Stimuli-responsive nanocomposites inspired by the sea cucumber dermis

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For many years, man has been fascinated with the amazing innovation and creativity of nature. Notable examples include the chameleon and the gecko. Recently, the scientific community has been able to come to a deeper understanding of the molecular level interactions which allow nature to perform its wonders. We now know that the chameleon can change the color of its skin by selectively releasing pigments from its cells (chromatophores), and that the gecko can climb on any surface despite the orientation due to the large amount of surface area available on its feet for van der Waals interactions.

Of particular interest to this seminar is the lesser-known sea cucumber. When threatened, sea cucumbers have the ability to rapidly change the mechanical properties of their skin, making it stiff to discourage and ward off predators. The mechanism behind this hardening process involves the release of a combination of the proteins stiparin and tensilin, which binds together collagen fibrils dispersed in a biomatrix to form a hard shell.[1,2] Reversal of this process is facilitated by stiparin-inhibitor, another protein which has a high affinity for binding stiparin, inhibiting its ability to cross-link collagen fibrils.[3] However, the mechanism of the entire process has not been elucidated; the path by which these proteins return to the cell (if they do at all) is not yet known. Taking all of these things into account, a model for the sea cucumber dermis, which includes four distinct categories (matrix, filler, inter-filler interactions, stimulus), can be constructed. The following composites that will be presented in this seminar all have components that fall into one of these four categories. However, the highlight of this talk is on the presence/absence of inter-filler interactions, and how that can impact the overall property of the material.[4]
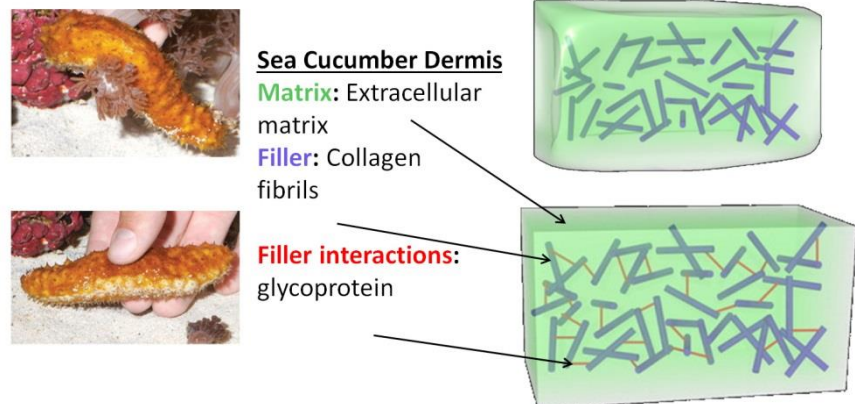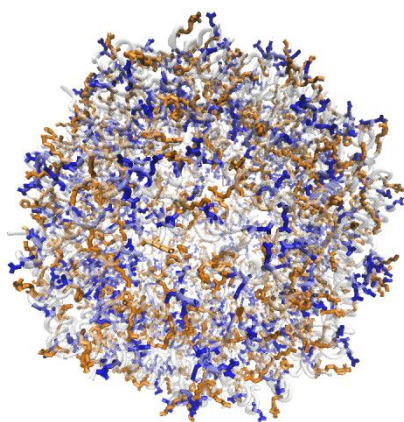

Figure 1. Pictures showing the soft and stiff state (top vs. bottom) of the sea cucumber, and cartoons depicting the structure and composition of the dermis.[5,6]

The stiffness and flexibility of materials are typically categorized by Young's modulus, which is simply a ratio of stress to strain.[7] Briefly, stress refers to the amount of force applied to a certain material, and strain denotes how the material responds. If a large amount of force is applied with little response in the material, it is characterized as having a large Young's modulus (diamond ~ 1220 GPa). The opposite is true for softer materials, such as Jell-O (~ 0.1 MPa). Sea cucumbers are capable of reversibly switching between states that have been characterized with Young's moduli of 5 MPa and 50 MPa.[8]

Hydrogels are a type of stimulus-responsive material that have been studied and developed for many years. Its ability to uptake large amounts of water dictates the mechanical properties of the gel's performance, thereby allowing it to respond to external factors. In 2004, Richter *et al.* thermally cross-linked a combination of polyvinyl alcohol (PVA) and poly acrylic acid (PAA) to create a pH-response hydrogel.[9] This represents an example of a system

dominated by matrix-matrix interactions. A change in pH ultimately affects the osmotic pressure in the system, which can induce the uptake or expulsion of liquid. Through the cycling of pH, and measurements done on a balance and quartz crystal microbalance (QCM), Richter et al. was able to show the reversibility their hydrogel system. The mechanical properties of the hydrogel were tested in both its swelled and de-swelled state (by varying the pH), revealing a Young's modulus range from 1.24 MPa to 4.2 MPa.

In the second example, Shin *et al.* shows the creation of an actuator system based on matrix-filler interactions.[10] Ferritin, a protein with an iron core, was introduced into a matrix of polyvinyl alcohol (PVA) with hopes that it would impart favorable mechanical properties to the composite. Carboxylic acids and amines scattered on the surface of ferritin allow for hydrogen bonds to be formed with PVA. As mentioned earlier, a change in pH induces swelling/de-swelling of the polymer due to a change in osmotic pressure, which is the basis for the actuation of this particular material. Unlike regular pH-responsive actuators, however, the incorporation of ferritin into this system prevents against degradation of the composite upon consecutive actuation cycles. Owing to the spring-like nature of the secondary structure of the protein, the composite is able to return to its original state through a pulling force originating from the protein. The absence of a restoring force manifests itself as a net elongation with additional cycles, which has been previously coined "creep". This design moves towards a system capable of use without degradation over time; the importance of this is obvious. Unfortunately, mechanical data were not collected for the material at pH extremes, and thus the only measurements taken describing Young's moduli were at performed at pH 7. At this pH, submerged in fluid, the Young's modulus of this system was 32 MPa.

Figure 2. The structure of ferritin, showing amines and carboxylic acids in blue and orange, respectively.[11]

The third example is one that is truly "inspired" by the sea cucumber. It incorporates a network of functionalized cellulose nanocrystals (CNC) in a matrix of polyvinyl acetate (PVAc). By functionalizing the surface of CNC's with carboxylic acids and amines (two separate systems), Way *et al.* were able to create a composite that responds to changes in pH, and capitalizes on the strength of inter-filler interactions.[12] More specifically, the inter-filler interactions are comprised of either hydrogen bonding or electrostatic repulsion, depending on the protonation/deprotonation of the functional group as the pH is varied. Experimentally, the trend shown is exactly as expected: upon an increase in pH, the system decorated with carboxylic acids shows a lower Young's modulus, indicative of a weakening of the material. The opposite response can be seen in the crystals with functional amines. Way et al. were able to achieve a Young's modulus switch of 40 MPa to 100 MPa with the carboxylic system, and a similar 34 MPa to 88 MPa with the amine system.

Clearly, there is a trend happening as these examples approach the sea cucumber's model of inter-filler interactions. This can be explained through the ability of each system to disperse stress. If fillers, which are physically hard objects (individual nanocrystals), are able to bond together, they form a network over which stress is able to percolate, providing the material with increased stiffness. Conversely, if fillers were exclusively bound to the matrix around it, there would be many regions of locally high stiffness, but such a system would not be able to transfer stress very far. This explains the increase in Young's modulus as inter-filler interactions become more realized. However, this is not to say that inter-filler interactions create the ideal composite. A major drawback of such a system is that the material breaks much easier.[13]

After all these examples and models are taken into consideration, the question becomes whether or not a system is capable of being designed so that it takes advantage of not only inter-filler interactions, but also matrix-filler interactions as well. Theoretically, this new composite would display stiffness values greater than previously mentioned. In 2013, Jorfi *et al.* created a system made of cellulose nanocrystals (CNC) fillers in a polyvinyl alcohol (PVA) matrix.[14] If the structures of CNCs and PVA are examined, it can be seen that there are numerous alcohol groups available for hydrogen bonding in the CNCs and the PVA, promoting inter-filler and filler-matrix interactions. Of course, hydrogen bonds can be disrupted by hydration, as water is a strong competitor for hydrogen bonding. The stimuli responsiveness of the material comes from its immersion in fluid, and has been shown to be reversible. The highest Young's modulus reported for this system is 11.7 GPa, with the hydrated state showing a modulus of 0.124 GPa.

If the current state of research is compared with the abilities of the sea cucumber, there is still much room for growth. The quest for these improvements spans many disciplines. For example, soft clothing that can instantly become bulletproof upon the touch of a button would be desirable in a situation where protection is needed. A material that drastically changes its properties upon exposure to a certain chemical/environmental stimuli would have its place in the world of sensor research. By continuing to gain greater understanding of the natural world, the scientific community can hope to develop more advanced materials

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