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Moisture as a Plasticity Switch in Blowouts: Glass-Transition Behavior, Viscoelastic Response, and Tension-Defined Shape

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Abstract

Human hair is a hierarchical α-keratin composite whose mechanical response is governed by the interplay between crystalline intermediate filaments and a moisture-sensitive amorphous matrix. This review synthesizes evidence from polymer physics, thermal analysis, and cosmetic science to reframe the blowout as a controlled glass-transition event. Water acts as a potent plasticizer for the keratin matrix, depressing the effective glass-transition temperature (Tg) from approximately 144 °C in the dry state to near ambient temperature at full hydration. When Tg falls below the working temperature, the matrix transitions from a rigid glassy state to a compliant rubbery one, opening a "shaping window" in which hydrogen bonds can be disrupted and reformed under applied tension. As moisture leaves the fiber during blow-drying, the matrix re-vitrifies, locking the imposed curvature through a reorganized hydrogen-bond network. The temporary set is therefore not a function of heat alone but of the time-dependent moisture gradient across the fiber cross-section. This framework connects glass-transition theory, viscoelastic relaxation models, and bond reorganization kinetics to provide a unified, materials-science account of everyday hair shaping.

Keywords hair, glass transition, viscoelasticity, hydrogen bonds, moisture

1. Introduction

The blowout - the act of reshaping wet hair into a new, temporarily stable configuration using a brush and a dryer - is among the most widely practiced hair-styling procedures worldwide. Despite its ubiquity, the physical mechanism by which moisture, heat, and tension cooperate to produce a temporary set has rarely been described in a unified, quantitative framework. Practitioners rely on empirically developed timing rules ("section must be 80% dry before wrapping") that, while effective, remain disconnected from the underlying materials science.

Human hair is a biological composite of α-keratin proteins organized at multiple hierarchical levels [1,2]. At the fiber scale, two mechanically distinct phases coexist: crystalline intermediate filaments (IFs) embedded in an amorphous matrix of keratin-associated proteins (KAPs) [3,4]. The IFs provide tensile stiffness and are essentially insensitive to moisture, whereas the KAP matrix absorbs water, swells, and undergoes dramatic changes in viscoelastic behavior as its glass-transition temperature shifts [5-7].

This two-phase architecture makes hair a natural shape-memory composite [8]. When the matrix is plasticized - by water, by heat, or by both - it becomes compliant, allowing the fiber to be reshaped. When the plasticizer is removed (the hair dries) or the temperature drops below Tg, the matrix re-vitrifies, and the new shape is locked in by a reorganized network of hydrogen bonds [9,10]. The set is reversible because re-wetting disrupts these bonds, and the fiber relaxes toward the configuration dictated by its permanent disulfide-bonded network [10,11].

The purpose of this review is to (1) compile and critically evaluate the evidence for moisture as the primary plasticity switch in temporary hair shaping, (2) connect glass-transition theory with viscoelastic relaxation models to describe the "shaping window" quantitatively, and (3) propose a mechanistic framework that links molecular-level bond reorganization to macroscopic styling outcomes. We draw on research from polymer physics, thermal analysis, fiber mechanics, and cosmetic science spanning more than four decades.

2. Literature Search Strategy and Methodology

2.1. Search Strategy

A systematic literature search was conducted across four major databases: PubMed/MEDLINE, Web of Science Core Collection, Scopus, and Google Scholar. The search covered publications from January 1959 through December 2025. Search terms were used in various combinations and included: "hair keratin glass transition", "keratin viscoelastic", "hair moisture mechanical properties", "α-keratin plasticizer", "hair hydrogen bond set", "keratin fiber stress relaxation", "hair shape memory", "wool keratin Tg", "Fox equation keratin", "hair temporary set mechanism", and "blowout hair science". Reference lists of identified articles were manually screened for additional relevant publications not captured by the electronic search.

2.2. Inclusion and Exclusion Criteria

Publications were included if they met at least one of the following criteria: (a) reported original experimental data on the thermal, mechanical, or viscoelastic properties of human hair or wool keratin fibers; (b) proposed or validated physical models for the glass transition, stress relaxation, or shape-memory behavior of α-keratin composites; (c) provided quantitative data on the effect of moisture on keratin mechanical properties. No restrictions were placed on publication language or article type (peer-reviewed original research, reviews, book chapters, and conference proceedings were all considered). Publications that addressed only chemical treatments (permanent waving, relaxing, coloring) without reporting physical or mechanical data relevant to temporary shaping were excluded. A total of 39 sources met the inclusion criteria and form the reference list for this review.

2.3. Data Visualization

All figures in this article are schematic representations created by the authors to summarize and integrate data reported across multiple primary sources. Figures were produced using scalable vector graphics (SVG) and rendered in HTML5 for iterative visual refinement before final export. No original experimental data were collected for this review; all quantitative values plotted in Figures 2 and 3 are derived from published experimental results as cited in the respective figure captions.

3. Hair as a Hierarchical Keratin Composite

3.1. Molecular and Supramolecular Architecture

Human hair fibers are formed from trichocytes - terminally differentiated epithelial cells - that are almost entirely filled with α-keratin intermediate filaments (IFs) and their associated matrix proteins [1,2]. At the molecular level, each IF is assembled from coiled-coil dimers of type I and type II keratins, which aggregate into protofilaments, protofibrils, and finally the ~7.5 nm diameter IF [12]. The IFs are embedded in a sulfur-rich matrix of globular keratin-associated proteins (KAPs), cross-linked extensively by disulfide bonds [2,13].

The ratio of IF to matrix varies across ethnic hair types and along the fiber length, but the general architecture - crystalline rods in an amorphous, cross-linked matrix - is universal [1]. This composite structure is the key to understanding hair's mechanical behavior: the IFs carry tensile load along the fiber axis, while the matrix transfers shear stress between filaments and provides lateral cohesion [3,4,14].

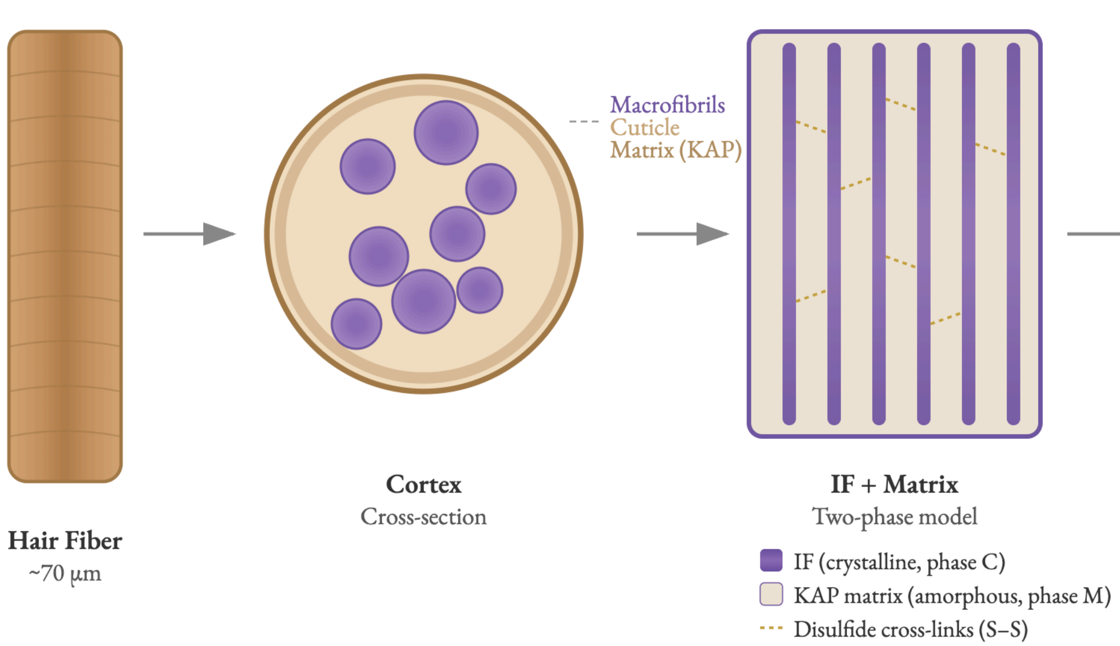

Figure 1. Hierarchical structure of human hair fiber. From left to right: the intact hair fiber (~70 μm diameter) showing overlapping cuticle scales; the cortex cross-section reveals macrofibrils (purple) embedded in the KAP matrix (tan), surrounded by the cuticle layer; the two-phase model shows crystalline intermediate filaments (IFs, phase C) aligned parallel to the fiber axis within the amorphous KAP matrix (phase M), cross-linked by disulfide bonds (S-S); the coiled-coil α-helix dimer (~45 nm) is the fundamental building block of each IF. Adapted from Feughelman [3,4] and Robbins [1].

3.2. The Two-Phase Mechanical Model

Feughelman's two-phase model [3,4], introduced in 1959 and refined over subsequent decades, remains the foundational framework for hair mechanics. In this model, the fiber is treated as a unidirectional composite of water-insensitive cylinders (IFs, phase C) embedded in a water-absorbing matrix (phase M). The key insight is that the elastic modulus of the IF phase is essentially independent of moisture content, whereas the viscoelastic properties of the matrix depend strongly on both moisture and temperature [3,15,16].

This separation has been confirmed experimentally. Yu et al. [5,6] showed that increasing relative humidity decreases the apparent Young's modulus of hair and increases extensibility, with the effect attributable to matrix softening; the stress-strain curve retains its characteristic shape (elastic region, yield/transformation region, post-yield region) across humidity levels, consistent with IF-dominated yielding in a progressively softer matrix [17]. Wortmann et al. [17] further demonstrated that dry straining beyond ~2% induces a strain-driven glass transition in the matrix, which then flows as a high-viscosity liquid - an observation that conceptually links mechanical deformation to the moisture-induced glass transition discussed in Section 4.

4. Moisture as a Plasticizer: Glass-Transition Behavior

4.1. The Glass Transition in Alpha-Keratin

Like all amorphous polymers, the keratin matrix undergoes a glass transition - a reversible change from a rigid, glassy state to a mobile, rubbery state - as temperature increases through a characteristic temperature Tg [18]. In the dry state, the Tg of human hair has been determined by differential scanning calorimetry (DSC) to be approximately 144 °C [7], substantially lower than the 174 °C reported for wool [19]. The difference has been attributed to a higher proportion of hydrophobic KAP proteins in the human hair matrix, which act as an "internal plasticizer" even in the absence of water [7,20].

Milczarek et al. [18] identified three thermal events in hair by DSC: (i) removal of loosely bound water near 70 °C, (ii) a broad endotherm near 155 °C in the amorphous matrix region (termed a "toughening transition" by the original authors, later reinterpreted as a glass transition by Wortmann et al. [7,19]), and (iii) melting/denaturation of the α-helical crystallites near 233 °C. Cao and Leroy [21] showed that the melting temperature of the α-form crystallites is itself moisture-dependent, dropping from ~205 °C (dry) to ~155 °C at 23% moisture content, following Flory-Huggins theory.

4.2. Water Depresses Tg: The Fox Equation

The relationship between moisture content and Tg in α-keratins is well described by the Fox equation:

$$1/T_g = w_k/T_{g,k} + w_w/T_{g,w}$$

where wk and ww are the weight fractions of keratin and water, respectively, and Tg,k and Tg,w are their respective glass-transition temperatures [7,19]. For human hair, Wortmann et al. [7] obtained Tg,k ≈ 144 °C (dry keratin) and used Tg,w ≈ -137 °C (amorphous ice), yielding a steeply declining Tg(moisture) curve.

The practical consequences are profound. At typical ambient conditions (~60% RH, corresponding to ~12-15% moisture by mass), the Tg of the matrix falls to approximately 60-80 °C - well within the range of blow-dryer air temperatures. At full saturation (~30% moisture, corresponding to freshly washed, towel-dried hair), Tg approaches 35-40 °C [22] - essentially body temperature. This means that fully wet hair is, from a polymer-physics standpoint, always above its glass-transition temperature: the matrix is rubbery, compliant, and permissive of molecular rearrangement.

Phillips [22] provided early DSC evidence for this in wool: at 22% moisture, the glass transition appeared at approximately 35 °C. Jinks et al. [20] extended the analysis to chemically modified hair, showing that esterification with progressively longer alkyl chains further depresses Tg in a humidity-dependent manner, supporting the "internal plasticization" hypothesis.

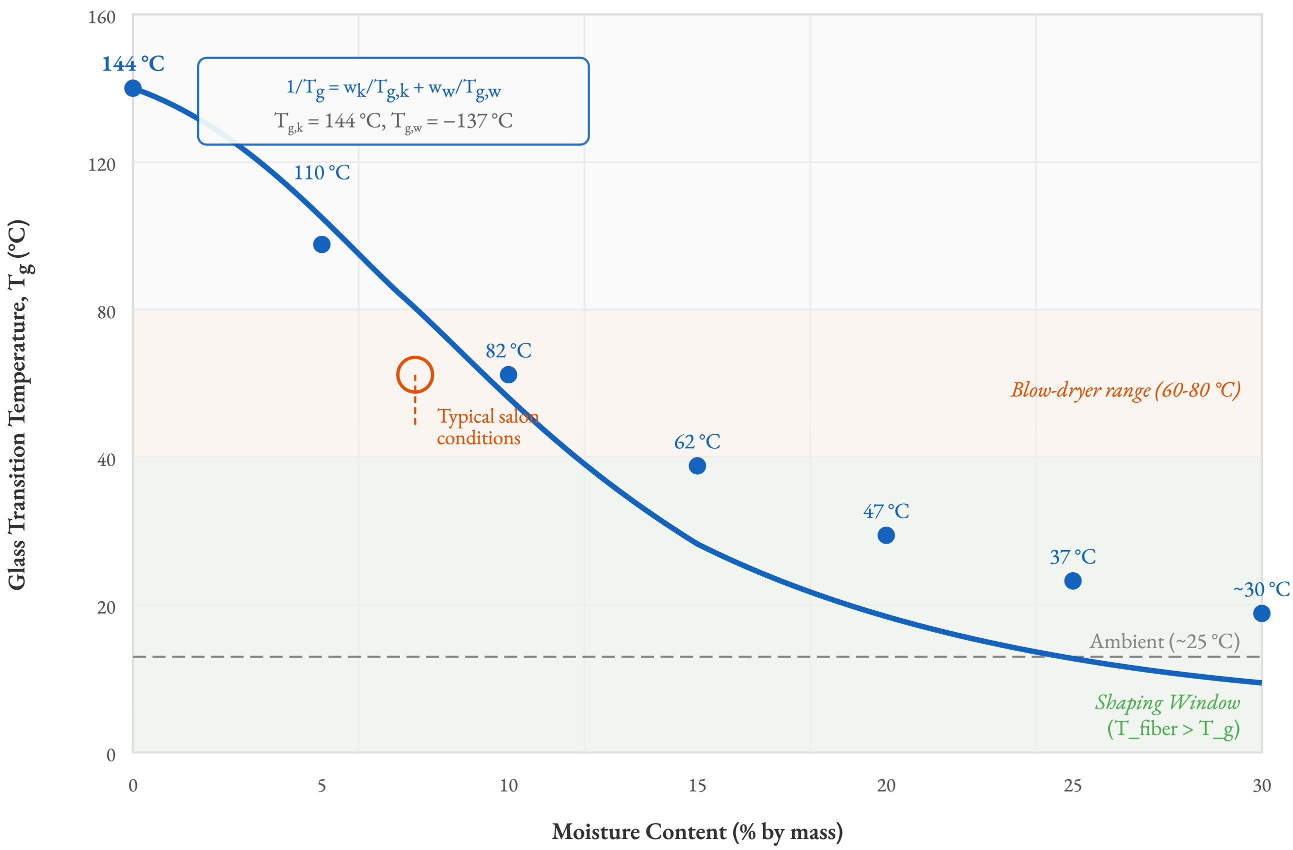

Figure 2. Glass-transition temperature (Tg) of the keratin matrix as a function of moisture content, calculated from the Fox equation using Tg,k = 144 °C and Tg,w = -137 °C [7,19]. The green shaded region indicates the "shaping window" where Tfiber > Tg and the matrix is in a rubbery, compliant state. The orange band marks the typical blow-dryer air temperature range (60-80 °C). At full hydration (~30% moisture), Tg drops below ambient temperature, meaning the wet matrix is always above its glass transition.

4.3. Implications for the Blowout "Shaping Window"

The glass-transition framework provides a precise definition of the "shaping window" - the time interval during which hair can be effectively reshaped:

The window OPENS when the matrix moisture content is sufficient to depress Tg below the working temperature (Tair from the dryer or ambient T). In practice, this occurs whenever the hair is wet.

The window CLOSES as moisture leaves the fiber and Tg rises back above the working temperature. The matrix re-vitrifies, and molecular mobility drops by orders of magnitude.

The shaping window is therefore not a fixed duration but a function of the evolving moisture profile across the fiber cross-section. Since water diffusion in hair is slow relative to surface evaporation [23], the outer cortex dries (and vitrifies) before the inner cortex, creating a radial gradient in mechanical state. This gradient explains the practical observation that "over-drying" a section before shaping it results in poor set: the outer matrix has already vitrified and resists reorganization.

5. Viscoelastic Response Under Tension

5.1. Hair as a Nonlinear Viscoelastic Material

Human hair is not an elastic solid. It is a viscoelastic material whose stress-strain response depends on time, strain rate, temperature, and moisture content [5,6,24,25]. Bendit [26] argued that there is no true Hookean (linear elastic) region in the stress-strain curve of keratin; what appears as a linear region at small strains is actually a pseudo-linear inflection point arising from opposing nonlinear contributions.

Stress-relaxation experiments confirm the viscoelastic nature: when hair is rapidly extended and held at constant length, the force decays continuously over time. Barnes and Roberts [24] showed that force drops to approximately 50% of its initial value within ~15 hours at moderate extensions (0.5-6.5%), with the isochronous stress-strain curve departing from linearity above ~1% strain.

5.2. Relaxation Spectra and the Maxwell-Wiechert Model

Yu et al. [5] performed systematic stress-relaxation and dynamic mechanical analysis (DMA) on human hair and fitted the data to a Maxwell-Wiechert (generalized Maxwell) model. They identified two characteristic relaxation time constants:

$\tau_1 \approx 11$ s (short-term relaxation, attributed to amorphous matrix-IF interface interactions)

$\tau_2 \approx 207$ s (long-term relaxation, attributed to cellular-level rearrangement)

The short-term constant is directly relevant to blowout practice: it defines the timescale over which tension applied during brushing produces measurable stress relaxation in the matrix. If the section is held under tension for at least several multiples of τ_1 (i.e., 30-60 seconds), significant matrix reorganization occurs.

The same study [5] identified a DMA glass transition at approximately 55 °C under wet conditions and showed that the strain-rate sensitivity of human hair ($m \approx 0.11$) drops to ~0.05 after cleavage of disulfide bonds, confirming that matrix cross-link density modulates the viscoelastic response.

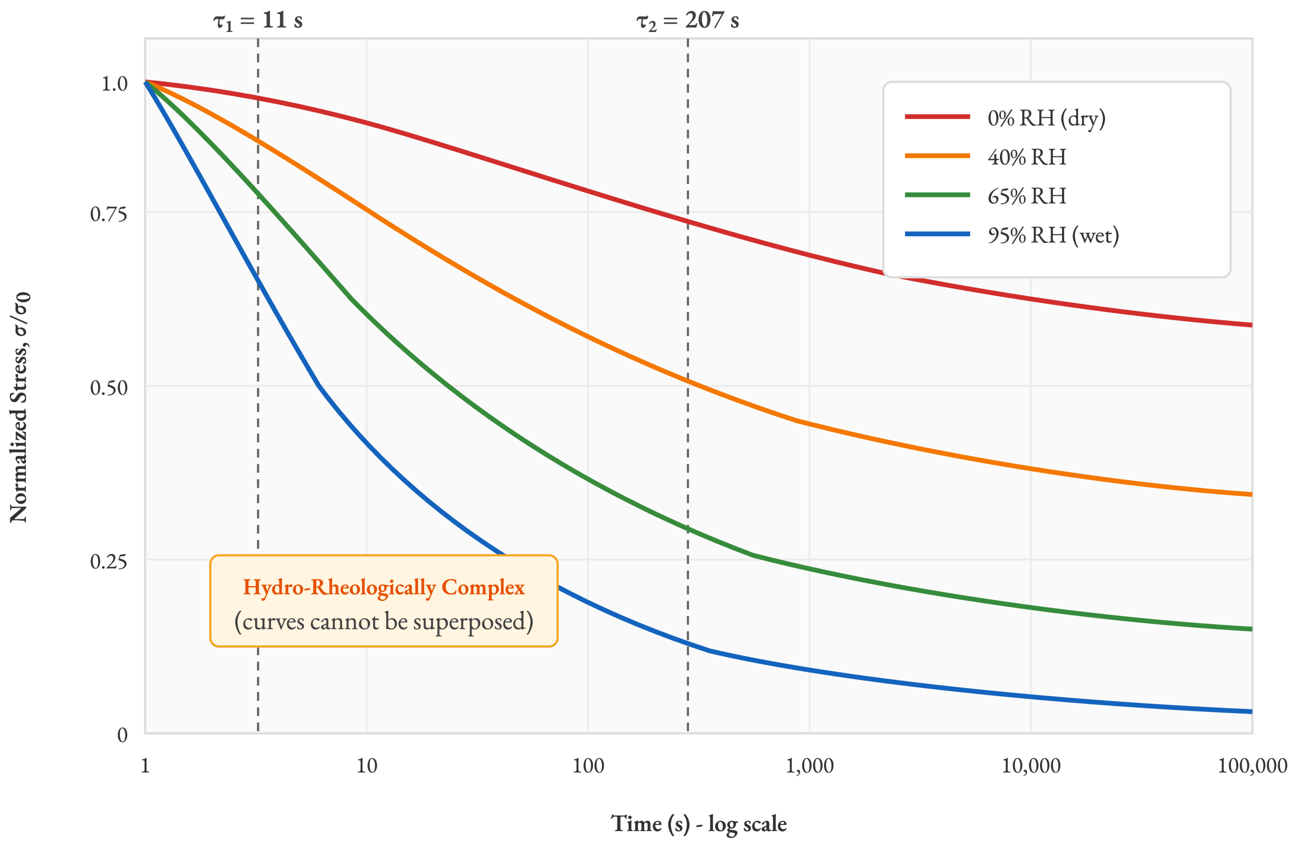

Figure 3. Schematic stress-relaxation curves for human hair at different relative humidity levels, based on data from Yu et al. [5], Zuidema et al. [25], and Wortmann et al. [27]. At higher moisture content, relaxation is faster and more complete. The vertical dashed lines mark the two characteristic relaxation time constants identified by Yu et al. [5]: $\tau 1 \sim 11$ s (matrix-IF interface) and $\tau 2 \sim 207$ s (cellular rearrangement). Hair exhibits hydro-rheologically complex (HRC) behavior: the shape of the relaxation function itself changes with humidity, precluding simple time-humidity superposition [25].

5.3. Humidity-Dependent Relaxation

The critical link between moisture and viscoelasticity was established by Zuidema et al. [25], who measured bending relaxation at different humidity levels. They found that relaxation time decreases significantly with increasing moisture content - covering roughly two-thirds of a decade over the 0-20% moisture range. Crucially, hair exhibits "hydro-rheologically complex" (HRC) behavior: it is not possible to construct a single master curve by simple time-humidity shifting. The shape of the relaxation function itself changes with humidity, reflecting a qualitative change in the molecular processes governing relaxation as the matrix transitions through Tg [25].

Wortmann et al. [27] quantified this further using bending recovery measurements and the Kohlrausch-Williams-Watts (KWW) stretched-exponential relaxation function. The relaxation rate increases strongly with humidity. The modulus ratio K0 (the ratio of short-time to equilibrium moduli in the matrix) remains constant at ~6.1 for moisture contents up to ~10%, then decreases linearly - suggesting a threshold effect that coincides with Tg crossing from above to below ambient temperature.

Benzarti et al. [28] confirmed these findings using relaxation tests, showing that hydration "substantially reduces the elastic modulus and changes the relaxation dynamics of hair fibers." The converging evidence is clear: moisture does not simply make hair "softer" in a static sense - it fundamentally alters the time-dependent mechanical response, accelerating stress relaxation and enabling faster reorganization under applied tension.

6. The Shaping Window: A Moisture-Controlled Plasticity Regime

6.1. Opening the Window: Wetting and Heating

The "shaping window" is the period during which the hair matrix is sufficiently above its glass transition to permit large-scale molecular rearrangement under tension. Two routes can open it:

(a) Wetting: Increasing moisture content from ~12% (ambient) to ~30% (saturated) depresses Tg from ~60-80 °C to ~35 °C, well below ambient temperature [7,22]. The matrix becomes rubbery.

(b) Heating: Raising the fiber temperature above Tg at the prevailing moisture content. A blow-dryer operating at 60-80 °C can push hair above its Tg even at intermediate moisture levels (~15-20%).

In practice, both mechanisms operate simultaneously during a blowout. The hair starts wet (Tg low, matrix rubbery); as it dries under hot airflow, Tg rises, but the air temperature compensates for a time. The shaping window remains open as long as Tfiber > Tg(moisturelocal).

6.2. Working Within the Window: Tension and Time

During the shaping window, the practitioner applies tension through a round brush while directing hot air at the section. The tension serves two purposes:

(1) It produces a defined curvature that will become the "target shape" once the set is locked in.

(2) It accelerates stress relaxation in the matrix by providing a sustained driving force for molecular reorganization [5,27].

The optimal working time is determined by the short-term relaxation constant ($\tau_1 \approx 11$ s): holding a section under tension for at least 3-5τ_1 (33-55 seconds) allows the majority of the fast-mode relaxation to occur, meaning the matrix has substantially reorganized around the new curvature. This aligns well with the empirical 30-60 second rule used by experienced stylists.

6.3. Closing the Window: Drying and Cooling

As water evaporates from the fiber surface and diffuses outward from the cortex, the local moisture content drops, and Tg rises above the local temperature. The matrix re-vitrifies radially inward - the outer cortex first, the medullary region last. Hydrogen bonds reform in the new molecular configuration, stabilizing the imposed shape [9,10,34].

The "cooling shot" - a blast of cool air applied to a freshly shaped section - accelerates window closure by dropping Tfiber below Tg at the current (nearly dry) moisture content, ensuring rapid and uniform vitrification. This is not merely a cosmetic trick; it is a thermodynamically sound quenching step that arrests molecular mobility before any relaxation can undo the set.

Breakspear et al. [9] quantified the kinetics of shape relaxation after thermal shaping, proposing that the rate-controlling mechanism involves thiol-disulfide reformation of intra-protein bonds rather than simple hydrogen-bond exchange. In air at ambient humidity, a well-set blowout relaxes slowly because the matrix moisture content is low (~12-15%) and Tg is above ambient; in humid conditions, moisture uptake depresses Tg, reopens the shaping window locally, and accelerates relaxation - explaining the well-known "frizz effect" of humidity.

7. Hydrogen Bond Reorganization and Temporary Set

7.1. The Molecular Basis of Temporary Shape

The temporary set produced by a blowout or water-wave is fundamentally different from a "permanent" wave, which relies on disulfide bond exchange through reduction/oxidation chemistry [8]. The temporary set is governed entirely by hydrogen bonds and, to a lesser extent, ionic (salt) bonds within the keratin matrix [10,11].

Breakspear et al. [10] estimated that keratin fibers contain approximately nine hydrogen bonds for every one disulfide bond. Under dry conditions, this dense hydrogen-bond network contributes significantly to fiber stiffness and shape retention. Under wet conditions, water molecules compete for hydrogen-bonding sites on the polypeptide backbone, effectively "annulling" a large fraction of the interchain hydrogen bonds [10] and causing the dramatic softening observed experimentally.

Cloete et al. [34] provided preliminary experimental evidence that weak hydrogen bonds are the molecular basis of temporary (cohesive) shape changes in curly human hair. When water disrupts hydrogen bonds, the fiber can be reshaped; upon drying, new hydrogen bonds form in the new configuration, stabilizing the temporary set. Re-wetting reverses the process entirely.

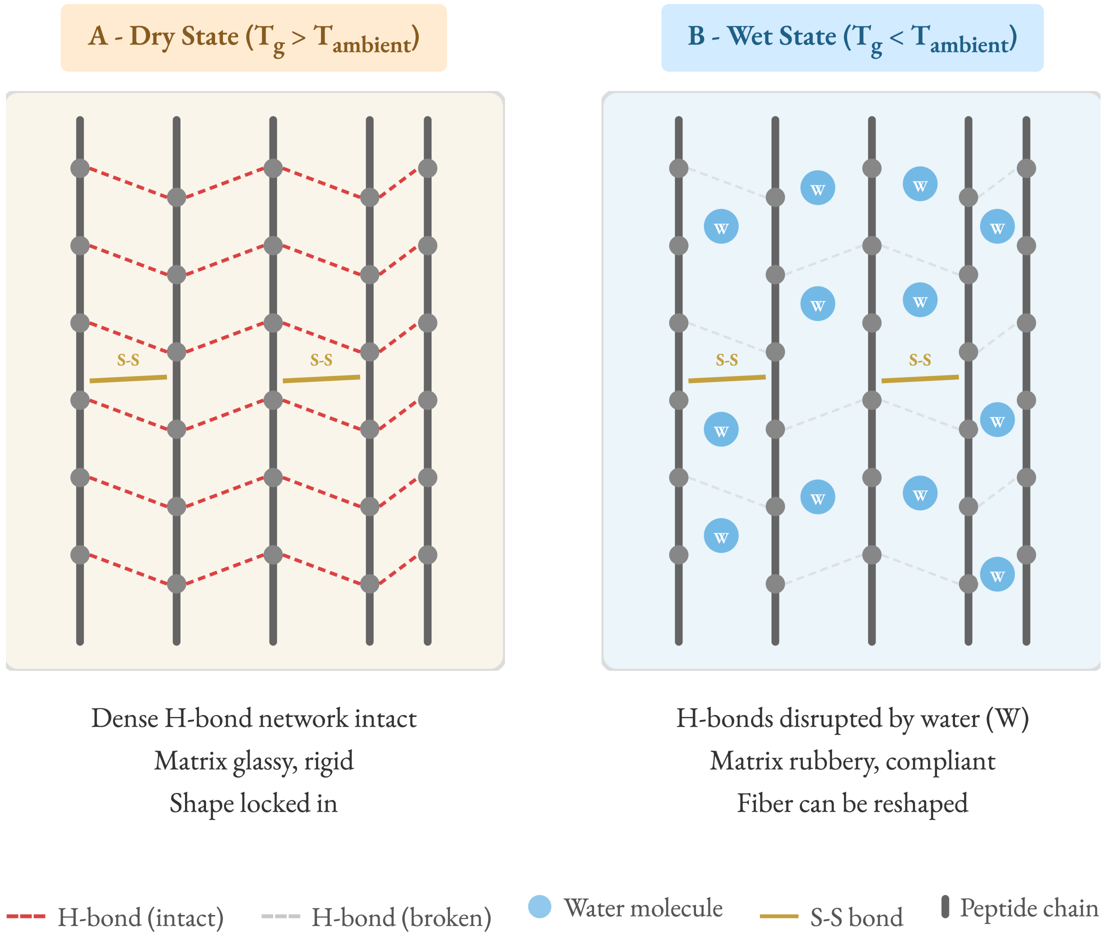

Figure 5. Schematic comparison of the hydrogen-bond network in dry (A) and wet (B) states. (A) In the dry state (Tg > Tambient), a dense network of interchain hydrogen bonds (red dashed lines) stabilizes the matrix in a glassy, rigid configuration. Disulfide bonds (S-S) define the permanent shape. (B) In the wet state (Tg < Tambient), water molecules (blue circles, W) compete for hydrogen-bonding sites on the peptide backbone, disrupting the majority of interchain H-bonds. The matrix becomes rubbery and compliant, allowing the fiber to be reshaped. Disulfide bonds remain intact and define the "permanent" shape to which the fiber returns upon re-wetting [10,34,35].

7.2. Two Types of Hydrogen Bonds

Breakspear et al. [35] proposed a mechano-chemical model in which two distinct populations of hydrogen bonds contribute to the elastic modulus:

Type 1 ("native"): Hydrogen bonds present in the original, undamaged fiber. These are relatively stable and resistant to humidity fluctuations.

Type 2 ("compensatory"): Hydrogen bonds that form when disulfide bonds are broken (by oxidative damage, bleaching, etc.). These compensatory bonds are more humidity-sensitive and less stable.

This distinction has practical implications: chemically treated hair (bleached, colored) relies more heavily on Type 2 hydrogen bonds for mechanical integrity, making it more susceptible to humidity-induced set loss than virgin hair [35].

7.3. Set Stability and Relaxation Kinetics

The stability of a temporary set depends on the balance between hydrogen-bond lock-in and hydrogen-bond exchange:

Lock-in: Upon drying, hydrogen bonds reform between peptide groups that are now in a new spatial configuration. The low moisture content (Tg > Tambient) ensures that molecular mobility is insufficient to undo these bonds spontaneously [27,29].

Exchange: Ambient humidity slowly reintroduces water molecules into the matrix, enabling localized hydrogen-bond exchange. Over time, this exchange allows the fiber to drift back toward its "permanent" shape (dictated by the disulfide network) [9,36].

Wortmann et al. [36] developed a mathematical model for the time- and humidity-dependent decay of a water wave (temporary set), showing that the cohesive set decays as a stretched exponential whose rate constant is a strong function of relative humidity. Itou et al. [37] demonstrated by near-infrared spectroscopy that treating hair with specific organic acids creates "strong and stable hydrogen bonds with hair proteins," suppressing the hydrogen-bond exchange that causes set degradation - a finding with direct implications for extending blowout longevity.

8. Toward a Unified Mechanistic Framework

The evidence reviewed above converges on a coherent, three-step mechanistic framework for the blowout:

Step 1 - Plasticization (Opening the Shaping Window): Water enters the fiber, plasticizes the amorphous keratin matrix, and depresses Tg below the working temperature. The matrix transitions from a rigid glass to a compliant rubber. Existing hydrogen bonds between polypeptide chains are disrupted by competition with water molecules. The fiber becomes extensible and mechanically pliable.

Step 2 - Shaping Under Tension (Working Within the Window): The practitioner applies a defined curvature by wrapping hair around a brush while directing hot air. The combination of sustained tension and elevated temperature (maintaining $T > T_g$ during drying) accelerates stress relaxation in the viscoelastic matrix. The two relaxation modes ($\tau_1 \approx 11$ s, $\tau_2 \approx 207$ s) govern the rate at which the matrix reorganizes around the new geometry. Holding tension for at least 30-60 seconds ensures that the fast mode is essentially complete.

Step 3 - Vitrification (Closing the Shaping Window): As moisture leaves the fiber, Tg rises above the fiber temperature. The matrix re-vitrifies, molecular mobility drops by orders of magnitude, and hydrogen bonds reform in the new configuration. The curvature is "frozen in." A cool-air blast accelerates this step by reducing T_{fiber} below the rising Tg. The resulting set is stable as long as ambient humidity remains low enough to prevent significant re-plasticization.

This framework explains several practical observations:

(a) "Over-drying before shaping" fails because the outer matrix has already re-vitrified ($T_g > T_{air}$) before tension is applied.

(b) Humidity causes set loss because moisture re-enters the matrix, depresses Tg locally, and enables hydrogen-bond exchange.

(c) Chemically damaged hair loses its set faster because it relies on humidity-sensitive Type 2 hydrogen bonds [35].

(d) The cool-shot technique works because it is a quenching step that arrests molecular mobility before relaxation can undo the set.

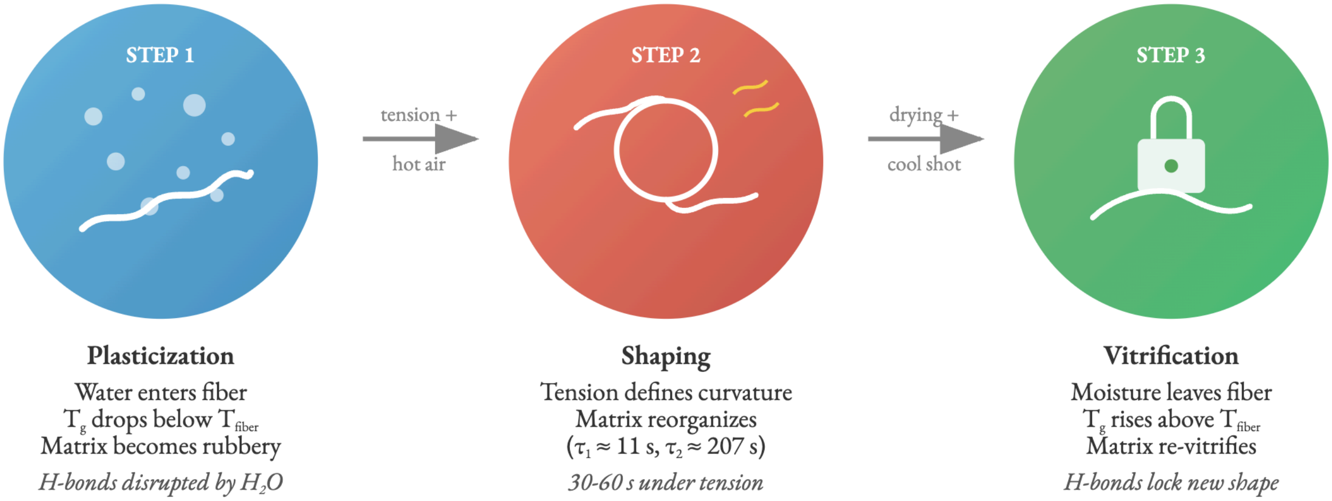

Figure 4. Three-step mechanistic framework for the blowout. Step 1 (Plasticization): Water enters the fiber and depresses Tg below the working temperature; the matrix becomes rubbery and hydrogen bonds are disrupted. Step 2 (Shaping): The practitioner applies tension through a round brush while directing hot air; the matrix reorganizes around the new curvature over ~30-60 s (governed by τ1 ~ 11 s and τ2 ~ 207 s). Step 3 (Vitrification): As moisture leaves the fiber, Tg rises above the fiber temperature; the matrix re-vitrifies and hydrogen bonds reform in the new configuration, locking the imposed curvature. A cool-air blast accelerates this step.

9. Conclusions and Future Directions

This review has presented evidence that the blowout is best understood as a controlled glass-transition event rather than a purely thermal process. The key conclusions are:

1. Moisture is the primary plasticity switch. Water depresses the glass-transition temperature of the keratin matrix from ~144 °C (dry) to near body temperature (fully wet), converting the matrix from a rigid glass to a compliant rubber [7,22].

2. The "shaping window" is defined by the condition Tfiber > Tg(moisture). It opens when the hair is wet and closes as drying proceeds, with the rate of closure governed by water diffusion kinetics [23].

3. Hair is a nonlinear viscoelastic material with well-characterized relaxation time constants (τ1 ≈ 11 s, τ2 ≈ 207 s) [5]. The relaxation rate is strongly humidity-dependent [25,27].

4. The temporary set is stabilized by hydrogen-bond reorganization upon drying and destabilized by humidity-driven hydrogen-bond exchange [9,10,34].

5. Chemically treated hair is more vulnerable to set loss because compensatory (Type 2) hydrogen bonds are more humidity-sensitive than native (Type 1) bonds [35].

Future research directions include: (a) in situ measurement of moisture gradients across the fiber cross-section during blow-drying, using techniques such as confocal Raman or near-infrared imaging; (b) development of predictive models that couple water diffusion, heat transfer, and viscoelastic relaxation in a single simulation framework; (c) systematic evaluation of how fiber diameter, cuticle integrity, and ethnic hair type modulate the shaping-window dynamics; and (d) design of styling products that selectively modulate Tg or hydrogen-bond stability to extend set longevity without compromising reversibility.

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