

Bio-Inspired Stimuli Responsive Reversible Actuation, Using Chelating Polymers And Metal Ion Binding, For Selective Growth

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ABSTRACT

In biologically engineered architectures, 'morphogenesis', a dual strategy for growth and form, exists where: (a) the mechanics of design using morphological constraints involves a practice of dynamic and continuous negotiation between design intent and material emergence; and, (b) the proposed biologically produced architecture will behave as an adaptive organism. These materials themselves are capable of self-repair for longevity, self-replication for reproduction, and growing or mutating new structures. In our study we are inspired by *Phragmatopoma californica* (Sandcastle worm), which builds protective tubes by joining sand grains together with secreted cement, and, the biological architecture, the actuating elements and deformation kinematics observed in *Aizoaceae* (The Ice Plant). In *Phragmatopoma californica* the cement forms bonds upon excretion from the worm with magnesium and calcium cations using phosphoserines, a post-translationally modified serine amino acid. This cement has been used as the inspiration for a synthetic hydrogel possessing polychelating properties. The chelating polymer uses phosphate functional groups to bind to metal cations within its structure forming crosslinks between multiple chains, vastly increasing the stiffness and decreasing the swelling potential of the hydrogel. In comparison, in *Aizoaceae*, bidirectional in-plane movements through cellular swelling cooperate to yield large anisotropic out-of-plane deformations (for plant seed deployment). In our study, we have been using (1) constrained acrylate based hydrogels (within 3D printed architectures) and (2) Ionoprinting hydrogels (a technique used to pattern hydrogels with metal cations) to create both 3D morphing polygons and the concept of a morphing joint. We developed a synthetic acrylate based hydrogel containing 20 mol% phosphate functionalised side groups; the phosphate functional group is found in many protein based underwater adhesives utilising polypeptide metal cation bonding to promote "wet" adhesion. For the morphing polygons, we introduce metal cations into the surface and near surface of a hydrogel (termed ionoprinting) creating localised ionic crosslinking and contraction, resulting in rapid structural morphing of the hydrogel. This technique offers a simple and effective way of creating morphing shape-changing hydrogels, a process that is both reversible and reprogrammable.

1 INTRODUCTION

Hydrogels consist of three-dimensional hydrophilic polymer chains crosslinked together to create a polymer network that swells in water but does not dissolve; creating a material that lies between a solid and a liquid, namely a gel. The amount of water absorbed by hydrogels can be varied by external stimuli such as pH, temperature or electric field [1]. One of the limitations of hydrogels is also one of their greatest assets, their ability to only act in aqueous media; allowing them to act in biological and wet environments, which are often inaccessible for other actuators [2]. Homogenous hydrogels when submerged into water will ultimately

result in homogenous swelling in all directions, inhomogeneous swelling can be produced by subjecting the hydrogel to an inhomogeneous environment [3]. The most widely used approach to achieve inhomogeneous shape change from homogenous hydrogels is to combine them with other homogenous hydrogels or materials, with the geometry of the material combination controlling the movement and final shape [4]. Another approach is to use ionoprinting, a technique used to print metal cations onto the surface and near surface of hydrogels allowing homogeneous hydrogels to shape change in an inhomogeneous manner by creating local inhomogeneity within the hydrogel. Ionoprinting uses the principles of electrolysis to create localised ionic crosslinking and shrinkage where the cations are deposited, creating a bending hydrogel [5-6].

Biological systems operate in a significantly more limited environment with a reduced range of elements than engineers and scientists, yet Nature is still able to create a vastly diverse range of materials. This work uses inspiration from biological systems to create reversible crosslinking that can operate in aqueous environments. Metal cation-polypeptide crosslinking to create tough and stiff materials has been the inspiration for many biomimetic materials, the one most widely used is the catechol-iron interaction found in mussel byssal threads [7-9]. It has been found that similar binding between phosphate functional groups with calcium and magnesium cations exists within the cement of the sandcastle worm [10-11]. This binding technique has been used to create dental adhesives that are required to work in wet environments [12]. The objective of our research was to generate a synthetic hydrogel that can be used to (1) activate a morphing joint through integration within 3D printed compliant architecture, and (2) remodel into a complex polygons from simple 2D configurations.

2 EXPERIMENTAL

Materials: Phosphoric acid 2-hydroxyethyl methacrylate ester (PHMA), 2-Hydroxyethyl acrylate (HEA), N,N'-Methylenebisacrylamide (MBAA), 2,2-Dimethoxy-2-phenylacetophenone (DMPA) and triethylamine (TEA) were obtained from Sigma-Aldrich (Poole, UK). 2-(methacryloyloxy)ethyl phosphate (MOEP) was extracted from PHMA with n-hexane and HEA was filtered through basic alumina, while DMPA, MBAA and TEA were used without further purification. **Preparation of hydrogels:** The monomers (HEA and MOEP) were combined in a molar ratio of 4:1, respectively, before being neutralised with TEA. Crosslinker (MBAA) and photoinitiator (DMPA) were added prior to dissolution with water:DMSO (2:1) resulting a precursor solution with total monomer, crosslinker and photoinitiator of concentration of 2.5M, 12.5mM and 3.0mM respectively. The precursor solution was degassed and then poured into PLA molds and sealed with glass slides prior to curing under a UV lamp (365/245nm, 4W) for 2 hours. Hydrogels were soaked in frequently changed di-ionised water prior to further tested. **Hydrogel swelling:** Hydrogels were swollen in 6.0ml of the test solution and allowed to equilibrate over 48 hours. Samples were pat dried with paper towel prior to weighing and were weighed to an accuracy of 0.01g. **Ionoprinting:** Hydrogels swollen in 0.1 M LiCl solution, unless otherwise stated, for a minimum of 48 hours were pat dried. Superficially dry samples were ionoprinted between an aluminium foil cathode and a copper, vanadium or iron anode using a Rapid DC Power Supply HY3003C. Current was measured with an iNLEC DT-830B Digital multimeter.

3 RESULTS & DISCUSSION

3.1 Hydrogel – soft morphing architecture

The soft compliant architecture in which hydrogel is contained is developed by 3D printing in Thermoplastic Polyurethane (NinjaFlex). As there is no adhesion between this hydrogel and thermoplastic polyurethane, the architecture cell wall would not pull inwards with shrinking of the hydrogel to a smaller, drier state. This meant that all movement of the architecture must be governed by outwards pushing of the soft material. Hydrogel hinge inserts were hence sized and cured in an external mould in order to match the architecture dimensions when at its dry state. It was necessary to keep samples as small as possible in

order to reduce the actuation time required.

3.2 Characterisation of soft morphing architecture

The introduction of hydrogel inserts within the compliant architecture successfully activated the structure to an overall average angular change of 23° . Initially, homogeneous swelling of all three capsules enabled rapid and steady movement up to 11.5° in 315 seconds, whilst the remaining angle was accomplished within an additional (on average) 3200 seconds. Hydrogel swelling ensures proportional total dimension change between dry and swollen states. It is known that this swelling does not occur linearly and this is illustrated by the high level of swelling initially, which slows with increasing angle (see Figure 1). However, since the hydrogel does not swell uniformly, the geometrical shape can play a role in actuation. The sharp corners resulted in a higher swelling rate at these points, and along with the initial curvature induced via differential curing through the samples, the corners begin to swell in the z-direction, thus distorting the architecture. Limited capability of the printers also resulted in lower volume of the centre capsule due to attachment of the arms further away from the root. This shorter arm dimension eventually led to fracture of the centre hydrogel insert (see Figure 3, insert image (c)).

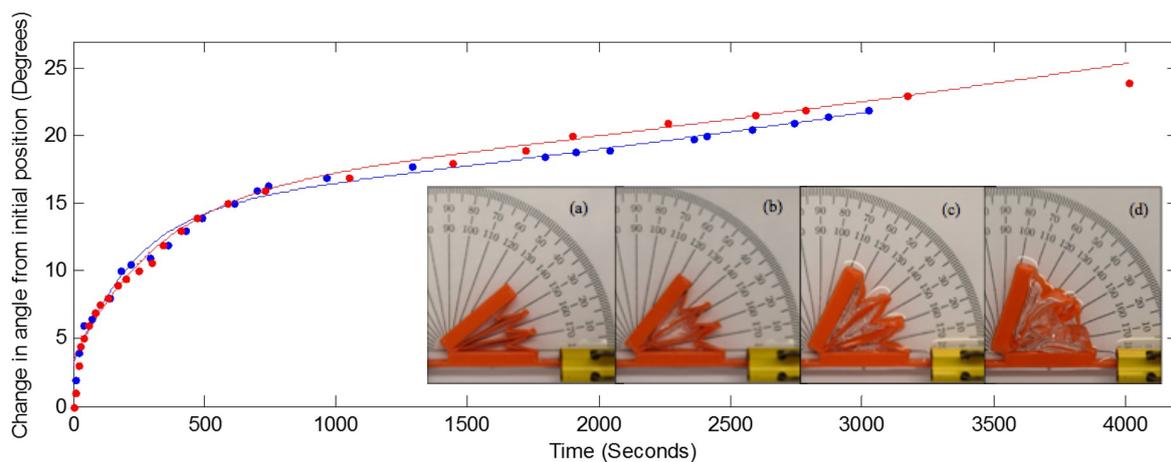


Figure 1: Actuation of morphing architecture, change in angle exhibited by each hinge as a function of time: Blue data – Makerbot FDM process; Red data – Ultimaker FDM process. Insert image illustrates hinge experiment (a) without inserts, (b) before with inserts (dry), (c) at 50% of maximum change in angle reached and (d) maximum angle reached

As Figure 3 illustrates, there is slight variation in the angle-time response between the two 3D printers. The Makerbot Replicator 2 has been adapted and optimised to operate using a 0.13 mm nozzle head, whereas the Ultimaker Original a 0.2 mm head. Printing with a finer nozzle and hence reduced thickness of layers increases the flexibility of the structure, thus allowing increasingly easier movement with the same force. This can be seen in the results where full deployment takes 330 seconds longer for the Ultimaker hinge. However, this increase in stiffness proves beneficial in the arms by providing increased structure, inducing more equal swelling from each capsule and keeping the inserts in the cells for a longer period of time, hence outputting a larger overall angle by 2° .

3.3 Hydrogel Ionoprinting

In our chosen system, the hydrogel significantly decreases its water content in the presence of multivalent metals cations through chain-cation-chain crosslinking. Metal cations have been localised to select regions through ionoprinting to create localised multi-chain cation crosslinks resulting in localised deswelling and surface contraction. Ionoprinting is a technique used to selectively pattern metal cations onto the surface/near surface of a

hydrogel, the technique was first described by Palleau *et al.* in their paper in 2013 [5]. Their work described the patterning of poly(acrylic acid) (PAA) with copper cations (Cu^{2+}) to form increased ionic crosslinking, reduction in water concentration and deswelling in the ionoprinted region. Ionoprinting utilises the principals of electrolysis but due to the presence of possible binding sites e.g. carboxylic acid groups, the cations produced do not diffuse rapidly away from the electrode and instead become bound. In this approach, it was noted that redox processes occurred at the aluminium cathode and the copper anode respectively [5]. Using standard electrode potential it can be determined that E_{cell} is -0.3419V giving the theoretical threshold voltage for ionoprinting [16]. Phosphate groups were used as the binding group for ionoprinting and the binding potential of various metal cations was used to select suitable metals for use as electrodes in the ionoprinting process. The metals chosen were vanadium and iron as both their trivalent cations produced significant deswelling. Their E_{cells} when used to produce hydrogen is 1.430V and 0.037V respectively. An iron electrode has been previously used to ionprint hydrogels containing catechol functional groups that bound to metal cations [6].

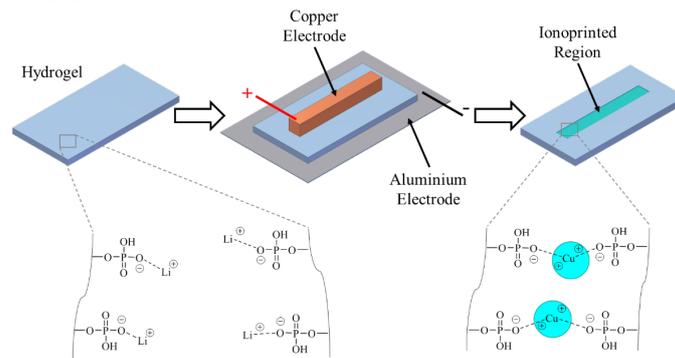


Figure 2: Schematic of ionoprinting of a hydrogel with a copper and aluminium electrode [5]

3.4 Ionoprinting to create 3D polygons

The ionoprinting technique was extended beyond the simple shapes created previously [5-6], and used to create 3D regular polygons of a cube, triangle based pyramid and an octahedron with printing angles of greater than 90° , 90° and less than 90° , respectively.

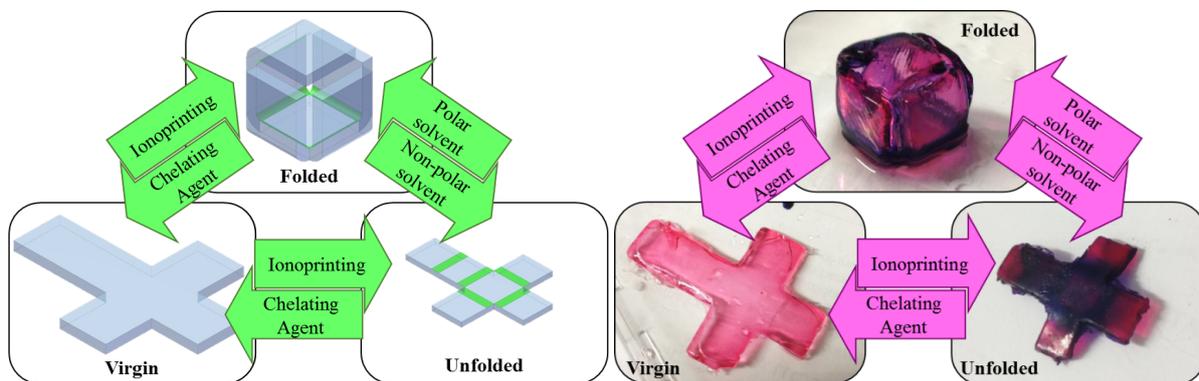


Figure 3: Left: Schematic of a cruciform folding into cube through ionoprinting or non-polar solvent and unfolding in a chelating agent or polar solvent. Right: Photographs of the same process. Hydrogel coloured with red food dye

A cube has been created from a flat cruciform by ionoprinting 5 lines as shown in Figure 3, the lines were printed with vanadium wire of diameter 1.5mm at 10V. The ionoprinted lines were printed until an angle of 90° was achieved, creating the cube. The cube was then unfolded in ethanol and then refolded in water twice, before placing the cube in water and regularly changing the water for a number of days. The ions defused into solution and into

the rest of the hydrogel removing the effect of the ionoprinted regions and reforming to the flat cruciform cross-section. The cruciform could be reprinted into a cube and the deswelling in ethanol and swelling in water successfully completed again. This shows that the ionoprinting produces two-way actuation when exposed to an appropriate stimulus, and can be reprogrammed for different actuation shapes by removing the printed ions and reprinting.

3.8 Ionoprinting into kinetic origami inspired 3D shapes

Origami is the Japanese art of paper folding and can be used to create complex three-dimensional shapes from flat sheets of paper. A subsection of origami is kinetic origami, which are origami shapes that have a dynamic property to them; the most famous is the crane, that flaps its wings when its tail and head are pulled away from each other. The kinetic origami design used to create a dynamic hydrogel is one of alternating mountain and valley folds at 45° degrees from each other extending from the centre of circle to the edge, in a similar manner to how an umbrella is folded up. Figure 4 shows the complex shape change undergone from unswollen to swollen. Unlike homogenous hydrogels the area displayed in each direction does not follow the normal trend of expansion, instead contraction is observed from the top view and expansion from the side view (see Figure 4).

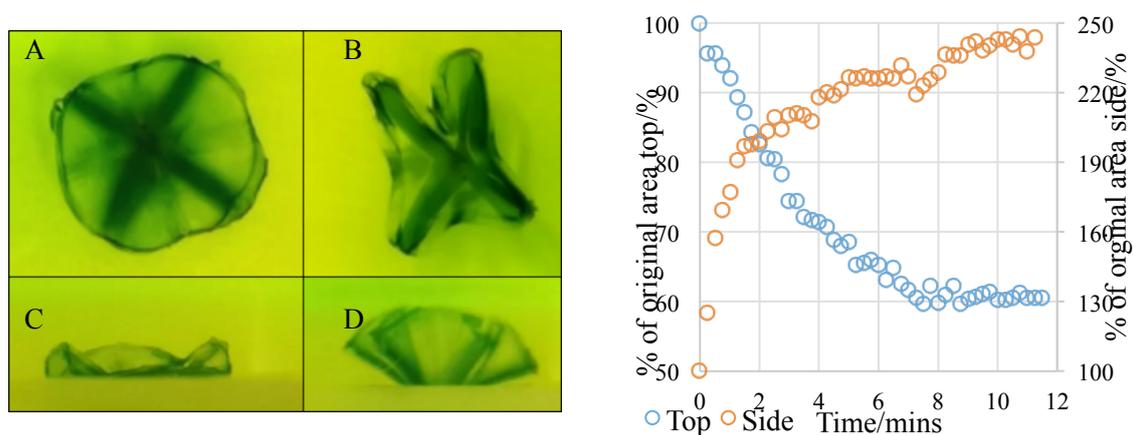


Figure 4: Left: Photographs of “umbrella” swelling in water after deswelling in acetone. A) Top view unswollen. B) Top view swollen. C) Side view unswollen. D) Side view swollen. Right: Graph of area of hydrogel from top and side against time

4 CONCLUSION

This research successfully illustrates the capability of exploiting bio-inspired movement upon actuation of hydrogel via two methods. Firstly, the development of a compliant architecture acting as a capsule containing a pliable matrix illustrates the capability of creating global and hierarchical movement which is completely reversible. Secondly, we have found that metal cations can be used to successfully trigger ionic crosslinks within a hydrogel; with tri- and tetra-valent metal ions being the most effective. The level of crosslinking was not only controlled by the cation but also the cation concentration levels as well, until a saturation point was reached. The cations could be successfully removed using a chelating agent, such as EDTA, to restore full swelling of the hydrogel. Ionoprinting effectiveness was improved by increasing print time and voltage and decreasing the salt concentration. These results were used to successfully print a range of three-dimensional shapes from their flat counterparts and were shown to be able to cycle from fold to unfolded either retaining or losing their ionoprinted regions each cycle. Ionoprinting offers a way to quickly and effectively change the shape of hydrogel through localised ionic crosslinking; the process is both reversible and reprogrammable and offers a wide range of possible applications include soft-robotics, artificial muscle tissue and biosensors.

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