

Thiol–Ene and Thiol–Yne Photopolymerisation in VPP: Stoichiometry, Oxygen Response and Network Architecture

Juan Segurola, PhD

3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: www.3Dresyns.com

3Dresyns Engineering Review ER-64 · Version 1.1 · No proprietary formulation composition disclosed

Statement of Significance

Thiol-ene, thiol-yne and thiol-acrylate formulations do not share one network-forming mechanism. Stoichiometry, ene or yne identity, hydrogen-transfer kinetics, oxygen response and post-exposure reaction jointly determine gelation, residual functionality and dimensional stability. This review defines a chemistry-specific reporting framework that separates oxygen tolerance from oxygen independence and requires both reactive groups, gelation, dark reaction and final dimensions to be measured.

Keywords: vat photopolymerisation; thiol-ene; thiol-yne; click chemistry; step-growth photopolymerisation; oxygen inhibition; stoichiometry; gelation; dark cure; VAM

Abstract

Vat photopolymerisation is dominated by chain-growth acrylate and methacrylate chemistry. Thiol-ene and thiol-yne reactions provide a different network-forming route in which thiyl-radical addition and rapid hydrogen transfer create a step-growth-like reaction cycle. Under appropriate functionality and stoichiometry, this can delay gelation to higher conversion, reduce oxygen sensitivity, limit early microgel formation and produce more uniform network connectivity. These advantages are conditional. Ene identity determines whether chain transfer or homopolymerisation dominates. Thiol-acrylate formulations contain a mixed step-growth/chain-growth mechanism rather than a pure thiol-ene network. Thiol-yne systems can consume two thiol equivalents per alkyne through a vinyl-sulfide intermediate, increasing potential connectivity while tightening stoichiometric control. Residual thiol, oxidation, odour, dark reaction, radical stabilisation, optical confinement and diffusion-limited conversion remain formulation-specific risks. Published light-based additive-manufacturing systems include tomographic thiol-ene VAM resins with TEMPO-defined thresholds, unmodified polybutadiene and polychloroprene elastomers, visible-light photoredox thiol-yne resins, degradable aliphatic-polycarbonate networks and CO₂-derived copolymer elastomers. These studies demonstrate broad chemistry access but also show that oxygen tolerance can weaken volumetric thresholding, solvent-assisted feedstocks can undergo very large drying shrinkage, and high conversion does not remove transport or network-state limitations. This review develops a reaction-classification and qualification framework for thiol-ene, thiol-yne and mixed thiol-acrylate VPP. It separates functional-group stoichiometry from monomer mass ratio, distinguishes oxygen tolerance from oxygen independence, and requires both thiol and ene/yne conversion, gelation, dark reaction, residual-functionality and dimensional evolution to be reported.

1. Introduction

The dominant VPP reaction is radical chain growth of multifunctional acrylates or methacrylates. Rapid propagation and early network formation provide useful green strength, but can also generate heterogeneous

microgel-rich networks, oxygen-sensitive surfaces and constrained shrinkage before high functional-group conversion is reached.

Radical thiol-ene chemistry follows a transfer-regenerated cycle: a thiyl radical adds to an ene, the resulting carbon-centred radical abstracts hydrogen from another thiol, and a new thiyl radical continues the reaction. Canonical reviews describe the route as a radical step-growth polymerisation capable of rapid, high-yield photochemical reaction and comparatively uniform networks [1].

thiyl addition -> carbon-centred radical -> H abstraction from R-SH -> regenerated thiyl radical

The engineering question is not whether a formulation contains thiol and alkene groups. It is whether the complete reaction network produces the gelation, optical confinement, residual-functionality state and final properties required by the intended printer and application.

2. Reaction classes that must not be conflated

Class	Dominant reaction architecture	Qualification consequence
Canonical thiol-ene	Alternating thiyl addition and hydrogen-transfer cycle between multifunctional thiols and non-homopolymerising or weakly homopolymerising enes.	Measure both functional groups and the gelation state; do not infer network uniformity from composition alone.
Thiol-acrylate hybrid	Thiol-mediated chain transfer occurs while acrylate homopolymerisation also contributes.	Treat as mixed step-growth/chain-growth chemistry; residual thiol and acrylate can evolve differently.
Thiol-yne	First thiol addition creates a vinyl-sulfide intermediate that can accept a second thiol addition.	Use functional-group stoichiometry based on two thiol additions per alkyne where complete reaction is intended.
Off-stoichiometric network	One functional group is deliberately left in excess.	Quantify residual groups and distinguish intended handles from incomplete cure.
Thiol-assisted crosslinking of unsaturated polymer	Commercial or synthesised polymer already contains pendent/backbone unsaturation.	Identify which alkene populations react and whether direct radical crosslinking also occurs.

3. Gelation and network development

Step-growth-like network formation commonly delays gelation relative to highly multifunctional acrylate chain-growth systems. In the classical real-time FTIR/photorheology study of Chiou and Khan, appreciable elastic modulus developed only after approximately 65% thiol conversion, and the formulation-specific Flory-Stockmayer gel conversion was calculated as 0.71 [2]. These numbers belong to that monomer pair and functionality; they are not universal thiol-ene constants.

Delayed gelation can allow more conversion before shrinkage becomes mechanically constrained, but it can also reduce early green strength. For VPP, the preferred reaction is therefore not automatically the one with the latest gel point. The gelation window must remain compatible with layer separation, object support, volumetric thresholding and wash resistance.

ER-61 addresses gelation, vitrification and mobility arrest as general cure-state transitions. ER-64 uses those concepts only to explain how thiol-mediated reaction architecture changes the conversion-to-network relationship.

4. Stoichiometric control

Stoichiometry must be stated using reactive functional groups, not only monomer mass or molecule count. A tetrafunctional thiol and a difunctional ene mixed at a 1:1 molecular ratio are not necessarily functionally stoichiometric. Thiol-yne formulations require an additional distinction because each alkyne can undergo two sequential additions.

Formulation state	Potential purpose	Main risk
Near functional equivalence	Maximise balanced network formation and minimise residual groups.	Functional-group conversion can still differ because of unequal reactivity or diffusion.
Thiol excess	Leave thiols for grafting, bonding or a second reaction.	Odour, oxidation, extractables and ageing.
Ene/yne excess	Leave unsaturation for post-cure or functionalisation.	Residual chain-growth, dark reaction or incomplete final network.
High functionality	Increase gel fraction and stiffness.	Early mobility loss, brittleness and diffusion-limited conversion.
Low functionality / long spacer	Increase extensibility and delay gelation.	Insufficient green strength, creep or soluble fraction.

5. Oxygen response and radical persistence

Thiol-ene reactions are generally more tolerant of oxygen than conventional acrylate radical polymerisation because hydrogen transfer from thiol can regenerate reactive thiyl species from oxygen-derived radical pathways [1]. This should be described as relative oxygen tolerance, not oxygen independence. Initiation rate, thiol structure, film thickness, irradiance and oxygen transport still influence the response.

The process consequence depends on the printing architecture. In layerwise VPP, reduced surface inhibition can improve conversion and reduce tack. In tomographic VAM, the same absence of a strong oxygen threshold can reduce dose selectivity. Cook and co-workers introduced TEMPO as a persistent radical scavenger to create the nonlinear threshold required for thiol-ene VAM and balanced inhibitor and initiator content against absorbed volumetric dose [3].

Moore and co-workers reported that working curves showed evidence of a “dark cure”, which they attributed to the thiol-ene reaction’s relative insensitivity to oxygen [5]. ER-64 retains this as the authors’ interpretation of working-curve behaviour, not as a direct time-resolved measurement of post-exposure conversion; conversion, depth extension and delayed gelation must be measured separately before the term is generalized.

6. Thiol-acrylate hybrid networks

Adding thiols to acrylate formulations can reduce oxygen sensitivity, alter chain length and introduce step-growth character, but acrylate homopolymerisation remains possible. Scott and co-workers combined thiol-ene chain extension of hydrogenated polybutadiene with acrylate crosslinking to produce printable hydrocarbon elastomers from low-molecular-weight feedstocks [4].

This route should not be reported as a chemically pure thiol-ene network. The relative contributions of chain transfer, ene addition and acrylate propagation determine gelation, network heterogeneity and residual functionality. Separate conversion measurements are preferable where spectral resolution allows them.

7. Direct use of unsaturated commercial polymers

Thiol chemistry can access polymers that are difficult to convert into conventional acrylate-functional resins. Moore and co-workers crosslinked unmodified commercial liquid polybutadiene through pendent unsaturation and printed complex geometries on commercial DLP systems [5]. In 2026, Moore and co-workers extended a solvent-assisted route to high-molecular-weight polychloroprene, producing DLP-printed articles with an ultimate tensile stress of 2.4 MPa and a strain at break of 1200% [11].

The polychloroprene study also demonstrates a central process warning. For 1 cm and 2 cm cubes printed from the 90 SH ODT formulation, side lengths shrank by roughly 46% and volumes by 85%, with most volume loss occurring within 24 h; the photoresin contained 88% solvent by volume [11]. Photochemical printability does not therefore establish final dimensional fidelity.

8. Thiol-yne network formation

Thiol-yne chemistry proceeds through a first addition to the alkyne and a second addition to the resulting vinyl sulfide. This can create greater network connectivity per yne group than a single thiol-ene addition, but the two steps need not possess identical rates. Residual alkyne, vinyl sulfide and thiol should therefore be distinguished where analytically possible.

Wu, Simpson and Jin reported a pendant-alkyne aliphatic polycarbonate resin printed by DLP at 405 nm with 50 μm layers and demonstrated fast hydrolytic degradation of printed objects in aqueous alkaline solution [6]. The result establishes an accelerated chemical-degradation route under the reported conditions; it does not establish environmental biodegradability or physiological degradation.

The same authors later used Eosin Y and fac-Ir(ppy)₃ photoredox catalysts for open-air 470 nm DLP thiol-yne printing. The optimized dual-catalyst formulation used 250 μm layers and a 5 mm h⁻¹ build rate and balanced geometric quality with reaction rate better than either single-catalyst formulation [7]. These are formulation- and machine-specific values.

9. Sustainable and degradable elastomer routes

Poon and co-workers printed CO₂- and bio-derived poly(carbonate-ester-carbonate) triblock copolymers using thiol-ene crosslinking. Crosslinker length and PEG content tuned hydrophilicity, swelling and accelerated mass-loss behaviour in 4 M NaOH at room temperature; P1X3 fully degraded within 65 days, whereas P1X2 and P1X1 lost 75% and 49% mass, respectively, after 85 days. The printed materials also exhibited printing-induced microphase separation and complex gyroid printability [8]. These accelerated alkaline results do not establish physiological or environmental degradation rates.

Renewable feedstock, hydrolytic cleavage and thiol-ene chemistry are independent design variables. A bio-derived component does not prove low environmental impact, and alkaline disintegration does not prove biodegradation. ER-74 remains responsible for cleavable and depolymerisable network end-of-life claims.

10. Diffusion-limited conversion

Thiol-ene systems can also become mobility-limited. Hu and co-workers developed a free-volume-based kinetic model that predicted kinetics and ultimate conversion within 5% of experimental values for the investigated system. Their model showed that crosslink density, reaction temperature and plasticiser loading change the conversion ceiling and that a thiol-ene mixture can remain at limited conversion even when its T_g is at or below the reaction temperature [9].

This result cautions against treating oxygen tolerance or delayed gelation as guarantees of complete cure. Functional groups may remain inaccessible because of local topology, diffusion and radical history even without a conventional glassy vitrification condition.

11. VAM and responsive-material demonstrations

Thiol-ene VAM has been used not only for structural materials but also for shape-memory polymers. Schwartz and co-workers reported VAM-printed structures with “nearly full shape recovery”; separate cyclic DMA tests on bulk-cast Th-b and Th-c specimens showed 97% recovery in the first cycle and 100% in the following three cycles [10]. This demonstrates chemical versatility but does not make shape memory intrinsic to thiol-ene chemistry; transition temperature, programming protocol, recovery force and cycling remain formulation-specific.

ER-75 addresses the complete chemistry of tomographic VAM thresholding. ER-64 retains only the thiol-ene-specific point that oxygen tolerance may require an intentionally added radical-scavenging threshold.

12. Measurement and reporting architecture

No published ISO, ASTM International or DIN standard directly governs simultaneous thiol and ene/yne conversion, the photo-gel point of a thiol-mediated VPP resin, oxygen-tolerance qualification, post-exposure reaction, residual thiol or odour, two-addition accounting in thiol-yne systems, or dimensional qualification after solvent removal. Adjacent methods may be used only for declared measurements: ISO 527-1:2019 and ISO 527-2:2025 or ASTM D638-22 for tensile properties of plastics; ISO 37:2024 for vulcanized or thermoplastic rubbers; ISO 11357-2:2020 for glass transition by DSC; ISO 6721-1:2019 for general DMA principles; ASTM D2765-16(2024) for gel content and swell ratio of crosslinked ethylene plastics; and ISO 6427:2025 for matter extractable by organic solvents. None of these methods validates a thiol-ene or thiol-yne reaction mechanism or supplies a universal VPP acceptance criterion [S1–S8].

Domain	Minimum measurement	Required interpretation
Initial formulation	Thiol, ene/yne and hybrid-reactant identity; functionality; functional-group ratio; viscosity; storage state.	Defines the chemical starting point rather than only a commercial monomer ratio.
Optical input	Wavelength, irradiance, exposure history and source spectrum.	Separates chemistry from lamp/printer effects.
Reaction	Time-resolved thiol and ene/yne conversion where possible.	Identifies imbalance and residual groups.
Network formation	Photorheology, gel fraction and declared gel criterion.	Links conversion to green-state connectivity.
Oxygen response	Matched air/inert or controlled-interface experiments.	Supports oxygen-tolerance claims.

Domain	Minimum measurement	Required interpretation
Post-exposure state	Conversion and dimensions versus delay after light removal.	Quantifies dark reaction or delayed cure.
Final network	DMA/DSC, extraction, swelling, mechanics and fracture.	Tests network architecture and residual soluble fraction.
Dimensional response	As-printed, washed, dried and post-cured geometry.	Separates cure shrinkage from solvent/extraction change.
Ageing	Residual thiol/odour, oxidation, humidity and thermal history.	Tests chemical stability of the finished material.

13. Proposed engineering descriptors

The following are proposed reporting aids and are not standardised performance indices.

13.1 Functional-group balance after cure

$$B_F = |\alpha_{SH,eq} - \alpha_{ene/yne,eq}|$$

The conversions must be expressed on a compatible functional-equivalent basis and reported with their analytical uncertainty. For thiol-yne systems, the yne term must account explicitly for the two sequential thiol additions expected per alkyne when complete reaction is intended. A lower value indicates more balanced equivalent consumption, not necessarily higher total conversion or better properties.

13.2 Dark-reaction increment

$$\Delta\alpha_{dark}(\Delta t) = \alpha(t_{light-off} + \Delta t) - \alpha(t_{light-off})$$

Report the delay, temperature, atmosphere and functional group. This descriptor distinguishes post-exposure reaction from exposure-time conversion.

13.3 Gel-conversion separation

$$\Delta\alpha_{G,j} = \alpha_{final,j} - \alpha_{gel,j}$$

The subscript j identifies the declared functional group or compatible functional-equivalent conversion used in the calculation. This is a bookkeeping measure of conversion accumulated after gelation. It does not quantify stress relaxation or network uniformity by itself.

14. Failure modes and interpretation errors

Observation	Possible error	Required control
Low surface tack	Oxygen independence inferred.	Matched oxygen-condition and surface-conversion measurements.
High conversion	Balanced thiol and ene consumption assumed.	Measure both groups where possible.
Rapid print	Uniform network inferred.	Gelation, extraction and property mapping.
Dimensional loss after drying	Cure shrinkage blamed exclusively.	Separate solvent, wash and chemical-shrinkage contributions.
Residual thiol intended for bonding	Incomplete cure mislabelled as functionality.	Quantify amount, stability and subsequent reaction.

Observation	Possible error	Required control
VAM background cure	Optics blamed without chemistry check.	Inhibitor/initiator and accumulated-dose map.
Alkaline degradation	Biodegradability claimed.	Identify products, conditions and biological degradation evidence.
Visible-light printing	Operator or biological safety inferred.	Application-specific radiometric and biological assessment.

15. Scope boundaries

ER-64 is restricted to thiol-mediated network formation and its process consequences.

- ER-59 addresses independently programmed dual-cure sequences. A thiol-ene formulation is not automatically dual cure.
- ER-61 addresses gelation, vitrification and mobility arrest across photopolymer classes. ER-64 addresses the reaction architecture that shifts those transitions.
- ER-62 addresses retained RAFT, photoiniferter or nitroxide-derived reactivation. Ordinary thiol transfer does not establish a living network.
- ER-66 addresses high-molecular-weight latex and pseudothermoplastic VPP. Direct thiol crosslinking of an unsaturated polymer is a different route.
- ER-74 addresses cleavable and depolymerisable networks. Thiol-yne chemistry is not inherently degradable.
- ER-75 addresses the complete tomographic VAM material window. ER-64 addresses only the chemistry-specific threshold problem created by oxygen-tolerant thiol-ene reactions.

16. 3Dresyns implementation boundary

No current standard 3Dresyns product is identified in this review as an independently validated thiol-ene or thiol-yne resin. Product names, elastomeric behaviour, degradability, oxygen tolerance or VAM compatibility must not be used to infer this reaction mechanism without controlled compositional and kinetic evidence.

A future custom thiol-mediated platform would require, at minimum:

- defined thiol and ene/yne identities and functionality;
- functional-group stoichiometry and storage-stability data;
- wavelength-specific conversion and gelation measurements;
- oxygen and post-exposure reaction controls;
- residual-thiol, extraction and ageing assessment;
- complete dimensional and mechanical qualification after washing, drying and post-cure.

17. Design rules

- Classify the reaction as canonical thiol-ene, thiol-acrylate hybrid, thiol-yne or polymer-unsaturation crosslinking.
- State stoichiometry by reactive functional groups.
- Measure both thiol and ene/yne conversion where analytically possible.
- Treat oxygen tolerance as conditional and process-specific.
- Quantify post-exposure reaction before using the term dark cure.
- Separate solvent-loss shrinkage from chemical cure shrinkage.
- Do not infer degradation or biological suitability from the thiol-ene label.

- Rebuild the optical and gelation window after every change in thiol functionality, inhibitor or photoredox system.

18. Conclusions

Thiol-ene and thiol-yne photopolymerisation provide VPP with a network-forming route distinct from conventional acrylate chain growth. Their principal value is not a universal claim of faster or more complete curing, but the ability to redesign the relationship among functional-group conversion, gelation, oxygen response, network uniformity and final material architecture.

The useful engineering sequence is:

functional-group stoichiometry -> reaction pathway -> gelation -> residual-group state -> optical/process window -> final network

A defensible thiol-mediated VPP material therefore requires chemical classification, separate functional-group conversion, declared gel criterion, oxygen and dark-reaction controls, residual-thiol assessment and dimensions measured after the complete solvent/wash/post-cure history.

Thiol chemistry changes the route to the network; it does not remove the need to qualify the network.

Limitations

The evidence spans layerwise DLP, tomographic VAM, hybrid thiol-acrylate networks, direct unsaturated-polymer crosslinking, thiol-yne systems and solvent-assisted elastomer feedstocks. Their kinetics, stoichiometry, gelation, oxygen response, dimensions and mechanics cannot be pooled as one material class.

Several mechanistic statements derive from canonical thiol-ene literature rather than VPP-only experiments. The proposed descriptors B_F, $\Delta\alpha_{\text{dark}}$ and $\Delta\alpha_{\text{G,j}}$ require independent review for ancestry, analytical comparability and uncertainty conventions before.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No current commercial 3Dresyns product is presented as an independently validated thiol-ene or thiol-yne resin.

Data availability

No new experimental dataset was generated for this review.

Company information

Legal company name: 3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: www.3Dresyns.com

References

[1] Hoyle, C. E.; Bowman, C. N. Thiol–Ene Click Chemistry. *Angewandte Chemie International Edition* 2010, 49(9), 1540–1573. DOI: 10.1002/anie.200903924.

- [2] Chiou, B.-S.; Khan, S. A. Real-Time FTIR and in Situ Rheological Studies on the UV Curing Kinetics of Thiol-ene Polymers. *Macromolecules* 1997, 30(23), 7322-7328. DOI: 10.1021/ma9708656.
- [3] Cook, C. C.; Fong, E. J.; Schwartz, J. J.; Porcincula, D. H.; Kaczmarek, A. C.; Oakdale, J. S.; Moran, B. D.; Champley, K. M.; Rackson, C. M.; Muralidharan, A.; McLeod, R. R.; Shusteff, M. Highly Tunable Thiol–Ene Photoresins for Volumetric Additive Manufacturing. *Advanced Materials* 2020, 32(47), 2003376. DOI: 10.1002/adma.202003376.
- [4] Scott, P. J.; Meenakshisundaram, V.; Chartrain, N. A.; Sirrine, J. M.; Williams, C. B.; Long, T. E. Additive Manufacturing of Hydrocarbon Elastomers via Simultaneous Chain Extension and Cross-linking of Hydrogenated Polybutadiene. *ACS Applied Polymer Materials* 2019, 1(4), 684-690. DOI: 10.1021/acsapm.8b00150.
- [5] Moore, L. M. J.; Saludo, V. M. Q.; Grasdahl, O. H.; Smith, K. M.; Kolibaba, T. J.; Marcischak, J. C.; Killgore, J. P.; Snyder, J. J.; Yandek, G. R.; Ghiassi, K. B. Polybutadiene Click Chemistry: A Rapid and Direct Method for Vat Photopolymerization. *ACS Applied Polymer Materials* 2023, 5(11), 9138-9146. DOI: 10.1021/acsapm.3c01601.
- [6] Wu, Y.; Simpson, M. C.; Jin, J. Fast Hydrolytically Degradable 3D Printed Object Based on Aliphatic Polycarbonate Thiol–Yne Photoresins. *Macromolecular Chemistry and Physics* 2021, 222(6), 2000435. DOI: 10.1002/macp.202000435.
- [7] Wu, Y.; Simpson, M. C.; Jin, J. 3D Printing of Thiol–Yne Photoresins through Visible Light Photoredox Catalysis. *ChemistrySelect* 2022, 7(10), e202200319. DOI: 10.1002/slct.202200319.
- [8] Poon, K. C.; Segal, M.; Bahnick, A. J.; Chan, Y. M.; Gao, C.; Becker, M. L.; Williams, C. K. Digital Light Processing to Afford High Resolution and Degradable CO₂-Derived Copolymer Elastomers. *Angewandte Chemie International Edition* 2024, 63, e202407794. DOI: 10.1002/anie.202407794.
- [9] Hu, Y.; Rynk, J.; Barcelona, J.; Bowman, C. N. Modeling Diffusion-Limited Kinetics of Thiol–Ene Photopolymerizations. *Macromolecules* 2025, 58(21), 11967-11980. DOI: 10.1021/acs.macromol.5c01791.
- [10] Schwartz, J. J.; Porcincula, D. H.; Cook, C. C.; Fong, E. J.; Shusteff, M. Volumetric Additive Manufacturing of Shape Memory Polymers. *Polymer Chemistry* 2022, 13(13), 1813-1817. DOI: 10.1039/D1PY01723C.
- [11] Moore, L. M. J.; Summers, M. E.; Robinson, A. M.; Auguste, A. D.; Elia, R.; Gibson, J. A.; Marcischak, J. C.; Martin, J. A.; Ghiassi, K. B. 3D-Printed, Ultrastretchable Polychloroprene Elastomers via Thiol-ene Photopolymerization. *ACS Applied Materials & Interfaces* 2026, 18(17), 25278-25286. DOI: 10.1021/acsami.6c03614.

Standards and method references

- [S1] International Organization for Standardization. ISO 527-1:2019. Plastics — Determination of tensile properties — Part 1: General principles. <https://www.iso.org/standard/75824.html>.
- [S2] International Organization for Standardization. ISO 527-2:2025. Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics. <https://www.iso.org/standard/85822.html>.
- [S3] ASTM International. ASTM D638-22. Standard Test Method for Tensile Properties of Plastics. <https://store.astm.org/standards/d638>.
- [S4] International Organization for Standardization. ISO 37:2024. Rubber, vulcanized or thermoplastic — Determination of tensile stress-strain properties. <https://www.iso.org/standard/86892.html>.
- [S5] International Organization for Standardization. ISO 11357-2:2020. Plastics — Differential scanning calorimetry (DSC) — Part 2: Determination of glass transition temperature and step height. <https://www.iso.org/standard/77310.html>.
- [S6] International Organization for Standardization. ISO 6721-1:2019. Plastics — Determination of dynamic mechanical properties — Part 1: General principles. <https://www.iso.org/standard/73142.html>.
- [S7] ASTM International. ASTM D2765-16(2024). Standard Test Methods for Determination of Gel Content and Swell Ratio of Crosslinked Ethylene Plastics. <https://store.astm.org/standards/d2765>.
- [S8] International Organization for Standardization. ISO 6427:2025. Plastics — Determination of matter extractable by organic solvents (conventional methods). <https://www.iso.org/standard/88109.html>.