Engineers demonstrate superstrong, reversible adhesive that works like snail slime (Update)

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Snails can anchor themselves in place using a structure known as an epiphragm. The snail's slimy secretion works its way into the pores found on even seemingly smooth surfaces, then hardens, providing strong adhesion that can be reversed when the slime softens. Penn Engineers have developed a new material that works in a similar way. Credit: Younghee Lee

If you've ever pressed a picture-hanging strip onto the wall only to realize it's slightly off-center, you know the disappointment behind adhesion as we typically experience it: it may be strong, but it's mostly irreversible. While you can un-stick the used strip from the wall, you can't turn its stickiness back on to adjust its placement; you have to start over with a new strip or tolerate your mistake. Beyond its relevance to interior decorating, durable, reversible adhesion could allow for reusable envelopes, gravity-defying boots, and more heavy-duty industrial applications like car assembly.

Such adhesion has eluded scientists for years but is naturally found in snail slime.

A snail's epiphragm—a slimy layer of moisture that can harden to protect its body from dryness—allows the snail to cement itself in place for long periods of time, making it the ultimate model in adhesion that can be switched on and off as needed.

In a new study, Penn Engineers demonstrate a strong, reversible adhesive that uses the same mechanisms that snails do.

Shu Yang, professor in the Department of Materials Science and Engineering and in the Department of Chemical and Biomolecular Engineering, led the study along with Hyesung Cho, a postdoctoral researcher in Yang's lab who is now at the Korea Institute of Science and Technology, and Penn Engineering graduate students Gaoxiang Wu and Jason Christopher Jolly. Lab member Yuchong Gao participated in the research as well. The team also included collaborators from Lehigh University: Engineering professor Anand Jagota, postdoctoral researcher Zhenping He, and graduate student Nicole Fortoul.

The study was published in the *Proceedings of the National Academy of Sciences*.

Yang and her lab members have a history of translating what nature creates through evolution into the lab setting. Yang has led studies on nanoscale structures inspired by giant clams, butterflies, and pollen, and is the director of AESOP, the Center for Analyzing Evolved Structures as Optimized Products, which aims to apply bioinspired properties to design and architecture.

According to Yang, she and her lab have been interested in adhesives for a while, but the predominant model for reversible adhesives in the natural world, geckos, weren't getting them far enough:

"Geckos can put one hand down and then release it, so the gecko's adhesion is reversible, but it's very low adhesion," Yang says. "A gecko is 50 grams, and a human is at least 50 kilograms. If you want to hold a human on a wall, it's not possible using the same adhesive. You could use a vacuum, but you have to carry a cumbersome vacuum pump. We've been working on this for a long time, and so have other people. And no one could have a better solution to achieve superglue-like adhesion but also be reversible."

The breakthrough came one day when Gaoxiang Wu was working on another project that involved a hydrogel made of a polymer called polyhydroxyethylmethacrylate (PHEMA) and noticed its unusual adhesive properties. PHEMA is rubbery when wet but rigid when dry, a quality that makes it useful for contact lenses but also, as Yang's team discovered, for adhesives.

When PHEMA is wet, it conforms to all of the small grooves on a surface, from a tree trunk's distinct ridges to the invisible microporosity of a seemingly smooth wall. This conformal contact is what allows PHEMA to stick to a surface.

"It's like those childhood toys that you throw on the wall and they stick.

That's because they're very soft. Imagine a plastic sheet on a wall; it comes off easily. But squishy things will conform to the cavities," says Yang.

Alone, this ability to conform to cavities is not enough to make a good adhesive. What really matters is what happens when the material begins to dry. As PHEMA dries, it becomes as rigid as a plastic bottle cap, but, uniquely, it doesn't shrink. Instead, the material hardens into the cavities, fastening itself securely to the surface.

"When materials dry, they usually shrink. If it shrinks from the surface, it no longer wants to conform to the microcavities and it'll pop out," says Yang. "Our PHEMA adhesive doesn't pop out. It stays conformal. It remembers the shape even when it's dry and rigid."

These properties that helped Yang's team identify PHEMA as a unique candidate for reversible, strong adhesion are the same properties found in a snail's epiphragm. On a sunny day, a snail's slimy epiphragm, initially wet, conforms to the surface it's on and hardens, barricading the snail from the dry environment and holding the snail firmly in place. At night, when the environment becomes moist, the epiphragm softens, allowing the snail to move freely again.

That reversibility between wet flexibility and dry adhesion is what the researchers wanted to put to the test with PHEMA. The team ran several tests on their PHEMA hydrogel, evaluating its ability to hold weight and the time it takes for water to infiltrate the adhesive and reverse its grip. They found that PHEMA acted remarkably similar to the snail epiphragm. It was 89 times stronger than gecko adhesion, but its hold was easily broken when it got wet.

"When it's conformal and rigid, it's like super glue. You can't pull it off. But, magically, you can rewet it, and it slips off effortlessly," says Yang.

"Additionally, PHEMA doesn't lose its strong adhesion when scaled up. Usually, there's a negative correlation between adhesion strength and size. Since PHEMA is not dependent on a fragile structure, it doesn't have that problem."

To demonstrate just how durable their PHEMA adhesive is, one of Yang's lab members and co-first author, Jason Christopher Jolly, volunteered to suspend himself from a harness held up only by a postage-stamp-sized patch of their adhesive; the material easily held the weight of an entire human body. Based on the lab tests, the team determined that, although PHEMA may not be the strongest adhesive in existence, it is currently the strongest known candidate available for reversible adhesion.

With that kind of power, the snail-slime adhesive could have a big impact on the scientific field as well as in industry. Yang sees durable, reversible adhesives like her PHEMA hydrogel as having massive potential for household products, robotics systems, and industrial assembly.

"Car assembly uses adhesives, and, you can imagine, if there are any mistakes putting parts together, the adhesive is set and the parts are ruined," Yang says. "A car is pretty big. Usually they don't glue things together until the last step, and you need a room-sized oven to host the car and cure the adhesives. An adhesive that's strong and reversible like PHEMA could completely change the process of car assembly and save money because mistakes wouldn't be so costly."

Despite its promise in applications like heavy manufacturing, PHEMA is not a fit for most industries because its reversibility is controlled by water. While water is the perfect control mechanism for a snail, you wouldn't want your car to fall apart in the rain. So, although PHEMA is the first of its kind in reversible adhesion, Yang acknowledges that it's just a starting point.

"With a lot of things, you don't want to use water. Water takes time to diffuse. In the future, we want to find the right material that can switch the property like that," says Yang.

The researchers hope to eventually find or engineer adhesives that could respond to cues like pH, specific chemicals, light, heat, or electricity, broadening the potential applications of reversible adhesion.

More information: Hyesung Cho el al., "Intrinsically reversible superglues via shape adaptation inspired by snail epiphragm," *PNAS* (2019). www.pnas.org/cgi/doi/10.1073/pnas.1818534116

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