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Small molecule kan lẹ untreated PTFE mó, lẹyìn nàà ethanol wẹ e kúrò

JACS paper kan report fluoro-crown ether phosphate adhesive tí ó bond notoriously inert PTFE nínú lab lap-shear test, tí ó sì remain removable ní ethanol washing. CyclicFP-fmoc dé 1.3 MPa lórí untreated PTFE pèlú ductile cohesive failure, related variant sì dé 2.3 MPa. Mechanism supported nípasẹ spectroscopic evidence fún fluorine-fluorine interaction ní PTFE pèlú hydrogen bonding àti pi-stacking nínú adhesive. Ó jẹ promising materials result, kì í tū ẹ commercial glue, universal recycling fix tàbí full environmental-safety assessment.

Written by Cinzia Vaglio · Cross-checked by Lucio Vaglio · Edited by Michele Renda · Figures by Michele Renda and Nova Vela · AI-assisted, human-reviewed

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 ọ̀rọ̀ láti lẹ̀ mọ́ fún ìdí kan

Polytetrafluoroethylene, tí a mọ́ sí PTFE, tí a sì ní ta lábẹ̀ trade name pẹ̀lú Teflon, wúlò apá kan nítorí pé kò fẹ́ interaction. Surface agbára rẹ̀ kéré. Ọ̀pọ̀ liquid máa ní bead lórí rẹ̀. Ọ̀pọ̀ glue fail lórí rẹ̀ bí a kò bá etch, roughen, plasma-treat ojú tàbí lò specialized primer.

Resistance yẹn dára gan-an fún nonstick coating àti chemically inert part. Ó jẹ́ ọ̀rọ̀ nígbà tí engineer fẹ́ so PTFE mọ́ part mǐràn láì permanently damage ojú.

Ìwé ìwádíí kan nínú Journal of the American Chemical Society report small-molecule adhesive kan tó ìkọ̀lù ọ̀rọ̀ náà láti unusual ìtọ́ṣọ̀nà. Kohei Kikkawa, Abir Goswami àti colleagues describe fluoro-crown ether phosphate molíkùlù tí ó lè adhere strongly sí untreated PTFE, deform ductilely ọ́ájú ìkùnà, lẹ́yìn náà jẹ́ removed láti PTFE plate ní ethanol washing.

Lead molíkùlù ni **CyclicFP-fmoc**. Nínú lap-shear ìdánwò, ó hold untreated PTFE plate pẹ̀lú adhesive strength 1.3 ± 0.1 MPa àti ọ̀ṣẹ́ of debonding **1300 N/m**. Nítorí 1 MPa dọ́gba sí 1 newton per square millimetre, measured peak stress 1.3 MPa jẹ́ pressure kan náà bí roughly weight apple 130-gram acting lórí square millimetre kòdòkan. Èyí jẹ́ unit-area analogy, kì í ọ̀ force tàbí contact geometry ìdánwò specimen. Reported ọ̀ṣẹ́ of debonding, 1300 N/m, equivalent sí 1300 joules separation agbára per square metre. Fún taara visual demonstration, dípò engineering load rating, ìwé ìwádíí fi hàn 7 cm^2 joint supporting 8 kg weight. Joint fail nínú adhesive layer, kì í ọ̀ ní PTFE interface. Èyí ọ̀ pàtàkì: ó tùmọ́ sí pé interface kì í ọ̀ weak kókó nínú ìdánwò.



Pencil rendering based on photograph iwé iwádíí ti adhesive strip supporting suspended weight (Figure 2, left). Kí í ẹ̀ original photograph, scale drawing tàbí engineering load-rating diagram.

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

èsì kì í ẹ̀ “PTFE ti solved.” Ó jẹ́ controlled yàrá ìdánwò ohun èlò èsì. Sùgbón ó jẹ́ clean example ti combination tó nira: lágbára adhesion, ductile ìkùnà àti wipe-off removal láti ojú tí ó famous fún resisting adhesion.

Kí ló dé tí ordinary strength àti easy removal fi n ja ara wọn?

Adhesive sáà ní ẹ̀ bargain. Rigid cross-linked polymer glue lè lágbára, sùgbón wọn sáà fail suddenly, wọn sì hard láti remove cleanly. Softer tape-like adhesive lè stretch àti dissipate agbára, sùgbón wọn usually give up strength.

Trade-off náà molecular. Strength fẹ́ efficient stress transfer. Ductility fẹ́ motion, rearrangement àti agbára dissipation. Easy removal fẹ́ bond tí a lè break láì destroy substrate. Requirement wònyí pull in yàtò ìtósónà.

Small-molecule adhesive attractive nítorí, in principle, wọn lè removable àti recyclable. Wọn kò form long entangled polymer network tí n make conventional glue tough. Èyí tún ni weakness wọn: láisí entanglement, small molíkúlù normally struggle láti deliver ductile, high-strength adhesion.

JACS iwé iwádíí gbìyànjú láti replace polymer entanglement pèlú stack reversible noncovalent interaction. Molecule combine fluorinated crown-ether phosphate region pèlú urethane-linked fmoc egbé. Ní plain èdè, fluorinated ring rẹ̀ lè interact pèlú fluorine-rich PTFE ojú, urethane egbé rẹ̀ lè hydrogen-bond sí neighbouring adhesive molíkúlù, flat fluorenyl egbé rẹ̀ sì lè stack lórí ara wọn. Design target kì í ẹ̀ magic bond kan. Ó jẹ́ set weak, reversible interaction tí ó cooperate:

- fluorine-fluorine interaction near PTFE;
- hydrogen bonding láàárín adhesive molíkúlù;
- pi-pi stacking láàárín fluorenyl egbé;
- àti molecular mobility tó tó láti relax stress dípò cracking immediately.

Ohun tí pàtàkì PTFE ìdánwò fi hàn

Àwọn ònkòwé fi CyclicFP-fmoc láàárín PTFE plate tí a kò surface-treat tàbí clean, wọn heat adhesive, wọn sì leave plate ní room temperature fún 10 minutes šáájú testing.

Fún quantitative testing, wọn lo lap shear. PTFE plate bonded pèlú CyclicFP-fmoc dé **1.3 ± 0.1 MPa** nínú tensile stress, reported gégé bí mean $\pm$ standard deviation fún measurement mètá. Applying adhesive around **50 C** pèlú hair dryer fún similar value, **1.1 ± 0.1 MPa**, dípò requiring high-temperature melting nìkan.

Àwọn ònkòwé fi wé value wònyí pèlú commercial epoxy, acrylic, silicone àti urethane adhesive nínú kan náà PTFE lap-shear setup. Control wònyí dé nìkan bí **0.1 sí 0.7 MPa**, fi wé pèlú **1.3 ± 0.1 MPa** fún CyclicFP-fmoc. Same-substrate, same-method ìfiwéra yí informative ju placing MPa value láti yàtò ohun èlò àti ìdánwò geometry lórí òkan leaderboard.

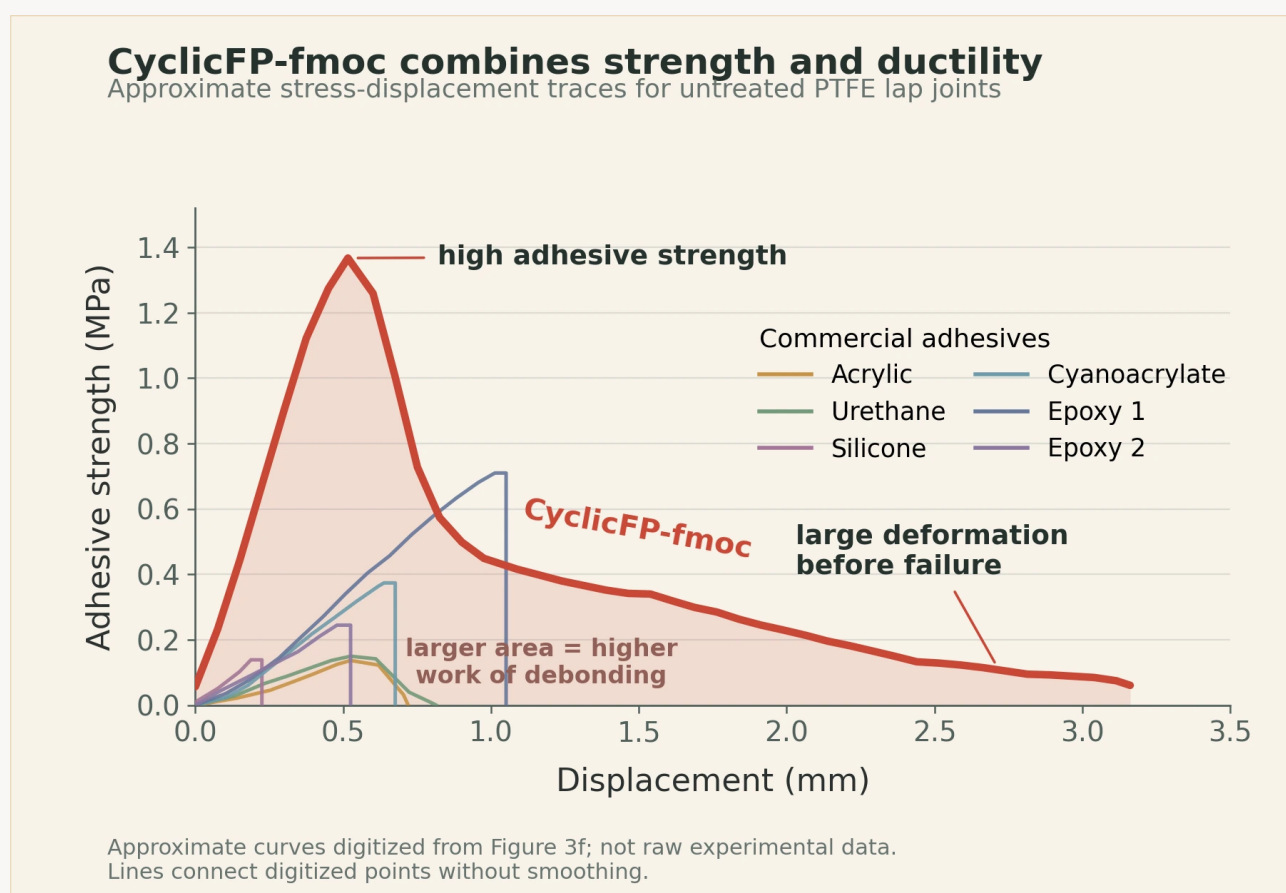
Nónbà náà stay similar lẹyin storage. Lẹyin 30 days ní ambient condition, adhesive strength jẹ 1.3 ± 0.2 MPa. Lẹyin plate forcibly separated, overlapped again àti reheated, strength jẹ 1.2 ± 0.2 MPa. Repeating cycle yẹn ten times si fún nńkan bí 1.3 ± 0.3 MPa.

Best variant kì í ẹe lead molíkúlù. Related molíkúlù pèlú fmoc ẹgbẹ mẹta, **CyclicFP-fmoc3**, dé 2.3 ± 0.2 MPa lórí PTFE. ìwé ìwádíí ẹi focus heavily lórí CyclicFP-fmoc nítorí pé ó fún full combination strength, ductility, mechanistic ẹrì àti wipe-off removal.

Ductility ni half kejì claim náà

Strength nńkan kò tó. Brittle adhesive lè reach high peak stress, lẹyin náà fail suddenly. Claim ìwé ìwádíí tó distinctive sí i ni pé CyclicFP-fmoc tún behave ductilely.

Nínú lap-shear curve, CyclicFP-fmoc dé maximum stress, lẹyin náà gradually lose stress bí displacement ẹe continue. Commercial adhesive tí ìwé ìwádíí idánwò behave sí i like brittle joint: ikùnà wá soon lẹyin peak stress.



CyclicFP-fmoc combine high stress peak pèlú long post-peak tail; shaded area jẹ editorial guide sí larger işẹ of debonding rẹ. Approximate curve digitized láti Figure 3f; kì í ẹe raw experimental dátà.

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

Àwọn òńkòwé quantify area labẹ stress-displacement curve yẹn gégẹ bí işẹ of debonding. CyclicFP-fmoc fún **1300**

N/m lórí PTFE. Tested commercial adhesive ààlà láti **26 sí 314 N/m**.

Failure mode bá interpretation yẹn mu. PTFE joint pèlú CyclicFP-fmoc fail cohesively, nínú adhesive. Èyí imply pé adhesive lè dissipate agbára nípa deforming internally, nígbà tí PTFE interface stay stronger ju bulk adhesive layer nínú ìdánwò wònyí.

Stress relaxation ìdánwò add molecular timescale. Ní 20 C, characteristic relaxation àkókò jẹ **60 ms**, Arrhenius ìtupalẹ̀ sì fún activation agbára **33.8 kJ/mol**. Ní plain terms, adhesive layer lè rearrange quickly enough láti soften sudden stress concentration dípò behaving as static brittle solid.

Kí ló dé tí àwọn ònkòwé fi ro pé fluorine ẹ̀ pàtàkì?

PTFE built láti carbon-fluorine bond. CyclicFP-fmoc ru fluorinated crown-ether egbé. Àwọn ònkòwé argue pé **F-F interaction** help adhesive bind PTFE, nígbà tí other interaction help adhesive layer hold together àti deform.

Several control ìdánwò kókó ní ìtòsọ̀nà yẹn. Nígbà tí fluorine atom nínú CyclicFP-fmoc replaced pèlú hydrogen atom, resulting CyclicP-fmoc bond PTFE much sí i weakly, nìkan bí **0.1 ± 0.0 MPa**. Linear fluoro-ether phosphate, AcyclicFP-fmoc, dé **0.3 ± 0.1 MPa** nìkan. Variant missing pi-stacking tàbí hydrogen-bonding unit tún perform worse.

Ìwé ìwádíí lẹ́yìn nàà lo spectroscopy àti crystal ìṣètò láti ẹ̀ àtílẹ́yìn fún interaction picture. Nínú CyclicFP-fmoc crystal, fluorine atom lórí neighbouring molíkúlù sit **2.49 sí 2.91 angstroms** apart, shorter ju **2.94 angstrom** van der Waals sum fún fluorine atom méjì. FT-IR àti variable-temperature NMR ẹ̀ àtílẹ́yìn fún hydrogen bonding, F-F interaction àti pi-pi stacking nínú amorphous adhesive.

Most taara fún PTFE, solid-state **19F MAS NMR** spectrum shift nígbà tí CyclicFP-fmoc mixed pèlú PTFE nanoparticle tàbí thin PTFE sheet. Nonfluorinated control kò produce kan nàà shift. Èyí jẹ̀ ẹ̀rì, kì í ẹ̀ àpẹ̀rẹ̀ sketch nìkan, pé fluorinated part adhesive interact pèlú PTFE.

Síbẹ̀ a kò yẹ kí a simplify èyí sí “F-F bond solve PTFE.” àwòṣe ìwé ìwádíí fúnra rẹ̀ layered sí i: interfacial F-F interaction help PTFE adhesion, hydrogen bonding àti pi-pi stacking contribute sí cohesion àti ductility nínú adhesive.

Wipe-off removal jẹ̀ gidi, sùgbón ó ní ààlà

Removal èsì ni practical hook. Àwọn ònkòwé wash detached PTFE plate pèlú ethanol, wọn sì report complete removal CyclicFP-fmoc láisí residue nínú demonstration wọn. Wọn tún recover adhesive, reuse repeatedly, maintaining nìkan bí **1.2 ± 0.1 MPa** adhesive strength nínú reuse ìdánwò.

Èyí important nítorí conventional lágbára adhesive sáà hard láti remove cleanly. Glue tí ó lè hold PTFE, lẹ́yìn nàà wash off, lè useful fún repair, disassembly àti reuse.

Sùgbón ààlà ẹ̀ pàtàkì. ìwé ìwádíí ìdánwò controlled àpẹ̀rẹ̀, kì í ẹ̀ every contaminated industrial ojú, weathered joint, solvent exposure tàbí long-term aging condition. Ethanol wipe-off lórí PTFE plate kì í ẹ̀ kan nàà as proving

full recycling ilàna fún assembly made láti many ohun èlò.

ìwé iwádíí tún sọ pé CyclicFP-fmoc kì í ẹ̀ẹ́ PFAS “forever chemical.” Statement yẹn kò yẹ kí a expand sí complete environmental-risk assessment. Persistence, toxicity, manufacturing scale, release pathway àti regulation jẹ separate ibéèrè.

Ohun tí èyí kò fi hàn

- **Kò fi hàn market-ready adhesive product.**
- **Kò fi ẹ̀rí múlẹ̀ pé PTFE bá yí lè glued reliably nínú every industrial setting láì ojú preparation.**
- **Kò fi hàn pé ethanol removal ẹ̀sẹ̀ equally well lórí every substrate, ojú condition tàbí aged joint.**
- **Kò fi ẹ̀rí múlẹ̀ pé F-F interaction alone explain adhesion.** Mechanism ìwé iwádíí combine F-F, hydrogen bonding àti pi-pi stacking.
- **Kò fi hàn complete plastic-recycling workflow.**
- **Kò establish full environmental tàbí toxicological ààbò profile fún adhesive molíkúlù.**
- **Kò tùmọ̀ sí pé commercial adhesive generally worse.** Ìfíwéra specific sí ohun èlò àti PTFE lap-shear setup tí ìwé iwádíí ìdánwò.

Báwo ni èsì náà ẹ̀ẹ́ lágbara tó?

Fún lab ohun èlò ìwé iwádíí, èsì lágbara nítorí ònkòwé ẹ̀ẹ́ ju reporting single high number lọ. Wọ̀n ìdánwò strength, ductility, durability over 30 days, water tolerance, repeated readhesion, ethanol removal, molecular variant àti spectroscopic ẹ̀rí fún proposed interaction.

Most persuasive combination ni ìkùnà mode plus control. Tí PTFE interface bá fail first, claim yòò weak sí i. Dípò bẹ̀ẹ̀, joint fail nínú adhesive layer. Nígba tí fluorinated cyclic ẹ̀sẹ̀ removed tàbí changed, PTFE adhesion drop sharply.

Remaining ibéèrè ni scale àti lò ọ̀ràn. Lap-shear ìdánwò standardized, useful, ẹ̀gbọ̀n gidi joint face peel, impact, fatigue, contamination, temperature cycle àti mixed ohun èlò. Molecule tí ó ẹ̀sẹ̀ beautifully láàárín controlled yàrá ìdánwò plate ẹ̀ ní láti di formulation, ilàna àti durability dataset ẹ̀ájú kí ó tó di engineering adhesive.

Ìdí tí ó fi ẹ̀ẹ́ pàtàkì

PTFE wà ní awkward ohun èlò ààlà. Inertness rẹ̀ ni àbùdá tó make it valuable, kan náà àbùdá náà sì make it hard láti integrate sínú repairable tàbí recyclable assembly.

ìwé iwádíí yí offer route tó chemically specific dípò brute-force. Dípò roughening tàbí chemically attacking PTFE ojú, ó àpẹ̀ẹ́ small molíkúlù tó lè interact pẹ̀lú ojú yẹn nígba tí ó maintain ductile, reversible adhesive layer.

Tí àpẹ̀ẹ́ logic yẹn bá generalize, ó lè help build adhesive tí easier láti remove àti reuse láì give up gbogbo mechanical

performance. Èyí ni gidi promise: kì í ẹ̀se molíkúlù kan gégé bí finished glue, ẹ̀gbọ̀n molecular strategy fún lágbára, ductile àti debondable adhesion.

Àkótán mímọ̀

Kikkawa, Goswami àti colleagues report fluoro-crown ether phosphate small molíkúlù gégé bí adhesive fún PTFE àti other substrate. Lead molíkúlù, CyclicFP-fmoc, bond untreated PTFE plate ní 1.3 ± 0.1 MPa nínú lap-shear ìdánwò, fail cohesively dípò ní PTFE interface, fi hàn iṣẹ́ of debonding 1300 N/m, retain performance léyìn storage àti repeated readhesion, ó sì lè removed láti PTFE plate ní ethanol washing. Related variant dé 2.3 ± 0.2 MPa. Spectroscopy àti control molíkúlù ẹ̀se àtílẹ̀yìn fún ọ̀nà iṣẹ́ níbi tí F-F interaction help PTFE interface, nígbà tí hydrogen bonding àti pi-pi stacking help adhesive layer dissipate stress. ẹ̀sì jẹ́ promising yàrá ìdánwò demonstration tí lágbára, ductile, wipe-off adhesion sí PTFE, kì í tì ẹ̀se commercial glue, universal recycling solution tàbí full environmental-safety assessment.

Àwọn orísun

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>