American Journal of Physics and Applications
2025, Vol. 13, No. 2, pp. 17-27
https://doi.org/10.11648/j.ajpa.20251302.11

Research Article

Experimental Study to Measure Conductive Heat Transfer Properties in New Materials with Environmental Waste Aggregates

Andrés Emanuel Díaz*, Alejandro Luís Hernandez

Department of Physics, Instituto de Investigaciones en Energía No Convencional, Salta, Argentina

Abstract

This study presents the design, development, and operational evaluation of the HD25 Hot Box, a guarded hot plate apparatus designed to measure the thermal conductivity of concrete specimens under steady-state conditions. The HD25 Hot Box was developed to assess the heat transfer properties of construction materials, particularly those incorporating environmental waste aggregates such as high- and low-density polyethylene and perlite. The device adheres to the Argentine standards IRAM 11559, IRAM 11549, and IRAM 11601, ensuring accurate and reliable measurements. The apparatus consists of two main units: a heating unit and a cooling unit, which work in tandem to establish a uniform, one-dimensional heat flow through prism-shaped concrete specimens. The HD25 Hot Box measures key thermal properties, including thermal conductivity, resistivity, resistance, and transmittance. The study highlights the impact of incorporating plastic waste into concrete, demonstrating that replacing traditional aggregates with plastic waste reduces the material's density and thermal conductivity while increasing its thermal resistance and resistivity. For instance, replacing 37% of coarse aggregate with plastic resulted in a 40% reduction in thermal conductivity and a 68% increase in thermal resistance compared to conventional concrete. The device's design includes a central heating plate surrounded by a guard section to ensure uniform heat distribution, and a cooling unit that uses a closed-loop water circulation system to maintain temperature stability. The HD25 Hot Box is compact, lightweight, and energy-efficient, making it suitable for laboratory use. The study concludes that the HD25 Hot Box is a reliable tool for evaluating the thermal properties of concrete, particularly those incorporating recycled materials, and provides valuable data for energy-efficient building design. The findings suggest that replacing up to 19% of traditional aggregates with plastic waste and perlite fines is optimal for maintaining both thermal and mechanical properties in construction materials.

Keywords

Guarded Hot Plate, Thermal Conductivity, Recycled Plastic, Concrete, Energy Efficiency

1. Introduction

Gaining insights into the heat transfer properties of concrete is central for various purposes, including compliance with regulations and specifications for design guidelines, for research into the material and its applications in construction, and for the verification of simulation models. Concrete is a construction material that allows the incorporation of waste in

*Corresponding author: andres@exa.unsa.edu.ar (Andrés Emanuel Díaz)

Received: 7 February 2025; **Accepted:** 19 February 2025; **Published:** 18 March 2025

its elaboration and consequently the development of new materials. The study of its thermophysical and mechanical properties leads to the formation of new elements and construction systems, taking advantage of natural resources and industrial waste. Recycling plastic waste to produce new materials is one of the solutions to dispose of large amounts of garbage [1]. Research has been reported into the use of plastic waste as fillers or aggregates in concrete, such as polyethylene terephthalate [2], polystyrene [3], expanded polystyrene [4], polyvinyl chloride [5], low-density polyethylene [6] and high-density polyethylene [7], in E-plastic waste; and in mortars (PET). Research also indicated that recycled plastic could be reused as a partial substitute for sand or coarse aggregate [8].

Several studies have explored the use of plastic waste in concrete, providing a foundation for the selected replacement percentages in this research. For example, [2, 17] investigated the effects of waste PET bottles as aggregates in concrete and found that replacing 20% of coarse aggregates with PET resulted in a 15% reduction in thermal conductivity while maintaining acceptable mechanical properties. Similarly, [7, 18] reported that replacing 10-30% of traditional aggregates with post-consumer plastics led to a decrease in density and thermal conductivity, with optimal performance observed at 20% replacement. These findings align with the 19% replacement ratio chosen in this study, which aims to achieve a balance between thermal insulation and structural strength. In another study, [5, 19] examined the properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. They found that replacing 25% of coarse aggregates with PVC resulted in a 30% reduction in thermal conductivity, but higher replacement ratios (up to 50%) led to a significant decline in compressive strength. This supports the decision in the current study to limit the maximum replacement ratio to 37%, as higher percentages could compromise the material's structural integrity.

Perlite, a volcanic glass that expands when heated, was also incorporated into the concrete mix as a partial replacement for cement. Perlite is known for its low density and excellent thermal insulation properties, making it an ideal additive for improving the thermal performance of concrete. In this study, perlite fines were used to replace 19% of the cement in one of the concrete mixes (SM5). The inclusion of perlite not only reduced the overall density of the concrete but also enhanced its thermal resistivity, further contributing to the material's insulation capabilities. The use of perlite in concrete has been widely studied for its thermal benefits. [10] demonstrated that adding perlite to self-compacting concrete significantly reduced its thermal conductivity, making it suitable for energy-efficient building applications. Similarly, [20] found that perlite-based plasters exhibited lower thermal conductivity compared to traditional materials, highlighting its potential as an insulating additive. These studies support the inclusion of perlite in the current research, as it complements the thermal benefits achieved by replacing traditional aggregates with plastic waste.

However, once the new material has been formed, it is necessary to determine the physical properties of heat transfer. Accordingly, the HD25 Hot Box was developed and experimentally evaluated. HD is an acronym from the name of its designers, Hernández and Díaz. Depending on the requirements that must be met by the specimens, the HD25 box determines the following properties: thermal resistance, thermal transmittance, mean thermal conductivity and thermal resistivity.

2. Properties of Conduction Heat Transfer Determined with HD25 Box

2.1. Thermal Conductivity and Resistivity

The property that characterizes the ability of the material to transfer heat by conduction is thermal conductivity (λ). It is a specific property of the material and is defined as the amount of thermal energy transmitted in one direction through a unit thickness and per unit time perpendicular to the direction of flow [9]. Determining thermal conductivity is important to understand heat flow in concrete [10]. To determine/estimate the mean thermal conductivity, specimens must be homogeneous or porous-homogeneous. Porous-homogeneous specimens are those in which any heterogeneity has measurements smaller than one tenth of the thickness of the specimen. When using the HD25 box, the thermal conductivity is calculated with Eq. (1). The multiple 2 in the denominator of Eq. (1) is because the guarded hot box equipment uses two test tubes.

In calculations, it is often more convenient to use the reciprocal of thermal conductivity, called thermal resistivity (r). This property is defined as the number of hours required for the transmission of a kilocalorie, through a square meter of surface in a material one meter thick, when the temperature difference between the external faces is one degree centigrade [9]. Thermal resistivity is expressed as Eq. (2).

2.2. Thermal Resistance and Transmittance

Thermal Resistance (R) is a measure of resistance to heat flow from either a single material or a combination of different materials of any thickness. It is defined as the number of hours necessary/required for the transmission of a kilocalorie, through a square meter of material, when there is a temperature difference of one degree Celsius between the surfaces limiting it [9]. Thermal resistance was calculated with Eq. (3) when specimens complied with homogeneous or porous-homogeneous conditions.

To determine the air conditioning energy consumption of a home or building, thermal transmittance (K) was used. This thermal property refers to the amount of energy transferred by conduction in the unit of time through the unit of the surface of a construction element when the difference in temperature between air masses is equal to the unit [11]. Thermal transmittance is the amount of energy that flows through a material or a combination of materials of a certain thickness. To calculate thermal transmittance, Eq. (4) was used. Table 1 shows units of the equations thermal properties obtained with the HD25 box.

Equations:

$$\lambda = \frac{\emptyset\, d}{2\, A\, (T_1 - T_2)} \quad (1)$$

$$r = \frac{1}{\lambda} \quad (2)$$

$$R = \frac{T_1 - T_2}{\emptyset} A \quad (3)$$

$$K = \frac{1}{R} \quad (4)$$

Where:
$\emptyset$=Heat Flow [W]
d=Specimen thickness [m]
T_1=Hot side temperature of the sample [℃]
T_2=Cold side temperature of the sample [℃]
A=Measurement area [m^2]

Table 1. *Equations of heat transmission properties.*

Thermal Property	Units
(1) Conductivity	W/mK
(2) Resistivity	mK/W
(3) Resistance	m^2K/W
(4) Transmittance	W/m^2K

3. Density

Density (ρ_d) is a fundamental parameter to distinguish the thermal conductivity of families of similar materials, such as concrete, aggregates and insulation. The moisture content of a material has a marked effect on the λ value of the material: the higher the moisture content, the higher the value of λ. Therefore, the first thing to be done was to condition the test specimens by drying them in an oven working between 47 ℃ and 57 ℃ for 24 hours [12]. At the end of the drying process, the concrete specimens were quickly placed in the HD25 box so that they absorbed no moisture again. The dry density ρ_d of the specimen conditioned for the test was calculated with Eq. (5).

$$\rho_d = \frac{M}{V} \text{ (Kg/m}^3\text{)} \quad (5)$$

Where:
M=Specimen mass [kg]
V=Specimen volumen [m^3]

4. The HD25 Hot Box

The term "guard hot plate" is applied to a fully assembled appliance, hence referred to as "guard hot plate appliance." The HD25 Hot Box is a hot plate appliance with a guard. Figure 1 shows the general characteristics of the apparatus with the heaters (A and C), test tubes (F), cooling units (E) and thermocouples installed (G, H and J). The HD25 box measures 39 cm x 39 cm x 19 cm. The outer box that surrounds the entire assembly was made of wood with two side doors and a sliding roof for handling the specimens.

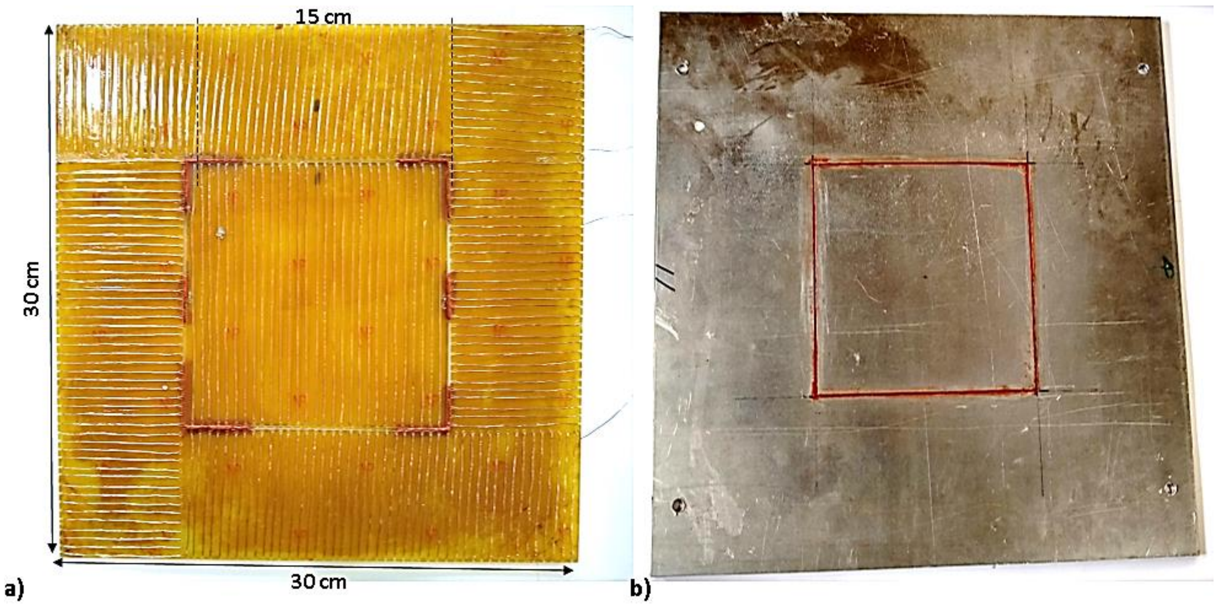

Figure 1. *a) Central heating plate and guard. b) Hot surface plate with guard.*

To firmly hold the entire set consisting of the heating plates, the samples to be tested and the cooling units, threaded rods with galvanized nuts were installed in the 4 vertices of the box, allowing the different elements to be adequately compressed and achieving good thermal contact between samples and hot and cold sources (Figure 1, right). In addition, they allowed the precise regulation of the spacing between the plates of the apparatus. The side doors and the roof of the wooden enclosure were secured with metallic exterior closures.

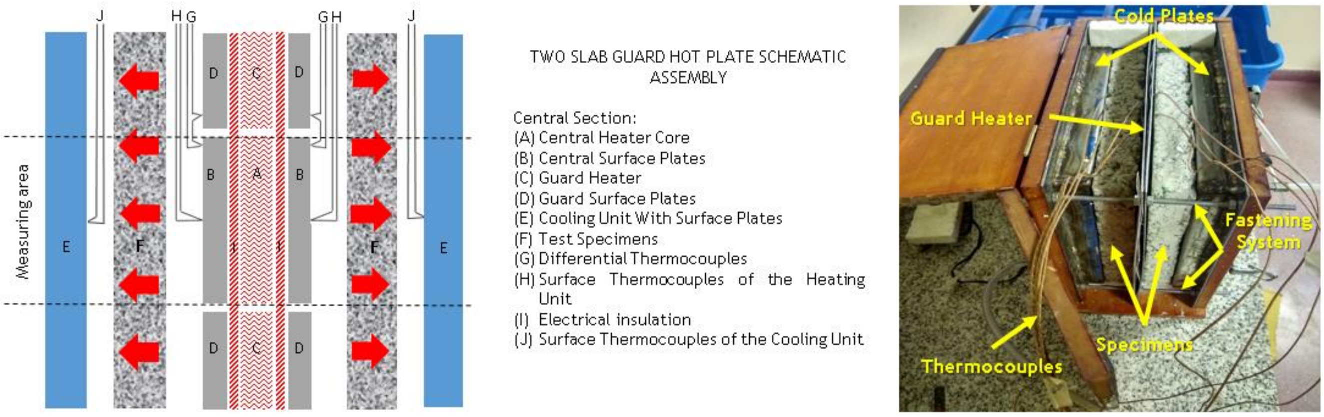

Figure 2. *Schematic Method of Two Slab-Guarded Hot Plates.*

4.1. Operating Principle of the HD25 Device

Using the HD25 apparatus, a uniform and one-dimensional heat flow perpendicular to the faces was established/obtained within the specimens, whose shape was that of a uniform plate with plane-parallel faces, under steady-state conditions [13]. The HD25 box was a guard hot plate apparatus for two approximately equal specimens, with a cooling unit for each specimen and a central heating unit.

4.2. Heating Unit

The heater unit (Figure 2a) consisted of a central metering section and a surrounding guard section constructed/built with a PCB (Printed Circuit Board) de Pertinax, from which copper was extracted with a ferrous oxide bath [14]. The central hot plate was square, measuring 15 cm x 15 cm x 0.2 cm, in which an electrical resistance of Nichrome wire (alloy of 80% Nickel and 20% Chromium) of 0.4 mm in diameter was wound, covering both sides of the plate. The value of the electrical resistance of this heater was 70 Ω (value measured at 20 ºC). The two ends of this winding came out through long terminals to plug them into the terminal block of the voltage variator that allowed selecting the working temperature. The guard section was made of Pertinax material measuring 30 cm x 30 cm x 0.2 cm with a central hole of 15 cm x 15 cm where the central hot plate was located. It had 0.4 mm diameter Nichrome wire windings on both faces of the guard plate, providing an electrical resistance of 220 Ω. The two ends of the electrical resistance of the guard went out to the terminal block of another voltage variator, allowing the working temperature of this strip to be equalized with that of the central plate. In this way/Thus, the existence of a one-dimensional heat flow was guaranteed in the central region of the concrete samples to be evaluated, perpendicular to their faces. To uniform the temperature on the faces of the samples facing the heating plate.

The heater unit has a gap between the plates of the center section and that of the guard. The space in this slot was filled with high temperature silicone. In order to avoid electrical contact between the aluminum plates and the electric heating elements, a polyester film called Mylar was sandwiched between them.

4.3. Heating Unit Power Supply

Both the central heating unit and the electric resistance of the guard were fed with Alternating Current. Each resistance had an Sitel model 0520 Dimmer regulator with which the voltages and the power dissipated in each of them were regulated until obtaining a uniform heat flow from both the central section and the guard.

4.4. Cooling Unit

The surface measurements of the cooling unit were the same as those of the heater unit, including the guard heater. The cooling unit was a system made up of three elements. The first consisted of a stainless-steel metal box 30 cm high, 30 cm wide and 3 cm thick in contact with each specimen to be tested. The second element was the distilled water that circulated at a rate of 1.25 l/min forced by a pump inside the stainless-steel boxes. The fluid entered the lower part of the metal box and exit through the upper part, extracting the heat that passed through the test specimen. The water that came out of the box, at a temperature higher than that it entered, passed into a crossflow air-water heat exchanger of the automobile radiator type to dissipate the heat extracted from the sample. The air circulated through this exchanger was at room temperature in the laboratory and driven by a fan.

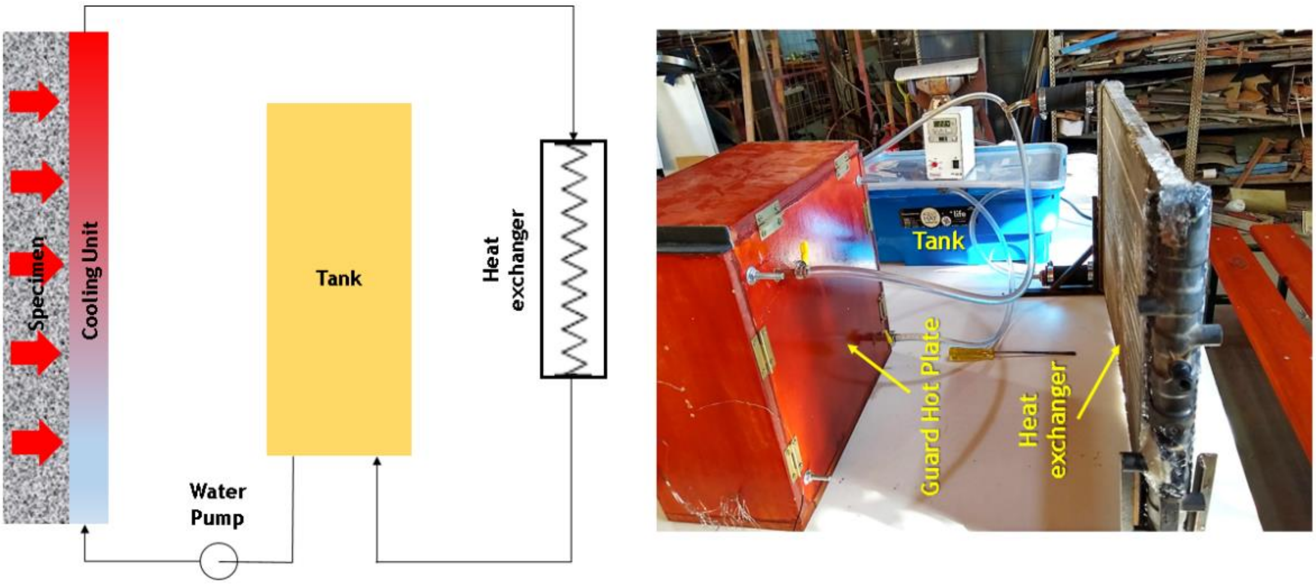

Figure 3. Diagram of the Cooling Unit.

Figure 3 depicts the closed-loop cooling system of the HD25 Hot Box, which ensures stable temperature control during thermal conductivity measurements. The system comprises three key components: Stainless Steel Cooling Plates: Two metal boxes (30 cm × 30 cm × 3 cm) in direct contact with the specimens. Distilled water circulates through these plates at 1.25 L/min to absorb heat transferred from the specimens. Crossflow Heat Exchanger: An automobile-style radiator dissipates absorbed heat into the ambient air. A fan drives airflow over the radiator, cooling the water before it returns to the system. Recirculation Circuit: A 40-liter plastic tank stores water, and a pump continuously cycles it through the cooling plates and radiator. This closed-loop design minimizes water usage (52.4 L per test) and stabilizes thermal conditions. Function: The cooling unit maintains a fixed cold-side temperature (20 ℃) to establish a steady-state temperature gradient across the specimens, critical for precise thermal conductivity calculations using Equation (1). The design replicates real-world heat dissipation while ensuring experimental repeatability and resource efficiency.

4.5. Lateral Thermal Insulation and Heat Loss

To minimize the heat loss from the heating plate to the outside and to avoid the formation of a two-dimensional heat flow through the test specimens, the side edges of the heating unit should be thermally insulated. Heat loss along these edges from the heater unit and the test tubes generated temperature gradients in the plates of the guard section perpendicular to the horizontal direction, producing a two-dimensional deviation in the ideal direction of the heat flow conceived as one-dimensional [15].

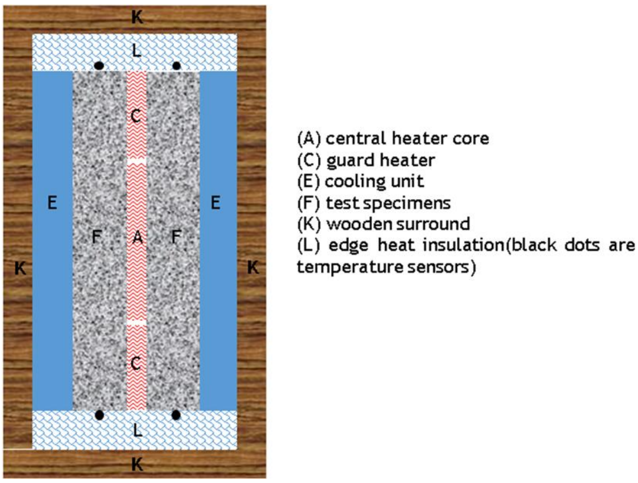

Figure 4. Configuration of the lateral and surrounding? insulation of the HD25 device.

Loss of heat to the outside would cause errors in the determination of the thermal conductivity of the samples. These errors were calculated for homogeneous, isotropic, and opaque specimens, under simplified boundary conditions. To minimize these errors, mean specimen temperatures were close to room temperature to minimize the thermal gradient across the side edge of the HD25 case. To achieve this, its lateral thermal insulation was made of 3 cm thick expanded foam whose density was 35 Kg/m^3 and its thermal conductivity 0.032 W/mK. Finally, the outer casing of the HD25 was made of 1.5 cm thick wood. Figure 4 shows the configuration of the lateral insulation and the wooden casing of the apparatus.

4.6. Electronic Control System

The temperature difference sensors between the central zone and the guard zone were connected differentially to directly measure such difference which, ideally, should be 0 ℃. The device used a small diameter 20 (0.51 mm) Type K solid thermocouple grade wire thermocouples (Cromel-Alumel), ISO 9001: 2008 certified, acceptable abrasion resistance and good humidity resistance up to 150 ℃ (the HD25 device worked at a max. temperature of 75 ℃). The surface temperatures on the central and guard zone were also measured with these thermocouples placed on the contact surfaces with the specimens.

To control the temperature of the Heating Unit and the Cooling Unit, the HD25 device used a digital thermostat with STC-1000 probe. First, we programed the Heating Unit, for example, setting a reference value (65 ℃) and a hysteresis value (0 ℃). In this way the thermostat will turn on the Heating Unit and the temperature will rise until reaching the reference value; at this value, the thermostat will turn off the heat source. As the temperature of the heating unit dropped below the given set point, the thermostat will turn back on and so on. Then we programed the Cooling Unit by entering a reference value (20 ℃) for the thermostat to turn on the water pump. The electronic control system is shown in Figure 5a.

The temperature data of all the sensors were recorded using a NOVUS datalogger, whose main characteristics were: 2 analog inputs with a range of 10 V, gain adjustable by software and the possibility of choosing between a resolution of 16 or 18 bits. To measure the electrical power delivered by the heating unit, from both the guard section and the central heating plate, an autotransformer model VARIAC was used.

Figure 5. *Electronic control system.*

5. Test Specimens

The HD25 is designed to accommodate two concrete specimens with different aggregates, identical/equal in shape, dimension, and constitution. The specimens were located vertically; their dimensions being 30 cm high, 30 cm wide and a minimum thickness of 4 cm or a maximum of 4.5 cm. The thickness of the two specimens had to differ by less than 2%. The maximum deviation of the real surface of the specimens in relation to the plane of the plates, both heating unit and the cooling unit, did not have to exceed 0.025% in all operating conditions. That is, assuming an ideal plane in contact with the surface at M in Figure 6, at any other point O on the surface the relationship between the distance NO from the plane and the distance NM from the reference contact point should be less than 0.025%.

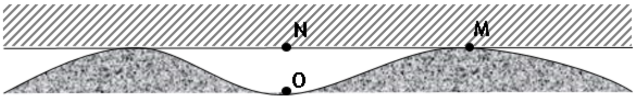

Figure 6. *Deviation of the surface of the specimen with respect to a plane of the plate.*

In Salta, Capital City, 58 tons of plastic are thrown daily. Only 5 tons are recovered daily. In expanding perlite production, 20% of the raw perlite is wasted. The solution is to develop concrete mixtures for the manufacture of bricks, blocks, and subfloors with aggregates of high- and low-density polyethylene and perlite fines [1]. Coarse and fine aggregates were replaced in varying mix volume percentages by recycled plastics. Raw perlite was used to replace part of the cement.

Table 2 details the specimens tested with concrete of different aggregates. The test tubes came from an investigation on concrete dosages [1]. Table 2 shows the weight of each component of the mixtures per m3 of concrete with which the specimens were formed, for the control specimen with only stone aggregates (SM1); with replacement of 19% coarse aggregate by plastic (SM2); with replacement of 37% coarse aggregate by plastic (SM3); with 19% plastic aggregate, 31% fine aggregate and 50% coarse aggregate (SM4); and with 19% of plastic aggregate plus the replacement of 19% of cement by perlite fines (SM5). The percentages of aggregates chosen result from their good behavior in the mechanical tests carried out on the mixtures.

Table 2. *Test specimens of concrete with different aggregates.*

Material (kg/m^3)	*SM1*	*SM2*	*SM3*	*SM4*	*SM5*
Water	140	140	140	140	140
Cement	260	260	259	259	210
Agg. thick	1364	1033	803	1094	999
Agg. fine	816	749	749	752	721

Material (kg/m³)	*SM1*	*SM2*	*SM3*	*SM4*	*SM5*
Plastic	0	78	152	60	79
Additive	1.6	1.6	1.6	1.6	1.3
Perlite	0	0	0	0	49

6. Calibration and Manufacturing Cost of the HD25 Apparatus

For the calibration of the equipment, concrete specimens were used with stone aggregates of different apparent densities, marble and hard wood, whose thermal conductivities are known and were used as reference specimens for the IRAM 11601 standard "Thermal conditioning of buildings. Calculation methods. Thermal properties of components and construction elements in steady state" [11].

7. Summary of Precision Control and Experimental Validation

(1) *Heat Flux (Φ)*: Measured via the electrical power input to the central heating plate (Nichrome wire, 70 Ω resistance). Power is calculated using $\Phi = V{*}I$, where voltage (V) and current (I) are regulated by a VARIAC autotransformer and monitored with a datalogger. The guard heater (220 Ω resistance) ensures unidirectional heat flow by matching the guard zone temperature to the central plate, minimizing lateral heat loss (validated by differential thermocouples).

(2) *Temperature Gradient (T_1-T_2):* Measured using Type K thermocouples (ISO 9001: 2008 certified) embedded on the hot and cold surfaces of the specimens. A digital thermostat (STC-1000) maintains T_1 at 65℃ (heating unit) and T_2 at 20℃ (cooling unit), ensuring steady-state conditions. Temperatures stabilize within 5.5 hours per test, confirmed by <1% variation in readings over 30 minutes.

(3) *Specimen Dimensions (d, A)*: Specimens are prismatic (30 cm × 30 cm × 4–4.5 cm) with surface flatness deviations <0.025% (per IRAM 11601). Thickness is measured using calipers (±0.1 mm precision) at multiple points to ensure uniformity.

(4) *Error Mitigation*: Lateral Insulation: Expanded polystyrene (3 cm thick, λ = 0.032 W/mK) and wooden casing minimize edge heat losses. Thermal Contact Resistance: Specimens are compressed using threaded rods to ensure full contact with heating/cooling plates, verified via pressure-sensitive films. Moisture Control: Specimens are oven-dried (47–57℃ for 24 hours) to eliminate moisture-induced λ variability.

(5) *Calibration and Standards*: The HD25 is calibrated using reference materials (marble, hardwood) with known λ values (per IRAM 11601). Discrepancies between measured and literature values are <2%, confirming accuracy. Compliance with IRAM 11559 (hot plate method) and IRAM 11549 (thermal definitions) ensures methodological rigor.

8. Results

Table 3 details the general characteristics of the HD25 apparatus, and the operating conditions used to obtain the thermal properties. With the closed-circuit system of the Cooling Unit, between 360 liters and 437 liters of fluid were saved in each test. The test time of the five tests lasted an average of 5.5 hours and between 37 Wh and 64 Wh of heat was used to keep the Heating Unit at a constant temperature.

Table 3. *General characteristics of the HD25 device.*

Appliance dimension	39 cm × 39 cm × 19 cm
Operating power	Between 37 W and 64 W
Max operating temperature	75℃
Specimen size	30 cm × 30 cm × thickness (between 4 cm and 4.5 cm)
Specimen orientation	Vertical
Volume of water used in the tests	52.4 liters (closed circuit)
Average hours for each trial	5.5 hours
Method used	Hot plate with guard for 2 test tubes
Device weight	9 kg

Tables 4 to 6 show the density of the samples and the thermal properties obtained with the HD25 apparatus. The values by which the density of the SM1 specimen was reduced ranged from 13% to 19.6%. This is due to replacing stone aggregates with plastic aggregates to decrease the overall thermal conductivity of concrete.

Table 4*. Composition of Agg. plastic (LWA) in the mixture and Dry Density (ρd) obtained with HD25.*

Specimen test	LWA (%)	density (kg/m^3)	Δρd (%)
SM1	-	2467 ±67	-
SM2	19	2147 ±61	-13
SM3	37	1983 ±58	-19.6
SM4	19	2217 ±63	-10.1
SM5	19	2111 ±69	-14.4

Table 5*. Thermal conductivity (λ) and resistance (R) obtained with HD25.*

Specimen test	Thermal conductivity (W/mK)	Δλ (%)	Thermal resistance (m^{2}K/W)	ΔR (%)
SM1	1.761 ±0.077	-	0.0210 ±0.0015	-
SM2	1.357 ±0.059	-2. 3	0.0273 ±0.0020	30
SM3	1.049 ±0.045	-40	0.0353 ±0.0025	68
SM4	1.442 ±0.063	-18.1	0.0257 ±0.0019	22.4
SM5	1.296 ±0.056	-26.4	0.0286 ±0.0020	36.2

Table 5 shows how the thermal conductivity of SM1 decreased between 18.1% and 40%, while thermal resistance increased between 22.4% and 68%.

Table 6*. Thermal resistivity (r) and transmittance (K) obtained with HD25.*

Specimen test	Thermal resistivity (mK/W)	Δr (%)	Thermal transmittance (W/m^{2}K)	ΔK (%)
SM1	0.568 ±0.024	-	47.6 ±3.4	-
SM2	0.737 ±0.032	29.7	36.6 ±2.6	-23.1
SM3	0.954 ±0.040	67.9	28.3 ±2.0	-40.5
SM4	0.693 ±0.030	22	38.9 ±2.7	-18.3
SM5	0.776 ±0.033	36.6	35.0 ±2.5	-26.5

The thermal resistivity values of the control specimen increased to values of 67.9 %, while thermal transmittance decreased to 40.5 % for the SM3 sample.

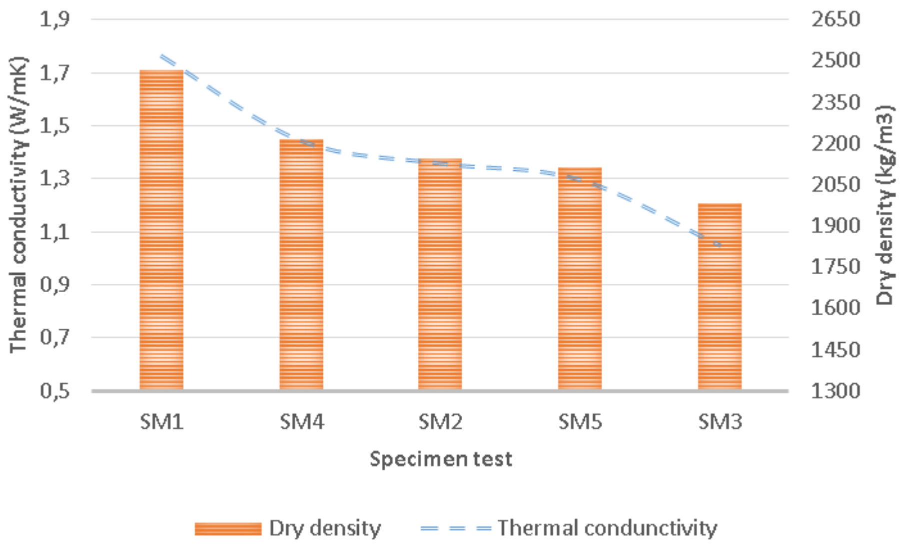

Figure 7. *Behavior of thermal conductivity with respect to density.*

Figure 7 illustrates the inverse relationship between thermal conductivity (λ) and dry density (ρd) of concrete specimens containing varying percentages of plastic aggregate. The graph demonstrates a clear trend: as the plastic aggregate content increases (from 0% in SM1 to 37% in SM3), thermal conductivity decreases linearly (from 1.761 W/mK to 1.049 W/mK), while dry density declines proportionally (from 2467 kg/m^3 to 1983 kg/m^3). This behavior aligns with established principles in porous materials, where the introduction of lightweight, low-thermal-conductivity aggregates (e.g., plastics) reduces both density and heat transfer capacity by increasing porosity and limiting conductive pathways. The sharpest reduction in thermal conductivity (−40%) and density (−19.6%) occurs in SM3 (37% plastic aggregate), suggesting that higher replacement ratios amplify insulating properties but may compromise structural integrity. Intermediate replacements (e.g., 19% in SM2 and SM4) yield moderate decreases in λ (18–23%) and ρd (10–13%), balancing insulation and mechanical performance. The inclusion of perlite fines in SM5 further enhances thermal resistivity (36.6% increase over SM1) by introducing additional air voids, corroborating findings by Gandage and Rao (2013) on perlite's insulating role.

The linear correlation between λ and ρ_d ($R^2 \approx 0.98$) underscores the dominance of density as a predictor of thermal performance in plastic-aggregate concrete. This trend matches prior studies [16], confirming that reduced density directly lowers thermal conductivity. However, the steep decline in SM3 highlights a critical threshold beyond which structural viability may be jeopardized, emphasizing the need for optimized replacement ratios (e.g., 19%) in practical applications. Plastic aggregates and perlite effectively reduce thermal conductivity by lowering density and increasing porosity, but replacement percentages must balance insulation gains with mechanical requirements.

The incorporation of waste materials, particularly plastics, into concrete has gained significant attention in recent years due to the growing need for sustainable construction practices and the reduction of environmental waste. Research has shown that plastic waste, such as polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC), can be effectively used as partial replacements for traditional aggregates in concrete. These materials not only help in waste management but also influence the thermal and mechanical properties of the resulting concrete. The rationale for selecting specific aggregate replacement percentages in this study is based on previous research that demonstrated the impact of plastic aggregates on concrete's thermal and mechanical performance. For instance, studies have shown that replacing coarse aggregates with plastic waste can significantly reduce the density and thermal conductivity of concrete, making it more suitable for insulation purposes. However, excessive replacement can compromise the mechanical strength of the material. Therefore, the selected replacement percentages (19% and 37% of coarse aggregate) were chosen to balance the trade-off between thermal performance and mechanical integrity. These percentages were derived from earlier mechanical tests that indicated good behavior in terms of compressive strength and durability.

Perlite, a volcanic glass that expands when heated, was also incorporated into the concrete mix as a partial replacement for cement. Perlite is known for its low density and excellent thermal insulation properties, making it an ideal additive for improving the thermal performance of concrete. In this study, perlite fines were used to replace 19% of the cement in one of the concrete mixes (SM5). The inclusion of perlite not only reduced the overall density of the concrete but also enhanced its thermal resistivity, further contributing to the material's insulation capabilities. The combination of plastic aggregates and perlite in concrete offers a dual benefit: it reduces the environmental impact by recycling waste materials and improves the thermal efficiency of construction elements. This approach aligns with the global trend towards sustainable building practices and energy-efficient design. The selected replacement percentages and the inclusion of perlite were carefully chosen based on their proven effectiveness in previous studies, ensuring that the resulting concrete maintains a balance between thermal performance and structural integrity. This literature review underscores the importance of optimizing aggregate replacement ratios to achieve sustainable and energy-efficient construction materials.

9. Conclusions

The HD25 Hot Box proved effective and precise for measuring thermal properties in recycled-aggregate concretes, validating 40% reductions in thermal conductivity (SM3: 37% plastic) and 68% increases in thermal resistance compared to conventional concrete (SM1). The inclusion of perlite (SM5) further enhanced insulation, reducing density by 14.4% and thermal conductivity by 26.4%, demonstrating its potential for energy-efficient building materials.

Practical Implications:

a) Sustainability: Replacing up to 19% of traditional aggregates with plastic and perlite provides an optimal balance between thermal insulation and mechanical strength, suitable for blocks, bricks, and subfloors.
b) Energy Efficiency: These materials could reduce building energy consumption by up to 40%, as inferred from future energy simulations.
c) Circular Economy: The methodology repurposes 58 tons/day of plastic waste (Salta, Argentina) into construction, addressing waste management challenges.

Recommendations for Future Research:

a) Investigate blends with other waste materials (e.g., textile fibers, rubber) and high-strength plastics (e.g., PET).
b) Assess long-term durability and performance under extreme climatic conditions.
c) Develop numerical models to predict thermo-mechanical behavior in full-scale applications.

This work establishes a foundation for innovative construction materials aligned with global sustainability and energy-efficiency goals.

Abbreviations

HD25	Hernández and Díaz 2025
PCB	Printed Circuit Board
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
IRAM	Instituto Argentino de Normalización y Certificación

Acknowledgments

The authors acknowledge the National Scientific and Technical Research Council (CONICET) and the Research Council of the National University of Salta (CIUNSa) by the funding provided.

Author Contributions

Andrés Emanuel Díaz: Conceptualization, Investigation, Methodology, Project administration, Software, Supervision, Writing – original draft

Alejandro Luis Hernandez: Formal Analysis, Methodology, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Díaz Andrés E. and Hernández A. Dosage test for concrete blocks, bricks and subfloors with plastic waste and pearlite fines. Advances in Renewable Energies and the Environment. 2018, Vol. 22, pp 01.71-01.82. https://doi.org/10.17632/h2rrhstg93.1

[2] Choi, Y.-W., et al. (2005). Effects of waste PET bottles aggregate on the properties of concrete. Cement and Concrete Research, 35(4), 776-781. https://doi.org/10.1016/j.cemconres.2004.05.014

[3] Tang, W., Lo Y., and Nadeem A., Mechanical and drying shrinkage properties of structural-graded polystyrene aggregate concrete. Cement and Concrete Composites, 2008. 30(5): p. 403-409. https://doi.org/10.1016/j.cemconcomp.2008.01.002

[4] Kan, A. and Demirboğa R, A new technique of processing for waste-expanded polystyrene foams as aggregates. Journal of Materials Processing Technology, 2009. 209(6): p. 2994-3000. https://doi.org/10.1016/j.jmatprotec.2008.07.017

[5] Kou, S. Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. Waste Management. 2009, 29(2), 621-628. https://doi.org/10.1016/j.wasman.2008.06.014

[6] Chaudhary, M., Srivastava V., and Agarwal V., Effect of waste low density polyethylene on mechanical properties of concrete. Journal of Academia and Industrial Research (JAIR) Volume, 2014. 3: p. 123-126. https://www.researchgate.net/publication/278300012_Effect_of_Waste_Low_Density_Polyethylene_on_Mechanical_Properties_of_Concrete

[7] Naik, T. R., et al. (1996). Use of post-consumer waste plastics in cement-based composites. Cement and Concrete Research, 26(10), 1489-1492. https://doi.org/10.1016/0008-8846(96)00135-4

[8] Albano, C., et al., Influence of content and particle size of waste pet bottles on concrete behavior at different w / c ratios. Waste Management, 2009. 29(10): p. 2707-2716. https://doi.org/10.1016/j.wasman.2009.05.007

[9] IRAM standard 11549-18. Thermal insulation of buildings. Definitions. https://catalogo.iram.org.ar/#/normas/detalles/530

[10] Gandage, A., & Rao, V. V. (2013). Effect of Perlite on Thermal Conductivity of Self-Compacting Concrete. Procedia - Social and Behavioral Sciences, 104, 188-197. https://doi.org/10.1016/j.sbspro.2013.11.111

[11] IRAM 11601-02 standard. Calculation methods. Thermal properties of components and building elements in steady state. https://catalogo.iram.org.ar/#/normas/detalles/572

[12] Tropea I., Villagrán Z., 2014. Drying of the evaluated concrete by means of the impact resonance frequency and the ultrasonic pulse velocity. https://www.researchgate.net/publication/301889988

[13] IRAM Standard 11.559-1995. Thermal conditioning of buildings. Method of determining the thermal conductivity of building materials using the hot plate apparatus. http://www.iram.org.ar/index.php

[14] Mitzner K., 2009. Complete PCB Design Using OrCAD Capture and PCB Editor. https://doi.org/10.1016/B978-0-7506-8971-7.X0001-7

[15] Di Filippo P., Ponte F., 1974. Design Criteria for Guarded Hot Plate Apparatus. In ASTM STP No. 544, Philadelphia, pp. 97-117. http://dx.doi.org/10.1617/s11527-013-0192-4

[16] Kook-Han, K., Sang-Eun, J., Jin-Keun, K. & Yang S. (2003). An experimental study on thermal conductivity of concrete. Cement and Concrete Research, 33, 363-371. https://doi.org/10.1016/S0008-8846(02)00965-1

[17] Chauhan Shailendra Singh, Jitendra Kumar Singh, Himanshu Singh, Sanjeev Mavi, Vaibhav Singh, Md Intzar Khan, (2021). An overview on recycling plastic wastes in bricks. Materials Today: Proceedings 47, 4067–4073. https://doi.org/10.1016/j.matpr.2021.05.697

[18] Maghfouri Mehdi, Vahid Alimohammadi, Rishi Gupta, Mohammad Saberian, Pejman Azarsa, Mohammad Hashemi, Iman Asadi, Rajeev Roychand, 2022. Drying shrinkage properties of expanded polystyrene (PS) lightweight aggregate concrete: A review. Case Studies in Construction Materials 16, e00919. https://doi.org/10.1016/j.cscm.2022.e00919

[19] Ahmed Nadia, (2023). Utilizing plastic waste in the building and construction industry: A pathway towards the circular economy. Construction and Building Materials 383, 131311. https://doi.org/10.1016/j.conbuildmat.2023.131311

[20] Carbonaro, C., & Cascone, Y. (2015). Energy assessment of a PCM-embedded plaster: embodied energy versus operational energy. Energy Procedia, 78, 3210-3215. https://doi.org/10.1016/j.egypro.2015.11.782