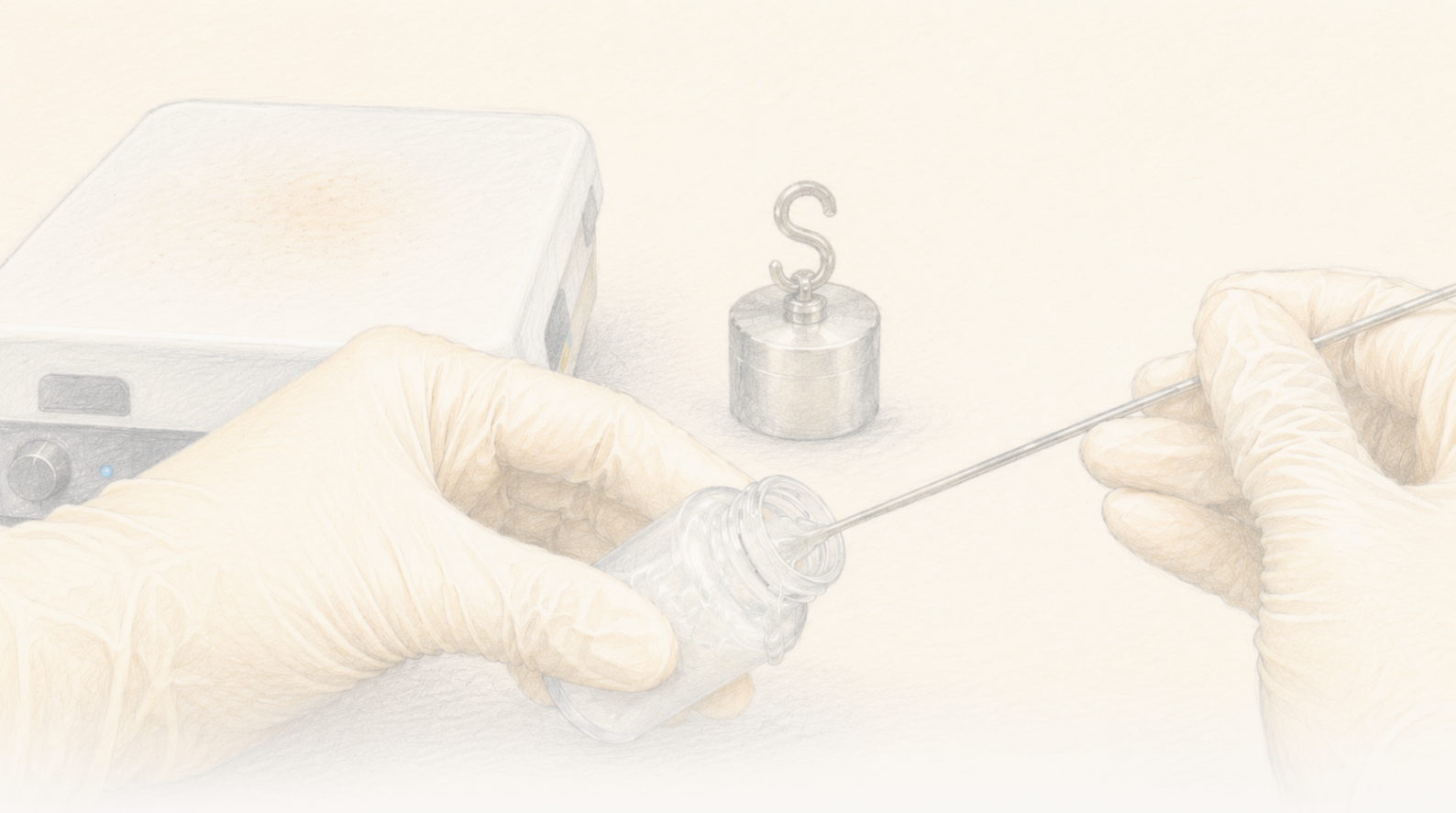


The Clean Paper

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

Molekuliin xiqqaan untreated PTFE maxxanse, sana booda ethanol'n dhiqamee irraa ba'e

Barruun JACS tokko fluoro-crown ether phosphate adhesives lab lap-shear tests keessatti PTFE baay'ee inert ta'e bond godhan, ethanol washing'n remove godhamuu danda'an gabaasa. CyclicFP-fmoc untreated PTFE irratti 1.3 MPa ga'e, ductile cohesive failure waliin; related variant 2.3 MPa ga'e. Mechanism fluorine-fluorine interactions PTFE bira, plus hydrogen bonding fi pi-stacking adhesive keessaa, spectroscopic evidence'n deeggarame. Kun materials result promising dha; commercial glue miti, universal recycling fix miti, full environmental-safety assessment miti.

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 irratti wanta maxxansuun maaliif rakkisaa akka ta'e sababni qaba

Polytetrafluoroethylene, PTFE jedhamee caalaatti beekamu, trade names Teflon dabalatee jalatti gurguramu, gartokkeen faayidaa qaba sababni isaa wal-interact gochuu hin barbaadne. Fuula anniisaa isaa gadi-aanaa dha. Liquids hedduun irratti bead godhu. Glues hedduun, fuula etched, roughened, plasma-treated ykn specialized primer waliin paired hin taane taanaan, irratti fail godhu.

Resistance kun nonstick coatings fi chemically inert kutaalee'f baay'ee gaarii dha. Garuu engineers PTFE fuula permanently hin miidhin kutaa biraa waliin wal qabsiisuu yeroo barbaadan rakkoo dha.

Barruun Journal of the American Chemical Society keessatti maxxanfame small-molecule adhesive rakkoo kana direction unusual irraa itti seenu gabaasa. Kohei Kikkawa, Abir Goswami fi colleagues fluoro-crown ether phosphate molekiyuulota untreated PTFE irratti cimsanii adhere gochuu, kufaatii dura ductile ta'anii deform gochuu, fi sana booda PTFE plates irraa ethanol'n dhiqamanii remove godhamuu danda'an ibsu.

Lead molekiyuulii **CyclicFP-fmoc** jedhama. Lap-shear qormaatawwan keessatti, untreated PTFE plates adhesive strength **1.3 ± 0.1 MPa** fi hojii of debonding **1300 N/m** qabaachuun qabate. Sababni 1 MPa = 1 newton tokkoon tokkoon square millimetre ta'eef, safarame peak stress 1.3 MPa jechuun dhiibbaa tilmaamaan ulfaatina apple 130-gram tokko square millimetre tokko tokko irratti hojjetu waliin walqixa. Kun analogy unit-area dha; force ykn contact ji'oometirii specimen qormaata miti. Gabaafame hojii of debonding 1300 N/m, separation anniisaa 1300 joules tokkoon tokkoon square metre waliin walqixa. Mul'ataa demonstration kallattii tokkoof, engineering load rating osoo hin taane, barruu joint 7 cm^2 tokko weight 8 kg baachuu agarsiisa. Joint adhesive layer keessaa fail godhe, PTFE walqunnamtii irratti miti. Kun barbaachisaa dha: walqunnamtii qormaata keessatti dadhabaa qabxii hin turre jechuu dha.

Pencil rendering suuraa barruu keessaa adhesive strip suspended weights baatu (Fakkii 2, bitaa) irratti hundaa'e. Jalqabaa photograph miti, safartuu drawing miti, engineering load-rating diagram miti.

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

Bu'aan "PTFE solved" miti. To'atame laaboraatoorii maateriyaalota bu'aa dha. Garuu combination rakkisaa tokkoof fakkeenya qulqulluu dha: cimaa adhesion, ductile kufaatii fi fuula adhesion resistance'n beekamu irraa wipe-off removal.

Idilee strength fi easy removal maaliif wal faallessu

Adhesives yeroo baay'ee bargain godhu. Rigid cross-linked polymer glues cimaa ta'uu danda'u, garuu yeroo baay'ee sudden fail godhu fi qulqulluun remove gochuun rakkisaa. Softer tape-like adhesives stretch fi anniisaa dissipate gochuu danda'u, garuu strength dhiisu.

Trade-off molekiyuulii dha. Strength efficient stress transfer barbaada. Ductility motion, rearrangement fi anniisaa dissipation barbaada. Easy removal bonds substrate hin balleessin cabuu danda'an barbaada. Requirements kun directions adda addaatti harkisu.

Small-molecule adhesives nama hawwatu sababni isaanii principle'n removable fi recyclable ta'uu danda'an. Dheeraa entangled polymer networks conventional glues hedduu tough godhan hin

uuman. Kun dadhabaa qabxii isaanii illee dha: entanglement malee, xiqqaa molekiyuulota yeroo baay'ee ductile, high-strength adhesion kennuuf rakkatu.

JACS barruu polymer entanglement stack reversible noncovalent interactions'n bakka buusu yaala. Molekiyuulii fluorinated crown-ether phosphate naannoo urethane-linked fmoc garee waliin combine godha. Afaan salphaatti, fluorinated ring isaa fluorine-rich PTFE fuula waliin interact gochuu danda'a; urethane gareewwan neighbouring adhesive molekiyuulota waliin hydrogen-bond gochuu danda'u; flat fluorenyl gareewwan walii irratti stack gochuu danda'u. Qophii galma magic bond tokko miti. Set dadhabaa, reversible interactions waliin hojjechuu danda'an dha:

- fluorine-fluorine interactions PTFE bira;
- haayidiroojiinii bonding adhesive molekiyuulota gidduu;
- pi-pi stacking fluorenyl gareewwan gidduu;
- fi molekiyuulii mobility gahaa stress tasgabbeessu, immediately crack gochuu mannaa.

Ijoo PTFE qormaata maal agarsiise

Barreessitoonni CyclicFP-fmoc PTFE plates surface-treated ykn cleaned hin taane gidduu kaa'an, adhesive ho'a godhan, plates room ho'a irratti 10 minutes dhiisanii booda qoran.

Quantitative qorannoo'f lap shear fayyadaman. PTFE plates CyclicFP-fmoc'n bonded **1.3 ± 0.1 MPa** tensile stress ga'an, sadii safartuuwwan'f giddugaleessa ± istaandaardii deviation ta'ee gabaafame. Adhesive naannoo **50 C** irratti hair dryer'n apply gochuun gatii walfakkaataa **1.1 ± 0.1 MPa** kenne, high-temperature melting qofa hin barbaachifne.

Barreessitoonni gatiiwwan kana commercial epoxy, acrylic, silicone fi urethane adhesives walfakkaataa PTFE lap-shear setup keessatti walbira qaban. Controls sun naannoo **0.1 hanga 0.7 MPa** ga'an, CyclicFP-fmoc **1.3 ± 0.1 MPa** waliin walbira qabamuun. Same-substrate, same-method walbira qabuu kun MPa gatiiwwan maateriyaalota fi qormaata geometries adda addaa leaderboard tokko irratti kaa'uu caalaa informative dha.

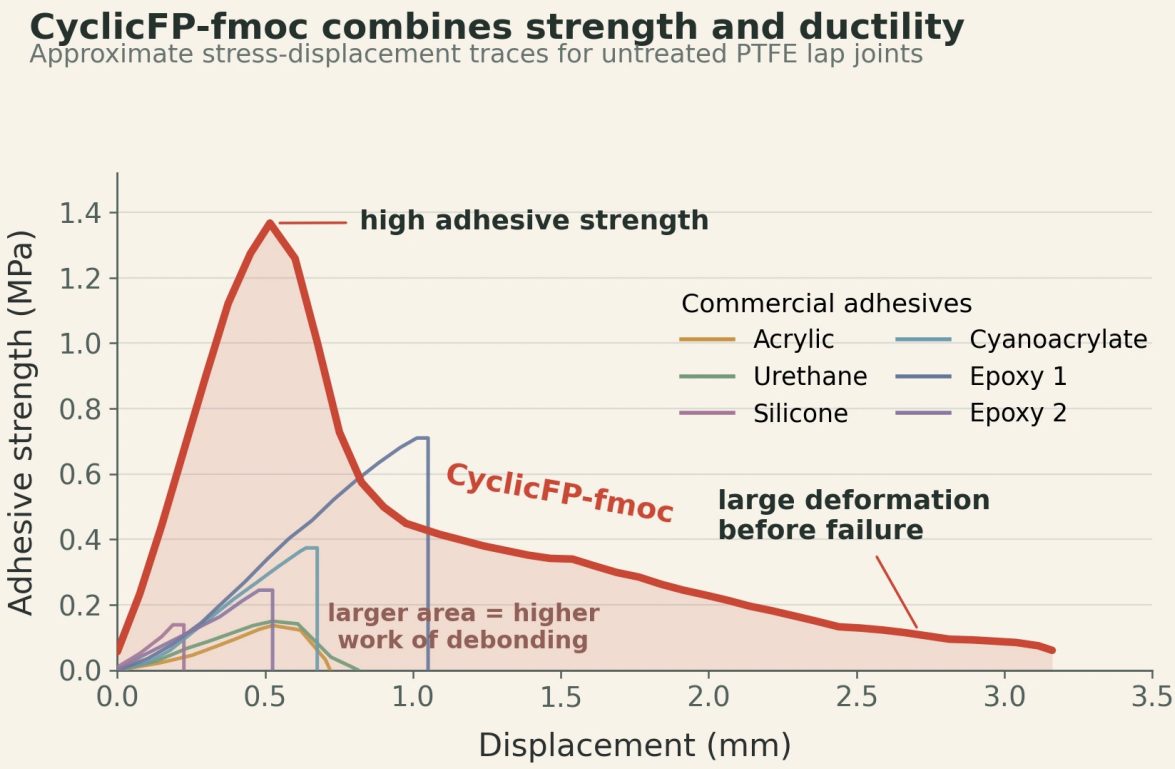
Lakkoofsi storage booda walfakkaataa hafe. Ambient haalawwan keessatti days 30 booda adhesive strength **1.3 ± 0.2 MPa** ture. Plates forcibly separated, deebi'anii overlap godhamanii reheated booda, strength **1.2 ± 0.2 MPa** ture. Marsaa kana ten yeroowwan repeat godhuun illee naannoo **1.3 ± 0.3 MPa** kenne.

Isa gaarii variant lead molekiyuulii miti. Related molekiyuulii fmoc gareewwan sadii qabu, **CyclicFP-fmoc3**, PTFE irratti **2.3 ± 0.2 MPa** ga'e. Barruu ammallee CyclicFP-fmoc irratti baay'ee xiyyeeffata sababni isaa combination guutuu strength, ductility, mechanistic ragaa fi wipe-off removal waan kennuuf.

Ductility himannaa keessaa kutaa lammaffaa dha

Strength qofa gahaa hin ta'u. Brittle adhesive peak stress ol ga'uu danda'a, sana booda sudden fail godha. Himannaa barruu caalaatti adda ta'e CyclicFP-fmoc ductile ta'ee illee behave godha jedhu.

Lap-shear qaxxaamuroota keessatti, CyclicFP-fmoc maximum stress isaa ga'ee sana booda displacement itti fufuun stress suuta suuta dhabe. Commercial adhesives barruu keessatti qoraman brittle joints caalaa fakkaatan: peak stress booda yeroo gabaabaa keessatti kufaatii dhufe.



Approximate curves digitized from Figure 3f; not raw experimental data.
Lines connect digitized points without smoothing.

CyclicFP-fmoc ol-aanaa stress peak fi dheeraa post-peak gara dhumaa walitti qaba; shaded bal'ina editorial qajeelfama hojii of debonding guddaa isaa agarsiisu. Qaxxaamuroota approximate Fakkii 3f irraa digitized; jalqabaa yaalii daataa miti.

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

Barreessitoonni bal'ina stress-displacement qaxxaamura jala jiru hojii of debonding ta'ee quantify godhan. CyclicFP-fmoc PTFE irratti **1300 N/m** kenne. Tested commercial adhesives **26 hanga 314 N/m** turan.

Kufaatii mode hiika sana waliin walii gala. PTFE joints CyclicFP-fmoc cohesive fail godhan, adhesive keessaa. Kun adhesive internally deform gochuun anniisaa dissipate gochuu danda'e, PTFE walqunnamtii immoo bulk adhesive layer caalaa cimaa ture jechuu dha.

Stress relaxation yaaliiwwan molekiyuulii timescale dabalatu. 20 C irratti characteristic relaxation

yeroo **60 ms** ture; Arrhenius xiinxala activation anniisaa **33.8 kJ/mol** kenne. Afaan salphaatti, adhesive layer sudden stress concentration soften gochuuf saffisaan rearrange gochuu danda'a, static brittle jajjabaa akka hin behave goone.

Maaliif barreessitoonni fluorine barbaachisaa jedhu

PTFE carbon-fluorine bonds irraa ijaarame. CyclicFP-fmoc fluorinated crown-ether gareewwan qaba. Barreessitoonni **F-F interactions** adhesive PTFE hidhachuuf gargaara, interactions biroo immoo adhesive layer walitti qabee deform gochuuf gargaara jedhu.

To'annoo yaaliiwwan hedduun direction sana akeeku. CyclicFP-fmoc keessatti fluorine atoms haayidiroojiinii atoms'n replace godhaman, CyclicP-fmoc resulting PTFE baay'ee laafaan bond godhe, naannoo **0.1 ± 0.0 MPa**. Linear fluoro-ether phosphate, AcyclicFP-fmoc, **0.3 ± 0.1 MPa** qofa ga'e. Variants pi-stacking ykn hydrogen-bonding units dhabaniis raawwii gadi-aanaa agarsiisan.

Barruu spectroscopy fi kiristaala caasaa fayyadamuun interaction picture deeggara. CyclicFP-fmoc kiristaala keessatti fluorine atoms neighbouring molekiyuulota irratti **2.49 hanga 2.91 angstroms** fageenya qabu, **2.94 angstrom** van der Waals sum fluorine atoms lamaa caalaa gabaabaa. FT-IR fi variable-temperature NMR amorphous adhesive keessatti haayidiroojiinii bonding, F-F interactions fi pi-pi stacking deeggaru.

PTFE irratti caalaatti kallattii ta'ee, solid-state **19F MAS NMR** speektra CyclicFP-fmoc PTFE nanoparticles ykn haphii PTFE sheets waliin mixed yeroo ta'u jijjiirama godhu. Nonfluorinated to'annoo jijjiirama walfakkaataa hin uumu. Kun qophii sketch qofa miti; fluorinated kutaalee adhesive PTFE waliin interact godhu jedhuuf ragaa dha.

Kunis "F-F bonds PTFE solve godhan" jedhamee salphifamuu hin qabu. Moodeela barruu mataa isaa layered dha: interfacial F-F interactions PTFE adhesion gargaara, haayidiroojiinii bonding fi pi-pi stacking immoo adhesive keessaa cohesion fi ductility gumaachu.

Wipe-off removal dhugaa dha, garuu daangaa qaba

Removal bu'aa hojiirra oolu hook dha. Barreessitoonni detached PTFE plates ethanol'n dhiqanii CyclicFP-fmoc residue malee guutumaan keessaa baasuu jechuun demonstration isaanii keessatti gabaasan. Adhesive rehammatanii irra deebi'anii fayyadaman; reuse qormaatawwan keessatti adhesive strength naannoo **1.2 ± 0.1 MPa** maintained.

Kun barbaachisaa dha, sababni cimaa conventional adhesives yeroo baay'ee ifaa remove gochuun rakkisaa. Glue PTFE qabatee boodaa wash off godhamuu danda'u repair, disassembly fi reuse'f faayidaa qabaachuu danda'a.

Garuu daangaa barbaachisaa dha. Barruu to'atame saamudawwan qora; contaminated industrial fuula hunda, weathered joint, solvent saaxilamuu ykn long-term aging haala hunda miti. Ethanol wipe-

off PTFE plates irratti ragaa guutuu recycling adeemsa assemblies hedduu maateriyaalota irraa ijaaraman miti.

Barruu CyclicFP-fmoc PFAS "forever chemical" miti illee jedha. Statement sun guutuu environmental-risk assessment'tti bal'ifamuu hin qabu. Persistence, toxicity, manufacturing safartuu, gadhiisuu pathways fi regulation gaaffilee adda adda.

Kun maal hin mirkaneessu

- Market-ready adhesive product **hin agarsiisu**.
- PTFE every industrial setting keessatti fuula preparation malee reliably glued ta'uu **hin mirkaneessu**.
- Ethanol removal substrate, fuula haala ykn aged joint hunda irratti equally gaariitti hojjeta **hin agarsiisu**.
- F-F interactions qofti adhesion ibsu **hin mirkaneessu**. Adeemsa hojii barruu F-F, haayidiroojiinii bonding fi pi-pi stacking combine godha.
- Guutuu plastic-recycling adeemsa hojii **hin agarsiisu**.
- Adhesive molekiyuulota'f guutuu environmental ykn toxicological nageenya profile **hin mirkaneessu**.
- Commercial adhesives generally caalaatti hamaa **jechuu miti**. Walbira qabuwwan maateriyaalota fi PTFE lap-shear setup barruu kana keessatti qoraman qofaaf.

Bu'aan hammam cimaa dha?

Lab maateriyaalota barruu tokkoof, bu'aa cimaa dha sababni barreessitoonni tokko ol-aanaa lakkoofsa qofa hin gabaasan. Strength, ductility, durability days 30, water tolerance, repeated readhesion, ethanol removal, molekiyuulii variants fi spectroscopic ragaa proposed interactions qoru.

Combination caalaatti persuasive kufaatii mode plus controls dha. Yoo PTFE walqunnamtii dura fail godhe himannaa laafaa ta'a ture. Garuu joint adhesive layer keessa fail godha. Fluorinated cyclic caasaa yeroo removed ykn changed, PTFE adhesion sharp gadi bu'a.

Gaaffileen hafan safartuu fi fayyadama haala dha. Lap-shear qormaatawwan standardized fi faayidaa qabu dha, garuu dhugaa joints peel, rukuttaa, fatigue, contamination, ho'a cycles fi mixed maateriyaalota argu. Molekiyuulii to'atame laaboraatoorii plates gidduu beautifully hojjetu, engineering adhesive ta'u dura formulation, adeemsa fi durability kuusaa daataa ta'uu qaba.

Maaliif barbaachisaa dha

PTFE maateriyaalota daangaa awkward tokko irratti taa'a. Inertness isaa amaloota gatii kennu isa; amaloota sanuma repairable ykn recyclable assemblies keessatti integrate gochuu rakkisa.

Barruu kun route chemically addaa, brute-force miti, dhiyeessa. PTFE fuula roughen ykn chemically haleellaa gochuu mannaa, xiqqaa molekiyuulii fuula sana waliin interact gochuu fi ductile, reversible adhesive layer maintain gochuu danda'u qophii godha.

Qophii logic kun generalize yoo ta'e, adhesives easier remove fi refayyadamuu danda'an, mechanical raawwii hundumaa osoo hin dhiisin, ijaaruuf gargaara. Promise dhugaa kun: molekiyuulii tokko finished glue ta'uu miti; molekiyuulii strategy cimaa, ductile fi debondable adhesion'f.

Cuunfaa gabaabaa

Kikkawa, Goswami fi colleagues fluoro-crown ether phosphate xiqqaa molekiyuulota PTFE fi substrates biroof adhesives ta'anii gabaasu. Lead molekiyuulii CyclicFP-fmoc untreated PTFE plates lap-shear qormaatawwan keessatti **1.3 ± 0.1 MPa** irratti bond godhe; PTFE walqunnamtii irratti osoo hin taane cohesively fail godhe; hojii of debonding **1300 N/m** agarsiise; storage fi repeated readhesion booda raawwii qabate; PTFE plates irraa ethanol wash'n remove godhamuu danda'e. Related variant tokko **2.3 ± 0.2 MPa** ga'e. Spectroscopy fi to'annoo molekiyuulota adeemsa hojii keessatti F-F interactions PTFE walqunnamtii gargaara, haayidiroojiinii bonding fi pi-pi stacking adhesive layer stress dissipate gochuuf gargaara jedhu deeggaaru. Bu'aan lab demonstration promising cimaa, ductile, wipe-off adhesion PTFE irratti dha; commercial glue miti, universal recycling furmaata miti, guutuu environmental-safety assessment miti.

Maddoota

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