Fibrewerks: An interscalar study into the viability of natural fibre composite rebar for cementitious materials

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Implementation of renewable materials and building systems research into practice has proven challenging. Technologies such as mass timber, engineered mycelium, or hempcrete have understandably garnered attention, but their widespread adoption has been hampered by specific, yet unsatisfied performance metrics. This paper proposes an interscalar approach for the early stage validation of such technologies and for the development of a practical framework to guide further research. This approach begins by analyzing the design problem and identifying relevant and quantifiable performance metrics, before organizing them under "performance scales" that reflect a particular research discipline. The resulting framework provides identification of insurmountable obstacles, identification of required research expertise, and organization of the research effort into manageable tasks. This paper presents a case study utilizing this approach, specifically regarding non-corroding natural fiber composite reinforcing, for cementitious materials.

Concrete is an indispensable component of infrastructure systems, but most of America's infrastructure was built with little concern for long term durability. Many of these structures are nearing the end of their service life and trillions of dollars must be spent to repair and maintain their operation. Only 2% of reinforced concrete is reinforcing steel by volume, but corrosion of that 2% leaves the remaining 98% of concrete at risk of failure. There are commercially available anti-corrosion rebar technologies available, but none are perfect solutions: some are easily damaged, others are incompatible with all concrete, and some are prohibitively expensive.

This paper aims to address these concerns by utilizing an interscalar approach to validate the viability of a non-corroding composite rebar made from natural fibers and thermoplastics. This approach found that at the structural scale, natural fiber composites could achieve the same strength as steel and the same elasticity of GFRP with a fiber ratio of 44%-50%. At the processing scale, preliminary experiments indicate that "jacketing" the natural fibers with thermoplastic during the commingling stage resulted in the best fiber saturation at the consolidation stage of production. Finally, at the environmental scale, preliminary calculations indicate that natural fiber composites can be produced with 30%-50% less embodied energy than other non-corroding rebar technologies. These results not only demonstrate the viability of natural fiber composite rebar, but also the benefits of using an interscalar approach for early stage technology validation.

INTRODUCTION

The impacts of climate change are readily observable. In 2021 alone, flooding in China and Western Europe caused $37 billion dollars worth of damage, the water level of Lake Mead on the Colorado River was at its lowest on record, and extreme weather events contributed to the displacement of over 2.6 million people across China, Vietnam, and the Philippines.[1] Despite this evidence, policy makers at all levels are not implementing the immediate and deep reductions in Greenhouse Gas (GHG) emissions needed to reverse course. Near term risks associated with exceeding 1.5°C above pre-industrial averages include *"increased frequency, severity and duration of extreme events [that] will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss"*.[2] Given the current state of government inaction, we ought to assume that these projected impacts are, to some degree, unavoidable. Furthermore, as stewards of the built environment, it is our responsibility to develop, and more crucially, implement appropriate resiliency strategies in response.

For researchers in the field of renewable materials and building systems, it is this implementation that has proven the most challenging. Articles and videos citing innovative technologies such as mass timber, engineered mycelium, or hempcrete are commonplace, yet widespread adoption of these technologies remains elusive; why is this? Mass timber is a renewable, low-carbon building system that provides exceptional acoustic performance, air tightness, erection speed, and fire protection. While the technology is sound, the United States material costs are inflated by a lack of mass timber suppliers and potential

Figure 1. Benefits of the interscalar framework. Daniel M. Cohen M.Sc., RA, LEED AP.

projects are limited by building codes that limit the maximum height of mass timber structures.[3] Engineered mycelium is a low energy bio-fabrication method that utilizes fungal growth and agricultural by-products to produce a variety of building materials, including acoustic and thermal insulation. However, these innovative materials can take nearly a month to produce, which cannot compete with their synthetic counterparts that are produced in mere hours.[4] Hemp-lime, commonly referred to by the misnomer “hempcrete”, is a low carbon bio-composite material composed of the wood-like core of the hemp plant (hurd) bound together with crushed, kiln-cooked limestone (lime). Hemp-lime is a non-toxic, vapor permeable, and low-carbon material that is well suited for above ground, non-structural wall assemblies. However, curing can take 6 to 10 weeks, which can be prohibitively long for cast-in-place assemblies and will struggle to compete as a precast unit when compared to traditional concrete blocks that only take 24 to 48 hours to cure.[5] As promising as these technologies appear, their adoption has been hampered by either economic, regulatory, manufacturing, logistical, or political factors. In order to tangibly impact the course of climate change, renewable materials and building systems must develop past the journal, and onto the job site.

This paper proposes an interscalar approach for the early stage validation of new renewable materials or building systems and the generation of a practical framework for guiding further research. This approach begins by analyzing the design problem and identifying quantifiable performance metrics, such as tensile capacity, production speed, or embodied energy. Once identified, these interrelated metrics are grouped together under a common “performance scale” heading, such as structural, processing, or environmental performance. The resulting framework (1) identifies any insurmountable obstacles to further development, (2) identifies the specific expertises needed by the larger research effort, and (3) organizes that research effort into manageable tasks. While similar approaches are known by other names, such as “interdisciplinary research”[6], “systems thinking”[7], or “holistic design”[8], this paper is not arguing that the interscalar approach is superior to these other methodologies. The efficacy of the interscalar approach cannot be measured without the evaluation of a significant number of renewable materials and building systems that were developed under this methodology. In the absence of such data, this paper presents our research into the feasibility of non-corroding natural fiber composite reinforcing bars for cementitious materials, as a case study on the interscalar approach.

THE CORROSION PROBLEM

The durability of concrete has made it an indispensable component of infrastructure systems, but even concrete can fall into disrepair. Every four years, the American Society of Civil Engineers (ASCE) surveys the nation’s infrastructure across multiple sectors to assess its current condition and quantify its anticipated funding needs. According to the 2021 Report Card for America’s Infrastructure, an additional $2.6 trillion dollars of funding over the next 10 years is needed for proper repair and maintenance.[9] Furthermore, infrastructure failure is uniquely dangerous as the systems are fundamentally interrelated, such as a power plant that provides energy to a water treatment facility.

> *“Findings from this final report show that weakening of multiple infrastructure systems will have a greater, compounding effect overall than simply adding the impacts for the individual infrastructure studies.”* [10]

While these reports focus on domestic infrastructure, their conclusions are based on global forces, such as rapid urbanization and climate change. Currently, 55% of the world’s population lives in urban areas and the UN projects that this figure will grow to 68% by 2050.[11] Numerous studies have concluded that an increased load on an already overburdened infrastructure will be detrimental to existing infrastructure and greater planning and investment is required to meet future service demand.[12] [13] Furthermore, these stresses are exacerbated by the impacts of climate change. Rising sea levels endanger coastal infrastructure[14] and rising atmospheric carbon dioxide levels accelerates carbonation-induced corrosion of concrete.[15] Most of the world's concrete infrastructure is approaching or has exceeded its designed service life[16] and urbanization and climate change are accelerating the rate of deterioration. However, a deeper understanding of reinforced concrete reveals the proportionally small, underlying causes of concrete failure.

Reinforced Concrete (RC) is a composite material composed of a concrete matrix, made from sand and gravel bound together by water-activated cement, and reinforcing material, typically made from steel bars. Cement is less than 20% of RC by volume, but its production is responsible for 4-8% of the world's carbon dioxide output. The sand used for aggregate must be rough enough to adhere to the surrounding cement, which can only be found along beaches, riverbeds, and the ocean floor. Consequently, the overwhelming demand for concrete has rapidly diminished the reserves of suitable sand and has resulted in severe habitat destruction, black market trading, and violence.[17] The production of steel is a very energy intensive process when made from raw material, but reinforcing steel is typically made with 64-97% recycled content, which requires about 75% less energy to produce.[18][19][20] Furthermore, because concrete reinforcing is only 1-5% by volume, the environmental impact of steel on the overall RC composite is proportionally small. However, when this small fraction of steel is compromised, the entire composite will eventually fail.

Typically, reinforcing steel is protected from the build up of corrosion solids by a thin film of oxidation, known as the "passive layer", that protects the underlying steel from further degradation.[21] However, the passive layer will fail if dissolved salts accelerate the oxidation process[22] or if enough carbon dioxide is absorbed to cause the pH value to fall below 8.3.[21] Once the passive layer fails, it is only a matter of time before corrosion solids develop on the surface of the steel. These solids apply outward pressure on the surrounding concrete, cracking it and exposing the remaining reinforcing, thereby accelerating the corrosion process. To mitigate, or ideally prevent this process, anti-corrosion reinforcing materials have been developed, which fall into two general categories: anti-corrosion barriers and non-corroding materials.

Anti-corrosion barriers utilize an applied coating of epoxy or zinc that impedes the ingress of dissolved salts from reaching the underlying steel. Epoxy coating is the more affordable of these two strategies, which has made it the second most popular corrosion prevention strategy in the United States, behind simply increasing the concrete coverage thickness.[23] However, because its performance is entirely reliant on maintaining the integrity of the coating, defects generated during the manufacturing or installation process can lead to premature failure of the underlying steel.[24][25] Similar to epoxy coatings, "hot dip galvanization" bonds a thin layer of zinc to steel through a metallurgical process that develops a more robust bond than epoxy coatings. Zinc is similar to steel in that a small portion of it is consumed to develop a protective "passive layer" when it is in contact with the high pH environment of wet cement. However, the pH of some concrete mixes is too high and the passive layer does not fully develop, inducing premature corrosion.[26] Although this can be avoided through proper construction coordination, galvanized rebar still relies on a sacrificial barrier that will eventually dissolve. Under the same conditions, it is estimated that corrosion would initiate after 44 years for galvanized reinforcing, compared to 15 years for ordinary steel[27], which is insufficient for infrastructure projects that typically require service lives of 50-100 years.

Non-corroding materials, such as stainless steel and fiber reinforced polymers, provide excellent service life by simply

Figure 2. Mechanical properties of various natural fibers. Daniel M. Cohen M.Sc., RA, LEED AP.

preventing the formation of corrosion solids. Stainless steel achieves this by adding chromium to steel, which creates an alloy with a significantly higher chloride threshold for corrosion development. In fact, the addition of chromium increases the threshold so much that engineers can reduce the concrete cover depth, which reduces load, surface, and shrinkage cracking.[28] However, stainless steel's high initial cost is often too high for most budgets, despite the cost savings generated by lowered lifetime service and maintained costs.[25]

Fiber reinforced polymers (FRPs) are a family of non-corroding reinforcing materials that are often more affordable than stainless steel. FRPs are composite materials composed of a high strength fiber, such as glass or carbon, set inside of thermoset plastic resin. FRPs are produced via a process known as pultrusion, where the reinforcing fibers are pulled through a resin bath before being formed into a bar by squeezing the saturated fibers through a metal die that shapes the material. There are numerous advantages to FRPs, including "corrosion resistance, high tensile strength, low specific gravity, fatigue resistance, nonmagnetic electrical insulation, and small creep deformations."[29] However, FRPs have a low modulus of elasticity, meaning they are significantly less stiff than steel reinforcing. This can be a problem because more FRP reinforcing bars would be needed to prevent the concrete from cracking under loading, than if the same design was reinforced with steel. Furthermore, these additional reinforcing bars mean the reinforced concrete has excessively high tensile strength, which is an inefficient use of materials.[30] Another drawback is that FRP's thermoset matrix cannot be bent or shaped once cured like traditional steel, which makes accommodating change orders or design inconsistencies logistically challenging and expensive.[31] Regardless, FRP has still found a commercial foothold because, "evidently, the higher initial cost associated with corrosion-resistant reinforcements may be recouped in the long term as a result of reducing repair costs and extending service lives of RC structures."[32]

The impacts of urbanization and climate change will accelerate the deterioration of existing concrete infrastructure, particularly in coastal environments with high chloride content. Eventually there will be an increased demand for non-corroding reinforcing materials as aging infrastructure is rehabilitated or replaced. Could renewable materials prove advantageous over effective, yet imperfect, existing technologies?

THE INTERSCALAR APPROACH

The interscalar approach answers this question by validating the new technology's potential at an early stage, the need for significant investment of time or resources. Furthermore, the interscalar approach develops a valuable framework to guide further research and development. This approach begins by reviewing the advantages and disadvantages of existing technologies, to identify the crucial performance metrics the new technology must address. For example, the crucial performance metrics for non-corroding natural fiber composite

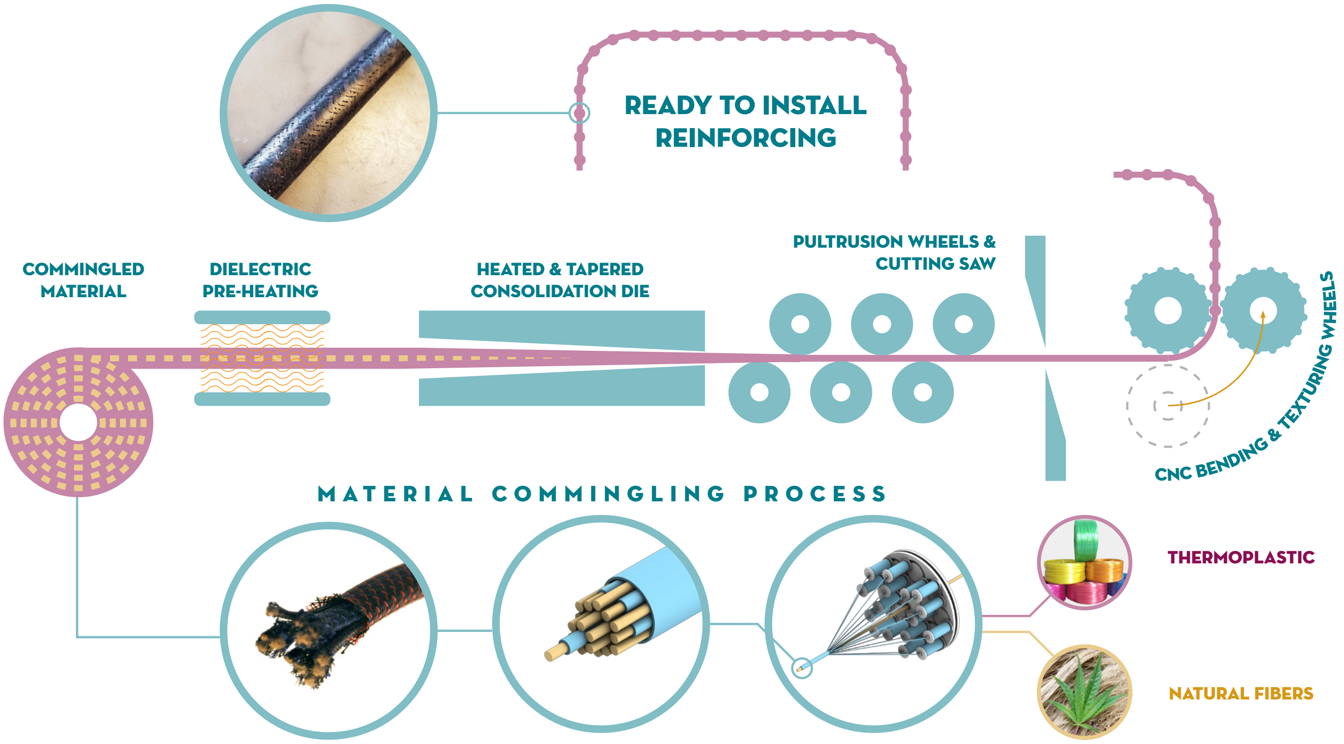

Figure 3. Commingling, consolidation, and fabrication processes diagram. Daniel M. Cohen M.Sc., RA, LEED AP.

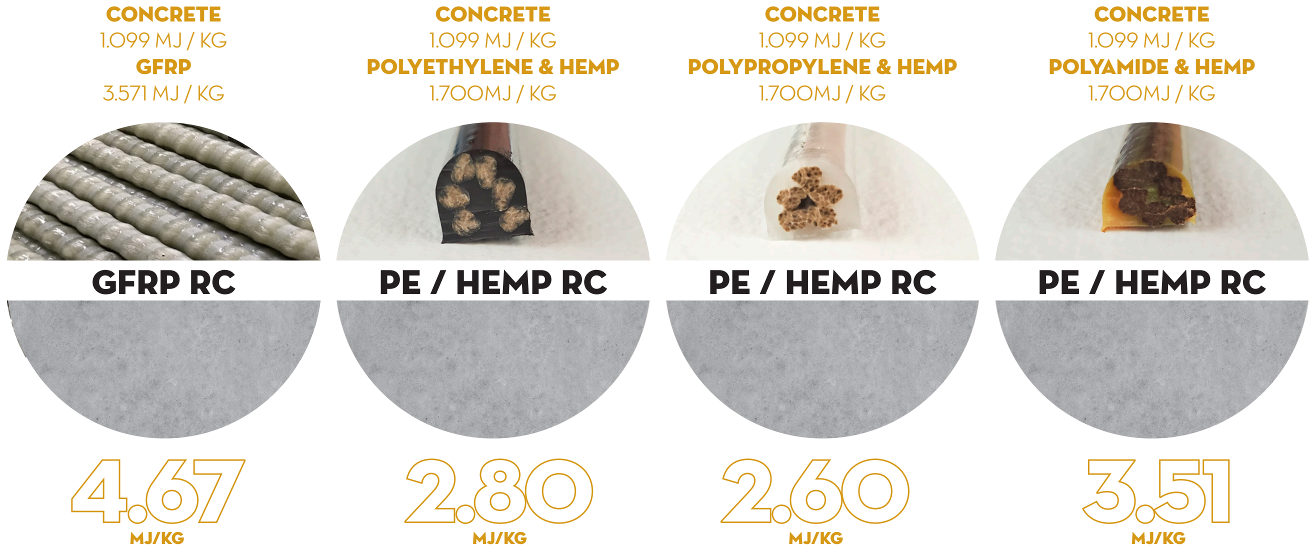

Figure 4. Embodied energy of various natural fiber composite rebar prototypes. Daniel M. Cohen M.Sc., RA, LEED AP.

reinforcing bar would include mechanical properties, thermal resistance, interfacial shear strength, material configuration, construction logistics, production rate, unit pricing, project administration, and ecological impact. These metrics are then arranged by their relative scale and are assigned corresponding nomenclature to reflect their common research disciplines: micro-scale metrics such as mechanical properties, thermal resistance, and interfacial shear strength are grouped together under "structural performance"; meso-scale metrics such as material configuration, construction logistics, production rate are grouped together under "processing performance"; and macro-scale metrics such as unit pricing, project administration, and ecological impact are grouped together under "environmental performance". Further performance metrics can be added or removed based upon further research or experimentation results as necessary. The resulting framework provides the following: (1) identification of any insurmountable obstacles to further development, (2) identification of specific expertises needed by the larger research effort, and (3) organization of that research effort into manageable tasks.

THE NATURAL OPPORTUNITY

From the structural performance perspective, it may seem counterintuitive that the mechanical properties of a natural fiber, such as hemp or flax, could compare favorably against a high strength synthetic fiber, such as glass or carbon. While synthetic fibers do have high tensile strength, it is their low elastic modulus, or their ability to resist deformation under loading, that is their governing mechanical property when used as concrete reinforcement. As mentioned earlier, FRP reinforced designs can require 50% more reinforcing than steel to account for this lack of stiffness, rendering their high tensile strength irrelevant. Therefore, a natural fiber that has comparable elasticity to synthetic fibers, with lower but sufficient tensile strength, could be developed into a reinforcing bar; in fact there are multiple natural fiber species that satisfy this criteria.[33] A reasonable structural performance concern when working with natural fiber is their thermal resistance, or their ability to maintain strength during a fire. In general, natural fibers begin to deteriorate when the temperature exceeds 200°C, with an increasing rate of deterioration as the temperature rises.[34] [35] While not ideal, this does not preclude the use of natural fibers, but rather informs further development at the processing scale in two ways: (1) the melting temperature of the corresponding thermoplastic matrix must be below 200°C in order for the fibers to avoid degradation during the consolidation process, and (2) an increase in the required concrete cover depth may be necessary to provide additional thermal resistance for the reinforcing.[36] In order for the mechanical properties of the natural fibers to provide reinforcement to the surrounding concrete, interfacial shear strength must be maintained at two different interfaces. First, the fibers and the selected thermoplastic must develop a robust bond, which is dependent on the particular natural fiber and thermoplastic materials selected and how those materials were processed before and during production.[33] [37] [38] Second, the resulting composite bar must develop a robust bond with the concrete, which is dependent on particular thermoplastic material selected, the particular concrete mix prepared, the surface profile of the bar, and the depth of rebar embedment.[39] [40][41] These performance metrics are multi-variable and can only be assessed by producing and testing physical prototypes. While such testing has not been performed to date, prototypes of various material selections, configurations, and processing methods are currently under development.

From the processing performance perspective, the commingling of fiber and matrix requires a greater degree of coordination when using a thermoplastic matrix, rather than the thermoset matrices found in FRPs. FRP are produced via

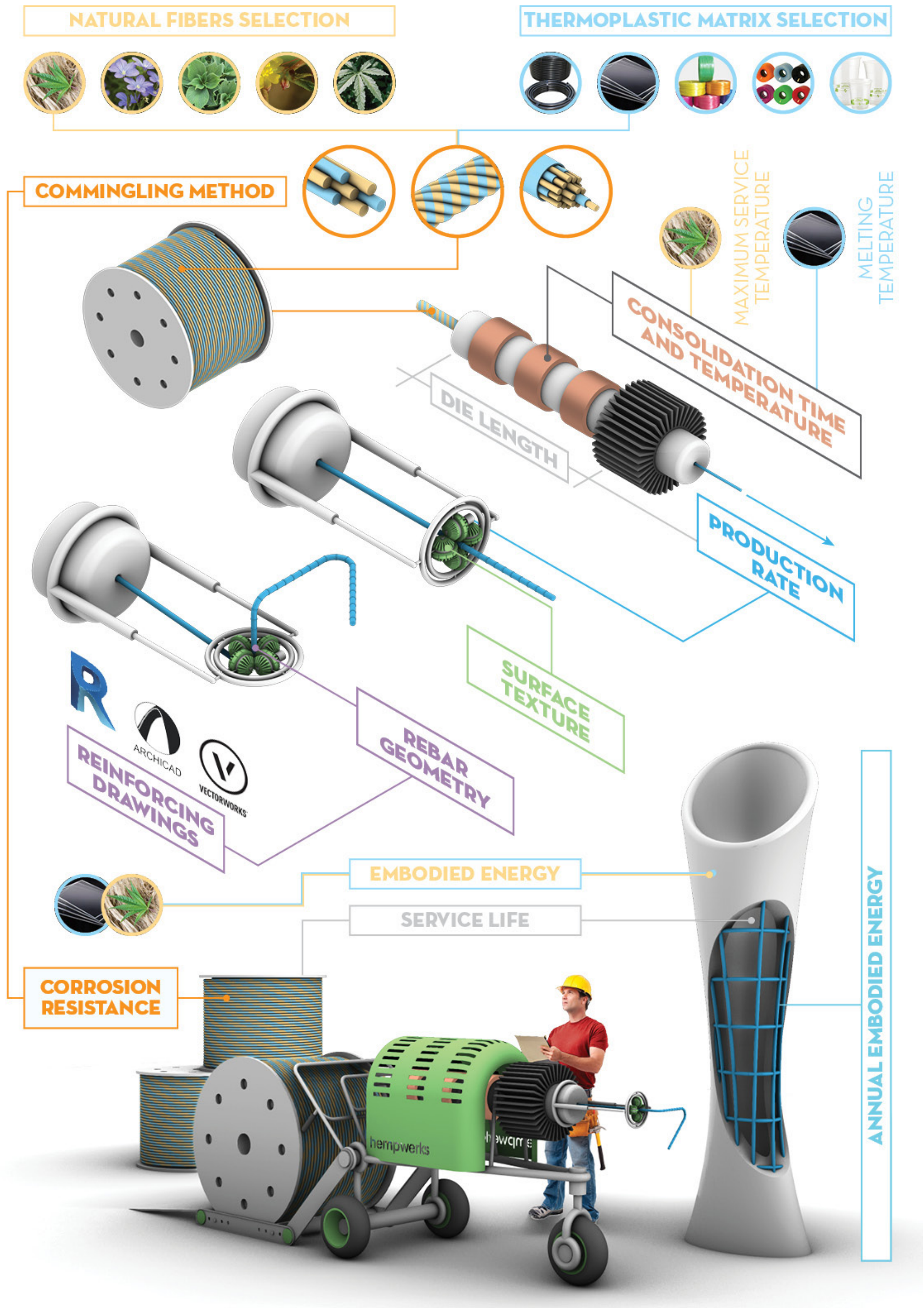

Figure 5. Interscalar framework of natural fibre composite rebar for cementitious materials. Daniel M. Cohen M.Sc., RA, LEED AP.

pultrusion, a process where synthetic fibers are continuously pulled from reels, bathed in liquid resin, and compressed together through a die before hardening into its final form. This single streamlined process begins with unconsolidated material and finishes with the final product. However, thermoplastics begin as a solid that must be melted before impregnating the natural fibers and cooling into a composite material. The particular geometric configuration of thermoplastic and fiber prior to the heating process will impact the resulting composite's mechanical properties, internal interfacial shear strength, and its resistance against chloride ingress. While this is similar to FRPs, in that the process of commingling the two materials will impact the composite's consolidation, thermoplastics allow for the commingling process to be divorced from consolidation. While still in a solid state, the two materials could be commingled into a rope or cable and maintain this arrangement for as long as necessary. This means that commingled, but unconsolidated reinforcing could be transported to the job site, which fundamentally changes the construction logistics. Traditional reinforcement is delivered to site as long straight bars that must be craned overhead to various staging areas for fabrication. However, the unconsolidated thermoplastic reinforcing can be easily transported without the need for cranes or large staging areas. Pairing this with small form factor consolidation machines would allow construction managers and contractors to have much more flexibility when staging rebar installation, but only if the machine could produce rebar at a logistically sound and financially solvent rate. This production rate is a function of both the materials' commingled geometry, the melting point of the thermoplastic, and the size of the machine. While the maximum service temperature of the natural fibers limits the available thermoplastic options, finer distribution of the two materials would result in faster consolidation.[42] Our preliminary studies show that a hoistway sized machine could maintain a 1 meter per minute output, but only if a microwave or radio frequency preheating stage was incorporated. While this does increase the complexity of the design effort, we do not see preheating as an insurmountable challenge.

From the environmental performance perspective, the specific selection of the materials and their processing methods directly impact the ultimate pricing of the reinforcing product. As is apparent from other innovative renewable material technologies, pricing is a critical metric in the adoption of any innovative technology and without industry adoption greater environmental impacts cannot be felt. While not a renewable material, GFRP rebar has gained a foothold in the rebar marketplace primarily because it is more affordable than stainless steel rebar, despite its logistical shortcomings.[43] However, accurately determining the unit price of a natural fiber composite rebar is difficult without more information on natural fiber and thermoplastic sourcing, processing methodology, and addressable market size. Even with this information, a direct rebar to rebar comparison could not account for the project administration advantages provided by decoupling the commingling and consolidation processes. As discussed earlier, this decoupling allows an on-site machine to handle material consolidation, which if coupled with a rebar bending module, could also be tasked with rebar fabrication. While the materials are still malleable, CNC controlled bending wheels can fabricate the reinforcing design with information digitally provided directly from building information modeling (BIM) software. This would streamline the design workflow by eliminating the need for the contractor to produce shop drawings and for the design team to review and approve them before fabrication. By directly transmitting the reinforcing design to the fabrication machine, the construction schedule can be accelerated and delay claims can be avoided. Furthermore, architects and structural engineers would be encouraged to pursue more complex or innovative structural solutions because this digital fabrication process would ensure accurate replication of their designs. But what about the ecological impact of natural fiber composite reinforcing? This paper began with quantified impacts of climate change; how can this technology's environmental performance be quantified? One way is by calculating the annual embodied energy, or the total amount of energy necessary to produce a unit of reinforcement divided by its anticipated service life. However, this is not a calculation of the rebar's annual embodied energy, but of the reinforced concrete composite. The non-corroding nature of the natural fiber composite material ensures that both it and its associated concrete will remain intact much longer than concrete reinforced with a material that can corrode. Preliminary studies indicate that concrete reinforced with natural fiber composite reinforcing would require 30-50% less annual embodied energy than concrete reinforced with GFRP, depending on specific material selection and processing methodology. However, this metric does not quantify the impact of reduced demand for non-renewable resources, such as sand, and climate contributing resources, such as cement. With further research, more accurate data can determine the true extent of natural fiber composite reinforced concrete's benefits.

CONCLUSION

Climate change has not changed course because of a lack of intelligent, creative, and committed teams focused on developing innovative technologies. Rather, by focusing on the technologies' development, researchers can lose perspective on the obstacles preventing future adoption. The interscalar approach has been a valuable tool for the early stage validation of our research, and has produced a framework for our team to use going forward. Each team member has an expertise in a particular field, and this framework allows us to focus our skills where they are most productive, while not losing sight of the larger research agenda. Furthermore, it has been helpful in identifying knowledge gaps, thereby guiding us to collaborate with experts in other fields. Truthfully, the benefits of the interscalar approach cannot be proven until natural fiber composite reinforcing, and other technologies developed using the interscalar approach, are common in the construction industry. It will be some time before we see these results, but we believe that this case study demonstrates the benefits of the interscalar approach, particularly for research and development of renewable materials and building systems.

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