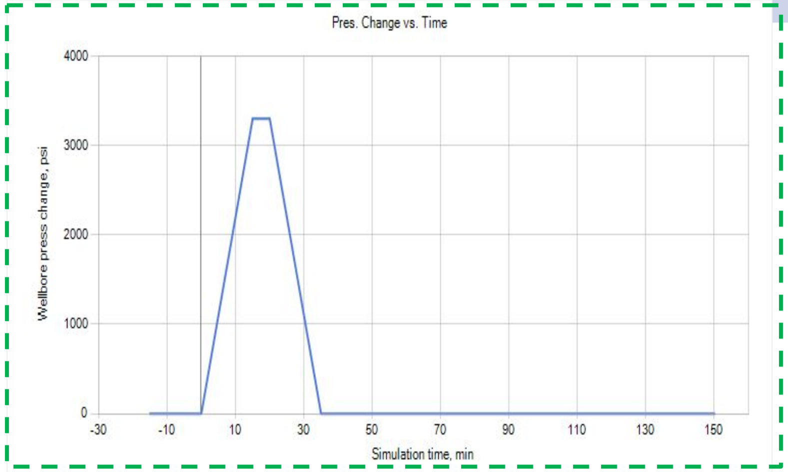
- Common input parameters.
    - Density.
    - Compressive and tensile strength.
    - Young's modulus and Poisson's ratio.
    - Cohesion and friction angle.
    - Thermal conductivity and SHC.

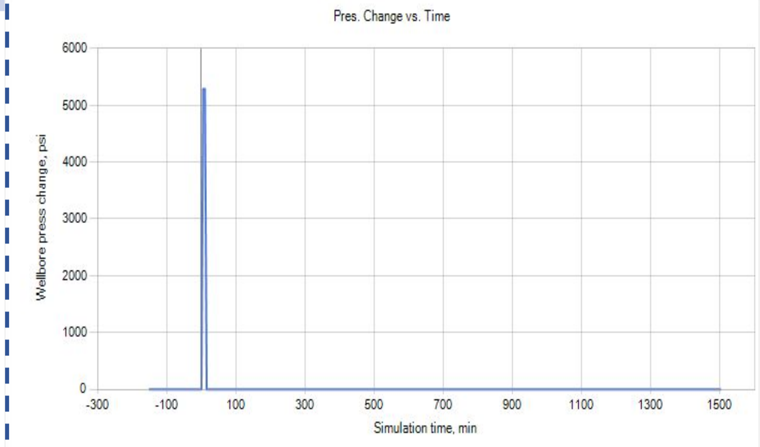


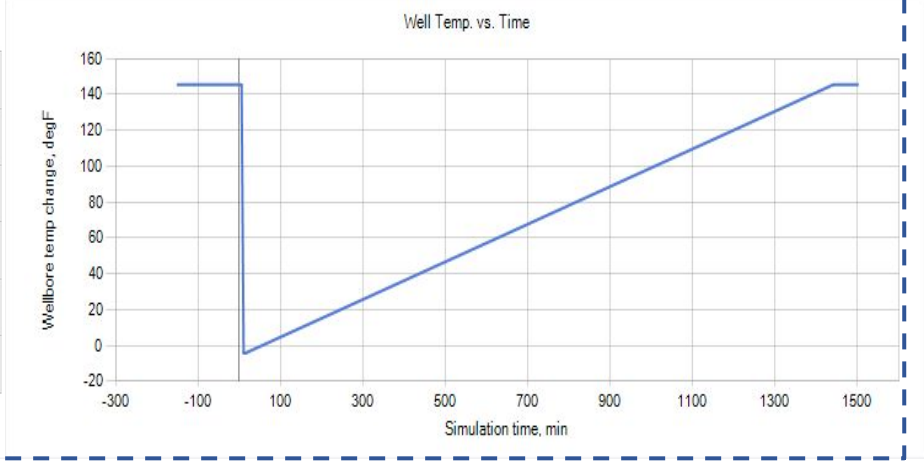
STRESS SCENARIOS

Pressure testing and injection

Scenario	Pressure, psi	Temperature Dynamic	Temperature, °C	Fluid density, sg	Formation depth, ft	Formation type	Initial radial stress, psi
Pressure testing	3303	Steady-state	63	1.2	2951	Shalestone	79
					3003	Sandstone	1357
Injection loading	5280	Cooling	63 to -20	1.2	2951	Shalestone	79
					3003	Sandstone	1357





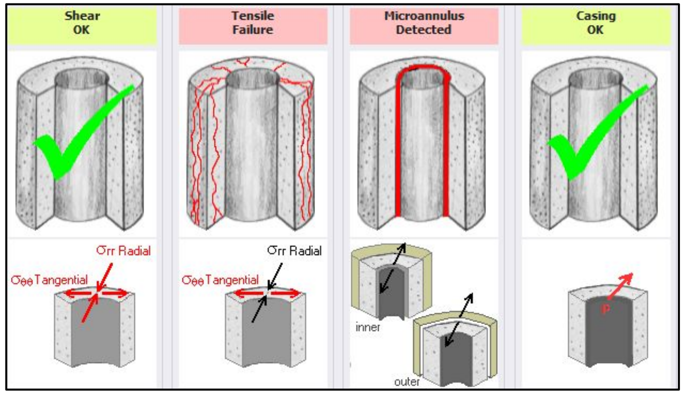


STRESS ANALYSIS

Results

- Data used from pre- and post-exposure to CO_2.
  - Class G.
  - CO_2-proof cement.
- 'Worst case' simulation
  - Injection loading scenario.
  - Confinement: Shalestone.
  - Post-exposure mechanical properties.

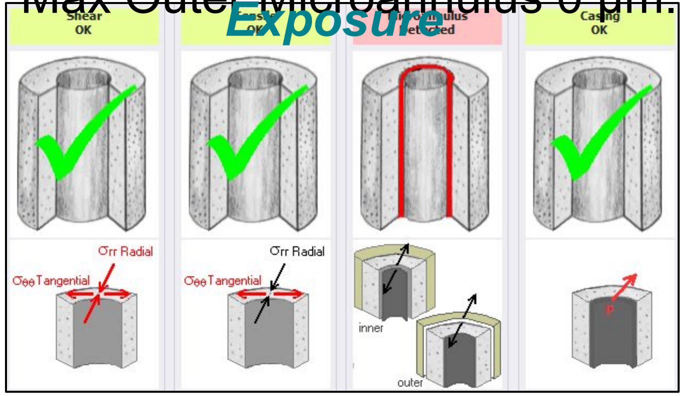
Class G | Post-CO2 Exposure



Maximum tensile stress: 440 psi.
Cement tensile strength: 170 psi.

Max Inner Microannulus 86.9 µm.
Max Outer Microannulus 0 µm.

CO_2-proof cement | Post-CO2 Exposure



Maximum tensile stress: 123 psi.
Cement tensile strength: 233 psi.

Max Inner Microannulus 88.4 µm.
Max Outer Microannulus 0 µm.

Overall, CO_2-proof cement durability correlated with experimental data.

The micro-annulus can be addressed by a proper addition of expanding agents to the cement slurry, unlike tensile strength which is only related to the mechanical properties of the cement.

CONCLUSIONS

Key findings of the study

- Cement Carbonation is a process that will certainly take place in well as long as the main reagents are present: CO_2, Water, and Calcium.
- Cement Carbonation can be a real problem for well integrity if the right materials and well insulation are not selected, especially cement.
- Cycle testing indicates that CO2-Proof cement fully resist to load applied for the selected cycles, while Class API Class G fails drastically
- Based on lab evidence and Stress analyses results, CO2-Proof cement appears to withstand better to injection stresses than Class G cement
  - Although CS and TS of the CO_2-proof solution decrease after exposure to CO_2, its significant decrease in YM and PR makes the solution more “elastic,” thus enabling it to withstand stress and not fail under tensile stress (as happens with Class G cement).

The combination of a thorough testing methodology and accurate stress analysis can certainly help predict the behavior of cement in wells and ensure proper well integrity.

THANKS FOR YOUR ATTENTION

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