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SYNERGISTIC OR ADVERSARIAL A CRITICAL REVIEW OF BIO-BASED FIBER AND RECYCLED AGGREGATE CONCRETE SYSTEMS FOR RESILIENT AND SUSTAINABLE INFRASTRUCTURE

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ABSTRACT

The two concurrent challenges for the construction sector are (1) decarbonization of the construction material supply chains, and (2) increasing the resilience of the aging construction sector stock. To meet these pressures, two independent material strategies have emerged: the first is use of recycled concrete aggregate (RCA) to replace virgin mineral resources and the second is the addition of bio-based fibers, particularly hemp fiber, for their ability to improve tensile toughness and crack control. This review critically discusses the combined effects of these two strategies: hemp fiber-reinforced recycled aggregate concrete (HFRAC). Each of the constituent technologies is well documented but the combination of these is less studied and poorly understood. This review is motivated by the central question of whether the combination is a synergistic one involving fibre bridging that overcomes the weakness of the interface between the RCA and the fibre or whether it is an additive one where both the materials are imperfect. Based on limited available literature, it can be concluded that hemp fiber has a positive effect on the post-peak performance and fracture energy of RAC systems, with reported increases of +17.9% and +14.4% for shear and bond fracture energy, respectively, compared to control specimens (Ghosn et al., 2023). Peak load improvements are still relatively small (about 4% or less), however, and may be compensative rather than improving. Importantly, there are three competing interface phenomena that are essentially unstudied: water competition, crack bridging vs weakening at the interface and chemical incompatibility. This review describes the current state of knowledge and highlights the gaps that are systematic and identifies a research agenda based on multi-scale interface characterization and life cycle-resilience co-assessment.

Keywords: Recycled Aggregate Concrete, Hemp Fiber, Bio-Based Composites, Interfacial Transition Zone, Resilience, Sustainability, Critical Review

1 INTRODUCTION

1.1 The Dual Imperative of Decarbonization and Resilience

About 30 billion tonnes of aggregate are used each year worldwide in the construction industry and it is estimated that 8-9% of anthropogenic CO₂ emissions are associated with the production of concrete. At the same time, the developed countries are faced with a large demand for the structural rehabilitation of their old infrastructure while the developing countries are undergoing a fast urbanization that must be met with a new construction. The need for both material saving and structural resilience has spurred research to find alternative cementitious systems that meet both environmental and performance requirements.

Construction and Demolition Waste (CDW) recycled concrete aggregate (RCA) is a direct solution for displacing virgin aggregate extraction, and for lowering the impacts on landfills. Trivedi et al. (2024) give a detailed overview of RAC properties and explained that it is a material that has environmental benefits, but with certain performance limitations, including an increased water absorption capacity from RACs, poor workability, reduced compressive strength properties, and most importantly, poor tensile toughness and durability properties in harsh environmental conditions. The restrictions are related to the basic micro-structure of RCA as it has a porous adhesive cement matrix with 20-50% mass of the material, which is porous, micro-cracked and chemically different from the fresh cementitious matrix. This creates weak and heterogenous interfacial transition zone (ITZ), which affects the mechanical performance and transport properties (Trivedi et al., 2024).

At the same time, natural fiber reinforcement has garnered increasing attention as a low cost, low carbon approach to enhancing the post-cracking behavior of concrete. Hemp fiber (HF) is derived from the plant *Cannabis sativa* L., a natural fibre with a favourable combination of high tensile strength (around 690 MPa), moderate Young's modulus (30-60 Gpa) and proven capacity to bridge cracks (Di Sarno et al., 2024). Hemp is a renewable reinforcement material because of its characteristics of quick growth, low pesticide use and carbon sequestration during cultivation (Di Sarno et al., 2024). The hydrophilic, alkaline sensitivity and dimensional instability makes HF difficult to incorporate into cementitious matrices, however (Santos & Archbold, 2022).

1.2 The Unexplored Intersection

The incorporation of RAC along with hemp fibre concrete (HFRAC) is still not so much explored even though the research on RAC and hemp fibre concrete separately are matured. There is no previous studies reported on mixtures with such a combination of hemp fibres and RCA as stated by Ghosn et al. (2023). The most relevant literature found was that conducted by Ghosn et al. (2023) in which they evaluated the flexural, shear and bond-splitting properties of hemp-recycled aggregate concrete (HRAC) with 0.75% hemp fiber by volume and 50% of recycled aggregate. The study results showed that the peak loads were within $\pm 4\%$ of the control group, with flexural, shear and bond-splitting modes showing increases of 3.6%, 17.9% and 14.4% in fracture energy, respectively, which is a more sensitive measure of toughness. From these results, it was determined that the contribution hemp fiber is making is the greatest in shear dominated brittle type of failure, which in terms of mechanics follows the fiber bridging behavior.

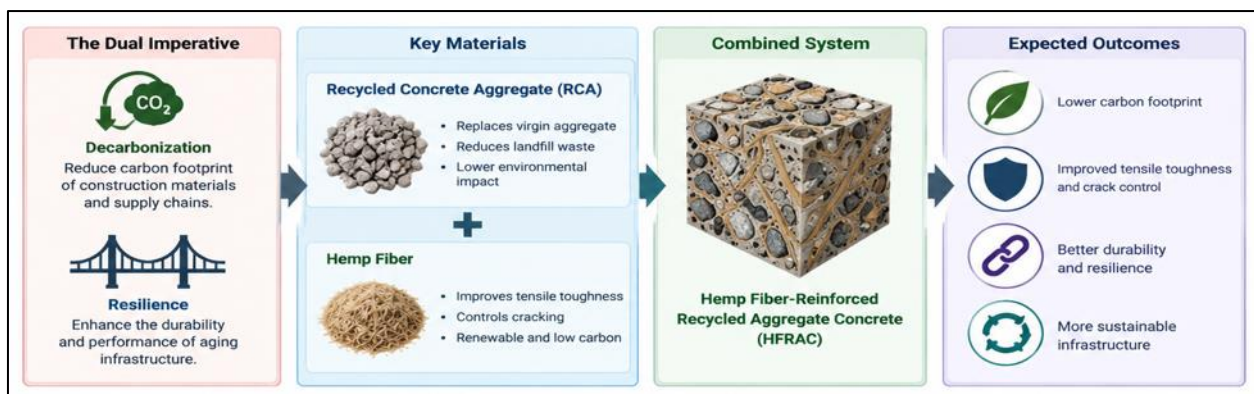


Figure 1: Schematic overview of the dual challenge, material strategies, and expected benefits of hemp fiber-reinforced recycled aggregate concrete (HFRAC) systems

These questions are answered in this review in a critical synthesis of the present literature. The central thesis is the 'synergy' must be achieved with a narrow range of mixes and depends on interfacial phenomena that are not well understood. The review is organised in six sections. In Section 2, the baseline problem is set up by summarizing the mechanical and durability limitations of RAC, focusing on failure mechanisms of relevance for fiber reinforcement.

Section 3 explores the principles of reinforcement and constraints of hemp fiber in cementitious composites. Hemp fiber and RCA interfacial interaction analysis is presented as Section 4 of the review, which is the intellectual core of the review. Section 5 assesses the evidence and trade-offs at the structural scale.

2 RECYCLED AGGREGATE CONCRETE: PERFORMANCE CEILING AND FAILURE MECHANISMS

2.1 Fresh-State Challenges and Their Root Causes

The addition of RCA to concrete creates immediate changes to fresh state properties that extend into hardened properties. The major reason is the higher water absorption normally in the range of 3-10% by mass for RCA and 0.5-1.5% for natural aggregate, depending on the amount of adhered mortar content and the quality of the original concrete (Trivedi et al., 2024). This absorption establishes a competition between the water that can be utilized to hydrate the cement and the water absorbed into the pores of the RCA during mixing.

Tam et al. proposed the two-stage mixing approach (TSMA) to address this issue, demonstrating that pre-wetting RCA or adjusting mixing sequences can partially mitigate the water demand (Trivedi et al., 2024). At water-to-cement (w/c) ratios equal or larger than 0.55, the workability of RACs is found to be similar to the workability of conventional concrete, while fluidity is shown to decrease with lower w/c ratio (Lavado et al., 2024; Trivedi et al., 2024). This observation is of practical significance: penalty for it is not 'built-in' to RCA but depends on the mix design. The water content increase to restore workability is however accompanied in practice with consequences on strength/durability that are often not sufficiently controlled.

2.2 Mechanical Deficiencies and the Interfacial Transition Zone

One of the limitations of the mechanical system of RCA is well documented and has a mechanism that is well understood. The chemically similar but materially different adhered mortar layer has high porosity, microcracking and a different pore structure than the new matrix. The creation results in a three phase ITZ system in RAC, that being the fresh paste, the adhered mortar and the old ITZ between adhered mortar and original aggregate (Trivedi et al., 2024). The presence of multiple weak interfaces alters stress transfer and crack initiation pathways.

The authors of the Trivedi et al. (2024) study highlight that the characteristics of the ITZ of RAC are more prone to degradation than of natural aggregate concrete (NAC). This is not just a durability issue, but a fundamental decrease in the material's ability to withstand crack propagation when loaded in any manner. There is a preferential path of moisture infiltration and crack formation through the porous ITZ.

2.3 Durability Under Coupled Environmental Attack

The remaining durability performance of RAC in combinations of environmental conditions is perhaps of greater concern than mechanical inadequacies. A single degradation mechanism in service of a concrete structure is almost never present alone; rather, there are interactions between them that accelerate the degradation.

The effects are far-reaching with RAC in particular. The porous ITZ will offer more pathways for ions to enter the material, and the ITZ's residual hydration products could respond differently to sulfate ions and chloride ions than would fresh cementitious products. To enhance the durability of RACs, the researchers of the Trivedi et al. (2024) suggest a fundamental approach to the ITZ, via supplementary cementitious materials, nanomaterials, fiber reinforcement or surface treatment. The question raised by the present review is: can bio-based fibres contribute to this ITZ-level improvement, or can they be used as an independent reinforcement mechanism that is acting on the mortar matrix as opposed to the aggregate-paste interface?

3 BIO-BASED FIBERS IN CEMENTITIOUS SYSTEMS: MECHANISMS AND LIMITS

3.1 Hemp Fiber: Properties and Reinforcement Mechanisms

This chapter discusses the properties and reinforcement mechanisms of hemp fiber. The hemp fibre is obtained from *Cannabis sativa* by separating the fibre from the hurd via microbial retting. Compared to water retting, fibers subjected to field retting have a higher cellulose content, thus resulting in higher mechanical properties of composites (Di Sarno et al., 2024) and lower cost. The chemical composition of the fiber, which is made up of about 60-70% cellulose, 15-20% hemicellulose and 10-15% lignin, dictates its mechanical properties and its susceptibility to chemical degradation in alkaline environments (Di Sarno et al., 2024).

On a reinforcement point of view, hemp fiber acts in two major ways. Firstly, fibers do not have a significant contribution to stiffness before cracking as their stiffness (Modulus) is lower than that of the cementitious matrix (30-60 GPa).

Second and importantly, once matrix cracks have started, the fibres bridge across the cracks and carry stress via interfacial shear. This bridging action reduces energy by pulling out the fiber and/or, in some instances, by breaking the fiber. Re-resulting is a ductility improvement and fracture energy, which are particularly important in shear dominated failure modes where brittle behavior is most dangerous.

The fiber's "crack-bridging capability is crucial for preventing crack propagation and enhancing fracture energy," states Di Sarno et al. (2024). Numerous studies have reported improvements in flexural properties, with the amount of improvement varying with fiber dosage, fiber length and matrix composition. The compressive strength effects are more inconsistent; for some reports, there is no significant difference with the addition of higher fiber content, while others show a decrease in compressive strength with increase in fiber content because of increased porosity and poor fiber-matrix interface (Di Sarno et al., 2024).

Huang et al. (2025) recently conducted a study on hemp fiber concrete for dam model materials, and their results indicated that the maximum flexural strength and the best crack-limiting effect were achieved at a mass admixture of 1.00%. Their study showed approximately positive correlation between the flexural strength and the content of fiber. This dosage-response relationship is useful to give guidance to the mix design for HFRAC, however the optimal dosage may change if there is RCA present because of water competition effects.

3.2 The Interfacial Problem: Hydrophilicity and Alkaline Sensitivity

The most important drawback of hemp fiber in cementitious systems is its interactions with water and alkaline pore solution. The surface of fiber is full of hydroxyl groups making it hydrophilic in nature. The reported water absorption capacities are up to 325% of the fiber mass which has significant implications for mix design and interfacial bonding (Santos & Archbold, 2022).

There are a number of forms of this hydrophilicity. In the mixing process, dry hemp fiber will compete with cement and aggregate for water, which may decrease the water-to-binder ratio in the surrounding matrix. Less obviously, the fibre's absorption-desorption causes dimensional instability, that is, fibres swell with water absorption and shrink with drying, causing the formation of microcracks at the fibre-matrix interface. A high moisture absorption rate and dimensional instability, according to Santos and Archbold (2022), "induce crack initiation and propagation within the concrete matrix."

Another challenge but related, is alkaline sensitivity. The pH of the cementitious pore solutions is usually between 12.5 and 13.5, and is largely comprised of alkali hydroxides and calcium hydroxide. Unlike cotton, the hemicellulose and lignin fractions of hemp fiber can be dissolved in alkaline solutions and once they have dissolved, the cellulose fibers become more susceptible to degradation (Santos & Archbold, 2022). This process can cause the fiber to become less effective over time, and erode the bond between the fiber and the matrix, possibly turning the fiber into a defect like a void.

Limits have been overcome by the development of pre-treatment strategies. Santos and Archbold (2022) found that treatment using NaOH 10% for 24 hours was able to enhance the properties of hemp fibre-reinforced concrete and reduce degradability in alkaline solution. The mechanism is the removal of weakly bonded non-cellulosic components, upon which, controlled alkaline exposure reveals cellulose microfibrils which further bond with cementitious matrix. The authors of Di Sarno et al. (2024) also report that the alkaline treatment produces fibres with fibrillation which allows for greater contact area with the matrix while calcium hydroxide treatment can facilitate hydration due to excess alkalis that can form more calcium silicate hydrate (CSH) products.

3.3 Shrinkage Mitigation: An Underappreciated Benefit

In a 2025 study investigating biochar and hemp fiber synergy in RAC, drying shrinkage was identified as a key issue for RAC performance, where the shrinkage was estimated to be 15–80% greater than for natural aggregate concrete, with some containing up to 90% of the shrinkage on account of drying. The unique finding of the study was that it proved hemp fiber when mixed with activated coconut biochar can reduce the drying shrinkage properties by the internal curing effect.

This internal curing mechanism has been well documented in the case of SLA and SPS. For SLA and SPS, the internal curing mechanism is well understood where water released from the material keeps the relative humidity in the mix at an appropriate level, allowing continued hydration to be carried out which minimises autogenous and drying shrinkage. The large water-absorption capacity of hemp fiber indicates that it may be used for a similar purpose, releasing the absorbed water gradually during the drying process of the matrix. The same study, however, indicates the potential role of hemp fiber in mitigating the drying shrinkage in both recycled aggregate concrete and natural aggregate concrete, has not been explored yet. This is a major gap in the literature that is directly relevant to the most practically relevant durability challenge for RAC.

4 THE CRITICAL INTERFACE: WHEN BIO-BASED FIBERS MEET RECYCLED AGGREGATES

4.1 Water Competition: A Zero-Sum Interaction

The closest and possibly least recognized interaction between hemp fiber and RCA is when they are fresh, both fighting for the water during mixing. The adhered mortar of RCA swells due to its water absorption capacity of 3% to 10% by mass (Trivedi et al., 2024) which leads to the formation of cavities between the brick and mortar. Hemp fiber has a water absorption capacity on its surface and in its lumen and cell wall structure, and can reportedly hold 325% of its weight in water (Santos & Archbold, 2022). If both materials are mixed together, the combined effects of both absorptions is the reduction of water available for cement hydration and water ability to function.

The ramifications of this competition could be profound. A lower value of effective water content in the matrix around the RCA particles would hinder the hydration of the fresh ITZ, already being the weakest link of RAC's microstructure. At the same time, a decrease in the amount of water used for fiber-matrix bonding would affect the anchorage of the fiber and reduce its crack-bridging ability. The combined effect might be the composite that both reinforcement mechanisms (which are not present) and fiber bridging work below their potential.

The HRAC study by Ghosn et al. (2023) most likely attempted to solve it by modifying the mix (pre-saturation of RCA or fibers, or adding water) but did not specify what this change was. The effects of this change on the interfacing microstructures are not included in the information available. This is a key gap. If the partitioning of the water between the cement and the RCA and hemp fiber is unknown, the mix design of the HFRAC is empirical, at best.

The difficulties associated with workability are also mentioned in the review of natural fiber reinforcements in 2026: "The significant slump reduction due to hydrophilic fibers makes casting, compaction, and self consolidating more complex and requires more advanced optimization of admixtures with the fibres". This workability challenge is exacerbated in RAC systems, due to the fact that RCA demands water as well, leading to a "double hydrophilicity" problem, which has not been mentioned in the literature.

4.2 Crack Bridging versus Interfacial Weakening: Spatial Mismatch

Hemp fiber reinforcement mechanisms and RAC failure mechanisms take place at different spatial scales and at various locations within the composite. The hemp fibers keep the mortar matrix intact and fill the gaps between them, preventing any stress from being transmitted across the cracks and energy being absorbed through pull-out. RCA's is, on the other hand, localized at the interface between the aggregate and the adhered paste (ITZ), such as the interface between the new paste and the original aggregate, and between the adhered paste and the original aggregate (Trivedi et al., 2024).

It is a fundamental question whether there is a "spatial mismatch" that can be balanced by the ability of the fibre to bridge weak points in the mortar matrix at the aggregate-paste interface. The response is dependent on the tortuosity of the crack path. In the event of cracks following the weak RCA ITZ, they could completely avoid the fibre bridging site. On the other hand, if the ITZ is sufficiently strong to open up cracks within the mortar matrix (which contains fibres) then fibre bridging can be engaged.

The answer to this question can be indirectly obtained from the results obtained by Ghosn et al. (2023) for the fracture energy. The large shear fracture energy increase (+17.9%) over the small flexural increase (+3.6%) implies that under distributed cracking, or failure mode, fiber bridging is most effective. Shear dominated failure will create several diagonal cracks, which will increase the chances of the cracks meeting the site of the fiber bridging. With flexural failure, one dominant crack can travel through areas where the fibers are not properly oriented and distributed.

The results of the peak loads are within $\pm 4\%$ of control, suggesting that fibers do not make significant contributions to the initiation of failure. This is consistent with our knowledge of fiber reinforcement as being most effective for propagation not initiation. This means that the benefits of HFRAC would manifest in the post cracking phase, potentially usefully in seismic applications, where energy dissipation and ductility would be the major concerns, but not for increasing ultimate strength.

4.3 Chemical Compatibility: The Unstudied Dimension

The chemistry of RAC may differ from natural aggregate concrete in such a way as to impact hemp fiber durability. For surfaces where the adhered mortar have been in service, these surfaces have been carbonated resulting in a lowered local pH in the ITZ range. The pH of the carbonated regions can be as low as 8–9 whereas the fresh pore solution is 12.5–13.5. Moreover, there may be some unhydrated cement particles in RCA that can still hydrate when it is wet, thus changing the chemistry (Trivedi et al., 2024).

For hemp fibre, the consequences of this heterogeneous chemico-environmental situation are unknown. The alkaline degradation (decomposition) of the fiber involves the degradation (dissolution) of hemicellulose and lignin as a function of pH, temperature and period of exposure. The degradation rate of fibers could be slower in the carbonated, lower pH, microenvironment around RCA particles than in the fresh, high pH, microenvironment. On the other hand, when the RCA structure is porous and able to allow the movement of ions, local zones of high alkali concentration could be formed (due to alkali release during subsequent hydration). There has never been any direct study to specifically investigate hemp fiber degradation process in RAC pore solution.

The available evidence is for the durability of hemp fibre in natural aggregate systems or hemp-lime composites, which do not represent the chemical heterogeneity of RAC as seen in the laboratory tests on RAC (Santos & Archbold, 2022). It is also recognized as a critical gap in the current state-of-the-art in the review of natural fiber reinforcements that is scheduled for 2026, which states that “The degradation mechanisms under realistic service conditions have not been thoroughly investigated.” The chemical complexity of HFRAC appears to be unique, owing to the carbonated and uncarbonated areas combined with hydration products of the cement and fibre breakdown products that has not been studied before.

4.4 Evidence from Confinement Studies: A Parallel Reinforcement Pathway

Indirect but significant evidence of fiber-RCA interaction from recent studies of hemp rope confined RAC is available. The study titled ‘Effect of axial compression for RAC cylinders in hemp rope confinement’ found that confinement of RAC cylinders resulted in an axial strain increase, which was systematically greater than that of compression strength, with the compressive strength increase also being significant. Of particular note, “confinement was found to be even more effective in thermally damaged specimens where the lateral deformability of the specimens is increased.”

It is unclear if the same synergy can be obtained if the hemp fibers are incorporated into the crack as discrete fibers in RAC. The results of the confinement study are promising, but these are not definitive answers to whether or not there are weaknesses in the distributed ITZ that internal fibers can overcome. The study does show that hemp reinforcement of RAC is not without use: it can be beneficial in the right configuration.

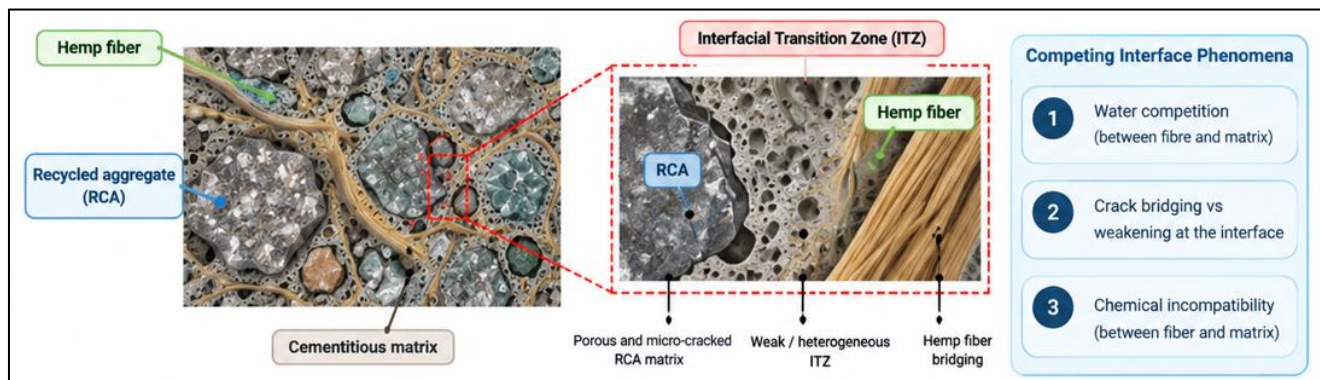


Figure 2: Schematic representation of the microstructural interactions in hemp fiber-reinforced recycled aggregate concrete (HFRAC), showing the key interfacial zones and competing mechanisms

5 STRUCTURAL-SCALE EVIDENCE AND LIFE-CYCLE TRADE-OFFS

5.1 The Beam Study: Evidence and Limitations

Ghosn et al.'s (2023) HRAC beam investigation remains the only structural-scale experimental study of hemp fiber-reinforced RAC. The optimum 50% replacement ratio of RCS and 0.75% hemp fiber content volume was applied in the study, which was conducted in a flexural, shear, and bond-splitting setup.

Table 1: Comparative performance of hemp fiber-reinforced RAC systems across experimental configurations

Performance Metric	Ghosn et al. (2023) HRAC Beams	Hoy et al. (2024) HFRC with RCA for Pavements	Biochar-Hemp Fiber RAC (2025) Internal Curing System	RAC Baseline (Without Fiber) Multiple Studies	Hemp Rope-Confined RAC (2026) Axial Compression
RCA Replacement Rate	50%	Not specified (RCA used)	Not specified (RAC base)	0–100% (range)	Not specified (RAC base)
Hemp Fiber Dosage	0.75% by volume	0.5–1.0% by volume	10–30 mm length (dosage varied)	0% (control)	External confinement (rope)
Peak Load / Strength vs. Control	Within $\pm 4\%$ (flexure, shear, bond-splitting)	Flexural: up to +7% improvement	Compressive: up to +28%; Flexural: up to +34% (with biochar synergy)	Compressive strength typically reduced by 10–30% at high RCA replacement	Strain enhancement consistently more pronounced than strength gain
Fracture Energy / Energy Dissipation	Flexure: +3.6%; Shear: +17.9%; Bond: +14.4%	Enhanced energy absorption and ductility at 0.5% hemp	Not directly measured; shrinkage reduction suggests improved matrix integrity	Energy dissipation reduced from ~85 kJ to ~55 kJ at 100% RCA	Cumulative energy dissipation increased by 143% at 2.0% drift (frame-level test)
Drying Shrinkage	Not reported	Not reported	Up to 96% reduction with biochar + hemp fiber synergy	15–80% higher than NAC; may account for up to 90% of total shrinkage	Not applicable (confinement configuration)
Water Absorption / Chloride Permeability	Not reported	Not reported	Remarkably reduced; chloride penetration resistance improved by obstructing ion transport	Generally higher than NAC due to RCA porosity	Not reported
Fatigue Performance	Not tested	Higher hemp content significantly improved fatigue life under repetitive loading	Not tested	Long-term fatigue remains a concern requiring conservative design	Not tested
Optimal Fiber Dosage Identified	0.75% (single mix tested)	0.5% (balance of mechanical gain vs. drawbacks)	30 mm fiber length with 30% biochar	N/A	N/A
Life-Cycle / Carbon Metric	LCA supported environmental advantage (specific values limited)	Not reported	Carbon reduction: 4.4 kg CO ₂ eq./m ³ /MPa (compressive scenario); 23.8 kg CO ₂ eq./m ³ /MPa (flexural scenario)	Reduction in GWP reported with optimized mix design methods	Not reported
Key Mechanistic Finding	Fiber contribution most pronounced in shear-dominated brittle failure; peak load compensation without enhancement	Hemp fiber reinforcing effect consistent across both NCA and RCA types	Biochar + hemp fiber synergy enables internal curing, reducing local w/c ratio during hardening	RCA ITZ porosity and microcracking govern strength limitation	Confinement more effective in thermally damaged specimens due to increased lateral deformability -

This is in line with the mechanistic understanding of fiber bridging, which is triggered by the cracking of the matrix and it is most effective in modes with multiple cracks.

There are limitations in this study, such that the results are not generalizable. Only one mix proportion (50% RCA, 0.75% fiber) was tested. The optimum dose and window of effective range is not known. There are no tests on columns, joints, shear walls, and slabs, structures that are all important to seismic performance, and which are completely unstudied. Hemp fiber's durability in the RAC alkaline environment was not evaluated over the long term in this study. Not least, no evidence is given in the study in the microstructural context of fiber-matrix bonding or of the characteristics of the RCA ITZ, which leaves the "synergy versus coexistence" question unanswered.

5.2 Life-Cycle Assessment: Methodological Challenges

The most suitable LCA for the HFRAC would be a durability normalized LCA, which would need service-life prediction models incorporating both fiber degradation and deterioration of RCA ITZ to be available.

This methodological question is an important one for HRAC. A traditional LCA would compare HFRAC with the conventional concrete, based on a per cubic meter basis, while not considering that HFRAC may have a lower compressive strength, but a higher fracture energy. A mechanical-normalised LCA would be balanced, which would mean that the lower strength from HFRAC would be penalised. The most suitable LCA for the HFRAC would be a durability normalized LCA, which would need service-life prediction models incorporating both fiber degradation and deterioration of RCA ITZ to be available.

5.3 Resilience Metrics: Beyond Strength and Stiffness

The term resilience in structural engineering has gone well beyond being strong and stiff, to include ductility, energy dissipation, redundancy and recoverability. When using seismic applications, the parameters of concern are displacement ductility, equivalent viscous damping, and the hysteretic response.

RAC has a lower energy dissipation capacity (85 kJ to 55 kJ at 100% replacement) which is a direct relationship with seismic resilience (Trivedi et al., 2024). Its worth is not just in terms of sustainability, but in actually improving its resilience if hemp fiber can help do so. This is where the fracture energy gains reported by Ghosn et al. (2023) are promising but fracture energy under monotonic loading is not the same as energy dissipation under cyclic loading. The hysteretic behaviour of the HFRAC elements, such as the loss of stiffness, pinching and strength loss under repeated cycles is completely unknown.

The hemp rope confinement study's finding that confinement is more effective in damaged specimens suggests a form of "adaptive resilience" that is particularly relevant to seismic design. Structures designed with conventional materials may have reserve capacity that is mobilized only after damage; HFRAC's fiber bridging mechanism may provide similar adaptive behavior. However, this hypothesis requires experimental validation through cyclic loading tests on HFRAC elements.

In recent years, hemp-FRP for seismic retrofit of a RC school building was shown to be effective by numerical work carried out by Meglio and Formisano (2025) which demonstrated the combination of seismic upgrading and environmental sustainable use of natural fibers. This study has employed hemp in an FRP form rather than as isolated fibers; however, it supports the findings that hemp-based materials are able to play a role to increase the seismic resilience of structural elements.

6 RESEARCH AGENDA: WHAT A PHD STUDENT SHOULD DO NEXT

6.1 Multi-Scale Interfacial Characterization

The most basic lack in the HFRAC literature is the lack of microstructural evidence of fiber-RCA interaction. It is recommended that a research program to achieve a PhD degree is started by systematically characterizing the composite's interfacial architecture using complementary characterization techniques: scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) for chemical mapping of fiber-matrix and RCA-matrix interfaces; X-ray computed tomography (micro-CT) for 3D visualization of fiber distribution, orientation and void structure; and nanoindentation for local mechanical property mapping of the ITZ regions.

The specific research questions are: Do hemp fibers tend to be closer or further from RCA particles? What is the chemical signature (e.g., depletion of calcium hydroxide and carbonation) of the region where fiber and RCA interact? Is there a change in the porosity/hydration product morphology of the fiber-matrix ITZ if the RCA is present? These questions demand a level of characterization detail that has not been previously presented in any study.

6.2 Mix-Proportion Mapping and Multi-Objective Optimization

The range of the effective synergy window is not specified by a single mix design (50% RCA, 0.75% fiber) as proposed by Ghosn et al (2023). The following is a systematical experimental program for mapping the response surface based on the different replacement rates of the RCA (0-100%), the various fiber contents (0-2%), the various lengths of the fibers (5-30 mm), and the various water-to-binder ratios. Besides the compressive strength (which is overrepresented in the literature), the response variables should be: fracture energy, drying shrinkage, water absorption and chloride penetrability.

Machine learning methods provide one way to navigate the multi-dimensional design space in an efficient manner. According to a review of machine learning applications in concrete property prediction in 2025, “multi-objective optimization in concrete design, considering mechanical performance, durability, workability, cost and carbon emissions, is becoming trendy, while existing research mostly concentrates on single objective designs.” A multi-objective approach to optimize fracture energy alongside drying shrinkage and embodied carbon would be truly new and useful, for HFRAC.

6.3 Long-Term Durability and Degradation Modeling

One of the main unknown parameters for RAC's use in structures is the durability of the hemp fiber in alkaline solution. Accelerated aging should be designed to mimic storage: Wet-dry cycling, sustained loading, immersion in synthetic pore solution and freeze-thaw cycling in the presence of sulfate and chloride ions at elevated temperatures. Fiber extraction and tensile testing should be used to monitor degradation of fiber mechanical properties and composite performance should be measured using residual fracture energy and transport property testing.

A Bayesian gamma process model is developed to model the defective concrete under coupled salt-freezing exposure, which offers a methodological template for a probabilistic durability model. This is especially suitable for HFRAC as the degradation process is likely to be non-stationary (accelerating as degradation increases with fibers' degradation and the accumulation of ITZ damage) and uncertain (with fiber variability and RCA heterogeneity). The use of a probabilistic reliability framework incorporating fiber degradation kinetics and RCA ITZ vulnerability would provide a great improvement in methodology.

6.4 Integrated Resilience-LCA Assessment

The last research pathway will focus on developing a single assessment tool for mechanical resilience and environmental sustainability. This will involve creating or modifying fragility curves for the elements of the HFRAC that take into account the effect of fiber bridging on ductility and energy dissipation, and then connecting these fragility curves with life-cycle environmental impact models.

The idea of a “resilience-carbon Pareto frontier” is helpful here. In any structural application, there is a trade-off surface; that is, the materials with the highest embodied carbon may have the highest resilience (ductility, energy dissipation) but the lower carbon materials may be less resilient. The possibility of the contribution of HFRAC is to further push the boundary beyond that: to be more resilient and less carbon-intensive than conventional options. The extent to which this potential will be realized, will depend on the mix design, structural configuration, and service environment. The development and demonstration of the methodology for quantifying this frontier, for a specific application, e.g. seismic resistant columns or bridge piers, would be an important contribution, especially as this could be a PhD thesis.

6.5 Closing the Gap: From Laboratory to Practice

Finally, research is only useful if it is translated to practice; practice is central to the value of research in the HFRAC.

The experimental evidence, reliability analysis and consensus building within the technical community would be required to develop the design guidelines for the HFRAC which include minimum dosage of fibres to achieve ductility, maximum percentage of replacement of RCA to achieve durability and appropriate safety factors.

7 CONCLUSIONS

In this review, the combination of two sustainable construction approaches, recycled aggregate concrete and hemp fiber reinforcement, has been explored. The main conclusion is that, although each technology is well understood by itself, there are few studies that have investigated them together and very little characterization of this combination. The current evidence, from the beam study conducted by Ghosn et al. (2023), indicates that hemp fiber enhances post-peak strength and fracture energy in RAC systems and that the best results are achieved in shear dominated failure modes. However, marginal improvements in peak load show that the increased toughness is a compensatory effect, rather than a strengthening effect: the toughness of fibres seems to be the same as that of the composite being added back to the

interfacial weaknesses of the RCA. The following three knowledge gaps stand out from this review. The first is that the water competition between the hemp fiber and the RCA, which are both high water absorption materials, has not been systematically studied and the impact of these relations on the interfacial hydration and fiber bonding are not known. Second, the spatial arrangement between fiber bridging (in the mortar matrix) and RCA failure (at the aggregate-paste interface) can cause a potential mismatch that can diminish the ability of fiber reinforcement to contribute to the strength. Third, the chemical compatibility of hemp fiber with the heterogeneous pore solution (carbonated and uncarbonated) of RAC has not been studied. The research agenda that we propose here will fill these gaps with multi-scale characterization of interfaces, systematic mapping of the mix proportions, long term durability evaluation, and integrated resilience-LCA modeling. The ultimate objective is to transform the intriguing laboratory curiosity that is HFRAC into a viable engineering material. The ability to achieve this goal will be determined based on answers to the basic questions raised in this review.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The author declare no conflicts of interest regarding this manuscript.

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