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RESEARCH ARTICLE

Advancing Sustainable Structural Solutions: Hemp Fiber-Reinforced Polymer (HFRP) Reinforcement Bars for Concrete Applications through Material Selection, Simulation, and Pathways for Future Development

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ABSTRACT

This paper investigates innovative Hemp Fiber-Reinforced Polymer (HFRP) rebars as a sustainable alternative to conventional Carbon Steel (CS) and Glass Fiber-Reinforced Polymer (GFRP) rebars used as reinforcement in concrete structures. The feasibility of HFRP rebars is assessed, focusing on mechanical properties and sustainability advantages. A virtual tensile test on a modeled M19 HFRP rebar, conducted using Autodesk's Fusion 360, demonstrates tensile strength comparable to CS 235 and greater environmental sustainability than GFRP, despite a slight reduction in stiffness. The study also considers the potential of graphene fiber integration to enhance mechanical properties, underscoring HFRP's adaptability. Findings suggest that HFRP rebars, being lightweight, eco-friendly, and cost-effective, are appropriate for applications requiring moderate strength and durability. However, further studies are essential, including large-scale production trials and rigorous laboratory testing, as well as research on long-term durability in harsh environments, to fully validate HFRP rebars for broader infrastructure applications.

Keywords: Hemp Fiber-Reinforced Polymers (HFRP), Sustainable construction materials, Concrete reinforcement, Building materials innovation, Carbon-negative reinforcement, Mechanical properties simulation

1. Introduction

According to a number of scholars [1–4] the construction sector is responsible for up to 40% of the global CO_2 emissions, affecting in big scale the global-warming issues of the modern world. Worldwide, there is a need for stronger, lighter, cheaper, and more sustainable reinforcement alternatives to steel rebars, known to be unfavorable for their durability features, as corrosive materials, and their environmental impacts, given the large, severe, and threating embodied equivalent carbon dioxide (CO_2) emissions they produce all over their life-cycle.

Fiber-reinforced polymer (FRP) rebars, such as Glass-FRP (GFRP), Carbon-FRP (CFRP), and Basalt-FRP (BFRP), are already well-documented and used in structural applications due to their corrosion resistance and high tensile strength [5–10].

However, as the construction industry seeks to align with global efforts to mitigate climate change and reduce carbon footprints, attention is shifting towards more sustainable alternatives. In this context, hemp has emerged as a promising construction material

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due to its environmental benefits. Hemp is a carbon sequester, a natural soil cover reducing water loss, protecting against soil erosion, a natural shelter for birds, and a food for animals [11]. Therefore, hemp is recently coming on strong as a potential greener alternative. Industrial hemp is composed of natural fibers that are the strongest in the plant kingdom and are non-corrosive.

Therefore, this paper proposes a novel technology to reinforcement bar solutions: Hemp Fiber-Reinforced Polymer (HFRP) reinforcement bars, which could serve as a sustainable and environmentally friendly alternative to Carbon Steel (CS) and other Fiber-Reinforced Polymers (FRPs) for reinforced concrete applications. To date, only a limited number of experimental HFRP designs have been developed, with a notable absence of actual product implementation, clear material properties, and comprehensive validation [12–14]. A most recent study from Scheibe et al. [15], investigated the use of HFRP in the shipbuilding industry, by evaluating the composite physical and mechanical properties and suggesting its use in structures with moderate strength requirements, such as plating for yachts, motorboats, and floating homes [15]. The primary objective of this study is to develop a rebar that can compare favorably to the existing viable construction alternatives, such as CS and GFRP reinforcement bars.

Fig. 1 presents an Artificial Intelligence-generated conceptual rendering of a bundle of eight M19 HFRP rebars, where each rebar is composed of hemp fibers embedded within a resin matrix.

To enhance the bonding performance with concrete, a filament winding technique has been applied around the bars to improve the mechanical interlock between the rebar and the surrounding concrete matrix. This rendering is intended for illustrative purposes and does not represent the final product, but rather provides an insight into the proposed material structure and surface treatment aimed at optimizing the composite behavior in reinforced concrete applications.

Fig. 1. AI-generated rendering of a bundle of eight M19 HFRP rebars.

2. Research motivation

The development of HFRP rebars could help address the construction industry's environmental footprint by offering a renewable, biodegradable, and strong material suitable for reinforcing concrete structures. As part of the research rationale and its significance, the following key aspects underscore the necessity for investigating HFRP reinforcement bars.

2.1. Weight

Because of their lower molecular weight, the use of hemp fibers may lead to a rebar that is lighter than a GFRP counterpart [16]. Hemp fibers have a lower density compared to glass fibers. Hemp's density is approximately 1.4–1.6 g/cm^3 [17], whereas glass fibers have a density of 2.5 g/cm^3 [18]. This significant difference means that, for a given volume, hemp fibers are lighter than glass fibers. The reduced weight of HFRP rebars provides several practical advantages in the construction process. Rebars, typically used in reinforced concrete applications, must be cut, transported, and assembled on-site. Using lighter reinforcement significantly decreases the dead load on the structure. A reduction in dead load allows for more efficient designs of other structural elements, such as beams, columns, and foundations. This can result in smaller or fewer supporting elements, which further reduces the total amount of construction materials required [19]. In seismic regions, lower dead loads are highly beneficial because structures with reduced weight experience lower inertial forces during an earthquake [20–22]. This allows for more efficient designs, reducing the size and quantity of other structural elements, such as beams and slabs, which ultimately lowers the total construction material required. From a sustainability perspective, lighter materials translate into lower fuel consumption during transportation, further reducing the overall carbon footprint of construction projects [5, 6].

2.2. Sustainability

Hemp is considered a carbon-negative material due to the intrinsic properties of hemp cultivation. Growing hemp and using it for creating reinforcement benefits our environment. While any reinforcement solution currently available in the market contributes to CO_2 productions, and therefore has a negative impact on the environment, the use of hemp fibers remove CO_2 from the atmosphere [16].

By integrating hemp fibers into reinforcement materials such as HFRP rebars, the construction industry can significantly reduce its carbon footprint. In fact, hemp fibers help offset the carbon emissions associated with the resin matrix and the manufacturing process. This positions HFRP as a leading material in achieving carbon-neutral or even carbon-negative construction practices, aligning with global sustainability goals aimed at reducing the overall environmental impact of infrastructure projects.

2.3. End-of-life phase and biodegradation process

The end-of-life phase of FRP materials is a crucial phase for life-cycle cost (LCC) and assessment (LCA) studies [5, 6]. Traditional construction materials, such as steel, at the end of their life are recycled through processes that are energy-intensive, requiring high temperatures, and emitting in air significant CO_2 emissions. Also costs come into consideration, as steel recycling is often associated with considerable energy and environmental costs [23], especially when compared to the potential benefits of biodegradable alternatives. Additionally, synthetic FRPs often present even greater challenges at the end of life, as they are not material easily crushable, leading to their accumulation in landfills or requiring the use of hazardous chemical processes to separate fibers from the resin matrix [24, 25]. According to global statistics, the construction and demolition waste (CDW) sector accounts for 25% to 30% of all waste generated in the EU alone [26].

With HFRP rebars, the end-of-life disposal process becomes far simpler and more environmentally sustainable. The hemp fibers, being natural, can easily decompose under the right conditions, while the resin (in particular, PLA-based resins and natural resins) can be composted or broken down in industrial composting facilities or controlled biodegradation environments [27, 28]. This results in a dramatically lower environmental footprint compared to steel or synthetic composites.

The biodegradability of HFRP rebars makes them especially useful for structures with a shorter lifespan, like pedestrian bridges, support frameworks, or other non-critical infrastructure. When these structures reach the end of their life, they can be dismantled, and the HFRP rebar can naturally break down, avoiding long-term environmental waste. This contrasts sharply with the fate of conventional steel reinforcement, which often requires extensive recycling or disposal efforts that continue to exert pressure on the environment long after the structure has been decommissioned [23]. The concept of biodegradable HFRP rebars is also in net alignment with circular economy. In a traditional linear economy, materials are extracted, used, and then discarded, often as waste. However, in a circular economy, the goal is to keep resources in use for as long as possible, extract maximum value during their service life, and then recover and regenerate materials at the end of their life cycle [23].

Therefore, the natural decomposition of HFRP rebars at the end of their life makes them an ideal choice for projects that prioritize environmental conservation and aim to minimize waste.

2.4. Cost savings

One major advantage of HFRP rebars lies in the potential cradle-to-gate cost savings they offer throughout production, transportation, and construction, especially when compared to traditional GFRP rebars. These savings come from two main factors: the wide availability of hemp fibers and the reduced weight of HFRP rebars. Since hemp is a renewable resource that grows easily, it is generally more affordable than synthetic fibers like glass, which involve high-energy manufacturing processes. This makes HFRP a more economical choice, both in terms of material cost and the energy needed to produce it [29]. Hemp is grown worldwide in a range of climates, and its cultivation requires fewer resources in terms of water and fertilizers compared to other natural fibers [30]. Additionally, the processing of hemp fibers into usable reinforcement material is relatively straightforward, involving lower-energy mechanical extraction methods [30]. Producing GFRP rebars is more expensive due to the complex chemical processes involved in making glass fibers. This requires melting raw materials like silica, limestone, and alumina at very high temperatures, which demands significant energy and drives up costs. In contrast, making HFRP rebars is simpler and more cost-effective. It only involves harvesting and processing hemp fibers, then mixing them with a biodegradable resin like PLA, which is also derived from renewable resources. This straightforward production process not only reduces costs but also aligns with sustainable practices.

Another major source of cost savings with HFRP rebars lies in their reduction in weight, which has important implications for transportation and handling costs. Transporting construction materials, particularly rebars, often involves significant fuel consumption, especially over long distances. The lighter weight of HFRP rebars reduces the overall load, thereby lowering fuel costs and carbon emissions associated with transportation. Additionally, lighter materials are easier to handle on-site, which can reduce labor costs, heavy machinery, and installation times during the construction phase. On a practical note, hemp fibers are not sharp cutting as GFRP bars, so workers on hemp FRP construction sites would not need to wear gloves, which is a very practical advantage [31].

While the biodegradability and corrosion resistance of HFRP rebars suggest potential for long-term cost savings, it is essential to acknowledge that the durability characteristics of these materials in real-world applications are not yet fully understood. Unlike traditional materials like steel and GFRP, which have been researched for decades, HFRP is still emerging, with limited data on how it performs over time across different environmental conditions. Theoretically, HFRP rebars could provide substantial savings by avoiding the corrosion issues common in steel and by resisting the environmental wear that affects synthetic polymers.

2.5. Thermal conductivity

HFRP rebars offer another advantage over their GFRP counterparts in terms of thermal conductivity. HFRP's thermal conductivity is 0.0852 W/m·K [17], compared to GFRP's 0.9 W/m·K [32], making HFRP a much better insulator. This reduces thermal bridging, enhances energy efficiency, and limits thermal expansion cracking, especially in structures exposed to temperature fluctuations. Additionally, HFRP's lower thermal conductivity helps prevent freeze-thaw cycle damage and synergizes well with concrete's natural insulating properties, resulting in improved long-term durability and thermal stability. These properties make HFRP an ideal choice for green construction and applications where thermal performance is critical.

3. Technology's limitations

3.1. Thermal resistance

One of the most significant limitations of HFRP rebars is their relatively low thermal resistance when compared to traditional materials like GFRP and steel. Natural fibers, such as hemp, are inherently flammable and exhibit a lower resistance to high temperatures, which makes them more vulnerable in applications where fire resistance is a critical design parameter, such as in certain types of high-rise buildings, industrial facilities, or infrastructure exposed to high temperatures.

However, it is essential to consider that reinforcement bars are typically embedded within concrete, a material with inherent fire-resistant properties. Concrete acts as a thermal barrier, significantly delaying the exposure of the embedded rebar to high temperatures during fire events. Moreover, fire-resistant additives can be incorporated into the resin matrix to enhance the thermal stability of HFRP rebars. While the reduced thermal resistance of natural fibers is a limitation, it should be noted that for non-exposed structural elements, the fire performance of the overall concrete structure remains largely determined by the concrete's behavior rather than the reinforcement.

3.2. Bonding with concrete

Another key limitation is the bonding performance between HFRP rebars and concrete. Hemp fibers offer inherently weaker interfacial bonding with the surrounding matrix [33, 34]. This is primarily due to the surface smoothness of natural fibers, which results in reduced mechanical interlocking compared to ribbed or deformed steel bars. Although the use of surface treatments such as filament windings, textured coatings, or sand coatings can improve the bonding between HFRP rebars and concrete, it is challenging to achieve bonding performance that compare to conventional reinforcement. This weaker bond can potentially result in a reduction in the composite action between the reinforcement and the concrete, leading to slippage or debonding under load, particularly in high-stress applications. The bond strength could be a limiting factor in certain load-bearing scenarios, and additional research is required to develop more advanced pre-treat surface treatments, such as means investigated by Zhou et al. [35], or explore hybrid systems that combine HFRP with other reinforcement materials to optimize bonding performance.

3.3. Variability in fiber properties

Unlike synthetic fibers, hemp fibers vary in diameter, cell wall thickness, and microfibril angle depending on cultivar, growth conditions, soil quality, and climate [36, 37]. Post-harvest processes such as retting, decortication, and cleaning further influence fiber morphology and surface chemistry, which in turn affect tensile strength, stiffness, and elongation at break [34, 38].

Typical tensile strengths for hemp fibers reported in the literature range from approximately 200 to 900 MPa, while moduli can vary between 15 and

70 GPa, with standard deviations often exceeding 15–25% of the mean [39, 40]. Such dispersion arises from natural heterogeneity and from measurement differences such as gauge length, conditioning humidity, and testing speed [41]. Additionally, the presence of defects, lumen size variation, and surface impurities can further reduce performance consistency.

Therefore, this variability can affect the consistency of mechanical properties, potentially making it more challenging to meet standardized performance requirements across batches of material.

3.4. Pultrusion changes

Pultrusion stands out as the most effective method for manufacturing FRPs. This technique involves drawing fibers through a resin bath, where they are thoroughly coated, then shaping and curing them into the final profile. While pultrusion is common with synthetic fibers like glass and carbon, hemp fibers pose distinct challenges that must be addressed to make HFRP production feasible. Two in particular are key aspects to consider for the proper pultrusion of hemp fibers: the effect of resin's viscosity on fibers [34] and the curing temperature [42]. Resin viscosity is crucial since highly viscous resins may not fully infiltrate the fiber bundles, potentially leaving voids or resin-poor areas that could weaken the final rebar's strength and stiffness.

More sustainable resins, such as thermoplastic resins like Polylactic Acid (PLA) require precise temperature conditions to melt, cure, and set effectively. However, hemp fibers are sensitive to excessive heat, and curing at temperatures that are too high can lead to fiber degradation, ultimately weakening their strength and durability. On the flip side, if the curing temperature is too low, the resin may not cure completely, resulting in insufficient fiber saturation and a weaker bond within the composite.

4. Manufacturing considerations to enable the analysis

4.1. Overcoming fiber variability and moisture issues

As previously mentioned in the limitations' technology, pultruding hemp fibers may be a challenge due to their natural variability in shape, size, and mechanical properties, which can result in inconsistent resin impregnation.

To overcome these issues, the following strategies could be employed:

- Pre-treatment of fibers: Hemp fibers can undergo drying processes to remove excess moisture before being used in the pultrusion process. Additionally, surface modification techniques (e.g., chemical treatments) could enhance fiber-resin adhesion, improving the mechanical strength of the final product [35].
- Fiber sizing: By grading and sorting hemp fibers according to diameter and mechanical properties, it may be possible to reduce variability and ensure more consistent impregnation during pultrusion. Automated optical or laser scanning systems can be employed for diameter control, ensuring more uniform resin penetration during pultrusion and reducing weak points in the final composite.
- Defect minimization: Gentle decortication and optimized retting techniques can help limit fiber breakage, preserve cell wall integrity, and reduce lumen collapse, all of which improve tensile performance consistency. This can be achieved by using low-impact rollers and staged processing for decortication, and by applying controlled water or enzymatic retting to loosen fibers without weakening them.
- Microfibril angle control: While fully controlling microfibril angle is challenging at an industrial scale, selecting cultivars with documented low microfibril angle dispersion can improve stiffness uniformity.
- Surface functionalization for variability compensation: For batches with slightly lower strength or stiffness, coupling agents, nanoparticle coatings, or hybrid fiber blending (e.g., small fractions of basalt or glass) can be used to stabilize performance without losing the sustainability advantages of hemp.

4.2. Viscosity and processing temperature control for PLA-based resin

Similarly to the fibers' variability challenge, hypothetical solutions to address viscosity and processing temperatures issues include:

- Optimizing resin viscosity: Adjusting the ratio of PLA to natural resin can help manage the viscosity of the mixture, ensuring that the hemp fibers are fully saturated during the pultrusion process. Additionally, incorporating small amounts of viscosity modifiers can further enhance the resin's flow characteristics, leading to better fiber impregnation.
- Precise temperature regulation: Advanced temperature control systems in the pultrusion equipment could ensure that the resin reaches its ideal curing temperature without degrading the fibers. This can involve using incremental heating

Table 1. Hemp fibers properties.

Property	Value	Sources
Tensile Strength (MPa)	582 ± 168	[36, 38–40, 44–47]
Young's Modulus (GPa)	75 ± 10	[36, 39, 48]
Density (g/cm^3)	1.542 ± 0.250	[36, 39, 44, 48]
Poisson's Ratio	0.24 (SD not reported)	[48]
Elongation at Break (%)	2.82 (SD not reported)	[37–40, 47]
Thermal Conductivity (W/m·K)	0.0446 (SD not reported)	[17]
Shear Modulus (MPa)	4,000 MPa (SD not reported)	[49, 50]

systems, which gradually raise the temperature of the resin to the optimal level as the material moves through the pultrusion process.

4.3. Addressing fiber-resin bonding

Achieving a strong bond between hemp fibers and the PLA-based resin depends on maximizing interfacial adhesion. One approach involves treating the fiber surfaces to boost their compatibility with the resin. For instance, alkaline washing [43] or applying silane coupling agents [41] can improve the chemical bonding between the fiber and resin. Additionally, fine-tuning the curing speed and fiber pulling rates during pultrusion helps ensure the fibers are fully saturated with resin before curing, resulting in stronger and more consistent HFRP rebars.

4.4. Feasibility of HFRP pultrusion

The main assumption of this study is that pultrusion of HFRP rebars is technically feasible given the existing technology and by implementing the above-mentioned solutions. The pre-treatment of hemp fibers, optimization of resin viscosity, and precise temperature control are all reasonable methods to overcome the challenges unique to natural fiber pultrusion.

Future research should focus on refining these processes and testing their applicability in industrial production environments. Successfully addressing these challenges will unlock the potential for scalable and sustainable production of HFRP rebars, paving the way for their use in a wide range of structural applications.

5. Modelling of the HFRP reinforcement bar

5.1. Fiber properties

The primary component of HFRP reinforcement bars is hemp fibers, which are derived from the stalks of the hemp plant. These fibers are characterized by their highest tensile strength among natural fibers. The material properties of hemp fibers are summarized in Table 1. References to the sources from which the corresponding property values are provided. Where multiple sources were available, an average value was calculated for each property. This calculation included the standard deviation (SD), which indicates how much the values from different studies vary from the average. A conservative approach was adopted: for instance, in determining the averaged tensile strength, greater weight was given to studies reporting lower values, providing a safety margin. This conservative weighting method was applied consistently for all material properties in the study.

5.2. Resin properties

The resin plays a crucial role in binding the fibers, distributing applied loads, and ensuring the mechanical integrity of the composite material. The PLA-based resin is derived from renewable sources such as corn starch or sugarcane [51], and it is biodegradable [52], aligning with the environmental goals of this study. Additionally, the natural resin component in the blend enhances its environmental compatibility and contributes to improved adhesion between the hemp fibers and the resin. Three resin types were evaluated: 100% PLA, 80% PLA + 20% Natural Resin, and 70% PLA + 30% Natural Resin, as shown in Table 2. The 80% PLA + 20% natural resin blend was chosen for the HFRP composite due to its balanced mechanical performance and environmental compatibility. This blend provides sufficient tensile strength and modulus to support moderate load applications, while the natural resin enhances the biodegradability and renewability of the composite, aligning with the sustainability goals of the study. The combination also ensures an adequate bonding interface with hemp fibers, promoting effective load transfer within the composite. Additionally, the PLA component offers more processability due to its lower processing temperature that reduces the risk of thermal degradation in natural fibers like hemp, facilitating their integration without compromising mechanical properties [53]. This blend of PLA and

Table 2. Properties of evaluated resins.

Properties	100% PLA	80% PLA + 20% Natural Resin	70% PLA + 30% Natural Resin	Sources
Tensile Strength (MPa)	50	58	65	[52, 54]
Young's Modulus (GPa)	2.7	2.9	3.45	
Density (g/cm^3)	1.2	1.2	1.3	
Elongation at Break (%)	6.5	6.2	6	
Thermal Conductivity (W/m·K)	0.16	0.18	0.19	
Poisson's Ratio	0.36	0.35	0.34	[55, 56]
Shear Modulus (MPa)	1,287	1,000	900	

natural resin enhances compatibility, making it easier to saturate and bond fibers uniformly within the composite.

5.3. Composite properties

The composite properties of HFRP rebars result from an average mix of the mechanical characteristics of hemp fibers (shown in Table 1) and the selected resin matrix (shown in Table 2), based on a 70:30 fiber-to-resin ratio. In this configuration, the hemp fibers predominantly enhance the tensile strength and stiffness of the composite, while the resin matrix plays a crucial role in bonding the fibers together, ensuring load transfer and cohesion within the composite material. This blended mix of properties was then inputted into Fusion 360 to model the HFRP rebar. Table 3 shows the computed HFRP composite properties. To facilitate direct performance benchmarking, two additional columns were incorporated into Table 3, presenting equivalent property values for traditional CS reinforcement and GFRP reinforcement. The mechanical and physical properties of CS (235) rebars and GFRP rebars were compiled using peer-reviewed academic sources and authoritative guidelines. Sbahieh et al. [57] provide comparative figures for tensile strength, elastic modulus, density, and elongation at break. Al Omar & Abdelhadi [58] corroborate typical strength and elastic modulus values. Additional values for thermal conductivity and shear modulus are drawn from ACI 440 [59] standards and manufacturer datasheets.

The stress-strain curve presented in Fig. 2 illustrates the theoretical tensile behavior of the modeled HFRP rebar under investigation, along with two comparative materials: a GFRP rebar and a CS 235 rebar. Both the GFRP sample, with a tensile strength of 850 MPa, and the CS 235 sample, with a yield strength of 235 MPa, were modeled using Fusion 360. For both materials, the Fusion 360 library database with predefined material properties was utilized, ensuring accurate and consistent baseline values for comparative analysis. Fig. 2 shows the direct comparison of the tensile properties of the three material samples, highlighting the distinctive elastic-brittle response of the FRP rebars in contrast to the ductile yielding observed in the steel counterpart.

One consideration that arises from the use of HFRP is its slightly lower stiffness compared to the GFRP counterpart. However, this reduction in stiffness is minor and should not pose a significant limitation in most structural applications where the concrete matrix largely compensates for any slight reduction in stiffness of the rebar, allowing the system to perform as intended under typical load conditions (as for the GFRP counterpart). Additionally, the slightly lower stiffness and lower tensile strength of HFRP rebars could potentially be compensated for by optimizing the fiber-resin interface or by incorporating graphene fibers. Using graphene fibers' average values from Rafiee et al. [60], Balandin et al. [61], and Lee et al. [62], a tensile strength of 130 GPa and Young's modulus of 1 TPa has been assumed. Therefore, the mechanical properties of the HFRP composite with 2%, 3%, and 4% graphene fiber additions were recalculated, reflecting targeted improvements in stiffness and tensile strength capacity, as shown in Table 4.

Table 3. Composite properties.

Property	Hemp Fibers (70%)	Resin (30%)	Composite Value	CS	GFRP
Tensile Strength (MPa)	582	58	424.8	370	850
Young's Modulus (GPa)	75.0	2.9	53.4	210.0	45.0
Density (g/cm^3)	1.54	1.20	1.44	7.85	1.90
Elongation at Break (%)	2.8	6.2	3.8	20.0	2.0
Thermal Conductivity (W/m·K)	0.04	0.18	0.08	50.00	0.30
Poisson Ratio	0.24	0.35	0.27	0.30	0.28
Shear Modulus (MPa)	4,000	1,000	3,100	79,000	17,000

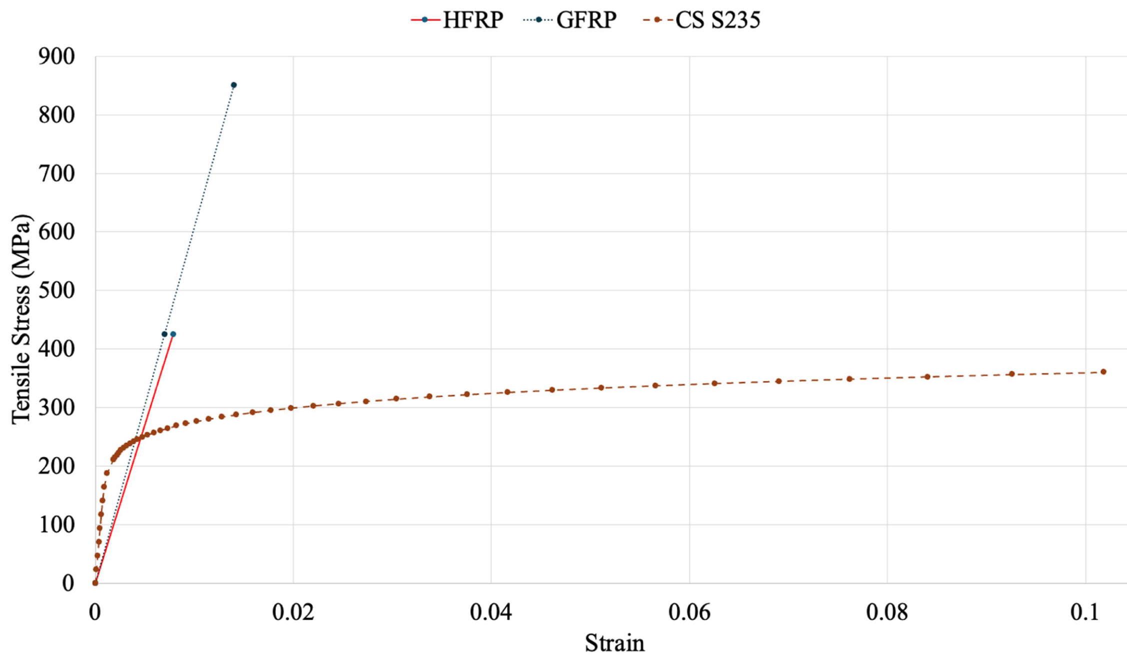

Fig. 2. Stress-strain curve comparison.

Table 4. Graphene fiber additions and resulting properties.

Graphene Addition (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Sources
0	424.8	53.37	[60–62]
2	492.16	64.74	
3	526.34	70.43	
4	560.52	76.12	

Even small additions of graphene fibers significantly enhance the mechanical properties of the hemp composite. At 4% graphene content, the tensile strength increased to 560.52 MPa, a considerable improvement over the baseline of 424.8 MPa. Similarly, the Young's Modulus of the composite was improved, making it an ideal candidate for high-strength, high-stiffness, and high-performance applications in structural engineering. The minimal graphene content required to achieve these performance gains ensures that the environmental benefits and sustainability advantages inherent to HFRP rebar remain largely unaffected. This makes the hybrid graphene-reinforced HFRP composite an attractive option for more critical structural applications, possibly combining superior strength with eco-friendly characteristics.

6. Virtual testing

To accurately assess the mechanical performance of the modeled HFRP rebar, a precise and well-suited geometry was defined within the simulation model. The M19 rebar (19.05 mm diameter) was chosen for this analysis due to its widespread use in structural engineering, making it a representative choice for evaluating the modeled HFRP rebar (Fig. 3).

Commonly used in beams, columns, foundations, and slabs, M19 rebar is a standard in medium- to high-strength applications, ensuring that the results are directly applicable to real-world construction applications. Furthermore, selecting a widely used size facilitates direct comparisons with testing results of conventional materials like CS and GFRP rebars, both of which are often tested with M19 samples.

The analysis followed the ASTM D7205 [63] standard, which specifies that the tensile test specimen for FRP rebar should have a length equal to 40 times the diameter of the rebar. For this study, the rebar diameter was 19.05 mm, resulting in a gauge length of 762 mm.

To simulate the tensile test in Fusion 360, the rebar was modeled and subjected to load conditions that replicate the physical test setup. One end of the rebar was fully fixed along all three axes (x, y, z) to represent the fixed end in the tensile testing machine, where the bar is clamped securely. The opposite end was constrained in the x and y axes, leaving the z-axis free to simulate the movement during a tensile load. This configuration mirrors the moving end in the testing machine, where the tensile force is applied to elongate the bar.

By constraining the model in this manner, the tensile test was accurately represented in the simulation, ensuring the stresses and strains in the rebar were computed correctly. The tensile load was applied

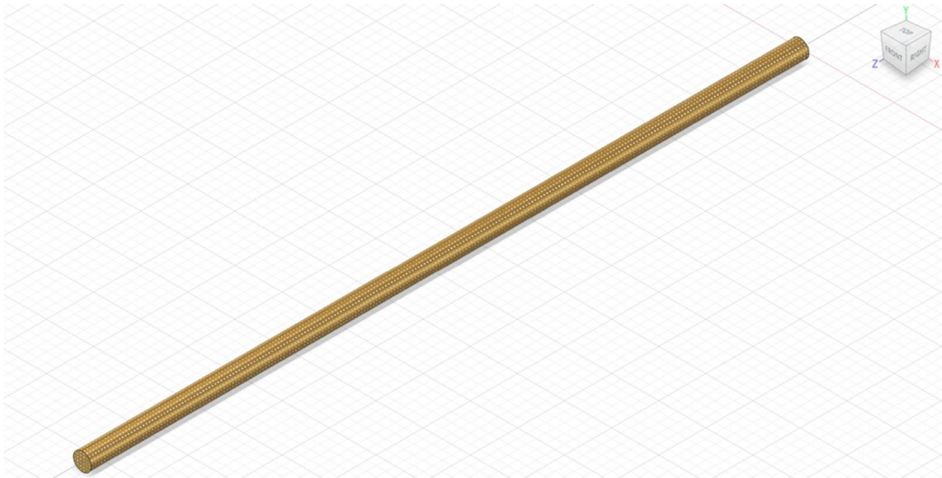

Fig. 3. HFRP rebar modeled in Fusion 360.

incrementally, and the resulting stress and safety factors were calculated based on the material properties of HFRP.

This approach ensured that the Fusion 360 analysis was consistent with real-world tensile testing standards, providing reliable and replicable results for evaluating the safety factors and failure probabilities of the M19 HFRP rebar under different loading conditions.

In Fusion 360, the safety factor is a concept used to assess the safety and reliability of a structure. It represents the ratio between the structure's strength or capacity and the applied load [64]. The formula for the safety factor is shown in Eq. (1).

$$Safety\ Factor\ (SF) = \frac{Material\ Strength}{Applied\ Stress} \tag{1}$$

A safety factor of 1 indicates that the structure is at its failure threshold, with the applied stress equaling the material's maximum capacity. While this theoretically represents a 0% likelihood of failure, in practice, the risk is significant because any increase in load or unforeseen factors can cause immediate failure [65]. The likelihood of failure can be estimated using Eq. (2).

$$Likelihood\ of\ Failure\ (\%) = \left(1 - \frac{SF}{1}\right) \times 100 \tag{2}$$

7. Simulation results

The results of the analysis for a M19 rebar are as follows:

- At 121 KN, the safety factor was 0.57, implying a high 43% chance of failure.
- At 100 KN, the safety factor was 0.7, corresponding to a 30% chance of failure, suggesting the rebar is overstressed but still intact.
- At 70 KN, the safety factor reached 1, meaning the load was exactly at the material's failure threshold with no margin for error.

Fig. 4 shows the simulation results of the M19 HFRP rebar under a 121 KN tensile load, displaying a minimum safety factor of 0.57, indicating a high 43% likelihood of failure. The red zones in the rebar simulation of Fig. 4 pinpoint regions where stress levels approach the material's tensile strength limit, making these areas particularly susceptible to failure under load.

In the displacement analysis presented in Fig. 5, the maximum displacements occurred at the loaded end of the HFRP rebar, where the tensile force was directly applied. The simulation recorded a maximum displacement of 6.663 mm, concentrated at the region of applied stress, as expected under axial loading conditions. This displacement value reflects the material's mechanical response to the applied load, with deformation increasing progressively toward the loaded end.

The color gradient in Fig. 6 displays regions with varying levels of stress concentration under a 70 KN tensile load (with respective safety factor of 1), where red areas represent zones closer to the failure threshold. Although the rebar is stressed, it remains intact at this load, showing resilience under moderate tensile conditions.

Compared to the previous analysis at 121 KN (Fig. 4) the reduction in load has improved the safety margin. However, the areas marked in red still

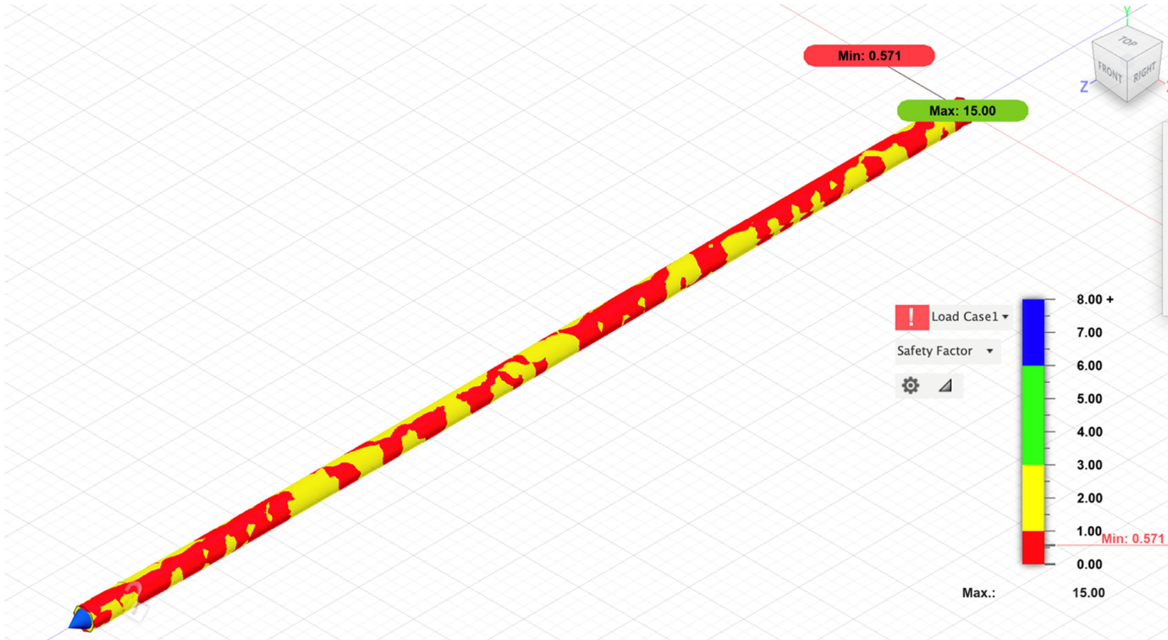

Fig. 4. Areas (in red) where likelihood of failure is concentrated at 121 KN.

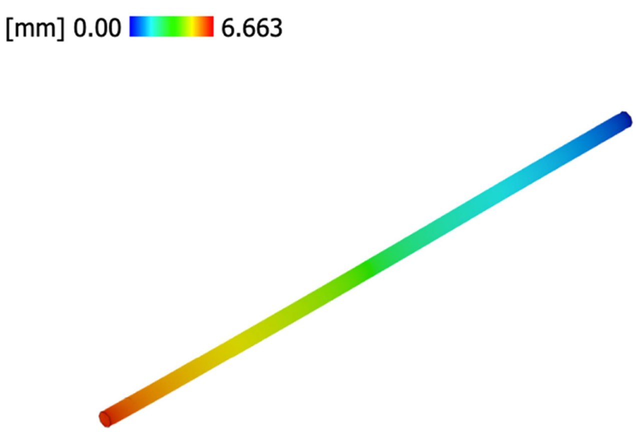

Fig. 5. Displacement analysis.

indicate that significant stress is present, which could compromise the rebar's performance in applications demanding high reliability.

Fusion 360 recommends a minimum safety factor of 3 for live loads to ensure structural safety, particularly for brittle materials like HFRP. Since brittle materials do not exhibit plastic deformation before failure, maintaining a conservative safety factor is critical to avoid operating close to risky load limits. In the present analysis, it was determined that a load of 23 KN yields a safety factor of 3, which aligns with the recommended standard for live load conditions. Simulation results for the 23 KN load are shown in Fig. 7. As visible in Fig. 7, this conservative load limit ensures the structural integrity of the HFRP rebar and prevents failure under typical operational conditions.

The American Concrete Institute (ACI) with the ACI 440.1R-15 [66] recommends an environmental reduction factor, CE , when designing with FRP rebars to account for the brittle behavior of the material and its susceptibility to environmental degradation. In severe exposure conditions, such as contact with moisture, alkaline solutions, or chlorides, a CE value of 0.2 is commonly applied, particularly for GFRP rebars. This factor significantly reduces the allowable design stress, ensuring that the rebar operates well below its ultimate tensile strength, preventing rupture. Applying this factor ensures that only 20% of the rebar's ultimate strength is used in design, preventing the material from approaching dangerous stress levels. Given this reduction, we determined that the corresponding SF in Fusion 360 would be approximately 5. Such value, would lead to an applied load for the M19 HFRP rebar of 14 KN. This would further ensure that the HFRP rebar remains well within safe limits, even under severe environmental exposure. This additional conservatism reflects current codes and standards practices and underscores the importance of avoiding failure in brittle materials like FRP.

8. Further studies

This paper outlines five critical areas requiring further research, particularly production, prototyping, testing, and long-term durability performance of HFRP rebars.

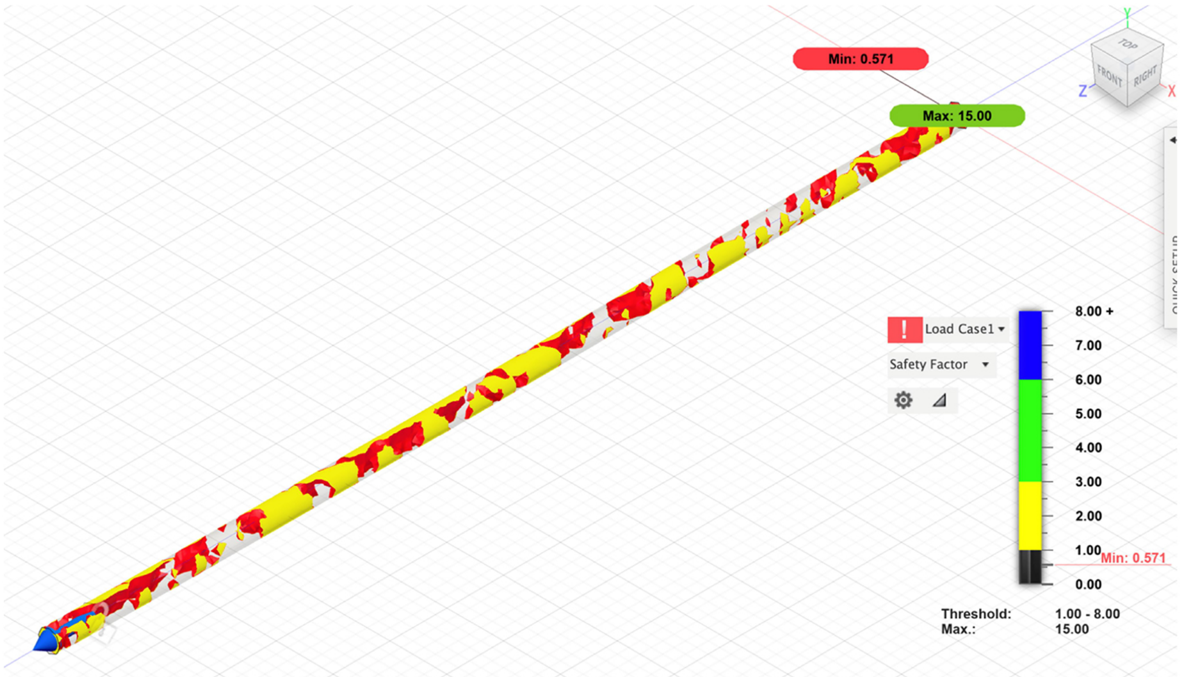

Fig. 6. Areas (in red) where likelihood of failure start developing and is concentrated just above the 70 KN threshold.

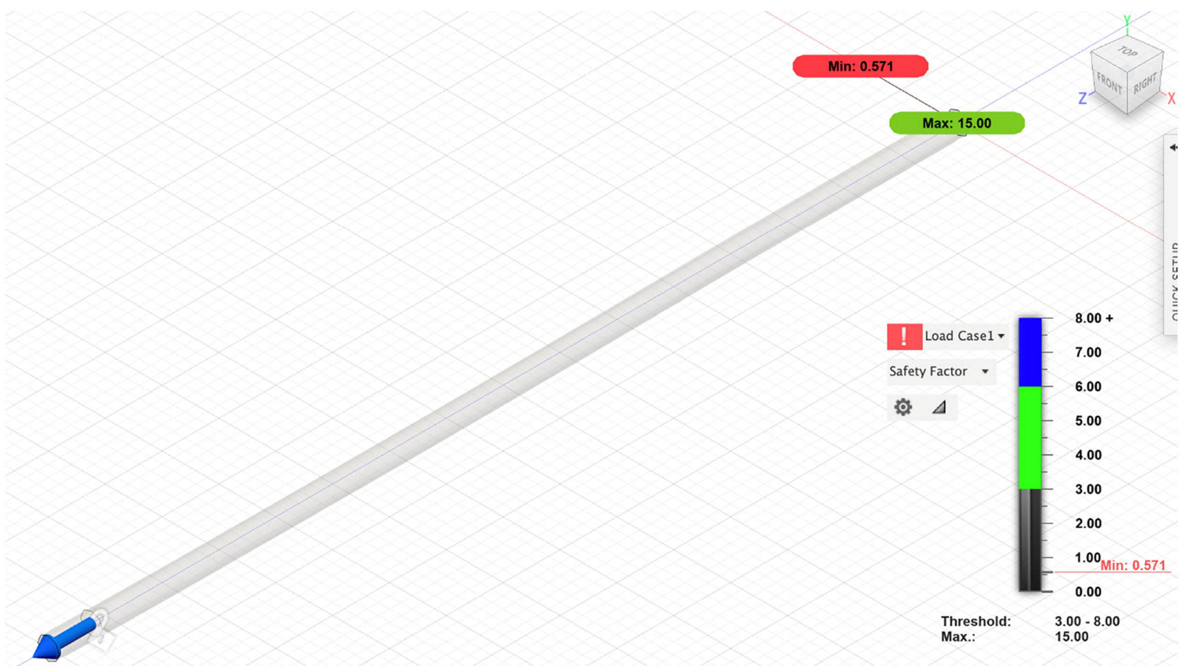

Fig. 7. No chances of failure at 23 KN (corresponding to a SF of 3).

8.1. Call to manufacturers

This paper urges manufacturers to produce the proposed HFRP rebar prototype detailed in this paper. By conducting production trials, manufacturers can provide valuable data on production efficiency, practical challenges, and productivity performance. These trials would be essential to improve production processes, enhance productivity, and, later, facilitate the transition from laboratory-tested prototypes to marketable products.

8.2. Prototype testing

Upon production, rigorous testing is essential to validate the technology. Key laboratory tests should include tensile, transverse shear, and longitudinal shear tests to assess rebar strength under various load directions, along with thermal expansion tests to evaluate material stability across temperature changes.

8.3. Composite interaction with concrete

It will be essential to further test the interaction between HFRP rebars and concrete for assessing bonding characteristics, potential slippage issues, and the effects of HFRP's slightly lower stiffness on the overall concrete structural performance. Physical tests on concrete beams and columns reinforced with HFRP rebars would provide insights into load transfer and composite action, further establishing its viability in construction.

8.4. Alkaline exposure and fiber/matrix interface degradation

Concrete structures often expose reinforcement materials to high alkaline environments due to the chemical composition of concrete. The long-term impact of such alkaline conditions on the mechanical properties of HFRP rebars, particularly their effect on hemp fibers and the fiber/matrix interface, has not yet been comprehensively investigated. Therefore, one of the key objectives of our future work is to simulate these conditions and assess their effects on the long-term performance of HFRP rebars.

This study suggests submerging HFRP rebars in two tanks, each containing a pH 12.7 alkaline solution, a typical condition for concrete environments. One tank will be maintained at a constant temperature of 23°C, representing ambient conditions, while the other tank will be set at 60°C to simulate accelerated aging, following a similar approach used by Emparanza, 2020 [67]. From these two conditioning tanks, rebar samples will be extracted and tested at various intervals over a period of up to 365 days. This approach will enable a detailed investigation into the degradation of hemp fibers and the fiber/matrix interface over time, providing insights into the durability of HFRP rebars in highly alkaline environments. The outcomes of this study will be essential for determining the long-term viability of HFRP rebars in concrete structures exposed to aggressive alkaline conditions.

8.5. Chloride-induced corrosion in marine environments

The second degradation mechanism to be investigated is chloride-induced corrosion, a critical issue in marine and offshore infrastructure. Structures such as seaports, marine bridges, seawalls, and subsea structures are continually exposed to chloride-rich environments, where the durability of conventional steel reinforcement is severely compromised by chloride-induced corrosion. This form of degradation is one of the most pervasive problems in marine construction, significantly reducing the service life of reinforced concrete structures.

Given the limitations of conventional materials, such as steel, in resisting chloride attack, there is an urgent need to explore the long-term performance of alternative reinforcement materials like HFRP rebars. From both a life-cycle cost and life-cycle assessment perspective, the use of conventional materials in marine applications is becoming increasingly unsustainable [5–8]. To address this, the second focus of future studies will be the evaluation of HFRP rebars under chloride-induced corrosion conditions. This will involve exposing HFRP rebars to simulated seawater environments and testing their long-term durability and mechanical integrity over time (as done by Emparanza et al. [68] with GFRP rebars). The goal is to establish the efficacy of HFRP rebars as a corrosion-resistant alternative to traditional steel reinforcement in marine and offshore structures, where resistance to chloride-induced degradation is paramount.

Both of these studies (alkaline exposure and chloride-induced corrosion) are critical to validating the long-term durability and performance of HFRP rebars in demanding construction environments. They will provide a comprehensive understanding of how these materials behave under the aggressive conditions that typically shorten the lifespan of conventional reinforcement materials.

8.6. Optimization of hemp fiber bonding with various matrices

Investigate the interfacial performance of hemp fibers bonded with different epoxy resins and composite matrices, considering the effects of fiber surface treatments, resin formulations, and curing conditions on mechanical and durability outcomes.

8.7. Integration of graphene fibers

Explore the incorporation of graphene fibers into the HFRP matrix to enhance mechanical properties, assess bonding mechanisms, and determine compatibility with natural fiber reinforcement systems.

8.8. Economic feasibility analysis

Prepare a detailed cost–benefit analysis comparing HFRP with conventional CS and GFRP, incorporating raw material costs, manufacturing energy requirements, and projected service life to evaluate competitiveness.

8.9. Environmental and safety factor modeling

Define and tabulate environmental boundary conditions (e.g., temperature, humidity, chemical exposure) for use in Fusion 360 modeling and safety factor determination. These parameters will be critical for translating laboratory findings into predictive models and for guiding full-scale validation testing.

9. Conclusions

This study demonstrates the viability of HFRP rebars as a sustainable and innovative alternative to conventional CS and GFRP rebars for reinforced concrete applications. The primary objective was to explore the feasibility of using HFRP rebars as a valid alternative to conventional rebars.

The pilot testing conducted using Fusion 360 allowed for a detailed assessment of the composite's mechanical properties without the need for costly and time-consuming physical prototypes. The simulation provided reliable and actionable data, which can serve as the foundation for further optimization and real-world testing of HFRP rebars. The findings from the computed analysis emphasize the importance of adopting a conservative approach when designing with HFRP rebars. The low safety factors observed under higher loads indicate that HFRP rebars may not be suitable for high-stress applications unless additional reinforcement strategies or design conservatisms are applied. Displacement results also suggest that while HFRP is mechanically viable, its lower stiffness could be a limiting factor in deflection-critical applications. Finally, applying an environmental reduction factor ensures long-term structural integrity, particularly when the rebar is exposed to aggressive environments. These considerations are critical for further development and optimization of HFRP technology for real-world structural applications.

HFRP rebars offer key advantages, such as:

- Environmental Benefits, given the fact that hemp growth captures carbon dioxide and the rebars are biodegradable, minimizing environmental impact at the end of their life-cycle.
- Cost Efficiency, due to hemp abundance and the lightweight nature of HFRP rebars, impacting production, transportation costs, and ease of handling.
- Durability, as initial indications suggest resilience against corrosion and environmental degradation.
- Mechanical Performance, making HFRP rebars a feasible alternative to conventional CS and GFRP rebars in appropriate structural settings.

This paper identifies several key areas for further research required to validate the HFRP rebar technology presented. Although HFRP rebars demonstrate strong potential, specific challenges remain, particularly concerning thermal resistance and the relatively unexplored performance of HFRP bonding with concrete. Additionally, the natural variability of hemp fibers can impact mechanical consistency. This paper calls upon manufacturers to produce HFRP rebar prototypes for extensive laboratory testing, which would yield critical data on real-world performance, production efficiency, and any practical limitations. Collaborative testing efforts are essential to refining and validating HFRP rebar technology for concrete applications. Moreover, assessing long-term durability in harsh environments, such as alkaline and marine conditions, is crucial to confirm HFRP's suitability for sustainable infrastructure projects.

Furthermore, the incorporation of graphene fibers shows promising potential for enhancing the mechanical properties of HFRP rebars, suggesting that this material is ripe for further optimization. As the construction industry increasingly seeks sustainable alternatives, the proposed HFRP rebar technology offers a compelling pathway forward, with the potential to reduce carbon footprints and support the global transition toward greener infrastructure.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article. Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Finally, all data and simulation results that support the findings of this study are available from the corresponding author upon a reasonable request.

Author's contributions

All of the authors have contributed equally to the article. Further, all of the authors have validated and approved the final manuscript.

Ethics

There are no ethical issues with the publication of this manuscript.

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