

Article

The Thermal, Hygric and Acoustic Insulation Potential of Cast in Place and Prefabricated Australian Hempcrete Buildings

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Abstract

Hempcrete is an emerging low-carbon alternative to conventional building materials, with flexible applications as render, cast in place and prefabricated systems. To address the absence of direct, building-scale comparisons between hempcrete and brick in Australia, this study assessed the hygro-thermal and acoustic insulative performance of three hempcrete structures against a conventional brick structure, observed over summer and winter seasons within a highly urbanised area of Sydney, Australia: Cast in Place Hempcrete (CIP); Prefabricated Hempcrete (PH); and Prefabricated Hempcrete with Greenwall (GW). Seasonal temperature, humidity and noise were recorded via thermal loggers and multi-parameter air-quality sensors. These findings show CIP and GW structures significantly outperformed brick during summer, most notably GW with a mean thermal lag more than double that of brick (319.7 vs. 152.6 min; $p = 0.0001$), while PH had significantly longer thermal lag during winter. Hygric assessments found both PH and GW reduced indoor %RH significantly more than brick. Acoustic insulation (outside-to-inside noise reduction, Leq dB) was nearly three times greater for CIP than brick (7.74 vs. 2.56 dB; $p = 0.001$), with PH also outperforming brick (5.85 dB). These findings demonstrate that hempcrete can match or exceed conventional insulative performance while offering clear environmental advantages.

Keywords: acoustic; bio-based building materials; hempcrete; insulation; thermal

1. Introduction

With over a third of the global energy consumption accounted for by the built environment [1], there is no surprise it is responsible for almost 40% of the world's carbon dioxide emissions [2]. The construction industry is responsible for the consumption of 50% of the world's natural resources [3], where the local Australian industry produces in excess of 18% of the national carbon footprint [4]—within which concrete is the most widely used material [5]. Conventional concrete consists of granular aggregates bound with a lime binder, predominantly Portland cement, and water; its widespread use is largely due to its versatility, compressive strength and durability [5]. Unfortunately, the multistep method of concrete production, including the extraction of such raw materials as limestone and clay, the calcination of limestone and the generation of high kiln temperatures to drive this reaction are all incredibly carbon-intensive [6].



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Global initiatives to remedy the prolific use of such carbon-intensive materials is best demonstrated through the Sustainable Development Goals (SDGs), notably Goal 9: Industry, Innovation and Infrastructure, and Goal 11: Sustainable Cities and Communities [7]. To limit the depletion of finite natural resources and offset the hazardous GHG emissions, the SDGs prioritise the need for sustainable urban development with a lower net carbon footprint, sourced from sustainable, renewable stock.

Bio-based building materials such as hemp lime concrete, or hempcrete, offer such an alternative. Hemp is a carbon sequestering, high-yield crop, and provides a multipurpose material [2], of which the waste product, the internal woody core known as the hemp shiv [8], can be substituted as a bio-aggregate in concrete. The substitution of hemp hurds into concrete not only reduces the requirement for the carbon-intensive lime binder, it also continues to retain and absorb carbon for the life span of the structure [9,10]. Just like its traditional counterpart, hempcrete can be poured and set on site in cast in place moulds, sprayed as a slurry for a render or prefabricated offsite as blocks for more immediate installation [11]. As hempcrete's structural attributes are characterised by low bulk density, high thermal mass and moisture buffering potential [12], it is largely employed as an insulative barrier, as load-bearing applications are not appropriate.

Early assessments of hempcrete's insulative potential established that the bulk density of the material was a strong predictor of thermal conductivity [13,14]. This was largely driven by the binder type [15], water content, final mix ratio [16,17] and tamping pressure [18], where an increase in bulk density would result in a subsequent increase in thermal conductivity and compromise in insulation potential [19–21]. Following this, a recent assessment of hemp hurds as bio-aggregates [22] found that when bast fibres were extracted from the raw hemp hurd via a natural retting process, the bulk density was reduced and both the thermal and acoustic insulative performance was optimised.

Considering the variety of formats hempcrete is available in, a recent review [23] highlighted the risks and rewards with prefabricated blocks. Though expedited construction time and convenient application were an immediate benefit, the presence of mortar joints to secure blocks within walls introduce thermal bridges, and thus an opportunity for increased heat flux through the building envelope otherwise avoided with cast in place homogeneous walls.

A study assessing the effect of thermal mass of the building envelope [24], conducted during a heat wave in Poland, found superior cooling and optimal thermal comfort was observed when thermal mass was increased. In opposition to this, Alayed et al. [25] observed structures of high thermal mass modelled to experience diurnal temperature fluctuations released previously absorbed heat into the buildings overnight and subsequently increased the ventilation and cooling requirements over this time.

Meanwhile, discrepancies between thermal resistance from modelled, estimated and direct measurements were explored by Biddulph et al. [26], who acknowledge the experimental constraints in achieving reliably modelled U- and R-values (thermal transmission and resistance, respectively). This gap is methodologically significant, as laboratory-based hempcrete characterisation isolates material properties under controlled, steady-state conditions, while building-scale performance is also shaped by construction effects such as thermal bridging, geometric variation and fluctuating climatic exposure. Indeed, one of the few building-scale comparative assessments to date, by Bennai et al. [27], evaluated hempcrete against conventional materials through simulation rather than direct field measurement. These contradictory findings from both laboratory and modelled experimental designs assessing both static and fluctuating climatic conditions further highlight the need for direct, in situ building-scale assessments within a dynamic natural environment.

The hygroscopic behaviour of hempcrete is primarily due to its open porosity and highly porous microstructure [16]. This provides ideal moisture buffering potential capable of absorbing ambient water vapour and stabilising internal relative humidity (%RH), even at extreme relative humidities. The hygric buffering potential was found to be impacted by the manufacturing process [13], where the study found when comparing the moisture buffering capacity of moulded, sprayed and precast concretes, that prefabricated blocks, with a lower moisture effusivity, experienced the poorest %RH reduction potential. Additionally, binder type was found to influence the pore size and distribution within the hempcrete matrix, where natural hydraulic lime was preferred over the hydrated lime binders [28]. Contradictory findings regarding material age were observed, with one study discovering reductions in material porosity and thus storage capacity over time. Meanwhile, another [29] observed a shift in the hempcrete microstructure over time leading to improved hygric behaviour believed to be related to the ongoing carbonation of the lime binder.

The binder type, mix ratio and format of hempcrete have similarly been found to influence acoustic insulation potential [30,31]. Where Kinnane et al. [32] observed that hydraulic lime binders were significantly outperformed by lime pozzolan binders, the study also interestingly found that the addition of a render compromised acoustic insulation. With regards to the construction process, if tamping of the hempcrete compounds during production was reduced, yielding a lower density medium, the acoustic insulation potential was optimised [18]. This is the constant trade-off between insulation and strength as the prioritised function—as tamping intensity increases, the materials’ porosity decreases and insulation performance drops, the mechanical strength improves.

While the aforementioned studies are predominantly laboratory based, in regards to field-based sound attenuation, the metric of interest, sound transmission loss, is referred to as level difference [33], measured in decibels and represents the delta between noise levels on either side of the barrier of interest.

Finally, the incorporation of greenwall technology has a wealth of potential advantages, both aesthetically, and functionally. Greenwalls are well recognised in providing an improvement in ambient air quality [34–36] through their remediation of volatile organic compounds and particulate matter. Their thermal insulative potential is similarly studied [37–39]; under Sydney conditions, Castiglia Feitosa and Wilkinson [39] reported peak temperature reductions of up to 9.0 °C in vegetated versus non-vegetated structures, alongside a reduction in the occurrence of dangerous heat-stress conditions from 1.3% to 0% of monitored time [39]. This thermal buffering capacity is of particular interest to the present study, given the novel synergy explored here between hempcrete and green-wall technologies.

The vast majority of investigations into the insulative performance of hempcrete [22,40–43], while following reliable experimental design and state-of-the-art sensor technologies, are laboratory based. Consequently, there is a paucity of real-world, building-scale studies, wherein the materials under assessment are subject to the unpredictable fluctuations of climate extremes—even less so, those within a subtropical, humid environment such as Sydney, Australia. Furthermore, this study is unique, to the authors’ knowledge, in being the first to combine such novel biotechnologies as hempcrete with emerging greenwall technology to investigate their combined insulative potential.

Study Aims

This research aims to evaluate the thermal, hygric and acoustic insulative potential of novel bio-based hempcrete infrastructure with regards to conventional brick standards. More precisely, this study aims to contribute real-world, in situ performance data from

building-scale infrastructure situated in a highly exposed, densely urbanised industrial area within a subtropical Australian climate—ultimately contributing to the current knowledge base and providing evidence for the use of sustainable construction alternatives.

2. Research Methodology

2.1. Test Site

The research facility (S 33°56′19.975″, E 151°11′58.19″) is situated within Sydney, Australia, and hosted four scaled down (1:25) structures (Figure 1). The study site is located in the middle of a busy industrial area with an international airport close by, which provides persistent exposure to both sound and air pollution, while its position within a vast paved industrial block is an apt representation of an environment subject to peak urban heat island conditions.



Figure 1. Test structures located within the controlled research facility (Botany, NSW, Australia). From left to right: cast in place (CIP), brick, prefabricated and prefabricated with greenwall (GW).

2.2. Test Structures

The standard brick structure with timber frame was employed as a conventional standard against which the novel hempcrete-based alternatives were compared. Brick veneer was selected as the conventional reference system as it remains the most widely adopted external wall construction method in Australian residential building, providing the most representative and practically relevant baseline against which to benchmark the insulative performance of the novel hempcrete alternatives. In order to assess the performance of hempcrete in both its common formats, both cast in place (CIP) and prefabricated structures (PH) were included, with a second prefabricated structure that was also fitted with floor to ceiling greenwall modules (GW) (Junglefy, Australia, FoliaNetwork P/L, Australia). Common to all four structures was the structural timber frame, internal flooring, Versiclad roofing and a 1500 mm × 300 mm × 35 mm wooden door to facilitate access. The conventional brick structure (height 2367 mm, breadth 1030 mm and depth 1030 mm) was constructed from standard brick, lined with a 6 mm OSB board and 10 mm white render; the CIP structure (height 2367 mm, breadth 1198 mm and depth 1198 mm) had hempcrete mixed, poured and tamped on site along with a breathable sealant lining and 10 mm internal render; the two prefabricated structures (height 2364 mm, breadth 1040 mm and depth 1040 mm) were also lined with a magnesium sulfate board and render, with the addition of 24 greenwall modules (495 mm × 495 mm × 133 mm) to the GW structure. The modules consisted of a hard polyethylene case that housed 16 plants within a loose-weave HDPE membrane securing 25 L of coconut coir-based substrate. Cross-sections identifying major

structural components for each of the test buildings are presented in Figure 2, with specific dimensions listed in Table 1.

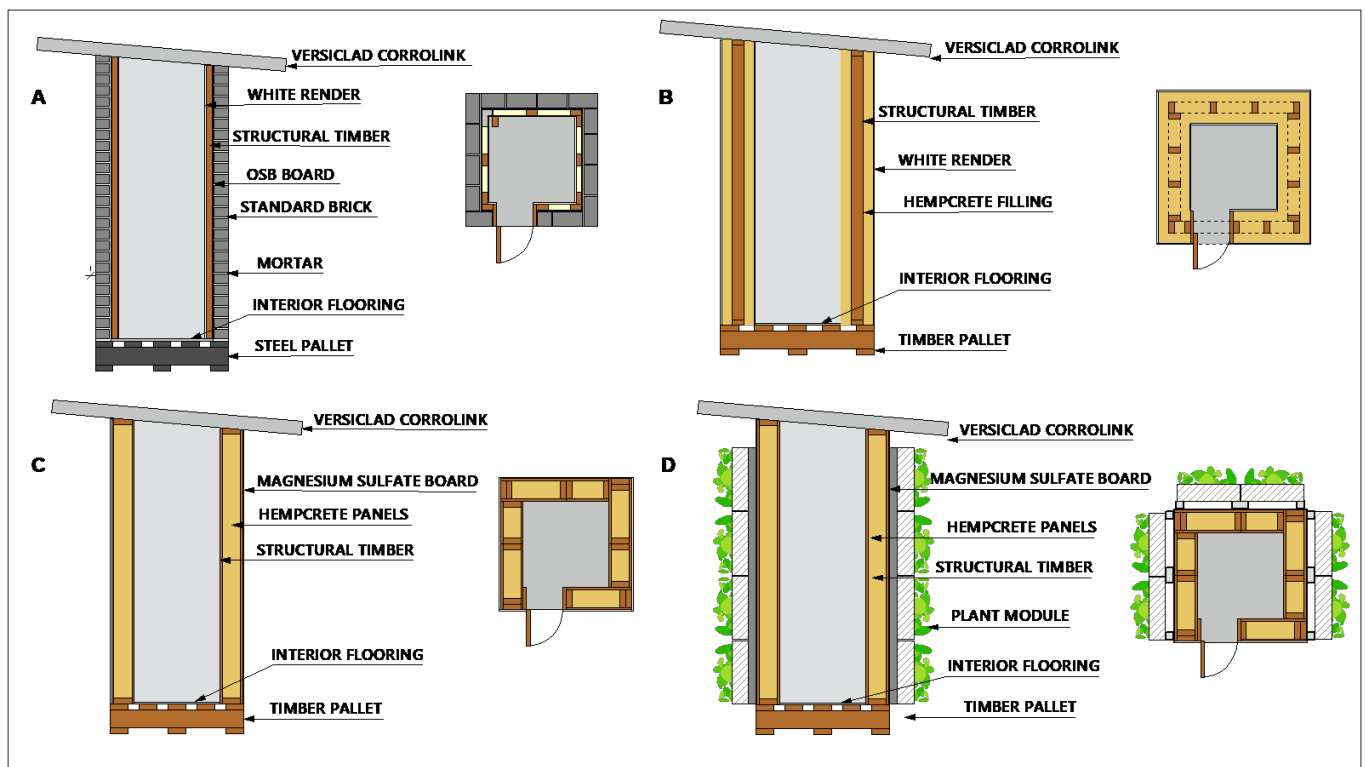


Figure 2. Cross-sections identifying major structural components for each of the test buildings ((A): brick; (B): cast in place; (C): prefabricated; and (D): greenwall). Specific dimensions as listed in Table 1(a–d).

Table 1. Itemised list of all components of each structure: dimensions as per builder specifications, properties sourced from the current literature. (a) Brick; (b) cast in place; (c) prefabricated; and (d) greenwall.

(a) Brick						
	Material	Thickness (m)	Surface Area (m ²)	Conductivity (W/m·K)	R	U
Roofing	Versiclad Corrolink 1000	0.100	1.061	0.041	2.457	0.407
	White render	0.010	4.872	1.000	0.010	100.000
	Structural timber	0.045	2.953	0.150	0.300	3.333
Walls	OSB board	0.006	6.017	0.130	0.046	21.667
	Ametalin insulation layer	0.004	5.076	0.040	0.100	10.000
	Duracoat door	0.035	0.426	0.120	0.292	3.429
	Brick	0.110	8.175	0.840	0.131	7.636
Flooring	Constructafloor	0.019	1.061	0.229	0.083	12.053
	Steel pallet	0.230	1.075	15.000	0.015	65.217
Wall Total			27.519		0.879	146.065
Building Envelope Total (area weighted)			30.716		0.183	26.872

Table 1. Cont.

(b) Cast in Place						
	Material	Thickness (m)	Surface Area (m ²)	Conductivity (W/m·K)	R	U
Roofing	Versiclad Corrolink 1000	0.100	1.435	0.041	2.457	0.407
	White render	0.010	9.608	1.000	0.010	100.000
Walls	Structural timber	0.045	2.953	0.150	0.300	3.333
	Hempcrete filling	0.250	9.608	0.099	2.525	0.330
	Duracoat door	0.035	0.426	0.120	0.292	3.429
Flooring	Constructafloor	0.019	1.435	0.229	0.083	12.053
	Timber pallet	0.230	1.451	3.000	0.077	13.043
Wall Total			22.595		3.127	107.158
Building Envelope Total (area weighted)			26.916		1.082	37.625
(c) Prefabricated						
	Material	Thickness (m)	Surface Area (m ²)	Conductivity (W/m·K)	R	U
Roofing	Versiclad Corrolink 1000	0.100	1.082	0.041	2.457	0.407
	White render	0.010	8.553	1.000	0.010	100.000
	Magnesium sulfate board (Firecrunch)	0.100	5.720	0.152	0.658	1.520
Walls	Structural timber	0.140	2.770	0.150	0.933	1.071
	Duracoat door	0.035	0.426	0.120	0.292	3.429
	Waterproofing (Solitex Extasana)	0.001	8.272	0.040	0.015	66.667
	Hempcrete panels	0.176	8.175	0.087	2.023	0.494
Flooring	Constructafloor	0.019	1.082	0.229	0.083	12.053
	Timber pallet	0.230	1.061	15.000	0.015	65.217
Wall Total			33.916		3.931	173.181
Building Envelope Total (area weighted)			37.141		0.700	40.565
(d) Greenwall						
	Material	Thickness (m)	Surface Area (m ²)	Conductivity (W/m·K)	R	U
Roofing	Versiclad Corrolink 1000	0.100	1.082	0.041	2.457	0.407
	White render	0.010	8.553	1.000	0.010	100.000
	Magnesium sulfate board (Firecrunch)	0.100	5.720	0.152	0.658	1.520
Walls	Structural timber	0.140	2.953	0.150	0.933	1.071
	Duracoat door	0.035	0.426	0.120	0.292	3.429
	Waterproofing (Solitex Extasana)	0.001	8.272	0.040	0.015	66.667
	Hempcrete panels	0.176	8.175	0.100	1.760	0.568
	Junglefy module (frame + vegetation)	0.200	5.762	0.250	0.800	1.250
Flooring	Constructafloor	0.019	1.082	0.229	0.083	12.053
	Timber pallet	0.230	1.061	15.000	0.015	65.217
Wall Total			39.861		4.468	174.505
Building Envelope Total (area weighted)			43.086		0.664	35.153

$$R = \text{Thickness} / \text{Thermal conductivity}; U = 1/R; R_{\text{weighted}} = \sum (R_{\text{component}} \times \text{Area}_{\text{component}}) / \sum \text{Area}_{\text{component}}$$

It should be noted that the four structures differed in external dimensions, internal volume and exposed surface area. This was an explicit component of our experimental design, which was directed at reflecting the practical constraints of each construction system rather than a controlled laboratory design. These geometric differences may independently influence thermal, hygric and acoustic responses, and results should therefore be interpreted as representative whole-structure performance under in situ conditions rather than as direct comparisons of intrinsic material properties.

The surface area-to-volume ratios differ across structures (approximately 5.81 m^{-1} for brick, 4.66 m^{-1} for CIP and 5.72 m^{-1} for PH and GW), which may independently influence the rate of heat and mass exchange. This is acknowledged as a limitation and reflects the practical dimensional constraints of each construction system as it would appear in practice. While not an explicit test of material properties, the dataset provided in our paper will be useful for validation of future numerical simulation-related research.

Raw hemp materials for both CIP and the two prefabricated structures were supplied by the Australian Hemp Masonry Company. The CIP hempcrete used a mix ratio of 9:5:10 hydrated lime binder to hemp aggregate to water, while the PH structures used 9:10:20. The CIP mix also contained sand, a common addition to reduce the binder content. The two mix ratios reflect the different manufacturing requirements of cast-in-place versus prefabricated production: the CIP mix incorporated sand to improve workability and reduce binder demand during on-site tamping, resulting in a higher bulk density, while the PH mix used a higher hemp-to-binder ratio suited to off-site panel production with controlled compaction. Detailed characterisation of the Australian hemp hurds used, including particle size distribution, water absorption (initial water content $\sim 165\text{--}190\%$; final water content $\sim 354\text{--}387\%$), dry bulk density and thermal conductivity, has been reported previously by our team in [22,30,44], which involved the same source material. Fresh and hardened density values for wall-application hempcrete using this material have been reported in the range of $350\text{--}530\text{ kg/m}^3$ [44,45]. Any potential difference in curing and drying times between hempcrete structures was accommodated by an acclimation period in excess of 6 months prior to the assessment period, wherein greenwall modules were also left to acclimatise to local environmental conditions after initial glasshouse-based potting and growing conditions.

2.3. Data Collection

During the summer observational period (October–November 2023) ambient air-quality monitors (Polludrone Pro, Oizom, India) were installed on site. One monitor served as an ambient environmental reference, located externally and in close proximity to the structures. The remaining monitors were positioned internally within each structure. All units recorded continuously at 5 min intervals temperature ($^{\circ}\text{C}$), humidity (% relative humidity) and noise (dB). Data reported from this study represents an $n = 17$ -day assessment period for each structure during summer, with winter thermal assessments a further $n = 14$ days for each structure. Alongside the Polludrones, thermal loggers (Thermochron TCS Temperature Logger DS1922L, Thermochron, Dallas, TX, USA) were also installed externally as well as internally for each structure (32 in total per structure). The thermal loggers were again installed at the same positions for a second, winter observational period between June and August 2024 to facilitate a seasonal temperature comparison. Test conditions were generally representative of the comparatively stable meteorological climatic conditions experienced in Sydney, making our cross-structure comparisons reasonable estimates for this climate. It is recognised that locations at greater latitudes experience far greater swings in climatic conditions including below freezing temperatures: our findings are thus limited to the climate in which they were performed, and should not be generalised to locations with more extreme weather conditions. Day (0700–1900) and night (1905–0655) periods were defined to approximate the core daylight and night-time hours experienced in Sydney across the summer and winter assessment windows, providing a consistent and conservative boundary applicable across both observation periods irrespective of seasonal daylight saving adjustments.

It is noted that the external thermal loggers record surface temperatures at the structure exterior rather than ambient air temperature; under direct solar radiation at the exposed

industrial test site, surface temperatures can substantially exceed ambient air temperature, consistent with urban heat island effects.

2.4. Data Analysis

Data yielded from thermal loggers were exported via eTemperature Software (<https://etemperature.com.au/>), while observations from the multi-parameter monitors was exported into Microsoft Excel. Analysis was completed via PAST Software (version 5.3) and IBM SPSS Statistics Package (version 30). Thermal logger and multi-parameter monitor datasets were not merged, as each captured distinct, non-overlapping parameters and fed separate analyses: surface temperature data informed the thermal lag and Table 2 comparisons, while air temperature, %RH and noise data informed the hygric and acoustic analyses.

Table 2. Summary of mean, minimum and maximum temperatures captured across both seasons for all test structures, separated by both day- and night-time recording windows.

Summer							
		Day Time			Night Time		
		Mean	Min	Max	Mean	Min	Max
Brick	outside	24.99	16.50	35.50	21.69	16.50	27.67
	inside	23.23	18.25	29.56	23.32	19.25	29.13
	$\Delta(i-o)$	−1.76	−7.79	3.25	1.64	−0.44	3.75
Cast in Place	outside	24.18	12.00	45.50	18.15	10.50	26.00
	inside	20.80	17.25	29.75	21.06	18.00	28.00
	$\Delta(i-o)$	−3.38	−25.50	8.25	2.91	−8.25	2.25
Prefabricated	outside	23.28	12.50	45.00	18.81	11.00	32.88
	inside	22.07	17.00	41.71	22.21	17.50	33.52
	$\Delta(i-o)$	−1.21	−22.50	8.00	3.40	−2.21	9.25
Green wall	outside	23.84	17.48	36.77	22.46	17.50	32.29
	inside	24.51	20.56	28.46	24.83	20.58	28.81
	$\Delta(i-o)$	0.66	−10.13	5.13	2.37	−4.04	5.20
Winter							
		Day Time			Night Time		
		Mean	Min	Max	Mean	Min	Max
Brick	outside	18.46	8.22	45.59	13.91	8.22	21.97
	inside	13.30	9.48	19.58	14.30	10.09	19.92
	$\Delta(i-o)$	−5.16	−31.57	2.27	0.39	−4.40	2.31
Cast in Place	outside	15.46	8.22	42.00	12.35	8.15	19.75
	inside	12.88	10.27	16.00	13.06	10.39	16.38
	$\Delta(i-o)$	−2.57	−29.42	3.53	0.71	−3.83	3.59
Prefabricated	outside	15.83	7.19	34.13	12.31	7.46	20.72
	inside	12.90	10.27	16.59	13.49	10.80	17.52
	$\Delta(i-o)$	−2.93	−19.81	4.40	1.18	−4.12	4.97
Green wall	outside	21.77	6.65	44.56	12.25	7.10	20.46
	inside	13.53	10.59	16.97	13.91	10.67	17.55
	$\Delta(i-o)$	−8.24	−28.97	5.49	1.65	−3.52	6.27

The maximum external temperature of 45.59 °C recorded during the winter period reflects a surface temperature measurement at the exposed, paved industrial test site under direct solar radiation, rather than ambient air temperature. Concurrent ambient air temperature was approximately 25 °C, consistent with Bureau of Meteorology records for Sydney in winter. Surface temperatures substantially exceeding ambient air temperature under direct solar exposure are consistent with urban heat island conditions at this site. This value was verified against raw logger data and is retained.

The lag time between temperature peaks (difference in minutes between peak temperature observed externally and corresponding internal peak temperature) was used to define the insulative potential for each of the structures, as the magnitude of the lag time can be attributed to the thermal mass of the structure [46]. To assess the insulative potential between each structure and season, two-way permutational analysis of variance (PERMANOVA) was conducted with Euclidean distance and 999 permutations. A separate PERMANOVA for each season was conducted if a significant interaction effect was observed, as well as pairwise comparison with sequential Bonferroni significance to locate the difference between structures. Similarly, the hygric and acoustic data were both evaluated with one-way PERMANOVA of the difference between internal and external observations (%RH delta and noise delta, respectively) as well as pairwise sequential Bonferroni significance. Both hygric and acoustic observations were further separated by day- and night-time observational periods with successive pairwise comparisons to isolate differences.

To examine the relationships between ambient air temperature, internal air temperature, internal surface temperature, internal relative humidity, and internal and external sound pressure level (Leq) within each structure, Pearson product-moment correlation matrices were computed for each structure independently. Correlation matrices are presented in Supplementary Materials (Figures S1–S4).

3. Results and Discussion

3.1. Thermal Assessments

3.1.1. Temperature Measurements

Throughout the summer assessment period (Figure 3) the ambient temperature ranged from 12.00 to 45.50 °C during the day-time and 10.50 to 32.88 °C during the night-time. After which, the winter assessment period experienced temperatures between 6.65 and 45.59 °C during the day and 7.10 and 21.97 °C overnight (Table 2). All structures, to varying degrees, observed a decrease in the magnitude of internal temperature fluctuations with respect to external temperatures—due to the thermal mass of each building and their respective ability to provide thermal insulation. At the hot extreme, CIP delivered the strongest buffering, with internal temperatures running up to 25.50 °C cooler than external at the peak summer day-time heat, followed by PH (22.50 °C), GW (10.13 °C) and brick (7.79 °C). At the cold extreme, GW performed best, with internal temperatures running up to 6.27 °C warmer than external at the coldest winter night-time point, followed by PH (4.97 °C), CIP (3.59 °C) and brick (2.31 °C), indicating active heat retention rather than passive insulation alone. These extremes are consistent with differences in thermal mass between the structures, which governs the capacity to absorb, store and gradually release heat, thereby dampening internal temperature fluctuations relative to external peaks.

Seasonal assessments for each of the structures showed that the CIP structure experienced the greatest mean indoor to outdoor difference (*i-o*) during summer days (−3.38 °C), while also experiencing the coolest mean internal temperatures overnight (Table 2). Meanwhile, the GW structure had the greatest cooling effect during winter days (*i-o* = −8.24 °C) and interestingly the study captured a positive mean *i-o* difference overnight (1.65 °C), larger than all other structures.

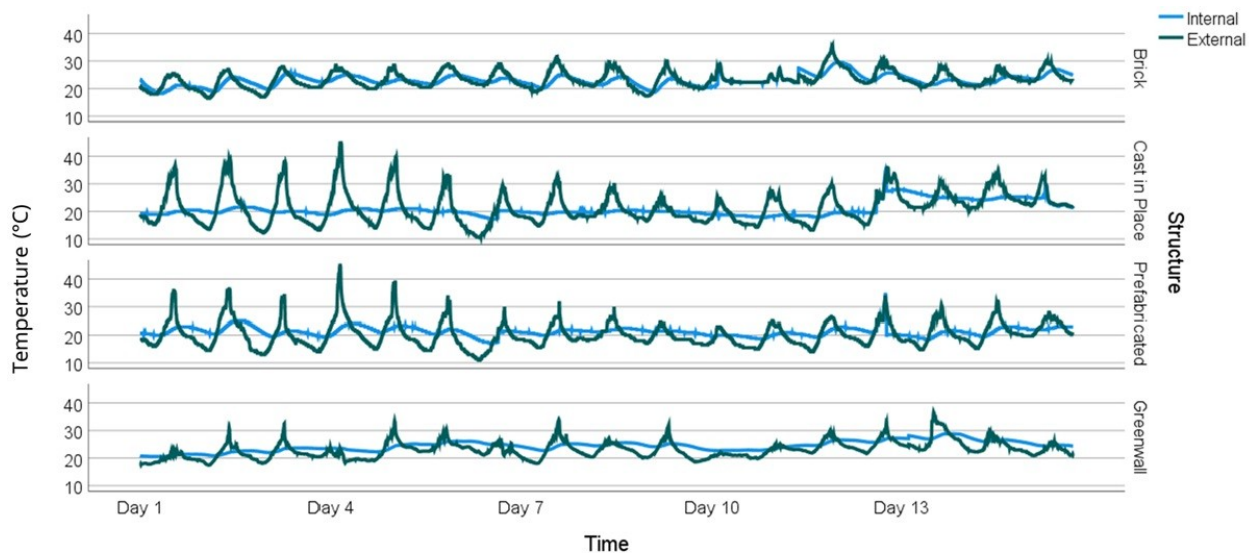


Figure 3. Temperature fluctuations recorded during the summer observational period, for both internal (blue line) and external (green line) temperature sensors, for all test structures.

3.1.2. Thermal Lag Time

With the environmental temperature ranges differing somewhat between the assessment period of each structure, a consistent insulation performance metric was required. Thermal lag time, the time taken for external temperature peaks to penetrate the building envelope and trigger internal temperature peaks [47], is representative of a materials' heat capacity [48] and thus insulation potential, and is illustrated for all structures across both seasons in Figure 4.

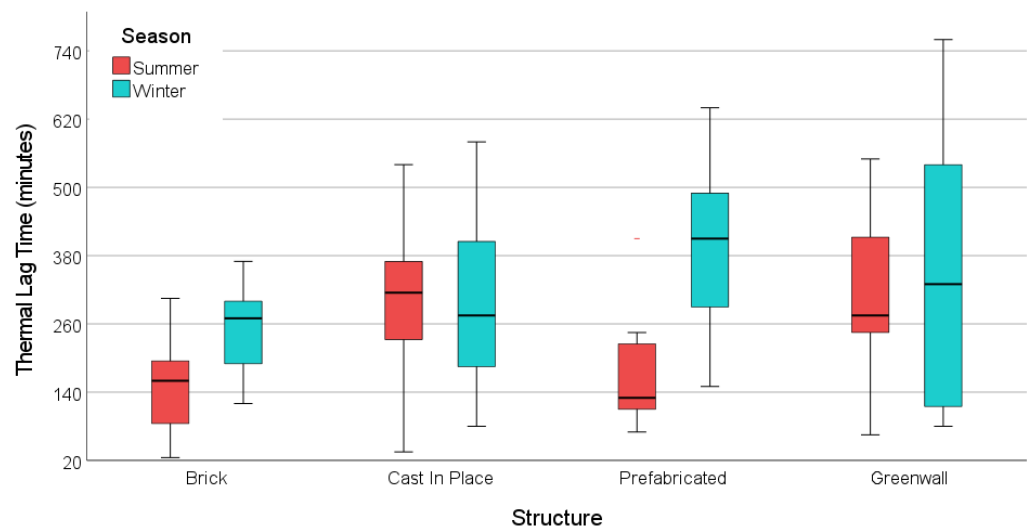


Figure 4. Boxplot showing thermal lag time data (difference in minutes between external temperature peak and internal corresponding peak) for each structure across both summer and winter seasons.

As a two-way PERMANOVA between seasons and structures showed a significant ($p = 0.0093$) interaction effect, the thermal performance between seasons was assessed independently. For the summer observation period, one-way PERMANOVA ($p = 0.0008$) with sequential Bonferroni correction for multiple pairwise comparisons was performed and significant differences were identified between brick and CIP ($p = 0.0036$) and brick and GW ($p = 0.0001$). This demonstrated that hempcrete structures experienced much longer thermal lag times than the conventional building (152.6, 310.9 and 319.7 min, for brick,

CIP and GW, respectively), though the PH structure (166.8 min) did not significantly outperform brick. The major consequence of longer thermal lag times is the reduction of internal temperature fluctuations and an extended period of relative cool within the building, thus reducing the demand of supplementary mechanical air cooling and reduced energy expenditure [48] and improved occupant comfort associated with temperature stability [49].

Differences in thermal performance of the hempcrete formats (cast in place walls or prefabricated blocks) may be due to their respective differences in density. A result of the manufacturing process, cast in place or poured on site hempcrete is generally of higher density and thus higher thermal conductivity and poorer thermal buffering potential, though this is not consistently reflected in the findings. Conversely, the advantage of prefabricated hemp-blocks is the ability to ensure uniform compaction and thus reliably meet thermal insulation standards.

During the winter assessment period, the one-way PERMANOVA ($p = 0.0493$) with pairwise comparisons located significant differences between the brick and PH structure ($p = 0.0019$). Here, the novel hempcrete structure experienced the longest thermal lag time (254.8 and 391.0 min, for brick and PH, respectively), while the CIP and GW structures (305.5 min and 353.2 min, respectively) improved marginally upon the brick standard, though not significantly.

The heat retention observed within the GW structure during winter nights may be advantageous in cooler climates, though this finding is in opposition to [50], wherein the hemp building required greater heating energy than the conventional standard. The distinction between [50] and this study is the additional presence of the greenwall, which may provide the additional thermal mass and subsequent release of stored heat overnight.

The superior performance of the GW structure during winter relative to the matching hempcrete structure without the greenwall was likely a function of the combined effects of the green wall system, which includes vegetation, substrate, retained water, shading effects, and evapotranspiration processes. Isolating the individual contribution of each element was beyond the scope of this study and represents a direction for future controlled investigation.

3.1.3. U and R Values

Thermal transmission and resistance (U- and R-values, respectively) are established commercial metrics for quantifying insulative potential, though they only represent a steady-state condition of heat flow, an acknowledged limitation [51,52]. And while U and R values are static estimations based on a singular linear cross-section of a wall boundary or building component, the Australian standard, as per the National Construction Code [53], requires the inclusion of potential compromises such as thermal bridging effects [54], which then requires consideration of the entire building envelope as a whole. As such, Table 1 documents all materials present within the test structures so that comprehensive building envelope estimations can be made, for both singular wall and area-weighted building envelope calculations.

It is important to note that the U- and R-values presented in Table 1 are theoretical estimations derived from published material thermal conductivity values and builder-specified dimensions, rather than direct measurements. They are subject to the acknowledged limitations of steady-state models and do not account for construction defects, moisture content variability or dynamic heat transfer effects. These values are provided as reference characterisations consistent with NCC requirements and should be interpreted alongside the dynamic thermal lag results rather than as independent performance indicators. Timber framing elements, which represent the primary thermal bridge pathway in these structures, are included in the area-weighted building envelope calculations in Table 1. Quantification

of thermal bridge effects through direct heat flux measurement represents a direction for future work.

Note that all iterations of the hempcrete test structures yielded higher R-values and lower U-values than the brick standard, for both wall totals and area-weighted calculations, which is in line with the current literature. A previous study [27], also contrasting brick buildings to hempcrete structures, albeit through a complex modelling platform as opposed to in situ observations, observed the building envelope of the brick structure to require significantly greater energy consumption, with the hempcrete alternatives providing greater insulative properties.

3.2. Hygric Assessments

The ambient %RH observed externally to each structure (Figure 5) shows fluctuations between 70 and 80% during the day, and up to 90% overnight. These variations are expected in an environment such as Sydney, where a subtropical, humid (Köppen Cfa) climate during a rainy summer observes an increase in humidity overnight as the temperature drops [55]. While all structures were shown to reduce and stabilise the internal %RH, the PH structure maintained a mean %RH closest to the established comfort threshold below 65% [27].

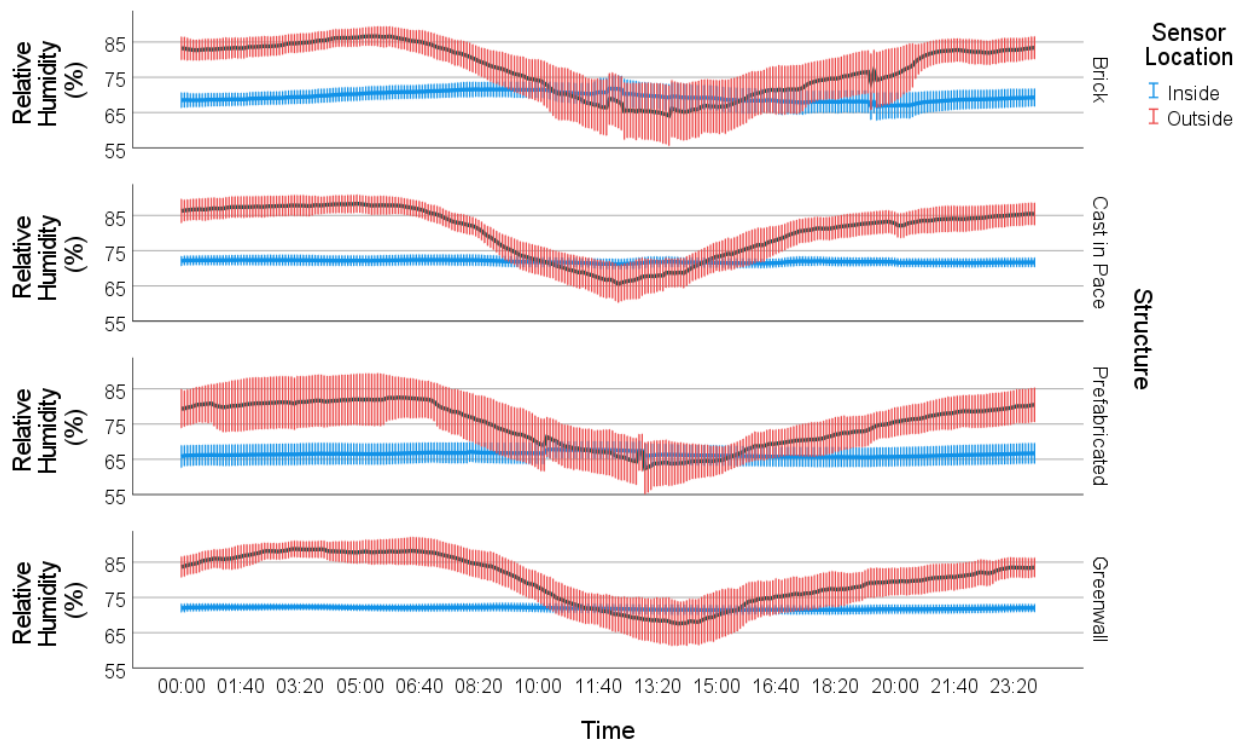


Figure 5. The mean Relative Humidity (%RH) (error bars indicating ± 1 standard deviation) across a 24 h period for all structures ($n = 17$).

When considering the fluctuating weather during the observational period (Table 3), it should be noted that the lowest total rainfall occurred during the conventional brick building assessments, though this does not correspond with lowest observed internal %RH.

To account for variance between ambient conditions during the assessment periods and avoid temporally influencing the findings, the difference between internal and external %RH was calculated for each structure ($\%RH_{\Delta} = \%RH_{\text{internal}} - \%RH_{\text{external}}$). Further distinction was made between day (0700–1900) and night (1905–0655) due to the aforementioned fluctuations between these periods.

A significant difference was detected between structures for day-time $\%RH_{\Delta}$, with one-way PERMANOVA ($p = 0.001$) with sequential Bonferroni corrections for pairwise com-

parisons finding distinctions between both brick and PH ($p = 0.001$) and brick and GW ($p = 0.001$), with both hempcrete structures successfully reducing indoor %RH more so than the brick standard. However, the CIP structure only marginally improved on the brick standard, though not significantly so ($p = 0.052$). Assessing hygric insulation overnight also yielded a significant distinction between structures, with a one-way PERMANOVA ($p = 0.001$) with pairwise comparisons showing the GW structure providing the lowest reduction in $\%RH_{\Delta}$, distinct from all other structures ($p = 0.001$). Here, the comparison of both CIP and PH to brick ($p = 0.633$ and 0.27 , respectively) demonstrated no significant difference in hygric insulation.

Table 3. Relative humidity (%RH) measurements for all structures, separated by day- (0700–1900) and night-time (1905–0655). Rainfall data as per Bureau of Meteorology [56] for the dates listed, from the closest weather station (Sydney Airport weather station; ID 94767).

Structure		Day Time		Night Time		Observation Period	Est. Total Rainfall
		Mean	SE	Mean	SE		
Brick	outside	72.91	0.29	83.24	0.17	16.11.23–23.11.23 and 13.12.23–21.12.23	45.2 mm
	inside	70.31	0.13	69.19	0.10		
	$\Delta(i-o)$	−2.59	0.20	−13.84	0.11		
Cast in Place	outside	74.89	0.20	86.02	0.13	9.11.23–15.11.23 and 25.11.23–03.12.23	58.2 mm
	inside	71.79	0.06	72.03	0.06		
	$\Delta(i-o)$	−3.10	0.17	−14.00	0.10		
Prefabricated	outside	70.89	0.28	80.88	0.24	31.10.23–06.11.23 and 05.12.23–11.12.23	60 mm
	inside	66.81	0.11	66.64	0.12		
	$\Delta(i-o)$	−4.08	0.23	−14.24	0.17		
Greenwall	outside	75.45	0.21	84.78	0.15	21.12.23–04.01.24	122.2 mm
	inside	71.78	0.05	72.03	0.04		
	$\Delta(i-o)$	−3.67	0.19	−12.75	0.13		

The performance of the hempcrete structures with respect to the brick standard follows the current literature expectations, with the moisture buffering capacity of brick ($0.4 \text{ g/m}^2 \cdot \%RH$ [57]) being far outweighed by that of hempcrete ($>2 \text{ g/m}^2 \cdot \%RH$ [58]). Previous work by Collet et al. [58], comparing the hygric regulation of sprayed, precast and moulded hempcrete, observed excellent moisture buffer values for each compound, though in contrast to this studies' findings, precast (prefabricated) was outperformed by the other formats.

From an occupant comfort perspective, supported by SafeWork NSW advice [59], indoor %RH ranges are optimally between 40 and 70%, with adverse health effects and discomfort associated with breaching these boundaries [60]. From a building safety perspective, the consequence of inadequate indoor hygric regulation, especially in sub/tropical environments, is excessive condensation risking mould growth [61], which the findings indicate hempcrete would be more likely to avoid than the standard structure.

With regards to the GW structure remediating elevated overnight %RH the least of all treatments, there are conflicting findings within the current literature to explain this. A recent review [62] indicated the presence of greenwalls in the indoor environment provides an increase in %RH due to the evapotranspiration process responsible for the ambient cooling effect they simultaneously provide. In opposition to this, ref. [63] found that the presence of retrofitted greenwalls exterior to a building façade could reduce internal %RH up to 32%, an order of magnitude greater than this study's findings.

3.3. Acoustic Assessments

Due to experimental constraints, the acoustic assessment of the structures was limited to the brick standard along with the CIP and PH structures, using the established metric of equivalent continuous sound level (L_{eq}) [64] to assess acoustic insulative performance.

It should be noted that the acoustic assessment presented here is based on field-measured equivalent continuous sound level differences ($L_{eq_{outside}} - L_{eq_{inside}}$) rather than standardised laboratory transmission loss metrics such as sound transmission class (STC) or weighted sound reduction index (R_w). While the current approach is consistent with in situ level difference methodology as described in the Australian Building Codes Board Sound Transmission Handbook [33], direct comparison with laboratory-derived indices is not possible and our findings should be interpreted in the context of the ambient field conditions under which they were obtained.

During the assessment period within a busy industrial location, noise pollution from the airport, surrounding traffic and construction resulted in ambient L_{eq} occasionally in excess of 80 dB during the day, with day-time L_{eq} between 65 and 75 dB and night-time ranges between 60 and 70 dB (Figure 6). Due to the observed fluctuations in ambient noise observed during assessments, both day- (0700–1900) and night-times (1905–0655) were assessed independently.

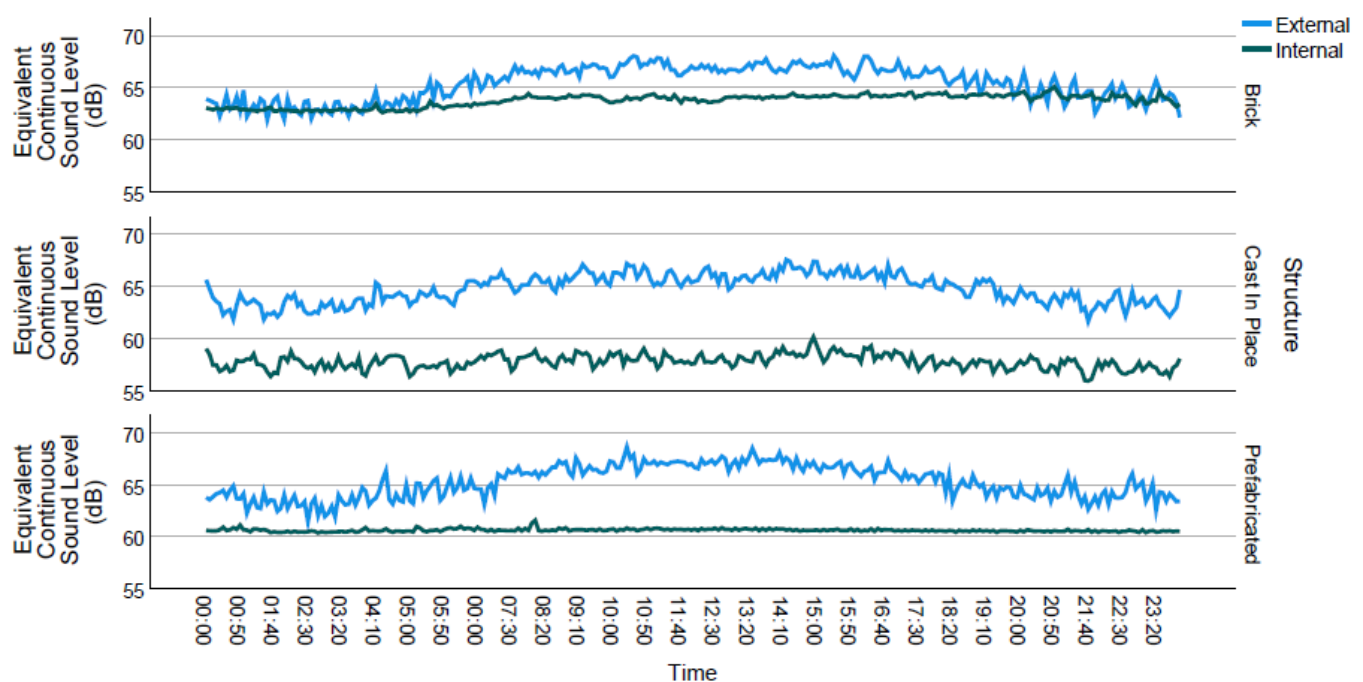


Figure 6. Mean Equivalent Continuous Sound Level (L_{eq}) (dB) across a 24 h period ($n = 17$) for brick, cast in place and greenwall structures.

To account for variation in ambient noise during the observation of each structure, acoustic insulation performance of the building envelope was calculated from the level difference [33], or mean sound reduction potential ($L_{eq_{outside}} - L_{eq_{inside}}$) for each structure. During the day, the mean sound reduction potential of structures varied significantly ($p = 0.001$), with brick (2.56 ± 0.09 dB) being outperformed by both CIP (7.74 ± 0.10 dB) and PH (5.85 ± 0.08 dB) ($p = 0.001$ for both comparisons). Meanwhile, the night-time observations again showed the insulation potential of brick (0.69 ± 0.09) to be significantly improved upon by both CIP (6.24 ± 0.10) and PH (3.39 ± 0.07) ($p = 0.001$ for both pairwise comparisons). Interestingly, while CIP was shown to have the largest level difference of the structures, it was PH that maintained the most stable internal L_{eq} .

Both hempcrete formats outperforming the brick standard is consistent with the previous literature [22], where the largest sound absorption was witnessed in materials with relatively lower bulk densities. A common laboratory-based metric used to describe the acoustic insulation potential of materials is the noise reduction coefficient (NRC) [33]. Review of a variety of building materials found hemp-based concretes to yield an NRC score of 0.40–0.59, while brick has an NRC of 0.02–0.05 [65], consistent with the observations from this study. In terms of optimising the NRC of a hempcrete-based material, Song et al. [18] recommends maximising the porosity and inter-pore volume of the media by limiting tamping during production.

Acoustic assessment of the GW structure was not possible during the observational period due to sensor availability constraints, representing a limitation of the study. Future work should incorporate acoustic monitoring of all four structures simultaneously. The broadband Leq metric used here does not permit frequency-resolved (1/3 octave) analysis; characterisation of frequency-dependent sound insulation across low-, mid-, and high-frequency bands would require impedance tube or reverberation room testing and is identified as a priority for laboratory follow-up.

3.4. Environmental Parameter Correlations

The Pearson correlation matrices (Figures S1–S4) provide further support for the thermal lag findings reported above. Coupling between ambient and internal surface temperature was comparably strong in brick ($r = 0.739$, $p < 0.001$) and PH ($r = 0.736$, $p < 0.001$), whereas this relationship was markedly weaker in CIP ($r = 0.263$, $p < 0.001$) and GW ($r = 0.535$, $p < 0.001$), indicating substantially greater thermal decoupling from external conditions in these structures. This pattern supports the summer thermal lag results, wherein CIP and GW significantly outperformed brick, reinforcing that surface-level thermal buffering strengthens the observed insulative advantage. A complementary pattern emerged in the acoustic data: external–internal Leq correlation was considerably stronger in PH ($r = 0.602$, $p < 0.001$) than in CIP ($r = 0.286$, $p < 0.001$), brick ($r = 0.14$, $p < 0.001$) or GW ($r = 0.261$, $p < 0.001$), suggesting internal noise in PH remained more closely coupled to external fluctuations despite its significant mean sound reduction relative to brick. Finally, GW was distinguished by a negative correlation between internal air and surface temperature ($r = -0.509$, $p < 0.001$), absent in the other structures, plausibly reflecting the buffering influence of the greenwall substrate and evapotranspirative cooling discussed in relation to winter heat retention.

4. Limitations and Future Directions

Differences in structure geometry, wall thickness and surface area-to-volume ratio that we incorporated to represent in situ construction methods across the four test structures will undoubtedly have influenced material performance. Thus the findings presented here are not directly representative of the behaviour of the respective building materials, rather the construction methods that utilise them.

In the current work, the tested construction systems were represented by single structures, and thus were not independently replicated in space. We thus employed time-for-space substitution in place of independent spatial replication. This is a common constraint of building-scale field studies and is consistent with the broader in situ hempcrete literature. While we performed testing across several seasons, it may be of benefit if future work considered longer term in situ assessments to ensure a broad range of climatic conditions were sufficiently incorporated.

5. Conclusions

The findings from this building-scale, in situ assessment provide evidence of the insulative performance of hempcrete systems under subtropical Australian conditions. Within the limitations of the single-structure design, differing geometric configurations and field-based measurement methodology, both cast in place and prefabricated hempcrete formats demonstrated thermal, hygric and acoustic performance meeting or exceeding the conventional brick standard across several metrics.

Thermally, CIP and GW structures significantly outperformed brick during summer, with mean thermal lag times of 310.9 and 319.7 min respectively, compared to 152.6 min for brick. During winter, PH demonstrated the longest thermal lag time of all structures at 391.0 min, compared to 254.8 min for brick. Area-weighted, estimated R-values for all hempcrete envelope configurations (CIP: 1.082, PH: 0.700, GW: 0.664 m²·K/W) exceeded that of the brick structure (0.183 m²·K/W), consistent with the current hempcrete literature.

Hygrically, both PH and GW reduced indoor %RH significantly more than brick during the day (PH: −4.08 vs. Brick: −2.59 %RH delta), with PH maintaining mean internal %RH closest to the recommended comfort threshold of 65%.

Acoustically, both CIP and PH outperformed the brick standard under field conditions, with daytime mean sound reductions of 7.74 ± 0.10 dB and 5.85 ± 0.08 dB respectively, compared to 2.56 ± 0.09 dB for brick. These findings are consistent with previously reported noise reduction coefficients for hemp-based concretes (NRC 0.40–0.59) relative to brick (NRC 0.02–0.05).

While our findings indicate that substituting conventional brick with current hempcrete structure designs may be associated with substantial building performance gains, the current results should be interpreted as indicative of whole-structure performance under the specific site conditions studied rather than as definitive characterisations of intrinsic material properties. These performance differentials further suggest that hempcrete structures may offer energy demand benefits relative to brick during cooler months—a hypothesis warranting direct measurement in future studies.

Continued research into the use of alternative, sustainable binders in hempcrete formulations is now required to further reduce the carbon-intensive lime content and optimise the sustainability of the urban environment while ensuring structural safety and occupancy comfort.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18147033/s1>, Figure S1: Pearson correlation matrix for environmental parameters measured in the brick structure. Figure S2: Pearson correlation matrix for environmental parameters measured in the Cast in Place hempcrete structure. Figure S3: Pearson correlation matrix for environmental parameters measured in the Prefabricated hempcrete (PH) structure. Figure S4: Pearson correlation matrix for environmental parameters measured in the Prefab hempcrete + Greenwall (GW) structure.

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Abbreviations

The following abbreviations are used in this manuscript:

CIP	Cast in Place
GW	Prefabricated Hempcrete with Greenwall
Leq	Equivalent Continuous Sound Level
NRC	Noise Reduction Coefficient
PH	Prefabricated Hempcrete
PERMANOVA	Permutational Analysis of Variance
RH	Relative Humidity
SDG	Sustainable Development Goal

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