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Development of Half-Sandwich Panels with Alkali-Activated Ceramic and Slag Wastes: Mechanical and Thermal Characterization

Norma Gaibor ^{1,*}, Dinis Leitão ², Ana Briga-Sá ³, Tiago Miranda ¹, Nuno Cristelo ⁴,
Eduardo N. B. Pereira ¹ and Vítor M. C. F. Cunha ¹

¹ University of Minho, ISISE, ARISE, IB-S, Department of Civil Engineering, 4800-058 Guimarães, Portugal; tmiranda@civil.uminho.pt (T.M.); eduardo.pereira@civil.uminho.pt (E.N.B.P.); vcunha@civil.uminho.pt (V.M.C.F.C.)

² University of Minho, CTAC, Department of Civil Engineering, 4800-058 Guimarães, Portugal; dleitao@civil.uminho.pt

³ University of Trás-os-Montes e Alto Douro, CQ-VR and ECT, School of Science and Technology, 5000-801 Vila Real, Portugal; anas@utad.pt

⁴ University of Trás-os-Montes e Alto Douro, CQ-VR, Centro de Química-Vila Real, Department of Engineering, 5001-801 Vila Real, Portugal; ncristel@utad.pt

* Correspondence: norma.gaibor@civil.uminho.pt

Abstract: This paper presents the development of two solutions for sandwich panels composed of a thin-layer alkali-activated composite (AAc) layer and a thicker insulation layer, formed by extruded polystyrene foam or expanded cork agglomerate (panels named AP_{XPS} or AP_{ICB}, respectively). The AAc combined ceramic waste from clay bricks and roof tiles (75%) with ladle furnace slag (25%), activated with sodium silicate. The AAc layer was further reinforced with polyacrylonitrile (PAN) fibers (1% content). The mechanical behavior was assessed by measuring the uniaxial compressive strength of cubic AAc specimens, shear bond strength, pull-off strength between the AAc layer and the insulation material, and the flexural behavior of the sandwich panels. The thermal performance was characterized by heat flux, inner surface temperatures, the thermal transmission coefficient, thermal resistance, and thermal conductivity. Mechanical test results indicated clear differences between the two proposed solutions. Although AP_{XPS} panels exhibited higher tensile bond strength values, the AP_{ICB} panels demonstrated superior interlayer bond performance. Similar findings were observed for the shear bond strength, where the irregular surface of the ICB positively influenced the adhesion to the AAc layer. In terms of flexural behavior, after the initial peak load, the AP_{XPS} exhibited a deflection-hardening response, achieving greater load-bearing capacity and energy absorption capacity compared to the AP_{ICB}. Finally, thermal resistance values of 1.02 m² °C/W and 1.14 m² °C/W for AP_{ICB} and AP_{XPS} were estimated, respectively, showing promising results in comparison to currently available building materials.

Keywords: half-sandwich panels; industrial wastes; alkali activation; mechanical behavior; thermal performance



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1. Introduction

The cement and concrete industry accounts for up to 10% of global anthropogenic CO₂ emissions [1,2]. As a result, developing sustainable construction materials with a lowered environmental footprint across both the manufacturing and operation stages is crucial. Alkali-activated materials are promising candidates for partially replacing ordinary

Portland cement (OPC), as their production allows up to a 70% reduction in greenhouse gas emissions [3].

In 2023, according to Manufacturing Economic Studies, global ceramic tile production reached 15,937 million m², a 5.5% decrease from 2022 [4]. However, ceramic waste (CW) remains a significant byproduct, with 30% originating from manufacturing [5] and 45% from demolition and construction wastes [6]. This waste is expected to increase due to the rapid growth in worldwide demand.

In terms of alkali activation, ceramic waste (CW) has favorable physical and chemical properties (most notably the amorphization degree and the aluminosilicate content) [7]. Additionally, ladle furnace slag (LFS) was incorporated in the present work as a complementary precursor, as an important source of calcium, silicon oxide, and alumina [8]. This contributes to the formation of cementitious calcium silicate hydrate (C–S–H) and/or calcium aluminum silicate hydrate (C–A–S–H) phases, which enhances the mechanical properties of the matrix [9] to be used in the panels' construction.

In general, several works have been conducted on studying the development of sustainable alkali-activated materials using industrial ceramic wastes [10–12] and the incorporation of different types of slag, mainly in civil engineering [13,14]. However, research about the combination of those two industrial wastes in alkali activation remains scarce, with the available findings presented in Table 1. Moreover, information on the feasibility of the PAN fiber reinforcement of alkali-activated materials is very limited; to the best of the authors' knowledge, only a couple of works on this topic are available [15,16].

Table 1. Alkali-activated materials based on ceramic waste (CW) and slag (S).

Ceramic Waste Type	Precursor (wt. Ratio), CW:S	Alkali Activator	Compressive Strength, 28 Days, MPa	Curing Conditions/ Temperature	Reference
Tile waste	50:50 60:40 70:30	NaOH (4M) ² :Na ₂ SiO ₃ , mass % 0.75	Up to ~73 Up to ~68 Up to ~32	Ambient T, 27 °C	[17]
	70:30	NaOH (2M) ² :Na ₂ SiO ₃ , mass % 0.75	Up to ~34	Cured in air	[18]
	50:50 60:40 70:30	NaOH (4M) ² :Na ₂ SiO ₃	Up to ~73 Up to ~68 Up to ~32	Ambient T, 25 °C	[19]
Red clay brick waste from the brick-making plant	20:80 40:60 60:40 80:20	Na ₂ SiO ₃ + Na ₂ CO ₃ (SiO ₂ /Na ₂ O, silica modulus of 1.5)	Up to ~100 Up to ~96 Up to ~70 Up to ~40	Room T or steam curing	[20]
Waste brick powder	100–50 ¹	NaOH (10M) ² + Na ₂ SiO ₃	Ranged from 24 to 93 MPa	Ambient T, 25 °C	[6]
Ceramic waste and red clay brick waste	10:90	Na ₂ SiO ₃ + Na ₂ CO ₃	Up to ~80 Up to ~83	37 ± 2 °C for 24 h, then tap water at 23 ± 2 °C	[21]

Table 1. Cont.

Ceramic Waste Type	Precursor (wt. Ratio), CW:S	Alkali Activator	Compressive Strength, 28 Days, MPa	Curing Conditions/ Temperature	Reference
Ceramic waste from CDW	75:25 50:50 25:75	NaOH (8M) ² [SH] or Na ₂ SiO ₃ [SS]	[SH]; [SS] ~18; ~50 ~15; ~50 ~5; ~38	70 ± 2 °C for 24 h, then ambient T, 21 ± 2 °C	[22]
Waste building ceramics	50:50	NaOH (2M) ² Na ₂ CO ₃ (99%)	Up to ~88	Standard conditions, 20 ± 2 °C	[23]

¹ At increments of 10% by volume, 0–50%; ² molar concentration of alkaline solution; T: temperature.

At the EU level, the building sector represents more than 40% of the total energy consumption [24], and half of that is utilized in space acclimatization and lost to the environment [25,26]. Hence, having in mind the enhancement in energy efficiency and decrease in the environmental impact of building operation, the importance of insulation materials for buildings and industrial facilities is growing [27]. Insulation materials are classified by their chemical or their physical structure as illustrated in Figure 1. In the European market, the dominant isolation materials are inorganic fibrous materials (e.g., stone wool and glass wool) and organic foamy materials (e.g., expanded polystyrene and extruded polystyrene). In this context, “organic” refers to carbon-based materials, often from petroleum, including synthetic polymers like expanded polystyrene (XPS). While chemically organic, these materials are synthetic, unlike biologically organic materials such as cork or cellulose. Each group represents about 60% and 30%, respectively, while all other materials accounted for less than 13%, the corkboard insulation included [24].

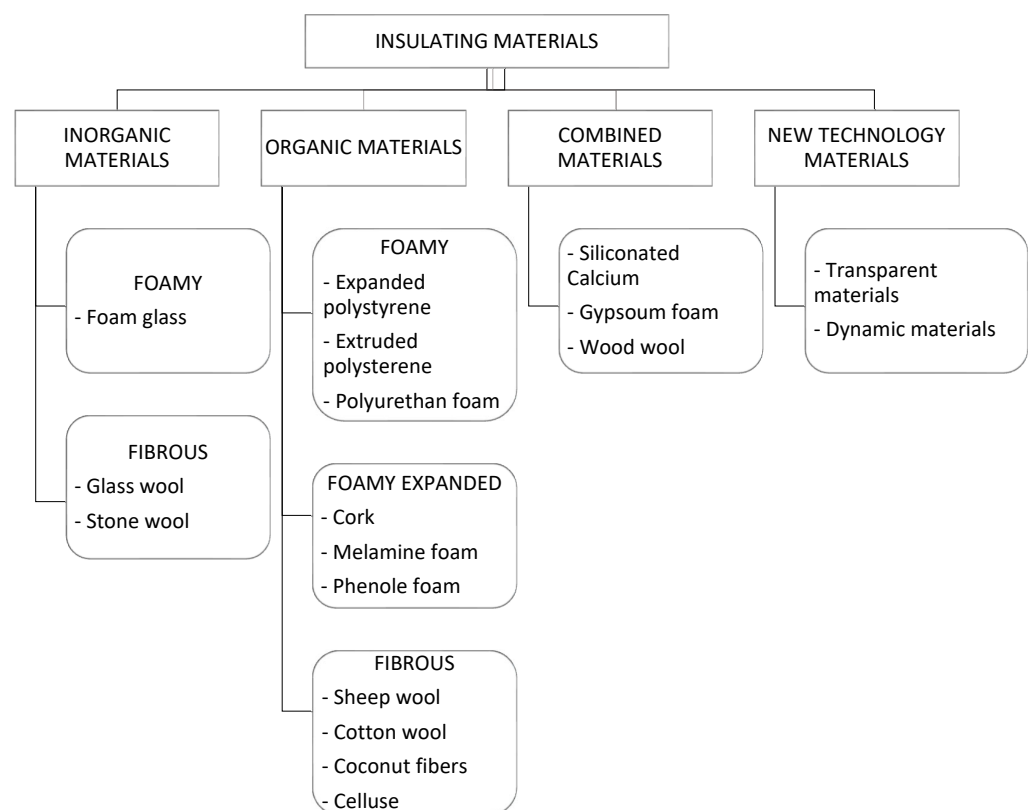


Figure 1. Classification of the dominant insulating materials in the European market [28].

The extruded polystyrene (XPS) consists of polyester grains (polymerized polystyrol, 1.5–2%) in an extruder, with the addition of a blowing agent, expanded polystyrene (air, 98–98.5%) [28]. XPS is characterized to have a higher specific heat capacity in comparison to expanded polystyrene (between 1.3 and 1.7 kJ/kg·K). Moisture negatively affects the values of thermal conductivity. The biopersistence of the XPS as waste is high; thus, it cannot be disposed of as common demolition waste, and specialized industries are needed for the recycling process due to their flammability and because burning releases dangerous gases into the atmosphere [29].

In contrast, agglomerated cork is a material that comes from the bark of the cork oak tree (*Quercus suber* L.) [30]. It is typically sourced from the Southern Mediterranean countries, although Portugal is the main producer, holding about one-third of the total cork tree area and representing 50% of worldwide production [31]. Cork is a common material used in the building sector due to its excellent thermal and acoustic performance, chemical stability, and durability [32]. Some of the main cork physical–mechanical properties are thermal conductivity, density, and specific heat, whose values range from 0.037 to 0.050 W/m·K, from 110 to 170 kg/m³, and from 1.5 to 1.7 kJ/kg·K, respectively [33]. In terms of ecological features, it is a 100% natural product and, therefore, easily recycled [34]. Tártaro et al. [27] concluded that it is the only insulation material present in the market with a negative carbon footprint, mainly because cork is a renewable raw material and biomass is used for its production.

2. Research Significance

While previous studies have widely explored alkali-activated materials, most have focused on systems based primarily on fly ash and slag as the main precursors for geopolymer binders. Very limited research has investigated the use of industrial ceramic waste, particularly in combination with ladle furnace slag (LFS), for the development of sandwich panels. Among the few available studies on geopolymer sandwich structures, most have centered on the structural performance and vibration behavior of fiber-reinforced panels incorporating conventional geopolymers and FRP connectors [35–39], with little to no attention paid to the thermal performance or the incorporation of biobased or recycled insulation materials.

In this context, the present study introduces a novel composite solution by developing and characterizing two half-sandwich panel configurations incorporating an alkali-activated matrix composed of 75% ceramic waste and 25% LFS, activated with sodium silicate and reinforced with 1% polyacrylonitrile (PAN) fibers. Distinct from previous research, this work not only explores the combined use of underutilized industrial wastes but also evaluates their performance within layered systems using extruded polystyrene (XPS) and expanded cork agglomerate (ICB) as insulation cores—materials that differ significantly in origin, structure, and environmental footprint. Importantly, the AAC matrix was cured at ambient temperature, further supporting eco-efficiency by eliminating energy-intensive thermal curing processes.

By integrating mechanical and thermal performance evaluation within a single experimental campaign, this work fills an important gap in the literature and proposes a sustainable alternative to traditional cementitious panel systems. It aims to promote circular economy practices while maintaining or improving mechanical behavior comparable to that of OPC-based materials.

3. Materials and Methods

This research campaign was carried out in three main stages, namely, (i) the panels' production, (ii) mechanical assessment, and (iii) thermal performance assessment. The studied

panels were composed of one layer (or skin) of alkali-activated ceramic waste-/slag-based cement, as an element that will contribute to the stiffness and strength of the composite solution, bonded with either extruded polystyrene (XPS) foam or expanded cork agglomerate (ICB) boards mainly contributing to the insulation properties.

3.1. Materials

In the present work, wastes from Portuguese industries were used as precursors of the developed alkali-activated cement (AAc), specifically, ceramic waste (CW) from a brick manufacturing company in Braga and ladle furnace slag (LFS) from melting scrap in an electric arc furnace from the ironwork company Megasa, located in Maia. The matrix was reinforced with polyacrylonitrile (PAN) fibers with a length of 8 mm and a diameter of 20 μm . For the reaction process, sodium silicate (SS; Na_2SiO_3) was used as an alkaline activator in solution form. The SS had a unit weight of 1.464 g/cm^3 at 20 $^\circ\text{C}$, a $\text{SiO}_2/\text{Na}_2\text{O}$ weight ratio of 2.0 (with a molar oxide ratio of 2.063), and a Na_2O concentration of 13.0% in solution. The blend also included a polycarboxylate-based superplasticizer (SP) with an SP/precursor weight ratio of 0.02 and a water-to-SS weight ratio of 0.05.

Regarding the mixture production, for alkali activation, the timing and sequence of adding precursors, alkali activator, and fibers are critical [40]. The mixing process involved three steps: First, the solid phase and activator solution were homogenized for one minute at 140 ± 5 rpm in an industrial mixer. Next, SP and water were added and mixed for two minutes at 285 ± 10 rpm. Finally, fibers were slowly incorporated and mixed for three minutes at maximum speed to ensure uniform PANf distribution. The total mixing time was six minutes. The detailed characterization of the physical, chemical, mechanical, and micro-structural properties of the developed alkali-activated cement can be found elsewhere: [15,16].

In this study, two different thermo-insulating materials of 30 mm thicknesses each were analyzed: a rigid extruded polystyrene foam (XPS) board with a grooved surface finish on one face and expanded cork agglomerate (ICB), standardized according to EN 13164:2013 [41] and EN 13170:2013+A1:2015 [42], respectively. Based on their corresponding technical sheets, the main properties of the insulation materials used for this study are displayed in Table 2.

Table 2. Technical specifications according to supplier datasheets for extruded polystyrene (XPS) [43] foam and expanded cork agglomerate (ICB) [44].

	XPS	ICB
Density (kg/m^3)	30 to 33	+/-110
Compressive strength (kPa) at 10% deformation	300	≥ 100
Tensile strength (kN/m^2)	50 to 80	≥ 600
Thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)	0.033	0.039
Water permeability	High resistance to water absorption Satisfactory diffusion of water vapor	Water absorption Permeability to water vapor
Reaction to fire	Euroclass E	Euroclass E
Environmental properties	100% recyclable 50-year durability Produced without CFCs and HCFCs GWP: 2.57 $\text{kg CO}_2\text{-Eq}/1 \text{ m}^2$ XPS board [45]	100% natural and fully recyclable Almost unlimited durability CO_2 sink (carbon-negative)

3.2. Mixture and Panel Manufacture

A mixture composition of 75% CW + 25% LFS-/SS-, reinforced with 1% (by volume) PAN fiber and ambient-cured ($20\text{ }^{\circ}\text{C}$ and $60\% \text{ HR} \pm 5\%$) [15], was used for the development of the present non-structural panels. Two sets of half-sandwich panels were manufactured: AAc + XPS (first set) and AAc + ICB (second set). The rigid layer composition for each panel is displayed in Table 3 and Figure 2.

Table 3. Non-structural panels based on alkali-activated cement with high ceramic waste; composition in kg/m^3 .

Precursor		Activator	SP	Water	PANf
CW	LFS	SS			
499.2	166.4	299.5	13.3	15.0	6.7

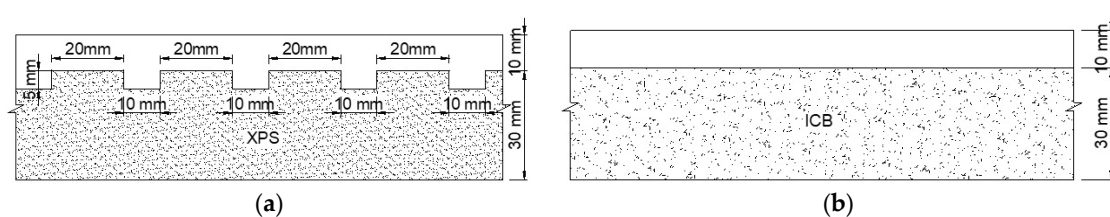


Figure 2. Vertical cross-section of semi-sandwich AAc panels with different thermo-insulating materials: (a) extruded polystyrene (AP_{XPS}) and (b) insulation corkboard (AP_{ICB}).

For easier reference, the panels' nomenclature for the test specimens is as follows: the first two letters "AP" are consistent all through the tests indicating the use of the developed AAc; the subscript letters denote the type of isolation: XPS or ICB. These lead to the panel identifiers AP_{XPS} and AP_{ICB} , respectively. For AP_{XPS} , when the direction of the grooves was considered, the following designations were used when parallel and when perpendicular, respectively: $\text{AP}_{\text{XPS}}^{\parallel}$ and $\text{AP}_{\text{XPS}}^{\perp}$.

Additionally, the XPS insulation was tested as received (including grooves) to replicate industrial applications, leading to localized AAc thickness variations (10–15 mm). While this introduces geometric non-uniformity, it reflects real-world conditions where grooves enhance mechanical interlock. Future studies will focus on isolating material properties using flat-surfaced specimens.

The AAc mixture was prepared in a 50 L industrial mixer at a low mixing speed ($40 \pm 3 \text{ rpm}$). To ensure consistent properties of the paste and mitigate the standard variation on the results of the tested specimens, each batch was around 15 L. Firstly, the dry components (CW and LFS) were mixed for three minutes. Then, the activator (SS) was added to the mixture, and it was stirred for two more minutes, followed by the incorporation of the water and SP for a further one minute. As it is known, the order of fiber incorporation during the mixing is important to achieve uniform fiber dispersion [40]. Consequently, in the last step, PAN fibers were gradually added to the fresh mix composition to avoid fiber balling, and it was mixed for a further 3 min to ensure a homogeneous distribution of fibers. Thus, the blend was mixed for a total of 9 uninterrupted minutes.

The workability of the fresh alkali-activated cement was verified using the slump flow test following the specifications of BS EN 12350-8 [46]. It was conducted by measuring the average horizontal free flow of the AAc in a perpendicular direction using a steel scale, and no segregation was observed. The workability of the AAc was measured by the average opened-out diameter, ranging from 100 mm to 135 mm (Figure 2a), which is a noticeable improvement of about 1.5% in comparison with the reference sample in Gaibor et al. (2023) [16].

Finally, one layer of 10 mm of fresh AAc was cast directly over the isolation materials; the total height of the panel was 40 mm. Each specimen was framed with PVC profiles, in which dimensions varied according to the test performed (Figure 3b), either mechanical or thermal tests, as detailed in Sections 3.3 and 3.4. Finally, specimens were vibrated for 2 min to release entrapped air. All panels were cured for at least 28 days in a climatic chamber (Fitoclima 28000 EDTU) under constant environmental conditions (20 °C (± 0.5 °C) and under an HR of 60% $\pm$ 5%) or until testing.

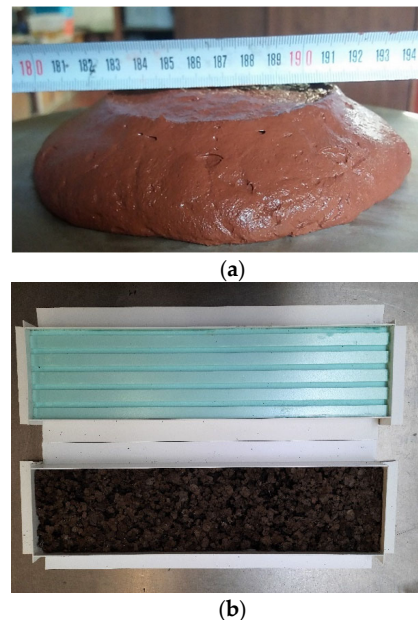


Figure 3. (a) Mini slump test; (b) preparation of isolation materials for casting.

3.3. Mechanical Testing Procedures

3.3.1. Compressive Strength

The uniaxial compressive strength (UCS) was assessed using eight cubic specimens ($50 \times 50 \times 50 \text{ mm}^3$) divided into two batches of four specimens each to evaluate consistency. The tests were performed at 28 days (Figure 4). The UCS was determined by adapting the methodology proposed in ASTM C39/C39M-18 [47]. A monotonic displacement rate of 0.005 mm/min and an actuator of a load capacity of 300 kN were used (Figure 4).

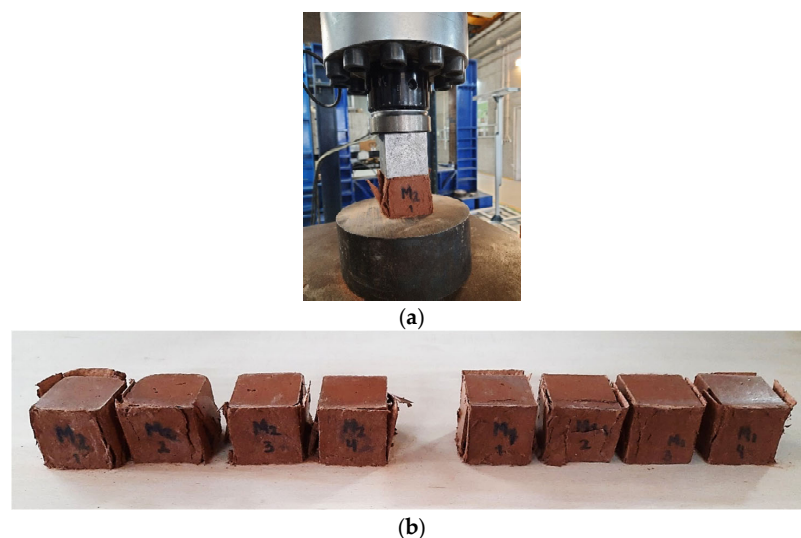


Figure 4. (a) Experimental set-up for the uniaxial compressive test; (b) cubic specimens of $50 \times 50 \times 50 \text{ mm}^3$ after test execution.

3.3.2. Pull-Off

The present work investigated the tensile bond strength performance of the AAC matrix with the isolation material, either XPS or ICB, using pull-off tests. A single specimen was manufactured for each half-sandwich panel (AP_{XPS} and AP_{ICB}) with dimensions of $600 \times 150 \times 40$ mm (length $\times$ width $\times$ height). As mentioned in Section 3.2, the AAC panels were cast immediately after completing the mixing process.

To ensure a final AAC thickness of 10 mm, PVC profiles (40 mm in height) were glued to the insulation material, and the excess mixture was removed with a plain spatula to achieve a smooth surface. Before testing, five equidistant circular cuts (50 mm diameter, 10 mm depth) were made per specimen on the AAC face of the panel, with 50 mm spacing between cuts (Figure 5a).

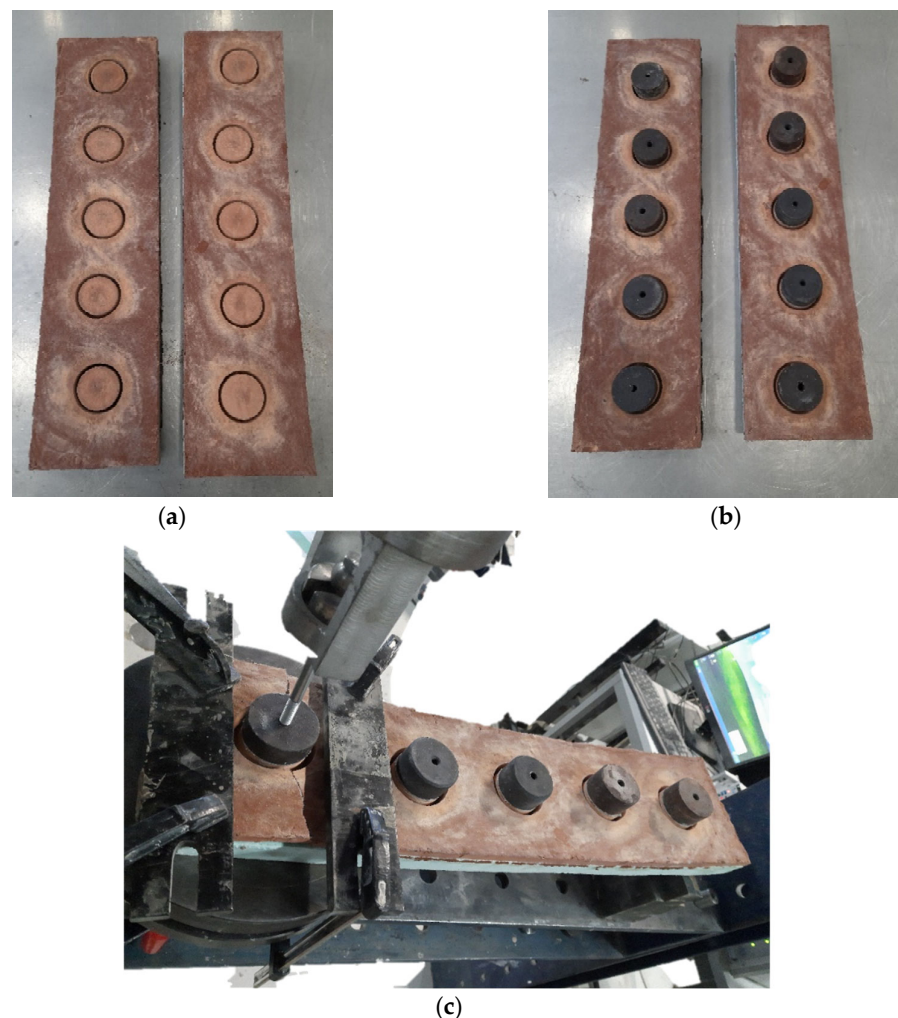


Figure 5. (a) Sample preparation; (b) bond of the metal disk to the samples' outer surface; (c) pull-off test set-up (real apparatus).

For each cut, a Sika Icosit® K 101 N epoxy resin was used to glue a metal disk (dolly) to the circular AAC surface of each cut (Figure 5b). This bonding process was completed 24 h before testing to prevent any potential damage that could affect interfacial strength. In total, 10 pull-off tests were performed—5 per specimen—ensuring a comprehensive evaluation of the bond strength.

The pull-off test (Figure 5c) was carried out in a servo-hydraulic testing machine with a load capacity of 25 kN, where a tensile force was applied at a constant rate of 0.003 mm/s. To calculate the bond stress (MPa), the ratio between the maximum pull-off load (kN) and

the loaded area (mm^2) was considered. The average of five results per AAC/XPS or ICB system is presented.

3.3.3. Direct Shear

To evaluate the shear bond behavior, four panels ($120 \times 120 \times 50 \text{ mm}$) were produced for each composite solution, namely, AAC + XPS or ICB. For the composite panels made with XPS, interfacial bond behavior was assessed in two distinct directions: parallel ($AP_{XPS}^{\parallel}$) and perpendicular ($AP_{XPS}^{\perp}$) to the grooves (Figure 6a). In total, 12 samples were tested across the three series. The load was applied on the lateral surface of the AAC, and the insulation material was fixed to the testing rig. Servo-hydraulic testing with a load capacity of 25 kN was used. The tests were carried out under displacement control at a rate of 0.005 mm/s. Before starting the test, a plate of the same height for the AAC layer (20 mm) and another for the insulating material (30 mm) was placed along the specimen to distribute the load and avoid deformation of the XPS or ICB plate, respectively, and the bond between the two layers of the panel was evaluated. Linear variable differential transformers (LVDTs) were also employed to measure the relative displacement between the two layers, hereinafter designated by slip (s). LVDTs were attached on small aluminum plates placed next to the actuator or on the AAC face layer of the specimen, and the other two were placed directly on the cross-section of the AAC on the opposite side, as shown in Figure 6b.

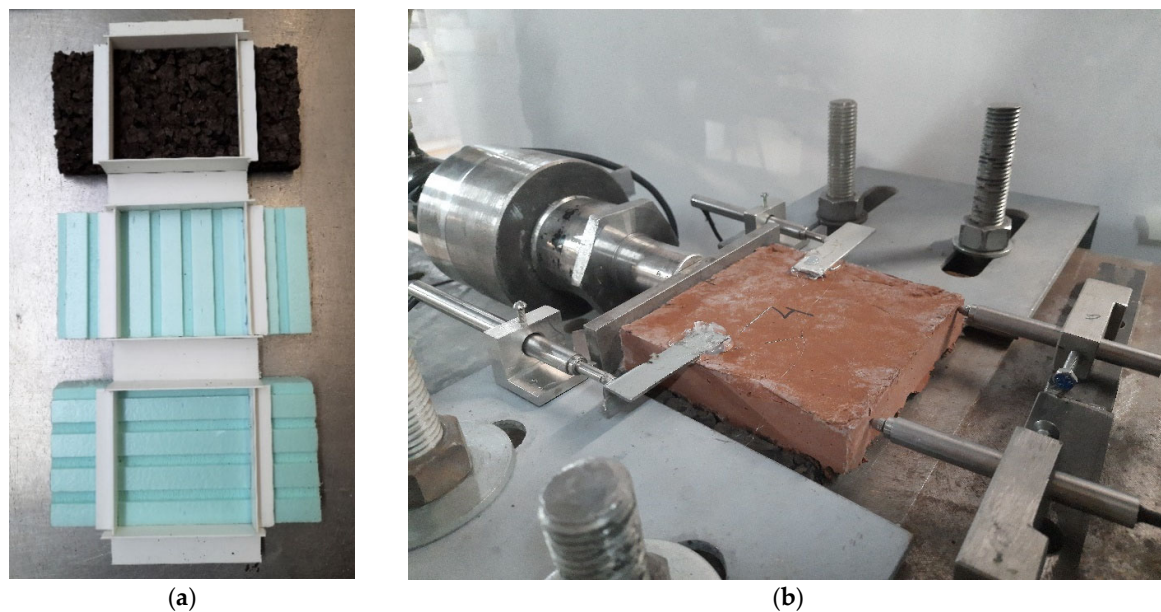


Figure 6. (a) Preparation of samples before casting; (b) set-up for the direct shear test.

3.3.4. Flexural Behavior

The flexural behavior of the two studied panel systems (AP_{XPS} and AP_{ICB}) was determined through a three-point bending test set-up (Figure 7). A total of eight specimens were manufactured and tested, with four specimens per series, each measuring $600 \text{ mm} \times 150 \text{ mm} \times 40 \text{ mm}$. A servo-hydraulic testing rig with a 100 kN load cell was used. The tests were performed under displacement control at a rate of 0.005 mm/s. The panels were tested with a 500 mm span. Prior to the test, low-density polyester putty was put on the center of the specimen to hold a metallic roll to distribute the load, which was applied at the mid-span. The deflection at the mid-span was assessed by linear variable differential transformers (LVDTs), as shown in Figure 7. In this preliminary stage, the bending tests were conducted with the AAC layer positioned upwards, reflecting a common installation orientation in façade or non-structural applications. Future work will

include testing in both directions (up and down the AAc) to fully evaluate the structural contribution of the alkali-activated layer under both compressive and tensile loading.

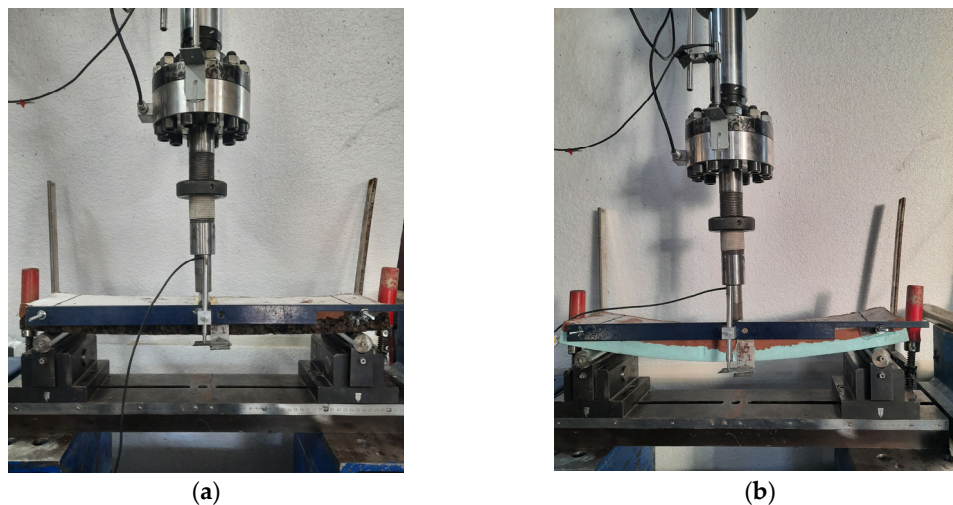


Figure 7. Experimental set-up of the three-point bending test on half-sandwich AAc panels with different thermo-insulating materials: (a) extruded polystyrene (XPS) and (b) insulation corkboard (ICB).

3.4. Thermal Testing Procedures and Analysis

3.4.1. Experimental Set-Up

The evaluation of the thermal behavior was performed following the experimental procedure indicated in ISO 9869 (1994) [48]. Two half-sandwich panels of $600 \times 500 \times 40$ mm (width $\times$ height $\times$ thickness) were manufactured, each comprising 30 mm thick XPS or ICB as thermal insulation material and 10 mm of the AAc, identified as AP_{XPS} and AP_{ICB} , respectively. Additionally, for comparison purposes, a panel of alkali-activated cement based on ceramic wastes and slag only (ACP) with an equivalent layer thickness (10 mm) was fabricated; therefore, a total of 3 panels were tested simultaneously.

This experimental test was carried out in a test room with dimensions of $4.0 \text{ m} \times 3.0 \text{ m} \times 2.5 \text{ m}$ (length $\times$ width $\times$ height). The set-up preparation first includes the replacement of the existing windows on the test room façade by an XPS board with dimensions of $3 \text{ cm} \times 76 \text{ cm} \times 64 \text{ cm}$ (thickness $\times$ width $\times$ height), which framed and held the AP_{XPS} , the AP_{ICB} , and the AAc uninsulated panel. Next, the panels were positioned in the test room to be north-facing and were simultaneously analyzed, allowing us to compare the thermal performance of the three different samples. The alkali-activated cement layer of the panels was placed towards the interior of the room (Figure 8a), and consequently, the face of the insulation materials was exposed to the exterior environment (Figure 8b). Then, each sample was meticulously sealed with the aid of polyurethane foam (PU) to avoid thermal bridges and noninsulated headers to ensure the absence of leaks and the experimental test's reliability.

The equipment used for the experimental work includes three heat flux systems; each one comprised a datalogger, two Hukseflux HFP01SC plate sensors (HF_1 and HF_2), and four inner surface temperature sensors (T_{si11} , T_{si12} , T_{si21} , and T_{si22}), which were fixed on the inner surface of each panel to measure the heat flux (q_1 and q_2) and the inner surface temperatures, respectively (Figure 9).



Figure 8. Thermal experimental set-up of the half-sandwich panels, AAC + extruded polystyrene (AP_{XPS}), AAC + insulation corkboard (AP_{ICB}), and uninsulated panel (ACP): (a) sealed interior view; (b) sealed exterior view.

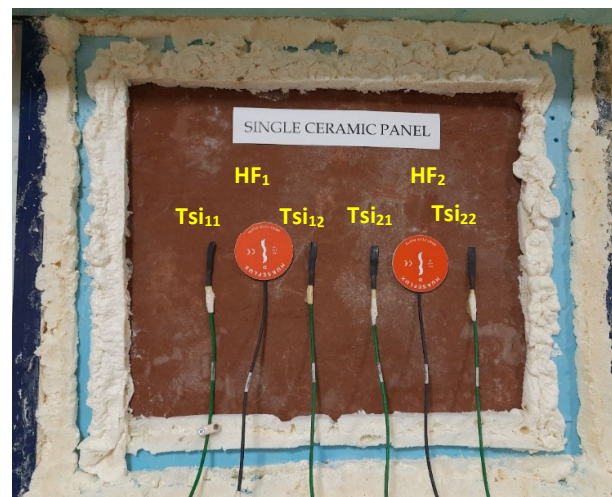


Figure 9. Utilized equipment for thermal performance analysis: heat flux sensors, HF_1 and HF_2 , and inner surface temperature sensors, Tsi_{11} , Tsi_{12} , Tsi_{21} , and Tsi_{22} .

Two Hanna Instrument HI 91610C thermohygrometers composed of a datalogger and a temperature probe were employed to ensure the measurement of the temperature inside (T_i) and outside (T_e) the test room. The information acquired and stored by the different dataloggers using the software LoggerNet and PC208W3.3 for the heat flux systems and 92000-16 for the thermohygrometers was then transferred to a computer for further analysis and thermal parameter estimation.

According to ISO 9869 [48], the maintenance of a high thermal gradient between the interior and the exterior environments is needed to ensure a significant heat flux through the panels with the same signal during the measurement period. So, the test room was thermally controlled by a heating system that was successfully employed in previous studies [49,50]. An interior temperature of $32\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ throughout the measurement period was guaranteed, as can be observed in the following sections. The experiment was carried out for 15 consecutive days in the early autumn; that is, the measurement period was from 12 to 28 September. The parameters $q_{1(n)}$ and $q_{2(n)}$; $Tsi_{(n)}$; $Ti_{(n)}$; and $Te_{(n)}$ were continuously obtained in 10 min intervals.

3.4.2. Analysis Procedure

For a multi-layer panel, thermal properties can be represented by the thermal transmission coefficient (U), defined as the heat flow that passes through a unit area of a complex component or inhomogeneous material due to a temperature gradient equal to 1 K [33]. For the assessment of U values for AP_{XPS}, AP_{ICB}, and ACP panels, the ISO 9869 guidelines [48] were followed. Thereby, some assumptions have been considered to characterize the thermal performance of the investigated panels using a heat flow meter. Firstly, assessing the temperature values on both sides of the sample and the average of the heat flow rate over an adequately long time provides an acceptable estimate of the steady-state conditions. The measurement period is defined based on the thermal inertia of the element under analysis; for high-inertia elements, a measurement period of 14 days is required, while for low-thermal-inertia ones, a minimum of 72 h is acceptable. Given that a measurement period of 15 days was considered for the panels with low thermal inertia, the steady-state conditions are guaranteed. Secondly, the thermal properties and the heat transfer coefficient of the studied materials do not vary with the range of temperature fluctuation during the experimental test. Thirdly, the difference in the amount of stored heat in the building element or material is insignificant in comparison with the amount of heat going through it. Moreover, the use of interior (T_i) and exterior (T_e) temperatures rather than surface temperatures is recommended to determine the thermal transmission coefficient. Finally, with the above-mentioned considerations, the calculation of U was based on the dynamic or average method by applying Equation (1) from Table 4.

Table 4. List of equations for the thermal performance assessment.

Equation n°	Parameter	Units	Equation	Description
(1)	Thermal transmission coefficient (U)	$W/m^2 \text{ } ^\circ C$	$U_{(ntotal)} = \frac{\sum_{n=1}^{ntotal} q_{(n)}}{\sum_{n=1}^{ntotal} (T_i(n) - T_e(n))}$	$q_{(n)}$: heat flow through the sample for the instant n $T_{i(n)}$: interior temperature $T_{e(n)}$: exterior temperature $ntotal$: total number of instants of registered data during the experiment Applied to each HF_i data set
(2)	Thermal transmission coefficient of each panel (U')	$W/m^2 \text{ } ^\circ C$	$U'_{(ntotal)} = \frac{U_{1(ntotal)} + U_{2(ntotal)}}{2}$	Use $U_{(ntotal)}$ values from Equation (1) Applied to HF_1 and HF_2 data set
(3)	Thermal resistance (R') for each panel	$(m^2 \text{ } ^\circ C/W)$	$R'_{(ntotal)} = \frac{1}{U'_{(ntotal)}}$	Use $U'_{(ntotal)}$ value from Equation (2)
(4)	Thermal resistance of the ACP layer (R'_{ACP})	$(m^2 \text{ } ^\circ C/W)$	$R'_{(ACP)} = R'_{(ntotal)} - R_{se} - R_{si}$	Use $R'_{(ntotal)}$ value from Equation (3) R_{se} : $0.04 \text{ m}^2 \text{ } ^\circ C/W$ [51] R_{si} : $0.13 \text{ m}^2 \text{ } ^\circ C/W$ [51] R'_{ACP} is estimated for the ACP layer
(5)	Thermal conductivity (λ)	$(W/m \text{ } ^\circ C)$	$\lambda_{ACP} = \frac{e_{ACP}}{R'_{ACP}}$	e_{ACP} : thickness of the ACP R_{ACP} : ACP thermal resistance from Equation (4)

In this case, as two heat flux sensors (HF_1 and HF_2) with their corresponding pair of temperature sensors ($T_{si11(n)}$ and $T_{si12(n)}$; $T_{si21(n)}$ and $T_{si22(n)}$) were used on each studied element, two heat flux values ($q_{1(n)}$ and $q_{2(n)}$) were obtained. Therefore, applying Equation (1) resulted in two U values ($U_{1(ntotal)}$ and $U_{2(ntotal)}$) where their average, as defined in Equation (2), was designated as the final U' value for each panel.

The inverse of the thermal transmission coefficient is the thermal resistance (R). Thus, the thermal resistance ($R'_{(ntotal)}$) of the proposed solutions was estimated using Equation (3). Given that the ACP solution is a single panel, it is possible to estimate the thermal resistance value of the ACP layer considering the external and the internal superficial thermal resistances, R_{se} and R_{si} , respectively, as indicated in Equation (4).

Finally, by estimating the thermal resistance value for the ACP layer (R'_{ACP}) of 10 mm thickness, the theoretical value of the thermal conductivity (λ) can be computed by applying Equation (5). Thus, the conductibility of the alkali-activated cement based on ceramic wastes and slag can be estimated and compared with currently available materials, such as ceramic, and other traditional construction materials.

4. Results and Discussion

4.1. Mechanical Behavior

In this section, the experimental results of the two proposed half-sandwich panels, AP_{XPS} and AP_{ICB} , are presented and analyzed. The compressive strength of the AAC was determined by averaging all sample measurements, resulting in an average value of 37.2 MPa and a coefficient of variation (CoV) of 10.6% at 28 days of curing.

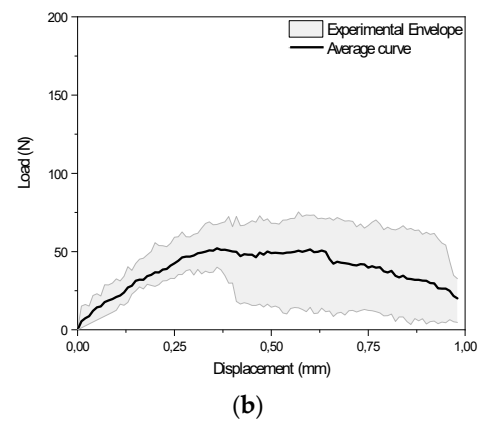
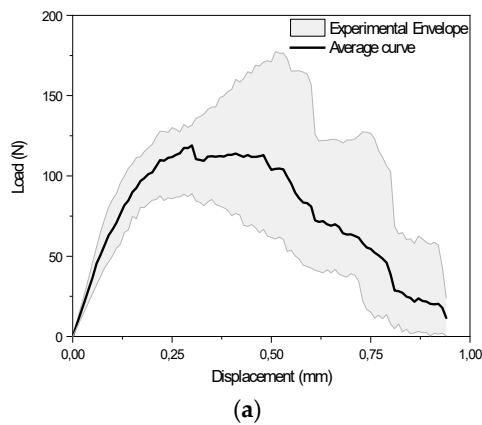
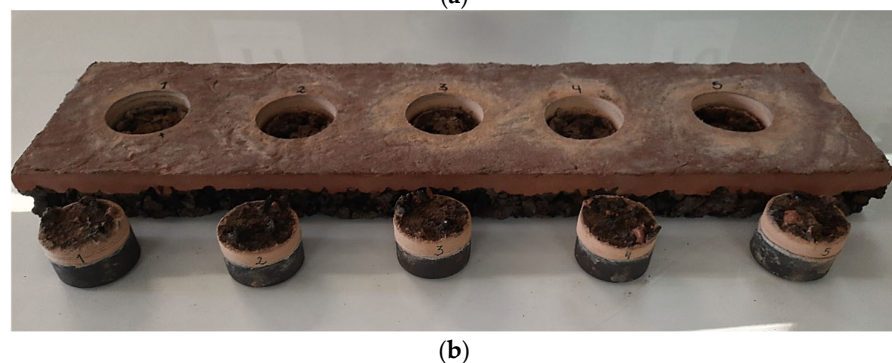
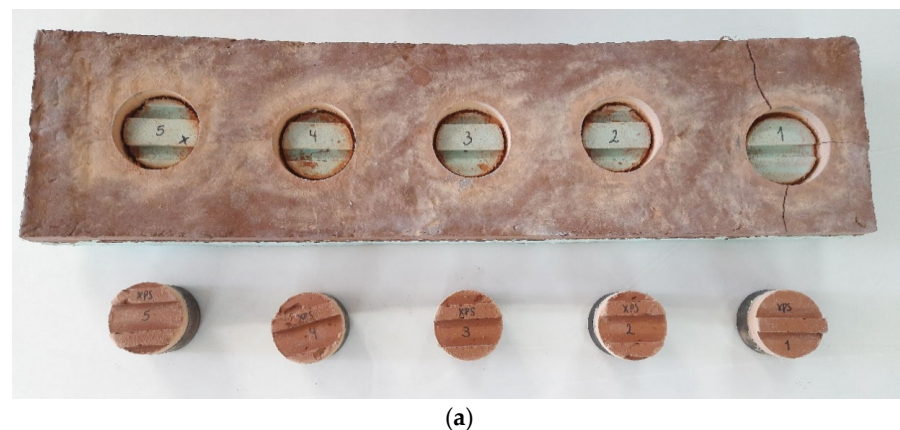
On the other hand, the nature and design of the insulating board used for each building solution were not experimentally assessed; however, they must be considered when interpreting the results. For instance, the grooved XPS insulation board used is a rigid foam material. In contrast, the ICB is an all-natural material acquired by expanding the cork granulates by steam-heating them. This feature makes the ICB panel have an irregular interface surface.

4.1.1. Pull-Off Tests

The tensile bond strength between the AAC and the insulation layer was determined based on five pull-off tests. Table 5 presents the average interfacial tensile strength computed accordingly to the procedure presented in Section 3.3.2. Figure 10 shows the pull-off force–displacement curves for each composite panel. A relatively high scatter of the responses was observed for AP_{XPS} ; this could be ascribed to the non-uniform distribution of the grooves within the circular area where the test was performed (Figure 11a). The highest tensile bond strength values were reported for AP_{XPS} panels, which were about 80% higher than for AP_{ICB} . The values for the latter can be regarded as the tensile strength of the cork particle board itself due to the observed failure mechanism, since two different types of failures were observed for the panels with AP_{XPS} and AP_{ICB} . In the first, i.e., the AP_{XPS} panels, debonding was observed at the interface between the AAC and the insulation layer (Figure 11a). The second type of failure occurred outside the interface region, i.e., within the bulk of the cork particleboard layer, indicating that the tensile bond strength between the AAC and the ICB exceeds the tensile strength of the ICB itself, revealing a weak internal structure of the ICB (Figure 11b). The latter can be related to the high porosity of the cork particle board used.

Table 5. Main bond properties of the developed panels' interface.

Panel ID	Shear Bond Strength (τ_{avg}) [kPa] (CoV, %)	Interfacial Tensile Strength [kPa] (CoV, %)
AP_{XPS}	$AP_{XPS}^{\perp}$ 89.0 (13.8)	86.4 (29.8)
	$AP_{XPS}^{\parallel}$ 79.3 (8.6)	
AP_{ICB}	46.4 (1.0)	52.4 (15.2)

**Figure 10.** Pull-off force–displacement relationships for (a) AP_{XPS} and (b) AP_{ICB} .**Figure 11.** Failure modes obtained from the pull-off tests: (a) AP_{XPS} and (b) AP_{ICB} .

4.1.2. Direct Shear Tests

The average shear bond strength (τ_{avg}) values of the AP_{XPS} and the AP_{ICB} were computed based on the maximum load and area of the interfacial surface. In general, the τ_{avg} of the AP_{XPS} series, loaded parallel ($AP_{XPS}^{\parallel}$) or perpendicular ($AP_{XPS}^{\perp}$) to the direction of the grooves, was higher than that of the AP_{ICB} tested specimens, which was about 90%

and 70% higher than the one observed for AP_{ICB} , respectively (Table 5). Moreover, as expected, the bond strength obtained for $AP_{XPS}^{\perp}$ was slightly higher ($\sim 12\%$) than $AP_{XPS}^{\parallel}$. The load–slip average curve for each type of the investigated half-sandwich panels is depicted in Figure 12. The experimental variability observed, represented by the shaded areas around the average curves, is primarily due to slight inhomogeneities in the materials, minor variations in specimen preparation, and small discrepancies in the alignment of load application during testing. Figure 13 shows representative images of the tested specimens in their final (post-unloading) states, demonstrating residual displacements and highlighting the interfacial zones where damage or relative slip occurred for the panel typologies studied.

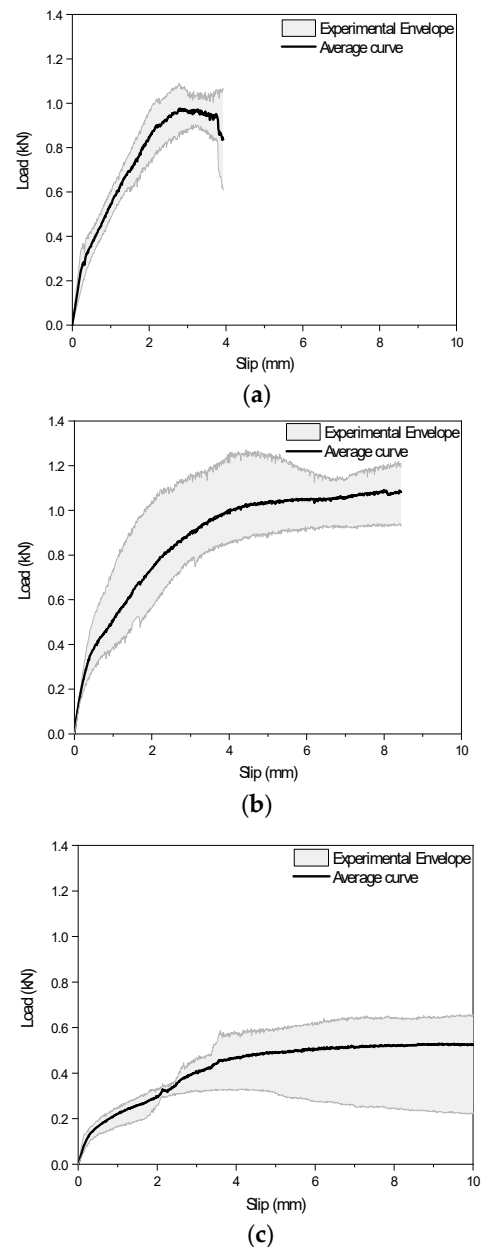


Figure 12. Mechanical shear behavior of panels with (a) XPS perpendicular grooves ($AP_{XPS}^{\perp}$); (b) XPS parallel grooves ($AP_{XPS}^{\parallel}$); and (c) ICB.

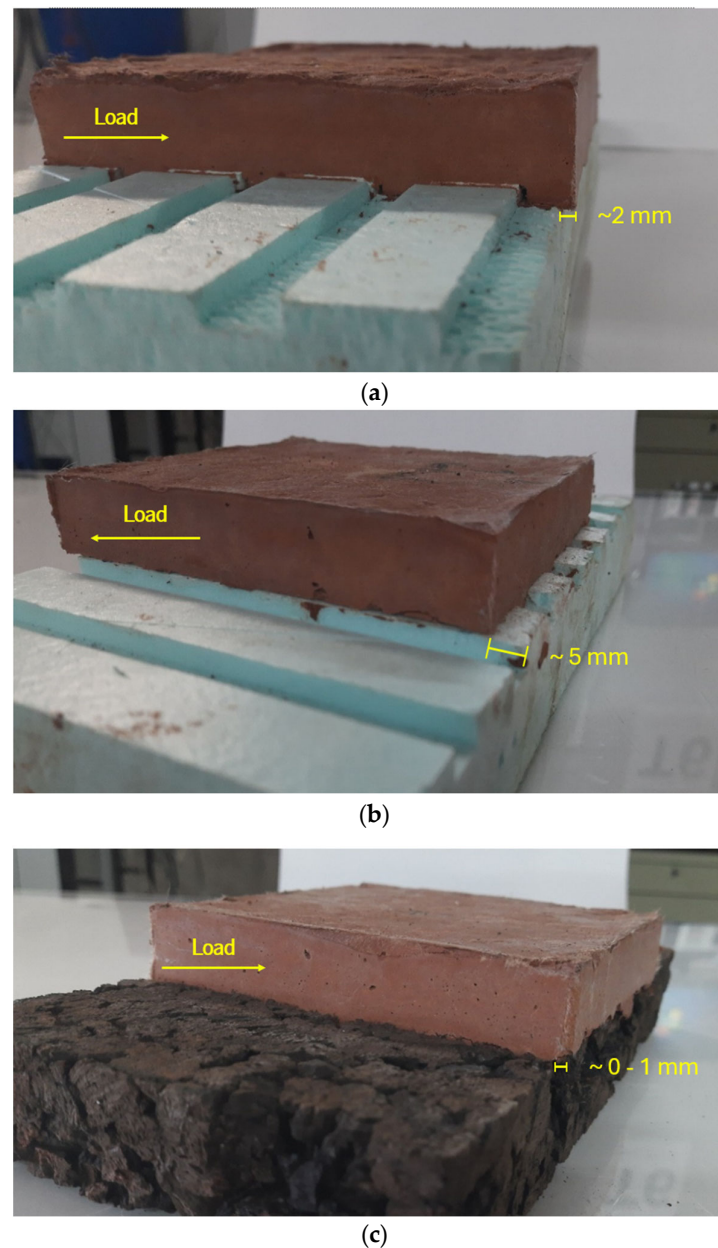


Figure 13. Post-test views of sandwich panels following direct shear testing: (a) $AP_{XPS}^{\perp}$ with XPS perpendicular grooves ($AP_{XPS}^{\perp}$); (b) $AP_{XPS}^{\parallel}$ with XPS parallel grooves ($AP_{XPS}^{\parallel}$); (c) AP_{ICB} .

In general, when the load was applied along the direction perpendicular to the grooves of the XPS, it was distinguished as an initial linear branch followed by a nonlinear section up to the peak load (Figure 12a). The test was stopped when the load remained more or less constant at an average slip of 8.5 mm, and a displacement of the AAc layer of about 2 mm was observed (Figure 13a). In this case, the perpendicular grooves of the XPS provided a mechanical interlock between the two components. When the load was applied in the parallel direction of the grooves of the XPS, a linear phase was also observed. However, the peak load occurred at an average relative displacement of ~ 3 mm, significantly lower than the one for $AP_{XPS}^{\perp}$ (Figure 12b). This was expected, since for $AP_{XPS}^{\parallel}$ the interfacial bond behavior was governed by chemical and frictional adherence, while for $AP_{XPS}^{\perp}$ there was the additional contribution of the grooves, which act as mechanical reinforcement mechanisms. Afterward, it was followed by a sudden softening branch attributed to the

unstable debonding process at the interfacial layer. The load was removed when the skin layer of $AP_{XPS}^{\parallel}$ slipped approximately 5 mm (Figure 13b).

Specimens with an ICB isolation layer showed a much higher slippage level, but with a lower shear resistance (Figure 12b). In addition, the AP_{ICB} panel layers did not debond due to chemical bond/friction between the ICB and the AAc, when the test was finished and the load was removed. The AAc layer almost returned to its original position (Figure 13c), i.e., with a low residual relative deformation. The surface roughness of the insulation board AP_{ICB} provided a better bond [52] between the ICB and the AAc, opposite to the AP_{XPS} shear behavior. Direct shear results are in accordance with pull-off findings (Table 5); i.e., in general, the values acquired for the behavior of the AP_{XPS} are almost double those from the results of the AP_{ICB} .

4.1.3. Flexural Behavior

Figure 14 displays the load–deflection curves of the two types of half-sandwich panels. In general, the two tested half-sandwich panels exhibited quite distinct flexural behavior, which can be ascribed to the distinct mechanical properties of the insulation materials, although these are mostly due to the distinct equivalent height of the reinforced AAc layer of the panel’s cross-section that will consequently translate to a higher flexural capacity.

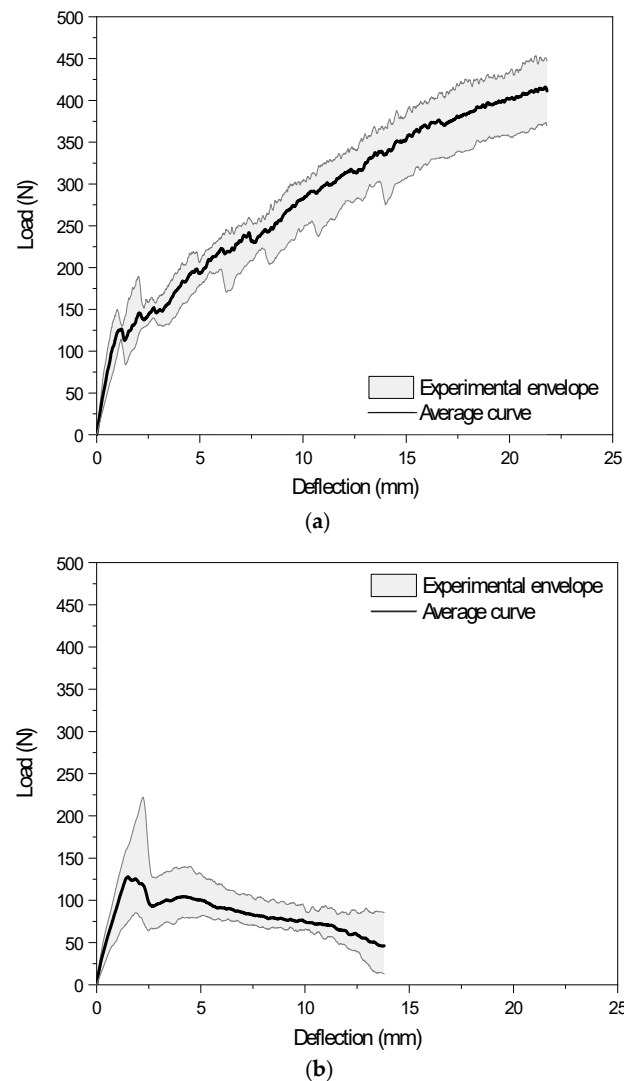


Figure 14. Load displacement curves under flexural loading for (a) AP_{XPS} and (b) AP_{ICB} , at 28 days of curing.

Regarding the flexural behavior of the AP_{XPS}, in the beginning, the skin layer (AAc) and the isolation material (XPS) act in a linear-elastic manner until the first peak. Since the cross-section flexural stiffness of the panel with XPS is considerably higher than the one from the ICB (see Figure 2) at this first peak, which is quite similar in both panels, it was expected to be higher for AP_{XPS} than that observed for AP_{ICB}. Regarding AP_{XPS} panels, after this initial peak, and regarding cracking initiation, a deflection-hardening behavior was observed (Figure 14a). Still, the appearance of sudden small drops in load along the hardening branch may be associated with the action of the PAN fibers of the AAc layer. In contrast, the bending behavior of the AP_{ICB}, after the initial peak, was characterized by a sharp softening branch (Figure 14b). For the latter panel, only the formation of a single crack was visible, in opposition to the multiple cracks observed on the AP_{XPS} panels.

The contrast between the flexural behavior of the two studied systems supports the hypothesis that the performance discrepancy between both panels is mainly due to differences in the cross-section of the AAc layer and, to a lesser extent, due to the isolation material strength.

4.2. Thermal Performance

The temperature conditions and the thermal parameters of the AP_{XPS}, AP_{ICB}, and ACP panels resulting from the experimental tests are presented in Table 6. As mentioned before, the measured data were recorded at 10 min intervals for fifteen days; therefore, the mean values of the different variables recorded for each sample are displayed in Table 6. The results will be discussed in the subsequent sections.

Table 6. Experimental conditions and thermal parameters of ACP, AP_{ICB}, and AP_{XPS} panels.

Panel ID	T_i (°C)	T_e (°C)	T_{si} (°C)	q_i (W/m ²)	$U'_{(ntotal)}$ (W/m ² °C)	$R'_{(ntotal)}$ (m ² °C/W)	R'_{ACP} (m ² °C/W)	λ_{ACP} (W/m °C)
ACP	32.04	15.37	26.15	65.94	3.91	0.26	0.09	0.12
AP _{ICB}			30.14	16.64	0.98	1.02	-	-
AP _{XPS}			29.62	14.86	0.88	1.14	-	-

4.2.1. Heat Flux

It can be observed from Figure 15 that, during the measurement period, the test room indoor temperature (T_i) was nearly constant and always higher than the outdoor temperature (T_e), which ensured the requirements specified in ISO 9869 [48] regarding the maintenance of the heat flux signal, in this case occurring from the interior of the test room to the exterior environment, were met. The T_i values stabilized at an average of 32.04 °C, while T_e fluctuated naturally, since it is not possible to be controlled; 7.35 °C and 24.52 °C were recorded as the minimum and the maximum values, respectively. During the execution of the experimental test, a positive differential between T_i and T_e was corroborated, and consequently, positive curves of $q_{1(n)}$ and $q_{2(n)}$ also resulted.

Regarding heat flux curves, higher values of $q_{1(n)}$ and $q_{2(n)}$ were observed for the noninsulated panel (ACP) compared to AP_{ICB} and AP_{XPS}, as expected, with significant peak variation related to diurnal and nocturnal periods. Average differentials of about 1.43 W/m², 0.23 W/m², and 0.08 W/m² were registered between $q_{1(n)}$ and $q_{2(n)}$ for ACP, AP_{ICB}, and AP_{XPS}, respectively, demonstrating that the heat flux sensors HF_1 and HF_2 were correctly placed at points where a uniform composition of the analyzed panels is reflected. It was also noted that no significant difference existed between the heat flux values of the AP_{ICB} and AP_{XPS} panels, since almost-overlapping curves can be seen in Figure 15. Nevertheless, the heat flux curves of the AP_{ICB} sample showed slightly larger fluctuations that can be attributed to voids present in the expanded agglomerated cork insulation panel

due to the nature of its composition, which also explains a higher average differential value between $q_{1(n)}$ and $q_{2(n)}$ in comparison to AP_{XPS} . Furthermore, it is also known that the ICB is characterized by a higher thermal conductivity value compared to XPS, which confirms the differential verified in the heat flux curves. In addition, when comparing the reference panel (ACP) with the two other solutions, AP_{ICB} and AP_{XPS} , reductions of 74.54% and 76.10% in the heat flux values were detected, respectively.

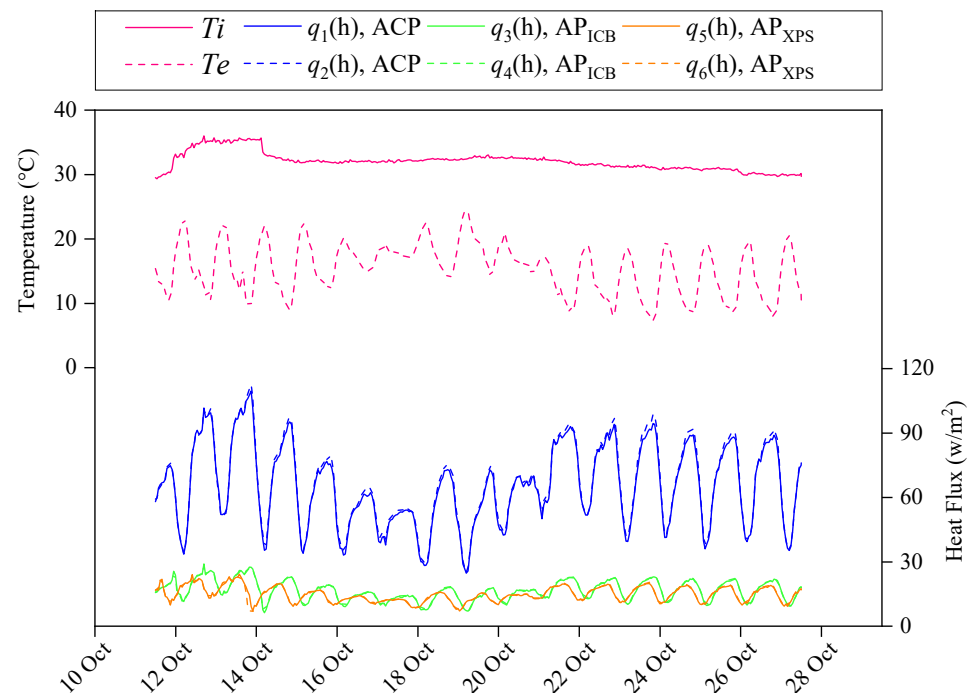


Figure 15. Indoor ($Ti(n)$) and outdoor ($Te(n)$) temperatures and heat flux ($qi(n)$).

4.2.2. Inner Surface Temperatures

The inner surface temperature curves obtained by the $Tsi_{11(n)}$ and $Tsi_{21(n)}$ sensors, for each panel sample studied, are shown in Figure 16, while the average values are given in Table 6. The reference sample (ACP) recorded a mean value of 26.2 °C, a minimum of 22.6 °C, and a maximum of 30.8 °C. Thus, concerning ACP, an increase of 15.4% and 13.5% in the mean surface temperatures was verified for AP_{ICB} and AP_{XPS} , respectively. In both cases, a minimum of around 26 °C and a slightly higher maximum value for AP_{ICB} (33.7 °C vs. 32.9 °C) were registered. It is worth mentioning that the greater oscillation detected in the ACP curve is an evident thermal behavior in the absence of an insulation layer in this sample.

The present results are consistent with the previous section in terms of heat flux variation. A similar oscillation pattern can be evidenced in the three panels studied. Moreover, the inner surface temperature curves of AP_{ICB} and AP_{XPS} are also nearly overlaid, as was expected given the results obtained for the heat flux curves. For the same indoor and outdoor temperature conditions, higher surface temperature values are obtained for panel solutions with higher thermal resistance values.

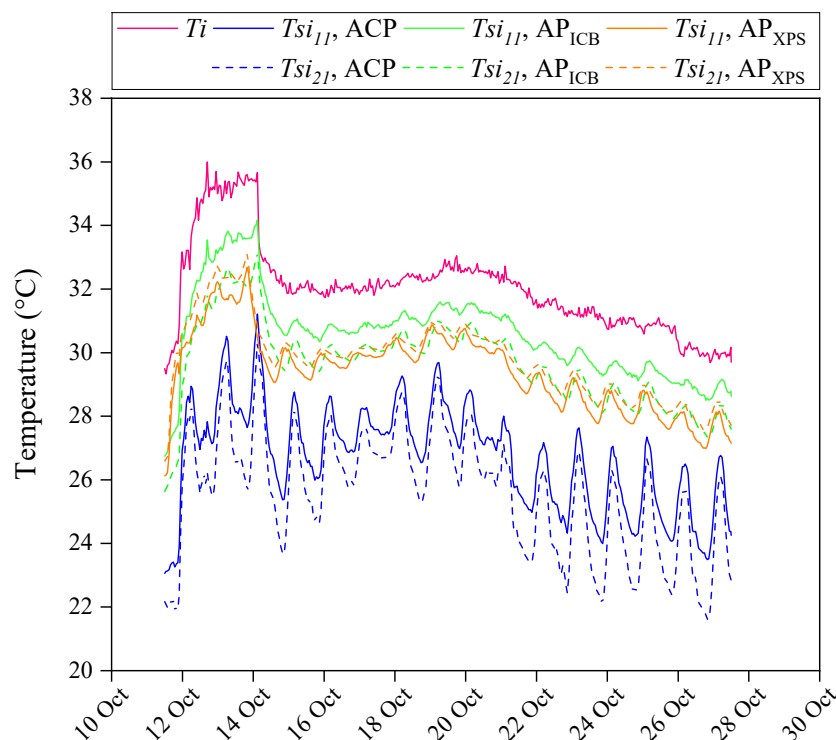


Figure 16. Interior ($T_{i(n)}$) and inner surface ($T_{si(n)}$) temperatures.

4.2.3. Thermal Transmission Coefficient

Considering that two heat flux sensors were used to define $q_{1(n)}$ and $q_{2(n)}$, it was also possible to estimate two heat transfer coefficients, $U_{1(ntotal)}$ and $U_{2(ntotal)}$, as illustrated in Figure 17. It is worth mentioning that $U_{(ntotal)}$ values were calculated five days after the start of the experimental test. In this way, the stabilization of the system is guaranteed. However, in the period from October 16 to 22, a slight depression can be observed in the heat transfer coefficient curves for the ACP sample. This can be explained by the fact that for the same period, shorter T_e peaks were identified in Figure 15, as outdoor conditions cannot be controlled, the differential of temperature was altered, and, consequently, heat fluxes were also affected. Since the other two panels, AP_{ICB} and AP_{XPS} , are composed of the thermal insulation layer, this change was not so perceptible.

In addition, the thermal transmission coefficient of each sample ($U'_{(ntotal)}$) resulted from the average of $U_{1(ntotal)}$ and $U_{2(ntotal)}$ (Table 6). It can be seen that the reference sample (ACP) is characterized to have significantly higher $U'_{(ntotal)}$ values in comparison to AP_{ICB} and AP_{XPS} , where decreases of 75.0% and 77.6% of the thermal transmission coefficient were found, respectively. In contrast, an increment of 11.7% in the $U'_{(ntotal)}$ of the AP_{ICB} was identified compared to AP_{XPS} , which was also expected given the higher density and the higher thermal conductivity of the expanded cork agglomerate board against the extruded polystyrene foam.

Additionally, the thermal resistance ($R'_{(ntotal)}$) of each studied panel was also computed (Table 6), which shows an approximately threefold increase in the value of $R'_{(ntotal)}$ for AP_{ICB} ($1.02 \text{ m}^2 \text{ }^\circ\text{C/W}$) and AP_{XPS} ($1.14 \text{ m}^2 \text{ }^\circ\text{C/W}$) with respect to ACP ($0.26 \text{ m}^2 \text{ }^\circ\text{C/W}$). It evidenced an inverse ratio between $U'_{(ntotal)}$ and $R'_{(ntotal)}$, where the ACP was demonstrated to have the lowest thermal resistance. Since the ACP is composed of a single layer of alkali-activated ceramic wastes and slag, these results were expected as mentioned in the previous sections. Regarding the two insulated solutions, the AP_{XPS} panel exhibited a slightly higher resistance, about 12%, than the AP_{ICB} , which is in line with the $U_{(ntotal)}$ results. Furthermore, comparing the calculated thermal resistance values of the three

studied panels with the available values for simple masonry walls with 10–11 cm of thickness [51], it can be determined that the reference panel (ACP) exhibited values of the same magnitude, being even higher in most of the cases. In addition, the proposed insulated panels, AP_{ICB} and AP_{XPS} , showed a considerably higher thermal resistance, i.e., about 2.7 and 3.2 times higher than the common hollow ceramic brick wall and the lightweight concrete blocks, respectively. In addition, considering a conventional solution for ceramic solid brick, significantly higher $R'_{(ntotal)}$ values were achieved for the AP_{ICB} and AP_{XPS} panels, resulting in values approximately 6.8 and 7.8 times higher, for each case. Thus, an improvement in the thermal performance can be achieved for the two insulated panels when compared to conventional wall solutions, as displayed in Table 7. Moreover, considering Equation (4), the thermal resistance of the ACP layer was determined, obtaining an R'_{ACP} value of $0.09 \text{ m}^2 \text{ }^\circ\text{C/W}$, which allowed calculating λ_{ACP} as described below.

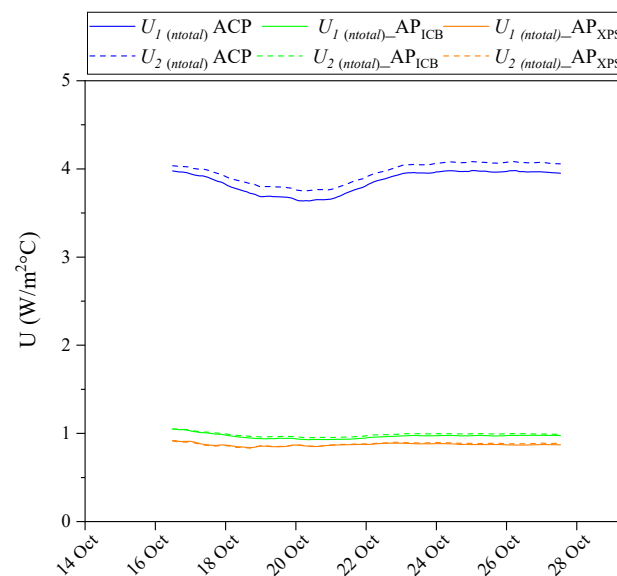


Figure 17. Thermal transmission coefficients: $U_{1(ntotal)}$ and $U_{2(ntotal)}$.

The thermal conductivity (λ) of a material can be quantified by knowing its thermal transmission coefficient. Therefore, a theoretical λ_{ACP} value of $0.12 \text{ W/m } ^\circ\text{C}$ was estimated for the developed ACP; when compared to other traditional construction materials, it presents significantly lower λ for its relatively high density value ($\sim 1950 \text{ kg/m}^3$), as shown in Table 7. For instance, the thermal conductivity of traditional ceramic materials is at least five times higher than that of the ACP. When comparing other conventional materials, such as standard concrete and “resistant” insulating concrete, λ values approximately tenfold and fivefold higher were found. It was also detected that the λ_{ACP} is 90% and 88% lower than the traditional and non-traditional mortars and renders or plasters, respectively. On the other hand, in the literature, limited studies about the thermal conductivity λ of alkali-activated ceramic wastes were found. Hwang et al. [53], studied alkali-activated pastes made of waste red clay brick powder and waste ceramic powder from contraction and demolition wastes and reported that the λ value is affected by the microstructure of the hardened paste and the thermal characteristics of its constituents; they also mentioned that, for alkali-activated materials, the thermal conductivity showed a decreasing trend with increasing curing age. But still, λ values ranging between 0.72 and $0.87 \text{ W/m } ^\circ\text{C}$ at 56 days of curing were registered, which are higher than those of the λ_{ACP} .

Table 7. Thermal conductivity (λ) of the ACP vs. traditional construction materials and thermal insulators [51].

Building Solution		ρ (kg/m ³)	$R'_{(ntotal)}$ (m ² °C/W)	λ (W/m °C)
Developed alkali-activated material	ACP	1950	0.26	0.12
	AP _{ICB}		1.02	-
	AP _{XPS}		1.14	-
Traditional masonry elements (0.10–0.11) m	Hollow ceramic bricks	-	0.27	-
	Solid ceramic bricks	-	0.13	-
	Concrete blocks	-	0.16	-
	Lightweight concrete blocks	-	0.27	-
Traditional construction materials	Ceramic materials used for bricks, blocks, roof tiles, and tiles	1800–2000	-	0.77
	Standard concrete	2000–2300	-	1.65
	Conventional cavernous concrete	1800–2000	-	1.35
	Cavernous concrete, with expanded clay aggregate, light sand, and no river sand	800–1000	-	0.33
	“Resistant” insulating concrete with expanded clay aggregate, light sand, and no river sand	1200	-	0.46
	“Resistant” insulating concrete with light sand and river sand ($\leq 10\%$)	1200–1400	-	0.70
	Perlite or expanded vermiculite aggregate concrete	400–600 600–800	-	0.24 0.31
	Traditional mortars and renders or plasters	1800–2000	-	1.3
	Non-traditional mortars and renders or plasters	1600–1800	-	1.0
	Fiber cement boards with asbestos fibers	1800–2200	-	0.95
	Fiber cement boards with cellulosic fibers	1400–1800	-	0.46
	Plywood panels	1000	-	0.24

Porosity also plays an important role, since a high porosity and a closed pore structure are positive factors to decrease thermal conduction, thus enhancing the thermal insulation performance [54]. Therefore, the outstanding thermal conductivity found in the present work can be ascribed to the relatively high porosity (21.71%, [16]) of the alkali-activated cement used for the manufacturing of the ACP. This finding is in line with the results found by Pommer et al. [55], who concluded that higher porosity (22–24%) led to lower thermal conductivity, after measuring the heat transport expressed by the thermal conductivity of alkali-activated ceramic wastes of four different particle sizes. However, higher λ values were reported, ranging between 1.49 and 1.89 W/m °C. These findings suggest that the alkali-activation processing technology improves the thermal conductivity of the developed ceramic waste-/slag-based cement.

5. Conclusions

In this research, an experimental campaign was carried out to characterize two half-sandwich panel solutions, composed of a thin layer of alkali-activated slag cement/ceramic residue and a thicker insulating layer of either extruded polystyrene foam (XPS) or ex-

panded cork agglomerate (ICB) as insulation materials. Based on the experimental mechanical and thermal results, the following main conclusions can be drawn:

Mechanical behavior point of view:

1. The AAC exhibited adequate performance in terms of compressive strength, up to around 37 MPa. It has been demonstrated that the AAC is a viable solution for developing building elements, e.g., non-structural panels, while contributing to a circular economy and sustainability in the construction sector. The grade of strengths achieved even enables its utilization for structural elements.
2. The pull-off test performed for the two proposed half-sandwich panels, AP_{XPS} and AP_{ICB} , revealed clear differences regarding the type of failure for the specimens with different insulation material typologies. Although higher pull-off load values were reported for AP_{XPS} panels than for the AP_{ICB} , the latter ones exhibited better bond strength when compared to its tensile strength, since the failure occurred outside of the AP_{ICB} interface region, revealing a weaker internal structure of the ICB. Therefore, the obtained value for the tensile bond strength of AP_{ICB} can be regarded instead as the tensile strength of the expanded cork agglomerate board itself.
3. The direct shear tests showed that the AP_{ICB} specimens, although having lower bond strength values than the AP_{XPS} series, showed high ductility levels. In regard to this matter, it is highlighted that the irregular surface of the ICB, i.e., high porosity, due to the cork granules, had a positive influence on the shear bond-slip behavior since it avoided the unstable interfacial debonding between the panel's layers. For the direct shear results of the AP_{XPS} panels, two distinct behaviors were observed, depending on the orientation of the grooves. When the load was applied perpendicular to the grooves' orientation ($AP_{XPS}^{\perp}$), the shear bond-slip behavior was similar to the one observed for the AP_{ICB} panels; however, a bond strength nearly two times greater was observed. On the other hand, the bonds in $AP_{XPS}^{\parallel}$ panels were much more fragile, since they relied only on the mobilization of the adhesion and frictional adherence, in opposition to $AP_{XPS}^{\perp}$ and AP_{ICB} , where a mechanical component was mobilized due to the grooves and paste that penetrated the ICB pores, respectively.
4. Different flexural behaviors were identified for the two studied systems, i.e., after the first peak load, the AP_{XPS} exhibited a deflection-hardening behavior, while AP_{ICB} exhibited a softening behavior. Therefore, AP_{XPS} showed a higher load-bearing capacity and energy absorption capacity when compared to the AP_{ICB} .

Thermal performance:

5. The thermal performance of the three studied panels was achieved by analyzing heat fluxes, inner surface temperatures, and thermal transmission coefficients. The results of the experimental work showed that the highest oscillation patterns of the heat flux and inner surface temperature curves corresponded to the noninsulated panel (APC), as expected, while no significant differences were detected between the heat flux values of AP_{ICB} and AP_{XPS} . However, slightly larger fluctuations of the heat flux curves of the AP_{ICB} sample were observed, ascribed to the existing voids in the expanded agglomerated cork insulation panel (due to the origin of its composition) and its higher thermal conductivity value compared to XPS.
6. Thermal resistance values of $1.02 \text{ m}^2 \text{ }^{\circ}\text{C}/\text{W}$ and $1.14 \text{ m}^2 \text{ }^{\circ}\text{C}/\text{W}$ for AP_{ICB} and AP_{XPS} were registered, respectively, which are about three times higher than those of APC ($0.26 \text{ m}^2 \text{ }^{\circ}\text{C}/\text{W}$). A slight increase ($\sim 12\%$) in the $R'_{(ntotal)}$ for AP_{XPS} with respect to AP_{ICB} was also observed, as expected, given that XPS presents a lower thermal conductivity value. The obtained results of the proposed insulated panels revealed that an improvement in the thermal properties can be achieved, since a thermal

resistance of about 2.7 and 3.2 times higher than that of the common hollow ceramic brick wall and the lightweight concrete blocks was detected, respectively, and the thermal resistance is at least 7 times higher when compared to a conventional solution of ceramic solid brick.

7. A theoretical value of $0.12 \text{ W/m}^\circ\text{C}$ was calculated for the thermal conductivity of the ACP solution, which is significantly lower than the specified λ of traditional construction materials, such as ceramic materials, standard concrete, the “resistant” insulating concrete, traditional and non-traditional mortars, and renders or plasters, among others. This may suggest that the alkali-activation technology enhances the thermal conductivity of the developed ceramic waste-/slag-based cement.

Overall, the developed half-sandwich panels, AP_{XPS} and AP_{ICB}, demonstrate significant potential as sustainable alternatives to conventional building materials. Compared to commercial solutions, these panels offer superior thermal resistance and mechanical performance while utilizing industrial wastes (75% CW + 25% LFS) and ambient curing, reducing both environmental impact and energy consumption. The alkali-activated matrix, reinforced with PAN fibers, highlights the innovation in waste valorization and low-carbon cementitious materials. These panels are particularly suitable for non-structural applications in energy-efficient buildings, combining thermal insulation with adequate load-bearing capacity. However, further research is needed to optimize production scalability, long-term durability under varying environmental conditions, and cost competitiveness relative to traditional insulation systems. Future studies should also explore hybrid designs and lifecycle assessments to fully validate their sustainability and economic viability for widespread adoption.

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