Assessment of the Hygrothermal Performance of Prefabricated Concrete Panel Materials for Modular Construction

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Abstract. The increasing housing shortage in Portugal, alongside the industrialisation of the construction sector, has driven growing interest in modular construction. This innovative method offers faster building times, cost efficiency, and reduced waste. However, despite its advantages, aspects such as the thermal performance of modular systems have often been overlooked in previous studies. This highlights the need for a deeper understanding of how modular construction materials can be optimised to address these challenges.

This research focuses on the hygrothermal behaviour of various concrete compositions through the investigation of their performance under different environmental conditions, with an emphasis on relative humidity and thermal conductivity. Experimental tests were conducted to provide critical insights into how different concrete compositions react to temperature and moisture fluctuations. The results revealed that lower water content in concrete leads to a decrease in thermal conductivity.

The results of this research can help optimize the design of prefabricated concrete panels to enhance thermal efficiency and hygrothermal performance. This would ensure more stable and comfortable indoor environments while minimizing energy consumption in modular buildings. By aligning material performance with sustainability goals, the research aims to support the broader objective of creating environmentally responsible, energy-efficient housing solutions. Ultimately, this work seeks to advance the understanding of concrete's hygrothermal behaviour, contributing to the development of sustainable practices and ensuring modular construction achieves a balance between performance, occupant comfort, and environmental sustainability.

Keywords: Hygrothermal Behaviour, Thermal Performance, Prefabricated Concrete Sandwich Panels, Modular Construction.

1 Introduction

Portugal faces a growing housing shortage driven by insufficient political intervention, urban population growth, and the expansion of short-term rentals, all contributing to rising house prices. Coupled with relatively low-income levels, these factors have made affordable housing increasingly inaccessible [1,2]. Modular construction offers a promising solution by industrialising the building process, reducing construction time and costs, improving quality control, and minimising waste and environmental impact [3]. However, significant financial, regulatory, technical, and cultural barriers remain [4, 5].

Given the technical and regulatory challenges still surrounding modular construction, understanding its thermal performance is crucial—particularly as national and European standards continue to evolve. Improving thermal behaviour can further reduce environmental impact and energy consumption, which is especially relevant in the context of climate change [6]. Factory-controlled environments also enable greater precision in building envelope construction, potentially reducing thermal bridging and enhancing energy efficiency compared to traditional on-site methods.

In modular construction, the use of Prefabricated Concrete Sandwich Panels (PCSPs) is common, with numerous studies highlighting their effectiveness in achieving thermally efficient façades [7]. These panels typically consist of two concrete wythes connected by shear connectors—often made of steel—and a thermal insulation core, as seen in Fig. 1.

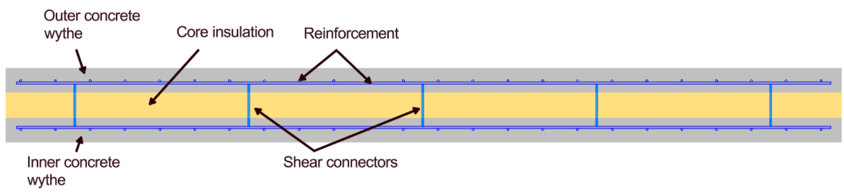

Fig. 1 Representation of a Prefabricated Concrete Sandwich Panel.

The common thermal reoccurring problem of PCSP depicted in the literature is the thermal bridge effect due to the steel sheer connectors, which can be solved with the use of Fiber Reinforced Polymer (FRP) due to its low thermal conductivity [7 - 10] or by staggering the shear connectors in order to provide a longer path for heat to travel, increasing the thermal resistance [11]. Although thermal bridging at the steel shear connectors in PCSPs is widely documented in the literature, it is important to acknowledge that other types of thermal bridges—such as those occurring at module junctions, corners, or interfaces with other construction elements—can also significantly affect the overall thermal performance of modular buildings and should be equally considered [12]. The composition of the used concrete, including aggregate type, water-to-cement ratio, and admixtures, may also significantly influence its thermal conductivity and moisture behaviour [13]. Similarly, the type and thickness of thermal insulation can impact not only thermal resistance but also moisture buffering and drying potential [14,15].

Despite the growing body of research on PCSPs, a comprehensive hygrothermal assessment of these systems remains lacking. It is therefore essential to evaluate how the composition of the concrete layers affects the overall hygrothermal behaviour of the panels, especially in relation to risks such as mould growth and freeze-thaw cycles, which may compromise durability and occupant comfort [16-18].

In this context, the present study aims to investigate the hygrothermal properties of different concrete compositions developed within the scope of the "R2UTechnologies – Modular Constructions" project [19]. An experimental campaign will be conducted to characterise the relevant thermal and moisture-related properties under controlled conditions.

2 Experimental campaign

In this study, the hygrothermal performance of different concrete compositions was assessed only through sorption curve analysis due to time constraints. Since the concrete compositions were developed within the framework of the "R2UTechnologies – Modular Constructions" project [19], the detailed composition of some concretes mixes is not available. Therefore, their thermophysical properties are evaluated solely based on their hygrothermal behaviour under varying relative humidity (RH) conditions, considering their water-to-cement (w/c) ratio (Table 1), and knowing that all samples use Portland cement. Furthermore, as for the aggregates, all concrete samples have coarse and fine gravel, the first column of Table 1, referring to CP, 25RCP, 30CC, 30CC15LFF, and 30BFA15LFF, include coarse and fine sand in their compositions, while the rest only fine sand.

Table 1. Different types of concrete under study.

Concrete ID	w/c	Concrete ID	w/c	Concrete ID	w/c
CP	0.45	BF1	0.45	BF8	0.46
25RCP	0.60	BF3	0.36	V1	0.42
30CC	0.64	BF5	0.37	V2	0.39
30CC15LFF	0.80	BF6	0.39		
30BFA15LFF	0.82	BF7	0.53		

For the hygroscopic tests, measurements were performed at different moisture content levels, following the procedures defined in ISO 12570 [20] and ISO 12571 [21]. The water content of a material in contact with air can vary from absolute zero (under 0% RH) to the critical moisture content reached after prolonged exposure to saturated conditions. In this study, RH setpoints of 15%, 35%, 50%, 75%, and 95% were selected to cover a broad range of environmental conditions.

Although ISO 12571 [21] recommends conducting measurements between 35% and 95% RH to characterise the hygroscopic region, an additional point at 15% RH was included to explore material behaviour under extremely dry conditions. Including this point might provide further insight into the lower boundary of moisture uptake [22].

As stated in ISO 12571 [21], before initiating sorption measurements, each sample was dried in an oven at 60 ± 5 °C until constant mass was achieved, as shown in Fig. 2. Constant mass is defined as a mass variation of no more than 0.1% across three consecutive weighings taken at 24-hour intervals.

Fig. 2. Concrete samples undergoing oven drying at 60 ± 5 °C until achieving constant mass, in accordance with ISO 12571 [21].

Following this drying phase, the sorption curve measurements were initiated. The specimens were placed in a climatic chamber (Fig. 3) maintained at a constant temperature of 23 ± 0.5 °C and exposed to each RH setpoint until mass stabilisation was observed, indicating equilibrium conditions.

Fig. 3. Samples placed in a climatic chamber at 23 ± 0.5 °C and exposed to different relative humidity setpoints for sorption curve measurements.

At each RH level, thermophysical properties were also measured, including thermal conductivity (λ) [W/(m·K)], volumetric heat capacity (c_ρ) [$\times 10^6$ J/(m^3·K)], and thermal diffusivity (α) [m^2/s] using the transient method with the Isomet 2114 device [23]. Since the samples were rigid, a surface (planar) probe was used. Each measurement lasted approximately 30 minutes at a controlled temperature of 20 ± 3 °C. The test procedure followed ASTM D5334-22 [24], ASTM D5930-17 [25], and ISO 22007-2 [26] standards. However, as transient methods such as the one employed may present limited reliability under certain conditions, particularly in heterogeneous or moisture-sensitive materials, complementary validation using steady-state heat flux measurements should be considered in future work to reinforce the robustness of the results.

The method evaluates the thermal response of each material to a controlled heat pulse generated by an internal electrical resistance within the probe. A surface (planar) probe was employed due to its suitability for testing rigid materials such as concrete. Given the small cylindrical geometry of the specimens (Fig. 4), measurements were taken at multiple locations—specifically, the top surface, the bottom, and once more on the top surface near the centre—to account for potential variability across the specimen and to ensure representative results. Measurements were conducted closer to the centre in order to minimise edge-related heat losses.

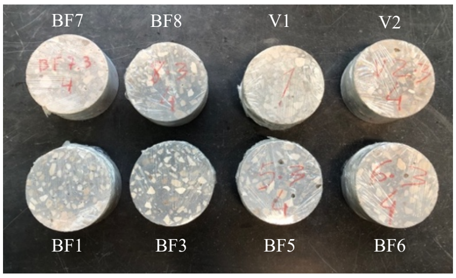

Fig. 4. Cylindrical concrete specimens used for thermal property measurements.

To further reduce thermal exchange with surrounding surfaces, specimens were placed on an insulating board during testing, as shown in Fig. 5. Additionally, each sample was wrapped in cling film to prevent moisture exchange with the surrounding environment during measurements.

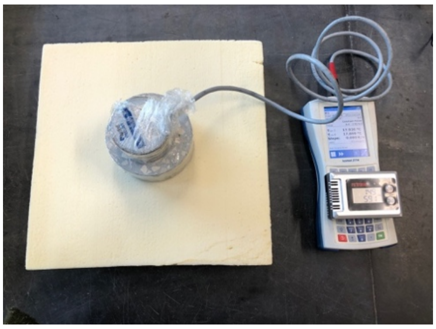

Fig. 5. Experimental setup for thermal property measurements using the Isomet 2114 device with a surface probe [23].

Each thermophysical property was measured three times, and the final reported value corresponds to the average of these three measurements. The results obtained from these measurements will be presented and discussed in the following chapters.

3 Results

This section presents the results obtained from the sorption experiments conducted on the concrete samples.

The sorption curves presented in Fig. 6 illustrate the relationship between equilibrium moisture content and relative humidity (RH) at a constant temperature. The measurements were carried out in accordance with ISO 12571 [21], and the values for moisture content by volume (Ψ) [m³/m³] were determined following ISO 12570 [20]. The selected RH setpoints—15%, 35%, 50%, 75%, and 95%—were chosen to capture both the lower and upper bounds of moisture adsorption. The results reflect the moisture uptake capacity of each sample and highlight differences in sorption behaviour.

As shown in Fig. 6, the sample of concrete 30CC15LFF exhibits the lowest sorption curve, indicating that it absorbs and retains less water vapour from the environment than the other concrete samples. This behaviour is unexpected, given its relatively high water-to-cement (w/c) ratio of 0.80, which would typically correspond to increased porosity and, consequently, greater moisture uptake.

On the other end of the spectrum, sample BF7 displays the highest sorption curve, despite having a moderate w/c ratio of 0.53, which is not the highest value among the tested mixtures.

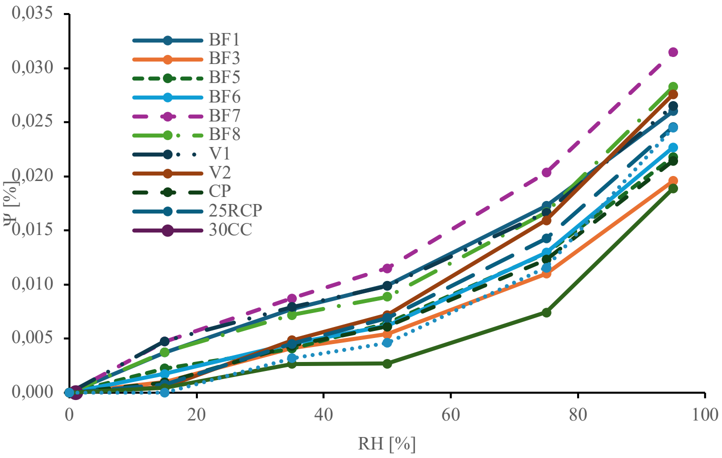

Fig. 6. Sorption curve of moisture content (Ψ) [m³/m³] as a function of RH [%] at constant temperature.

These results suggest that moisture uptake cannot be explained by the w/c ratio alone. Other factors, such as the type and dosage of additives or fillers, aggregate dimensions, the degree of hydration, pore structure, or curing conditions, play a significant role in defining the hygroscopic behaviour of the concrete. This highlights the complexity of moisture transport in cementitious materials [13].

The results for thermal conductivity (Fig. 7), generally exhibit the expected trend of increasing values with rising relative humidity. As moisture is absorbed into the concrete's pore structure, its thermal conductivity increases, indicating a decline in its insulating capacity.

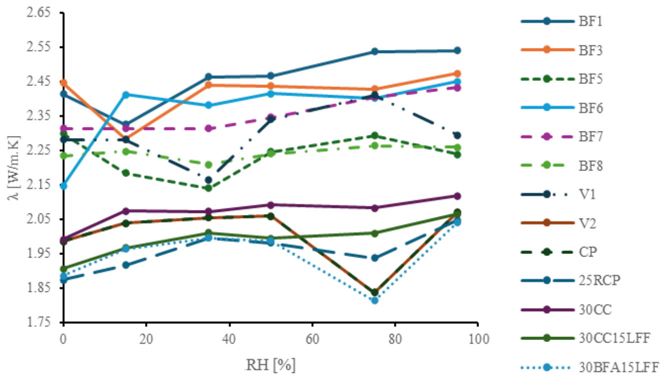

Fig. 7. Sorption curve of thermal conductivity λ [W/(m·K)] as a function of RH [%].

In Fig. 8, it can be observed that the volumetric heat capacity of the concrete samples increases with rising RH. This trend indicates that the materials' ability to store thermal energy is enhanced by the presence of moisture. Among the samples, 25RCP exhibits the highest sensitivity to humidity changes, as reflected by its notably elevated values of volumetric heat capacity.

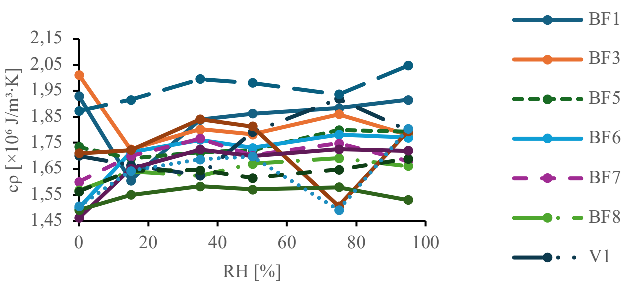

Fig. 8. Sorption curve of volumetric heat capacity c_ρ [W/(m·K)] as a function of RH [%].

Fig. 9 does not reveal a clear trend in thermal diffusivity across the different relative humidity levels. The values fluctuate for all samples, showing both increases and decreases without a consistent pattern, indicating an unstable or non-monotonic behaviour. The observed variability could also suggest that the microstructural response of each concrete composition to moisture is non-linear, depending on factors such as porosity, pore connectivity, and aggregate-matrix interaction. It is also possible that minor experimental variability or sensitivity of the transient method at certain moisture levels contributes to this irregular behaviour, particularly given the relatively small size of the specimens. Further investigation, including more RH setpoints and complementary microstructural characterisation techniques, such as mercury intrusion porosimetry (MIP), may be necessary to better understand the underlying causes of these fluctuations.

In conclusion, the pore network plays a critical role in the uptake and retention of moisture, which directly influences heat transfer processes and thermal storage within the material. A more detailed understanding of these microstructure should be pursued in future works to support the interpretation of thermal behaviour.

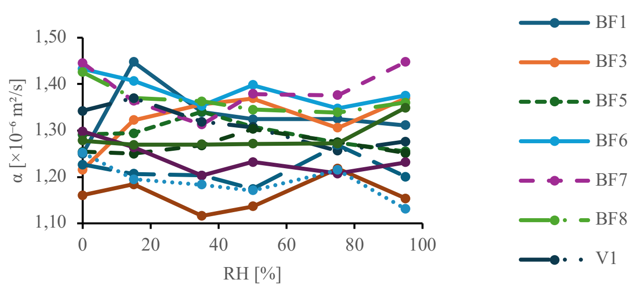

Fig. 9. Sorption curve of thermal diffusivity α [m^2/s] as a function of RH [%].

4 Discussion

This study assessed the hygrothermal behaviour of different concrete compositions by analysing their sorption characteristics and key thermophysical properties under varying RH conditions. The findings demonstrate that moisture uptake, as reflected by the sorption curves, does not correlate solely with the w/c ratio. For instance, although sample 30CC15LFF exhibited the highest w/c ratio, it showed the lowest sorption capacity, whereas sample BF7, with a lower w/c ratio, displayed the highest sorption capacity. These results highlight the multifactorial nature of moisture transport in cementitious materials, where factors such as additive dosage, aggregate dimensions, pore structure, and curing conditions significantly influence hygroscopic behaviour.

The thermal conductivity of all samples generally increased with RH, indicating reduced insulating performance due to moisture absorption. Similarly, volumetric heat capacity also increased with RH, confirming that the presence of moisture enhances the material's thermal energy storage capacity. Among the samples, 25RCP exhibited the highest sensitivity to humidity variations in this respect.

In contrast, thermal diffusivity did not exhibit a consistent trend across the RH range. The irregular fluctuations observed suggest complex interactions between moisture and the concrete microstructure, potentially influenced by by variations in pore connectivity, matrix-aggregate interfaces, and microstructural heterogeneity. These inconsistencies may also be partially attributed to limitations inherent in the transient measurement method. Steady-state methods, where heat flux can be directly measured, should be considered to obtain more reliable and comprehensive conclusions. Further studies involving a broader RH range and complementary characterisation techniques are recommended to clarify the mechanisms governing thermal diffusivity in moist concrete.

Overall, the results underscore the importance of incorporating moisture-dependent thermophysical behaviour when evaluating the performance of concrete in energy-efficient and durable construction applications. In particular, understanding these parameters is critical for the accurate development of hygrothermal simulations of PCSP, as they enable more reliable predictions of moisture transport and thermal behaviour under real-world boundary conditions. Such simulations can support the early identification of potential issues such as condensation, thermal bridging, and long-term durability concerns within the building envelope.

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