

Humidity-Responsive Photopolymer Actuators: Sorption, Swelling, Geometry, Hysteresis and Environmental Stability

Qualifying moisture-driven shape change by sorption history, diffusion length, differential swelling and repeatable response across humidity cycles

Juan Seguro

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

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Abstract

Humidity-responsive photopolymer actuators convert water sorption into differential swelling, modulus change or internal stress. Their response depends on equilibrium uptake, diffusion kinetics, geometry and the path by which relative humidity is changed. Printed anisotropy and post-cure can alter free volume and hydrophilicity, while bilayer or gradient designs amplify small material strains into large curvature. Qualification therefore requires sorption and actuation to be measured together. Mass uptake, dimensional strain, curvature, response time and hysteresis over controlled adsorption-desorption cycles establish whether the device is reversible or merely history dependent. The evidence supports an operating humidity window, a geometry-specific response-time limit and a cycle-stability requirement tied to retained dry and wet reference states. [1,2,3]

Keywords: humidity-responsive actuator; sorption; swelling; hydrogel; bilayer; hysteresis

1. Qualification problem: humidity-responsive photopolymer actuators

For the humidity actuator, acceptance concerns the relative-humidity interval that gives controlled deformation, the response time for the chosen geometry, and the amount of hysteresis or residual strain tolerated through cycling. Sorption, diffusion and mismatch strain are therefore quantified separately instead of being inferred from tip displacement alone.

1.1 Scope boundary.

ER-373 treats ambient water activity as the commanded stimulus for sorption-driven deformation. ER-379 considers humidity as an interferent in chemical sensing, and ER-359 addresses gravity, drainage and sedimentation in uncured resin; those questions do not replace equilibrium sorption, diffusion and bilayer-mismatch evidence in the finished actuator.

2. Governing balances for humidity-responsive photopolymer actuators

Humidity actuation begins with sorption, but shape change is controlled by how absorbed water couples to network expansion and mechanical constraint. At equilibrium, uptake is set by water activity and polymer chemistry; transiently, diffusion and surface transfer govern the gradient. In a bilayer or patterned structure, differential hygroscopic strain generates bending or twisting. Because modulus itself can decrease with water uptake, the relationship between sorption and curvature is nonlinear and may evolve during a humidity step. [1,2,3]

Water sorption changes polymer volume and often modulus; spatial gradients in uptake create transient stress before equilibrium is reached. [1,2]

Bilayers convert mismatch strain into curvature, while programmed orientation or porosity can bias the direction and speed of deformation. [1,2]

Adsorption and desorption need not follow the same path because network relaxation, hydrogen bonding and capillary condensation can generate hysteresis. [1,2,3]

The engineering state is fully specified only when humidity history, uptake, transport length and mechanical mismatch are preserved together, because each can shift curvature by a different mechanism.

3. Regime boundaries for humidity-responsive photopolymer actuators

At low humidity the response may be small because few sorption sites are occupied and the network remains stiff. In an intermediate range, uptake and swelling can provide a useful reversible stroke. At high humidity, plasticisation, large swelling, slow desorption or interfacial stress may dominate, increasing hysteresis and reducing force. Geometry can shift these regimes by changing diffusion distance and bending stiffness. A qualified device therefore needs an operating humidity interval rather than a single response value. [1,2,3]

Table 1 distinguishes equilibrium uptake, diffusion-controlled response and mismatch strain, allowing slow transport to be separated from a genuinely narrow humidity operating window.

Table 1. Regime indicators and engineering use.

Qualification therefore follows the slowest controlling process: uptake range, diffusion time and swelling mismatch must all remain inside the measured envelope for the selected geometry.

Indicator	Engineering meaning	Use
water uptake per dry polymer mass	Quantifies the equilibrium sorbed-water state that drives polymer expansion.	Used to define the humidity interval over which deformation is supported by measured sorption data.
diffusion length squared divided by exposure time	Compares geometry-controlled transport time with the available humidity step duration.	Used to determine whether a response-time claim transfers to another thickness or exposure schedule.
active/passive swelling mismatch	Represents the differential strain that generates curvature while also loading the interface.	Used to bound useful stroke before hysteresis, residual curvature or delamination dominates cycling.

4. Couplings that move the humidity-responsive photopolymer actuators

Material and environmental variables are inseparable. Temperature changes relative humidity, diffusion rate and modulus; post-cure changes network density and available polar groups; surface coatings modify both sorption rate and interfacial stress. Repeated cycling can generate microcracks or delamination in bilayers even when the polymer remains chemically stable. These couplings make simultaneous mass, shape and temperature measurements central to mechanism assignment. [1,2]

Post-cure and conversion affect residual hydrophilic groups and crosslink density, shifting both uptake and mechanical restraint. [1,2]

Feature thickness and porosity change diffusion distance, so a geometry change can alter response time without any chemistry change. [2,3]

Temperature is controlled together with humidity because sorption equilibrium and transport rate can both change with thermal state. [1,2]

5. Failure signatures and false diagnoses

A slow response can result from low diffusivity, excessive thickness or a surface barrier; a small final stroke can result from low uptake, high stiffness or poor layer mismatch. Hysteresis can originate in sorption itself, viscoelasticity or interface slip. Thickness variation, isolated-layer controls and sorption measurements provide the discriminating evidence. If mass recovers but shape does not, mechanical or interfacial damage is implicated rather than irreversible water retention. [1,2,3]

Reduced humidity response is separated into insufficient uptake, slow diffusion, interface failure and residual network relaxation. Mass uptake, thickness scaling, microscopy and repeated adsorption/desorption cycles provide different signatures for those possibilities.

Table 2. Failure-mode discrimination and required evidence.

Failure mode	Observable signature	Discriminating evidence
irreversible swelling or plasticization	dry-state dimensions fail to recover after desorption	mass and dimension recovery after extended dry hold
interfacial delamination in bilayers	curvature changes abruptly with edge separation or blistering	microscopy during humidity cycling
kinetic lag misread as equilibrium hysteresis	loop area shrinks strongly with longer dwell time	dwell-time sweep at fixed humidity endpoints
environmental ageing	progressive loss of wet-dry stroke over repeated cycles	cycle-block comparison with dry and wet reference checks

6. Measuring humidity-responsive photopolymer actuators with traceable uncertainty

Humidity-responsive actuation should be tied to water activity or relative humidity with controlled temperature, because relative humidity alone changes meaning when temperature changes. The measurement chain should record specimen mass, dimensional change or curvature, local temperature and the full humidity step history. Sorption and desorption branches must be measured separately because hysteresis in uptake can propagate directly into hysteresis in shape. [1,2,3]

Time constants should be interpreted together with thickness and exposed area. A faster response after perforation or thinning may result from shorter diffusion distance rather than a different swelling coefficient. Gravimetric sorption, dynamic vapour sorption or an equivalent uptake measurement can therefore be paired with curvature to determine whether kinetics are transport limited or mechanically limited. Repeated humidity cycling should include dry-state recovery so residual swelling and permanent set are visible. [1,2]

Relative humidity and temperature must be calibrated at the specimen position. Record specimen mass, one or more dimensional strains and the actuator output, such as curvature or tip displacement, during the same humidity programme. Equilibrium criteria should be explicit, for example a mass-change threshold over time, because a fixed dwell time can be adequate for one thickness and inadequate for another. [1,2,3]

7. Experiments that discriminate competing mechanisms

Bilayer bending provides a useful mechanism challenge because geometry and material contrast can be varied independently. Reversing the active/passive layer order should reverse bending direction if differential swelling is dominant. Changing active-layer thickness alters both water uptake and bending stiffness; using matched mass uptake with different thickness ratios helps test whether observed curvature follows laminate mechanics. [1,2,3]

Temperature is a critical interferent. A material can appear humidity gated when thermal expansion or temperature-dependent modulus changes during humidification. Controlled isothermal tests and combined humidity-temperature matrices are therefore required when

service conditions vary. Surface coatings or printed skin layers should also be challenged because they can slow sorption and produce gradients that increase transient curvature or internal stress. [1,2]

Construct adsorption and desorption isotherms on flat coupons before testing actuators. Then run humidity steps on at least two thicknesses to separate diffusion control from equilibrium swelling. For bilayers, measure curvature together with each layer thickness and modulus in dry and humid conditions. Cycling should include periodic long dry holds to distinguish recoverable water retention from permanent network change. [1,2]

8. Model identification and validation for humidity-responsive photopolymer actuators

A useful model combines a sorption isotherm, a diffusion law and a swelling-to-stress relation. Each layer in a bilayer should retain its own hygroscopic expansion coefficient and modulus. Fitting curvature alone is insufficient because different combinations of uptake and modulus mismatch can generate similar shapes. Independent sorption data and mechanical tests at several humidity states improve identifiability. [1,2,3]

Validation should include both equilibrium and transient responses. A model that reproduces final curvature but not response time cannot support cycle-frequency design, while one that reproduces kinetics but not the desorption branch cannot predict hysteresis. Transfer to another specimen thickness should preserve diffusion scaling; failure of that scaling is evidence for surface resistance, non-Fickian transport or humidity-dependent network relaxation. [1,2,3]

A humidity-actuator model first maps equilibrium water uptake against activity and then couples that sorption relation to diffusion through the active thickness. Mechanical curvature or extension is predicted from the measured swelling mismatch rather than used to infer sorption parameters. Bilayer constitutive parameters are obtained independently where possible.

Identifiability is tested with at least two thicknesses or exposure durations because diffusion and surface-transfer resistance can produce similar response curves. Heating the specimen at fixed water activity provides an additional check on whether apparent hysteresis comes from network relaxation or from an uncorrected thermodynamic change.

Uncertainty in humidity, dry mass, specimen thickness and curvature is propagated separately. The equilibrium operating window is limited by sorption uncertainty, the response-time decision by diffusion-length uncertainty, and the cycling decision by repeatability of residual curvature and mismatch strain. Shared thickness measurements are treated as correlated inputs.

9. Qualification envelope and technology decisions

Qualification should define equilibrium stroke or force, response and recovery time, hysteresis, residual deformation and retained response after cycling over a specified humidity-temperature domain. A calibration obtained at one temperature should not be transferred to another merely by matching relative humidity. The accepted envelope is the intersection of sorption stability, mechanical reversibility and required response time. [1,2,3]

Table 3. Technology-decision matrix.

ER-373 accepts a humidity window from equilibrium uptake and deformation, a response-time limit from geometry-specific diffusion evidence, and a cycling limit from residual strain and hysteresis. These decisions are coupled in service but are not interchangeable in the qualification record.

Decision	Minimum evidence	Acceptance logic
operating relative-humidity window	Calibrated measurements spanning the proposed limit for operating relative-humidity window, with at least one independent replicate near the boundary and the controlling water uptake per dry polymer mass reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'mass and dimension recovery after extended dry hold' does not trigger irreversible swelling or plasticization or move dry-state dimensions fail to recover after desorption outside the qualified range.
geometry-specific response-time limit	Calibrated measurements spanning the proposed limit for geometry-specific response-time limit, with at least one independent replicate near the boundary and the controlling diffusion length squared divided by exposure time reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'microscopy during humidity cycling' does not trigger interfacial delamination in bilayers or move curvature changes abruptly with edge separation or blistering outside the qualified range.
cycle-stability and hysteresis limit	Calibrated measurements spanning the proposed limit for cycle-stability and hysteresis limit, with at least one independent replicate near the boundary and the controlling active/passive swelling mismatch reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'dwell-time sweep at fixed humidity endpoints' does not trigger kinetic lag misread as equilibrium hysteresis or move loop area shrinks strongly with longer dwell time outside the qualified range.

10. Design consequences for humidity-responsive photopolymer actuators

Device design should select geometry according to the required humidity window, force and response time rather than maximize free curvature. High-swelling materials may provide large motion but can suffer slow recovery, creep or loss of dimensional precision. Patterned active regions, bilayer thickness ratio and cut geometry can amplify motion while keeping local strain below a damage threshold. [1,3]

For photopolymer printing, post-cure can change crosslink density and residual polarity, thereby changing both sorption and modulus. Qualification should therefore lock post-cure, conditioning humidity and specimen thickness. Protective coatings may improve environmental durability but must be treated as diffusion barriers whose ageing and adhesion are part of the actuator state. [1,2]

Large stroke can be obtained by increasing swelling mismatch, but that also increases interface stress and may slow equilibration if thicker active regions are used. Thin active layers, controlled porosity and mechanically robust interfaces therefore provide a more transferable route than maximizing water uptake alone. Encapsulation should be treated cautiously because it may suppress or delay the very stimulus being used. [1,2,3]

Production control records active/passive layer thicknesses, cure history and conditioning humidity before any curvature comparison. Changes in coating thickness are screened through diffusion time, whereas chemistry or post-cure changes are screened through sorption and equilibrium swelling before cycling evidence is reused.

11. Evidence gaps for humidity-responsive photopolymer actuators

The literature needs more datasets that connect water uptake directly to force and fatigue rather than only curvature. Long-term cycling across broad humidity ranges should report mass, residual deformation, crack initiation and any shift in sorption hysteresis. Such measurements would distinguish reversible hygromorphic actuation from progressive network damage. [1,2,3]

A second gap is operation under coupled environmental loads. Real devices can experience simultaneous humidity, temperature and mechanical bias. Factorial tests across those variables are needed to define whether humidity response is separable or whether thermal softening changes the mechanism. That evidence is essential before a laboratory calibration can be transferred to an uncontrolled environment. [1,2]

Data are sparse for long-duration humidity cycling of printed photopolymer actuators under simultaneous mechanical load. Another gap is the transfer from chamber-controlled humidity to liquid splash, condensation or sweat-like environments where capillary water and dissolved species change the mechanism. Standardized reporting should include dry-state conditioning, ramp rate, dwell criterion and temperature. [1,2,3]

For humidity actuators, the missing dataset is a time-resolved combination of water uptake, local humidity, temperature and deformation for more than one thickness. Including desorption and repeated cycles would allow equilibrium hysteresis to be separated from diffusion lag and interfacial damage.

Primary two-photon-printing evidence shows that humidity actuation can be both geometry-programmed and cycle-tested. Lv et al. fabricated PEGDA hydrogel microstructures with crosslink-density-controlled swelling and reported repeatable humidity-responsive actuation over 10,000 cycles. That result does not establish durability for every printed photopolymer, but it demonstrates that crosslink state, geometry and cycle count can be quantified together rather than inferred from a single curvature image. [4]

12. Qualification outcome for humidity-responsive photopolymer actuators

The engineering outcome is a humidity-response envelope tied to the printed geometry, conditioning history and temperature. Changes in thickness, active/passive layer ratio, coating, post-cure or service temperature alter transport or mechanics and therefore require renewed calibration rather than simple interpolation.

The qualified state is a joint domain of relative humidity, temperature, thickness, printed orientation, post-cure and cycle history. Operating range, response time and hysteresis are separate acceptance limits, and no universal humidity sensitivity is claimed.

References

1. Dai M, Picot OT, Verjans JMN, Bastiaansen CWM, Schenning APHJ. Humidity-Responsive Bilayer Actuators Based on a Liquid-Crystalline Polymer Network. *ACS Applied Materials & Interfaces*. 2013;5:4945-4950. doi:10.1021/am400681z.
2. Verpaalen RCP, Souren AEJ, Debije MG, Engels TAP, Bastiaansen CWM, Schenning APHJ. Unravelling humidity-gated, temperature responsive bilayer actuators. *Soft Matter*. 2020;16:2753-2759. doi:10.1039/D0SM00030B.
3. Basak S, Bandyopadhyay A. Next-gen biomimetic actuators: bilayer hydrogel evolution in the 21st century and its advancements from a post-2020 perspective. *RSC Applied Polymers*. 2024;2:583-605. doi:10.1039/D4LP00089G.
4. Lv C, Sun XC, Xia H, Yu YH, Wang G, Cao XW, Li SX, Wang YS, Chen QD, Yu YD, Sun HB. Humidity-responsive actuation of programmable hydrogel microstructures based on 3D printing. *Sensors and Actuators B: Chemical*. 2018;259:736-744. doi:10.1016/j.snb.2017.12.053.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-373 contains no comparative recommendation between commercial products.

Data availability

ER-373 is a literature-based engineering review; no new experimental dataset was generated.