Integrating Recycled and Low-Carbon Materials in Residential Construction: A Multi-Criteria Approach to Enhancing Sustainability, Affordability, and Structural Performance

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Abstract: Growing environmental concerns have spurred interest in using recycled and low-carbon materials within residential construction. The study investigates the potential of materials such as, Hemp-crete, geo-polymer concrete, reclaimed wood, and Bamboo in enhancing building sustainability, cost efficiency and structural integrity. A Multi-Criteria decision approach (MCDA) was used to assess the feasibility of each selected material. The findings support the viability of these materials and emphasize their importance in promoting eco-conscious, environmentally sustainable built environment.

Keywords: *Recycled Materials, Low-Carbon Materials, Sustainable Residential Construction, Multi-Criteria Decision Analysis (MCDA), Affordability and Structural Performance.*

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I. INTRODUCTION

The Construction industry contributes to global environmental degradation, resulting in almost 39 percent of emissions (1). Residential construction affects natural resource use, energy consumption, and waste generation(2). The construction industry is experiencing rapid growth, but this expansion is frequently associated with environmental degradation, increased carbon emissions, and construction waste (3). Sustainable construction practices have become more recognized, with one focus on exploring the integration of recycled and low-carbon materials to mitigate these effects (4). Researchers have identified that low-carbon materials, such as Geopolymer concrete in the form of fly ash instead of Portland cement, have shown significantly reduced carbon emissions by 20% (5). Cross-laminated timber (CLT) which offers structural performance similar to concrete and steel, and bio-based insulation materials (Hempcrete and cellulose) offer considerable reductions in carbon emissions (6).

These recycled and low-carbon materials enhance energy efficiency, contributing to long-term environmental performance(7). Using recycled materials like steel, concrete aggregates, and glass enhances circular economy principles by reducing landfill waste and the need to use more resources to manufacture new products, thereby reducing material waste and enhancing sustainability.

Despite the promising nature of recycled and low-carbon materials, their adoption has been affected by factors related to cost, material performance, and market acceptance (8). Although there is existing literature on sustainable construction, it often generalizes green materials. This study evaluates specific materials like hempcrete, geo-polymer concrete, bamboo reclaimed wood, and recycled aggregates, analyzing actual impact based on environmental impact and performance data through exploration of the following areas:

- Identify common low-emission materials used in residential construction
- Identifying the obstacles to adopting these materials.
- Propose strategies to streamline the adoption recycled and low-emission materials, thereby enhancing sustainability, affordability, and structural performance.

This paper seeks to adopt an MCDA framework assessing sustainability, affordability, and structural performance of recycled and low-carbon materials, thereby providing a practical decision-making tool for the selection of construction materials. Through a combination of insights from stakeholder and qualitative performance data, the

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research provides an understanding of barriers to material adoption thereby forming a background for sustainable research in the built environment. The study emphasized climate resilience and waste reduction by emphasizing materials and resource efficiency, promoting the shift towards a circular economy.

II. LITERATURE REVIEW

The construction industry is among the most significance consumers of global energy and raw materials, contributing to environmental degradation (9). According to (Urge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015), Residential construction makes up about 20 percent of national energy consumption, mainly heating and cooling (10). Labaran, Mathur, and Farouq (2021) noted that cement and steel are responsible for almost 40% of carbon dioxide emissions. (11). Due to urbanization and an increase in population, which has been the driver of housing demands and resource consumption, there is a need to reduce reliance on this high-carbon material. Low-emission technologies are crucial to advancing sustainability (Omer, 2008). Recycled concrete aggregate helps divert waste from landfills and reduce the carbon footprint associated with new material. (12). Chen et al. (2023) conducted a comprehensive review on green construction strategies for achieving low-carbon urban development, incorporating recycled and low-carbon material in residential construction, which proffers a promising solution to sustainability challenges(13). Xing, Tam, Le, Hao, and Wang (2022) critically reviewed the life cycle environmental impacts of recycled aggregate concrete; they noted that recycled Concrete aggregates (RCAs), produced by crushing concrete offer environmental benefits through the reduction of landfill waste and lower carbon footprints (14)(15). Recycled steel used in reinforcements and framing has the same quality as virgin steel while using 60% less energy for production. (16). Also, reclaimed wood reduces deforestation activities, although its application is limited due to the risk of contamination (17).

Adopting these materials has been restricted due to technical challenges ,such as material quality and fire resistance. Water absorption in bio-based materials like hempcrete, remains a major concern for long-term reliability (18)(19). Additionally, there is limited market acceptance due to limited awareness among stakeholders (20). The regional availability of materials like bamboo and hemp hinders scalability (21).

The theoretical underpinnings of this adoption are circular economy (CE) theory, which emphasizes resource efficiency and recycling (22), and Life Cycle Assessment (LCA), involving overall evaluations of material in all phases of use (23). The Triple Bottom Line (TBL) the framework highlights importance of balancing environmental and economic benefits (24). Empirical studies also support the integration of recycled and low-carbon materials in construction. RCAs and recycled steel have proven to be cost-effective and structurally viable when appropriately properly (25). Low-carbon materials like geo-polymer and hempcrete reduce carbon pollution and improve energy performance (26).

Additionally, affordability is enhanced in recycled and low-carbon materials over a long-term period due to reduced energy use(27). The structural performance of recycled materials can match that of traditional materials when quality is prioritized(28). While previous studies have used MCDA tools to evaluate cost, performance and sustainability, this research integrates a multi-dimensional and economically focused decision-making framework by uniquely examining environmental and economic performance. Previous research has evaluated individual materials and centered on a sustainability approach .This study adopts a comprehensive mixed methods approach, including stakeholder input, empirical data, and a theoretical model to evaluate the factors affecting adoption.

III. METHODOLOGY

This research employed a mixed methods design, combining both qualitative and quantitative approaches to assess the feasibility and impact of incorporating recycled and low-emission materials. The research structure comprises of two phases: a qualitative phase using semi-structured interviews with stakeholders and a quantitative approach using a MCDA to evaluate material alternatives.

Firstly, data would be collected through structured interviews with carefully selected stakeholders in the built environment, including architects, engineers, construction managers, and developers. This would help gather insights into knowledge, adoption challenges, and probable benefits of adopting low-carbon and recycled material integration. Participants were selected for interviews based on their experience and expertise relevant to the topic of discussion. The individuals interviewed were selected based on their experience level and relevance to the discussion area. A total of 20 interviews are conducted. The major interview questions are:

- Level of knowledge and awareness of material among selected professionals.
- Barriers to adoption of material.
- Potential for material integration and alignment with current industry trends
- Policy structures and frameworks that influence the choice of sustainable and low-carbon materials.
- Perception of material performance, including safety, durability, and energy efficiency.

The second phase involves using an MCDA to evaluate identified recycled and low-carbon materials based on a standard criteria set, thereby making informed decisions by balancing environmental, economic, and technical factors in selecting construction materials. The materials selected for this study evaluation are

- Recycled Aggregates
- Reclaimed wood
- Geopolymer Concrete

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- Bamboo
- Hempcrete

Data for evaluating these selected materials are drawn from secondary sources, majorly peer-reviewed journals. The following steps were used for the MCDA evaluation:

- Step 1: Weighting Criteria based on level of importance based on stakeholder input and literature review using a Likert scale of 1-5
- Step 2: Material scoring using data derived from secondary sources; materials are scored on a scale of 1-10
- Step 3: Weighted score calculation by multiplying scores by their weighted criterion and adding a weighted score for each identified material.
- Step 4: Sensitivity Analysis to test the robustness of varying outcomes and observing changes in ranking

IV. RESULTS AND DISCUSSIONS

A. Structured Interview Discussion

Table 1 and Figure 1 shows a structured interview conducted with 20 professional stakeholders in the built environment, including architects (n = 5), Civil engineers (n = 6), construction/project managers (n = 4), and Developers (n = 5). The findings are discussed by organizing the analysis thematically based on research questions and participant roles.

Table 1 Analysis of Interviewed Individual

Role	No	Years of experience	Sustainability Focus
Architect	5	8 - 10 Years	Medium - High
Civil Engineer	6	12 - 15 Years	Medium - High
Construction / Project Manager	4	9 - 12 Years	Medium - High
Developer	5	6 - 9 Years	Medium - High

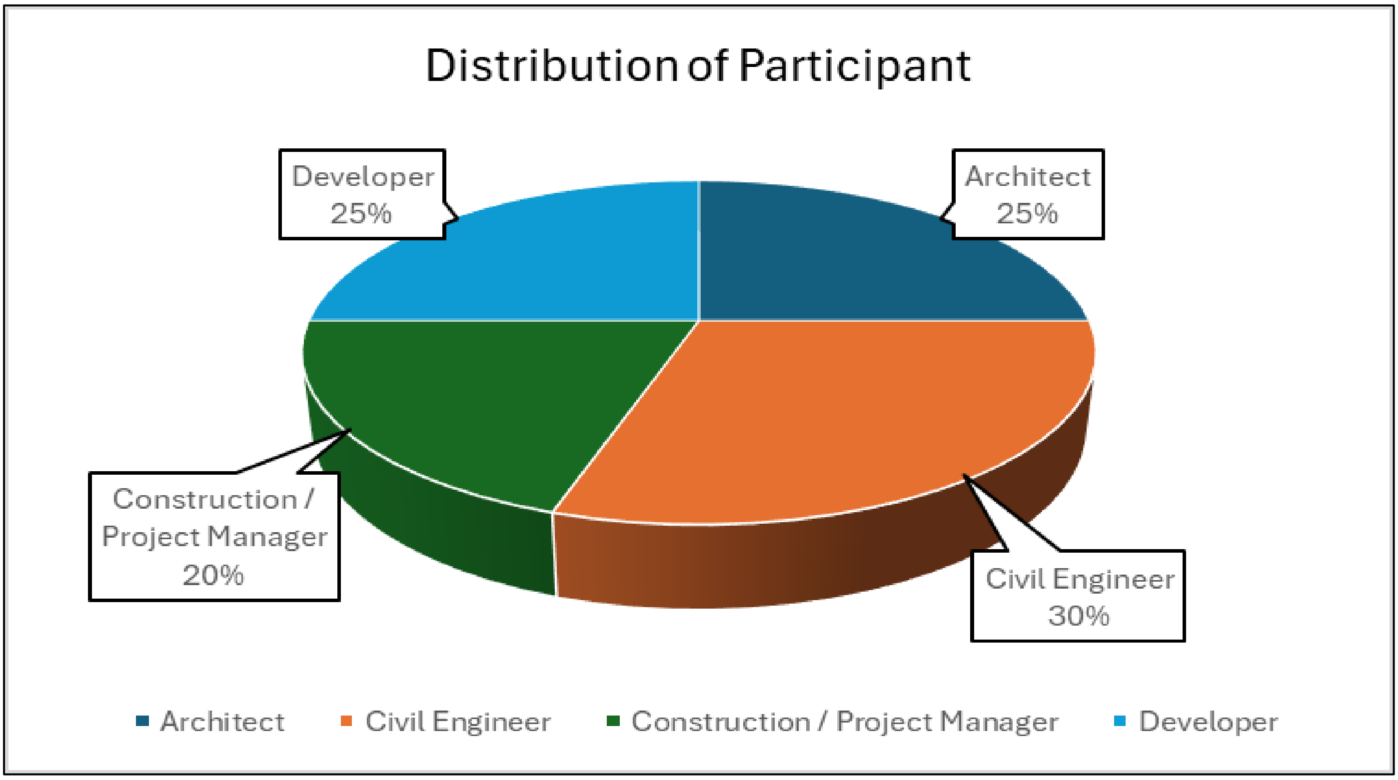

Fig 1 Distribution of Participants.

- *Level of Knowledge and Awareness of Recycled and Low-Carbon Materials.*

The study found, as represented in Figure 2 below, that there is a moderate to high Level of awareness of recycled and low-carbon materials. Architects and Civil engineers show the highest level of awareness for materials like RCA, reclaimed wood and low-carbon concrete (Polymer). Construction/ project managers and developers show more familiarity with economic and procurement factors and minimal familiarity with technical specifications.

The findings indicate that the knowledge of sustainable materials is significant among professionals. Although the level of awareness cannot be generalized to its application and use, developers and construction/project managers noted that it adoption is often influenced by cost, client preference, and supply chain limitations.

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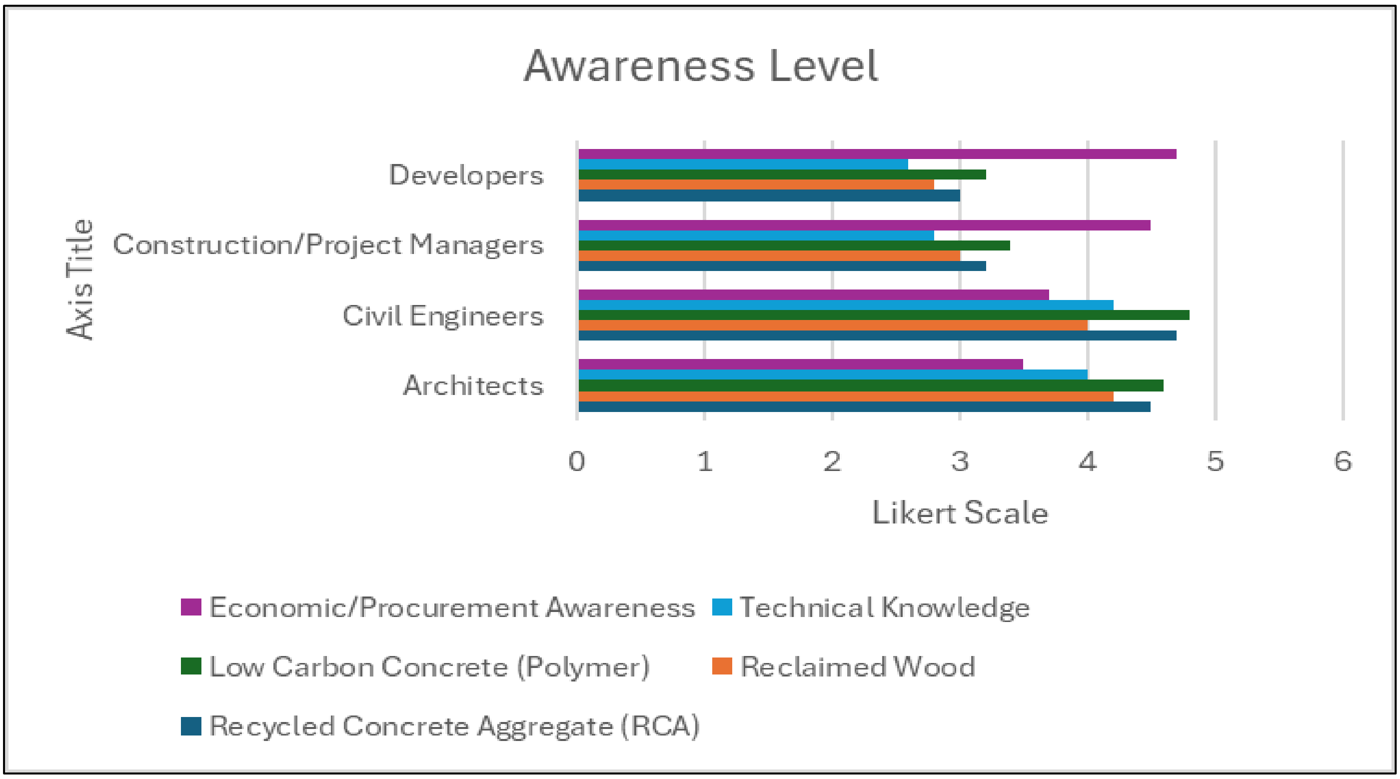

Fig 2 Level of Knowledge and Awareness of Materials

➢ *Barriers to Adoption of Recycled and Low-Carbon Materials*

According to professionals, engineers, and project managers, Table 4.2 shows that cost uncertainty and material availability are the highest-cited barriers. A lack of standardization and performance data influences adoption. Developers also noted regulatory issues and a lack of incentives affecting its adoption. This reinforced the notion that various barriers exist to adopting of recycled and low-carbon materials. Although environmental consciousness is established, factors such as cost and regulations affect the adoption of recycled and low-carbon materials.

Table 2 Perceived barriers to sustainable adoption

Barrier	**Frequency of mention (n=20)**	**Professional Roles**
Cost and Investment return concern	17/20	Developers, construction/project managers
Lack of Performance Data	15/20	Engineers, construction/project Managers
Regulatory Issues and lack of incentives	12/20	Developers and Architect
Limited supply chain	10/20	All professionals

➢ *Potential for Material Integration and Possible Alignment to Industry Trends.*

The interview revealed that a majority of the professionals (n = 17) support the trend toward sustainability, green environment and greater material adoption. Architects and civil engineers emphasized the increasing demands for sustainable buildings and developers showed positivism for integration when aligned with incentives and regulatory codes.

- *Policy Structures and Frameworks that Influence Sustainable and Low-Carbon Materials.*

Most participants (n = 15) interviewed noted that there is insufficient enforcement of existing green building codes. They collectively share the motive that incentives and subsidies would accelerate adoption. Participants noted positive initiatives like California’s Buy Clean Act, although inconsistency across states was mentioned as a disadvantage. Green construction legislation and policy lack cohesion and uniformity.

With evolving trends in sustainability, the policy is a great propeller of its adoption. Federal and state levels need to provide a clearer guidelines for approved materials and support for innovation in sustainable and green products.

- *Perception of Material Performance, Including Safety, Durability and Energy Efficiency.*

Architects and developers noted the importance of client perception and the aesthetically pleasing nature of structures, which can sometimes be biased against recycled materials. Civil engineers and construction/Project managers showed skepticism about long-term durability and structural integrity These findings corroborate with the need for performance benchmarks and a certification system to suit sustainable materials (29). Nonetheless, all stakeholders emphasized the possibility of some materials like cross-laminated timber and fly-ash being durable and meeting performance standard in some cases.

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➢ *Inter Connected Role Observation*

As a result, technical performance shows to be a concern which emphasize the need for education, real time demonstration, and data monitoring to enhance confidence and shift towards the acceptance of sustainable material use.

Table 3 Role-Based Summary of Key Findings

Profession	Major Findings/Concerns
Architects	Client Perception, Regulatory hurdles, and Design Integration
Civil Engineers	Structural performance, Code Compliance and, Safety
Construction/Project Managers	Supply Chain and, Cost control
Developers	Return on Investment, Marketability and, Incentives

Table 3 shows the various barriers and their peculiarity with different professions. It also denotes a common need for clearer regulation and economic viability. This emphasis on economic viability correlates with previous literature that cost perception is a major dominant factor in delaying sustainability inventions adoptions in construction(30). The findings of this study also indicate a favorable position for integrating these materials driven by a relatively high level of awareness and alignment with industry trends and sustainability objectives.

B. *Multi Criteria Decision Analysis (MCDA)*

The second phase of the research methodology used a MCDA to evaluate five identified low-carbon and recycled construction materials : recycled aggregates, reclaimed wood, geo-polymer concrete, bamboo, and hemp-crete. This evaluation was categorized into three major criteria which is environmental impact, economic viability and technical performance, these was categorized based on stakeholders interview and literature which reflects most noted concerns among practitioners in the construction showing a balance between sustainability, and structural reliability.

➢ *Rationale for Weighting*

The importance of each criterion was rated using a 5 point Likert scale ranging from 1 (least important) to 5 (most important). An average score was calculated to determine the weight of each criterion.

Table 4 Weighting Factor Criteria

Criteria	Average Likert Rating	Normalized Weight (%)
Environmental Impact	4.7	40
Economic Viability	3.4	28
Technical Performance	3.9	32

These findings indicates a strong stakeholders preference for materials with low environmental impact high sustainability focus and need for carbon elimination design. Technical performance and economic viability also followed with a 32% and 28% respectively emphasizing a balance need for ecological goals and functional project.

➢ *Material Evaluation Matrix*

The recycled and low-carbon materials (recycled aggregates, reclaimed wood, geo-polymer concrete, bamboo, and hemp-crete was evaluated and scored on a scale of 1 - 10 using secondary peer reviewed data sources, the scores was multiplied by criterion weights to achieve a weighted total score for comparison and ranking.

Table 5 Material Evaluation

Material	Environmental Impact (40%)	Economic Viability (28%)	Technical performance (32%)	Total Weighted score
Recycled Aggregates	7 x 0.40 = 2.80	8 x 0.28 = 2.24	7 x 0.32 = 2.24	7.28
Reclaimed Wood	8 x 0.40 = 3.20	7 x 0.28 = 1.96	6 x 0.32 = 1.92	7.08
Geopolymer Concrete	6 x 0.40 = 2.40	6 x 0.28 = 1.68	9 x 0.32 = 2.88	6.96
Bamboo	9 x 0.40 = 3.60	5 x 0.28 = 1.40	6 x 0.32 = 1.92	6.92
Hempcrete	10 x 0.40 = 4.00	4 x 0.28 = 1.12	5 x 0.32 = 1.60	6.72

It can be inferred from table 5 that Recycled Aggregates ranked highest with a score of 7.28 due to favourable environmental impact, economic viability and technical performance which makes them a scalable option for integrating sustainable material. Reclaimed wood with a total weighted score of 7.08 has a good score in environmental performance which proves its potential for reuse, as a result of its ability to maintain cultural and aesthetic value. Although it has a low technical score which can be a concern in terms of strength and potential to degradation.

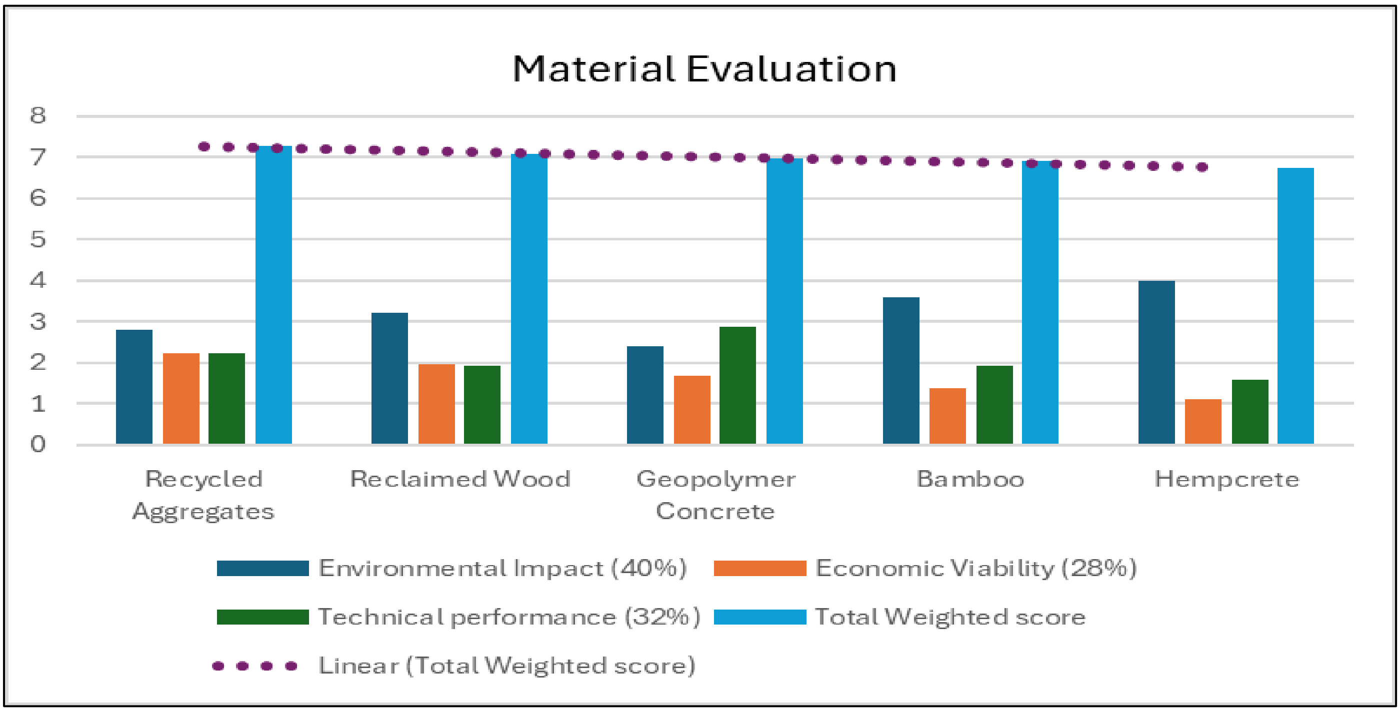

Fig 3 Material Evaluation Matrix

Geo-polymer concrete with a ranking of 6.96 led in technical performance as a result of its high tensile strength and thermal strength making it an alternative for low-carbon alternative for portland cement although market availability and high cost may hinder its adoption. Bamboo with ranking score of 6.92 as a result of its low-carbon excelled in environmental criteria although stakeholder show concerned about durability.

Hemp-crete with score of 6.72 has the highest environmental performance ranking because it anti carbon and biodegradable although it scored lower in economic and technical criteria which makes it unsuitable for structural loads, limited market penetration.

➢ *Sensitivity Analysis*

A sensitivity analysis was performed to evaluate the robustness of the MCDA results under various weighting scenarios, this analysis is important in decision making models, because it helps to identify final rankings are influenced by some factors. Figure 4 shows the weighted factors environmental impact, economic viability and technical performance were varied to simulate alternative decision contexts.

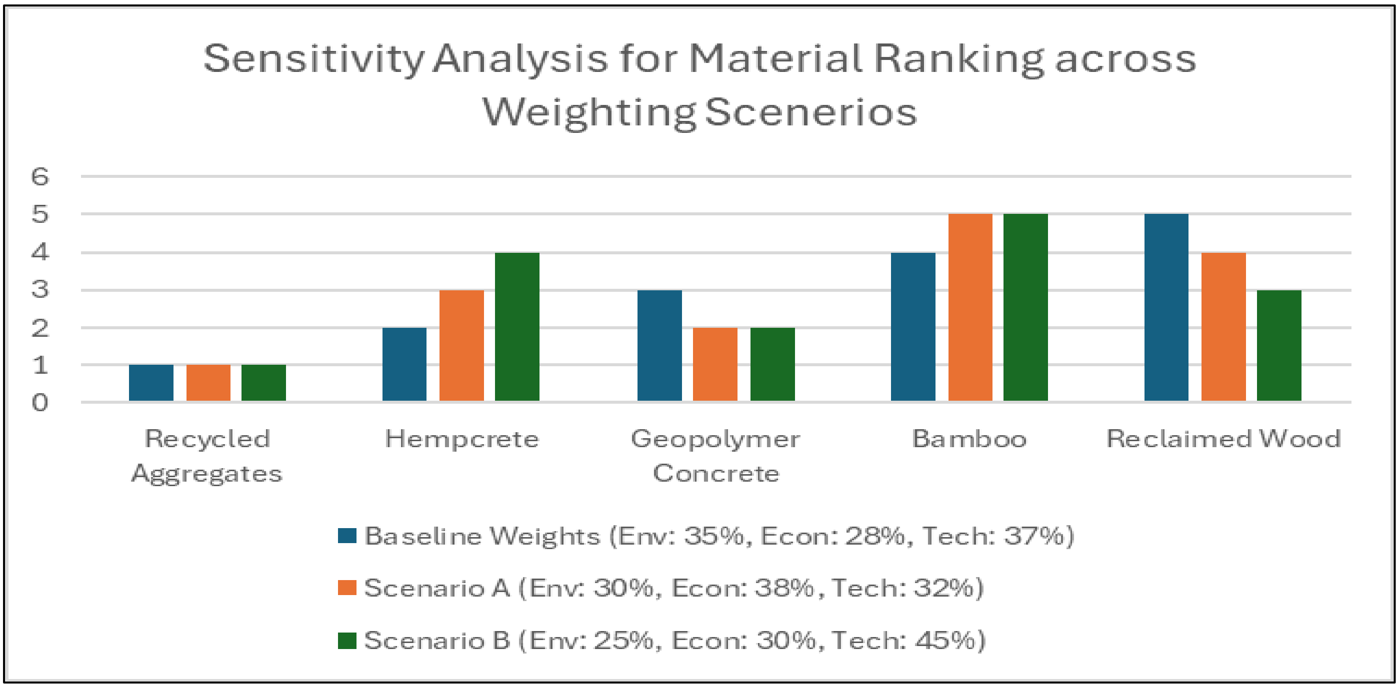

Fig 4 Sensitivity Analysis

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Economic viability was increased from 28% to 38% with environmental and technical performance adjusted to 30% and 32% respectively, recycled aggregates maintained its top ranking which shows resilience across multiple evaluation conditions. The consistency of the recycled aggregates out of all the three criteria these offer a balanced solution which shows alignment with sustainability goals and financial constraints. Technical performance was also prioritized it remained competitively ranked due to its proven durability, and compliance with regulations.

Hemp-crete with highest score on environmental performance shows volatility in their ranking when technical performance was emphasized it dropped in its ranking. Bamboo also ranked lower for economic factor as a result of concerns about cost and compliance code.

V. CONCLUSION

Based on the findings discussed above, a well detailed into current level of awareness, challenges and opportunities associated with adoption of recycled and low-carbon materials. The findings revealed an optimistic outlook towards integration of sustainable material, the level of awareness of sustainable materials was found to be moderate to high most importantly among architects and civil engineers based on better understanding they demonstrated for recycled concrete aggregates, reclaimed wood and low-carbon concrete. Although demonstration of this knowledge is quite distinct from real application. Construction/project managers and developers shows more economy drive acknowledging concerns over cost, challenges of procurement and client preference as a major factor affecting adoption of recycled and low-carbon materials.

Also the study revealed that cost uncertainty, lack of sufficient performance data, inconsistencies in regulations and supply chain limitations recognized by developers and architect are one of the major challenges of adoption of recycled and low-carbon materials this emphasize the need for cohesive and enforceable green building policies.

However all the professionals supported adoption of sustainable and low-carbon materials noting that incentives and well detailed and clear policy structures would establish a great support mechanisms and bridge the gap between strategy awareness and adoption of recycled and low-carbon materials. Misconceptions regarding material performance in terms of safety, durability and aesthetics can be addressed with establishing performance benchmarks and certifications for sustainable materials.

The interconnections between the professionals validates the idea that adoption is shaped by interconnected factors across disciplines emphasizing on need for regulatory clarity and economic viability. The study findings revealed a positive possibility of integrating recycled and low-carbon materials in construction provided the above discussed issues were addressed.

The study concludes that while the industry possess awareness and willingness for adopting sustainable and low-carbon materials in residential construction, addressing cost related uncertainties, enhancing material performance data, enhancing policy structure and improving supply chain process would influence a wider adoption as these issues requires to be addressed for smooth transition from awareness to scalable implementation of sustainable and low-carbon materials in residential construction.

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