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Jonkers, Henk M.

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Toward bio-based geo- & civil engineering for a sustainable society

Henk M. Jonkers[a,*]

[a]*Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*

Abstract

The since 2010 running research program 'Bio-Based Geo & Civil Engineering for a Sustainable Society (BioGeoCivil)', funded by the Dutch technology foundation STW, aims to develop novel bio-based construction materials that can be used in Civil- and Geo-engineering constructions to enhance the sustainability performance of the sector. Rationale is that the sector produces still today excess amounts of waste in all life cycle phases of a construction, from building to use phase as well as end-of-life phase. Aim of the program is to mimic nature as 'building' processes in nature do not produce any waste as all elements, also residual material. is considered a high grade resource. In order to substantially improve the sustainability profile of the sector, upgrading of secondary- or byproducts must be achieved to allow functional performance similar to primary materials and resources. The challenge of the six currently running projects within the BioGeoCivil program is therefore not only to mimic nature but also to include bio-based materials or processes in civil- or geo-engineering applications which result, in comparison to traditional building products, in drastically improved performance both on sustainability and durability level. The six projects comprise: 1. Fungal biofilms (coating) for wood protection, 2. Bacteria-based repair and performance improvements of aged concrete structures, 3. Bacteria-based ground stabilization to mitigate liquefaction and piping of granular sediments, 4. Engineering of bacterial biofilms on buildings and infrastructure as a basis for natural protection, 5. Lift up Lowlands: upgrading of natural materials (bio-remediation of sludge) for sustainable lift up of low lying polder areas, and 6. Towards the development of carbon dioxide neutral renewable cement.

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Keywords: Bio-based processes; civil- and geo-engineering; soil; concrete; cement

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* Corresponding author. Tel.: +31 15 278 2313; fax: +31 12 278 6383.
E-mail address: h.m.jonkers@tudelft.nl

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1. Introduction

Traditionally the disciplines of Civil- and Geo engineering sciences focus on building structures that are durable, i.e. last long. In recent decades sustainability practices are becoming more and more important and minimizing production of waste, emission of harmful components, saving of energy and recycling of elements and materials have become standard practices. However, in order to further and substantially improve both durability and sustainability performances of construction materials, technological innovations are required. Eminent requirement for these novel materials is that for their production and subsequent lifetime phases use of energy and dependence on use of finite resources, and emission of harmful substances for humans and environment are minimal. Use and implementation of bio-based materials and processes could make an important contribution to this aim as these are renewable by nature. The projects currently running in the BioGeoCivil program build further on concepts that have been are still being developed. One example is the development of self-healing materials in which limestone production by specific bacteria result in self-healing of cracks in concrete [1]. The ability to self-heal is widespread in nature and the used building concept here is based on damage management rather than damage prevention as in current man-made constructions [2]. The damage management concept used in nature generally requires much less resources in comparison to damage prevention as constructions built according to latter concept are usually over-dimensioned with respect to their required functional performance.

Main objectives of the BioGeoCivil program are therefore the development of biology-based materials as well as processes which can help to solve engineering challenges addressing sustainability performance while at the same time safeguarding required durability aspects such as sufficient strength are functional service lifetime performance. Figure 1 shows a schematic drawing of the main aim of the program, i.e. mimicking in trying to establish a fully circular resource and material approach in which no waste or other emissions are produced as all residual materials provide useful resources for other products or life cycle stages of the construction.

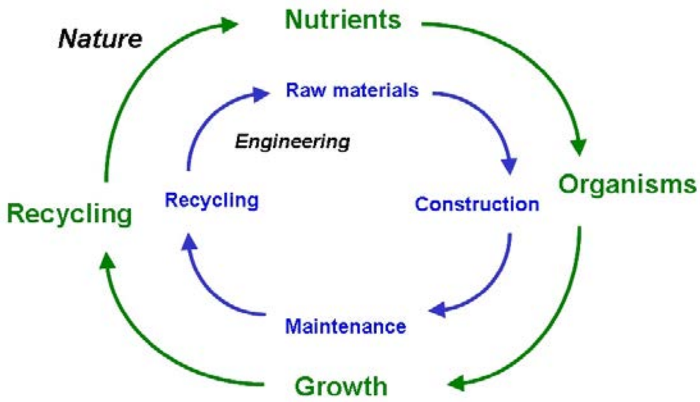

Figure 1: Resources and materials cycle in nature taken as inspiration for establishing fully circular material use in the civil- and geo-engineering building cycle.

In order to increase the chance of success, requirement for all six projects currently running in the BioGeoCivil program was that scientists from the different scientific disciplines biology and civil- and geo-engineering work closely together within each individual project.

The following main objectives were defined in the program [3] to achieve this goal:

1. Increase our fundamental knowledge of mechanisms nature uses to solve construction and functionality challenges we face in the field of geo and civil engineering
2. Develop robust biology-based technology, methods and processes that enable improved functionality and reduced environmental burden in geo and civil engineering applications

3. Define and demonstrate the requirements for upscaling: application of these findings in materials and processes in geo and civil engineering
4. Create a Dutch knowledge-platform of bio-based geo and civil engineering, combining representatives from research and industry, that enables the development of a strong research and economic infrastructure focused on sustainable geo and civil engineering

Six projects, in all of which as mentioned under objective 4 also industrial partners and governmental institutes defined as end-users participate, have been funded within the program scheme and these are titled:
1. Fungal biofilms (coating) for wood protection
2. Bacteria-based repair and performance improvements of aged concrete structures
3. Bacteria-based ground stabilization to mitigate liquefaction and piping of granular sediments
4. Engineering of bacterial biofilms on buildings and infrastructure as a basis for natural protection
5. Lift up Lowlands: upgrading of natural materials (bio-remediation of sludge) for sustainable lift up of low lying polder areas
6. Towards the development of carbon dioxide neutral renewable cement

2. BioGeoCivil Engineering program projects

2.1. Biofilms for Wood Protection (BioWoPro)

This research project builds further on findings by Sailer et al [4]. In latter research project it was found that specific species of fungi such as Aureobasidium pullulans can form biofilms on wood products which provide a protective natural and living coating. Growing such protective coatings on exposed outdoors wood constructions can provide a much more sustainable solution to wood protection in comparison to synthetic products which are usually based on environmentally unfriendly volatile organic solvents containing other environmental harmful active chemicals. Challenges in this project are particularly on characterization of microbial communities which develop on exposed outdoors wood products and furthermore to analyze how specific timber-protective fungal species can start to dominate these communities on the longer term. Also, the mechanistic functionality of fungal protection of timber products must be clarified.

In a subsequent study it was found that living biofilm coatings do provide functional protection of oil-treated wood surface against UV light and bio-degradation. Different types of wood such as from Yellow pine, beech, and Oregon pine treated with olive oil or linseed oil developed biofilm featuring different microbial communities. It was concluded in that study that the wood-oil-biofilm combination allows full recyclability while featuring at the same time a high eco-friendly profile, and is considered safe for humans both in application and during use [5].

2.2. Bio-based Repair and Performance Improvements of Aged Concrete Structures (BioRetrofit)

In the BioRetrofit project novel repair systems for existing aged and damaged concrete constructions are being developed. In contrast to currently available repair systems which are usually based on environmentally unfriendly materials such as acrylic raisins, epoxy- or urethane or silicone-based polymers, these novel ones are based on bacteria that can precipitate specifically under alkaline conditions copious amounts of limestone. The produced limestone seals pores and cracks in concrete, resulting in waterproofing, protection of the embedded steel reinforcement against corrosion, and increased resistance against frost damage.

The process of bacterial limestone formation is based on metabolic conversion of specific feed sources such as calcium lactate under alkaline conditions according to the following bio-chemical reactions:

$$Ca(C_3H_5O_3)_2 + 6O_2 \text{ --> } CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

and subsequently:

$$5CO_2 + 5Ca(OH)_2 \text{ --> } 5CaCO_3 + 5H_2O \quad (2)$$

The metabolic conversion of one molecule of calcium lactate thus results in the production of 6 molecules of calcium carbonate (limestone) provided that calcium hydroxide (portlandite) minerals are still present on the concrete crack or pore surface as these react with metabolically produced carbon dioxide to additional calcium carbonate.

Based on this principle two different concrete repair systems were developed, one liquid based two-component system and one cement-based repair mortar. Application of the liquid repair system resulted in substantial reduction of water permeability of cracked concrete specimens both before and after freeze and thaw cycles (Fig 2).

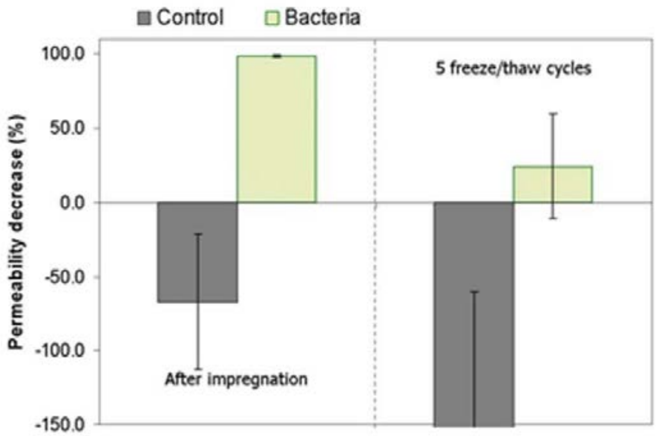

Figure 2. Water permeability of cracked control- and bacteria-based mortar specimens treated with liquid-based bacterial repair system before (left part of image) and after subjection to five freeze/thaw cycles (right part of image). Decrease of permeability was in both cases significantly higher in bacteria-based repair system treated specimens [6]

The developed cement-based repair mortar also featured, in addition to limestone-producing bacteria, PVA (polyvinyl alcohol) fibers. Latter fibers help to decrease shrinkage and improve better bonding between the freshly applied repair mortar and the underlying aged concrete. Micro cracks which might still occur during setting of the repair mortar are subsequently self-healed due to filling with limestone due to metabolic conversion of calcium lactate by bacteria which are both also included in the mortar (Figure 3).

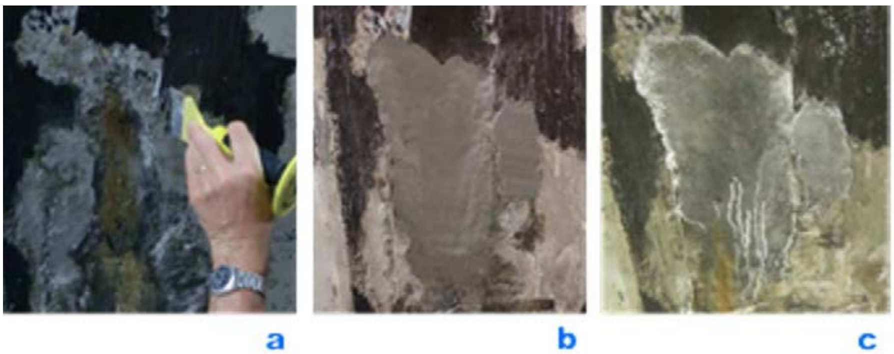

Figure 3. Self-healing mortar applied in practice: a) Surface preparations, b) Application, c) Visible limestone formation (white lines) on the surface of the set repair mortar [7]

Conclusion of this study was that incorporation in of bacteria, which precipitate limestone under alkaline conditions, in the two novel developed repair products can significantly enhance functional properties such as water tightness and frost resistance in aged concrete constructions.

2.3. Bacteria-based ground stabilization to mitigate liquefaction and piping of granular sediments

Liquefaction, a process in which loose sands suddenly turn liquid, can results in dramatic erosion rates and thus loss of fertile agricultural land. A similar soil eroding process termed 'piping' is caused by rapidly flowing groundwater that can result in collapse of constructions such as dikes and dams. In this research project a solution to this problem is sought in soil bacteria which can stabilize and consolidate sand through metabolic production of calcium carbonate based binders and that way avoid ground liquefaction and piping phenomena. This proposed bio-based technology represents an alternative to traditional cement-based grouting techniques and is therefore expected to be more sustainable with respect to CO_2 footprint. In a series of initial studies van Paassen and colleagues [8, 9] established soil stabilization successfully by applying microbial-induced carbonate precipitation via enzymatic hydrolysis of urea (Figure 4).

However, after further analysis of this technology, the research team concluded that this urea-based process was not only costly but also much less environmental friendly than expected due to the massive production of ammonium requiring costly and energy intensive post treatment cleaning [9]. In the presently running research project the research team investigates alternative microbial-induced carbonate precipitation pathways which are superior to the urea pathway with respect to costs and sustainability performance. Using nitrate and organic compound rich industrial wastewater as nutrients the researchers established precipitation of calcium carbonate based minerals by endogenous microbial communities via the denitrification pathway [10]. In this research project it was concluded that this novel strategy is not only economically competitive to traditional cement-based grouting but also significantly more sustainable with respect to CO_2 footprint and environmental nitrogen loading.

Figure 4. Pilot scale (100m^3) bio-grouting experiment by van Paassen and colleagues.
Image courtesy of Leon van Paassen, Delft University of Technology

2.4. Engineering of bacterial biofilms on buildings and infrastructure as a basis for natural protection

Bacteria are sometimes blamed for attacking building materials such as for example in the case of microbial induced corrosion of steel. However, bacteria could possibly also play a protective role, just depending on the type of metabolism, resulting in possible formation of protective compounds. Such a potentially positive role is investigated in this research project in which the aim is to find microbes or specific microbial communities who's concerted metabolic activity result in protection of particularly steel constructions. In a series of studies performed on different field sites in the Netherlands it was found that specific mineral deposits are formed on the surface of steel sheet pilings (see Figure 5) present for up to 67 years in soil [11].

Analysis of the microbial communities associated with these mineral deposits revealed the presence of bacteria mainly related to methanogenic (methane forming) species of bacteria. Although methanogenic species in both fresh- and marine water environments and particularly sulfate-reducing bacteria in the marine environment are known to degrade steel by inducing corrosion, it was found in the present studies that particularly methanogenic bacteria subsequently protect steel due to formation of a dense layer of calcium- and iron carbonate based mineral deposits what prevents further corrosion. Ongoing research aims to further clarify this microbially induced protective mechanism, in order to enable active measures to stimulate these protective biofilms in situ, e.g. by providing specific nutrients or substrates to favor growth of protective microorganisms at the cost of material degrading ones.

Figure 5. Crusts of mineral deposits formed by microbial communities on the surface of sheet pilings. Image courtesy of Michael Asanajef, Delft University of Technology

2.5. Lift up Lowlands: upgrading of natural materials (bio-remediation of sludge) for sustainable lift up of low lying polder areas

Delta areas worldwide and particularly polders (reclaimed land areas) are often situated below the surface level of surrounding waters. Also land areas suffering from soil subsidence have to cope with regular flooding if water runoff cannot be adequately managed. Aim of this research project is to supplement (lift up) these low lying areas using dredged sediments from elsewhere. In The Netherlands rivers and some coastal regions are continuously dredged to enable commercial shipping activities. However, these dredging activities result in excess dredging sludge amounting to 100.000.000 m^3 often of poor quality due to presence of organic contaminants. Strategy of the current research project is to create a win-win situation by applying sludge remediation, a process in which through microbial activity contaminated material is cleaned, making it suitable and valuable as building material to uplift low lying areas.

2.6. Towards the development of carbon dioxide neutral renewable cement

Portland based concrete is generally blamed for not being sustainable due to the high amount of CO_2 emitted to the atmosphere during the production process of cement. According to some studies between 5 and 10% of the total anthropogenic CO_2 is due to the production of Portland cement [12]. In order to substantially decrease the CO_2 footprint of cement a novel type of biomass-based binder is under development in this project. Certain types of biomass derived ashes such as rice husk ash and sugar cane bagasse are known to feature pozzolanic properties and are therefore suitable to replace at least a part of Portland cement in concrete mix designs. The main aim of this research project is to develop a functional hydraulic biomass-ash based binder that can fully replace Portland cement in concrete product applications. Such as bio-based binder would be almost fully CO_2 neutral as the CO_2 produced during biomass combustion can be taken up again in the process of photosynthesis during biomass growth replacing the biomass that was combusted. In order to produce Portland cement-like minerals such as alite, belite, calcium aluminate, and calcium aluminoferrite, the input biomass must at least feature precursor elements required for the formation of these minerals. Second to the element/mineral composition of the input biomass, also the combustion process (temperature regime and process time) likely affects the type and hydraulic functionality of the minerals formed.

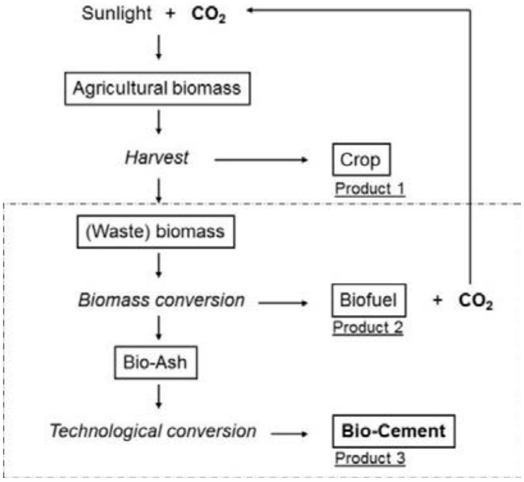

Figure 6. Scheme of biomass-based BioCement production. Its production is considered sustainable when, in contrast to production of Portland cement, CO2 production and fixation are balanced. In this research project focus will be on processes depicted in the boxed part, thus starting with (residual) biomass from the agro-industrial sector.

Moreover, the main idea of this project is not to specifically grow crops to produce bio-based cement, but rather to use agricultural biomass-waste or by-products as an input source for biomass combustion. In this way two or three different products can be obtained from the same crop (Figure 6).

In a series of experiments it was shown that with proper pretreatment of ashes and a specific firing regime (ramp rate of 25°C/minute and an ultimate temperature for 4h at 1240°C) belite minerals could be formed [13, 14]. Conclusion of these studies is that production of a virtually CO_2 neutral hydraulic binder for concrete applications is possible providing that quality (mineral element composition) and combustion regimes of biomass input raw material is suitable.

3. Conclusions

Traditional geo- and civil engineering techniques are typically characterized not only by a high CO_2 footprint but also by massive use of finite resources while at the same time producing harmful emissions to humans and environment. In contrast, the bio-based processes and materials applied in the six research projects within the STW Perspective program 'Bio-based geo- and civil engineering for a sustainable society' demonstrate that a bio-based approach can provide in many cases an economically viable and environmentally more sustainable alternative to established traditional geo- and civil engineering techniques.

Acknowledgements

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