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Analytical Study of Conventional and Geopolymer Concrete with Partial Replacement of Fine Aggregates Using Hemp Hurds

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ABSTRACT
This study evaluates the potential of hemp hurds, an agricultural by-product, as a partial replacement for fine aggregates in concrete. Hemp hurds at replacement levels of 5%, 10%, and 15% by volume, and its effects on the mechanical and durability properties of concrete through both experimental and analytical approaches. Laboratory tests assessed compressive strength, tensile strength, workability, and durability, while finite element analysis using ANSYS simulated the mechanical performance under various loading conditions. Results indicated that incorporating hemp hurds improved workability due to its water absorption and retention characteristics. Compressive strength showed a moderate reduction, with more significant losses at higher replacement levels, while tensile strength was minimally affected at lower percentages. Durability testing revealed that hemp hurds enhances moisture retention, contributing positively to the mix's performance under environmental stresses. Analytical results from ANSYS simulations aligned closely with experimental data, validating the observed trends. Additionally, the use of hemp hurds promotes sustainability by reducing reliance on natural aggregates and utilizing agricultural waste. This study concludes that hemp hurds is a viable, eco-friendly alternative in concrete, particularly at lower replacement levels, offering a promising pathway toward sustainable construction practices.

Keywords: Mechanical Properties, Thermal conductivity, Specific heat, CO_2 absorption.

1. INTRODUCTION

Concrete is a versatile and widely used building material recognized for its durability and strength. Composed of cement (typically Portland cement), aggregates (like sand and gravel), and water, it undergoes hydration to harden. Its moldability makes it suitable for diverse construction projects, from pavements to skyscrapers. Concrete boasts high compressive strength, making it ideal for load-bearing structures, and its resistance to fire, weather, and chemicals enhances its longevity. However, the production of cement is energy-intensive and a significant source of CO_2 emissions, raising environmental concerns.

Geopolymer concrete offers a sustainable alternative to traditional concrete, aiming to mitigate the environmental impact of cement production. Instead of Portland cement, it utilizes aluminosilicate materials (such as fly ash, slag, or metakaolin) combined with an alkaline solution. This reaction forms a hardened binder with a three-dimensional polymer network, providing similar or superior mechanical properties to conventional concrete while reducing reliance on energy-intensive processes.

Hemp

Hemp hurds, or hemp shives, are the woody inner core of the hemp stalk, created as a by-product of removing outer bast fibers. Lightweight and highly porous, they are rich in cellulose and resistant to mold and pests. Hemp hurds are primarily used in hempcrete, a sustainable material mixed with lime-based binders and water, providing thermal insulation, moisture regulation, fire resistance, and CO_2 sequestration. They also serve as animal bedding, mulch, and compost, and can be processed into paper and biodegradable packaging. Hemp cultivation requires low water and pesticide use and absorbs significant CO_2, though regulatory barriers and limited processing infrastructure hinder wider adoption.

Figure 1 Hemp hurds

Figure 2 Hemp hurds Powder

Hemp-Based Concrete

Hemp fibers are explored as eco-friendly additives in conventional and geopolymer concrete to enhance sustainability. However, untreated hemp fibers face challenges such as high water absorption, leading to issues like mold growth and reduced bonding strength. To improve performance, sodium hydroxide (NaOH) treatment enhances the durability and moisture resistance of hemp hurds by reducing their hydrophilicity and increasing bonding with concrete matrices. Untreated and NaOH-Treated Hemp Hurds

Untreated Hemp Hurds: Maintain their natural hydrophilic nature, leading to moisture retention, mold growth, and weaker bonding. Best suited for non-structural applications like insulation blocks and lightweight walls.

NaOH-Treated Hemp Hurds: Exhibit reduced water absorption, improved resistance to mold, and better compatibility with alkaline environments. They are suitable for structural applications requiring durability and moisture resistance but involve higher costs and careful handling due to the caustic nature of NaOH.

2. LITERATURE REVIEW

This study investigates the thermal conductivity of concrete incorporating hemp and synthetic fibers using the Transient Line Source method. Concrete samples homogenized during mixing and cured for 7 and 28 days before testing. Results showed that hemp fiber significantly increased thermal conductivity, with a 46% rise after 7 days and 43% after 28 days, attributed to its good adhesion and impact on water absorption despite introducing air into the matrix. In contrast, synthetic fibers had minimal effect. These findings highlight hemp fiber as a sustainable option for enhancing thermal properties, making it suitable for thermo-active foundations and geothermal energy piles. This research underscores the potential of natural fibers to improve the energy efficiency of concrete in construction.[1]

This study evaluates the carbon footprint of hemp concrete (hempcrete) as a sustainable alternative to traditional construction materials, using a Life Cycle Analysis (LCA) methodology. The research combines literature review, on-site monitoring, and laboratory tests, including CO2 monitoring of normal and hemp concrete over a month. Findings reveal that hempcrete emits significantly less CO2 than conventional concrete, making it an eco-friendly option for green construction. Experimental results suggest that an M25 grade concrete mix can include a 5% replacement of fine aggregates with hemp hurds without compromising performance. This study highlights hempcrete's potential for reducing embodied carbon, offering architects, engineers, and policymakers a sustainable solution for a greener built environment.[2]

This paper evaluates the performance of geopolymer concrete incorporating hemp fibers as a natural aggregate, emphasizing its sustainability and green construction potential. The study examines the impact of preserving hemp fibers in a wet anaerobic state, which enhances the fibers' structural and mechanical properties by promoting cellulose nanofibril (CNC) growth. This method improves the plasticity, thixotropy, and rheology of hempcrete while reducing water requirements by up to thirtyfold compared to other formulations. This process eliminates the need for additional pre-treatments, further reducing production costs and resource consumption. Enhanced mechanical resistance and workability, combined with lower CO2 emissions during production, position hempcrete as a cost-effective and environmentally friendly alternative to conventional concrete, supporting the circular economy and sustainable construction practices.[4]

Cement production, a major contributor to global CO2 emissions, necessitates sustainable methods to reduce its environmental impact while supporting the growing concrete industry. This study explores CO2 sequestration in concrete, a process where CO2 is injected into fresh concrete, chemically reacting to form stable minerals like nanosized CaCO3 that fill voids and enhance material properties. Experimental results show that CO2-sequestered concrete achieves higher compressive strength and density compared to conventional concrete, with significant gains at 7, 14, and 28 days of curing. The process requires additional water due to consumption during the CO2 reaction, and injecting CO2 in an enclosed system ensures effective results by minimizing gas loss. The findings highlight that CO2 sequestration not only reduces environmental impact but also accelerates strength development, offering a practical and eco-friendly advancement for the concrete industry.[7]

3. METHODS AND METHEDOLOGY

3.1 Materials used

Cement: Ordinary Portland Cement of Grade 53 grade conforming to IS 12269-2013 was used in the preparation of the concrete test specimen which also includes fly ash. GGBBS, silica fume. The Specific gravity of Cement, fly ash, GGBS and Silica Fume are 3.07, 2.13 and 2.14 are chemical composition are used.

Aggregates: Coarse aggregate (size<20 mm) were used. The specific gravity and fineness modules were 2.67 and 6.68 respectively.

Fine aggregate: M sand passing through 4.75 mm sieve was used. The specific gravity and fineness modules were 2.3 and 3.8 respectively.

Hemp aggregate: Hemp passing through 4.75 mm sieve was used. The specific gravity and fineness modules were 1.06 and 4.16 respectively.

Alkali Activators: The most common alkali activators used are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

3.2.Mix proportion

The mix design for M30 grade concrete was conducted for both conventional and geopolymer high-density concrete. Conventional concrete followed IS 10262-2019, with cement as the binder and a fixed water-cement ratio of 0.45. Trial mixes included 5%, 10%, and 15% replacement of fine aggregate with hemp hurds, with adjustments to aggregate content based on density. Geopolymer concrete used fly ash (55%) and GGBS (45%) as binders, following the design method by Abhishek C. Ayachit et al. (2016). A constant water-geopolymer solids ratio of 0.45 and NaOH:Na_2SiO_3 ratio of 1:2.5 were used. Hemp hurds were incorporated at 5%, 10%, and 15% replacement levels, and mix proportions were calculated using the absolute volume method.

3.3 Methodology

This study investigates the mechanical and durability properties of conventional and geopolymer concrete with partial fine aggregate replacement using hemp hurds (5%, 10%, and 15%) in treated and untreated forms. Treated hemp hurds undergo pre-treatment with lime or sodium hydroxide to improve interfacial bonding, while untreated hurds are used as-is after sieving to <4mm. Compressive strength, split tensile strength, workability, and density are evaluated at 28 days of curing, along with durability tests such as water absorption and chemical resistance. The results analyse the impact of hemp hurd incorporation on concrete performance, identifying optimal replacement levels and treatment methods for sustainable construction applications.

3.3.1 Thermal Conductivity

Thermal conductivity quantifies a material's ability to conduct heat, critical in construction and engineering applications. The Hot Wire Method measures this property by heating a wire and observing heat transfer to the material.

Procedure (Thermocouple-based Hot Wire Method)

1. Prepare two dry mortar cubes with flat, room-temperature surfaces.
2. Create a 0.4 mm groove on one cube for the Nichrome wire and a perpendicular groove (2 mm apart) for the multimeter probe. Place the Nichrome wire and probe in their grooves.
3. Sandwich the setup with the second cube on top.
4. Connect the Nichrome wire to a DC power supply (5–8V).
5. Turn on the power and record current, voltage, and temperature until it rises by 2°C.

3.3.2 Specific Heat

Specific heat is the heat energy required to raise the temperature of a unit mass by 1°C, critical for thermal performance in concrete. In geopolymer concrete with hemp hurds, specific heat is affected by the binder composition, moisture content, and density, altering its thermal behavior compared to conventional concrete.

Procedure:

1. Insulate a bucket and lid; insert a thermocouple through a hole in the lid to measure water temperature.
2. Fill the bucket with 5 kg of water and record its initial temperature.
3. Place a wooden block at the bottom to prevent direct contact with the heated concrete cube.
4. Heat the concrete cube to 60–80°C in a furnace and measure its temperature with a laser temperature

gun.
5. Immerse the heated cube into the bucket, ensuring it rests on the wooden block, and seal the lid.
6. Record water temperature every 2 minutes until the temperature rise stabilizes.

3.3.3 CO_2 absorption

Thermogravimetric Analysis (TGA) is used to study CO_2 absorption by measuring mass changes under controlled conditions. The sample, typically in powder form, is placed in a TGA furnace and pre-treated with inert gas to remove moisture and impurities. CO_2 is introduced at a controlled flow rate and temperature, and the mass changes are recorded. The resulting thermogram provides data on the absorption capacity and rate, making TGA suitable for evaluating materials like geopolymers and carbonates in CO_2 capture applications. Desorption can also studied by switching back to an inert atmosphere.

4. RESULTS AND DISCUSSION

4.1 Mechanical Properties

4.1.1 Compressive Strength

Concrete samples, both treated and untreated, cured for 28 days. After curing, the samples dried at room temperature (27°C) and test for compressive strength using a compression testing machine. The experimental results, shown in Table 1 and Figure 3, compared with analytical results obtained through finite element analysis.

Figure 3 Experimental

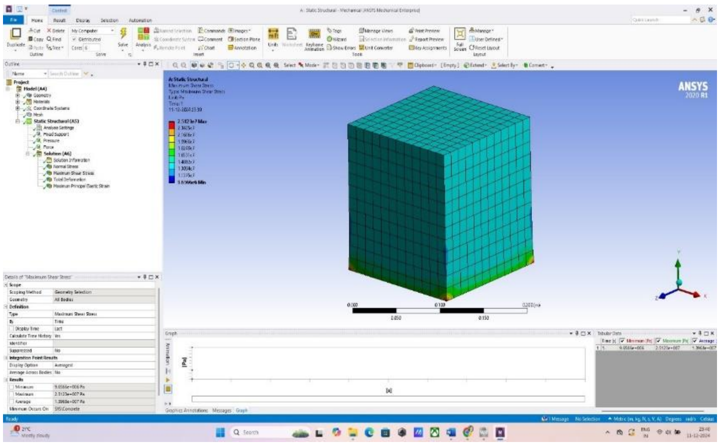

Figure 4 Analytical

Table 1 Compressive strength of Experimental and Analytical

Sl. No	Material	Experimental	Analytical
1	CC 0%	28.54	28.06
2	CCUH 5%	26.82	26.36
3	CCTH 5%	32.73	32.17
4	CCUH 10%	23.18	22.79
5	CCTH 10%	27.74	27.27
6	CCUH 15%	19.61	19.28
7	CCTH 15%	23.29	22.89
8	GC 0%	29.81	29.30
9	GCUH 5%	28.74	28.25
10	GCTH 5%	32.61	32.05
11	GCUH 10%	26.77	26.31
12	GCTH 10%	27.9	27.42
13	GCUH 15%	22.07	21.69
14	GCTH 15%	24.91	24.48

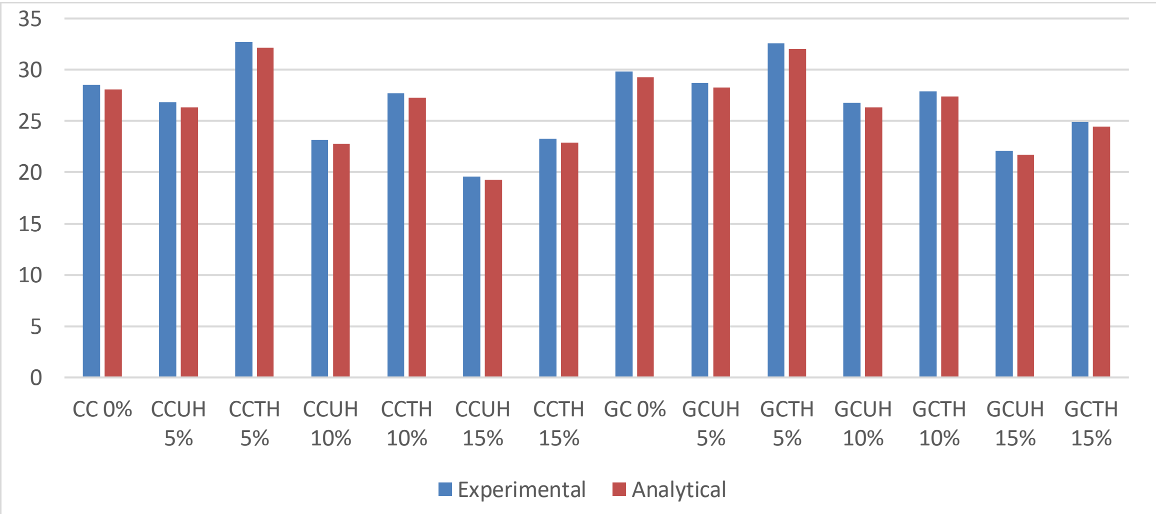

Figure 5 Compressive Strength

Treated hemp hurds consistently improved compressive strength compared to untreated samples, and analytical results closely matched experimental values, validating the reliability of the analytical model. The strength reduction in untreated mixes highlights the importance of pre-treatment in enhancing bond strength and performance.

4.1.2 Split Tensile strength

Concrete samples, both treated and untreated, were cured for 28 days. After curing, the samples were dried at room temperature (27°C) and tested for split tensile strength using a compression testing machine. The experimental results, shown in Table 2 and Figure 4, compared with analytical results obtained through finite element analysis, and validating the observed trends.

Figure 6 Experimental

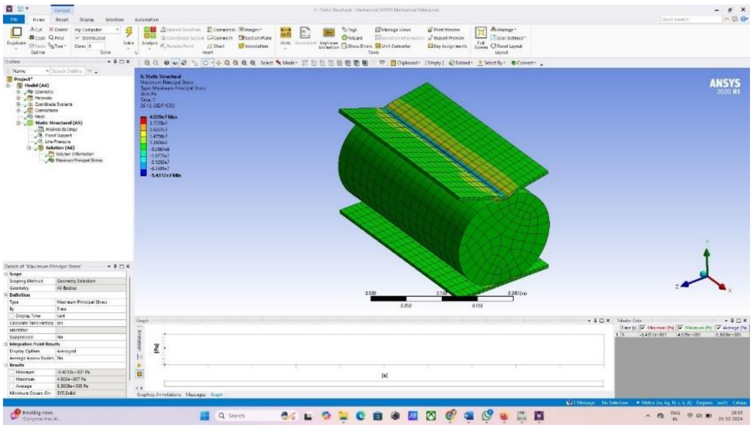

Figure 7 Analytical

Table 2 Split tensile strength of Experimental and Analytical

Sl No	Materials	Experimental	Analytical
1	CCUH 5%	5.03	5.76
2	CCUH 10%	4.76	5.24
3	CCUH 15%	4.69	5.17
4	GCUH 5%	5.16	5.63
5	GCUH 10%	4.88	5.36
6	GCUH 15%	4.60	4.43

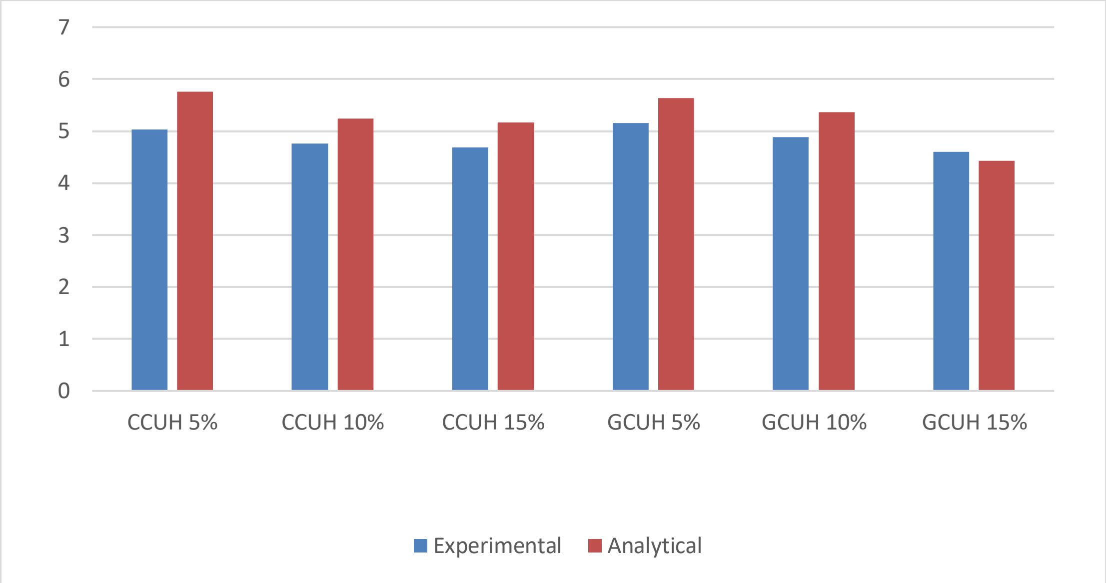

Figure 8 Split tensile strength

Experimental results generally align with analytical predictions, with minor variations across replacement levels. Geopolymer concrete (GCUH) exhibits slightly better alignment, particularly at higher replacement percentages. The observed discrepancies are within acceptable limits, validating the analytical model and emphasizing its accuracy for split tensile strength estimation.

4.1.3. Flexural Strength

Concrete samples, both treated and untreated, cured for 28 days. After curing, the samples dried at room temperature (27°C) and test for flexural strength using a universal testing machine. The experimental results, shown in Table 3 and Figure 5, compared with analytical results obtained through finite element analysis.

Figure 9 Experimental

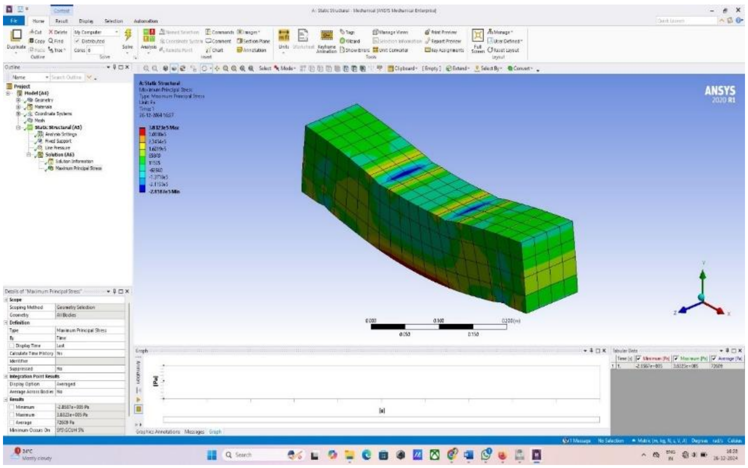

Figure 10 Analytical

Table 3 Flexural Strength of Experimental and Analytical

Sl No	Materials	Experimental	Analytical
1	CCUH 5%	5.03	5.76
2	CCUH 10%	4.76	5.24
3	CCUH 15%	4.69	5.17
4	GCUH 5%	5.16	5.63
5	GCUH 10%	4.88	5.36
6	GCUH 15%	4.60	4.43

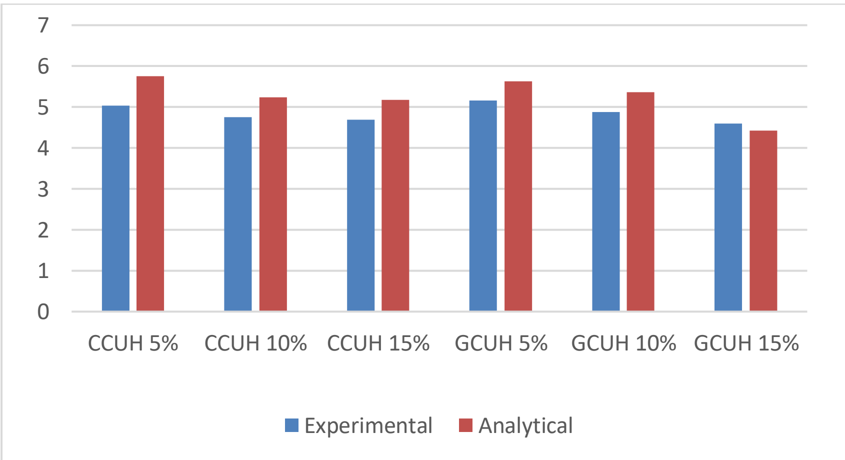

Figure 11 Flexural strength of Experimental and Analytical

The experimental results show a consistent trend of reduced split tensile strength with increasing hemp hurds replacement. In general, the experimental values are slightly lower than the analytical results for most cases, indicating a conservative estimate from the analytical model. However, at higher replacement percentages, the experimental value for geopolymer concrete (GCUH) at 15% replacement is slightly higher than the analytical prediction, suggesting that factors such as the interaction between geopolymer binder and hemp hurds may contribute to improved performance.

4.2 Thermal Conductivity

The prepared cube of Treated conventional and geopolymer concrete with hemp hurds and untreated conventional and geopolymer concrete with hemp hurds (0%, 5%, 10% and 15%). The test is conducted on this type of concrete blocks. The readings are below table 3.

Figure 5 Hot Wire Method

Table 3 Thermal Conductivity

Type of concrete	Different % of Hemp hurds	Heat flux (q)	Temperature (Ω)			Initial time t_1 (s)	Final time t_2 (s)	Thermal conductivity k (W/m·K)
			T_1	T_2	ΔT			
Untreated conventional concrete	0%	124	25	31	6	35	100	1.72
	5%	95	27	32	5	40	112	1.56
	10%	83	26	30	4	44	108	1.48
	15%	98	27	33	6	52	102	1.36
Untreated Geopolymer concrete	0%	92	25	31	6	38	104	1.23
	5%	87	24	32	8	38	108	0.90
	10%	72	27	34	7	43	112	0.78
	15%	69	29	35	6	58	121	0.67
Treated conventional concrete	0%	124	25	31	6	35	100	1.72
	5%	93	26	32	6	37	135	1.60
	10%	95	27	31	4	41	119	1.44
	15%	82	29	34	5	45	116	1.24
Treated Geopolymer concrete	0%	124	25	31	6	38	104	1.23
	5%	94	24	30	6	42	92	0.98
	10%	76	23	28	5	43	86	0.84
	15%	63	28	32	4	49	80	0.61

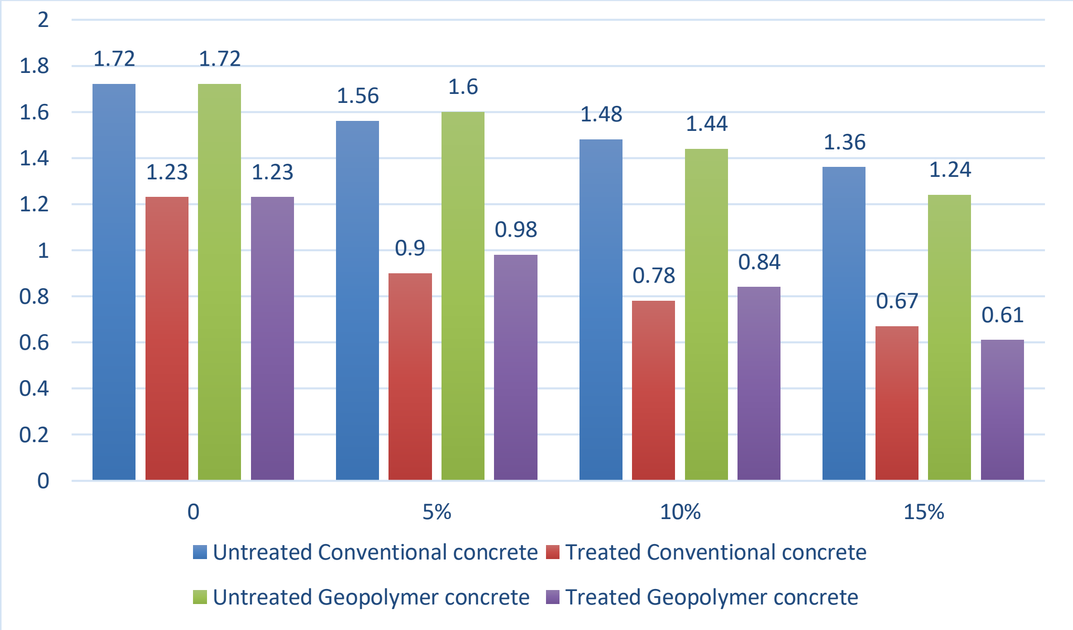

Figure 12 Thermal Conductivity

Geopolymer concrete with hemp hurds provides better thermal insulation than conventional concrete. Untreated hemp hurds yield the lowest thermal conductivity, especially in geopolymer mixes, making them ideal for maximum insulation. Treated hemp hurds improve bonding and durability but slightly increase thermal conductivity. Overall, geopolymer concrete with untreated hemp hurds is optimal for insulation, while treated hemp hurds offer a balance of insulation and strength.

4.3 CO_2 absorption

Thermogravimetric Analysis (TGA) reveals distinct CO_2 absorption trends for normal and geopolymer concretes with treated and untreated hemp hurds. Normal concrete absorbs more CO_2 due to calcium hydroxide carbonation, while increasing hemp hurds reduces this absorption by lowering calcium hydroxide content. Untreated hurds show higher weight loss from organic decomposition (200–400°C), whereas treated hurds improve carbonation resistance and compatibility. Geopolymer concrete, with minimal carbonation due to aluminosilicate reactions, shows increased organic decomposition with hemp hurds but no significant change in CO_2 absorption. Treated hurds enhance durability, reduce porosity, and improve structural performance in both concrete types. (Anon., n.d.)

Table 4 Mass loss in different Temperature

Material	Mass loss (250°C) (% Volatile Organics)	Mass loss (500°C) (% Organaic Decomposition)	Mass loss (750°C) (% Moisture)	Mass loss (%) at 1000°C =<
CC 0%	0	0.05	0.2	99.75
CCUH 5%	0.15	0.2	0.28	99.37
CCTH 5%	0.08	0.21	0.30	99.41
CCUH 10%	0.30	0.45	0.56	98.69
CCTH 10%	0.15	0.38	0.50	98.97
CCUH 15%	0.45	0.63	0.85	98.07

CCTH 15%	0.23	0.47	0.96	98.34
GC 0%	0.06	0.1	0.17	99.67
GCUH 5%	0.13	0.15	0.19	99.53
GCTH 5%	0.06	0.12	0.25	99.57
GCUH 10%	0.25	0.31	0.38	99.06
GCTH 10%	0.13	0.38	0.50	98.99
GCUH 15%	0.38	0.46	0.58	98.58
GCTH 15%	0.19	0.42	0.75	98.64

the mass loss observed in the 600–900°C range during TGA testing. This range typically corresponds to the decomposition of carbonates, such as calcium carbonate ($CaCO_3$), which releases CO_2.
The decomposition reaction of calcium carbonate is:
$CaCO_3 \rightarrow CaO + CO_2$

- Molar Mass of $CaCO_3$ = 100 g/mol
- Molar Mass of CO_2 = 44 g/mol

Mass of $CO_2 = \frac{44}{100} \times$ Mass of $CaCO_3$
For every 100 g of $CaCO_3$ decomposed, 44 g of CO_2 is released.
Mass Loss in the 600–900°C Range
From the TGA results:
mass loss percentage in the 600–900°C range for each sample.
Convert this percentage into actual mass loss based on the sample's initial weight.

$$\text{Mass Loss (g)} = \frac{\text{Mass Loss (\%)}}{100} \times \text{Sample Mass (g)}$$

Table 5 CO_2 absorption in hemp hurds used in conventional and geopolymer concrete

Material	Mass of $CaCO_3$ (g)	Mass of CO_2 released (g)	CO_2 absorbed (g)
CC 0%	20.7	9.1	0.48
CCUH 5%	44.7	19.7	10.9
CCTH 5%	43.7	19.2	10.4
CCUH 10%	87.5	38.5	29.6
CCTH 10%	71.3	31.4	22.5
CCUH 15%	114.6	50.4	41.3
CCTH 15%	103.6	45.6	36.5
GC 0%	25.1	11.0	6.9
GCUH 5%	32.8	14.4	10.23
GCTH 5%	31.2	13.7	9.53
GCUH 10%	60.3	26.5	22.2
GCTH 10%	68.2	30.0	25.7
GCUH 15%	79.1	34.8	30.4
GCTH 15%	83.0	36.5	32.1

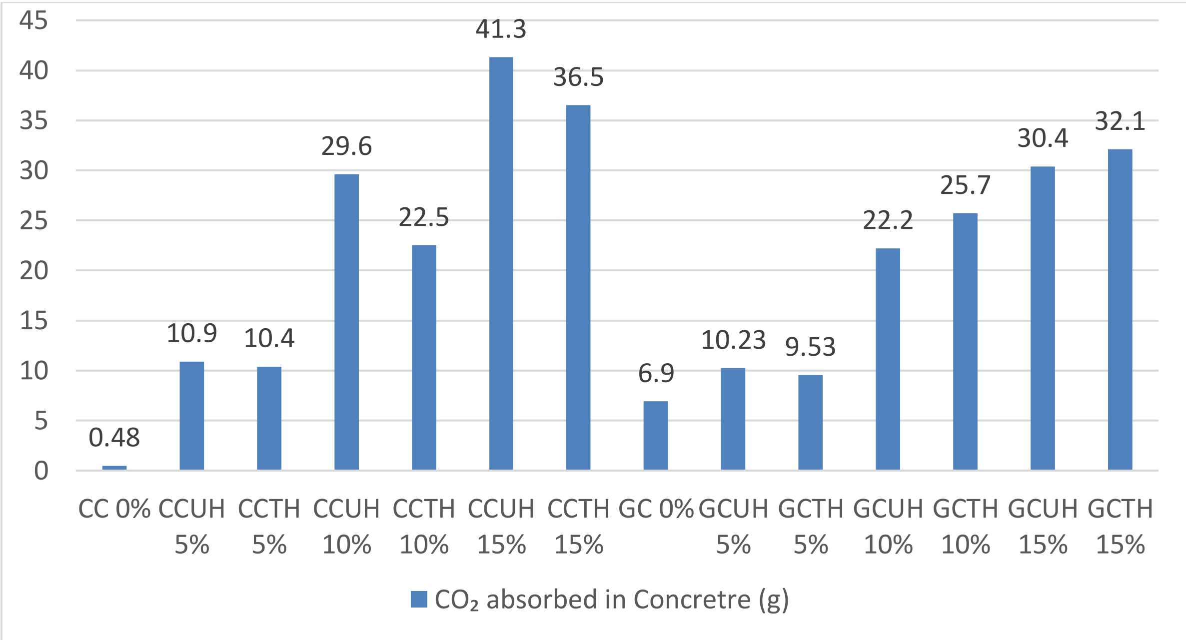

Figure 13 CO_2 absorption in hemp hurds used in conventional and geopolymer concrete

Using hemp hurds, particularly at higher replacement percentages, significantly enhances CO_2 absorption in both conventional and geopolymer concretes. Untreated hemp performs better in conventional concrete, while treated hemp shows better performance in geopolymer concrete at higher percentages. This suggests the potential of hemp hurds as a sustainable material for carbon sequestration in concrete production.

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