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# ECO-FRIENDLY CONCRETE: MERGING FLY ASH AND HEMP FOR GREEN BUILDING PRACTICES

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**Abstract**

*The global construction industry significantly contributes to greenhouse gas emissions, highlighting the urgent need for innovative and environmentally beneficial building materials. This study presents Fly Ash Hemp Concrete (FAHC), a novel and eco-friendly alternative to traditional concrete. FAHC is an impressive combination of hemp shives, a widely available renewable natural fiber, fly ash, a useful byproduct of burning coal, and a lime-like binding substance. This cutting-edge composite material offers superior durability and thermal insulation while drastically reducing carbon emissions. Fly ash greatly enhances the workability and compressive strength of hempcrete. Additionally, it promotes carbonation, which effectively retains $CO_2$ within the structure for its entire lifespan. Studies indicate that the optimal amounts of fly ash yield remarkable mechanical properties, establishing FAHC as a strong choice for sustainable construction. This study advances FAHC as a revolutionary solution for environmentally conscious building practices by leveraging the synergistic properties of fly ash and hemp, aligning the building sector with essential sustainability goals and paving the way for a more sustainable future.*

## INTRODUCTION

In recent years, the world has been facing several environmental issues like global warming and climate change. The building and construction industry is responsible for 19% of greenhouse gas emissions and 32% of the world's energy [1]. As a result of this current situation, the use of environmentally friendly building materials is getting promoted [2]. Sustainable construction materials are being used due to their positive impact on the environment and human health [3].

The most appropriate and frequently utilized construction material is concrete. For every year, world production is around 1 m3 of concrete per head of population, and each ton of cement emits about 900 kg of $CO_2$ [4]. The carbon dioxide emissions generated during the manufacture of

Portland cement seem to indicate that concrete is not particularly environmentally friendly or in line with the principles of sustainable development [5].

Because they are renewable resources with superior insulation qualities, natural fibres (NF), including cotton, flax, bamboo, hemp, and more, have garnered a lot of research interest in response to cement's carbon dioxide emissions [6]. It is widely recognized that NF lowers prices, energy consumption, and carbon emissions [7].

Hemp fibre (HF) is considered to have one of the highest tensile strengths among the NF plants [8]. Among the different fibre crops that can be used to create bio-based products, industrial hemp is unique. It possesses excellent thermal, hygric, and soundproofing properties, quick growth, and resilience to different climates [9].

So, we make a sustainable building material out of hemp. Lime serves as a binder and hemp shavings as bio-aggregates to create hempcrete, a sustainable building material [10]. Hempcrete is a sustainable building material composed of lime as a binder and hemp shives as bio-aggregates. Hempcrete's strong thermal insulation and low thermal conductivity help to maintain consistent indoor temperatures. Because of this, it performs better than many other agro-residues, such as straw bales or rice husks, which sometimes require additional layers of insulation [11].

By carbonation—the process by which lime absorbs $CO_2$ from the atmosphere as it dries and solidifies—the lime binder in hempcrete also enhances carbon sequestration. Because hemp and lime binder work together, hempcrete effectively stores carbon dioxide, preventing it from escaping during the building's lifetime [12]. Nonetheless, hempcrete with a binder like lime aids in $CO_2$ absorption and offers exceptional durability and thermal insulation, although its compressive strength is less than that of regular concrete [13].

Fly ash is added to hempcrete to improve its qualities, especially its compressive strength [14]. Because of this, hempcrete is thought to be a useful and environmentally friendly building material. Incorporating fly ash into hempcrete formulas is a comprehensive strategy that enhances the material's durability and compressive strength while also encouraging greener construction methods [15].

In comparison to Portland cement, fly ash is more granular and will fit into even tighter spaces than cement particles, which are frequently filled with water. Because of this, concrete becomes stronger and less permeable [16]. Therefore, a sustainable construction material is created by substituting cement with natural fibers like fly ash and hemp fiber, referred to as "fly ash hempcrete " [17].

Fly Ash Hemp Concrete is a groundbreaking, environmentally friendly construction material that merges hemp shiv (hurds) and fly ash with an appropriate binder, such as lime, resulting in a lightweight, insulating, and long-lasting alternative to standard concrete [18]. Fly ash hempcrete is a potentially sustainable building material with exceptional thermal, acoustic, and ecological characteristics [19]. Therefore, it is now feasible to use it as a building material for a sustainable future. It is also an exceptional material with greater strength than conventional concrete and the ability to endure a range of temperatures.

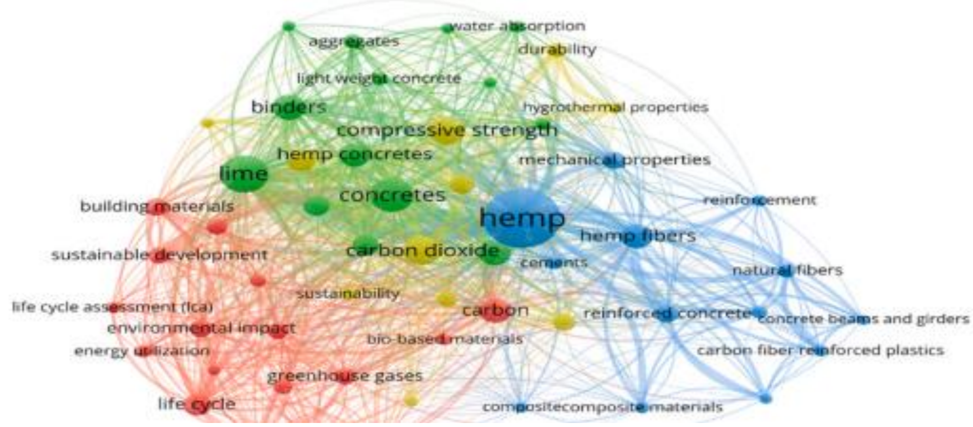


***Figure 1:*** *A bibliometric network illustrating keyword co-occurrence related to hemp-based concrete and similar materials.*

Despite the increasing interest in sustainable materials such as hempcrete, a significant limitation persists in its relatively low compressive strength, which restricts its use in structural applications. Previous studies have explored the thermal and ecological benefits of hemp-based composites, yet there remains a lack of comprehensive research on optimizing mechanical performance, particularly through the incorporation of industrial byproducts like fly ash. Most existing literature either focuses on the insulation properties of hempcrete or examines fly ash in isolation without fully exploring their synergistic potential. This study addresses this gap by investigating how the addition of fly ash can enhance the compressive strength of hempcrete while maintaining its sustainability benefits. By systematically evaluating Fly Ash Hemp Concrete (FAHC), this research aims to develop a more structurally competent, eco-friendly alternative to traditional concrete, thereby expanding the practical applications of bio-based building materials.

### 1.1. BACKGROUND

Considering that the construction sector accounts for over 19% of global greenhouse gas emissions, it is crucial that it adopts strong actions to reduce its carbon footprint. Conventional concrete emits a considerable quantity of $CO_2$, underscoring the urgent necessity for eco-friendly alternatives. Fly ash enhances the strength and sustainability of hempcrete, whereas hemp fibres and eco-friendly binders such as lime reduce dependence on cement. With new research confirming its efficacy as a major step towards a more sustainable built environment, Fly Ash Hemp Concrete (FAHC) is a potent option for ecologically aware building. In the context of sustainable construction innovation, stakeholder engagement and implementation frameworks are critical to adoption. As highlighted by Akram et al. (2023), effective delivery of infrastructure projects in Pakistan—especially under public-private partnerships (PPPs)—relies heavily on regulatory support, innovation incentives, and alignment with long-term sustainability goals. The integration of alternative building materials such as FAHC within PPP frameworks could help mitigate traditional construction risks while promoting environmental responsibility. However, as noted in their findings, challenges such as lack of awareness, institutional inertia, and limited technical capacity still hinder material innovation in large-scale PPP projects in Pakistan's construction sector [20].



## LITERATURE REVIEW

| Year | Author | Objective | Methods | Materials | Conclusion |
|---|---|---|---|---|---|
| 2020 | [21] | To examine the best percentage of fly ash to put in hemp concrete and the possible applications of hemp fibre.<br>To compression split tensile strength test of hempcrete with conventional concrete. | Casting, curing, and analysing | Hemp, Fiber Cement, Fly Ash, Fine Aggregate, Water. | It was found that the compression and split tensile strength increase for a 15 % replacement of cement with hemp.<br>Fly Ash-Hemp concrete paves the way to develop a sustainable concrete. |
| 2020 | [18] | To understand how the strength of modified mortars is affected by the addition of shives, hemp fibres, and processed fly ash. | Fiber characterization, Workability testing, Strength testing. | Fly ash, hemp fibers, and shives. | Shives and hemp fibres are used to help achieve an acceptable workability.<br>It is discovered that |

| | | | | | |
|---|---|---|---|---|---|
| | | To investigate the mechanisms of strength growth. | | | 3% hemp fibre is the ideal amount to use in the modified mortar. |
| 2022 | [7] | To evaluate how well composites reinforced with both kinds of fibres perform.<br>To recognise how important it is in establishing the composite material's ultimate characteristics. | Analyzing the fiber-matrix interface, Characterizing lignocellulosic fibers | Lignocellulosic fibers, Portland cement, and Synthetic fibers. | The fiber-cement matrix contact is essential to the composite's ultimate characteristics.<br>The advantage of natural fibre composites over synthetic fibre composites is their lower density. |
| 2023 | [12] | To assess Lime Hemp Concrete's (LHC) energy needs and CO2 emissions using unfired binders.<br>To compare it to standard LHC and traditional building materials, using Life Cycle Assessment (LCA) | EnergyPlus simulations for Operational Energy (OE) | Lime, hemp, sand, water | LHC with 100% unfired binders lowers CO2 emissions and overall energy use.<br>The overall energy requirements and $CO_2$ emissions along the life cycle of the building are significantly low. |
| 2024 | [14] | To determine the best component combination to achieve the maximum compressive strength.<br>To significantly increase the compressive strength of hempcrete. | Mixture Design, Specimen Preparation, Compressive Strength Testing. | Hemp hurds, Hydrated lime, magnesium oxide (MgO), Metakaolin, fly ash, and nanosilica. | The study's examined methods resulted in a significant increase in hempcrete's compressive strength (from 58 psi to 655 psi).<br>Sand, additives, and magnesium oxide (MgO) as a binder greatly increased compressive strength. |
| 2025 | [4] | To compare the GHG emissions associated | Input-Output Table Analysis, | Timber, concrete, and steel | The results demonstrate the |

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|---|---|---|---|---|---|
| | | with constructing timber.<br>To examine the advantages of using lumber for the environment, in addition to building costs. | Design Stage Evaluation. | | substantial environmental benefits of employing wood in check dam construction.<br>The study highlights how important it is to take GHG emissions into account. |
| 2025 | [16] | To lessen the reliance on cement production.<br>To explore how incorporating FA and WGB affects the fresh and hardened properties of FC. | Material Preparation, Characterization Techniques, Analysis and Optimization. | Waste gypsum plasterboard (WGP) and fly ash (FA), Ordinary Portland Cement (OPC) | The presence of FA positively modified the pore structure in the hardened WGP-FC products.<br>Mechanical properties tend to decline by over 10 % of WGB. |
| 2025 | [5] | To find out how the distances needed to transport raw ingredients impact the carbon footprint of concrete.<br>To examine how cement content and carbon emissions in the manufacturing of concrete are affected by supplemental cementitious materials (SCMs). | Carbon Emission, Calculation SCMs Analysis. | Fly ash, slag, silica fume, sand. | Aggregate transport distances have a big influence on concrete's carbon footprint.<br>Make the use of SCMs a priority to lower carbon emissions during the manufacture of concrete. |
| 2025 | [17] | To assess the effects of different weight fractions of fly ash filler and sabai grass fibre on hardness and tensile strength.<br>To look into the mechanical characteristics of laminate composites | Surface Modification and Characterization of Fiber. | *Sabai grass fiber, Fly Ash Filler.* | The toughness of the composites was greatly enhanced by the addition of fly ash.<br>Sabi grass is an inexpensive, environmentally beneficial substitute for synthetic |

| | | | | | |
|---|---|---|---|---|---|
| | | reinforced with fibres from sabai grass. | | | reinforcements. |
| 2025 | [2] | To analyse how these challenges affect green buildings' overall sustainability performance. | Creation of a conceptual framework to deal with operational challenges. | SPSS or R (e.g., SPSS, MATLAB) | Finally, green building is a means to achieve sustainable growth. |
| | | To investigate alternative remedies to overcome these obstacles. | | | Additionally, investigating the return on investment (ROI) and other financial impacts of green construction initiatives. |

The reviewed literature highlights growing interest in enhancing hempcrete through the integration of supplementary cementitious materials, particularly fly ash. Multiple studies confirm the environmental and thermal advantages of hempcrete; however, only a few address its mechanical limitations—especially low compressive strength. While researchers like Kana et al. (2020) and Hamzaoui et al. (2020) demonstrate improvements using hemp and fly ash, the outcomes vary significantly due to inconsistent material proportions, binder types, and curing practices. Moreover, most existing research isolates material behavior or emphasizes thermal performance, without holistically optimizing the mix design for structural applications. This indicates a clear gap in the literature: a lack of comprehensive experimental approaches aimed at enhancing both the strength and durability of hempcrete while maintaining its eco-friendly characteristics. To address this gap, the present study focuses on two key objectives: (1) to improve the strength and durability of hempcrete through the synergistic use of fly ash and lime, and (2) to make the resulting composite material more compatible with conventional concrete in terms of mechanical performance. By targeting these aims, the study contributes to the development of a more structurally viable and sustainable alternative for modern construction. In addition to environmental benefits, the adoption of sustainable materials like FAHC must be assessed for financial feasibility to ensure wider industry acceptance. Akram et al. (2024) emphasize that cost-benefit analysis and long-term returns are essential for integrating green technologies in the construction sector [22].

By increasing its strength and durability through pozzolanic reactions and densification, fly ash greatly enhances hempcrete. By replacing cement, it can also increase insulation, increase workability, and reduce environmental impact [23]. Hempcrete's strength, workability, and sustainability are all significantly improved by fly ash.

## 3. METHODOLOGY

The study's approach comprised a rigorous testing procedure, mixture preparation, and a careful selection of materials. Particular attention was paid to the characteristics and ratios of the ingredients used in the creation of FAHC, which comprised hemp hurds, fly ash, limestone powder, cement, and aggregates [24]. To attain the desired consistency, the ingredients are first mixed dry to guarantee even distribution, and then they are wetted with a regulated amount of water. Under carefully monitored circumstances, the resultant slurry was cured and dried after being poured into molds. A Universal Testing Machine (UTM) was then used to test the compressive strength of the hardened concrete samples to assess their mechanical performance.

## 3.1. MATERIALS

### 3.1.1 HEMP

Hemp is a yearly plant that grows rapidly (1.54 m in height) and is primarily cultivated for its natural fiber, which possesses a high tensile strength and develops in the stalk surrounding the woody center of the plant. A hemp plant is cut and then retted to separate the hurd from the bast, freeing the fibres [25]. The mechanical and structural composite properties are affected by the hemp origin, soil, climate, and retting method. Hemp shives have a lower density compared to conventional concrete aggregates, resulting in hempcrete having a significantly lower density than regular concrete [11]. Hemp is favored for composite materials too, due to its durability, stiffness, and lightweight properties.

*Figure 2: Hemp Hurd Powder*

*Table 1: Properties of Hemp*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Water absorption | 85% |
| 2 | Specific gravity | 1.5 |



### 3.1.2 FLY ASH

Fly ash is occasionally called pulverised fuel ash (PFA) or flue ash. It is a byproduct of the combustion of coal, particularly in power generation facilities that generate electricity. It is formed when tiny coal-burning particles combine in suspension and are released along with flue gases [26]. The combined material solidifies as it is pushed out of the combustion chamber, resulting in glass-like particles referred to as fly ash. Particle filtration systems are typically employed in modern coal-fired power plants to capture fly ash before it is released into the chimneys [27]. Fly ash is categorized into two types: Class C and Class F.[28]. The type of coal that is combusted and its source will influence the chemical makeup of fly ash. Fly ash usually contains calcium oxide (CaO), silicon dioxide ($SiO_2$), and aluminium oxide ($Al2O_3$) if the coal comes from coal-bearing geological layers [29].

*Figure 3: Fly Ash*

*Table 2: Properties of Fly Ash*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Water absorption | 8.7% |
| 2 | Specific gravity | 2.2 |

**3.1.3 LIMESTONE**

Limestone powder (LS) has been extensively utilized in cement-based materials, and it has been reported that it can affect their properties through filler, nucleation, dilution, and chemical effects [30]. Due to its exceptional qualities, lime has been utilized as a building material for an extended period and is still widely used. Due to its durability, versatility, and toughness, lime can support construction weights without deterioration [31]. Furthermore, it allows for ventilation, enabling moisture to escape and reducing the risk of mold and moisture accumulation.

*Figure 4: Limestone Powder*

*Table 3: Properties of Limestone*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Water absorption | 0.51% |
| 2 | Specific gravity | 3.4 |

**3.1.4. CEMENT**

Commonly used cement, Ordinary Portland Cement (OPC), is mostly made of gypsum, clinker, and other ingredients [32]. Due to its exceptional compressive strength, longevity, and versatility, it can be employed in a variety of construction scenarios [33]. In building, cement, a fine, grey powder, serves as a binder. It can bind together other elements like sand, gravel, and crushed stone to produce concrete and mortar when combined with water [34]. In short, it is the binding agent that keeps our roads, bridges, and buildings intact.

*Figure 5: Cement*

*Table 4: Properties of 53 Grade Cement*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Water absorption | 0.4 % |
| 2 | Specific gravity | 3.1 |
| 3 | Initial setting time | 55 mins |
| 4 | Final setting time | 10 hours |

### 3.1.5 AGGREGATE

An essential component of concrete, aggregate lowers shrinkage and has an impact on the economy [35]. The gradation of aggregates is one of the key elements that affects how workable concrete is [36]. We utilize two different sizes of course aggregate to properly fill the voids to avoid producing gaps in concrete blocks.

*Figure 6: Course Aggregate*

*Table 5: Properties of Course Aggregate*

| Sr | Properties | Values |
|---|---|---|
| 1 | Fineness modulus | 7.30 |
| 2 | Moisture absorption | 4% |
| 3 | Specific gravity | 2.4 |

*Table 6: Sieve analysis of coarse aggregate*

| Sieve size | Weight retained (kg) | Cumulative weight retained (kg) | Cumulative % retained | Cumulative % Passing |
|---|---|---|---|---|
| 19mm | 1.519 | 1.519 | 30.380 | 69.620 |
| 12.5mm | 2.143 | 3.662 | 73.240 | 26.760 |
| 9.3mm | 1.301 | 4.963 | 99.260 | 0.740 |
| 4.75mm | 0.037 | 5 | 100 | 0 |
| **Total** | **5** | | **729.64** | |

Fineness Modulus of coarse aggregate = 729.64/100 = 7.30

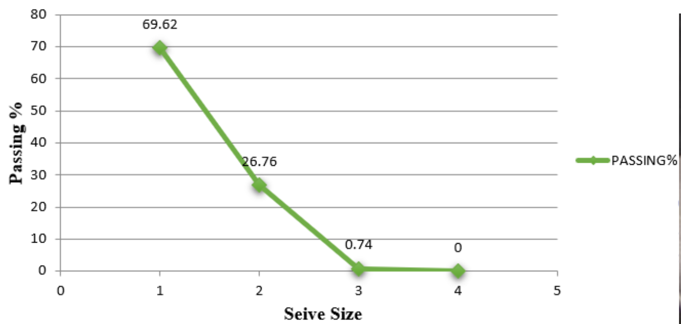



*Figure 7: Sieve Aggregate*

### 3.1.5. FINE AGGREGATE (SAND)

Sand is used as a filler in concrete to give the construction more strength and stability. The size, shape, and grading of the sand particles influence the strength of the concrete mix [29]. Sand that has been properly sorted enhances the interlocking of aggregate particles, resulting in a more compact concrete matrix [37]. By comprehending the significance of sand and taking into account elements like particle size distribution, workability, bonding, and environmental issues, construction professionals may produce concrete mixtures that satisfy the particular needs of each project [38].

*Figure 8: Sand*

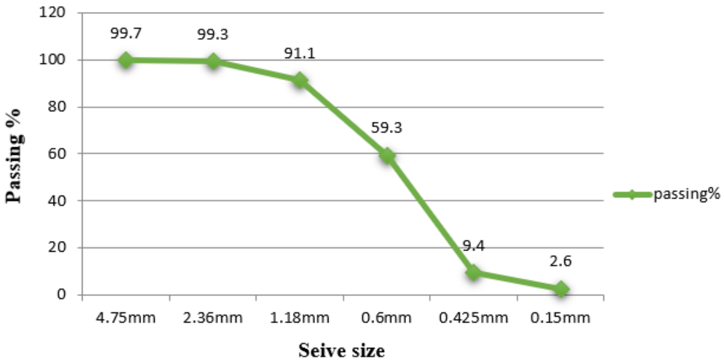
*Table 7: Properties of Sand*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Water absorption | 3% |
| 2 | Specific gravity | 2.5 |

*Table 8: Sieve analysis of fine aggregate*

| Sieve size | Weight retained (grams) | Cumulative weight retained (grams) | Cumulative % retained | Cumulative % Passing |
|---|---|---|---|---|
| 4.75mm | 3 | 0.3 | 0.3 | 99.7 |
| 2.36mm | 4 | 0.4 | 0.7 | 99.3 |
| 1.18mm | 82 | 8.2 | 8.9 | 91.1 |
| 0.6mm | 318 | 31.8 | 40.7 | 59.3 |
| 0.425mm | 499 | 49.9 | 90.6 | 9.4 |
| 0.15mm | 68 | 6.8 | 97.4 | 2.6 |
| **Total** | **1000** | | **238.6** | |

**Fineness Modulus of fine aggregate = 238.6/100 = 2.384**




### 3.1.6. WATER

The water utilized for the concrete mixture was guaranteed to be devoid of harmful chemicals and organic matter [39]. Water is the material used for mixing the above materials to make concrete.

*Table 9: Properties of Water*

| Sr. No. | Properties | Values |
|---|---|---|
| 1 | Specific gravity | 1.0 |
| 2 | Water to Cement ratio (1:2:4) | 0.40 |

### 3.2. METHODS

*3.2.1 Material Ratios:*

*Cement, sand, aggregate ( 1:2:4 ) Hemp hurds: 5%, Lime: 3%, Fly ash: 10%, Water: Adjust as necessary*

*3.2.2 Mixing, Casting, and Curing Process*

Combine all the dry ingredients to ensure even distribution. Mix for 3-5 minutes until the dry components are completely blended. Gradually add water while mixing. The mixture should achieve a consistency similar to concrete. Mix for an additional 5-10 minutes to ensure homogeneity. Moulds measuring 6 x 6 mm and 150 mm in diameter are used for casting. The moulds are filled with freshly mixed concrete, and the top finish is smoothed with a trowel. The cast is set for a full day and then allowed to cure naturally in the formwork for 24 to 48 hours before being taken out of the mould. The components are allowed to fully dry after curing to lower the moisture. This is done naturally in the open air.

***Figure 9: Mixing of Materials***

***Figure 10: Mould Used***

***Figure 11: Cubes in Curing Tank***

***Figure 12: Cubes Drying***

### 3.3 Testing & Performance Evaluation

#### 3.3.1 Setting Time Test for Cement

- **Vicat Apparatus**

**Test:** Measure the setting time of cement. It is utilized to assess the consistency of cement paste, which is essential for its workability. Too little water,

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and the cement is difficult to handle. Too much, and it might be weak. Cement setting time can also be measured using the Vicat instrument [40]. The cement paste takes this amount of time to solidify. In construction, this attribute is crucial.


*Figure 13: Vicat Apparatus*

**3.3.2 Compressive Strength Test**

- Universal Testing Machine **(UTM)** ISO 6259

The machine is used to evaluate the fly ash hempcrete samples' compressive strength. This test, which is carried out in compliance with ISO 6259 guidelines, attempts to determine the maximum load that the material can withstand before failing. The UTM determines the material's resistance to compression by applying a rising load to the samples, which is a crucial criterion for assessing the material's suitability for building applications. The load applied at the failure point is divided by the area of the sample to find the compressive strength.

**Compressive Strength = Applied Load / Area**

*Figure 14: Cube Being Tested for Compressive Strength*

## 4. RESULTS

- **Setting Time Test :**

The Vicat Apparatus is the instrument used to measure the cement setting time. This evaluation's goal is to determine how long cement takes to set. This test is used to determine the cement paste's consistency, which is essential for determining its workability. The importance of the cement paste's water content is emphasized in the paper; too little water might make the cement difficult to work with, while too much water can result in a fragile cement combination. Thus, the Vicat device is used to determine how long it will take for the cement paste to set, which is a crucial aspect of building.

| Sr. No. | PENETRATION (MM) | MINUTES |
|---|---|---|
| 1 | 4mm | 10 |
| 2 | 15mm | 20 |
| 3 | 34mm | 30 |

Weight of cement ( 400 grams)

| Sr. No. | Amount of water | Vicat apparatus reading |
|---|---|---|
| 1 | 5ml | 3mm |
| 2 | 65ml | 4mm |
| 3 | 7ml | 6mm |

**Compressive Strength Test:**

Fly ash hempcrete's compressive strength is assessed at various curing times using a Universal Testing Machine (UTM). The load at which the samples failed after 7, 14, and 28 days of curing is determined by a test. The results of the compressive strength test showed a steady increase in the material's strength over time. 9.4 MPa was the compressive strength after seven days; it increased gradually over the following fourteen days, reaching 20.8 MPa after twenty-eight days. It illustrates the progressive strength gain, durability, and adaptability of fly ash hemp concrete using lime as a binder.

***Table 10: Compressive Strength Results on Different Curing Days***

| Ratio of mixture | Days | Compressive strength in MPa |
|---|---|---|
| Hemp (5%), Fly ash (10%), Limestone (2%) | 7 | 9.8 |
| | 14 | 14.9 |
| | 28 | 21 |

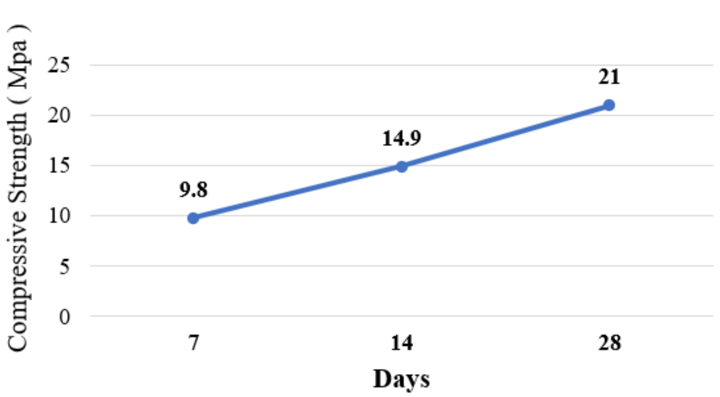


***Figure 15: Fly Ash Hempcrete's Compressive Strength at 7, 14, and 28 Days***

## 5. DISCUSSION

According to this study, a reasonable compromise between employing hemp and achieving a good compressive strength might be achieved by substituting 5% hemp for cement and adding 10% fly ash [20]. Our analysis of the compressive strength growth of fly ash hemp concrete revealed that it grew stronger over time. At 7 days, the material's compressive strength is 9.4 MPa; at 14 days, it increases by 6%; and at 28 days, it increases by 12%. These findings demonstrate that fly ash hemp concrete can become noticeably stronger in a relatively short period.

Including fly ash and hemp as essential ingredients in environmentally friendly building materials is one way to lessen the negative environmental effects of conventional construction methods [41]. This research emphasizes the combined benefits of incorporating fly ash and hempcrete into concrete mixtures, particularly in enhancing material properties and decreasing carbon emissions. The role of hempcrete in carbon capture is among the study's important findings. In addition to allowing hempcrete to gradually absorb $CO_2$, which helps mitigate the greenhouse gas effect, the carbonation process of lime in hempcrete also seems encouraging for decreasing the carbon footprint associated with conventional cement manufacturing[42] [43]. Since the production of cement contributes significantly to global $CO_2$ emissions, the use of materials like hempcrete marks a significant breakthrough towards sustainable construction techniques.

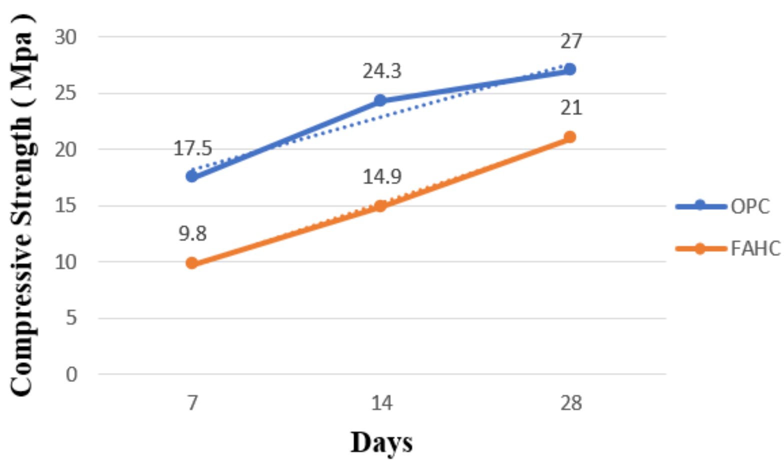


*Figure 16: Comparison Between the Compressive Strength of FAHC And OPC*

The compressive strength analysis between Fly Ash Hemp Concrete (FAHC) and Ordinary Portland Cement Concrete (OPC) shows clear patterns over various curing durations. After 7 days, OPC reveals a markedly higher compressive strength of 17. 5 MPa, in contrast to FAHC's 9.8 MPa [44]. This suggests that OPC acquires strength more quickly during the initial curing period. As the curing period extends to 14 days, OPC retains a greater strength (24.3 MPa), yet the gap narrows, with FAHC's strength rising to 14. 9 MPa, indicating a significant proportional increase [24]. By the time 28 days have elapsed, OPC's strength achieves 27 MPa, while FAHC's strength reaches 21 MPa, further decreasing the difference. Although OPC displays superior compressive strength, especially early on, the primary benefit of FAHC lies in its eco-friendliness [45]. FAHC utilizes fly ash, a residue from coal burning, alongside hemp, a sustainable resource, thereby lessening dependence on OPC, which is linked to considerable $CO_2$ emissions. The gradual strength gain of FAHC implies its capability for long-term durability, presenting it as an effective option for particular uses. Specifically, while OPC is typically preferred for structural functions that require high initial strength, FAHC can be appropriate for non-load-bearing uses where aspects like sustainability and thermal insulation are more critical [24].

The literature on the development of fly ash hemp concrete's compressive strength is, as far as we realise, somewhat restricted. Studies on hemp concrete (commonly referred to as "hempcrete") lacking fly ash have indicated that the type of binder and the mix design influence the compressive strength of the concrete [21]. Additionally, research on alkali-activated mortars that contain fly ash usually shows a progressive strength increase, which is in line with the pattern observed in our fly ash hemp concrete [46]. Researchers also agree on the ideal proportions of fly ash and hemp fibres, according to the literature review. To generate a more sustainable concrete substitute, Keren Kana et al. found that a 15% hemp substitution for cement produced positive results in both compressive and tensile strength. The optimal dose for modified mortars was also determined by Hamzaoui et al. to be 3% hemp fibre, which lends credence to the continuous research into the mechanical characteristics of hempcrete compositions [18].

The results we obtained, which indicate a 28-day compressive strength of 20.8 MPa, seem encouraging given that hempcrete is frequently valued for its insulating and thermal qualities rather than its high structural strength. Additional investigation contrasting our particular fly ash-based formulation with conventional hempcrete combinations may provide important information about how fly ash affects the mechanical qualities [47]. This enhancement is critical, as one of the major limitations of traditional hempcrete has been its comparatively lower compressive strength compared to conventional concrete. The ability of fly ash to fill voids and enhance the material's density not only contributes to structural integrity but also increases the overall durability of the composite, making it suitable for various applications in construction [48]. The achieved strength at 28 days suggests that this material could be suitable for non-load-bearing applications such as infill walls, insulation layers, and possibly some load-reducing structural elements in low-rise construction. The workability and overall performance of fly ash hempcrete emerge as standout attributes in this research. The synergy between hemp fibers and fly ash not only improves workability but is also essential for adapting construction methods to a variety of architectural designs [49]. This flexibility is becoming more and more important as the building sector looks for creative answers to changing design problems.

Notwithstanding the encouraging outcomes, it is crucial to take the study's limitations into account when assessing the results. The compressive strength of the concrete is measured using a particular fly ash hemp mix formulation. The impact of changing the ratios of fly ash, hemp fibers, and other ingredients on the final compressive strength requires more investigation [50]. Additionally, the gain in strength was only monitored for a total of 28 days. A more thorough grasp of this material's resilience and appropriateness for long-lasting building applications would be possible by evaluating its long-term strength performance [51]. It would have been advantageous for a more direct performance evaluation if the study had directly compared the performance of fly ash hemp concrete with that of conventional concrete or other sustainable building materials under the same conditions.

Future research should focus on improving fly ash hemp concrete's mixture design to increase its compressive strength while maintaining its advantageous thermal and insulating properties [41]. The application of AI tools can support data-driven decision-making in the planning and performance monitoring of sustainable materials like FAHC. As noted by Zia et al. (2024), AI enhances project management by optimising resource allocation, forecasting, and real-time risk mitigation, which can be particularly beneficial in scaling up eco-material implementation [52]. For practical applications, evaluating the strength and durability characteristics after 28 days is crucial [53]. Furthermore, a better grasp of the benefits and drawbacks of fly ash hemp concrete would be possible through comparative research with conventional concrete and other sustainable alternatives. It would also be beneficial to investigate how different fly ash sources, as well as variations in the length and composition of hemp fibres, affect compressive strength [54]. Lastly, evaluating this material's appropriateness in various climates requires examining how it performs in various environmental circumstances, such as freeze-thaw cycles and moisture fluctuations [55]. This study provides compelling evidence that fly ash hempcrete is a novel substitute for traditional concrete, offering a combination of practical, economical, and environmental benefits [56]. Future studies should focus on wide-ranging applications, precise material proportion optimisation, and thorough lifetime evaluations to establish fly ash hempcrete as a key component of sustainable construction in the years to come.

Given its improved compressive strength and sustainability profile, FAHC presents several promising practical applications. With a 28-day compressive strength of 21 MPa, it is well-suited for **non-load-bearing infill walls**, particularly in residential or low-rise buildings where thermal insulation and carbon reduction are priorities. Its enhanced durability and reduced density also make it viable for **light-duty pavements**, such as pedestrian walkways, garden paths, or paving blocks in low-traffic areas. While FAHC does not yet match the early strength or structural load-bearing capacity of traditional concrete, it holds potential for use in **hybrid foundation systems** or **insulated substructures**, especially where thermal performance and reduced environmental impact are desired. Further optimisation and field testing would help assess its long-term behaviour under dynamic loading and environmental stressors, particularly for broader use in structural or infrastructure-scale applications.

## 6. CONCLUSION

Fly Ash Hemp Concrete (FAHC) is an innovative building material that addresses environmental issues related to traditional concrete. The substance helps combat climate change by gradually absorbing $CO_2$. FAHC uses environmentally friendly, renewable materials to address the growing need for sustainable building approaches. It offers a practical solution that enhances building performance. Continued research and investment can strengthen FAHC's role in promoting sustainability in the construction industry. The substitution of fly ash reduces the amount of cement used. The development of sustainable concrete is made possible by fly ash-hemp concrete.

This study demonstrated that Fly Ash Hemp Concrete (FAHC), with 10% fly ash and 5% hemp, achieved a 28-day compressive strength of 21 MPa—more than double the strength of standard hempcrete, which typically ranges between 5–10 MPa. This reflects a 120% improvement, confirming the effectiveness of fly ash and lime in enhancing mechanical performance. Alongside its carbon sequestration and insulation benefits, FAHC offers a durable, eco-friendly alternative to conventional concrete for non-load-bearing and thermally sensitive applications.

## 7. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

The long-term durability of fly ash hempcrete requires more investigation, particularly into moisture, freeze-thaw cycles, and possible alkali-aggregate interactions [26]. A range of climate field tests and additional long-term testing are required. The consistency of hempcrete is impacted by fly ash variation. To ensure quality, future studies should look at different kinds of fly ash and offer consistent tests. Comparing fly ash hemp concrete to conventional concrete and other environmentally friendly substitutes to better grasp the benefits and drawbacks of this material. Investigating how the length and composition of hemp fibers, as well as the various kinds and sources of fly ash, affect compressive strength. To determine this material's applicability in various climates, researchers are examining how well it performs in various environmental settings, including freeze-thaw cycles and moisture fluctuations.

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