Technische Universiteit Eindhoven
University of Technology

NWO Applied and Engineering Sciences

TISCA User day

A Numerical-Experimental Study on chemo-mechanical degradation of COncrete sewer Pipes (NESCOP)

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29th of May 2019

Introduction

Problem Statement

Assessment Methods

- Age determination
- CCTV

Need for better measurements or better prediction methods/design rules

Image retrieved from: https://sunburstev.com/drain-line-camera-inspection-cctv-technology/

Image retrieved from: https://www.wellingtondrainage.co.nz

Project Goals

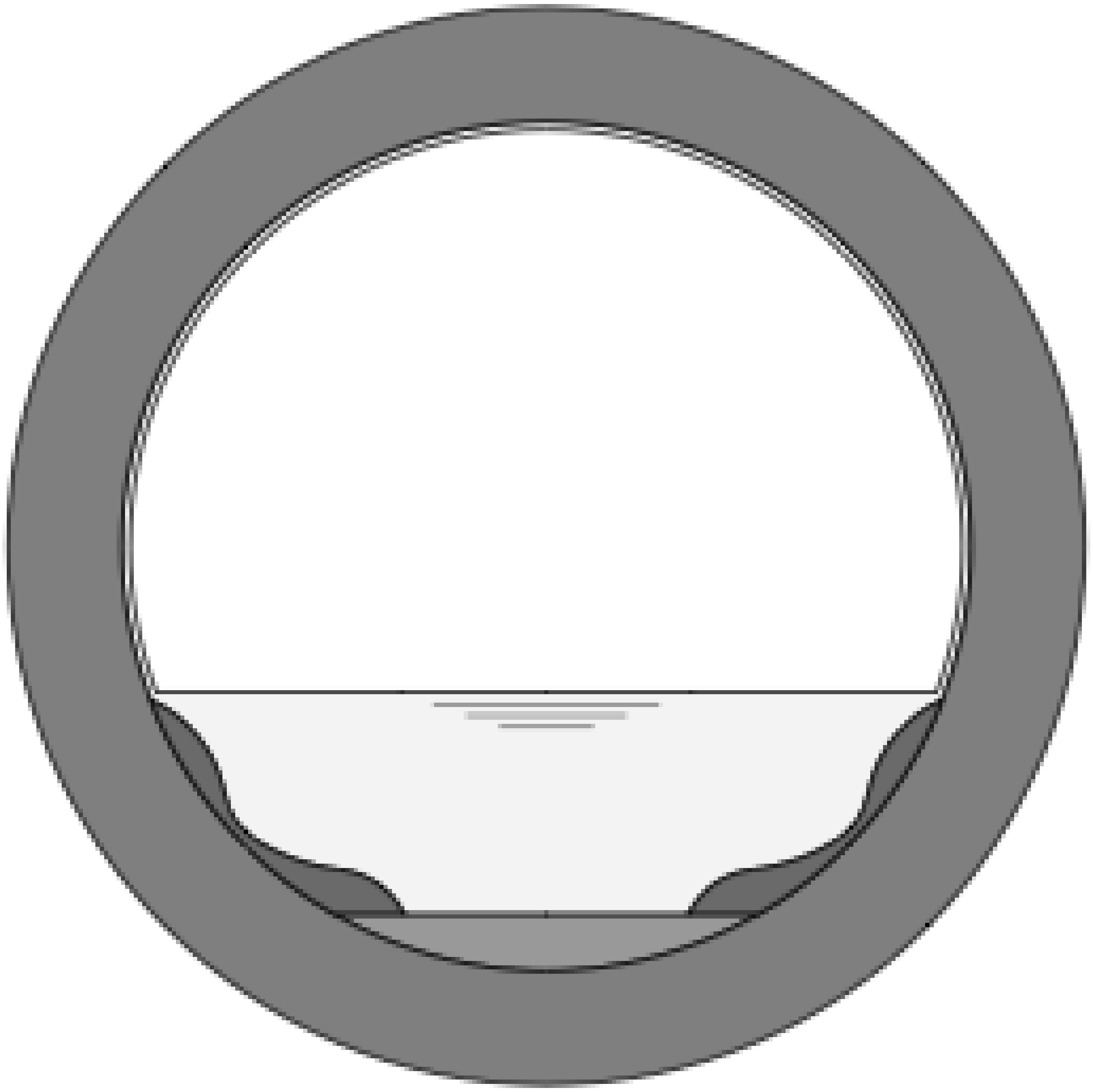
Chemo-mechanical model

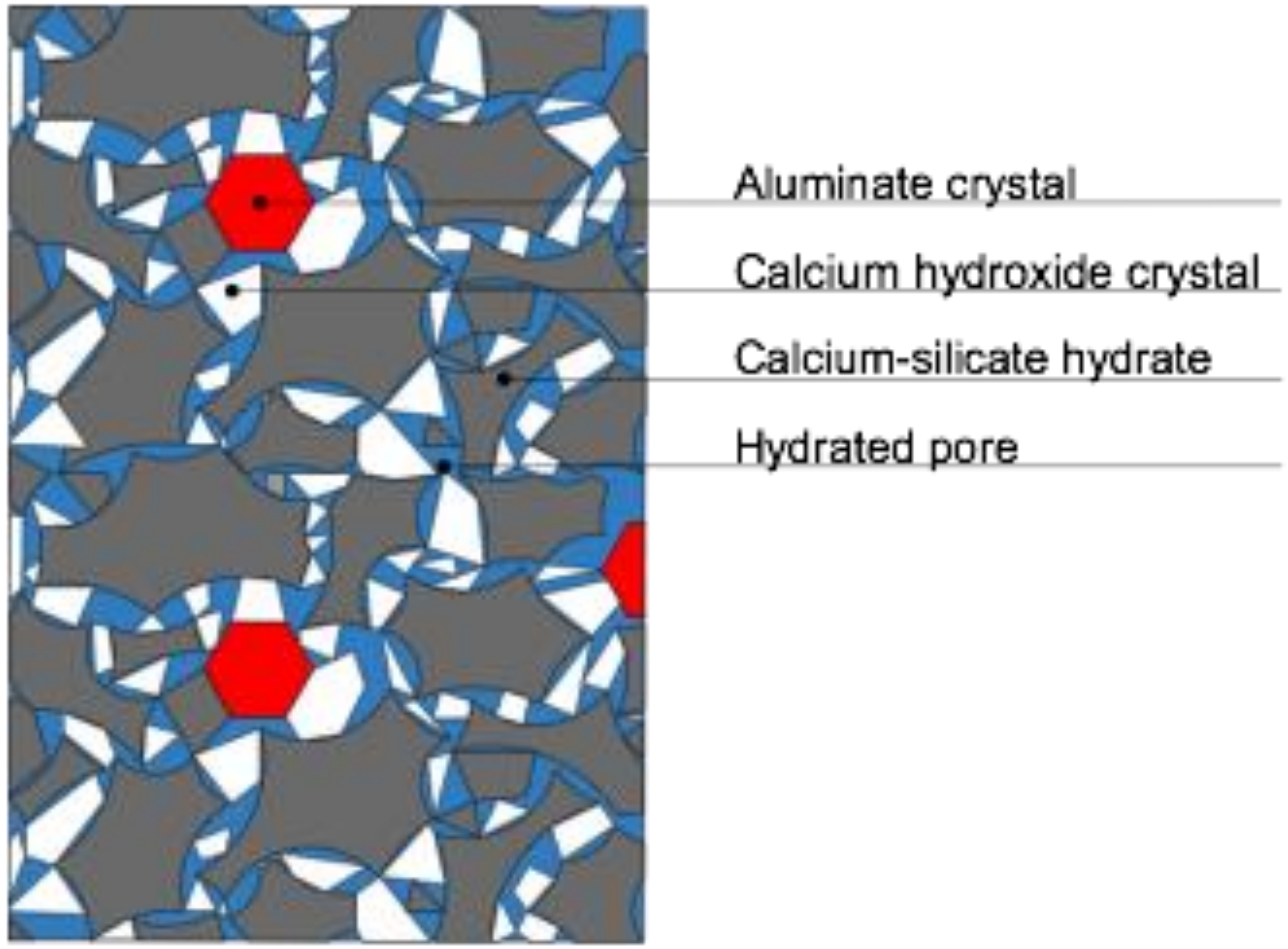
- Prediction of remaining load bearing capacity
- Focus on transferability instead of complexity

Experiments

- Used to calibrate and validate the chemo-mechanical model

Biogenic Sulfide Corrosion: process





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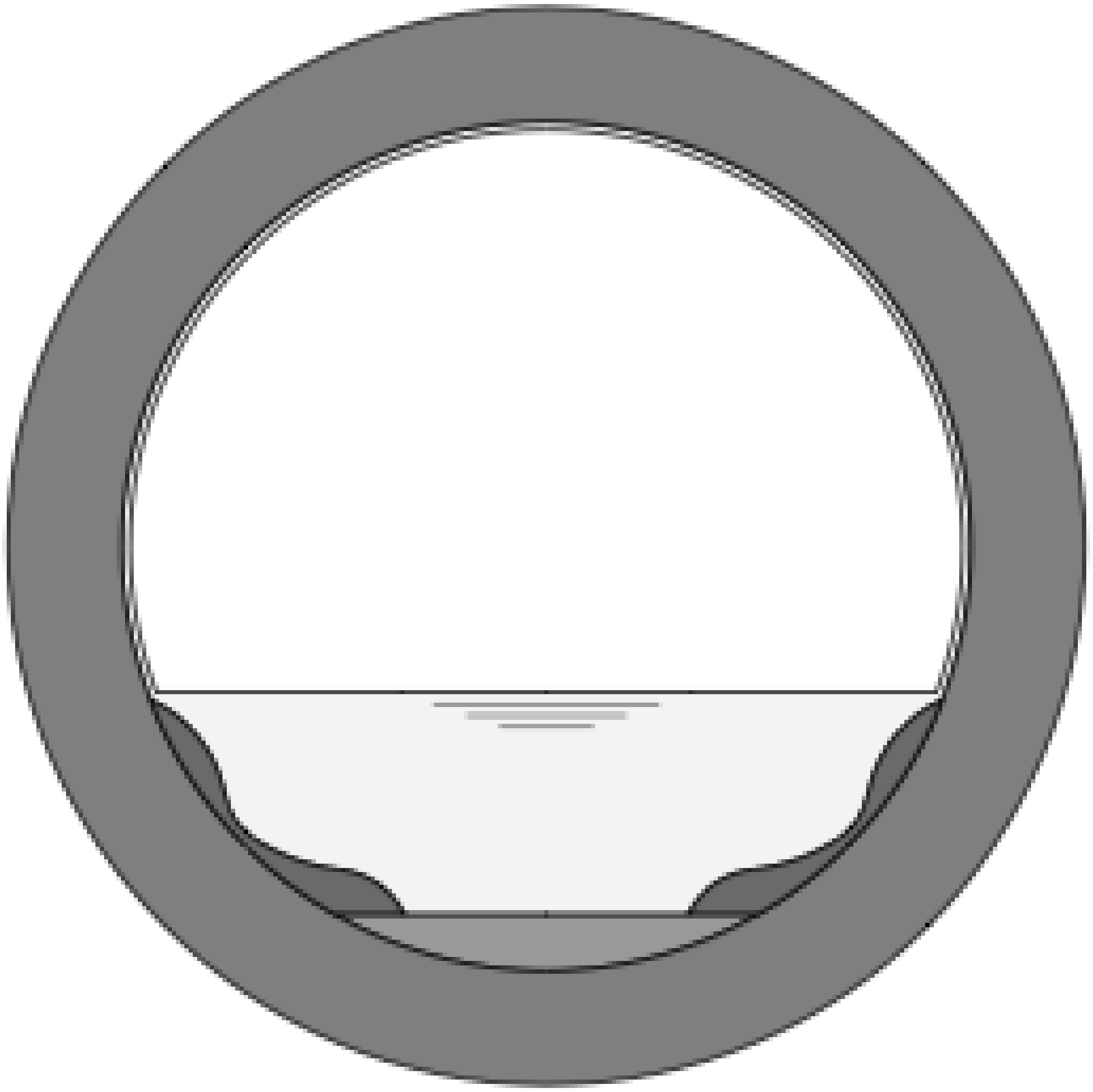
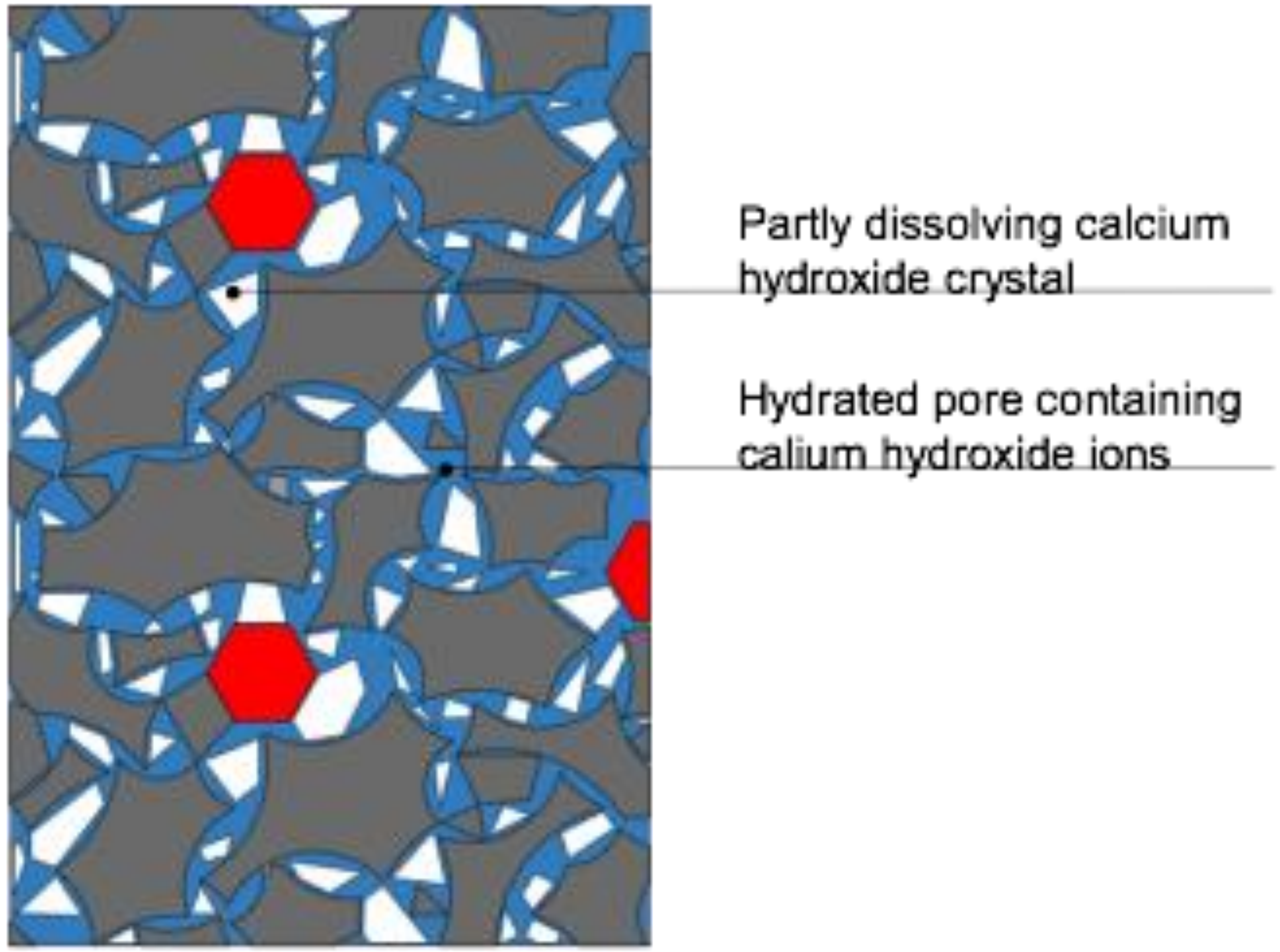
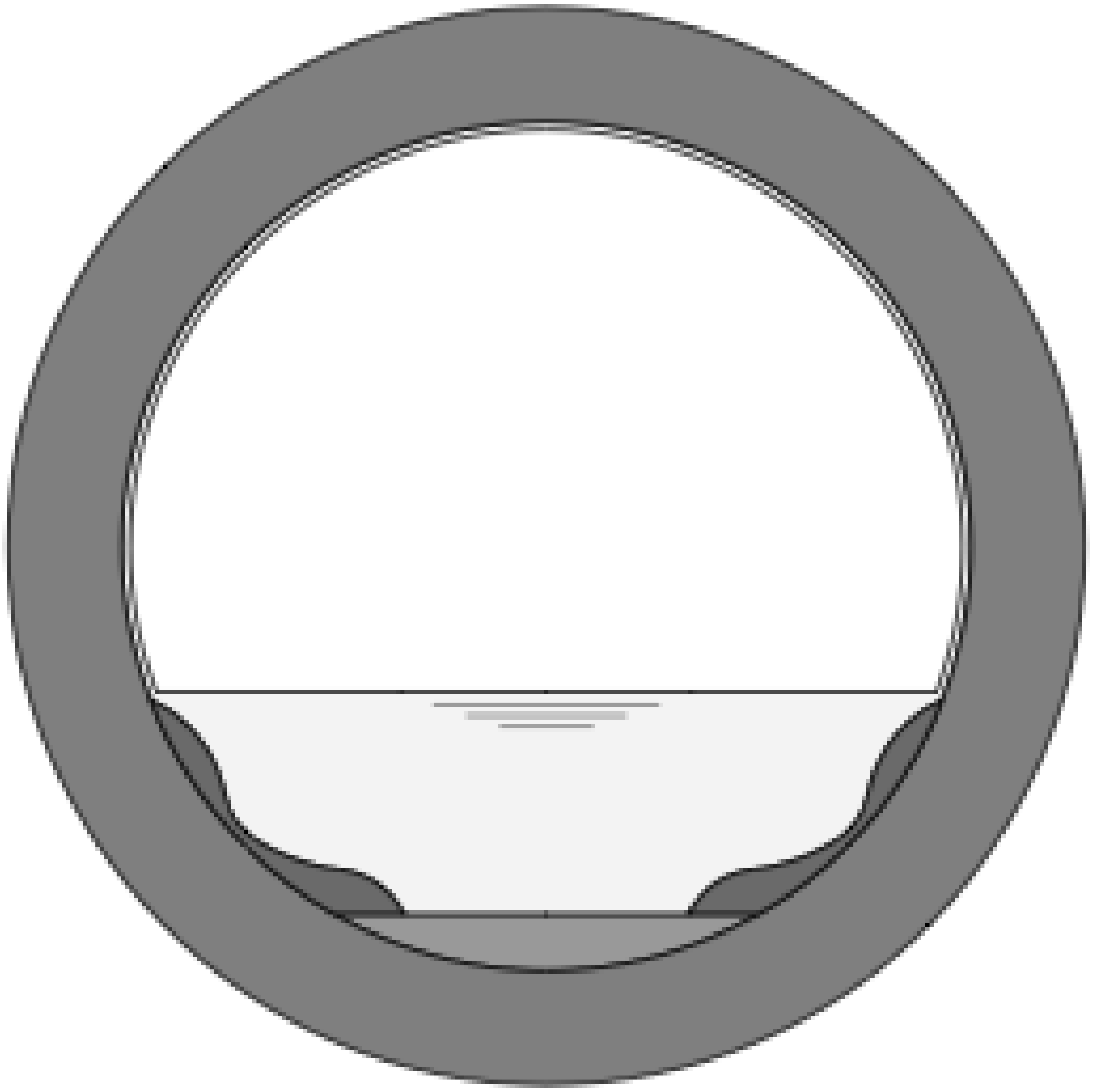
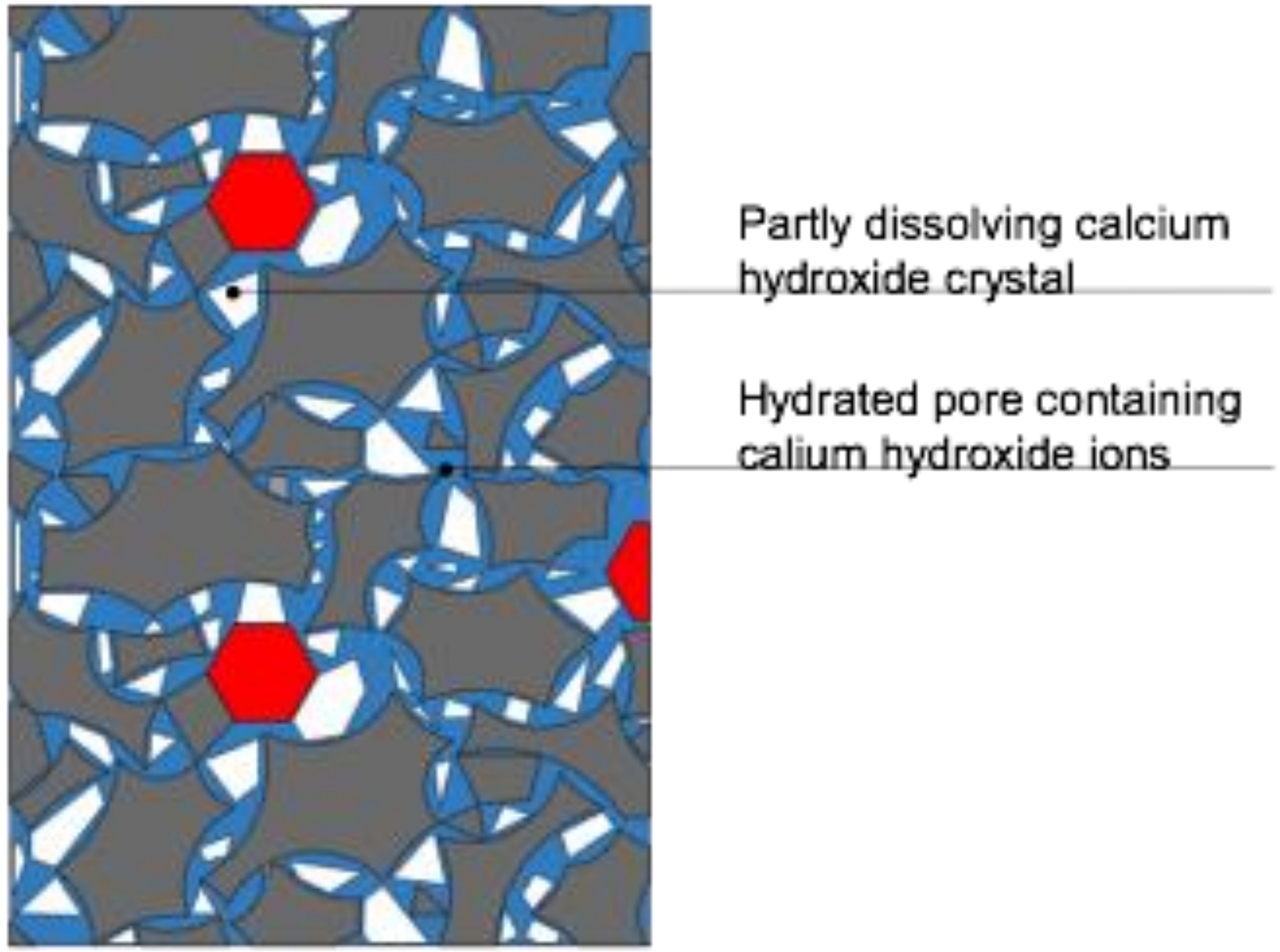




$$Ca(OH)_2(s) \Longleftrightarrow Ca^{2+}(aq) + 2(OH^-)(aq)$$

Biogenic Sulfide Corrosion: process



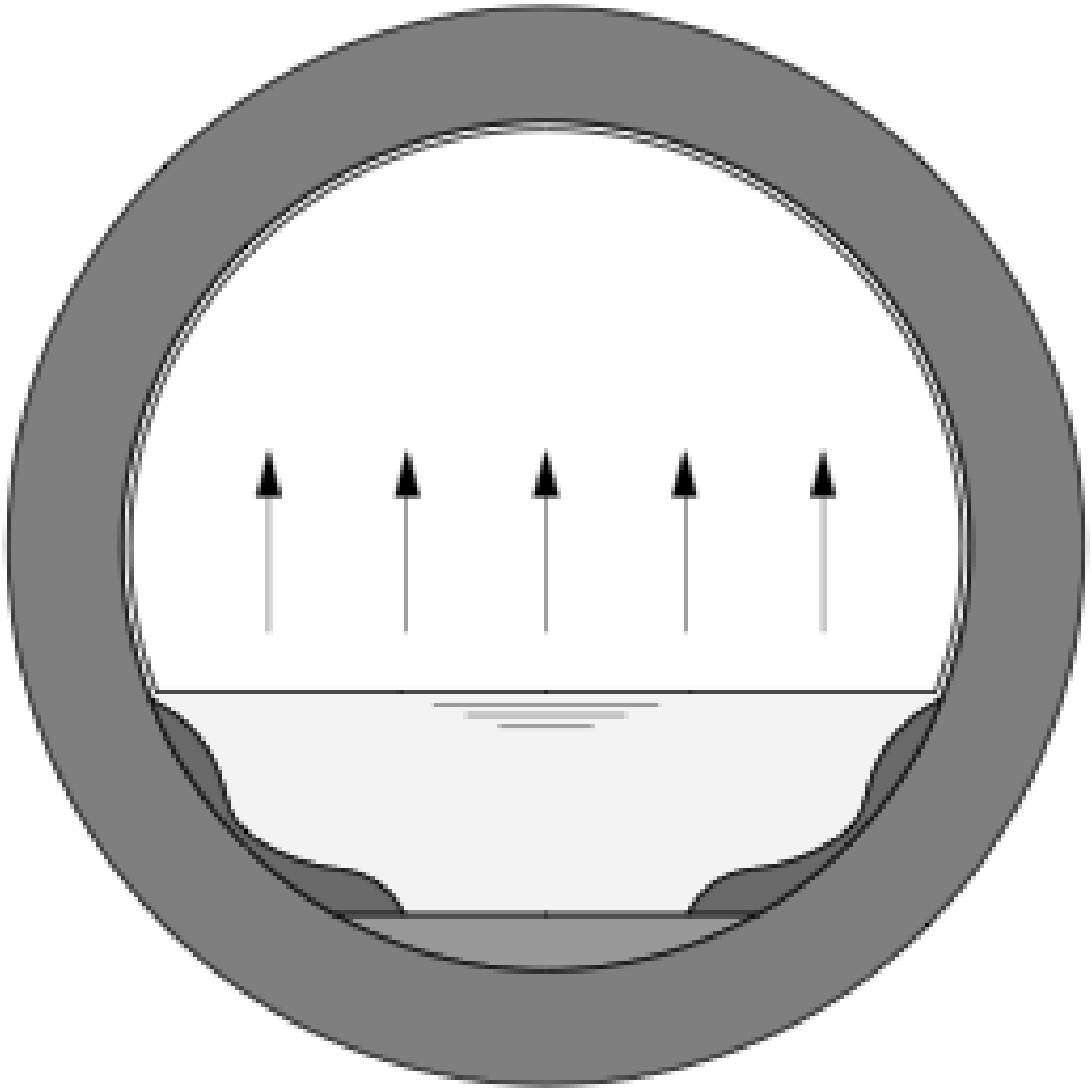


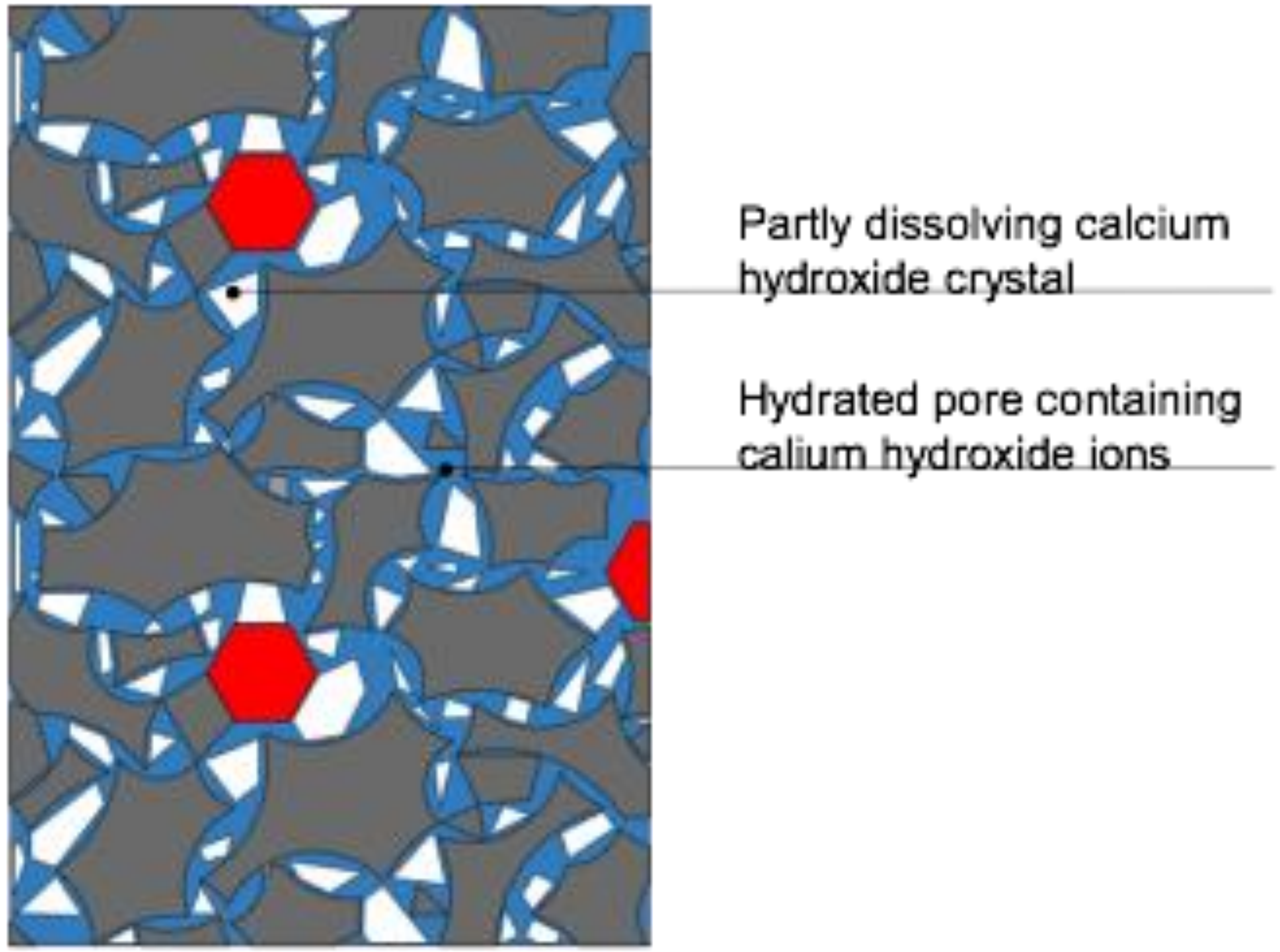
$$SO_4^{2-}\ (aq) + \text{S-comp.} \longrightarrow S^{2-}\ (aq)$$

$$\text{Org. comp} \longrightarrow \underline{H_2 + CO_2 + O_2}$$

$$H^+\ (aq) + S^{2-}\ (aq) \longrightarrow H_2S\ (aq)$$

Biogenic Sulfide Corrosion: process





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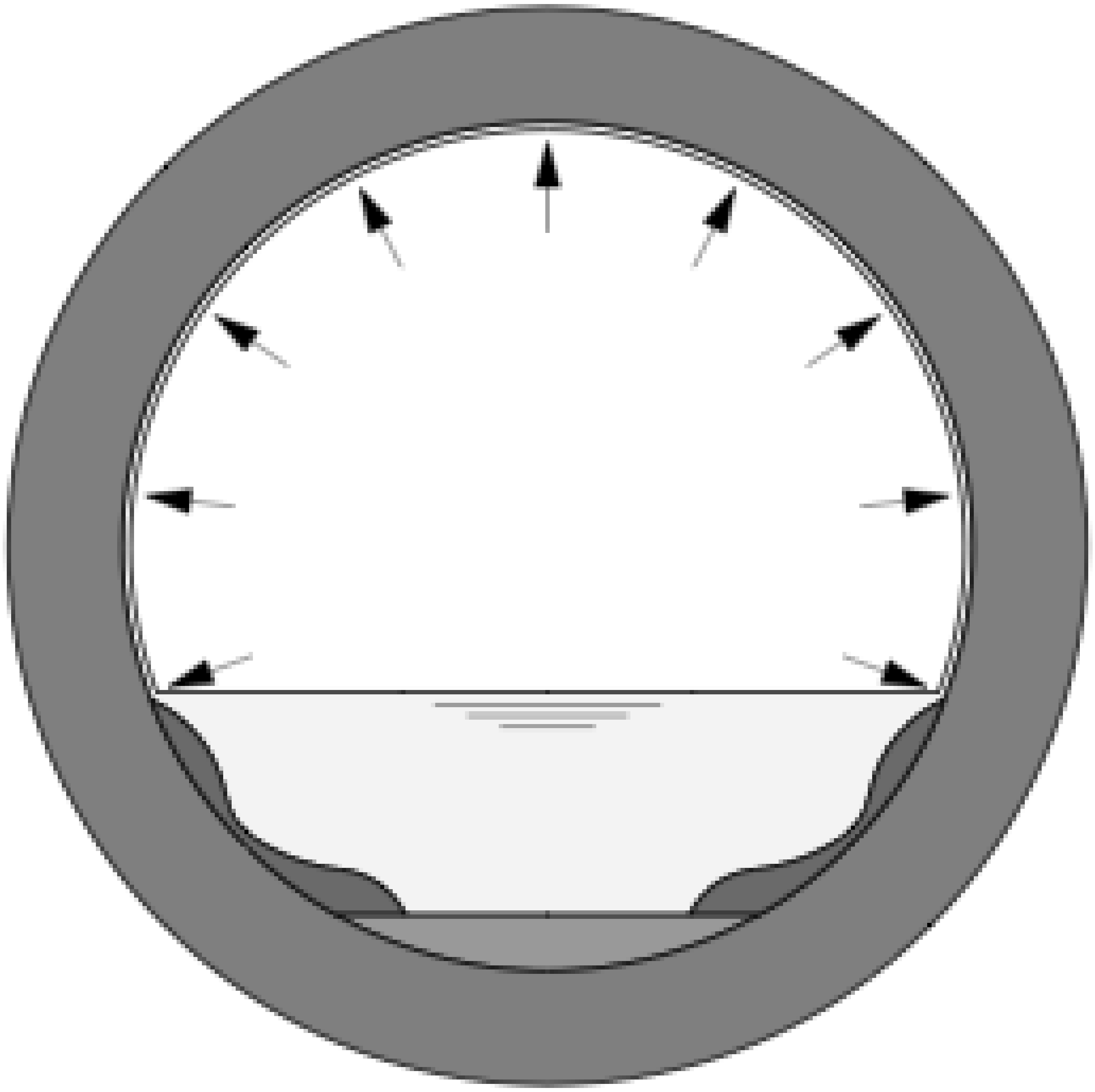
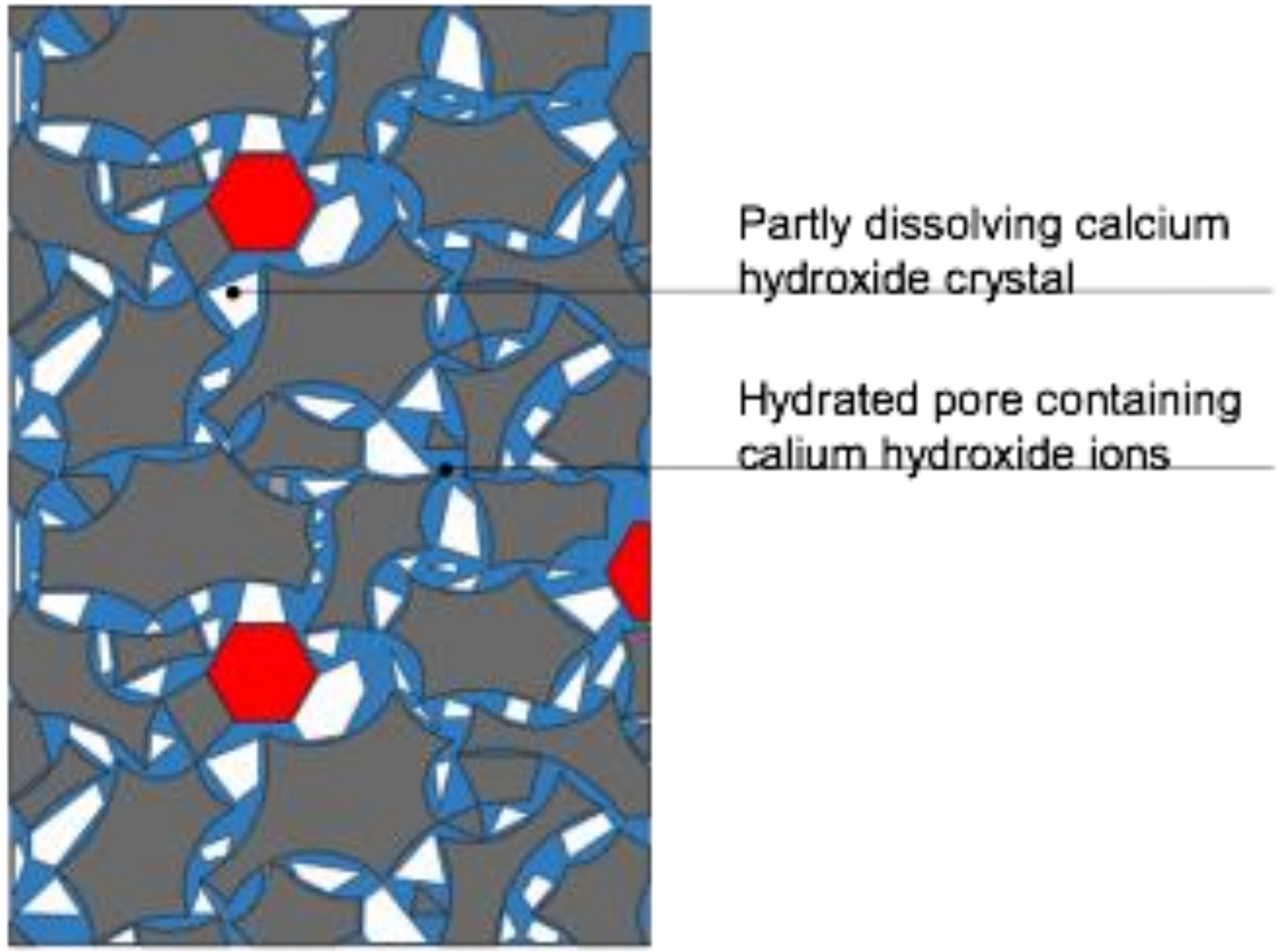
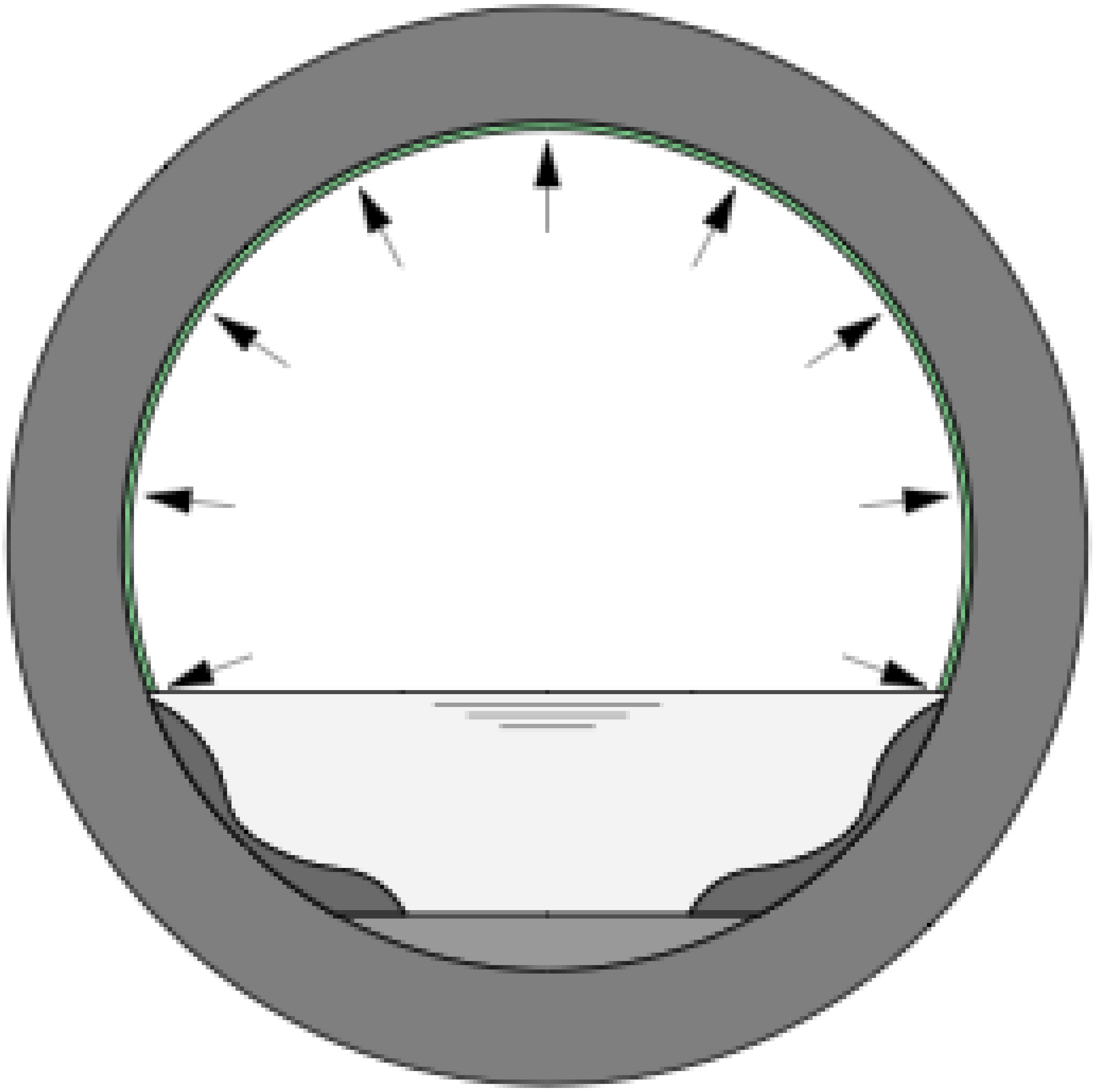
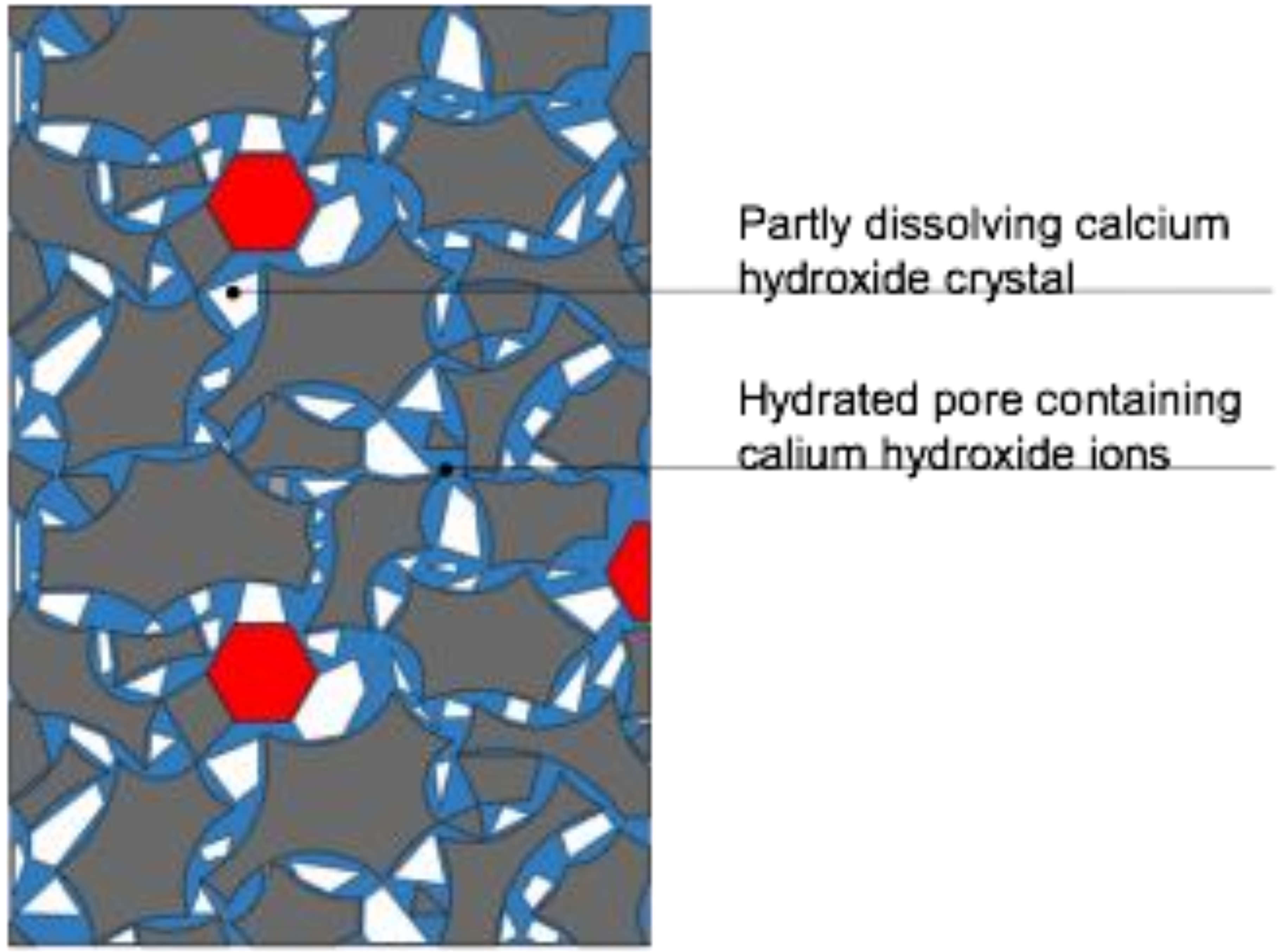


$$H_2S\ (g) \longrightarrow H^+\ (aq) + S^{2-}\ (aq)$$



Biogenic Sulfide Corrosion: process

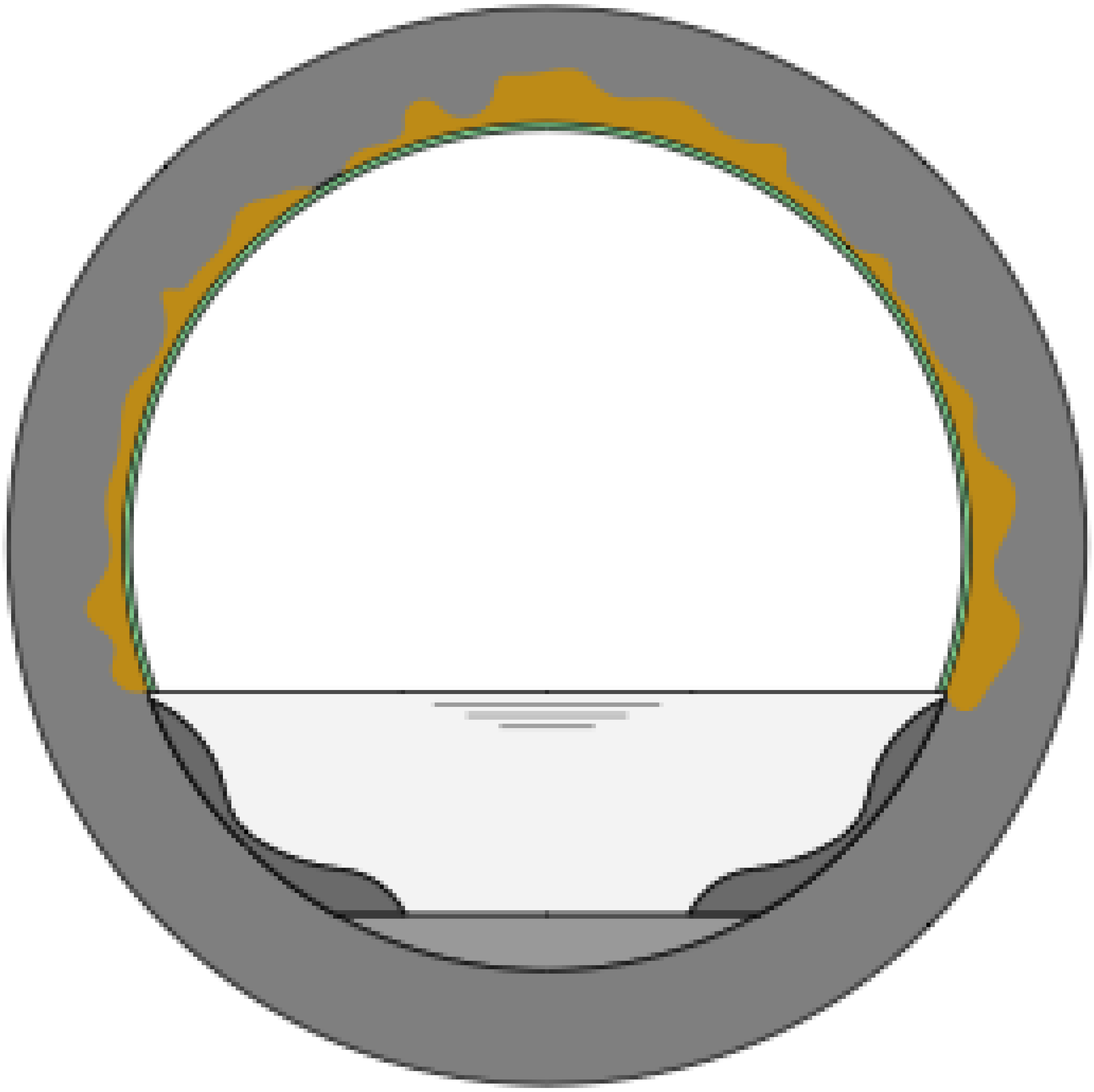


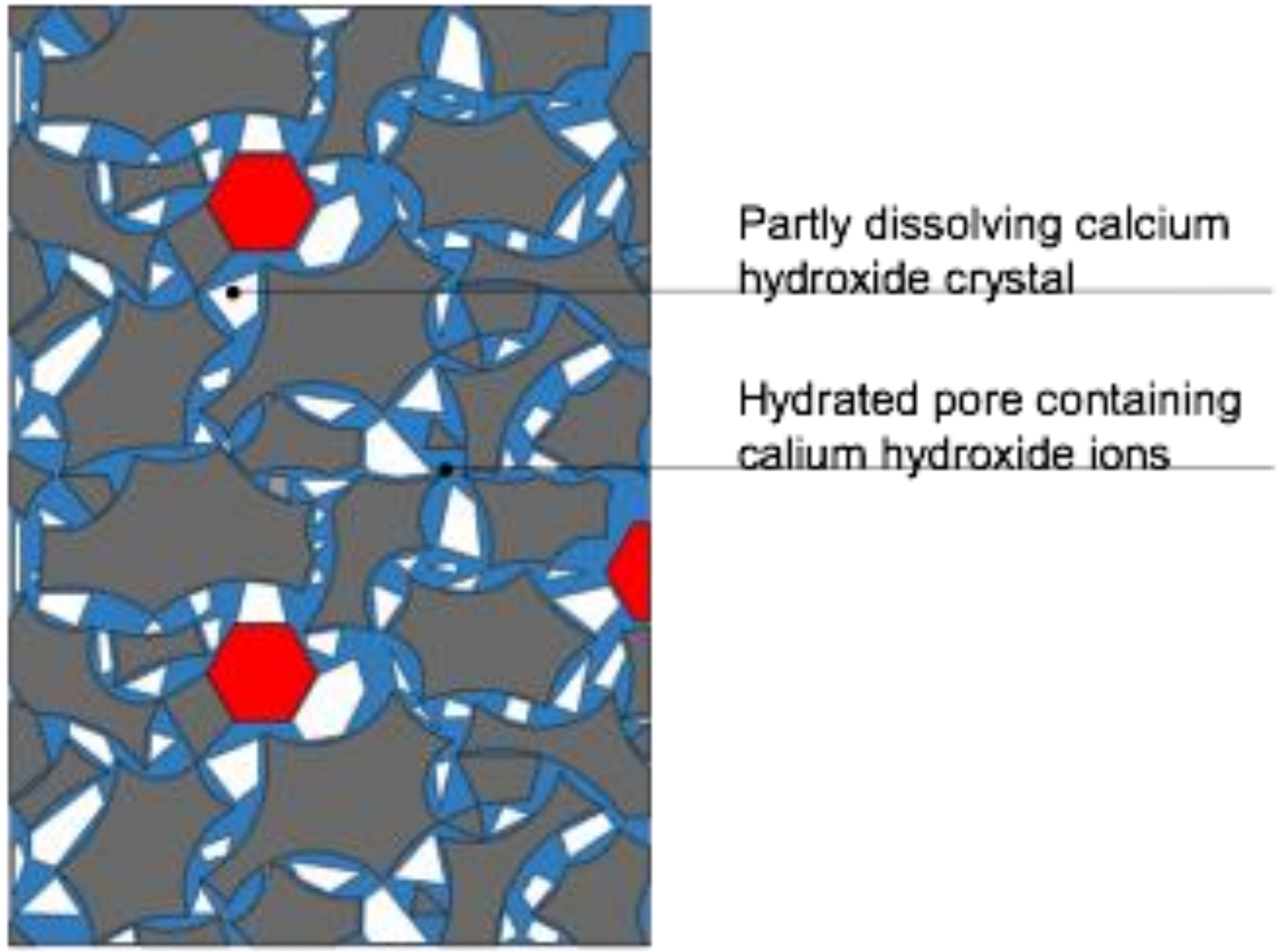


Possible reasons for pH reduction:

- Carbonation
- H_2S concentration
- Fungi

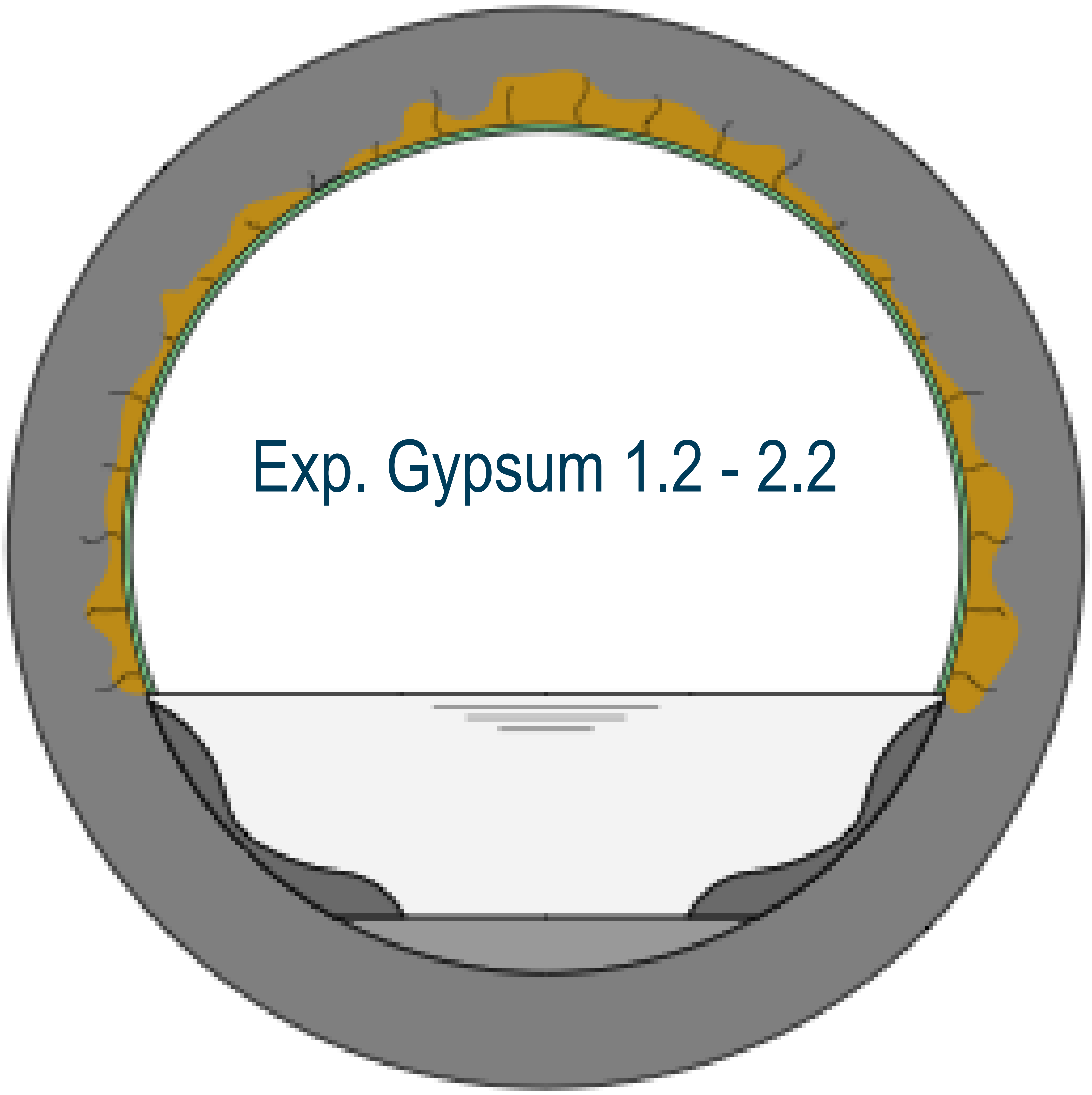
Biogenic Sulfide Corrosion: process

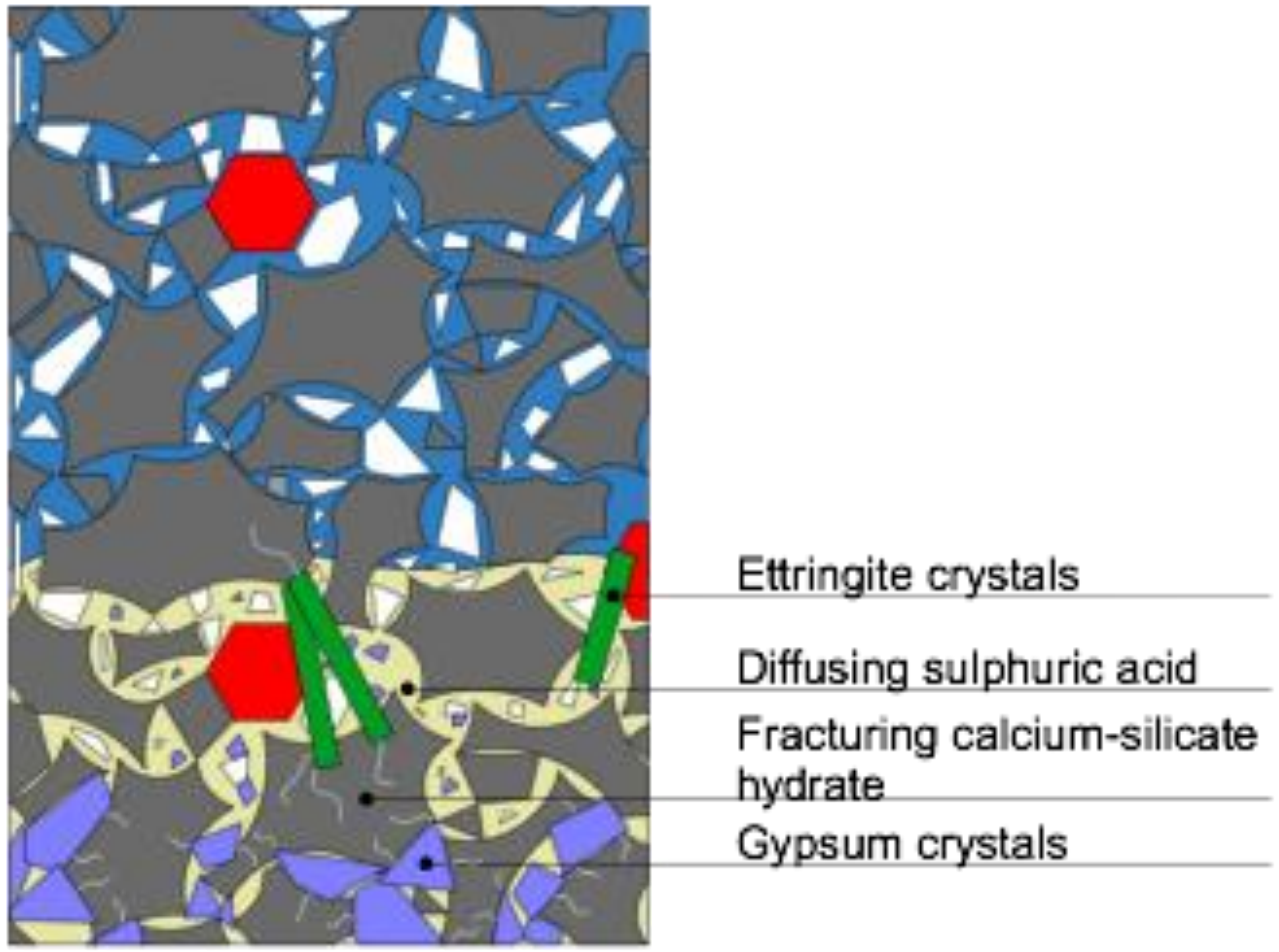




Theooxidans: $2H^{+}\ (aq) + S^{2-}\ (aq) \longrightarrow H_2SO_4\ (aq)$

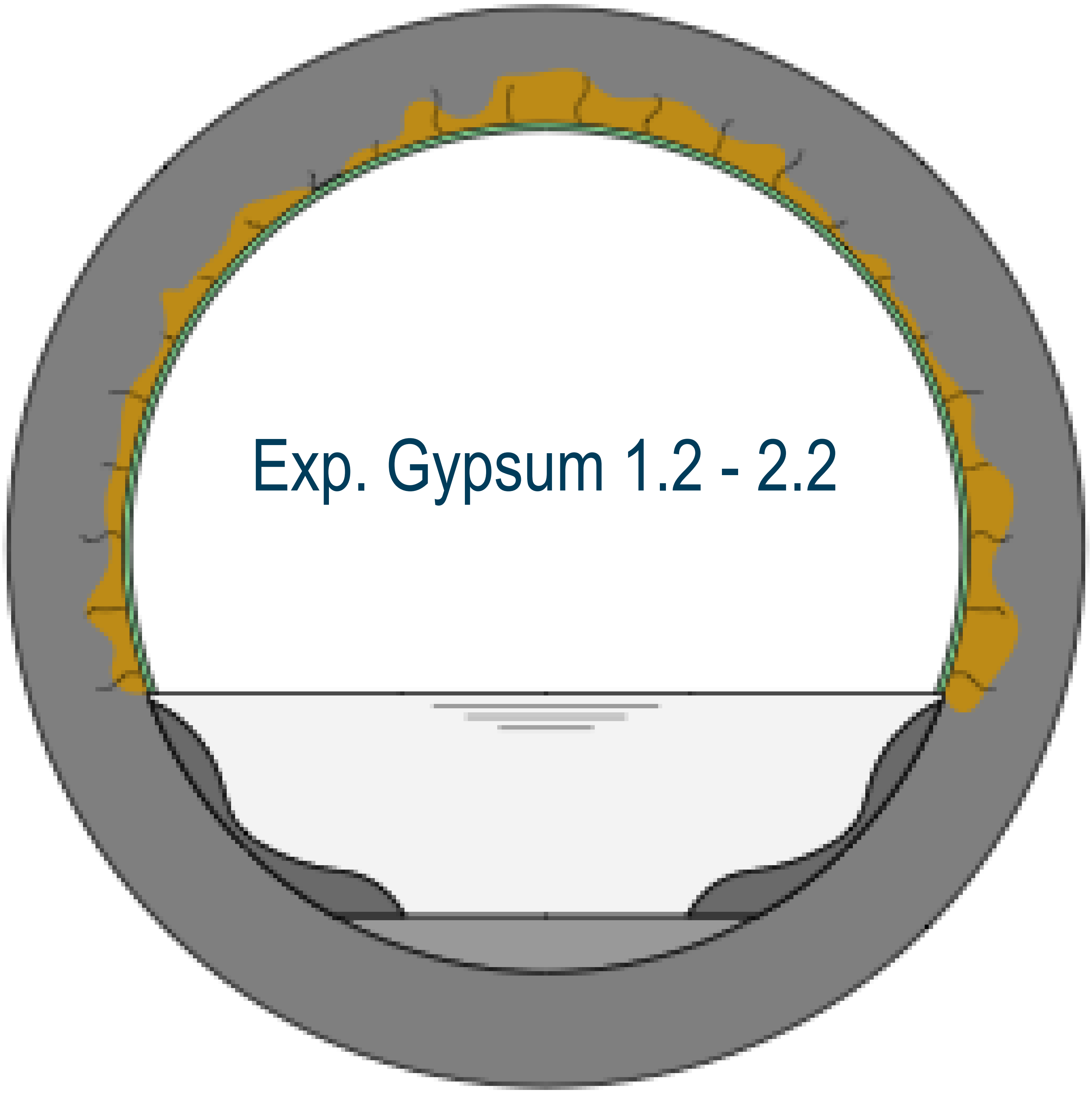
Biogenic Sulfide Corrosion: process

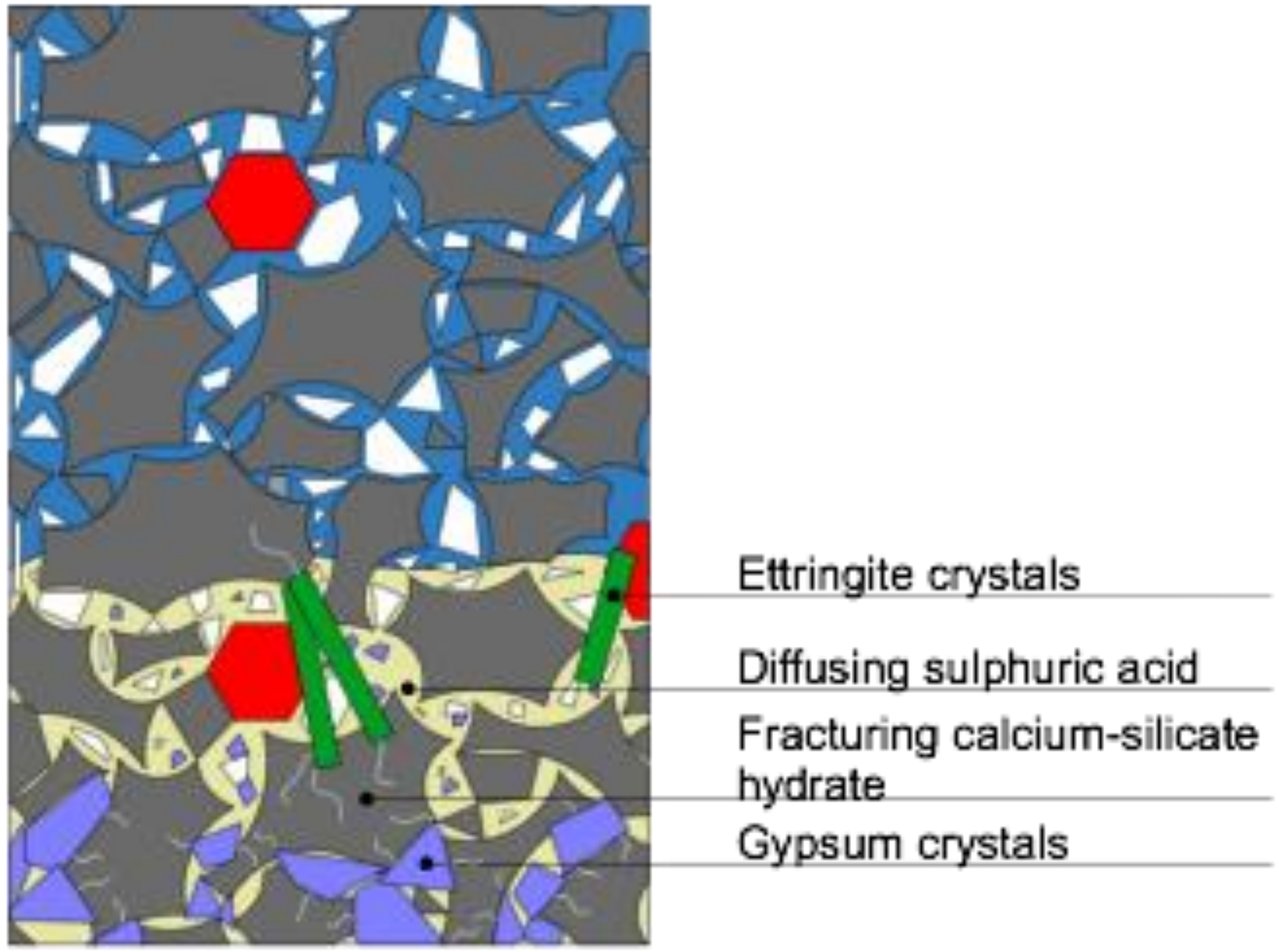




$Ca(OH)_2$	$+ H_2SO_4$ (aq)	$\longrightarrow CaSO_4 \cdot 2H_2O$
Calcium hydroxide	Sulfuric acid	Gypsum
$Ca^{2+} + 2OH^-$	$+ 2H^+ + SO_4^{2-}$ (aq)	$\longrightarrow CaSO_4 \cdot 2H_2O$

Biogenic Sulfide Corrosion: process

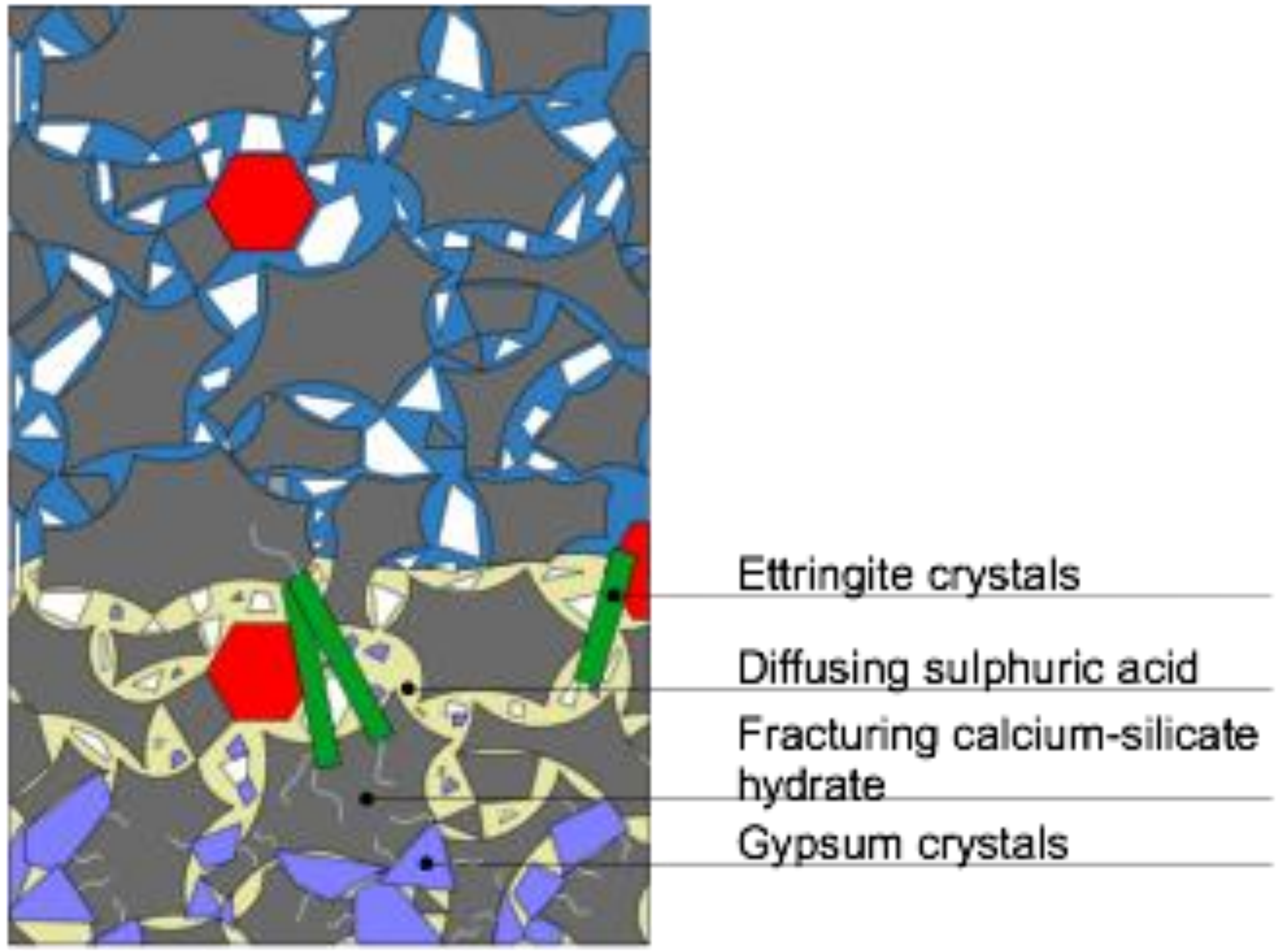




$$3CaO \cdot 2SiO_2 \cdot 3H_2O + H_2SO_4\ (aq) \longrightarrow CaSO_4 \cdot 2H_2O + Si(OH)_4$$

Calcium-silicate hydrate + Sulfuric acid → Gypsum + Silicic acid

Biogenic Sulfide Corrosion: process



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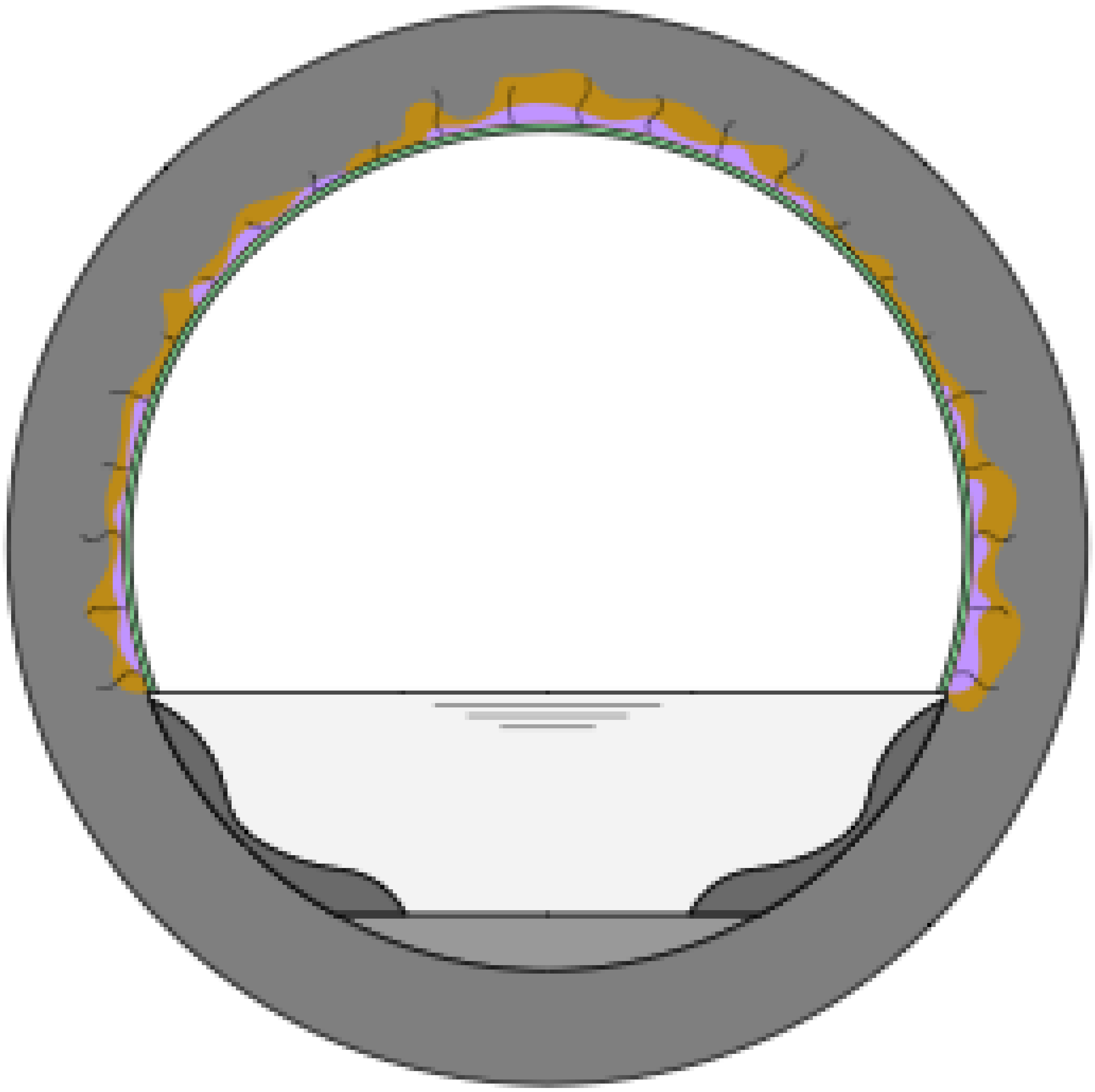
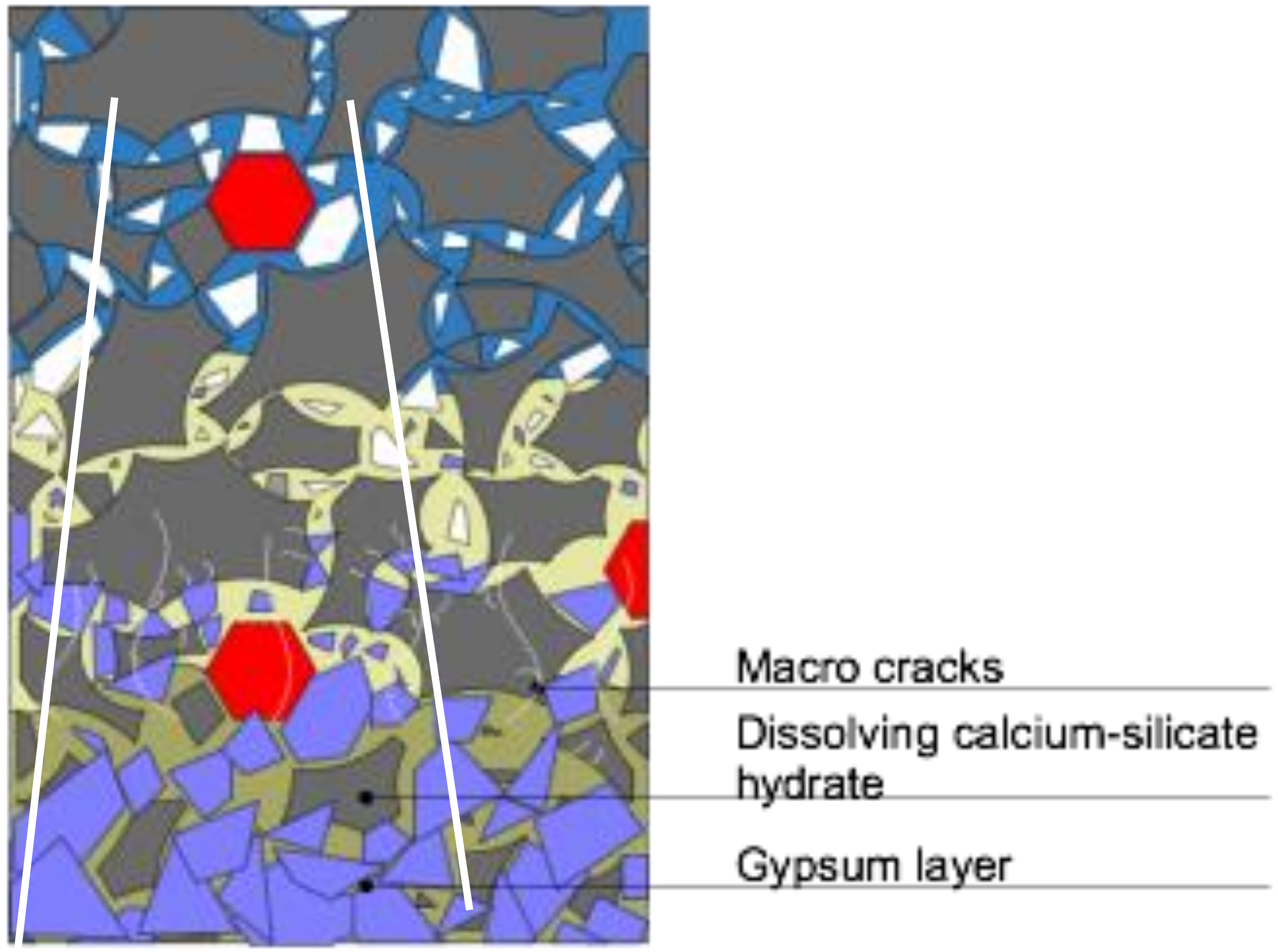
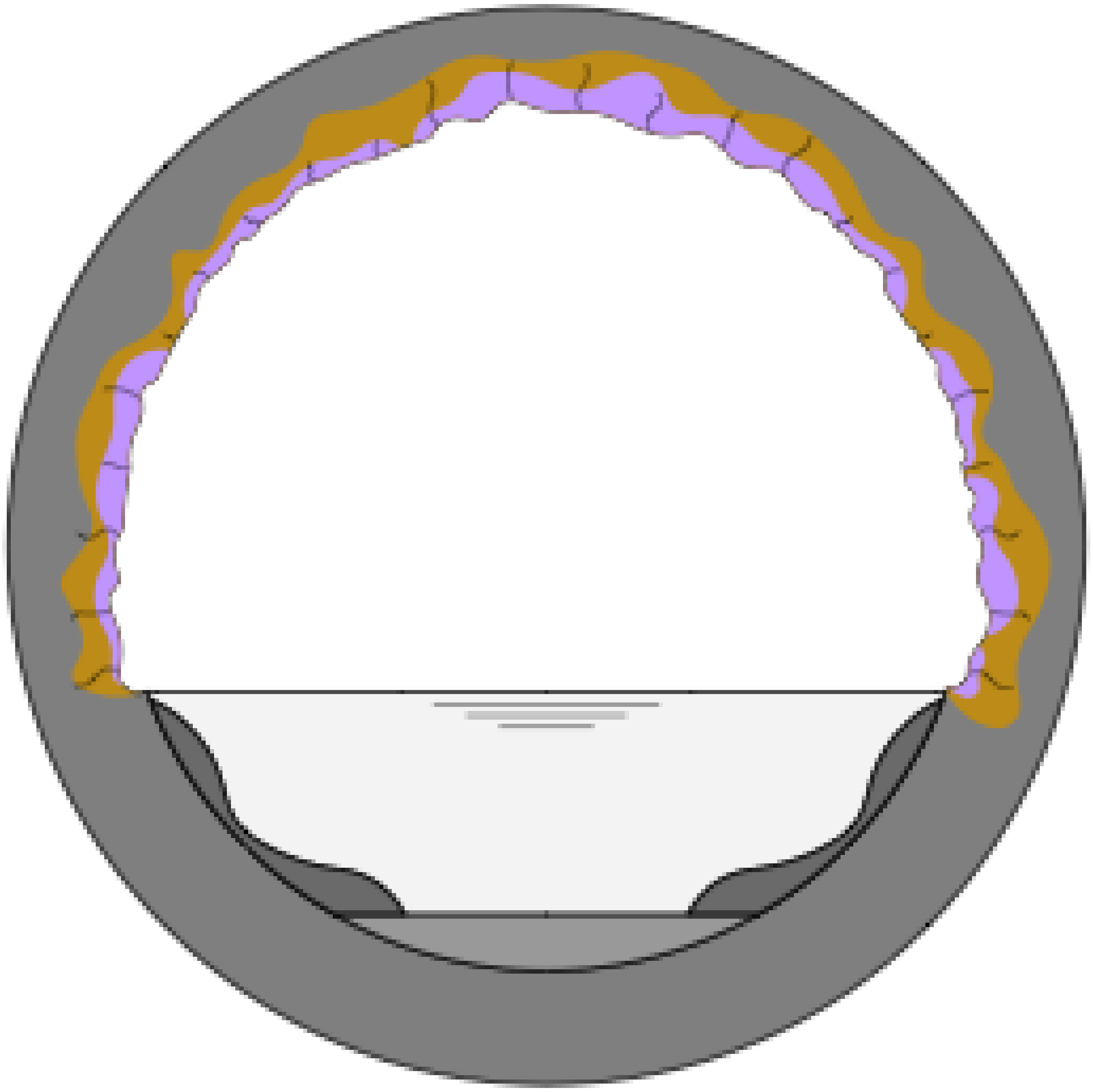




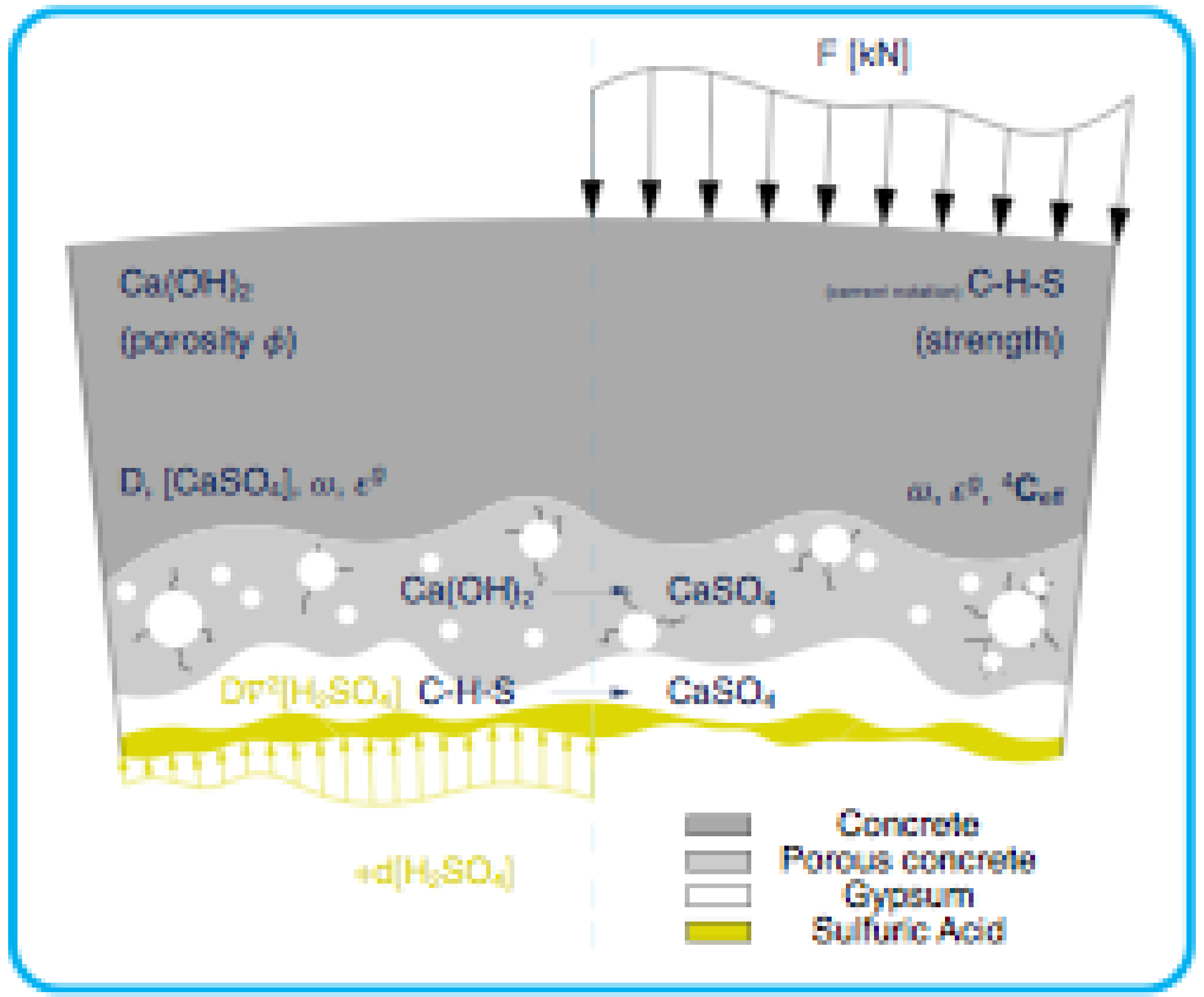
Biogenic Sulfide Corrosion: process



Modelling Approach

Diffusion Processes

$$\frac{\partial [C_i]}{\partial t} = \nabla \cdot \left(D_i \nabla [C_i] \right) + \mathbf{R}_{1\times m} \mathbf{Q}_{m\times 1}$$



$$\boldsymbol{\sigma} = (1-\omega)\, {}^4\mathbb{C}_0 : \boldsymbol{\varepsilon}^e$$

Continuum Damage Mechanics

Diffusion Processes

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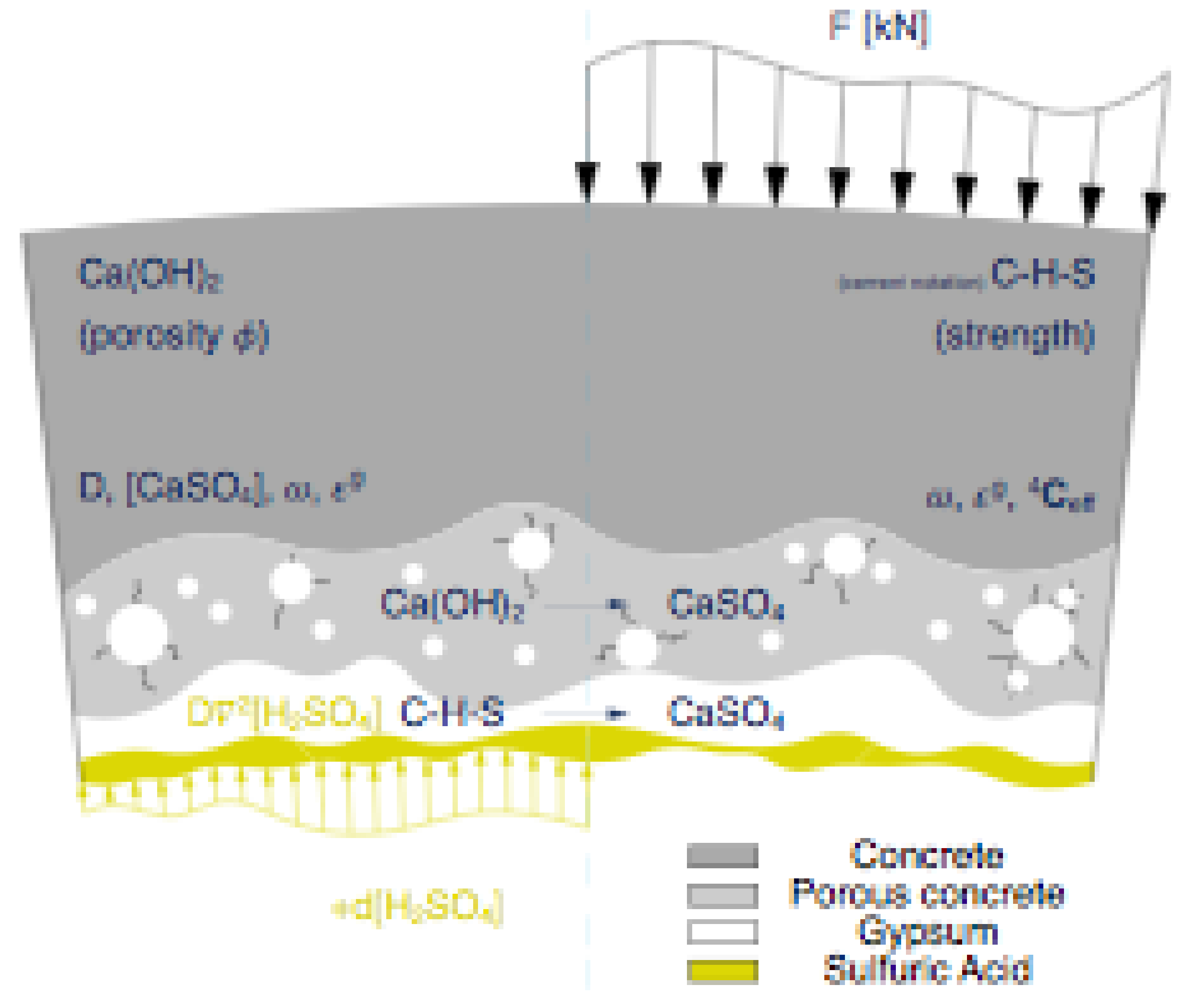

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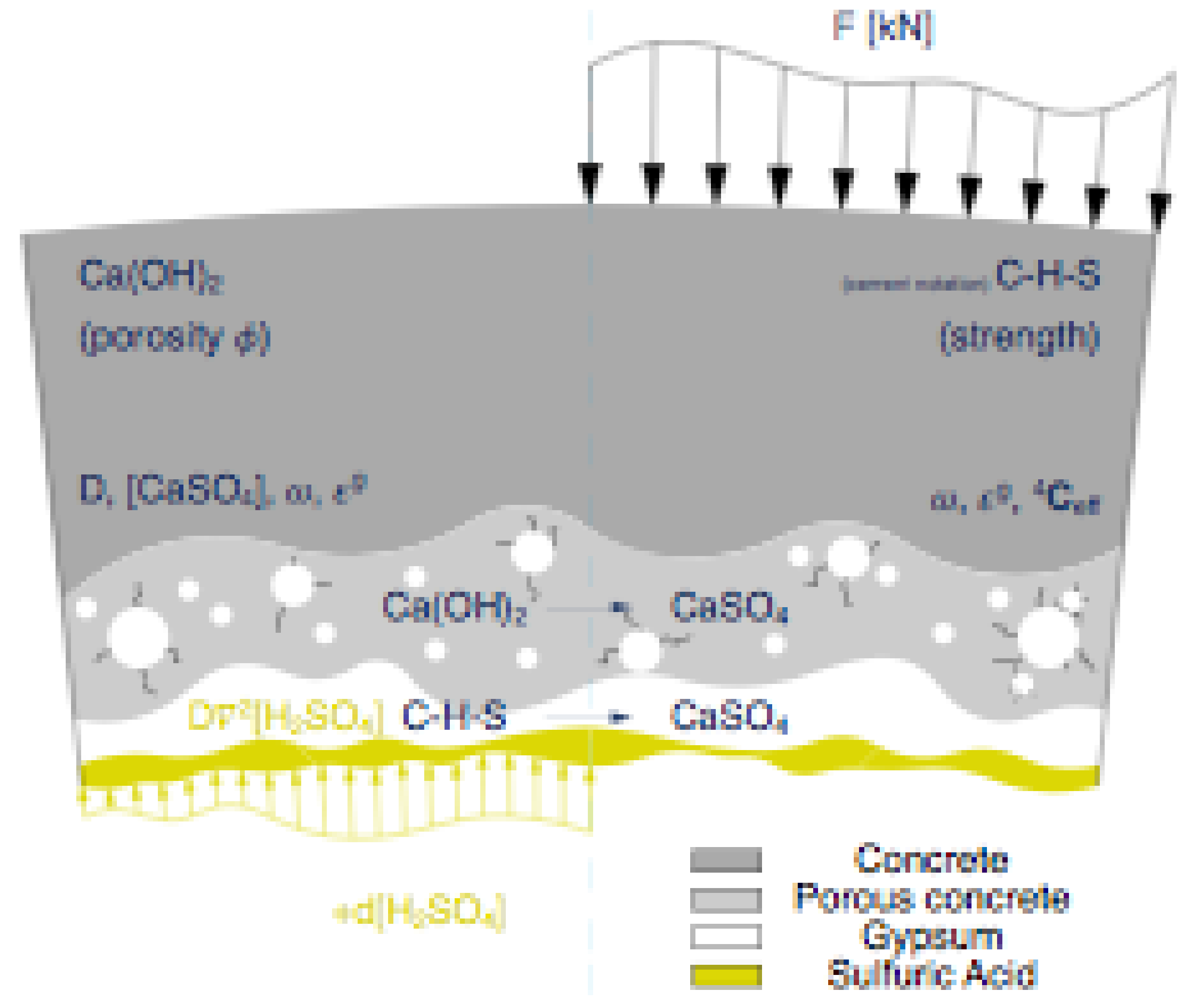
Continuum Damage Mechanics

Diffusion Processes

$$\frac{\partial [C_i]}{\partial t} = \nabla \cdot (D_i \nabla [C_i]) + \mathbf{R}_{1\times m}\mathbf{Q}_{m\times 1}$$

$$D = D(\omega)$$



$$\omega = \omega(\kappa)$$

$$\boldsymbol{\varepsilon}^e = \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^g$$

$$\varphi = \frac{[CSH]}{[CSH]_0}$$

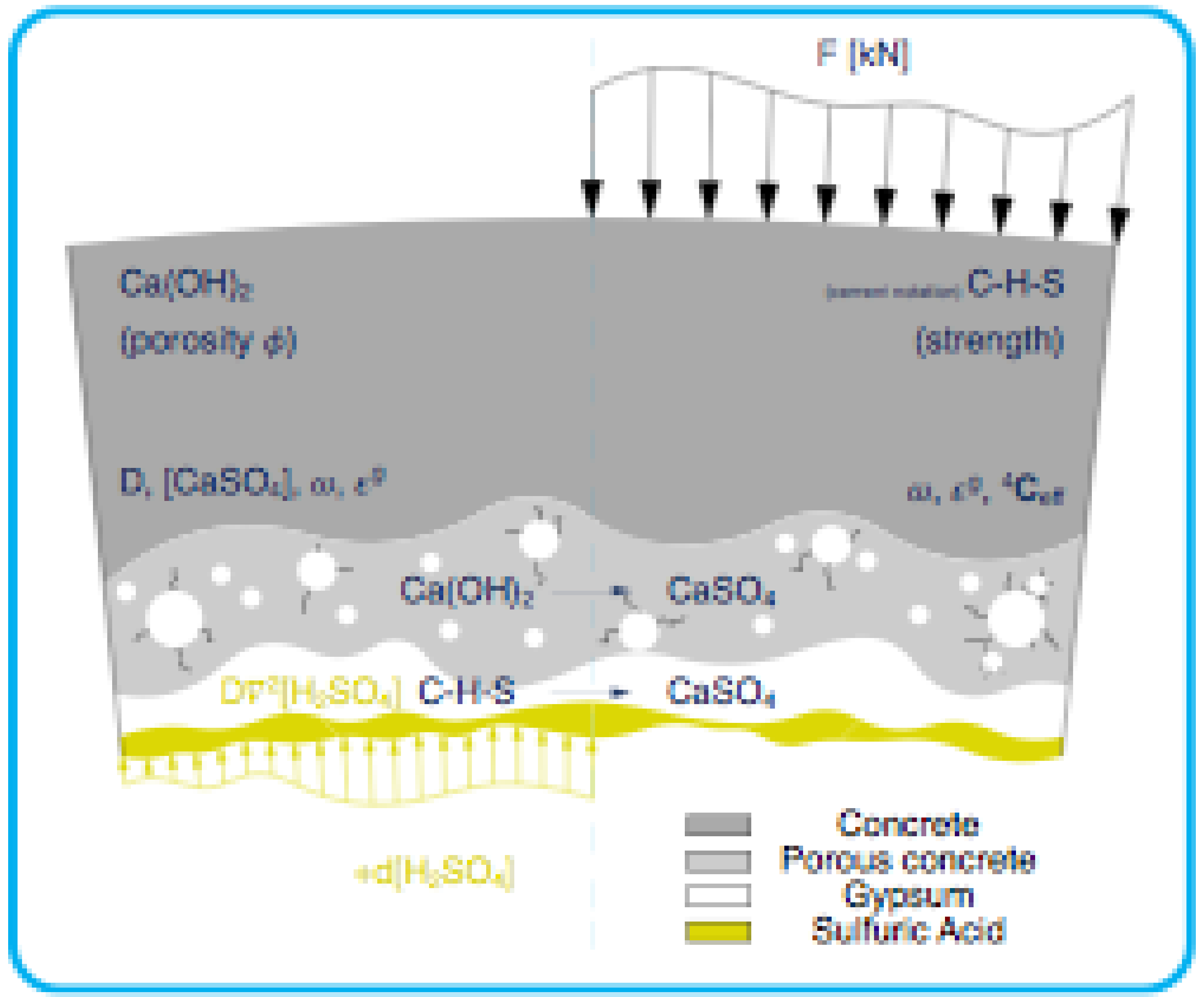
$$\boldsymbol{\sigma} = (1-\omega)\, {}^4\mathbb{C}_0 : \boldsymbol{\varepsilon}^e$$

Continuum Damage Mechanics

Diffusion Processes

For all relevant chemical species i, involved in m reactions:

$$\frac{\partial C_i}{\partial t} = \nabla \cdot \left(D_i(\omega) \nabla C_i \right) + \mathbf{R}_{1\times m}\mathbf{Q}_{m\times 1}$$



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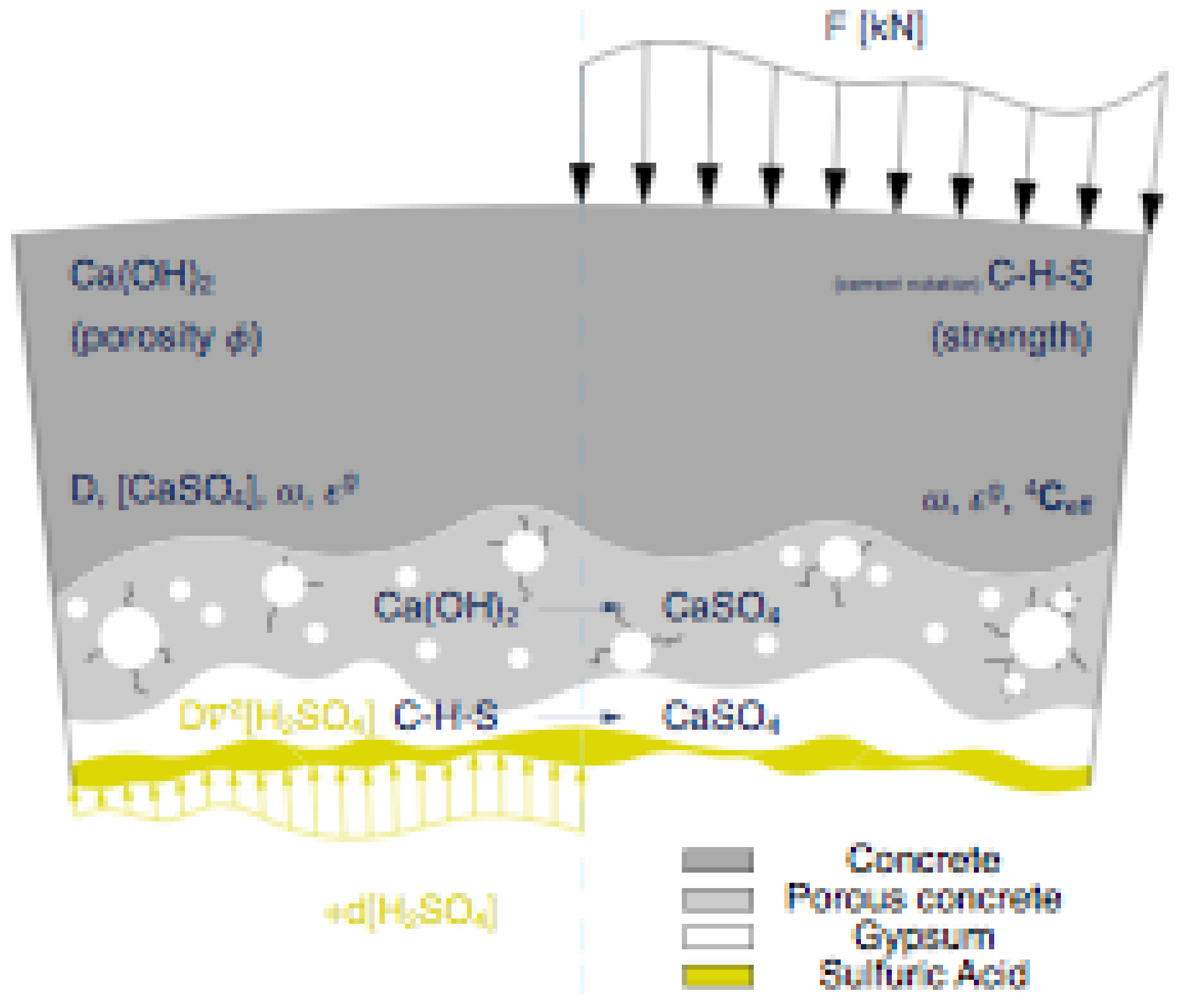
$$\frac{\partial C_i}{\partial t} = \nabla \cdot \left(D_i(\omega) \nabla C_i \right) + \mathbf{R}_{1\times m} \mathbf{Q}_{m\times 1}$$

C_{CaSO_4} → C_{CHS}

$$\underbrace{\varphi = \frac{C_{CHS}}{C_{CHS}|_0}}_{\text{Volume fraction of C-H-S}} \qquad \underbrace{\epsilon^{chem} = \epsilon^{g} C_{CaSO_4} \mathbf{I}}_{\text{Growth strain tensor}}$$



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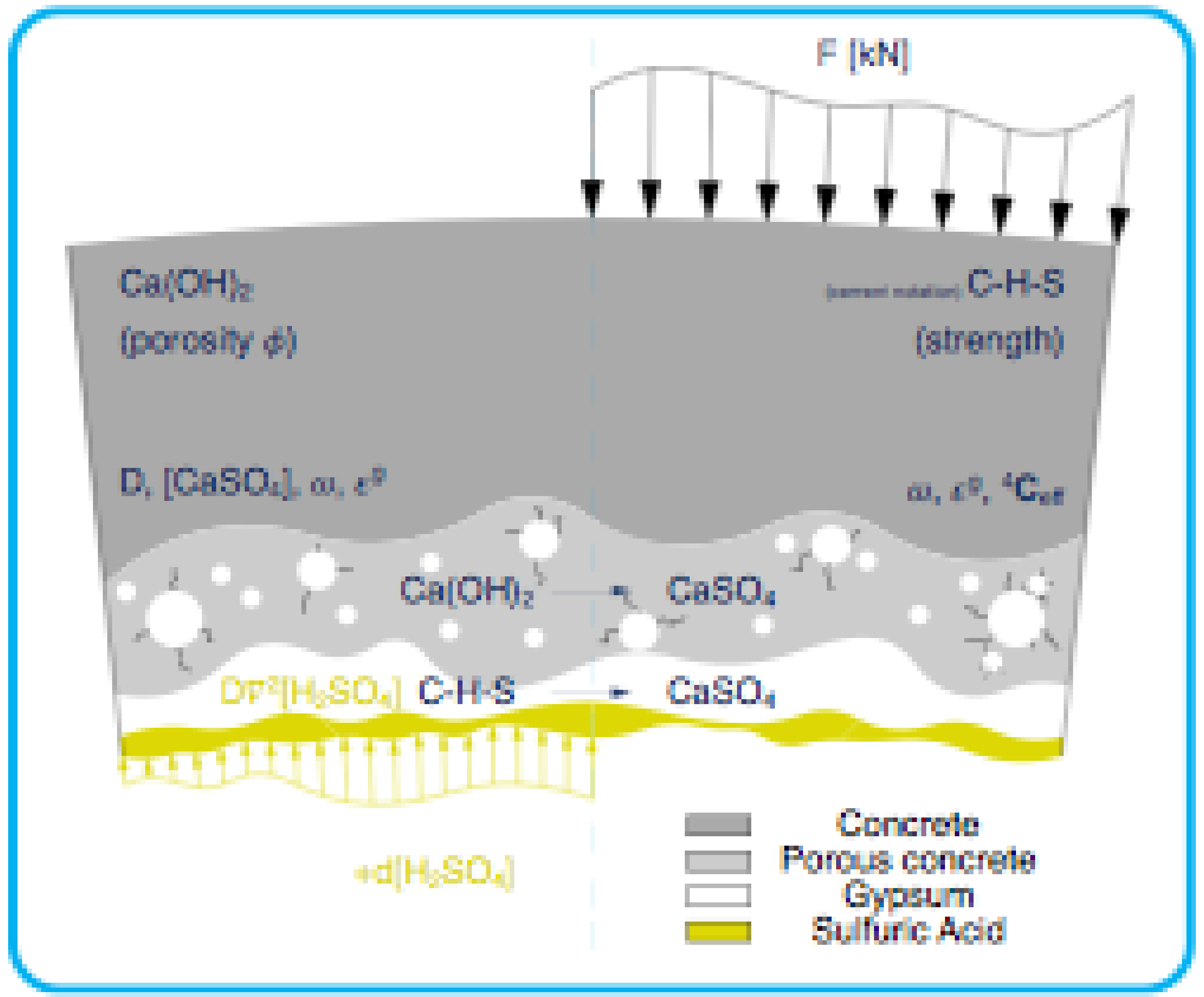
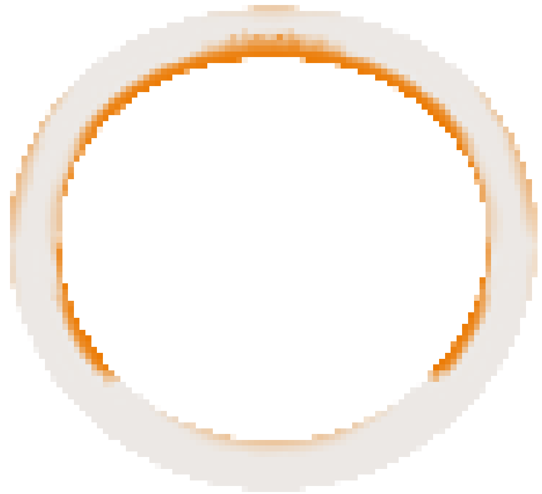
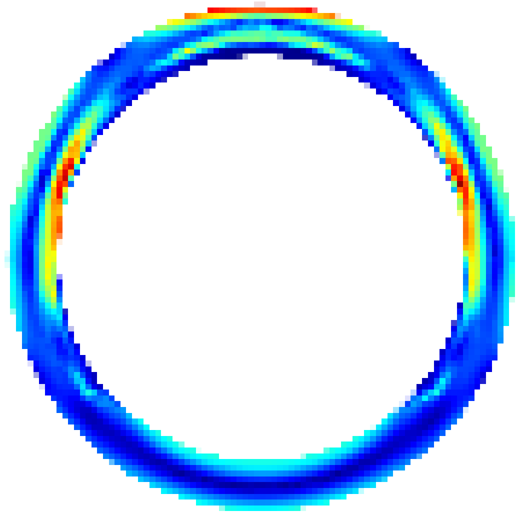


Total Damage:

$$\Omega = \left(1 - \omega_n(\kappa)\right)\left(1 - \varphi\right)$$



$$\boldsymbol{\sigma} = \Omega\, {}^4\mathbf{C}_{CHS,0} : \left(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}^{chem}\right)$$



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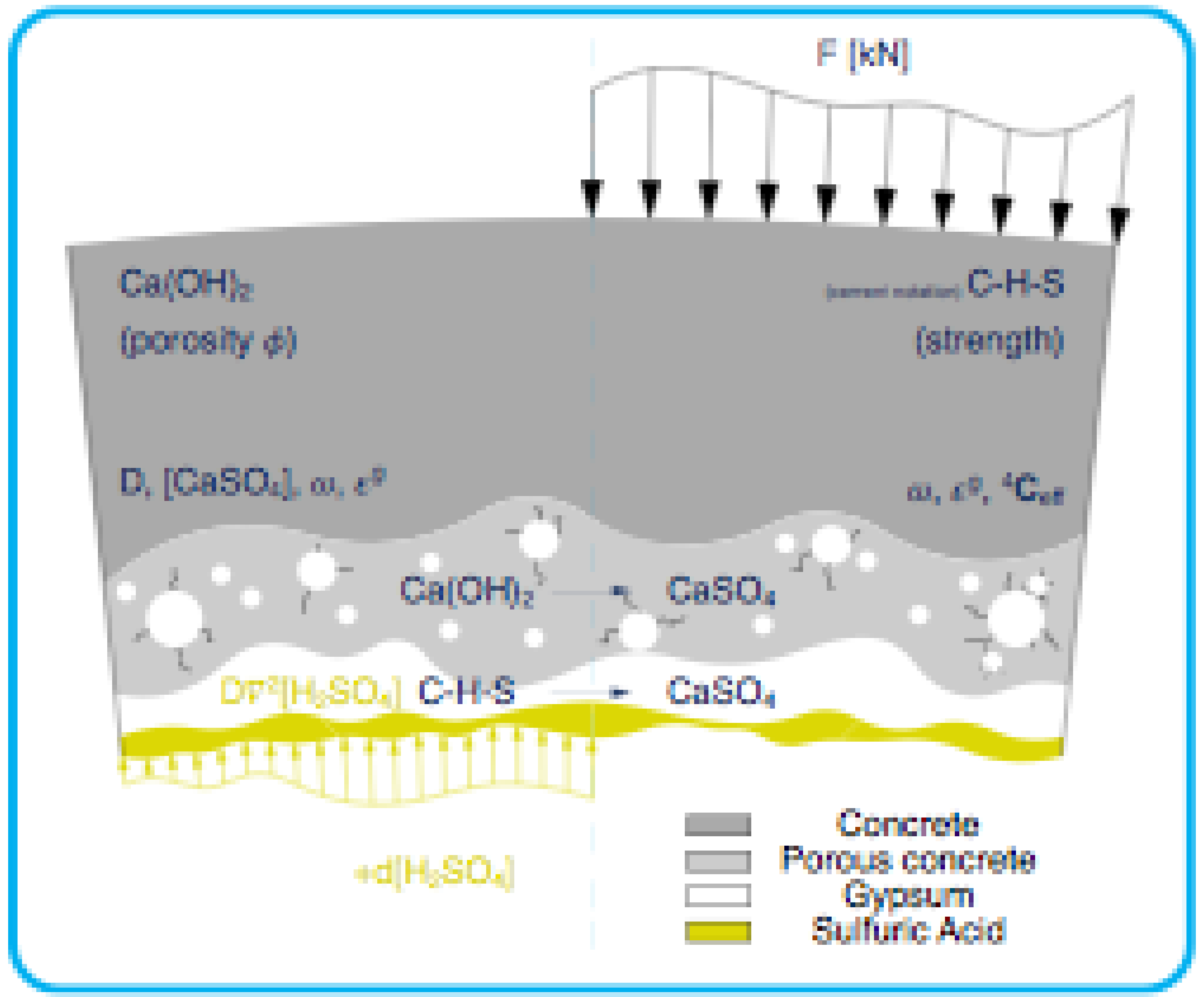

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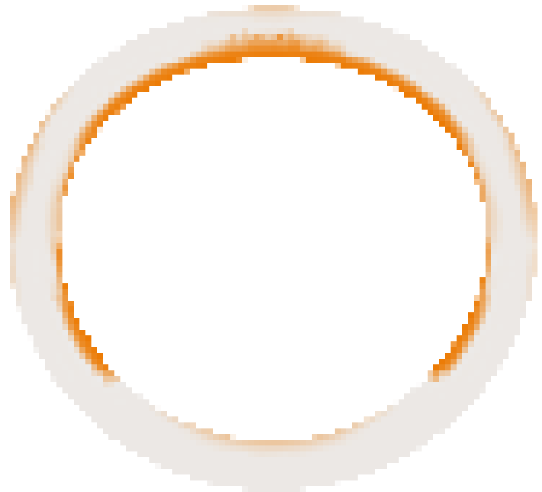

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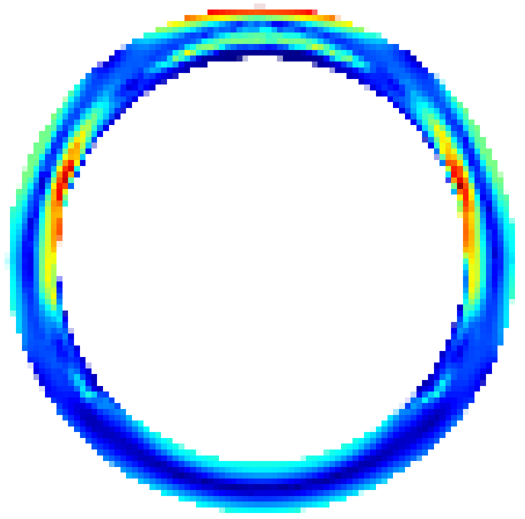
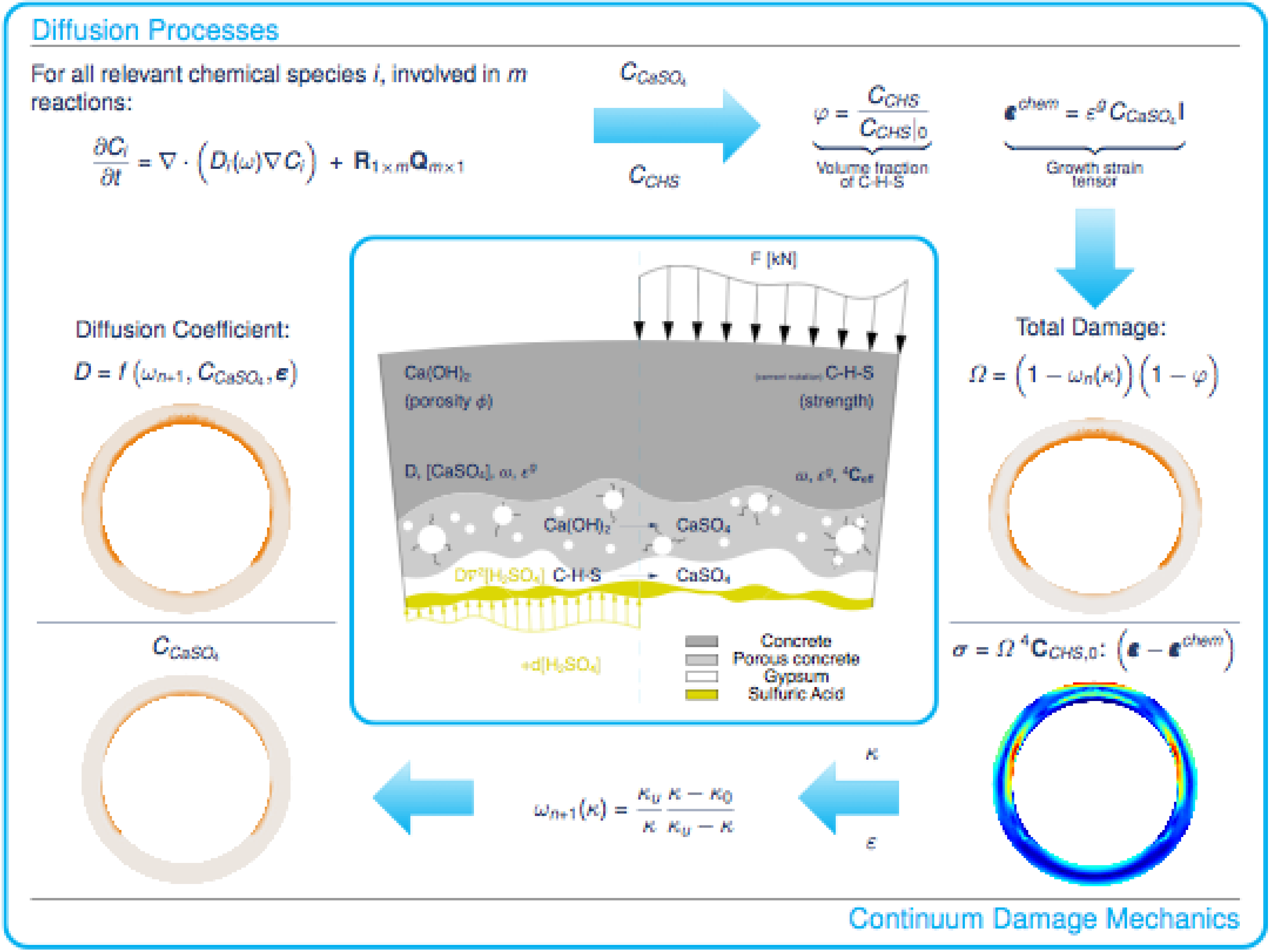


κ

ε

$$\omega_{n+1}(\kappa) = \frac{\kappa_u}{\kappa} \frac{\kappa - \kappa_0}{\kappa_u - \kappa}$$

Continuum Damage Mechanics


Diffusion Processes
For all relevant chemical species i, involved in m reactions:
$\frac{\partial C_i}{\partial t} = \nabla \cdot \left(D_i(\omega) \nabla C_i \right) + \mathbf{R}_{1\times m} \mathbf{Q}_{m\times 1}$
C_{CaSO_4}
C_{CHS}
$\varphi = \frac{C_{CHS}}{C_{CHS}|_0}$
Volume fraction of C-H-S
$\boldsymbol{\epsilon}^{chem} = \varepsilon^g C_{CaSO_4} \mathbf{I}$
Growth strain tensor
Diffusion Coefficient:
$D = f\left(\omega_{n+1}, C_{CaSO_4}, \boldsymbol{\epsilon}\right)$
F [kN]
Ca(OH)₂
(porosity ϕ)
C-H-S
(strength)
D, [CaSO₄], ω, ε^g
ω, ε^g, $^4\mathbf{C}_{\mathrm{eff}}$
Ca(OH)₂
CaSO₄
C-H-S
CaSO₄
Concrete
Porous concrete
Gypsum
Sulfuric Acid
Total Damage:
$\Omega = \left(1 - \omega_n(\kappa)\right)\left(1 - \varphi\right)$
C_{CaSO_4}
$\sigma = \Omega\, ^4\mathbf{C}_{CHS,0} : \left(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}^{chem}\right)$
κ
$\omega_{n+1}(\kappa) = \frac{\kappa_u}{\kappa} \frac{\kappa - \kappa_0}{\kappa_u - \kappa}$
ε
Continuum Damage Mechanics

Diffusion Processes

For all relevant chemical species i, involved in m reactions:

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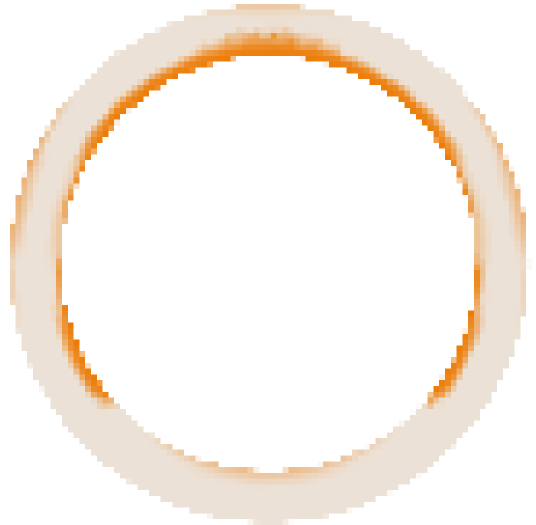
$D(\omega)$

Diffusion Coefficient:

$$D = f\left(\omega_{n+1}, C_{CaSO_4}, \boldsymbol{\varepsilon}\right)$$



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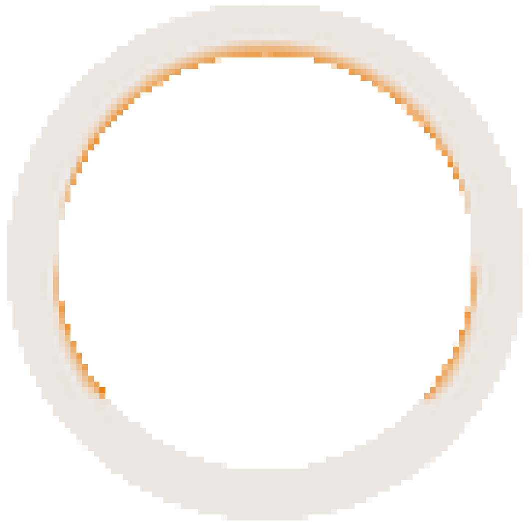

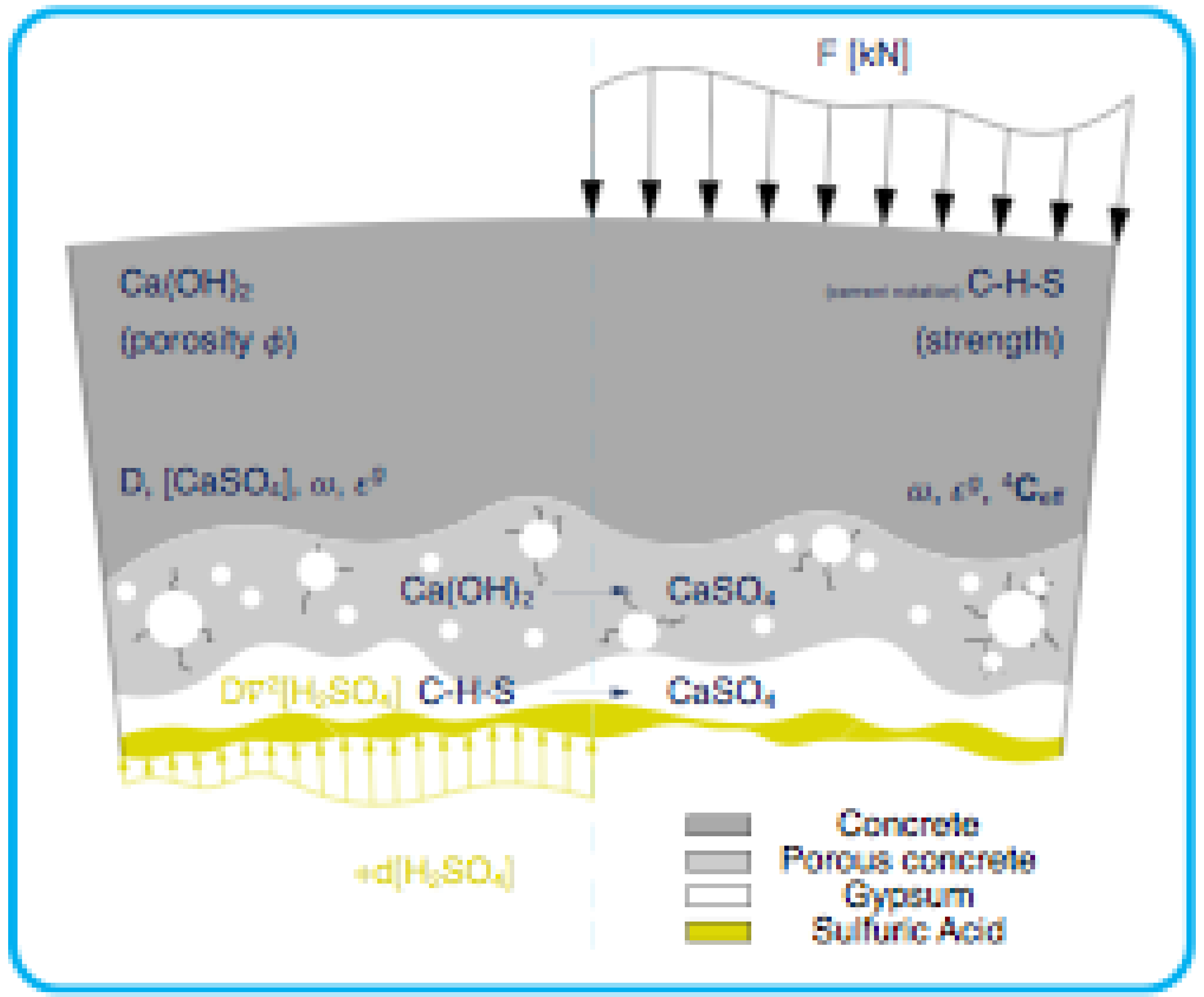

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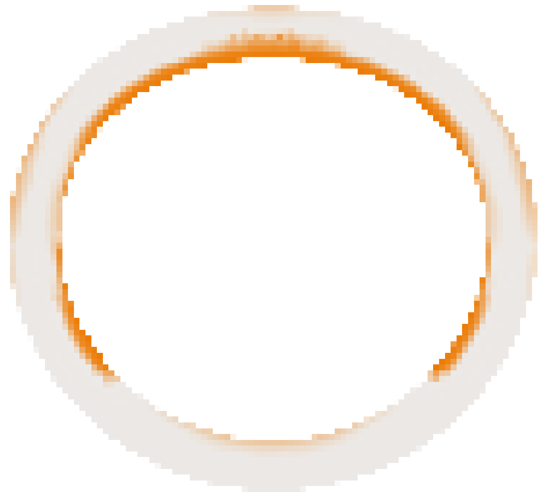
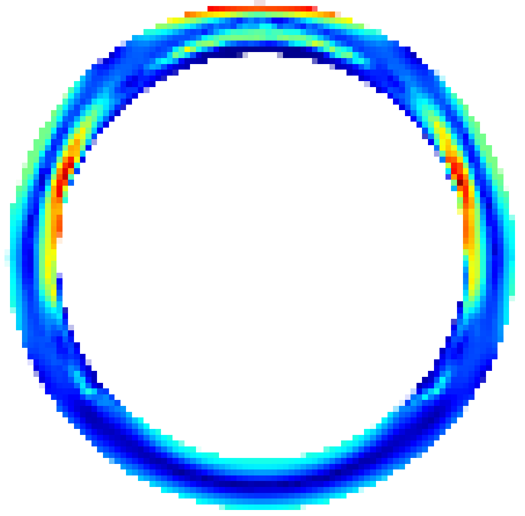


$$\boldsymbol{\sigma} = \Omega\, {}^4\mathbf{C}_{CHS,0} : \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{chem}\right)$$



κ

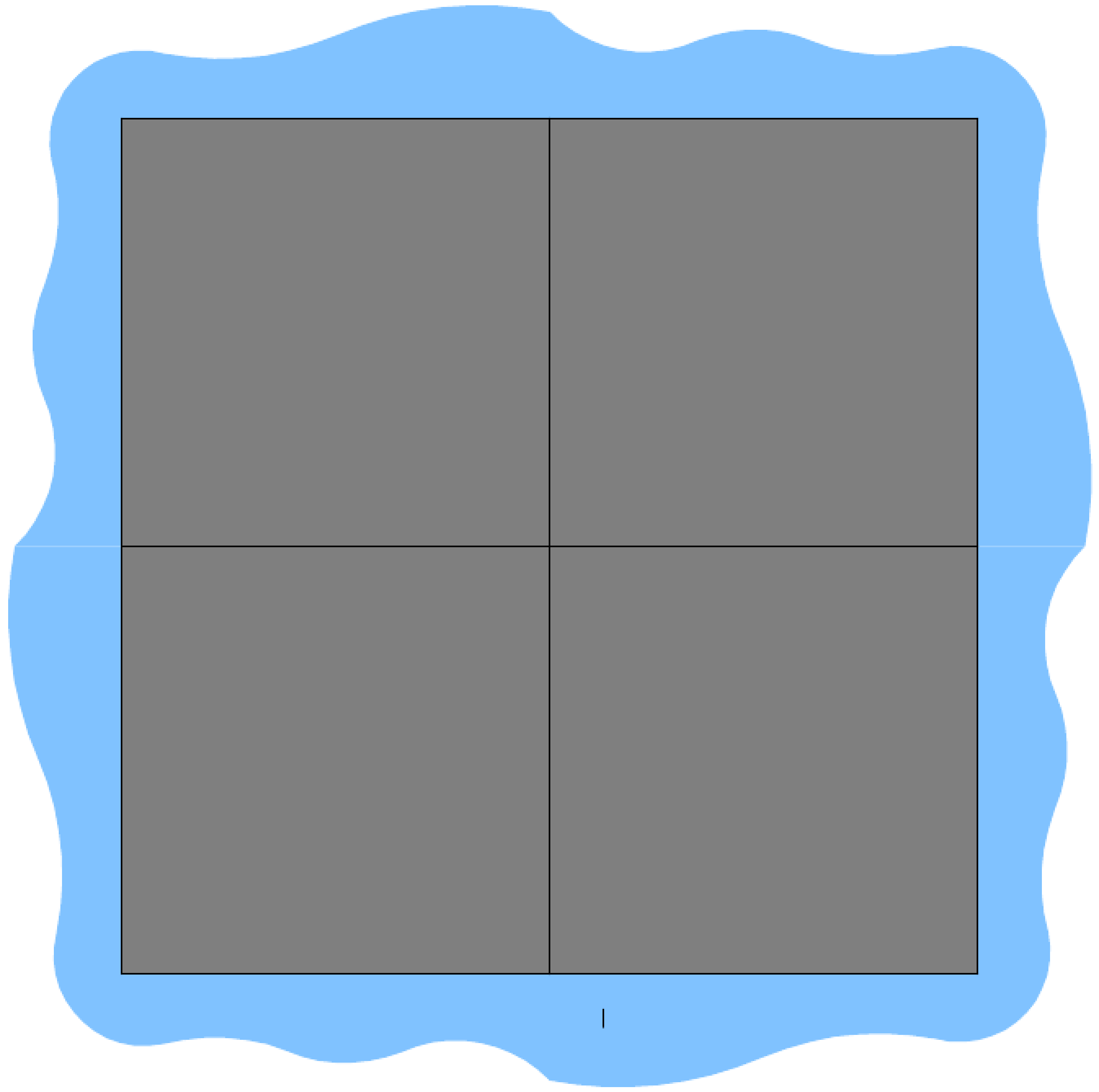
ε

$$\omega_{n+1}(\kappa) = \frac{\kappa_u}{\kappa} \frac{\kappa - \kappa_0}{\kappa_u - \kappa}$$

Continuum Damage Mechanics

Parameters

Parameters



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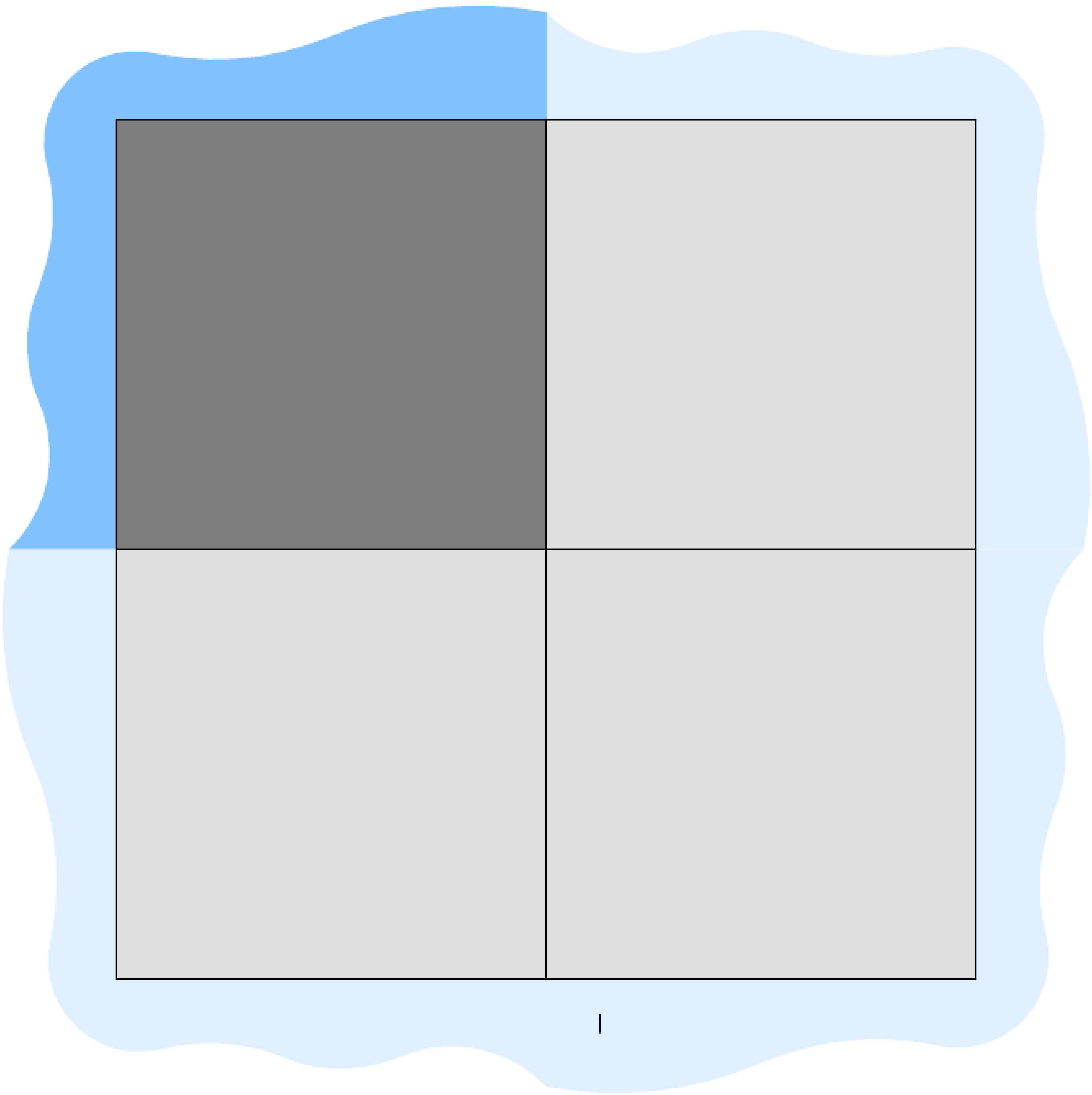

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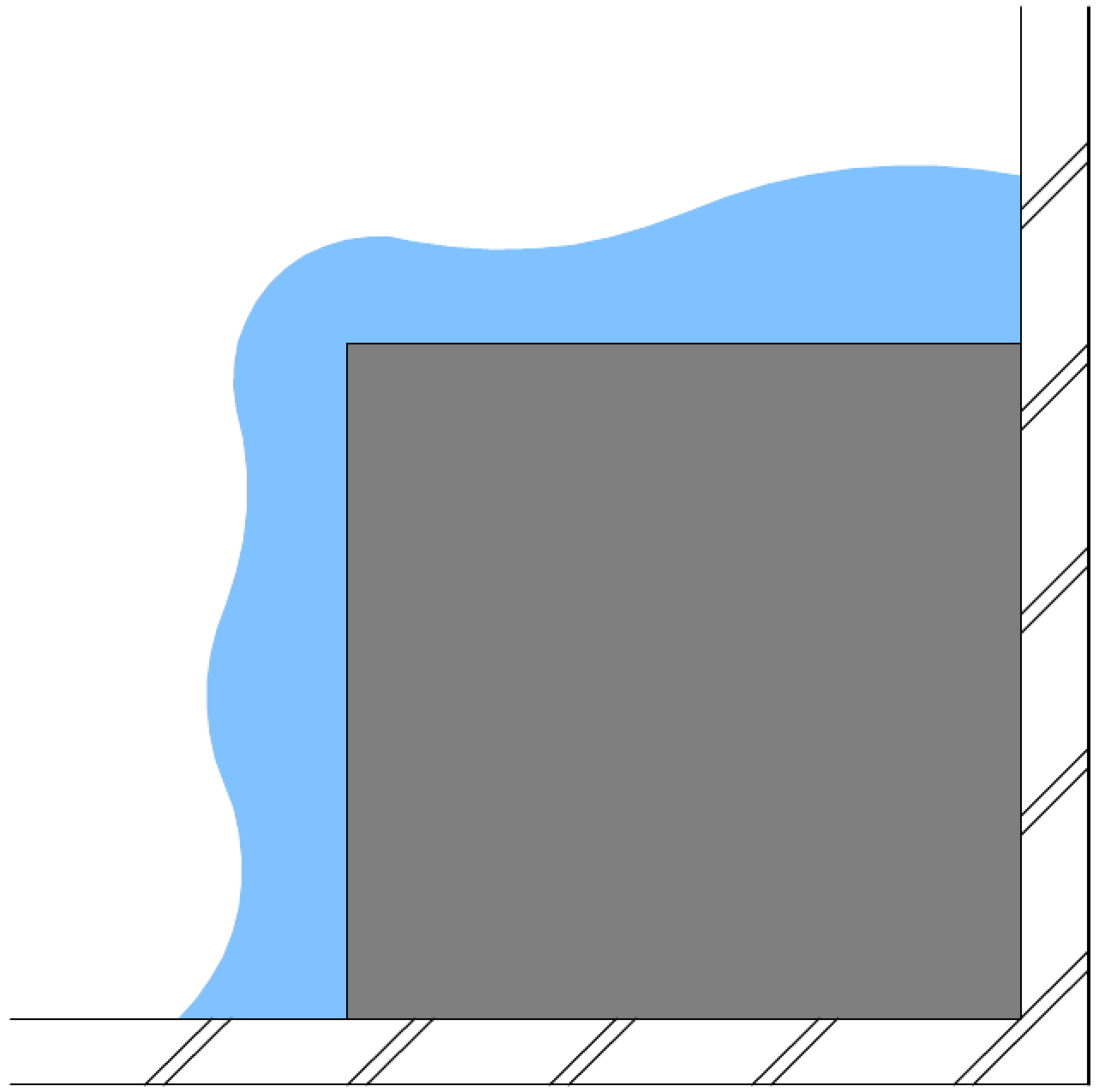
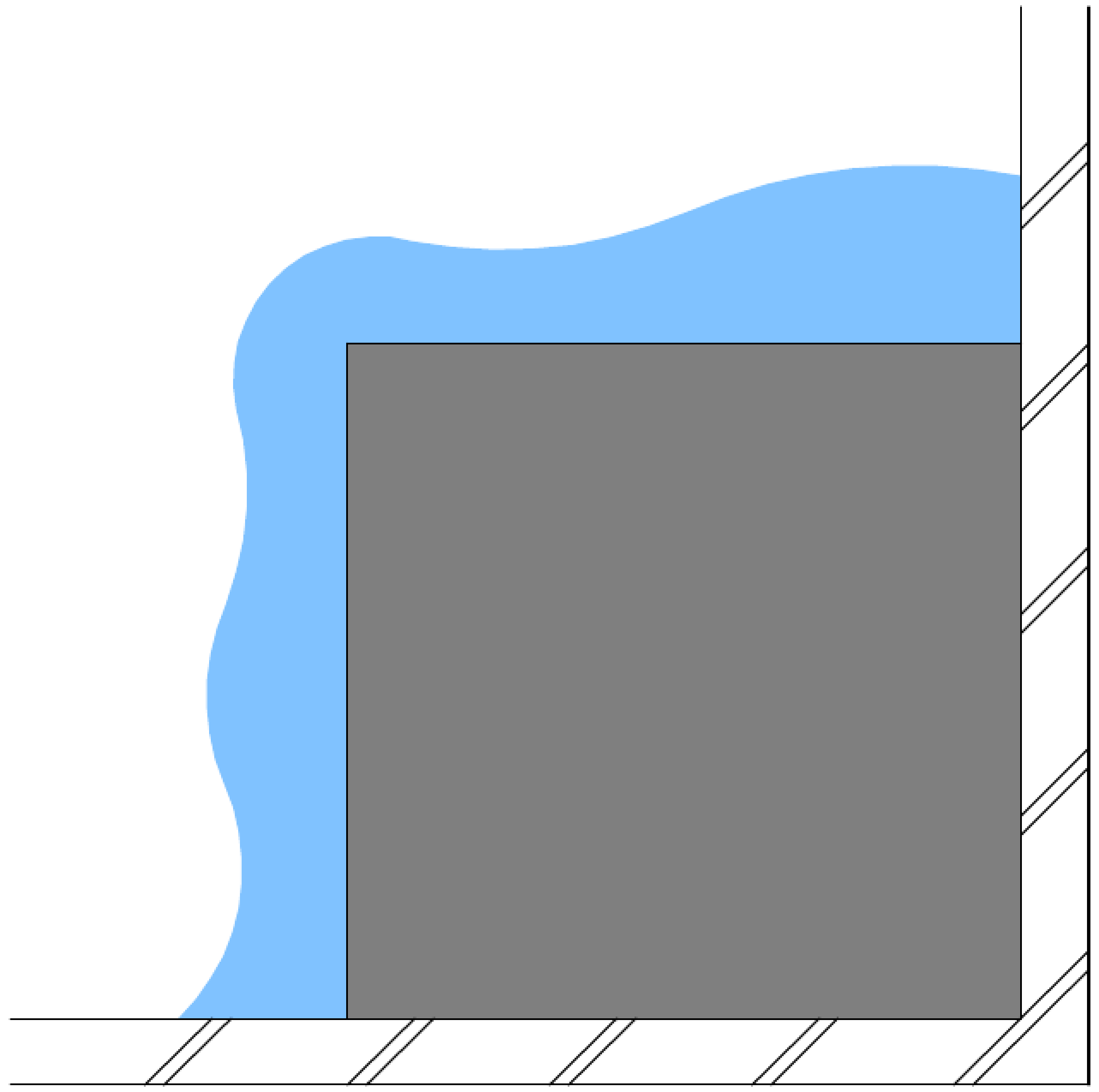


CH dissolution

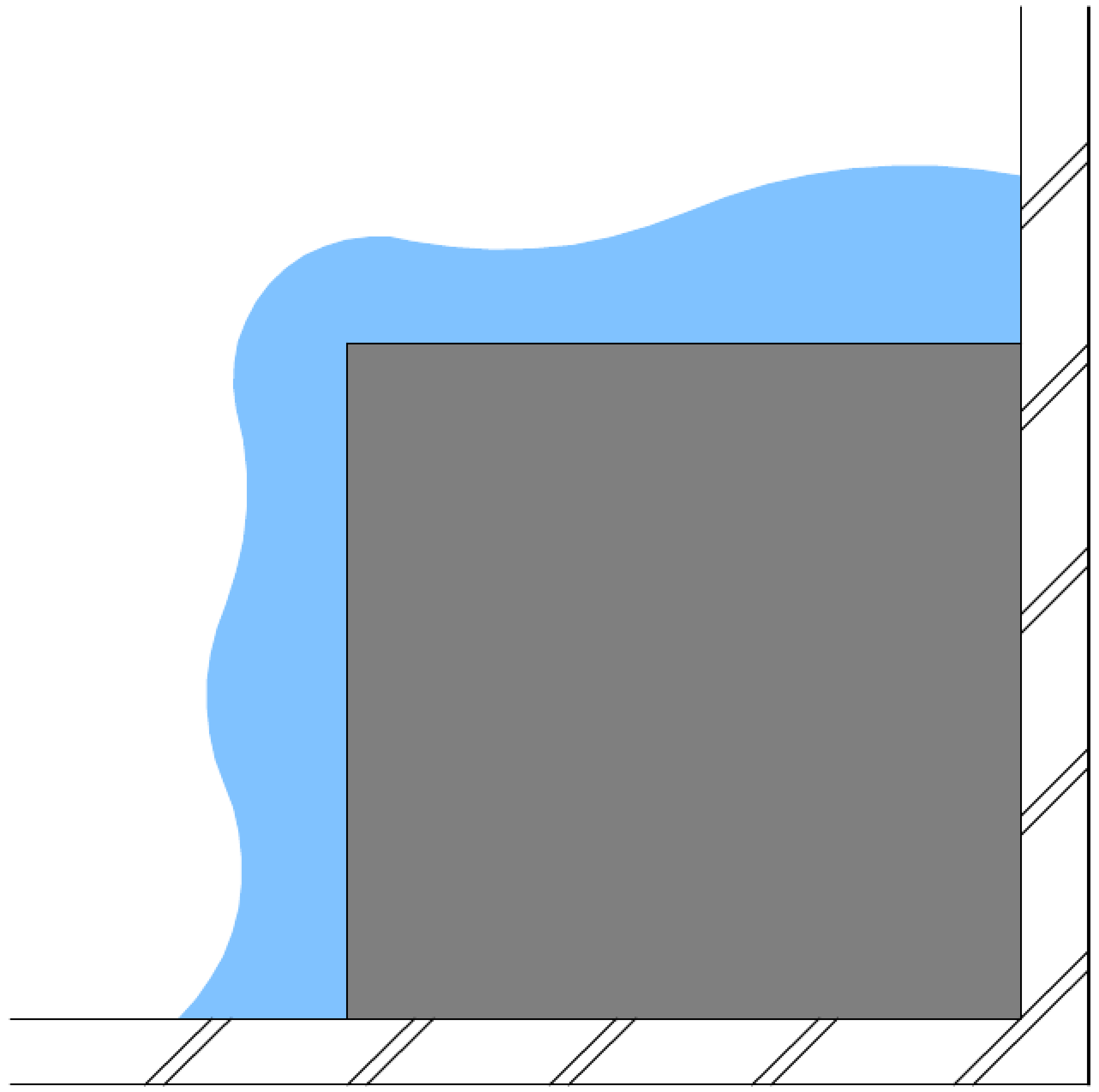
$$Ca(OH)_2 \rightleftarrows Ca^{2+} + 2OH^-$$



CH dissolution

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{2OH^-}$$

$$\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right) \\
\frac{\partial[Ca^{2+}]}{\partial t} &= D_0\nabla^2[Ca^{2+}] && - k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right) \\
\frac{\partial[OH^-]}{\partial t} &= D_0\nabla^2[OH^-] && - 2k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right)
\end{aligned}$$



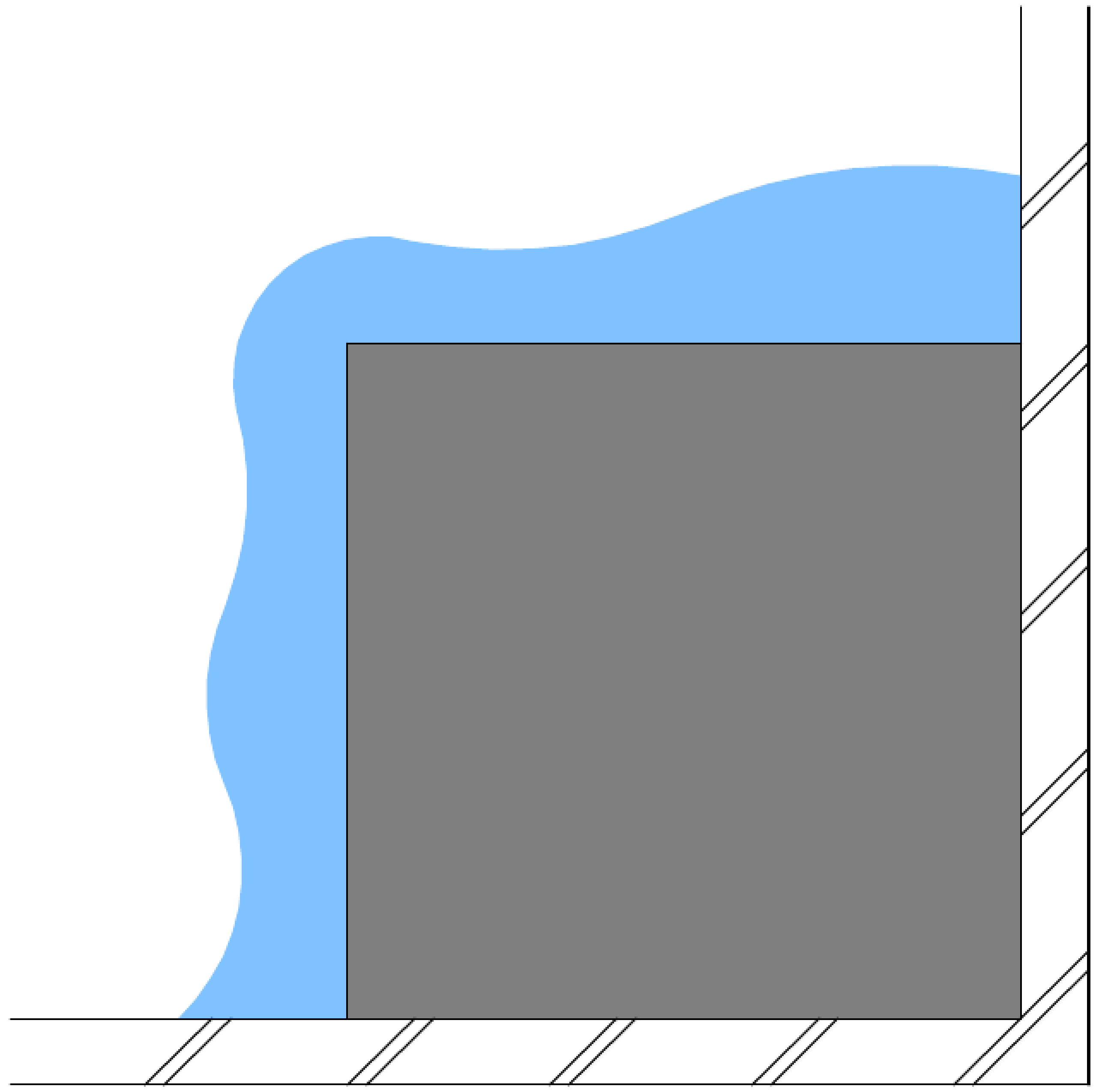
CH dissolution

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + 2\mathrm{OH^-}$$

$$\frac{\partial [CH]}{\partial t} = \qquad + k_{CH} Q_{CH}$$

$$\frac{\partial [Ca^{2+}]}{\partial t} = D_0 \nabla^2 [Ca^{2+}] - k_{CH} Q_{CH}$$

$$\frac{\partial [OH^-]}{\partial t} = D_0 \nabla^2 [OH^-] - 2k_{CH} Q_{CH}$$



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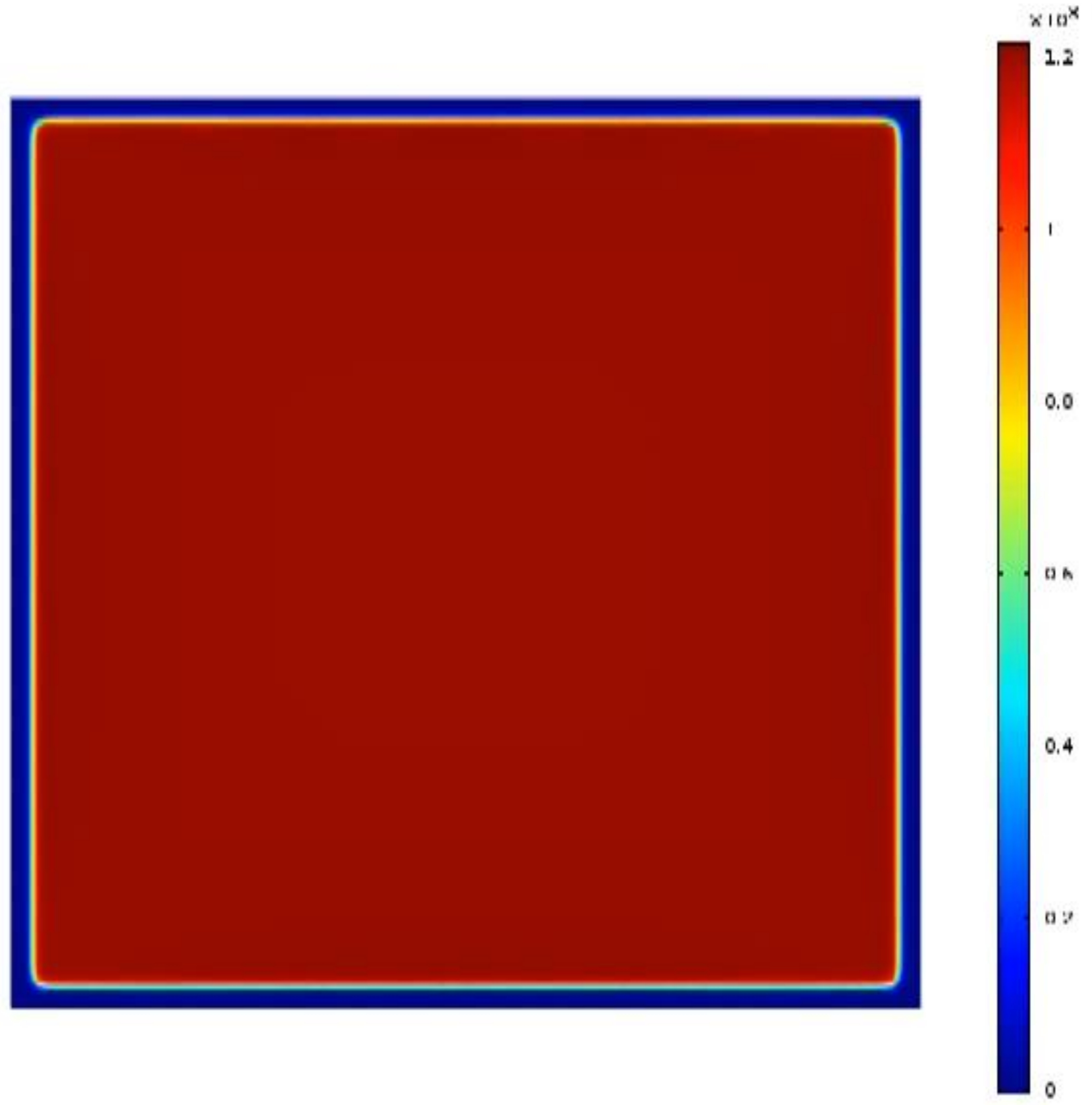
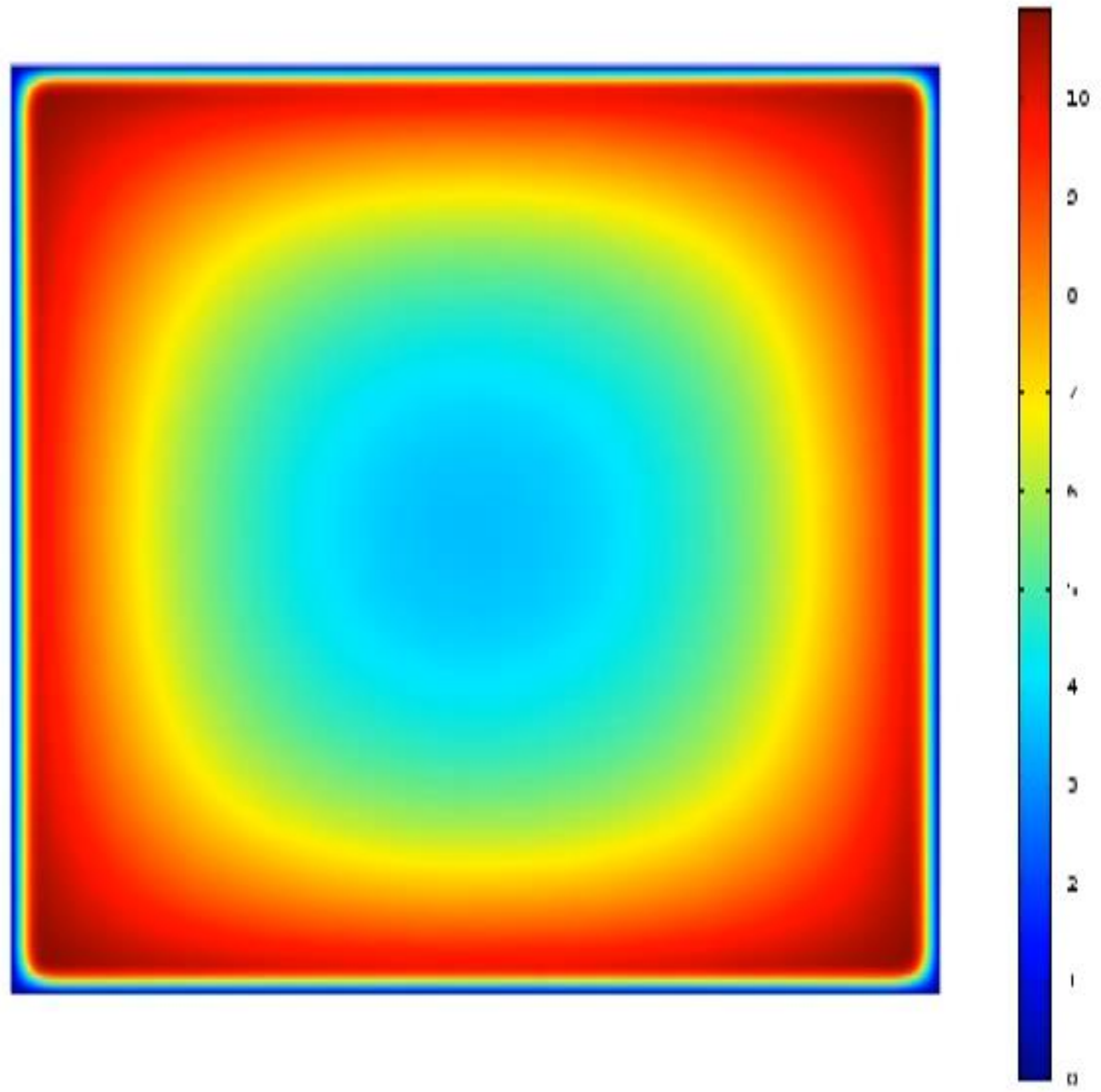
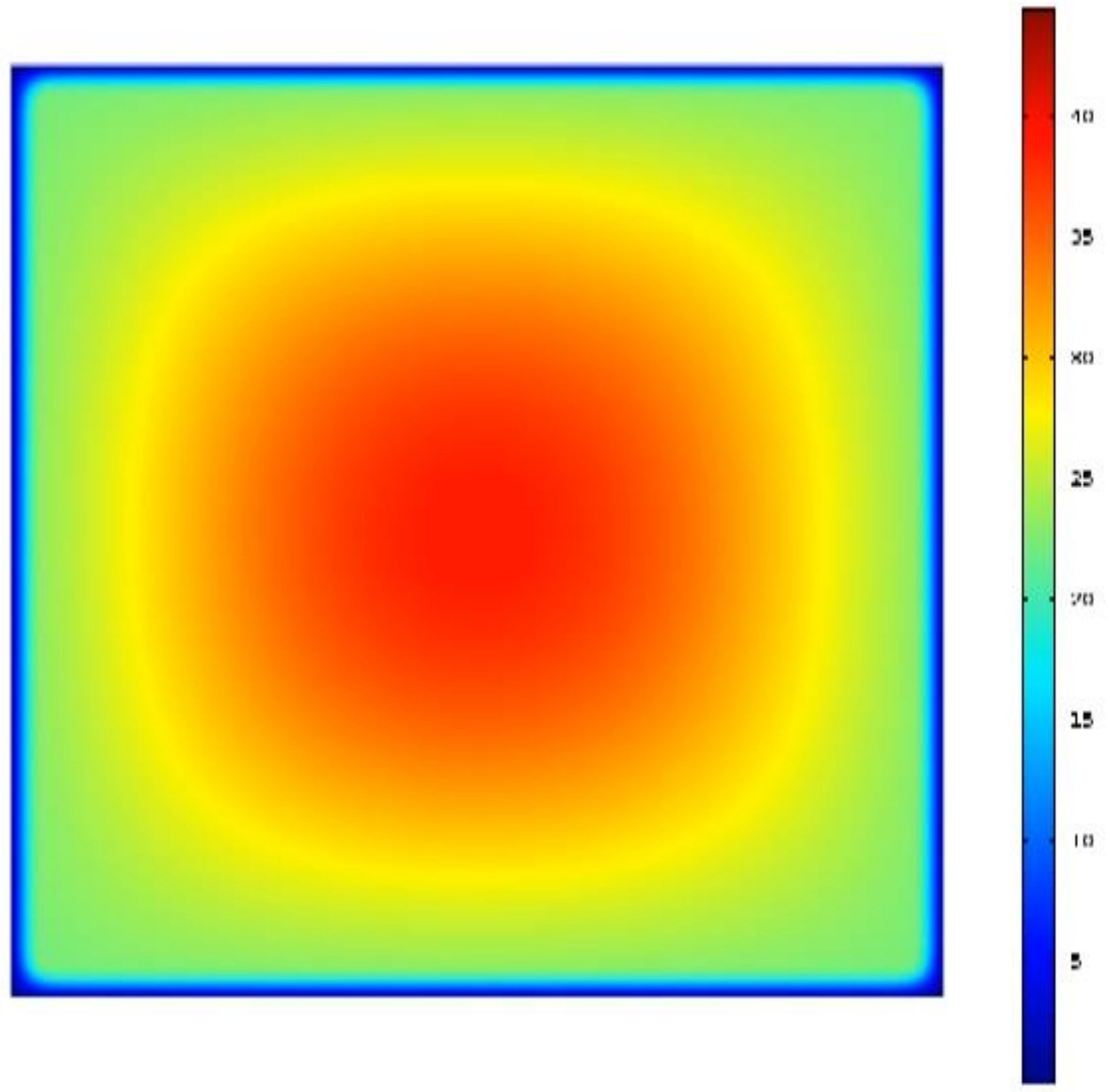
CH (Calcium Hydroxide)



Ca (Calcium)



OH (Hydroxide)



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Gypsum formation

$$Ca(OH)_2 \rightleftarrows Ca^{2+} + 2OH^-$$

$$CaSO_4 \rightleftarrows Ca^{2+} + SO_4^{2-}$$

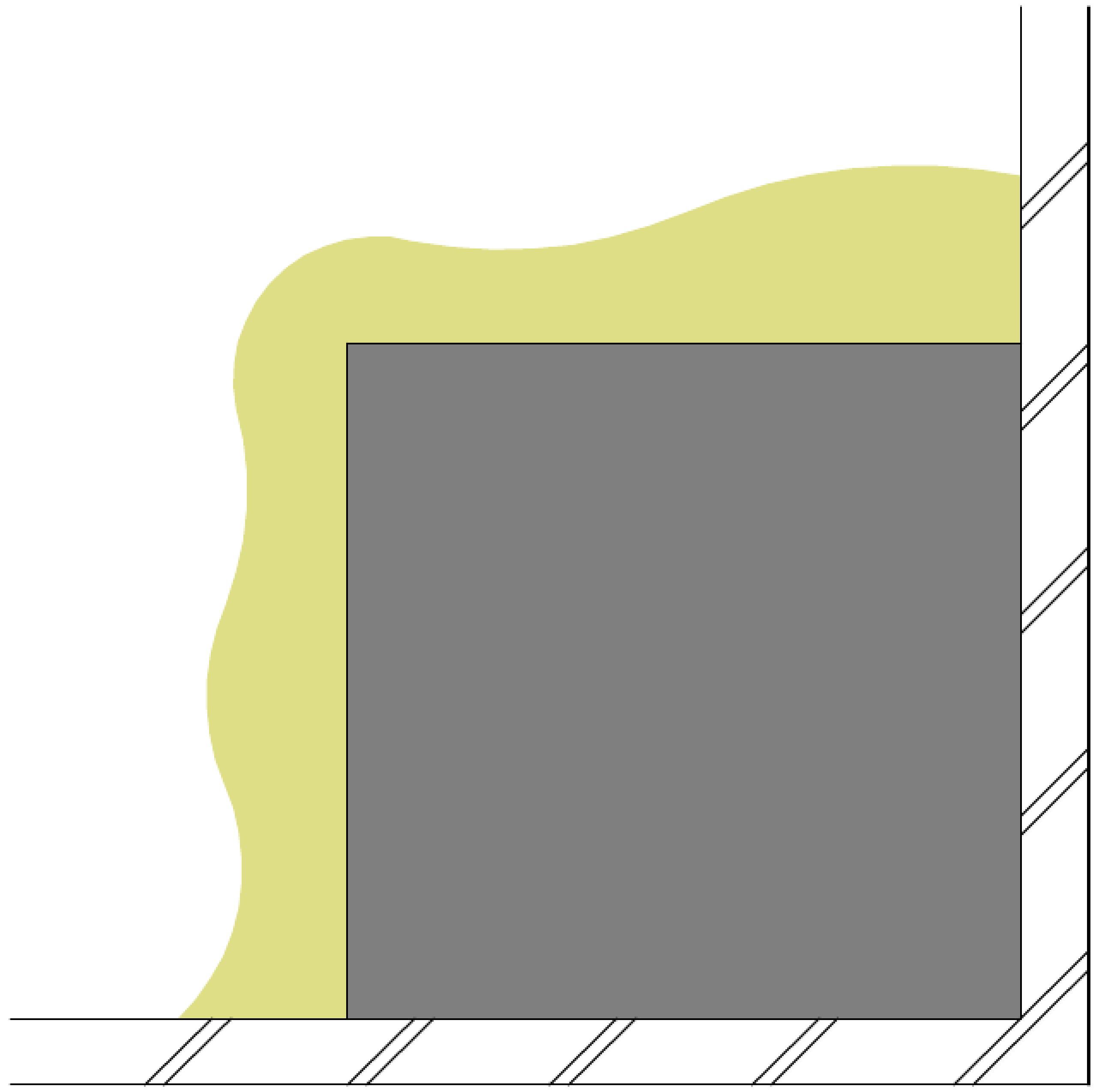
$$\frac{\partial[CH]}{\partial t} = + k_{CH}Q_{CH}$$

$$\frac{\partial[CaSO_4]}{\partial t} = + k_{CaSO_4}Q_{CaSO_4}$$

$$\frac{\partial[Ca^{2+}]}{\partial t} = D_0\nabla^2[Ca^{2+}] - k_{CH}Q_{CH} - k_{CaSO_4}Q_{CaSO_4}$$

$$\frac{\partial[OH^-]}{\partial t} = D_0\nabla^2[OH^-] - 2k_{CH}Q_{CH}$$

$$\frac{\partial[SO_4^{2-}]}{\partial t} = D_0\nabla^2[SO_4^{2-}] - k_{CaSO_4}Q_{CaSO_4}$$



Gypsum formation

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + 2\mathrm{OH^-}$$

$$\mathrm{CaSO_4} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{SO_4^{2-}}$$

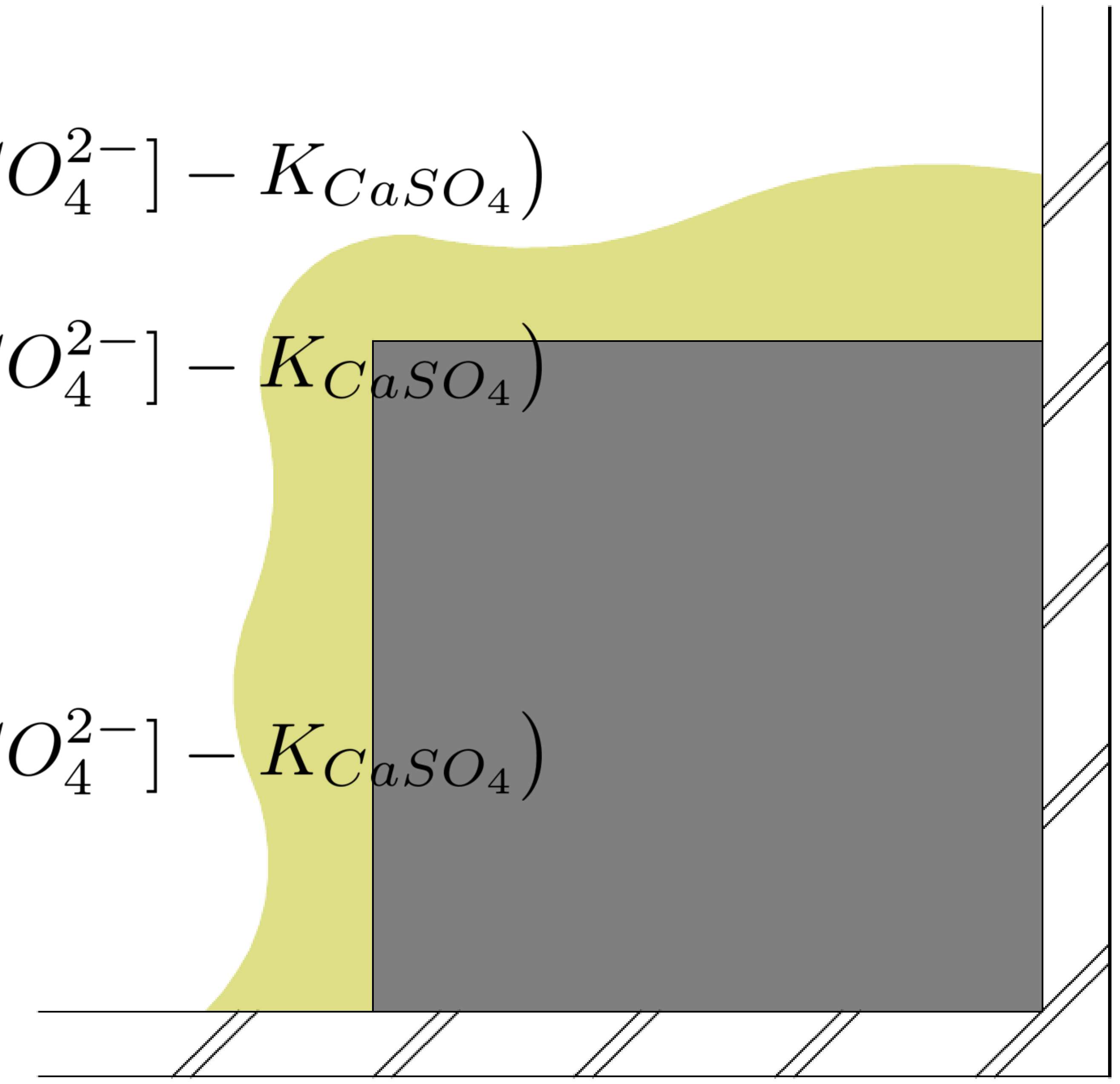
$$\frac{\partial [CH]}{\partial t} = + k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right)$$

$$\frac{\partial [CaSO_4]}{\partial t} = + k_{CaSO_4}\left([Ca^{2+}][SO_4^{2-}] - K_{CaSO_4}\right)$$

$$\frac{\partial [Ca^{2+}]}{\partial t} = D_0\nabla^2[Ca^{2+}] - k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right) - k_{CaSO_4}\left([Ca^{2+}][SO_4^{2-}] - K_{CaSO_4}\right)$$

$$\frac{\partial [OH^-]}{\partial t} = D_0\nabla^2[OH^-] - 2k_{CH}\left([Ca^{2+}][OH^-]^2 - K_{CH}\right)$$

$$\frac{\partial [SO_4^{2-}]}{\partial t} = D_0\nabla^2[SO_4^{2-}] - k_{CaSO_4}\left([Ca^{2+}][SO_4^{2-}] - K_{CaSO_4}\right)$$

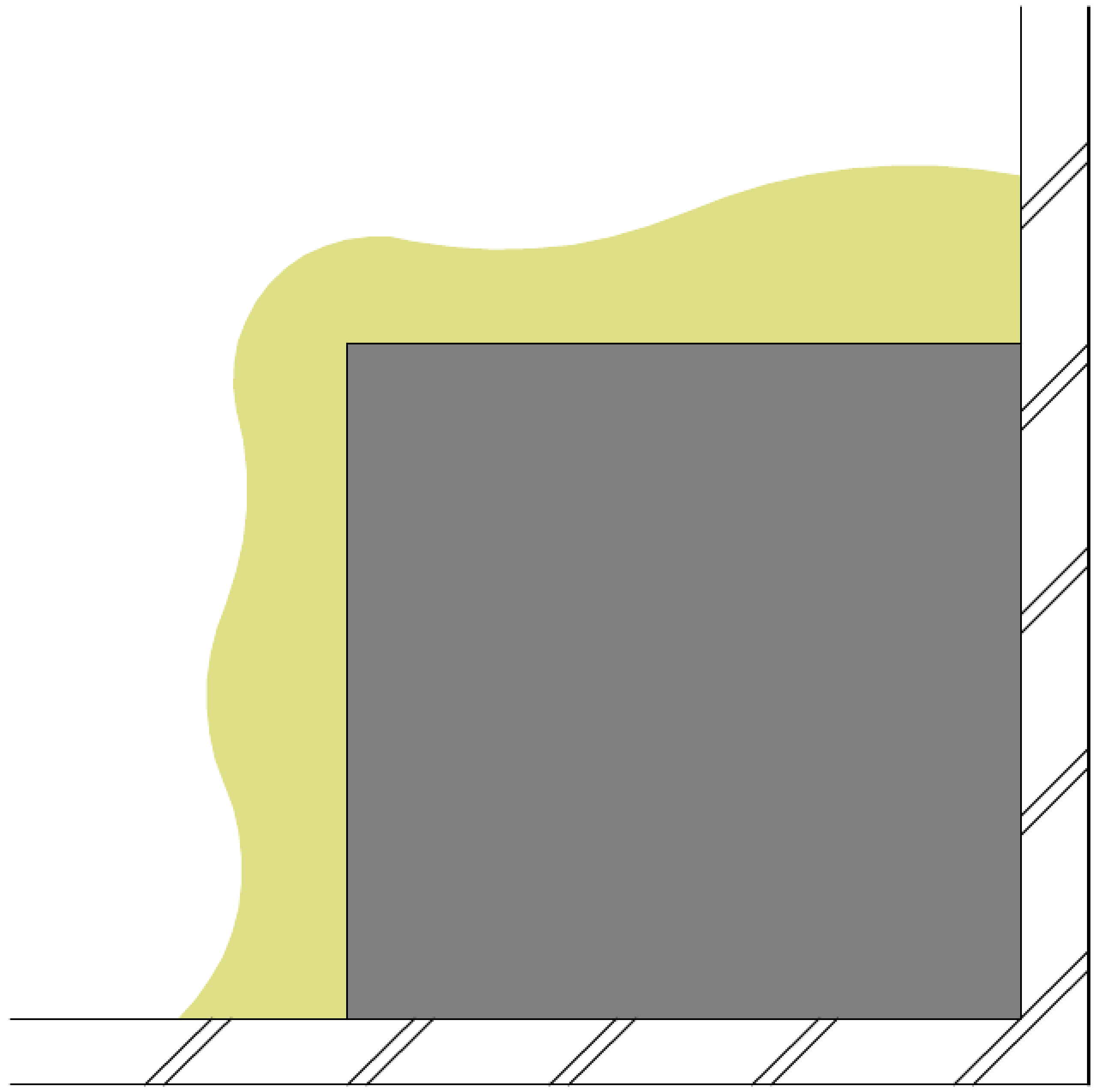


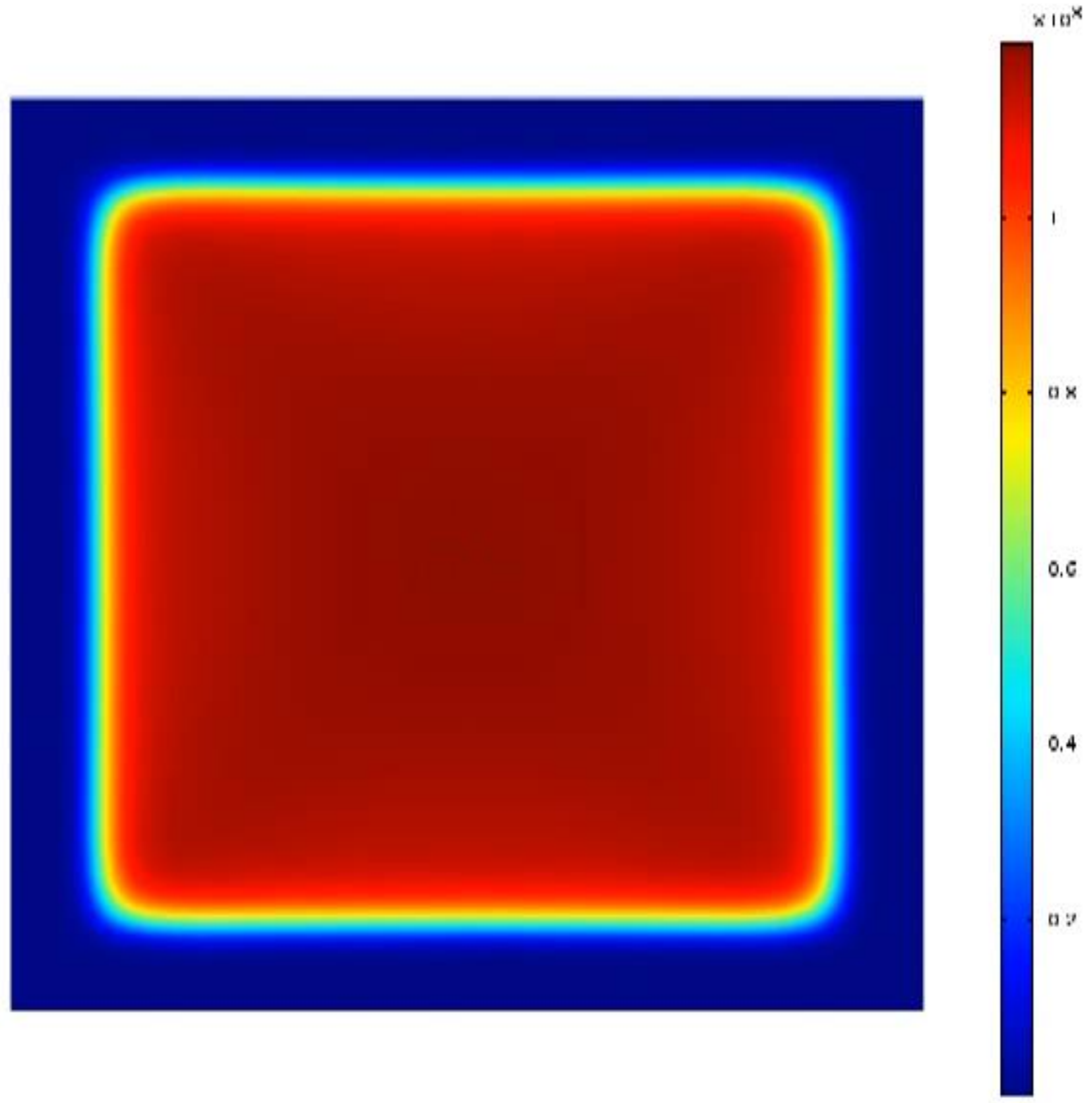
Gypsum formation

$$Ca(OH)_2 \rightleftharpoons Ca^{2+} + 2OH^-$$

$$CaSO_4 \rightleftharpoons Ca^{2+} + SO_4^{2-}$$

$$\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} && \\
\frac{\partial[CaSO_4]}{\partial t} &= && && + k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[Ca^{2+}]}{\partial t} &= D_0\nabla^2[Ca^{2+}] && - k_{CH}Q_{CH} && - k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[OH^-]}{\partial t} &= D_0\nabla^2[OH^-] && - 2k_{CH}Q_{CH} && \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= D_0\nabla^2[SO_4^{2-}] && && - k_{CaSO_4}Q_{CaSO_4}
\end{aligned}$$

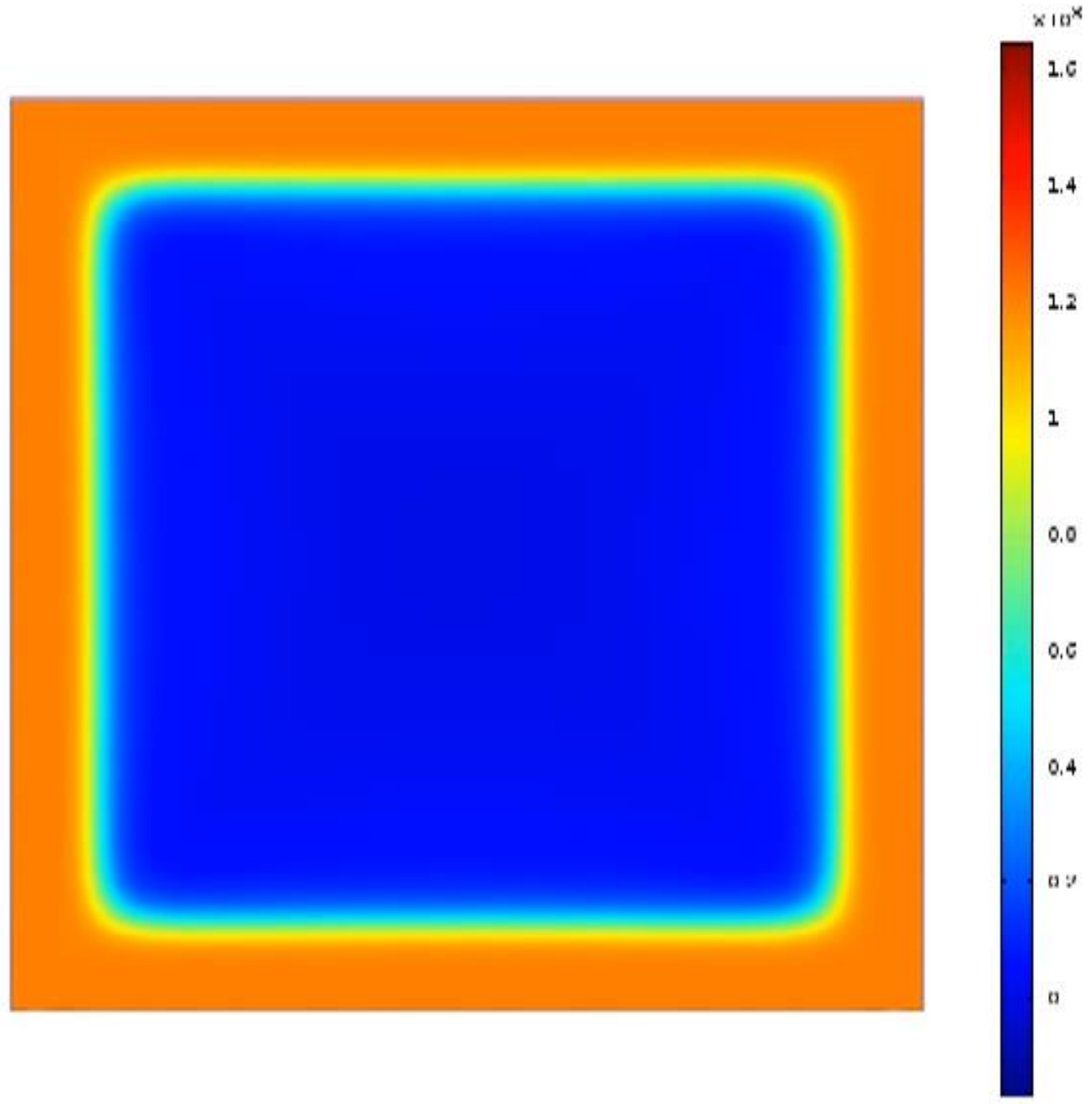




CH (Calcium Hydroxide)

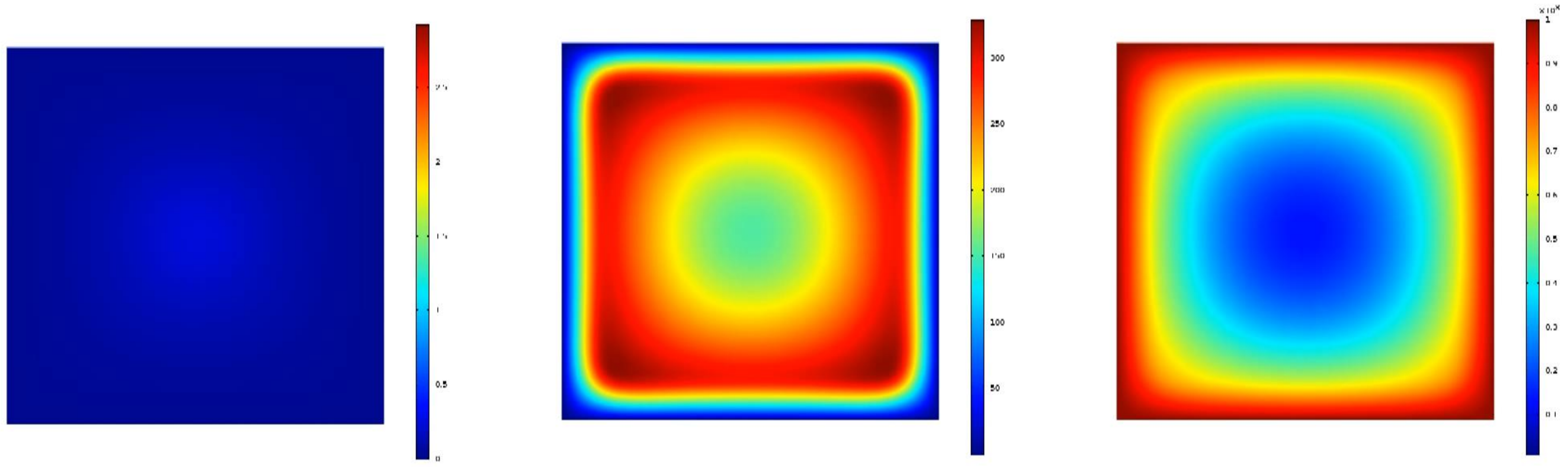
$$Ca(OH)_2 \rightleftharpoons Ca^{2+} + 2OH^-$$

$$CaSO_4 \rightleftharpoons Ca^{2+} + SO_4^{2-}$$



CaSO4 (Gypsum)

Ca OH SO4



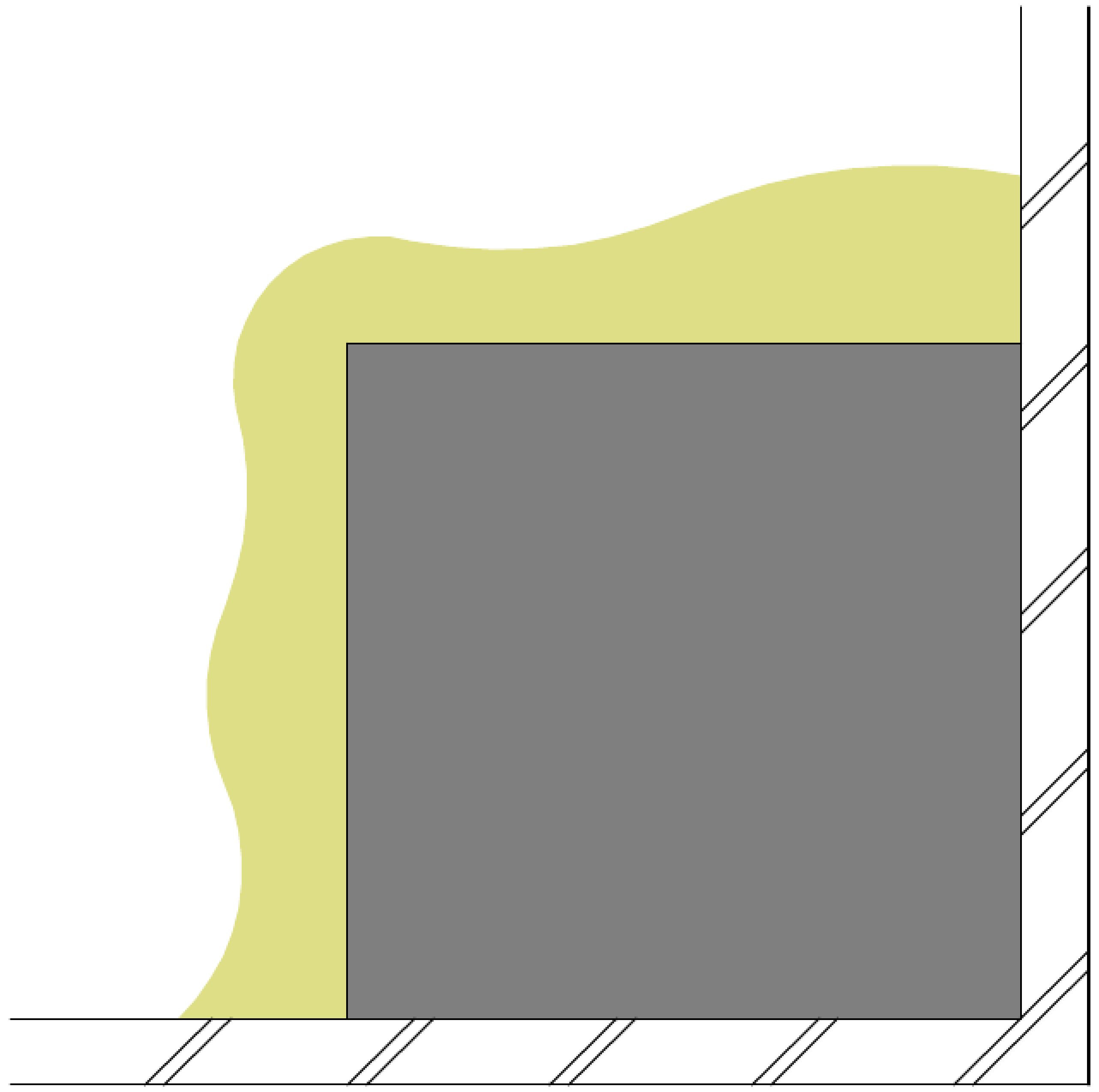
Linear Elastic Mechanics

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + 2\mathrm{OH^-}$$

$$\mathrm{CaSO_4} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{SO_4^{2-}}$$

$$\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} & \\
\frac{\partial[CaSO_4]}{\partial t} &= && & + k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[Ca^{2+}]}{\partial t} &= D_0\nabla^2[Ca^{2+}] && - k_{CH}Q_{CH} & - k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[OH^{-}]}{\partial t} &= D_0\nabla^2[OH^{-}] && - 2k_{CH}Q_{CH} & \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= D_0\nabla^2[SO_4^{2-}] && & - k_{CaSO_4}Q_{CaSO_4}
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\sigma} &= {}^4\mathbb{C}_0\boldsymbol{\varepsilon}^e \\
\text{where: } \boldsymbol{\varepsilon}^e &= \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^g \\
&= \boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\mathbf{I}
\end{aligned}$$



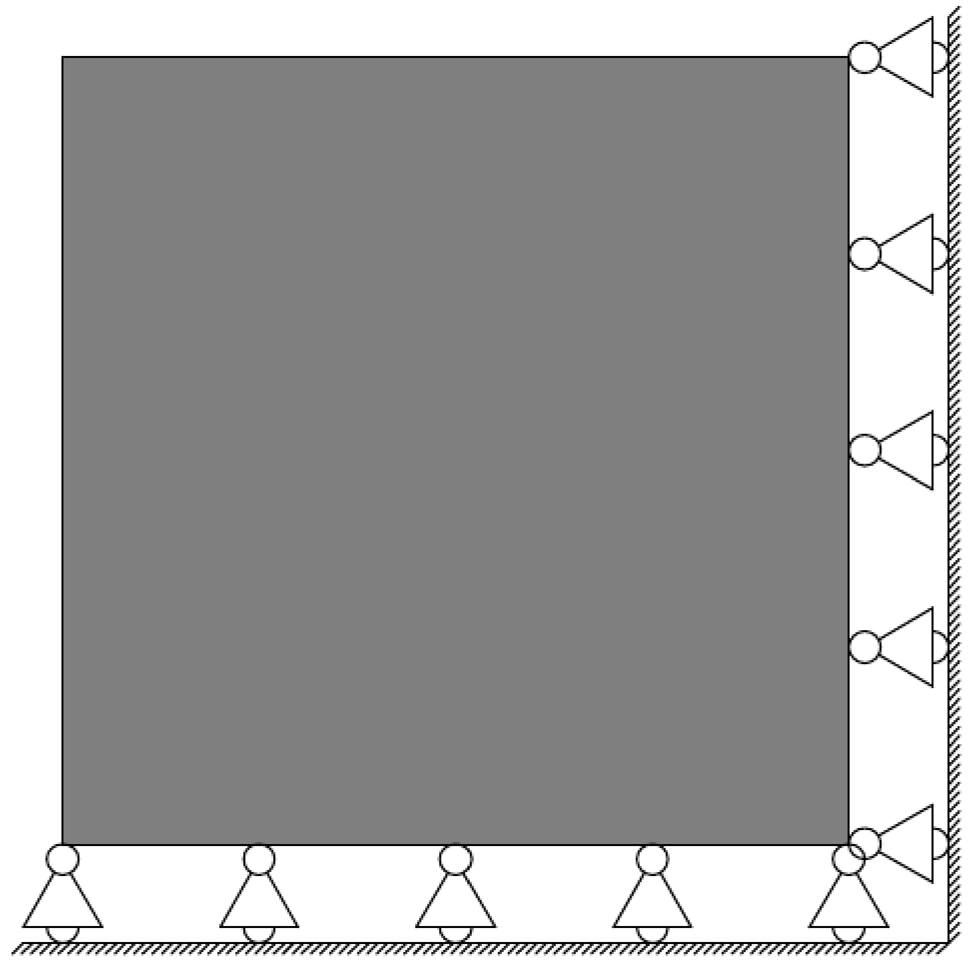
Linear Elastic Mechanics

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{2OH^-}$$

$$\mathrm{CaSO_4} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{SO_4^{2-}}$$

$$\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} \\
\frac{\partial[CaSO_4]}{\partial t} &= && && + k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[Ca^{2+}]}{\partial t} &= D_0\nabla^2[Ca^{2+}] && - k_{CH}Q_{CH} && - k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[OH^-]}{\partial t} &= D_0\nabla^2[OH^-] && - 2k_{CH}Q_{CH} \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= D_0\nabla^2[SO_4^{2-}] && && - k_{CaSO_4}Q_{CaSO_4}
\end{aligned}$$

$$\begin{aligned}
\boldsymbol{\sigma} &= {}^4\mathbb{C}_0\boldsymbol{\varepsilon}^e \\
\text{where: } \boldsymbol{\varepsilon}^e &= \boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^g \\
&= \boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\mathbf{I}
\end{aligned}$$



Linear Elastic Mechanics

$$\mathrm{Ca(OH)_2} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{2OH^-}$$

$$\mathrm{CaSO_4} \rightleftharpoons \mathrm{Ca^{2+}} + \mathrm{SO_4^{2-}}$$

$$\frac{\partial[CH]}{\partial t} = + k_{CH}Q_{CH}$$

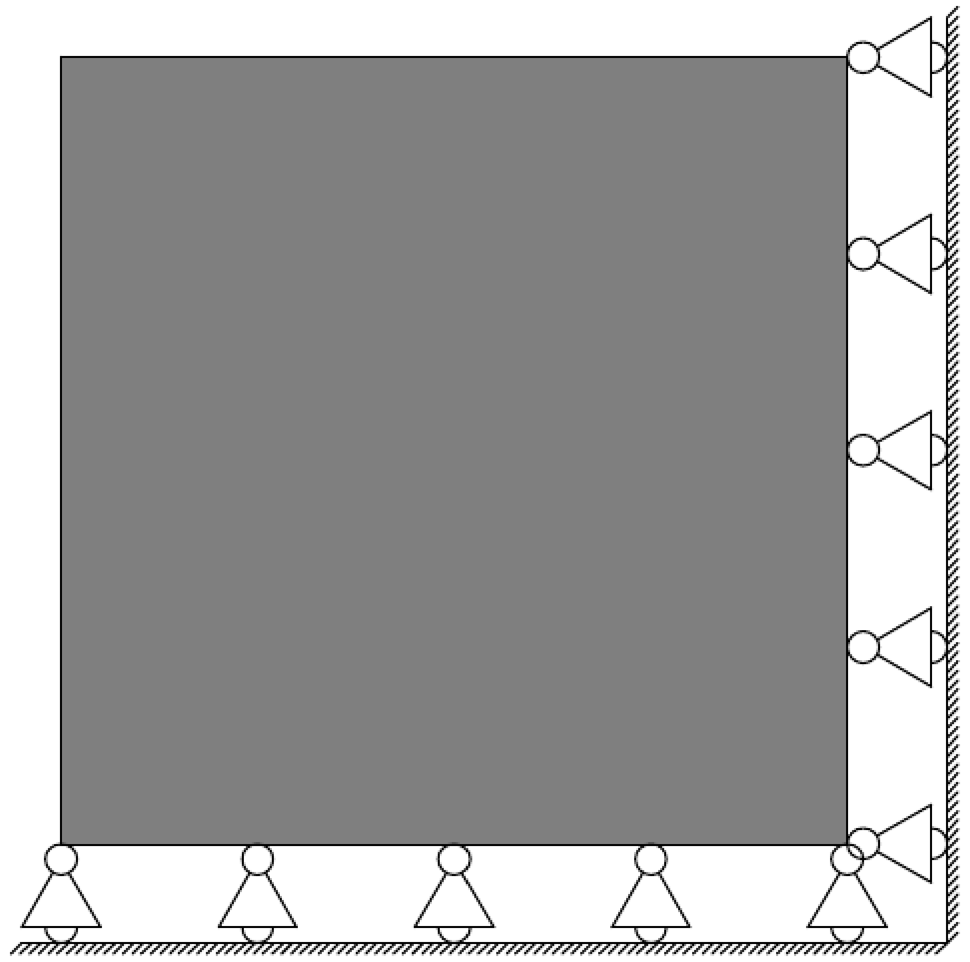
$$\frac{\partial[CaSO_4]}{\partial t} = + k_{CaSO_4}Q_{CaSO_4}$$

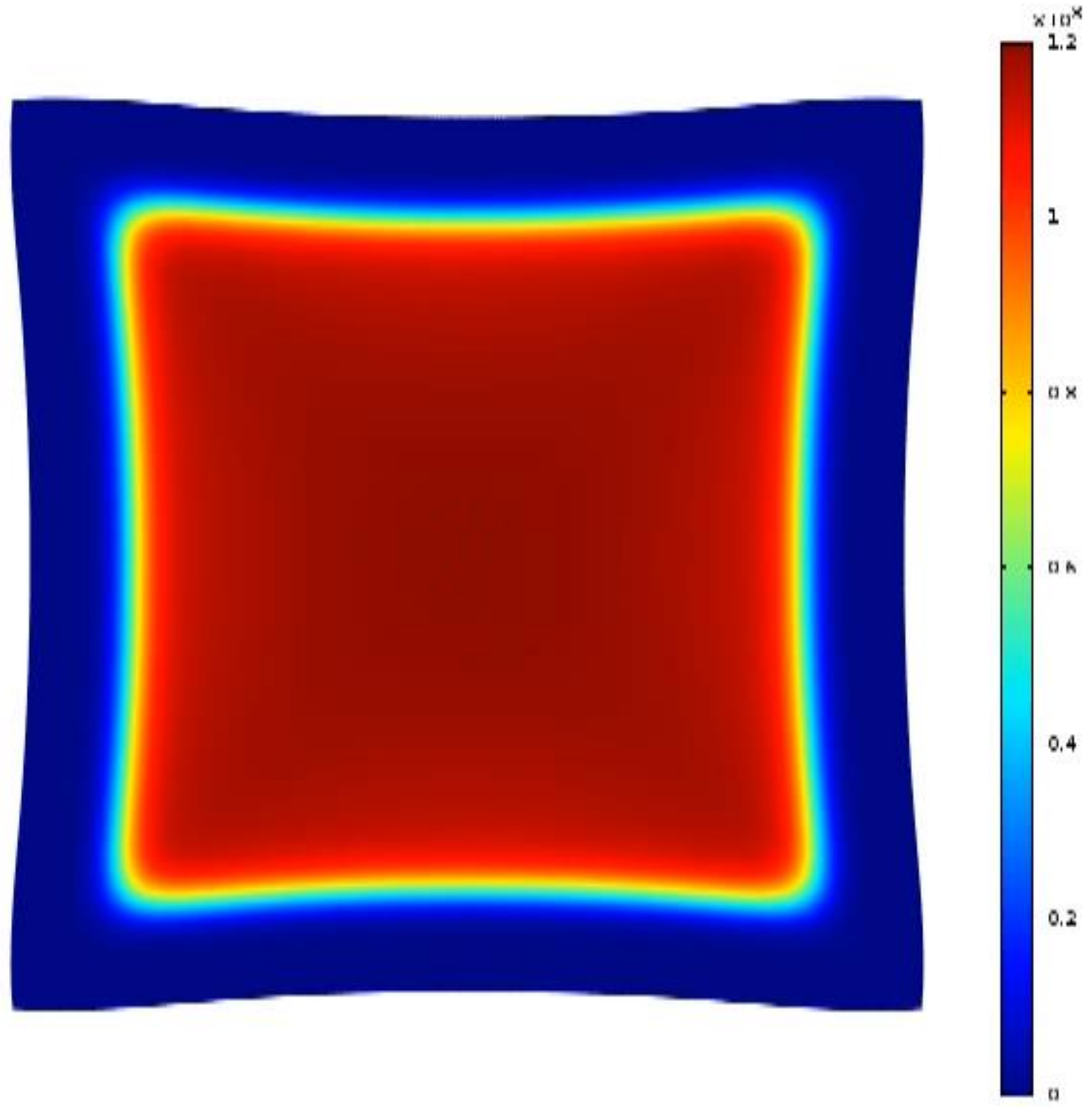
$$\frac{\partial[Ca^{2+}]}{\partial t} = D_0\nabla^2[Ca^{2+}] - k_{CH}Q_{CH} - k_{CaSO_4}Q_{CaSO_4}$$

$$\frac{\partial[OH^-]}{\partial t} = D_0\nabla^2[OH^-] - 2k_{CH}Q_{CH}$$

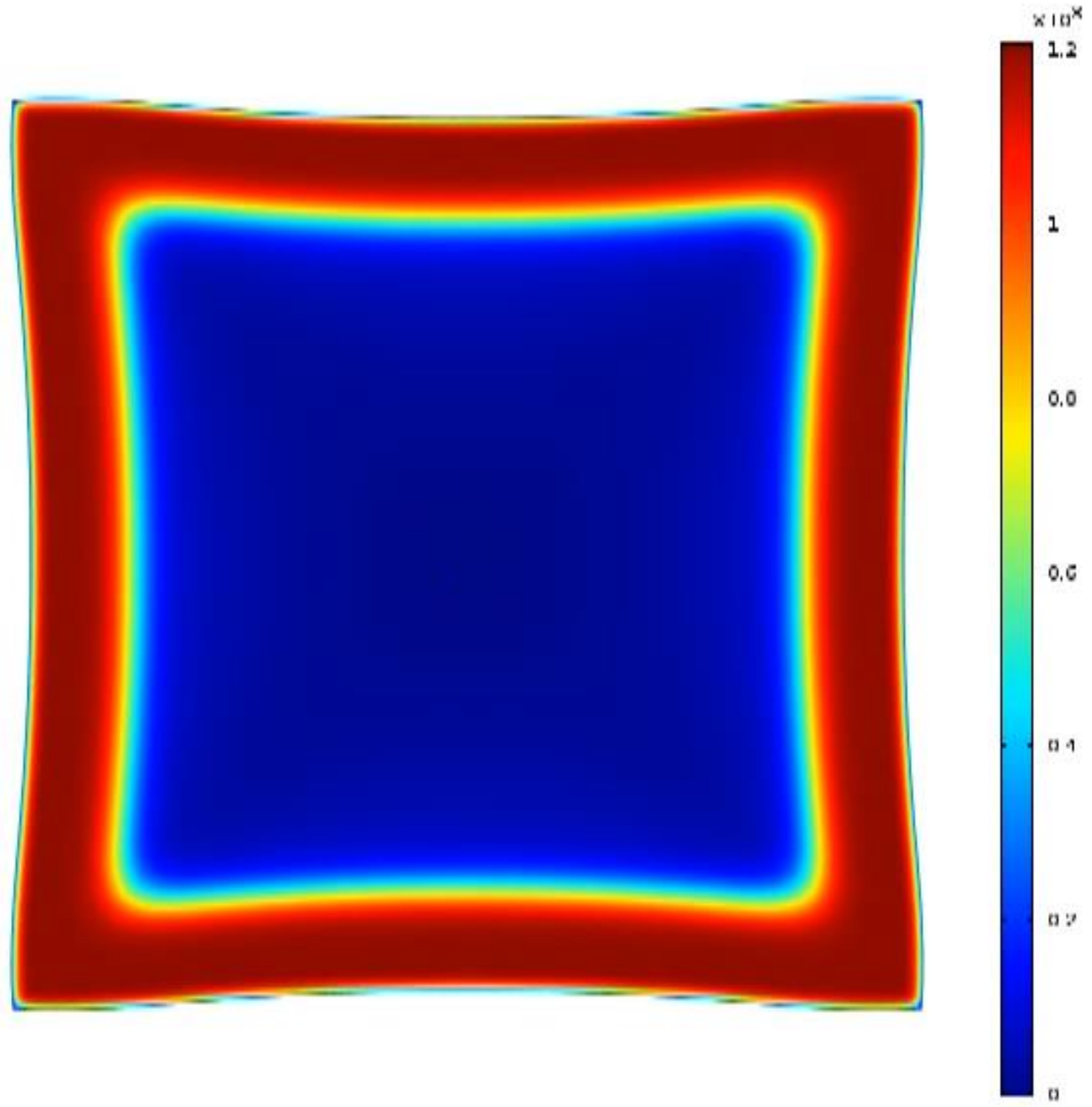
$$\frac{\partial[SO_4^{2-}]}{\partial t} = D_0\nabla^2[SO_4^{2-}] - k_{CaSO_4}Q_{CaSO_4}$$

$$\boldsymbol{\sigma} = {}^4\mathbb{C}_0\left(\boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\mathbf{I}\right)$$



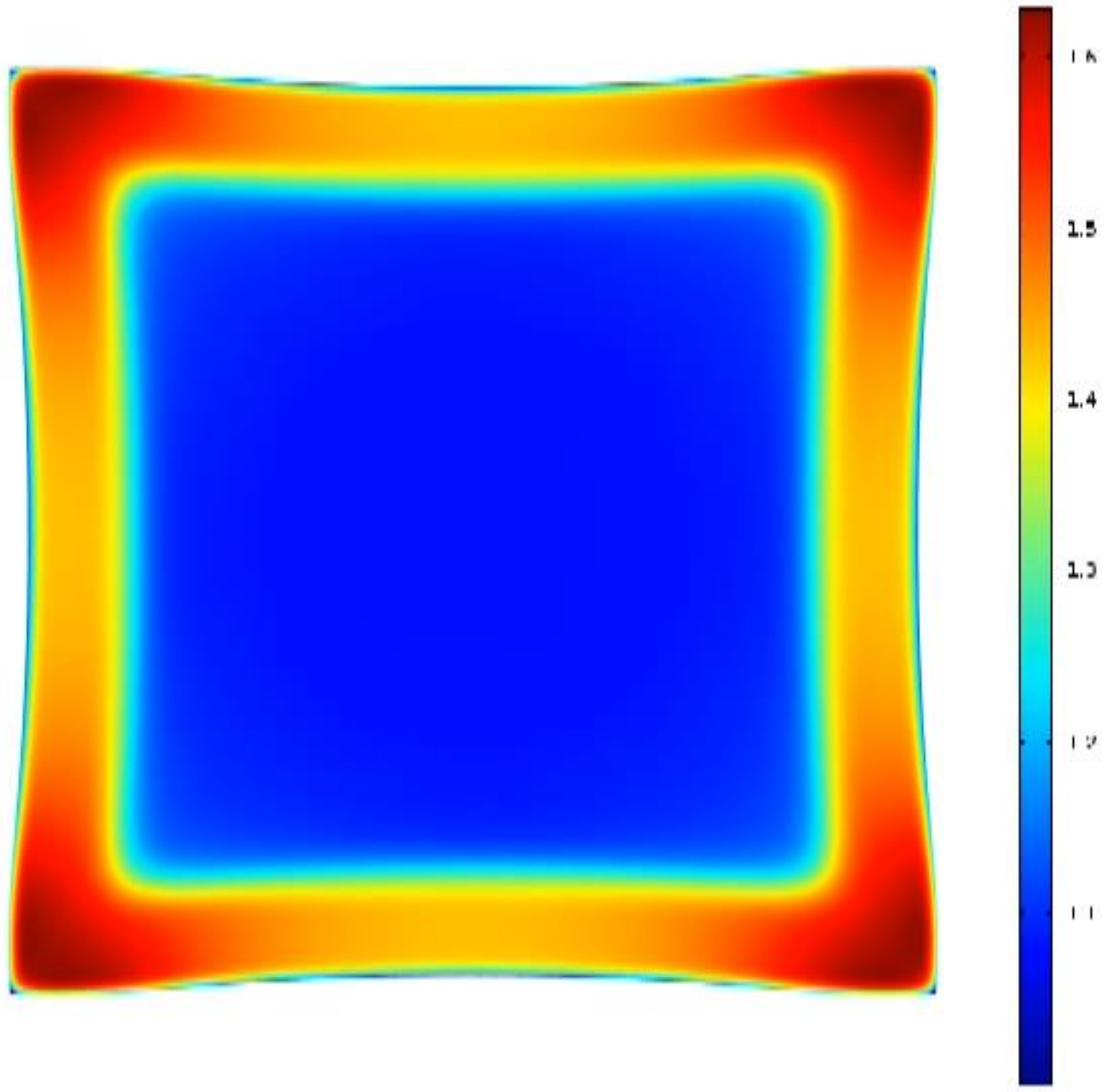


CH

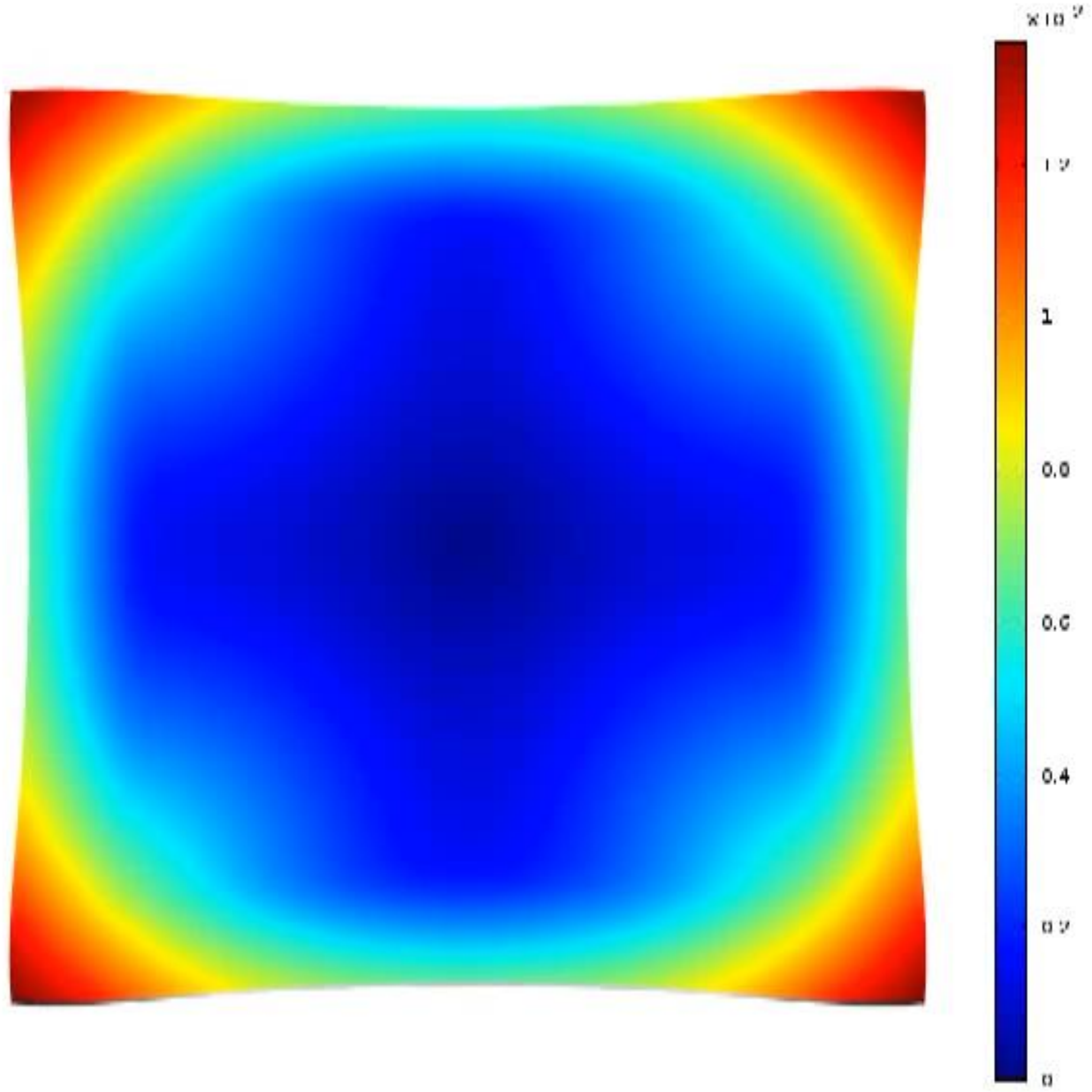


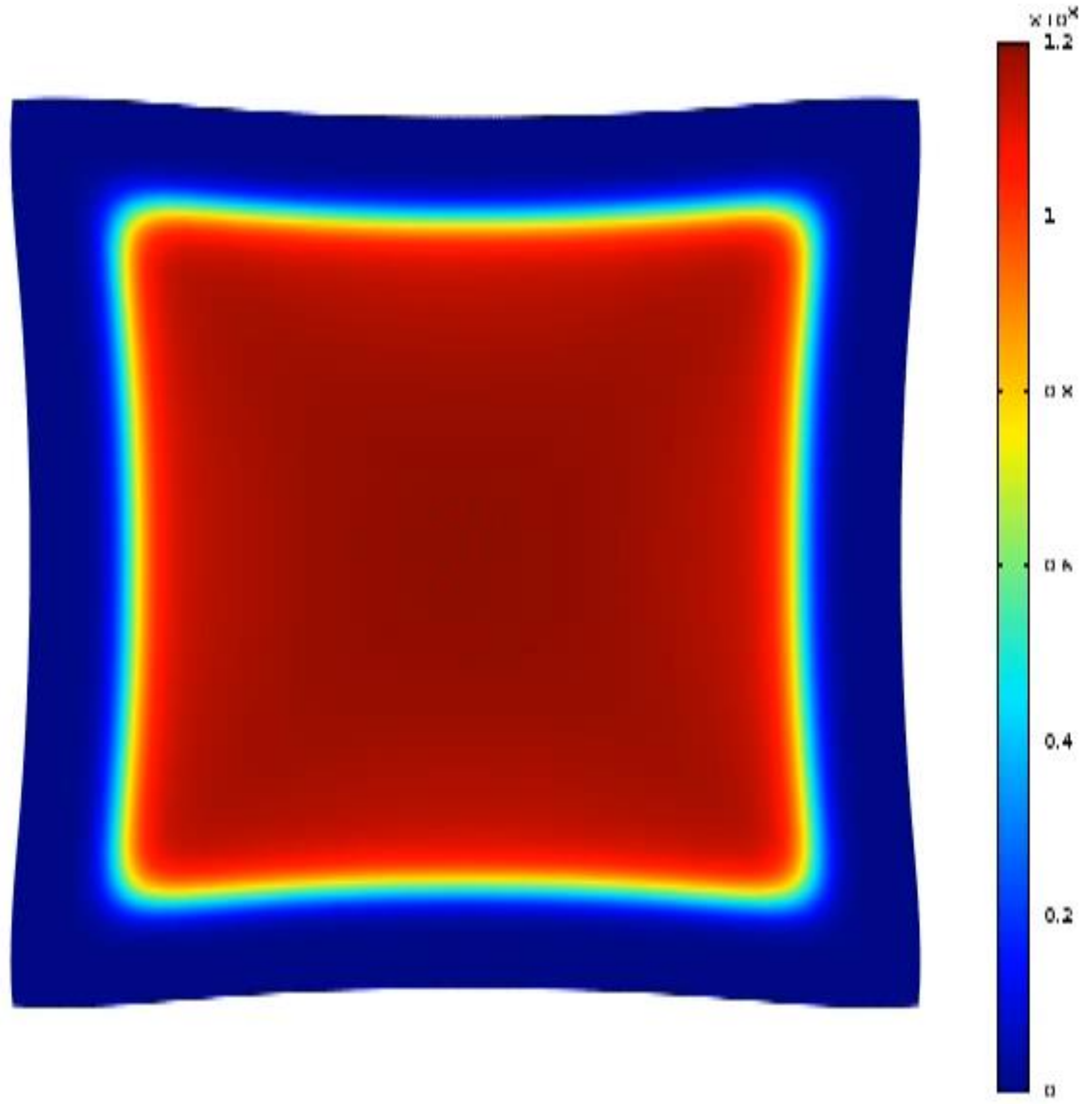
CaSO4

Vol. Strain

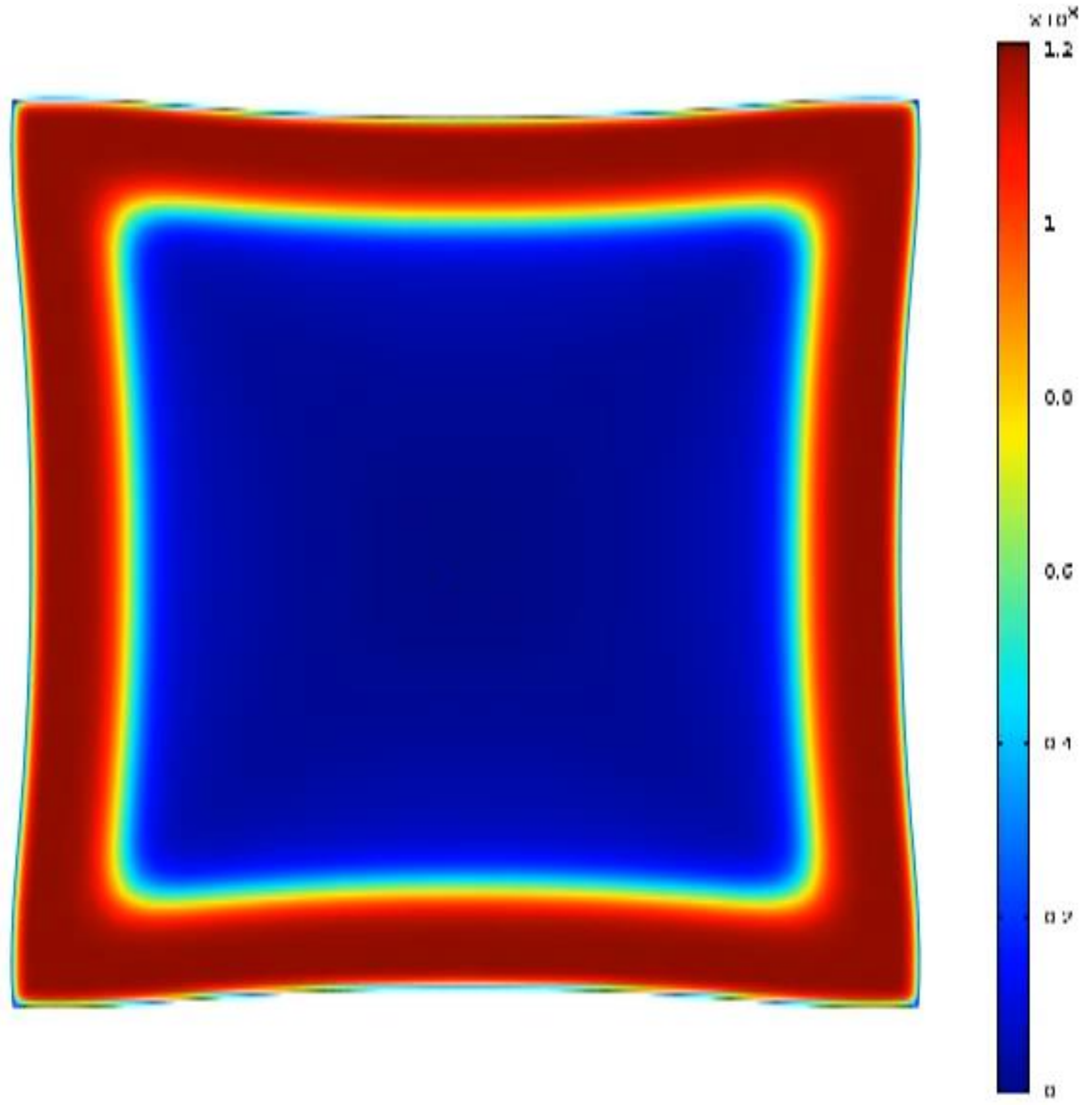


Displacements



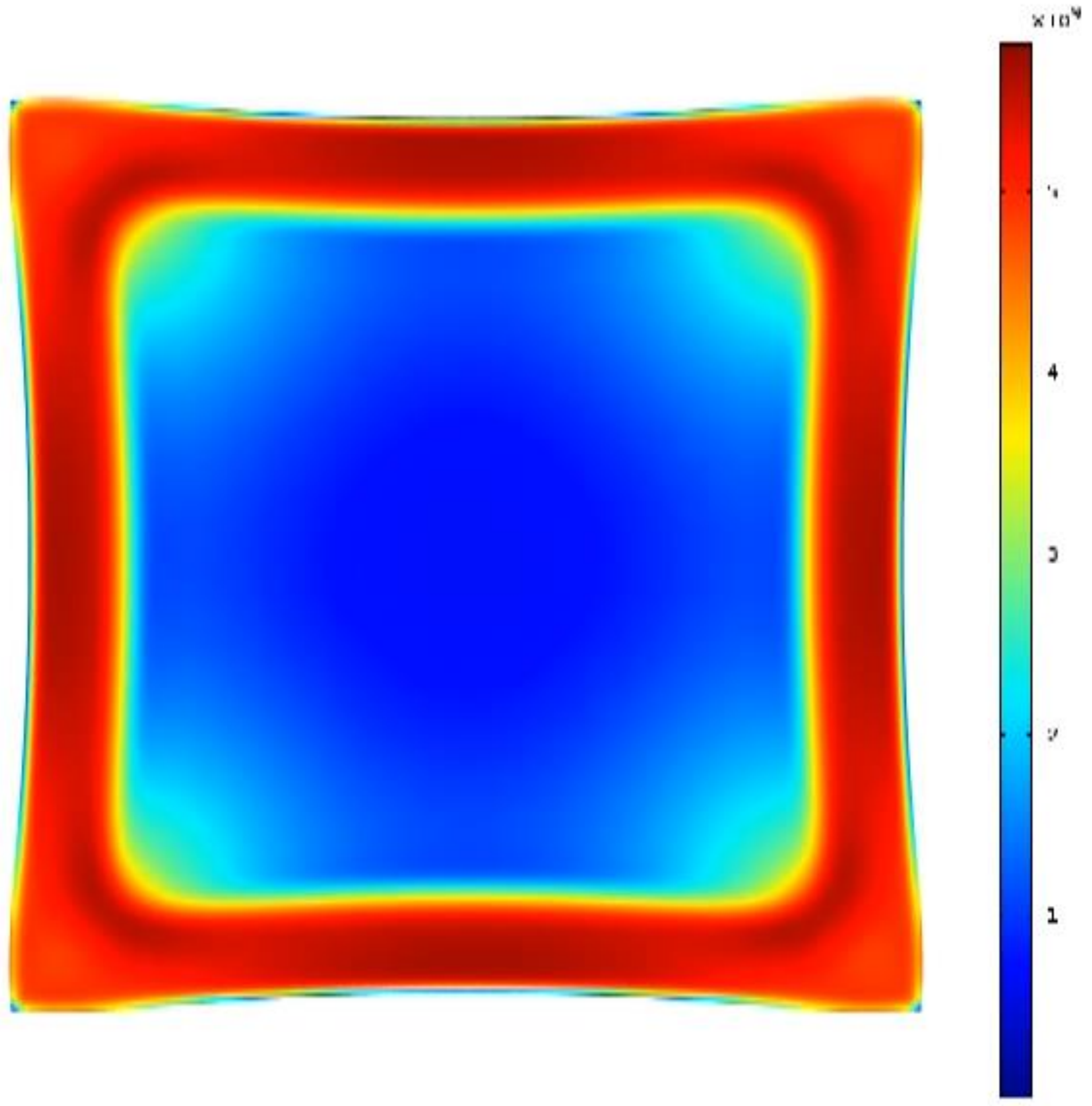


CH

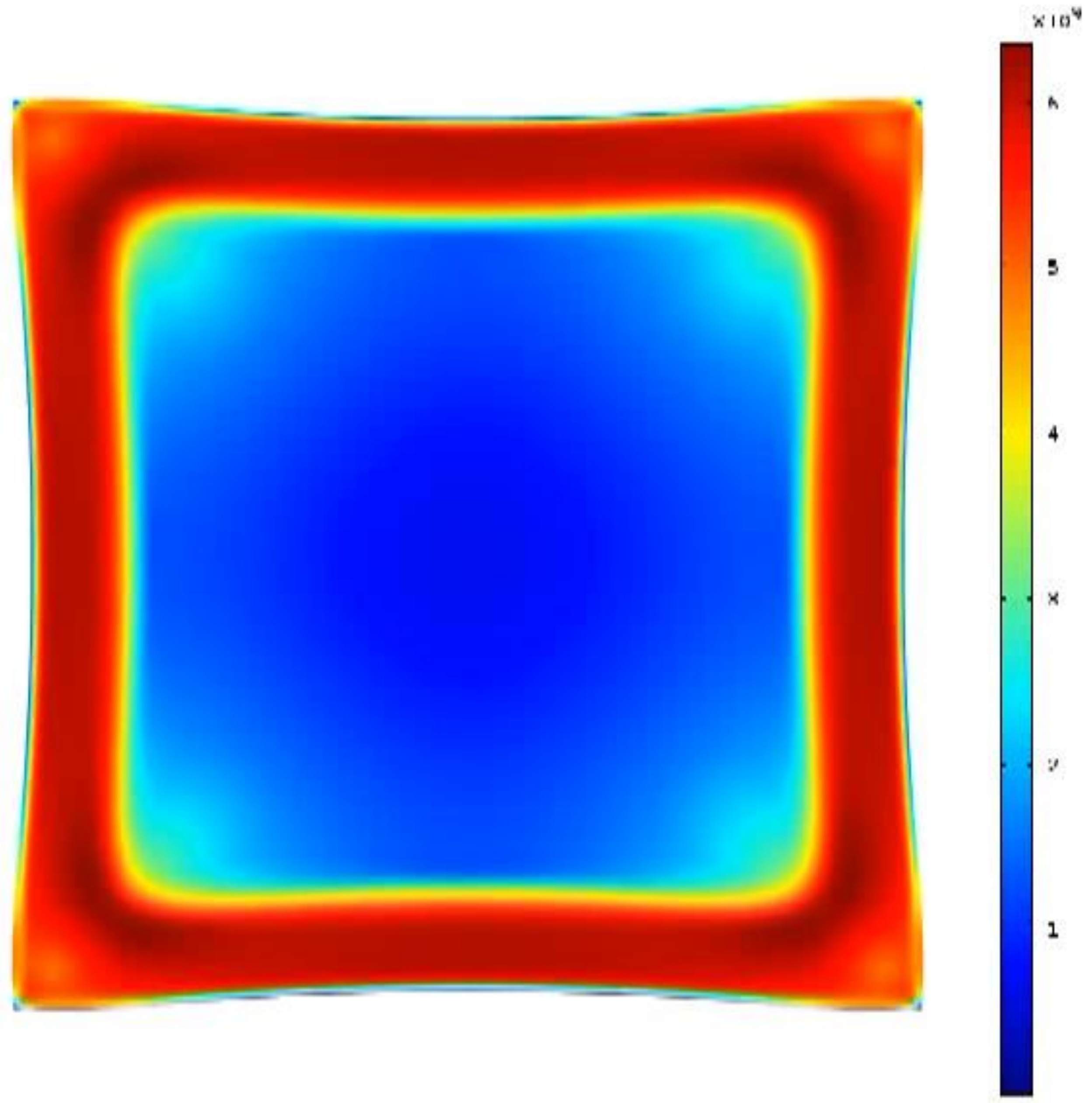


CaSO4

Stress (von Mises)

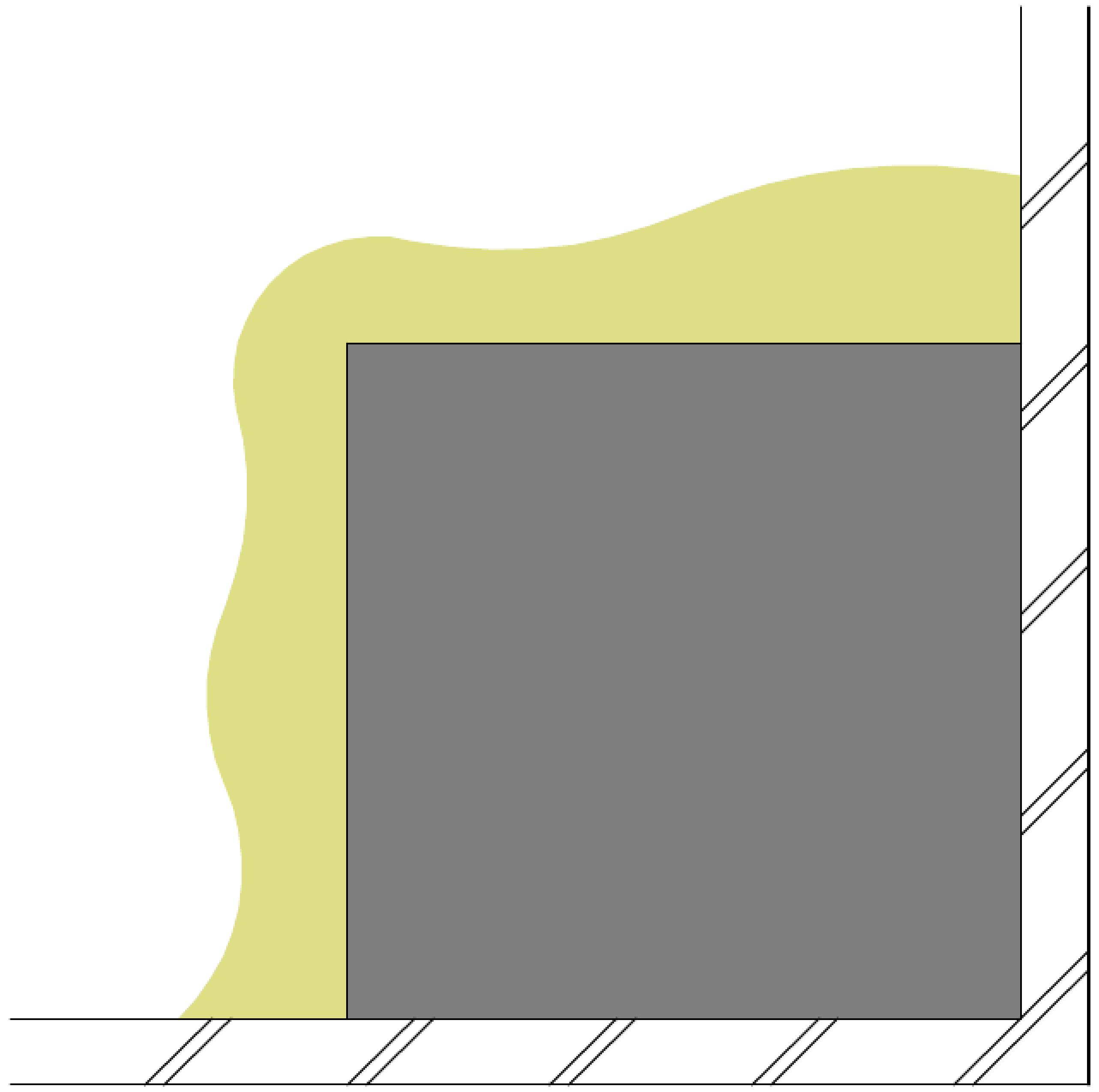


Stress (Tresca)



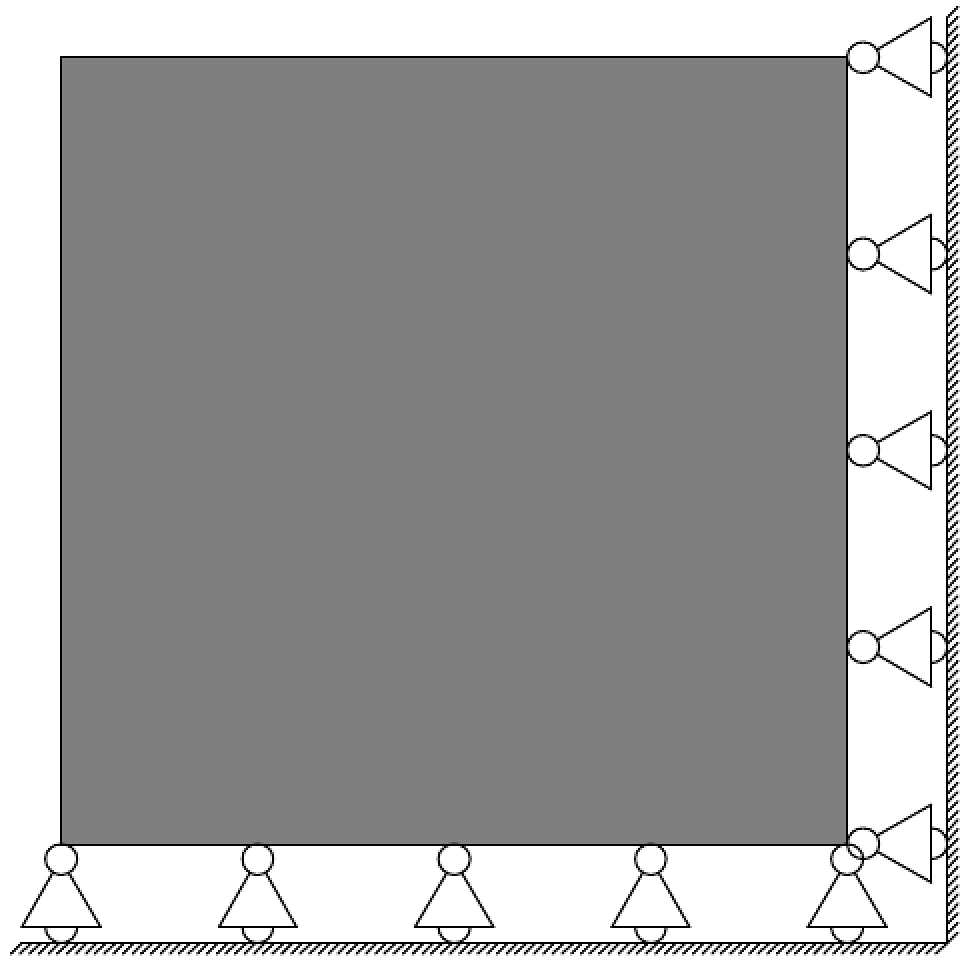
Continuum Damage Mechanics

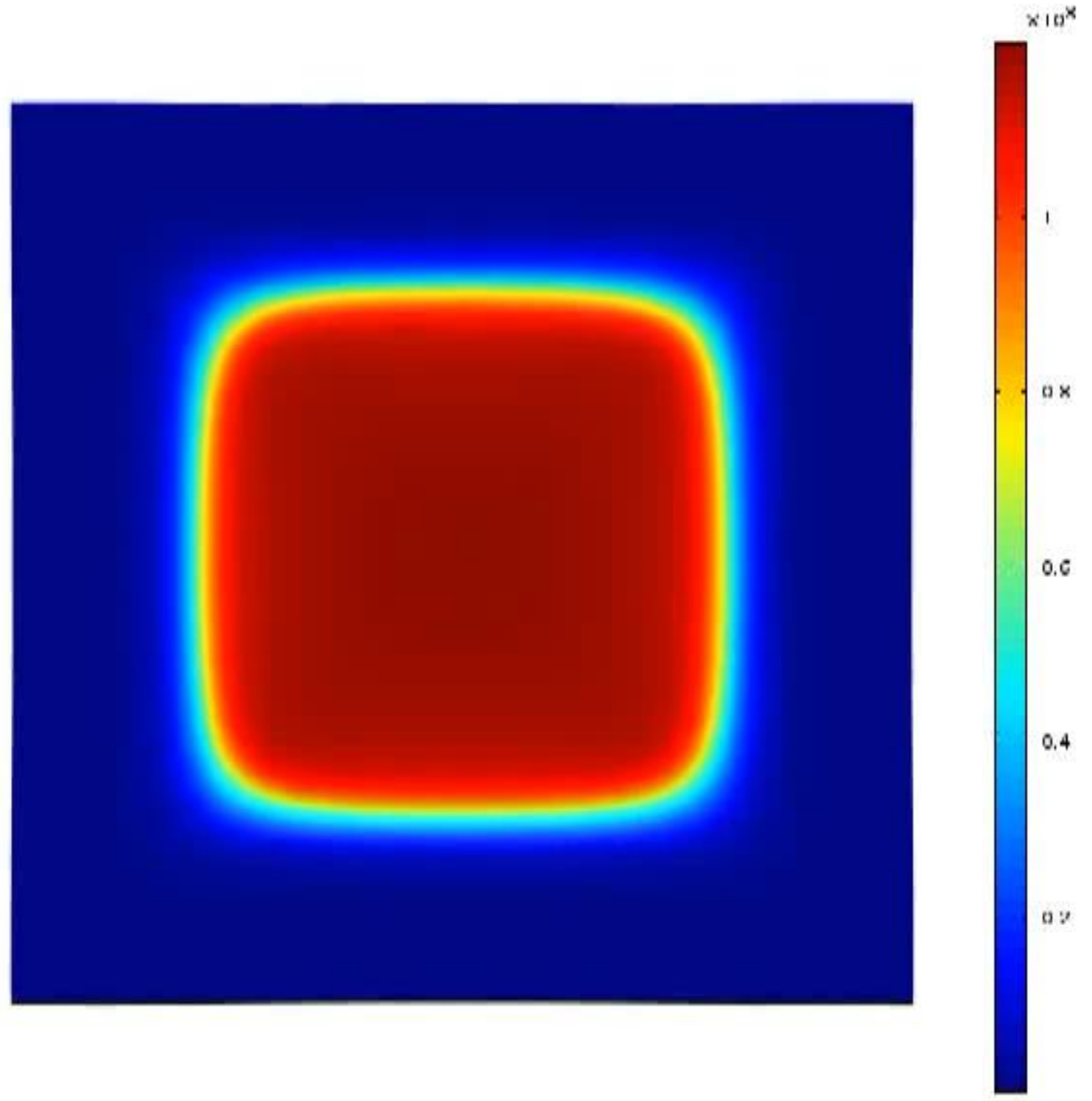
$$
\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} && \\
\frac{\partial[CaSO_4]}{\partial t} &= && && + k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[Ca^{2+}]}{\partial t} &= \nabla \cdot \left(D(\omega)\nabla[Ca^{2+}]\right) && - k_{CH}Q_{CH} && - k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[OH^{-}]}{\partial t} &= \nabla \cdot \left(D(\omega)\nabla[OH^{-}]\right) && - 2k_{CH}Q_{CH} && \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= \nabla \cdot \left(D(\omega)\nabla[SO_4^{2-}]\right) && && - k_{CaSO_4}Q_{CaSO_4} \\
\boldsymbol{\sigma} &= (1-\omega)\ {}^4\mathbb{C}_0 \left(\boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\mathbf{I}\right) && &&
\end{aligned}
$$



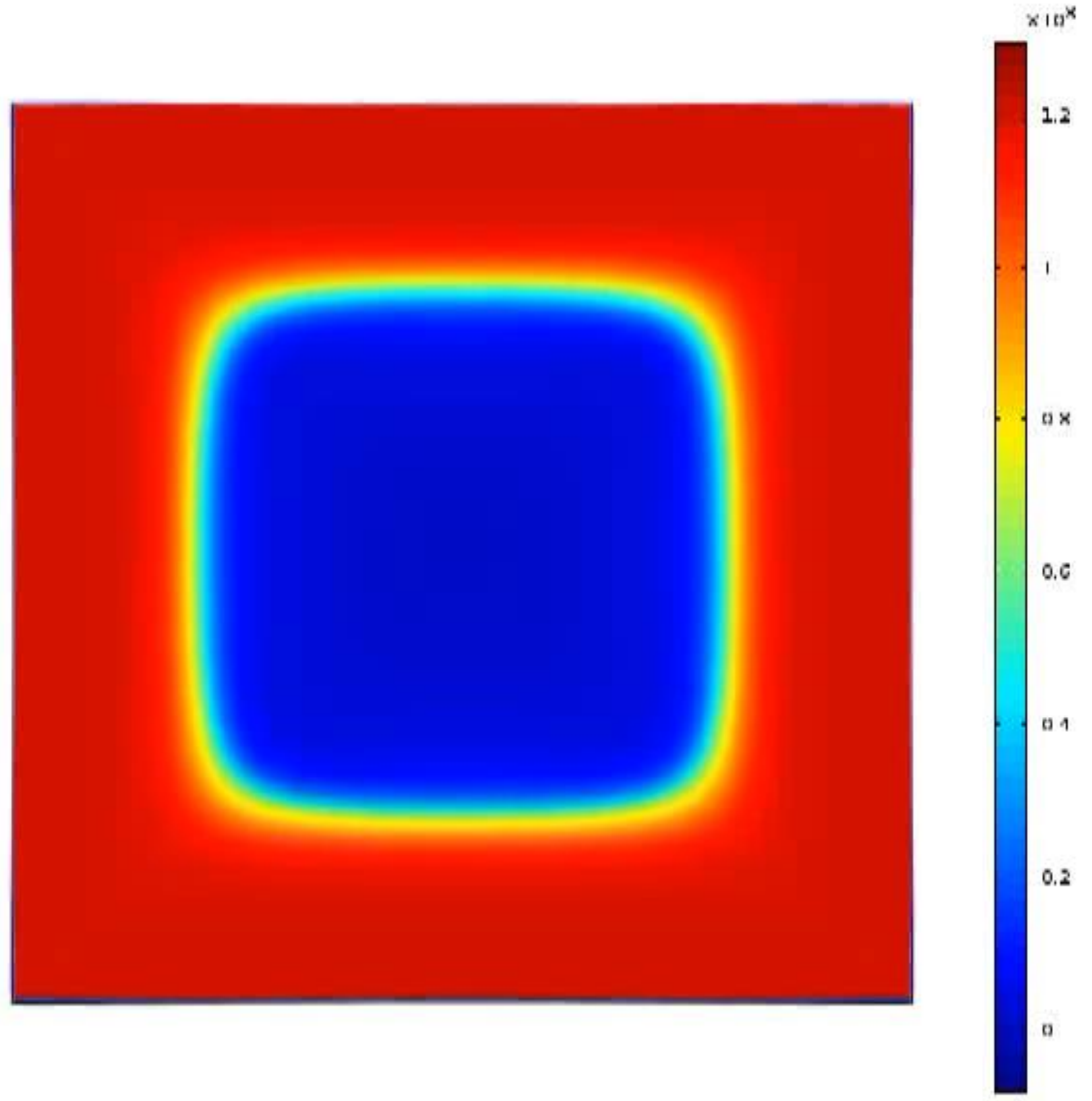
Continuum Damage Mechanics

$$
\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} \\
\frac{\partial[CaSO_4]}{\partial t} &= && && + k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[Ca^{2+}]}{\partial t} &= \nabla\cdot\big(D(\omega)\nabla[Ca^{2+}]\big) && - k_{CH}Q_{CH} && - k_{CaSO_4}Q_{CaSO_4} \\
\frac{\partial[OH^-]}{\partial t} &= \nabla\cdot\big(D(\omega)\nabla[OH^-]\big) && - 2k_{CH}Q_{CH} \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= \nabla\cdot\big(D(\omega)\nabla[SO_4^{2-}]\big) && && - k_{CaSO_4}Q_{CaSO_4} \\
\boldsymbol{\sigma} &= (1-\omega)\ {}^4\mathbb{C}_0\left(\boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\mathbf{I}\right)
\end{aligned}
$$



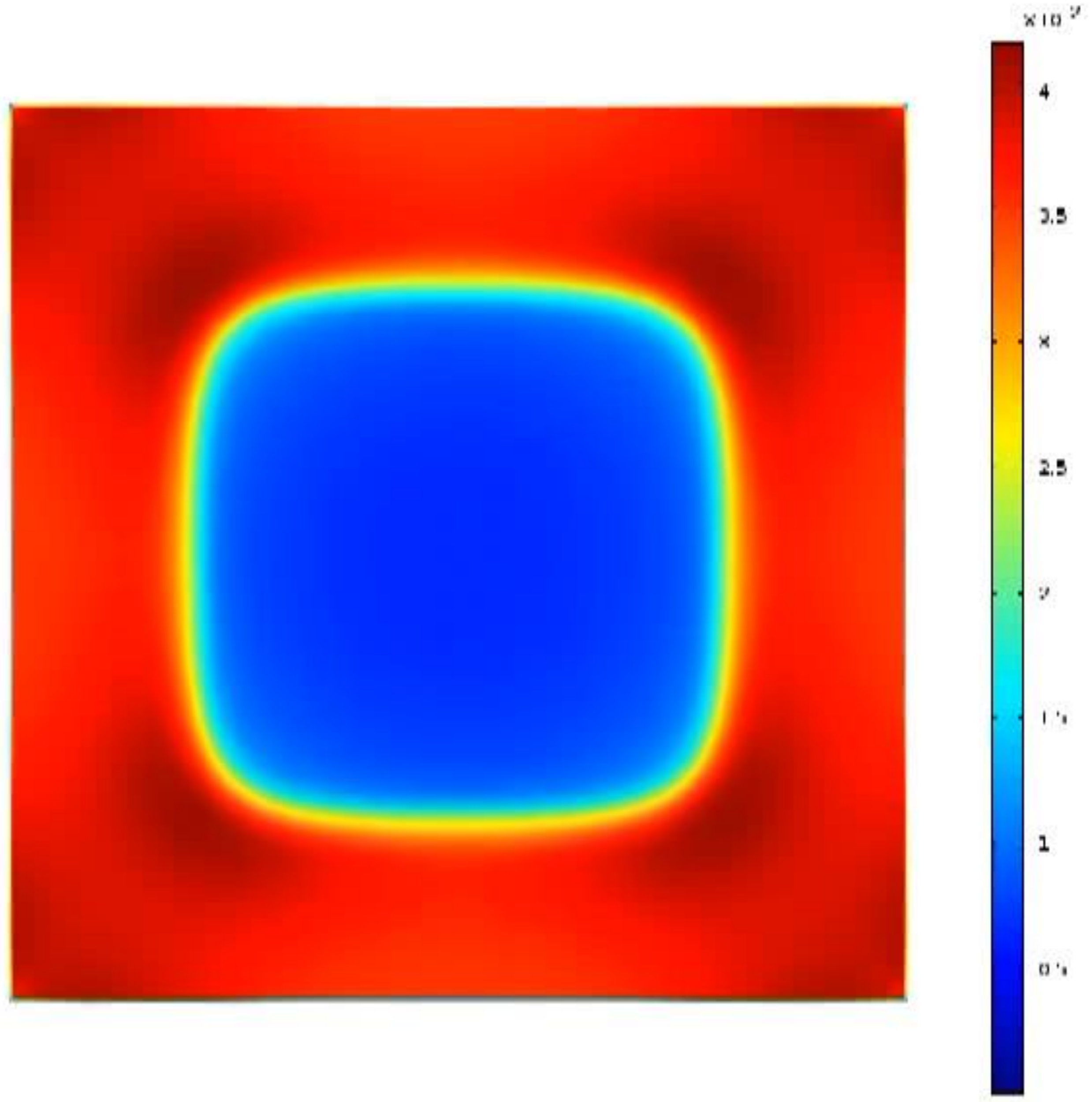


CH

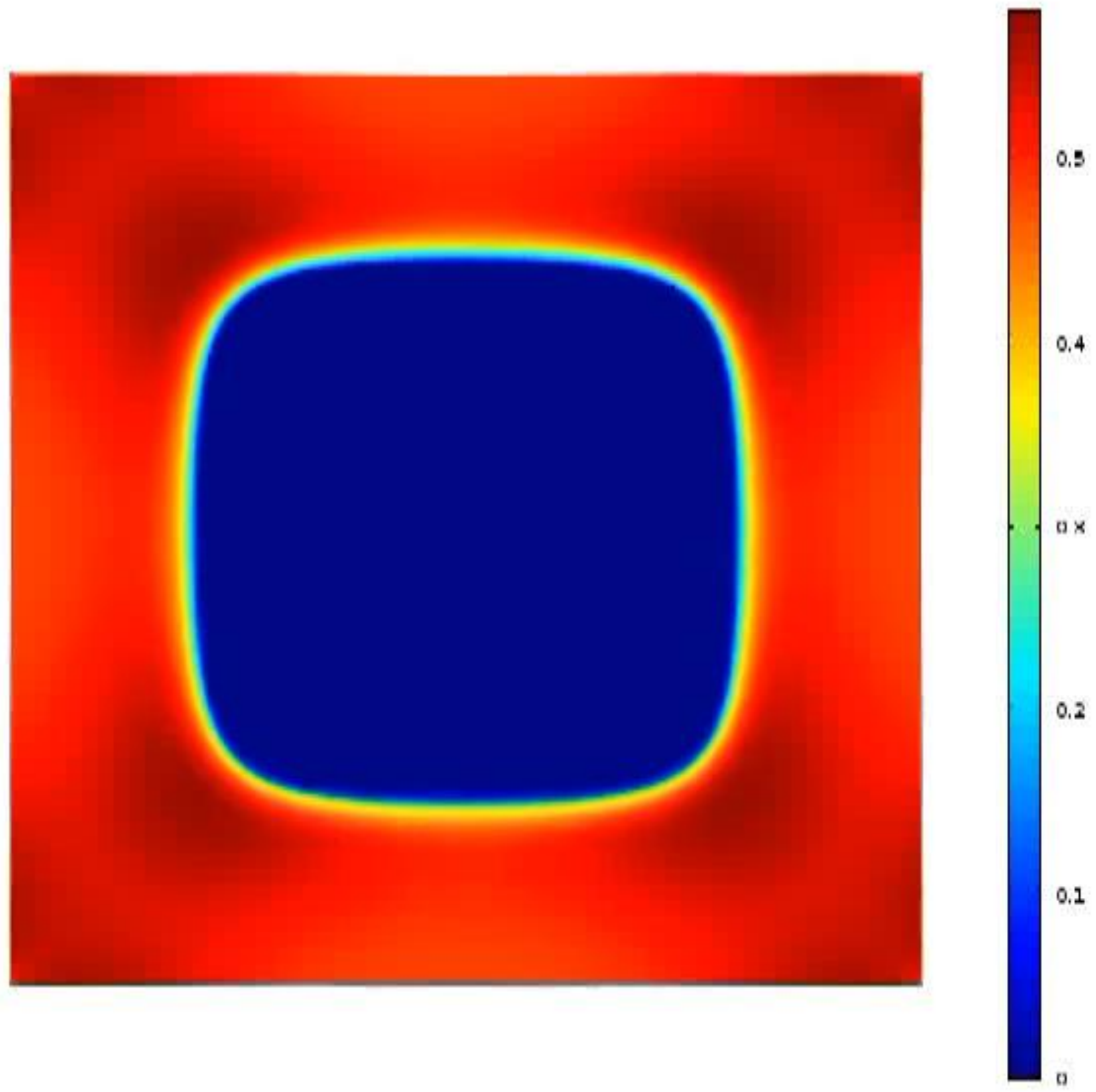


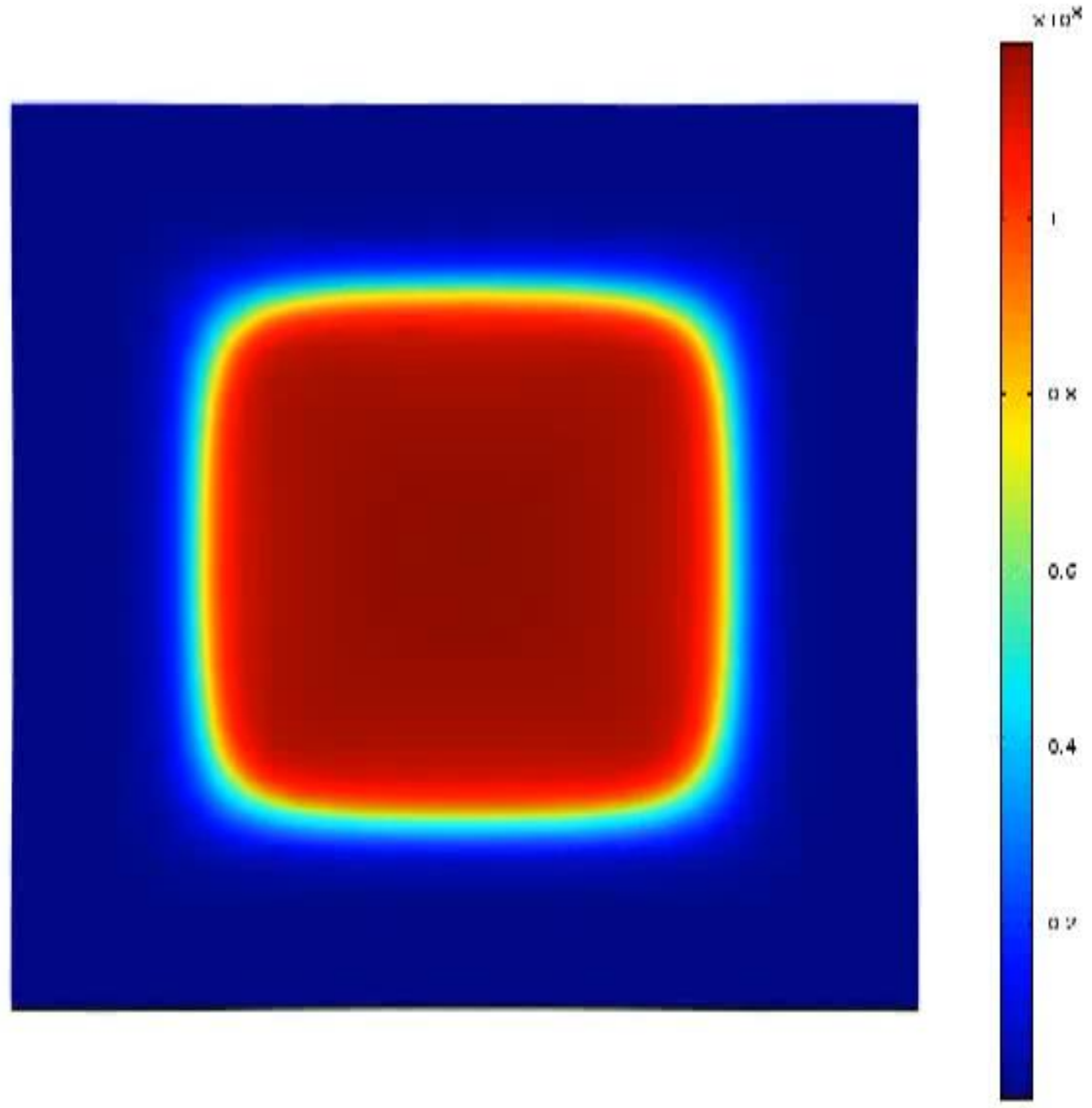
CaSO4

Equivalent strain



Damage Parameter



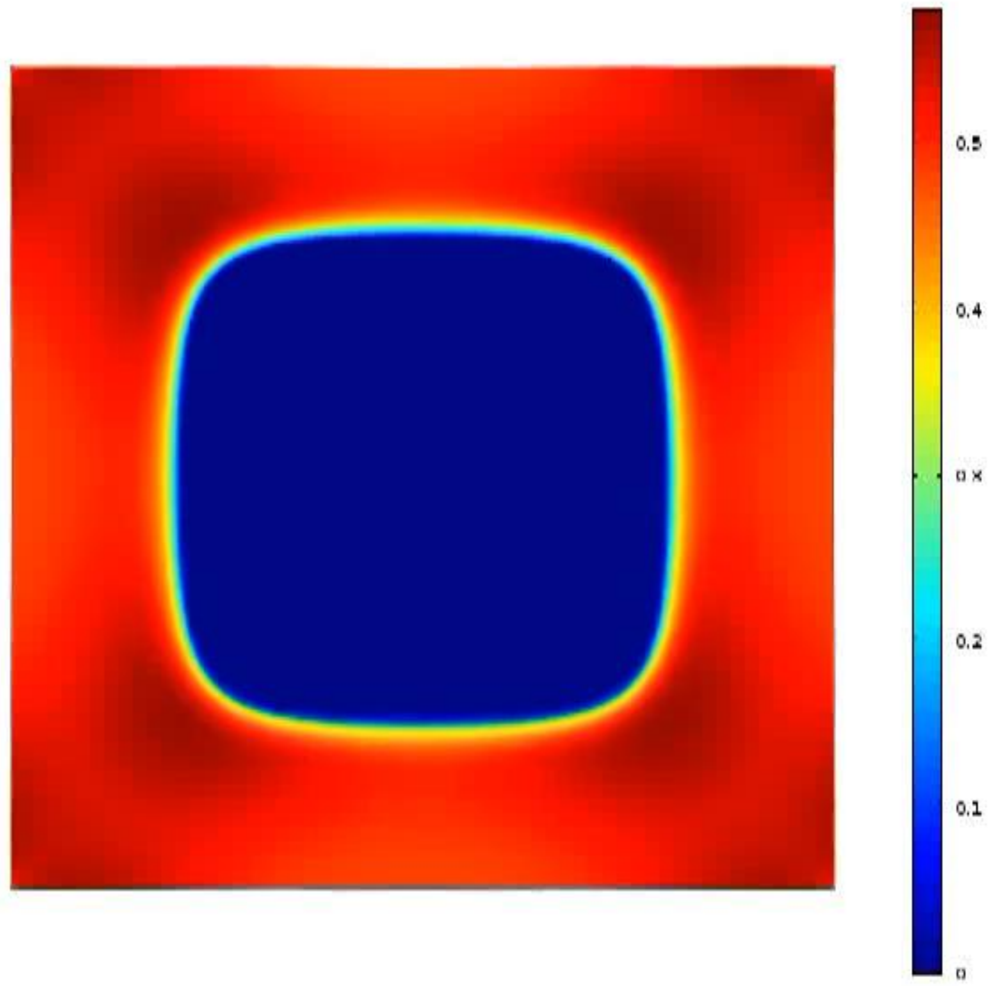


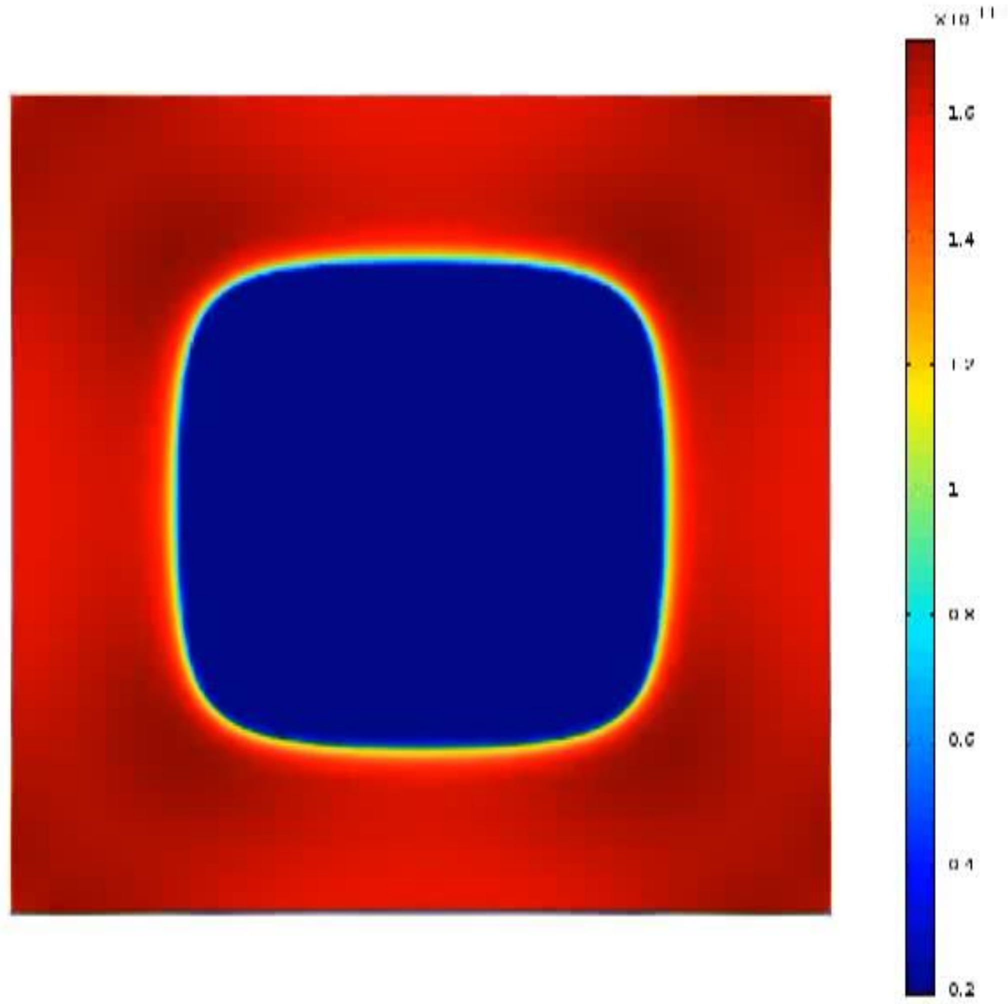
CH

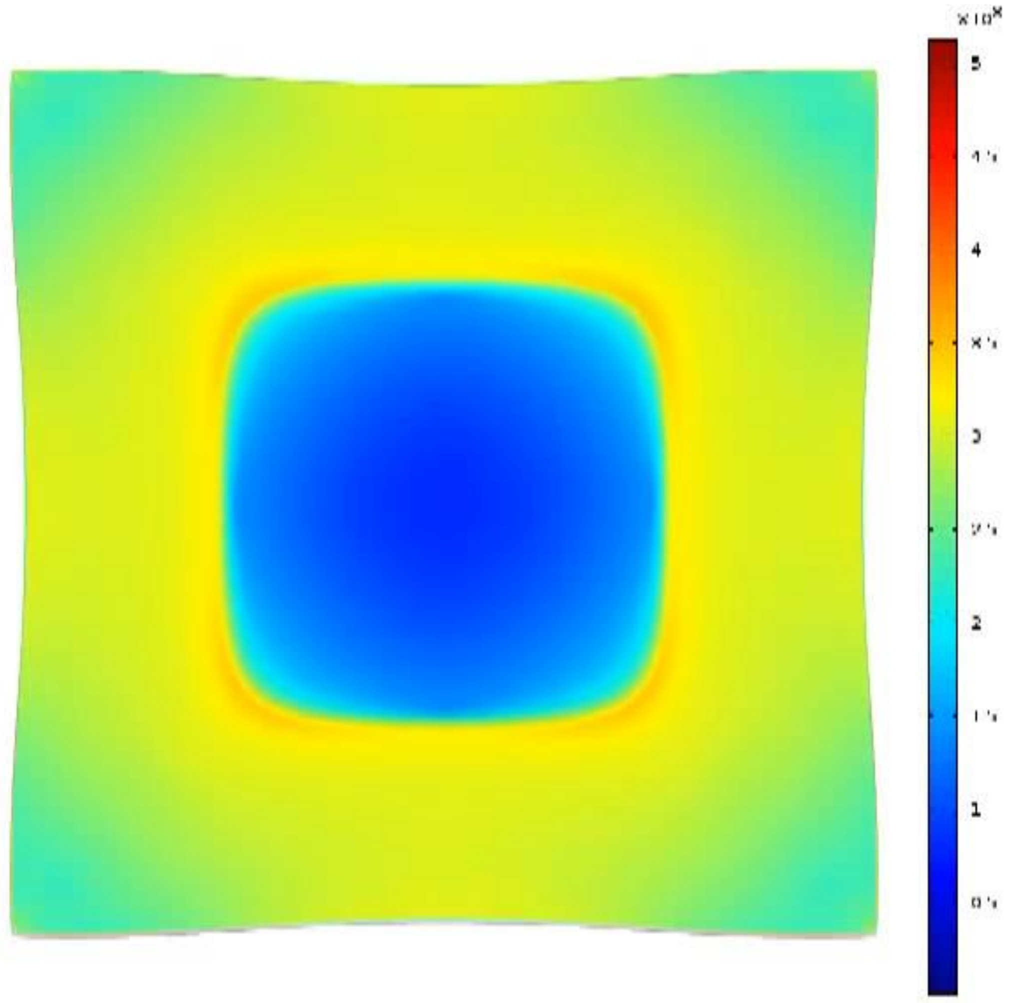
Damage Parameter

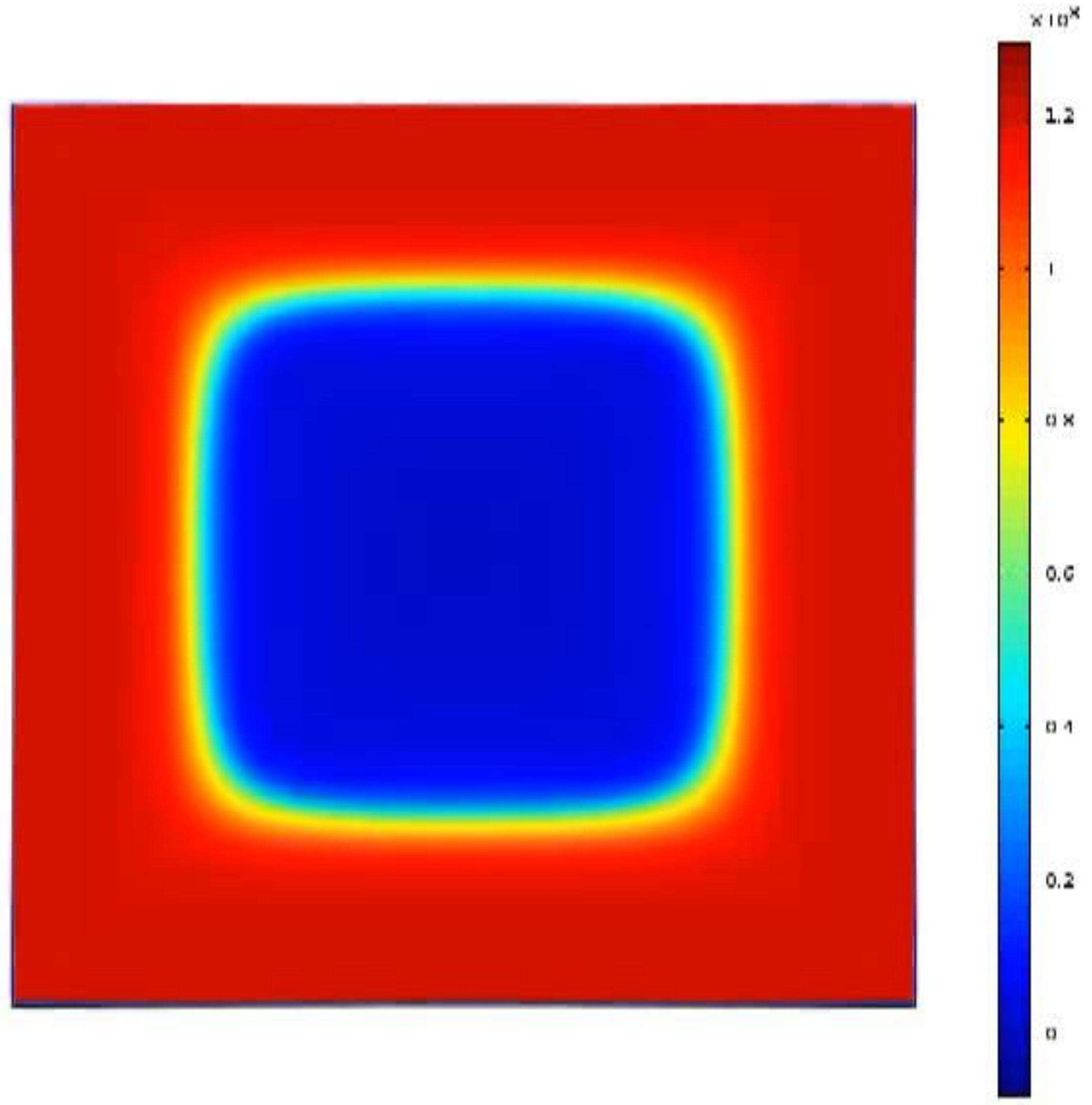
Diffusion Coëfficient

Stress (Tresca)









CaSO4

Parameters

$$
\begin{aligned}
\frac{\partial[CH]}{\partial t} &= && + k_{CH}Q_{CH} && && \\
\frac{\partial[CSH]}{\partial t} &= && && && + k_{CSH}Q_{CSH} \\
\frac{\partial[CaSO_4]}{\partial t} &= && && + k_{CaSO_4}Q_{CaSO_4} && \\
\frac{\partial[Ca^{2+}]}{\partial t} &= D_0\nabla^2[Ca^{2+}] && - k_{CH}Q_{CH} && - k_{CaSO_4}Q_{CaSO_4} && - k_{CSH}Q_{CSH} \\
\frac{\partial[OH^-]}{\partial t} &= D_0\nabla^2[OH^-] && - 2k_{CH}Q_{CH} && && - 2k_{CSH}Q_{CSH} \\
\frac{\partial[SO_4^{2-}]}{\partial t} &= D_0\nabla^2[SO_4^{2-}] && && - k_{CaSO_4}Q_{CaSO_4} &&
\end{aligned}
$$

$$\boldsymbol{\sigma} = (1-\varphi)(1-\omega)\ {}^4\mathbb{C}_0\left(\boldsymbol{\varepsilon} - \varepsilon^g[CaSO_4]\right)$$

Future Developments

Experiments

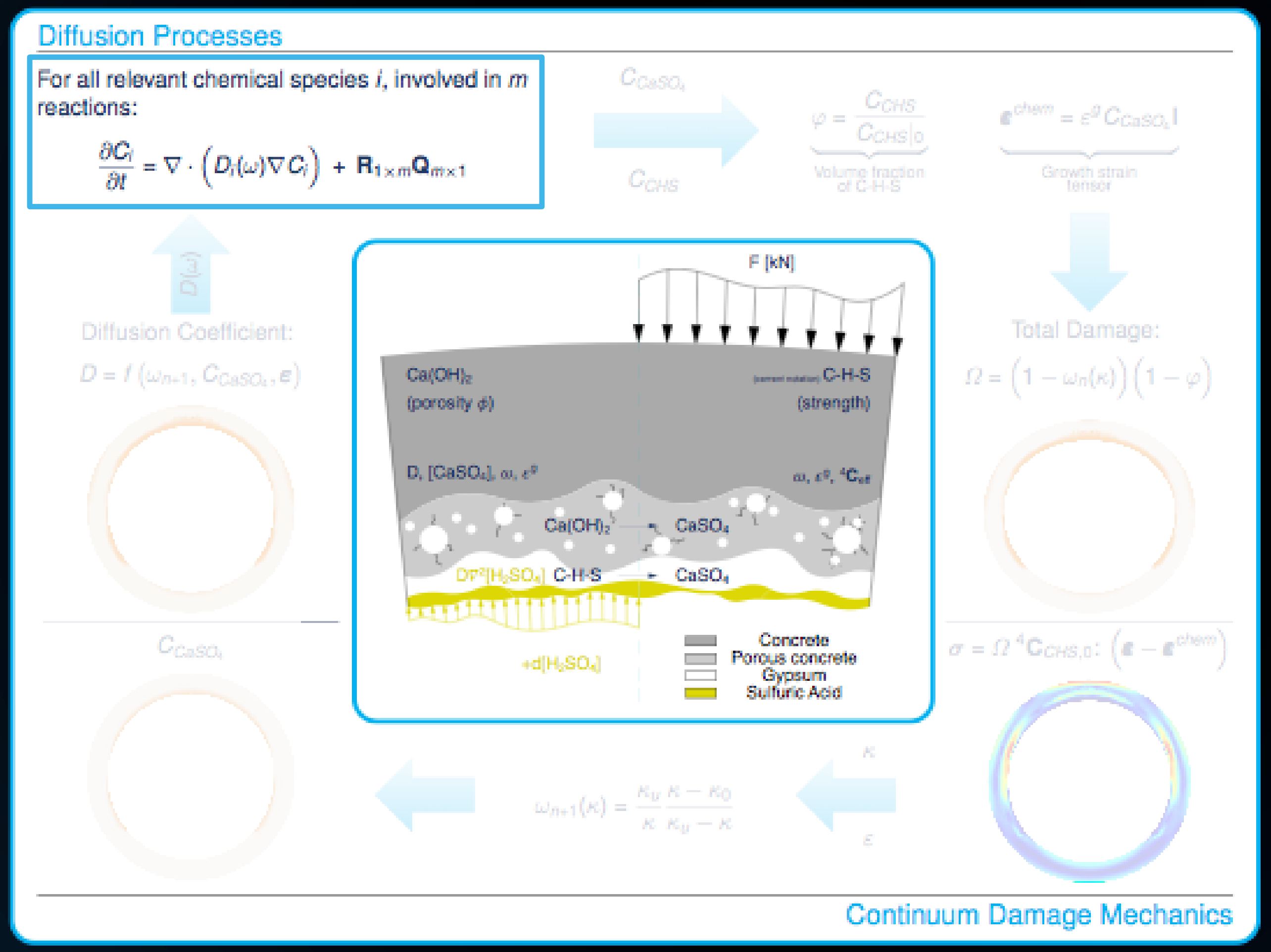
- Concrete casting starts end of June

Numerical Simulations

- Finishing and combining last parameters (chemical damage, CSH)
- Calibrating and validating small numerical models
- Benchmarking the model on literature
- Finishing first paper

Questions?

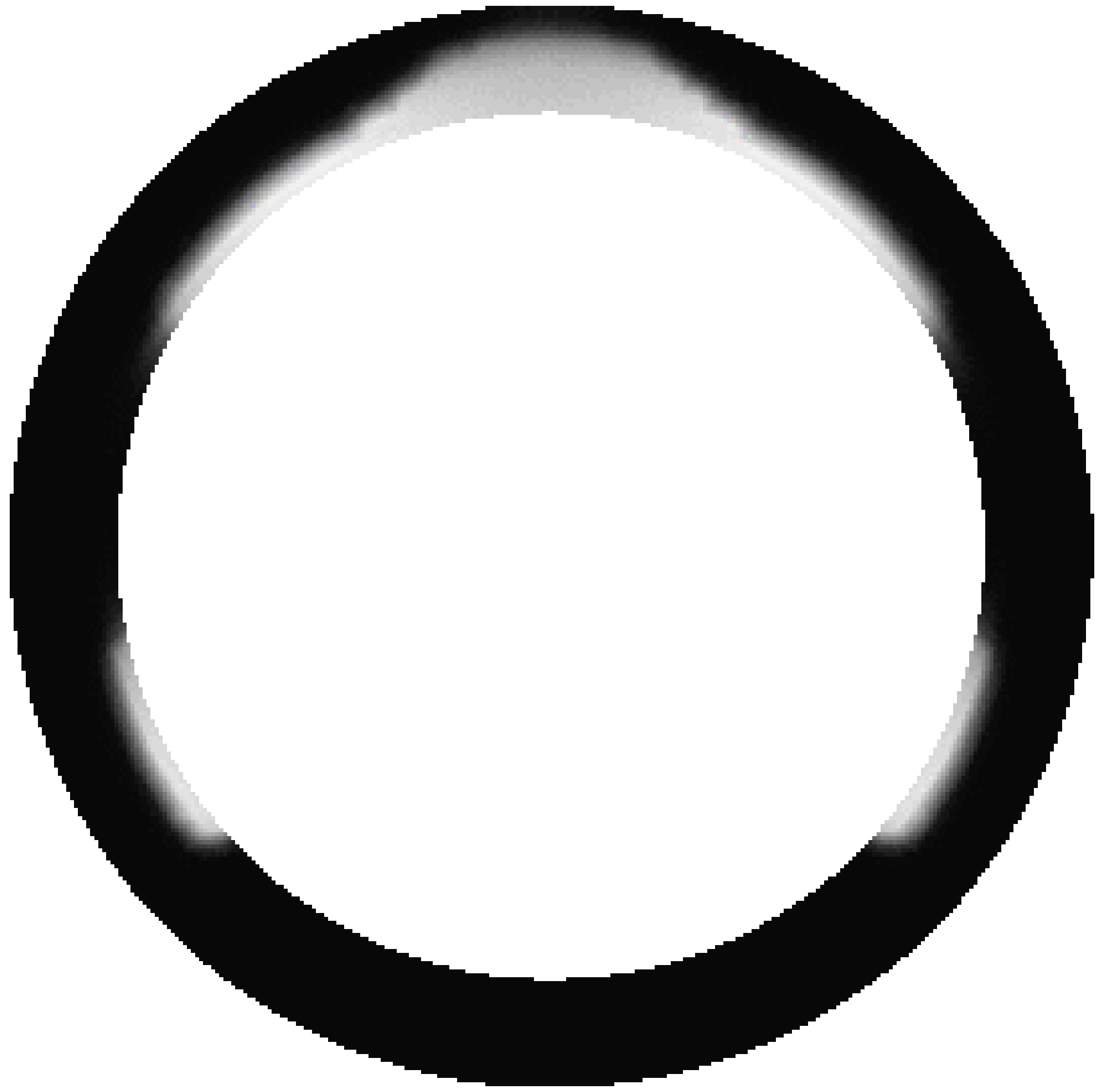
Additional / Explanatory Slides



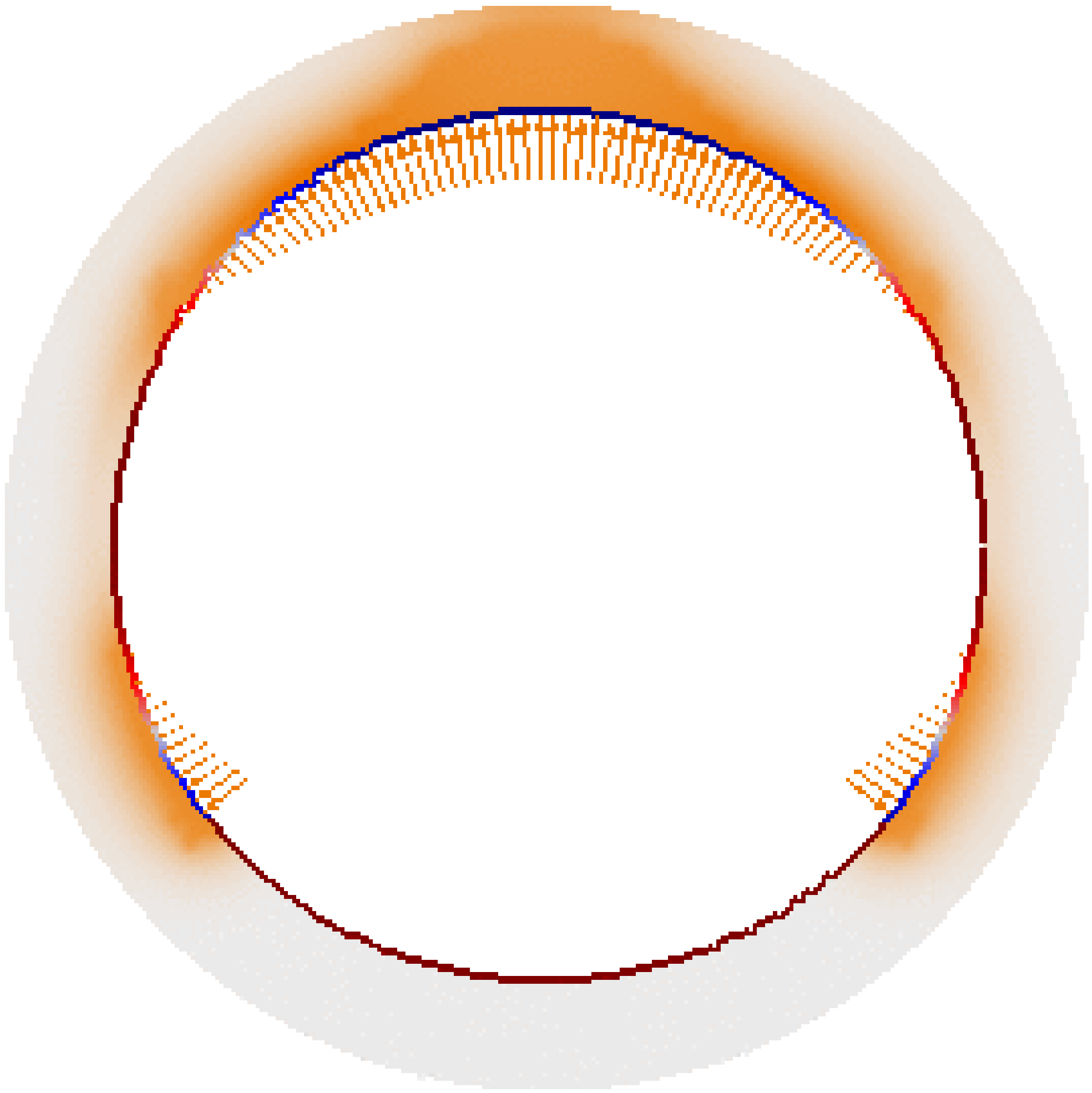
Diffusion Models

$$\frac{\partial}{\partial t}\begin{bmatrix}[Ca(OH)_2]\\ [Ca^{2+}]\\ [OH^-]\\ [SO_4^{2-}]\\ [CaSO_4]\end{bmatrix} = \nabla\cdot\left(D\nabla\begin{bmatrix}0\\ [Ca^{2+}]\\ [OH^-]\\ [SO_4^{2-}]\\ 0\end{bmatrix}\right) + \mathbf{R}_{5\times4}\mathbf{Q}_{4\times1}$$

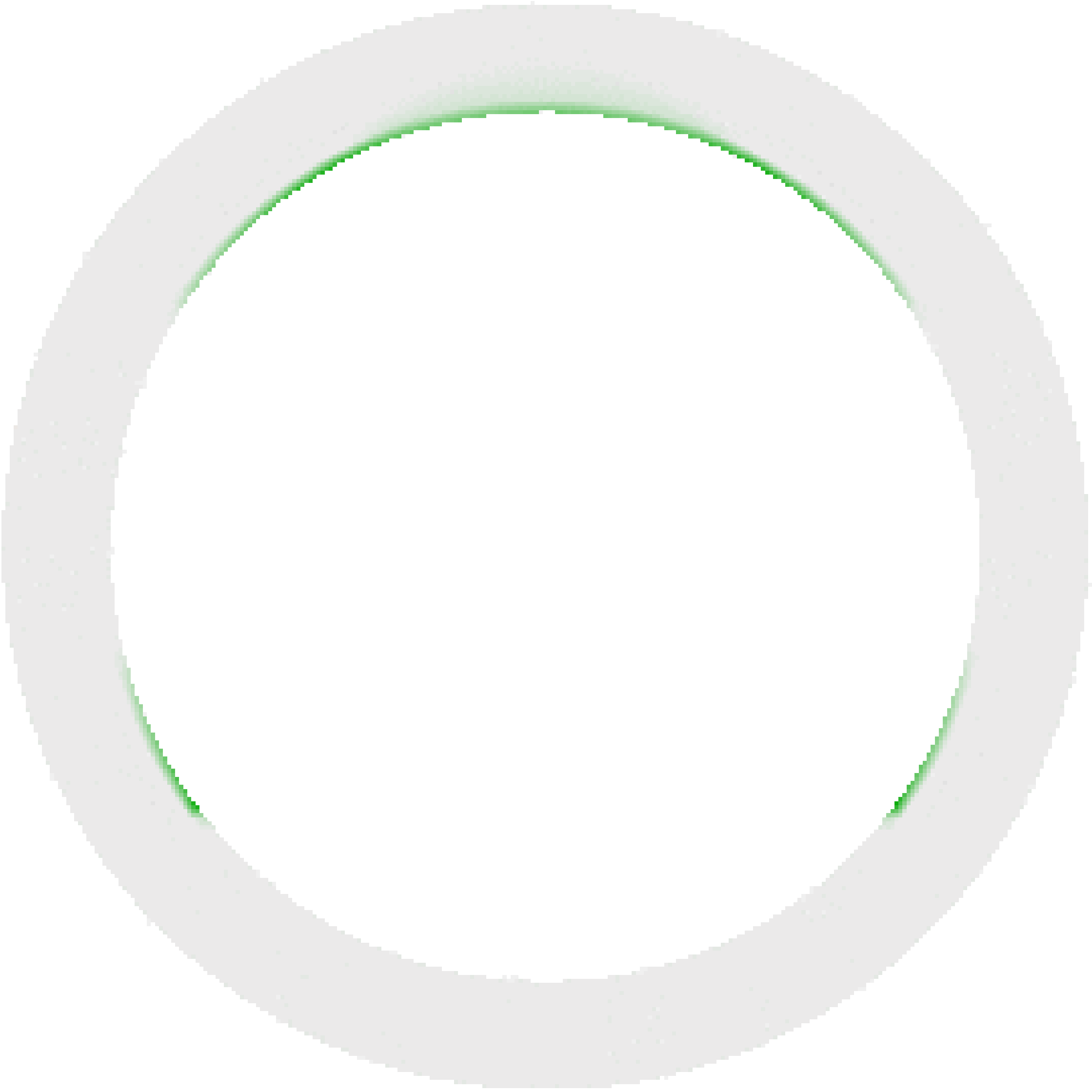
Calcium Hydroxide $[Ca(OH)_2]$

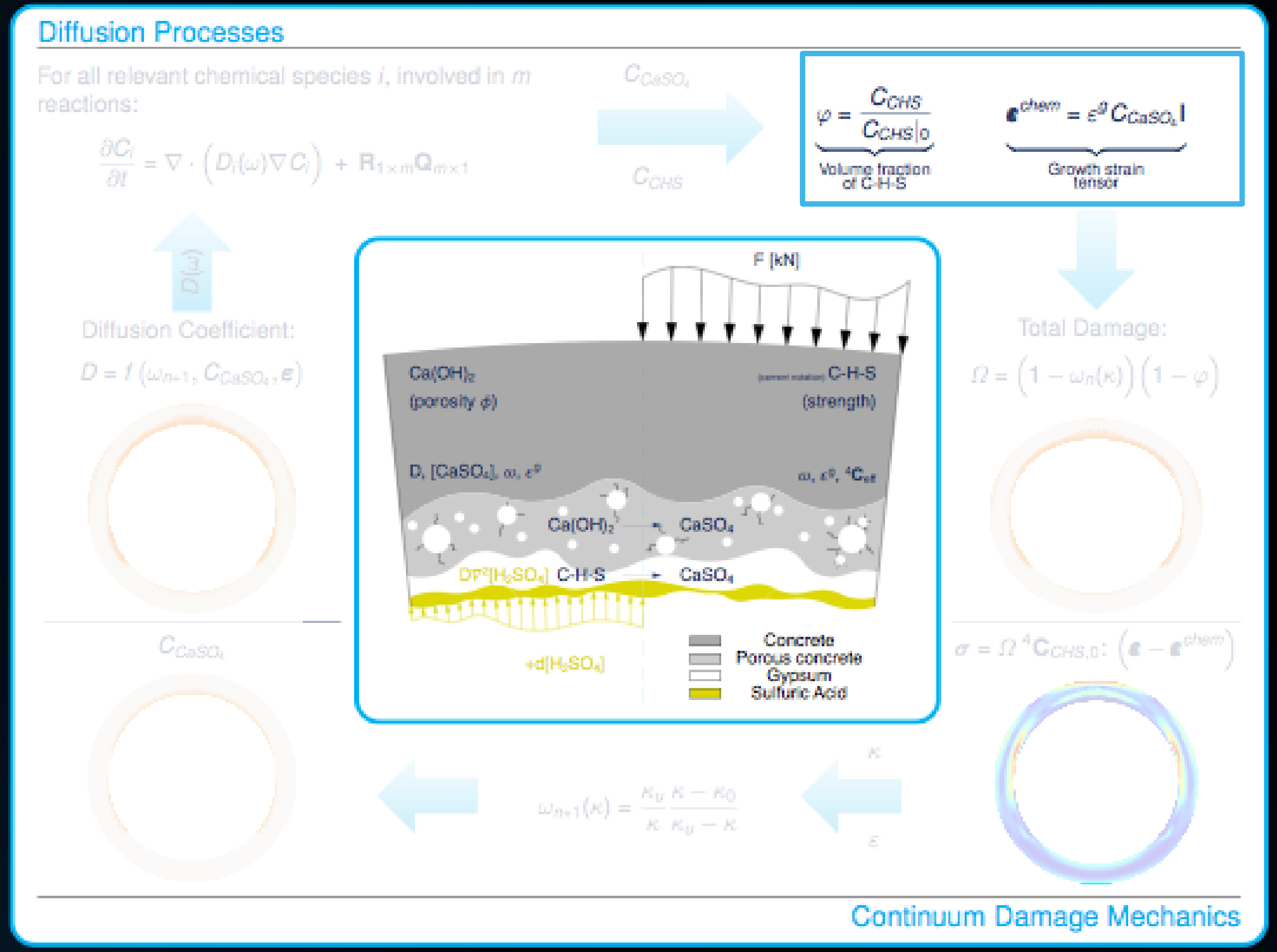


Sulfate ions $[SO_4^{2-}]$



Gypsum $[CaSO_4]$

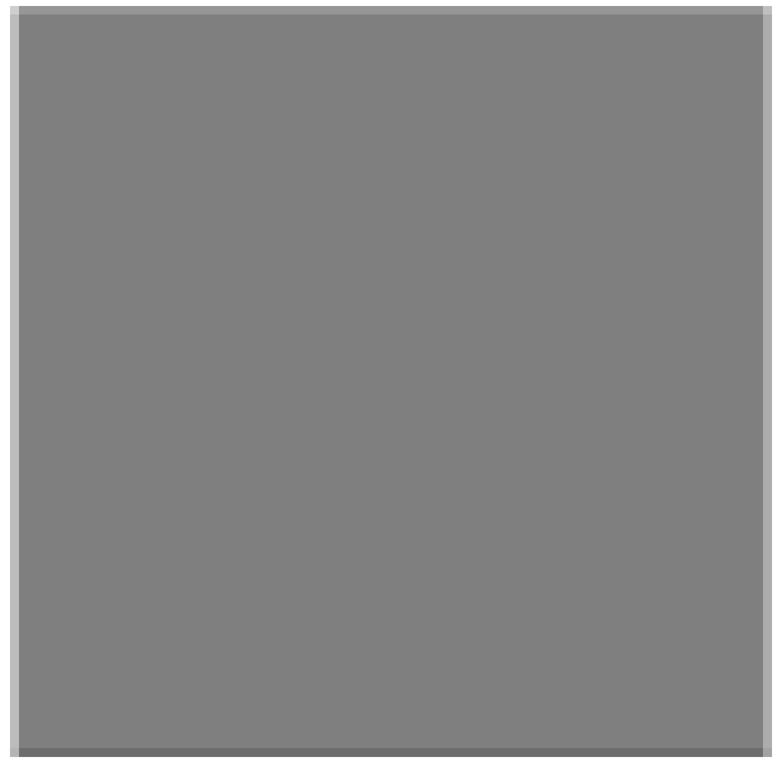




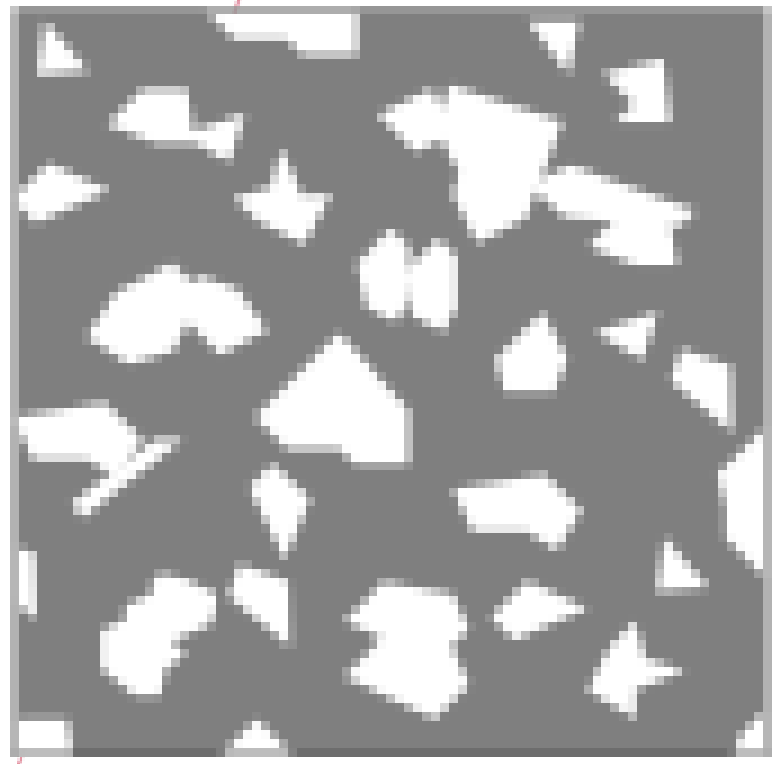
Chemical Damage

$$\varphi = \frac{[CSH]}{[CSH]_0}$$

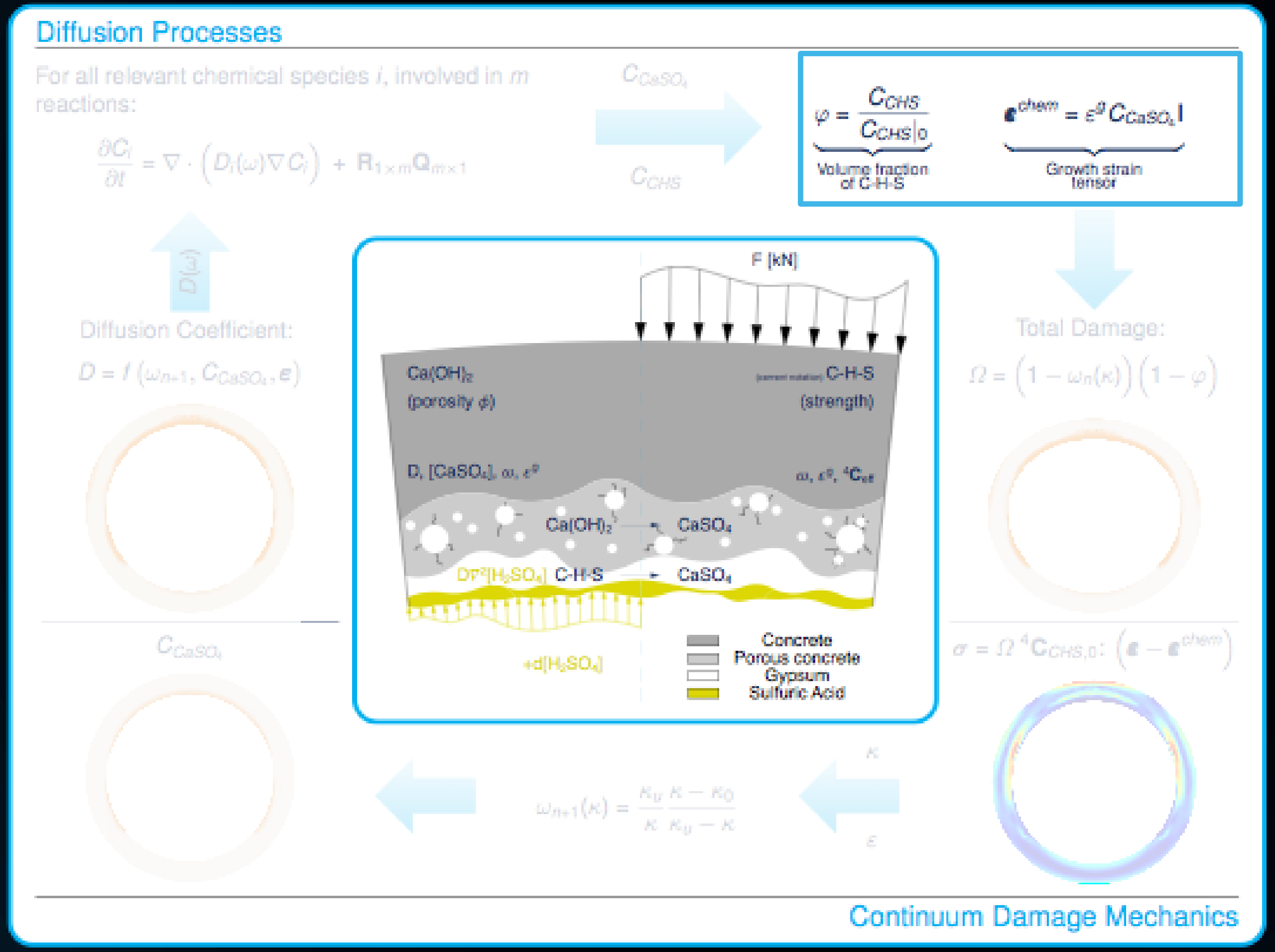
$\varphi = 1$



$\varphi = 0.5$



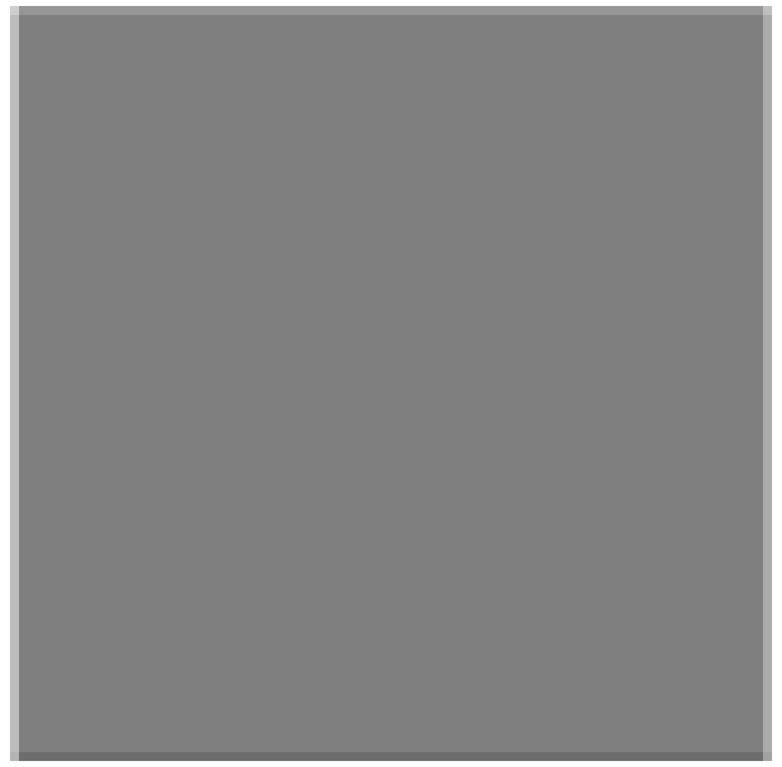
$\varphi = 0$



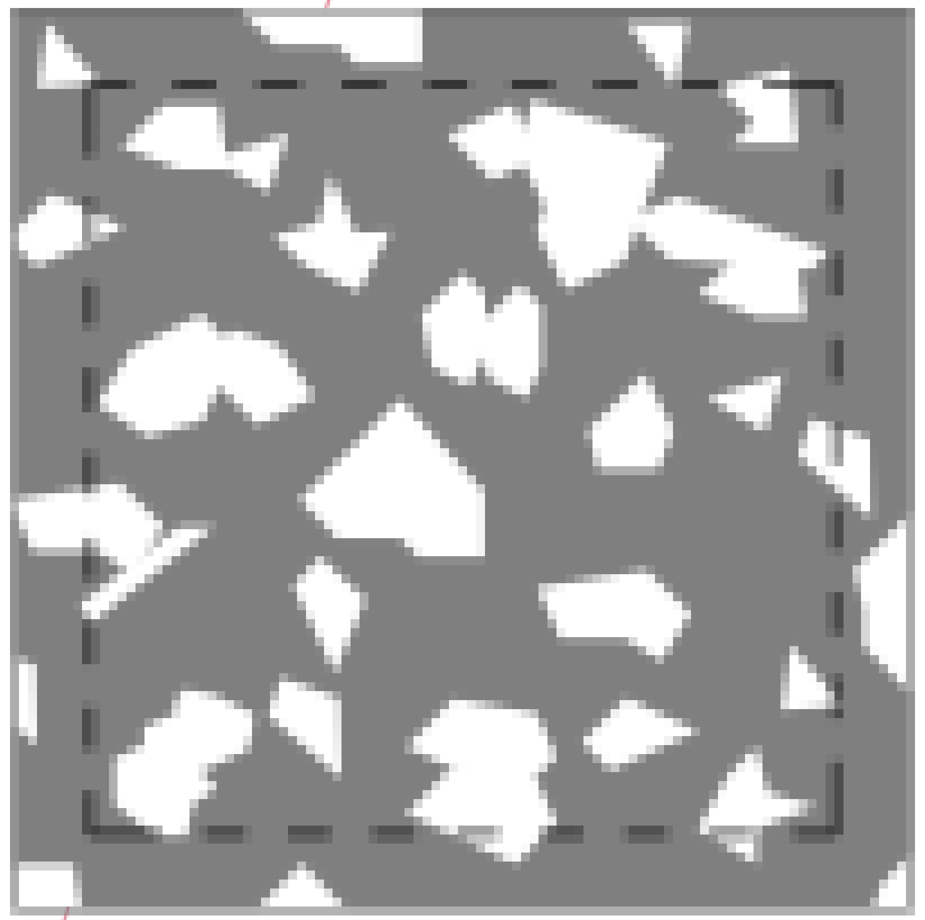
Gypsum Expansion

$$\boldsymbol{\varepsilon}^{chem} = \varepsilon^g [CaSO_4]\mathbf{I}$$

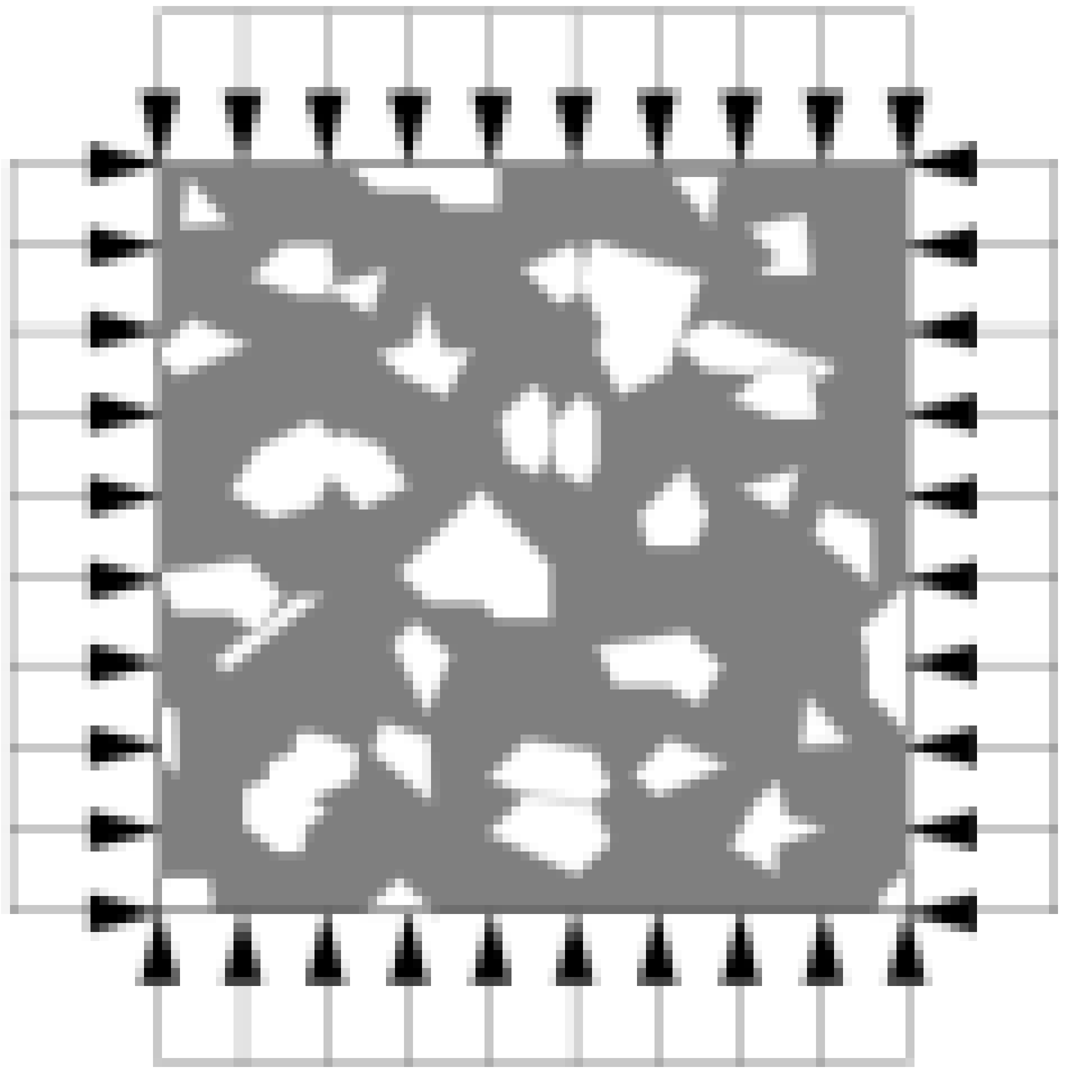
$$\boldsymbol{\varepsilon}^{chem} = 0$$

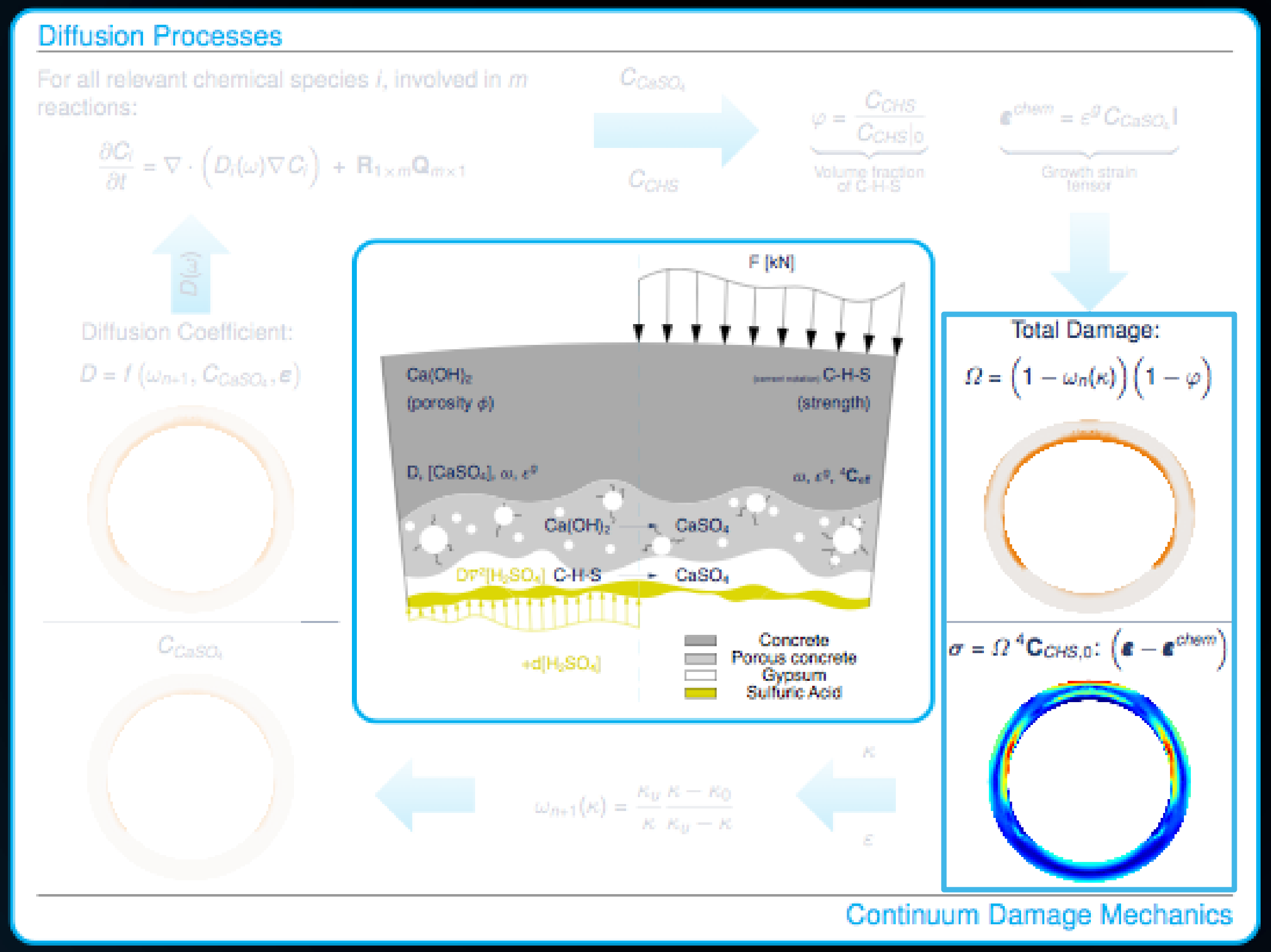


$$\boldsymbol{\varepsilon}^{chem} = \varepsilon^g [CaSO_4]\mathbf{I}$$



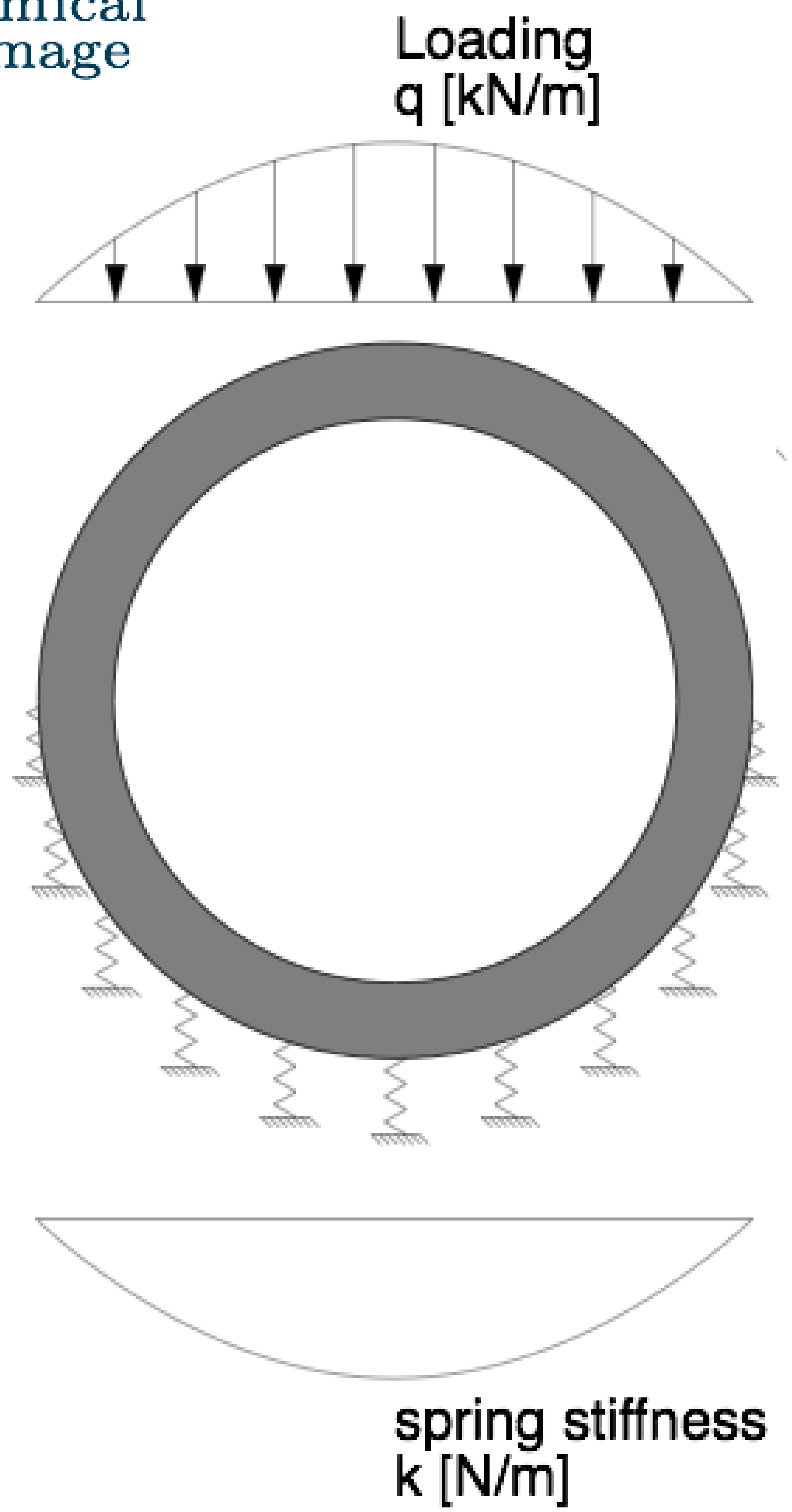
$$\boldsymbol{\varepsilon}^{tot} = \boldsymbol{\varepsilon}^{chem} + \boldsymbol{\varepsilon}^{e}$$

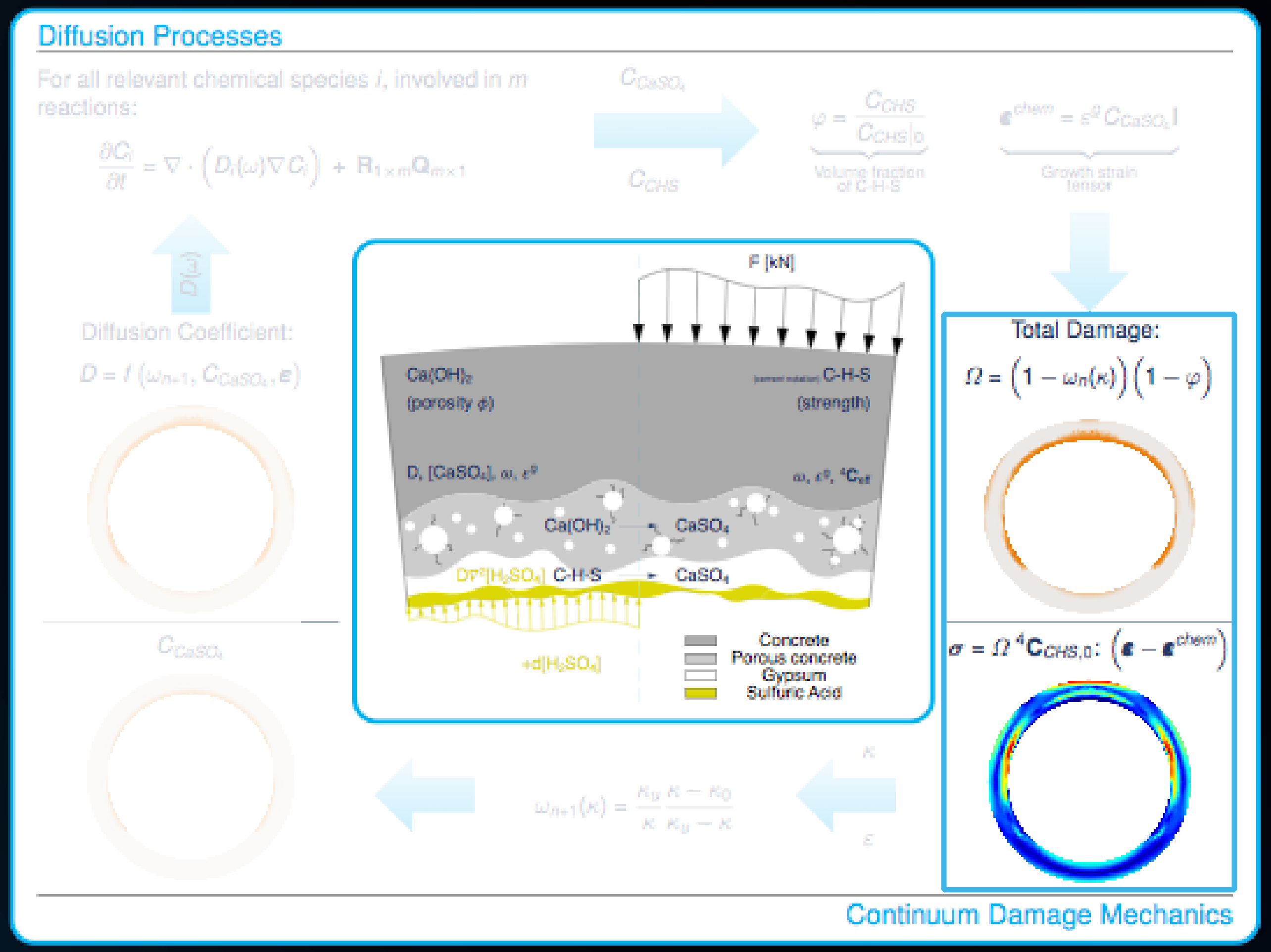




(Continuum Damage) Mechanical Model

$$\boldsymbol{\sigma} = \underbrace{\left(1 - \omega_n(\kappa)\right)}_{\text{Mechanical Damage}} \underbrace{(\varphi)}_{\text{Chemical Damage}} \; {}^4\mathbb{C}_0 : \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{chem}\right)$$

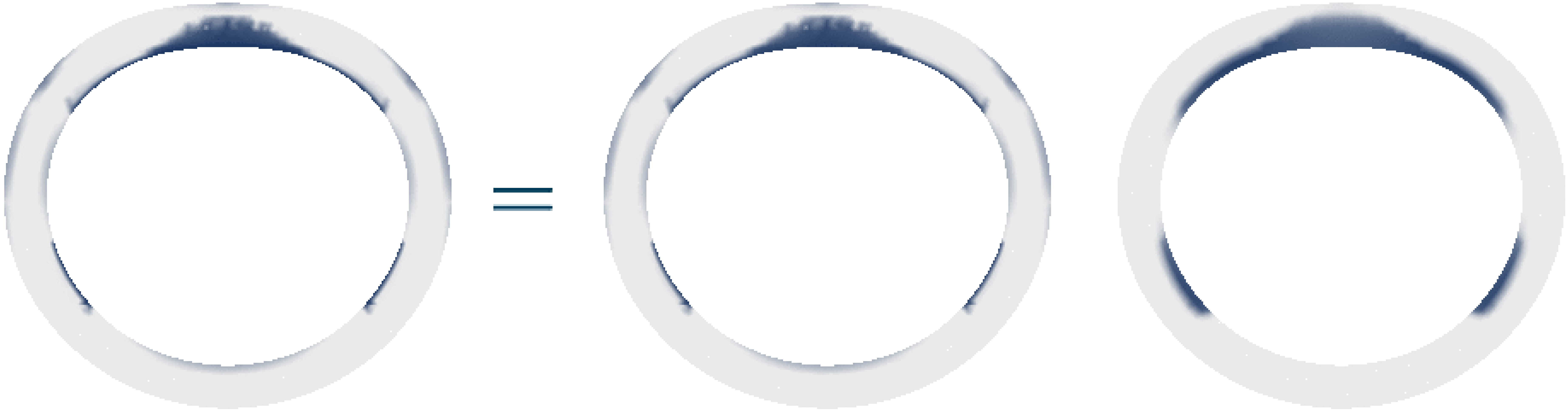


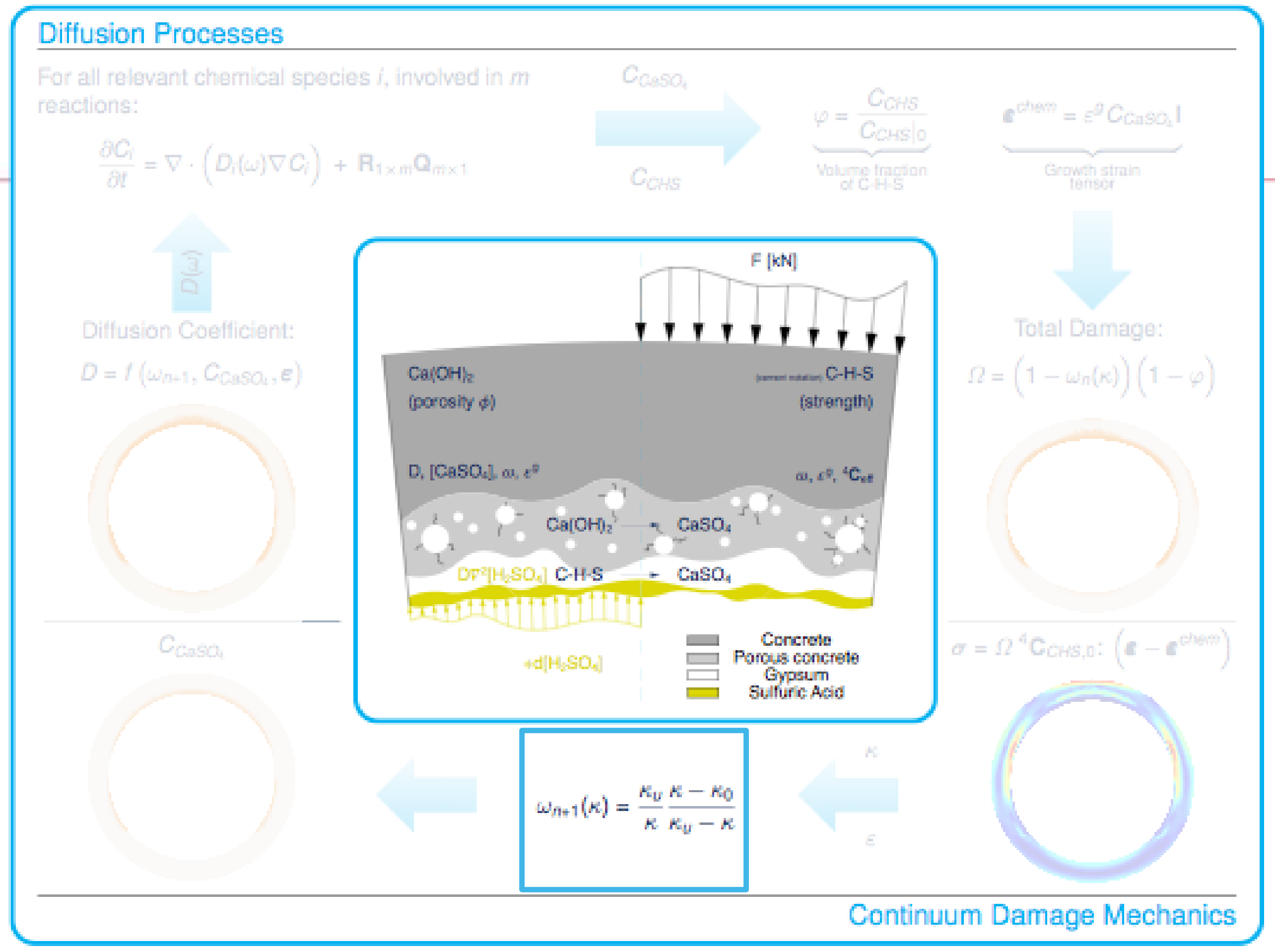


(Continuum Damage) Mechanical Model

$$\boldsymbol{\sigma} = \underbrace{\underbrace{\left(1-\omega_n(\kappa)\right)}_{\text{Mechanical Damage}}\ \underbrace{\left(\varphi\right)}_{\text{Chemical Damage}}}_{\text{Total damage}}\ {}^4\mathbb{C}_0 : \left(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{chem}\right)$$

Total Damage (Ω) Mechanical damage (ω) Chemical damage (φ)





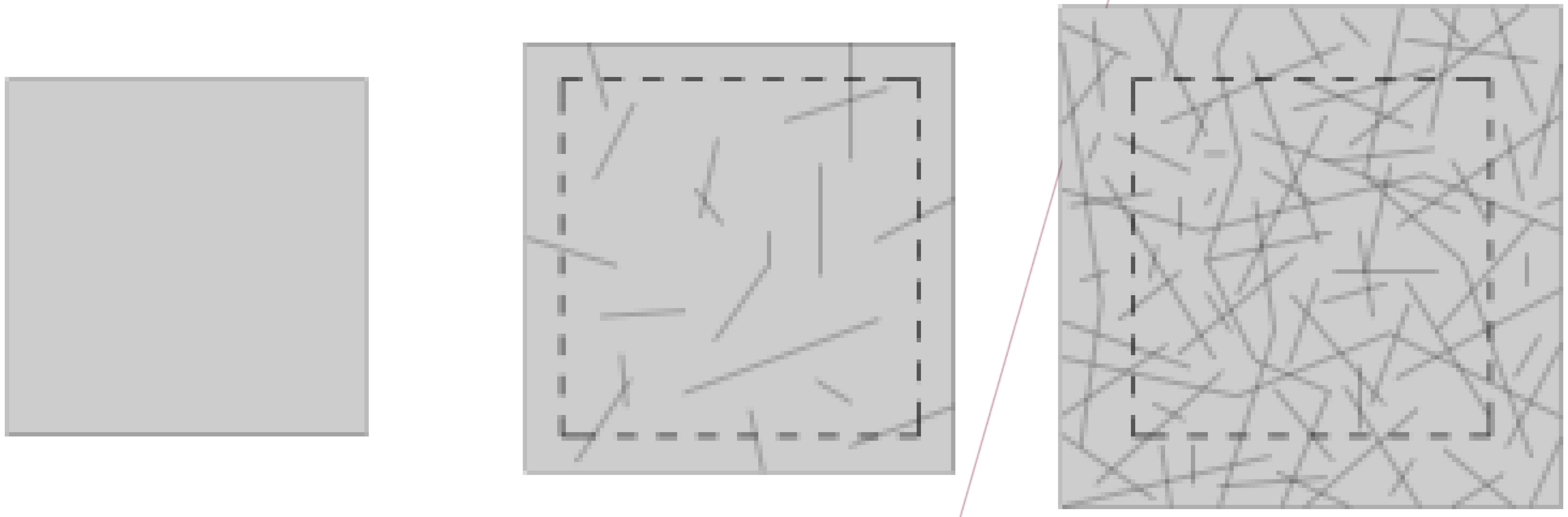
Mechanical Damage

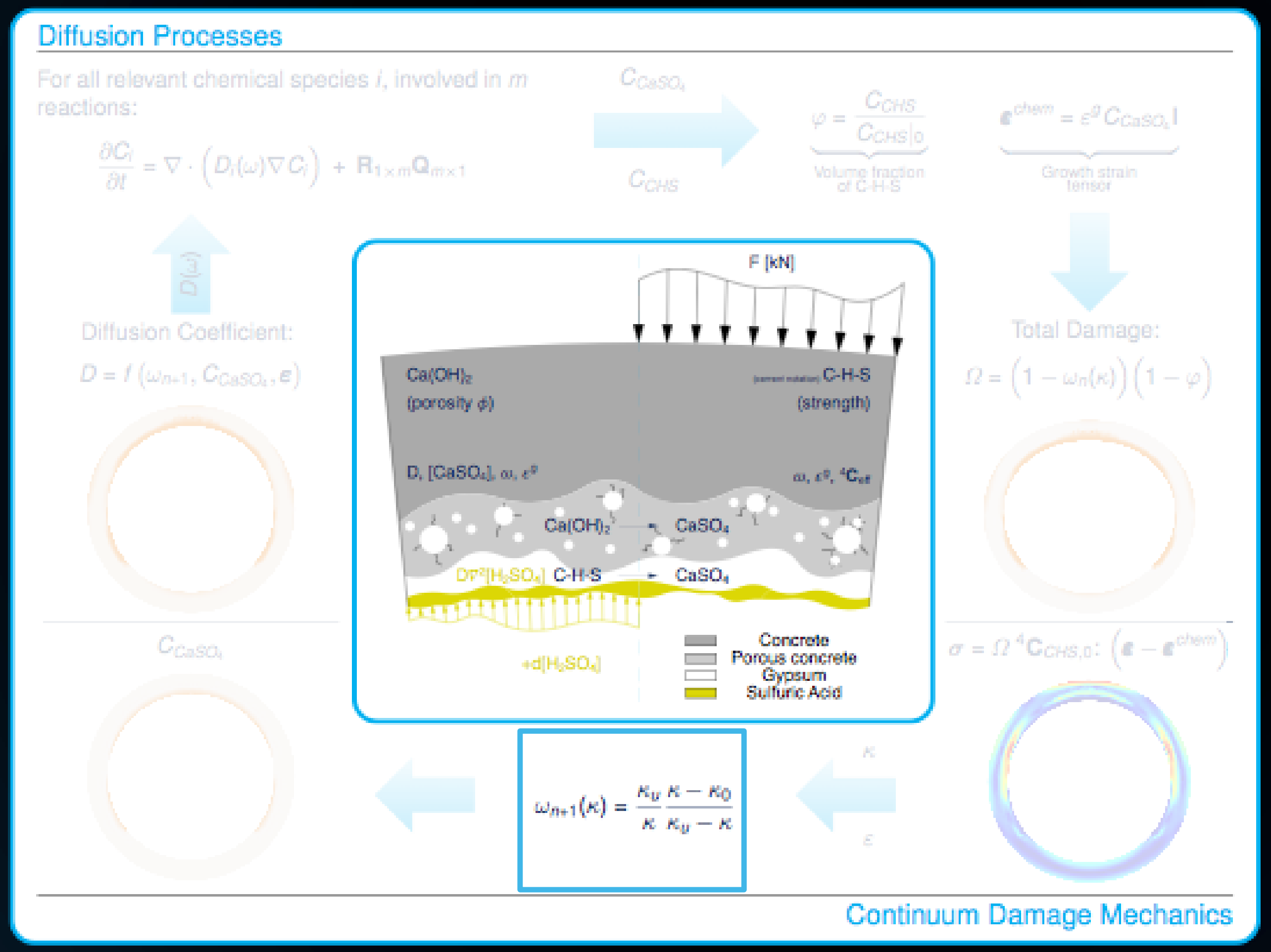
$$\begin{aligned} \tilde{\varepsilon} &= 0 \\ \kappa &= \kappa_0 \\ \omega(\kappa) &= 0 \end{aligned}$$

$$\begin{aligned} \tilde{\varepsilon} &= \tilde{\varepsilon}_t \\ \kappa_0 < &\ \kappa < \kappa_u \\ 0 < &\ \omega(\kappa) < 1 \end{aligned}$$

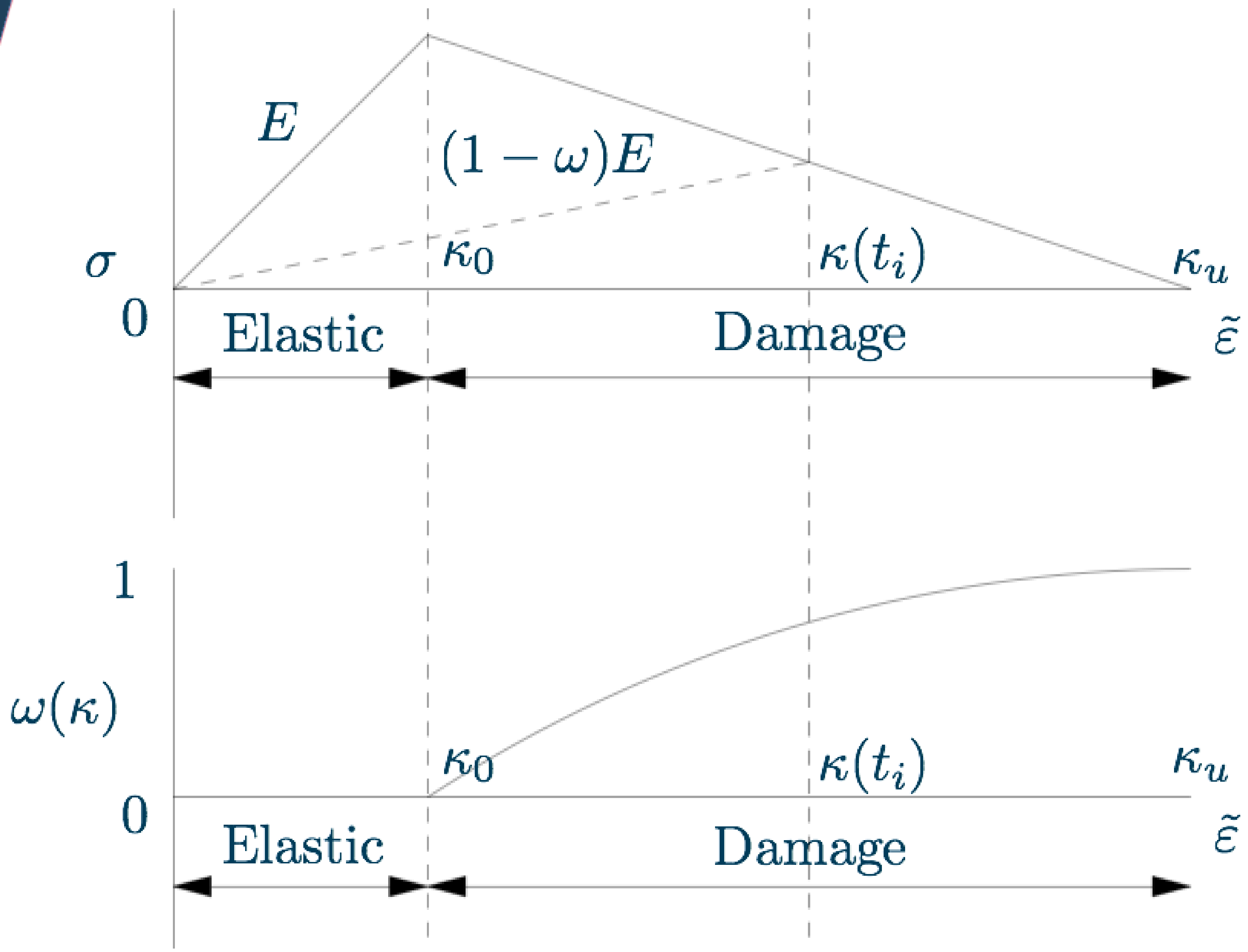
$$\begin{aligned} \tilde{\varepsilon} &= \tilde{\varepsilon}_{t+1} \\ \kappa &= \kappa_u \\ \omega(\kappa) &= 1 \end{aligned}$$

$$\begin{aligned} \tilde{\varepsilon} &= 0 \\ \kappa &= \kappa_u \\ \omega(\kappa) &= 1 \end{aligned}$$

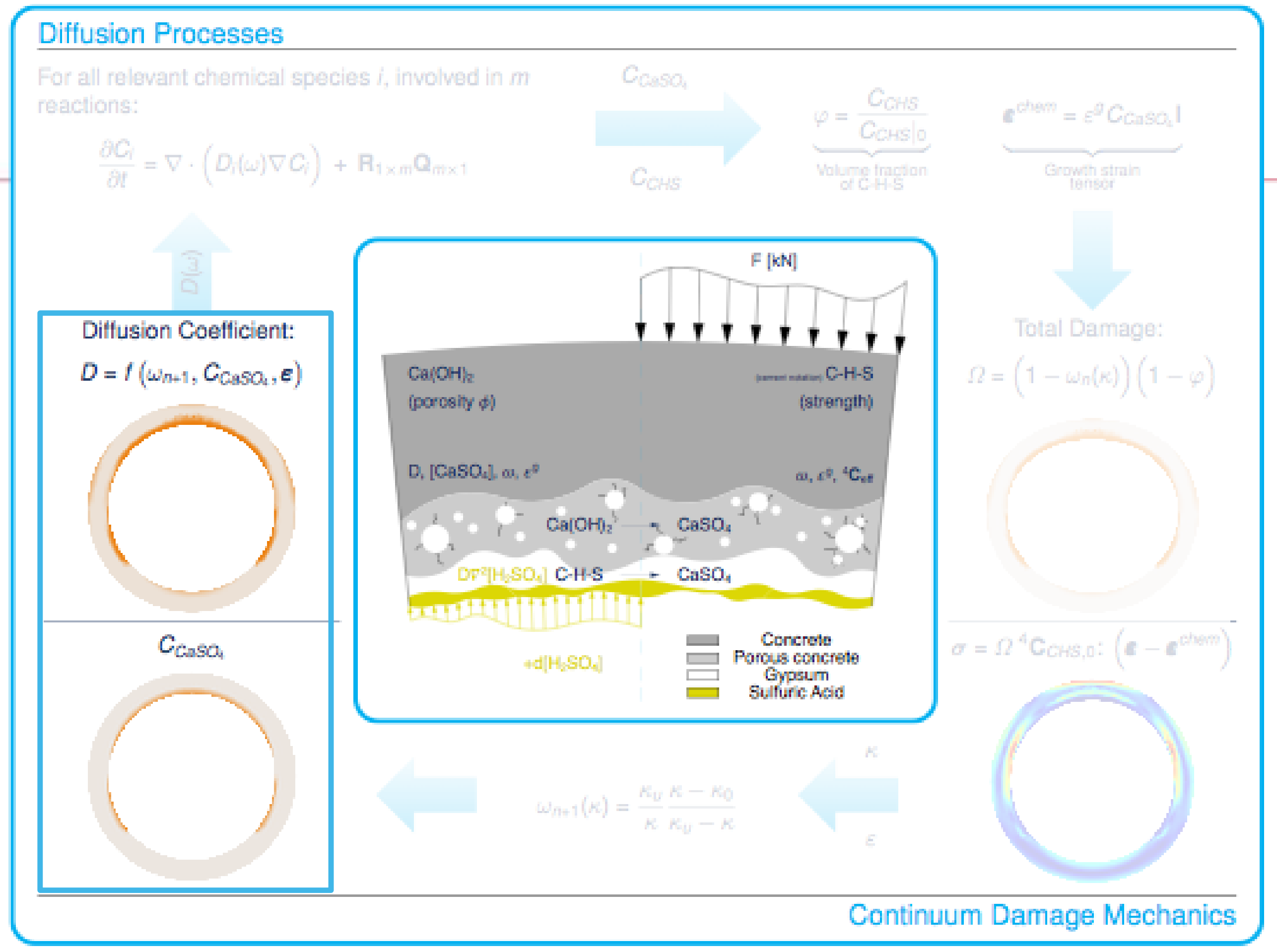




Mechanical Damage



$$\omega(\kappa) = \frac{\kappa_u(\kappa - \kappa_0)}{\kappa(\kappa_u - \kappa_0)}$$



Diffusion Properties

$$\begin{aligned} \omega &= 0 \\ D(\omega) &= D|_0 \end{aligned}$$

$$\begin{gathered} 0 < \omega < 1 \\ D(\omega) = (1+\omega)D|_0 \end{gathered}$$

$$\begin{aligned} \omega &= 1 \\ D(\omega) &= 2D|_0 \end{aligned}$$

$$\begin{aligned} \omega &= 1 \\ D(\omega) &= 2D|_0 \end{aligned}$$