ouronova

Accelerating DeepTech Innovation

Cement Integrity

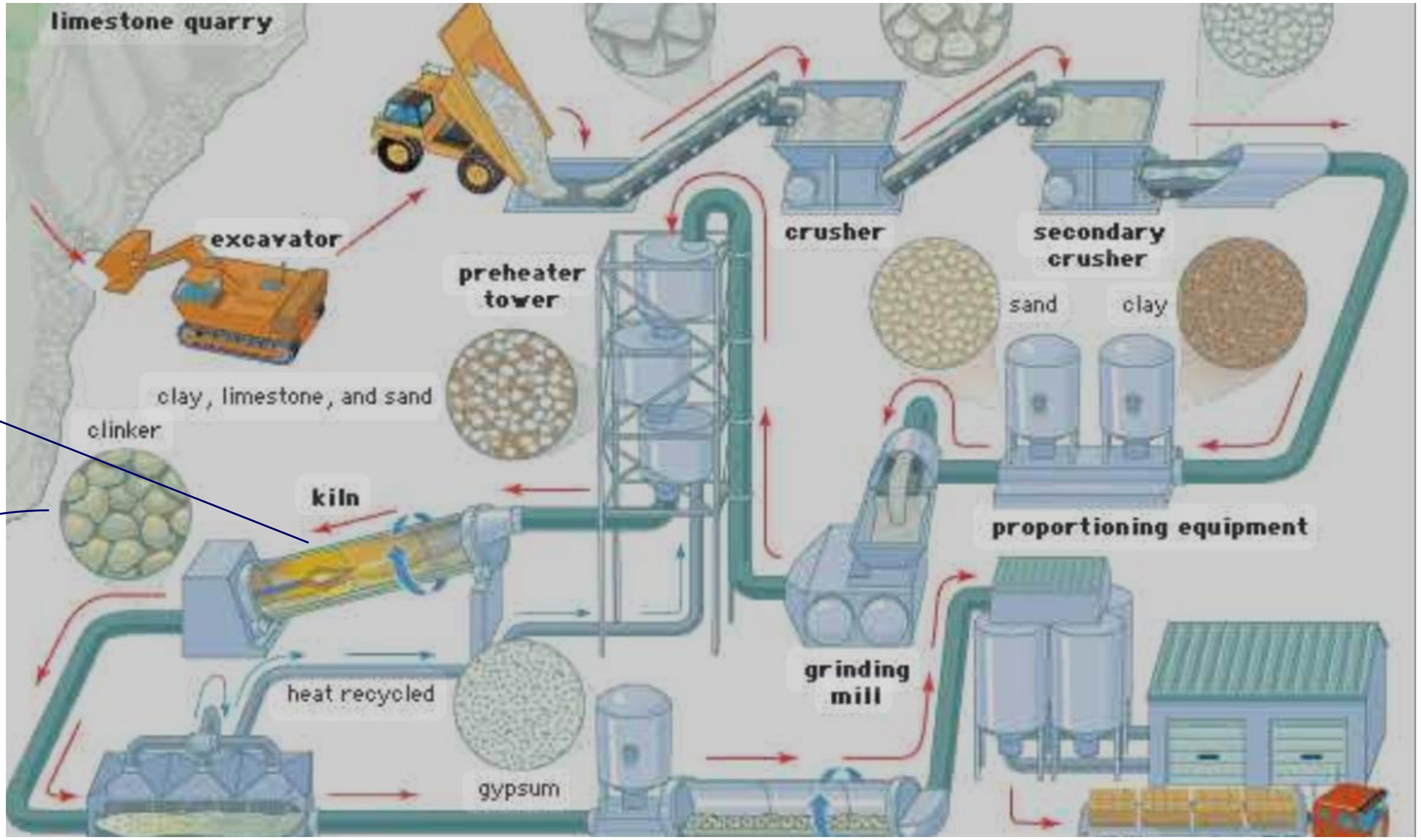
Overview

- What Is Cement Integrity?
- Integrity Threats
- Cement Design Approaches
- Cement Integrity Evaluation Tools
- Emerging Technologies
- Final Thoughts

Cement Manufacturing of Portland Cement

Rotary Kiln (±1450 ° C)

Clinker

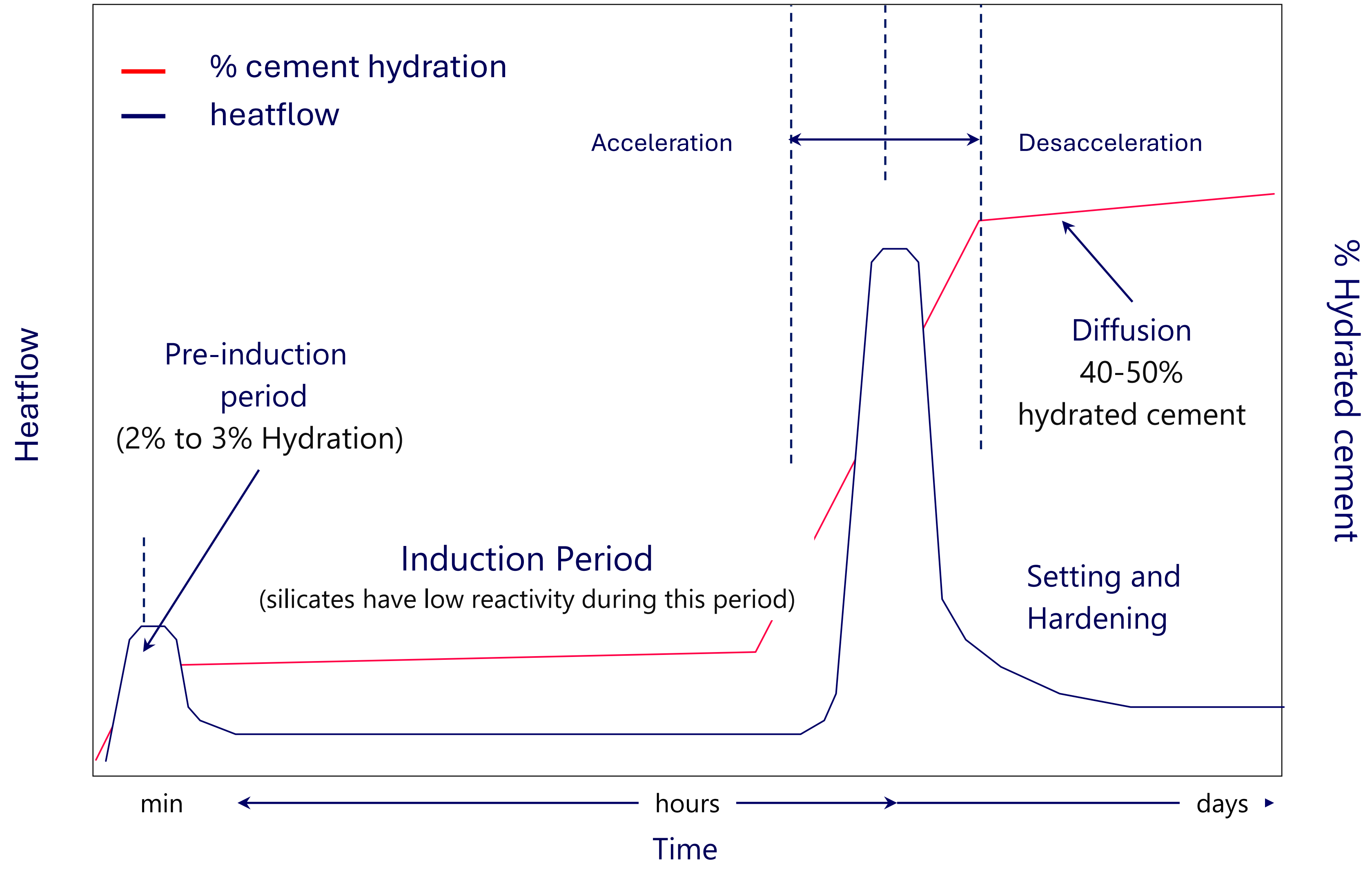


Joseph Aspdin, 1824

Class G Cement Clinker Composition

Compound	Abbreviation	Chemical Formula	%	Contribution on performance
Tricalcium Silicate (Alite)	C_3S	$3\ CaO.\ SiO_2$	45 - 60%	Durability and total resistance
Dicalcium Silicate (Belite)	C_2S	$2\ CaO.\ SiO_2$	15 - 30%	Long term durability
Tricalcium aluminate	C_3A	$3\ CaO.\ Al_2O_3$	5 - 12%	Durability and early setting
Tetracalcium aluminoferrite	C_4AF	$4\ CaO.\ Al_2\ O_3\ Fe_2O_3$	6 - 12%	No effect on durability
Gypsum (added during grinding)	CSH_2	$CaSO_4\ 2H_2O$	2 - 10%	Prevents early setting

Heatflow During Cement Hydration

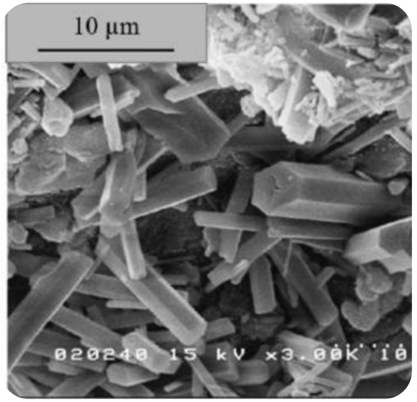


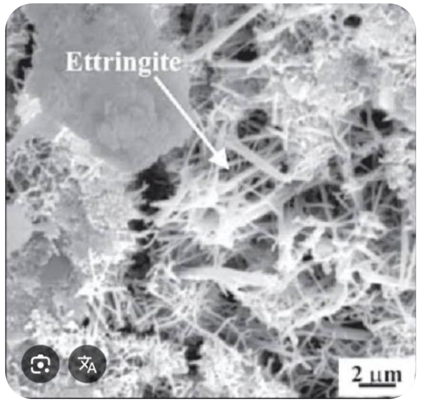
What is Set Cement?

Ettringite is formed during the initial hydration of cement when C_3A reacts with gypsum ($CaSO_4.2H_2O$) in the presence of water:
$Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$

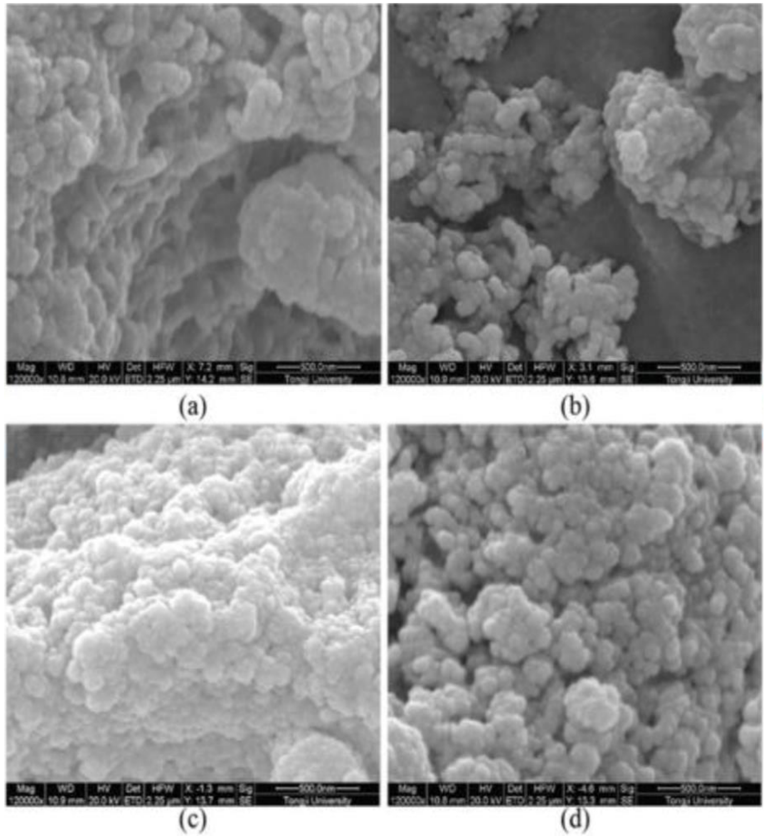
It controls thickening time and cement setting time.

Compound	Chemical formula	Abbreviation	Typical Mass (%)	Contribution on performance
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A	5 -12%	Durability and early setting





What is Set Cement?



C-S-H (Calcium Silicate Hydrate) is the main phase which keeps the cement particles binded together, providing cohesion and resistance. It does not have a defined chemical formula and is amorphous. It is formed from the hydration of Portland cement silicate phases:

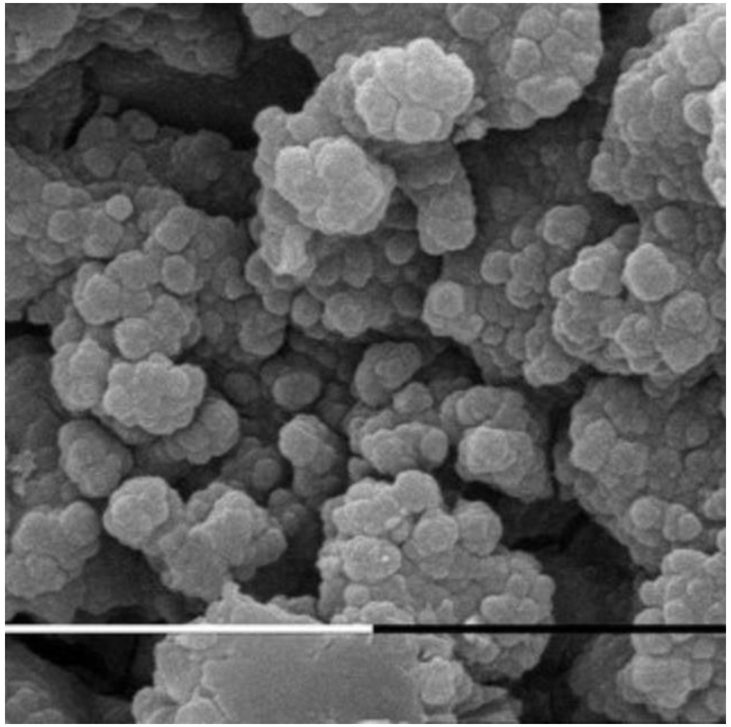
$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3\ Ca(OH)_2$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$$

It controls cement permeability (gelled structure which fills the pore spaces), besides resisting to chemical attacks, and improve cement durability over cement long term life.

Compound	**Abbreviation**	**Chemical Formula**	**Typical Mass** (%)	**Contribution on performance**
Tricalcium silicate (Alite)	C_3S	$3CaO{\cdot}SiO_2$	45–60%	Durability and total resistance
Dicalcium silicate (Belite)	C_2S	$2CaO{\cdot}SiO_2$	15–30%	Long term durability

What is Set Cement?



$Ca(OH)_2$ (Calcium Hydroxide) is byproduct of Portland cement silicate phases hydration:

$2C_3S + 6H \rightarrow C_3S_2H_3 + 3\ Ca(OH)_2$

$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$

It is also called hydrated lime or portlandite.

It provides alcalinity (high pH) to the pore solution, helping metal protection against corrosion in harmful environments. It is also one of the main reactants to CO_2 attack (carbonation reaction).

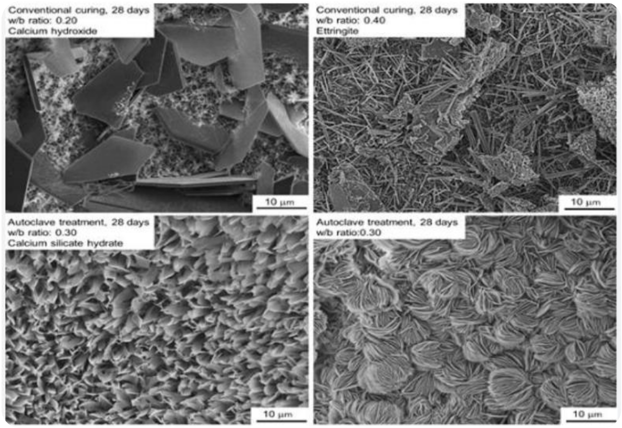
Compound	**Abbreviation**	**Chemical Formula**	**Typical Mass** (%)	**Contribution on performance**
Tricalcium silicate (Alite)	C_3S	$3CaO{\cdot}SiO_2$	45–60%	Durability and total resistance
Dicalcium silicate (Belite)	C_2S	$2CaO{\cdot}SiO_2$	15–30%	Long term durability

What is Set Cement?

The main products generated by the cement hydration process are the Calcium Silicate Hydrate gel – CSH – and the Calcium Hydroxide – $Ca(OH)_2$.

CSH is semi-amorphous material, similar to a gel, which make up approximately 70% in weight of hydrated cement and is the main particles binder.

$Ca(OH)_2$ is crystalline and make up approximately 15 to 20% in weight of hydrated cement.



Nelson e Guillot, 2006)

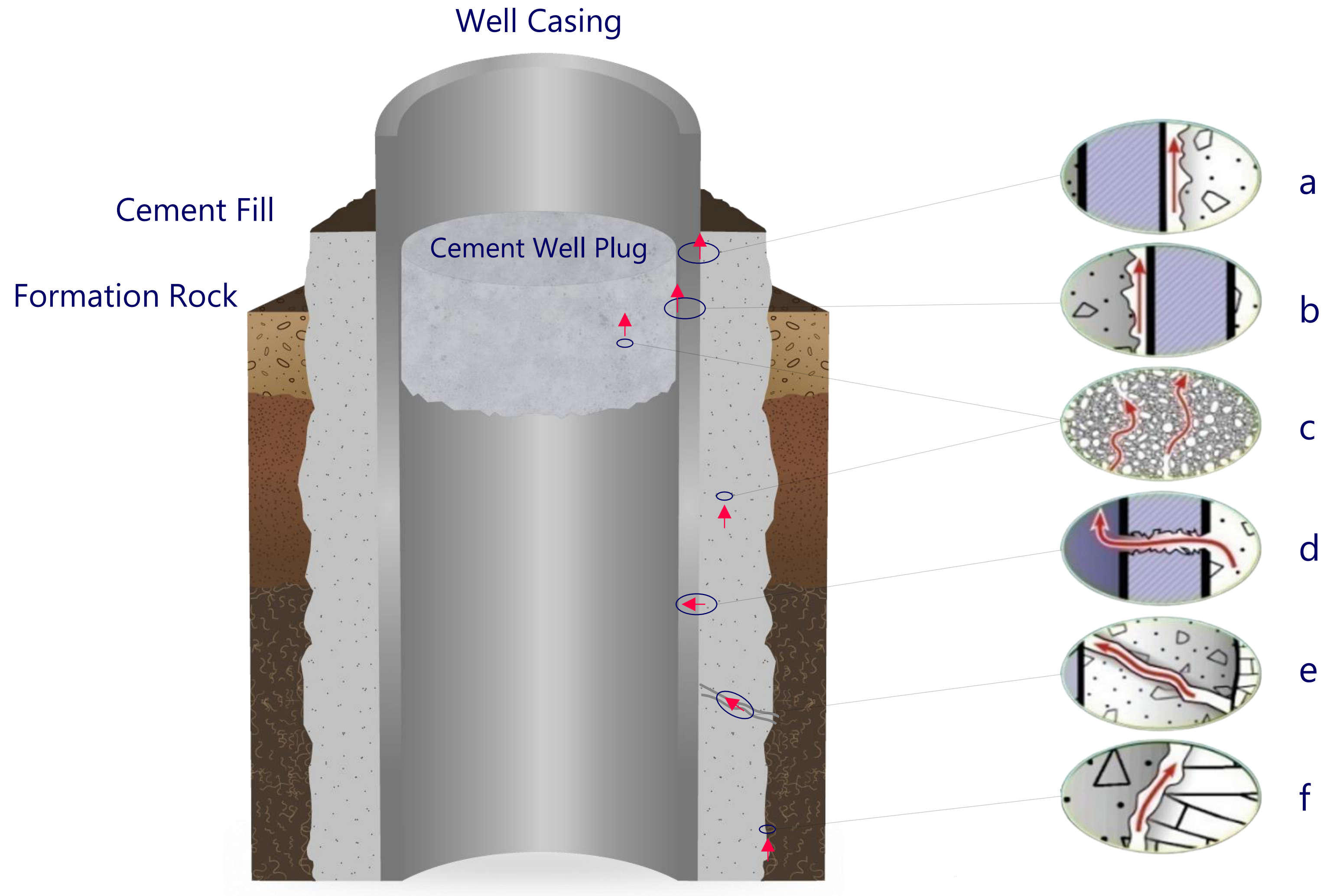
What Is Cement Integrity?

- Key Aspects:
- Mechanical strength
- Bonding (casing and formation)
- Resistance to downhole environments
- Long-term chemical durability

Key Integrity Threats

- Key Chemical Degradation (CO_2, H_2S, Salts)
- Microannuli and Stress-Induced Cracks
- Gas Migration and Fluid Channels
- Cement Aging and Retrogression
- Poor Mud Removal and Placement Practices

Integrity Tests: Potential Leakage Pathways



Gasda et al., 2004 and 2005

Integrity Threat : HPHT Conditions

- Mitigation: Silica, pozzolans, optimized W/C ratio
- Standards: API RP 10B-5, ISO 10426-5

Integrity Threat : HPHT Conditions

1

$C_3S_2H_3$ becomes unstable and transforms itself in a hydrated C_2S of low resistance.

2

The crystallization degree of the hydrated byproducts is limited, and the dehydration of crystals further deteriorate the compressive strength of cement.

3

Increase of porosity and formation of microcracks compromise the structural integrity of set cement.

Integrity Threat : HPHT Conditions

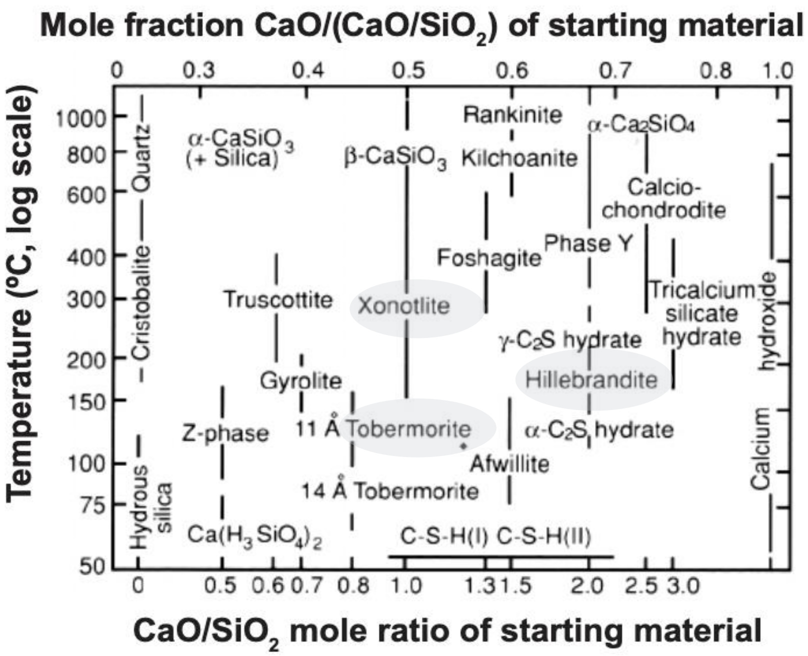


Figure 1: Phase changes in Portland cement submitted to elevated temperatures.

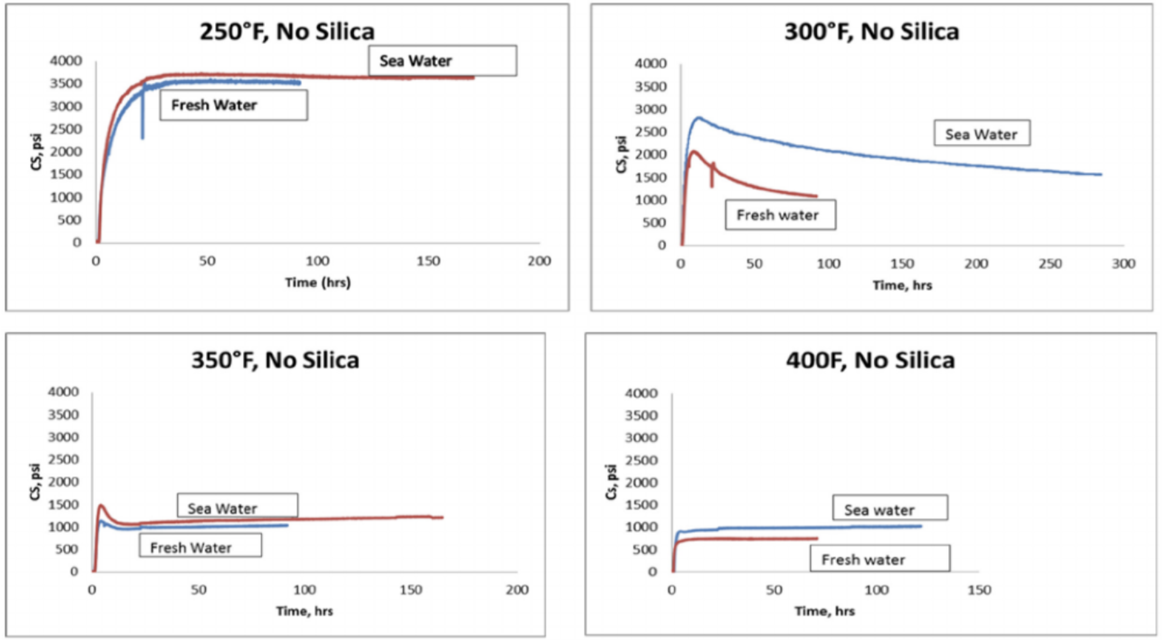
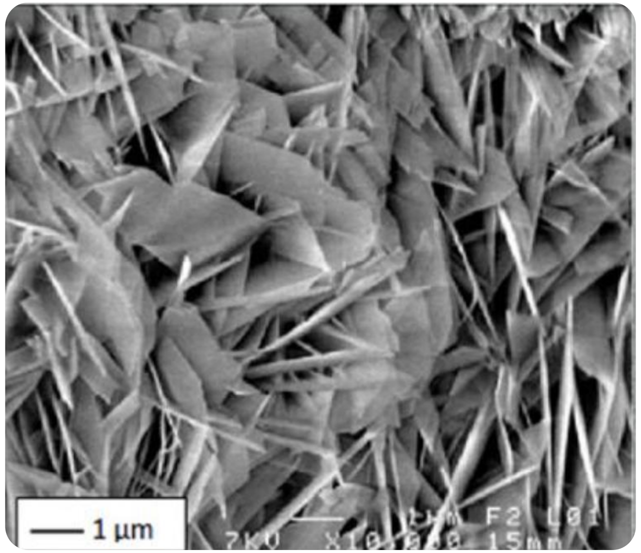


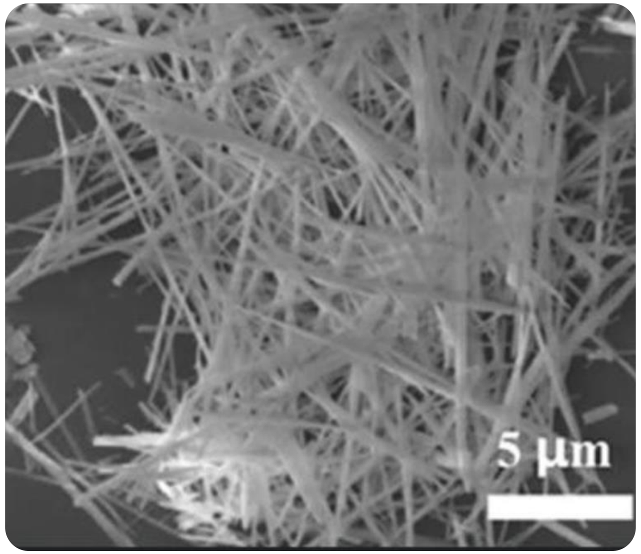
Figure 2: Early strength development patterns for fresh and sea water formulations without silica flour.

ouronova

Integrity Threat : HPHT Conditions

Tobermorite → Xonotlite





Xonotlite is formed at higher temperatures than Tobermorite

Integrity Threat : CO_2 and H_2S and HCl Attack

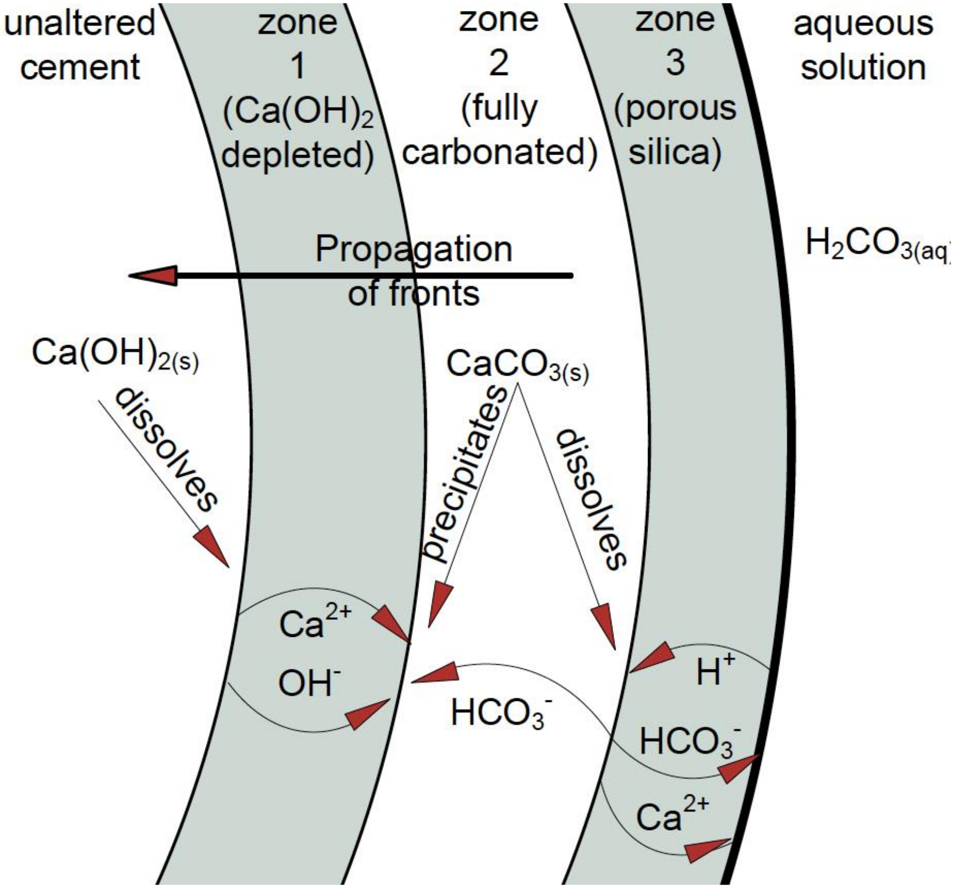
- Reactions: CH + CO_2 → $CaCO_3$, then leaching
- Mitigation: CO_2-resistant cements, Sulfate resistant cements, fly ash, geopolymer, MgO, latex-modified

Integrity Threat : CO_2 Attack

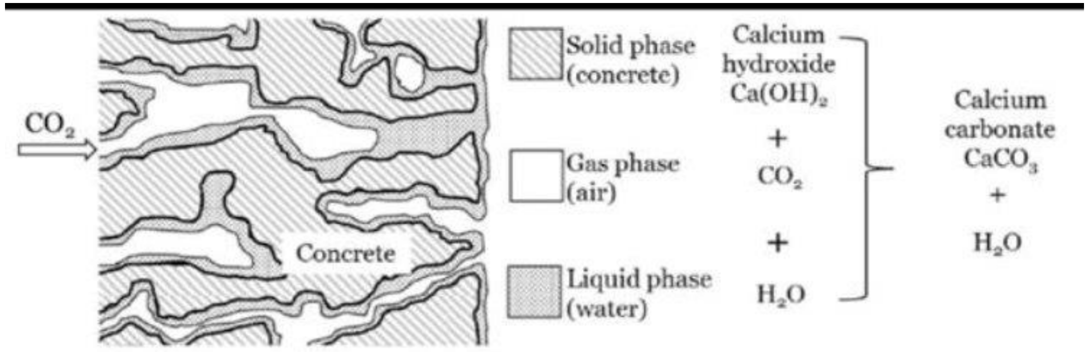
1. $CO_2 + H_2O \rightarrow H_2CO_3$ (carbonic acid)
2. $H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$
3. C-S-H and/or crystalline phases + H2CO3

   → CaCO3 + SiO2 (gel) + H2O
4. CaCO3 + H2CO3→Ca(HCO3)2

Integrity Threat : CO_2 Attack



The dissolution and calcium migration and formation of distinct zones in the set cement.



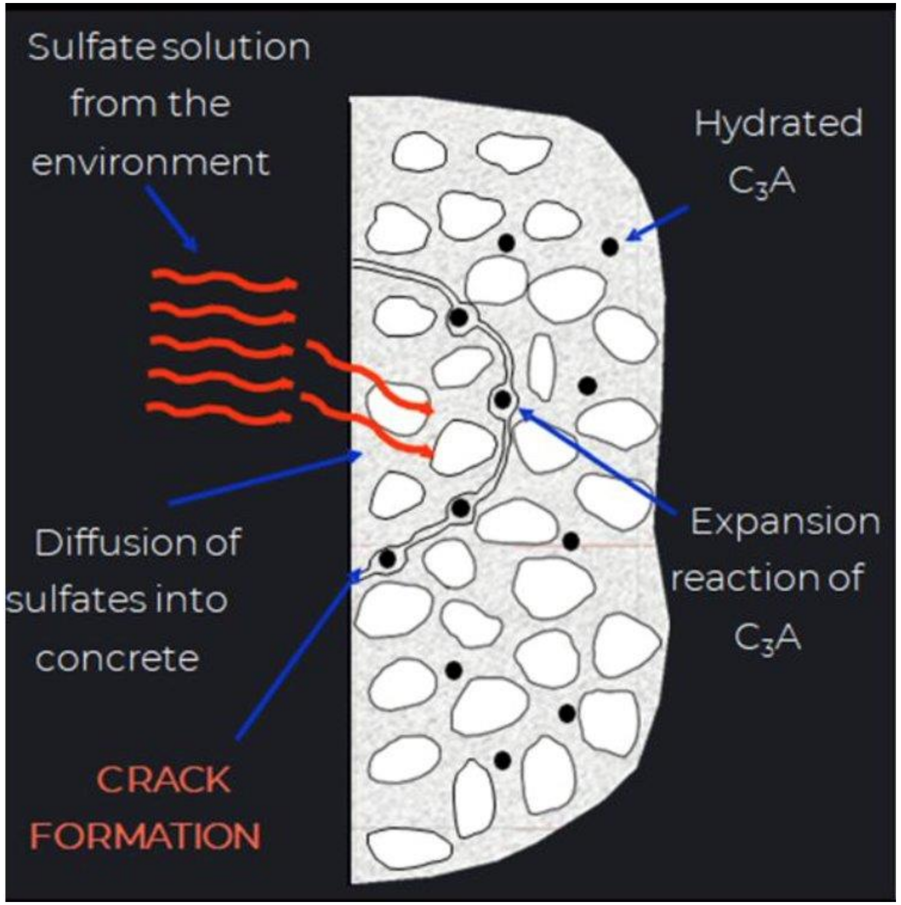
Step 1:	Step 2:	Step 3:
Diffusion inwards of CO_2	Reaction between CO_2 and water molecules	Reaction between resultant H_2CO_3 and the $Ca(OH)_2$ of concrete resulting in calcium carbonate $CaCO_3$ and water

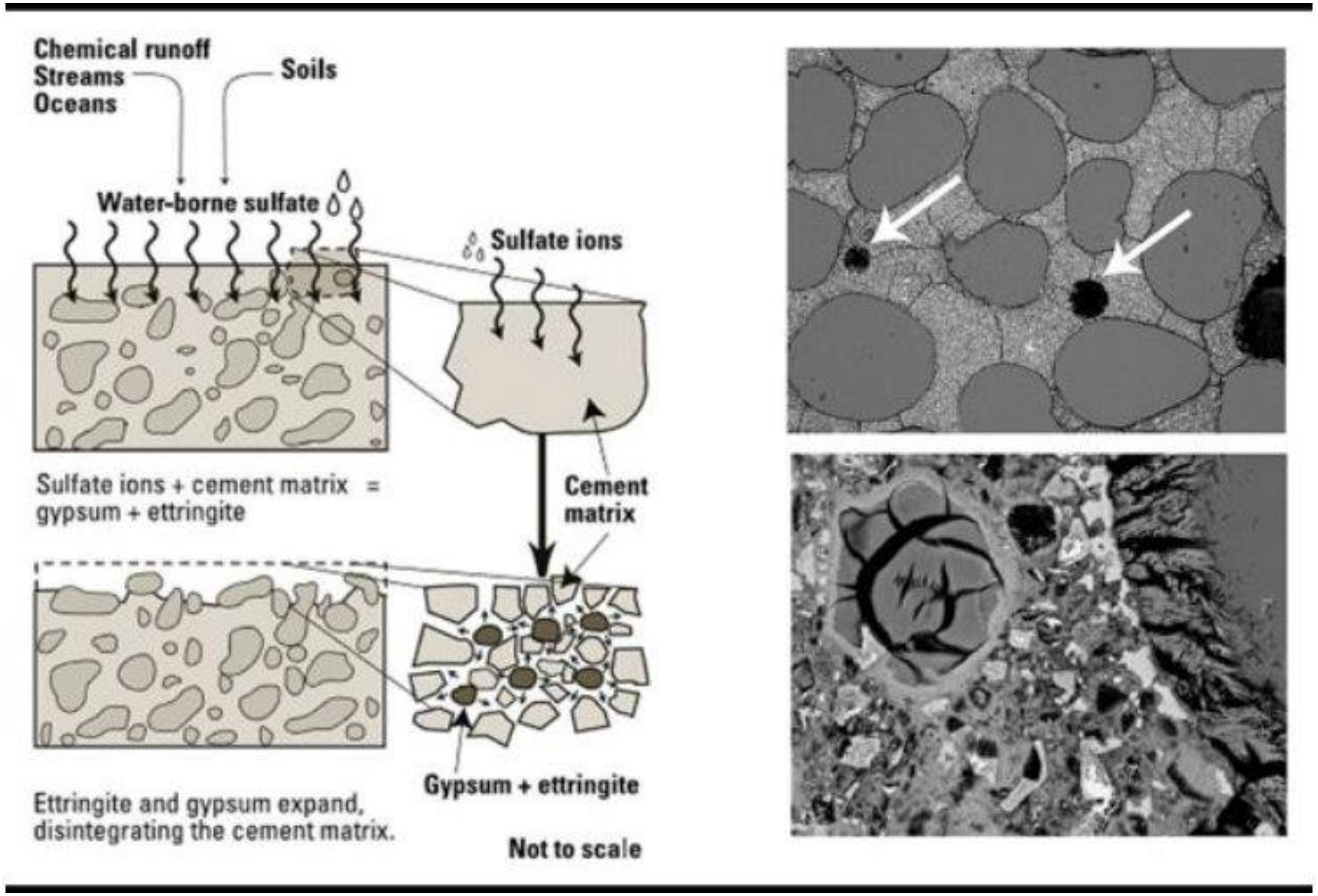
(Kutchko et al., 2007)

Integrity Threat : H_2S Attack

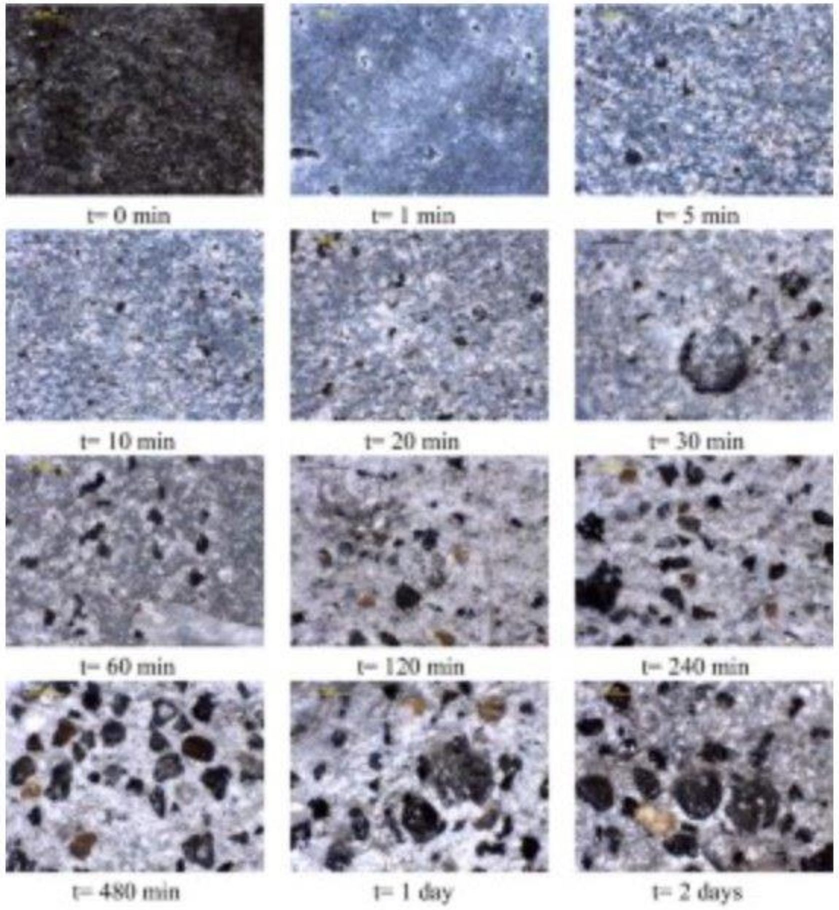
1. $H_2S + Ca(OH)_2 \rightarrow CaS + 2H_2O$
2. $CaS + 2H_2O + CO_2 \rightarrow CaCO_3 + H_2S\uparrow$
3. Monosulfates react with C_3A, forming expansive crystals:
   - Ettringite:
     $C_3A + 3(CaSO_4{\cdot}2H_2O) + 26H_2O \rightarrow$
     $C_6A\check{S}_3H_{32}$ $(3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O)$
   - Gypsum $(CaSO_4{\cdot}2H_2O)$:
     Can also form if excess sulfate reacts with calcium hydroxide (portlandite)

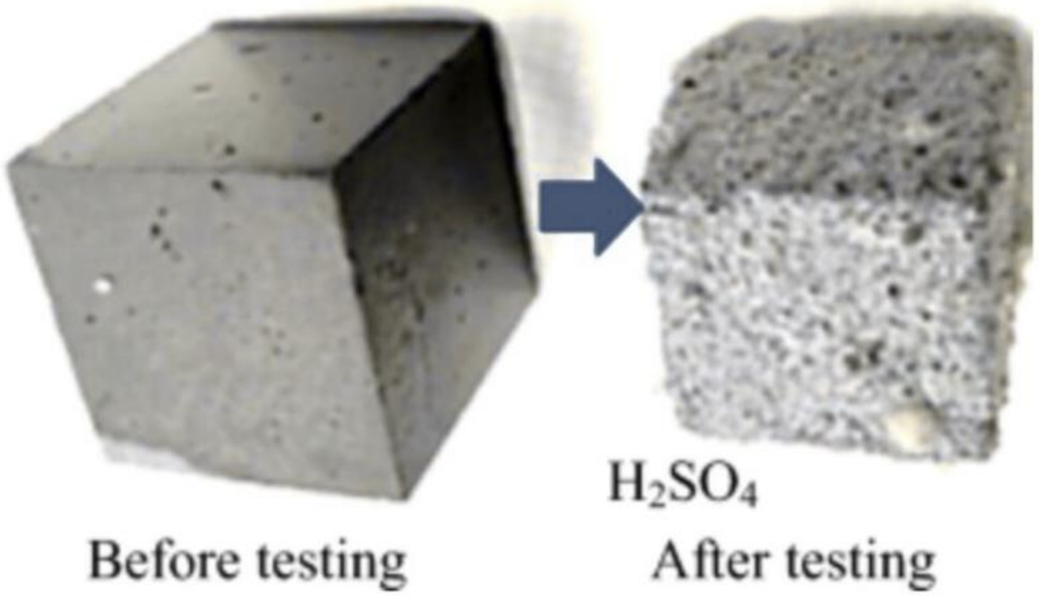
Integrity Threat : H_2S Attack





Integrity Threat : H_2S Attack



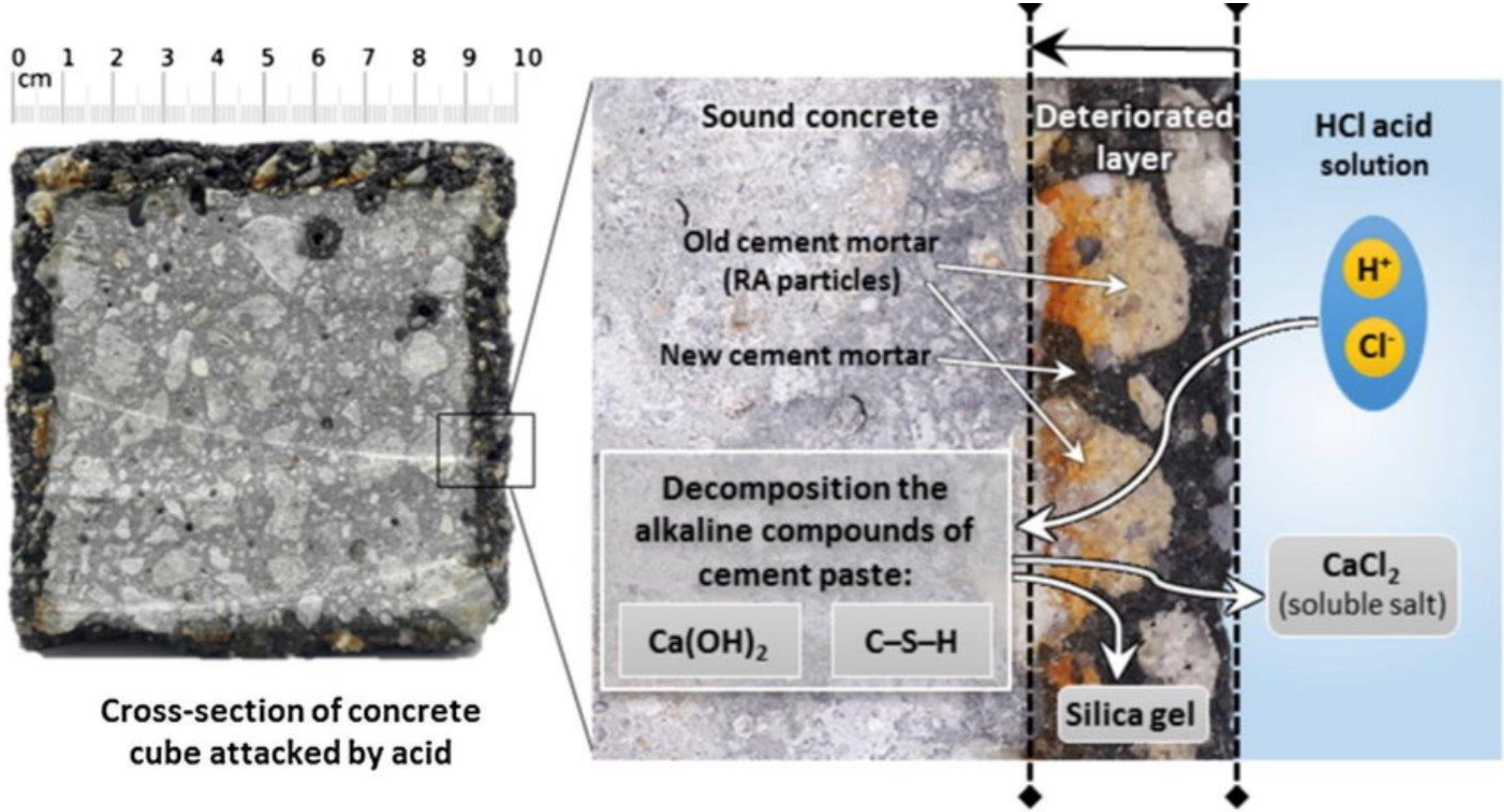


Integrity Threat : HCl Attack

1. $2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O$
2. $CSH + 2HCl \rightarrow SiO_2 . xH_2O$ (gel) $+ CaCl_2$
3. Reaction with Ettringite :

   $C_6A\check{S}_3H_{32} + 12HCl \rightarrow AlCl_3 + CaCl_2 +$ byproducts
4. $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2\uparrow + H_2O$

Integrity Threat : HCl Attack



Cross-section of concrete cube attacked by acid

Integrity Threat : CO_2 and H_2S and HCl Attack

Dissolution:

Loss of $Ca(OH)_2$ reduces alcalinity.

Precipitation:

Formation of secondary minerals such as $CaCO_3$ and CaS.

Structural alterations in high temperature:

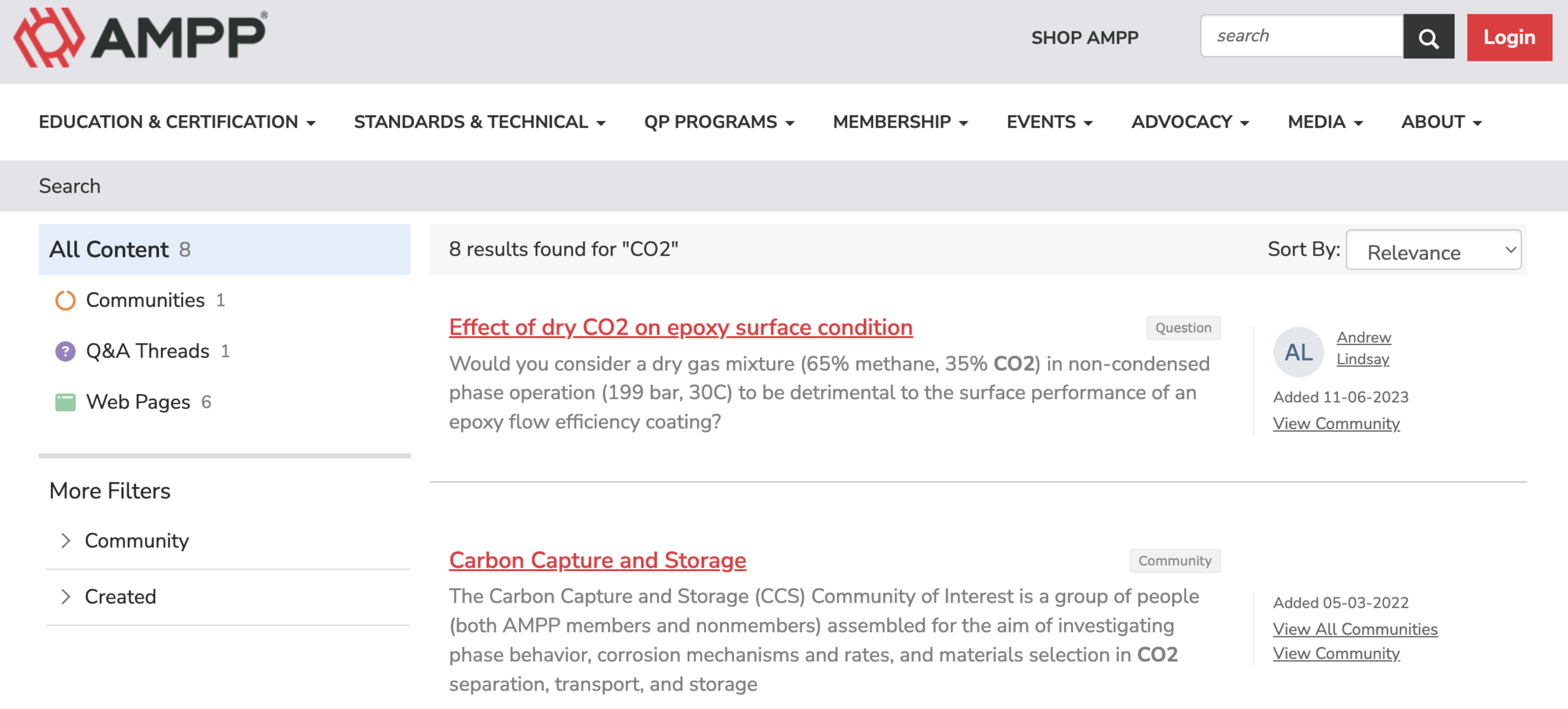
Increase of porosity and micro fissures reduce mechanical resistance.

API testing for CO_2 environments

- There is no API RP protocol for testing cement slurries exposed to CO_2;
- API TR 10TR3 covers, however:
  - General view of CO_2 chemical attack (carbonation process);
  - Discussion of strategies on cement designs exposed to CO_2 environment;
  - Orientation on materials selection (for example, pozzolans, silica, special binding materials);
  - Recommendations and considerations on set cement durability, micro-structure analysis, and required chemical additives.

CO_2 testing (other organizations)

AMPP (Association for Materials Protection and Performance)



CO_2 testing (other organizations)

CSA GROUP

CSA GROUP

Cart (0) › Login / Register › English ⌄ USD ⌄ CSA OnDemand™

Search Products

Browse Catalogue ⌄ Services ›

Home › CSA Group › CSA Z625:16 (R2021)

CODES & STANDARDS - PURCHASE

CSA Z625:16 (R2021)

Well design for petroleum and natural gas industry systems

SKU: 2424656 | Published by CSA Group | Publication Year 2016 | Reaffirmed in 2021 | 48 pages

Product Details

Preface/Scope | Updates

Thanks to the financial contribution of the Western Regulators Forum (WRF), CSA Group is providing the CSA Petroleum and Natural Gas standards in a downloadable PDF format for no fee to Canadian customers only (Click for more detail). If you are not in Canada, please reach out to one of the following licensed CSA Group resellers to purchase these standards or contact your local reseller:

- Accuris: (https://store.accuristech.com/)
- Intertek Inform: (https://www.intertekinform.com/)

Add To Wishlist

©Request Copyright Permissions

Buy	$275.00 USD
Quantity	1 - +

Add To Cart

This product is only available to residents of Canada.

FAQs | Contact Us | Email Product

GST REG No R119441681
QST REG No R1006017360

1.2
This Standard addresses

a) casing, including casing design for various types of wells, including but not limited to horizontal and directional wells;

b) cementing, including cement design and centralization issues and practices; and

c) wellhead, including design, and assembly.

1.3
This Standard does not apply to

a) completion;

b) operations;

c) abandonment;

d) remedial cementing;

e) interventions;

f) suspensions;

g) competencies;

h) management system requirements;

i) drilling operations;

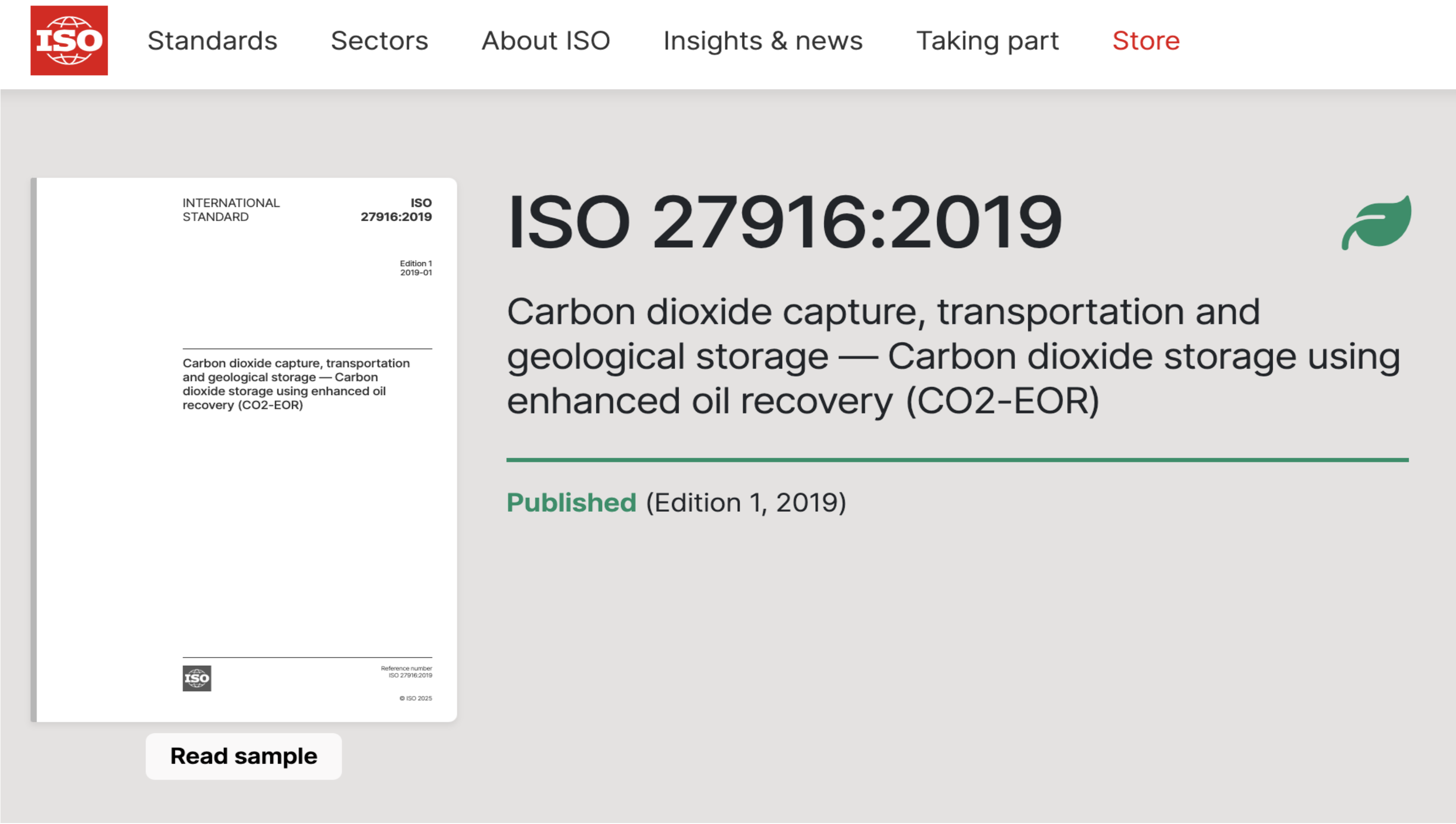
j) emerging technologies;

k) design tools; and

l) offshore and arctic applications.

CO_2 testing (other organizations)

ISO 27916



API testing for H_2S

- There is no API RP or exclusive TR to test cement resistance to H_2S. However, H_2S resistance is indirectly approached through specifications of sulfate resistant cements and general cement testing protocols.

- Service companies, operators and research institutions lean on:
  - Exposure tests in autoclave machines with H_2S rich gas mixtures;
  - Long immersion of set cement in sulfide brines;
  - Petrographic analysis, SEM and XRD of set cement degration;
  - Strength and permeability testing after exposure to H_2S / sulfate brines;
  - Special binding materials (for exemple: pozzolanic mixtures, Classe G + silica fume, latex modified systems…)

API Specifications - Sulfate Resistance

- API cement graduation in respect to sulfate resistance:
  - O (ordinary)
  - MSR (moderate sulfate resistance to SO_4)
  - HSR (high sulfate resistance)

H_2SO_4 testing (other organizations)

ASTM C1898-20

- Standard Test Methods For Determining The Chemical Resistance Of Concrete Products To Acid Attack
  - These test methods are intended to evaluate the chemical resistance of cement paste, mortar and concrete materials. This method is loosely based on Test Methods C267, however the solution is more rigorously defined and flexural strength is used. These test methods provide for the determination of changes in the following properties of the test specimens and test medium after exposure of the specimens to the medium:
    - Mass of specimen
    - Appearance of specimen,
    - Appearance of test medium, and
    - Strength of specimens.

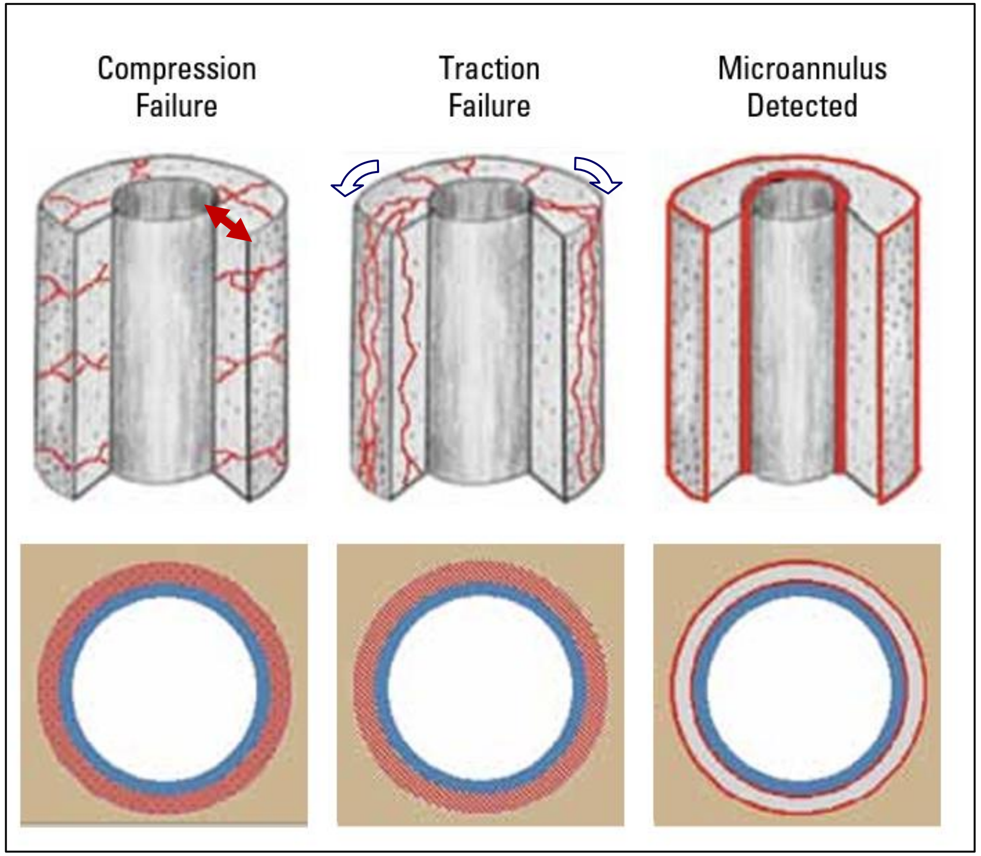

Designation: C1898 – 20

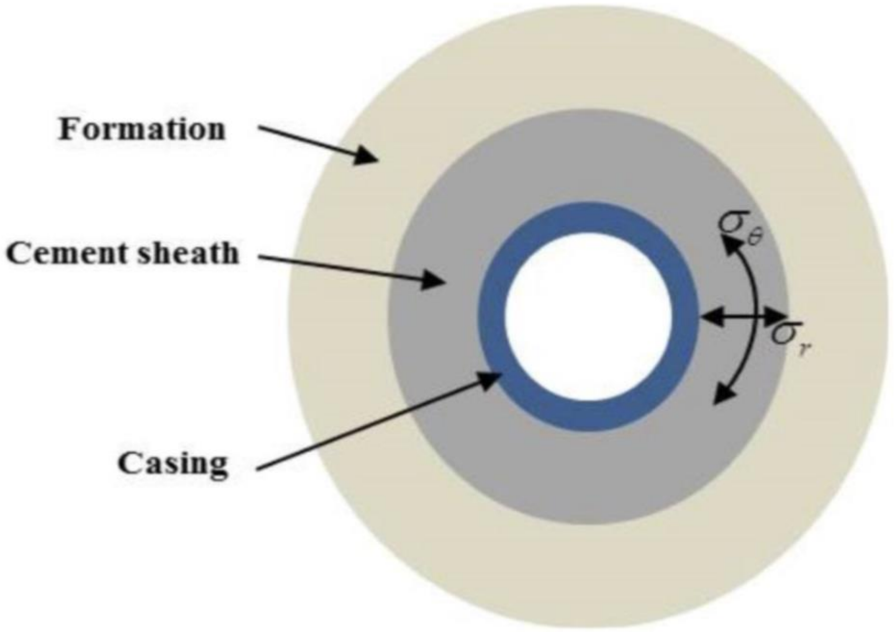
Standard Test Methods for
Determining the Chemical Resistance of Concrete Products
to Acid Attack[1]

Integrity Threat : Mechanical Failure

- Effects: Microcracks, debonding, microannulus
- Solutions: Flexible/self-healing cement, FEM analysis

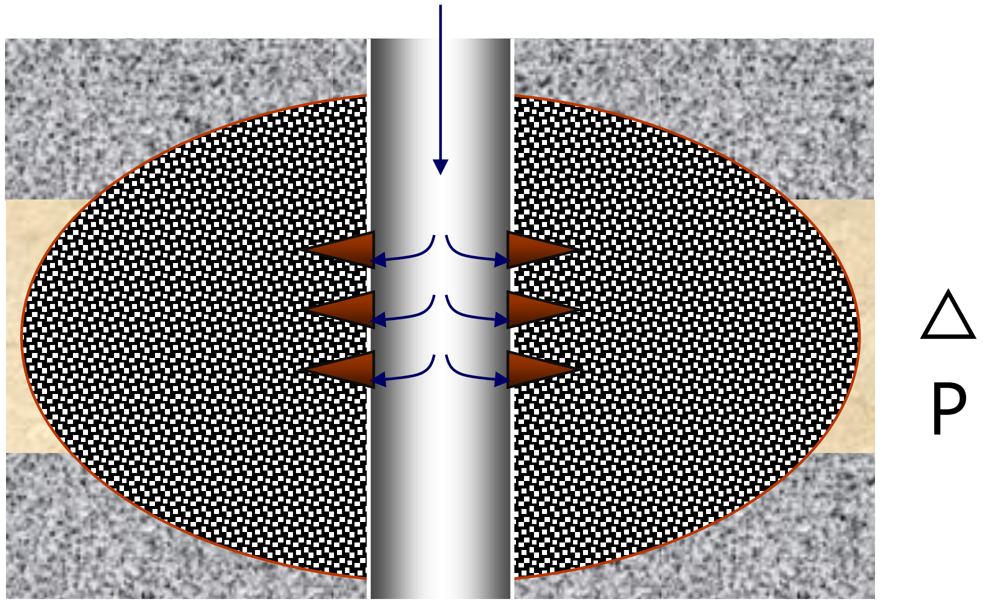
Integrity Threat : Mechanical Failure



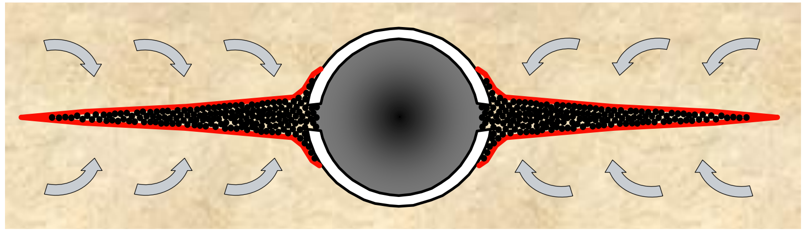


Integrity Threat : Mechanical Failure by Fracturing

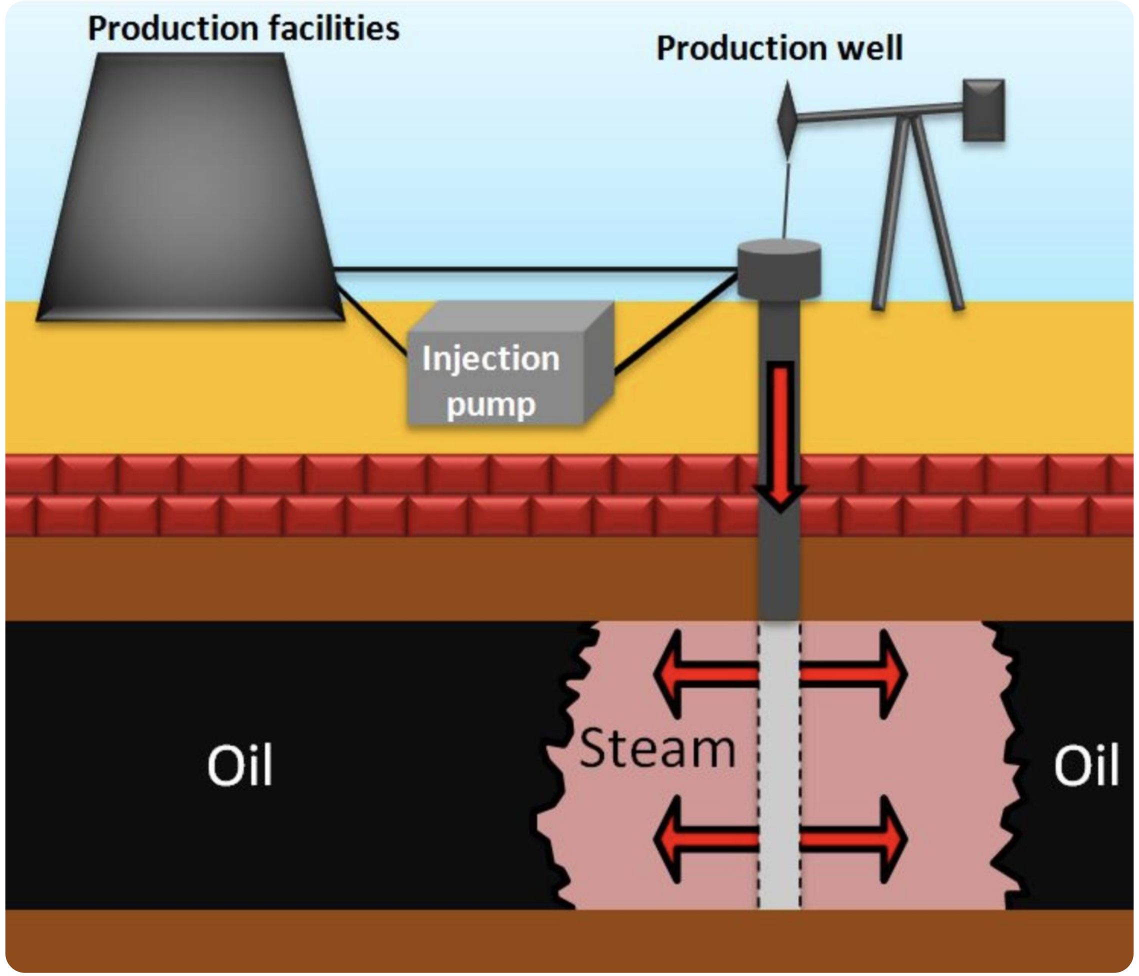
- High rate and high pressure pumping, injecting frac fluids into the formation, creating fractures...
- After the fractures are created, sustaining agents, also called proppants, are pumped in...
- The fracture is filled in by proppants, at the end of the pumping, in order to keep it open and to facilitate fluids from the reservoir to the well.



Pressure Cycling

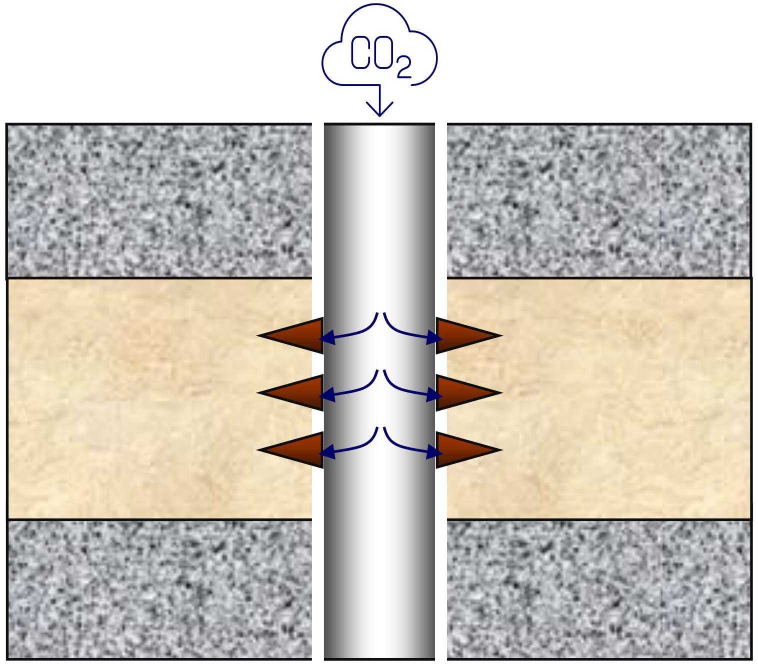


Integrity Threat : Mechanical Failure By Steam Injection



△T

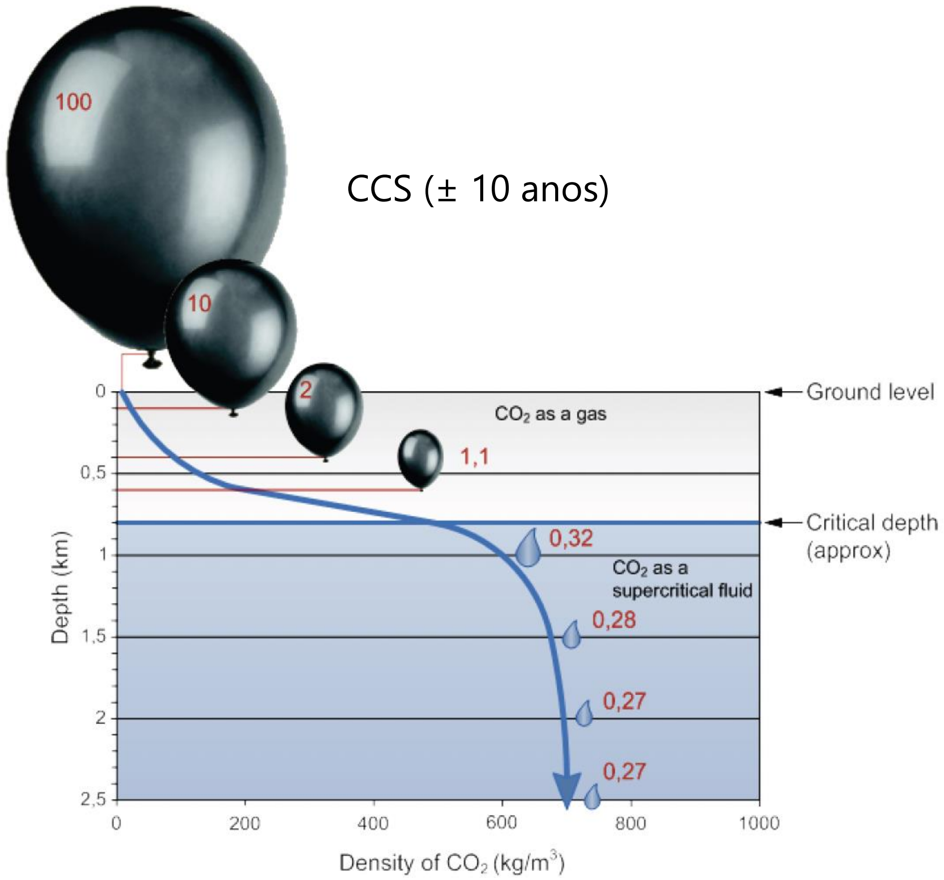
Integrity Threat : Mechanical Failure By CO_2 Injection

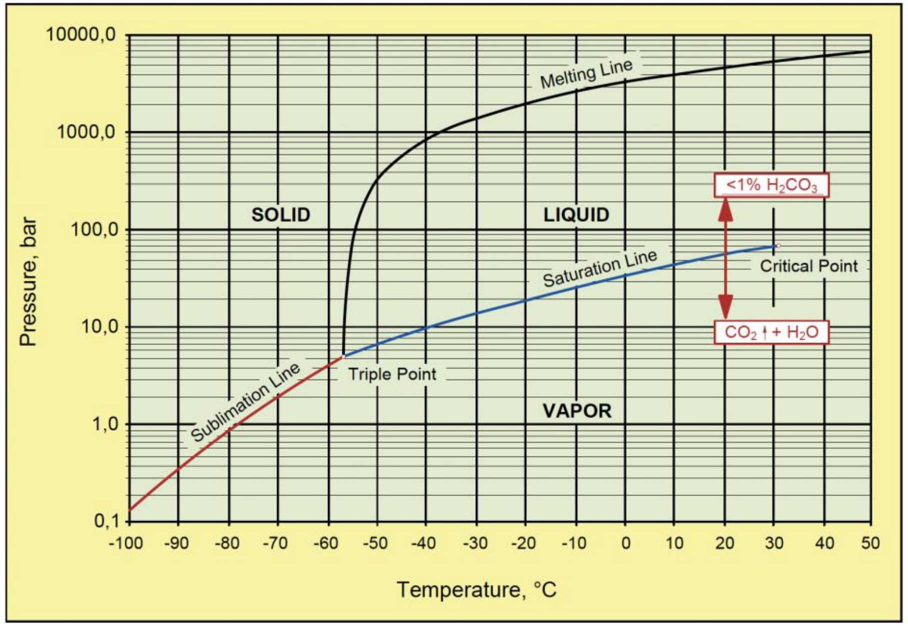


- CO_2 injection is a proven EOR technique (± 45 years);
- Injected CO_2 reduces oil viscosity and interfacial tension;
- Under high pressure, CO_2 becomes miscible with oil, improving recovery;
- It helps to keep reservoir pressure and improves oil sweep efficiency;
- Recovery increases by 10 to 20% or more in comparison with water injection;
- Captured industrial CO_2 can be reutilized, contributing to carbon management;
- Importance to set cement: wells should keep integrity when exposed to CO_2.

Integrity Threat : Mechanical Failure By CO_2 Injection

CCS (± 10 anos)

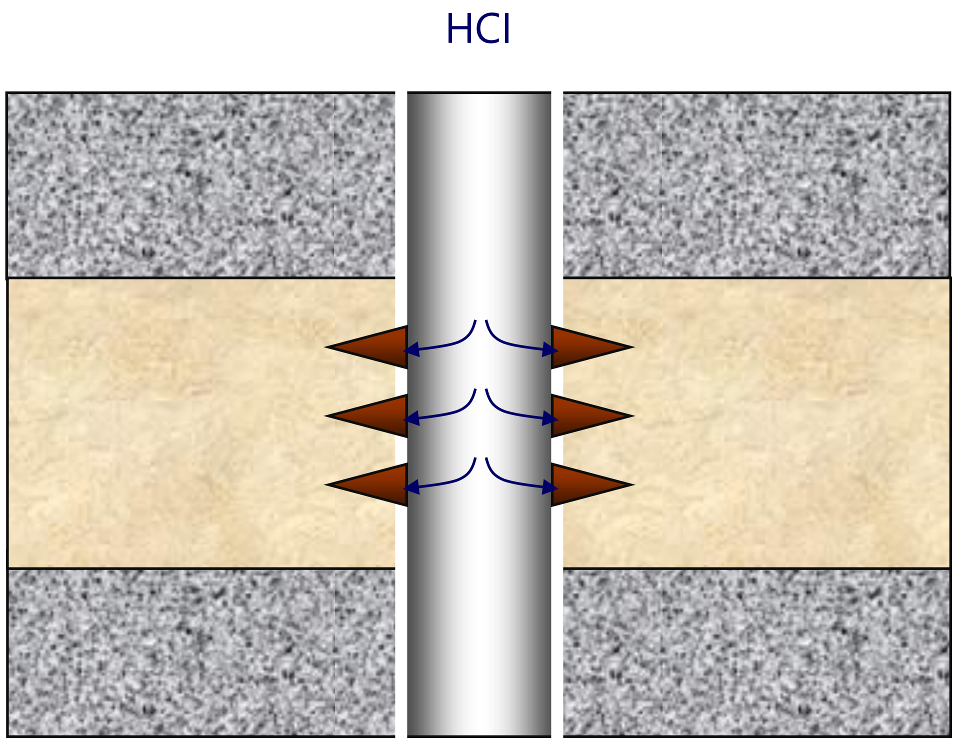




IEA, 2008

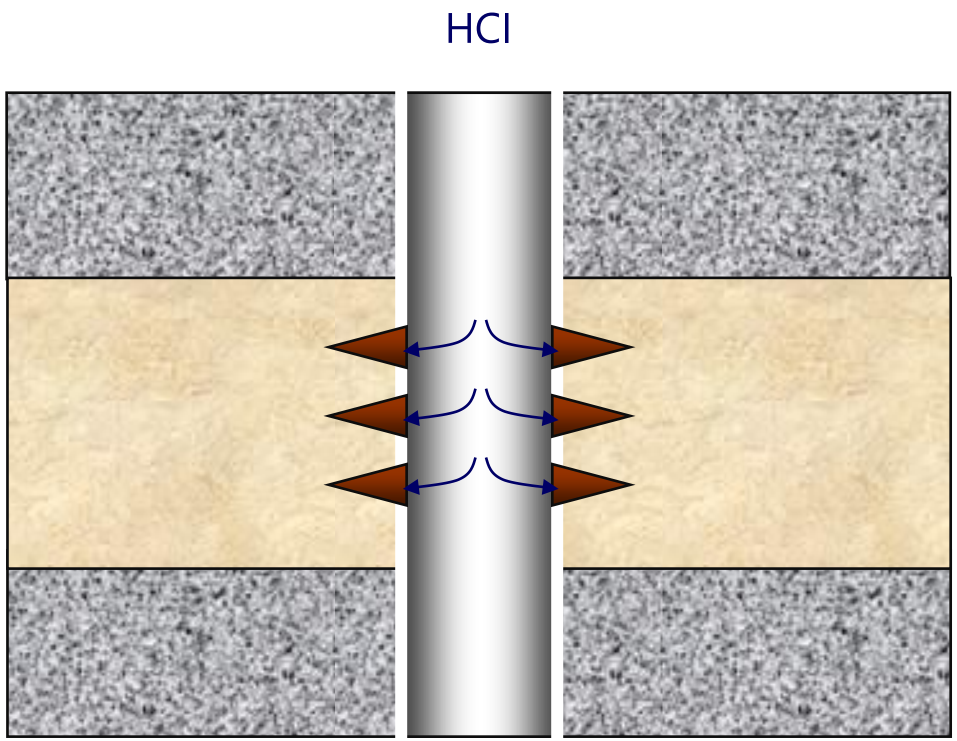
Integrity Threat : Mechanical Failure By Stimulation

- Acid stimulation fluids, especially hydrochloric acid (HCl), can cause serious damage to set cement if they come into contact with it. Here's what happens:
  - Dissolution of Cement Phases
    - HCl aggressively reacts with $Ca(OH)_2$ and other cement hydrates, such as calcium silicate hydrate (C–S–H), which are key to the strength of set cement.
    - This leads to decalcification, weakening the cement structure.
  - Increase in Porosity and Permeability
    - As acid dissolves cement compounds, it opens up the cement matrix, increasing porosity and permeability.
    - This compromises the sealing capability of the cement, potentially allowing fluid migration along the annulus.



Integrity Threat : Mechanical Failure By Stimulation

- Strength Loss
  - Progressive acid attack leads to loss of compressive strength, making the cement sheath unable to withstand pressure or mechanical loads.
- Zonal Isolation Failure
  - Damaged cement can lead to zonal isolation failure, resulting in crossflow between formation layers, gas migration, or sustained casing pressure (SCP).
- Risk of Well Integrity Compromise
  - In severe cases, acid-induced degradation of cement jeopardizes overall well integrity, requiring expensive remediation or re-cementing.



Integrity Threat : Early Gas Migration

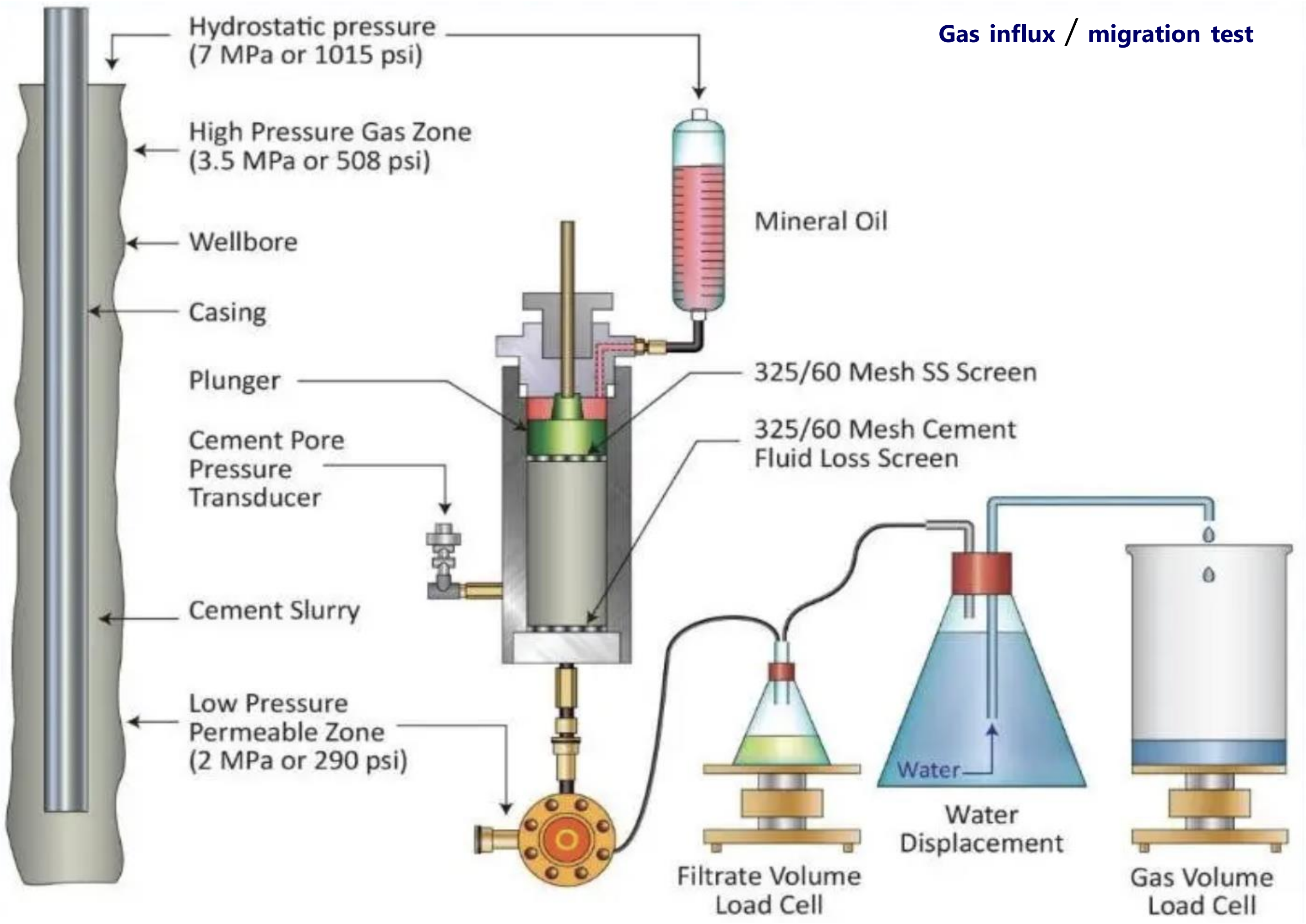
- Tests: Static gel strength, thixotropy behavior
- Design: Accelerators, latex, foam, proper centralization

Foam Cement

ouronova

Integrity Threat : Early Gas Migration

Static Gel Strength Analyzer



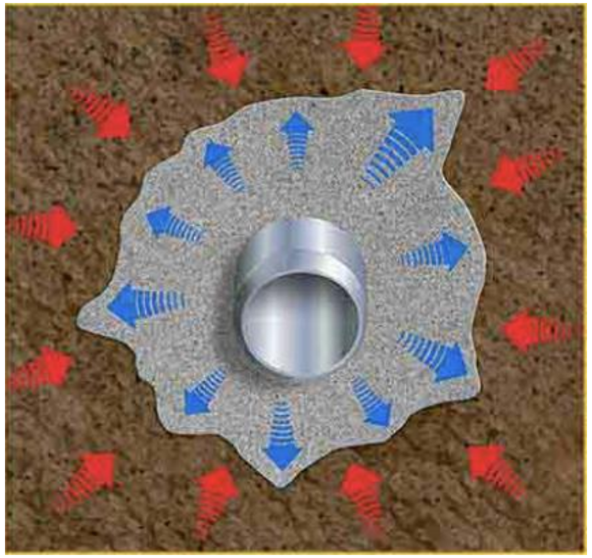
Integrity Threat : Cement Design

- Poorly designed cement jobs may lead to catastrophic failures on well integrity
- Mitigation: the use of simulators, adequate cement systems and mud removal techniques, tailored to well conditions

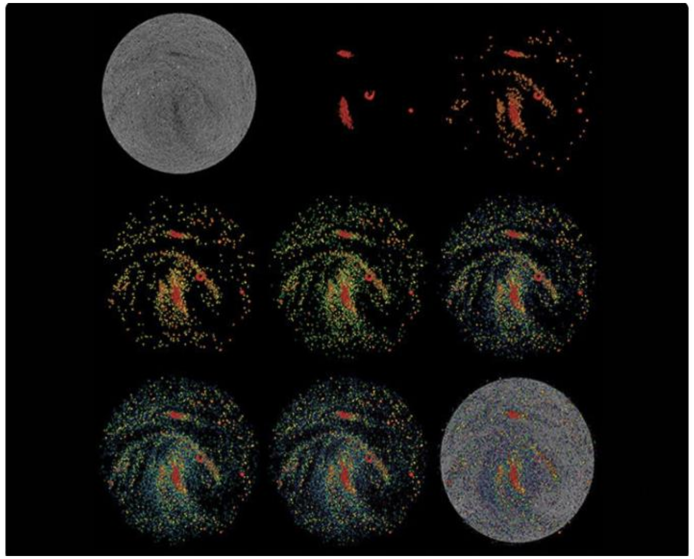
Cement Design

- Expandable systems
- Lightweight/foamed cements
- Self-healing additives
- Compatibility with formations (salt, shale, fractured zones)
- Environmental stewardship (bio-based additives, recycled byproducts, and low-carbon cement alternatives)

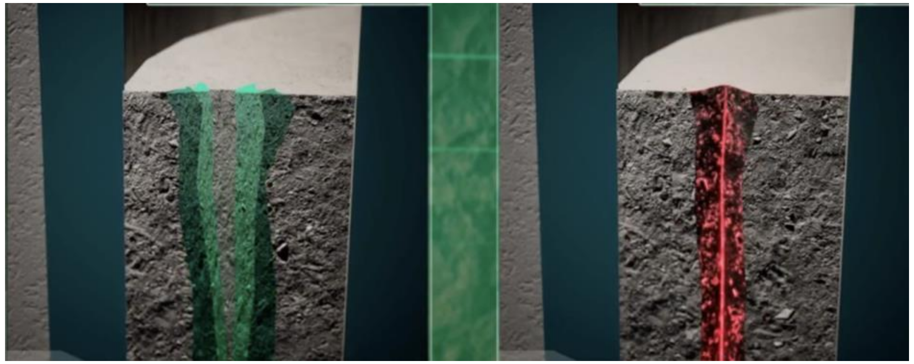
Cement Design



Flexible Cement



Foamed Cement

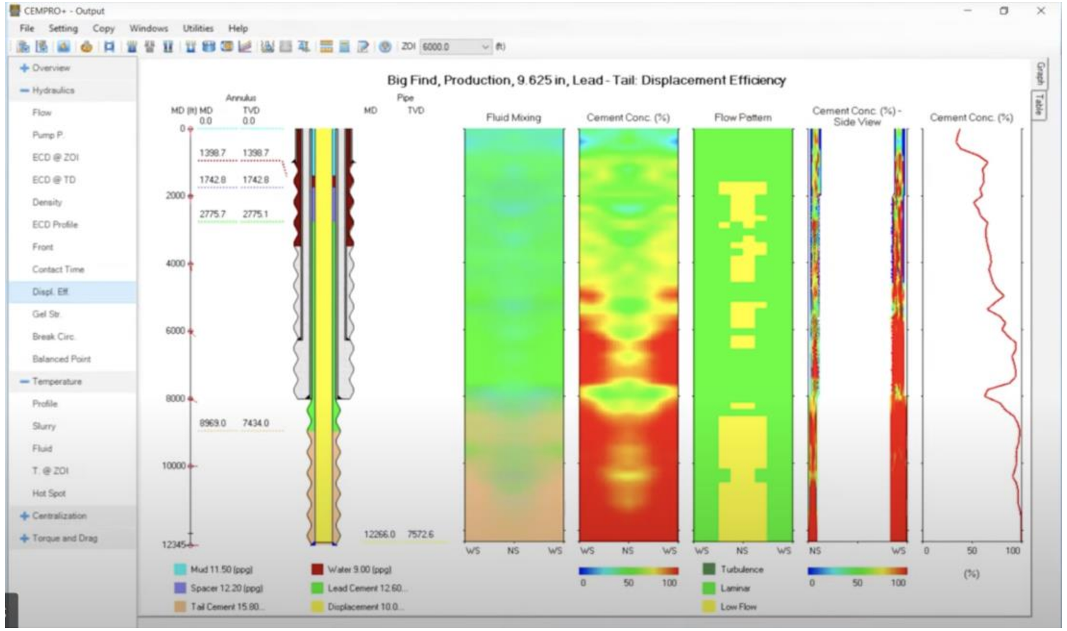


Self-healing Cement

ouronova

Cement Design Simulators

- Sources:
  - Service companies;
  - Independent specialized software companies.



Cement Design

Composition of high-density cement slurries. Unit wt. %.

180º C

Material which replaces Portland cement, helping compaction

Density (kg/m³)	Cement	Wanter	Fluid Loss Reducer	Retarder	Dispersant	Slica Fume (Mesh)	Weighting Agent (Mn)	Slag	Resin
2.0	100	41	7	2.5	2	35	16	20	8
2.1	100	42	7	2.5	3	35	32	18	8
2.2	100	44	6	2.2	4	35	52	18	8
2.3	100	45	6	2	4.5	35	79	16	10

100 mesh: 150μ m ; 300 mesh: 48μm

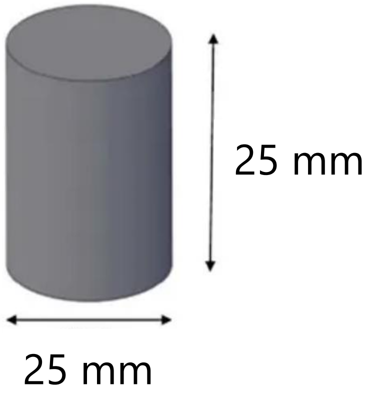
Added material which in high temperatures, reacts with cement hydrated silicates to generate tobermorite and xonotlite, reducing the ratio of C/S from 2 to 3:1 to approximately 1:1

Material which protects cement matrix, mitigating corrosion

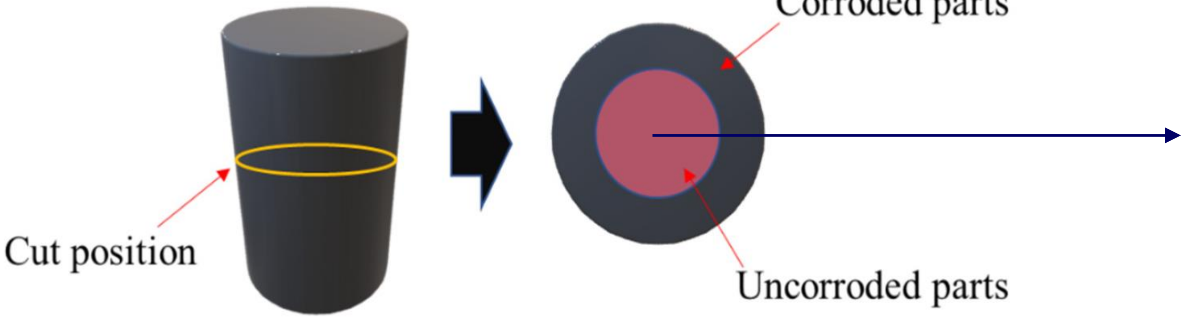
ouronova

Cement Design

30 Mpa = 4.350 psi
180ºC

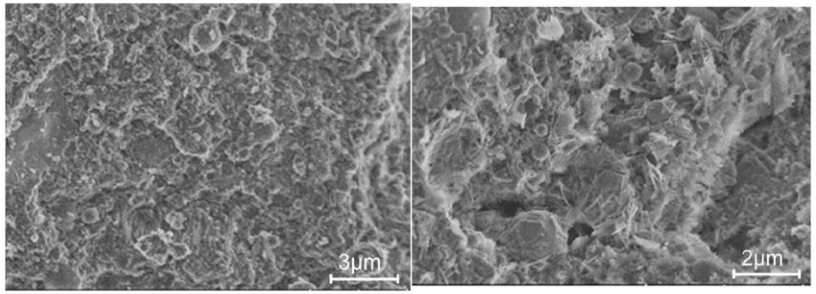


The cement cylinders were retrieved after 7 and 30 days for evaluation



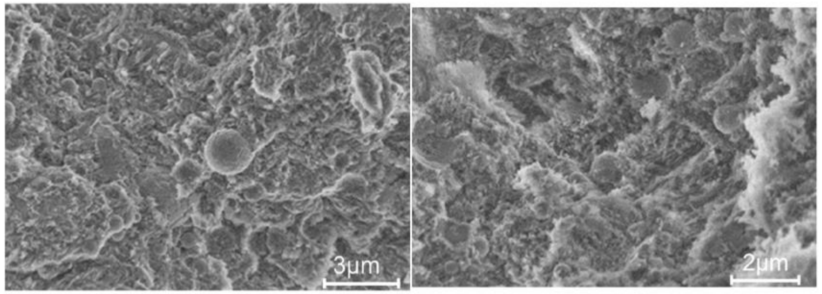
Most integral part = alcaline region (presence of Ca), indicated by phenolphetalein coloration (red)

Cement Design



(a) (b)

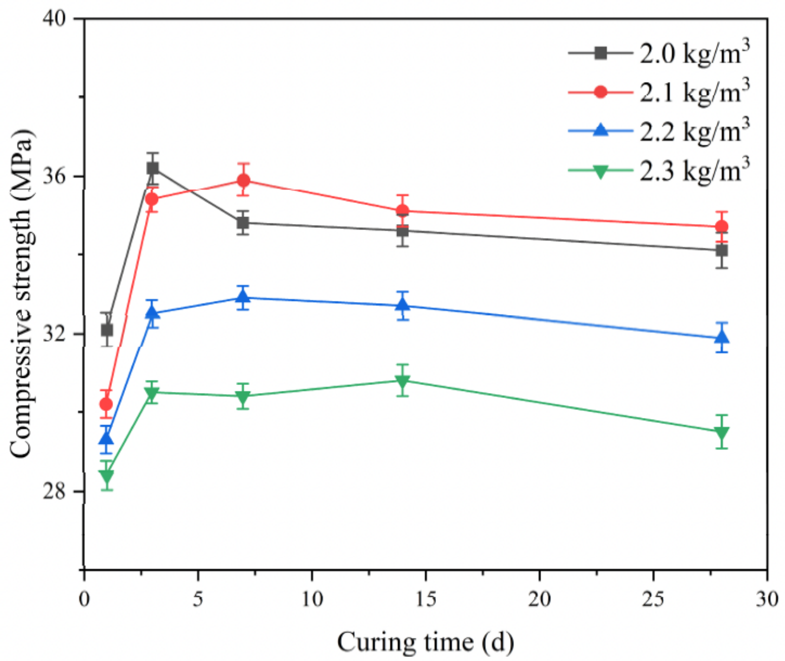
Figure 13. Morphology of 2.0 kg/m^3 cement sample: (**a**) non-corroded; (**b**) corroded.

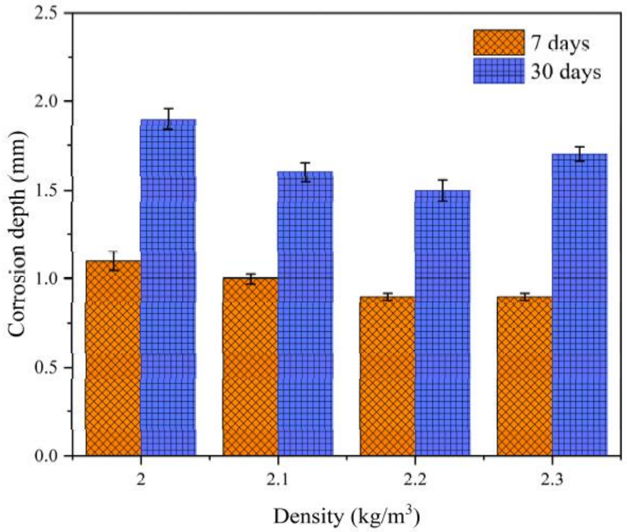


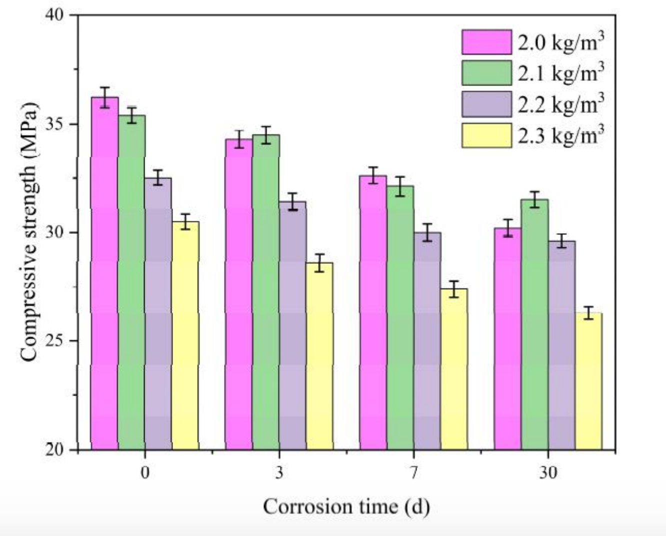
(a) (b)

Figure 14. Morphology of 2.3 kg/m^3 cement sample: (**a**) non-corroded; (**b**) corroded.

Cement Design



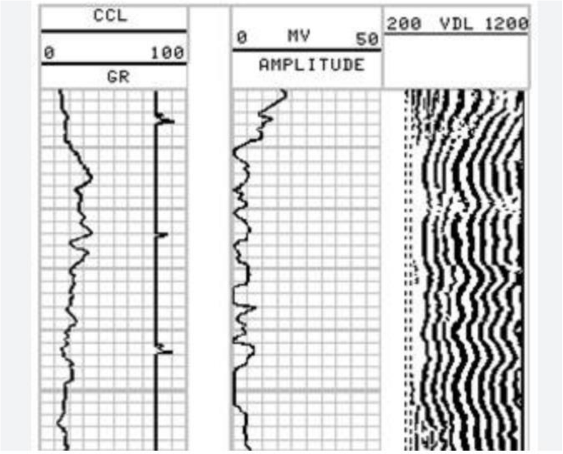




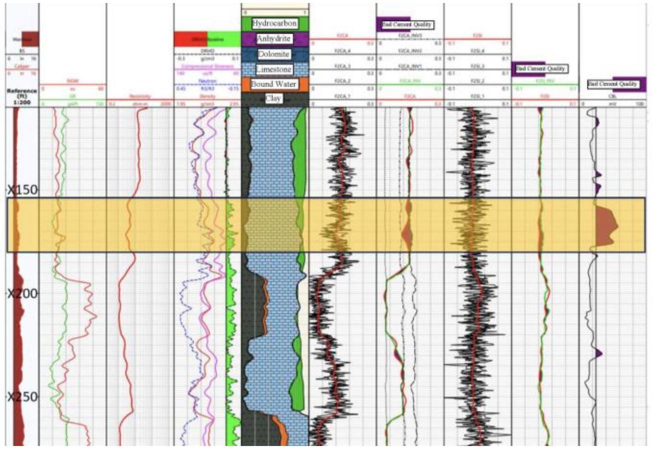
Cement Evaluation Tools Overview

- CBL (Cement Bond Log)
- Ultrasonic (USIT / Isolation Scanner)
- Pulsed Neutron Logs (PNL)
- Fiber Optics (DAS/DTS)
- Temperature & Pressure Surveys

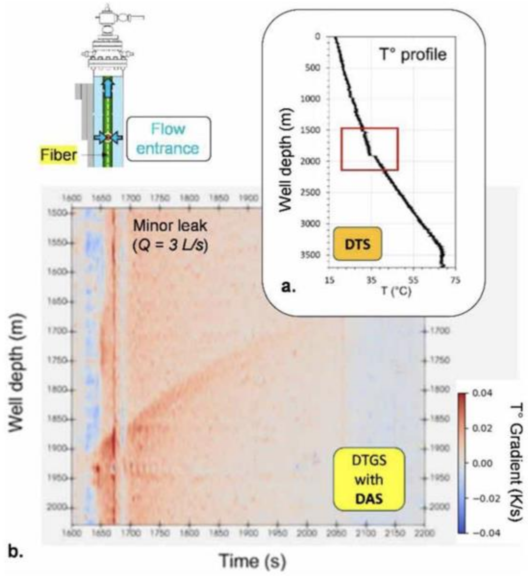
Cement Evaluation Tools Overview



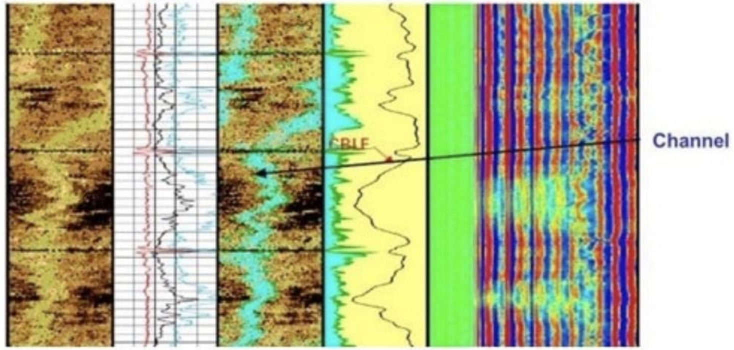
CBL & VDL



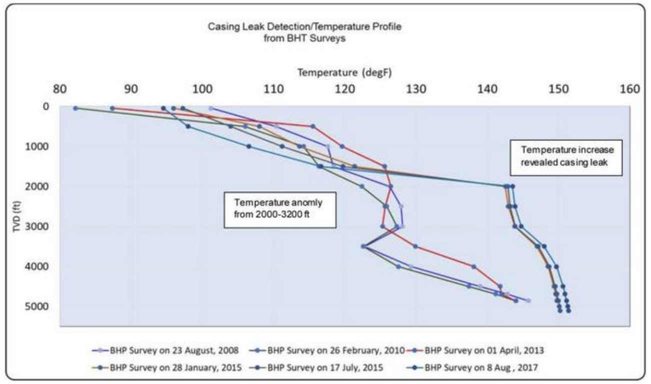
Pulse Neutron Logs



Fiber Optics Sensing



USIT



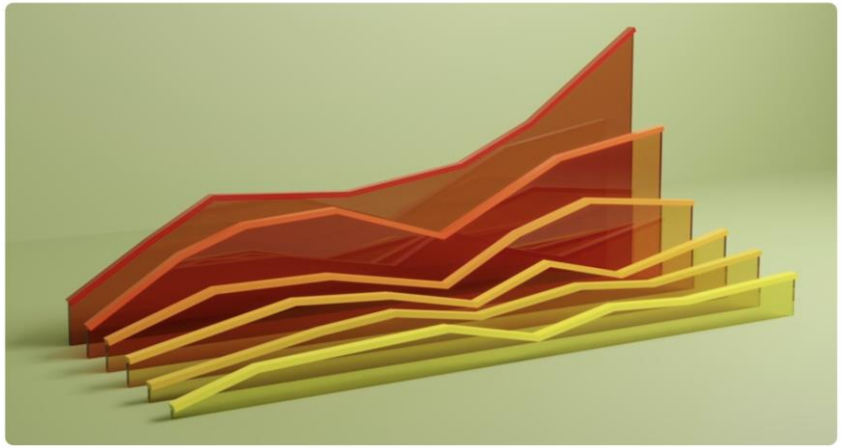
Pressure & Temperature Sureveys

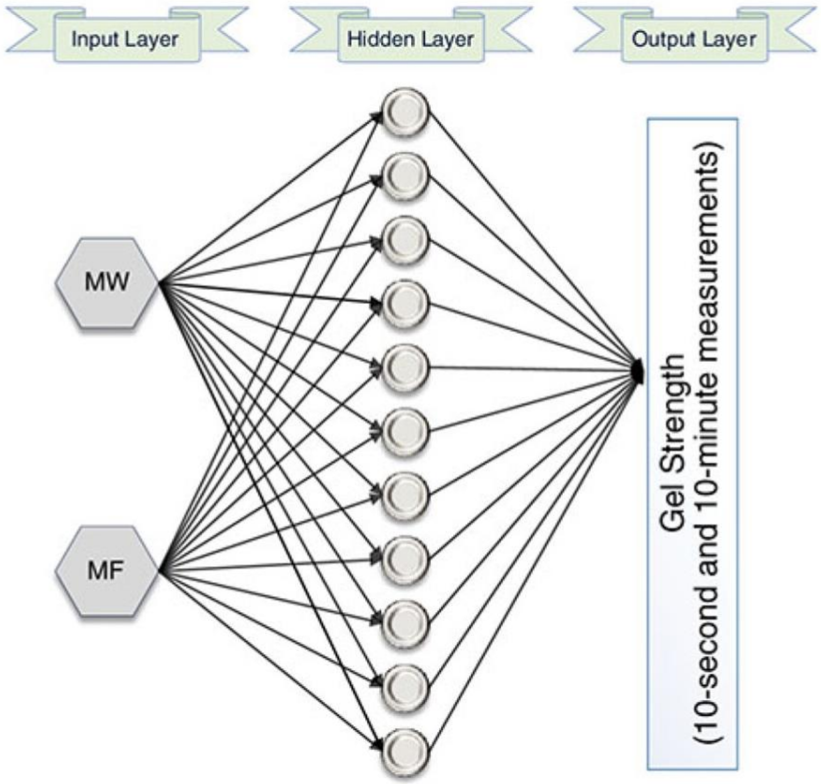
Tool Comparison Table

Tool	Detect Bond?	Good for Light Cement?	Notes
CBL	Yes	No	Good for hard cement
VDL	Yes (waveform)	No	Qualitative only
USIT	Yes	Yes	Good for gas zones
PNL	Indirectly	Yes	Requires base log
DAS	Yes (fluid flow)	Yes	Real time detection

Cement Integrity Monitoring Trends

- Machine learning prediction of isolation failure
- Smart cements (sensing materials, self-healing)
- Permanent downhole sensors





Integration Strategy

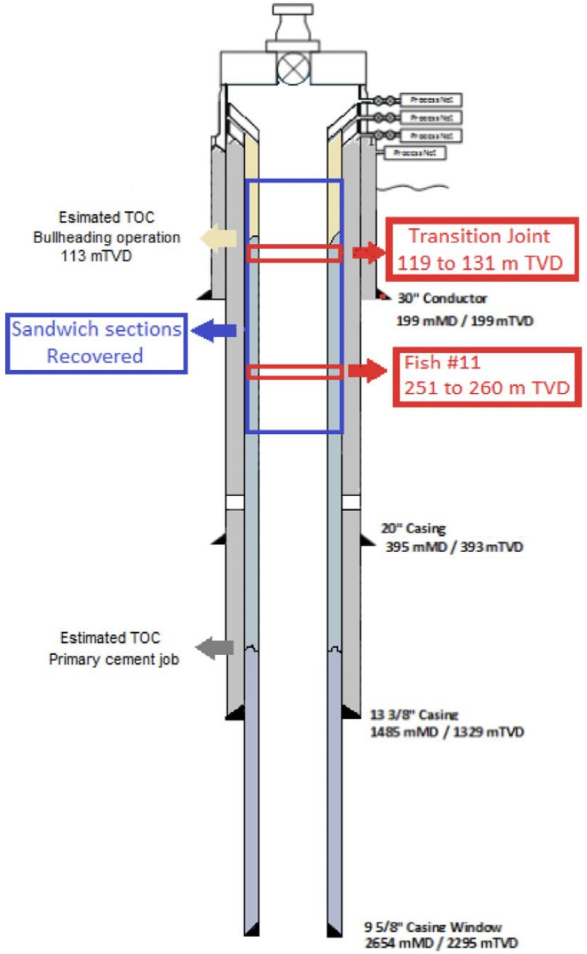
- Early Evaluation (while rig is on site)
- Long-Term Surveillance (DTS, casing pressure)
- Life-cycle Integrity Plan

Final Thoughts

- Evaluation must match design and environment
- Digital tools and smart cements are the future

Thank You!

Investigation of well integrity of a 33 years old offshore well in Norway



69 m water depth

Well design showing the location of sections. In purple the twenty three recovered sections and in red the two sections, our object of study.

Investigation of well integrity of a 33 years old offshore well in Norway

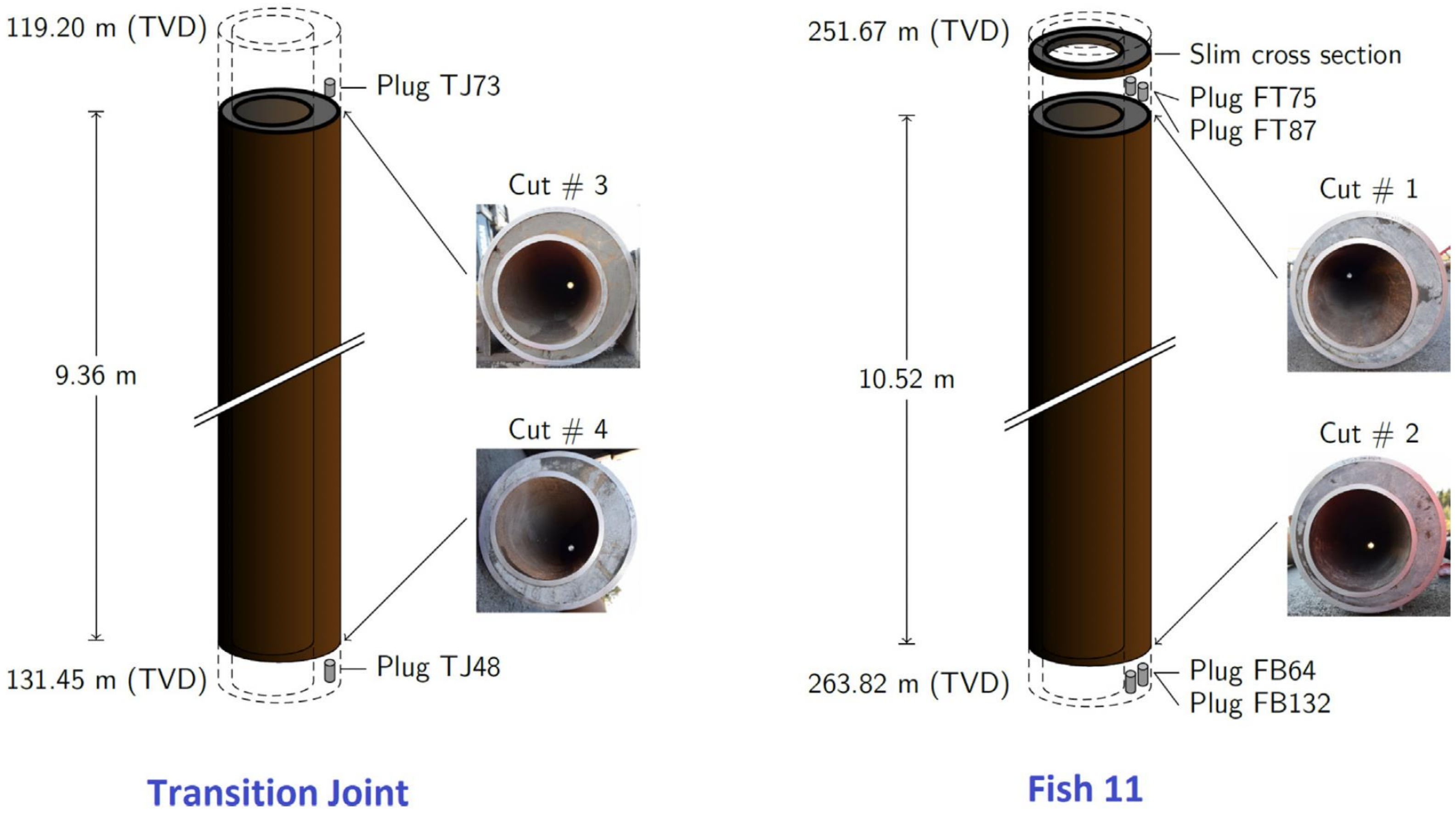


Fig. 2. Transition Joint and Fish # 11 diagram including pictures of the ends (Bottom and Top).

Investigation of well integrity of a 33 years old offshore well in Norway

Table 1 – Sandwich sections under study

	Transition Joint	Fish # 11
Well depth (m)	119.2-131-5	251.7-263.8
Final length (m)	9.36	10.56
Min. Sand off (m)	0.01057	0.01250
Max. Eccentricity %	70	64

Shallow depth (low temperature)

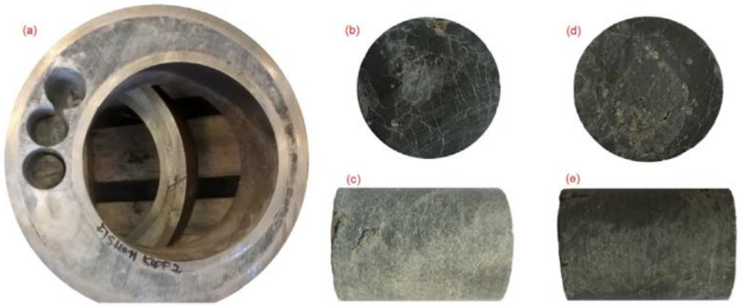


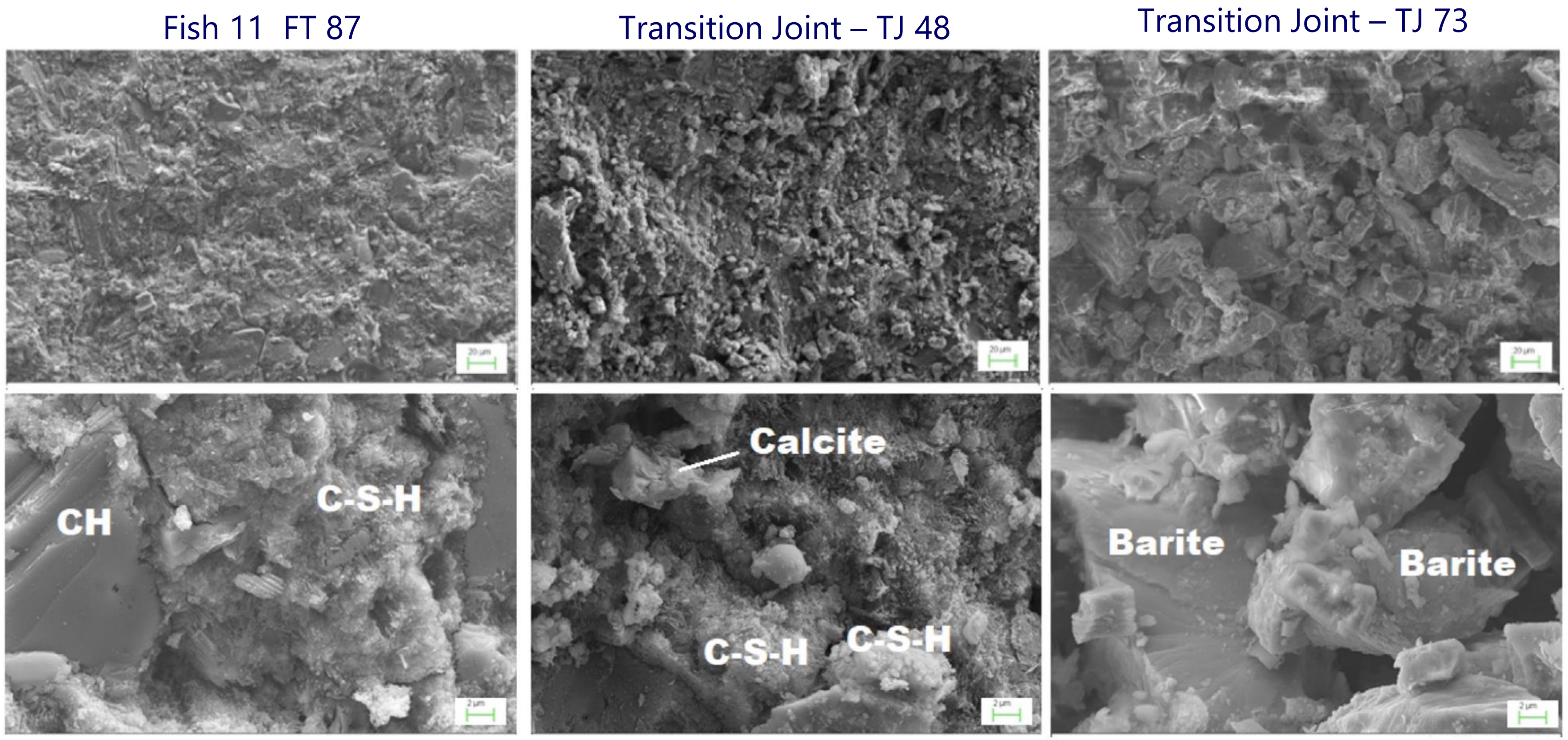
Fig. 3. Core plugs obtained from Fish 11 (Bottom). (a) Drilling of core plugs, (b) FB 64 top view, (c) FB 64 lateral view, (d) FB 132 top view and (e) FB 132 lateral view.

Investigation of well integrity of a 33 years old offshore well in Norway

Selection name	Core Plug	Petrophysical Properties			Mechanical Properties		Compositional Analysis		
		Porosity	Permeability	CT scan	E	UCS	SEM-EDS	XRF	XRD
Transition Joint	TJ48 TJ73	✓ ✓	✓ ✓	✓ ✓	✓	✓	✓ ✓	✓ ✓	✓
Fish# 11	FT 75 FT87 FB 64 FB132	✓ ✓ ✓ ✓	✓ ✓ ✓ ✓	✓ ✓ ✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓ ✓	✓ ✓

CT: Computer Tomography Scanning | **E:** Young's Modulus | **UCS:** Uniaxial compressive strength | **SEM:** Scanning electron microscopy | **EDS:** Energy dispersive spectroscopy | **XRF:** X-ray Fluorescence | **XRD:** X-ray Diffraction.

Investigation of well integrity of a 33 years old offshore well in Norway



Comparison of SEM Images at magnifications 1.0 kX (upper panels) and 10.0 kX (lower panels) for material extracted from FT87, TJ47 and TJ 73 core plugs.

we are on it

www.ouronova.com