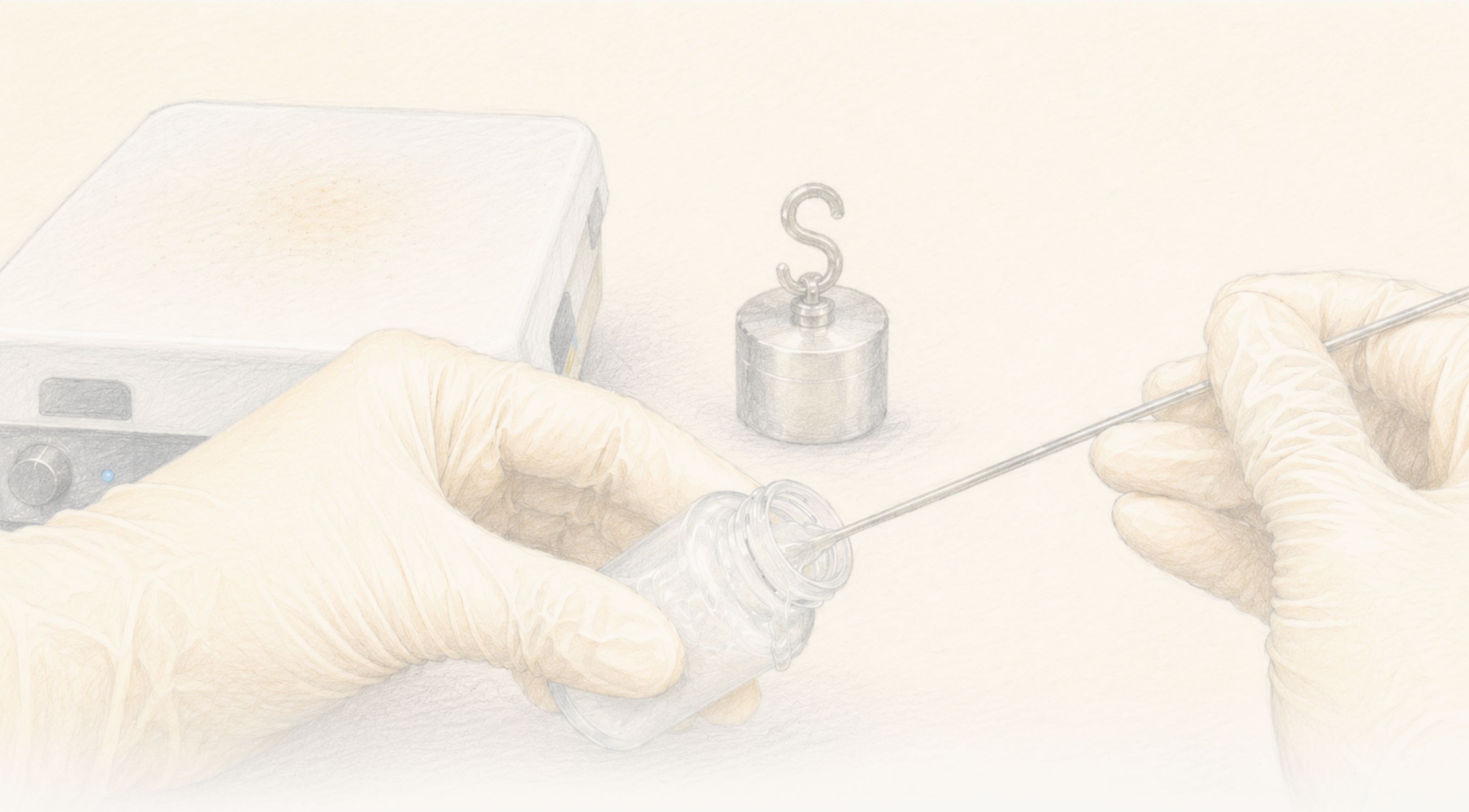

The Clean Paper

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

A small molecule glued untreated PTFE, then washed off with ethanol

A JACS paper reports fluoro-crown ether phosphate adhesives that bond notoriously inert PTFE in lab lap-shear tests while remaining removable by ethanol washing. CyclicFP-fmoc reached 1.3 MPa on untreated PTFE with ductile cohesive failure, and a related variant reached 2.3 MPa. The mechanism is supported by spectroscopic evidence for fluorine-fluorine interactions at PTFE plus hydrogen bonding and pi-stacking inside the adhesive. It is a promising materials result, not yet a commercial glue, a universal recycling fix or a full environmental-safety assessment.

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Paper: *Small-Molecule Adhesives with Strong and Ductile Adhesion to PTFE, Yet Allowing Easy Wipe-Off Removal*, Kohei Kikkawa, Abir Goswami, Kiyoshi Morishita, Hao Wang, Takashi Nakamura, and Takuzo Aida, Journal of the American Chemical Society 148, 29138-29145 (2026) · DOI: 10.1021/jacs.6c07886

PTFE is hard to stick to for a reason

Polytetrafluoroethylene, better known as PTFE and sold under trade names including Teflon, is useful partly because it does not want to interact. Its surface energy is low. Many liquids bead on it. Many glues fail on it unless the surface is etched, roughened, plasma-treated or paired with a specialized primer.

That resistance is excellent for nonstick coatings and chemically inert parts. It is a problem when engineers want PTFE to join another part without permanently damaging the surface.

A paper in the Journal of the American Chemical Society reports a small-molecule adhesive that attacks that problem from an unusual direction. Kohei Kikkawa, Abir Goswami and colleagues describe fluoro-crown ether phosphate molecules that can adhere strongly to untreated PTFE, deform ductilely before failure and then be removed from the PTFE plates by washing with ethanol.

The lead molecule is called **CyclicFP-fmoc**. In lap-shear tests, it held untreated PTFE plates with an adhesive strength of **1.3 ± 0.1 MPa** and a work of debonding of **1300 N/m**. Because 1 MPa equals 1 newton per square millimetre, the measured peak stress of 1.3 MPa is the same pressure as roughly the weight of a 130-gram apple acting on each square millimetre. This is a unit-area analogy, not the force or contact geometry of the test specimen. The reported work of debonding, 1300 N/m, is equivalent to 1300 joules of separation energy per square metre. For a direct visual demonstration, rather than an engineering load rating, the paper shows a 7 cm^2 joint supporting an 8 kg weight. The joint failed inside the adhesive layer, not at the PTFE interface. That matters: it means the interface was not the weak point in the test.

Pencil rendering based on the paper's photograph of the adhesive strip supporting suspended weights (Figure 2, left). It is not the original photograph, a scale drawing or an engineering load-rating diagram.

AI-generated adaptation — The Clean Paper; source photograph: Kikkawa et al., JACS 2026, Figure 2 (left) Fair-use assertion

The result is not "PTFE is solved." It is a controlled laboratory materials result. But it is a clean example of a difficult combination: strong adhesion, ductile failure and wipe-off removal from a surface famous for resisting adhesion.

Why ordinary strength and easy removal fight each other

Adhesives usually make a bargain. Rigid cross-linked polymer glues can be strong, but they often fail suddenly and are hard to remove cleanly. Softer tape-like adhesives can stretch and dissipate energy, but they usually give up strength.

The trade-off is molecular. Strength asks for efficient stress transfer. Ductility asks for motion, rearrangement and energy dissipation. Easy removal asks for bonds that can be broken without destroying the substrate. Those requirements pull in different directions.

Small-molecule adhesives are attractive because they can, in principle, be removable and recyclable. They do not form the long entangled polymer networks that make many conventional glues tough.

That is also their weakness: without entanglement, small molecules normally struggle to deliver ductile, high-strength adhesion.

The JACS paper tries to replace polymer entanglement with a stack of reversible noncovalent interactions. The molecule combines a fluorinated crown-ether phosphate region with a urethane-linked fmoc group. In plain language, its fluorinated ring can interact with the fluorine-rich PTFE surface, its urethane groups can hydrogen-bond to neighbouring adhesive molecules, and its flat fluorenyl groups can stack against one another. The design target is not one magic bond. It is a set of weak, reversible interactions that can cooperate:

- fluorine-fluorine interactions near PTFE;
- hydrogen bonding between adhesive molecules;
- pi-pi stacking between fluorenyl groups;
- and enough molecular mobility to relax stress instead of cracking immediately.

What the main PTFE test showed

The authors placed CyclicFP-fmoc between PTFE plates that had not been surface-treated or cleaned, heated the adhesive and left the plates at room temperature for 10 minutes before testing.

For quantitative testing, they used lap shear. PTFE plates bonded with CyclicFP-fmoc reached **1.3 ± 0.1 MPa** in tensile stress, reported as mean ± standard deviation for three measurements. Applying the adhesive around **50 C** with a hair dryer gave a similar value, **1.1 ± 0.1 MPa**, rather than requiring only high-temperature melting.

The authors compared those values with commercial epoxy, acrylic, silicone and urethane adhesives in the same PTFE lap-shear setup. Those controls reached around **0.1 to 0.7 MPa**, compared with **1.3 ± 0.1 MPa** for CyclicFP-fmoc. This same-substrate, same-method comparison is more informative than placing MPa values from different materials and test geometries on one leaderboard.

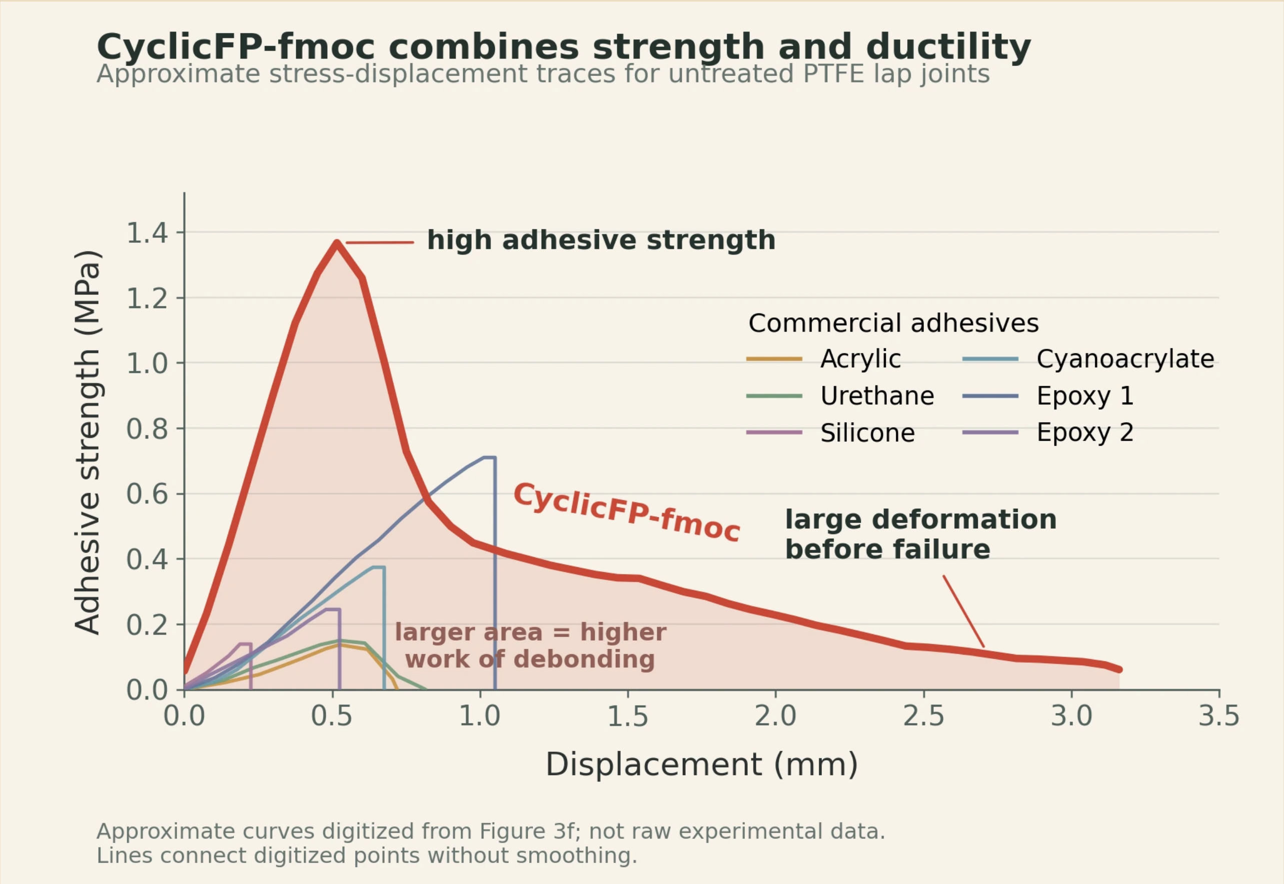
The number stayed similar after storage. After 30 days at ambient conditions, the adhesive strength was **1.3 ± 0.2 MPa**. After the plates were forcibly separated, overlapped again and reheated, the strength was **1.2 ± 0.2 MPa**. Repeating that cycle ten times still gave about **1.3 ± 0.3 MPa**.

The best variant was not the lead molecule. A related molecule with three fmoc groups, **CyclicFP-fmoc3**, reached **2.3 ± 0.2 MPa** on PTFE. The paper still focuses heavily on CyclicFP-fmoc because it gives the full combination of strength, ductility, mechanistic evidence and wipe-off removal.

Ductility is the second half of the claim

Strength alone would not be enough. A brittle adhesive can reach a high peak stress and then fail suddenly. The paper’s more distinctive claim is that CyclicFP-fmoc also behaves ductilely.

In lap-shear curves, CyclicFP-fmoc reached its maximum stress and then gradually lost stress as displacement continued. The commercial adhesives tested in the paper behaved more like brittle joints: failure came soon after their peak stress.



CyclicFP-fmoc combines a high stress peak with a long post-peak tail; the shaded area is an editorial guide to its larger work of debonding. Approximate curves digitized from Figure 3f; not raw experimental data.

The authors quantified the area under that stress-displacement curve as work of debonding. CyclicFP-fmoc gave **1300 N/m** on PTFE. The tested commercial adhesives ranged from **26 to 314 N/m**.

The failure mode fits that interpretation. PTFE joints with CyclicFP-fmoc failed cohesively, inside the adhesive. That implies the adhesive could dissipate energy by deforming internally, while the PTFE interface remained stronger than the bulk adhesive layer in these tests.

Stress relaxation experiments add the molecular timescale. At 20 C, the characteristic relaxation time was **60 ms**, and the Arrhenius analysis gave an activation energy of **33.8 kJ/mol**. In plain terms, the adhesive layer can rearrange quickly enough to soften a sudden stress concentration rather than behave as a static brittle solid.

Why the authors think fluorine matters

PTFE is built from carbon-fluorine bonds. CyclicFP-fmoc carries fluorinated crown-ether groups. The authors argue that **F-F interactions** help the adhesive bind PTFE, while other interactions help the adhesive layer hold together and deform.

Several control experiments point in that direction. When the fluorine atoms in CyclicFP-fmoc were replaced with hydrogen atoms, the resulting CyclicP-fmoc bonded PTFE much more weakly, around **0.1 $\pm$ 0.0 MPa**. A linear fluoro-ether phosphate, AcyclicFP-fmoc, reached only **0.3 $\pm$ 0.1 MPa**. Variants missing pi-stacking or hydrogen-bonding units also performed worse.

The paper then uses spectroscopy and crystal structure to support the interaction picture. In a CyclicFP-fmoc crystal, fluorine atoms on neighboring molecules sit **2.49 to 2.91 angstroms** apart, shorter than the **2.94 angstrom** van der Waals sum for two fluorine atoms. FT-IR and variable-temperature NMR support hydrogen bonding, F-F interactions and pi-pi stacking in the amorphous adhesive.

Most directly for PTFE, solid-state **19F MAS NMR** spectra shift when CyclicFP-fmoc is mixed with PTFE nanoparticles or thin PTFE sheets. The nonfluorinated control does not produce the same shift. That is evidence, not just a design sketch, that fluorinated parts of the adhesive interact with PTFE.

This still should not be simplified to "F-F bonds solve PTFE." The paper's own model is more layered: interfacial F-F interactions help PTFE adhesion, while hydrogen bonding and pi-pi stacking contribute to cohesion and ductility inside the adhesive.

Wipe-off removal is real, but bounded

The removal result is the practical hook. The authors washed detached PTFE plates with ethanol and report complete removal of CyclicFP-fmoc without residue in their demonstration. They also recovered adhesive and reused it repeatedly, maintaining about **1.2 $\pm$ 0.1 MPa** adhesive strength in reuse tests.

That is important because conventional strong adhesives are often hard to remove cleanly. A glue that can hold PTFE and later wash off would be useful for repair, disassembly and reuse.

But the boundary matters. The paper tests controlled samples, not every contaminated industrial surface, weathered joint, solvent exposure or long-term aging condition. Ethanol wipe-off on PTFE plates is not the same as proving a full recycling process for assemblies made from many materials.

The paper also says CyclicFP-fmoc is not a PFAS "forever chemical." That statement should not be expanded into a complete environmental-risk assessment. Persistence, toxicity, manufacturing scale, release pathways and regulation are separate questions.

What this does not prove

- It does **not** show a market-ready adhesive product.
- It does **not** prove that PTFE can now be glued reliably in every industrial setting without surface preparation.
- It does **not** show that ethanol removal works equally well on every substrate, surface condition or aged joint.
- It does **not** prove that F-F interactions alone explain the adhesion. The paper's mechanism combines F-F, hydrogen bonding and pi-pi stacking.
- It does **not** show a complete plastic-recycling workflow.
- It does **not** establish a full environmental or toxicological safety profile for the adhesive molecules.
- It does **not** mean commercial adhesives are generally worse. The comparisons are specific to the materials and PTFE lap-shear setup tested in this paper.

How strong is the result?

For a lab materials paper, the result is strong because the authors do more than report a single high number. They test strength, ductility, durability over 30 days, water tolerance, repeated readhesion, ethanol removal, molecular variants and spectroscopic evidence for the proposed interactions.

The most persuasive combination is the failure mode plus the controls. If the PTFE interface had failed first, the claim would be weaker. Instead, the joint fails inside the adhesive layer. And when the fluorinated cyclic structure is removed or changed, PTFE adhesion drops sharply.

The remaining questions are scale and use case. Lap-shear tests are standardized and useful, but real joints see peel, impact, fatigue, contamination, temperature cycles and mixed materials. A molecule that works beautifully between controlled laboratory plates still has to become a formulation, a process and a durability dataset before it becomes an engineering adhesive.

Why it matters

PTFE sits at an awkward materials boundary. Its inertness is the feature that makes it valuable, and the same feature makes it hard to integrate into repairable or recyclable assemblies.

This paper offers a route that is chemically specific rather than brute-force. Instead of roughening or chemically attacking the PTFE surface, it designs a small molecule that can interact with that surface while maintaining a ductile, reversible adhesive layer.

If that design logic generalizes, it could help build adhesives that are easier to remove and reuse without giving up all mechanical performance. That is the real promise: not one molecule as a finished glue, but a molecular strategy for strong, ductile and debondable adhesion.

Clean summary

Kikkawa, Goswami and colleagues report fluoro-crown ether phosphate small molecules as adhesives for PTFE and other substrates. The lead molecule, CyclicFP-fmoc, bonded untreated PTFE plates at 1.3 ± 0.1 MPa in lap-shear tests, failed cohesively rather than at the PTFE interface, showed a work of debonding of 1300 N/m, retained performance after storage and repeated readhesion, and could be removed from PTFE plates by ethanol washing. A related variant reached 2.3 ± 0.2 MPa. Spectroscopy and control molecules support a mechanism in which F-F interactions help the PTFE interface while hydrogen bonding and pi-pi stacking help the adhesive layer dissipate stress. The result is a promising laboratory demonstration of strong, ductile, wipe-off adhesion to PTFE, not yet a commercial glue, universal recycling solution or full environmental-safety assessment.

Sources

Kikkawa et al., Small-Molecule Adhesives with Strong and Ductile Adhesion to PTFE, Yet Allowing Easy Wipe-Off Removal, Journal of the American Chemical Society 148, 29138-29145 (2026)
https://doi.org/10.1021/jacs.6c07886