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NATURAL FIBERS FOR SUSTAINABLE CONCRETE MIXES

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To meet the sustainable development goals, novel concrete mixes are necessary. Natural fibers are becoming an interesting new element for concrete mixes, because these fibers are biomaterials recovered from residual biomass and fit in the concept of the circular bioeconomy. In this paper, we catalog research insights on concrete mixes with natural fibers and pay special attention to natural fibers that are available in the Metropolitan District of Quito, Ecuador, to use local bio-based materials. We focus on examining information from the literature on how natural fibers influence the mechanical properties of concrete, namely the tensile, compressive, and flexural strength. Based on this analysis, we have developed recommendations on which natural fibers are of interest for further experimental research, with the aim to develop sustainable concrete mixes for Quito. Moreover, this paper gives insights in how natural fibers influence the mechanical properties of concrete and proposes a framework that translates to other regions and cities for the selection of local and adequate natural fibers.

Keywords: Banana industrial residues, Bio-based concrete, Circular bioeconomy; Coconut industrial residues, Literature review.

1 INTRODUCTION

This paper focuses on the integration of natural fibers into concrete mixes as a means to reduce the environmental impact of concrete and promote sustainable development. The use of natural fibers aligns with the principles of the circular bio-economy and offers advantages such as renewability. Our specific focus is on the Metropolitan District of Quito, where local bio-based materials can be utilized to develop environmentally-friendly concrete mixes.

The addition of natural fibers to concrete holds promises for sustainable construction practices. By leveraging the abundance of natural fibers available and processed in Quito, the region can adopt a localized approach to creating eco-friendly concrete mixes. Understanding how different natural fibers affect the mechanical properties of concrete, such as toughness (post-peak behavior), is essential for formulating effective and sustainable mixes.

Through a comprehensive analysis of the existing literature, this paper aims to provide insights into how natural fibers influence the concrete's mechanical properties. The goal is to identify natural fibers with potential for further experimental research based on the available resources of the city of Quito. Additionally, the paper proposes a framework that can be applied to other regions and cities, facilitating the selection of suitable local natural fibers for sustainable concrete construction.

2 LITERATURE REVIEW

2.1 Concrete Mixes with Natural Fibers

The integration of natural fibers and natural fine materials into concrete mixes offers a promising solution for sustainable construction and reducing the impact of concrete production. By replacing a portion of cement with natural fine materials, the carbon footprint can be decreased while the novel mixes align with the principles of the circular bio-economy by encouraging a lower use of cement. Cement production is an important source of CO_2 emissions and is estimated to contribute to 5-8% of the global CO_2 emissions, according to He *et al.* (2019). This paper focuses on researching and cataloging insights on concrete mixes with natural fibers and natural fine materials, with a specific emphasis on materials available in Ecuador and in the city of Quito.

Considering the availability and environmental impact of transportation, it is crucial to prioritize locally available natural fibers in Quito. An inventory conducted at Universidad San Francisco de Quito revealed several natural fibers and fine materials studied previously in Quito. These materials are either naturally available in Quito, processed in the industry of the city, or brought from other parts of the country. Fibers such as African palm rachis, banana rachis, and rice husk, among others, were identified as potential candidates for sustainable concrete mixes. Moreover, as these natural fibers have been used in other projects at Universidad San Francisco de Quito, the chemical composition and properties are available and known. Additionally, other fibers like abaca, caraua, sisal, jute, ramie, and linen have been studied by other researchers like Guerrero *et al.* (2011) in Quito, and these materials were identified as good candidates for use in biobased materials.

2.2 Influence of Natural Fibers on Mechanical Properties

The use of natural fibers in concrete mixes represents a recent advance, with limited experiments reported in the literature. In this study, we have concentrated on references investigating the mechanical properties in comparison to a reference concrete mix without fibers.

In a first category, we examine studies where fibers were processed into ash to serve as pozzolanic materials. Hakeem *et al.* (2022) focused on rice husk ash (RHA) in conjunction with olive waste ash (OWA). Their findings revealed a notable increase in tensile strength, specifically by 41.33%, when 20% of the cement volume was replaced with RHA and an additional 5% with OWA, as compared to the reference mix.

Furthermore, Wahyuni *et al.* (2014) suggested that RHA could be blended with seashell ash (SSA) and bamboo fiber (BF) to enhance the tensile strength of hardened concrete. This blend achieved strengths of 3.6 MPa at 28 days and 3.9 MPa at 90 days. In contrast, the control mix exhibited tensile strengths of 3.4 MPa at 28 days and 3.8 MPa at 90 days. Notably, this improvement was achieved by replacing 30% by weight of the original fine aggregates with a blend consisting of a 36:65 ratio of RHA to SSA and an additional 2.5 kg/m³ of BF. The 30% replacement mentioned refers to the fine aggregates (sand) only, not the cement. The initial mention of pozzolanic materials, such as RHA and SSA, indeed relates to their role as partial replacements for fine aggregates rather than cement. These materials were added to enhance the properties of the concrete, serving both pozzolanic and compaction purposes.

In the second set of experiments from the literature, natural fibers were employed. Noor Abbas *et al.* (2023) introduced a novel concrete-like material: kenaf fiber-reinforced geopolymer concrete (KFRGC). Optimal results were achieved by incorporating a 1.25% volume fraction of 30 mm long kenaf fiber. This composition led to an increase in tensile strength ranging from 20% to 27% compared to a reference plain geopolymer mix.

Similarly, Gulzar *et al.* (2023) found that jute fiber (JF) enhanced concrete tensile strength when 0.5% by volume of JF was added to the mix alongside a superplasticizer (SP) and 25% by volume of ground granulated blast furnace slag (GGBS). This combination resulted in a 27% increase in tensile strength compared to a mix without jute fiber and without GGBS when tested at 28 days.

Additionally, Rama Rao and Ramakrishna (2021) suggested that spikelet (SP) and stalk (ST) fibers that come from oil palm empty fruit bunch fiber (OPEFB) can increase the properties of cement mortar. An optimal increase in the tensile strength of the mortar can be found when using SP fiber with a length of 15 mm at 2% of cement mass needed for one cubic meter of mortar or when using ST fiber with a length of 20 mm long at 3% of cement mass for one cubic meter of mortar as well.

One local reference regarding the influence of natural fibers on the mechanical properties is identified. Caizaguano and Terán (2020) investigated the use of rachis of African oil palm and coconut bast. They found that the tensile strength is improved by 3.67% and 0.71% as compared to the tensile strength of a control mix when 2% bast or 2% palm, respectively, are placed in the mix. In this case, the control mix was designed for a concrete cylinder compressive strength of $f'_c = 21$ MPa ($f'_{cr} = 29$ MPa as the average tested value). On the other hand, for a control mix designed to have a specified concrete compressive strength of $f'_c = 24$ MPa ($f'_{cr} = 32$ MPa), only for the mix with an addition of 2% coconut bast an increase in 7.86% of the tensile strength was found.

An important aspect to consider is that the characteristics of the fibers are already studied in each article. For instance, some of the aspects provided are diameter, density, tensile strength (of the fiber alone), Young's modulus, specific gravity, and water absorption capacity. These characteristics are clearly outlined in order to get an overview of each fiber, and predict a certain behavior when mixed with concrete. Furthermore, some articles also explore ground natural products through XRD and EDX analyses to determine their chemical composition relative to cementitious materials commonly used in traditional concrete mixes like fly ash.

3 AVAILABLE NATURAL FIBERS IN QUITO

To find a sustainable mix design for concrete incorporating natural fibers and ash sourced from local, environmentally friendly sources, it is essential to consider products that are readily accessible within the region. The practice of importing materials from distant coastal areas is not deemed environmentally friendly, primarily due to the associated carbon footprint resulting from transportation via fossil fuel-consuming trucks. Fortunately, Ecuador's relatively compact geographical size mitigates this concern, as the short travel distances involved in transporting fibers have a minimal impact. Nevertheless, in a concerted effort to further reduce the carbon footprint, an inventory was conducted at Universidad San Francisco de Quito (USFQ). The objective was to comprehensively identify natural fibers readily available with minimal transportation requirements. These fibers were subsequently categorized into three groups: available natural fibers, accessible bio-based aggregates, and obtainable ash products suitable for use as cementitious materials.

The locally available fibers that could be used in concrete mixes to explore the influence on the mechanical properties are: African palm rachis, banana rachis, mango endocarp, brewer's spent grain (BSG), rice husk, and cacao pod. These are shown in Figures 1 and 2.

Figure 1. African palm rachis, banana rachis, mango endocarp (left to right).

Figure 2. BSG, rice husk, cacao pod (left to right).

Potential biobased aggregates locally available are quinoa residue, banana biochar, rose plantation residue, and hydrochar made out from mango endocarp, rice husk, blackberry residue, moringa peel, and cacao pod. In terms of biobased ash products that can be used as a supplementary cementitious material, rice husk can be used to make rice husk ash. The materials available at USFQ at the moment of doing the inventory are shown in Figure 3.

Figure 3. Banana biochar, rose plantation residue, mango endocarp hydrochar (left to right).

As it can be noted, some of these fibers have a connection with the literature review presented, and some of the fibers in the inventory are new in relation to the contents of the review. For rice husk, Hakeem *et al.* (2022) and Wahyuni *et al.* (2014) can be used as a reference while for African palm rachis, Caizaguano and Terán (2020) can give guidance on the trial mix design. It must be considered that RHA should be prepared at 600 °C for 2 hours heating at 10 °C/min, then cooled at 1.67 °C/min with an additional cooling in air at room temperature for 35 min, and lastly a screening with a 75 μm sieve before mixing with concrete, according to Hakeem *et al.* (2022). On the other hand, the methodology of Caizaguano and Terán (2020) for preparing African palm rachis involves a chemical treatment of placing the fibers in a water solution mixed with 10 g of lime hydroxide per liter of water for 48 hours, and then washing with clean water for a repetitive number of times until the water comes out clear. Afterwards, these fibers are cut at a length of 38 mm to then be placed in the concrete mix.

The other natural fibers available at USFQ are not discarded from this study, and represent a good starting point for new, locally relevant research that will broaden the perspective of materials about which information in the literature can be found. For these materials additional characterization of the fiber properties may be necessary as a starting point for the research.

4 RECOMMENDATIONS FOR FIBER SELECTION

The experience presented in this paper can serve as a basis for other cities and regions where there may be an interest in locally developing concrete mixes with natural fibers and natural products as part of the transition to the circular economy. From our pilot study, we can give the following recommendations as a framework for those who may want to apply our strategy:

- Prioritize locally available natural fibers by emphasizing the use of natural fibers that can be sourced locally to support the concept of the circular economy and reduce carbon emissions associated with transportation.
- Prioritize fibers that result from existing industries, like banana rachis residues from local snack producers, to minimize the environmental tradeoff by giving preference to natural fibers with low embodied energy, renewable sourcing, biodegradability, and potential for waste valorization to minimize the carbon footprint of concrete and promote sustainability.
- Assess fiber characteristics with the evaluation of the physical and mechanical properties of natural fibers, such as length, diameter, strength, elasticity, moisture content, absorption, and degradation in an alkaline environment to ensure their suitability for concrete mixes.
- Evaluate the fiber performance in concrete by the examination of the influence of natural fibers on the concrete's mechanical properties, including compressive strength, tensile strength, modulus of elasticity, flexural strength, and durability at various points in time.
- Obtain experimental data and compare theoretical insights to better understand how different fibers perform in concrete mixes.
- Consider availability and cost-effectiveness to assess the practicality of sourcing and incorporating selected natural fibers in large-scale concrete production, considering their availability and cost. Evaluate their compatibility with existing supply chains in the local construction industry.

The findings presented in this paper aim to close the gap between research and practical applications. They will serve as a valuable resource for researchers, engineers, and policymakers, not only in Quito but also in other regions, seeking to implement eco-friendly and circular construction practices. In synthesis, the integration of natural fibers in concrete has the potential to contribute to sustainable innovation in the construction industry.

5 SUMMARY AND CONCLUSIONS

This study focuses on incorporating natural fibers into concrete mixes in Quito to create sustainable alternatives for the local construction industry. By prioritizing local, bio-based materials, the aim is to reduce the carbon footprint and support the circular bio-economy. The research examines the impact of natural fibers on concrete’s mechanical properties based on the literature review. Concrete mixes that have been studied in the literature and that have resulted in improved properties as compared to the reference mix include biomaterials such as rice husk ash, olive waste ash, seashell ash, bamboo fiber, kenaf fiber-reinforced geopolymer concrete, and jute fiber.

The study's inventory of natural fibers at Universidad San Francisco de Quito identifies readily available materials like African palm rachis, banana rachis, mango endocarp, and rice husk for concrete production.

Overall, the study emphasizes the potential of natural fibers to develop sustainable concrete mixes in Quito and beyond. By considering fiber availability, characteristics, and environmental benefits, stakeholders can make informed decisions to reduce the environmental impact of concrete and promote eco-friendlier construction practices that are aligned with the transition to a circular economy. Ultimately, the findings and recommendations serve as a valuable resource for advancing sustainability goals in construction locally in Quito, and internationally by applying our recommendations.

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References

Caizaguano, O. P., and Terán, G. E., *Caracterización del Hormigón con Fibras Naturales del Raquis de la Palma Africana de Aceite y la Estopa del Coco*, Bachelor Thesis, Escuela Politécnica Nacional, Quito, November, 2020.

Guerrero, V. H., Dávila, J., Galeas, S., Pontón, P., Rosas, N., Sotomayor, V., and Valdivieso, C., *Nuevos Materiales: Aplicaciones Estructurales e Industriales*, Escuela Politécnica Nacional, December, 2011.

Gulzar, M. A., Ali, B., Barakat, O., Azab, M., Najemalden, A. M., Mohammed, A. S., and Alashker, Y., *Influence of Jute Fiber on Tensile, Electrical, and Permeability Characteristics of Slag Concrete: A Better, Cheaper, and Eco-friendly Substitute for Conventional Concrete*, Journal of Natural Fibers, Taylor & Francis, 20(1), 2170947, 2023.

Hakeem, I. Y., Agwa, I. S., Tayeh, B. A., and Abd-Elrahman, M. H., *Effect of Using a Combination of Rice Husk and Olive Waste Ashes on High-strength Concrete Properties*, Case Studies in Construction Materials, Elsevier, 17, e01486, December, 2022.

He, Z., Zhu, X., Wang, J., Mu, M., and Wang, Y., *Comparison of CO_2 Emissions from OPC and Recycled Cement Production*, Construction and Building Materials, Elsevier, 211, 965–973, June, 2019.

Noor Abbas, A.-G., Nora Aznieta Abdul Aziz, F., Abdan, K., Azline Mohd Nasir, N., and Fahim Huseien, G., *Experimental Evaluation and Statistical Modeling of Kenaf Fiber-Reinforced Geopolymer Concrete*, Construction and Building Materials, Elsevier, 367, 130228, February, 2023.

Rama Rao, P., and Ramakrishna, G., *Experimental Investigation on Mechanical Properties of Oil Palm Empty Fruit Bunch Fiber Reinforced Cement Mortar*, Materials Today: Proceedings, Elsevier, 46(1), 471–477, 2021.

Wahyuni, A. S., Supriani, F., Elhusna, and Gunawan, A., *The Performance of Concrete with Rice Husk Ash, Sea Shell Ash and Bamboo Fibre Addition*, Procedia Engineering, Elsevier, 95, 473–478, 2014.