Dissolution *in vitro* of mineral fibres. Examples.

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**European Mineralogical Union School**

Mineral fibres: crystal chemistry, chemical-physical properties, biological interaction and toxicity

*Modena (Italy) June 19-23, 2017*
Why do we need to study fibre dissolution?

Dissolution rates of mineral fibres are used as a proxy of their biodurability (i.e. the ability to resist to chemical/biochemical alteration).

Investigation of the dissolution mechanism of fibres may provide an insight on the interaction between fibres and biological environment.

Investigation of the dissolution mechanism of fibres is the key to understand the behaviour of the fibres during weathering.
The fibre dissolution experiments: the *in vitro* tests

- **cellular *in vitro* investigation** includes the treatment of cultured cells (usually alveolar macrophages) with fibers, followed by microscopic examination of the intracellular fibers to determine the change in their diameter and composition.

- **acellular *in vitro* investigation** includes leaching of the fibers into dissolution media.
The dissolution media

- Inorganic buffered solutions
- Simulated biological fluids

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The dissolution media

Inorganic buffered solutions

- pH < 5 (i.e. alveolar macrophages pH 4.5, acidic rain) can be maintained by acids (HCl, HNO₃, CH₃COOH).

- Intermediate pH conditions (i.e. physiological pH 7.4, natural waters pH 6.5-8.5) can be obtained with phosphate buffer solutions (Na₂HPO₄ + NaH₂PO₄).

- pH > 9 (CO₂ sequestration processes by serpentinites) can be maintained by carbonates or Na (or K) hydroxides.
The dissolution media

Simulated biological fluids

• **Artificial lysosomal fluid (pH 4.5)** is employed to mimic the environment with which inhaled particles would come into contact after phagocytosis by alveolar and interstitial macrophages.

• **Gamble’s solution (pH 7.4)** simulates the interstitial lung fluid and airway lining fluid.

• **Gamble’s solution (pH 4.5)** simulates environment with which inhaled particles would come into contact after phagocytosis by alveolar and interstitial macrophages.
The role of organic acids such as citric, oxalic, malic, or salicylic, present in soil (weathering process) and/or in the human body (biodurability), can be also investigated.
**Experimental**

**Batch reactor**  
**Flow-through reactor**

Solid:solution ratio between 2 and 10 gL\(^{-1}\)

Aliquots of the suspension are periodically withdrawn, filtered and analysed for the desired elements (Si, Al, Mg...)

Atomic absorption spectr.  
Inductively coupled plasma spectr.
Experimental

**Batch reactor**

Inert container where a known mass of fibres is kept in contact with a fixed volume of fluid.

The ions released during mineral dissolution accumulate in the solution, whose composition evolves and may reach saturation, so that fibre dissolution could be inhibited.

Batch reactor is a **closed system**. It may represent some portions of the lung (e.g. fiber inside a **macrophage**) that behave as at least partially closed system.
Batch reactor: dissolution rate calculation

\[
Rate_j (\text{mol g}^{-1} \text{s}^{-1}) = -\frac{1}{v_j M} \frac{dC_j}{dt} \cdot V
\]

\(v_j\) is the stoichiometric coefficient of component j

\(V\) is the volume of solution (L)

\(M\) is the mineral mass (g)

\(\frac{dC_j}{dt}\) is the variation of the concentration of the component j \((C_j)\) with time (t)

Rates may be normalized to the BET surface area (m\(^2\) g\(^{-1}\))
The flow-through reactor is an opened system. It is recommendable to avoid reaching equilibrium, which may restrict dissolution, and is more representative of dissolution occurring in biological medium.
Flow-through reactor: dissolution rate calculation

\[ \text{Rate}_j (\text{mol g}^{-1} \text{s}^{-1}) = - \frac{1}{\nu_j M} q (C_{j,\text{out}} - C_{j,\text{in}}) \]

\( \nu_j \) is the stoichiometric coefficient of component j.
M is the mineral mass (g).
q is the volumetric fluid flow (mL min\(^{-1}\)).

\( C_{j,\text{out}} \) and \( C_{j,\text{in}} \) are the concentrations of the j component in the output and input solutions, respectively.

Rate < 0 for dissolution \hspace{1cm} \text{Rate} > 0 \text{ for precipitation}
Flow-through reactor: dissolution rate calculation

\[
Rate_j (\text{mol g}^{-1} \text{s}^{-1}) = \frac{1}{v_j M} \left( C_{j, \text{out}} = C_{j, \text{in}} \right)
\]

The dissolution rate of silicates is generally calculated from Si concentrations \( R_{Si} \) in the output solution as it is considered as the rate-limiting step in the dissolution reaction.

In chemical kinetics the overall rate of a reaction is approximately determined by the slowest step, known as the rate-limiting step.
Flow-through reactor:

dissolution rate calculation

\[ \text{Rate}_j (\text{mol g}^{-1} \text{s}^{-1}) = \frac{1}{v_j M} q (C_{j,\text{out}} = C_{j,\text{in}}) \]

The dissolution rate is calculated at steady-state.

For silicates, the steady state is assumed to prevail when the Si output concentration remained fairly constant (i.e. ±6%).

At steady-state, dissolution is expected to proceed under far-from-equilibrium conditions.
Dissolution rate calculation

Flow – through experiments

\[ \text{Rate}_j (\text{mol g}^{-1} \text{s}^{-1}) = -\frac{1}{v_j M} (C_{j,\text{out}} - C_{j,\text{in}}) \]

Batch experiments

\[ \text{Rate}_j (\text{mol g}^{-1} \text{s}^{-1}) = -\frac{1}{v_j M} \frac{dC_j}{dt} \]

Modified from Rozalen et al. (2008)

Modified from Rozalen et al. (2013)

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Dissolution in vitro of mineral fibres. Examples.
General form of the rate law for heterogeneous mineral surface reaction

\[ \text{Rate} = k_0 A_{\text{min}} e^{-E_a/RT} a_{H^+}^{n_H} g(I) \prod_i a_i^{n_i} f(\Delta G_r) \]

General form of the rate law for heterogeneous mineral surface reaction

\[
Rate = k_0 A_{\text{min}} e^{-E_a/RT} a_{H^+}^{n_{H^+}} g(I) \prod_i a_i^{n_i} f(\Delta G_r)
\]

\(k_0\) is an intensive rate constant (moles/cm\(^2\)/sec) and incorporates all the pre-exponential factors involving the mineral surface dynamics.
General form of the rate law for heterogeneous mineral surface reaction

\[ \text{Rate} = k_0 A_{min} e^{-E_a/RT} a_{H^+}^{n_{H^+}} g(I) \prod_{i} a_i^{n_i} f(\Delta G_r) \]

$k_0$ is an intensive rate constant (moles/cm$^2$/sec) and incorporates all the pre-exponential factors involving the mineral surface dynamics.

$A_{min}$ is the surface area of the mineral (m$^2$)
Effective surface area vs BET surface area

Atomic Force Microscopy of the \{10\overline{1}4\} calcite cleavage surface after dissolution in presence of NaH$_2$PO$_4$. (From Klasa et al. 2013).

High reactive sites:
Formation of etch pits

Non/less reactive sites
What surface area I should use?

(A–C) Model evolution of a dissolving particle’s surface (From Luttge et al. 2013).

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General form of the rate law for heterogeneous mineral surface reaction

\[ Rate = k_0 A_{min} e^{-E_a/RT} a_H^{n_H^+} g(I) \prod_i a_i^{n_i} f(\Delta G_r) \]

- \( k_0 \) is an intensive rate constant (moles/cm²/sec) and incorporates all the pre-exponential factors involving the mineral surface dynamics.
- \( A_{min} \) is the surface area of the mineral (m²).
- \( e^{-E_a/RT} \) is the dependence for T;
- \( E_a \) is the apparent activation energy.
General form of the rate law for heterogeneous mineral surface reaction

$$Rate = k_0 A_{min} e^{-E_a/RT} a_{H^+}^{n_{H^+}} g(I) \prod_i a_i^{n_i} f(\Delta G_r)$$

$a_{H^+}^{n_{H^+}}$ is the activity of the hydronium ions in the solution; $n$ is the order of reaction with respect to $a_{H^+}$, i.e. pH dependance.
General form of the rate low
for heterogeneous mineral surface reaction

\[ \text{Rate} = k_0 A_{\text{min}} e^{-\frac{E_a}{RT}} a_H^{n_{H^+}} g(I) \prod_i a_i^{n_i} f(\Delta G_r) \]

\( g(I) \) is the possible dependance on the ionic strength of the solution

\[ I = \frac{1}{2} \sum_i c_i z_i^2 \]
\( c_i \) is the concentration of the species \( i \)
\( z_i \) is the charge of the species \( i \)
General form of the rate law for heterogeneous mineral surface reaction

\[ \text{Rate} = k_0 A_{\text{min}} e^{-\frac{E_a}{RT}} a_{H^+}^{n_{H^+}} g(I) \prod a_i^{n_i} f(\Delta G_r) \]

\(a_i^{n_i}\) is the activity of the species \(i\) in the solution e.g. interaction with the mineral surface. It incorporates possible catalytic or inhibitory effects on the overall rate.
General form of the rate law for heterogeneous mineral surface reaction

\[
Rate = k_0 A_{\text{min}} e^{-\frac{E_a}{RT}} a_{H^+}^{n_{H^+}} g(I) \prod a_i^{n_i} f(\Delta G_r)
\]

\(f(\Delta G_r)\) is a function of the saturation state of the solution

\[
\Delta G_r = 2.3 \log \left( \frac{IAP}{K_{eq}} \right)
\]

IAP = ion activity product

\(K_{eq}\) = equilibrium constant

\[
\log \left( \frac{IAP}{K_{eq}} \right) = \text{Saturation Index}
\]

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Dissolution in vitro of mineral fibres. Examples.
Saturation state of the solution

\[ \Delta G_r = 2.3 \log \left( \frac{IAP}{K_{eq}} \right) \]

- \( \Delta G_r < 0 \) a mineral should dissolve
- \( \Delta G_r > 0 \) a mineral should precipitate

Chrysotile: \( \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 + 6\text{H}^+ \leftrightarrow 3\text{Mg}^{2+} + 2\text{SiO}_2(\text{aq}) + 5\text{H}_2\text{O(l)} \)

\[ IAP = \frac{a_\text{Mg}^{2+}a_\text{SiO}_2^{aq}}{a_\text{H}^+} \]

\[ K = 10^{30.0} \quad \text{pH} < 9; \ T = 37 \ ^\circ \text{C}; \ P = 1\text{atm} \]

Tremolite: \( \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 + 14\text{H}^+ \leftrightarrow 2\text{Ca}^{2+} + 5\text{Mg}^{2+} + 8\text{SiO}_2(\text{aq}) + 8\text{H}_2\text{O(l)} \)

\[ IAP = \frac{a_\text{Ca}^{2+}a_\text{Mg}^{2+}a_\text{SiO}_2^{aq}}{a_\text{H}^{14+}} \]

\[ K = 10^{58.6} \quad \text{pH} < 9; \ T = 37 \ ^\circ \text{C}; \ P = 1\text{atm} \]

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Dissolution in vitro of mineral fibres. Examples.
Saturation index for chrysotile and tremolite in blood plasma, human lung and stomach tissues

Saturation Index \( (SI) = \log \left( \frac{IAP}{K_{eq}} \right) \)

SI < 0 a mineral should dissolve

SI > 0 a mineral should precipitate

<table>
<thead>
<tr>
<th>Elements</th>
<th>Weighted Mean* (mg/L)</th>
<th>Saturation Index†</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Blood Plasma</td>
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<tr>
<td>Na</td>
<td>3162</td>
<td>Chrysotile</td>
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<tr>
<td></td>
<td></td>
<td>pH 1.2: -44.8</td>
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<td></td>
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<td>pH 4: -27.9</td>
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<td>pH 7: -10.0</td>
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<tr>
<td>Cl</td>
<td>3610</td>
<td>Tremolite</td>
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<tr>
<td></td>
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<td></td>
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<td>pH 4: -64.3</td>
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<td></td>
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<td>pH 7: -22.3</td>
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<tr>
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<td>Si</td>
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<td>Ca</td>
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<th>Elements</th>
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<th>Saturation Index†</th>
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<td></td>
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<td>Lung Tissue</td>
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<td>Na</td>
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<td>Chrysotile</td>
</tr>
<tr>
<td></td>
<td>(2120 \times 10^{-6})</td>
<td>pH 4: -44.7</td>
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<tr>
<td></td>
<td></td>
<td>pH 7: -26.3</td>
</tr>
<tr>
<td>Mg</td>
<td>(9.84 \times 10^{-1})</td>
<td>Tremolite</td>
</tr>
<tr>
<td>Si</td>
<td>(57 \times 10^{-6})</td>
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<tr>
<td>Ca</td>
<td>(10.5 \times 10^{-1})</td>
<td>pH 7: -74.7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Elements</th>
<th>Weighted Mean* (mg/L)</th>
<th>Saturation Index†</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Gastric-Intestinal Tract Tissue (Stomach)</td>
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<tr>
<td>Na</td>
<td>(1000 \times 10^{-6})</td>
<td>Chrysotile</td>
</tr>
<tr>
<td></td>
<td>(1400 \times 10^{-6})</td>
<td>pH 1.2: -60.9</td>
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<tr>
<td></td>
<td></td>
<td>pH 7: -25.2</td>
</tr>
<tr>
<td>Mg</td>
<td>(15 \times 10^{-3})</td>
<td>Tremolite</td>
</tr>
<tr>
<td>Si</td>
<td>(110 \times 10^{-4})</td>
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<tr>
<td>Ca</td>
<td>(11 \times 10^{-3})</td>
<td>pH 7: -71.5</td>
</tr>
</tbody>
</table>

* Weighted mean values are from Iyengar et al. (1978).
† Saturation Index (SI) for each mineral was calculated using Visual MINTEQ (Gustafsson 2006) and the Lindsay database.

From Oze C. and Solt K. (2010)

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Dissolution in vitro of mineral fibres. Examples.
Relationship between rate and $f(\Delta G_r)$ (Lasaga, 1995)

$$f(\Delta G_r) = -\frac{\Delta G_r}{RT}$$  \textit{Linear relationship in the near-equilibrium region}

Rate $= -\frac{1}{v_{Si}M} \frac{V dSi}{dt}$

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Dissolution in vitro of mineral fibres. Examples.
Relationship between rate and \( f(\Delta G_r) \) (Lasaga, 1995)

\[ f(\Delta G_r) = \text{constant value.} \quad \text{Dissolution plateau for very unsaturated solutions} \quad (\Delta G_r \rightarrow \infty), \text{ i.e. in the far-from-equilibrium region} \]
General form of the rate low
for heterogeneous mineral surface reaction

$$Rate = k_0 A_{min} e^{-E_a/RT} a_{H^+}^{n_{H^+}} g(I) \prod_{i} a_{i}^{n_i} f(\Delta G_r)$$

Experiment in the far-from-equilibrium region

Fixed temperature $T = 37 \, ^\circ C$ (physiological $T$) or $T = 25 \, ^\circ C$ (room $T$)

Ionic strenght between 0.01 and 0.02 M (neglibile effect)

No ligands in the solution

$$Rate = k \, a_{H^+}^{n}$$

Rate vs pH
pH effect on the reaction kinetics

- Dissolution in batch reactor
- pH range: 1–13.5, inorganic buffered solutions, T = 25 ºC
- Incubation time: 30-35 days
- Solid/solution ratio 0.5 – 2 gL⁻¹
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Tremolite $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

pH = 4

Anthopyllite $\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$

pH = 4

Chrysotile $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$

pH = 4

pH = 8

pH = 10

pH = 10

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Dissolution in vitro of mineral fibres. Examples.
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Modified from Harley and Gilkes (2000)
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Tremolite

Montmorillonite

Modified from Rozalen et al. (2008)
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Tremolite

\[ \log R_{Si} = -12.13(\pm 0.02) - 0.19(\pm 0.01)pH \]
\[ r^2 = 0.995 \]

\[ \log R_{Si} = -15.18(\pm 0.6) + 0.26(\pm 0.06)pH \]
\[ r^2 = 0.847 \]

\[ pH = -\log[H^+] \]
\[ a\log[H^+] = \log([H^+]^a) \]

\[ R_{Si}(molg^{-1}s^{-1}) = 10^{-12.13(\pm 0.02)} a_{H^+}^{0.19(\pm 0.01)} \quad pH < 6 \]

\[ R_{Si}(molg^{-1}s^{-1}) = 10^{-15.2(\pm 0.6)} a_{H^+}^{-0.26(\pm 0.06)} \quad 8 < pH < 13.5 \]

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Dissolution in vitro of mineral fibres. Examples.
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Anthophyllite

\[
\log R_{Si} = -9.92(\pm 0.06) - 0.20(\pm 0.01)pH \\
\rho^2 = 0.983
\]

\[
\log R_{Si} = -12.72(\pm 0.09) + 0.08(\pm 0.01)pH \\
\rho^2 = 0.983
\]

\[pH = -\log[H^+]\]

\[a\log[H^+] = \log([H^+]^a)\]

\[
R_{Si}(molg^{-1}s^{-1}) = 10^{-9.92(\pm 0.06)} \cdot a_{H^+}^{0.20(\pm 0.01)} \quad 1 < pH < 9.5
\]

\[
R_{Si}(molg^{-1}s^{-1}) = 10^{-12.72(\pm 0.09)} \cdot a_{H^+}^{-0.08(\pm 0.01)} \quad pH > 9.5
\]

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Dissolution in vitro of mineral fibres. Examples.
pH effect on the reaction kinetics: results of Rozalen et al. (2014)

Chrysotile

\[ \log R_{Si} = -10.87(\pm 0.08) - 0.27(\pm 0.02)pH \]
\[ r^2 > 0.9 \]

\[ \log R_{Si} = -13.37(\pm 0.06) + 0.06(\pm 0.01)pH \]
\[ r^2 > 0.9 \]

\[ pH = -\log[H^+] \]
\[ \alpha \log[H^+] = \log([H^+]^\alpha) \]

\[ R_{Si}(mol g^{-1}s^{-1}) = 10^{-10.87(\pm 0.08)} a_{H^+}^{0.27(\pm 0.02)} \quad pH < 7 \]

\[ R_{Si}(mol g^{-1}s^{-1}) = 10^{-13.37(\pm 0.06)} a_{H^+}^{-0.06(\pm 0.01)} \quad 8 < pH < 12 \]

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Dissolution in vitro of mineral fibres. Examples.
General mechanism for fibre dissolution at acidic pH

\[ R_{Si} \left( \text{mol} g^{-1} s^{-1} \right) = 10^{-12.13(\pm 0.02)} a_{H^+}^{0.19(\pm 0.01)} \]

- \( pH < 6 \) tremolite
- \( 1 < pH < 9.5 \) anthophyllite
- \( pH < 7 \) chrysotile

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Dissolution in vitro of mineral fibres. Examples.
### General mechanism for fibre dissolution at neutral and basic pH

From Rozalen et al. (2014)

<table>
<thead>
<tr>
<th>Batch</th>
<th>pH in</th>
<th>pH out (average)</th>
<th>log R § (mol g⁻¹ s⁻¹)</th>
<th>log R Mg (mol g⁻¹ s⁻¹)</th>
<th>ΔG_i (kcal mol⁻¹)</th>
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<tbody>
<tr>
<td><strong>Tr_1m_1</strong></td>
<td>0.94</td>
<td>0.85</td>
<td>-12.29</td>
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<td>-206.17</td>
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<td><strong>Tr_1m_2</strong></td>
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<td><strong>CrLx_1m_9</strong></td>
<td>9.59</td>
<td>9.41</td>
<td>-12.88</td>
<td>-14.78</td>
<td>1.28</td>
</tr>
<tr>
<td><strong>CrLx_1m_10</strong></td>
<td>10.57</td>
<td>10.40</td>
<td>-12.74</td>
<td>-</td>
<td>0.59</td>
</tr>
<tr>
<td><strong>CrLx_1m_11</strong></td>
<td>11.83</td>
<td>11.57</td>
<td>-12.68</td>
<td>-</td>
<td>8.08</td>
</tr>
<tr>
<td><strong>CrLx_1m_12</strong></td>
<td>12.85</td>
<td>12.68</td>
<td>-12.66</td>
<td>-</td>
<td>4.24</td>
</tr>
<tr>
<td><strong>CrLx_1m_13</strong></td>
<td>13.78</td>
<td>13.61</td>
<td>-12.58</td>
<td>-</td>
<td>-0.96</td>
</tr>
</tbody>
</table>

From Rozalen et al. (2014)

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Dissolution in vitro of mineral fibres. Examples.
Dissolution rates of different mineral fibres in inorganic solutions

modified from Rozalen et al. (2017)

\[ R_{Crx} > R_{Ant} \gg R_{Trm} \]

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Dissolution in vitro of mineral fibres. Examples.
Effect of ligands on the reaction kinetics

Dissolution kinetics and biodurability of tremolite in mimicked lung fluids:
Effect of citrate and oxalate

- Dissolution in flow-through reactor
- Modified Gamble’s solution at pHs 4 (macrophages), 7.4 (interstitial fluids), 5.5 (intermediate point), $T = 37^\circ\text{C}$
- Incubation time: 40-75 days
- Solid/solution ratio: 2 – 10 gL$^{-1}$
- Oxalate and citrate concentration: 0.15, 1.5, and 15 mM for each ligand
Effect of ligands on the reaction kinetics: results on tremolite (Rozalen et al., 2013)

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Effect of ligands on the reaction kinetics: results on tremolite (Rozalén et al., 2013)

- **Citrate**
  - Log Rate vs pH graphs for different concentrations of citrate.
  - Changes in rate with pH due to citrate addition.

- **Oxalate**
  - Log Rate vs pH graphs for different concentrations of oxalate.
  - Changes in rate with pH due to oxalate addition.

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Dissolution in vitro of mineral fibres. Examples.
Fibre dissolution in simulated lung fluids

Biodurability estimation using the fibre shrinking model equation (Hume, 1991)

\[ t = \frac{3d}{4V_mR} \]

- \( t \) is the residence time of the fibre (s)
- \( d \) is the fibre diameter (m)
- \( V_m \) is the molar volume (m\(^3\) mol\(^{-1}\))
- \( R \) is the dissolution rate
Fibre dissolution in simulated lung fluids

Biodurability estimation for tremolite (Rozalen et al., 2013)

- Fibre lifetime (0.1 µm diameter) is 
  ~40 years at pH 4 and 90 years at pH 7.4.
Biodurability estimation for chrysotile (Hume and Rimstidt, 1992)

- Chrysotile lifetime (0.1 µm diameter) is ~ 1 month at pH 4.
- Tremolite lifetime (0.1 µm diameter) is ~ 40 years at pH 4.
- Amorphous silica lifetime (0.1 µm diameter) is ~ 100 years at pH 4.
Fibre dissolution in simulated lung fluids: Gamble solution at pH 4

Fibre diameter = 0.1 µm

from Gualtieri et al. (2017)
Alteration mechanism of mineral fibres

from Gualtieri et al. (2017)

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Dissolution in vitro of mineral fibres. Examples.
Surface alteration mechanism of amphibole asbestos

UICC crocidolite

\[ B(Na_{1.7}Ca_{0.1}Mg_{0.2})_{\Sigma=2}C(Fe^{2+}_{2.1}Fe^{3+}_{2.3}Mg_{0.6})_{\Sigma=5}^TSi_{8}O_{22}O^3(OH)_2 \]

Tremolite

\[ B(Ca_{1.9}Mg_{0.1})_{\Sigma=2}C(Fe^{2+}_{0.2}Mg_{4.8})_{\Sigma=5}^TSi_{8}O_{22}O^3(OH)_2 \]

- Dissolution in batch reactor
- Solution buffered at pH 7.4 with KPB (0.5 M), with H\(_2\)O\(_2\) (0.1 M), T = 37 °C
- Incubation time: up to 1 month
- Solid/solution ratio ca. 10 gL\(^{-1}\)
- Multi-analytical approach: ICP-OES, XPS, and TEM

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Dissolution in vitro of mineral fibres. Examples.
Surface alteration mechanism of amphibole asbestos

UICC crocidolite

pristine

24h

1 week

Tremolite

pristine

48h

1 week

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Dissolution in vitro of mineral fibres. Examples.
Conceptual model of amphibole asbestos alteration

1) Incongruent dissolution takes place in the first stages of surface alteration
2) Formation of a cation depleted amorphous surface layer
3) Congruent dissolution takes place in the later stages of surface alteration
4) Fe-oxidation and formation of Fe-bearing nanoparticles during dissolution

1), 2), 3) and 4) are expected to rule the asbestos reactivity and toxicity

From Pacella et al. (2015)
Thanks for your attention