



Advances in Sustainable Composite Materials for Civil Infrastructure Applications

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Abstract

Aging, corrosion-prone steel-reinforced concrete and the carbon footprint of conventional construction materials have pushed civil infrastructure toward an expanding family of composite alternatives: fiber-reinforced polymer (FRP) reinforcement, natural-fiber and bio-based composites, geopolymer binders, and the recycling and circularity technologies that increasingly surround all of them. This article synthesizes that literature across five themes: the material and mechanical foundations of glass, carbon, and basalt FRP composites; the multi-year durability evidence for FRP reinforcement in alkaline, marine, and acid concrete environments; structural applications spanning internal reinforcement, external strengthening, and integrated bridge deck systems; natural-fiber, bio-based, and geopolymer alternatives alongside self-healing composites that extend service life by design; and the life-cycle assessment and end-of-life recycling literature, including the quantified environmental and cost tradeoffs among mechanical, thermal, and chemical CFRP recovery routes and the emerging practice of repurposing decommissioned wind turbine blade composite into new civil structures. Read together, the evidence supports FRP and related composite technologies as an increasingly well-evidenced, appropriately bounded option for specific infrastructure problems -- corrosion-prone reinforcement, rapid deck replacement, retrofit strengthening, and circular reuse of composite waste -- while leaving geopolymer-FRP durability compatibility, multi-stressor exposure testing, natural-fiber's structural ceiling, and recycling economics as an open research and standardization agenda.

Keywords: fiber-reinforced polymer; sustainable composites; civil infrastructure durability; geopolymer concrete; composite recycling and circularity

1. Introduction

Civil infrastructure is aging faster than most owners can afford to replace it, and the material that built most of the twentieth century's bridges, decks, and reinforced structures — steel-reinforced concrete — carries a durability weakness that is now expensive in every sense of the word: the reinforcing steel corrodes, the surrounding concrete cracks and spalls, and the repair bill for a single deteriorated bridge deck can rival the cost of building a new one. At the same time, the concrete and steel industries are themselves under growing pressure to cut embodied carbon, and owners increasingly ask not just "will this structure carry the load" but "what did it cost the planet to build, and what will it cost to maintain for the next fifty years." Composite materials — fiber-reinforced polymers (FRP), natural-fiber composites, geopolymer-based systems, and the recycling and circularity technologies that increasingly surround all of them — sit at the intersection of both pressures. They do not corrode the way steel does, they can often be manufactured with a smaller life-cycle footprint than conventional materials, and after three decades of research and a growing base of field installations they have moved from a laboratory curiosity to a mainstream, if still specialized, structural option.

The idea of using fiber-reinforced polymers in civil infrastructure is not new. Karbhari and Seible's 1999 overview of FRP composites for civil infrastructure in the United States captured a field that was, at the time, mostly aspirational: promising coupon-level mechanical data, a handful of demonstration bridges, and a research community trying to convince a conservative industry that a material developed for aerospace and marine applications could be trusted to carry traffic loads for decades without the benefit of a fifty-year track record [1]. A quarter-century later, that track record exists. FRP reinforcing bars, prestressing tendons, bridge deck panels, and external strengthening systems are specified in real projects, design guidance has matured, and — critically for a synthesis like this one — enough structures have now been in service long enough that researchers can report multi-year, and in some cases multi-decade, durability data rather than only accelerated laboratory aging.

This article synthesizes that literature, organized around five themes that map onto how a practicing engineer or

a materials researcher would actually need to think about the topic. First, the mechanical and material foundations of FRP composites as structural reinforcement — what they are made of, and why fiber type and matrix chemistry matter for infrastructure specifically. Second, the durability and service-life literature, which is arguably the single most consequential body of work for whether these materials genuinely displace steel in aggressive environments rather than merely supplementing it. Third, the structural application literature — reinforcement, external strengthening, and bridge deck systems — where the material properties from the first section actually get turned into structures. Fourth, the sustainability side of the ledger specifically: natural-fiber and bio-based composites, geopolymer binders, and the growing literature on self-healing systems that extend service life by design rather than by inspection and repair. Fifth, the life-cycle assessment and end-of-life recycling literature that determines whether "sustainable composite" is a genuinely defensible label or merely a marketing one.

It is worth being honest about scope from the outset. This is a literature synthesis, not a set of new experimental results, and the claims made here are only as strong as the studies they summarize. Composite materials research spans an enormous range of fiber types, resin systems, and application geometries, and no single article can do justice to all of it; we have tried to weight the discussion toward the sub-literatures — FRP reinforcing bars and bars durability, bridge deck systems, and end-of-life composite recycling — that have accumulated the largest and most consistent body of applied civil-infrastructure evidence, while giving representative coverage to natural-fiber and geopolymer alternatives that are earlier in their development trajectory but increasingly relevant to the sustainability half of the topic.

2. Fiber-Reinforced Polymer Composites: Materials and Mechanical Foundations

The basic architecture of an FRP composite for civil infrastructure use is simple to state and consequential in its implications: continuous fibers, typically glass, carbon, aramid, or basalt, embedded in a polymer matrix, usually a thermosetting resin such as vinyl ester, epoxy, or polyester, that transfers load between fibers and protects them from the environment. The fibers

carry essentially all of the tensile load; the matrix's job is to keep the fibers aligned, distribute stress between them, and — this is the part most relevant to a durability discussion — act as the first line of defense against moisture, alkalinity, and other environmental attack that would otherwise reach the fibers directly. Glass fiber reinforced polymer (GFRP) dominates the reinforcing-bar and rebar-substitute market because glass fiber is inexpensive relative to carbon, while carbon fiber reinforced polymer (CFRP) is reserved for applications — external strengthening laminates, prestressing tendons, some bridge cable systems — where its substantially higher stiffness and strength justify the cost premium.

Basalt fiber occupies an intermediate and increasingly interesting position in this landscape. Dhand and colleagues' widely cited review of basalt fiber reinforced polymer composites lays out why the material has attracted sustained research attention over the past decade: basalt fiber is manufactured by melting quarried basalt rock, a single mineral raw material rather than the multi-component glass batch chemistry that glass fiber manufacturing requires, giving it a simpler and generally lower-energy production route, while its mechanical properties — tensile strength and modulus — sit competitively between glass fiber and carbon fiber, with better thermal stability and chemical resistance than E-glass in a number of the aggressive-environment comparisons the review surveys [2]. A decade on, Chen and colleagues' 2024 review of efforts to engineer tougher basalt fiber composites shows the field has moved from characterizing basalt fiber's baseline properties to actively re-engineering the fiber-matrix interface and hybridizing basalt with other reinforcements to address its principal weakness relative to glass and carbon: comparatively low fracture toughness and impact resistance in the unmodified composite [3]. For civil infrastructure specifically, that toughness question matters more than it might in, say, a sporting-goods application, because structural composites need to tolerate impact damage, freeze-thaw cycling, and construction-site handling without a catastrophic loss of residual strength.

Basalt fiber's growing role in bridge engineering is a useful illustration of how a material's laboratory-level property profile translates into structural application. Wang and colleagues developed and tested a composite

bridge deck system built around a prestressed basalt fiber reinforced polymer shell filled with concrete, explicitly framing the design as an attempt to combine concrete's compressive economy with BFRP's corrosion resistance and tensile capacity in a single prefabricated deck element suitable for rapid bridge construction and replacement [4]. A companion study by largely the same research group subjected the same deck concept to fatigue loading, reporting on the crack development and stiffness degradation behavior of the BFRP-shell concrete composite deck under repeated load cycling representative of in-service traffic — a necessary complement to any static strength claim, since a deck that performs well under a single design load but degrades rapidly under millions of fatigue cycles would be a poor candidate for real bridge service [5]. Taken together, this pair of studies is a good microcosm of how the FRP-for-infrastructure literature actually develops: a novel composite structural system is proposed and shown to work under static load, and only in follow-on work does the fatigue and long-term behavior get characterized, which is precisely the sequence a skeptical bridge owner should want to see before specifying a genuinely new deck system.

3. Durability and Service-Life Performance in Concrete Environments

If there is one question that determines whether FRP reinforcement is a genuine long-term alternative to steel rather than a niche specialty product, it is durability inside concrete: does the composite retain its strength and stiffness over the multi-decade service lives that bridges and buildings are designed for, given the alkaline pore-water chemistry, moisture ingress, and sustained stress that concrete reinforcement is inevitably exposed to? This is precisely the question that a substantial and increasingly mature body of GFRP durability literature has set out to answer, and the good news for the technology is that the answer, on balance, is encouraging — with important caveats about exposure conditions and time horizons.

The most directly persuasive evidence comes from long-duration exposure studies rather than short accelerated tests. Wu and colleagues report an eight-year field and laboratory durability study of GFRP bars embedded in an alkaline concrete environment, tracking mechanical property retention over a genuinely multi-year timescale rather than the weeks-to-months

accelerated aging protocols that dominated earlier durability literature [6]. Eight years is still short relative to a design life measured in decades, but it is long enough to move past the concern that accelerated testing — typically conducted at elevated temperature to compress a simulated service life into a laboratory-feasible timeframe — might be extrapolating from a regime that does not actually represent how the material behaves under realistic, slower degradation kinetics. Davalos, Chen, and Ray's durability prediction models for GFRP bars in concrete address exactly this extrapolation problem directly, developing models intended to translate accelerated-aging data into defensible long-term service-life predictions, which is the methodological bridge that connects a laboratory study measured in months to an engineering design life measured in decades [7].

Exposure condition matters as much as exposure duration. Zhang and Deng examined GFRP bar durability specifically under the combination of a simulated marine environment and sustained compressive stress, a combination relevant to coastal infrastructure where chloride-laden moisture and mechanical loading act simultaneously rather than sequentially [8]. Yan and Lin's companion line of work on bond durability — the interface behavior between GFRP bar and surrounding fiber-reinforced concrete under saline solution exposure — is a useful reminder that a reinforcing bar's bulk tensile strength is not the only property that matters: if the bond between bar and concrete degrades faster than the bar itself, the composite section as a whole can lose load-carrying capacity well before the bar's coupon-level tensile strength would suggest [9]. Zhou, Chen, and Chen extended the environmental envelope further still, examining GFRP bar durability and service-life prediction specifically under acid environment exposure, a condition relevant to industrial and some wastewater infrastructure applications where the pore-water chemistry departs from ordinary concrete's alkalinity in the opposite direction [10]. Pan and Yan's comparison of plain GFRP bars against carbon/glass hybrid FRP bars aged in alkaline solution adds a materials-engineering dimension to the same durability question: does hybridizing glass fiber with a fraction of carbon fiber, which is intrinsically more alkali-resistant, meaningfully improve the alkaline durability of the resulting bar relative to an all-glass design, a question

with direct implications for whether hybridization is worth its cost premium in aggressive-environment applications [11].

Read as a set, this durability literature supports a specific and appropriately qualified conclusion: GFRP reinforcement's long-term behavior in concrete is now characterized across a meaningfully wide range of realistic exposure conditions — plain alkaline concrete, marine chloride exposure under sustained load, acid environments, and bar-concrete bond specifically rather than only bulk bar properties — and the resulting picture is one of gradual, predictable, and generally moderate strength loss rather than the catastrophic degradation that early skeptics worried alkaline concrete pore water might cause to glass fiber. That said, the degradation is real and environment-dependent, which is exactly why the prediction-model literature exemplified by Davalos et al. matters: durability design for FRP reinforcement increasingly means applying an environmental reduction factor calibrated to actual long-term data, not assuming the material is simply immune to the concrete environment the way marketing materials sometimes imply [7].

4. Structural Applications: Reinforcement, Strengthening, and Bridge Systems

Durable material properties only matter if they can be turned into buildable, inspectable, maintainable structures, and the applications literature for FRP in civil infrastructure has three fairly distinct strands: internal reinforcement (bars and tendons replacing or supplementing steel inside new concrete members), external strengthening (composite laminates and wraps applied to existing structures to increase capacity or extend service life), and integrated bridge deck systems that use FRP as a primary structural material rather than only as reinforcement within a conventional concrete section.

On internal reinforcement, Abdalla's early study of deflection behavior in concrete members reinforced with FRP bars addressed a serviceability concern that is fundamental to using a lower-stiffness reinforcement material: because FRP bars have a substantially lower elastic modulus than steel for a given tensile strength, FRP-reinforced concrete members deflect more under service load than an equivalent steel-reinforced member, and designing for that deflection — rather than simply substituting FRP bar area for steel bar area on a

strength-equivalent basis — is essential to avoid serviceability failures even when the strength design is adequate [12]. This is a good example of how adopting a new reinforcing material is rarely a drop-in substitution; it requires revisiting design assumptions that steel-reinforced concrete design codes had, often implicitly, built around steel's specific stiffness.

External strengthening is, in some respects, the application where FRP composites have achieved the broadest real-world adoption, because it addresses an acute and widespread problem — an existing structure that needs more capacity, whether from load rating deficiencies, seismic retrofit requirements, or accumulated deterioration — without the disruption of full replacement. Belarbi and Acun's review of FRP systems for shear strengthening of reinforced concrete structures surveys the mechanics of bonding FRP sheets or strips to the exterior of a concrete member to supplement its shear capacity, a technique that has become close to routine in seismic retrofit and bridge rehabilitation practice specifically because it can be installed with minimal disruption to a structure's continued use [13]. Saini and Prakash's more recent analytical study of hybrid FRP strengthening for slender reinforced concrete columns pushes the same external-strengthening concept toward a more demanding structural problem — columns, where buckling and second-order effects under axial load interact with the confinement that an FRP wrap provides in ways that a simple beam-strengthening analysis does not capture — and specifically explores hybridizing FRP material types to tune the strengthening system's stiffness and confinement behavior to the column's failure mode [14]. The trajectory across these two studies, roughly a decade apart, tracks the broader field's progression from establishing that external FRP strengthening works to optimizing how and where different fiber and layup choices perform best for a given structural problem.

Bridge deck systems represent the most structurally ambitious use of FRP composites, because here the material is not supplementing a concrete or steel structure but substantially replacing it. Zhou and Keller's work on joining techniques for FRP composite bridge deck systems addresses a problem that is easy to overlook in a purely materials-focused discussion but is decisive in practice: a bridge deck is assembled from

panels, and how those panels connect to each other and to the supporting girders determines whether the deck behaves as a continuous structural system or a series of independently flexing pieces, with direct consequences for load distribution, fatigue performance at the joints, and long-term watertightness [15]. He and Aref's optimization work on FRP web-core sandwich bridge deck panels addresses the companion structural-efficiency question — how to arrange the internal web geometry of a hollow or foam-filled composite panel to maximize stiffness and strength per unit weight, since weight savings relative to a conventional concrete deck is one of FRP decking's principal selling points for rapid replacement and load-rating-constrained bridges [16]. Lombardi and Liu's glass fiber reinforced polymer and steel hybrid honeycomb sandwich concept pushes the same weight-efficiency logic further by combining FRP face sheets with a lightweight steel or composite honeycomb core, an explicit attempt to capture FRP's corrosion resistance at the exposed surfaces while managing cost by limiting how much of the section needs to be full FRP [17]. The BFRP-shell concrete deck systems discussed in the previous section belong to this same structural family, and the field as a whole illustrates a genuine diversity of engineering approaches to the same underlying goal: a lightweight, corrosion-resistant, rapidly installable deck system that performs at least as well as conventional reinforced concrete over the deck's service life.

5. Natural Fiber, Bio-Based, and Geopolymer Alternatives

Fiber-reinforced polymer composites address corrosion durability directly, but their sustainability credentials are more mixed than is sometimes assumed: the thermosetting resins typically used are petroleum-derived, glass and carbon fiber production is energy-intensive, and — as the life-cycle assessment section below discusses — end-of-life disposal of thermoset composites has historically been a genuine weakness rather than a strength. Two parallel bodies of research address this gap from different directions: natural-fiber and bio-based composites, which aim to reduce embodied impact on the input side, and geopolymer binders, which aim to reduce the embodied carbon of the cementitious matrix that composite reinforcement is typically embedded in.

Natural-fiber composites replace glass or carbon fiber with plant-derived fibers — flax, hemp, jute, sisal, and similar bast or leaf fibers — that require substantially less processing energy to produce and are, in principle, biodegradable or at least far less persistent as waste than glass or carbon fiber. Jariwala and Jain's review of the mechanical behavior of natural fiber reinforced polymer composites surveys the tradeoffs at the heart of this substitution: natural fibers generally offer lower tensile strength and stiffness than glass fiber, considerable batch-to-batch variability tied to agricultural growing conditions, and moisture sensitivity that glass fiber does not share, but at a fraction of the embodied energy and with genuine end-of-life advantages [18]. Prem Kumar and colleagues' review of hybridization strategies for natural fiber composites addresses the most common engineering response to that tradeoff: rather than using natural fiber alone, combine it with a smaller fraction of glass or synthetic fiber to recover some of the lost strength and stiffness while still capturing a meaningful share of the sustainability benefit, a strategy the review finds has been applied across a wide range of natural fiber and hybridization-partner combinations with generally favorable mechanical results relative to the natural-fiber-only baseline [19]. Siakeng and colleagues' review of natural fiber reinforced polylactic acid composites narrows the same substitution logic to its most complete form: pairing natural fiber reinforcement with a bio-based, biodegradable polylactic acid (PLA) matrix rather than a conventional petroleum-derived thermoset, producing a composite that is, at least in principle, fully bio-based on both the fiber and matrix side, though the review is candid that PLA's own mechanical and thermal limitations currently confine this combination to less structurally demanding applications than conventional FRP composites target [20].

For civil infrastructure specifically, the more mature bio-based and low-carbon substitution has arguably occurred on the matrix side rather than the reinforcement side, through geopolymers binder systems that replace ordinary Portland cement — whose manufacture is responsible for a substantial share of global industrial carbon dioxide emissions, largely from the calcination reaction that produces clinker — with an aluminosilicate binder activated by an alkaline solution rather than produced through high-temperature clinker calcination. Patel and Shah's development of

self-compacting geopolymer concrete demonstrates that this alternative binder chemistry can be engineered to meet the workability requirements of modern placement practice, not merely the strength requirements that earlier geopolymer research had focused on, which matters for practical adoption because a structurally adequate concrete that cannot be placed using standard construction equipment and schedules has limited commercial viability regardless of its sustainability credentials [21]. Islam, Kafle, and Al-Ameri's more recent comprehensive review of natural clay as a pozzolanic precursor material in geopolymer concrete pushes the raw-material sourcing question further, surveying the case for using locally available natural clays rather than industrial byproducts such as fly ash or ground granulated blast furnace slag — materials whose future availability is itself uncertain as the coal power and blast furnace steel industries that produce them are phased down — as the aluminosilicate source for geopolymer binders, an argument the review frames explicitly around long-term feedstock security for green construction rather than only near-term carbon accounting [22]. Geopolymer binders and FRP composite reinforcement are not competing technologies; if anything, geopolymer concrete's typically higher alkalinity and different pore solution chemistry relative to ordinary Portland cement concrete is itself an open question for FRP durability that the alkaline-exposure literature discussed earlier has generally studied in conventional concrete rather than geopolymer concrete specifically, a gap we return to in the discussion of open challenges below.

A third and structurally distinct sustainability strategy extends service life by design rather than by reducing embodied impact: self-healing composites and concretes that autonomously repair microcracking before it propagates into structurally significant damage. Adil, Rabbi, and Tasnim's critical review of microcapsule-based self-healing composites surveys the dominant mechanism in this space — embedding microcapsules containing a healing agent (commonly a monomer or resin) within the composite matrix, such that a propagating crack ruptures nearby capsules, releases the healing agent into the crack plane, and triggers a polymerization reaction that seals the crack — and the review's particular value for a civil-infrastructure audience is its systematic treatment of the factors that determine whether this mechanism

actually works reliably at structural scale: microcapsule size and shell-wall thickness, healing-agent chemistry, achievable healing efficiency, and the thermal and long-term stability of the embedded capsules under the manufacturing and service conditions a real structural composite experiences [23]. Self-healing extends the useful service life of both conventional FRP composites and cementitious composites, and is best understood as complementary to, rather than competing with, the durability-focused material selection strategies discussed earlier in this article: a self-healing mechanism reduces the consequences of the microcracking that occurs despite good material selection, rather than replacing the need for good material selection in the first place.

6. Life-Cycle Assessment, End-of-Life Recycling, and Circularity

A material cannot honestly be called sustainable on the strength of its in-service properties alone; the full life cycle — raw material extraction, manufacturing energy, transportation, in-service performance, and what happens when the structure or component reaches the end of its useful life — has to be accounted for, and this is precisely where fiber-reinforced polymer composites have historically faced their most serious sustainability critique. Das's life-cycle assessment of carbon fiber reinforced polymer composites, one of the earlier systematic LCA treatments of the material, laid out the core tension that has shaped the field's sustainability discussion ever since: carbon fiber manufacturing is extremely energy-intensive on a per-kilogram basis relative to conventional structural materials, meaning CFRP's sustainability case rests heavily on lightweighting benefits realized during the use phase — reduced fuel consumption in a vehicle, reduced foundation and substructure material in a lightweight bridge deck — being large enough to offset that manufacturing-phase energy burden over the component's service life [24]. For a static civil structure that is not moved or does not burn fuel to support its own weight the way a vehicle does, that use-phase offset argument is weaker than it is for CFRP's traditional aerospace and automotive markets, which is one reason GFRP rather than CFRP dominates the higher-volume civil reinforcement market: glass fiber's substantially lower embodied energy relative to carbon fiber matters more when the material's sustainability case cannot lean as heavily on use-phase weight savings. Cadenazzi and

colleagues' life-cycle cost and life-cycle assessment of a full-scale, monumental FRP-reinforced concrete structure is a useful corrective to a purely manufacturing-phase framing of this tradeoff, because it accounts for the avoided corrosion-related maintenance and repair activity that FRP reinforcement's durability delivers over the structure's full service life, finding that the reduced maintenance burden can offset FRP reinforcement's higher initial material cost and embodied impact over a multi-decade horizon in a way that a manufacturing-only accounting would miss entirely [25].

Table 1: Comparative cumulative energy demand (CED), global warming potential (GWP) and processing cost per kilogram of CFRP waste across four end-of-life recycling routes, as reported by Vogiantzi and Tserpes [26].

Recycling Route	CED (MJ/kg)	GWP (kg CO ₂ eq/kg)	Cost (EUR/kg)
Mechanical recycling	5.82	0.218	0.106
High-voltage fragmentation	4.97	0.0796	155
Pyrolysis	66.3	2.84	4.66
Solvvolysis (supercritical water)	66.3	2.49	51.2

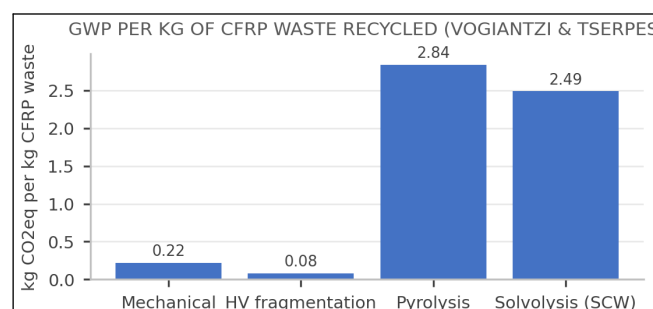


Figure 1: Global warming potential per kilogram of CFRP waste processed, compared across four end-of-life recycling routes, as reported by Vogiantzi and Tserpes's comparative life-cycle assessment — mechanical recycling and high-voltage fragmentation are markedly lower-impact than the thermochemical recovery routes, pyrolysis and solvolysis, that are typically needed to recover longer, higher-quality fibers [26].

End-of-life management has historically been the more acute weakness, because thermoset composite matrices — cured by an irreversible chemical crosslinking reaction rather than melting reversibly the way a thermoplastic does — cannot simply be remelted and reformed the way steel or aluminum can, and for decades the practical end-of-life options for most thermoset FRP waste amounted to landfill or, at best, downcycling into low-value filler material. Vogiantzi and Tserpes's comparative environmental and economic analysis of CFRP recycling processes provides exactly the kind of quantified, multi-method comparison this discussion needs: examining mechanical recycling,

high-voltage fragmentation, pyrolysis, and solvolysis side by side using both life-cycle assessment and life-cycle costing, the study reports that mechanical recycling and high-voltage fragmentation are substantially less energy- and carbon-intensive than the thermochemical recovery routes — cumulative energy demand of roughly 5 to 6 megajoules per kilogram of CFRP waste processed for mechanical recycling and high-voltage fragmentation, against roughly 66 megajoules per kilogram for pyrolysis and supercritical-water solvolysis, with global warming potential following a broadly similar pattern — while also being dramatically less expensive, at a small fraction of a euro per kilogram for mechanical recycling versus tens to well over a hundred euros per kilogram for the solvolysis and high-voltage fragmentation routes examined [26]. The practical implication is a genuine tradeoff rather than a simple ranking: mechanical recycling and fragmentation are cheap and low-impact but typically recover only degraded, shortened fibers suitable for lower-value applications, while pyrolysis and solvolysis are far more energy- and cost-intensive but can recover longer, higher-quality fibers closer to virgin fiber properties — meaning the "best" recycling route genuinely depends on what the recovered material needs to be good enough to be reused for, not on a single universal efficiency ranking.

That end-of-life question is not merely theoretical for civil infrastructure, because one of the largest emerging sources of decommissioned composite material is itself an infrastructure asset: wind turbine blades. Shen, Apraku, and Zhu's review of recycling and recovery options for end-of-life wind turbine blade composites frames the scale of the problem directly — blades are large, long-lived structures built from glass or carbon fiber composite that eventually reach the end of their service life in large volumes as aging wind farms are repowered, creating a waste stream that existing recycling infrastructure was never sized to absorb — and surveys the same broad families of recovery technique (mechanical, thermal, chemical) that Vogiantzi and Tserpes examine for CFRP more generally, applied specifically to the blade-composite waste stream [27]. Liu, Meng, and Barlow's economic comparison of wind turbine blade end-of-life options adds a directly relevant civil-infrastructure angle to this picture: among the options compared is repurposing decommissioned blade sections as structural or semi-structural elements

in new construction — most prominently, using cut blade segments as prefabricated structural members for small pedestrian bridges — an application that converts a waste-management problem into a source of low-cost, already-manufactured composite structural material for exactly the kind of civil infrastructure this article is concerned with, and one the study finds can be economically competitive with conventional blade disposal routes under a range of assumptions about transport distance and repurposing-site availability [28]. This blade-repurposing trend is a useful closing note for the sustainability-and-circularity theme of this article, because it exemplifies a distinctly infrastructure-native form of composite recycling that does not appear in the vehicle-lightweighting or aerospace contexts that dominate earlier CFRP life-cycle literature: civil infrastructure is not only a consumer of new composite material but an increasingly plausible destination for composite material recovered from a different, unrelated infrastructure sector entirely.

7. Open Challenges

Several gaps recur across the literature synthesized here and deserve to be stated plainly rather than left implicit. First, geopolymer-FRP compatibility is, to our knowledge, substantially under-studied relative to how well each half is understood separately: the alkaline-durability literature reviewed above was conducted almost entirely in ordinary Portland cement concrete, and geopolymer concrete's different pore solution chemistry and typically higher and more variable alkalinity mean that the GFRP durability data summarized here cannot be assumed to transfer directly to a geopolymer matrix without dedicated study [6,22]. Given that both technologies are independently marketed on sustainability grounds, resolving whether they are also mutually compatible at durability-relevant timescales is a meaningful open question rather than a minor detail.

Second, the durability literature itself, while genuinely strong for plain alkaline exposure and reasonably developed for marine and acid conditions, remains thinner on the combined, multi-stressor exposure conditions — simultaneous freeze-thaw cycling, sustained load, and chloride exposure, for instance — that a real bridge deck in a cold, coastal climate actually experiences, as opposed to the single-variable exposure protocols that dominate most of the individual studies

reviewed here [8,10,11]. Third, natural-fiber and bio-based composites remain confined, by the reviewed literature's own account, to less structurally demanding applications than conventional glass or carbon FRP addresses, and the batch-to-batch mechanical variability tied to natural fiber's agricultural origin is a genuine barrier to the kind of reliability-based structural design that civil infrastructure codes require, not merely an engineering inconvenience to be optimized away [18,20].

Fourth, end-of-life recycling economics, as the Vogiantzi and Tserpes comparison makes concrete, currently force a real choice between low-cost, low-impact recovery of degraded fiber and expensive, higher-impact recovery of higher-quality fiber, and no reviewed study reports a recycling route that is simultaneously cheap, low-impact, and capable of recovering fiber suitable for reuse in demanding structural applications [26]. Whether that three-way tradeoff is a temporary state of a still-maturing recycling industry or a more fundamental limitation of thermoset composite chemistry is not yet resolved by the literature synthesized here. Fifth, and more mundane but no less real: reporting standards across the durability and life-cycle literature are inconsistent, with some studies reporting environmental impact per kilogram of material, others per functional structural unit, and durability studies varying between reporting residual tensile strength, residual modulus, and mass or diameter change as their primary metric, which makes direct cross-study comparison harder than it should be for a field this mature. We do not think these gaps undermine the overall case for sustainable composite materials in civil infrastructure — the consistency with which independent research groups, working on FRP durability, natural-fiber substitution, geopolymer binders, and end-of-life recycling, have converged on cautiously positive but appropriately qualified conclusions is itself meaningful evidence — but they are the honest state of the field, and claims of unqualified sustainability or unlimited service life for any single composite technology should be read against these open questions.

8. Conclusion

The literature reviewed here supports a specific and reasonably confident claim: fiber-reinforced polymer composites, and the broader family of sustainable composite technologies surrounding them, have moved

from a promising alternative to steel-reinforced concrete to a genuinely evidenced one for a meaningful, if still bounded, range of civil infrastructure applications. Multi-year durability studies across alkaline, marine, and acid exposure conditions now support GFRP's use as internal reinforcement in demanding environments with appropriate, data-calibrated design allowances rather than an assumption of immunity to environmental degradation [6,7,8,10,11]. External strengthening with FRP laminates has moved from a novel technique to close to routine practice for shear and column retrofit [13,14], and integrated FRP and hybrid bridge deck systems have progressed from static-load demonstrations to fatigue-characterized structural systems [15,16,17,4,5].

On the sustainability side specifically, the picture is more mixed but still meaningfully positive: natural-fiber and bio-based composites offer a genuine, if currently structurally limited, lower-embodied-impact alternative for less demanding applications [18,19,20], geopolymer binders offer a credible low-carbon substitute for the cementitious matrix that composite-reinforced concrete is typically built around [21,22], self-healing mechanisms offer a service-life-extension strategy that reduces the practical consequences of material aging [23], and — perhaps most concretely of all — the end-of-life recycling and circularity literature now provides quantified, decision-relevant comparisons between recovery routes rather than a vague assurance that composite waste is "recyclable," alongside a genuinely infrastructure-native circularity pathway in the repurposing of decommissioned wind turbine blade composite into new civil structures [24,26,27,28].

None of this amounts to a claim that composite materials should or will fully displace steel-reinforced concrete across civil infrastructure; basalt fiber's toughness limitations, natural fiber's structural ceiling, geopolymer-FRP compatibility's open status, and end-of-life recycling's persistent cost-versus-quality tradeoff are all real constraints rather than solved problems [3,18,26]. What the literature synthesized here does support is a more measured conclusion: sustainable composite materials are now a evidence-backed, appropriately specified option for the specific infrastructure problems — corrosion-prone reinforcement, rapid bridge deck replacement, retrofit strengthening, and increasingly, circular reuse of

composite waste streams from other sectors — where their particular combination of properties genuinely outperforms conventional materials, and the field's task going forward is less about proving the basic case for these materials and more about closing the specific, well-identified gaps in multi-stressor durability data, geopolymer compatibility, and recycling economics that stand between a strong evidence base and a fully mature, code-integrated design practice.

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Ethical Approval

Not applicable. This work is a synthesis of previously published literature and did not involve human participants, animal subjects, or the collection of primary experimental data.

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