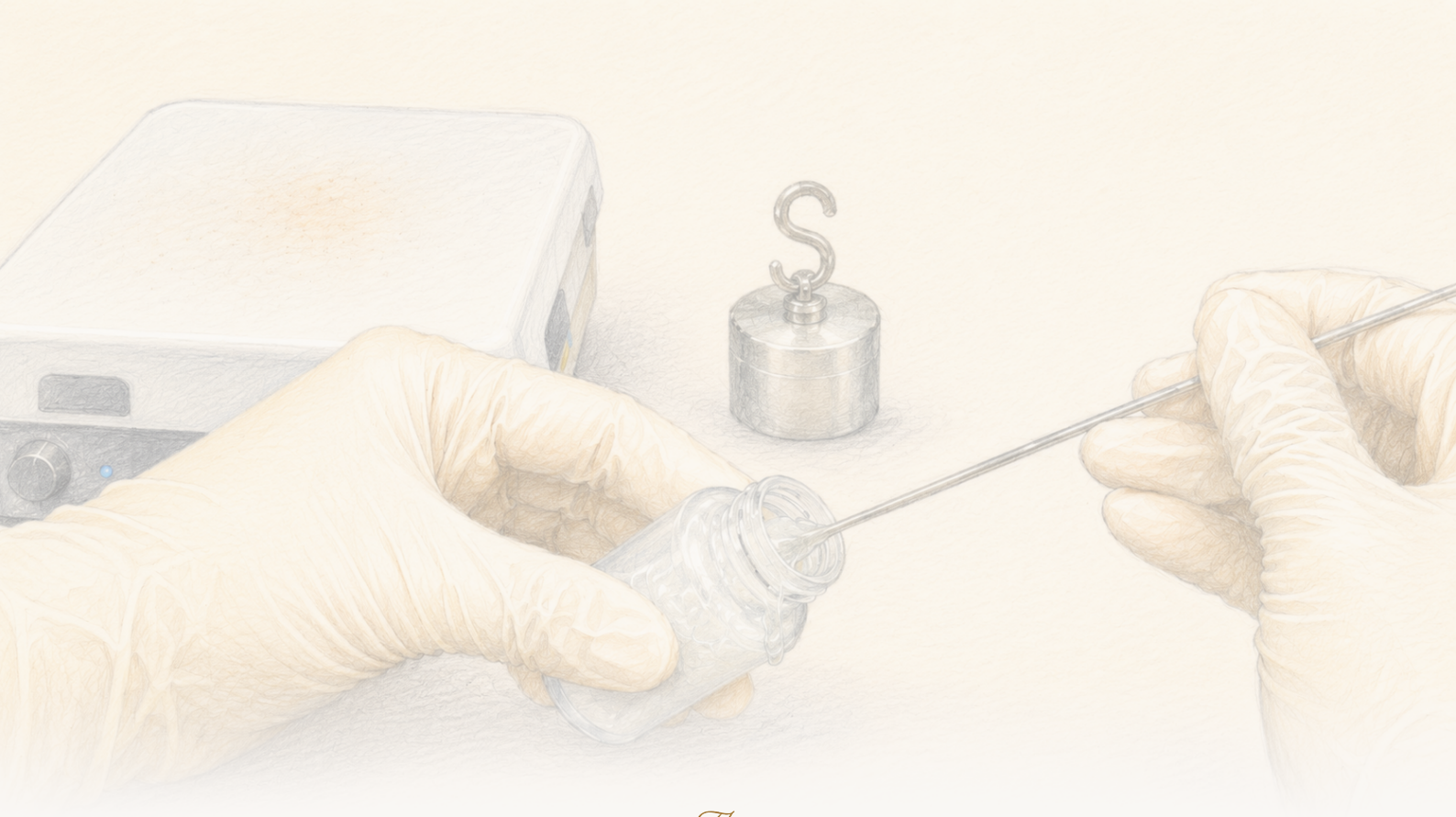

The Clean Paper

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

# Karamin molecule ya manne wa PTFE da ba a yi masa treatment ba, sannan ethanol ya wanke shi ya tafi

*Wata takarda a JACS ta rahoto fluoro-crown ether phosphate adhesives da ke manne wa PTFE mai matukar inert a laboratory lap-shear tests, yayin da daga baya za a iya cire su ta wankewa da ethanol. CyclicFP-fmoc ya kai 1.3 MPa a untreated PTFE tare da ductile cohesive failure; wani related variant ya kai 2.3 MPa. Spectroscopic evidence yana goyon bayan mechanism inda fluorine-fluorine interactions suke taimaka wa interface da PTFE, yayin da hydrogen bonding da pi-stacking suke taimaka wa adhesive layer. Promising materials result ne, ba commercial glue ba tukuna, ba universal recycling solution ba, kuma ba cikakken environmental-safety assessment ba.*

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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

# Akwai dalilin da ya sa manne wa PTFE yake da wuya

Polytetrafluoroethylene, wanda aka fi sani da PTFE kuma ake sayar da shi da sunaye na kasuwanci ciki har da Teflon, yana da amfani a wani ɓangare ne saboda ba ya son yin hulɗa da sauran abubuwa. Surface energy ɗinsa ƙasa ne. Ruwa da sauran liquids da yawa suna taruwa kamar ɗigo a kansa. Manne da yawa ba sa kama shi sai an yi wa saman etching, an ƙara masa roughness, an yi plasma magani ko kuma an yi amfani da primer na musamman.

Wannan juriyar hulɗa tana da kyau ƙwarai ga nonstick coatings da sassa masu jure sinadarai. Amma tana zama matsala idan injiniyoyi suna son haɗa PTFE da wani sashe ba tare da lalata samansa har abada ba.

Wata takarda a Journal of the American Chemical Society ta ba da rahoton wani manne na ƙananan molecules da ya tunkari matsalar ta wata hanya da ba a saba gani ba. Kohei Kikkawa, Abir Goswami da abokan aikinsu sun bayyana fluoro-crown ether phosphate molecules waɗanda za su iya manne sosai ga PTFE da ba a yi masa surface magani ba, su miƙe su sauya siffa kafin su karye, sannan a cire su daga faranti na PTFE ta hanyar wanke su da ethanol.

Babban molecule ɗin da aka fi gwadawa ana kiransa **CyclicFP-fmoc**. A gwajin lap shear, ya haɗa faranti na PTFE da ba a yi musu magani ba da ƙarfin manne na **1.3 ± 0.1 MPa** da work of debonding na **1300 N/m**. Saboda 1 MPa yana daidai da newton 1 a kowane square millimetre, peak stress na 1.3 MPa da aka auna yana da pressure kamar nauyin apple mai gram 130 da ya matsa a kan kowane square millimetre. Wannan misali ne na pressure a unit area, ba ƙarfin da aka ɗora ko geometry na specimen ɗin gwaji ba. Work of debonding na 1300 N/m da aka rahoto yana daidai da joules 1300 na separation energy a kowane square metre. Don nuna abin da ake gani kai tsaye, ba don ba da engineering load rating ba, takardar ta nuna haɗin mai girman 7 $cm^2$ yana ɗaukar nauyin 8 kg. Haɗin ya karye a cikin layer ɗin manne, ba a interface ɗin PTFE ba. Wannan yana da muhimmanci: yana nufin interface ɗin ba shi ne wuri mafi rauni a gwajin ba.

Zanen fensir da aka yi bisa hoton takardar wanda ya nuna tsirin manne yana rike da nauyin da aka rataya (Figure 2, hagu). Ba ainihin hoton ba ne, ba zane ne mai ma'auni ba, kuma ba engineering load-rating diagram ba ne.

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

Sakamakon ba yana nufin "an warware matsalar PTFE" ba. Sakamako ne na materials science a dakin gwaji da aka sarrafa. Amma yana nuna wani haɗin halaye masu wahalar samu tare: manne mai ƙarfi, iya sauya siffa kafin karyewa, da cire manne ta gogewa ko wankewa daga saman da ya shahara da ƙin manne.

## Me ya sa ƙarfi da sauƙin cirewa suke jan juna zuwa saɓanin hanya

Manne yawanci yana yin wani ciniki tsakanin halaye. Polymer glues masu rigid cross-links za su iya zama masu ƙarfi, amma sau da yawa suna karyewa kwatsam kuma suna da wahalar cirewa cikin tsabta. Manne masu laushi irin tape za su iya miƙewa su sha energy, amma yawanci suna rasa wani ɓangare na ƙarfi.

Dalilin yana matakin molecule. Ƙarfi yana buƙatar a watsa stress yadda ya kamata. Ductility tana buƙatar motsi, sake tsara molecules da shan energy. Sauƙin cirewa yana buƙatar bonds da za a iya karya ba tare da lalata substrate ba. Waɗannan buƙatun suna jan juna zuwa hanyoyi dabam.

Manne na ƙananan molecules yana da jan hankali domin, a ka'ida, za a iya cire shi kuma a sake amfani da shi. Ba ya samar da dogayen polymer networks masu cunkushewa da juna waɗanda suke sa manne na gargajiya ya zama mai tauri. Amma wannan ma shi ne rauninsa: idan babu irin wannan cunkushewar, ƙananan molecules yawanci suna da wahalar samar da manne mai ƙarfi wanda kuma zai iya miƙewa ba tare da karyewa ba.

Takardar JACS ta yi ƙoƙarin maye gurbin polymer entanglement da tarin reversible noncovalent interactions. Molecule ɗin ya haɗa fluorinated crown-ether phosphate region da fmoc group da aka haɗa ta urethane. A sauƙaƙe, ring ɗinsa mai fluorine zai iya yin hulɗa da saman PTFE mai yalwar fluorine; urethane groups ɗinsa za su iya yin hydrogen bonds da molecules na manne da ke kusa; sannan flat fluorenyl groups za su iya jeruwa a kan juna. Manufar design ɗin ba bond guda ɗaya mai sihiri ba ce. Tarin weak, reversible interactions ne da za su yi aiki tare:

- hulɗar fluorine-fluorine kusa da PTFE;
- hydrogen bonding tsakanin molecules na manne;
- pi-pi stacking tsakanin fluorenyl groups;
- da isasshen motsin molecules da zai ba layer ɗin damar rage stress maimakon ya tsage nan da nan.

# Abin da babban gwajin PTFE ya nuna

Marubutan sun saka CyclicFP-fmoc tsakanin faranti na PTFE da ba a yi musu surface magani ko tsaftacewa ba, suka dumama manne, sannan suka bar farantin a room temperature na mintuna 10 kafin gwaji.

Don gwajin da ake auna lambobi, sun yi amfani da lap shear. Faranti na PTFE da aka haɗa da CyclicFP-fmoc sun kai tensile stress na **1.3 ± 0.1 MPa**, wanda aka rahoto a matsayin mean ± standard deviation na ma'aunai uku. Sanya manne a kusan **50 C** da hair dryer ya ba da kusan irin wannan ƙima, **1.1 ± 0.1 MPa**, maimakon sai an narke shi a babban zafi kawai.

Marubutan sun kwatanta waɗannan ƙimomin da commercial epoxy, acrylic, silicone da urethane adhesives a cikin irin wannan PTFE lap-shear setup. Controls ɗin sun kai kusan **0.1 zuwa 0.7 MPa**, idan aka kwatanta da **1.3 ± 0.1 MPa** na CyclicFP-fmoc. Wannan kwatancen da aka yi a substrate iri ɗaya da method iri ɗaya ya fi amfani fiye da jera MPa ƙimomi daga materials da test geometries daban-daban a tebur guda.

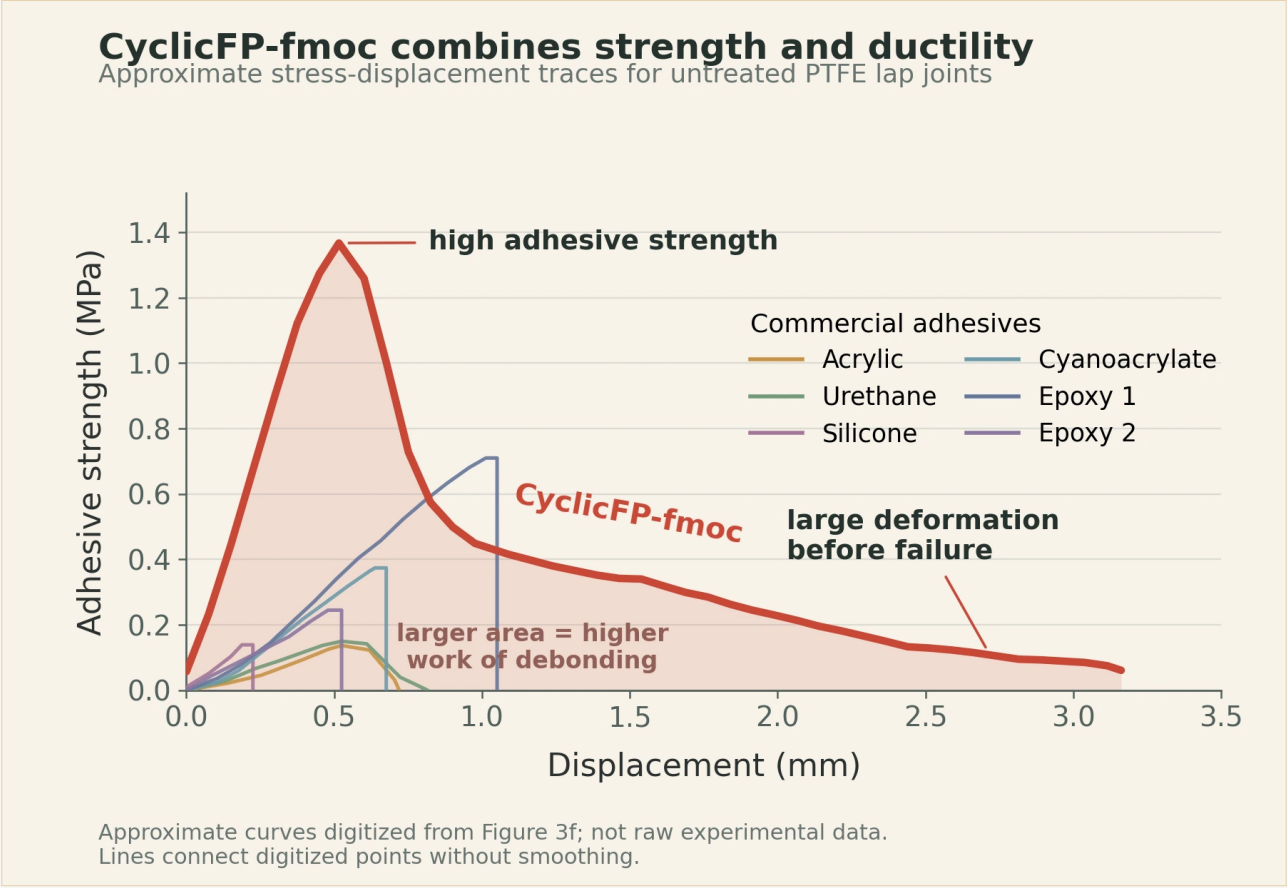
Karfin ya kasance kusan iri ɗaya bayan ajiya. Bayan kwanaki 30 a ambient conditions, adhesive strength ya kasance **1.3 ± 0.2 MPa**. Bayan an raba farantin da ƙarfi, aka sake ɗora su juna sannan aka sake dumama, ƙimar ta kasance **1.2 ± 0.2 MPa**. Ko bayan maimaita wannan zagayowar sau goma, har yanzu an samu kusan **1.3 ± 0.3 MPa**.

Variant mafi ƙarfi ba shi ne babban molecule ɗin ba. Wani molecule mai alaƙa da shi mai fmoc groups uku, **CyclicFP-fmoc3**, ya kai **2.3 ± 0.2 MPa** a PTFE. Duk da haka takardar ta fi mayar da hankali ga CyclicFP-fmoc domin shi ne ya haɗa ƙarfi, ductility, shaidar mechanism da kuma cirewa ta wankewa.

# Iya miƙewa kafin karyewa shi ne rabin da'awar na biyu

Karfi kaɗai bai isa ba. Manne mai brittle zai iya kai high peak stress sannan ya karye kwatsam. Da'awar da ta fi bambanta wannan aikin ita ce CyclicFP-fmoc kuma yana nuna ductile behavior.

A lap-shear curves, CyclicFP-fmoc ya kai maximum stress sannan stress ɗin ya ragu a hankali yayin da displacement ke ci gaba. Commercial adhesives da aka gwada a takardar sun fi kama da brittle joints: sun karye jim kaɗan bayan sun kai peak stress.




CyclicFP-fmoc yana haɗa high stress peak da doguwar post-peak tail; shaded area editorial guide ce don nuna girman work of debonding. Curves ɗin approximate ne da aka digitize daga Figure 3f; ba raw experimental bayanai ba ne.

Chart by The Clean Paper; approximate values digitized from Kikkawa et al., JACS 2026, Figure 3f (source figure not relicensed) CC BY 4.0

Marubutan sun auna area ɗin da ke ƙarƙashin stress-displacement curve a matsayin work of debonding. CyclicFP-fmoc ya ba da **1300 N/m** a PTFE. Commercial adhesives da aka gwada sun kasance tsakanin **26 da 314 N/m**.

Yadda haɗin ya karye ya dace da wannan fassarar. PTFE joints da CyclicFP-fmoc sun yi cohesive gazawa, wato karyewar ta faru a cikin manne. Wannan yana nuna manne ya iya shan energy ta hanyar sauya siffa a cikinsa, yayin da interface ɗin PTFE ya kasance ya fi bulk adhesive layer ƙarfi a waɗannan gwaje-gwajen.

Stress-relaxation gwaje-gwaje sun ƙara bayanin timescale na molecules. A 20 C, characteristic relaxation time ya kasance **60 ms**, kuma Arrhenius nazari ya ba da activation energy na **33.8 kJ/mol**. A sauƙaƙe, layer ɗin manne yana iya sake tsara molecules cikin sauri isasshe don rage sudden stress concentration maimakon ya yi hali kamar brittle solid mai tsauri.

# Me ya sa marubutan suke ganin fluorine yana da muhimmanci

PTFE an gina shi da carbon-fluorine bonds. CyclicFP-fmoc yana ɗauke da fluorinated crown-ether groups. Marubutan suna ganin **F-F interactions** suna taimaka wa manne ya kama PTFE, yayin da sauran interactions suke taimaka wa adhesive layer ya riƙe kansa tare kuma ya sauya siffa.

Control gwaje-gwaje da dama suna goyon bayan wannan. Lokacin da aka maye gurbin fluorine atoms na CyclicFP-fmoc da hydrogen atoms, molecule ɗin da aka samu, CyclicP-fmoc, ya manne wa PTFE da rauni sosai: kusan **0.1 ± 0.0 MPa**. Linear fluoro-ether phosphate mai suna AcyclicFP-fmoc ya kai **0.3 ± 0.1 MPa** kawai. Variants da ba su da pi-stacking ko hydrogen-bonding units ma sun yi ƙasa.

Sannan takardar ta yi amfani da spectroscopy da crystal structure don goyon bayan hoton interactions ɗin. A crystal na CyclicFP-fmoc, fluorine atoms na neighbouring molecules suna tazarar **2.49 zuwa 2.91 angstroms**, ƙasa da **2.94 angstrom** van der Waals sum na fluorine atoms biyu. FT-IR da variable-temperature NMR suna goyon bayan kasancewar hydrogen bonding, F-F interactions da pi-pi stacking a amorphous adhesive.

Abin da ya fi kai tsaye game da PTFE shi ne spectra na solid-state **19F MAS NMR** suna sauyawa idan aka haɗa CyclicFP-fmoc da PTFE nanoparticles ko thin PTFE sheets. Nonfluorinated control ba ya haifar da irin wannan shift. Wannan shaida ce, ba design sketch kawai ba, cewa sassan manne masu fluorine suna hulɗa da PTFE.

Duk da haka bai kamata a taƙaita wannan zuwa “F-F bonds sun warware PTFE” ba. samfurin takardar tana da matakai da dama: interfacial F-F interactions suna taimaka wa adhesion ga PTFE, yayin da hydrogen bonding da pi-pi stacking suke taimaka wa cohesion da ductility a cikin adhesive layer.

# Cirewa ta wankewa gaskiya ne, amma yana da iyaka

Sakamakon cire manne shi ne ɓangaren da ya fi jan hankali a aikace. Marubutan sun wanke faranti na PTFE da aka raba da ethanol kuma suka rahoto cewa CyclicFP-fmoc ya tafi gaba ɗaya ba tare da residue ba a demonstration ɗinsu. Sun kuma dawo da manne suka sake amfani da shi sau da yawa, tare da adhesive strength na kusan **1.2 ± 0.1 MPa** a reuse tests.

Wannan yana da muhimmanci domin manne masu ƙarfi na gargajiya sau da yawa suna da wahalar cirewa cikin tsabta. Manne da zai iya riƙe PTFE sannan daga baya a wanke shi zai iya zama da amfani wajen gyara, warware assemblies da sake amfani da sassa.

Amma iyakar shaidar tana da muhimmanci. Takardar ta gwada controlled samples ne, ba kowanne industrial surface mai datti, weathered joint, solvent exposure ko long-term aging condition ba. Cire manne da ethanol daga PTFE plates ba daidai yake da tabbatar da complete recycling process ga assemblies da aka yi da materials da yawa ba.

Takardar ta kuma ce CyclicFP-fmoc ba PFAS “forever chemical” ba ne. Bai kamata a faɗaɗa wannan jumla zuwa cikakken environmental-haɗari assessment ba. Persistence, toxicity, manufacturing scale, release pathways da regulation tambayoyi ne daban.

# Abin da wannan bai tabbatar ba

- Bai nuna **market-ready adhesive product** ba.
- Bai tabbatar cewa yanzu za a iya manne PTFE cikin aminci a kowane industrial setting ba tare da surface preparation ba.
- Bai nuna cewa cirewa da ethanol zai yi daidai a kowane substrate, surface condition ko aged joint ba.
- Bai tabbatar cewa F-F interactions kaɗai suke bayyana adhesion ba. Mechanism ɗin takardar ta haɗa F-F interactions, hydrogen bonding da pi-pi stacking.
- Bai nuna cikakken plastic-recycling workflow ba.
- Bai kafa cikakken environmental ko toxicological safety profile na adhesive molecules ba.
- Bai nufin commercial adhesives gaba ɗaya sun fi muni ba. Kwatancen ya shafi materials da PTFE lap-shear setup da aka gwada a wannan takarda kawai.

# Yaya ƙarfin sakamakon yake?

Ga materials takarda na dakin gwaji, sakamakon yana da ƙarfi domin marubutan ba su tsaya ga high number guda ɗaya ba. Sun gwada ƙarfi, ductility, durability na kwanaki 30, water tolerance, repeated readhesion, cirewa da ethanol, molecular variants, da spectroscopic shaida ga interactions da suka gabatar.

Haɗin shaidar da ya fi ƙarfi shi ne gazawa mode da controls. Da interface ɗin PTFE ne ya fara karyewa, da'awar za ta fi rauni. Maimakon haka, haɗin yana karyewa a cikin adhesive layer. Kuma idan aka cire ko aka sauya fluorinated cyclic structure, adhesion ga PTFE yana raguwa sosai.

Tambayoyin da suka rage sun shafi scale da use case. Lap-shear tests standardized ne kuma suna da amfani, amma real joints suna fuskantar peel, impact, fatigue, contamination, temperature cycles da mixed materials. Molecule da ke aiki da kyau tsakanin controlled laboratory plates har yanzu sai an mayar da shi formulation, process da durability dataset kafin ya zama engineering adhesive.

# Me ya sa wannan yake da muhimmanci?

PTFE yana zaune a wani awkward materials boundary. Inertness ɗinsa shi ne halin da ya sa yake da amfani, kuma wannan halin ne yake sa ya yi wahalar haɗawa cikin assemblies da ake son a iya gyarawa ko sake amfani da su.

Wannan takarda ta gabatar da wata hanya mai takamaiman chemistry maimakon brute force. Maimakon roughening ko chemically attacking surface ɗin PTFE, an tsara ƙaramin molecule da zai iya yin hulɗa da wannan surface yayin da adhesive layer ɗinsa ya ci gaba da kasancewa ductile kuma reversible.

Idan wannan design logic ya yi aiki a sauran systems, zai iya taimakawa wajen gina adhesives da suka fi sauƙin cirewa da sake amfani da su ba tare da rasa duk mechanical performance ba. Wannan shi ne ainihin alkawarin: ba cewa molecule guda ɗaya ya zama finished glue ba, sai dai molecular strategy don adhesion mai ƙarfi, mai ductility, kuma mai iya debonding.

# Takaitaccen bayani

Kikkawa, Goswami da abokan aikinsu sun rahoto fluoro-crown ether phosphate small molecules a matsayin adhesives ga PTFE da wasu substrates. Babban molecule, CyclicFP-fmoc, ya haɗa untreated PTFE plates da **1.3 ± 0.1 MPa** a lap-shear tests, ya yi cohesive gazawa maimakon karyewa a PTFE interface, ya nuna work of debonding na **1300 N/m**, ya riƙe performance bayan ajiya da repeated readhesion, kuma za a iya cire shi daga PTFE plates ta wankewa da ethanol. Wani related variant ya kai **2.3 ± 0.2 MPa**. Spectroscopy da control molecules suna goyon bayan mechanism inda F-F interactions suke taimaka wa PTFE interface, yayin da hydrogen bonding da pi-pi stacking suke taimaka wa adhesive layer ya sha stress. Sakamakon promising laboratory demonstration ne na manne mai ƙarfi, mai ductility kuma mai iya cirewa daga PTFE - ba commercial glue ba tukuna, ba universal recycling solution ba, kuma ba cikakken environmental-safety assessment ba.

## Majiyoyi

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