

Hempoxies 54

*Programmable Epoxidized Hempseed Oil
Vitrimers Composites for #MissionNATO*

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The 2036 Strategic Imperative demands zero-compromise performance combined with independent supply chains.

Global defense infrastructure relies heavily on vulnerable, environmentally taxing petroleum feedstocks.

Industrial hemp presents a multi-domain biological solution.

Biomass efficiency is unprecedented: **1 hectare of hemp** yields the equivalent biomass of **4 hectares** of timber, requiring **50% less water** for cultivation.

25%

Petroleum
Displacement

40%

Carbon Emission
Reduction

400 MPa

Tensile Strength
Target

50 GPa

Modulus
Target

Hempoxies 54 merges a dynamically crosslinked bio-resin with a 6-phase hierarchical carbon architecture



Vitrimers break the compromise between thermoset strength and thermoplastic reprocessability.

Conventional Petroleum Epoxies

Non-recyclable

Brittle fracture

Highly petroleum-dependent

Thermoplastic CFRPs

High processing temperature

Limited toughness

High melt viscosity

Hempoxies 54

Ambient-stable recyclability

Thermal self-healing

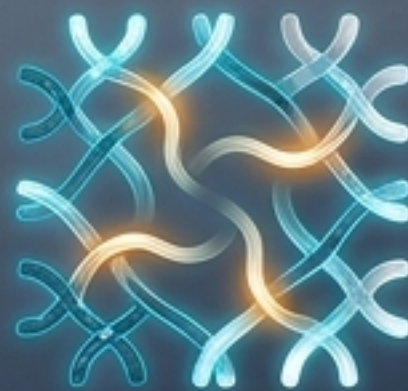
Fully bio-sourced matrix

Low-viscosity VARTM processing



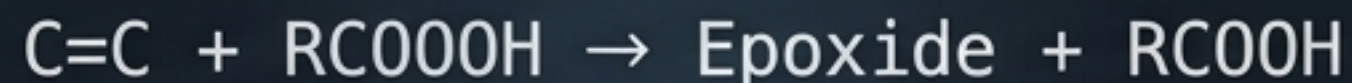
Traditional Epoxy:
Brittle, Permanent

Thermal
Trigger



Vitrimer:
Dynamic, Thermal Re-knitting

Hempseed oil yields high unsaturation density for optimal peracid epoxidation.



Hempseed oil viability is driven by high polyunsaturated fatty acid content: Linoleic (~55%) and α -linolenic (~17%) acids.

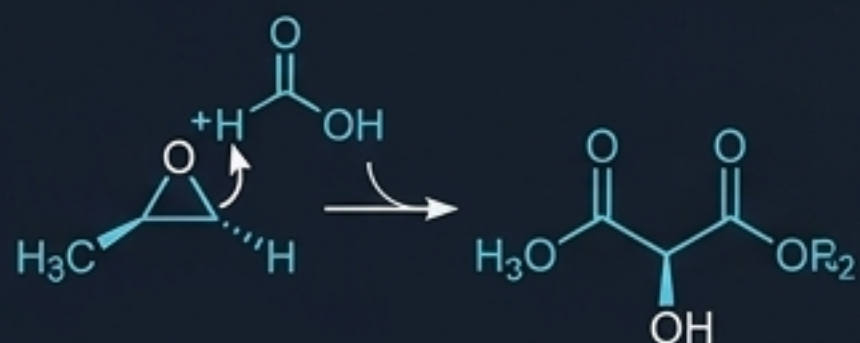
KEY EHO PARAMETERS

Iodine Value	~145–165 g I ₂ / 100 g
OOC (Oxirane Oxygen Content)	4–7 wt% target
Functionality	4–6 oxirane groups per triglyceride
Viscosity	~40–60 mPa·s at 25°C

The network forms and activates through a precise three-stage chemical sequence.

Stage 1: Initiation

90°C 2h



Acetic Acid acts as a proton donor, opening the epoxide ring to generate β-hydroxy esters.

Critical target: $[\text{OH}]/[\text{ester}]$ r-ratio = 1.0–1.2

Stage 2: Crosslinking

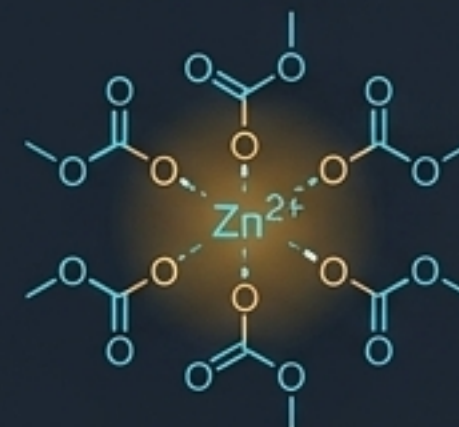
140°C 6h



The network fully cures into a solid, load-bearing crosslinked state.

Stage 3: Activation

180°C 3h

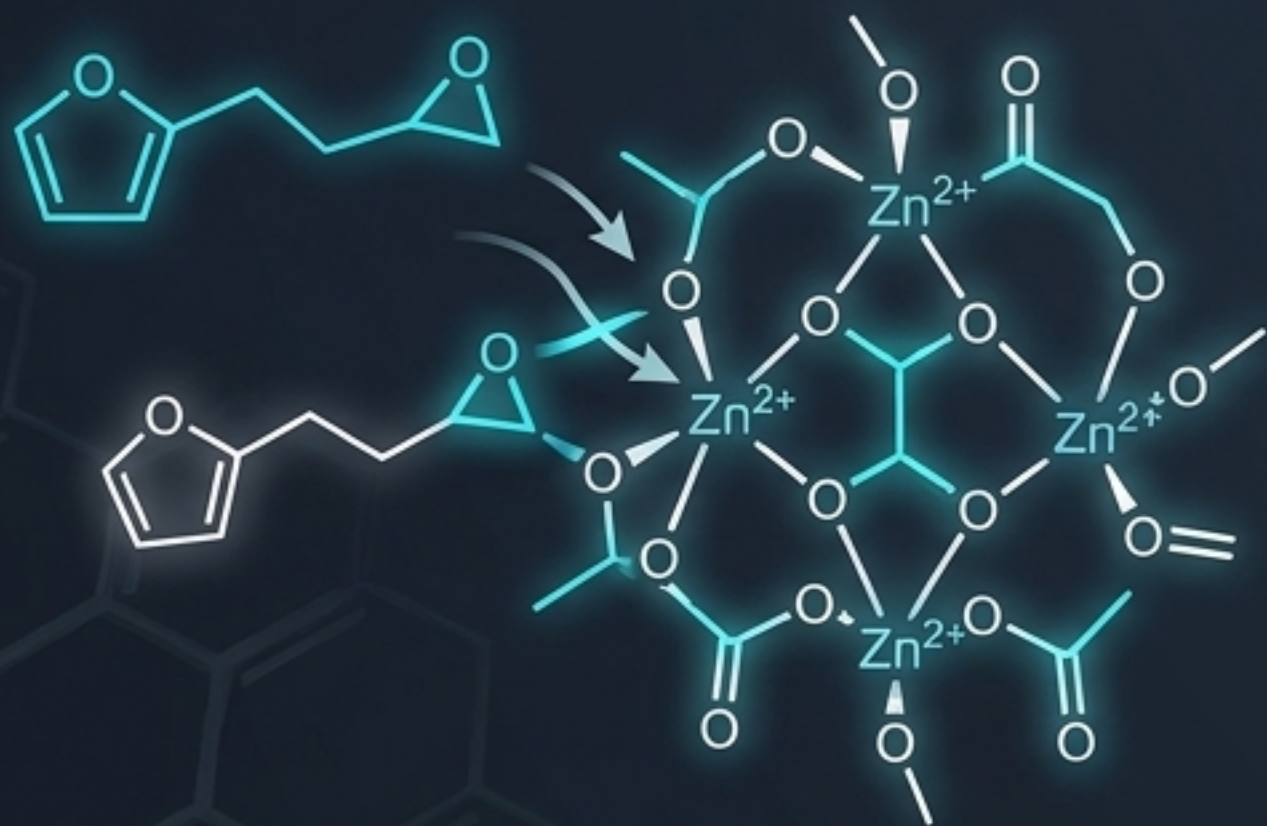


Zinc-Catalyzed Transesterification

Associative bond exchange allows the network to rearrange its topology while maintaining overall crosslink density.

Furfuryl Glycidyl Ether (FGE) is the universal translator between the bio-resin and the graphitic carbons.

Role 1: Reactive Diluent



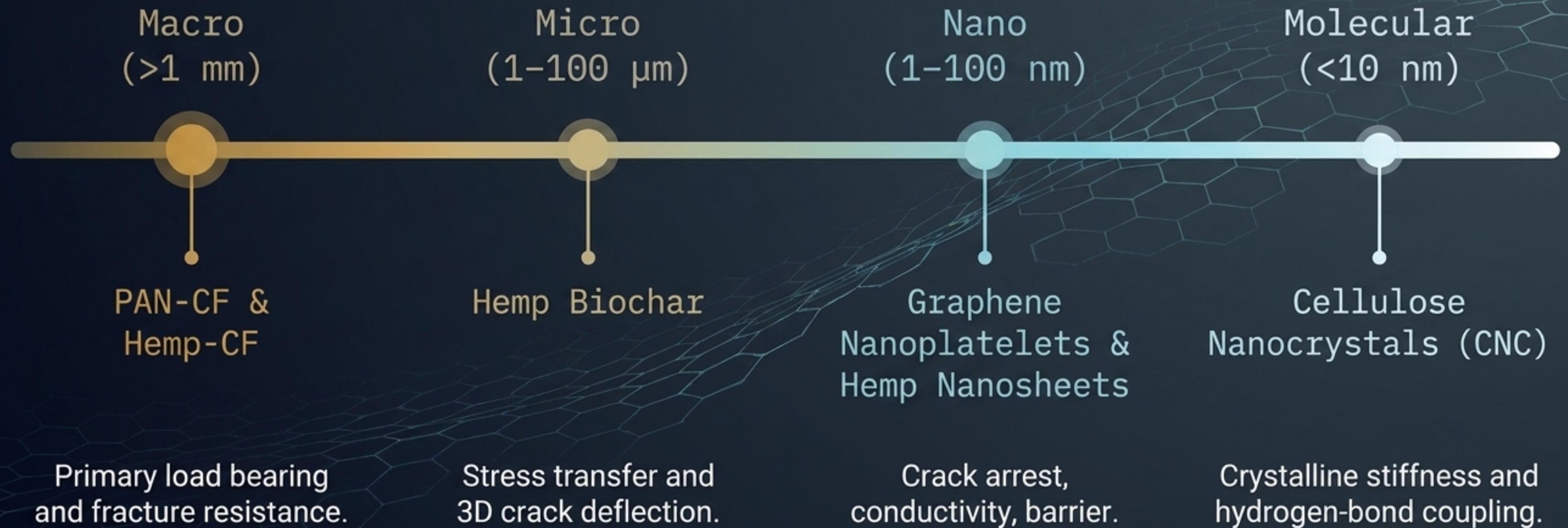
5–15 wt% FGE drops processing viscosity from ~40-60 mPa·s down to ~15-25 mPa·s, allowing void-free fiber impregnation.

Role 2: The Molecular Velcro



π - π Interfacial Coupling:
 $\Delta G \approx -0.3$ to -0.5 eV per ring.

Multi-scale synergy requires overlapping reinforcement from the macroscopic to the molecular.



PAN-CF and Hemp-CF anchor the composite's structural and dimensional stability.

PAN-CF (Synthetic Backbone)



Modulus: >200 GPa

Loading: 20-50 wt%

Role: Longitudinal stiffness and low CTE for extreme thermal cycles.

Hemp-CF (Sustainable Alternative)



Modulus: 10-60 GPa

Loading: 5-25 wt%

Role: High-value, carbonized bast fiber replacing petroleum dependency via 700-1000°C pyrolysis.

Interfacial Surface Treatment (PAN-CF)

1. Oxidative treatment

(introduces functional groups)

2. APTES silane coupling

(forms covalent fiber-matrix bond alongside FGE pi-pi stacking)

3. Dry

(80°C for 2h)


Expected ILSS improvement:
30-60%.

Hemp biochar manages isotropic stress and dictates micro-crack deflection

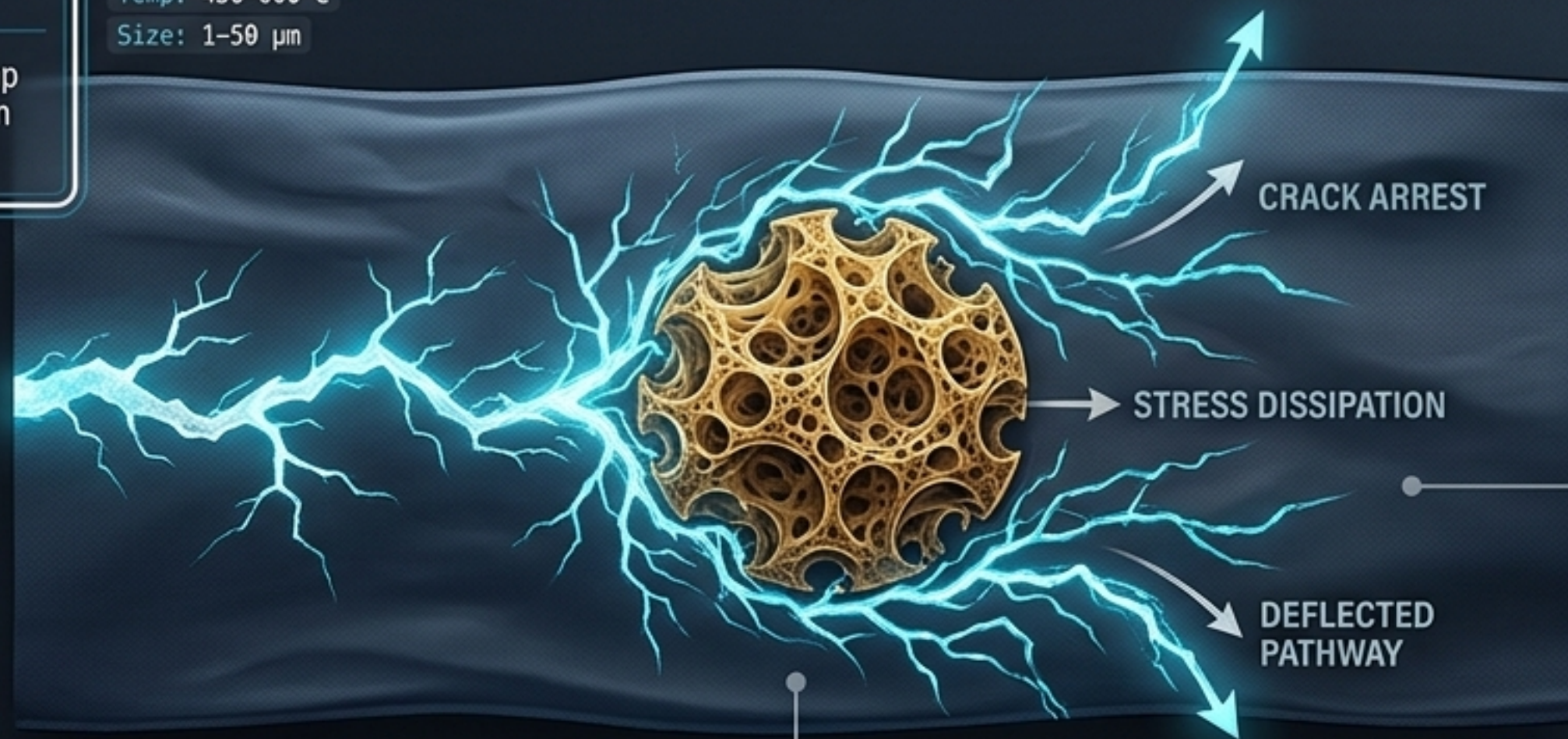
1. Synthesis:

Produced via slow pyrolysis of hemp hurd at 450-600°C. Ball-milled to an equiaxed 1-50 μm particle size.

Process: Pyrolysis

Temp: 450-600°C

Size: 1-50 μm



Role: 3D Buffer

Application: Biocomposite Armor

Feature: Isotropic Reinforcement

2. Function:

Acts as a 3D stress buffer, managing off-axis impacts critical for isotropic reinforcement in biocomposite armor.

3. Synergy:

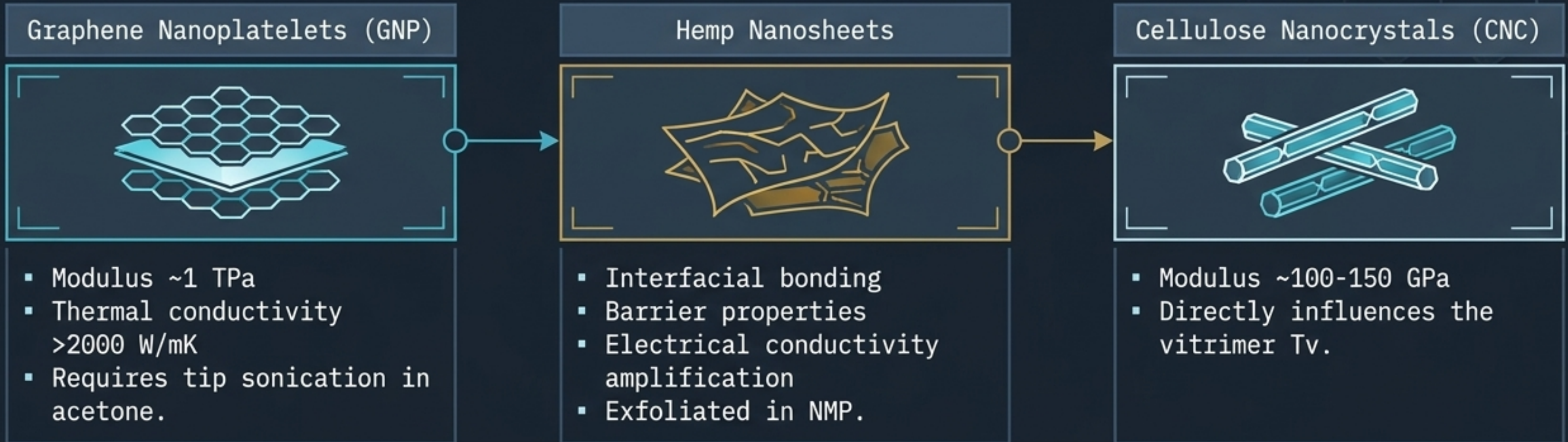
Liquid resin physically flows into the micro-pores prior to cure, locking the particle via mechanical interlocking combined with π - π chemical coupling.

Mechanism: Mechanical Interlocking

Coupling: π - π

Phase: Pre-Cure

Nano and molecular additives amplify modulus, conductivity, and network topology.



WARNING: CNC Agglomeration via H-bonding. Surface TEMPO oxidation or PEG grafting is strictly required prior to addition to prevent clusters.

Property-Morphology Influence Map: The quantitative basis for a programmable composite

	Tensile Strength	Stiffness/Modulus	Toughness	Thermal Stability	Conductivity	Barrier Properties	Tv Control	Reprocessability
PAN-CF								
Hemp-CF								
Hemp Biochar								
Hemp Nanosheets								
GNPs								
CNCs								

REF: TABLE 1. DATA MATRIX V1.4

REV: SLASD9-1, DMR12-1 RDM: AT3 CONFIDENTIAL // TECHNICAL DOSSIER
REV: 000123 1/ 2/3 RDM: 00012

Key Design Insight: PAN-CF is the structural anchor, GNP owns conductivity, and CNC is the primary Tv lever. No single phase dominates all properties; multi-phase loading unlocks the full programmable performance envelope.

Expected Material Performance & Environmental Tolerance

⚠ **Research Hypothesis Disclosure:** Theoretical targets pending experimental validation.

Tensile Strength

80–400 MPa

(depends on CF loading)

Modulus

5–50 GPa

(multi-scale reinforcement)

Glass Transition (T_g)

60–120°C

(tunable via polyol/acid ratio)

Topology Freezing (T_v)

140–180°C

(Arrhenius-controlled)

Self-Healing

Mod–High

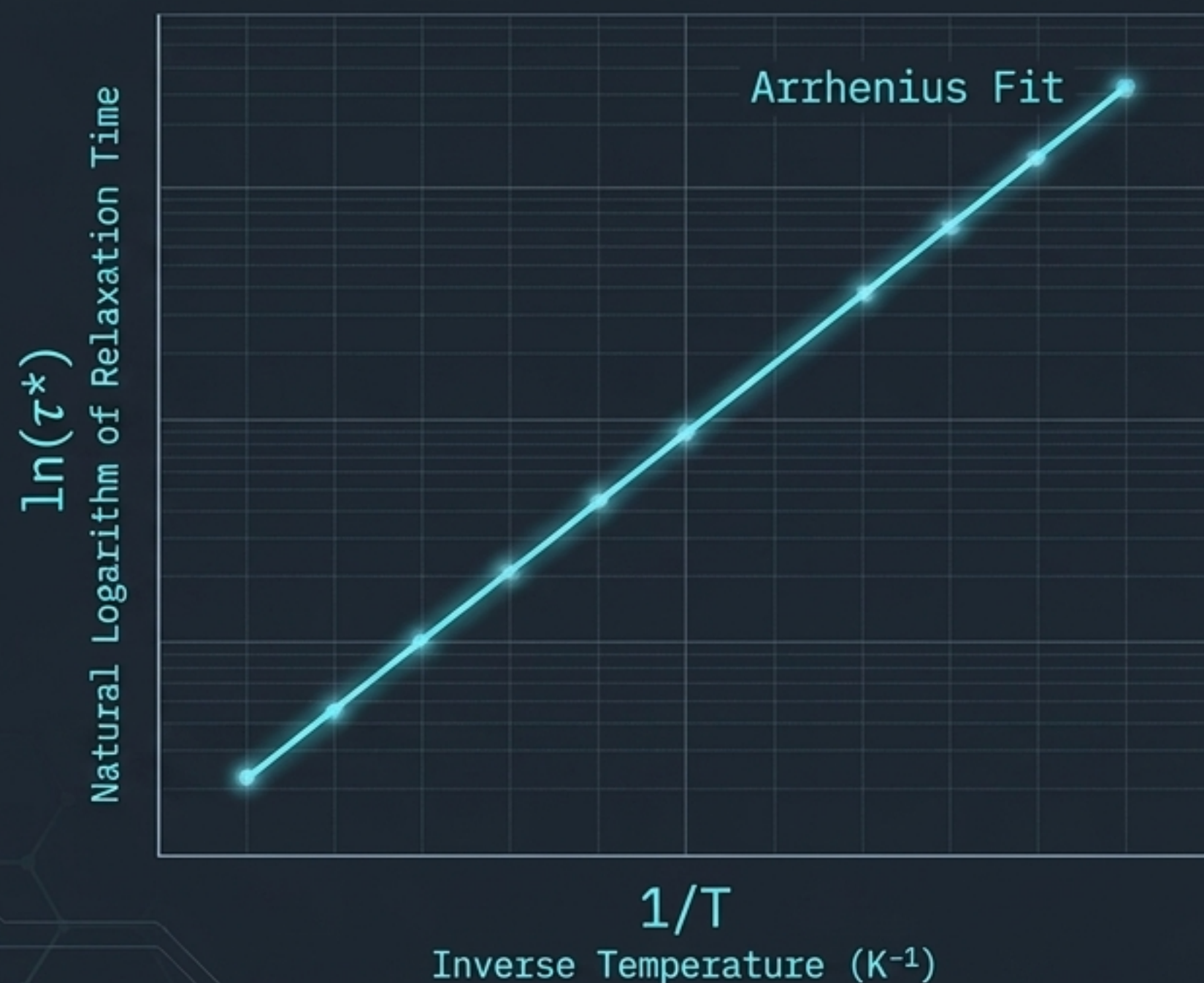
(thermal activation at $T > T_v$)

Recyclability

High

(Vitrimers transesterification)

Arrhenius stress relaxation confirms true Covalent Adaptable Network (CAN) behavior.



Vitrimers exhibit an Arrhenius temperature dependence of viscosity:

$$\eta(T) = \eta_0 \cdot \exp\left(\frac{E_a}{RT}\right)$$

Topology freezing (T_v) is defined where viscosity reaches 10^{12} Pa·s. For zinc-catalyzed EHO, $E_a \approx 80$ - 120 kJ/mol.

DIAGNOSTIC CALLOUT: If the Arrhenius plot is curved, the system is exhibiting dissociative exchange or catalyst plasticization.

Unlocking full chemical circularity and high-value fiber recovery

Decommissioned
Composite Component

Solid-State Reprocessing (Thermal)

Grind to <5 mm particles

Compression mold at
160-180°C

Cool under pressure

Recovery: 70-90% tensile strength on first cycle.
(Limitation: CNC degrades after 3 cycles above 180°C).

Solvolysis (Chemical)

Immerse in ethylene glycol
at 150-180°C

Matrix solubilizes in 1-4
hours via ester exchange

Filter intact fibers

Outcome: >80% retention of PAN-CF and Hemp-CF
tensile strength without energy-intensive pyrolysis.

Laboratory Characterization Protocol for Vitrimer Validation

METHOD	PROTOCOL	KEY OUTPUT
DSC	Heat-cool-heat to 200°C	Output: Tg (60-120°C) and cure enthalpy.
DMA	Single-cantilever, 1 Hz	Output: Modulus (E') and tan δ.
TGA	Up to 800°C	Output: Thermal stability (T _{d,5%} >200°C) and char yield.
Stress Relaxation	1% strain isothermal	Output: Tv, Ea extrapolation.
FTIR	Real-time monitoring	Output: 910 cm ⁻¹ (epoxide) and 1735 cm ⁻¹ (ester).

Reaction Kinetics & Critical Formulation Levers

Control Board



1. Epoxide Conversion Fraction
(Target >90%)



2. Zn²⁺ Concentration
(Kinetic control of exchange rate)



3. Hydroxyl-to-Ester Ratio
(Lock to $r \approx 1.0-1.2$)



4. Reinforcement Dispersion Quality

Tradeoff Matrix

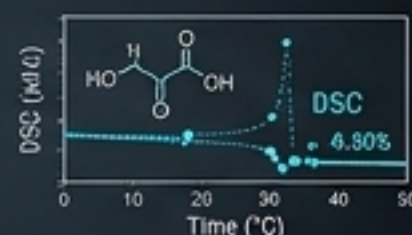
PARAMETER	INCREASE EFFECT	RISK
Increase Zn Catalyst	→ Faster exchange,	BUT risk of creep.
Increase Acetic Acid	→ More OH groups,	BUT risk of plasticization.
Increase Polyol	→ Higher crosslinking,	BUT risk of brittleness.

Industrial Troubleshooting: Mitigating Morphological and Chemical Failure Modes

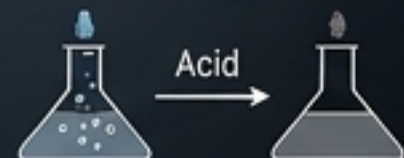


OVER-PLASTICIZATION

Diagnostic:
T_g < 40°C via DSC



Fix: Reduce acid loading



WEAK FIBER INTERFACE

Diagnostic:
Fiber pullout



Fix: APTES silane coupling

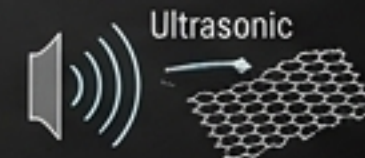


POOR GRAPHENE DISPERSION

Diagnostic:
SEM Agglomerates

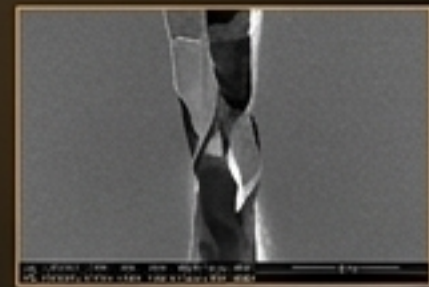


Fix: rGO upgrade / extended sonication



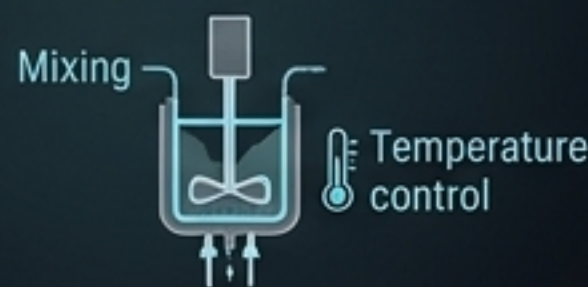
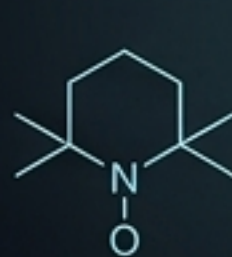
BIOCHAR OVERLOADING

Risk: Brittleness above ~15 wt%



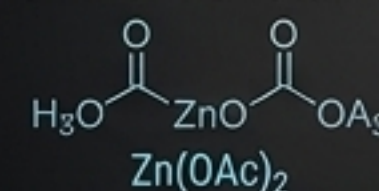
CNC AGGLOMERATION

Fix: TEMPO oxidation, high-shear <60°C

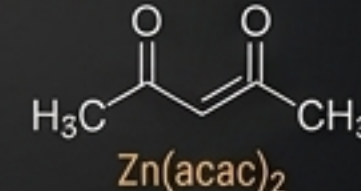


CATALYST DEPLETION

Fix: Replace Zn(OAc)₂ with Zn(acac)₂ for thermal stability



Stability, data ~ 0.95%



Stability, data > 0.65%

The Priority Optimization Stack for Biorefinery Scaling

1. Perfect GNP/Nanosheet dispersion
(FGE π - π anchoring + sonication).



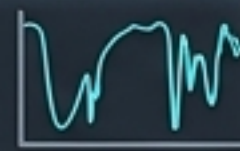
2. Optimize FGE to **8-12 wt%**
(Confirm viscosity drop via rheometry).



3. Lock Zn catalyst to **~2-3 wt%**.



4. Lock acetic acid to **~4-5 wt%**
(Verify via FTIR).



5. Apply APTES surface treatment
to all carbon fibers.



6. Control cure ramp
precisely via DSC.



7. Verify T_v via stress relaxation
at three temperatures.





Hempoxies 54 is the material substrate for a secure, localized, circular defense economy.

By replacing permanent, petroleum-based thermosets with programmable EHO vitrimers, we unlock self-healing armor, fully recyclable structural airframes, and decentralized biorefinery production.

1

25% Petroleum Displacement

2

40% Carbon Reduction

3

Target Year:
2036