EXPLORING SELF-REPAIRING MATERIALS AND THEIR APPLICATION TOWARDS SUSTAINABLE DESIGN

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Self-repairing materials are materials with the built-in ability to autonomously repair damage to themselves without the need of human intervention or any external diagnosis. Whilst self-repairing materials aren’t a new technology, they have begun to be further developed in recent years due to computational design methods and an increasing interest in the architectural discipline. Yet, it is still unclear what are the potential applications of these self-repairing materials and in what ways can they address issues of sustainability, reliability, safety and constructability?

There are numerous applications in our day to day lives as well as in the built environment that may benefit from such properties. Sonar & Haick argue that “Devices integrated with self-repairing ability can benefit from long-term use as well as enhanced reliability, maintenance and durability”. In terms of the built environment, DARPA (Defense Advanced Research Projects Agency) have begun research into developing “living materials that combine the structural properties of traditional building materials with attributes of living systems, including the ability to rapidly grow, self-repair, and adapt to the environment.” (Gallivan, 2017), each of these articles suggest that there is a need for materials to have self-repairing capabilities.

With a vast selection of potential applications, research into material choices will define how far the possibilities can go. Each application will highlight issues resolvable by incorporating self-repairing materials, showcasing the practicality of the self-repairing properties. This research could then be further continued by putting the materials to the test, deeming the theory successful or not and in turn, highlight the beneficial factor of self-repairing materials in a sustainable future.

Keywords. Self-repairing; 3D-printing; Hydrogel; Sustainable; Application.

1. Introduction: Research Motivations

Self-repairing materials can be defined as synthetically or artificially created substances with the built in ability to autonomously repair damage to themselves without the need of human interaction or external diagnosis. The most common types of self-repairing materials being polymers (plastics, resins, etc.) or elastomers, however self-repairing also includes certain metals, ceramics and cementitious materials.

Each material contains unique properties; however the methods of recovery are the same, with the materials being able to be defined into two types of groups. Materials may be autonomic, repairing themselves without the need of a trigger or non-autonomic, requiring a trigger to activate the healing property, i.e. water, heat and UV light.

Knowing that these types of materials are being developed for use in other fields, this research sets out to explore the potential applications of self-repairing materials in the built environment, aiming at ways to aid sustainable design.

2. Research Aims and Objectives

The aim of this research is to discover and explore various types of self-repairing materials, in order to theorise potential applications of these materials in the built environment, aiding sustainable design.

This research seeks out self-repairing materials that have been created for uses both within and outside of the built environment, allowing for a larger scope of possible applications to be explored.

3. Research Questions

Self-repairing materials are being developed in laboratories for specific applications, i.e. medical use, skin-like prosthetics, wearable sensors but are also being seen in certain building applications e.g. the BioConcrete material.

With this knowledge and range of materials exhibiting various properties, what are the applications when these self-repairing materials are applied to the built environment, particularly focusing on sustainable design?

4. Methodology

To conduct this research, interviews with members of industry were conducted in order to determine: what types of potential applications they could foresee for self-repairing materials in projects, any other type of potential application as well as what they conceived to be the limitations for these types of materials in the built environment.

This information was used alongside the applications that the materials were initially designed for. Having applications outside of the built environment, opens possibilities that could latter affect materials used in construction and design, e.g. smartphone screen technology being applied to windows and other glass elements in buildings, hence their inclusion in this research.

5. Background Research

There are two main categories of self-repairing materials; intrinsic and extrinsic. Within these two main categories are further sub-categories defining the types of healing these materials undergo.

5.1. INTRINSIC SELF-REPAIRING

Intrinsic self-repairing materials are based on specific molecular structures that enable crack healing (most common stimulant being heating). It is possible for these types of materials to be both autonomic and non-autonomic. Within intrinsic self-repairing materials, the three types of healing are; *"(i) physical interactions, (ii) chemical interactions and (iii) supramolecular interactions."(*Zhang and Rong, 2011, p. 11)

5.1.1. Physical Interactions

Thermal activation would have to be the most common form of self-repairing triggering found in intrinsic materials. There are five phases during the healing process: *"(i) surface rearrangement, which affects initial diffusion function and topological features; (ii) surface approach, related to healing patterns; (iii) wetting; (iv) diffusion, the main factor that controls recovery of mechanical properties and (v) randomization, ensuring disappearance of cracking interface."* (Zhang and Rong, 2011, p. 11)

In terms of thermoplastics self-repairing, a heat source causes a bubble in the thermoplastic to expand, forcing the melting thermoplastic into the fracture/crack, healing the damage and re-joining the surface.

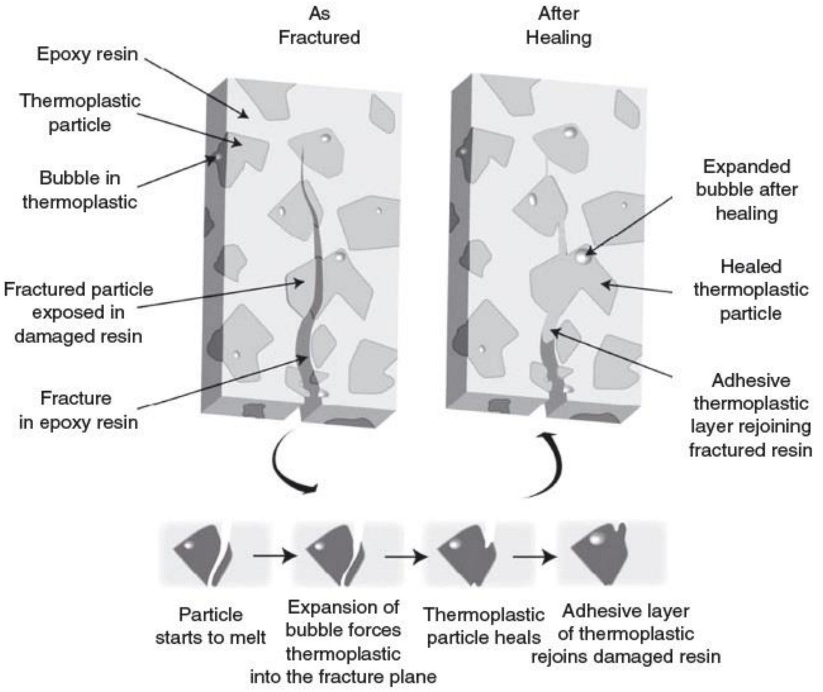

Figure 1. Simulation of thermal activation (image source: Zhang and Rong, 2011, p.15)

Ballistic stimulus is another form of thermal activation, however is seen in more specific applications. This type of healing works as the material weakens, allowing the bullet to penetrate through. As it passes, the thermal heat of the passing bullet activates the material to begin melting and re-joining, allowing the surface to regain its strength as the heat dissipates.

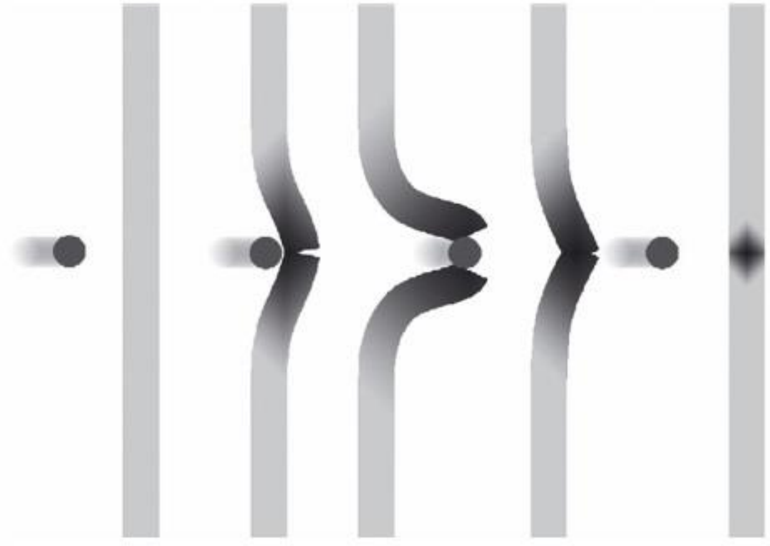

Figure 2. Simulation of ballistic healing (image source: Zhang and Rong, 2011, p.16)

5.1.2. Chemical Interactions

Chemical interactions, recombination of the broken molecules, are focused more towards nanoscopic deterioration rather than healing cracks. Such deterioration factors can include heat, light and external mechanical force. Triggers can include certain chemicals causing a chain reaction or may be as simple as the material reacting to oxygen or ultraviolet light.

Another possibility with chemical interactions is reversible bonds. *"Reversible polymers share one property in common – reversibility, either in the polymerization process or in the cross-linking process."* (Zhang and Rong, 2011, p.19) These reversible bonds offer repeated healing, potentially being able to heal cracks infinitely without additional healing agents.

5.1.3. Supramolecular Interactions

Supramolecular interactions are a type of intrinsic self-repairing which do not require the aid of healing agents or external stimuli. These types of materials are the most common types seen when searching for self-repairing materials.

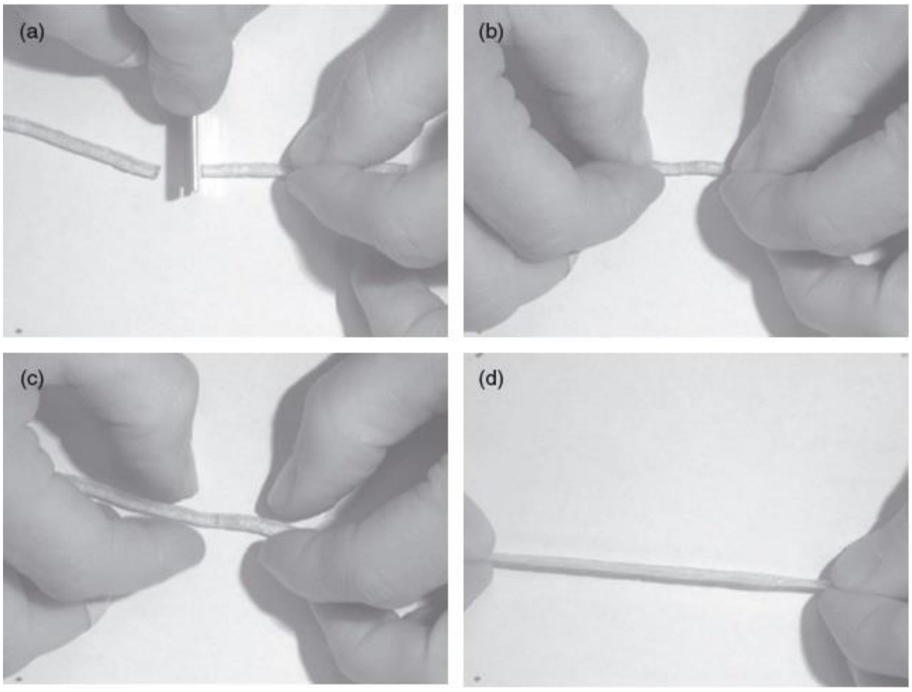

Figure 3. Sequential images displaying the healing of a supramolecular rubber after being cut, repaired than stretched (image source: Zhang and Rong, 2011, p.27)

5.2. EXTRINSIC SELF-REPAIRING

Extrinsic self-repairing materials are materials where the healing mechanism is stored in some form of media and embedded into the materials in advanced. Two main forms of extrinsic self-repairing activity are: *"(i) self-repairing in terms of healant loaded pipelines and (ii) self-repairing in terms of healant loaded microcapsules."* (Zhang and Rong, 2011, p. 30)

5.2.1. Healant Loaded Pipelines

The first type of extrinsic healing is often accomplished by loading a polymerizable medium into brittle-walled vessels (in this case, tubes) acting as the healant in the material. This polymerized medium would travel and fill in any cracks present, repairing any damage. As a result of experimentation with glass tubes and glass fibres, three types of pipeline systems were developed: *"(i) single - part adhesive: all hollow pipettes contained only one kind of resin like epoxy particles (that can be flowable upon heating and then cured by the residual hardener) or cyanoacrylate (that can be consolidated under the induction of air); (ii) two - part adhesive: in general, epoxy and its curing agent were used in this case; they were filled into neighboring hollow tubes, respectively and (iii) two - part adhesive: one component was incorporated into hollow tubes and the other in microcapsules."* (Zhang and Rong, 2011, p. 30)

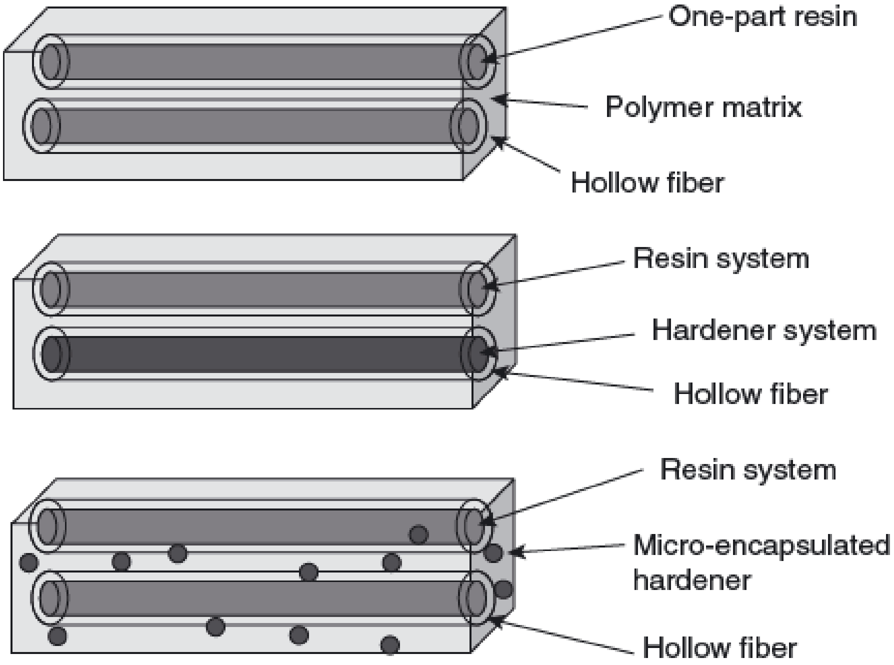

Figure 4.Diagram showing the three pipeline systems(Zhang and Rong, 2011, p.31)

5.2.2. Healant Loaded Microcapsules

Much like the previous method of extrinsic healing, a healant is loaded into a medium, this time instead of it being a pipeline it is loaded into microcapsules. One of the main advantages in this technique is that microencapsulation has been rapidly developed since its emergence in the 1950s, meaning that mass production of such capsules can be easily integrated into industrial processes.

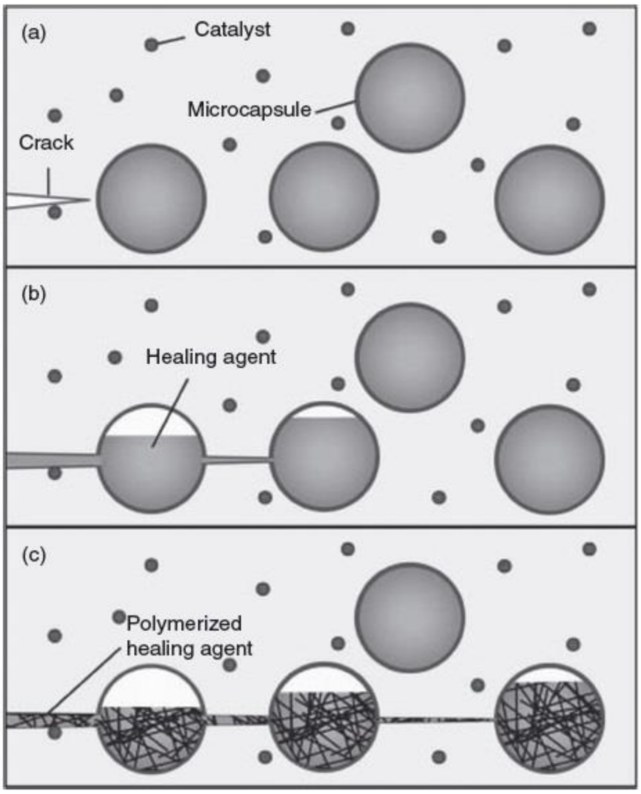

Figure 5.Diagram of healant loaded microcapsules in action (image source: Zhang and Rong, 2011, p.38)

5.3. SUSTAINABLE DESIGN

Now knowing the groups and categories of self-repairing materials, it is crucial to understand what sustainable design is. According to 'The Philosophy of Sustainable Design', sustainable design is *"the philosophical basis of a growing movement of individuals and organizations that literally seeks to redefine how buildings are designed, built and operated to be more responsible to the environment and responsive to people"* (McLennan, 2004, p.4)

From this definition and from the information gathered by industry, the following criteria have been used to pick appropriate self-repairing materials: constructability, reliability, safety and sustainability.

Moving forward with the chosen criteria, there have been three suitable material choices, two being a form of hydrogel and the other being BioConcrete. Each of these materials have unique properties and correlate to the various groups of self-repairing materials.

5.4. MATERIAL CHOICES

5.4.1. Hydrogel-A

The first material explored was a hydrogel from the 'Advanced Materials' journal article 'Skin-Inspired Multifunctional Autonomic-Intrinsic Conductive Self-Healing Hydrogels with Pressure Sensitivity, Stretchability, and 3D Printability', this material will be referred to as Hydrogel-A.

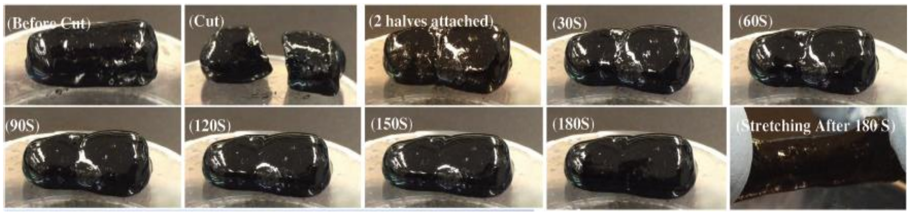

Figure 6. Display of hydrogel-A repairing (image source: Darabi et al., 2017, p.3)

Hydrogel-A was initially designed for use in the medical field, with its ability to mimic human skin it was set for use in soft robotics, prosthetic and wearable sensors. The properties of this material are as follows: Mechanical and electrical self-repairing, 100% mechanical recovery in 2 minutes, electrical recovery with 90% efficiency in 30 seconds, ultrastretchabilty – able to stretch 1500% of its original size, pressure sensitivity and 3D printability. (Darabi et al., 2017, p.1)

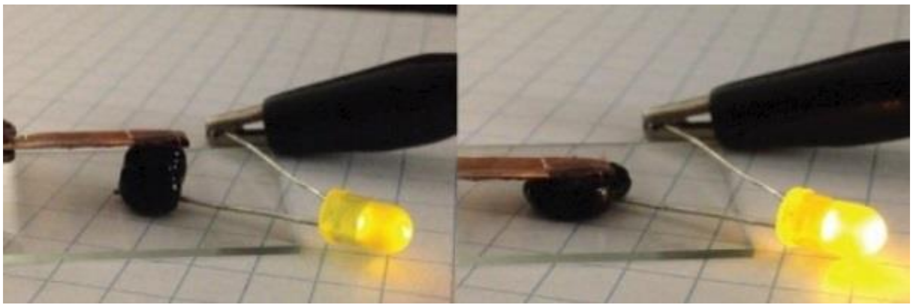

Figure 7. Hydrogel-A showing pressure sensitivity affecting current (image source: Darabi et al., 2017, p.5)

What makes this material attractive is its relatively quick recovery rates, the fact it is able to conduct electricity as well as that electrical signal being able to be controlled by pressure and that it is 3D printable. Repeated tests of this material showed the same self-repairing efficiency. As this material does not require a trigger for its healing effect it is classified as an intrinsic self-repairing material, more specifically a supramolecular polymer.

5.4.2. Hydrogel-B

The second hydrogel (Hydrogel-B) comes from the National Academy of Sciences' article 'Rapid self-healing hydrogels', the goal of this research being to *"demonstrate that permanently cross-linked hydrogels can be engineered to exhibit self-healing in an aqueous environment."* (Phadke et al., 2012, p.4383) It has also been tested and reported to stick to various plastics and surfaces with ease as a protective coating.

Hydrogel-B, when compared to hydrogel-A can be viewed as superior due to its quicker repairing properties but also due to the fact that it's healing is reversible. Being a reversible self-repairing material places it under the intrinsic group, specifically chemical interactions.

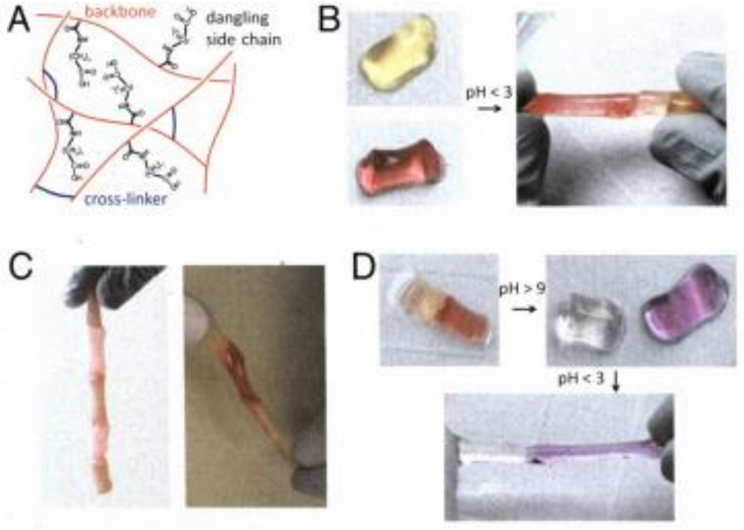

Figure 8. A) Illustration of the hydrogel structure, displaying the side chains. B) Demonstration of two cylindrical hydrogels repairing after being exposed to a low pH solution. C) Demonstration of healed hydrogels retaining their mechanical properties, even when stretched. D) Demonstration of hydrogels being separated in a high pH solution then re-joined in a low pH solution (image source: Phadke et al., 2012, p.4384)

The material can achieve this reversibility as the polymer network is connected with dangling hydrocarbon side chains, acting as a middle field between separation and solidification. The trigger for the healing effect in this case is pH, a lower pH results in the material healing, a high pH causes separation. Repair speed of this hydrogel is said to be almost instantaneous (within 2 seconds) as well as the material being hydrophobic, hydrogel-B can sustain multiple cycles of healing and separation without compromising its mechanical properties.

5.4.3. BioConcrete

The third material in this study is known as BioConcrete. The material was developed by Henk M. Jonkers in an attempt to create a sustainable, self-repairing concrete in order to reduce maintenance costs.

BioConcrete falls under the extrinsic group of self-repairing materials. The way it heals is via clay microcapsules loaded with calcium lactate and an alkali-tolerant bacteria known as Bacillus Pseudofirmus. Once a crack forms, the clay microcapsule releases the bacteria and calcium carbonate. As water seeps into the crack, the bacteria begin to germinate, feeding off the calcium lactate and oxygen to produce limestone, filling in any cracks.

It is crucial for these bacteria to be alkali-tolerant as the concrete mixture has a high pH level. The bacteria are also able to remain dormant and produce spores for decades without the need of food or oxygen. Another key feature is that the bacteria are able to consume oxygen, preventing any internal corrosion of reinforcement in the concrete. Repair times vary depending on the size of the crack (mainly developed for micro cracks – <0.2mm but can heal cracks up to 0.5mm), seeing limestone produced between 3 to 28 days.

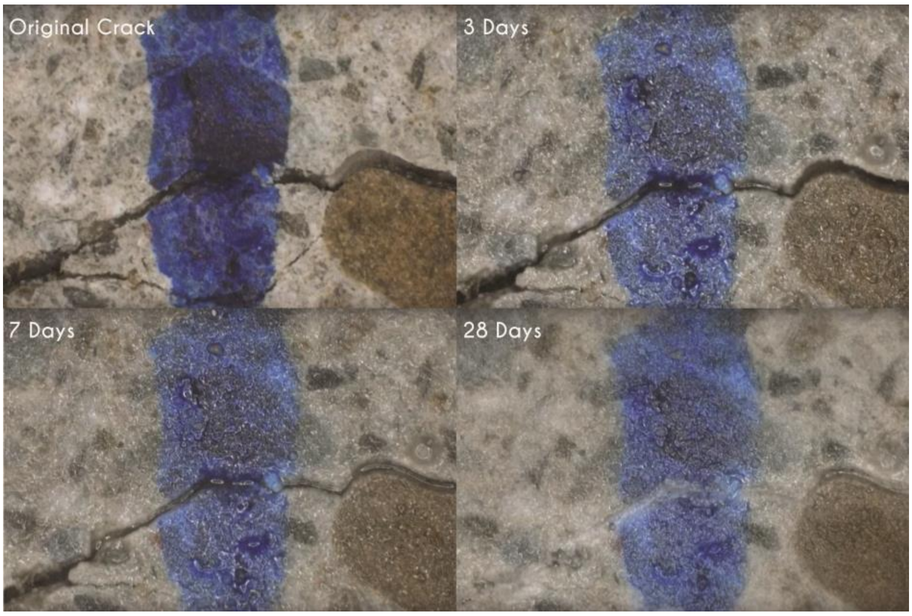

Figure 9. Example of BioConcrete producing limestone to repair a crack (image source: Jonkers, 2010)

One downfall to this material is that in order for the BioConcrete to be able to repair itself, 20% of aggregates used to strengthen the material are removed in order to mix in the healing agent. This reduced strength (25% reduction) would deem the concrete mix unsuitable for high rise building applications as its compressive strength is weakened.

6. Framework for Self-Repairing Material Applications within and outside of the Built Environment

Using the criteria, as well as having a clear understanding of the potential self-repairing materials chosen, applications may be theorized alongside the information gathered from industry. Keeping in mind the properties of each material, the following applications were accumulated: smartphone screens, solar panels, workshop benches/spaces, curtain wall gaskets, pipe fittings, laboratory containment, waterproofing membrane, mechanical seals, ETFE film and Engineered Living Materials.

6.1. SMARTPHONE SCREENS

Smartphone screens and mobile phones for the matter are particularly well known to damage easily and be expensive to repair. Statistics from Motorola in 2015 revealed that 50% of people globally have experienced a cracked smartphone screen, on top of that 42% of people say the expense of fixing their cracked screen is the reason they choose not to.

A recent patent by Motorola suggests that the company is working on a self-repairing screen, enabling users to fix their own damaged screens. *“Many displays or surface layers of modern electronic devices are manufactured from glass or plastic. Either of these materials is susceptible to deformation such as scratching, breakage or bending.”* (Morby, 2017) The device would use heat as a trigger for the screen to repair, classifying it as an intrinsic self-repairing material.

Researchers from the University of Melbourne have also been working on developing a 3D printable self-healing gel to be used as a coating for such devices like smartphones, suggesting there is a demand for such a product and need for it, as well as showing stark similarities to hydrogel-A.

6.2. SOLAR PANELS

Solar panels are another application where damage can result in costly repair bills. On average, homeowners in the U.S. spend $619 repairing their solar panels. Such damage may be due to natural hazards i.e. rocks, tree branches, hail and thermal shock. Any damage present will result in a drop of peak efficiency as well as replacement of the photovoltaic cells.

Whilst there isn’t much of a direct connection to the built environment, solar panels are used often to reduce electricity costs and in turn, make a building more sustainable. Having a self-repairing photovoltaic cell could potentially change the way building are designed, embedded the cell itself into windows or glass panes as well as in other elements of the structure. Hydrogel-A could offer solutions to a self-repairing, conductive and flexible photovoltaic cell to be embedded into surfaces and/or other elements of structures.

6.3. WORKSHOP SPACES

Workshop spaces, in particular benches and other surfaces are prone to damage from blades and other sharps due to improper use from human interaction. Often these elements are made of timber or molded plastic, materials which are often left unrepaired.

With the knowledge gained of how well hydrogel-B can adhere to various surfaces, this material may be used as a protective surface (and in this case, a cutting surface) for not only benches but other surfaces such as tables, kitchens and other surfaces that are subjected to such damage.

6.4. CURTAIN WALL GASKETS

Curtain wall gaskets are a common cause of curtain wall failure. Gaskets are strips of synthetic rubber or plastic compressed between the glazing and the frame, forming a watertight seal. As they age, gaskets being to dry out, shrink and crack. They are subjected to UV radiation and freeze-thaw cycles, which progresses the issues just mentioned.

As the gasket degrades, the elastic begins to act like an old rubber band, making it brittle and allowing air and moisture through the glass panes, with the worst case scenario seeing the glass panes themselves falling out as the gasket pulls away from the frame.

On top of this, curtain wall replacements may cost upwards of $175-250 per square foot. A replacement project by SWR Institute ran through the process and costs in restoring a 2-story, 30 year old building that still had its original curtain wall system. The entire project was estimated to cost $2,000,000 and finished with less than $400,000. Given that the hydrogels are a similar material to that of the rubber used for these gaskets, potentials for a sustainable, self-repairing gasket are present, removing the need for gasket replacements and having a safer, more sustainable building.

6.5. PIPE FITTINGS

PVC and CPVC are one of the most extensively used plastic piping materials. Pipe fittings and pipes themselves are subject to cracking and bursting from natural hazards e.g. freeze/thaw cycles causing soil to shift and damaging piping systems, seismic activity and underground debris/rocks leading to friction and soil movement results in damaged systems.

Looking into gas pipes revealed that the combination of stresses resulted in cracking along defects in the pipeline wall, especially in corrosive environments. Despite all these natural hazards, 53.4% of failure is caused by third party activity, mainly accidental puncture whilst excavating.

Although self-repairing materials may be used to seal up pipes that are punctured, it is uncertain to say whether this will act as a temporary fix or only prevent the problem till it escalates further. Instead of a self-repairing pipe, a suggestion into flexible pipe fittings was made, allowing pipes to bend during seismic activity and building settlement, offering a leeway instead of guaranteed damage.

6.6. LABORATORY CONTAINMENT

Containment of spilt chemicals is crucial to prevent the potential hazards such as: flammability, reactivity to air or water, corrosion and high toxicity. Whether it is in a laboratory environment or digital fabrication workshop, any chemical spills need to be contained and responded to immediately to ensure the chemical does not spread and come in contact with anyone and/or the environment.

Chemical injuries to the eye represent between 11.51%-22.1% of ocular traumas according to the American Academy of Ophthalmology (Trief, Chodosh and Colby, 2017). As with workshops, safety gear is worn but isn’t always a guaranteed safety factor. Studying the properties of hydrogel-B, a self-repairing material that heals when exposed to low pH, it seems fitting to be used as a protective coating in both transportation and containing chemicals as the low pH of acids would cause the hydrogel to heal alongside its hydrophobic properties keeping it contained in a vessel.

6.7. WATERPROOFING MEMBRANE

The most common causes of failure in waterproofing include: poor workmanship & preparation, failure to prime surfaces prior to applying the membrane and residual moisture in the substrate. According to the Australian Institute of Waterproofing, 90% of all failures in waterproofing are accountable to poor workmanship.

Building movement and settlement is another contributing factor which may cause the membrane to tear or rip loose from edges or flooring. In this case, hydrogel-B would be an ideal candidate as a self-repairing membrane. Its hydrophobic properties allow it to repel water and other liquids, alongside the ability to repair any cracks or tears. It is also able to stick to various surfaces with ease, making it theoretically the solution to all the problems present.

6.8. MECHANICAL SEALS

As seen earlier with curtain wall gaskets, mechanical seals are another rubber product subject to wear and tear from thermal shock, vibration and rubbing. Most consumers experience seal failure rates greater than 85%, most of which are easily correctable.

Failure can also be a result of operator error, improper seating, cracking and corrosion i.e. chemicals and/or acids eating away at the seal. While these seals are mainly seen in machinery, there are various applications of seals and sealants used in building systems much like curtain walls and kinetic facades. Having a self-repairing seals will not only help improve the longevity of the application but also reduce time and money spent on maintenance.

6.9. ETFE FILM

ETFE film is seen as a sustainable building material as it allows daylight to penetrate into building interiors as well as being able to reflect heat and glare for thermal comfort.

Another benefit of ETFE is the ability to have flexible photovoltaic cells attached to the membrane to produce an alternate form of energy. ETFE cushions are another use of the material, being able to have LEDs integrated to create internal lighting effects. However, ETFE is subject to tearing and damage from external elements such as hail, rain, wind, ice and even birds picking at the material.

Current repairing methods involve an ETFE foil patch being applied to patch up any small damage while more significantly damaged piece requiring removal and replacement. Whilst it may not be possible to make ETFE a self-repairing material, it may potentially be used in conjunction with one, e.g. hydrogel-A being lined within the ETFE, using its conductive properties to link LEDs and photovoltaic cells together.

Whilst all of these applications aren’t specifically related to the built environment, they all fit under the criteria of; constructability, reliability, safety and sustainability. There is however one more application that draws a strong link to the built environment and its methodologies like biomimicry and morphogenesis, and that is Engineered Living Materials.

6.10. ENGINEERED LIVING MATERIALS

Engineered Living Materials (ELM) is a program run by DARPA (Defense Advanced Research Projects Agency) aiming to create a new class of materials by combining structural properties of current building materials with attributes of living systems. They aim to incorporate *“the ability to rapidly grow, self-repair, and adapt to the environment”* (Gallivan, 2017) in order, to solve existing problems present in construction and maintenance.

As of current, they are unable to easily control the size and shape of these materials in ways that would make them useful for construction, hence the need for their development. The program is split into two fields of research, one being hybrid ELMs and the other being programmable ELMs.

6.10.1. Hybrid ELMs

Hybrid ELMs aim to cross inert structural scaffolds in order to sustain and support the growth of living cells, essentially merging the best features of existing materials with these biological functions.

6.10.2. Programmable ELMs

Programmable ELMs seek to take the hybrid material further by exploring structural features involved in biological systems, to genetically program living materials. *"Teams performing in Programmable ELM will seek to invent methods to program the development of multicellular systems and tunable patterns and shapes."* (Gallivan, 2017)

Essentially the team is looking to remove the need of scaffolds and external supports, controlling the desired shape and properties in the living material itself.

Given that these materials are still in development, it is uncertain how far off the use of such materials will be for construction purposes. So how do ELMs relate to the built environment? Well when looking at how we already use nature and biology in design, the first thing that comes to mind is biomimicry.

6.11. BIOMIMICRY AND ITS APPLICATION TO SUSTAIN DESIGN

"Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies" (Biomimicry Institute, n.d.) Biomimicry in the built environment often sets out to explore ways in which designs can emulate nature in order to be more sustainable in terms of energy consumption by maximizing natural resources but to also explore material-driven design.

Menges demonstrates this in his works and study by looking into the potential in biomimetic design. An example of this is his work with Steffen Reichert on hygroscopically actuated wood, making timber respond and adapt to weather changes as well as go beyond its physical form in the production process. Using grooves, which are milled into the wood elements alongside the hygroscopic element, deformation can be controlled as moisture is absorbed, expanding or contracting the wood.

6.11.1. Silk Pavilion

Another example of biomimicry in the built environment is the Silk Pavilion by M.I.T. Inspired by the performance of silkworms and how they generate silk, the pavilion utilises digital technologies by threading hexagonal boards via a robot arm to control the pathway of the silk worms. 6,500 silkworms are then placed onto this framework, creating the pavilion purely from silk. The silkworms and framework are then removed, leaving behind the pavilion showing how *"the blind instinct of silkworms is sometimes revealed as almost machine-like."* (Stott, 2013)

6.11.2. BioMason

Turning to the other spectrum of biomimicry, we see materials being re-invented to reach sustainability goals, one of those materials being BioMason. BioMason is a project started by Ginger Krieg Dosier, in an attempt to change the way bricks (and cement) are produced.

As of 2015, China is the biggest consumer of cement, having used three times more cement than the next nine top producers combined. The issue present is that *"40% of global carbon dioxide emissions are linked to the construction industry"* (Foster, 2014) with for every ton of cement produced an almost equivalent quantity of CO2 is released into the atmosphere. Whilst Australia is not in the top 10 producers, it is in the top 5 for emissions per capita, with 18.6t per person.

BioMason seeks to reduce CO2 emissions by turning to nature and drawing inspiration from coral growth. Coral skeletons are the closest natural material linked to cement. The material is created by mixing bacteria and sand to ‘grow’ cement and make bricks. Instead of releasing CO2 into the atmosphere, CO2 is bonded and absorbed into the brick to which the bacteria feeds off and produces calcium carbonate, which acts as the glue.

Half of the emissions come from the energy required in order to fire and cure normal bricks, BioMason however is cured at room temperature naturally in two to three days, already reducing half the CO2 usage in traditional brick making. The rest of the emissions are a result of extracting the raw material and transportation. The bacteria required can be obtained from natural sources, including recycling industrial waste stream and the sand used is an abundant source.

BioMason has been tested to withstand 26,000 pounds of force to a shoe box-sized block before it breaks. Currently there are three *"preliminary installations – two courtyards in San Francisco and a series of small walls – are testing the bricks' resilience in the real world."* (Dosier, 2017)

This material already aids sustainability by reducing CO2 emissions, so what benefits are there by incorporating self-repairing materials? Given the close similarities between BioMason and BioConcrete, two materials driven by bacteria, could it be possible to develop a self-repairing, sustainable concrete? After the bacteria in BioMason has cured, it is said to be dead whilst in BioConcrete, the bacteria remains dormant until the microcapsule is cracked and water seeps in, germinating the bacteria and allowing it to feed off the calcium carbonate and produce limestone. Both materials utilise calcium carbonate and should theoretically, be compatible with one another. Thus driving the need and demonstrating the use of self-repairing materials in the built environment.

7. Significance of Research

The significance of this research is to open up potential possibilities of incorporating self-repairing materials into the built environment. The knowledge gained here involves three separate self-repairing materials, all unique and developed mainly for use, mainly outside of the built environment with BioConcrete being the exception.

These materials have been applied to applications which theoretically could resolve the issues currently present. This is merely a stepping stone onto which further development is required.

8. Evaluation of research project

The research involved in this project is purely theoretical, having involved members of industry and research into sustainability, the applications chosen can benefit from self-repairing material integration.

Logically, the materials chosen should be able to be applied to the various scenarios and work as functioned, however given that they are still relatively new materials with little to no real world testing, it is difficult to give a final outcome on how they will perform. Given the time span, lack of specialist knowledge and accessibility of materials for this project, performance testing was not possible, hence the set-up of a framework for future development of applying self-repairing materials to the built environment.

9. Conclusion

To conclude, the research strongly shows that there are indeed potential uses for applying self-repairing materials in everyday objects as well as construction methods in the built environment. Knowing how much CO2 is emitted from the construction industry alongside how designers are using biomimicry to emulate natural properties to create sustainable buildings, a combination of self-repairing and natural materials can seek to improve methods and create a more sustainable future.

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10. Appendix

Upon interviewing and having discussions with members of industry from HDR, there was discussion of targeting remote locations and/or hard to reach areas where self-repairing materials would eliminate the need for human intervention.

Potential applications ranged from: water proofing membrane, gaskets/seals, pipes/pipe fittings, solar panels, flexible joints, glass embedded solar cells and uses as a medium between joints, i.e. like how cartilage is used in the human body.

A secondary interview offered suggestions and future questions on limitations such as: Would the bacteria from the BioConcrete and BioMason projects react with contaminate soils through the foundations? What stops the bacteria in BioConcrete from creating more limestone than required, thus creating a bubble or further expansion? Due to the lack of real case studies on material behaviour, what is the life cycle and aging of the materials? Would it be possible to do curved walls in numerous pours and then in time the concrete would self-repair the gaps or the pour joint so it could appear seamless? Can the material withstand its own weight?

Other applications in and outside of the built environment included use of hydrogels as a lining of biohazard suits to repair rips/punctures, intermediate cable lining (between the cable itself and the outer layer), hydrogels in waterproofing applications, thermal applications, Hydrogel-A could have application in electrical wiring insulators, door seals, sealing holes in tyres and using BioConcrete in coastal applications where the structure is semi submerged or prone to potential impact, i.e. wharf piers.