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A Comparative Study on Conventional and Geopolymer Concrete with Partial Replacement of Fine Aggregates using Hemp Hurds

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ABSTRACT

This study explores the viability of hemp heard as a partial replacement for fine aggregates in concrete. Hemp hurd, an agricultural by-product, was incorporated at replacement levels of 5%, 10%, and 15% by volume of fine aggregate. The influence of this substitution on concrete properties, including compressive strength, tensile strength, workability, and durability, was assessed through a series of laboratory tests. Results showed that incorporating hemp heard led to a moderate reduction in compressive strength, with greater reductions observed at higher replacement percentages. The workability improves due to the unique water absorption characteristics of hemp hurd, which can enhance moisture retention in the mix. Tensile strength was minimally affected at lower replacement levels, suggesting a balance between sustainability and performance. Additionally, the use of hemp hurd contributes to environmental benefits by reducing the demand for natural aggregates and promoting waste recycling. This study concludes that hemp hurd can serve as a viable, eco-friendly alternative in concrete, particularly at lower replacement percentages, offering promising potential for sustainable construction practices.

Keywords: Thermal conductivity, 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 were 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. Its lightweight nature reduces the overall structural weight, while incorporating hemp hurds (agro-waste) addresses waste management and land erosion. 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. The wet preservation also allows year-round usability, overcoming climate-related cultivation constraints. 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).

Table 1: Chemical Properties of Fly ash

SL. NO.	Chemical Composition	values
1	Silicon dioxide (SiO_2) plus aluminium oxide (Al2O:) plus iron oxide (Fe2O:), percent by mass, (Minimum)	86.56
2	Silicon dioxide (SiO2), percent by mass. (Minimum)	51.96
3	Magnesium oxide (MgO), percent by mass - (Maximum)	1.81
4	Total Sulphur as Sulphur trioxide (SO3), percent by mass, (Maximum)	0.16
5	Loss on ignition, percent by mass, (Maximum)	3.02
6	Available alkalis as sodium oxide (Na2O), percent by mass, (Maximum)	0.78
7	Total Chlorides in percent by mass, (Maximum)	0.004

Table 2:Chemical Properties of GGBS

SL. no	Characteristics in %	Test Result
1	Manganese Oxide (MnO)	0.12
2	Magnesium Oxide (MgO)	7.83
3	Sulphide Sulphur(S)	0.51
4	Sulphate (as SO3)	0.24
5	Insoluble Residue (I.R)	0.29
6	Chloride Content (Cl)	0.009
7	Glass Content	92
8	Loss on Ignition (L.O.I)	0.18
9	Moisture Content	0.01

10	$\frac{CaO + MgO + \frac{Al_2O_3}{3}}{SiO_2 + \frac{Al_2O_3}{3}}$	0.01
11	$\frac{CaO + MgO + Al_2O_3}{SiO_2}$	1.11

3.2 Mix proportion

Several trail mixes were conducted on the conventional high-density concrete; the mix design was carried out for M30 grade of concrete. Cementitious materials were cement, The procedure of the mix design is taken from the code book IS 10262-2019. Three trial mixes were made with use of Coarse aggregate and the partially replacement of fine aggregate using Hemp hurds (5%, 10% and 15%) hence the aggregates content changed with respect to their densities and water cement ratios was kept constant for all the three mixes i.e., 0.45. In the same way several trail mixes were conducted for Geo-polymer High-Density concrete, the mix design was carried out for M30 grade of concrete. Cementitious materials include fly ash (55%), GGBS (45%). The procedure of the mix design is taken from the (Abhishek C Ayachit et.al., 2016). Three trial mixes were made with use of Coarse aggregate and the partially replacement of fine aggregate using Hemp hurds (5%, 10% and 15%). The Water-geopolymer solids ratio were kept constant for all the three mixes i.e., 0.45, Ratio of NaOH to Na_2Sio_3 was 1:2.5. The mixes were proportioned by absolute volume method and mix proportions were calculated for all the mixes.

3.3 Methodology

This study investigates the comparative performance of conventional concrete and geopolymer concrete with partial replacement of fine aggregates using hemp hurds. Hemp hurds, sieved to a particle size of below 4mm, are incorporated as a partial substitute for fine aggregates in both treated and untreated forms. The treated hemp hurds are subjected to a pre-treatment process, such as soaking in a lime or sodium hydroxide solution to enhance their bonding properties, while untreated hemp hurds are used directly after sieving. Concrete mixes are prepared with varying replacement levels of hemp hurds (5%, 10%, and 15%), and the mechanical properties of both conventional and geopolymer concrete are analyzed. Compressive strength, split tensile strength, workability, and density are assessed at different curing ages (7, 14, and 28 days) to determine the impact of hemp hurd incorporation. Additionally, durability tests such as water absorption and resistance to chemical attacks are conducted. The results are compared to evaluate the effect of hemp hurd replacement on the overall performance of the concrete and to identify the optimal replacement level and treatment method. This study aims to explore the potential of using hemp hurds as an eco-friendly alternative material in concrete, contributing to sustainable construction practices.

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 (e.g., Nichrome) 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.
3. Place the Nichrome wire and probe in their grooves.

4. Sandwich the setup with the second cube on top.
5. Connect the Nichrome wire to a DC power supply (5–8V).
6. Turn on the power and record current, voltage, and temperature until it rises by 2°C.

3.3.2 CO_2 absorption

Thermogravimetric Analysis (TGA) is a precise method to study CO_2 absorption in materials by continuously measuring mass changes under controlled conditions. The procedure involves preparing the sample, typically as a fine powder, and placing it in a TGA furnace. After pre-treating the sample with inert gas (e.g., nitrogen) to remove moisture and impurities, CO_2 is introduced at a controlled flow rate and temperature. The TGA records mass changes as the sample absorbs CO_2, providing data on absorption capacity and rate. Optionally, desorption can be studied by reverting to an inert atmosphere. The resulting thermogram quantifies CO_2 absorption, making TGA ideal for evaluating materials like geopolymers and carbonates for CO_2 capture applications.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

A total cubes for each were casted for treated and untreated of conventional and Geopolymer concrete. The samples were demoulded after 24 hours of pouring. Conventional concrete was kept for water curing and geopolymer concrete were kept for water curing for 7 days and 28 days. After 7 and 28 days the samples were taken out form the curing tank and kept for drying at room temperature(27^{0}C) and strength was conducted in compression testing machine. The results obtained are shown in figure 3 and figure 4.

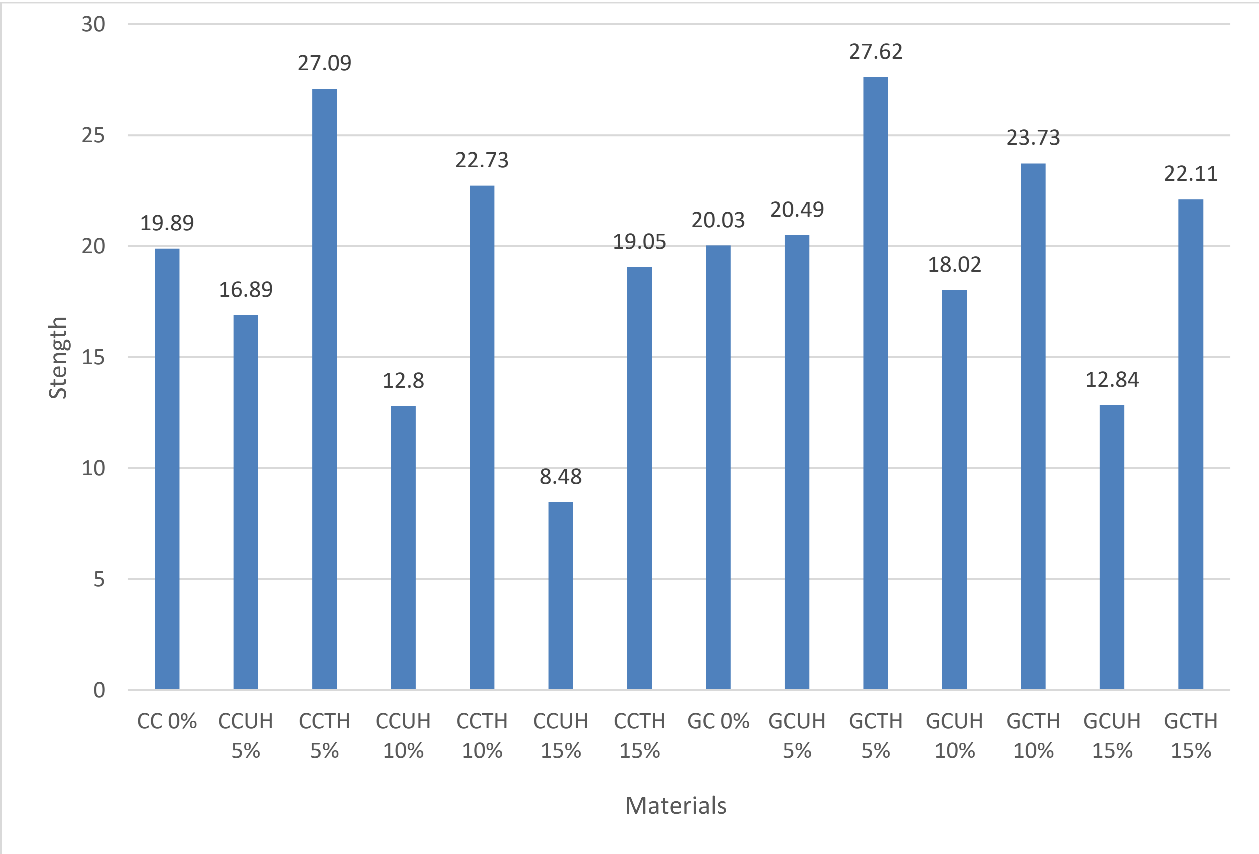

Figure 3 Compressive strength of Conventional and Geopolymer concrete after 7 days of curing.

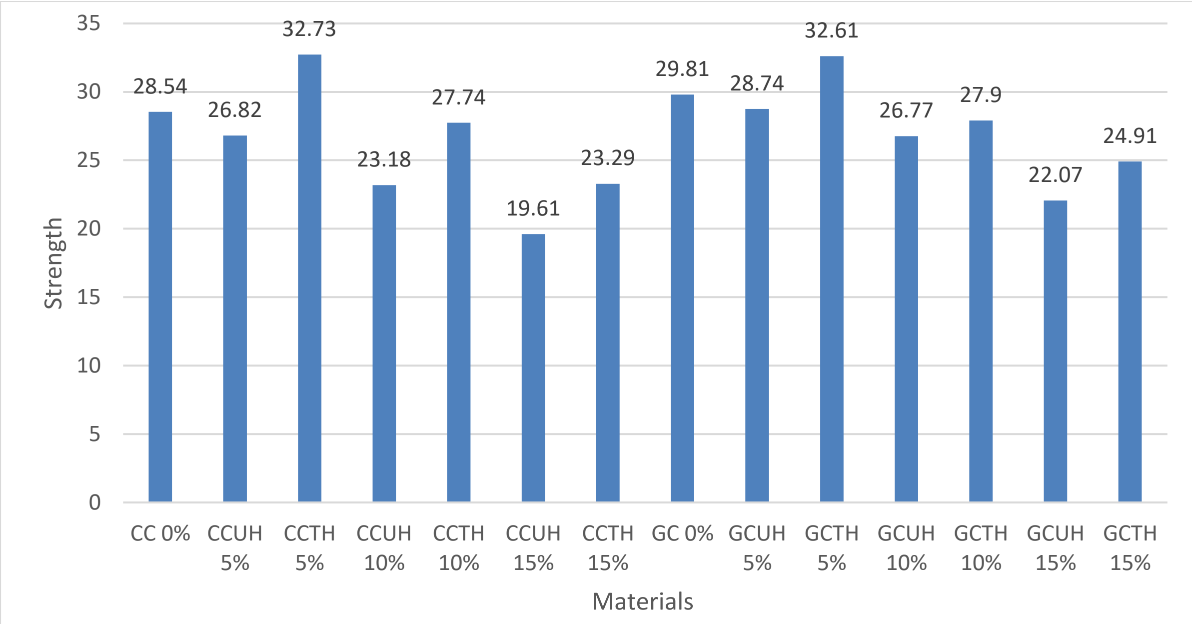

Figure 4 Compressive strength of conventional and Geopolymer concrete after 28 days of curing.

Treated hemp hurds significantly enhance the compressive strength of both conventional and geopolymer concrete at 7 and 28 days, especially at 5% replacement. Geopolymer concrete consistently outperforms conventional concrete, demonstrating better strength retention and suitability for sustainable applications. Untreated hemp hurds result in lower strength, emphasizing the importance of treatment. Future studies should focus on durability and optimizing mix designs.

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 conducted on this type of concrete blocks. The readings are below table 3.

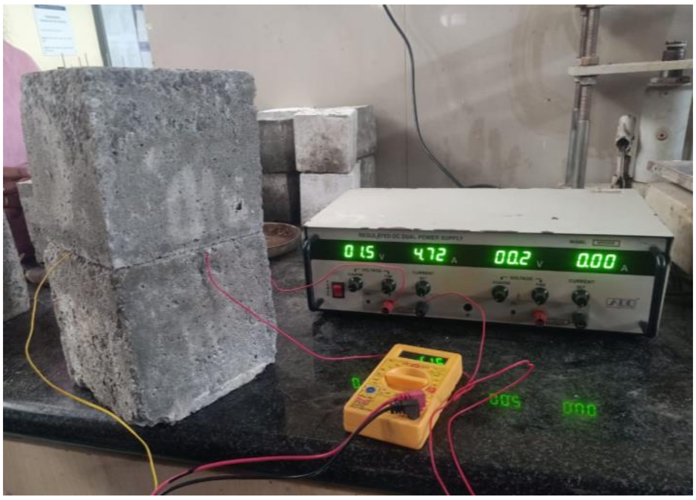

Figure 5 Hot Wire Method

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

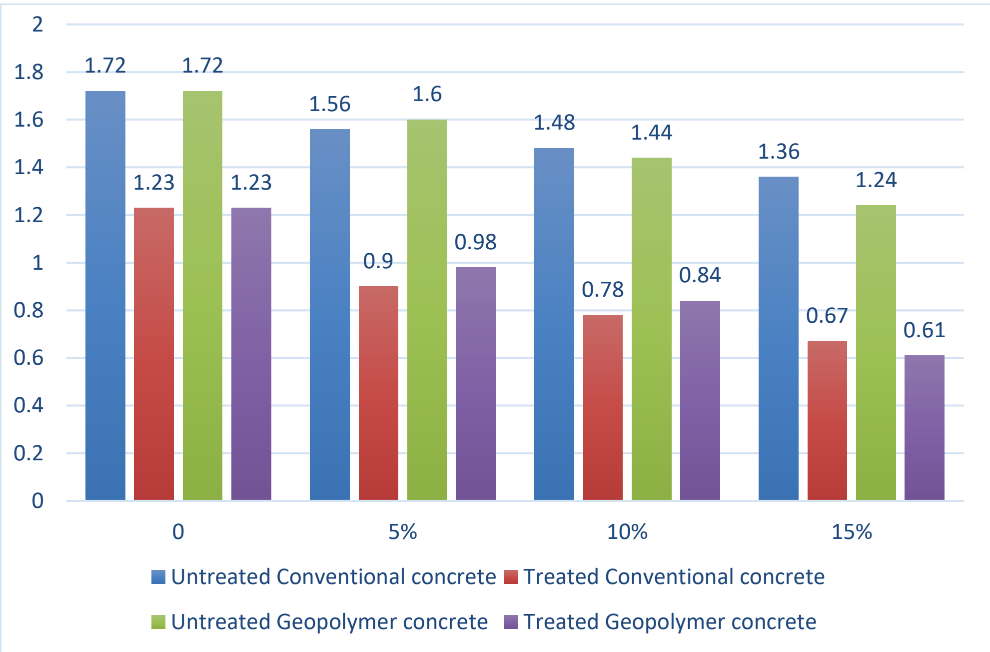

Figure 1 Thermal Conductivity

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.

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

$$\text{Mass of } CO_2 = \frac{44}{100} \times \text{Mass of } CaCO_3$$

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

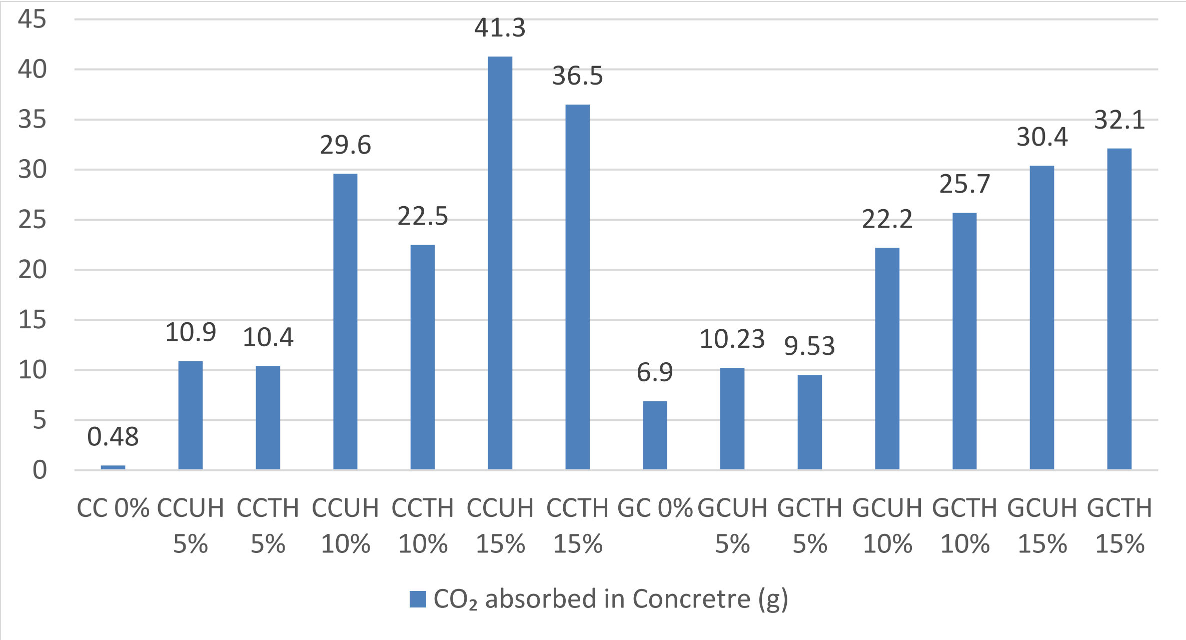

Figure 2 CO_2 absorption in hemp hurds used in conventional and geopolymer concrete

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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