Self-healing soil: Biomimetic engineering of geotechnical structures to respond to damage

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ABSTRACT

The concept of self-healing, whereby materials such as polymers, composites and cementitious construction materials are able to sense damage or deterioration and regulate, adapt and repair themselves automatically, is applied here to natural and anthropogenic soil structures. Damage in such structures can be difficult to detect and monitor, and will have significant consequences, but maintenance and repair are costly and disruptive. This paper presents an overview of the self-healing concept, its potential within geotechnical engineering and results from preliminary experiments exploring the potential for self-healing through the actions of living organisms such as bacteria. We report a simple experimental example, which demonstrates the potential for bacterial activity in microbially induced calcium carbonate precipitation of coarse-grained soils to persist and heal damage. Sands stabilized through calcium carbonate precipitation effected by *Sporosarcina pasteurii* were sheared and rehealed with only additional supply of nutrients, recovering a proportion of the original strength. This example is a simple demonstration of the ability of living organisms to adapt and respond to damage, and suggests the potential for this ability to be harnessed by engineers to design structures that can heal themselves.

Keywords: self-healing; microbially-induced carbonate precipitation; durability; *Sporosarcina pasteurii*

1 INTRODUCTION

Geological materials, particularly soils, are used in significant quantities for construction purposes, and structures comprising these materials are ubiquitous. However, these structures and ground improvement systems used to enhance their performance are subject to damage, deformation and deterioration through natural weathering processes in combination with the stresses induced in service. As a consequence, structural performance can be reduced and durability can be compromised, with significant implications for infrastructure resilience. Currently, such issues are addressed either through initial overdesign, implementation of maintenance programmes, or both. This paper will explore the potential for providing such geotechnical materials and structures with the ability to self-heal - to automatically respond to damage or deterioration, instigating a healing process that restores or even enhances the desirable properties of the material or structure. Self-healing allows autonomous, point of damage repair, both temporally and spatially. Such technology will take inspiration from research into self-healing in cementitious, polymeric and other engineering materials, as well as existing ground improvement methods and natural soil properties.

Infrastructure is ubiquitous, and geotechnical structures are a highly significant component. They play major roles within transportation networks, energy networks, water supply etc. Currently, much infrastructure around the world is in a relatively poor state, for example estimates of $3.6 trillion have been made as necessary to restore US infrastructure to an acceptable standard (American Society of Civil Engineers, 2013). It is a similar case with UK infrastructure, with maintenance and renewal for transportation networks alone estimated at around £10 billion per year (Mills *et al*., 2011). Repair and maintenance costs in construction have been estimated to be similar to the total cost of new construction, as reported by Joseph *et al.* (2011). Geotechnical structures comprising soil and/or rock are often less visible as infrastructure than ‘buildings’ but may be far more extensive. For example, significant numbers of structures such as cuttings and embankments are present in the transport network and require maintenance and it has been reported that remediation of slope instability on the UK’s highway network alone costs around £20 million per annum (Arup, 2010). Maintenance is expensive and disruptive - consider the disruption if a section of motorway had to be partially or fully closed for repairs to underlying soil structures. Reduction in the need for maintenance, repair or replacement would have significant benefits through reduced disruption, reduced material use and waste generation, and improved safety and serviceability.

Ways to enhance the durability and resilience of geotechnical infrastructure are therefore welcome. In this paper, we explain the concept behind self-healing materials, with a particular focus on biological mechanisms. We then consider the implications of this for geotechnical infrastructure, including potential applications and mechanisms, and demonstrate the potential for this new class of geotechnical structure through a simple experimental example of biological self-healing.

2 SELF-HEALING MATERIALS

2.1 General concepts

The class of materials known as *smart materials* broadly describes those that encompass an ability to sense and detect properties of their environment or condition, and subsequently activate a process in response to such properties exceeding particular thresholds. Essentially, such materials are able to act independently of any human agency within the bounds of their design and capabilities. *Self-healing materials* are a sub-set of these - they are capable of detecting that damage has occurred, and responding automatically to heal this and prevent or limit further deterioration. Such abilities are typically considered to allow materials to recover structural, mechanical and even electrical properties. They are often compared to living systems, particularly healing of wounds in animals.

Certain existing materials naturally exhibit an automatic ability to heal damage. For example, oxidation products of certain metals and alloys (e.g. aluminium) form a coherent and tough surface layer – damage that exposes the underlying material to an oxidising atmosphere will naturally be healed through oxidation, limiting further deterioration. Such materials are labelled *autogenic*. Alternatively, materials that are deliberately engineered to exhibit self-healing behaviour are labelled *autonomic*.

With any self-healing material, there are a number of important parameters that must be considered. The healing mechanism must be sufficiently durable to be capable of operating throughout the desired lifetime of the material or component. The mechanism must be sensitive to damage or deterioration, but not to other factors such as in-service loading or natural environmental changes. It must also be capable of being triggered at the correct time, i.e. that healing occurs at the point of, or soon after, the damage event, and not at any other. It also must be able, for all properties of the material that are of concern, to restore an acceptable degree of performance. Finally, an ideal system would be able to respond to multiple, distributed and repeated events over time.

2.2 Healing mechanisms

Autogenic and autonomic healing mechanisms have been explored in a range of materials (Table 1). The concept of autonomic cementitious and polymeric materials have been considered for some time, with particular focus on the use of repositories of chemical healing agents contained within the material (e.g. Dry, 1994; White *et al.*, 2001). White *et al.* (2001) embedded capsules containing a polymerising healing agent within an epoxy matrix, alongside deposits of a suitable catalyst. As cracks propagated through the matrix, they passed through these capsules, releasing the healing agent. Upon contact with the catalyst, the agent polymerised, healing the crack. This mechanism and variations thereof are commonly used to imbue materials with self-healing abilities.

There is currently considerable interest in self-healing materials generally, as evidenced by the increasingly large body of research and numbers of research groups involved around the world. Currently in the EU, there are several major funded research programmes in relevant areas, including the Marie Curie Training Network ‘SHeMAT’ and the EU-FP7 project ‘HealCON’. The M4L project (Lark *et al.*, 2013) is focusing on self-healing in conglomerate materials (including concrete etc) at micro, meso and macro scales through physical, chemical and biological means.

Table 1. Examples of self-healing mechanisms in various material classes.

Mechanism	**Material**	**Examples**
Encapsulation of healing agents (e.g. cyanoacrylate glues) in microcapsules or supplied *via* embedded 'vascular' systems. Fracture of these elements during crack propagation releases and activates the healing agents.	Cementitious materials	Dry (1994) Joseph *et al.* (2010)
	Polymers	White *et al.* (2001)
	Ceramics	Nakao and Abe (2012)
Biological healing through calcium carbonate generation. Cracks allow activation of bacterial cells or spores that generate carbonate ions. May also include encapsulation (as above) of growth media and nutrients.	Cementitious materials	Jonkers *et al.* (2010)
Material coatings may contain encapsulated healing agents to heal the coating itself, or may protect the underlying material by releasing, for example, corrosion inhibitors.	Coatings and paints	Hughes *et al.* (2010)
Autogenic healing of cementitious materials through presence of unhydrated cement particles within the monolith. Upon cracking, ingress of moisture will hydrate exposed unhydrated material and heal cracks.	Cementitious materials	Kishi *et al*. (2007)
Shape memory polymers as reinforcement	Cementitious material	Isaacs *et al.* (2013)
Inclusion of conducting materials that on heating (e.g. by induction) melt the material, causing flow and removal of flaws.	Bituminous materials, asphalt	García *et al.* (2012)

2.3 Focus on biological self-healing mechanisms in cementitious materials

Creation of inorganic minerals through bacterial action is a natural process recently harnessed for engineering purposes and has applications in geo-materials such as building stone and soils (de Muynck *et al.*, 2010; DeJong *et al.*, 2013) as well as cementitious materials. The most common process to date involves hydrolysis of urea, which generates carbonate ions and maintains pH at a suitable level for calcium carbonate mineralisation (at least in materials with lower natural pH than Portland cements). This or related mineralisation processes have particularly been applied to 'seal' cementitious surfaces, preventing ingress of deleterious substances that may cause corrosion or other deterioration (Bang *et al*., 2001), but also to 'heal' materials, restoring structural performance lost through damage (Jonkers *et al.*, 2010). The environment within these materials is not conducive to long-term survival of living organisms due to both the elevated pH and also the gradual reduction of pore space during hydration reactions, leading to crushing of both spores and cells. Jonkers *et al.* (2010) did provide evidence that spores mixed directly with the concrete were able to regenerate and mineralise calcite to a degree, although viability decreased rapidly over time. Therefore, much effort has gone into exploring ways in which bacterial cells or spores can be protected such that they remain viable. This has included encapsulation or immobilisation within compatible materials, including polyurethane (Bang *et al.*, 2001; Wang *et al.*, 2012), silica gel (Wang *et al.*, 2012), hydrogels (Wang *et al.*, 2013; Harbottle *et al.*, 2013) and within specialist aggregate materials themselves, such as expanded porous aggregate (Wiktor *et al.*, 2011). Such materials must not only protect the organisms but also allow 'triggering' of the organisms when damage occurs and ensure that mineralisation products are formed in a manner that heals appropriately. Although some success has been made in sealing surfaces, strength regain through healing is often more difficult to attribute to bacterial mineralisation, with the encapsulating materials often responsible for a significant proportion.

3 SELF-HEALING IN SOILS – AUTOGENIC AND AUTONOMIC

3.1 Autogenic self-healing of soils

Particular soils in certain situations can exhibit natural, autogenic self-healing properties. Eigenbrod (2003) summarises basic mechanisms that can occur, particularly in soils with no or low plasticity, or in highly active swelling soils such as bentonites. The focus is on fractures that occur through freeze-thaw mechanisms that in fine-grained soils can lead to significant increases in hydraulic conductivity. Particles in soils with little or no plasticity and cohesivity are susceptible to erosion and movement – fractures encourage fluid flow, thus mobilising particles that can clog the fractures: moisture flow is the trigger that causes healing. Highly plastic swelling clays, conversely, swell with access to moisture: increased fluid flow through the macroporous network created by fracture exposes these soils to moisture and, depending on fracture size, swelling of the particles can block the fracture, resealing the soil. Several studies have explored these mechanisms in a range of situations including landfill liners (e.g. Shi and Booth, 2005; Sari and Chai, 2013) and earth dam cores (e.g. Kakuturu and Reddi, 2006). Sari and Chai (2013) determined that in geosynthetic clay landfill liners, fractures of up to 30 mm could be healed, albeit with slightly poorer performance than the surrounding undamaged material.

3.2 Engineered self-healing soil structures

Self-healing capabilities are ideally suited to geo-materials as their deformation and deterioration is a continuous process over significant spatial and temporal scales whilst accessibility for maintenance or renewal is frequently limited or problematic. Self-healing mechanisms previously considered for other materials are likely to also be applicable to soils and soil structures. As before, a mechanism should be activated by damage, must be durable, resilient and disregard events below a suitable threshold.

Grouted soils and soil-cement mixes, used for ground improvement purposes as well as other geoenvironmental applications, are likely to be able to directly incorporate existing mechanisms for cementitious materials. The treated soil behaves as a low-permeability monolith, and so damage manifests itself through fractures and flaws, exposing embedded healing agents to new environments and offering a relatively simple triggering mechanism as often the trigger is the ingress of moisture where previously there was little, allowing both chemical and biological reactions to take place. Alternatively, fractures or deformation may rupture shells encapsulating healing agents.

Non-monolithic, untreated soils may also benefit from similar mechanisms to those discussed above. In particular, low permeability, fine-grained soils may offer sufficient protection to healing agents (encapsulated or otherwise) in a similar manner to a grouted monolith. However, self-healing in more coarse-grained media may prove more difficult as deformation or damage in structures fashioned from such soils is realised through different mechanisms of failure; there may be no sudden ingress of moisture, and cracks may not propagate through such effectively ductile agglomerations. In such cases, there is scope for new mechanisms such as ‘active’ reinforcement (e.g. responsive geotextiles or soil restraint using shape-memory materials) but which again may take inspiration from existing mechanisms in other materials.

3.2.1 Biological self-healing

Mechanisms induced by microorganisms are ideal for the incorporation of self-healing capabilities into geo-materials. Building stones, soils and rock are known habitats for many species of micro- and macro-organism and offer relatively benign environments for the introduction of new organisms or stimulation of existing species, in particular through the mild chemical environment and the availability of moisture offered by the porosity of these structures. Such communities are self-sustaining as evidenced by the existence of biofilm structures in the geo- and built environment, and so there is the potential to develop self-healing systems with considerable durability. The products of biological healing mechanisms in geo-materials are directly compatible with geo-materials with microbial production of minerals such as calcite, struvite, whewellite and others (Burford *et al.*, 2006; De Muynck *et al.*, 2010) allowing mechanisms to be selected to match the substrates concerned.

Bacterial mineralisation of calcium carbonate is an excellent example of how the recent exploration of biological aspects of geotechnical engineering may be applied here. It has been applied in the healing and strengthening a range of construction materials, including building stone (Le Métayer-Levrel *et al.*, 1999) and soils (DeJong *et al.*, 2006; Van Paassen *et al.*, 2010), and has been shown to work in both laboratory and field environments. Similar technologies have been considered in the self-healing of cementitious materials (Van Tittelboom *et al.*, 2010), adapting soil microbial processes for use in this environment. It is the persistence of bacteria, particularly in the form of spores (*Sporosarcina pasteurii* and other organisms used are known to sporulate), that may already imbue this ground improvement technique with self-healing properties, as such spores are likely to remain encased within the calcium carbonate matrix following cementation, ready to respond should the matrix be fractured in some way. A simple example of this is presented in Section 3.3 that demonstrates the ability of cementation produced by bacteria to be healed by those bacteria following damage to the structure.

The ability of living organisms to persist over time within the soil matrix, either as individual organisms or as self-sustaining communities, may allow a number of other mechanisms of self-healing to be considered. Both micro- and macroorganisms respond naturally to damage and so natural structures that contribute to soil physical properties, e.g. biofilms, will grow into a fracture or shear zone and help strengthen it even if originally damaged by the damage event itself. Because these organisms adapt to the damage and continue to grow, they should have the ability to heal future damage events.

3.3 Preliminary laboratory investigation

3.3.1 Experimental goals

A simple experiment is reported demonstrating the potential for sand healed by microbially induced carbonate precipitation (MICP) to respond to damage. MICP has previously been used in cementation of coarse-grained soils (DeJong *et al.*, 2006; Van Paassen *et al*., 2010). The bacterial strain used here to bring this about, *Sporosarcina pasteurii*, is a known spore-forming organism (Yoon *et al*., 2001). Although there is likely to be significant attrition of vegetative cells due to their acting as nucleation sites for carbonate precipitation and subsequently being encapsulated, spores are likely to be able to survive. Damage to a cemented soil monolith would expose encapsulated spores, allowing them access to moisture and various chemical species and encouraging regeneration of bacteria and possible healing of the damage. Here, following initial microbial cementation, damage was inflicted through destructive shear strength measurement. Provision of further nutrients was made to determine the potential for healing of the damaged structure.

3.3.2 Methodology

Sporosarcina pasteurii (NCIMB, UK; strain NCIMB8221), an aerobic, ureolytic bacterium, was cultured in nutrient broth (Oxoid CM001, 13 g/L) amended with urea (20 g/L) for 48 hours at 30ºC. Prior to use, cells were pelletised by centrifugation of the cell suspension at 1450 RCF for 20 minutes, then washed with phosphate-buffered saline prior to resuspension in growth medium (Oxoid CM001 nutrient broth – 3 g/L; urea – 20 g/L; $NaHCO_3$ – 2.1 g/L; NH_4Cl – 10 g/L; sterile-filtered past 0.2 μm membrane filter [DeJong *et al*., 2006]). Six sand specimens were prepared comprising 50 g dry, autoclave-sterilised, poorly graded medium sand placed aseptically in sterile, 50 ml polypropylene vials (length 115 mm, outer diameter 30 mm). Sufficient growth medium containing *S. pasteurii* (10 ml) was added aseptically to four of these sand specimens to fully occupy the pore space. With the two remaining specimens, 10 ml of tap water was added – these acted as control specimens.

All specimens were incubated at 30ºC for 20 days. During this period, the growth medium was partially replaced several times to provide a continued source of nutrients and carbon source – on a weekly basis, gravity-assisted drainage removed approximately 2 ml of fluid, which was replaced by an equivalent amount of fresh, sterile growth medium (no replacement took place in control specimens). After this period of initial healing, an artificial damage event was instigated by shearing the specimen. A manually-operated, bench-mounted Wykeham Farrance shear vane was used to cause the damage as well as measure the shear strength of each specimen according to BS 1377-7:1990 (British Standards Institution, 1990). Whilst it is appreciated that such tests are generally used for cohesive, fine-grained soils, the sand samples tested were saturated during testing and it is used as a simple demonstration of differences in shear strength. A small (12.7 mm depth, 12.7 mm diameter) vane, sterilised initially using Virkon (1% solution) was located at the centre of the specimen surface and then pushed slowly, without rotation, into the soil until the upper vane edge was 25 mm below the surface. Manual rotation of the vane was then carried out slowly until shear failure occurred.

Following testing of the initial healing strength, two bacterial specimens were refrigerated for two weeks at approximately 4ºC to prevent spore regeneration and limit activity of *S. pasteurii*. Over the same period, the control specimens and remaining bacterial specimens were incubated at 30ºC once more. Again, fluid was replaced weekly in all bacterially-treated specimens, as above. Finally, the shear vane was located in the same position used for testing following the initial phase, and applied in an identical fashion to determine shear strength following this secondary healing phase.

3.3.3 Results and commentary

Results are presented (Figure 1) showing the average shear strength in each specimen pair. Control specimens exhibited relatively low strength with little change in average strength over the two incubation periods. These conform to expectations – no initial or secondary healing was expected.

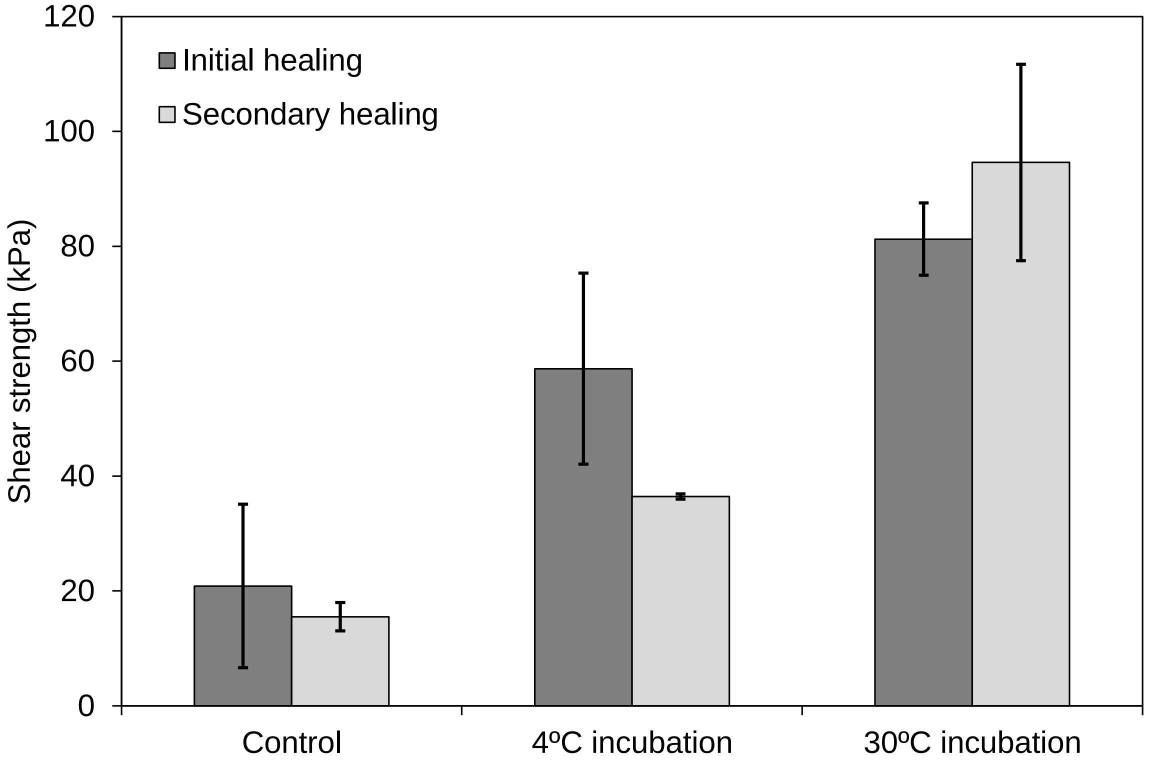

Figure 1. Shear strength recovery following damage (error bars represent ±1 standard deviation).

In the presence of *S. pasteurii* and a suitable growth medium, substantial strength increases of 300 to 400% were found in the initial healing stage (on average) in all four specimens tested ('Initial healing' bars in Figure 1) and white, crystalline precipitate was observed at the sand surfaces. Following subsequent incubation at 4ºC, shear strengths were reduced compared to the initial healing period, although were still elevated compared to control specimens. This does not necessarily indicate that any healing was present, however, as the presence of calcium carbonate in a sheared form will reduce porosity and increase grain contact, leading to an elevated shear strength.

Incubation at 30ºC in the secondary healing phase returned average shear strengths slightly greater than the initial strengths (on average), suggesting that regenerated spores or surviving cells of *S. pasteurii* were able to heal the damage caused by the initial shear vane measurement. This is only a simple, short-term demonstration that damage can be healed, and recent related work has shown similar effects (Montoya and DeJong, 2013). It is likely that vegetative *S. pasteurii* cells survived incomplete encapsulation and so healing in this case may not have required spore regeneration. However, consideration of system longevity through sporulation and consequent bacterial persistence in the long term is required for application in geotechnical infrastructure. This demonstration is also not fully representative of self-healing as intervention through the supply of growth medium was required. Current work at Cardiff is exploring these issues and other aspects of self-healing in geotechnical structures.

4 CONCLUSION

The potential for developing geotechnical structures that are able to respond automatically to damage and deterioration through a range of self-healing mechanisms has been explored here. Mechanisms already undergoing investigation in other materials have been explained and the application of selected systems to soil structures has been discussed. In particular, the ability of macroscopic and microscopic organisms in the soil to firstly heal or strengthen, and then reheal or restrengthen should damage occur, has been explored. A simple mechanism showing that damage to bacterially cemented sand can be overcome by allowing those organisms to continue to operate in the correct environment has been presented.

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