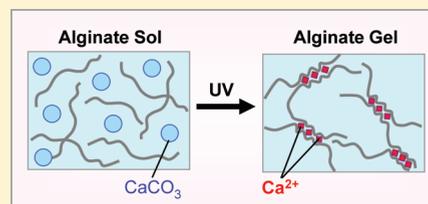


Light-Activated Ionic Gelation of Common Biopolymers

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ABSTRACT: Biopolymers such as alginate and pectin are well known for their ability to undergo gelation upon addition of multivalent cations such as calcium (Ca^{2+}). Here, we report a simple way to activate such ionic gelation by UV irradiation. Our approach involves combining an insoluble salt of the cation (e.g., calcium carbonate, CaCO_3) with an aqueous solution of the polymer (e.g., alginate) along with a third component, a photoacid generator (PAG). Upon UV irradiation, the PAG dissociates to release H^+ ions, which react with the CaCO_3 to generate free Ca^{2+} . In turn, the Ca^{2+} ions cross-link the alginate chains into a physical network, thereby resulting in a hydrogel. Dynamic rheological experiments confirm the elastic character of the alginate gel, and the gel modulus is shown to be tunable via the irradiation time as well as the PAG and alginate concentrations. The above approach is easily extended to other biopolymers such as pectin. Using this approach, a photoresponse can be imparted to conventional biopolymers without the need for any chemical modification of the molecules. Photoresponsive alginate gels may be useful in creating biomaterials or tissue mimics. As a step toward potential applications, we demonstrate the ability to photopattern a thin film of alginate gel onto a glass substrate under mild conditions.



1. INTRODUCTION

The use of light as an external stimulus for tuning material properties is being actively investigated by engineers and scientists.^{1–6} Compared to other stimuli such as temperature and electric fields, light offers significant advantages in that it can be directed precisely at a location of interest with micrometer-scale resolution and from a distance (i.e., avoiding direct contact). Accordingly, numerous researchers have been seeking to impart photoresponse to materials so that the properties of the material can be tuned by light. In the context of self-assembly, which involves weak, noncovalent interactions, there have been many attempts at creating assemblies that can be switched from one morphology to another using light. For example, light-responsive self-assembly has been used as the basis for photo-rheological (PR) fluids,⁷ which are fluids whose rheological properties can be tuned by light. One example is a system that undergoes a light-induced sol-to-gel (fluid-to-solid) transition because of the light-induced assembly of individual molecules into a nanofibrous network.^{3–5} Such self-assembly-based gelation is distinct from UV-activated cross-linking (free-radical polymerization). Specifically, self-assembled gels are weak networks that can be subsequently liquefied either by irradiation with a different wavelength of light or by changes in temperature, pH, or composition.^{3–5}

We have recently become interested in imparting photoresponse to assemblies such as micelles,^{8,9} reverse micelles,¹⁰ and nanoparticle networks.¹¹ While most previous work in this area focused on designing novel photoresponsive molecules (such as azobenzene-modified surfactants^{2,12} or molecular gelators^{3–5}), we have focused on finding simpler routes to photoresponsive systems that involve no chemical synthesis (i.e., the materials

can be prepared by mixing commercially available entities). For example, we have created photoresponsive micelles by doping common surfactants with a cinnamic acid derivative.^{8,9} In another study, we developed a photoresponsive aqueous dispersion of clay nanoparticles that transformed from a sol to a gel upon UV irradiation.¹¹ The concept in this case was to combine the nanoparticles with an amphiphilic stabilizer and a photoacid generator (PAG). PAGs are commercially available molecules that have been used for a long time in the microelectronics industry.^{13–16} Their distinctive property is that they get photolyzed by UV light to form an acidic moiety.^{13–16} In our system, the photolysis of the PAG caused the pH to drop by about 3 units, and in turn, the charges on the edges of the clay nanoparticles switched from negative to positive.¹¹ This charge reversal drove the initially separated particles to cluster into a gel network.¹¹

In this study, we show how to impart photoresponsive properties to solutions of biopolymers. We again use a PAG as the photoactive component of the system. The biopolymers employed here are sodium alginate and pectin, and the property shared by these is that their solutions undergo gelation in the presence of multivalent cations such as Ca^{2+} , Ba^{2+} , and Al^{3+} .^{17–19} Alginate, in particular, is a popular biopolymer that is extensively used for encapsulating biological cells and for other biomedical applications.^{17,20} For such applications, it would be advantageous to have an alginate formulation that could be cross-linked by light rather than by the addition of ions. Indeed, two research groups

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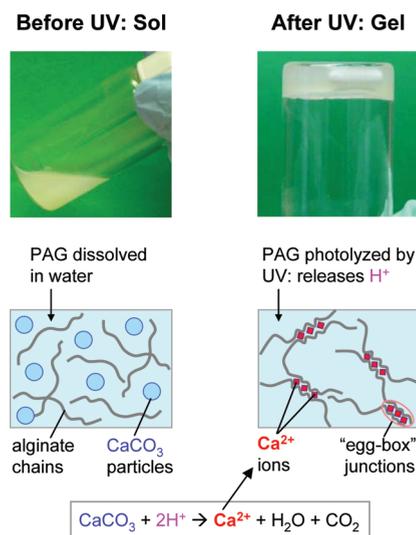


Figure 1. Schematic and visual depiction of UV-induced alginate photogelation. Sodium alginate (2 wt %) is combined with 15 mM of $CaCO_3$ particles (insoluble) and 30 mM of a photoacid generator (PAG). The resulting sample is a turbid dispersion (sol) that flows freely in the vial. Upon exposure to UV light, the PAG gets photolyzed and thereby releases H^+ ions, which react with $CaCO_3$ to form soluble Ca^{2+} ions. These ions gel the alginate, and the sample holds its weight upon vial inversion. The cross-links in the gel are domains of Ca^{2+} bridging adjacent chains, as shown in the schematic, and these are referred to as egg-box junctions.

have recently explored this very idea.^{21,22} One group synthesized a derivative of alginate modified with methacrylate groups, and this polymer was covalently cross-linked into a gel by a free-radical mechanism.²¹ A second group utilized a light-sensitive caged-calcium compound, which upon UV irradiation released Ca^{2+} ions that cross-linked alginate into a gel.²² These approaches required either additional chemical synthesis steps or the use of expensive molecules such as caged calcium, which impedes their large-scale applicability. For example, whereas the latter method was suitable for use with small amounts of material in a microfluidic device, the authors noted that it was unsuitable for creating bulk gels.²² Also, with regard to covalently cross-linked alginate, one issue is that those gels cannot be liquefied (reversed) by the addition of sodium citrate or other calcium chelators. Reversibility is a useful property because it permits the release of entrapped species such as cells or nanoparticles from the gel.

Here, we report a simple photogelation scheme using relatively inexpensive, commercially available components that can be used to create bulk gels and films of alginate and other biopolymers. The gels are physically (noncovalently) cross-linked, allowing for subsequent reversal to a sol state. Our scheme for the photogelation of alginate is illustrated in Figure 1. The components of the aqueous system are sodium alginate, an insoluble calcium salt, typically calcium carbonate ($CaCO_3$), and the photoactive PAG component, which here is diphenyl-iodonium nitrate. When the sample is irradiated with UV light, the PAG gets photolyzed to generate acid (H^+). The acid triggers the dissolution of $CaCO_3$ to generate free Ca^{2+} ions by the reaction shown. The Ca^{2+} ions then electrostatically bind to the L-gulonate (G) blocks of adjacent alginate chains to create cross-links ("egg-box" junctions),^{23,24} and in the process an

alginate gel is formed. The same method can be used with other Ca^{2+} -responsive biopolymers, and we demonstrate this with a second polysaccharide, pectin. The gels are also shown to be reversible by the addition of calcium chelators such as sodium citrate. We note that our approach is analogous to the gelation of alginate by the in situ dissolution of an insoluble calcium salt upon the slow hydrolysis of D-glucono- δ -lactone (GdL) to gluconic acid; the difference here is that acid formation is triggered by light via the PAG.^{20,25}

Photogellable alginate solutions may be useful for the encapsulation of cells or biomolecules, especially because the use of light allows gelation to be realized in a local and spatially selective manner. Recently, there has been considerable interest in producing micro- and mesoscale patterns of alginate gels and films on various substrates as a means to interface soft biological components to hard devices.^{26–28} Toward this end, we demonstrate herein the creation of microscale, chemically erasable patterns of alginate hydrogel films using our photogellable alginate in conjunction with rudimentary photolithographic techniques.

2. EXPERIMENTAL SECTION

Materials. Sodium alginate (product number W201502) was purchased from Sigma-Aldrich. Its molecular weight was specified to be in the range of 12–40 kDa. Low-methoxy (LM) deamidated pectin from fruit (product number 400505) was purchased from Carbomer. Its molecular weight was specified to be 500–600 kDa, and its degree of esterification was 33–35%. Precipitated calcium carbonate ($CaCO_3$) particles (mean particle radius of 70 nm) were obtained from Specialty Minerals, Birmingham, U.K. Diphenyliodonium nitrate, a type of photoacid generator (henceforth abbreviated as PAG), was purchased from Sigma-Aldrich. Quantofix calcium indicator strips were purchased from CTL Scientific. The calcium chelator salt, sodium citrate dihydrate (NaCit), was purchased from Fisher Scientific. Distilled–deionized (DI) water was used for all of the experiments.

Sample Preparation. Samples were prepared by combining the $CaCO_3$ particles with a solution of sodium alginate and PAG in DI water. Each mixture was stirred overnight by a magnetic stirring bar and was then sonicated using a Branson 1510 sonicator for 45 min at 40 kHz. Stock samples of 10–15 mL were prepared to enable multiple experiments. A similar procedure was used with the pectin samples; however, because the as-supplied pectin gave an acidic solution, it was first neutralized with 0.01 M NaOH to pH 7 before adding the PAG and $CaCO_3$.

Sample Response before and after UV Irradiation. Samples were irradiated with UV light from an Oriel 200 W mercury lamp. A dichroic beam turner with a mirror reflectance range of 280–400 nm was used along with a filter (<400 nm) to access the UV range of the emitted light. Samples (2 mL) were placed in either a Petri dish of 60 mm diameter or a 20 mL vial, covered with a quartz cover glass, and irradiated with UV through the cover. During irradiation, the sample was stirred with a magnetic stirring bar.

Rheological Studies. An AR2000 stress-controlled rheometer (TA Instruments) was used to perform steady and dynamic rheology experiments. All rheological experiments were done at 25 °C using cone-and-plate geometry (40 mm diameter and 2° cone angle). A solvent trap was used to minimize drying of the sample during measurements. Dynamic stress sweep experiments were first performed on a sample to identify its linear viscoelastic (LVE) region, and dynamic frequency sweeps were then performed within the LVE region.

Hydrogel Patterning. A given sample (500 μ L) was smeared on a portion of a glass slide, and this region was then exposed to UV through a

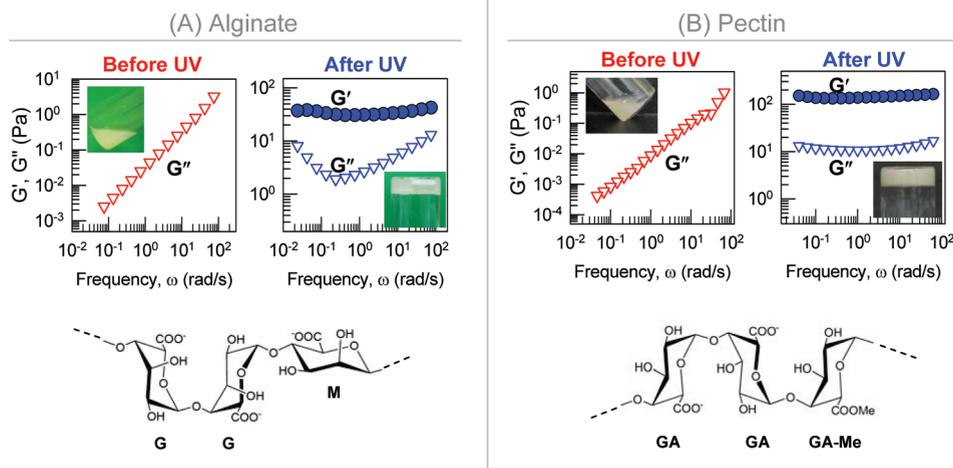


Figure 2. Dynamic rheological data demonstrating the photogelling of aqueous solutions of two biopolymers: (A) alginate (2 wt %) and (B) pectin (0.9 wt %). In each case, the sample also contains 15 mM CaCO_3 and 30 mM PAG. Before UV irradiation, both samples show a viscous response, with the viscous modulus G'' varying strongly with frequency and the elastic modulus G' being negligible. After 45 min of UV irradiation, the samples are both converted into gels, which show an elastic response (i.e., $G' > G''$) with the moduli being nearly independent of frequency. The chemical structures of the two polymers are also shown.

homemade photomask or stencil. After 20–25 min of UV exposure, the slide was rinsed with 1% NaCl to wash off the ungelled portions, thus revealing the photopatterned features. Certain samples were doped with a small number of fluorescently labeled, carboxylate-modified polystyrene latex particles (2 μm diameter, from Sigma-Aldrich), and the corresponding patterns were imaged with a fluorescence microscope (Olympus MVX10 Macroview). Images were analyzed using ImageJ software from NIH to quantify the fluorescence intensity.

3. RESULTS AND DISCUSSION

Figure 1 demonstrates the photogelling response of an alginate sample. The Ca^{2+} -induced gelling ability of alginate is known to depend on its ratio of α -L-guluronate (G) to β -D-mannuronate (M) units (structure in Figure 2A). It is the G units that have the ability to bind to Ca^{2+} ions, and for interchain cross-linking to occur, blocks of G units on adjacent chains must come into close proximity to one another (resulting in egg-box junctions),^{23,24} as depicted in Figure 1. For our photogelling experiments, we typically prepared a sample of 2 wt % sodium alginate, 30 mM solubilized PAG, and 15 mM dispersed CaCO_3 particles. The particles were a nanosized precipitated form of CaCO_3 , with a mean particle radius of ~ 70 nm as stated by the manufacturer and confirmed by us using dynamic light scattering (DLS). Using sonication, these particles could be homogeneously dispersed in the polymer solution. No aggregation or settling of the particles was observed over a period of several hours after sonication, during which time the UV irradiation was conducted. As shown by the photograph in Figure 1, the initial mixture is a low-viscosity sol. When exposed to UV light for 45 min, the PAG gets photolyzed, releasing acid (H^+).^{13–16} The acid reacts with the insoluble CaCO_3 particles to generate free Ca^{2+} ions, which cross-link the alginate chains into a gel network.^{20,25} The resulting alginate gel is strong enough to hold its weight in the inverted vial (Figure 1); note also the stirring bar trapped in the gel.²⁹

The above rheological changes were quantified using dynamic rheology. Frequency spectra (i.e., plots of the elastic modulus G' and the viscous modulus G'' as functions of the frequency ω) are

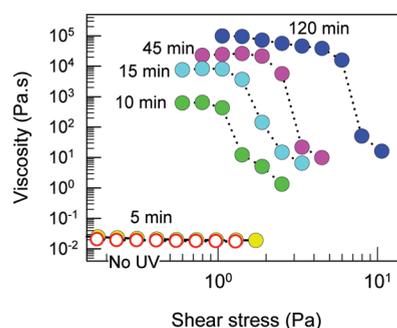


Figure 3. Effect of UV irradiation time on sample rheology. Steady-shear rheological data are shown for a sample containing 2% alginate + 15 mM CaCO_3 + 30 mM PAG before and after UV irradiation for various periods of time. The sample is transformed from a low-viscosity Newtonian fluid to a gel with a yield stress.

shown in Figure 2A for the above sample before and after UV irradiation. Before UV irradiation, the alginate/ CaCO_3 /PAG mixture responds as a purely viscous sol (i.e., its G'' is a strong function of ω ($G'' \approx \omega^1$) but its G' is too small to be measured accurately).³⁰ However, after 45 min of UV exposure, the sample shows an elastic, gel-like response (i.e., in this case, G' exceeds G'' over the range of frequencies tested and G' is nearly independent of frequency).³⁰ From the data, the gel modulus (i.e., the value of G' as $\omega \rightarrow 0$) is about 40 Pa, which is comparable to moduli reported previously for Ca^{2+} -induced gels of alginate at similar concentrations.²⁰ Note that the value of the gel modulus depends on the source of the alginate, which influences its molecular weight, its ratio of G to M units, and the blockiness (distribution pattern) of the G units.^{19,20}

To confirm the generality of our approach, we investigated the photogelation of another biopolymer, pectin, which is also known to undergo Ca^{2+} -induced cross-linking.^{18,19} Pectin is a polymer composed mostly of α -D-galacturonate (GA) residues, and its structure is shown in Figure 2B. In the case of a low-methoxy (LM) pectin, such as the one used here, a fraction of the

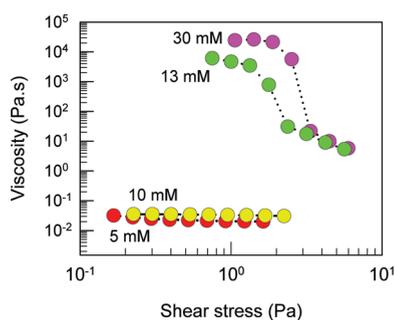


Figure 4. Effect of PAG concentration on photogelling. Steady-shear rheological data are shown after 45 min of UV irradiation for samples containing 2% alginate + 15 mM CaCO_3 + varying amounts of PAG.

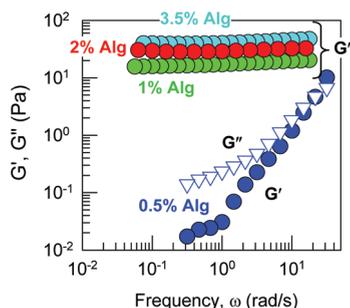


Figure 5. Effect of alginate concentration on photogelling. Dynamic rheological data are displayed after 45 min of UV irradiation for samples containing different concentrations (wt %) of sodium alginate along with 15 mM CaCO_3 and 30 mM PAG. For the 0.5% alginate sample, both G' and G'' are shown, but for the rest of the samples, only G' is shown.

carboxylic acid groups are esterified with methanol. Short blocks of GA units from adjacent chains can interact with Ca^{2+} ions, resulting in egg-box junctions (much like in the case of alginate; note that GA and G are almost mirror images) and thereby a hydrogel.^{18,19} We used a 0.9 wt % solution of LM pectin, which was first neutralized with NaOH to a pH of 7 and then combined with 30 mM PAG and 15 mM CaCO_3 particles. The above mixture is initially a low-viscosity sol, as indicated by its dynamic rheological response in Figure 2B (i.e., here again, its $G'' \approx \omega^1$ but its G' is too low to be measured accurately). Upon UV irradiation for 45 min, the sample is transformed into a gel that holds its weight upon vial inversion. Dynamic rheology confirms the gel-like character (i.e., G' exceeds G'' over the range of frequencies and both moduli are nearly independent of frequency). Note that the gel modulus in the case of 0.9% pectin is about 150 Pa, which is higher than that of the 2% alginate gel.

The above results show that our photogelation scheme can be easily applied to any Ca^{2+} -responsive polymer without the need for any prior synthesis step. As stated earlier, the mechanism for photogelation involves the release of free Ca^{2+} upon reaction with H^+ produced by PAG photolysis. This mechanism is supported by a series of control experiments and related observations. As a first control, we confirmed that mixtures of sodium alginate with CaCO_3 (i.e., in the absence of PAG) did not gel upon exposure to UV radiation. Similarly, mixtures of alginate and PAG (i.e., in the absence of CaCO_3) also showed no gelation upon exposure to UV light. Next, we measured pH changes caused by UV irradiation in samples containing alginate/PAG

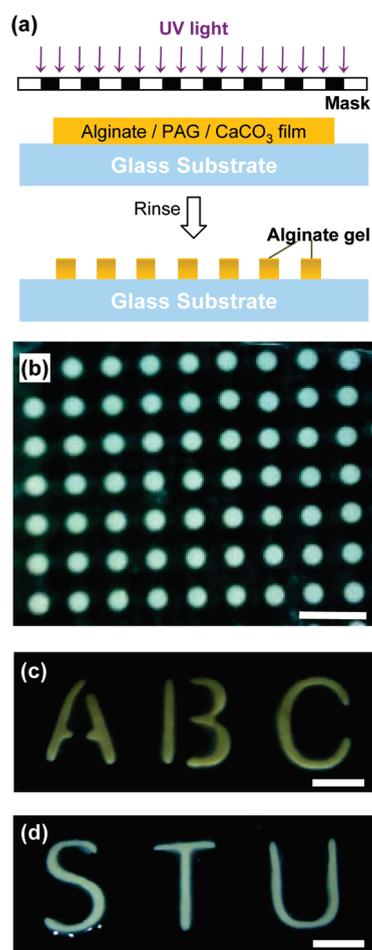


Figure 6. (a) Schematic depiction of alginate photopatterning. The photogellable alginate sample is spread as a thin film and UV irradiated through a mask. After being rinsed, gelled regions corresponding to the pattern in the mask are revealed. (b) Alginate gel patterned as an array of $\sim 900 \mu\text{m}$ dots using a steel photomask. The scale bar is 3 mm. (c, d) Alginate gel patterned as adjacent letters of the alphabet using a stencil. The scale bars represent 5 mm.

and alginate/PAG/ CaCO_3 . In the former case, the pH dropped from ~ 7 to ~ 4 , and in the latter case, the pH drop was from ~ 9 to ~ 7.4 . These pH changes are consistent with the release of acid upon PAG photolysis; the reason why the pH changes are not identical for the two cases is probably due to the buffering ability of Ca^{2+} salts. Next, we used a Ca^{2+} indicator strip to confirm qualitatively the UV-induced release of free Ca^{2+} when PAG and CaCO_3 are both present. Together these results indicate that (a) both PAG and CaCO_3 are required for photogelation; (b) the photolysis of PAG releases H^+ ; and (c) the reaction of H^+ and CaCO_3 generates free Ca^{2+} , which as expected is effective at cross-linking alginate.

To probe the photogelation phenomenon further, we performed additional experiments with alginate. First, the effect of the UV irradiation time was studied, and the results are shown in Figure 3. The sample again consisted of 2% alginate, 30 mM PAG, and 15 mM CaCO_3 . Two milliliters of the above sample was irradiated for different lengths of time, followed by rheological testing. Data from steady-shear rheology for the apparent viscosity versus shear stress are shown in the figure. We plot the data versus shear stress (rather than the shear rate) because it

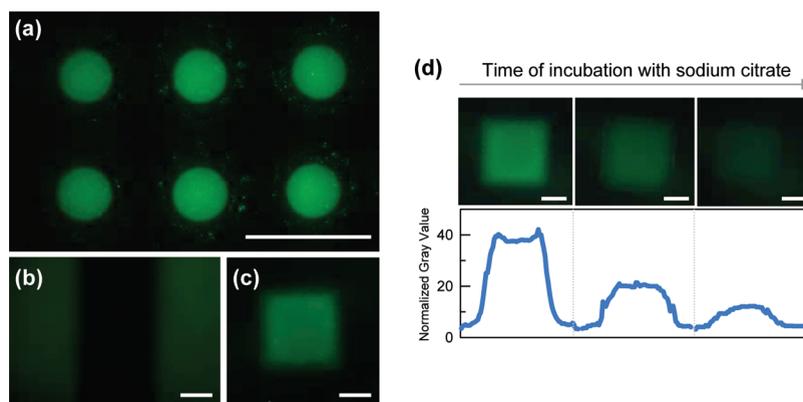


Figure 7. (a–c) Patterns of alginate gel with embedded fluorescent microparticles. Three different patterns are shown: (a) dots, (b) stripes, and (c) squares. In each case, the patterned regions show green fluorescence from the microparticles. (d) Pattern erasure by incubation with sodium citrate (NaCit). The fluorescence intensity is observed to decrease with incubation time, and this is quantified in the plot. The scale bars in all images correspond to 2 mm.

clearly reveals the emergence of a yield stress in the sample. Before UV irradiation, the sample is a Newtonian liquid with a viscosity of 28 mPa.s. No appreciable changes in rheology occur with 5 min of UV exposure. However, after 10 min of UV exposure, the sample viscosity is enhanced by a factor of 10^5 at low shear stress, followed by a shear-thinning response at higher shear stress. Further exposure to UV causes continued growth in the low-shear viscosity. After 45 min of UV exposure, the viscosity is very high (essentially infinite) at low shear stress and then drops sharply around a stress of 3 Pa (which is the yield stress of this sample³⁰). Further UV exposure up to 120 min causes the yield stress to increase to ~ 8 Pa. Taken together, the data show that a macroscopic sample (2 mL) requires tens of minutes to reach a photogelled state. However, the rate of photogelling appears to be controlled by the rate of UV absorption by the PAG molecules (once UV is absorbed, the PAG photolyzes in nanoseconds).^{8,11} This means that more rapid photogelling can be achieved for small or thin samples, and indeed this will be seen later in our experiments with thin alginate films. Similar trends in kinetics have been noted for other self-assembly-based photorheological fluids.^{8,11}

Next, we studied the effect of PAG concentration on photogelling. For this, we fixed a mixture of 2% alginate and 15 mM CaCO_3 , and to this we added varying amounts of PAG (5 to 30 mM). Steady-shear rheological data for the viscosity versus shear stress are shown in Figure 4 for these samples after 45 min of UV exposure. The initial (before UV) viscosities of the samples were low and identical (data not shown). Samples with small amounts of PAG (5 or 10 mM) did not show a change in viscosity upon UV irradiation. However, samples with higher concentrations of PAG (13 or 30 mM) underwent photogelling (i.e., a significant ($>10^5$) increase in the low-shear viscosity and the emergence of a yield stress can be seen in Figure 4 for these samples). Thus, a minimum amount of PAG (>13 mM) is required to photogel a given alginate/ CaCO_3 sample. The above amount presumably correlates with the minimum concentration of Ca^{2+} required to form a sample-spanning network of alginate chains.

We then studied the effect of alginate concentration on photogelling. In this case, samples with 15 mM CaCO_3 and 30 mM PAG were combined with varying amounts of alginate (0.5 to 3.5 wt %). The samples were UV irradiated for 45 min and

then studied by dynamic rheology (Figure 5). All samples exhibited a viscous response before UV irradiation (data not shown). After UV irradiation, the sample containing 0.5% alginate showed a viscous or viscoelastic response in a dynamic frequency sweep (i.e., $G'' > G'$, with both moduli varying strongly with frequency). Presumably, there are not enough alginate chains to form a sample-spanning network at this concentration. In comparison, samples with higher concentrations of alginate (1, 2, and 3.5%) all show a gel-like frequency response after UV exposure (i.e., $G' > G''$ and negligible frequency dependence of the moduli). The alginate concentration has only a modest effect on the gel modulus, however: for example, the modulus of the 3.5% alginate sample is only a factor of 2 higher than that of the 1% alginate sample.

The above photogels of alginate and pectin can be easily converted back to the solution state by the addition of a calcium chelator such as sodium citrate (NaCit). Such chemical reversibility can be a useful property because it can allow entrapped species within a gel to be subsequently released. Here, we studied the chemical reversibility of alginate photogels using NaCit. We began with a sample of 2% alginate, 30 mM PAG, and 15 mM CaCO_3 , which was then exposed to UV for 45 min to create a photogel. To this we added a small amount (2 μL) of concentrated NaCit solution so as to bring the overall NaCit concentration in the sample to 100 mM. As expected, the sample immediately ungelled into a freely flowing solution because the Ca^{2+} cations detached from the alginate chains and instead became preferentially bound to the citrate anions.

Finally, we describe the use of our photogellable alginate formulation for creating patterned films of alginate gels. As mentioned in the Introduction, there is considerable interest from the biomaterials community in forming patterns of alginate gels on various substrates.^{26–28} Such patterns have been created thus far mostly using chemical^{27,28} or electrochemical²⁶ techniques. If patterning could instead be done by light,²² it would be easier, more convenient, and potentially amenable to higher resolutions. Moreover, photopatterning could make use of the techniques and infrastructure currently employed in photolithography. Here, as an initial step in this direction, we demonstrate a few basic photopatterning experiments with alginate. The inherent idea, as shown in Figure 6a, is that when a thin layer of alginate/ CaCO_3 /PAG is exposed to UV light through a patterned mask only the exposed regions get cross-linked into a

solid gel. The unexposed areas can then be washed away to reveal the pattern corresponding to the mask. Figure 6b–d shows a few simple patterns created using a steel photomask with equally spaced holes or a commercial stencil. In this case, we used a mixture of 3 wt % alginate, 15 mM CaCO₃, and 70 mM PAG as the sample formulation. This liquid sample was spread as a thin layer on a glass slide and UV irradiated through the mask/stencil for 20–25 min, followed by rinsing with 1% NaCl. As can be seen, alginate gel films are formed on the glass slide in patterns corresponding to the respective masks (i.e., an array of microdots in the case of the steel mask (Figure 6b) and letters from the alphabet in the case of the stencil (Figure 6c,d)).

Next, we show the use of these patterned gels for the entrapment and release of microstructures. We used fluorescently labeled polystyrene latex microparticles (2 μm diameter) as a model payload, and we added these particles to the above sample of alginate/PAG/CaCO₃. The resulting mixture was used to pattern gels of alginate on a glass slide using either the steel mask from above or other homemade masks. Images of the patterns via a fluorescence microscope are shown in Figure 7, and all of the patterns are observed to show green fluorescence due to the embedded microparticles. We then took the square pattern and exposed it to 10 mM NaCit solution. As shown by the time-lapse images in Figure 7d, the fluorescence from the patterned region decreased with time, and this decrease is quantified by the plots in Figure 7d. The fluorescence was completely erased in about 50 min. The decrease in fluorescence is due to the NaCit-induced erosion of the alginate matrix and the resultant release of the entrapped microparticles. Thus, patterns of alginate can be chemically erased under mild conditions, allowing the release of embedded microstructures. The results suggest that our photogellable alginate formulation could be a useful material for interfacing cells or biomolecules to substrates in a spatially controlled fashion.

4. CONCLUSIONS

We have presented a simple photogelation scheme for alginate and other biopolymers wherein we combine alginate with nanoparticles of insoluble CaCO₃ and a PAG. Upon exposure to UV, the PAG generates H⁺ ions, which solubilize the CaCO₃ to produce free Ca²⁺, and these ions in turn cross-link the alginate into a gel. The scheme was extended to pectin in this study, and it can also be applied to other Ca²⁺-sensitive biopolymers. The method is simple because it involves no chemical modification of the parent polymers and uses relatively inexpensive, commercially available components. We have also used our photogellable alginate in photopatterning studies, wherein a patterned alginate gel is formed on a glass substrate by irradiating the solution through a photomask. The patterned gels can be used to immobilize payloads such as microparticles, and the patterns can be subsequently erased under mild conditions by subjecting the gels to a calcium chelator. We expect that photogellable alginate will prove to be a useful material for building the biology–device interface.

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