Cement-Free GGBS Binders and Concrete for Green Construction

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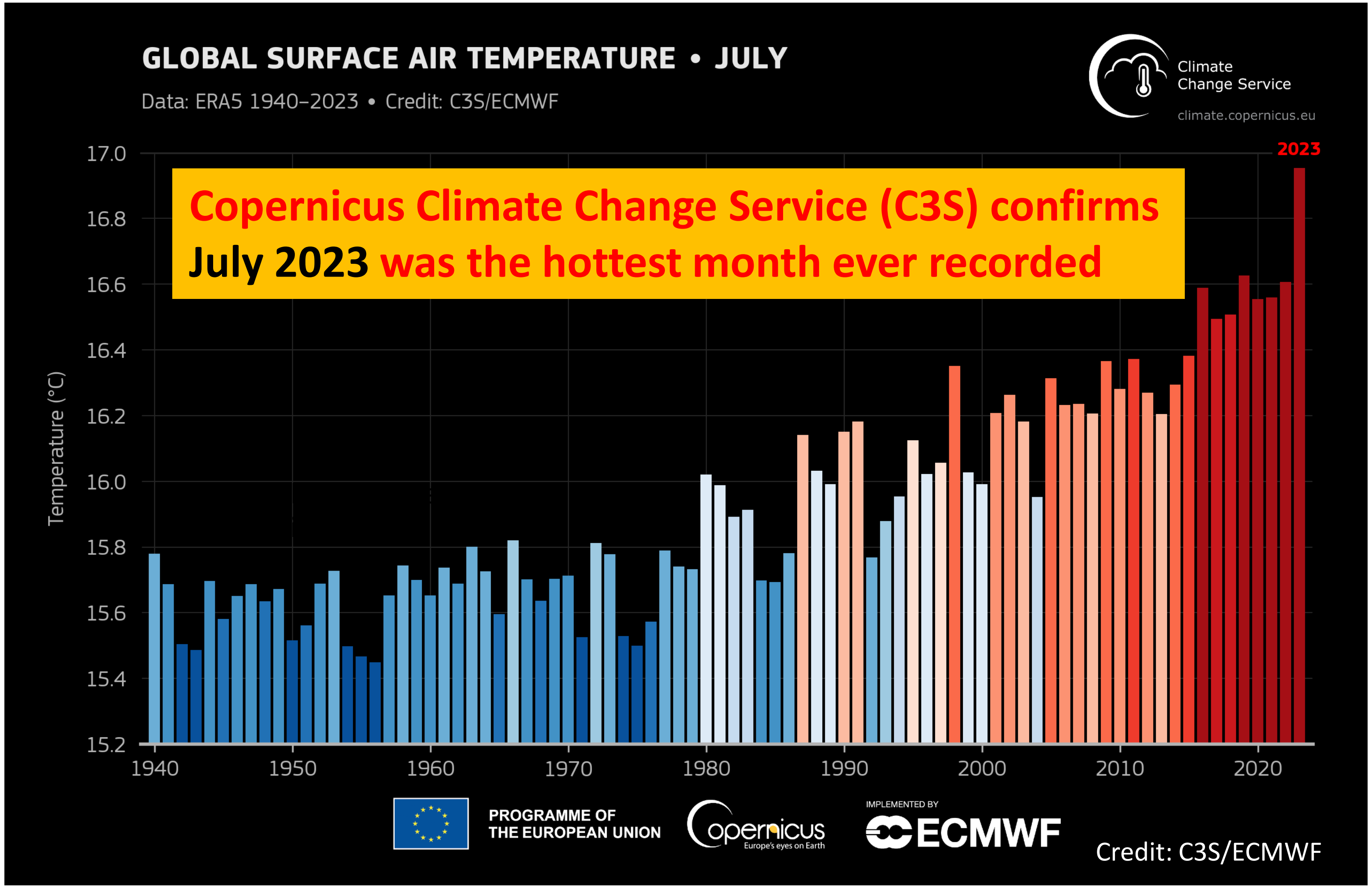
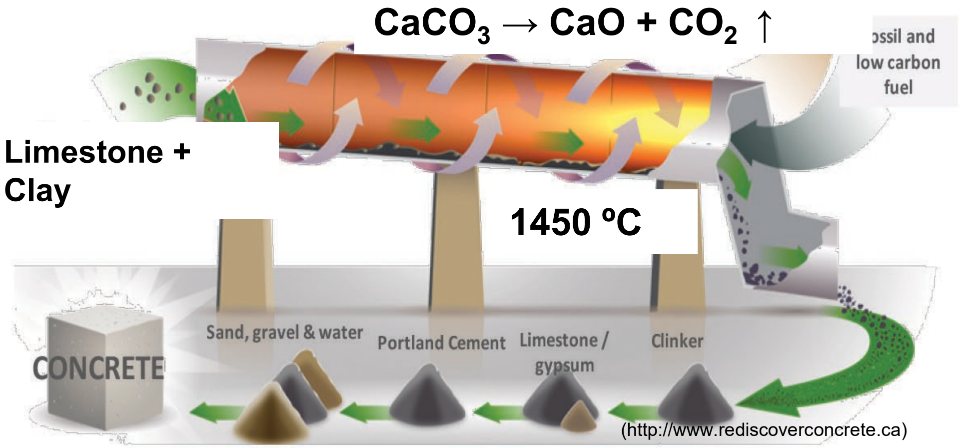
Cement and concrete production is one of the major contributors to climate change



7% of man-made CO_2 emissions



1 ton cement → 0.85 ton CO_2

The urgent demand for Low-Carbon Concrete that meets the sustainability requirements of civil infrastructure

Accelerating hydration of GGBS binder using solid activators for general application

GGBS

Ordinary Portland Cement

Liquid activator

Solid activator

Two-part Cement-free GGBS

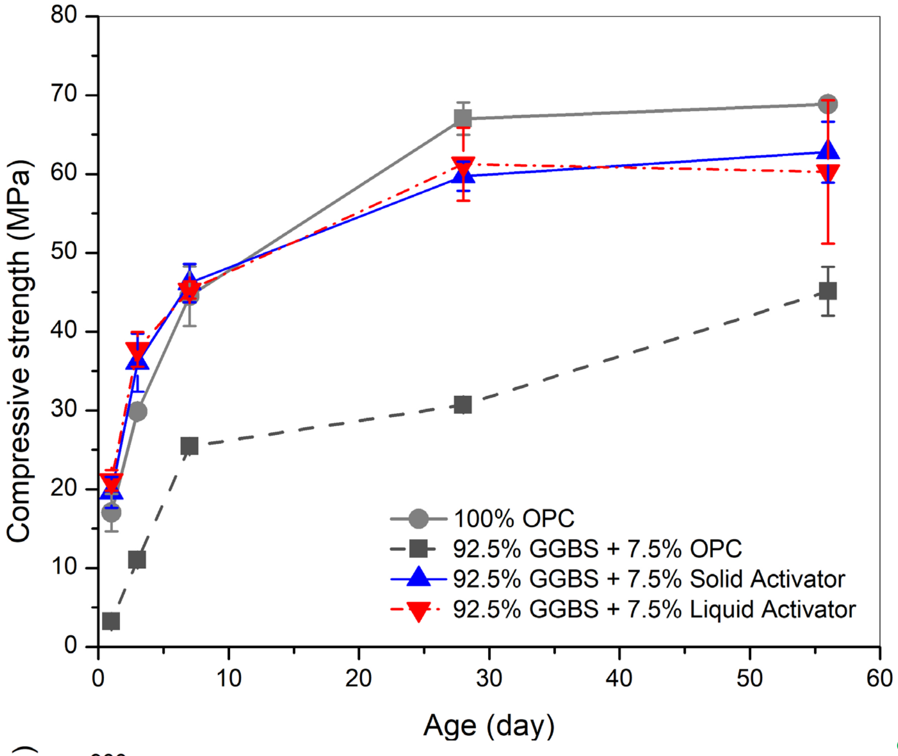
- User unfriendly
- Corrosive solutions
- Liquids are susceptible to carbon dioxide

Blended GGBS cement

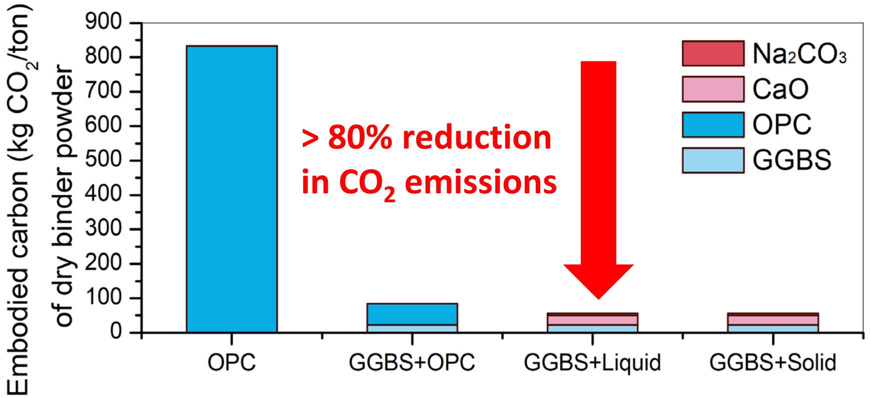
- Lower early compressive strength

One-part Cement-free GGBS

- User friendly
- Promising for in-situ applications



Significantly accelerated strength development



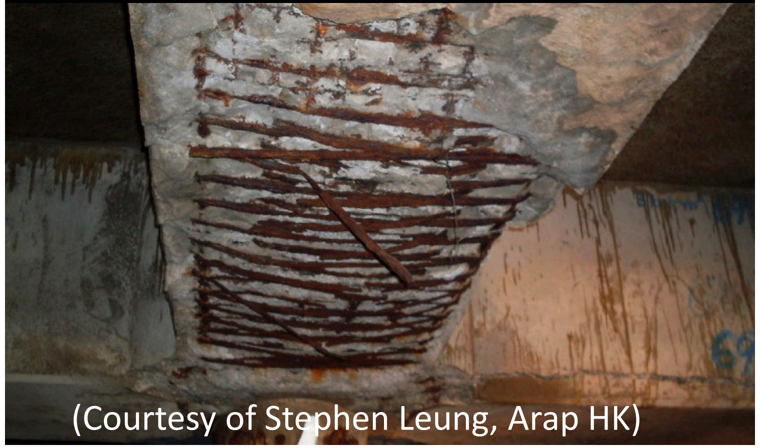
Solid activator is formulated using low-carbon materials (e.g., sodium carbonate, recycled cement fines)

Application in the construction sector: standards are essential

- **British Standards Institute (BSI) Publicly Available Specification PAS 8820:2016**
  - Performance-based – comparison to PC concretes of known good performance
- **China Standards JGJ/T 439-2018**
  - Technical standard for application of alkali-activated slag concrete (城礦渣混凝土應用技術標準)
- **American Society of Testing Materials (ASTM) work item ASTM WK86609**
  - New Specification for Standard Performance Specification for Alkali-Activated Cementitious Materials

Pros of Alkali-Activated GGBS Concrete: High durability and stability under extreme working environments

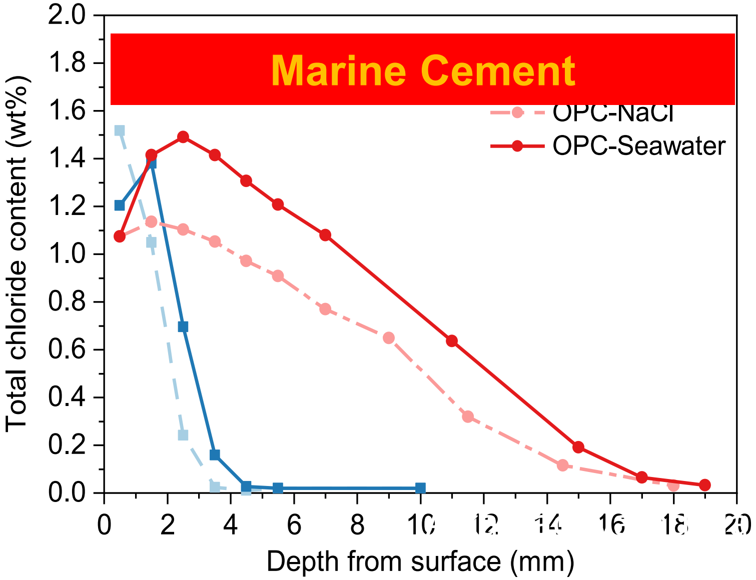
Marine Environment


(Courtesy of Stephen Leung, Arap HK)

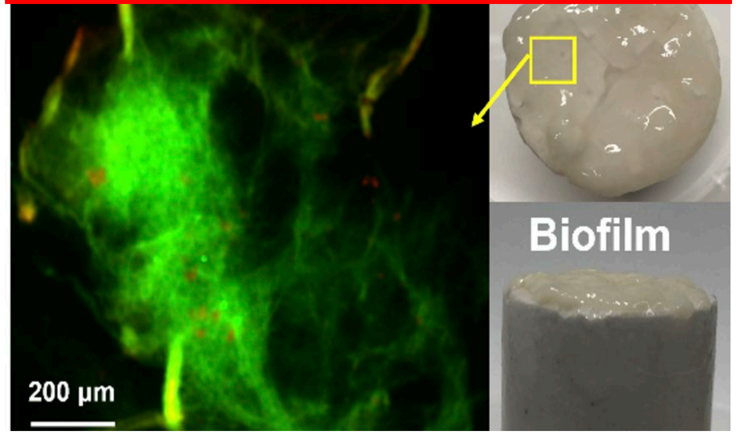
Sewer Environment

Other General and Special Application of GGBS materials

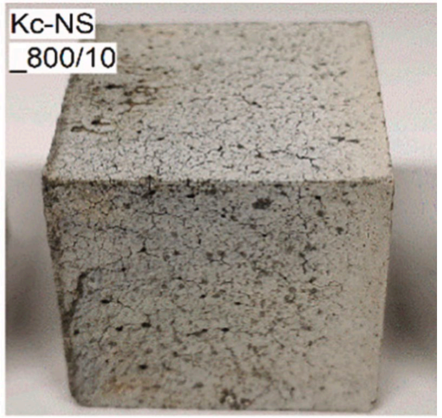
Marine Cement



Biochemical-Resistant Cement



Fire resistant High-Strength Cement

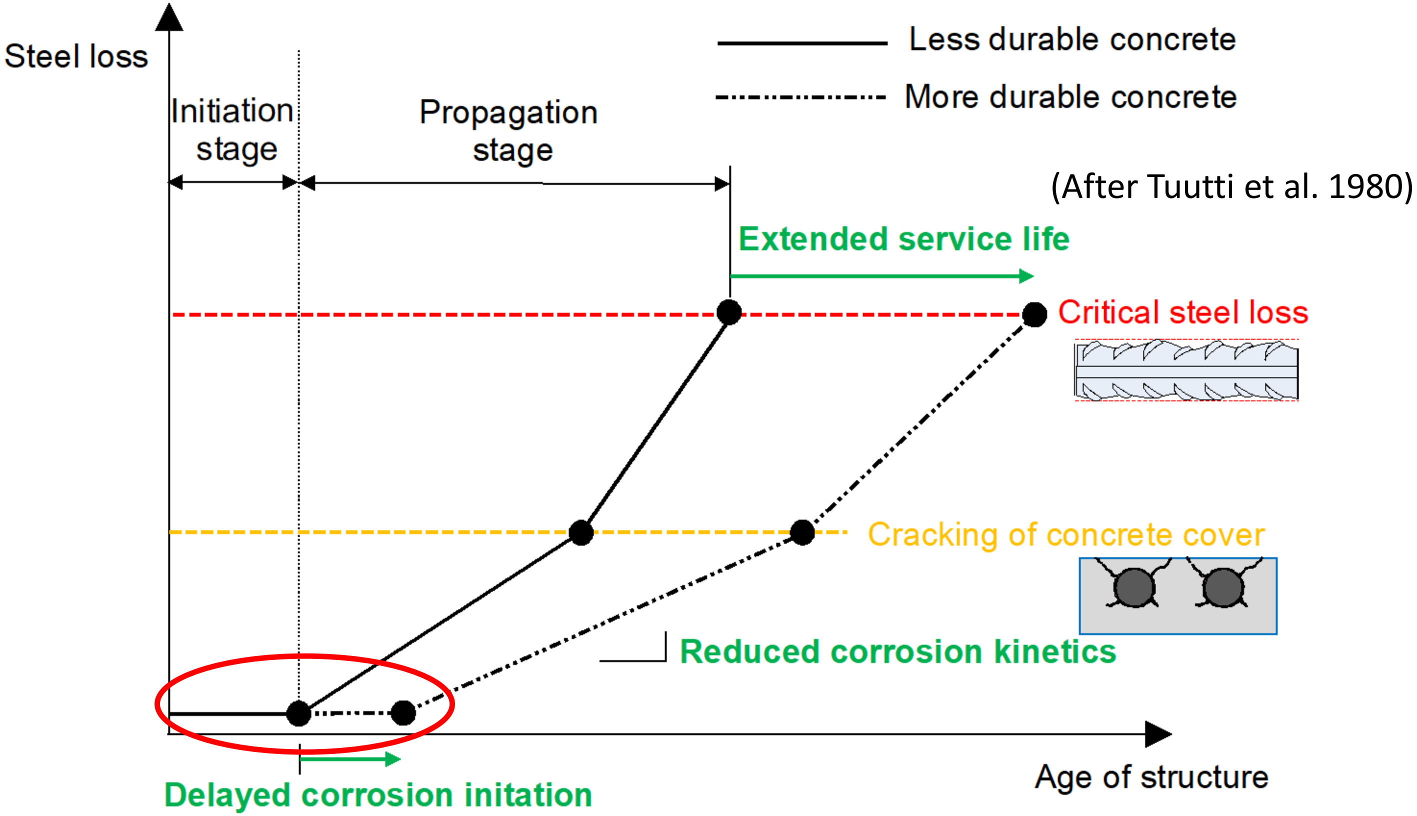


Soil Stabilization Binder

Waste Treatment

Chloride-induced steel corrosion is the most common durability problems of RC structures in the marine environments

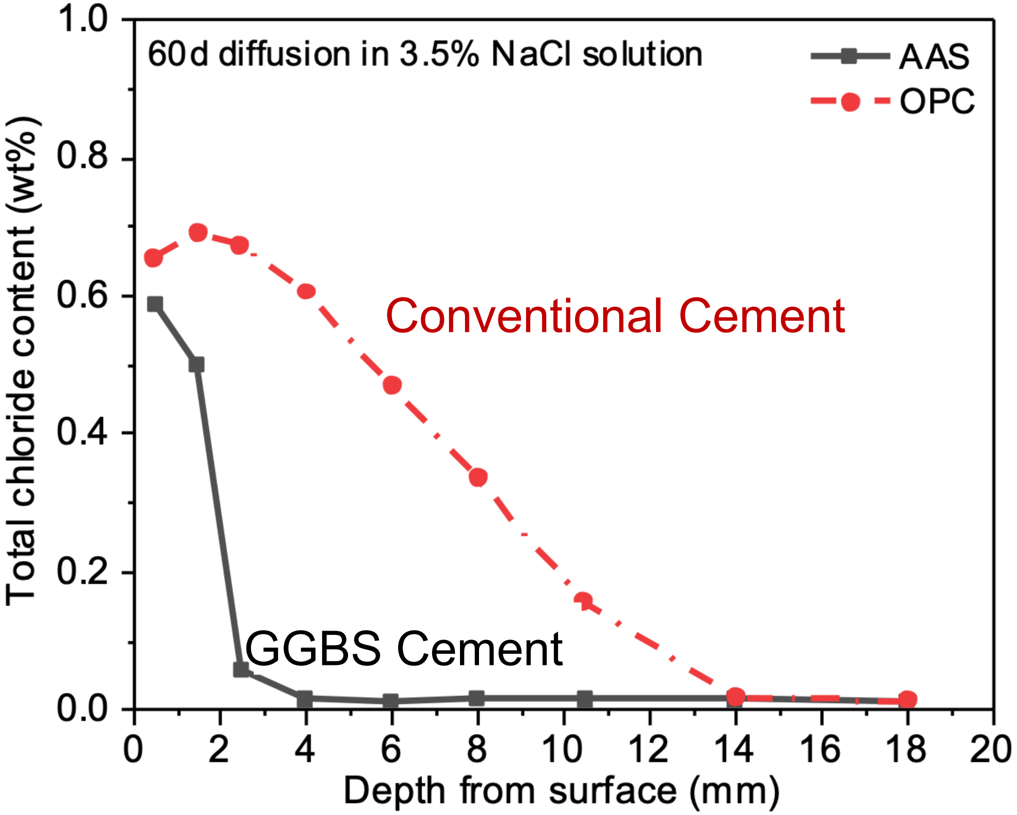
The total cost of corrosion is about 4% of the national GDP, some of which is directly related to infrastructure, including roads, bridges, ports, and piers.



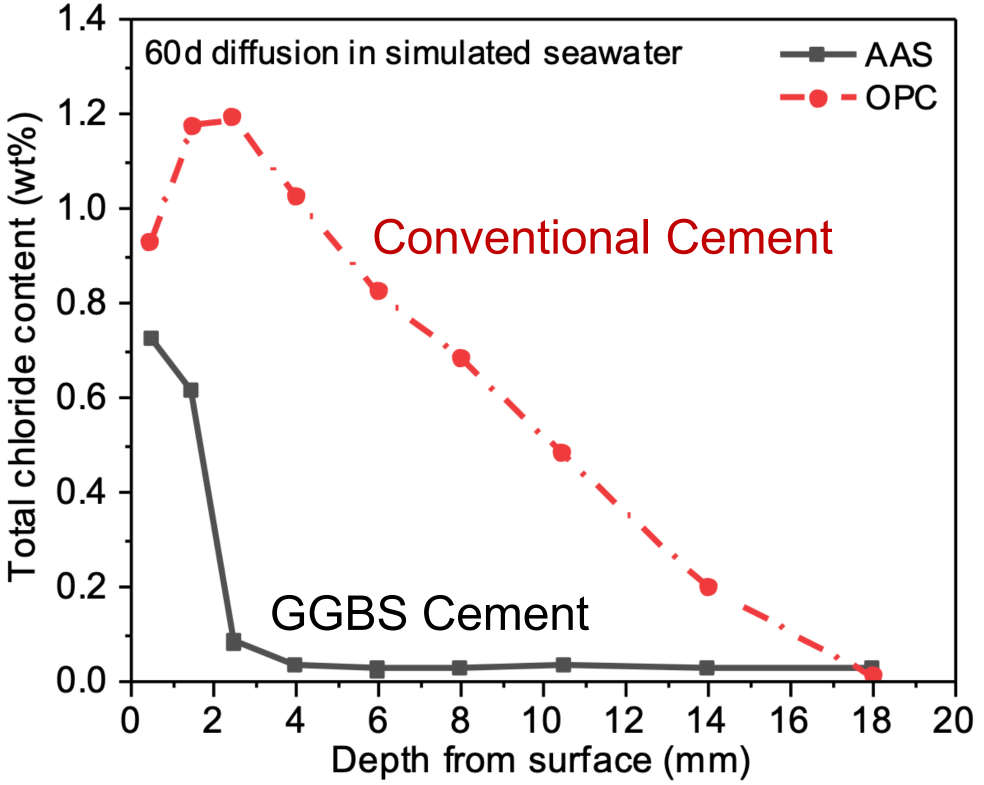
- Resistance to **seawater**
- Resistance to **steel corrosion**

The chloride diffusion coefficient of cement-free GGBS mortars is one order of magnitude smaller than that of OPC mortars

3.5% NaCl



Seawater

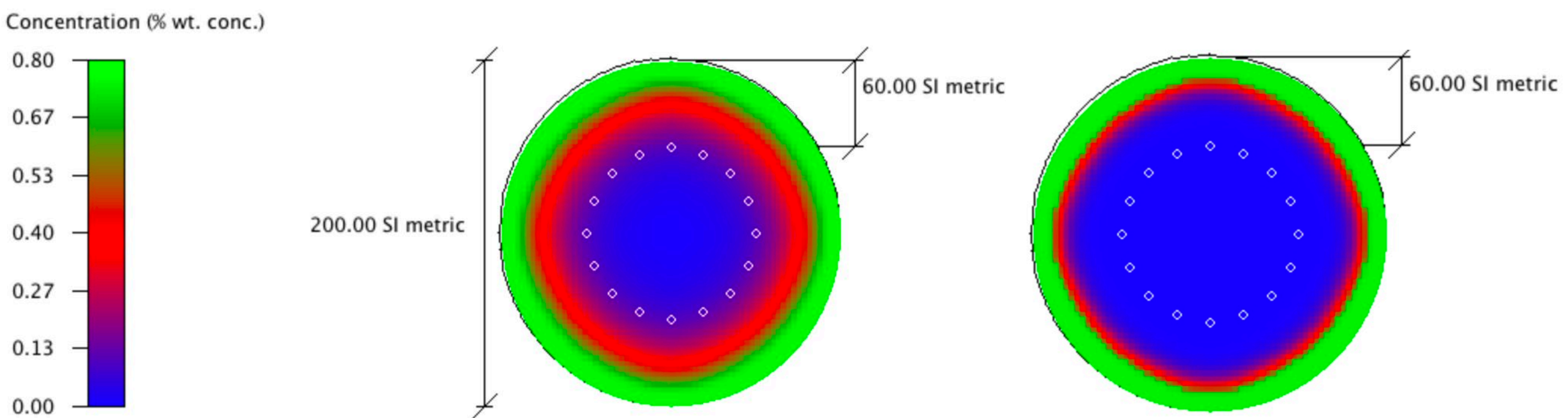


Chloride diffusion coefficient (m^2/s)
after 60-day diffusions

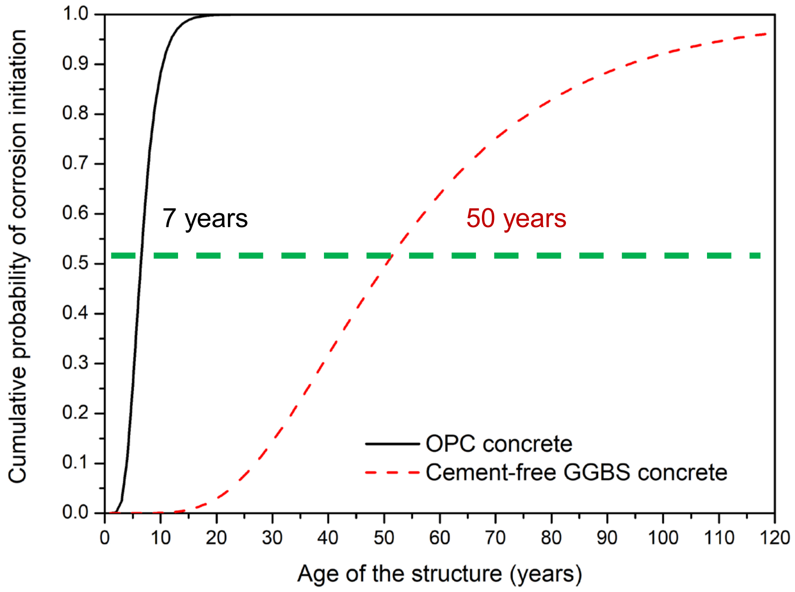
	3.5% NaCl	Seawater
OPC Mortars	8.06×10^{-12}	11.1×10^{-12}
GGBS Mortars	0.49×10^{-12}	0.77×10^{-12}

Implication on the service life of concrete structures (time of corrosion initiation)

Case study on service life (time of corrosion initiation)



OPC concrete **Cement-free GGBS concrete**

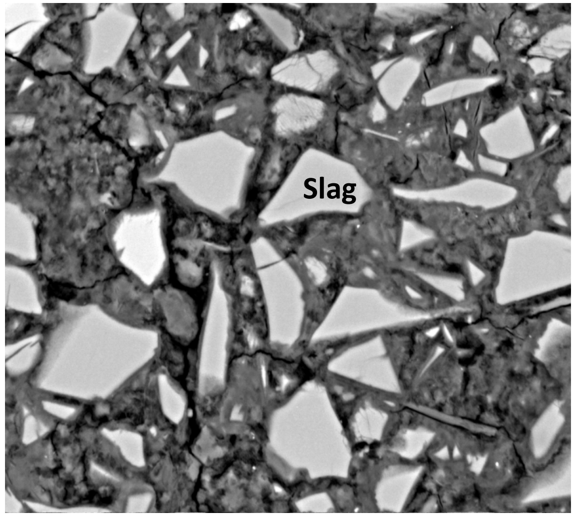


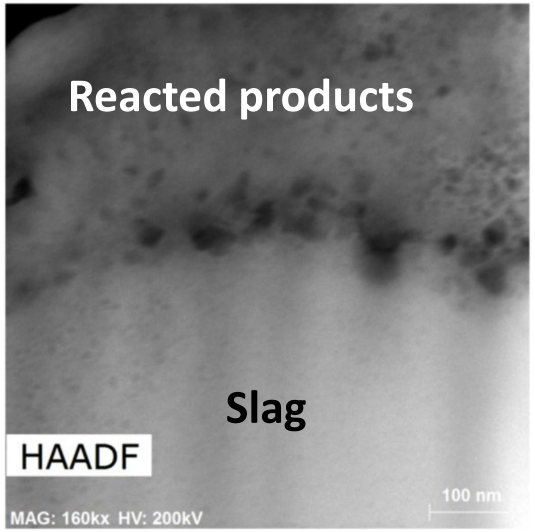
Ingredients and properties of concrete		C45 OPC concrete	C45 Cement-less GGBS Concrete
Binder type		100% OPC	90% GGBS + 10% Activator
Binder content	kg/m^3	400	400
Diffusion coefficient at 28 days	$\times 10^{-12}\ m^2/s$	**10.4**	**1.2**
Aging coefficient, *m*		0.25	0.25*
Total CO_2 emission/m^3 of concrete	$kgCO_{2\ eq.}/m^3$	360	**50**

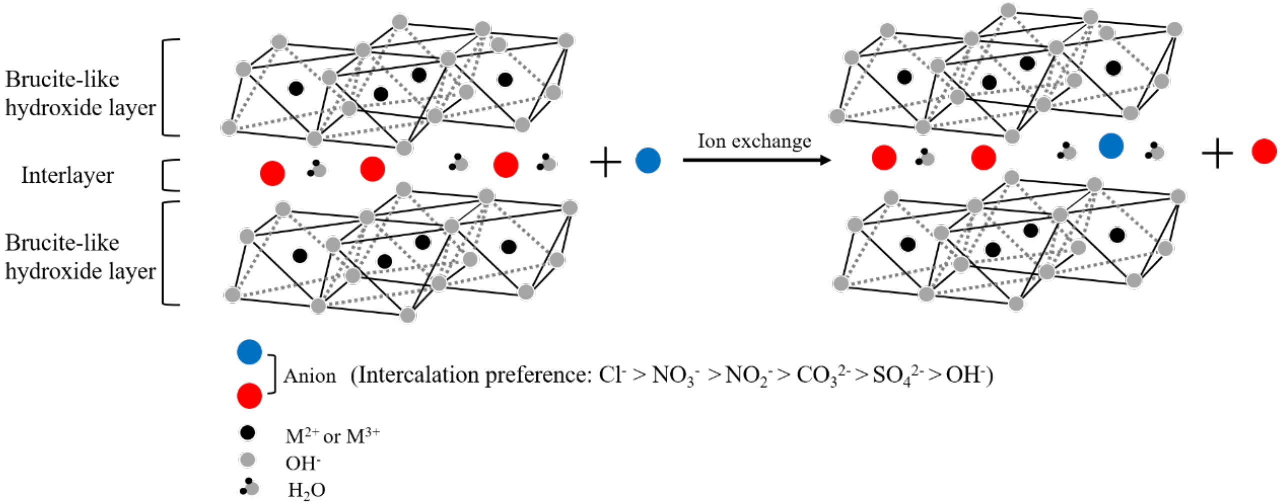
- Maximum surface chloride: 0.8%wt. concrete
- Critical chloride content: 0.05 % wt. concrete

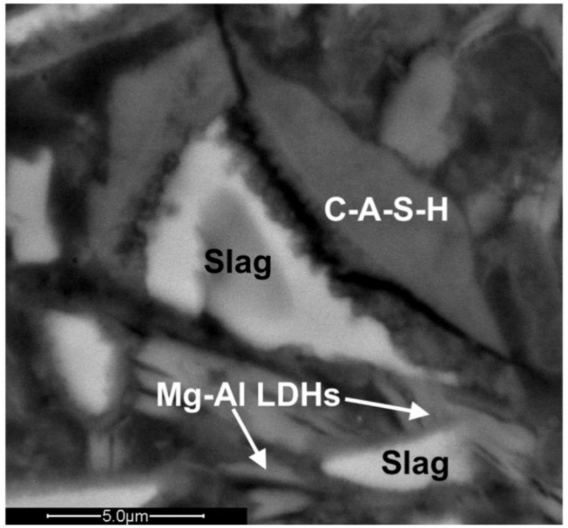
Carbon emission is reduced by ~80%

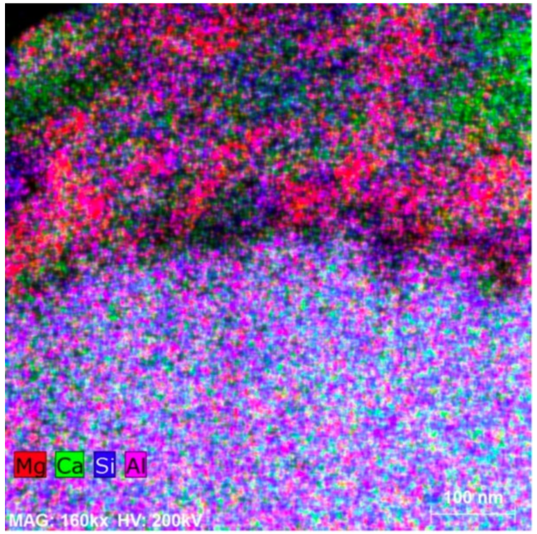
Chemistry of GGBS is different from conventional Cement: The role of Layered double hydroxide (LDH) in marine durability





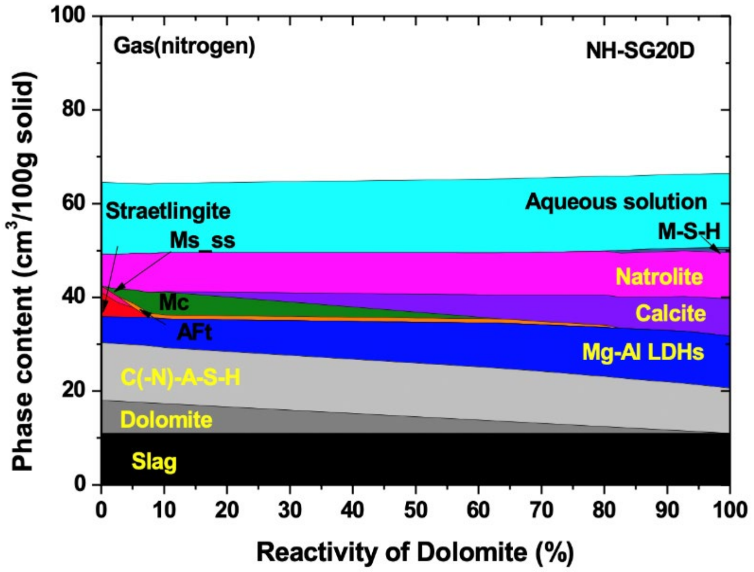






- Layered double hydroxide (LDH) is one of the main reacted products in AAS
- LDH uptakes and immobilizes free chloride, thus lowering down the driving force for chloride ingress

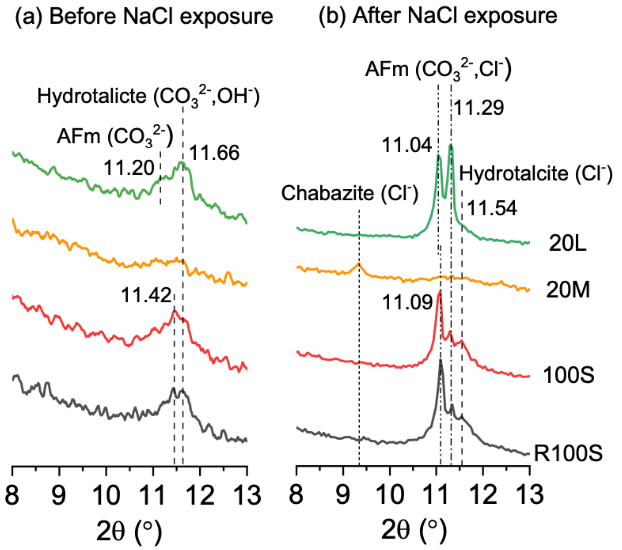
Designing Ultradurable Marine Cement based on GGBS

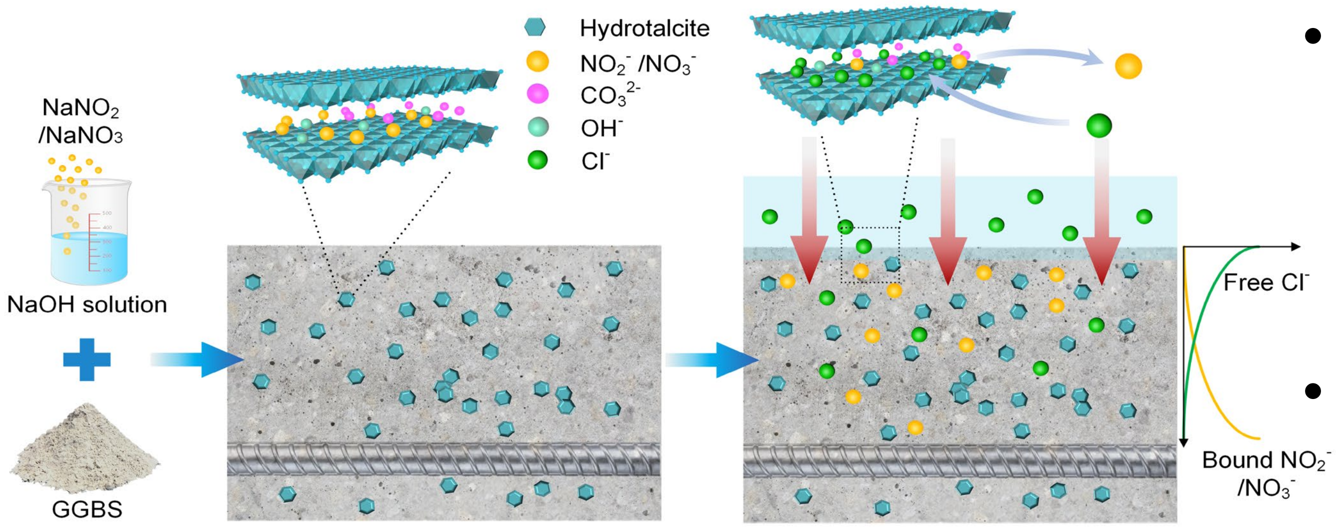


- Reactive MgO
- Dolomite ($CaMg(CO_3)_2$ Minerals)

$CaMg(CO_3)_2 + 2NaOH \rightarrow Na_2CO_3 + Mg(OH)_2 + CaCO_3$

- Metakaolin (Aluminosilicate Minerals
- Limestone ($CaCO_3$ Minerals)





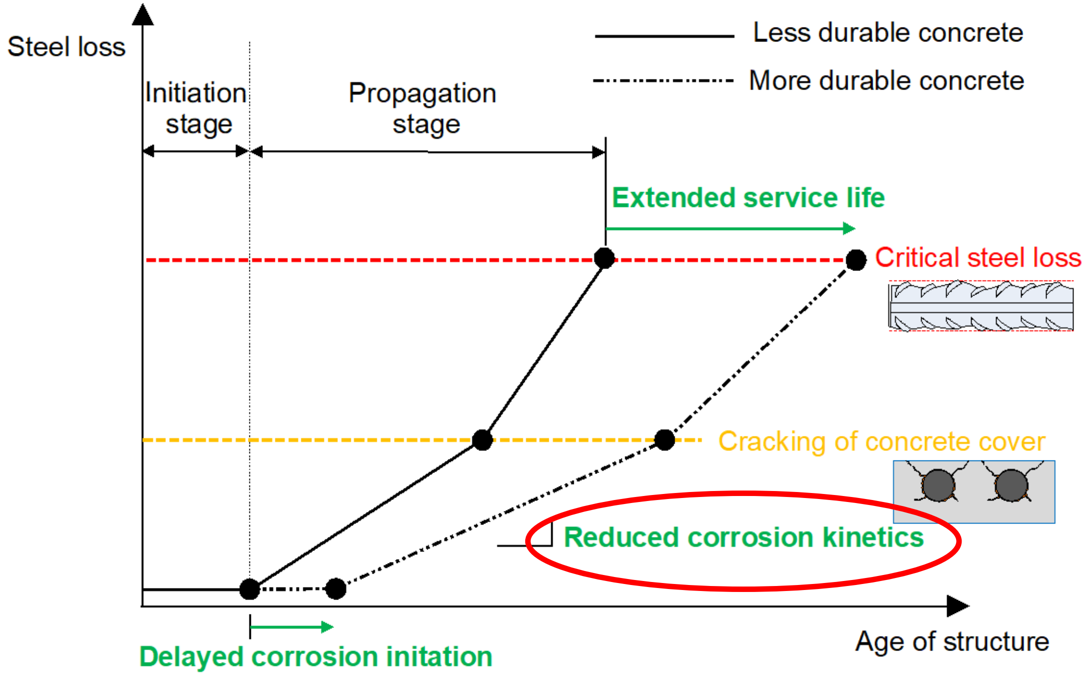
- Nitrite salts have a long proven track record as corrosion inhibitors

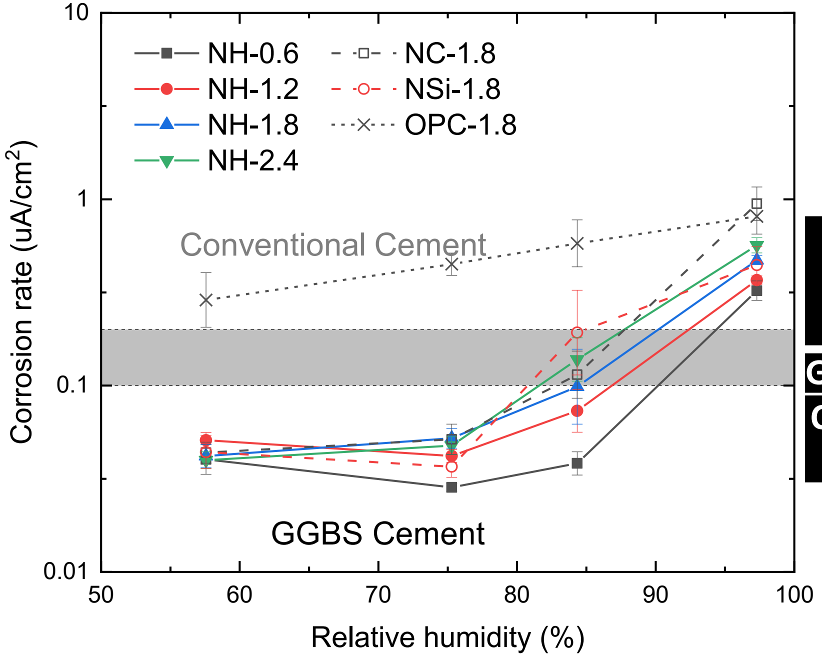
$$2Fe^{2+} + 2OH^- + 2NO_2^- \rightarrow 2NO + Fe_2O_3 + H_2O$$

$$Fe^{2+} + OH^- + NO_2^- \rightarrow NO + \gamma\text{-}FeOOH$$

- Use LDHs as nanocontainer to encapsulate inhibitory ions thus limiting leaching

GGBS-based alkali-activated binder shows stronger corrosion resistance than OPC under the same condition

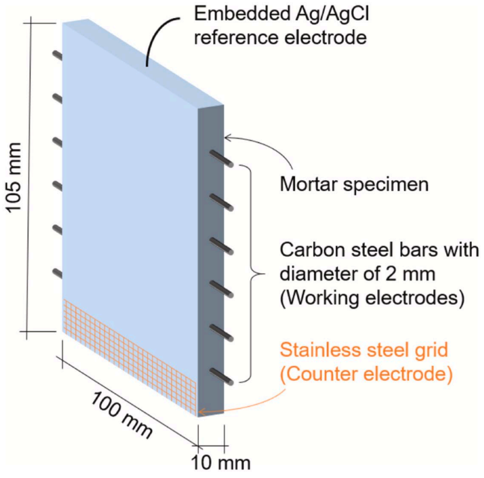


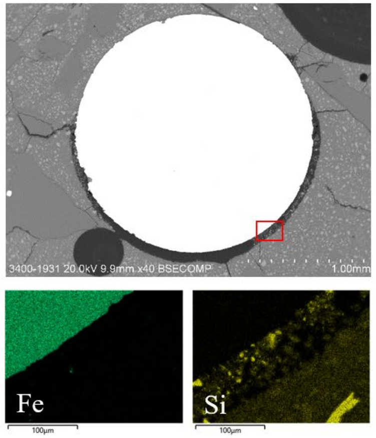


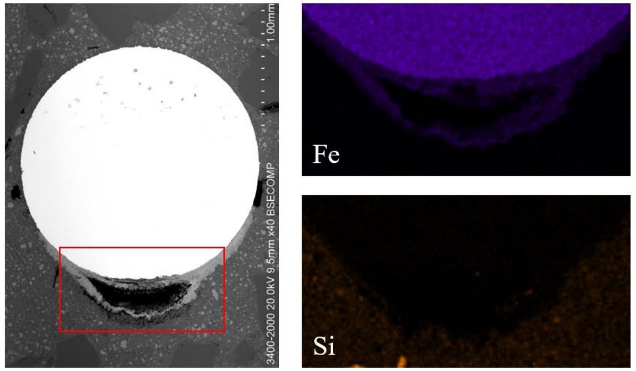
Electrical resistivity and formation factor

Mix	Resistivity (Ohm*m) (28 day)	Formation factor (28 day)
GGBS Cement	219.0	3287
Conventional Cement	49.1	905

- GGBS-based binder shows **stronger corrosion resistance** than OPC under the same condition, before carbonation
- The resistivity of GGBS-based binder is about **4-5 times larger** than that of OPC counterparts



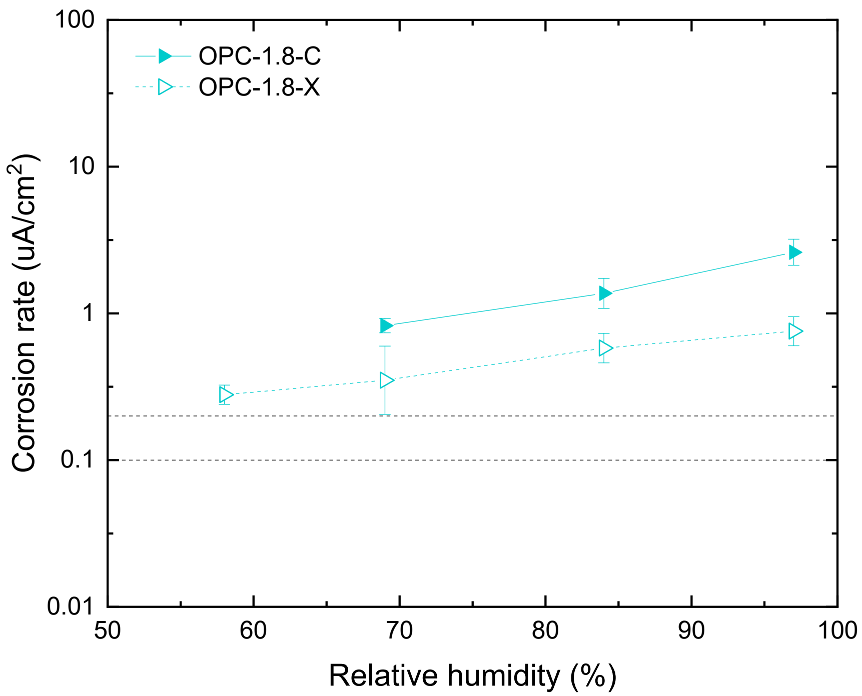


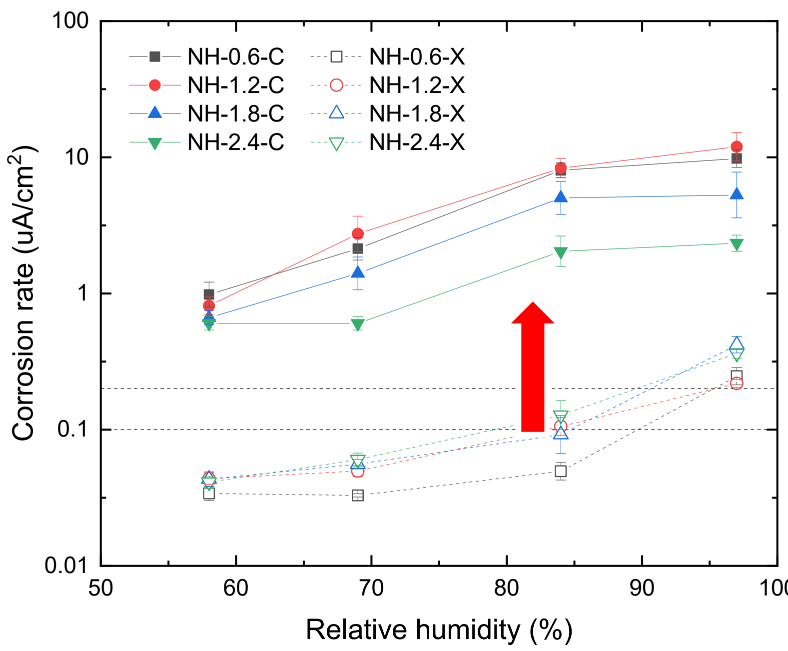


In NH-1.8, the gap is filled reacted products but less corrosion rust. In OPC-1.8, the gap is filled with rust.

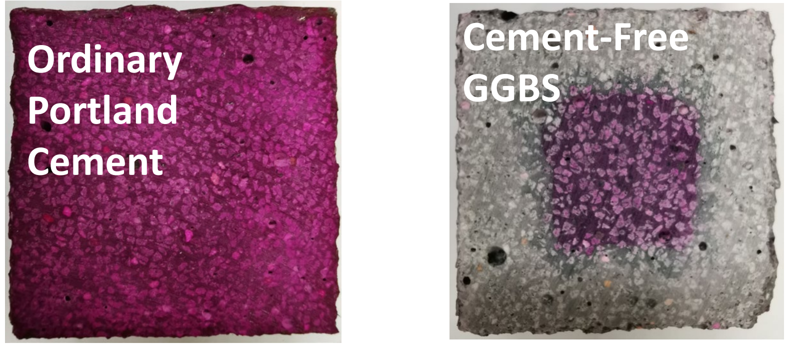
(a) AAS (b) OPC

Fully-carbonated GGBS concrete show significantly degraded corrosion resistance





- Steel corrosion resistance of Cement-Free GGBS material is **significantly degraded after carbonation**
- It is due to the deterioration of pore structure and increase of chloride to hydroxide ion concentration ratio.



Accelerated carbonation tests (10% CO_2)

Under **natural condition**, the carbonation rate of cement-free GGBS may not be as high as seen in the accelerated carbonation tests

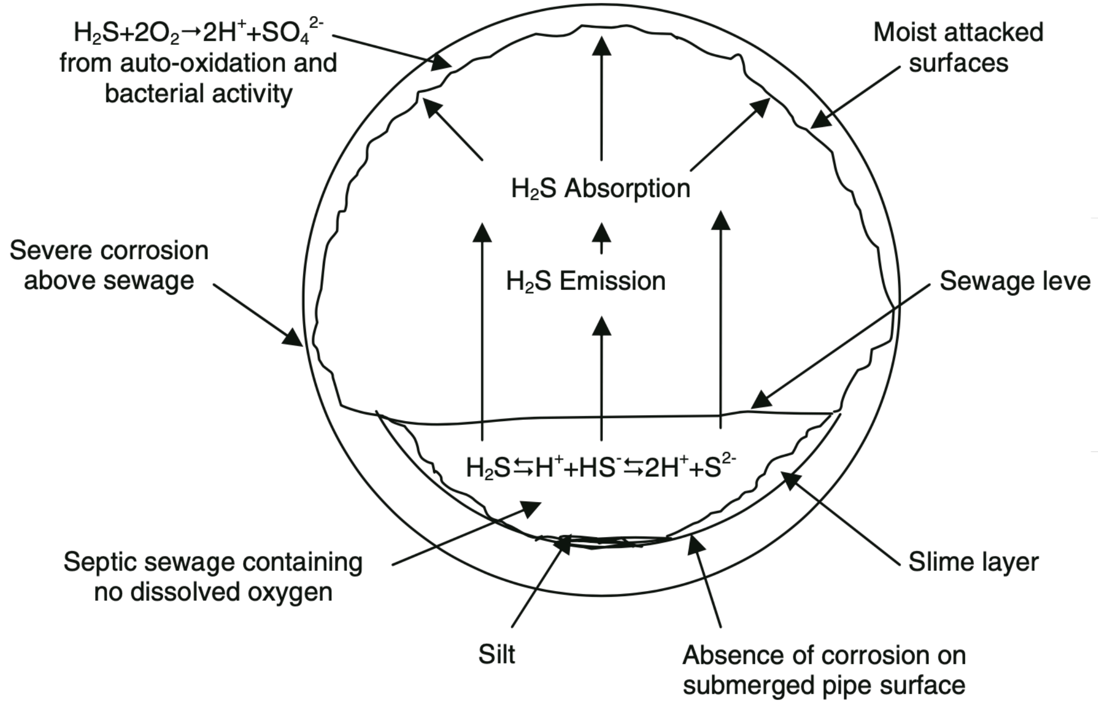
- Reduced gas diffusion
- High alkalinity and LDHs (layered double hydroxides) that absorbs CO_2
- Carbonation mechanism is shifted by accelerated carbonation

Durability problem in the Sewer Environments

Microbial Induced Concrete Corrosion (MICC)

Bacterial activity causes microbially induced concrete corrosion in sewerage environments

Causes: Biogenic Sulfuric Acid (H_2SO_4) due to Bacterial (Microorganism) Activity



Oxidation

Oxidation state	Name	Formula
-2	Sulfide	S^{2-}
0	Elemental sulfur	S^0
+2	Sulfur monoxide	(SO)
	Thiosulfate	$S_2O_3^{2-}$
+3	Dithionite	$S_2O_4^{2-}$
+4	Sulfite	SO_3^{2-}
	Sulfur dioxide	SO_2
	Disulfite	$S_2O_5^{2-}$
+5	Dithionate	$S_2O_6^{2-}$
+6	Sulfate	SO_4^{2-}
	Sulfur Trioxide	SO_3

(Suzuki, 1999)

Reduced sulfur compounds

SOB activity

End-product (H_2SO_4)

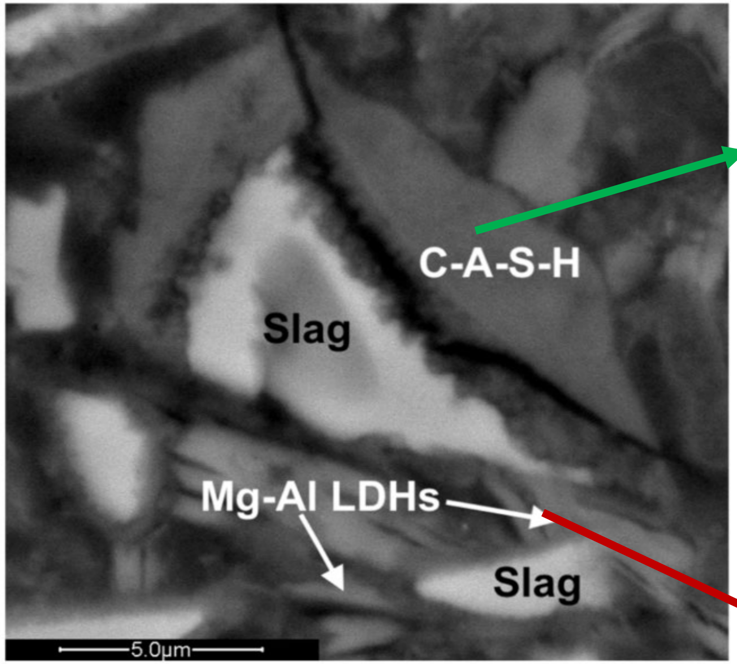
Upon biogenic sulfuric acid attack, the constituents in conventional concrete break down :

Biogenic H_2SO_4 + OPC Cement → Gypsum (no strength)

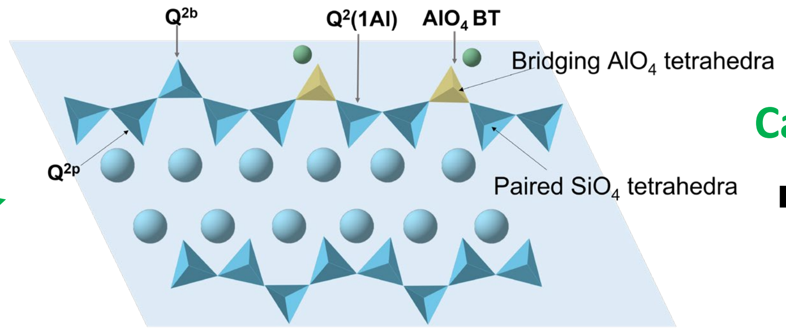
Our proposed solution: Antimicrobial Alkali-Activated GGBS

Designing biologically-resistant GGBS materials against biocorrosion of concrete

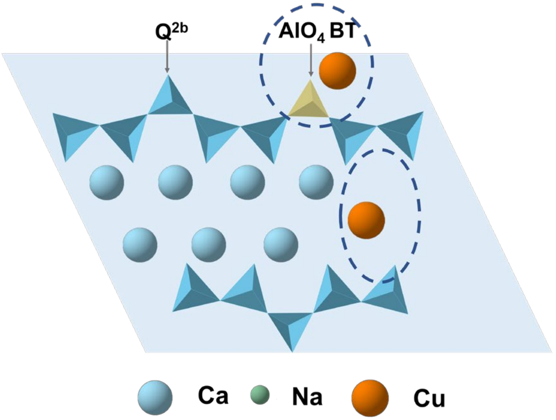
Antibacterial Cu-exchanged GGBS materials



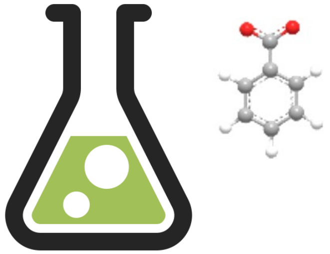
Microstructure of GGBS binder



Cation exchangeability

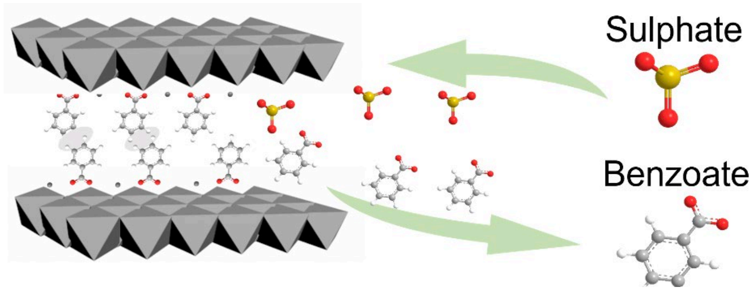


Antibacterial LDHs-modified GGBS materials



Activator incorporating **antibacterial anions**

Anion exchangeability

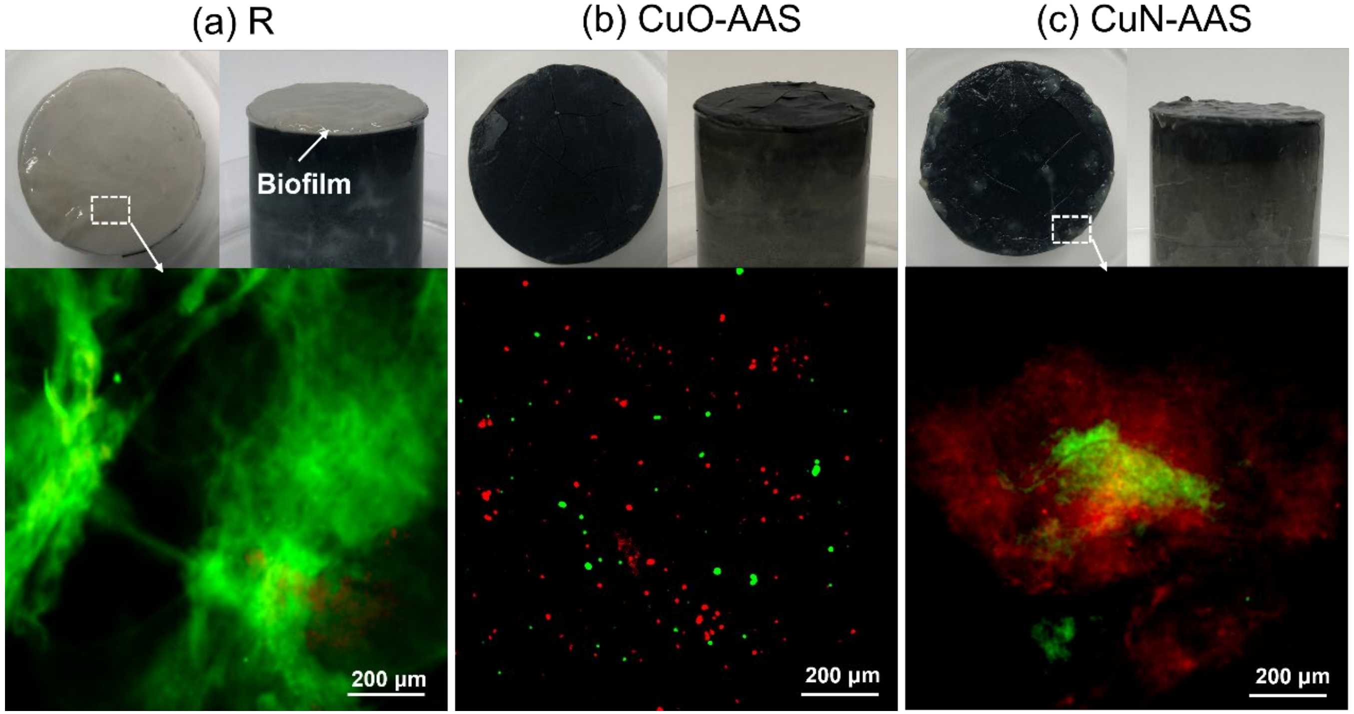


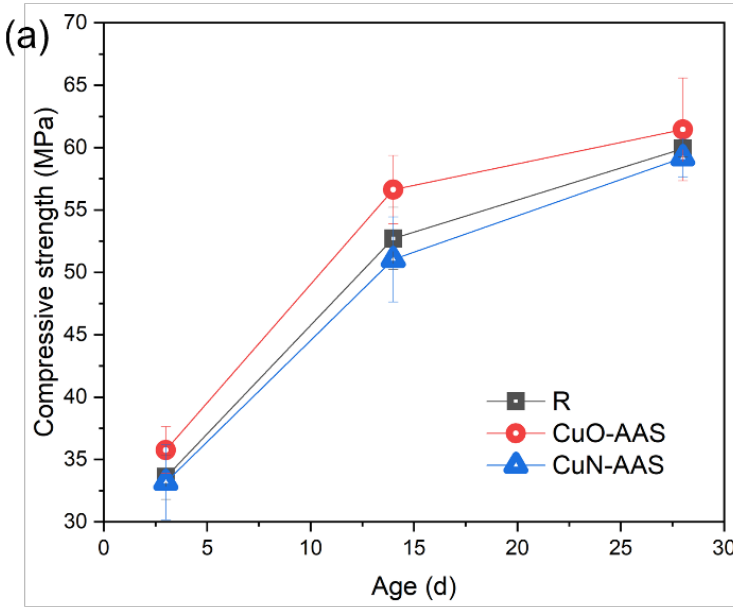
Antimicrobial Cu-doped GGBS cement

Mix proportion of Cu-doped AAS.

Group	Reference	CuO-AAS	CuN-AAS
Slag /%	100	100	100
CuO /%	0	1	0
$Cu(NO_3)_2$ /%	0	0	2.35
NaOH /%	7.74	7.74	7.74
DI water /%	40	40	40

Equivalent elemental Cu content of 0.8 wt. % of GGBS.

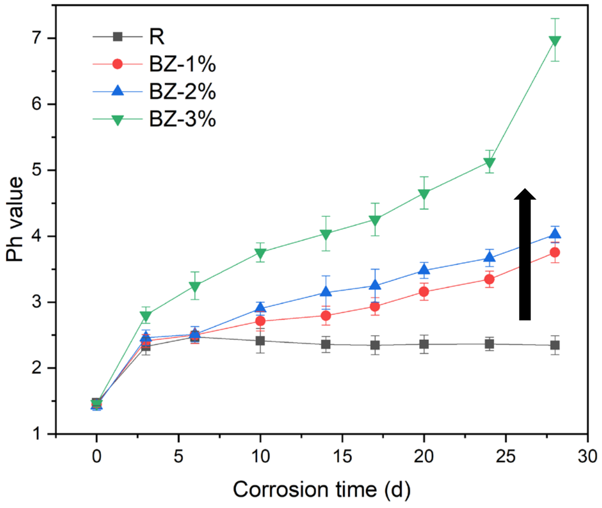


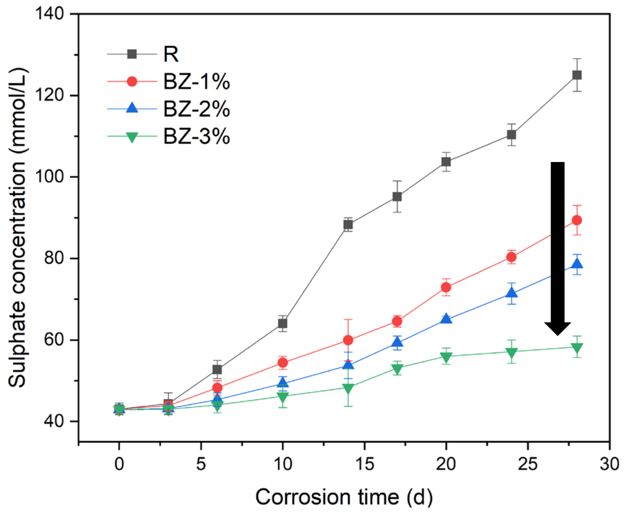


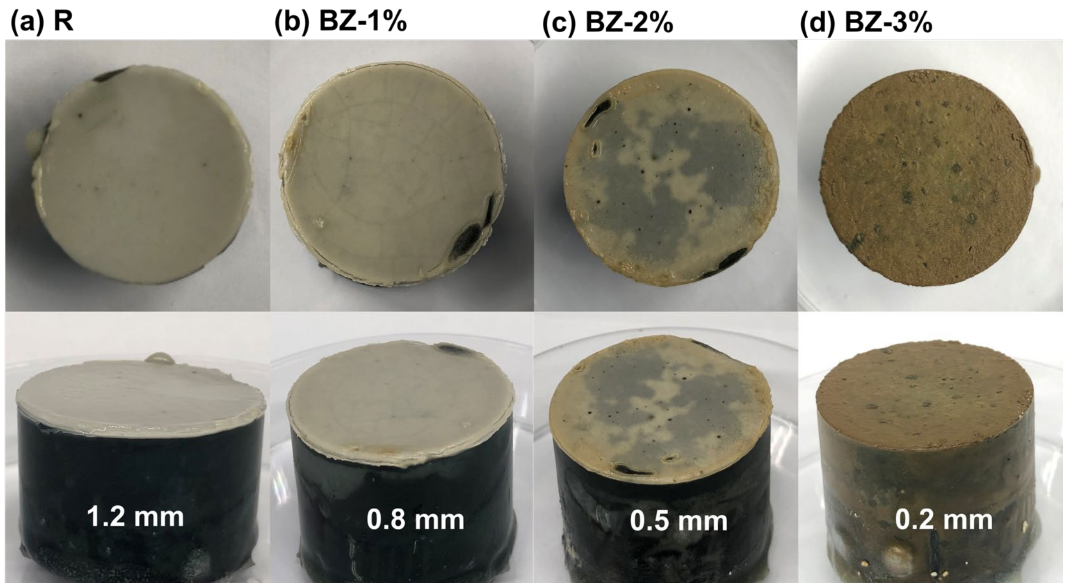
- CuO-modified GGBS cement **completely restricts biofilm formation**, with only a small number of live bacteria (green) being detected.

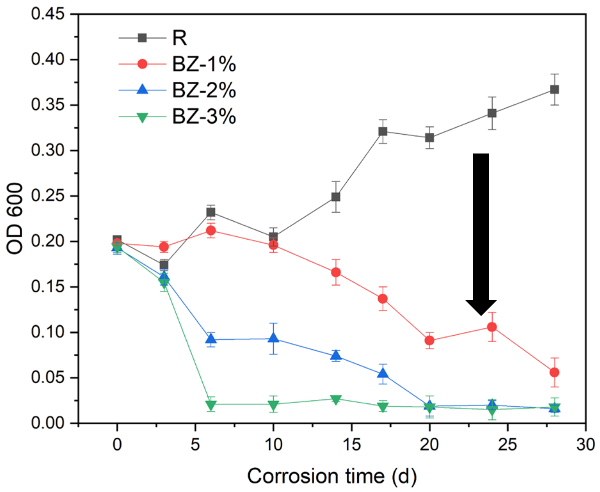
The functional benzoate-modified AAS shows antibacterial properties in killing *Acidithiobacillus. thiooxidans*

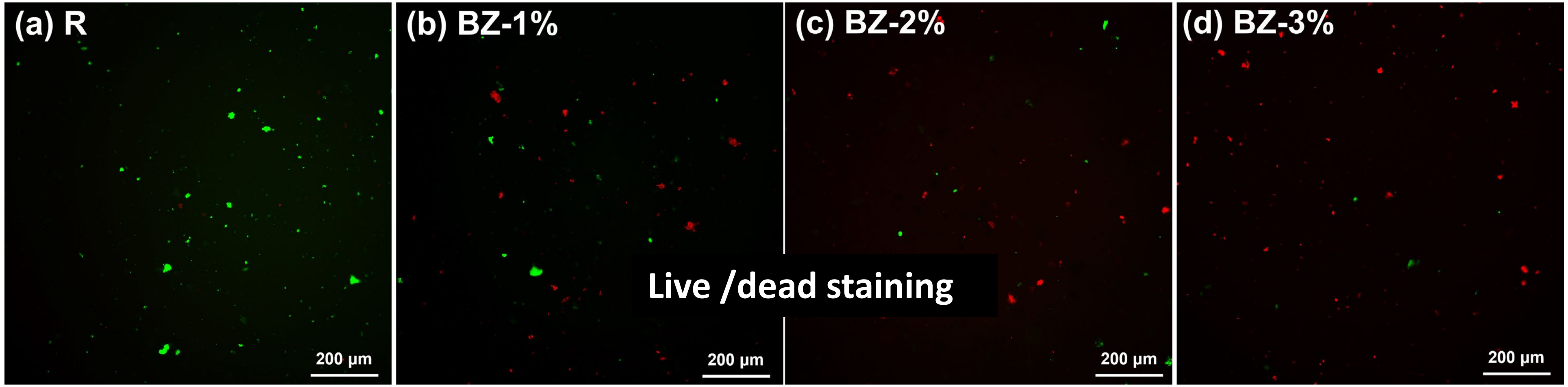
Bacterial activity assessments, and fluorescence staining





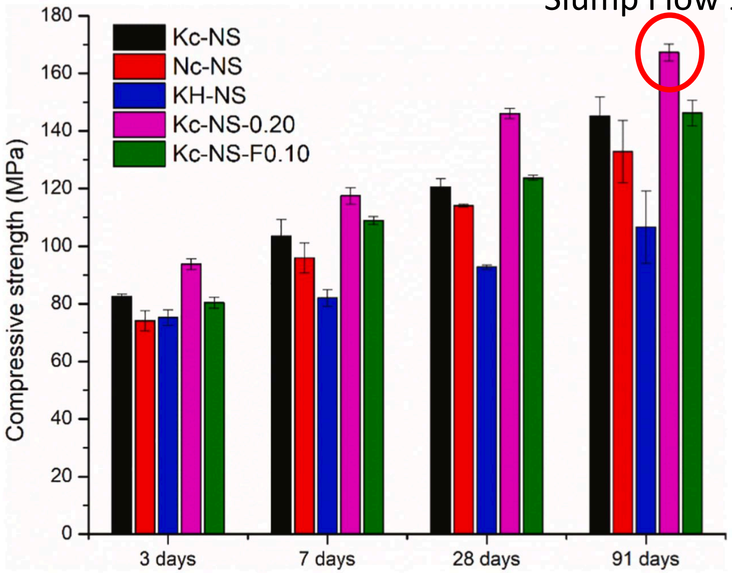


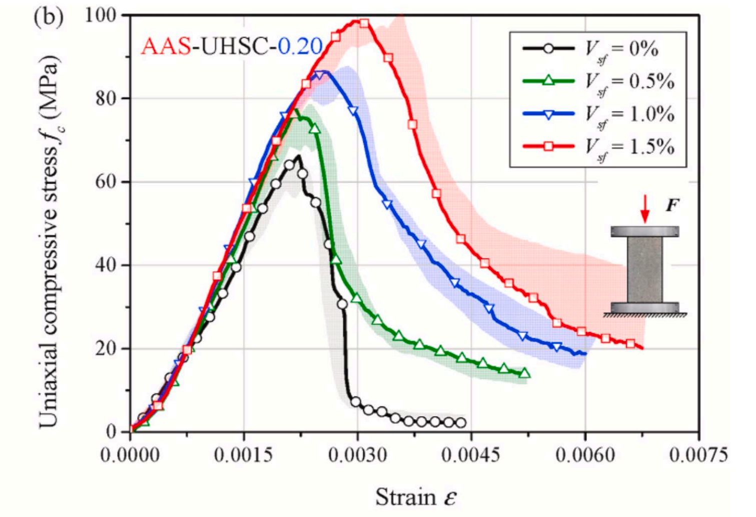




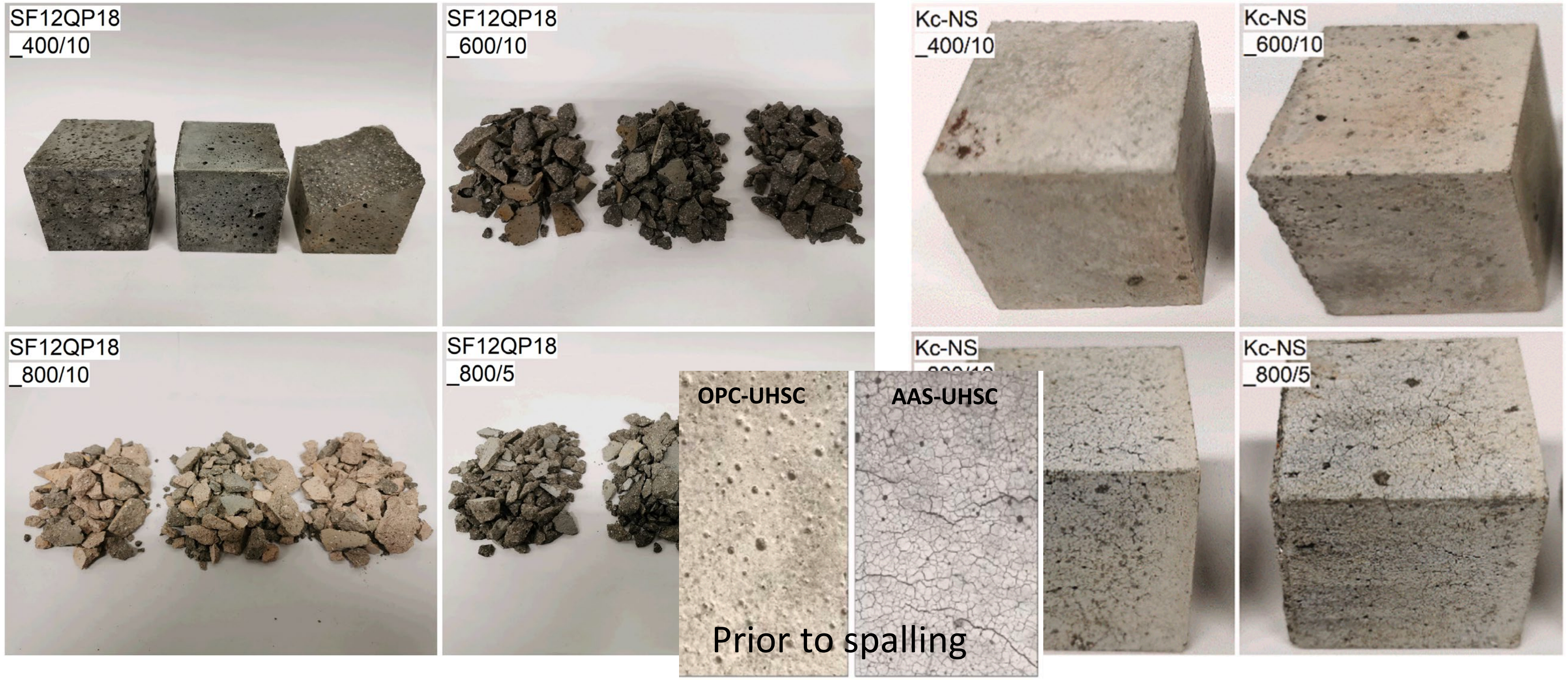
GGBS-based high-strength concrete is more fire-resistant

Slump Flow 186 cm





OPC High-Strength Concrete **GGBS High-Strength Concrete**



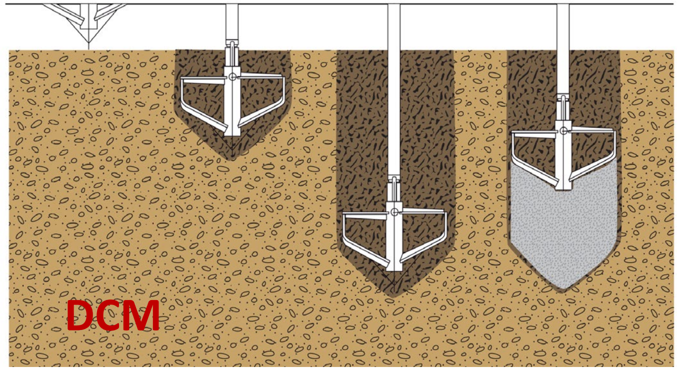
- GGBS-based high-strength concrete **(> 150 MPa)** shows NO sign of explosive spalling; while OPC counterpart spalled at temperature exceeding 600 ℃.

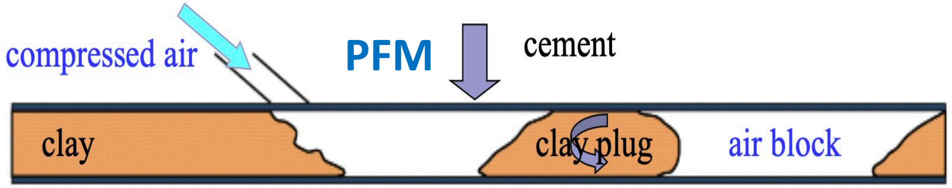
Cement-Free GGBS binder for soil stabilization (dredged soil) in sustainable land reclamation

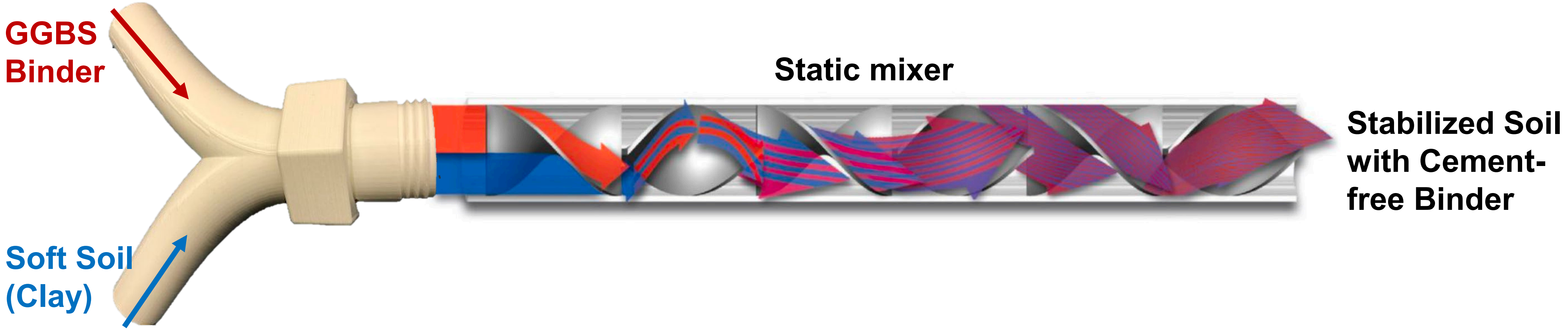
Soil - Cement Mixing Technology

- **Deep cement mixing (DCM)** (In-situ method)
  - Cement is injected into the ground and stirred with soil by mixing machines
- **Pneumatic flow mixing (PFM)** (Ex-situ method)

  - Cement was mixed with soil during transporting in a pipeline

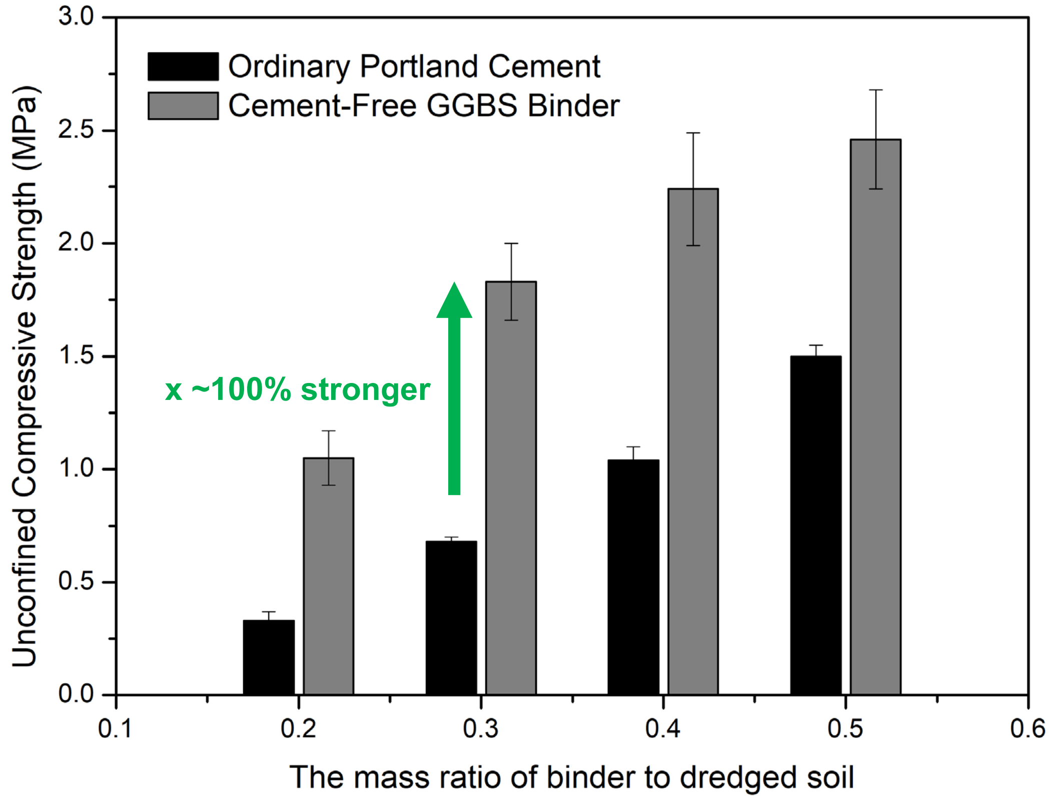






Cement-Free GGBS binder for soil stabilization (dredged soil) in sustainable land reclamation

Unconfined Compressive Strength (UCS @7-day)



- Cement-free GGBS seems to have **better compatibility** with dredged soil, depending on the exact composition and minerology
- The clay minerals (aluminosilicate minerals) in dredged soil may be activated by alkalis during mixing
  - Na_2CO_3+ CaO (activator) + Seawater → **NaOH** + $CaCO_3$
  - **NaOH** + **GGBS** (Calcium aluminosilicate) → Calcium-Aluminosilicate-Hydrate (C-A-S-H gel phase)
  - **NaOH** + **Clay Minerals** (Aluminosilicate) → Sodium-Aluminosilicate-Hydrate (N-A-S-H gel phase)

- **Seawater** was used in mixing (additional alkalis are introduced);
- Dredged soil has approx. 56% SiO_2 (quartz), 21% Al_2O_3, 6.6% Fe_2O_3, 3.5% CaO;
- The initial water content of dredged soil was around 50%;
- Total water content of the soil-binder mixture was controlled at 90%;

Summaries

- Cement-free GGBS-based binder can have up to 80% reduction in carbon emission in comparison to OPC-based binder, while offering high durability, especially under marine and sewerage conditions.
- Alkaline activation of GGBS using solid-based activator (one-part GGBS binders) can significantly accelerate the chemical reaction and strength development of GGBS-based binder. Its early-age and later-age strengths (up to 56 days) can be comparable or even higher than those of OPC binders.
- Further investigation of new chemical admixtures that can control and regulate the fresh and hardened properties of GGBS-based cement-free binders and concrete is needed.

Thank you ! Questions ?

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