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RESEARCH ARTICLE

Mechanical, Thermal and Fire Behaviour of Hemp-Based Composites with Different Binders for Sustainable Building Applications

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ABSTRACT

This study investigates the physical, mechanical and thermal properties of hemp-based composites produced with traditional binders such as lime, cement, gypsum, clay, and water-based glue. Hemp fractions of different sizes (splinter, shiv, fiber and powder) were combined with these binders to manufacture cube and plate specimens, which were tested for physical, mechanical, thermal, and temperature resistance properties. The study aims to compare the mechanical, physical, thermal, and fire behaviour of these composites to assess their suitability for sustainable construction applications. The hemp-based composites were tested for unit weight, water absorption, compressive strength and thermal conductivity. Most specimens are lightweight (<1000 kg/m^3), and exhibit good thermal insulation performance and high compressive deformability, making them suitable for seismic-prone regions. The glue-based composite had the lowest unit weight, measured as 330 kg/m^3. Thermal conductivity ranged from 0.051 to 0.243 W/m·K, with several mixtures performing better than natural pumice. While cement-based composites showed the highest compressive strength, ranging from 5.5 to 24.8 kg/cm^2, natural hydraulic lime is the lowest. Water absorption was high, and moisture release occurred slowly across all hemp fractions. Combustion tests indicated that hemp-based materials have moderate temperature resistance, with charring temperatures ranging from 238–265°C for raw hemp and 300–385°C when mixed with binders. Overall, hemp-based composites are lightweight, eco-friendly, and suitable for non-load-bearing construction and insulation applications. However, improvements in moisture resistance and long-term durability are necessary to enhance their practical applicability.

Keywords: Binder, Building materials, Fire resistance, Hemp, Sustainability, Thermal conductivity

1. Introduction

Building materials are of vital importance in the construction industry and there is a growing trend to focus on sustainability and environmental friendliness. Hemp, known for its diversity, renewability and carbon-negative characteristics, has emerged as a potential alternative for producing environmentally friendly building materials. Recent research has examined the physical and mechanical properties of hemp composites formed with different binders, highlighting the potential of industrial hemp as a natural fiber source for construction purposes [1]. Additionally, studies on surface treatment of hemp fibers to improve fiber/matrix interfacial bonding have contributed significantly to

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the mechanical performance of hemp composites [2].

Hempcrete, a hemp-lime mixture, is a well-known hemp-based material due to its favorable properties and low carbon profile. Hempcrete houses have been built in many countries, and research on this topic has increased substantially [3]. Combining hemp shivs with lime-based binders provides effective thermal and acoustic insulation, enabling construction without additional insulation layers [4–6]. Beyond lime, alternative binders such as gypsum, geopolymers and starch have also been explored to produce ecological building materials with low density and promising thermal conductivity [7].

Hemp materials can be manufactured in various forms and used in both construction and insulation applications [8]. Their total carbon emission balance is negative, and previous research shows that using organic materials in cement production reduces CO_2 emissions [9]. Hempcrete walls also demonstrate a high CO_2 absorption capacity [10], and bio-based insulation materials combining flax and hemp offer competitive thermal performance [11]. Furthermore, hemp blocks exhibit favorable thermal behaviour and fire resistance, with flaming combustion temperatures reaching up to 700 °C [12].

Previous work has investigated a wide variety of hemp-based composite configurations. Studies include polyethylene film-coated hemp composites, evaluating water absorption, mechanical strength, and dynamic behaviour [13]; hemp fiber–polyurethane composites to determine critical fiber length [14]; and composites incorporating hemp fiber powder, which improves compressive strength [15, 16]. Layered hemp-based composites have also been shown to provide high-quality acoustic insulation. Hempcrete mixtures generally show a dry unit weight of 200–800 kg/m^3 and thermal conductivity coefficient between 0.06-0.12 W/m·K [17]. Additionally, the heat capacity of hemp-reinforced composites has been reported to be around 1500 J/kg·K [18].

Other studies have focused on the mechanical properties of hemp-reinforced polypropylene [19], physical properties of hemp shiv and fiber [20], and the suitability of hemp materials for installation insulation [21]. Research shows that using only cement as a binder in hempcrete can lead to design limitations, resulting in inferior performance compared to alternative natural binders such as clay and lime, and does not improve material strength. Hempcrete is nearly seven times lighter than traditional concrete [5], making it an attractive lightweight material for construction. With the increasing use of hemp in the construction sector, it has become important to determine its mechanical, thermal, and physical properties, particularly for non-load-bearing applications [22–24]. Studies have also examined the integration of hemp shivs with various binders in frame structures for both structural and insulation purposes [25].

This study aims to evaluate and compare the physical, mechanical, thermal, and fire behaviour of hemp-based composites produced with different traditional binders, in order to assess their suitability for sustainable building applications.

2. Material and methods

Industrial hemp was obtained from the Institute of Hemp at Ondokuz Mayis University. Five different hemp fractions were used: coarse splinter (T1), medium shiv (T2), fine shiv (T3), powder (T4), and fiber (T5). T1 represents the woody shredded hemp shiv with an average length of 15 mm, a width of 2 mm, and a thickness of 1.5 mm. T2 and T3 dimensions were obtained by reducing the dimensions of T1 length, while T4 consisted of particles smaller than 1 mm. Traditional binders used in the study included cement (CEM I 42.5), lime putty, natural hydraulic lime (NHL 3.5), plaster, clay, and polyvinyl acetate (PVAc) water-based glue, all used without chemical modification.

The proportions of hemp and binders were determined based on practical workability and traditional mixture ratios. Total hemp content ranged from 14% to 30% by weight in the mixtures. The quantities of materials used are presented in Tables 1 and 2.

2.1. Specimen preparation

The specimens for partition elements were produced as 15 cm cubes, while 20 × 30 cm and 30 × 30 cm plates with a thickness of 3 cm were prepared for cladding and insulation tests. For fire-temperature resistance tests, 10 cm cube specimens were manufactured. All mixtures in Table 1 were prepared using a dynamic mixer and placed manually into molds. Plate-type specimens were compacted using a standard testing machine (capacity: 2000 kN) by applying pressures of 15 kg/cm^2 (20 × 30 cm plates) and 20 kg/cm^2 (30 × 30 cm plates). The specimens containing cement binder were removed from the molds after one day. They were cured by watering three times a day. All other specimens were demolded after three days.

Minimum curing was applied to lime and gypsum mixtures (watering once per day). Specimens with water-based glue were air-dried without any additional curing. Clay-based specimens were kept in a closed environment for 1–2 days after demolding,

Table 1. Quantities and proportions of hemp products and binders.

Components	Cem	%	NHLP1	%	GLK1	%	PLK	%	LK1	%
Coarse splinter (g)	450	3.36	850	7.11	1000	14.49	375	3.61	350	5.04
Coarse shiv (g)	450	3.36	1000	8.37	975	14.13	375	3.61	300	4.32
Medium shiv (g)	325	2.43	550	4.60	650	9.42	250	2.40	150	2.16
Fine shiv (g)	325	2.43	550	4.60	625	9.06	250	2.40	150	2.16
Powder (g)	225	1.68	350	2.93	425	6.16	175	1.68	100	1.44
Fiber (g)	225	1.68	350	2.93	475	6.88	175	1.68	100	1.44
Hemp (g)	2000	14.94	3650	30.54	4150	60.14	1600	15.38	1150	16.56
Binder (g)	7900	58.96	4800	40.17	2750	39.86	5600	53.85	5200	74.82
Water (g)	3500	26.12	3500	29.29			3200	30.77	600	8.63
	13400	100	11950	100	6900	100	10400	100	6950	100

*The labels in the ingredients section are respectively (Cem-Cement, NHL-Natural Hydraulic Lime, GL-Polyvinyl Acetate Glue (PVAc glue), PL-Plaster, L-Lime), those ending with P1 indicate 30 × 30 × 3 cm plates, and those ending with K indicate 15 × 15 × 15 cm cubic blocks.

Table 2. Summary of specimen groups, dimensions, binders, and relevant standards.

Specimen Type	Dimensions	Binder Type	Hemp Fraction	Test Performed	Standard/Device
Cube specimen	15 × 15 × 15 cm	Cement, Lime Putty, NHL, Clay, Plaster, PVAc Glue	T1–T5	Compressive strength, deformation	EN 12390-1 (standard testing machine, 2000 kN)
Plate specimen	30 × 30 × 3 cm	Cement, Lime Putty, Clay, Plaster, PVAc Glue	T1–T5	Thermal conductivity	ISO 8302 (KD2 Pro)
Plate specimen	20 × 30 × 3 cm	Cement, Lime Putty, Clay, Plaster, PVAc Glue	T1–T5	Thermal conductivity	ISO 8302
Fire test specimen	10 × 10 × 10 cm	Clay, Lime Putty, Plaster	T1–T5	Charring temperature	Muffle furnace (ASTM E119 concept)

Fig. 1. Sample sets made using various binders.

then allowed to dry under air circulation in a shaded area for an additional two days. They were rotated once or twice per day to improve moisture evaporation. After one month, all samples except the glue-based ones were oven-dried at 105°C for 48 hours. Glue-based specimens were dried at 50°C for 48 hours. The prepared specimen sets are shown in Fig. 1.

Water absorption and water reabsorption behaviour of the hemp fractions were examined separately. For this purpose, 600 g of material (100 g from each fraction shown in Fig. 2) was dried at 105 °C for 48 hours, soaked for 48 hours, and weighed twice daily to monitor moisture releases.

Statistical evaluations were conducted using IBM SPSS v25. Normal distribution of data was verified using the Kolmogorov–Smirnov test ($p > 0.05$), allowing the use of parametric methods based on split-plot experimental design. Significant differences were further analyzed by the Duncan multiple comparison test.

3. Results

The results presented in this section provide the comparative mechanical, thermal, and fire performance of hemp-based composites, directly supporting the main objective of evaluating their suitability for sustainable building applications.

3.1. Water absorption and moisture retention

The results of water absorption and reabsorption of hemp products at the end of 5, 7 and 10 days with reference to oven dry weights. In the experiments on water-moisture properties, it was observed that in the natural state of hemp products, the least moisture was found in the coarse splinter (10.07%) and the most moisture was found in the fiber (20.08%). In the water impregnation experiment (48 hours, mains water and 20–25 °C ambient temperature), the amount and rates of water absorption were found to be quite high (Table 2). Although the fraction of hemp presented high capacit of water absorption, ranging

Fig. 2. Hemp products used for water/moisture properties.

Table 3. Time-dependent water absorption and water return values of hemp.

Hemp Specimen	Natural, g	Dry, g	Humidity, %	48 hours water absorbed		5 days dried		7 days dried		10 days dried	
				Weight, g	Water, %	Weight, g	Water, %	Weight, g	Water, %	Weight, g	Water, %
Coarse splinter/stem	100	90.85	10.07	148.22	63.15	125.18	37.79	113.46	24.89	101.86	12.12
Coarse shiv (T1)	100	87.45	14.35	249.42	185.21	224.07	156.23	194.91	122.88	124.86	42.78
Medium shiv (T2)	100	87.82	13.87	244.31	178.19	217.97	148.20	188.47	114.61	113.64	29.40
Fine shiv (T3)	100	85.43	17.05	306.68	258.98	278.96	226.54	245.95	187.90	167.8	96.42
Powder (T4)	100	83.75	19.40	347.37	314.77	332.96	297.56	276.59	230.26	124.01	48.07
Fiber	100	83.28	20.08	194.23	133.23	166.13	99.48	135.83	63.10	94.56	13.54
Tot./Aver.	600	518.58	15.70	1490.23	187.37	1345.27	159.41	1155.21	122.76	726.73	40.14

from 63% (coarse splinter) to 315% (powder) after 2 days immersion, moisture release of fine fractions was relatively slow, retaining up to 96% moisture after 10 days drying. The result of water absorption and moisture retention was shown in Table 3.

3.2. Unit weights

The dry unit weights of hemp-based composites ranged from 330 to 1050 kg/m^3, indicating that all materials fall within the lightweight category (Table 4). The lowest unit weight was observed in the glue-based composite (330 kg/m^3, followed by lime putty and natural hydraulic lime composites (<500 kg/m^3). Only one mixture exceeded 1000 kg/m^3, which was the clay-based cubes.

The relationship between different binder materials and dry unit weights of the specimens formed using traditional binders with hemp additives was examined and the statistical difference between different binders and dry unit weights was found to be very significant ($p < 0.01$). As a result of the multiple comparison analysis performed to determine this difference, it was determined that the dry unit weight values of the clay binder material were statistically lower than those of the other binder materials.

Table 4. Unit volume weights of all samples.

Specimen name*	Specimen component name	Dry unit volume weight (kg/m^3)	Dry unit weights (aver. ± std. deviation)
GLK	Glue + hemp-cube	330	0.333 ± 0.006^{a}
LK1	Lime putty + hemp-cube1	440	0.437 ± 0.006^{ab}
NHLK1	Natural hydraulic lime + hemp-cube1	460	0.457 ± 0.046^{ab}
CLP1	Clay-hemp-platter1	520	0.550 ± 0.010^{bc}
LP2	Lime putty + hemp-platter2	540	0.613 ± 0.006^{cd}
PLK	Plaster + hemp-cube	550	0.626 ± 0.086^{cd}
LK2	Lime putty + hemp-cube2	610	0.635 ± 0.059^{cd}
NHLP1	Natural hydraulic lime + hemp -platter1	640	0.663 ± 0.067^{cd}
NHLK2	Natural hydraulic lime + hemp -cube2	660	0.703 ± 0.029^{de}
NHLP3	Natural hydraulic lime + hemp -platter3	680	*
NHLP2	Natural hydraulic lime + hemp -platter2	710	0.725 ± 0.044^{def}
CLP2	Clay + hemp-platter2	730	0.748 ± 0.010^{def}
CemK	Cement + hemp-cube	820	0.820 ± 0.020^{ef}
LP1	Lime putty + hemp-platter1	870	0.870 ± 0.156^{f}
CLK1	Clay + hemp-cube1	1050	1.055 ± 0.021^{g}

* Plaques with P1 and P3 at the end are 30 × 30 × 3 cm, plaques with P2 are 30 × 20 × 3 cm, cubes with K, K1, K2, K3 are 15 × 15 × 15 cm.
*There is a statistical difference between the averages shown in the same column with different letters.
*Natural hydraulic lime + hemp-plate3 (NHLP3) sample was not included in the statistical analysis because it was produced as a spare sample. $0.01 < p < 0.05$ significant * $p < 0.01$ very significant **,

Fig. 3. Compressive strength test and longitudinal-transverse strain measurement.

3.3. Mechanical behaviour

The compressive strength tests were carried out using a standard testing machine (2000 kN capacity) in the laboratories of Ondokuz Mayıs University, Department of Civil Engineering. All tests were performed on cube specimens with a side length of 15 cm. Since the device was not equipped with longitudinal and transverse strain gauges, two needle dial gauges were mounted to measure vertical and horizontal strain (Fig. 3). According to the mechanical properties obtained, the transverse and longitudinal strain rates, Poisson's ratios and compressive stress changes of the specimens are presented in Fig. 4. According to the compressive test results, the average proportional changes in the volume and dimensions of the specimens are shown in Fig. 5.

The highest compressive strength was found to be 24.8 kg/cm^2 (2.43 MPa) in the set produced from cement and hemp products, whereas the lowest tensile value was 5.5 kg/cm^2 (0.54 MPa) in the set using natural hydraulic lime. The average strengths of the other specimens produced were 6 kg/cm^2 (0.59 MPa) for glued, 9 kg/cm^2 (0.88 MPa) for plastered, 12 kg/cm^2 (1.18 MPa) for lime, 13 kg/cm^2 (1.27 MPa) for lime + silica sand + brick clay and 18 kg/cm^2 (1.77 MPa) for clay specimen.

3.4. Thermal conductivity coefficient "k" (W/m·K)

The coefficient of thermal conductivity was measured with a KD2 Pro device. The obtained coefficients were compared with the coefficient of thermal conductivity (k) of 10 different materials with good insulation properties or directly used as "insulation materials". Samples used as reference for determining the coefficient of thermal conductivity values are given in Fig. 6. The average values of the measurement results made on the samples and the reference material measurements are given in Table 5.

Four different hemp samples have a thermal conductivity coefficient between 0.065–0.069, and five different hemp samples have a thermal conductivity coefficient between 0.072–0.085 W/m·K (equivalent to the measured natural pumice) and are considered as materials that can be reproduced as "insulation materials". Only five of the 15 different hemp samples had a thermal conductivity coefficient in the range of 0.115-0.243 W/m·K. The sample with the highest thermal conductivity coefficient of 0.243 W/m·K was the sample produced with water-based glue with the lowest unit volume weight (330 kg/m^3). Although the glue-based composite had the lowest unit weight (330 kg/m^3), it exhibited the highest thermal conductivity (0.243 W/m·K). This counterintuitive result is related to the polymeric PVAc binder, which forms continuous solid bridges between hemp particles. These solid bridges create uninterrupted heat-transfer pathways despite the low bulk density. Similar behaviour has been observed in bio-based composites containing organic adhesives, where polymer continuity increases thermal conductivity independent of density.

When the results of the study on the determination of the usability of the samples formed using traditional binders with hemp additives as insulation elements were examined, the relationship between

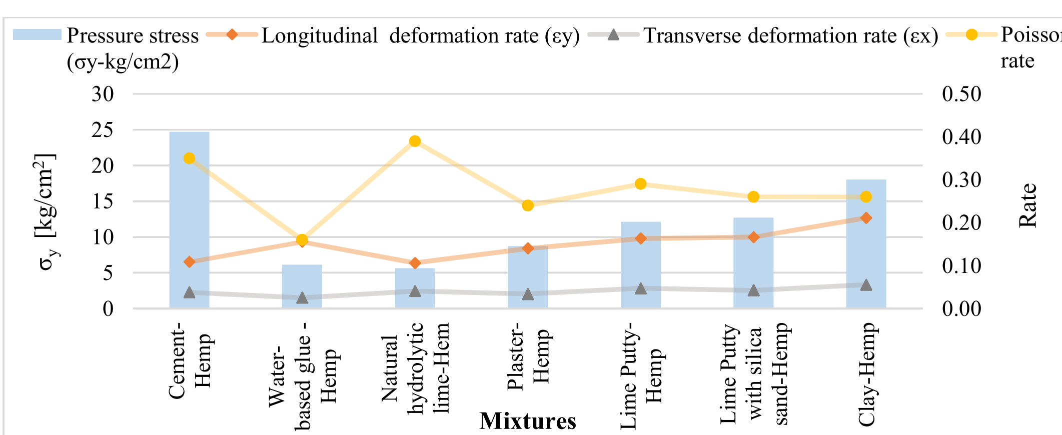

Fig. 4. Variation of mechanical properties in the error bars.

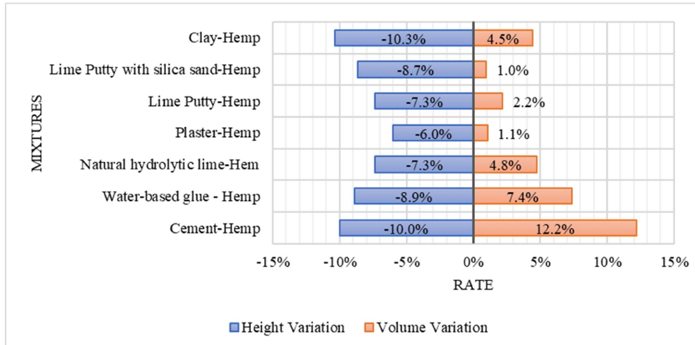

Fig. 5. Size and volume changes of the mixtures with pressure.

Fig. 6. Materials for which reference measurements were made for thermal conductivity (a: Iso-wall, b: Sandwich panel, c: Bims hollow core, d: Fiberboard, e: PS foam-cement coated).

Table 5. Average thermal conductivity coefficients of hemp and reference samples.

Specimen name*	Description Heat 24–26 °C, $r^2 = 0.9984–0.9999$ (k = W/m·K)	Thermal conductivity value (aver. ± std. deviation	Average k = W/m·K	Reference (Heat 26 °C, $r^2 = 0.9961–0.9996$) (k = W/m·K))	Average k = W/m·K
LK2	Lime putty + hemp-cube2	0.05 ± 0.0001^{a}	0.051	Iso-wall-PS Foam-White	0.027
CLP1	Clay + hemp-platter1	0.067 ± 0.0058^{ab}	0.065	Sandwich panel-Foam filler	0.029
LP1	Lime putty + hemp-platter1	0.07 ± 0.0001^{abc}	0.066	PS Foam-Cement covered	0.033
NHLK2	Natural hydraulic lime + hemp-cube2	0.07 ± 0.0001^{abc}	0.067	Iso-wall-XPS Foam-blue	0.034
NHLP2	Natural hydraulic lime + hemp -platter2	0.07 ± 0.0001^{abc}	0.069	PS Foam- Cement Covered-Range	0.059
NHLK1	Natural hydraulic lime + hemp-cube1	0.073 ± 0.0058^{abcd}	0.072	Iso-wall-Natural pumice	0.074
PLK	Plaster + hemp-cube	0.077 ± 0.0058^{abcd}	0.075	Bims Hollow	0.104
CLP2	Clay + hemp-platter2	0.083 ± 0.0153^{abcd}	0.083	Styrofoam reinforced concrete	0.143
NHLP3	Natural hydraulic lime + hemp -platter3	0.084 ± 0.0055^{abcd}	0.084	Fibreboard (2.5 cm)	0.152
LK1	Lime putty + hemp-cube1	0.087 ± 0.0116^{abcde}	0.085	Cement Binder Pumice	0.172
NHLP1	Natural hydraulic lime + hemp -platter1	0.1 ± 0.0424^{bcde}	0.115		
CemK	Cement + hemp-cube	0.115 ± 0.0071^{cde}	0.118		
LP2	Lime putty + hemp-platter2	0.118 ± 0.0179^{de}	0.130		
CLK1	Clay + hemp-cube1	0.13 ± 0.0001^{e}	0.133		
GLK	Glue + hemp-cube	0.243 ± 0.0058^{f}	0.243		

*The nomenclature given in the components section refers to the materials that make up the components (Cem-Cement, CL-Clay, NHL-Natural hydraulic lime, GL- Polyvinyl Acetate Glue, PL-Plaster, L-Lime putty), P1 indicates a 30 × 30 × 3 cm plate and K indicates a 15 × 15 × 15 cm cube.

the different binder materials used and the thermal coefficient values was examined and the statistical difference between the different binders and the thermal coefficient values was found to be very significant ($p < 0.01$). As a result of the multiple comparison analysis performed to determine this difference, it was determined that the internal carbonization progression of lime binder material was statistically higher than the other binder materials.

3.5. Fire performance

The temperature resistance of the hemp products used in the experiments (staple types, fibers and splinters) were tested in their natural state and in the binder/compounding agent. This study was carried out to determine the relationship between flaming combustion temperature and non-flaming combustion temperature studied in the literature.

Table 6. Burning temperature resistance of hemp products.

Specimen	Description	Combustion temperature (°C)	After combustion	Specimen	Combustion temperature (°C)
Stalk, T1	Section size: 4–5 mm Length: 15–16 mm	251°		Clay + hemp	385
Stalk, T2	Section size: 3–4 mm Length: 10–12 mm	250°			
Stalk, T3	Section size: 1–2 mm Length: 4–5 mm	240°		Lime putty + hemp	385
Stalk, T4	Section size: <1 mm Length: <2 mm	240°		Powder lime + hemp	300
Fiber	Diameter: Various Length: 3—5 cm (Long)	238°			
Stalk (Stem)	Extro diameter: 15–25 mm Length: 12–15 cm (Quarter stem)	265°		Plaster + hemp	300

In order to determine the combustion values of hemp products, the staple types and fiber samples were subjected to incineration in a muffle furnace. T1 (Thick), T2 (Medium), T3 (Fine), T4 (Very fine powder), T5 (Fiber) and T6 Splinter (Stalk) samples were used in the study. These samples were prepared without using any binder/compounding agent and 5 grams of material was used. Before the start of the experiment, the muffle furnace was preheated at 200°C and all materials were placed in the muffle furnace at the same time. The combustion temperature of the materials used in the experiment was taken as the temperature values at which partial or complete charring was observed. The obtained combustion/charring temperatures are given in Table 6. No flaming combustion was observed since the experiment was conducted in a closed environment. In order to exemplify the building materials that can be obtained by mixing hemp products with binder/combining materials, clay was used as a binder, lime (lime putty and powdered plaster lime) and plaster plaster were used as binders. Considering that a muffle furnace will be used in the study, the samples were produced as 10 × 10 × 10 cm cubes. The combustion temperature of the four different types of materials subjected to the experiment was recorded as the temperature at which charring was observed. The obtained combustion/charring temperatures are given in Table 6.

At the determined carbonization temperature, it was observed that the samples carbonized by decreasing from the outside to the inside. Therefore, the effect of gradual temperature increase was investigated to determine the amount of charring progression. Plaster plaster specimens were not included in the next experimental group because they lost their integrity at 300°C. 8 specimens of each combination with 3 different combinations were prepared and subjected to the experiment with an initial temperature of 260°C, increasing by 20°C up to 400°C and waiting for 20 minutes at each temperature value. Before the materials were placed in the muffle furnace, they were dried in an oven at 105°C for 48 hours and their dry weights were measured. Protection was provided with aluminum foil to prevent material loss in the muffle furnace (foil weight was eliminated in weighing). Each sample set was placed in the muffle furnace at the specified temperature for 20 minutes, then removed, cooled and weighed. The weight values obtained are given in Table 7. It was observed that there was a linear relationship in the weight changes of the clay-hemp blended samples against temperature and the weight changes of the samples

Table 7. Weights (g) of dry samples at 260–400 °C temperature and 20 min time.

		Clay + Hemp			Lime Putty + Hemp			Powder Lime + Hemp		
Specimen	Ash Furnace Temperature (°C)	Dry Specimen	After Furnace Weight	Lost (%)	Dry Specimen	After Furnace Weight	Lost (%)	Dry Specimen	After Furnace Weight	Lost (%)
1	260	791.69	749.62	5.31	550.86	541.7	1.66	580.44	556.96	4.05
2	280	785.91	749.58	4.62	578.57	568.43	1.75	544.74	520.61	4.43
3	300	803.59	766.01	4.68	531.87	513.11	3.53	601.29	577.24	4.00
4	320	788.34	770.03	2.32	578.47	562.35	2.79	576.77	569.74	1.22
5	340	764.09	744.09	2.62	565.77	558.18	1.34	579.03	562.38	2.88
6	360	706.9	694.28	1.79	571.7	559.05	2.21	595.23	572.07	3.89
7	380	767.39	755.54	1.54	577.2	563.15	2.43	619.55	592.08	4.43
8	400	742.72	736.32	0.86	560.23	539.36	3.73	497.18	448.86	9.72

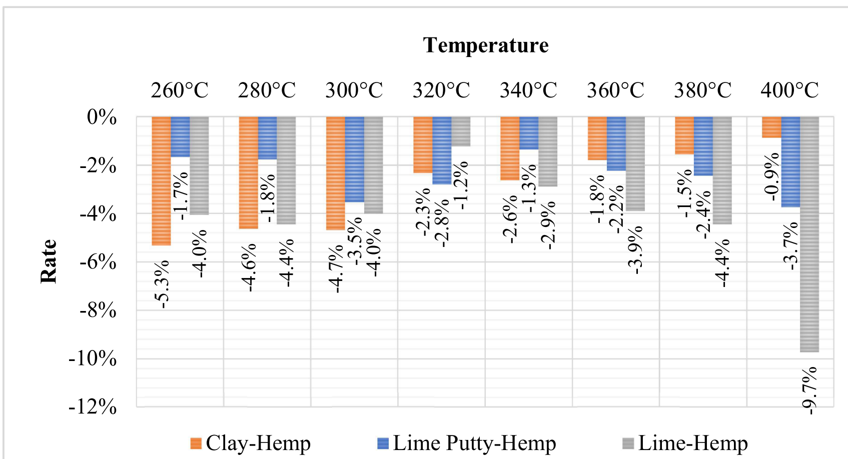

Fig. 7. Weight changes of the samples for 260–400 °C temperature and 20 min time.

decreased as the temperature value increased. There was no linear relationship between temperature and weight changes in the lime putty-hemp and powdered lime-hemp mixtures. It could not be determined whether the temperature effect was directly effective on weight changes. The weight change rates of the samples at the end of the determined temperature and time are given in Fig. 7.

Visual inspection of the samples removed from the muffle furnace and weighed according to the gradual temperature increase showed that the charring progress was not the same everywhere. For this reason, it was decided to determine the progression values of this carbonization with larger (10 × 10 × 10 cm cube) samples. At 400 °C constant temperature, charring progress values were determined and recorded for 20, 40 and 60 minutes. The carbonization progress of the samples was found by taking 5 measurements from the sample surface. The carbonization forms of the samples are given in Table 8 and the average measurements of the carbonization progress are given in Table 9.

As a result of the multiple comparison analysis performed to determine this difference, it was determined that the internal carbonization progress of lime binder material was statistically higher than the other binder materials. The statistical data of the combustion progress of the binder materials are given in Table 10.

Table 8. Visuals of the combustion state of 10 × 10 × 10 cm cube samples at 400 °C.

Waiting time (min)	Clay + Hemp	Lime Putty + Hemp	Powder Lime + Hemp
20			
40			
60			

Table 9. Burning distances of 10 × 10 × 10 cm Cube samples from outside to inside at 400 oC.

		Clay + Hemp			Lime Putty + Hemp			Powder Lime + Hemp		
Time (min)	Temperature (°C)	Edge	Diagonal	Internal	Edge	Diagonal	Internal	Edge	Diagonal	Internal
20	400	1	1.5	1	1	2	1	1.5	2.5	1.5
40	400	2	2.5	3.5	1.5	2.5	3.5	2.5	3	4
60	400	4	4.5	4.5	4	4.5	5	3	3.5	4.5

Table 10. Statistical representation of the combustion progress of the materials.

Specimen	Clay (mean ± SD)	Lime putty (mean ± SD)	Lime (mean ± SD)	p
Edge	1.880 ± 1.392	2.052 ± 1.546	1.132 ± 0.469	0.558
Internal process	$2.132^{b} \pm 1.562$	$2.902^{c} \pm 1.841$	$1.232^{a} \pm 0.466$	<0.01

* Different superscript letters in the same row indicate statistically significant differences ($p < 0.05$). $0.01 < p < 0.05$: significant (); $p < 0.01$: very significant (**).*

Table 11. Statistical data of charring at different holding times at 400 °C constant temperature.

Holding time (min)	20 (mean ± SD)	40 (mean ± SD)	60 (mean ± SD)	p
Edge	$0.748^{a} \pm 0.555$	$1.493^{b} \pm 0.392$	$3.773^{c} \pm 0.779$	<0.01
Internal process	$0.675^{a} \pm 0.449$	$2.644^{b} \pm 1.052$	$4.395^{c} \pm 0.666$	<0.01

* Different superscript letters in the same row indicate statistically significant differences ($p < 0.05$).

Table 12. Statistical data for different holding times and material combustion interaction at constant temperature.

Parameter	Time (min)	Clay (mean ± SD)	Lime putty (mean ± SD)	Lime (mean ± SD)	p
Edge	20	$0.485^{e} \pm 0.395$	$0.790^{e} \pm 0.674$	$0.970^{d} \pm 0.469$	0.011
	40	$1.555^{c} \pm 0.395$	$1.380^{cd} \pm 0.379$	$2.500^{bc} \pm 0.412$	
	60	$3.600^{ab} \pm 0.659$	$3.985^{a} \pm 0.857$	$3.000^{ab} \pm 0.515$	
Internal process	20	$0.495^{d} \pm 0.324$	$0.600^{d} \pm 0.441$	$0.930^{d} \pm 0.466$	<0.01
	40	$2.005^{c} \pm 1.003$	$3.215^{b} \pm 0.677$	$4.000^{ab} \pm 0.320$	
	60	$3.895^{b} \pm 0.605$	$4.890^{a} \pm 0.155$	$4.500^{ab} \pm 0.280$	

Different superscript letters in the same row indicate statistically significant differences ($p < 0.05$). $0.01 < p < 0.05$: significant (*); $p < 0.01$: very significant (**).*

The statistical difference between the different holding times of the samples at constant temperature was found to be very significant ($p < 0.01$) for both internal and edge charring progress. As a result of the multiple comparison analysis performed to determine this difference, it was found that the holding time of 60 minutes at 400 °C resulted in statistically higher inner and edge charring progress compared to the other holding times. The statistical data for the holding time at constant temperature are given in Table 11.

The statistical difference between the materials was found to be very significant ($p < 0.01$) for internal carbonization progression and significant ($p < 0.05$) for edge progression. As a result of the multiple comparison analysis, it was determined that the lime binder material showed statistically higher internal carbonization progression at constant temperature compared to the other binder materials. The statistical data for the interaction between different holding times and materials are presented in Table 12.

3.6. Statistical analysis

The study investigated the usability of samples produced with traditional binders incorporating hemp additives as insulation materials. The relationship between the type of binder used and the resulting compressive strength was analyzed. Regression analysis was conducted to examine the correlation between the compressive stress values of samples prepared with different binders across various pressure ranges and the predicted strength values at those pressures. Based on the regression analysis, predictive equations for compressive strength at different pressure ranges were established. The statistical data corresponding to these predictive equations are presented in Table 13.

The compressive stress values at different pressure ranges were found to be statistically significant ($p < 0.01$) in mixtures prepared with all binder materials. In order to determine the relationship between different pressure ranges and compressive stress, regression analysis results were analyzed and linear equation

Table 13. Prediction equations obtained as a result of regression analysis.

Binder	Equation	R^2
Cement		
Lineer	$y = 0.0041x + 0.8331$	0.998
Glue		
Lineer	$y = 0.0042x + 0.08$	0.997
Lime		
Lineer	$y = 0.0042x + 0.1518$	0.999
Plaster		
Lineer	$y = 0.0042x + 0.1728$	0.998
Lime putty		
Lineer	$y = 0.004x + 0.2755$	0.999
Lime putty + silica		
Lineer	$y = 0.0042x + 0.2576$	0.999

estimation was performed for each binder material. The obtained pressure-tension graphs are given in Fig. 8.

4. Discussion

The results indicate that hemp-based materials absorb water rapidly but release moisture more slowly. Fine hemp fractions showed particularly high water absorption rates and slower moisture release, aligning with previous findings on the hydrophilic nature of hemp [1]. This behaviour suggests that hemp-based materials may require additional precautions in high-humidity environments, yet they remain suitable for applications in low-humidity or interior conditions. Overall, the water-moisture performance confirms the importance of improving long-term durability through appropriate binder selection or surface modification.

Tests on composite specimens produced with different binders showed that unit volume weight remained below 1000 kg/m^3 in 14 out of 15 mixtures. In three mixtures, those incorporating water-based, lime putty, or natural hydraulic lime, the unit weight dropped 500 kg/m^3. These findings are consistent with previous hempcrete studies reporting similarly low densities [26, 27]. Lightweight materials are advantageous for seismic-prone regions, as reduced mass contributes to lower inertial forces. Therefore, the low density of the composites supports their potential use in lightweight partition walls or non-load-bearing structural elements.

Mechanical test results showed that cement-based composites exhibited the highest compressive strength (24.8 kg/cm^2 $\approx$ 2.43 MPa), aligning with a previous study [16]. Natural hydraulic lime produced the lowest strength values (5.5 kg/cm^2 $\approx$ 0.54 MPa), while glue, gypsum, and clay-based composites exhibited intermediate performance. The inclusion of hemp increased deformability and improved elastic response, as all mixtures exceeded the deformation limits of the standard testing machine. Observed dimensional and volumetric changes also reflect the compressible nature of hemp fibers within the matrix. Taken together, the mechanical findings indicate that while hemp composites are not suitable for load-bearing systems, they perform sufficiently well for lightweight structural and architectural applications.

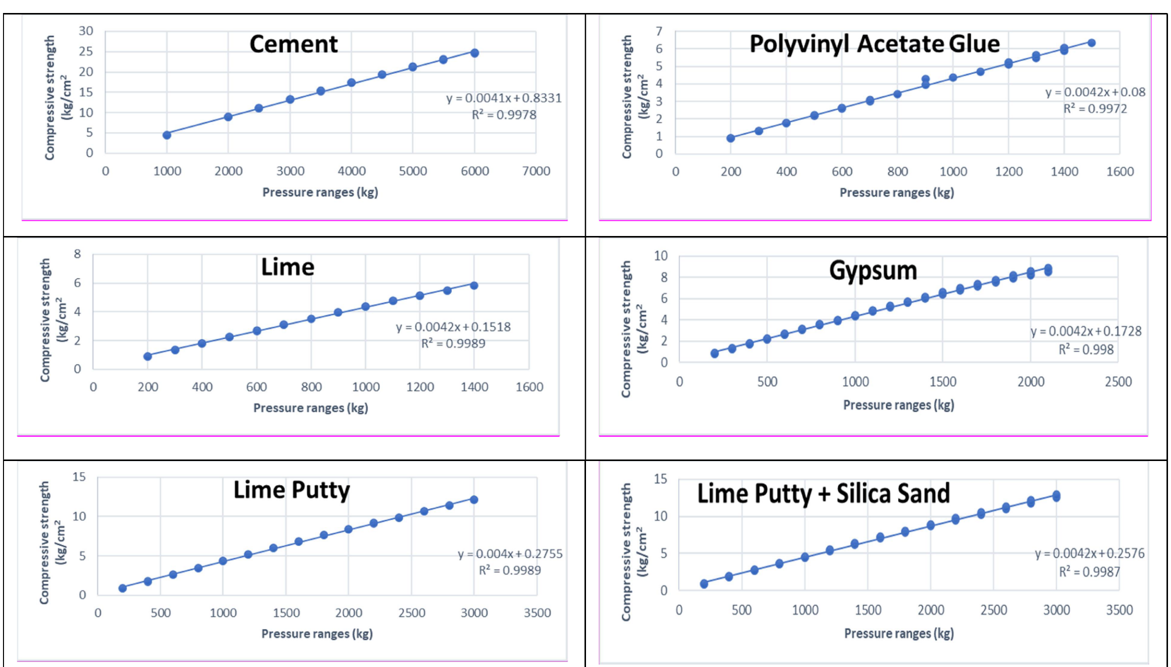

Fig. 8. Compressive-tension behaviour of the specimens.

Thermal conductivity values ranged broadly between 0.051 and 0.243 W/m·K. The sample with the lowest conductivity (0.051 W/m·K) contained high hemp content and low lime putty, and was compacted under pressure, aligning with high-performance insulation materials reported in literature [23, 24]. Several mixtures (0.065–0.085 W/m·K) demonstrated thermal performance comparable to natural pumice. Conversely, the glue-based composite exhibited the highest thermal conductivity (0.243 W/m·K) despite having the lowest unit weight (330 kg/m^3). This counterintuitive behaviour can be explained by the continuous polymer bridges formed by the PVAc binder, which create effective heat-transfer pathways regardless of bulk density. Such phenomena have been similarly reported in organic adhesive–based composite systems. Overall, the results show that hemp-based composites can provide competitive insulation performance when appropriate binder proportions and compaction strategies are used.

The calculated ignition temperature of hemp shiv (206 °C) aligns with studies reporting ignition thresholds slightly below those of wood and cellulose-based materials [28]. In this study, flameless combustion tests showed that raw hemp charred at 238–265°C, while binder-based composites charred at 300–385°C. This improvement in charring resistance indicates that binder incorporation contributes to thermal stability and may offer additional protection in fire scenarios. The controlled charring depths observed in larger specimens provide valuable insight into fire-related material behaviour, which should be considered in future design guidelines.

Overall, the discussion confirms that the physical, mechanical, thermal, and fire performance results collectively support the main objective of the study: evaluating the suitability of hemp-based composites produced with traditional binders for sustainable and lightweight building applications. The varying performance across binder types demonstrates the importance of binder selection, mixture ratio optimization, and moisture management strategies. While the composites show strong potential for insulation, partitioning, and low-impact structural use, further improvements in moisture resistance and long-term durability are required for broader practical implementation.

5. Conclusion

This study investigated the physical, mechanical, thermal, and fire behaviour of hemp-based composites, produced with six different traditional binders. All mixtures exhibited lightweight characteristics with unit weights ranging from 330 to 1050 kg/m^3. The glue-based composite had the lowest unit weight (330 kg/m^3), followed by mixtures containing lime putty and natural hydraulic lime (<500 kg/m^3).

Thermal conductivity values varied between 0.051 and 0.243 W/m·K, and six mixtures showed lower conductivity than natural pumice ($k = 0.074$ W/m·K). The best thermal performance was observed in lime-putty composites (0.051 W/m·K). In contrast, the glue-based composite showed the highest thermal conductivity despite its low density, which is attributed to the continuous polymer bridges created by the PVAc binder. Combustion tests revealed that raw hemp materials char between 238-265°C, while binder-based composites indicated increased charring resistance (300–385 °C). For 10 × 10 × 10 cm cube samples exposed to 400 °C, charring progression ranged from 3 to 5 cm after 60 minutes.

Compressive strengths ranged between 5.67 kg/cm^2 (0.56 MPa) and 24.69 kg/cm^2 (2.42 MPa), with cement-based composites achieving the highest values. Due to the deformation limits of the testing device, measured values represent minimum strengths rather than ultimate capacities. The inclusion of hemp contributed to greater deformability and improved elasticity in all mixtures.

Overall, the findings confirm that hemp-based composites offer promising performance for non-load-bearing construction, insulation applications, and lightweight building elements, particularly in seismic-prone regions where reduced mass is advantageous. However, high water absorption and slower moisture release underline the need for further improvement in durability. Future research should focus on enhancing moisture resistance, optimizing binder combinations, and investigating long-term hygrothermal performance to support wider application in sustainable building systems.

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Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, A.A. and F.B.; methodology, S.A. and H.A.S.; investigation, A.A. and A.K.A.; data curation, A.A.; writing-original draft preparation, A.A.; writing-review and editing, F.B. and I.I.; supervision, F.B. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The data supporting this study are available from the corresponding author upon reasonable request.

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Institutional review board statement

Not applicable.

Use of AI for writing assistance

AI tools (ChatGPT and Gemini) were used solely for grammar checking and language editing. All scientific content, analysis, and conclusions were generated by the authors.

Dataset

Not applicable. All data generated or analysed during this study are included in this published article.

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