Comparative Analysis of Sustainable Materials in Construction using PRISMA Method

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Comparative Analysis of Sustainable Materials in Construction using PRISMA Method

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Abstract: *The construction sector accounts for 37% of global emissions, driving demand for green building practices. This has resulted in several solutions, including the development of sustainable building materials. This study examined the use of such materials, particularly in concrete, in the context of Philippine civil engineering. Bamboo culms, natural fibers, and sustainable aggregates, three Philippine-native concrete materials, were compared to deformed steel bars, synthetic fibers, and fine aggregates for their structural performance, economic viability, and environmental impact using a systematic literature review and comparative analysis. Due to their durability and standardization, traditional materials outperform sustainable alternatives in high-load and large-scale applications, though bamboo, natural fibers, and sustainable aggregates have cost-effectiveness and environmental sustainability potential. Each sustainable material had similar mechanical properties, but durability and standardization could be improved through innovation and treatment. The research concludes that a hybrid approach, which incorporates both traditional and sustainable materials, provides a balanced solution for improving the sustainability of construction, though research and industry collaboration are needed to improve processing methods and further promote sustainable materials in the Philippines.*

Keywords: sustainability; green concrete; comparative analysis

1. INTRODUCTION

1.1 Background of the Study

With the rise of climate change and increased global carbon emissions, there has been a push for environmentally conscious building practices to combat these crises and promote sustainable development. Traditional construction, in particular, has a reputation for being unsustainable, depleting natural resources, and contributing to greenhouse gas emissions. This is due to its reliance on both limited raw materials commonly sourced from forests and the production of energy-depleting materials such as concrete or steel [1, 2]. The impacts of construction are most pronounced in low-income countries, which are disproportionately affected by climate change. The Philippines, for instance, is a country rich in natural resources, making it immediately vulnerable to unsustainable construction. The advancement of urbanization in the country worsens this vulnerability and poses a significant threat to the depletion of the natural resources of the country. As of 2020, the Philippines had a population of 109 million, with 54.0% of its citizens living in urban areas [3]. This constant increase will put pressure on sustainable development, prompting a need for environmentally friendly solutions to accommodate this growth.

Previous studies have examined different sustainable building materials on a global scale. According to Chen et al. [4], the selection of sustainable building materials is based on comfort, health benefits, and cost-effectiveness. This served as a reference for identifying building materials that could potentially be produced in the Philippines. Among these, bamboo culms, natural fibers such as abaca, banana, and bamboo fibers, along with sustainable aggregates like crushed glass, sawdust, and rice husk ash emerged as promising choices for sustainable construction in the Philippines. Another study by Sandanayake et al. [5] states that factors such as local availability, life cycle behavior, transportation distance, and life cycle costs should be considered to evaluate the sustainability of these materials. The materials chosen fit the criteria, backed by several studies, and were further assessed. Bamboo, specifically bamboo culm, was selected due to its growth, which allows for sustainable harvesting without causing deforestation. Additionally, it has been known to replace the use of conventional materials such as wood, brick, concrete, and steel [6]. Natural fibers such as abaca, banana, and bamboo fibers were chosen for their ability to enhance concrete properties, improving tensile strength, bending strength, and post-crack performance [7]. They are also sustainable and cost-effective as they are derived from by-products of agricultural waste as opposed to traditional reinforcement materials. Similarly, sustainable aggregates such as sawdust, crushed glass, and rice husk ash (RHA) were selected for their environmental benefits, such as minimizing landfill waste [8] and effectiveness as replacements for fine aggregates in concrete improving strength durability, and workability [9]. Furthermore, the application of these building materials often involves integrating them into existing construction practices or using them complementary to other materials. Moreover, the materials chosen are all reproducible, native to the Philippines, and can be integrated into civil engineering projects. Besides this, there seems to be a lack of studies available on local sustainable building materials and practices.

The most commonly used materials in concrete construction in the Philippines include reinforcing steel bars, synthetic fibers, and fine aggregates. Reinforcing steel bars, also known as rebar, are a commonplace material in construction projects due to their compatibility with concrete and their ability to compensate for their weak tensile strength [10]. However, its limitations come in the form of low cost-effectiveness due to the high cost of steel, significantly impacting budgets for large-scale construction projects. Synthetic fibers, more commonly macro-synthetic fibers, are used in construction to improve the ductility of concrete and reduce cracking [11]. This benefits not only the quality of construction projects but also their cost-effectiveness due to the reduction of damage. However, the air content in synthetic fibers may decrease certain properties of concrete, such as workability, strength, and durability [12]. Finally, fine aggregates are commonly used due to their ability to improve the handling and durability of concrete [13]. These natural materials are mostly composed of crushed stone or sand, with the most common fine aggregate used in the Philippines being river sand. The limitations of this material are mainly due to sustainability issues, as it can lead to the depletion of natural resources.

The research gap lies in the limited Philippine-based research regarding the viability of locally sourced sustainable building materials and the comparison of these materials to their traditional counterparts. This gap presents an opportunity to find sustainable materials that can function similarly, if not better, than traditional materials, which can improve not only the environment but also the economic condition of the Philippines.

1.2 Research Objectives

The general objective of this study is to investigate the integration of sustainable building materials, particularly sustainable concrete, in Philippine civil engineering projects. The study has two specific objectives, each with two sub-objectives:

1. To evaluate the structural performance of selected sustainable concrete materials: bamboo culms, natural fibers (abacá, banana, bamboo fibers), and sustainable aggregates (sawdust, crushed glass, rice husk ash) compared to traditional materials (deformed steel bars, synthetic fibers, and fine aggregates) used in civil engineering projects

1.1 Assess the tensile strength, compressive strength, flexural strength, and durability of selected sustainable concrete materials as alternatives to their traditional counterparts

1.2 Conduct a comparative analysis of the structural integrity of these materials by evaluating their performance in terms of tensile strength, compressive strength, flexural strength, and long-term durability

2. To analyze the economic and environmental impacts of integrating sustainable concrete into construction practices

2.1 Collect a cost-benefit analysis of the selected sustainable building materials versus traditional materials

2.2 Gather a life cycle assessment of the selected materials to evaluate environmental impacts throughout their life cycles

2. METHODOLOGY

To accomplish the objectives of the study, the following procedures will guide the research process:

2.1 Review of Related Literature

Prior research on sustainable and traditional building materials was examined to obtain insights into the feasibility of incorporating these sustainable materials into engineering projects. The studies reviewed included both international and Philippine contexts, ensuring a well-rounded perspective for the research. This review included studies focused on material performance, environmental impact, cost-effectiveness, and adaptability to local construction projects. Sources were carefully selected from a diverse range of academic journals and technical reports to ensure reliability and relevance.

To ensure an up-to-date analysis, the study primarily utilized sources published within the last ten years. Exceptions were made for foundational materials, such as definitions of terms or key concepts, which remained relevant despite their earlier publication dates. Additionally, the study incorporated a review of local industry-standard specifications for traditional building materials. This was essential for understanding the benchmarks against which sustainable materials could be evaluated, ensuring compatibility and compliance with existing construction practices and standards.

2.2 Analysis

The study integrated findings from prior research to assess the feasibility of using sustainable building materials in Philippine civil engineering projects. A comparative analysis following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework served as the foundation for evaluating the technical properties of these materials, focusing on tensile capacity, compressive strength, and flexural performance. PRISMA is a set of evidence-based guidelines aimed at improving the transparency, reproducibility, and rigor of systematic reviews and meta-analyses by offering a structured approach for literature identification, screening, eligibility assessment, and study inclusion. This method was chosen to minimize selection bias and ensure that only high-quality, relevant studies were considered in the comparative analysis of sustainable and traditional construction materials. The use of PRISMA allowed the researchers to critically evaluate the technical, economic, and environmental aspects of various materials through a clearly documented and replicable process. Prior studies in the field of construction materials research have also used PRISMA to assess the sustainability and performance of innovative building solutions, underscoring its suitability for this type of systematic evaluation.

Sustainable materials were systematically compared against traditional materials. Industry-standard specifications, including those outlined in the National Structural Code of the Philippines [10], were used as benchmarks to ensure the comparisons were robust and aligned with current construction practices. In addition to technical performance, the study examined the environmental and economic impacts of integrating sustainable materials. A life-cycle assessment was reviewed to evaluate the materials' environmental footprint, while a cost-benefit analysis explored their economic viability in local construction contexts.

2.3 Research Design

The PRISMA framework is conducted in four stages: (1) Searching Records & Duplicates, proceeding through (2) Abstract-level Screening and (3) Full-text Screening, and then (4) the Final Included Studies and Reports. A

PRISMA flow diagram was created to visualize this process. These methods contributed to facilitating a comparative analysis of three sustainable building materials—bamboo, natural fibers, and sustainable aggregates—with traditional building materials, namely deformed bars, synthetic fibers, and fine aggregates. By integrating these methods, the study aimed to comprehensively assess the practicality, feasibility, and effectiveness of adopting sustainable building materials in the Philippine civil engineering context.

2.4 Data Collection Methods

The literature search for this study was conducted using both global and local academic databases such as Google Scholar, ResearchGate, JSTOR, and Scopus to ensure reliability and relevance. In addition, locally published research from Philippine sources, including studies recommended and provided by our research advisor, was reviewed to enhance the applicability of the findings within the Philippine construction context. Keywords for the search focused on sustainable and traditional building materials. For sustainable materials, terms included "Bamboo culm in structural applications," "Natural fibers (abacá, banana, and bamboo) for fiber reinforcement," "Sustainable aggregates (sawdust, crushed glass, rice husk ash) in concrete," and "Sustainability in Philippine construction." For traditional materials, keywords included "Steel deformed bars," "Synthetic fibers in concrete," and "Fine aggregates for concrete mixtures." To maintain relevance, only peer-reviewed articles, journals, and conference papers published within the last ten years (2014–2024) were included, with exceptions for foundational studies deemed critical to the research.

The relevant papers compiled underwent a two-stage process for inclusion. First, a preliminary screening was done by going over the titles and abstracts of each study to determine its relevance. Articles that did not align with the objectives of this paper were excluded. The remaining studies were then given a full-text review for a full assessment of their relevance, and the inclusion and exclusion criteria were decided by the researchers. A PRISMA flow diagram (See Figure 1) visually represented the selection process, documenting the number of records identified, screened, excluded, and ultimately included in the final review. For the inclusion criteria, studies that examined bamboo culm, natural fibers (abacá, banana, and bamboo), and sustainable aggregates (sawdust, crushed glass, rice husk ash) were included. Moreover, research evaluating the structural, economic, and environmental performance of those materials along with deformed bars, synthetic fibers, and fine aggregates in construction was considered. Priority was given to studies that focused on material applications in tropical climates or in the Philippines. The exclusion criteria included papers that did not have quantitative performance data or were outdated and lacked foundational relevance.

A total of 71 studies were initially identified through database searches. After removing 8 records due to irrelevance or other reasons before screening, 63 studies proceeded to the screening stage. Following a detailed review, 29 studies were excluded for not meeting the study's focus or methodological criteria, leaving 34 reports sought for retrieval. All 34 reports were successfully retrieved and assessed for eligibility. No reports were excluded at this stage due to lack of methodological rigor, irrelevance, or insufficient data. Consequently, 34 studies were included in the final review, forming the basis of the comparative analysis in this research.

Data extracted from each selected study included the type of material (sustainable or traditional), key findings such as performance metrics (e.g., tensile strength, compressive strength, and durability), environmental impact (e.g., carbon footprint, waste reduction), and economic considerations (e.g., cost savings, accessibility). Contextual information, such as the geographic location, climate conditions, and relevance to the Philippine setting, was also recorded. Additionally, life cycle assessments (LCA) were reviewed to analyze the environmental impact of materials from production to end-of-life, focusing on greenhouse gas emissions, resource depletion, and waste reduction. Cost-benefit analyses (CBA) were also examined to evaluate the economic feasibility of integrating sustainable materials, comparing initial costs, operational savings, and long-term benefits against traditional materials.

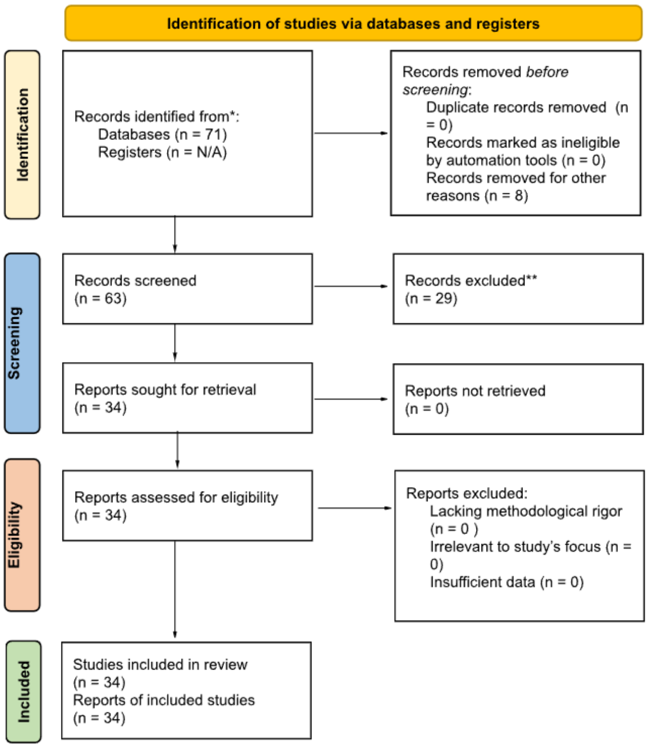

Fig. 1. PRISMA Flow Diagram of Study Selection Process

The collected data were synthesized using thematic analysis to identify trends, patterns, and key insights. Materials were grouped into categories—bamboo culm, natural fibers, sustainable aggregates, and traditional materials (steel reinforcement bars, synthetic fibers, fine aggregates) and compared. The analysis focused on evaluating their mechanical performance, environmental impact, and cost-effectiveness, providing a comprehensive basis for assessing the feasibility of integrating sustainable materials into Philippine civil engineering practices. Any recurring patterns or trends were discussed through thematic analysis, along with the interpretation of results. To address concerns regarding reporting bias, studies with incomplete or selectively reported results were marked, and their influence on the overall findings was assessed.

2.5 Data Analysis

The data analysis strategy for this study focused on synthesizing and analyzing the data obtained from the comparative analysis. This approach aimed to provide a comprehensive understanding of the comparative analysis of sustainable building materials versus traditional materials.

The analysis focused on three key areas: performance evaluation, environmental impact assessment, and economic feasibility, integrating insights from literature. Performance evaluation involved comparing material properties such as tensile strength, compressive strength, flexural capacity, and durability between sustainable materials like bamboo culm, natural fibers, and sustainable aggregates, and traditional materials such as deformed bars, synthetic fibers, and fine aggregates. These comparisons were benchmarked against industry standards, including ASTM specifications and the National Structural Code of the Philippines, to ensure accuracy and relevance.

The environmental impact assessment was based on life cycle assessment (LCA) data gathered from the reviewed literature. Metrics such as carbon emissions, energy consumption, resource depletion, and waste reduction were evaluated. The findings from the literature were synthesized to compare the environmental impacts of sustainable materials against traditional ones. The economic feasibility analysis relied on cost-benefit analysis (CBA) data from the reviewed literature, focusing on factors such as initial costs, long-term maintenance expenses, and potential cost savings.

The results from the systematic literature review were synthesized using thematic analysis to identify trends, patterns, and actionable insights. Materials were categorized into bamboo culm, natural fibers, sustainable aggregates, and traditional materials and evaluated across the dimensions of performance, environmental impact, and cost-effectiveness.

3. REVIEW OF RELATED LITERATURE

3.1 Sustainable Building Materials in the Philippines

In this portion, research on the types of sustainable concrete materials in the Philippine context is discussed. This includes benefits and various factors such as price, quality, accessibility, and durability.

3.1.1 Bamboo Culm

Bamboo Culm was selected due to it being the "fastest-growing and most versatile plant on Earth" [14, 15], as well as having high durability. According to Chaowana et al. [6], bamboo culm is a renewable and lightweight material with high tensile strength. It was also found that different culm sizes affected the load it could withstand, making it a viable alternative to wood, brick, concrete, and steel, although they were not directly compared in the study. This is reinforced by Kumar et al. [16], stating that the compressive, flexural, and tensile strength of bamboo is comparable to steel. It is also mentioned that it can be used for floorings, ceilings, walls, windows, roofs, trusses, and rafters in buildings. Not only that, but it can also be utilized as structural materials found in civil engineering projects, such as bridges, water transportation, and scaffolding.

The load-bearing capacity of bamboo culms was also assessed in the study, wherein different species of bamboo native to Thailand were examined by subjecting them to pressure using a universal testing machine. The study found that culm diameter and wall thickness affect the received ultimate load. A larger culm diameter with a thicker wall can receive more ultimate load. Despite the geographical difference, this study provides insights that can be applied to bamboo species in the Philippines. By comparing the structural properties and performance of Thai bamboo species to those found in the Philippines, parallels between the two can be drawn, thereby inferring potential applications. Due to both regions sharing the same climatic conditions, it allows for a practical comparison, allowing Chaowana et al.'s findings as a reference for evaluating the load-bearing capacity of Philippine bamboo.

The study concluded with recognizing bamboo as a sustainable building material, which can be used for both architectural and engineering applications. "Its lightweight and superior physical and mechanical properties have attracted the attention of civil engineers, architects, academics, designers, and artists.". Despite the excellent qualities of bamboo, its durability and resistance to weathering might be compromised because it decays unlike conventionally manufactured materials. This can be solved through treatment of the bamboo. According to Adier et al. [17], bamboo can be treated by natural methods such as drying, heating (boil, fired, oven), steaming, soaking, smoking, oil application, and impregnation of natural resin (e.g., rosin). The use of natural treatment for bamboo is environmentally friendly compared to chemical treatment, especially for the local communities who better understand the workings of bamboo.

3.1.2 Natural Fibers

Abacá is a great option for a natural fiber to be used to reinforce concrete. According to Tampi et al. [7] showcases benefits such as an increase in compressive strength, fracture energy, tensile strength, and load-bearing capacity, which are the structural integrity that has been analyzed. Additionally, abacá can also be used to mitigate cracking in cement due to its ability to reduce autogenous shrinkage of cement concrete products [18]. Tampi states that abacá fiber helps make the cement lightweight, as when more abacá fiber is added, the weight of the concrete becomes lighter than normal concrete. However, increasing the abacá fiber lessens the compatibility with concrete, as when more abacá fiber enters the mixture, the slump value increases, making the mixture difficult to mix. It is stated that abacá belongs to the Musacae family (Banana family). Abacás are also known as male bananas, which are abundant in the Philippines, making them a very accessible resource for Philippine construction use. While the bamboo data referenced in this study pertains to species grown in Thailand, this information remains relevant to the Philippine context due to the similar climatic conditions shared by both countries. Thailand and the Philippines are located in Southeast Asia and experience tropical climates characterized by high temperatures, significant rainfall, and distinct wet and dry seasons. These climatic similarities suggest that the mechanical and physical properties of bamboo grown in Thailand can reasonably be compared or extrapolated to bamboo species cultivated in the Philippines.

Banana fiber is another excellent natural fiber that can be utilized in the reinforcement of concrete. Attia et al. [10] state that banana fibers can be used to compensate for the inherent weaknesses of concrete because they provide advantages such as higher bending strength, enhanced post-crack load-bearing capability, increase in tensile and flexural strength, and cost-effectiveness. Banana fibers are also easily accessible because it is just agricultural waste from banana farming, making them a more beneficial and cost-effective option compared to artificial fibers [19]. Using banana fibers also reduces the amount of agricultural waste dumped and impairs air pollution if agricultural waste is burned [20]. Attia also mentions a loss in workability from banana fibers which can be avoided or reduced in a number of ways, which include pretreatment of fibers, prewetting of fibers, and adding of water-reducing plasticizer.

Bamboo is a promising natural fiber for concrete reinforcement, offering improved tensile strength, flexural capacity, and post-crack performance. It is a cost-effective, sustainable, and abundant resource, often derived from waste, which helps reduce environmental impact. Challenges such as reduced workability can be addressed through pretreatment. Additionally, its rapid growth and renewability make bamboo an eco-friendly and practical alternative for construction, especially in tropical regions [21, 22].

3.1.3 Sustainable Aggregates

Aggregates are raw materials made from natural sources like gravel, crushed stone, and sand. They are most commonly bound with water, cement, or asphalt to improve the compressive strength and durability of concrete and other compound materials [23, 24]. Aggregates are a fundamental part of the construction industry, and as such, the need for sustainable aggregate resource management is emphasized.

According to Olaiya et al. [25], sawdust can be used and recycled as an effective, sustainable material made into sturdy concrete blocks and bricks. The researchers used an experimental methodology, partially replacing fine aggregates with sawdust in incremental amounts. In the paper, it was found that sawdust can be converted into structural concrete by either replacing 5–17% of sand with sawdust or 5–15% of cement with sawdust. The structural concrete that was manufactured with sawdust included in the process displays compressive strength greater than concrete manufactured without sawdust by a potential of at least 3 MPa. The conversion of sawdust into concrete blocks and bricks may prevent sawdust from being inappropriately disposed of and from contributing to greenhouse gas emissions, atmospheric degradation, and harming aquatic and organic products. These natural fibers are composed mainly of lignin, cellulose, and hemicellulose, which are organic compounds that may degrade or decompose in the highly alkaline environment of concrete. This raises concerns about their long-term contribution to compressive strength unless treated or coated to improve durability and bonding with the cement matrix. In practice, natural fibers are usually used as supplementary reinforcement to control cracking and improve tensile and flexural properties rather than to significantly enhance compressive strength [12].

The use of sawdust to manufacture concrete includes benefits such as being lightweight and producing less harmful chemicals when in use; this, in turn, can improve the safety of construction workers when handling structural concrete. Furthermore, the sawdust composites present prominent sound absorption and efficient heat conductivity [26]. Naturally, the cost of sawdust will not be very high as it is just a waste product, making it very accessible, especially in the Philippines [27].

Recycled materials, like crushed waste glass and rice husk ash (RHA), can also be effective aggregates due to their potential to reduce landfill waste and lower the demand for natural resources like sand. According to Epure et al. [28], crushed glass can be utilized in concrete production due to its advantageous physicochemical properties, such as non-biodegradability, chemical resistance, and high hydraulic conductivity. This enhances the workability of concrete and reduces water absorption, making it an effective aggregate in various applications. Another study by Alsaed & Mufti [29] focused on using RCA as a cement replacement material in concrete. The researchers found that it improved compressive strength, durability, and reduced air permeability, while slightly decreasing workability with increased replacement. There is a potential presence of harmful salts, such as chlorides and sulfates, in waste-derived materials like sawdust, rice husk ash, and crushed glass, which can negatively affect the durability of reinforced concrete by promoting steel corrosion. However, studies have shown that properly processed rice husk ash contains minimal amounts of chlorides and can be safely used as a supplementary material in concrete without significantly increasing the risk of corrosion. The utilization of RHA has also led to reduced CO_2 emissions associated with concrete production as a result of it being an agricultural by-product [30]

3.2 Traditional Building Materials Used in the Philippines

In this section, research on commonly used materials in concrete, such as steel reinforcement bars, synthetic fibers, and fine aggregate,s is discussed, focusing on the benefits, limitations, and impact on the environment and construction industry.

3.2.1 Deformed Bars

Deformed Bars (also known as debar, reinforcing bars or rebar, or the Filipino term kabilya) are a fundamental component in concrete construction, widely used to compensate for the weak tensile strength of concrete [31, 32]. Debars are round steel bars with protrusions called deformations. Due to its compatibility with concrete, rebar has become a commonplace material in both residential and commercial construction projects.

The purpose of integrating debar within concrete is to improve its tensile strength and tensile strain capacities, thereby making the concrete reinforced and better equipped to withstand various loads and stresses [33]. The design of reinforced concrete (RC) ensures that the debar handles tensile stresses while the concrete manages compressive stresses. The effectiveness of RC is guaranteed by the joint work of steel and concrete called adherence [34]. This adherence is crucial to structural integrity. It allows for RC to perform effectively under a combination of forces. By providing tensile strength, debar enables concrete to be used in structural elements like beams, columns, and beam-column joints [35]. This makes RC structures one of the most widely used structural systems in civil construction.

As per the National Structural Code of the Philippines 2015, the standard specifications of deformed bars adhere to the ASTM Designation A615/A615M-12, established by the American Society of Testing and Materials

(ASTM). The specification covers deformed and plain carbon-steel bars in cut lengths and coils for concrete reinforcement. According to the specification, bars are of four minimum strength levels: 40 000 psi [280 MPa], 60 000 psi [420 MPa], 80 000 [550 MPa], and 100 000 psi [690 MPa], designated as Grade 40 [280], Grade 60 [420], Grade 80 [550], and Grade 100 [690], respectively. Deformed bars, while essential in construction, come with several limitations. One significant concern is the high cost of steel. This can significantly impact construction budgets, especially for large-scale projects requiring substantial quantities of debars. Additionally, steel corrosion is a significant issue, as corrosion can lead to severe durability and safety problems, such as concrete cracking and loss of bond strength. Moreover, as stated in previous studies, the production of concrete contributes significantly to carbon emissions and resource depletion.

3.2.2 Synthetic Fibers

Synthetic fibers are man-made fibers that can be used to reinforce concrete, creating concrete that displays multiple advantages. The most commonly used synthetic fibers are Macro-Synthetic Fibers due to their ability to increase the ductility of concrete and improve the post-cracking capacity. Erica states that the increase of ductility and improved post-cracking capacity in concrete is possible because macro-synthetic fibers have a length ranging from 30–65 mm long, making them a sole reinforcement in many concrete structures.

The macro-synthetic fibers can be reinforced in concrete, displaying advantages in the mechanical properties that include the enhancement of tensile strength, reduction of cracking, and improvement of the energy consumption capacity of the structure. Wagner mentions that the reduction of cracking in concrete is not only beneficial for the structure but also benefits the cost-effectiveness of the construction because of the reduction of damage and cracks. Additionally, it is stated that the reduction of cracks saves time and labor for the construction and also makes it easier and safer for the construction workers to remove potential hazards in the worksite.

The standard specifications for fiber-reinforced concrete conform to the ASTM Designation C1116/C1116M-10a [36]. The specification outlines the requirements for fiber-reinforced concrete, covering all forms delivered in a uniformly mixed condition, and classifies it based on the material type of fibers used.

Despite all the benefits that synthetic fibers provide in the construction industry, there are still limitations that come with it. The limitation that synthetic fibers present is the negative effect that it has on workability, strength, and durability. Guerini mentions that the air content in the synthetic fibers may hinder and decrease the effectiveness of the concrete's workability, strength, and durability [37, 38]. It was mentioned by Bayasi and Soroushian that the increase of fibers also increases the air content which may affect the workability of the concrete [40].

3.2.3 Fine Aggregate

Fine aggregates are natural materials mostly composed of crushed stone or sand, commonly used in construction projects [41]. Fine aggregates improve the workability of concrete and mortar, enabling easier mixing, handling, and application. These materials also contribute to the strength and durability of concrete by reducing space between larger particles, resulting in a denser structure [42]. Traditionally, locally sourced river sand has been the most common fine aggregate used in Philippine construction; however, the rising demand for sand in the Philippines has led to concerns over its environmental sustainability.

The ASTM Designation C33/C33M-13 serves as the standard specification for fine aggregates [37]. The specification defines the requirements for grading and quality of aggregate, the nominal maximum size of the aggregate, and other specific grading requirements.

Recent studies have looked into other sources of fine aggregates that could improve the sustainability and quality of concrete production. For instance, the aforementioned recycled materials, like crushed glass or rice husk ash (RHA), can be effective alternatives due to their potential to reduce landfill waste and lower the demand for natural resources like sand [43]. The use of these locally sourced materials can cut down on transportation costs and carbon emissions associated with material sourcing, not only improving the sustainability of construction projects but also benefiting local economies by creating demand for recycled materials [44].

4. RESULTS AND DISCUSSION

In this section of the paper, the collected data from the literature review is used to create a comparative analysis of the selected materials. This includes the comparison and evaluation of their characteristics with regard to their viability in Philippine civil engineering contexts. The characteristics include their structural performance; tensile strength, compressive strength, flexural strength, and durability, along with their economic and environmental impacts throughout their life cycle.

4.1 Bamboo Culm and Deformed Bars

Bamboo culms and deformed bars provide different structural advantages in construction. Bamboo culms are lightweight, renewable materials that exhibit high tensile and compressive strength. However, bamboo is susceptible to moisture absorption, biological degradation, and dimensional instability, which requires them to undergo treatments such as heat processing, resin impregnation, or fiber reinforcement to improve durability.

Deformed bars are designed to enhance tensile strength and ductility in RC. They adhere to ASTM specifications, ensuring high strength, durability, and reliability in structural applications. However, deformed bars face challenges such as susceptibility to corrosion, high costs, and environmental impact due to the carbon-intensive steel manufacturing process. In terms of cost effectiveness, bamboo fiber-reinforced concrete presents as a cost-effective alternative, especially for low-load structures. While treatment and processing add to initial costs, bamboo offers long-term savings through lower material, transport, and labor expenses. It is 15% to 40% cheaper than steel in common structural applications, with pavement dowel bars showing up to 89.84% savings [45]. Its abundance, sustainability, and potential for government incentives further enhance its economic viability in Philippine construction.

Bamboo is a sustainable and cost-effective material with notable tensile and compressive strength, but it requires treatment to improve durability and adhesion with concrete. In contrast, deformed bars provide a much more superior mechanical performance and long-term reliability, making them ideal for high-load structures, though they come with a higher cost and risk of corrosion over time. Bamboo's tensile strength ranges from 140 to 250 MPa [16], while deformed bars offer 420 to 725 MPa (ASTM, n.d.), ensuring better resistance to tensile stresses in reinforced concrete. Similarly, bamboo's compressive strength varies between 40 and 80 MPa [6], whereas reinforced concrete can withstand 20 to 100 MPa [31]. While bamboo is renewable and environmentally friendly, it is susceptible to moisture absorption and biological degradation, requiring treatments to enhance longevity. Meanwhile, deformed bars, although structurally robust, are prone to corrosion, which can compromise concrete integrity over time. Ultimately, the choice between bamboo and deformed bars depends on structural requirements, cost considerations, and sustainability goals.

The findings suggest that bamboo culms and deformed bars can be used strategically based on structural demands. A hybrid reinforcement approach—combining bamboo with steel reinforcement—could enhance sustainability without compromising performance. The selection between the two materials should be based on structural requirements, cost constraints, and long-term durability to achieve an optimized construction solution.

4.2 Natural Fibers and Synthetic Fibers

Natural fibers such as abacá, banana, and bamboo increase the concrete's structural integrity by amplifying the compressive strength, tensile strength, and load-bearing capacity. However, natural fibers have a tendency to reduce workability, which can be lessened through fiber pretreatment or the use of plasticizers. Additionally, natural fibers offer a cost-effective alternative as they are environmentally friendly and reduce pollution by repurposing agricultural waste. Natural fibers like abacá, banana, and bamboo—especially abacá, a key Philippine export—offer cost-effective reinforcement options in concrete. Abacá fiber typically costs around ₱50 per kilogram, while processed natural fibers range between ₱100–200/kg. In comparison, synthetic fibers cost significantly more, averaging ₱300–400/kg. Moreover, natural fibers leverage agricultural by-products, lowering disposal fees and environmental impact [10]. Despite the benefits of natural fibers, additional treatment will be required to enhance their compatibility and durability in concrete applications. Though additional treatments may slightly increase costs, their innate biodegradability and established local supply chains make natural fibers economically attractive. Synthetic fibers like macro-synthetic fibers enhance ductility, tensile strength, and crack resistance in concrete. Synthetic fibers follow the standards of ASTM and reduce long-term maintenance costs. However, the increased air content in synthetic fiber-infused concrete can negatively impact workability and durability. Moreover, the environmental footprint of synthetic fiber is also a concern as they are non-biodegradable.

Both natural and synthetic fibers have their advantages and disadvantages. Natural fibers offer a sustainable and cost-effective construction experience, especially in regions where they are abundant. Synthetic fibers are suitable for high-performance applications as they provide superior mechanical performance and durability. Combining both natural and synthetic fibers can be an optimal solution as a hybrid fiber system to balance sustainability and performance. The hybrid fiber system will be able to leverage the strengths of each type while mitigating their respective drawbacks. The choice will depend on what is best suited for the project, including cost considerations and sustainability goals.

4.3 Sustainable Aggregates and Fine Aggregates

Fine aggregates, such as natural river sand and crushed stone, are essential components in concrete production, contributing to its strength, density, and workability. These materials are widely used in the construction industry and adhere to established standards such as ASTM C33/C33M-13, which specify grading requirements and physical properties to ensure structural integrity. However, the increasing demand for river sand has raised concerns about resource depletion, environmental degradation, and costs. Additionally, too much sand mining disturbs ecosystems, leading to sustainability issues in construction material sourcing.

Sustainable alternatives, such as sawdust, crushed glass, and rice husk ash, offer a viable solution to these concerns. These materials derive from industrial and agricultural waste, making them environmentally friendly and cost-effective. Sawdust, for example, can partly replace fine aggregates, improving the concrete's compressive strength when used in controlled amounts. Crushed glass enhances workability while reducing water absorption, and rice husk ash serves as a supplementary cementing material, lowering carbon emissions. However, despite these benefits, sustainable aggregates require more refinement and standardization to ensure consistent quality and durability in large-scale construction applications.

Both traditional fine aggregates and sustainable alternatives offer distinct advantages and challenges. Fine aggregates are already well-established in the industry, providing high durability and workability. However, their environmental impact and cost concerns create the need for better alternatives. Sustainable materials, such as sawdust and crushed glass, have demonstrated promising results in improving compressive strength and reducing environmental waste. Sawdust infused concrete, for example, has shown an increase in compressive strength by at least 3 MPa when replacing 5-17% of sand. Crushed glass improves workability and durability, while rice husk ash contributes to carbon footprint reduction by replacing a portion of cement. While sustainable aggregates present a more eco-friendly and cheaper option, some materials may require additional treatment to optimize their performance and compatibility with concrete mixtures.

In terms of cost effectiveness, Sustainable aggregates such as sawdust, rice husk ash (RHA), and crushed glass substantially reduce material expenses compared to conventional river sand. Sawdust and RHA are often nearly free (₱0–50/kg) since they are agricultural by-products, while crushed glass is priced at around ₱150–250/kg. In contrast, river sand costs approximately ₱500–700 per cubic meter [39]. Besides financial savings, these alternatives support waste reduction and sustainable practices. However, meeting concrete quality standards may require modest processing, which minimally increases preparation costs.

The integration of sustainable alternatives in concrete production is an emerging field with promising research findings. Studies indicate that materials such as sawdust, crushed glass, and rice husk ash can enhance structural properties while addressing sustainability concerns. However, large-scale implementation is still limited, and further research is needed to develop industry-wide standards for these materials. Combining both traditional fine aggregates and sustainable alternatives may serve as an optimal solution, balancing performance, cost-efficiency, and environmental sustainability in construction.

5. CONCLUSIONS

There are ongoing trade-offs between the sustainability, structural performance, and cost of the discussed construction materials. Based on the findings of the study, some common themes can be found regarding the comparisons of sustainable and traditional materials. For structural performance, bamboo, natural fibers, and sustainable aggregates all offer promising mechanical properties, but each comes with challenges that should be addressed before they can be fully implemented in the industry, especially with large-scale applications. Given that conventional materials have the edge in terms of widespread adoption due to their being standard in the industry, they remain the most reliable choices in terms of structural performance. However, given their issues in regard to environmental and economic stability, the findings of this research point toward a hybrid approach in construction, integrating both traditional and sustainable materials to provide an effective balance between sustainability and structural integrity. The selection between these materials should also be suited to the project based on structural demands, cost constraints, and sustainability goals.

Future research on this topic should focus on improving the treatment and processing of sustainable materials to enhance their compatibility with concrete. This would include more advanced chemical treatments, modification techniques, and processing methods to ensure their long-term stability. There is also room for experimental testing to be done with regard to hybrid reinforcement systems to optimize their structural performance. The construction industry can help in the adoption of sustainable materials through investing in research, updating building standards, and conducting larger-scale pilot projects to assess their feasibility in real-world applications. There would also be benefits from strengthened collaborations within research institutions, construction firms, and the government to develop guidelines for the application of these materials in construction projects. By improving treatment methods and standardizing the use of these sustainable materials, the construction industry in the Philippines can more easily transition toward a better and more sustainable environment.

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