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Article

Thermal and Moisture Content Monitoring of a Full-Scale Load Bearing Hemp Lime Arch Prototype

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Abstract: Today, bio-sourced materials represent an important technological field of study, as they could sink atmospheric carbon dioxide into buildings. Little-processed construction materials would also reduce the environmental impact of the construction sector, which emitted more than 2.9 Mt of CO_2 in 2020. Hemp-lime is a material that meets both these requirements. It is an insulating mix that can take different forms and be used in various parts of a building. The challenge is providing it with enough mechanical strength to make it loadbearing, at least to some extent. This research focuses on the construction and monitoring of a pointed arch, based on a previous experimental hemp-lime construction at Cardiff University in 2009, under the direction of architect David Lea. Since 2022, such an experiment on a possible loadbearing hemp-lime mix is being repeated at the Politecnico di Torino as part of a wider project called "experimental pavilions of vegetarian architecture". The design and numerical analysis of the Cardiff prototype led to the modification of both the geometry and the composition of the mix using only pozzolanic air lime as the binder. The construction of the arch ended in December 2023. Observing the thermo-hygrometric conditions of this hemp-lime mix once in place is the main purpose of this article. A strong correlation is revealed between outdoor conditions with temperature and moisture content in the core of the arch. Building a full-size outdoor prototype allows for the avoidance of mathematical correction to the results obtained and allows the assessment the mix's resistance in relation with environmental conditions. Due to some similarities of nature and function between lime and cement, many studies of lime mixes do not exceed a duration of 28 days, which cannot be considered the appropriate observation time for its curing. Therefore, we analysed this lime-based material for around 6 months, according to its own temporality and chemical kinetics. Through continuous monitoring at 10-min intervals, it was possible to highlight several significant aspects of rammed hemp-lime. The results show that the temperature within the mix is influenced by the outside temperature, but the sun exposure of certain areas drives up the corresponding temperature values more rapidly. Furthermore, while the absorption of water in the form of vapour is very rapid, desorption takes longer, as does re-establish a balance between the material and its context. Finally, solar exposure affects particularly 30-cm-thick elements, while elements that are 60 cm thick are not affected in the short term but only in long-term exposure conditions like season changes.

Keywords: hemp; pozzolanic lime; vegetarian architecture; full scale prototyping; hands-on workshop

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1. Introduction

The global warming potential of conventional construction materials such as concrete, brick and steel are high and problematic [1]. The construction sector emitted more than 2.9 Mt of CO_2 in 2020 [2]. Finding alternatives in bio-based materials could help decrease GHG emissions by sinking the atmospheric carbon dioxide into buildings [3]. Among these environmentally friendly materials, hemp-lime is an option worth considering as it represents a combination of a mineral-based binder with undeniable technical performance and durability and a plant-based aggregate derived from hemp industrial waste. The combination of these two materials in a single product has benefits for sustainable development, human health and indoor comfort. According to some studies [4], considering the carbon sequestration of hemp's growth phase and the carbonation of lime, the embodied carbon index of hemp-lime is -0.15 kgCO^2/kg, and the embodied energy (EE) is 3.72 MJ/kg ($\approx$1 kWh/kg). In accordance with its thermal properties and ability to absorb and release moisture from the air, it considerably reduces energy consumption for internal heating. In fact, its thermal conductivity varies between 0.06–0.23 W/m·K [5,6] (depending on the mixture drying time and density), and its water vapour resistance factor does not exceed 5, whereas that of EPS is 60. Thus, hemp-lime is more and more used in construction, mainly thanks to its insulating capacity. It seems particularly challenging to see if some mixture of lime and hemp can bear external loads.

This research focuses on the construction and monitoring of a pointed arch, based on a previous experimental hemp-lime construction at Cardiff University in 2009 [5], under the direction of architect David Lea [6]. This paper presents the search for a correlation between atmospheric conditions and the thermo-hygrometric characteristics of a hemp-lime mixture, monitored on a full-scale arch-prototype built entirely with hemp-lime [7], providing detailed results depending on the orientation and height of the data capture.

Research on hemp-lime is essentially based on observations made of contained samples [8–10]. We studied a life-size prototype, thus avoiding the application of a theoretical scaling factor to the results. The boundary conditions are not fixed because the prototype was built outdoors, which is all the more interesting in the long term because it makes it possible to record the behaviour in relation to several external parameters such as temperature, humidity, solar radiation and wind. These variables were then related to two monitored features inside the material: temperature and water content. Moreover, the maturation time for the analysis of hemp-lime is, in many studies, the characteristic setting time of the concrete (28 days) [11,12]. Instead, we analysed this material for 6 months, according to its own chemical kinetics and temporality. It is worth pointing out, however, that the larger the cross-sectional area of the material, the less water evaporates; this is, of course, dependent on the local climate and weather conditions. In addition, the carbonation of the lime causes water to be released and CO_2 to be absorbed. So, the quantity of water in the core indicates the progress of the lime's carbonation. However, during the same time, the hemp shiv may absorb the excess water and increase its evaporation time. This seems to be reflected by the gradual rise of humidity in the moisture content and rainfall plots onwards.

Previous studies have recorded the temperature and relative humidity in a prototype hemp-lime housing unit [13], but they focus on indoor comfort; that is not considered here.

2. Literature Review

Numerous experiments have been carried out in recent years to produce a hemp concrete with the mechanical and thermo-physical properties required for the construction industry. Density ranges from 200 to over 500 kg/m^3, depending on whether the hempcrete is used in roofs or as wall infill or floor screed [14]. In addition to the composition of the mix, the laying technique (formwork, compaction or spraying) is to be taken into account.

The thermo-physical properties of hemp-lime seem to be closely linked to the drying conditions of the mixture after hydration [15]. In our experiment, the outdoor temperature and relative humidity fluctuated considerably, ranging respectively from 0 to 35 °C and from 40 to 90%. Some analyses show that environmental conditions are a major factor in the quality of the binder setting, depending on the binder hydraulicity. It seems that relative humidity is an important factor. The amount of water in the air can influence the setting of lime [16].

It is also important to consider the geometry of the hemp shive particles, as the binder-aggregate composite must be able to resist the tearing of bonds [17]. The smaller particles, up to 3 mm in length, reduce the porosity of the mixture simply by reducing aqueous transfer within the plant particles because they are separated by the mineral binder [16].

It has been proven that the water/lime ratio is relevant to the mechanical strength of the mixture. The strongest mixture has a water/lime weight ratio of around 0.5 ([18], Figure 5). Despite more promising results in terms of strength with organic binders such as PLA ([19], Figure 8), only one type of mineral binder has been used here, consisting of air lime mixed with micronised pozzolan. This improves the strength and speeds up the setting process.

Hemp-lime is considered here as a soil, composed of a solid matrix, an aqueous phase and a gas phase. The basic assumption is that only the solid matrix remains unchanged, whereas the liquid and gaseous components fluctuate. The water content (by volume) is determined, using a capacity sensor capable of measuring the electrical charge storage capacity.

3. Methodology

3.1. Programming Arduino Sensors

The circuit consisted of an Arduino Uno board, which the analogue acquisition sensors were connected to with a 16-channel multiplexer. This allowed the number of connected sensors to be multiplied fourfold, as the Arduino Uno board only supports four analogue inputs by default. Three types of sensors were used: the first combined the temperature and relative humidity of the air, the second probed the temperature in the mixture, and the third probed the water content of a relatively homogeneous medium such as soil. The whole system was linked to a battery-powered clock, so it was possible to record the precise moment of acquisition of each data item. Data were acquired via a continuous internet connection and a NodeMCU platform, which enabled the data to be transferred in real time, based on IoT (Internet of Things) technology. To power the entire circuit, an off-grid photovoltaic power supply set up with a 50 W panel and a 17 Ah battery was installed. The scheme of the entire system is shown in Figure 1.

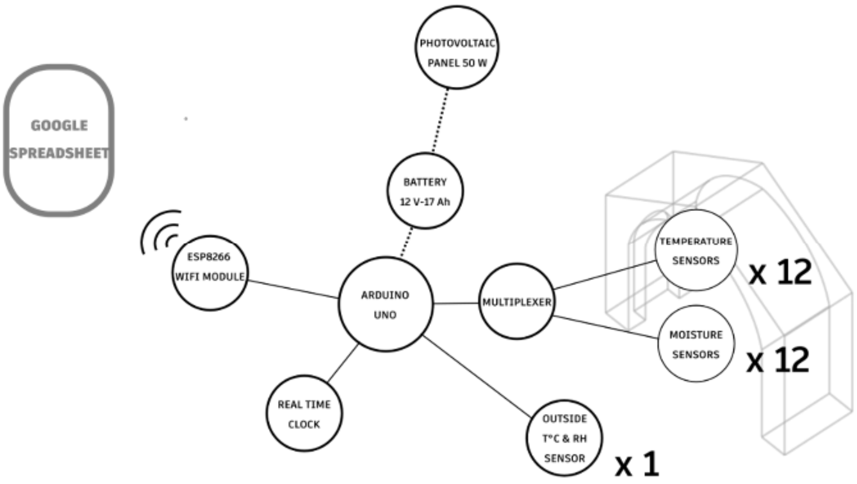


Figure 1. Data acquisition system.

3.2. Positioning the Probes

The sensors were positioned in such a way as to acquire temperature and water content values throughout the prototype. The temperature sensors were immersed in the centre of the horizontal sections, taking care to preserve the homogeneity of the hemp-lime mix around each of them. In this way, possible interferences were eliminated. The water content was probed in the middle and on the outer face of each crucial area of the arch. The moisture content sensors were named A, A', B, B', C, C', D, D', E, E', while the temperature sensors were named V, W, X, Y, Z (Figure 2).

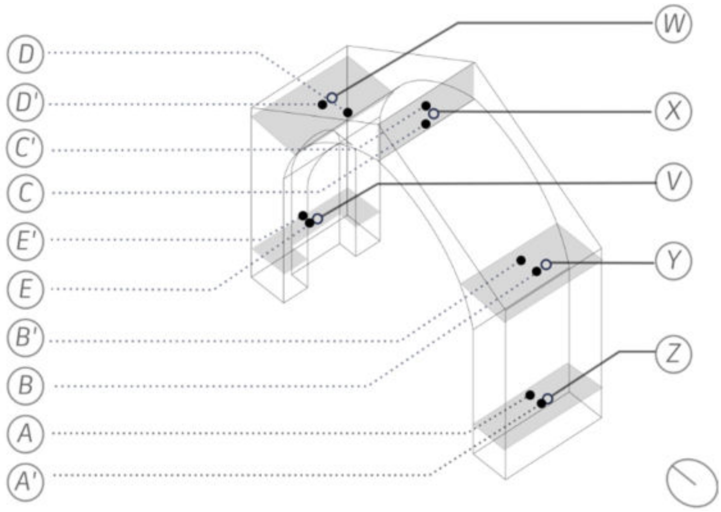


Figure 2. Position of sensors: moisture content (A~E′)—temperature (W~Z).

3.3. Data Acquisition Procedure

3.3.1. Temperature Acquisition

The "DS18B20" sensor (manufacturer: Hilitchi, Shenzhen, China) directly read the temperature value in °C. It was therefore not necessary to correct the input received. The accuracy was ±0.5 °C, and the acquisition range was from −55 to 125 °C. The DS18B20 is a 1-Wire bus device, that requires only one data line for communication with a central microprocessor. The acquisition voltage was 5 V DC.

3.3.2. Relative Moisture Content Acquisition

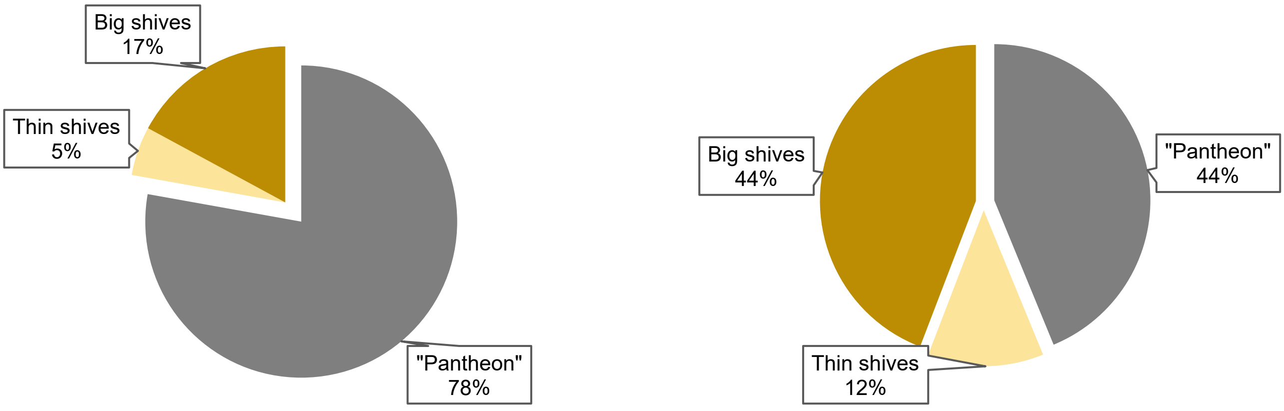
The "Hygrometer Modul V1.2" sensor (manufacturer: Sing Fat, Honk Kong) also received a voltage of 5 V DC. We were considering a charge-storing capacity approach and not a resistance approach. It connected to the Arduino circuit via a phase cable, a ground cable and a data acquisition cable. Arduino Uno supports 10-bit ADC, which means the resolution of the output was 2^{10} = 1024. Therefore, in order to convert the analogue-received resistivity value R into relative water content, we performed the following Equation (1).

$$mc_{rel} = 100 - \left(\frac{\mathrm{R}}{1023}\right) \times 100 \tag{1}$$

This involves converting the analogue value of the signal into a digital value. It was impossible for us to express the value of the volumetric water content because we did not know the density of the dry mixture beforehand, which is why we opted for a scale of relative values. Furthermore, in order to calibrate the values from each sensor, measurements were taken beforehand in a dry environment and in an environment saturated with water, making it possible to calculate the relative position of the raw values from each probe.

4. Composition of the Mixture

The hemp-lime mixture used in this research was made manually from hemp shives and pozzolanic lime according to proportions based on encouraging precedent studies [2]. Shives of two different particle sizes were used: the coarser particles ranged from 0 to 25 mm in diameter, while the finer particles did not exceed 6 mm. The "Pantheon" pozzolanic lime came from a kiln in the province of Trento and featured a 28-day compressive strength of over 12 MPa. The dry mass proportions are shown in Figure 3, while the water/binder and hemp/binder ratios are represented in Table 1.



(**a**) (**b**)

Figure 3. Proportion of hemp shives with respect to lime: (**a**) hemp-lime dry mass composition and (**b**) hemp-lime dry volume composition.

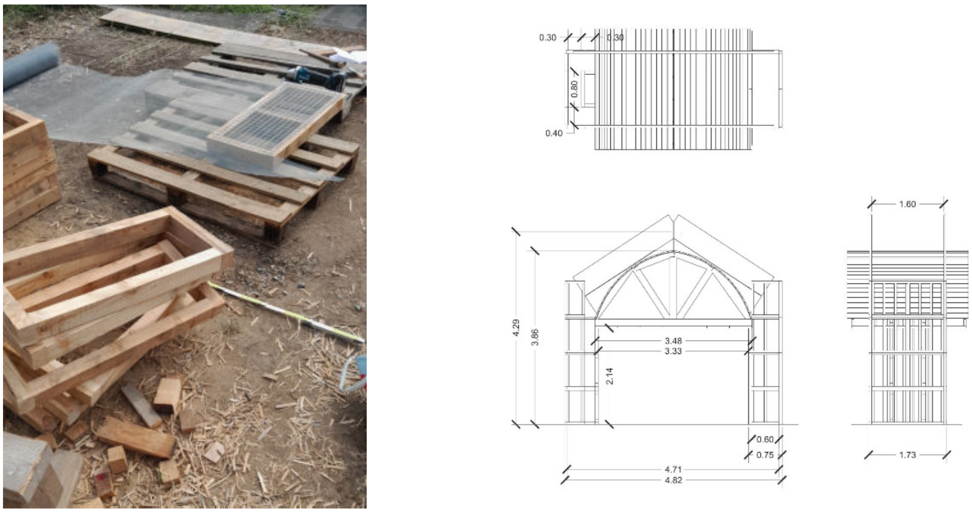
Table 1. Composition of the mixture.

		Mass	**Volume**	**Total Weight**	**Total Wet Volume**	**w/b**		**h/b**		**Compaction Rate**
		[kg]	**[m^3]**	**[kg]**	**[m^3]**	**(in mass)**	**(in volume)**	**(in mass)**	**(in volume)**	**[-]**
hemp-lime		-	-	8551	10,996	0.85	0.47	0.29	1.28	0.757
	thin shives	260	2000	-	-	-	-	-	-	-
	big shives	880	7333	-	-	-	-	-	-	-
	"Pantheon" lime	4000	7273	-	-	-	-	-	-	-
	water	3411	3411	-	-	-	-	-	-	-

5. Construction Steps and Installation of the Probes

5.1. Piers Formwork

To ensure the rigidity of the formwork panels, we used wooden battens with a cross-section of 5 × 7 cm and a gauge 11′ wire grid with 10 mm spacing. A finer mesh with gauge 23′ and 6.35 mm spacing was used to hold the mix in place. To avoid obstructions during the pouring and compaction phases, the formwork was erected gradually (Figure 4).



(**a**) (**b**)

Figure 4. Details of the formwork building process: (**a**) making the formwork units and (**b**) design of the entire formwork.

Particular attention was paid to the design of a modular and demountable formwork. The formwork panels were superimposed in different stages so as to compact the mixture from the inside without being obstructed by the finished assembly. At the four corners of each pier, we set wooden uprights vertically so that we could fix each level as we went up.

5.1.1. Compacting the Mixture inside the Piers

The mixture was produced in a 300 L concrete mixer, and each batch took 30′ to be ready. They were carried within troughs and then poured into the formwork. Compaction was carried out by hand with a timber self-produced tamper, reducing the height of the mix by half from 20 to 8~10 cm of compressed material.

5.1.2. Arch Shoring and Scaffolding

To ensure the stability of the formwork and the mix, the arch was supported by a system of wooden stays and beams. On top of this, the hangers were fixed, linked by a 2 cm-thick wooden battens layer.

5.1.3. Compacting the Mixture inside the Arch

The arch could not be compacted by gravity using a manual compaction hammer, so the solution was to obtain a pneumatic hammer that could act as a light tamper. In this way, compaction could take place on an inclined plane orthogonal to the compression the arch would receive once it was stripped (Figure 5).

Figure 5. Homemade electric tamper.

5.1.4. Placing the Probes

As mentioned above, the probes were embedded in the mass during the compaction phase in order to obtain an intimate contact surface between the material and the sensors. The sensitive electronic parts of the probes had been previously hermetically protected. All connections to the probes were made in the laboratory, then threaded through the formwork. The final connections to the Arduino Uno circuit were made on-site after completion of the construction (Figure 6).

(**a**) (**b**)

Figure 6. Pictures showing the work of placing the probes: (**a**) embedding the probes and (**b**) welding the hardware system.

5.1.5. Time for Setting

According to Elfordy et al. [20], the setting time for a hemp-lime mix whose binder is made up of different limes and pozzolanic matter is about a month. However, the blocks studied were of limited dimensions. On the contrary, the experiment described here was an arch with a total volume of 9 m^3 and a maximum thickness of 60 cm. The time of carbonation was longer due to the high thickness of the piers. Consequently, the strength was supposed to take more time to acquire an acceptable value (Figure 7).

Figure 7. Life-size prototype at the Grugliasco experimental site.

6. Monitoring Results and Discussion

The results were obtained via the network, enabling the system's performance to be monitored constantly and remotely. The values were taken 10 min apart so that any bugs or missing data could be ironed out. The accuracy could remain consistent in case the data receiving aborted. There is an interesting, intrinsic relationship between the construction and its context. By orienting the faces of the arch according to the cardinal points, we have a certain understanding of the hygrometric behaviour and thermal inertia. Thanks to a deliberately long duration (more than 6 months of data acquisition), we were able to observe how the upward solar excursion was a decisive factor for the integrity of the material. In fact, the mixture never froze because the 2023–2024 winter was particularly mild in Turin. The prototype was therefore able to release the excess water gradually and without causing stress to the hardening of the lime.

6.1. Temperature Monitoring

Work started at the beginning of November 2023. The major risk at that time was frost, but temperatures did not fall below 0 °C. Frost is detrimental to the carbonation of lime. Observation lasted from 22 December 2023 to 13 May 2024. Evaluating the effect of boundary conditions on the temperature inside the mass for each critical part of the arch such as piers, vault hinge and top was crucial for discussing the importance of the hemp-lime thickness for temperature. The Z probe seemed to have failed, probably due to the damp constructive process. The plot showed regression curves calculated according to a moving average over a period of 145 values, easing the readability. The sampling for each value represents 24 h, which is still reasonable for such a long-term observation.

The sensor inside the north pier (probe V) recorded higher values than the others, with a mean value along the whole observation period of 1.17 °C higher than the mean of probes W, X and Y. In fact, despite its northerly aspect, it received sunlight all day long except for the short hours when it was shaded by the south pier—a duration too insignificant to influence probe V due to the low thermal effusivity. (Thermal effusivity indicates the rate at which the surface temperature of a material rises.) Assuming the following Equation (2):

$$\beta = \sqrt{\rho \cdot c_p \cdot \lambda}\ [\mathrm{W} \cdot \sqrt{\mathrm{h}}/\mathrm{m}^2 \cdot \mathrm{K}] \tag{2}$$

where: ρ = density [kg/m^3]; c_p = specific heat [Wh/kgK]; and λ = thermal conductivity [W/mK], we can observe, according to Oliva et al. [21], that hemp-lime effusivity is lower than that of standard infill materials (Table 2).

Table 2. Thermal effusivity of infill construction materials.

	Hemp-Lime	Perforated Bricks	Solid Bricks	Stone (gen.)	Wood (gen.)	Concrete (gen.)
thermal effusivity $\left[\mathrm{W} \cdot \sqrt{\mathrm{h}}/\mathrm{m}^2 \cdot \mathrm{K}\right]$	4.8	9.3	26.1	45	9.5	33.9
specific heat [W·h/kg·K]	0.42	0.29	0.28	0.28	0.44	0.28

Furthermore, the north pier thickness is 30 cm, while sensors W, Y and Z are placed in 60 cm thick elements. During the periods when the temperature increased (four weather periods can be recognised, (1)-(a); (2)-(b); (3)-(c); (4) as represented on Figure 8) we observe that the heat of hemp-lime heated up faster as the solar radiation increased. In addition, during period (2) when there were 9 days of stable daily radiation of 15 MJ/m^2, probe V recorded temperatures 3 °C higher on average than probes W, X and Y. Similarly, the other sensors took 5 days instead of 9 to reach the peak temperatures.

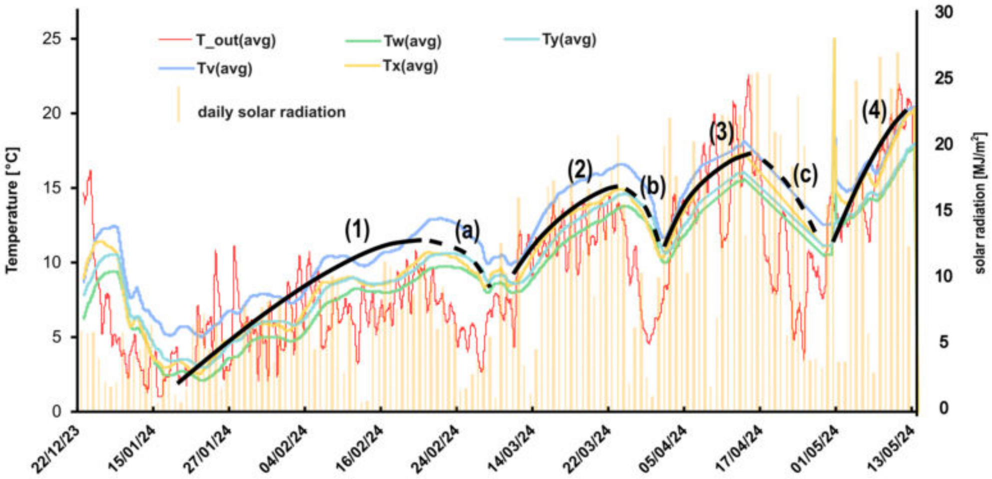


Figure 8. Temperature curves for the setting period.

We can also see that the X probe at the top of the prototype recorded a faster increase in temperature from March onward when the sun reached it. The temperature probes all suffered malfunctions in mid-May—they transmitted little data, which rendered it difficult to observe particularities. These failures could be explained by a lack of waterproofing of the sensors.

6.2. Moisture Content Monitoring

Moisture content was measured from 22 December 2023 to 11 July 2024. The method applied for data acquisition reveals the trend of moisture content, because the equipment does not record the absolute amount of water but records an electrical resistivity value, changing relative to the amount of moisture inside the mixture. Compared to the relative humidity measured inside a hemp-lime prototype like the HemPod, built in June 2010 at the University of Bath [13], the moisture content showed a trend more responsive to the weather conditions. The indoor air is a result of a thermo-hygrometric balance between outside and inside, which is not the case here, where no pressure gradient from face-to-face exists (Figure 9).

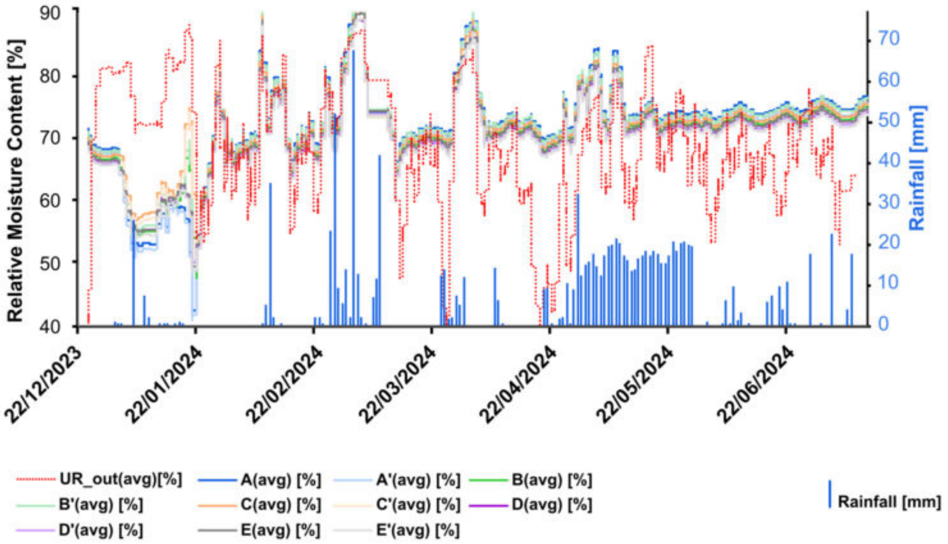


Figure 9. Moisture content and rainfall plots.

When there was a lot of rainfall, the moisture content rose. There were three events of this kind: the last week of February, the last week of March and one month from the end of April to the end of May.

The linear regressions represented in Figure 10 indicate the trends of the mean moisture inside the mixture and the relative humidity of the air. It is interesting to notice the opposite sign of the two coefficients. If the coefficient of the outdoor air is negative (−0.0132), i.e., air has been drying from winter to summer, the coefficient of the hemp-lime mixture is positive and four times higher (0.0489). This means that the mixture contained an increasing amount of water.

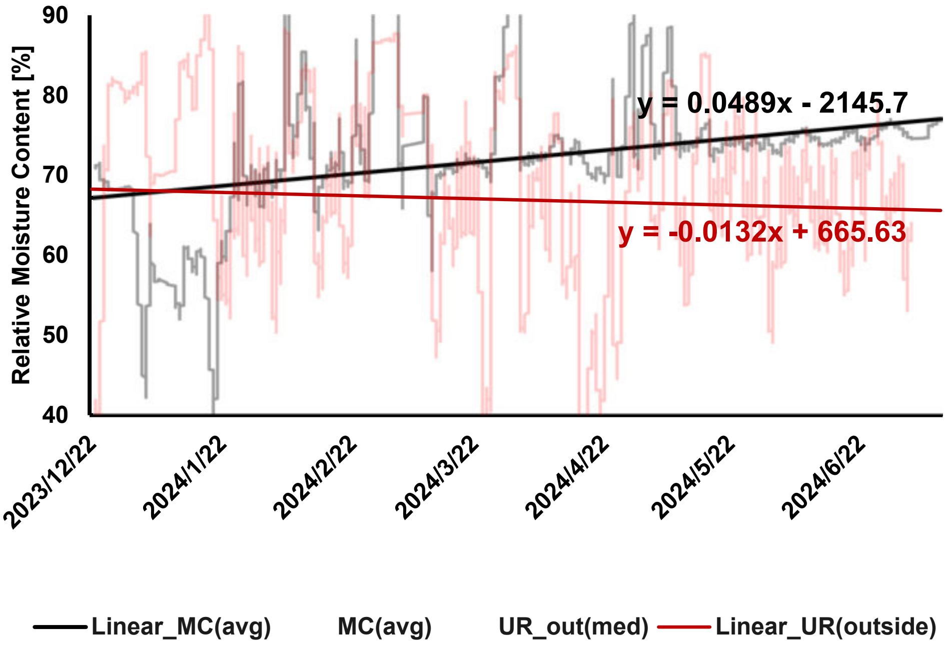


Figure 10. Moisture content linear regression.

This is explained by the chemical-setting lime reaction (Equation (3)) induced inside the mixture. Carbonation releases water, and evaporation is not enough to counteract the increase in moisture content in the material.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \tag{3}$$

6.2.1. Moisture Content Alignment

During the period from January 16 to January 20, the A–A′ and C–C′ probes were in opposition to each other. That is, for probes A and A′, the relative moisture content fell by 22 points, while for probes C and C′, it rose by 30 points. Rainfall exceeded 1.3 mm in these days, which led the external relative humidity to rise by 25 points and moistened the top of the arch, while the pier probes A and A′ remained unaffected (Figure 11).

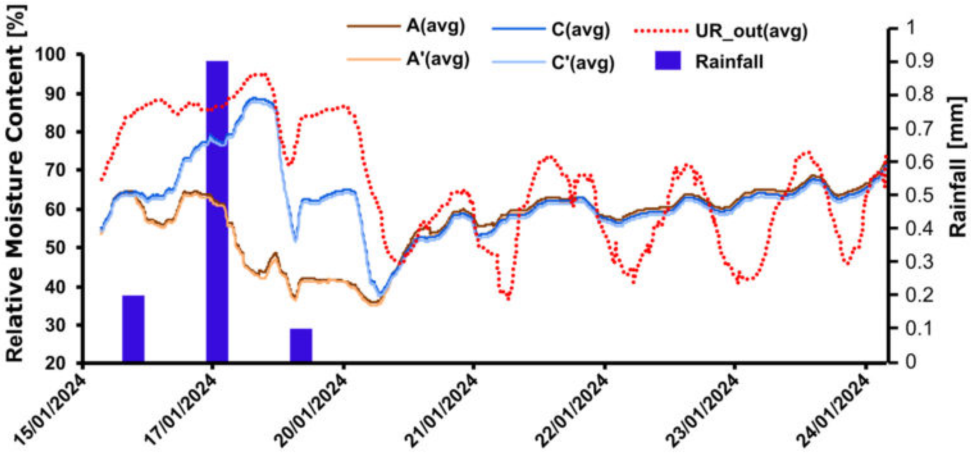


Figure 11. Relative moisture content and rainfall at the beginning of the setting.

6.2.2. Sorption/Desorption

Hemp shiv is very porous [20] and is therefore subject to rapid weathering. Figure 4 shows how reactive the mixture is according to the hygrometric conditions. The smoother curve is due to the mass involved in the hygrometric balance ratio, while the sawtooth curve shows the outdoor humidity. This period was shortly after the construction, so the mixture might not have set yet, which could explain the closeness of the curves.

While this porous material seemed to quickly absorb water (Figure 12), the desorption was relatively slower. Once the mix had taken up water in the form of gas, there were periods when it seemed very difficult to release it. As can be seen in Figure 13, the air relative humidity dropped in one day, but the mixture only underwent a 7-point drop over the following 5 days. The absence of sunshine or significant wind may be responsible for this. Indeed, as referred to Figure 14, we see that it is three times greater than the seasonal average (14 m/s on average from 16 April 2024 to 18 April 2024 as compared to an average of 1.9 m/s over the whole month of April) [22].

Moreover, as this period was 4 months after construction, the mixture may have set enough to be less dependent on weather conditions. Indeed, looking back to Figure 9, we realise that the mixture began to react gently from that moment on.

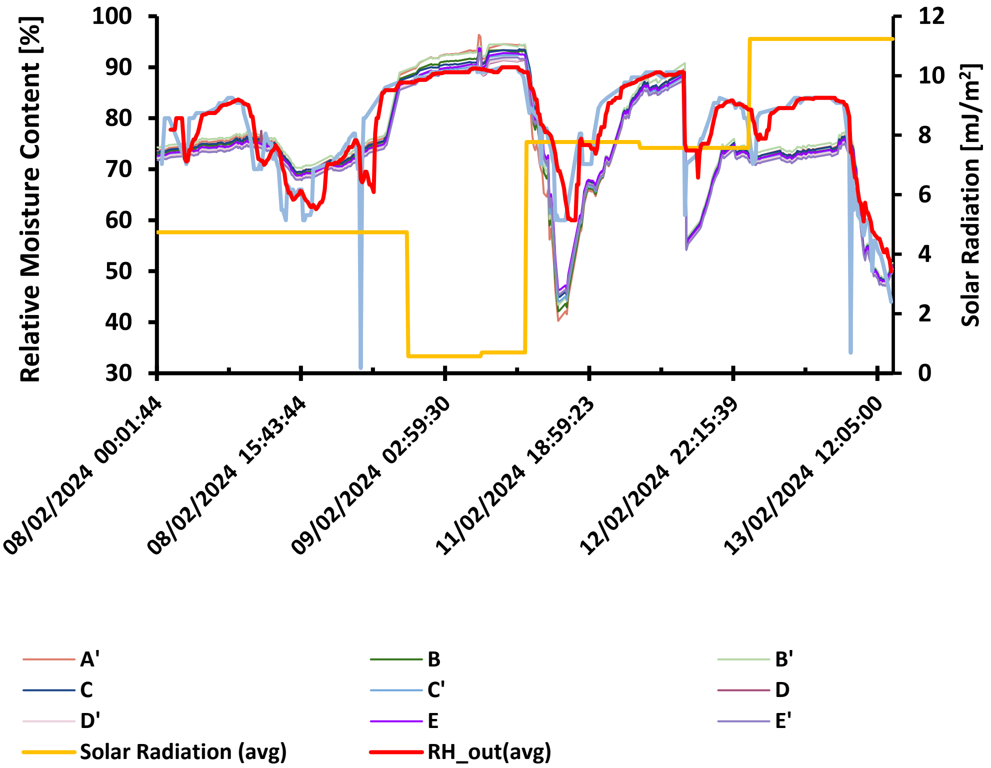


Figure 12. Mixture sorption behaviour.

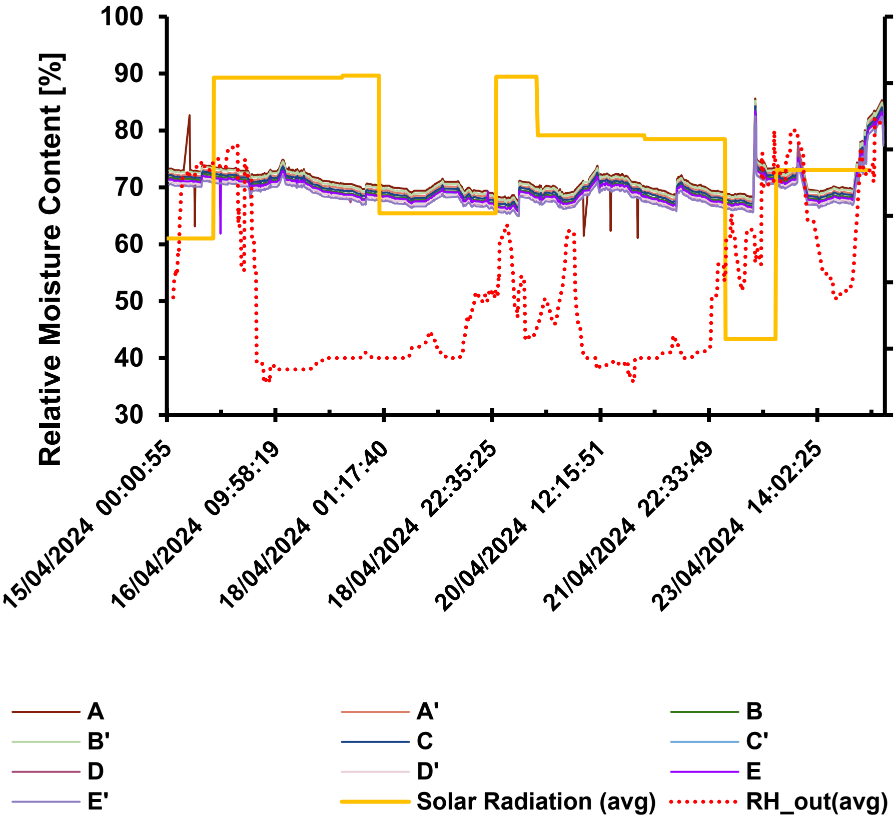


Figure 13. Moisture desorption behaviour.

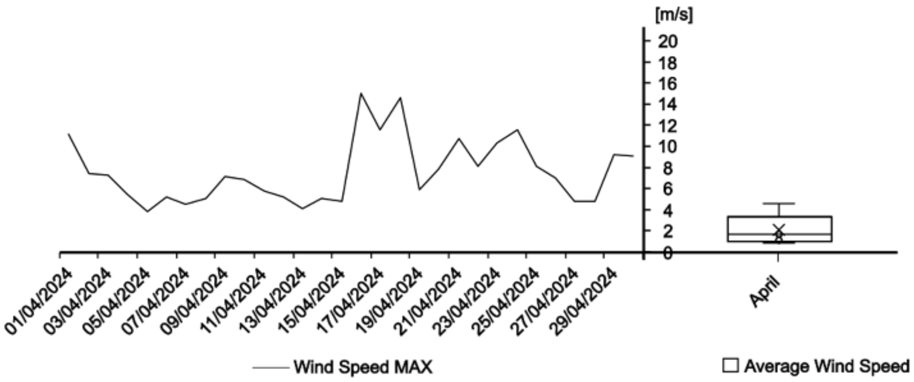


Figure 14. Measurement of wind in April 2024.

7. Discussion and Conclusions

The prototype enabled us to observe that hemp-lime is a material that reacts to its climatic context, even many weeks after its production. Testing it under natural conditions allowed us to obtain an appreciation of its thermal and hygrometric reactivity.

The temperature of the mixture was clearly influenced by the outside temperature. Thermal lags show that the mixture took 1 to 4 days to lose heat. Thanks to its low effusivity ($4.8\ \mathrm{W}\cdot\sqrt{\mathrm{h}}/\mathrm{m}^2\cdot\mathrm{K} = 288\ \mathrm{J}/\mathrm{K}\cdot\mathrm{m}^2\cdot\sqrt{\mathrm{s}}$) and high specific heat ($0.42\ \mathrm{W}\cdot\mathrm{h}/\mathrm{kg}\cdot\mathrm{K} = 1.512\ \mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$) [21], hemp-lime absorbs an important amount of solar radiation energy and releases such heat even after a week. We noticed that if the thickness increased from 30 to 60 cm, the duration of heat absorption doubles, and, conversely, the thicker the wall was, the slower the temperature decreased. We also observed that the temperature peaks inside the mass were higher than the peaks at its edge. This indicates that the studied mixture absorbed solar energy radiation in an effective way thanks to its peculiar combination of high specific heat and low thermal effusivity.

During the first month after construction, the water content of the mixture showed no relationship to the outdoor relative humidity. It then balanced out quite steadily. We also found that it absorbed and released water vapour more quickly in a windless environment. Wind was therefore an important parameter in the drying process of the mixture.

The water content of the mixture has relatively followed the fluctuations in outdoor relative humidity. However, there has been a slight and steady increase since May 20, despite the very pronounced fluctuations in the outdoor relative humidity. In fact, since the mixture was formed, it has steadily gained around 10 points, apart from singular events of weather change.

The monitoring of the setting state will allow the formwork to be removed in time when the material reaches an acceptable mechanical strength. Nevertheless, it seems interesting to notice that, during the curing phase, the mixture began to behave more independently from the relative humidity and rainfall. Such a response may be the signal of a deep carbonation. A chemical approach using a pH indicator like phenolphthalein to quantify such carbonation would be an interesting complement to our investigation. This would serve the purpose of discovering whether the moisture content and the internal temperature would provide any hints on when the state of a self-supporting structure is reached. Such a study would imply a correspondence between the curing time of the hemp-lime and its moisture content.

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Conflicts of Interest: The authors declare no conflict of interest.

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