

Article

Effect of Technological Variables on Thermal Conductivity and Compressive Strength of Hemp–Lime Composites

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Abstract

Hemp–lime composites are bio-based building materials with carbon sequestration potential, yet their properties exhibit significant variability depending on manufacturing variables, and standardized production guidelines remain lacking. This study investigates the influence of water-to-binder ratio ($W/B = 1.75, 1.95, 2.15$) and compaction degree ($CD = 150\%, 170\%, 190\%$) on the thermal conductivity and compressive strength of hemp–lime composites using a full 3×3 factorial design at a binder-to-shiv ratio of $B/S = 1:1$. Results were synthesized with previously published investigations from a systematic research programme, enabling a comparative assessment of four technological variables across an extended dataset spanning densities from 227 to 518 kg/m³. The binder-to-shiv ratio was identified as the dominant factor governing both properties, primarily through its effect on bulk density and the mechanical character of the composite. Compaction degree was the most effective parameter for adjusting properties within a fixed mix design, with the strongest gains observed at the transition from $CD = 150\%$ to $CD = 170\%$. The water-to-binder ratio exerted only marginal influence on bulk density and thermal conductivity, while its effect on compressive strength remained inconclusive at $B/S = 1:1$. Hemp shive particle size had a limited effect on thermal conductivity and no detectable influence on compressive strength. Both properties exhibited strong positive linear relationships with bulk density across the extended dataset. The findings support the standardization of hemp–lime composite production and the development of practical design guidelines.

Keywords: hemp–lime composite; thermal conductivity; compressive strength; water-to-binder ratio; bulk density; bio-based building material; sustainable construction



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1. Introduction

The construction sector remains the most emissions-intensive sector of the global economy, accounting for 37% of global greenhouse gas emissions [1]. Concurrently, the 2023 United Nations Environment Programme (UNEP) report indicates that the global building floor area is projected to double by 2060 [1]. As the operational energy efficiency of new buildings improves, the need to address embodied carbon associated with material production and construction processes becomes increasingly urgent. These challenges are reflected in emerging regulatory frameworks worldwide, including the European EPBD IV directive and similar requirements in Canada, the United States, and China [2–6], which mandate whole-life carbon assessment of buildings. In response to these regulatory requirements, the International Energy Agency (IEA) and numerous research institutions emphasize the necessity of broader adoption of bio-based materials as a key strategy for reducing the whole-life carbon footprint of buildings [7]. These materials, through

biological carbon sequestration during plant growth, offer the potential to achieve negative carbon balance [8].

Among bio-based building materials, hemp–lime composites (HLC)—consisting of hemp shive aggregate bound with a lime-based binder—have attracted increasing research attention due to their low thermal conductivity, vapour permeability, and capacity for carbon sequestration during both plant growth and binder carbonation. Reviews of the material confirm its potential as a sustainable building component [9,10], while experimental studies demonstrate that HLC walls offer significantly longer thermal phase shift compared to mineral wool assemblies, indicating better attenuation of outdoor temperature fluctuations and improved indoor thermal comfort [11]. Despite growing popularity, HLC properties exhibit significant scatter in values depending on composition and technological manufacturing parameters. The literature reports wide ranges: compressive strength from 0.1 to 1.2 MPa [12,13], with an extreme case of 5.75 MPa using magnesium-based binder [14], and thermal conductivity 0.06–0.13 W/(m·K) [15–18]. Properties are influenced by: binder type [19–21], and most prominently by the binder-to-shive ratio (B/S), which governs composite density and determines the trade-off between mechanical and thermal performance. Increasing B/S raises compressive strength and thermal conductivity while reducing vapour permeability, with reported B/S values ranging from 0.69 to 4.82 across the literature [15,22–27]. This relationship is not strictly linear. Studies show that the effect of increasing B/S on thermal conductivity is more pronounced at higher ratios [28], suggesting a threshold behaviour in binder-aggregate interaction. Further variables influencing composite properties include curing conditions [27], aggregate particle size [29], composite age [26,27], compaction degree [30,31], and even forming direction [30]. An additional source of value scatter is the diversity of methods for determining compressive strength: Ref. [31] identified 6 distinct strength criteria, with methodological details such as specimen size or loading rate differing even within a single criterion. Significant scatter also characterizes the global warming potential (GWP), which can range from -9.696 to $+10.165$ kg CO₂eq/m² [32], depending not only on HLC composition and manufacturing technology, but also on constituent origin [33]. In the context of increasing regulatory requirements for whole-life GWP calculation in buildings, this scatter, encompassing both negative and positive carbon balances, becomes a critical issue requiring standardization of manufacturing processes.

The choice of B/S ratio therefore involves a fundamental trade-off: beyond its effect on thermal and mechanical properties, increasing B/S ratio simultaneously raises embodied emissions and eliminates CO₂ sequestration potential [33,34], constituting a critical design trade-off between mechanical performance and environmental impact. Within a fixed mix design, material compaction degree (CD) during forming provides an additional means of controlling properties through porosity changes [31], yet is rarely quantified in the literature. Descriptions of the forming process are typically qualitative and non-reproducible, ranging from “slight compaction” to “tamped to avoid large air voids” [35,36], making cross-study comparison of results unreliable. Compaction efficiency is in turn governed by mixture workability, which depends on both B/S and the water-to-binder ratio (W/B). Water plays a dual role in the composite: insufficient water impairs binder hydration and reduces mechanical strength, while excess water causes binder segregation, increases density and thermal conductivity, and prolongs drying time [37–39]. Despite this critical influence, clear compositional guidelines for water content are lacking. In practice, the required amount of water is most commonly determined by experience or qualitative consistency assessments such as the “damp muesli” criterion [40], which are inherently subjective and difficult to reproduce between research groups. The aggregate itself also plays a role: hemp shive particle size influences both mechanical and thermal properties, although reported

effects vary considerably across studies. Differences in thermal conductivity attributable to particle size range from as little as ~6% to as much as ~34% [29,41]. This variability likely reflects the confounding influence of density, which is itself affected by particle size through changes in packing efficiency, as finer fractions produce denser composites with higher thermal conductivity. However, this effect is difficult to isolate from direct particle geometry effects when density is not controlled between compared mixtures. Additionally, particle chemical composition varies depending on country of origin and production method [42], further complicating cross-study comparison. Alongside these manufacturing variables, long-term durability represents a further critical consideration: cyclic exposure to water and temperature causes microstructural degradation [43], emphasizing the importance of proper structure formation during production.

In response to the identified challenges, a systematic research programme was undertaken to develop objective methodologies and determine the influence of technological variables (Figure 1). The starting point was exploratory research [25] demonstrating significant influence of B/S ratio and revealing methodological difficulties and an underappreciated variable—water content. The program encompassed development of: (1) image analysis method for hemp shive particle characterization (ImageJ), enabling more objective determination of particle length distribution than traditional sieve analysis—the influence of three fractions on thermal conductivity was examined, demonstrating a relatively marginal effect (~6%) [17]; (2) Compaction Degree (CD) method, defining compaction as the ratio of compacted material density to loose-fill density, eliminating the subjectivity of qualitative descriptions—the influence of three compaction levels (CD = 150%, 170%, 190%) was examined, demonstrating significant influence on strength [31]; and (3) a criterion for determining compressive strength based on 1% permanent deformation (EN 408 standard), which proved most universally applicable [31]. Parallel investigations [34] encompassing three different B/S ratios for wall, roof, and floor applications provided broader property context.

Despite described progress, a fundamental knowledge gap remains: no study to date has systematically investigated all four technological variables within a unified experimental framework, nor assessed their relative importance and mutual interactions. Previous investigations, including those conducted within the present programme, followed a one-variable-at-a-time approach, which precludes direct comparison of variable influence across different mix proportions and excludes interaction effects by design. Specifically, the influence of W/B ratio on composite properties has not been systematically investigated, as in previous studies [17,31] the W/B ratio was held constant; direct comparison of the influence of individual variables at different B/S ratios is lacking; and the CD method requires verification under conditions of varying mixture consistency, as water content may affect the reference loose-fill measurement.

This work aims to address these gaps through:

1. Systematic investigation of W/B influence on thermal conductivity and compressive strength using a 3×3 factorial design ($W/B = 1.75, 1.95, 2.15 \times CD = 150\%, 170\%, 190\%$), enabling identification of interactions between variables;
2. Synthesis of results with previous investigations [17,31] to provide a comparative assessment of the influence of four technological variables (B/S, W/B, particle size, CD) on thermal and mechanical properties;
3. Critical evaluation of the CD method and proposal for refinement. Investigations were conducted at B/S = 1:1 (density ~300 kg/m³), complementing previous studies at B/S = 2:1 and 3:1 [17,31] and the range B/S = 1:1, 1.8:1, and 2.25:1 [34].

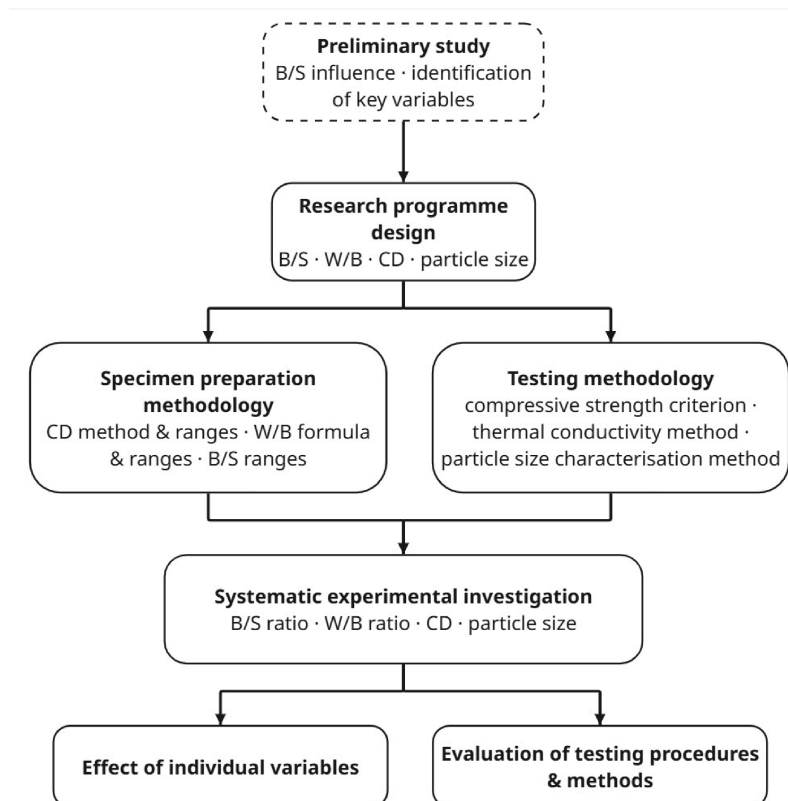


Figure 1. Schematic diagram of the systematic research programme showing the two-stage methodology development (specimen preparation and testing protocols) followed by investigation of four technological variables.

The combination of factorial design with synthesis of the entire research programme results represents, to the authors' knowledge, the first systematic comparative assessment of all four key technological variables—B/S ratio, W/B ratio, compaction degree, and hemp shive particle size—within a single unified framework, enabling a qualitative ranking of their relative influence and identification of interaction effects between W/B ratio and compaction degree.

2. Materials and Methods

2.1. Materials

2.1.1. Hemp Shives

Hemp shives derived from the Futura 75 variety were produced in Poland by Podlaskie Konopie (Dobrzyniówka, Poland). The hemp harvest took place in 2023, followed by natural retting during the decortication process. The supplied hemp shives were sieved to obtain three distinct particle size fractions. This process yielded three particle size groups: fine (F), medium (M), and coarse (C). The sieve sizes of 2 mm and 4 mm were selected based on preliminary observations of the particle size distribution of the supplied hemp shives. Sieves with apertures larger than 4 mm retained only a negligible proportion of material, while sieves finer than 2 mm allowed the passage of fine dust and fine residual fibres. The selected size range therefore captures the most representative and practically relevant portion of the supplied hemp shive material, while simultaneously enabling effective dust removal. Material retained on the 4 mm sieve constituted fraction C, material passing through 4 mm and retained on 2 mm constituted fraction F, while fraction M was obtained by blending F and C in equal proportions by mass (50/50 wt.%). The current study utilized fraction C.

The same batch of hemp shives was used throughout the research programme, with different particle fractions employed in individual studies: publication [31] utilized fraction F, while [17] examined all three fractions (F, M, C). Relying on the same batch of hemp shives produced in the same season using the same decortication method (natural retting) ensures consistency of chemical properties across the entire research program. It has been demonstrated that region and harvest timing, and particularly the retting method of industrial hemp, affect not only the chemical composition of the raw material but also the properties of the finished HLC [42,44]. Chemical components present in hemp, such as pectins, lipids, hydrocarbons, and proteins, influence the binding of mineral binder [44]. Studies [34] showed that hemp shive from France, where chemical decortication is commonly employed, exhibited relatively low specific heat compared to natural field retting, which may result from a kind of “sterilization” of plant particles from microorganisms naturally present during traditional retting. This single-batch approach eliminates inter-batch variability as a confounding factor, ensuring that observed differences in composite properties across studies can be attributed to the investigated technological variables rather than to raw material inconsistency.

2.1.2. Binder Characteristics

The mineral binder consisted of three components in the following mass proportions: 75% hydrated lime CL 90-S (ALPOL Gips, Trzebinia, Poland), 15% Portland cement CEM I 42.5R (Holcim S.A., Małogoszcz, Poland), and 10% metakaolin type L05 (Mikrosilika Trade, Warsaw, Poland).

Hydrated lime is the most commonly used binder in HLC due to its availability and compatibility with the material’s vapour permeability and the shives’ water absorption capacity. Calcium hydroxide, the main component of hydrated lime, exhibits high porosity supporting water absorption and thermal insulation properties [27,35]. In addition, it creates a highly alkaline environment ($\text{pH} \approx 12$), which protects hemp shives from biological corrosion and mould growth while improving the composite’s fire resistance [45]. Due to the slow setting process of lime binder, additives supporting early strength development were incorporated, primarily needed for technological reasons. Portland cement CEM I 42.5R was used for this purpose. Additionally, to reduce the carbon footprint of the binder, metakaolin type L05 was employed, a natural pozzolan that improves durability through reaction with calcium hydroxide [46]. A detailed description of the binder’s chemical composition and the chemical reactions occurring within it is presented in publication [31].

2.1.3. Water

Tap water (Faculty of Civil Engineering, Warsaw University of Technology, Warsaw, Poland) at a temperature of approximately 20 °C was used for mixture preparation.

2.2. Methods

This study employs standardized protocols developed within a systematic research programme on hemp–lime composites. Three key methodologies were applied:

1. Image analysis for particle characterization,
2. The Compaction Degree (CD) method for compaction level quantification,
3. The Proposed Method based on the permanent deformation criterion for compressive strength determination.

Consistent application of these protocols across all investigations (particle size [17], compaction [31], and water content—current study) ensures valid synthesis of results despite different mixture proportions (B/S ratio). Furthermore, all three studies employed

identical specimen curing conditions, ages, production methods, and thermal conductivity measurement procedures, and utilized materials from the same suppliers.

2.2.1. Particle Characterization

Geometric characterization of hemp shives was performed according to the image analysis methodology described in detail in [17], using ImageJ software version 1.54 g (National Institutes of Health, Bethesda, MD, USA). In brief, scanned images of 3 g samples were processed to binary contrast and analyzed to determine particle area, perimeter, Feret diameter, and minimum Feret diameter, from which equivalent diameter, circularity, and elongation were derived. A sample size of 15 g was established in [17] as sufficient for representative characterization of particle size distribution.

These parameters were selected because shape descriptors such as elongation and circularity provide information beyond what sieve analysis can offer. Since ImageJ measures the projected area of the largest particle face, elongated or irregular particles have a greater actual surface area relative to their projected area—a distinction relevant to binder demand, as more surface area requires more binder paste for adequate coating. Furthermore, shape parameters are expected to influence mix workability, particle packing efficiency, and resistance to compaction, though a systematic investigation of these relationships falls outside the scope of the present study and is identified as a direction for further research. Geometric characteristics of fraction C are presented in Figure 2 and Table 1 based on detailed characterization published in [47].

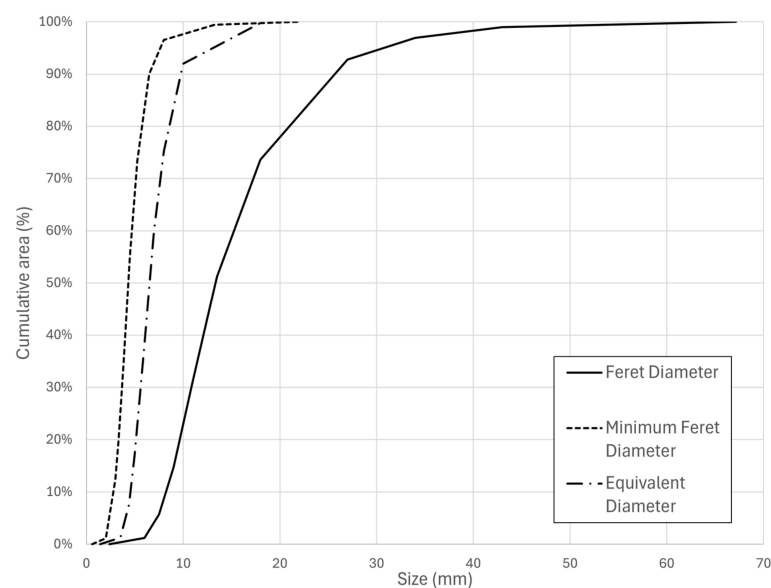


Figure 2. Particle size distribution of hemp shives (fraction C).

Table 1. Mean characteristics of hemp shives (fraction C).

Bulk Density (kg/m ³)	Particle Feret (mm)	Minimum Feret (mm)	Equivalent Diameter (ED) (mm)	Area (mm ²)	Circularity (-)	Elongation (-)
97.5	12.34	4.01	5.79	36.49	0.45	3.33

2.2.2. Compaction Level Quantification

The method for determining the Compaction Degree (CD) involves relating the density of compacted material to the density of loose fill according to the formula (1):

$$CD [\%] = (\rho_C / \rho_L) \cdot 100 \quad (1)$$

where

ρ_C —bulk density of specimen after compaction [kg/m^3]

ρ_L —bulk density of specimen in loose state [kg/m^3]

To determine ρ_L , fresh mix was freely poured into a $30 \times 30 \times 8$ cm mould without any compaction, then weighed (Figure 3). Based on the calculated CD value and target mould volume, the mass of mixture needed to fill the mould at the assumed compaction degree was determined. This measured mass of material was divided into an appropriate number of layers: four layers for $30 \times 30 \times 8$ cm moulds and two layers for $15 \times 15 \times 15$ cm moulds. Each layer was tamped with a wooden tamper ensuring uniform compaction across the entire specimen surface. Three compaction levels were applied in the research programme. The lower bound (CD = 150%) was established empirically as the minimum compaction level at which specimens maintained sufficient green cohesion upon demoulding after 24 h—that is, the specimens could be handled and transferred to the curing chamber without loss of structural integrity. Below this threshold, the low binder content (B/S = 1:1) combined with insufficient compaction resulted in specimens that could not sustain their own weight after demoulding. The upper bound (CD = 190%) corresponds to the practical limit of manual compaction: above this level, the elastic springback of hemp shives prevented further densification, as the material partially recovered its volume between successive tamping events, making higher compaction degrees unachievable without mechanical assistance. The intermediate level (CD = 170%) was selected as the midpoint between these two bounds, enabling assessment of the non-linearity of the compaction effect.



Figure 3. Key stages of specimen preparation and testing: (a) empty reference mould; (b) loose-fill material for ρ_L determination; (c) compacted specimen showing layered structure (dye visualization); and (d) thermal conductivity testing in FOX 314 apparatus.

It should be noted that the loose-fill density, used as the reference value in the CD method, is sensitive to mixture workability. Consequently, variables that affect workability,

such as water content and aggregate particle size, may indirectly influence the CD measurement. A detailed analysis of this phenomenon and its impact on results is presented in Section 4.3.

2.2.3. Compressive Strength Criterion

Various testing criteria can be applied to determine the compressive strength of HLC. Publication [31] compared methods existing in the literature and proposed a new approach (Proposed Method). The specific deformation character of HLC under loading means that some traditional methods have limited applicability. The maximum stress-based method is applicable only to certain mixtures, while methods based on loss of linearity in the stress–strain curve are sensitive to researcher interpretation. Methods utilizing 5–10% total strain better describe serviceability state than actual material strength and omit the elastic strain component, whereby the same strain value may indicate different degrees of material damage depending on the elastic modulus. For these reasons, within the research programme, the Proposed Method was selected and applied in all conducted investigations, including the present work. This method involves determining composite strength as the stress corresponding to 1% permanent deformation in the material, adapted from standard [48] for structural timber testing. The method is described and illustrated in detail in [31]. This approach better corresponds to the specific deformation behaviour of hemp–lime composite under compressive loading. Moreover, in cases where the material works in conjunction with timber structures—which frequently occurs in building practice—it constitutes the most appropriate solution among analyzed methods. It should be noted, however, that the applicability of the Proposed Method depends on the presence of a clearly defined inflection point in the stress–strain curve. At low binder content ($B/S = 1:1$), this condition may not be met across all compaction levels, which limits the method's reliability for such mix designs. This limitation is discussed in detail in Section 4.1.

2.3. Experimental Design

To evaluate the influence of water content and compaction level on material properties, a full 3×3 factorial design was employed to examine the effects of both variables and their potential interaction. The water-to-binder ratio was varied across three levels. To identify the optimal W/B for the binder composition employed, water demand data reported in the literature for hemp–lime composites with comparable binder compositions were collected and a best-fit curve was applied to the dataset, yielding the empirical formula (2):

$$W_B = 1.95 \cdot B_S^{-0.51} \quad (2)$$

where

W_B is the water-to-binder ratio (W/B);

B_S is the binder-to-shiv ratio (B/S).

The formula describes the relationship between mix proportions and optimal water demand across a range of B/S ratios reported in the literature [15,27,35]. For the tested mixture ($B/S = 1:1$), the formula yields $W/B = 1.95$, which was adopted as the reference (optimal) level. To examine the effects of water deficiency and excess relative to this optimum, the W/B ratio was decreased and increased by 0.2, yielding three levels: $W/B = 1.75$, 1.95, and 2.15. This step size was selected to produce a meaningful variation in mix workability while remaining within the range of practically achievable water contents for the tested binder and shiv combination. The compaction degree was varied across three levels ($CD = 150\%$, 170% , 190%) established within the CD methodology developed in

the research programme. The combination of these variables created nine experimental conditions (Table 2), enabling evaluation of:

1. The main effect of water-to-binder ratio at constant compaction;
2. The main effect of compaction degree at constant water content;
3. Interaction effects between W/B and CD.

Table 2. Sample designations for hemp–lime composites based on compaction degree and water-to-binder ratio.

Compaction Degree	Water-to-Binder Ratio		
	1.75	1.95	2.15
CD = 150%	HLCL150	HLCM150	HLCH150
CD = 170%	HLCL170	HLCM170	HLCH170
CD = 190%	HLCL190	HLCM190	HLCH190

To enable comprehensive synthesis across the research programme, complementary measurements were conducted: thermal conductivity on specimens from [31] and compressive strength on specimens from [17], following identical protocols (Sections 2.2.2 and 2.2.3). Table 3 provides an overview of all series included in the programme, their mix design parameters, and the properties measured in each case. Series for which complementary measurements were added in the present work are indicated separately. These additional data, combined with the factorial design results, enabled comparative analysis of all four technological variables (B/S, W/B, CD, and particle size).

Table 3. Overview of all series in the research programme. B/S = binder-to-shiv ratio (by mass); W/B = water-to-binder (L-low, O-optimal, H-high); CD = compaction degree (%); Hemp Shive Group (F-fine, C-coarse, M-medium) according to [17]; ● = measured in source publication; ○ = not measured; † = complementary measurement added in the present work.

Series ID	B/S	W/B	CD	Hemp Shive Group	Thermal Conductivity	Compressive Strength	Source
HLCL150	1	L	150%	C	●	●	This study
HLCM150	1	O	150%	C	●	○	This study
HLCH150	1	H	150%	C	●	●	This study
HLCL170	1	L	170%	C	●	●	This study
HLCM170	1	O	170%	C	●	○	This study
HLCH170	1	H	170%	C	●	●	This study
HLCL190	1	L	190%	C	●	●	This study
HLCM190	1	O	190%	C	●	●	This study
HLCH190	1	H	190%	C	●	●	This study
HLC.150	2	L	150%	F	○	●	[31]
HLC.170	2	L	170%	F	○ [†]	●	[31]
HLC.190	2	L	190%	F	○	●	[31]
HL1.C	2	O	150%	C	●	○	[17]
HL1.F	2	O	150%	F	●	○	[17]
HL1.M	2	O	150%	M	●	○ [†]	[17]
HL2.C	2	H	150%	C	●	○	[17]
HL2.F	2	H	150%	F	●	○	[17]
HL2.M	2	H	150%	M	●	○	[17]
HL3.C	3	H	150%	C	●	○ [†]	[17]
HL3.F	3	H	150%	F	●	○ [†]	[17]
HL3.M	3	H	150%	M	●	○ [†]	[17]

2.3.1. Specimen Preparation

The specimen preparation procedure followed the established protocol from previous programme studies [17,31], ensuring methodological consistency. All components were weighed according to mixture proportions (Section 2.1). Dry binder constituents (hydrated lime CL 90-S, Portland cement CEM I 42.5R, metakaolin) were combined with water and mixed for 2–3 min in a planetary mixer to form homogeneous paste. Hemp shives were subsequently added gradually in portions to ensure uniform particle coating and prevent agglomeration. Total mixing time was 6–8 min.

Mixture workability varied significantly with water content. At low water level ($W/B = 1.75$), the mixture exhibited increased resistance to mixing: shives wedged more strongly and displayed reduced mutual slip, impeding material flow through mixer blades and requiring careful handling to prevent spillage. Conversely, at high water content ($W/B = 2.15$), shives were thoroughly moistened; however, the relatively low binder content ($B/S = 1$) prevented paste runoff, with binder remaining adequately adhered to shiv surfaces. Specimens were formed in two geometries following the methodology established in [17]: $300 \times 80 \times 300$ mm slabs for thermal conductivity measurements and $150 \times 150 \times 150$ mm cubes for compressive strength testing. During preparation of thermal conductivity specimens, the number of tamping strokes required to achieve target compaction levels was recorded as an indicator of mixture workability (Table 4). The results showed that compaction degree had a dominant effect on the number of strokes required: at $CD = 150\%$, an average of 4–6 strokes per layer were sufficient regardless of water content, while at $CD = 170\%$, this number increased markedly to 10–22 strokes. No clear monotonic relationship between W/B ratio and the number of strokes was observed, suggesting that workability is governed primarily by the target compaction level rather than water content alone. Each stroke delivered approximately 49 J of compaction energy (10 kg hammer released from 0.5 m height). It was also noted that the number of strokes required increased slightly with each successive layer during casting, which may indicate elastic springback behaviour of the hemp shive (see Section 2.2.2), as the progressively compacted mass beneath each new layer offered increasing resistance, suggesting the material partially recovers its volume after each tamping event. All specimens were demolded after 24 h and cured following the protocol established in [17,31] until testing at 28 days.

Table 4. Mean number of tamping strokes per layer required to achieve target compaction levels.

Compaction Degree	CD = 150%	CD = 170%	CD = 190%
Mean tamping strokes per layer	4–6	10–22	n.d. *

* n.d.—not determined; at $CD = 190\%$, the self-weight of the tamping rod was insufficient to achieve the target compaction level and additional manual force was applied by the operator.

2.3.2. Testing Methods

Thermal conductivity was determined following EN 12667 standard [49] using a FOX 314 heat flow meter (TA Instruments, New Castle, DE, USA) with a 10×10 cm measurement area, as described in [17]. Specimens were positioned between temperature-controlled plates maintaining a 20 K differential at mean temperature of 20 °C. Heat flow direction was oriented perpendicular to the specimen compaction axis, simulating actual conditions in formwork-constructed walls.

Compressive strength was evaluated on 28-day specimens using an Instron 3382 universal testing machine (100 kN capacity) at 5 mm/min crosshead displacement rate, with loading direction parallel to the moulding axis. Testing continued until reaching 13.3% strain or pronounced stress reduction. The compressive strength determination method is described in detail in Section 2.2.3, while the complete testing procedure is provided in [31].

3. Results

3.1. Samples Density

The results demonstrate a clear increase in bulk density with both CD and W/B (Figure 4). This is consistent with the expected effects of increased material densification and improved mix workability at higher W/B. Mean bulk density across all series ranged from 233.2 to 296.3 kg/m³, reflecting the combined influence of both variables within the investigated ranges. The effect of compaction on density is more pronounced than that of water content. Density increased by an average of 9.4% between CD = 150% and CD = 170%, and by 12.4% between CD = 170% and CD = 190%, indicating a non-linear response.

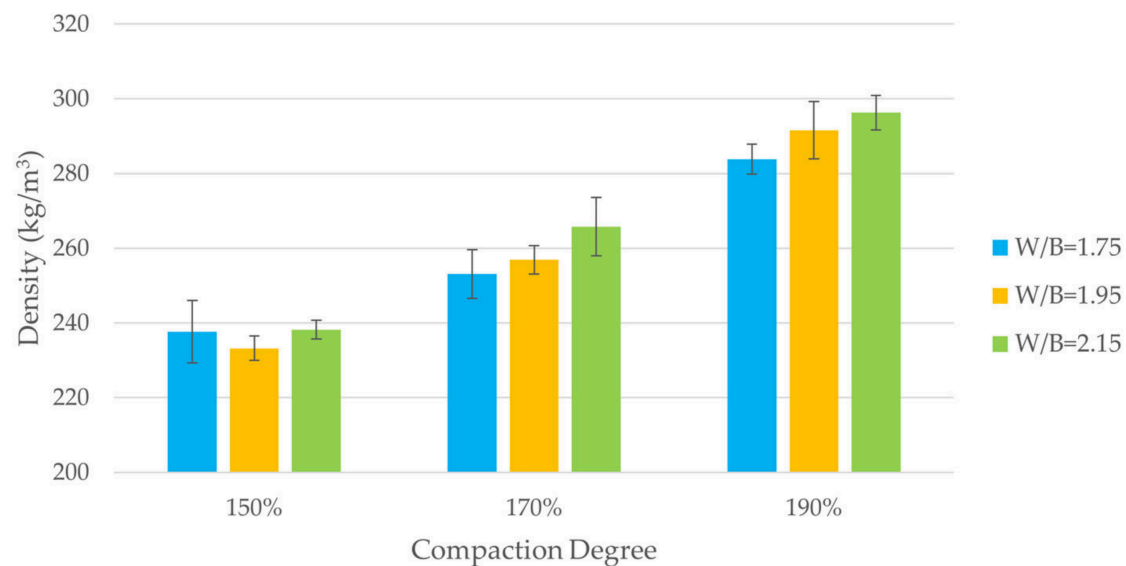


Figure 4. Mean density for each series grouped by compaction degree.

The influence of W/B on bulk density is visible but secondary. At CD = 150%, the difference in density between the lowest (W/B = 1.75) and highest (W/B = 2.15) water content is negligible, amounting to only 0.3%. At CD = 170% and CD = 190%, the effect becomes more apparent, with density increases of 5.0% and 4.4% respectively between the extreme W/B levels. The W/B effect on density was thus compaction-level dependent.

It should be noted that series HLCM150 deviates from the general trend, exhibiting a lower mean density than both HLCL150 and HLCH150. This anomaly occurs exclusively at the lowest compaction level (CD = 150%), where the effect of water content on density is minimal. At higher compaction degrees, density increases monotonically with W/B ratio.

The effect of W/B on density was also reflected in the loose bulk density of the fresh mix prior to compaction. An increase in W/B ratio resulted in a higher loose bulk density (Table 5), though this relationship was not strictly monotonic: series HLCM150 exhibited a higher value than HLCH150.

Table 5. Loose bulk density (kg/m³) of fresh hemp–lime composite mixes prior to compaction.

W/B Ratio	1.75 (Low)	1.95 (Optimal)	2.15 (High)
Loose bulk density (kg/m ³)	264.4–273.1	290.4–293.8	287.0–313.9

3.2. Thermal Conductivity

The thermal conductivity (λ) of the tested specimens ranged from 0.0840 to 0.0991 W/(m·K). Mean values for each series are presented in Table 6; results for individual specimens are shown in Figure 5. A clear positive relationship between volumetric density and thermal conductivity

was observed across all series, consistent with the linear trend fitted to the data (Figure 5, $R^2 = 0.8383$).

Table 6. Mean values of density and thermal conductivity (λ) for all experimental series. W/B = water-to-binder ratio; CD = compaction degree; SD = standard deviation.

Series	W/B	CD	Density (kg/m^3)		λ ($\text{W/(m}\cdot\text{K)}$)	
			Mean	SD	Mean	SD
HLCL150	1.75	150%	237.6	8.4	0.08873	0.00116
HLCM150	1.95	150%	233.2	3.3	0.08526	0.00116
HLCH150	2.15	150%	238.2	2.5	0.08906	0.00018
HLCL170	1.75	170%	253.1	6.5	0.08879	0.00163
HLCM170	1.95	170%	256.9	3.8	0.08974	0.00198
HLCH170	2.15	170%	265.7	7.9	0.09212	0.00151
HLCL190	1.75	190%	283.8	4.0	0.09328	0.00100
HLCM190	1.95	190%	291.6	7.7	0.09335	0.00059
HLCH190	2.15	190%	296.3	4.6	0.09704	0.00175

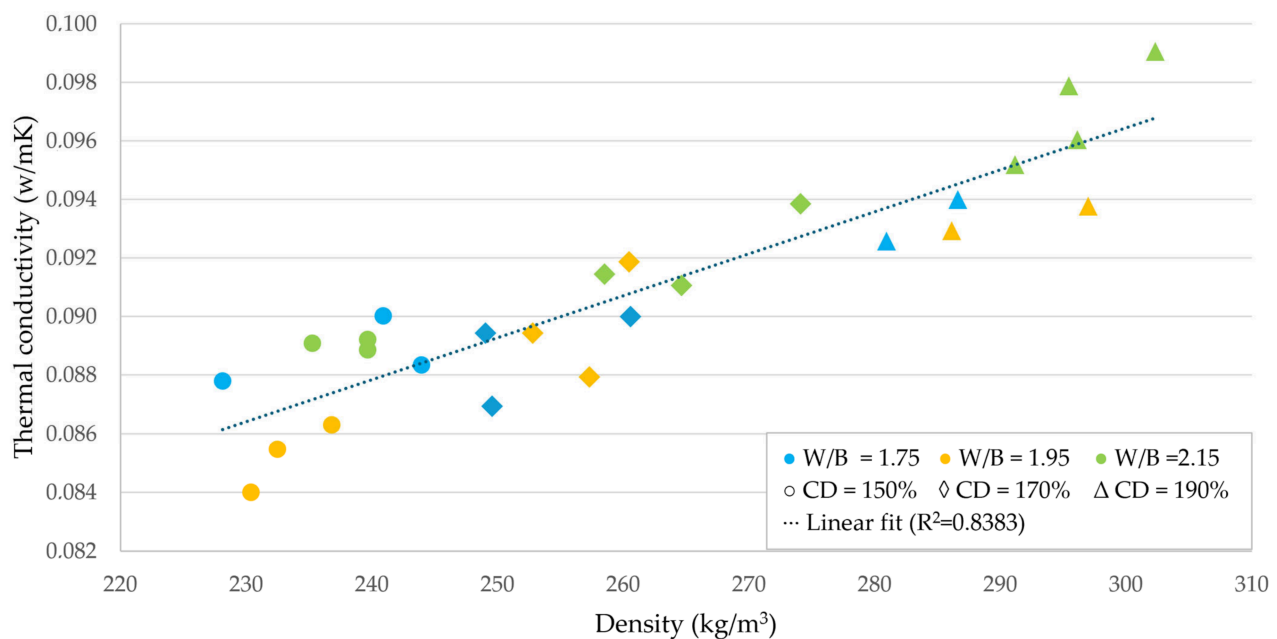


Figure 5. Relationship between thermal conductivity and density for all tested specimens.

Regarding the effect of compaction degree, the total increase in λ from CD = 150% to CD = 190% ranged from 5.1% to 9.5% depending on the W/B group. The distribution of this increase across compaction levels differed between series: for W/B = 1.75, nearly the entire increase occurred between CD = 170% and CD = 190%, with virtually no change between CD = 150% and CD = 170%. For W/B = 2.15 and W/B = 1.95, the increase was more evenly distributed across both steps (Table 6).

Regarding the effect of W/B, no consistent monotonic trend was observed (Figure 6). At CD = 170% and CD = 190%, mean λ increased monotonically with W/B ratio, with total increases of +3.8% and +4.0% respectively from W/B = 1.75 to W/B = 2.15. At CD = 150%, the net difference across the full W/B range was negligible (+0.4%). The anomalously low λ of the HLCM150 series at this compaction level coincided with its anomalously low mean density (see Section 3.1 and Table 6).

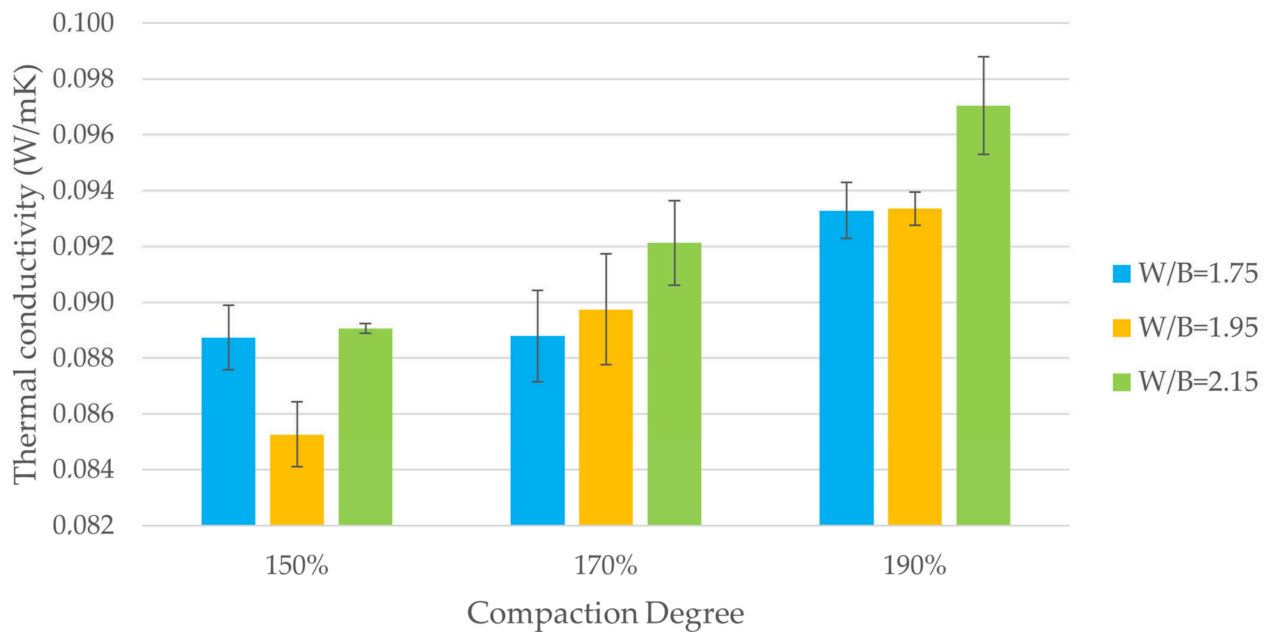


Figure 6. Mean thermal conductivity for each series grouped by compaction degree.

It should be noted that series HLCL190 and HLCM190 were tested on $n = 2$ specimens each (compared to $n = 3$ or $n = 4$ for the remaining series), which limits the reliability of the standard deviation estimates for those series.

3.3. Compressive Strength

Compressive strength was determined using the Proposed Method (described in Section 2.2.3). While this method proved applicable across the majority of tested series, its application was limited in specific cases where the stress–strain curve did not exhibit a sufficiently pronounced change in slope—the inclination changed minimally throughout the test, causing the offset line to intersect the curve at a strain far beyond the typical range, or not at all within the measured deformation. This behaviour was observed across all compaction levels examined. Strength values at 5% strain (Method 3 of [28]) are reported alongside the Proposed Method results for the affected series as a supplementary reference (Figure 7).

Series HLCM150 ($W/B = 1.95$, $CD = 150\%$) and HLCM170 ($W/B = 1.95$, $CD = 170\%$) were excluded from the compressive strength analysis. In both cases, the specimens exhibited anomalously low compressive strength compared to all other series at the same compaction level. Strength values were 3–4 times lower than those of series produced at the same compaction degree with different W/B ratios. This magnitude of difference falls outside the range attributable to W/B variation alone. Notably, the series produced at the same W/B but higher compaction (HLCM190, $CD = 190\%$) yielded strength values consistent with the general trend. This suggests that the combination of low binder content ($B/S = 1:1$), intermediate water content, and insufficient compaction resulted in an inadequately bonded composite matrix. This observation is also relevant in the context of the broader literature: studies reporting compressive strength at comparable B/S ratios typically employed mechanical rather than manual compaction [26,27]. This likely produced higher compaction levels and correspondingly higher strength values than those achievable by hand. This further illustrates the importance of reporting compaction level when comparing results across studies. The precise mechanism responsible for this anomalous behaviour remains to be systematically investigated and is identified as a direction for further research. Of particular interest is the interaction between water content, compaction

level, and binder matrix formation at low B/S ratios. The results of these two series are therefore not considered representative of the tested mix design and were not included in the interpretation. The influence of binder content and compaction on composite matrix formation is discussed further in Sections 4.1 and 4.2.

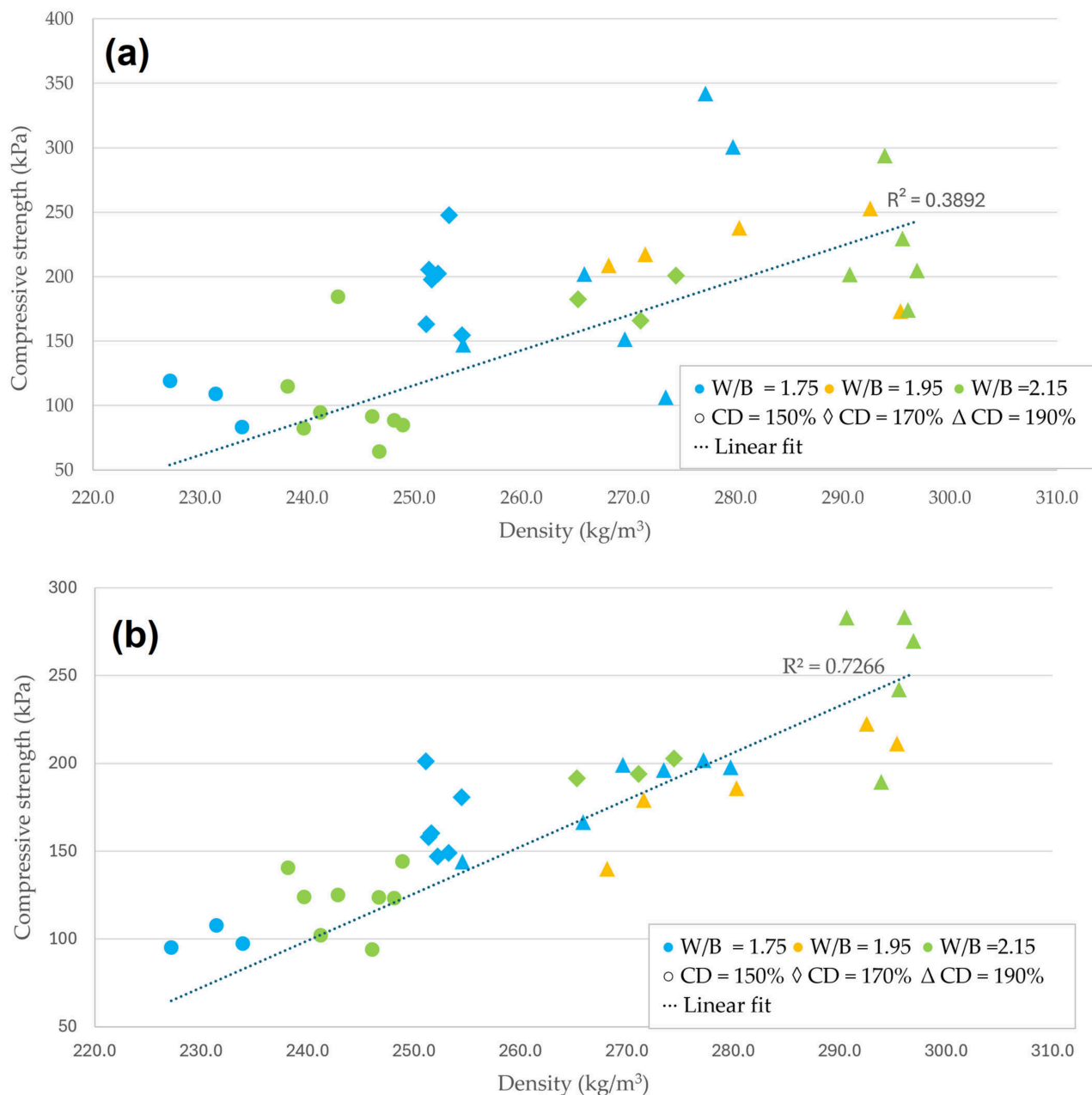


Figure 7. Compressive strength as a function of bulk density: (a) Proposed Method; (b) 5% strain criterion. Series HLCH150 and HLCH170 are excluded from both plots due to specimen preparation defects.

Within series HLCH150, HLCH190, and HLCH190, isolated specimens exhibited stress-strain curves with no distinct inflection point, causing the 1% offset line to intersect the curve at strains 2–3 times larger than the series average and producing strength values 1.5–3.2 times higher than the minimum. These outliers inflated series means and increased scatter substantially, with the most pronounced effect in HLCH190 (CV = 44.9%, the highest of all series). The supplementary 5% strain criterion (Method 3 of [31]), which is not affected by inflection-point identification, yields more consistent results for these series. The impact

of outlying specimens on the dataset is reflected in the goodness of fit of the compressive strength–density relationship: excluding series HLCM150 and HLCM170, $R^2 = 0.389$ for the Proposed Method compared to $R^2 = 0.727$ for the 5% strain criterion.

For series where the Proposed Method yielded reliable results, the effect of compaction degree on compressive strength was consistent and pronounced. Representative stress–strain curves for three series sharing the highest water-to-binder ratio ($W/B = 2.15$) but differing in CD are shown in Figure 8. The curves illustrate a clear increase in stress level with increasing CD, with a markedly larger increment between CD = 150% and CD = 170% than between CD = 170% and CD = 190%. The same pattern was observed for $W/B = 1.75$. This saturation of the compaction effect above CD = 170% was consistent across both W/B groups and both strength criteria, with the strength increment for the CD = 150% to CD = 170% transition approximately 6–9 times larger than for the CD = 170% to CD = 190% transition (Figure 9).

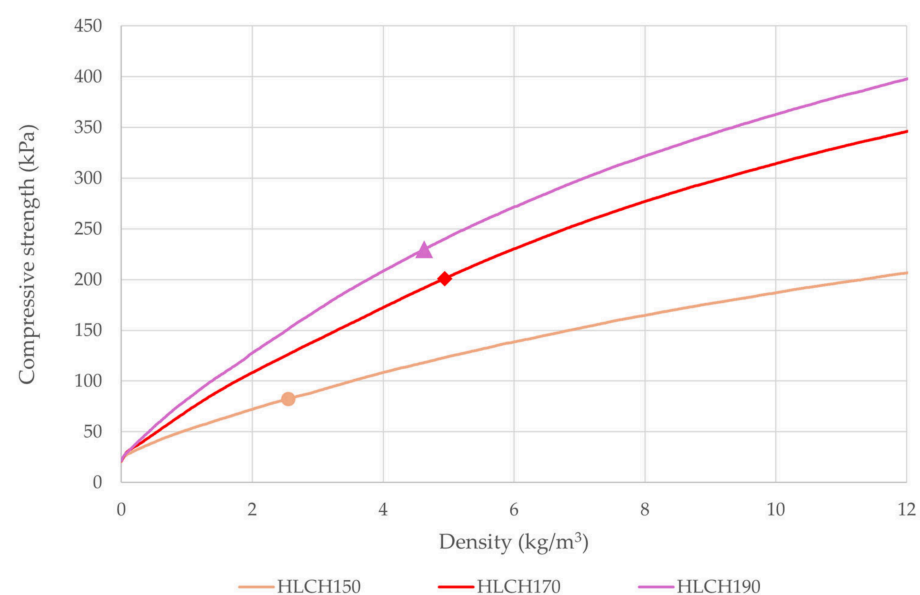


Figure 8. Representative compressive stress–strain curves for the HLCH series ($W/B = 2.15$) at three compaction degrees. Markers indicate the stress and strain values at which compressive strength was determined using the Proposed Method.

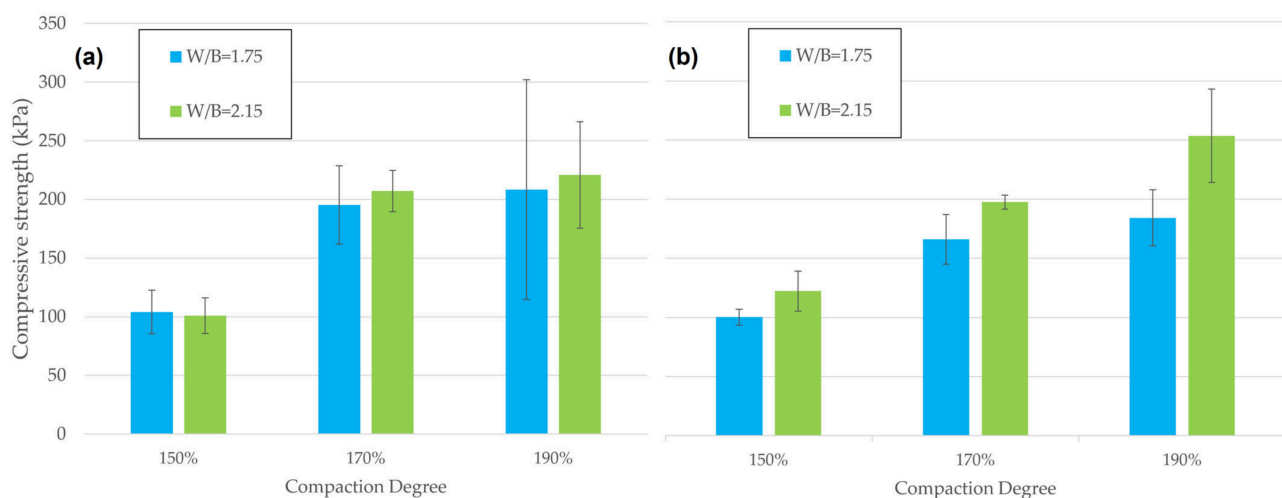


Figure 9. Mean compressive strength as a function of compaction degree for $W/B = 1.75$ and $W/B = 2.15$: (a) Proposed Method; (b) 5% strain criterion.

The effect of the water-to-binder ratio was assessed at CD = 190%, the only compaction level at which results from all three W/B groups were available (Figure 10). Using the Proposed Method, mean strengths were 208 kPa (HLCL190, W/B = 1.75), 218 kPa (HLCM190, W/B = 1.95), and 221 kPa (HLCH190, W/B = 2.15), corresponding to increments of +4.6% and +1.3% per step increase in W/B—all within the range of within-series variability. The 5% strain criterion yielded 184 kPa, 188 kPa, and 254 kPa respectively, pointing to a more substantial difference at the highest W/B tested (W/B = 2.15). This pattern is not confirmed by the Proposed Method and may reflect the sensitivity of the 5% criterion to elastic modulus differences between series rather than genuine strength differences. The effect of W/B on compressive strength therefore remains inconclusive at the compaction levels examined.

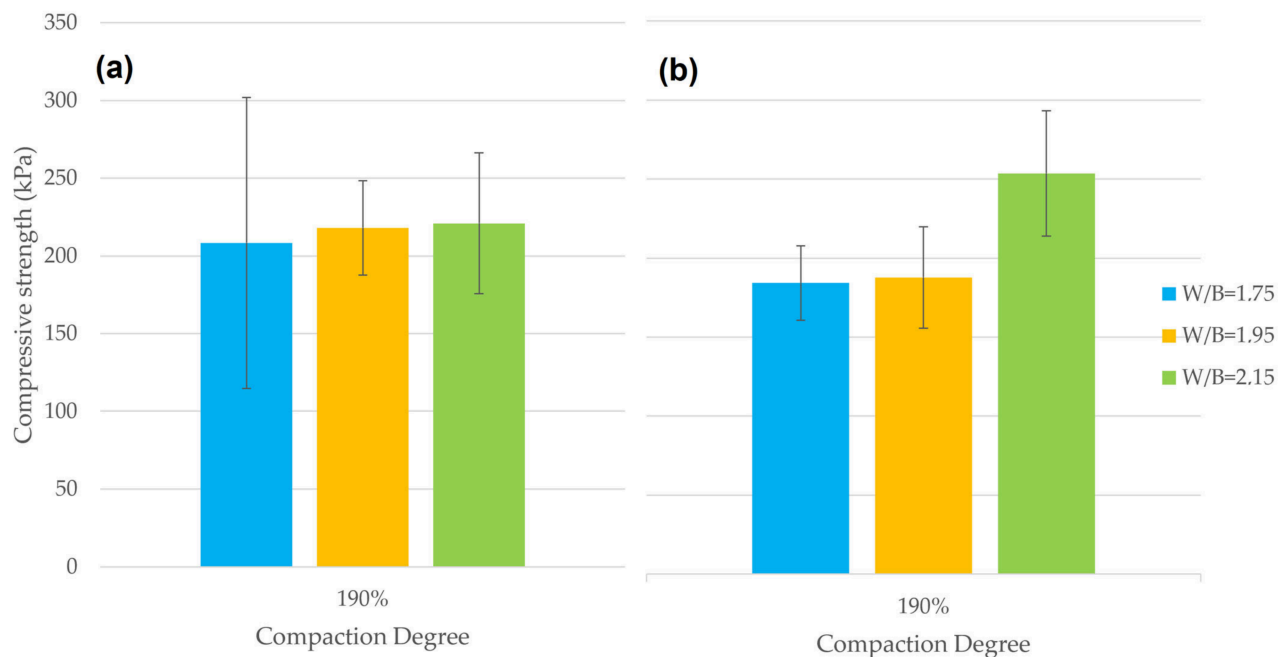


Figure 10. Mean compressive strength as a function of water-to-binder ratio at CD = 190%: (a) Proposed Method; (b) 5% strain criterion.

3.4. Extended Dataset

To place the results of the present study in a broader context, Figures 11 and 12 present scatter plots consolidating all results from the research programme. The dataset comprises results published in [17,31], results from the present study, and the complementary measurements identified in Table 3. The combined dataset spans a density range of approximately 227 to 518 kg/m³, substantially wider than the range covered by the present study alone (227–296 kg/m³), and reflects the diversity of mix designs investigated across the programme, including variations in B/S, W/B, compaction degree, and hemp shive particle size.

As shown in Figure 11, thermal conductivity exhibits a strong positive linear relationship with density across the full dataset ($R^2 = 0.9403$, $n = 55$). Figure 12 shows the corresponding plot for compressive strength. A positive linear relationship with density is also evident across the extended dataset ($R^2 = 0.6842$, $n = 68$). The coefficient of determination is markedly higher than that obtained for the present study alone ($R^2 = 0.389$), which, as discussed in Section 3.3, was depressed by the inflated mean values of series affected by within-series outliers.

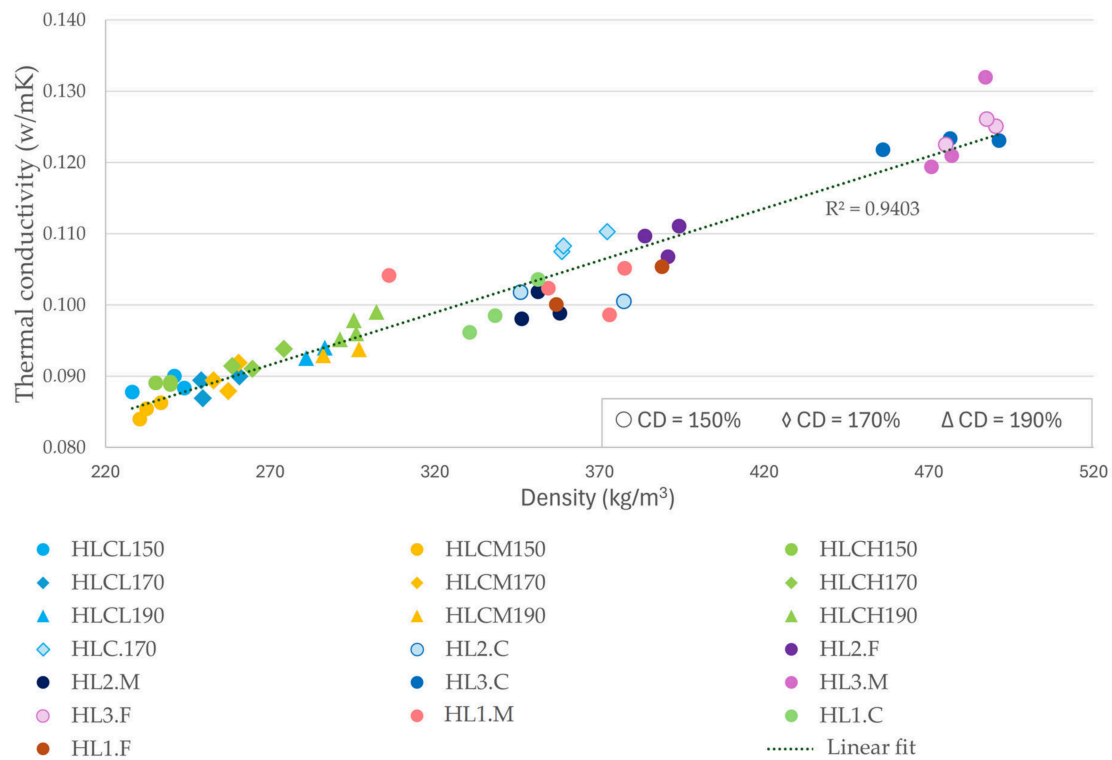


Figure 11. Thermal conductivity as a function of density for the extended dataset comprising results from [14,28], the present study, and previously unpublished measurements for selected series.

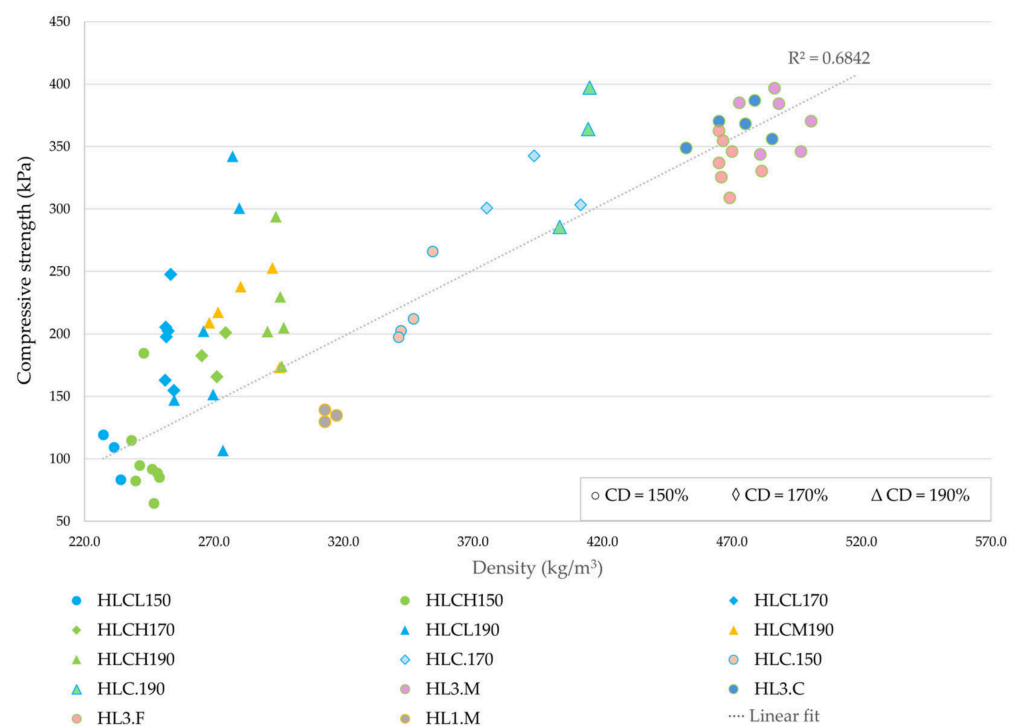


Figure 12. Compressive strength (Proposed Method) as a function of density for the extended dataset comprising results from [17,31], the present study, and previously unpublished measurements for selected series.

4. Discussion

4.1. Effect of Binder-to-Shiv Ratio on Composite Properties

The B/S ratio is the most influential technological variable investigated across the research programme, governing both thermal conductivity and compressive strength primarily through its effect on bulk density. Across the extended dataset, spanning B/S ratios from 1:1 to 3:1 [17], with densities from approximately 227 to 518 kg/m³, both λ and f_c increased with rising B/S ratio. At a comparable compaction level (CD = 150%), the increase in λ between the lowest and intermediate B/S ratio was approximately 18%, and between the intermediate and highest approximately 19%.

These findings are consistent with the literature. Sinka et al. demonstrated that regardless of binder type, an increase in B/S ratio from 1:1 to 2:1 resulted in a 17–23% increase in thermal conductivity [15]. Abdellatef et al. report an increase of approximately 30% for the same change in proportions [50]. Some researchers report even stronger effects. Sassoni et al. obtained a 34% increase in λ when B/S increased from 1.5 to 2.5 [51]. Brzyski observed an increase of 38% for a smaller step from B/S = 1.5 to 2.0 [23]. It should be noted, however, that changing the B/S ratio also alters mix workability and its susceptibility to compaction. In many of the cited studies, compaction level is not clearly defined or directly measured. The reported effect of binder content on thermal conductivity may therefore be confounded by uncontrolled differences in compaction. Within the present research programme, the effect of B/S ratio on thermal conductivity was investigated in [34] using a different binder composition. For mix designs with B/S ratios of 1:1 and 2.25:1, λ increased by 31% at comparable compaction levels. The effect of B/S ratio on density, and consequently on thermal conductivity, is thus substantial. Its influence on mechanical properties is, however, even more pronounced.

The B/S ratio also determines the fundamental mechanical character of the composite. At low binder content (B/S = 1:1, present study), the binder matrix is insufficient to dominate the mechanical response under compressive loading. The stress–strain curve lacks a well-defined inflection point, the material behaves as a low-density insulating fill, and the applicability of the Proposed Method is limited across all compaction levels examined. This behaviour is consistent with observations in [34], where the B/S = 1:1 mixture used as infill between rafters exhibited an identical deformation character. Arnaud and Gourlay identified the dominant role of shive particles in mixes with insufficient binder content, characterized by the absence of a clear elastic period and with a high level of plasticity [27]. This results in inferior mechanical properties due to the increased porosity of the composite [52]. This behaviour can be explained by the microstructural role of the binder phase. At low binder content, aggregate particles are connected by discrete binder bridges, with the shive network dominating the mechanical response and producing extended plastic plateaus under compression. At intermediate binder content, aggregates are partially coated by hydration products of varying thickness. At high binder content, the binder forms a continuous matrix encapsulating the aggregate particles, predominantly governing mechanical behaviour and producing a more pronounced elastic zone and more brittle failure [27,52,53]. Higher binder content therefore extends the elastic zone by shifting load transfer progressively to the mineral matrix [53], which explains why the Proposed Method, based on identification of the inflection point, yields reliable results mostly at B/S $\geq$ 2:1.

It should be noted that compaction also significantly affects the mechanical response of the composite: as demonstrated in [31,54], even at lower B/S ratios, a stiffer material with a more pronounced elastic zone can be obtained by applying a higher CD during production. The nature of the stress–strain curve, and in particular the clarity of its inflection point, therefore depends on both B/S ratio and compaction level, which jointly determine

the applicability of strength determination methods. The Proposed Method, based on the 1% permanent strain criterion, yields reliable and repeatable results for mixes with higher binder content, typically used in wall applications. This criterion is consistent with engineering practice for other materials, including wood loaded perpendicular to the grain [48], making it particularly appropriate for hemp–lime composites interacting with timber elements in frame structures.

4.2. Effect of Compaction Degree on Composite Properties

Within a fixed B/S ratio, CD is the most effective lever for adjusting composite properties. In both [31] (B/S = 2:1) and the present study (B/S = 1:1), the transition from CD = 150% to CD = 170% produced the largest single-step gains in density and compressive strength. Further compaction to CD = 190% yielded substantially diminishing returns. The significant influence of compaction on strength is confirmed by other authors: Williams et al. [30] reported a 175% increase in compressive strength when compaction increased from 30% to 60% volume reduction. Similarly, at a fixed B/S ratio, intensive compaction during production leads to a pronounced strength increase through reduction in void space within the composite [26,54].

Compaction produces comparable absolute gains in compressive strength regardless of B/S ratio. Between CD = 150% and CD = 170%, these amounted to approximately 97 kPa at B/S = 2:1 [31] and 91–106 kPa at B/S = 1:1 in the present study. The underlying mechanism is, however, fundamentally different. At higher binder content, compaction improves the continuity of the binder matrix, producing a well-defined inflection point in the stress–strain curve and reliable results from the Proposed Method. At B/S = 1:1, compaction primarily reduces the void space between shive particles without proportionally improving binder matrix continuity. Despite a real strength gain, the inflection point therefore remains poorly defined and the applicability of the Proposed Method is limited.

The effect of CD on thermal conductivity is indirect, operating through changes in bulk density. λ responds primarily to bulk density regardless of the B/S ratio, as confirmed by the strong λ – ρ correlations observed across the extended dataset. The total increase in λ from CD = 150% to CD = 190% ranged from approximately 5% to 10% depending on the W/B group, corresponding to the density increases observed over the same range. For the lowest W/B series, the increase in λ between CD = 170% and CD = 190% exceeded that between CD = 150% and CD = 170%. Given the measurement uncertainty, however, a definitive interpretation of this pattern is not possible. These findings are broadly consistent with [30,55], where compaction level differences accounted for most of the variation in λ between series of nominally similar composition. This is supported by Collet and Pretot, who demonstrated that at a fixed mix composition, a change in composite density alone can nearly double the value of λ [35]. The loose-fill density used as the reference in the CD method depends on how the material fills the measuring container. This is influenced by shive particle size and mix consistency, among other factors. The CD method describes compaction relative to the uncompacted state. This makes it potentially useful for on-site verification, where the ratio of the fresh mix volume to the volume of the completed partition element can be determined.

4.3. Effect of Water-to-Binder Ratio on Composite Properties

The W/B ratio influences the final bulk density of the composite. It might be expected that excess water evaporates during maturation and does not affect the density of the material. The results indicate, however, that a higher water content in the mix translated into a higher dry bulk density of the composite. The mechanism responsible for this relationship is likely the improved workability of the mix at higher W/B. The material filled

the measuring container used to determine loose-fill density more readily and completely. Loose bulk density therefore does not solely reflect the water content, but also the packing efficiency of all constituents within the measuring container. This effect is more pronounced at $CD = 170\%$ and $CD = 190\%$, where a greater mass of material was required to achieve the target compaction level. The loose-fill density differences therefore accumulated and produced a more noticeable effect on the final composite density. The absolute magnitude of this effect remains modest, with the density increase between the lowest and highest W/B amounted to approximately 5%.

The influence of W/B on thermal conductivity mirrors its effect on density and operates through the same mechanism. Increasing W/B leads to a marginal increase in λ consistent with the corresponding density increase. An exception is the HLCM150 series ($W/B = 1.95$, $CD = 150\%$), which exhibited a lower λ than the extreme W/B series at the same compaction level. At $CD = 150\%$, only a relatively small mass of mix is required to produce the specimen. The difference in loose-fill density between W/B groups has a negligible cumulative effect on the final composite density, and the lower density of this series reflects a technological effect of specimen preparation rather than a material property. Overall, the W/B effect on λ is very small, and when standard deviations are considered, differences between series frequently fall within measurement uncertainty. This is consistent with [17], where two water content levels were applied at $B/S = 2:1$, and the difference in thermal conductivity between series amounted to 1–6%, comparable to that observed in the present study.

No significant effect of W/B ratio on compressive strength was identified in the present study. As noted in Section 3.3, two series at the intermediate W/B level (HLCM150 and HLCM170) exhibited anomalously low strength values. These are attributed to technological difficulties arising from the low binder content ($B/S = 1:1$) rather than to the W/B ratio itself, as at this B/S ratio, the amount of binder is insufficient to form a coherent composite matrix. In the series that yielded reliable results, a tendency for strength to increase with W/B was observed. This may, however, reflect the associated density increase rather than a direct improvement in binder hydration quality. A W/B increment of 0.2 at $B/S = 1:1$ may be too small to produce a statistically significant effect on strength at such a low binder content.

Regardless of the above, a higher water content in the mix should generally favour the mechanical properties of the composite. Abdellatef et al. highlight the high capacity of hemp shives to absorb water from the mix, which limits its availability for binder hydration and carbonation [38]. This effect may be particularly pronounced in composites with low binder content, as in the present study, where the ratio of water to binder directly governs the quality of the binding matrix. To properly assess the influence of W/B on mechanical properties, further investigation at higher B/S ratios is needed. At higher binder content, changes in water quantity will be more significant relative to the total binder mass, and differences in hydration degree more discernible.

4.4. Effect of Hemp Shive Particle Size on Composite Properties

Shive particle size consistently reduced thermal conductivity across all B/S ratios and compaction levels examined in [17]: larger fractions produced lower composite density and correspondingly lower λ , with the total reduction from fine to coarse fraction reaching 7.6% at $B/S = 2:1$ and averaging approximately 4.1% across all series. The mechanism is straightforward: larger particles create larger inter-particle voids in the uncompacted state, and although compaction partially closes these voids, a residual porosity advantage is preserved in the compacted composite. This is consistent with findings in the literature,

where shive characteristics were shown to influence the insulating properties of hemp–lime composites, albeit to a modest degree [28,29,56].

No detectable effect of particle size on compressive strength was identified from supplementary measurements at B/S = 3:1 (previously unpublished), where series HL3.F (fine fraction, mean density 469.1 kg/m³), HL3.M (medium fraction, 491.9 kg/m³), and HL3.C (coarse fraction, 471.4 kg/m³) yielded mean compressive strengths of 338, 378, and 366 kPa respectively. The ranking of mean strengths corresponds to the ranking of mean densities, with no systematic offset attributable to particle size fraction. This suggests that at B/S = 3:1, compressive strength is governed by the density of the binder matrix rather than by aggregate geometry. Differences in packing arising from granulometry are absorbed by the binder phase and do not translate into differences in compressive strength. It should be noted that although compaction degree was kept constant across compared fractions, different particle sizes resulted in different final composite densities due to differences in packing efficiency. Since both thermal conductivity and compressive strength are strongly density-dependent, effects attributed to particle size may partly reflect these density differences rather than direct particle geometry effects. A fully rigorous assessment of particle size influence would require maintaining comparable final densities across fractions. This is consistent with the conclusion from [17] that the B/S ratio exerts a considerably stronger influence on both thermal and mechanical properties than shive granulometry, and that the particle size effect on λ —while real—is secondary to the effects of mix composition and compaction.

An important technological aspect observed during specimen preparation is the deterioration of mix workability with increasing particle size—larger shives are more difficult to mix homogeneously and more resistant to compaction, which may represent a significant practical limitation during production. It should also be noted that hemp–lime composites can be produced using finer shive fractions than those employed in the present programme. The literature reports shive fractions with mean particle lengths not exceeding 5 mm [41,57,58]. The finest fraction used in the present programme had a mean particle length of approximately 9 mm, reflecting the processing characteristics of Polish hemp shives. Precise granulometric characterization through image analysis is therefore particularly important when comparing results across studies using shive fractions of different origins and processing methods, as differences in particle geometry may otherwise be confounded with differences in raw material quality. The effect of particle size on λ may be more pronounced in studies using finer and more uniform fractions, as differences in packing geometry are amplified at smaller absolute particle sizes.

5. Conclusions

This study investigated the influence of W/B ratio and CD on the thermal conductivity and compressive strength of hemp–lime composites. Previously published investigations conducted within the research programme were incorporated into the analysis, and complementary measurements were added to selected series, enabling a comparative assessment of four technological variables: B/S ratio, CD, W/B ratio, and hemp shive particle size. The following conclusions are drawn from the systematic research programme as a whole:

- The binder-to-shive ratio (B/S) is the dominant technological variable governing composite density, thermal conductivity, and compressive strength. Beyond its quantitative effect, B/S determines the fundamental mechanical character of the composite and the applicability of strength determination methods: at B/S = 1:1 the material behaves as a plastic insulating fill and the Proposed Method shows limited applicability, while at B/S $\geq$ 2:1 the binder matrix dominates load transfer and the Proposed Method yields

reliable results. The 5% strain criterion is recommended for low-binder mixes where serviceability rather than strength governs design.

- Compaction degree (CD) acts as the most effective lever for adjusting composite properties within a fixed B/S ratio, with a non-linear response: the transition from CD = 150% to CD = 170% produced the largest gains in both compressive strength and density, with substantially diminishing returns at CD = 190%. From a practical standpoint, CD = 170% therefore represents an effective compaction target. The CD method provides a consistent and objective measure of compaction applicable under both laboratory and field conditions. A key limitation identified during the research programme is the sensitivity of the loose-fill reference density to mixture workability. To minimize this effect, determination of loose-fill density using a wide shallow mould ($300 \times 300 \times 80$ mm) is recommended.
- The water-to-binder ratio had a moderate influence on composite properties at the investigated binder content (B/S = 1:1). Increasing W/B resulted in a marginal increase in bulk density ($\leq 5\%$) and a corresponding increase in thermal conductivity, with differences between series frequently within measurement uncertainty. The effect of W/B on compressive strength remains inconclusive at this B/S ratio: the low absolute binder content limits the quality of the binding matrix regardless of water availability, and the investigated W/B increment of 0.2 may be insufficient to produce a detectable effect on strength. These findings should not be generalized to mixes with higher binder content, where W/B effects on mechanical properties are expected to be more pronounced. The empirical formula developed within the programme for determining W/B appears well-suited to the binder composition employed; however, its applicability may require verification for different binders and shiv origins. Investigation of W/B effects on mechanical properties at higher B/S ratios is recommended as a direction for further research.
- Hemp shive particle size had a limited but real effect on thermal conductivity: in investigations at B/S = 2:1, coarser fractions yielded lower composite density and correspondingly lower λ , with the total reduction from fine to coarse fraction reaching approximately 7.6%. No systematic effect of particle size on compressive strength was identified. Given the moderate influence of granulometry on both properties investigated, the selection of shiv fraction in practice should be guided primarily by technological considerations and raw material homogeneity. It should be noted that finer fractions improve workability and compactability, which facilitates the production process, but leads to higher composite density and ultimately higher thermal conductivity.
- Image analysis enables more objective determination of hemp shive particle size distribution than traditional sieve analysis, while also providing geometric parameters such as elongation and circularity relevant to binder demand and mix workability. A 15 g sample was found sufficient for reliable characterization.
- Across the extended dataset, comprising all series from the research programme over a density range of approximately 227 to 518 kg/m³, both thermal conductivity and compressive strength exhibited strong positive linear relationships with bulk density ($R^2 = 0.94$ and $R^2 = 0.68$, respectively). Bulk density therefore serves as a reliable intermediate descriptor linking technological variables to composite performance across a wide range of mix designs.

The results of the present research programme identify several directions for further investigation. First, the influence of W/B ratio on compressive strength should be examined at higher B/S ratios, where changes in water quantity represent a more significant fraction of the total binder mass and differences in hydration quality are expected to be more

discernible. Second, statistical analysis of interactions between technological variables, which the present programme investigated qualitatively through factorial design, would enable more rigorous quantification of their relative contributions. Third, the effect of specimen age on strength development deserves systematic investigation, as the 28-day testing protocol adopted in the present programme may not fully capture the long-term strengthening potential of lime-based binders. Finally, the establishment of minimum strength requirements for hemp–lime composites in different applications, such as wall infill, roof insulation, and floor fill, would provide a practical framework for translating the findings of the present programme into design guidelines.

The results of the research programme contribute to the standardization of hemp–lime composite production and may serve as a basis for developing design guidelines for broader application of this material in construction.

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Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HLC	Hemp–lime composite
B/S	Binder-to-shiv
CD	Compaction degree
W/B	Water-to-binder

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