

# Programmatic Carbon Morphologies in Composites

8 messages — Author: Marie-Soleil Seshat Landry <ceo@marielandryspyshop.com>

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Lets discuss the programmativity of carbon morphologies in epoxy and bioepoxy composites

The programmability of carbon morphologies within epoxy and bioepoxy matrices represents a shift from passive reinforcement to active, architecture-driven material design. In this context, "programmability" refers to the ability to dictate the final macroscopic properties of a composite by precisely controlling the spatial distribution, orientation, and hybridization of carbon allotropes.

## 1. Morphological Dimensionality and Percolation

The geometric nature of the carbon reinforcement determines the efficiency of the "program." Each morphology offers distinct advantages based on its dimensionality:

- **1D (Carbon Nanotubes/Nanofibers):** High aspect ratios allow for low-threshold electrical and thermal percolation. Programmability here often involves magnetic or electrical field alignment to create anisotropic pathways.
- **2D (Graphene/Graphene Oxide):** These provide massive surface area for interfacial bonding. "Programming" involves managing the exfoliation state to prevent restacking, which can negate the high surface energy benefits.
- **3D (Carbon Scaffolds/Aerogels):** The most programmed approach, where a pre-formed 3D architecture is infiltrated with resin. This ensures a guaranteed, continuous network that does not rely on random dispersion.

## 2. Interfacial Programming in Bioepoxy Systems

Bio-based epoxies—often derived from epoxidized vegetable oils (EVOs) or lignin—present different chemical environments than traditional DGEBA (Diglycidyl ether of bisphenol A). Programming these composites requires:

- **Surface Functionalization:** To match the polarity of bio-resins, carbon surfaces are often modified with oxygen-containing groups or bio-compatible surfactants. This ensures the "stress transfer" program is executed without interfacial failure.
- **Cure Kinetics Manipulation:** Carbon morphologies, particularly those with high surface acidity or alkalinity, can act as catalysts or inhibitors for the epoxy cross-linking reaction. The morphology effectively "programs" the density and uniformity of the polymer network surrounding it.

### 3. Triple-Phase and Hybrid Morphologies

The highest level of programmability is achieved through **Triple-Phase Reinforcement**. This involves the strategic combination of different carbon scales to create a hierarchical toughening mechanism:

| Morphology Type  | Primary Function         | Secondary Function      |
|------------------|--------------------------|-------------------------|
| Micro-scale (CF) | Load-bearing & Stiffness | Crack deflection        |
| Nano-scale (CNT) | Interlaminar toughening  | Electrical conductivity |
| Atomic/Molecular | Chemical cross-linking   | Thermal stability       |

By layering these, the composite is programmed to handle multi-axial loads and provide multi-functional responses (e.g., structural health monitoring via piezoresistivity).

### 4. The Role of Synthesis Precision

The shift from stochastic (random) mixing to deterministic placement is where the "programming" becomes literal. Advanced methods include:

- Laser-Assisted Synthesis:** Utilizing localized energy to induce specific carbon phases (like turning amorphous carbon into crystalline nanothreads) directly within a precursor.
- Vapor Deposition:** Growing carbon nanotubes directly onto larger fibers (the "fuzzy fiber" approach) to program the interface at the molecular level.

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YOU

Theres a bunch of hemp-derived carbons

Hemp serves as an exceptional feedstock for "programming" carbon morphologies because its hierarchical structure—from macro-fiber bundles to molecular lignin—can be thermochemically converted into distinct allotropes. In epoxy systems, these hemp-derived carbons act not just as fillers, but as architectural determinants of the composite's failure mode and conductivity.

## 1. Hemp-Derived Morphological Taxonomy

The "programmability" of hemp carbon is primarily dictated by the conversion temperature and the specific component of the plant used (bast vs. shiv).

- **Hemp Carbon Fibers (HCF):** Derived from the high-cellulose bast fibers. These retain the high aspect ratio of the original fiber but transition from a semi-crystalline cellulose structure to a turbostratic carbon.
  - **Function:** Primary load-bearing and crack bridging.
- **Hemp-Based Biochar:** Produced via low-temperature pyrolysis (450–600°C). It is a heterogeneous morphology containing both amorphous carbon and residual functional groups (–OH, –COOH).
  - **Function:** Enhances interfacial adhesion in bio-epoxies due to hydrogen bonding with the matrix.
- **Activated Carbon Nanoparticles (ACNPs):** Derived from hemp shiv or chemical activation of biochar. These offer extremely high surface area (> 1000 m<sup>2</sup>/g).
  - **Function:** Programming thermal stability and electrical conductivity thresholds. Research indicates that even 1.0 wt% loading of hemp AC NPs can significantly delay thermal decomposition ( $T_d \approx 300^\circ\text{C}$ ) in biocomposites [2.4.1].

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## 2. Competitive Morphological Programming: Hemp vs. PAN

While Polyacrylonitrile (PAN)-based carbon fibers are the industry standard, hemp-derived carbons offer a "non-explosive" failure mechanism that is highly desirable in structural health monitoring.

| Feature                  | Petroleum-Based (PAN)     | Hemp-Derived Carbon                                |
|--------------------------|---------------------------|----------------------------------------------------|
| Microstructure           | Highly ordered, graphitic | More amorphous/turbostratic                        |
| Interfacial Shear (IFSS) | Often requires sizing     | High inherent IFSS due to lignin-derived aromatics |
| Failure Mode             | Brittle, explosive        | Gradual, non-explosive [2.5.2]                     |
| Connectivity             | Stochastic dispersion     | Potential for programmed 3D scaffolds              |

### 3. Programming the "Lignin Link"

Lignin, which makes up about 10–15% of hemp, is the "aromatic glue" that can be programmed to bridge the gap between carbon morphology and bio-epoxy matrices.

1. **Fractionation:** Isolating hemp lignin via acetone separation creates a precursor with high aromatic density.
2. **Epoxidation:** By introducing ethylene oxide structures directly into the hemp-carbon framework, the reinforcement becomes chemically identical to the epoxy matrix "program," leading to superior cross-linking [2.5.1].

### 4. Synthesis Control: The Laser Variable

Recent advancements in **Laser-Induced Carbonization** allow for the "in-situ programming" of hemp fibers. By applying precise laser energy, it is possible to synthesize carbon nanothreads directly from hemp precursors at lower pressures ( $\approx 5$  GPa) than traditional synthetic methods. This allows for:

- **Spatial Selective Reinforcement:** Programming specific "zones" of a composite to be conductive or ultra-stiff.
- **Triple-Phase Reinforcement:** Simultaneously managing micro-fibers, nano-tubular structures, and the atomic interface.

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**Keywords:** Hemp-Derived Carbon, Bio-Epoxy, Morphological Programming, Lignin-Based Carbon, Biochar Reinforcement, Interfacial Shear Strength.

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YOU

So you can program epoxy filler

Yes. In the context of advanced materials science, programming a filler means moving away from simply "dumping" particles into a resin. Instead, you treat the filler as a set of instructions that dictates how the composite will behave under stress, heat, or electrical load.

When using carbon morphologies—especially those derived from hemp—this programmability is executed through three primary "coding" layers:

## 1. Geometric Programming (The Architecture)

You program the macro-response of the material by choosing the dimensionality (1D, 2D, 3D) of the carbon.

- **Isotropic vs. Anisotropic:** By using magnetic or electrical fields during the curing process, you can "program" carbon nanofibers or fibers to align in a specific direction. This creates a material that is ultra-stiff in one direction but flexible in another.
- **Percolation Control:** You can program the exact weight percentage (wt%) needed to make the epoxy conductive. For example, high-aspect-ratio hemp carbon fibers can create a conductive "circuit" through the plastic at much lower concentrations than spherical carbon black.

## 2. Interfacial Programming (The Connection)

The "program" often fails at the interface—where the carbon meets the epoxy. To fix this, we use chemical programming:

- **Surface Functionalization:** By "tagging" the surface of hemp-derived carbon with oxygen or nitrogen groups, you program the epoxy molecules to wrap tightly around the filler.
- **The Lignin Bridge:** In bio-epoxies, using lignin-derived carbon allows the filler and the matrix to "speak the same language," leading to a chemical bond rather than just a physical mixture. This prevents the filler from pulling out of the matrix during a crash or high-stress event.

## 3. Synthesis Programming (The Transformation)

This is the most advanced level, where the "program" is written during the creation of the carbon itself.

- **Triple-Phase Reinforcement:** You can program a hierarchical system where micro-scale fibers provide the "bones," nano-scale threads provide the "nerves" (conductivity), and the atomic interface provides the "skin" (bonding).
- **Laser-Assisted Synthesis:** Utilizing precise energy signatures to convert organic precursors into specific carbon morphologies in-situ. For example, using lasers to synthesize nanothreads at 5 GPa allows for the "printing" of reinforcement patterns directly into a part.

## The Outcome: Functional Material

When you successfully program an epoxy filler, the resulting composite is no longer a passive plastic. It becomes a **functional system** capable of:

- **Self-Sensing:** The material can "feel" when it is about to break because the carbon network registers a change in electrical resistance.
- **Gradual Failure:** Unlike standard carbon fiber which can shatter, a programmed hemp-carbon composite can be designed for "non-explosive" failure, absorbing energy through a gradual breakdown of the programmed hierarchy.

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**Keywords:** Material Programming, Epoxy Fillers, Triple-Phase Reinforcement, Interfacial Shear Strength, Hemp-Derived Carbon, Bio-nanocomposites.

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YOU

So the memory form

Of the future is basically a kind of vitrimer epoxy programmed with carbon pollution and biochars??

That is a precise distillation of the emerging "Circular Memory" material paradigm. You are essentially describing a material that functions as a **biological hardware**—where the polymer (vitriimer) acts as the logic gate and the carbon (pollution/biochars) acts as the signal conductor.

In this framework, the "memory" is both structural and functional:

## 1. The Vitriimer Matrix (The Memory Substrate)

Unlike traditional epoxies that are "permanently set," a vitriimer utilizes **Dynamic Covalent Networks (DCN)**.

- **Bond Exchange:** At specific temperatures ( $T_v$  or Topology Freezing Temperature), the chemical bonds literally swap places while the material remains solid.
- **Programming:** This allows you to "program" a shape into the material. If it gets crushed or deformed, applying heat triggers the "memory" of its original bond topography, and it snaps back.

## 2. Carbon "Pollution" as Functional Logic

By integrating recovered carbon (from industrial emissions or pyrolysis), you aren't just adding filler; you are adding a **responsive network**:

- **Photothermal Actuation:** Carbon nanostructures are excellent at absorbing light (NIR/Laser) and converting it to heat. You can "address" specific parts of the material with a laser to trigger the shape-memory effect only in that spot.
- **Piezoresistive Sensing:** The carbon network allows the material to "remember" its stress history. If the material is deformed, the electrical resistance changes. This turns the composite into its own sensor—it "knows" it has been tampered with or stressed.

## 3. Biochar: The Interfacial Stabilizer

While "pollution" (like carbon black or nanotubes) provides high performance, **Hemp-derived biochar** provides the compatibility.

- **Chemical Continuity:** Biochar often contains residual oxygen groups ( $-OH$ ) that bond more naturally with bio-epoxy vitrimers (like those derived from hempseed or soybean oils) than pure synthetic carbon does.

- **The TRL 1-2 Landscape:** In systems like **Hempoxies**, the biochar acts as a bridge, ensuring that the "programming" instructions from the carbon nanostructures are accurately translated to the bio-based resin without interfacial failure.

## The "Memory Form" Synthesis

| Component        | Origin              | Role in the "Program"                         |
|------------------|---------------------|-----------------------------------------------|
| Bio-Vitrimer     | Hemp/Soy/Tung Oil   | The reconfigurable "code" (dynamic bonds)     |
| Carbon Pollution | Recovered Emissions | The "processor" (thermal/electrical stimulus) |
| Hemp Biochar     | Pyrolyzed Biomass   | The "bus" (interfacial communication)         |

This combination allows for **Closed-Loop Materials**: you can program them, use them, break them, and then "reformat" them (recycle/reprocess) by simply triggering the bond exchange again.

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**Keywords:** Vitrimer Epoxy, Biochar Reinforcement, Shape Memory Polymers, Dynamic Covalent Networks, Circular Economy, Carbon Recovery.

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