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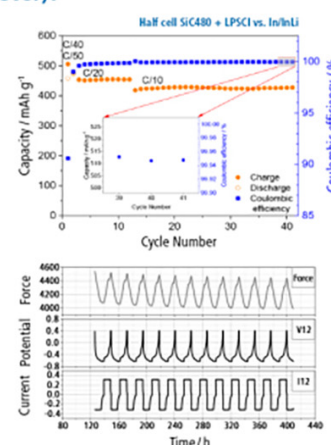
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Innovative Thermal Conductivity Analysis of Castable Materials via Spherical Geometry: Preliminary Study

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Abstract. This preliminary study introduces a cost-effective and innovative methodology for characterising the thermal conductivity of mortars, addressing the limitations of traditional steady-state methods. The proposed approach utilises a spherical specimen geometry to ensure perfect symmetry and isolate one-dimensional (1D) radial heat flow, effectively overcoming common issues related to surface contact resistance and edge effects. The research evaluates and compares three numerical models – *Fourier*, *Maxwell-Cattaneo*, and *temperature-dependent $\lambda(T)$* – against experimental transient data obtained during the cooling phase of various lime-based mortars. The results demonstrate that all models provide optimal fits ($R^2 > 0.999$), with the $\lambda(T)$ approach proving particularly robust in capturing the dynamic thermo-dependent behaviour of bio-based composites. The derived dry-state thermal conductivity values are consistent with the density-dependent trends reported in EN 1745:2020. This methodology offers a straightforward and accurate tool for generating thermal parameters for building energy simulations. Finally, this work lays the foundation for future applications of spherical transient analysis to complex surface morphologies, suggesting a potential pathway to bridge the gap between intrinsic material properties and the thermal performance of finished building components.

1. Introduction

In building physics, thermal efficiency is crucial for minimizing energy consumption and reducing environmental impact. High-performance insulation is strictly regulated to reduce the dependency on *Heating, Ventilation, and Air Conditioning (HVAC) systems*, and to preserve natural resources[1]. The efficiency of these materials is determined by their thermal conductivity (k). For masonry and rendering mortars, this property typically ranges from 0.074 to 1.11 [W/m·K], depending on dry density[2]. While these materials provide additional advantages such as improved indoor comfort, noise reduction, and fire protection[3]. Their primary value lies in their ability to retard heat flow. However, the practical realisation of these benefits depends entirely on precise material characterisation. Inaccurate thermal conductivity data can lead to significant discrepancies between predicted and actual building performance. Therefore, it is crucial to develop a reliable, affordable, and rapid measurement methodology, especially for castable



materials where standard laboratory conditions often fail to replicate real-world surface irregularities and moisture dynamics.

The accurate characterisation of this physical property is essential for ensuring material performance, and the standard methodologies to obtain this parameter are the *Guarded Hot Plate* (GHP) and the *Heat Flow Meter* (HFM)[4]. However, the application of these traditional methods is often constrained by significant geometric and surface limitations. Standardised testing protocols – such as ISO 8302:1991[5] and EN 12939:2000[6] – require large, plane-parallel specimens with precise dimensions, which, in a standard university laboratory, the equipment required to house such large-scale specimens is often unavailable or cost-prohibitive.

Furthermore, castable building materials, such as the mortar investigated in this study, present unique challenges regarding surface roughness. According to EN 12667:2001[7], which governs the testing of specimens with high and medium thermal resistances, there are strict "accepted" ranges for surface flatness. In real-world applications, however, these materials present superficial irregularities and rough textures that create microscopic air gaps at the sensor-specimen interface. These gaps introduce thermal contact resistance, impeding heat flow and leading to a systematic under- or overestimation of the material's true conductivity[8]. Consequently, conventional data may not accurately reflect real-world conditions, as they are typically derived from perfectly polished laboratory specimens. The main goal of this preliminary study is to develop a simple, fast, and cost-effective methodology to overcome these limitations. By employing a spherical geometry and a dual temperature monitoring (core and surface), both values are recorded as point measurements; however, the internal temperature is influenced by the integrated thermal contribution of the entire surface area. In this configuration, the inherent roughness and surface irregularities of the material are effectively normalised, ensuring that measurement errors arising from minor surface "ripples" are significantly mitigated by the overall spherical geometry. This effect is particularly relevant considering that the inner temperature is measured over a discrete area of about 1 mm^2 , and its variation is averaged across a total surface area of approximately 15000 mm^2 . This ensures that the thermal response remains representative of the bulk material rather than being skewed by localised surface defects. To evaluate the experimental data, the Fourier, Maywell-Cattaneo, and linear temperature-dependent models are utilised, as detailed in section 2.2.3 (*Mathematical Formulation*).

2. Materials and Methods

2.1 Materials

Internal and external temperatures (T) were monitored using *shielded K-type thermocouples (Class 1 tolerance)*, connected to a *Raspberry Pi Pico 2 microcontroller* equipped with a *MAX31856 thermocouple-to-digital converter*. Heating was performed using a *Hewlett-Packard 5890 Series II gas chromatograph* functioning as a highly turbulent flow oven, while the data processing and analysis were conducted using *Python (v3.13)* and *Spyder (v6.0.7)*. The castable material was a *premixed lime-based plaster* supplied by a local industrial partner, using *natural hydraulic lime (NHL)* as the binder. Two types of samples were prepared: *thermal samples (TS)* and *historic samples (HS)*. The TS samples shared the same formulation as the HS samples, with the addition of either an organic fibre (TS_OF) or glass spheres (TS_G). Polyethylene (PE) hollow spheres with an internal diameter of 69 mm were used as moulds.



Figure 2.1: Experimental setup inside the GC HP 5890 series II oven. The spherical mortar specimen is placed on a needle-shaped thermocouple, while another is attached on the side for the surface measurements. The white sensor on the left is used to measure the temperature (T) and relative humidity (RH) throughout the experiment.

2.2 Methods

2.2.1 Specimen geometry and casting

As this was a preliminary study, it was necessary to determine the optimal geometry for measuring thermal conductivity – specifically, the most suitable diameter in terms of both measurement accuracy and ease of fabrication. For this purpose, preliminary analyses were performed on mortar and polylactic acid (PLA) specimens with diameters of 39 mm and 69 mm. To ensure homogeneity and eliminate macro-porosity, the mortar was mechanically vibrated immediately after the casting into the spherical moulds, and after 3 days of curing the specimens were removed from the PE shells as outlined in the BS EN 1015-11:2019 standard. In both cases, the specimens exhibited identical thermal conductivity values regardless of their dimensions and according to the tabulate values of both materials.

The selection of the 69 mm diameter was driven by two critical factors related to the experimental environment and specimen consistency. Firstly, the highly turbulent airflow within the GC oven prevents thermal stratification and ensures a highly uniform ambient temperature around the spherical specimen. Within this controlled environment, the 69 mm diameter was specifically chosen to enhance the thermal inertia of the measurement zone and to minimise the impact of the edge-related convective fluctuations.

Furthermore, the larger diameter provides a more representative volume of the mortar's bulk properties. While all specimens were vibrated to eliminate entrained air during casting, the potential presence of accidental internal voids poses a greater risk to data integrity in smaller volumes. By increasing the specimen size to 69 mm, the relative volumetric influence of any such defect is significantly reduced, ensuring more consistent and repeatable thermal conductivity measurements. As these specimens were cast within PE moulds, their surfaces were characteristically smooth.

2.2.2 Experimental Setup and Data Acquisition

The thermal characterization was performed on a spherical mortar specimen with a radius of $r = 34.5$ mm. The spherical geometry was selected to ensure one-dimensional radial heat flow, thereby simplifying the analytical and numerical treatment of the conduction problem.

To monitor the core temperature (T_{int}), one of the two *Type K thermocouples* was needle-shaped and was placed at the centre of the sphere. This was achieved through a 3 mm diameter channel, pre-formed during the casting phase by a rod of equal diameter as the sensor. This internal sensor's shape stabilises the specimen, preventing its significant displacement

during the analysis. The surface temperature (T_{ext}) was monitored using the second thermocouple embedded at a depth of 1 mm, while the environmental temperature was kept constant at 60 °C in the GC oven. To secure both sensors and ensure accurate thermal readings free from external interference, a drop of silicone was applied to each sensor, forming a thin film of approximately 50 μm thick with a *specific heat capacity* comparable to that of lime mortar. Prior to thermal analysis, specimens were conditioned at temperature (T) 23 ± 2 °C and relative humidity (RH) $35 \pm 5\%$. The temperature data were logged at a sampling interval of $\Delta t = 2.0$ s. The thermal cycle consisted of two distinct stages: a *heating phase*, during which the specimen reached thermal equilibrium with the oven at 60 °C, and a subsequent *cooling phase*. To monitor the evaporation process, the oven's internal atmosphere was monitored using a combined *temperature* (T) and *relative humidity* (RH) sensor. The *absolute humidity* (AH) was subsequently derived through post-processing of the RH and T data. By comparing the AH levels at the initial ambient conditions and at the 60 °C thermal plateau, a clear increase in water vapor concentration was detected, confirming the moisture release from the mortar specimen. This indirect psychrometric validation was further supported by a mass balance performed before and after the test: the recorded mass loss (approx. 0.05 g) was found to be consistent with the total evaporated mass estimated from the AH differential. This evidence confirms that the specimen reached a physically stabilized state before to the start of the cooling phase analysis.

2.2.3 Mathematical Formulation

The heat transfer process was modelled as a one-dimensional transient conduction problem in rdial coordinates. To account for different spcimen geometries (spherical or cylindrical), the equation of energy conservation was written in a generalised radial form[9]:

$$\text{Equation 2.2-1} \quad \rho c_p \frac{\partial T}{\partial t} = \frac{1}{r^S} \frac{\partial}{\partial r} \left(r^S k(T) \frac{\partial T}{\partial r} \right)$$

where ρ is the material density [kg m^{-3}], c_p is the specific heat capacity [$\text{J kg}^{-1} \text{K}^{-1}$], and $k(T)$ is the temperature-dependent thermal conductivity [$\text{W/m}\cdot\text{K}$], and S is a shape factor ($S = 1$ for cylindrical and $S = 2$ for spherical coordinates). In this study, $S = 2$ represents the theoretical limit for a smooth, ideal sphere. However, slight reductions in the value of S may be introduced to calibrate the model for specimens that exhibit macroscopic surface roughness or minor deviations from a perfectly spherical geometry, as these factors alter the effective area-to-volume ration and the radial symmetry of the heat flux.

While mortar is a complex capillary-porous material where heat and mass transfer are inherently coupled by *Luikov*[10] and influenced by the *Soret effect*[11], these phenomena are predominantly active during the initial heating phase. In this study, the choice to perform the inverse analysis on the *cooling phase* (dry phase) is aimed at decoupling these effects. By reaching a thermal plateau at 60 °C and verifying the stabilization of absolute humidity and mass loss, the specimen is considered to be in a physically stabilised dry state. In this condition, moisture migration is negligible, allowing for the characterisation of the material's intrinsic thermal properties.

To describe the thermal behaviour during the cooling transient, three distinct models for heat conduction were evaluated and compared during the inverse analysis:

1. *Standard Fourier model*[4] assumes an instantaneous heat propagation and a constant thermal conductivity ($\lambda_0 = -q/(\partial T/\partial r)$). This serves as the baseline model, representing the

standard approach utilised in most normative frameworks, where k is treated as a scalar independent of local temperature variations.

2. *Maxwell-Cattaneo model*[12] introduces a thermal relaxation time τ [s] to account for non-Fourier hyperbolic heat conduction $\left(\tau(T) \frac{\partial q}{\partial t} + q = -\lambda(T) \nabla T\right)$. This model was tested to investigate whether the complex micro-porous structure of the mortars induced a significant delay in the heat flux propagation.
3. *Linear temperature-dependent model*[13,14] ($\lambda(T)$) is a phenomenological model assuming instantaneous propagation but a variable thermal conductivity. To describe the thermal behaviour during the cooling transient, the apparent thermal conductivity is defined as a linear function of the local temperature:

Equation 2.2-2
$$\lambda(T) = \lambda_{ref} + \beta \cdot (T - T_{ref})$$

where λ_{ref} is the thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$] at the reference temperature T_{ref} (typically the start of the cooling phase), and β is the linear temperature coefficient [$\text{W m}^{-1} \text{K}^{-2}$]. This coefficient β quantifies the sensitivity of the material's conductivity to temperature changes: a negative value indicates that the material becomes more conductive as it cools, whereas a positive value indicates a decrease in conductivity at lower temperatures.

4. *Exponential decay proxy model*[15] is finally introduced as a diagnostic tool to assess the stabilization of the specimen. Unlike the previous models, this approach treats the apparent thermal conductivity as a thermo-dependent variable to account for any residual transient phenomena:

Equation 2.2-3
$$\lambda(T) = \lambda_{dry} + \Delta\lambda \cdot e^{-b\Delta T}$$

where λ_{dry} is the intrinsic conductivity of the dry material [$\text{W m}^{-1} \text{K}^{-1}$], $\Delta\lambda$ represents the additional thermal contribution potentially linked to residual moisture [$\text{W m}^{-1} \text{K}^{-1}$], b is the decay constant [K^{-1}], ΔT is the temperature difference relative to the initial state of the cooling transient, defined as $\Delta T = T_i - T_f$ [K].

In this study, the exponential decay model acts as a physical proxy to confirm that moisture-related effects, such as Soret effect and latent heat, are negligible during the cooling phase. The convergence of $\lambda(T)$ toward a stable λ_{dry} validates the cooling transient as a purely conductive process. This ensures that the derived parameters (λ_{ref} and β) reflect the true material matrix properties rather than transient hydric artifacts.

The mathematical model was defined by uniform initial temperature $T(r, 0) = T_{initial}$ and specific boundary conditions. A Dirichlet condition ($T = T_{\infty}$) was applied at the surface ($r = R$), justified by the high *Biot number* ($Bi \gg 1$) typical of forced-convection environments[4]. Finally, a symmetry condition was enforced at the centre ($r=0$) to ensure radial heat flux consistency.

2.2.4 Numerical Solution and Inverse Analysis

Data processing and modelling were performed in a Python environment, utilizing *NumPy* and *SciPy* libraries for scientific computing. The governing *Partial Differential Equation* (PDE) was

discretized using a *Finite Difference Method* (FDM) with a forward-time centred-space scheme on a spatial grid of $N = 35$ radial nodes.

To determine the unknown thermophysical parameters, an *Inverse Heat Conduction Problem* (IHCP) approach was utilized[8]. The parameter set P varied according to the selected constitutive model (e.g. $P = [k_{dry}]$ for the standard Fourier model; $P = [k_{ref}, \beta]$ for the linear temperature-dependent model). A distinction was made between the simulation timeline and the fitting window. The numerical solution $T_{num}(t, P)$ was integrated starting from $t = 0$ s (defined as the onset of the cooling phase), using the actual initial temperature profile to ensure the correct reconstruction of the specimen's thermal history and the development of the internal radial thermal gradient. The parameter estimation was performed by minimising the sum of squared residuals (S) between the measured and simulated temperatures within the valid window:

$$\text{Equation 2.2-4} \quad S(P) = \sum_{t_i}^{t_{end}} [T_{exp}(t_i) - T_{num}(t_i, P)]^2$$

where $T_{exp}(t_i)$ denotes the experimental temperature measured at time step t_i , and $T_{num}(t_i, P)$ represents the numerical temperature predicted by the model for the parameter set P .

The minimization was executed using the Trust Region Reflective algorithm (*scipy.optimize.least_squares*), which allows for bound constraints on the physical parameters. To ensure physically meaningful results (e.g. $k > 0$). The goodness of fit was evaluated via the coefficient of determination (R^2) and residual analysis.

3. Results and Discussion

The geometric and physical parameters of the analysed samples are shown in *Table 3.1*. To ensure consistency across the different mathematical inversions, the specific heat capacity was assumed to be constant ($1000 \text{ J/kg} \cdot \text{K}$), in accordance with *EN ISO 10456:2007*[12] and *EN 1745:2020*[2].

Table 3.1: Geometric and physical parameters of the sample.

	Unit	TS_OF	TS_G	HS1	HS2	HS3
Diameter ($\emptyset$)	mm	69	69	69	69	69
Initial Mass	g	283.19	97.62	295.09	290.37	254.68
Final Mass	g	283.12	97.57	295.04	290.31	254.63
Bulk density (ρ)	g/cm^3	1.65	0.57	1.72	1.69	1.48
Specific Heat Capacity	$\text{J/kg} \cdot \text{K}$	1000	1000	1000	1000	1000

As illustrated in *Table 3.2*, the results obtained from the Fourier, Maxwell-Cattaneo (M-C) and the *linear temperature dependent* ($\lambda(T)$) models gave similar results. The calculated thermal relaxation timer (τ) is negligible for most specimens, causing the M-C hyperbolic equation to collapse into the classical Fourier parabolic form. However, the linear dependent model provides a more nuanced characterisation. While the estimated conductivity values remain comparable to those of the stationary models, the $\lambda(T)$ approach consistently yields higher coefficients of determination (R^2). This is particularly evident in specimen *TS_OF* and *HS3*. This $\lambda(T)$'s higher fitting could suggest that the internal thermal dynamics of porous mortars, especially those with lightweight or bio-based aggregates, are better captured by accounting for the conductivity's sensitivity to temperature gradients during the transient.

Table 3.2: Estimated *thermal conductivity* and *coefficient of determination* (R^2) with *sphericity* (S) equal to 2 by the *Fourier*, *Maxwell-Cattaneo* (M-C), *linear temperature-dependent* ($\lambda(T)$) of the analysed samples.

	Unit	S	TS_OF	TS_G	H1	H2	H3
Fourier (R^2)	W/m·K	2	0.5359 ± 0.0008 (0.999126)	0.1922 ± 0.0003 (0.998851)	0.6827 ± 0.0008 (0.999554)	0.7143 ± 0.0004 (0.999913)	0.7534 ± 0.0015 (0.999084)
M-C (R^2)	W/m·K	2	0.5358 ± 0.0008 (0.999128)	0.1921 ± 0.0003 (0.998855)	0.6827 ± 0.0005 (0.999556)	0.7143 ± 0.0004 (0.999914)	0.7533 ± 0.0014 (0.999167)
τ	s	2	0.1084 ± 0.0042	2.6697 ± 0.9957	0.0886 ± 0.0007	0.0834 ± 0.0004	7.2086 ± 0.9296
$\lambda(T)$ (R^2)	W/m·K	2	0.5829 ± 0.0019 (0.999390)	0.1849 ± 0.0007 (0.998908)	0.6756 ± 0.0019 (0.999561)	0.7086 ± 0.0009 (0.999917)	0.6932 ± 0.0018 (0.999717)
$\lambda_{10,dry}$ (Fourier)*	W/m·K	2	0.52	0.19	0.66	0.70	0.73
$\lambda_{10,dry}$ ($\lambda(T)$)*	W/m·K	2	0.55	0.18	0.64	0.67	0.65

* Calculated using the model ($\lambda_{10,dry} = \lambda_{dry} \cdot e^{f t(10-T)}$) presents in the EN ISO 10456:2008 with the *temperature conversion coefficient* (f_T) of 0.001 K^{-1} [16].

To provide a standardised characterisation for building energy simulations, the reference thermal conductivity at 10°C ($\lambda_{10,dry}$) was derived. For the lightweight specimen (TS_G), whose 0.57 g/cm^3 of density, the models yield a $\lambda_{10,dry}$ of $\sim 0.17 \text{ W/m}\cdot\text{K}$. This result is highly consistent with the theoretical expectations for a lime-based mortar with glass sphere inclusions, showing a high reliability of the inverse numerical procedure.

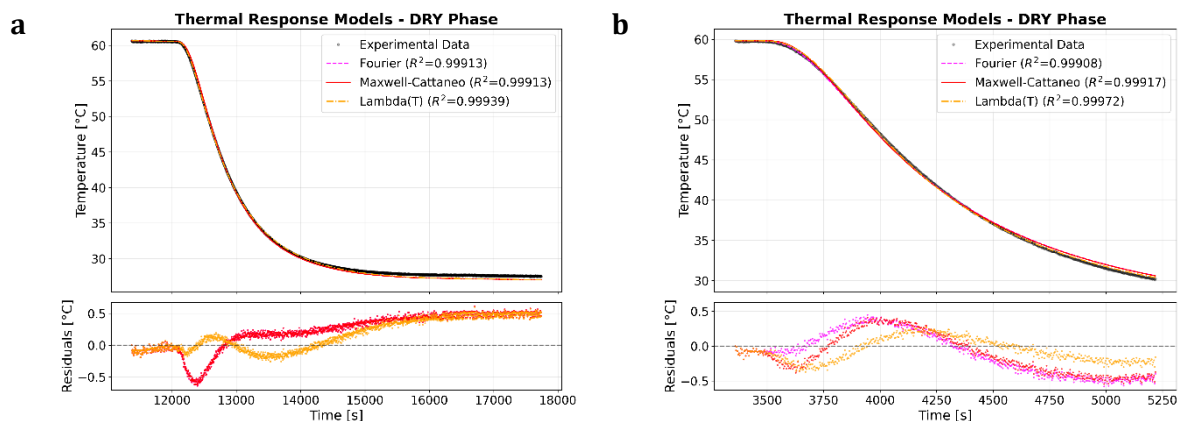


Figure 3.1: Thermal transient fitting and error analysis. Top: experimental temperature decay fitted with *Fourier* (magenta), *Maxwell-Cattaneo* (red), and *temperature-dependent* $\lambda(T)$ (orange) models. Bottom: distribution of the temperature residuals. The graphs illustrate the thermal behaviour of (a) the TS_OF sample and (b) the HS3 sample.

4. Conclusion

In this study, spherical geometry was chosen for the radial thermal analysis due to its inherent symmetry, which minimises edge and corner effects and allows for a precise isolation of one-dimensional (1D) radial heat transfer.

The comparative analysis of the *Fourier*, *Maxwell-Cattaneo* (M-C), and *temperature-dependent* $\lambda(T)$ models showed a strong convergence, confirming that all three approaches successfully captured the fundamental transient behaviour of the specimens (Table 3.1). Among these, the $\lambda(T)$ model proved to be the most robust (Figure 3.1), particularly for mortar containing *bio-based aggregates*. By accounting for the temperature-dependent thermal conductivity (Equation 2.2-2), this model reflects the dynamic behaviour of the sample during the cooling phase. The results are

consistent with the density-dependent values reported in EN 1745:2020 for lime mortars[2], with the exception of TS_OF sample, whose thermal response was influenced by its specific organic fibre reinforcement.

Future research will focus on expanding this methodology by:

- Utilising a climatic chamber to investigate material behaviour under controlled temperature and relative humidity conditions.
- Experimentally determining the specific heat capacity (c_p) as a function of bulk density to further refine the models.
- Conducting Guarded Hot Plate (GHP) and heat flow meter (HFM) tests to cross-validate this transient approach with established steady-state standards.

Finally, this methodology offers a promising framework for evaluating the thermal performance of castable building materials with complex surface textures. Future research could investigate rough finishes, such as *harling* (Scottish roughcast), to assess how surface morphology and finish thickness influence the overall thermal conductivity of the building component. A potential development involves the introduction of a sphericity index to quantify the deviation of these textured surfaces from the ideal spherical geometry. This would allow for a more nuanced correlation between intrinsic material properties and the effective thermal behaviour of finished components, effectively bridging the gap between laboratory characterisation and real-world surface performance.

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