Sustainability of construction and biomimicry opportunities

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SUMMARY

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- **Biomimicry approach to sustainability**
- **Biomimicry examples from the past**
- **Biomimicry applied to construction**
- **Polymerization of clay aluminosilicates**
- **Diagenesis of earth sediments**
- **Enzyme-induced calcite precipitation**
- **Hydroxyapatite formation in bone tissues**

Sustainability of current construction practices

The adjective sustainable describes a product or a technology that *"fulfils the needs of the present without compromising the ability of future generations to meet their own needs"*

- world population of around 7 billion has continuously increased since the end of the Black Death in the XIV century when it stood at 370 million
- demographic rates have been particularly high during the past two centuries with further growth to 10 billion predicted by 2050

Construction is one of the largest industries in Europe with 10-11% of GDP and, as such, must commit to developing sustainable practices

The building sector is the largest consumer of raw minerals and produces 33% of all the waste in Europe

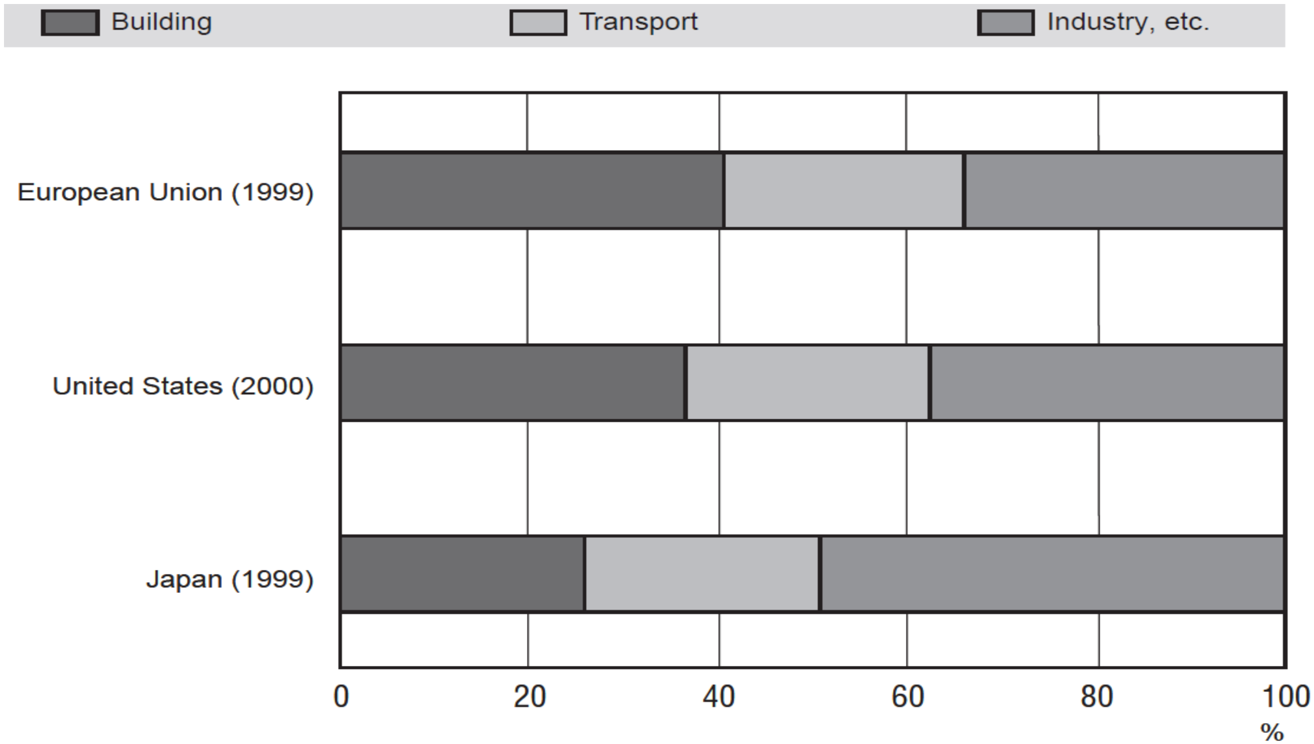
Cement production alone accounts for 5% of all carbon emissions worldwide and is likely to grow from 1 billion tons in 2000 to 5 billion tons by 2050

Operation of buildings accounts for more than 40% of the energy consumed in Europe

Sustainability of current construction practices

The energy consumed over the lifetime of a building can be broken down into three components: embodied, operational and end-of-life

- **embodied energy is the energy consumed during construction**
- **operational energy is the energy consumed during operation of structures**
- **end-of-life energy is the energy spent to demolish a structure and dispose, or reuse, the resulting waste**



Sustainability of current construction practices

In this context, the long-term sustainability of construction can only be assured by:

- **promoting the use of natural, locally-sourced and less resource-intensive materials (reduction of embodied energy)**
- **improving the energy efficiency of buildings over their lifetime (reduction of operational energy)**
- **using construction materials that are easily recyclable or safely disposable (reduction of end-of-life energy)**

Biomimicry approach to sustainability

To solve the current sustainability problem we can learn by Nature which has faced similar problems during 4 billion years managing to overcome them ….

…. in fact plants and animals have evolved in response to resource-constrained contexts offering elegant examples of adaptation to changing environments

***"When we look at what is truly sustainable, the only real model that has worked over long periods of time is the natural world"* - Janine Benyus**

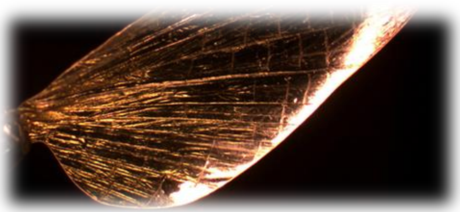
The term biomimicry is composed of two parts: bio which means life and mimicry which means imitation

Besides being sustainable, Nature's design is also efficient and economical …

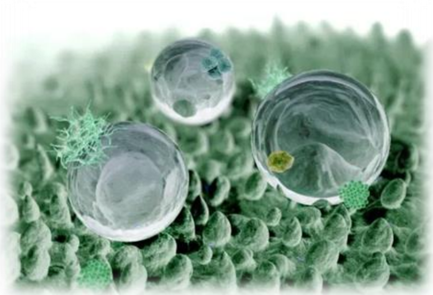
Biomimicry approach to sustainability

Nature's design is efficient because it can fabricate:


optimized load-bearing structures



strong bio-degradable composites (shrilk)




self-cleaning surfaces

etc.

… using only renewable energy and readily available constituents with zero waste

Biomimicry approach to sustainability

The term biomimicry was coined during the early 80s to designate a science that studies nature's models to solve human problems

This stemmed from the acknowledgement that most problems faced today by humanity have already been solved by plants, animals, insects and … microbes (never underestimate the power of microbes)

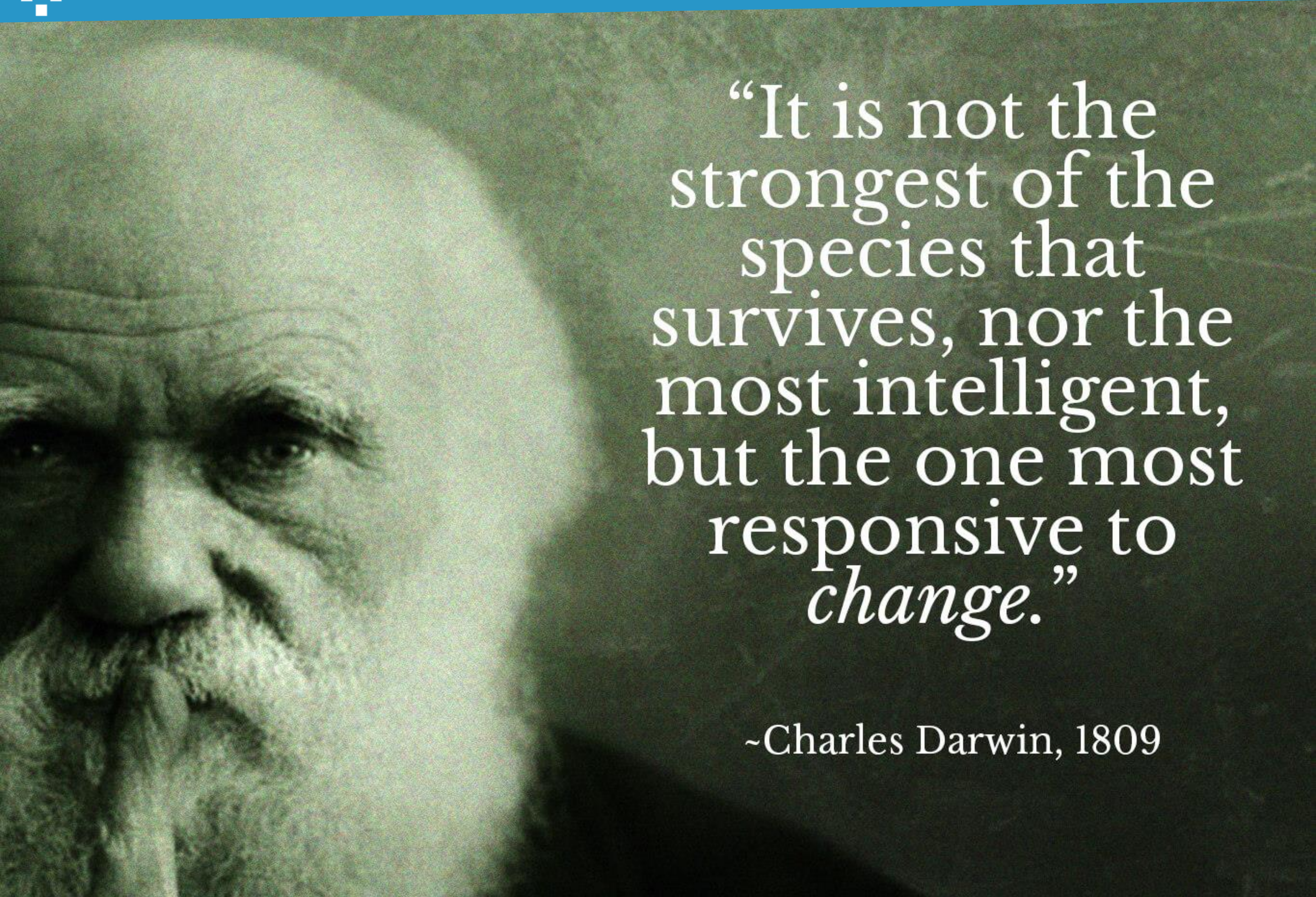
According to etymology, biomimicry concerns the imitation of all natural processes involving living things

Nowadays, biomimicry tends to encompass the entire ecosystem including all living and non-living things across the animal, vegetable and mineral kingdoms

The primacy of the Earth's ecosystem in responding to environmental constraints has already inspired human design throughout history …

… let us see some notable examples

Biomimicry approach to sustainability



Biomimicry examples from the past

One of the early biomimicry examples was the study of birds to build a human "flying machine“ by Leonardo da Vinci (1452–1519)

Leonardo was a keen observer of the anatomy and flight of birds, and made notes and sketches on his observations

Though unsuccessful, Leonardo's studies inspired subsequent engineers to the design of current airplanes

The Wright Brothers, who succeeded in flying the first heavier-than-air aircraft in 1903, allegedly derived inspiration from the observation of pigeons

"… man may make various inventions … but it will never discover a more beautiful, more economical, or a more direct one than nature's, since in her inventions nothing is wanting and nothing is superfluous …"

Leonardo Da Vinci

Biomimicry examples from the past

Another historical biomimicry example is the design of the (yet-unfinished) Sagrada Familia church in Barcelona by Antoni Gaudi (1852 – 1926)

Gaudi studied the fractal patterns found in nature and incorporated some of the natural hyperbolic paraboloid, hyperboloid and helicoids forms in his designs

Replication of natural geometries are exemplified by the famous study of oleander plants for the design of a new column (the double twisted column)

Columns are designed after the weight-distribution pattern of trees, stairways mimic spirals in nature, honeycomb windows allow for effective passage of light

"… the best way to honor God is to design buildings based on his work …"

Antoni Gaudi

Biomimicry applied to construction

Concrete and fired bricks are excellent building materials (the best we have found so far) but they could be better …

The embodied energy of standard concrete is estimated at 0.75 MJ/kg while embodied carbon is 0.11 kgCO2/kg

The embodied carbon of fired bricks is estimated at 3 MJ/kg while embodied carbon is 0.24 kgCO2/kg

Both materials come from natural mineral resources (crushed rock, limestone, chalk, clay … basically what we call “soil” or “earth”) but processed at very high energy costs

We might use the same material, i.e. earth, but cemented as nature does it …

Biomimicry applied to construction

The Smithsonian magazine published a catalogue of 40 things to know about the next 40 years topped by the prediction that "sophisticated buildings will be made of mud"

Many living creatures (insects, bacteria, earthworms, snails, fungi, badgers, moles, gophers, snakes, turtles) inhabit homes that are either dug in soil or made out of soil

Also many human beings live in earth dwellings, especially in very hot climates, and have reported very high degree of comfort

Use of raw earth might even facilitate recycling or disposal of demolition waste

… but there is a problem!

Formation of minerals or mineraloids takes place through either abiotic or biotic processes generally consisting in the precipitation of ions from an aqueous phase

Precipitation promotes the creation of bonding “bridges” between loose particles to generate coherent media

This is, for example, the case of sedimentary rocks such as sandstones or arenites, which originate from the cementation of loose sands

Natural mineralization requires very long times so imitation of these processes must utilize accelerating catalysers

Alternative earth stabilization (cementation) methods based on these biomimicry principles rather than on conventional cement and lime could improve sustainability of construction

We will explore here 4 potential methods that fall in this category:

- **Polymerization of clay aluminosilicates (inverse biomimicry)**
- **Diagenesis of earth sediments (direct biomimicry)**
- **Enzyme-induced calcite precipitation (direct biomimicry)**
- **Hydroxyapatite formation in bone tissues (direct biomimicry)**

Polymerization of clay aluminosilicates

The ability of carbon to “polymerize” is shared by two neighbour elements on the periodic table, namely silicon and aluminium

Silicon and aluminium, together with oxygen, form about 82% of the Earth’s crust

Polymerization of carbon is the basis of life as polymerization of silica (silicon-oxygen tetrahedrons) and alumina (aluminium-oxygen octahedrons) is the basis of rocks

Carbon forms organic polymers while silicon and aluminium form inorganic polymers

A large part of aluminosilicate minerals exist as clay in the form of finely particulate materials resulting from chemical wheathering of aluminosilicate minerals (feldspar) in igneous or metamorphic rocks

Chemical weathering is the alteration of rock by chemical reactions (oxidation, hydrolysis, carbonation) which produces either a rock of different nature or the complete destruction of minerals

Polymerization of clay aluminosilicates

Smectites, zeolites and silica gel are alumino-silicate with extremely high moisture storage capacity

They share a similar chemical composition but have distinct origin which implies different molecular structures

Smectites and zeolites are natural hydrous aluminosilicates produced by the weathering of feldspars

Smectite clays originate from chemical whethering of feldspar

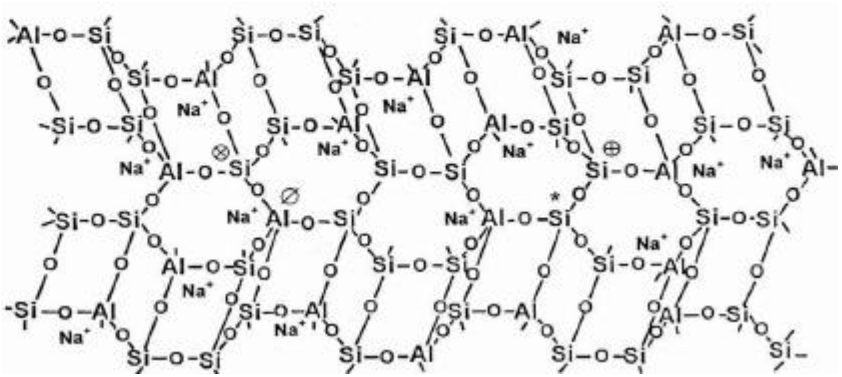
Polymerization of clay aluminosilicates

This hygrothermal buffering capacity, if accompanied by good mechanical characteristics, could provide an excellent construction material

In the last decades research has focused on understanding the chemistry of the mineral reign and synthesize natural rocks, e.g. zeolites or diamonds

It is now possible to reverse weathering of feldspars into clays by chemically transforming argillaceous sediments back into parent feldspathic minerals

This synthetic polymerization of clay aluminosilicates (i.e. minerals containing alumina and silica) is named "geopolymerization"



Polymerization of clay aluminosilicates

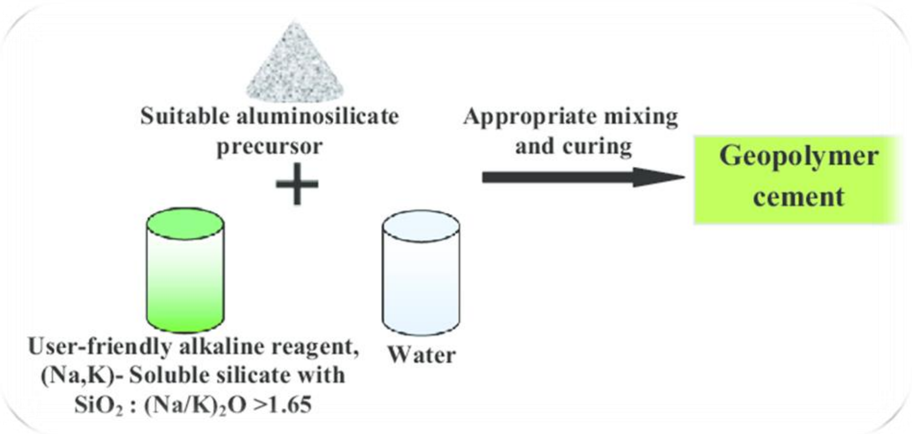
Geopolymers are synthesized by dissolving an aluminosilicate feedstock source in a highly alkaline solution

Upon evaporation, the mix precipitates a three-dimensional network of silica and alumina molecules that resembles natural zeolites

Natural clays (kaolinite, illite and smectite) are inherent to earth materials and are readily accessible sources of aluminosilicates

An argillaceous soil could therefore be used to manufacture a geopolymer binder similar to ceramic but without firing it at 1000° but at ambient temperature

Geopolymers show high durability, fire/acid resistance and strength but properties are very sensitive to the reactive Si/Al balance, amount and type of alkalis in the catalyst solution and curing time



Diagenesis of earth sediments

"Diagenesis" indicates the ensemble of physio-chemical reactions producing a transformation of the sediments into coherent rocks

"Lithification" is the early stage of diagenesis taking place at relatively shallow burial depths up to 3 km and is most relevant to biomimicry

The two main factors of lithification are:

- the powerful compaction of sediments under self-weight which reduces porosity to about 15%-20%
- the mild heat to which sediments are exposed under a geothermal gradient of about 25° per km of burial

At 3 km of burial, this results in a pressure between 50 and 100 MPa and a temperature of about 90° at 3 km of burial

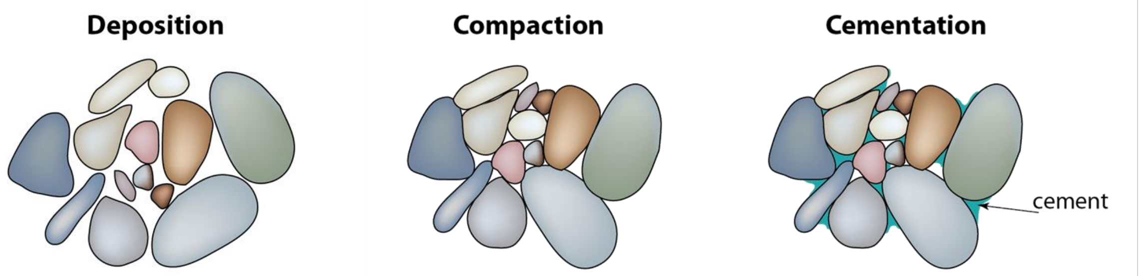
Diagenesis of earth sediments

The physio-chemical mechanism leading to the lithification of sediments is twofold:

1. **The large overburden pressure confers to sediments the strength and stiffness of a low porosity rocks**

2. **The large stress concentration at particle contacts produces dissolution of pressurized minerals under the catalysing action of moderate heat**

Dissolved minerals migrate through the pore fluid to precipitate around particle contacts where stresses are much lower, which produces cementation of sediments



This process is named "pressure solution" and has been widely studied in the fields of geology and poromechanics

Enzyme-induced calcite precipitation

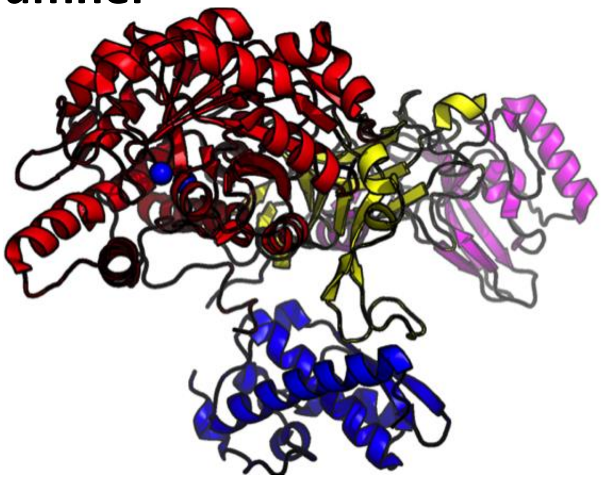
A significant portion of all Earth's carbonate has been formed biogenically through the metabolic activity of bacteria, fungi and multicellular organisms

Hydrolysis of urea or ureolysis is a very energy efficient calcite precipitation process

It involves relatively small changes of free energy compared to other biogenic processes such as denitrification, iron reduction and sulphate reduction

Hydrolysis of urea is catalysed by the urease enzyme, a protein widely occurring in nature, e.g. in bacteria and plants (often as a single chain protein)

In 1926 Jack Bean urease was the first protein to be crystallised which earned a Nobel Prize to James B. Sumner



Enzyme-induced calcite precipitation

The ureolysis reaction starts by transforming the urea $CO(NH_2)_2$ **into carbamic acid** NH_2COOH **and ammonia** NH_3

The carbamic acid is further hydrolised into ammonia plus carbonic acid H_2CO_3

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{urease enzyme}} NH_2COOH + NH_3 + H_2O \longrightarrow 2NH_3 + H_2CO_3$$

The 2 moles of ammonia and 1 mole of carbonic acid are then hydrolised into 2 moles of ammonium ions ${NH_4}^+$ **and 1 mole of carbonate ions** ${CO_3}^{-2}$

$$2NH_3 + H_2CO_3 + 2H_2O \longrightarrow 2{NH_4}^+ + 2OH^- + {CO_3}^{-2} + 2H^+ \longrightarrow 2{NH_4}^+ + {CO_3}^{-2} + 2H_2O$$

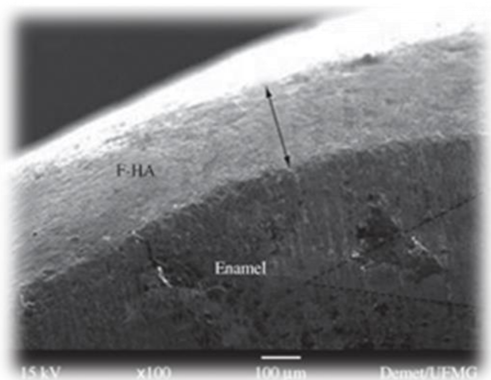
Finally, in the presence of calcium ions (Ca^{+2})**, carbonate ions precipitates to form calcium carbonate (**$CaCO_3$**), which cements sediments**

$$Ca^{+2} + {CO_3}^{-2} \longrightarrow CaCO_3$$

The only byproduct of these reactions is ionised ammonium ${NH_4}^+$

Hydroxyapatite formation in bone tissues

Hydroxyapatite is a form of calcium phosphate encountered in biological hard tissues such as bones, teeth and tendons



Calcium phosphate grows inside human at physiological pH levels between 6.5 and 7.5 and mild temperature levels between 36.5° and 37.5°

Calcium phosphate is an excellent fertilizer which could facilitate recycling of stabilized earth upon demolition by disposing the material into agricultural soil

Hydroxyapatite formation in bone tissues

Medical research has explored the in vitro precipitation of hydroxyapatite on orthopaedic implants made of titanium, bioglass and bioceramics

The implant is soaked in a simulated body fluid (SBF), an aqueous solution of Na^{+}, K^{+}, Mg^{+2}, Ca^{+2}, Cl^{-}, HCO^{-3}, HPO_4^{-3} and SO_4^{-3} ions with concentrations similar to blood

The SBF is a highly supersaturated calcium phosphate solution where precipitation of hydroxyapatite spontaneously occurs

Precipitation rates are tuned by adjusting ions concentration levels or by buffering the solution pH

Hydroxyapatite formation in bone tissues

Similar processes to those use in medicine might be used to stabilize raw earth materials

Hydroxyapatite deposition is further enhanced by the presence of nucleation sites for heterogeneous crystallization

Nucleation "seeds" act as inception points from where precipitation will propagate throughout the material

These seeds might consist of biogenic apatite particles, with sizes of some tens of microns

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