

Research Article

Development and Validation of an Experimental Method for the Thermophysical Characterization of Thermal Conductivity in Porous Building Materials: Application to Stone in the Context of Sustainable Construction

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Abstract

The thermophysical characterization of construction materials is a fundamental area of research in building physics and energy efficiency. Over the years, various experimental techniques have been developed to determine key thermal properties such as thermal conductivity, diffusivity, and heat capacity. While these methods have provided valuable results, their accuracy and applicability remain limited in many cases due to uncertainties in the input parameters and assumptions regarding material homogeneity and saturation levels. These limitations often require researchers to implement additional experimental protocols to refine the measurements and adapt them to real-world conditions. This paper proposes a new experimental method that builds on two well-established techniques: the "hot wire" method and the "guarded hot probe" method. The proposed technique is specifically designed for the characterization of unsaturated porous construction materials, which pose particular challenges due to their complex structure and moisture content. It enables the reliable measurement of apparent thermal conductivity under variable saturation conditions and offers greater adaptability in laboratory and field settings. Experimental thermal tests were performed on a typical construction material to validate the method. The results show that the new technique improves the precision of thermophysical parameter estimation and provides a more accurate reflection of material behaviour under realistic conditions. This approach contributes to the on-going development of energy-efficient construction practices by supporting the selection and optimization of materials based on scientifically validated thermal performance criteria.

Keywords

Thermo Physical Characterization, Stone, Hot Wire, Thermal Conductivity

1. Introduction

Stone has been a primary construction material for thousands of years, long before the advent of modern technologies. This noble material has been utilized across various fields by

humans since the earliest civilizations. In ancient Egypt, massive stones were used to build the pyramids, symbols of power and the lasting durability of construction, reflecting the

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skill and ingenuity of ancient builders. Similarly, the Greeks utilized durable stone for their majestic temples, such as the Parthenon, a perfect example of the harmony between aesthetics and function. Stone's resistance to the ravages of time has made it central to the construction of monuments and buildings, many of which continue to inspire admiration, offering both a solid foundation and great symbolic value [1].

Over the centuries, the use of stone has evolved with advancements in technology and changes in modern architectural styles. During the middle Ages, stone became indispensable for building large fortifications and Gothic churches. Its defensive qualities and ability to support massive structures made it the ideal choice for castles and city walls. Medieval architecture used stone not only for its strength but also for its sacred and spiritual dimensions, as seen in the soaring vaults and colorful stained glass windows of cathedrals. With the Renaissance came the artistic use of stone in civil buildings and public monuments, where intricate details and ornamentation added beauty and symbolism to the structures [2].

In the modern era, although new materials like concrete and steel have become dominant, stone still holds significant value in architecture. Today, it is often integrated into restoration and renovation projects to preserve the integrity of historical heritage. Stone allows for the restoration of old buildings while maintaining their original character, preserving the collective memory of past civilizations. It also finds a place in contemporary construction, where it is used to add prestige and refinement. Modern architects use stone not only for its durability but also for the richness of its textures and colors, creating an interesting contrast with more industrial materials. Despite its less frequent use in modern buildings, stone continues to fascinate and inspire, representing the perfect blend of functionality and timeless beauty [1, 3].

The use of stone in Moroccan construction dates back centuries and plays a fundamental role in the country's architectural identity. Moroccan builders have skillfully utilized local natural resources, particularly stones from regional quarries, to construct iconic structures. The historical medinas of cities such as Rabat, Salé, Fes, Marrakech, and Meknes stand as true testaments to the craftsmanship of Moroccan stoneworkers. The Almohad and Merinid constructions, for instance, are renowned for their imposing walls and simple yet delicate ornamentations, primarily made of limestone and marble. The materials chosen were not only valued for their solidity but also for their ability to withstand Morocco's extreme climatic conditions, including the intense summer heat and temperature fluctuations. The ramparts of ancient cities, like those in the medinas of Salé and Marrakech, are striking examples of stone's use in defensive structures [4, 5].

Beyond its functional role, stone in Morocco also carries an aesthetic dimension, especially in palace and mosque architecture. The stone mosaics, or zellige, are a Moroccan architectural tradition that combines stone with ceramics to create intricate patterns that adorn the walls and floors of religious

and public monuments. The Kasbah des Oudayas in Rabat and the Bou Inania Medersa in Fes stand as examples of the elegance and refinement of this use of stone. According to researchers such as M. Berriane [6], this tradition of stone in Moroccan architecture is not just decorative but embodies principles of durability and resilience against the test of time [7].

The techniques of stone cutting and assembly used by Moroccan artisans are passed down from generation to generation, ensuring the longevity of this unique craftsmanship. In rural areas, stone also serves as a traditional building material for homes and kasbahs, offering both thermal comfort and security.

The characterization of stone in the context of sustainable construction is becoming increasingly important, especially for its role in the energy efficiency of buildings. As a natural material, stone possesses unique thermal properties that can help regulate building temperatures, reducing the need for heating and cooling. Its ability to store and release heat, known as thermal inertia, helps maintain more stable indoor temperatures throughout the year. This characteristic is particularly beneficial in regions with significant temperature fluctuations between day and night, such as Mediterranean or desert areas. By incorporating high-thermal-capacity stones into walls or floors, energy consumption for heating in winter and cooling in summer can be reduced. According to a study by C. Santos et al. (2013) [8], considering the thermophysical properties of materials like stone can reduce a building's energy consumption by 10 to 20% [8].

Moreover, stone offers significant ecological advantages when used in sustainable construction projects. Its exceptional durability, low carbon footprint, and recyclability make it an ideal choice for low-impact construction. Unlike more modern building materials, which require energy-intensive manufacturing processes, stone, when locally sourced and used, generates minimal greenhouse gas emissions. Furthermore, recent research has shown that using natural stones in façades and external building elements not only enhances energy efficiency but also improves acoustic comfort and indoor air quality—key factors for sustainable buildings. A study by M. K. Abdelaziz et al [9] highlights that using local stones, adapted to a region's specific climate, optimizes thermal and acoustic performance while reducing reliance on external energy systems. These findings underscore the importance of characterizing stone for the development of more eco-friendly and energy-efficient buildings.

Current research on experimental methods for characterizing stone in the context of energy-efficient, sustainable buildings focuses on evaluating its thermal and physical properties to optimize its use in construction. Scientists use advanced techniques such as measuring thermal conductivity, heat capacity, and heat diffusion to assess the ability of different stones to regulate building temperatures. For example, laboratory tests, like those described by R. P. S. Kumar et al [10], measure the thermal resistance and heat absorption

capacity of various stones to identify those that provide the best thermal performance. Numerical simulations, combined with physical tests, have also become common to predict the thermal behaviour of materials under real conditions. These approaches help identify more specific solutions tailored to local climate needs, thus optimizing building energy efficiency while adhering to current environmental standards.

However, several challenges remain in implementing these experimental methods for stone characterization. One key difficulty is the great variety of stone types available and their intrinsic properties, which can vary significantly depending on their geological origin. The diversity of stones, including limestone, marble, granite, and other less common types, complicates the establishment of reliable comparative data. Additionally, the variability of local climatic conditions and stone manufacturing methods can influence experimental test results, making data interpretation sometimes ambiguous. Another significant challenge is the cost and duration of the tests, which require specialized equipment and strict testing conditions to obtain precise measurements. According to a study by P. W. Shearer et al. [11] standardizing testing protocols and creating common databases for stone properties are major challenges for uniform results across different regions and types of materials. These obstacles hinder the widespread use of stone as a material of choice in sustainable construction, despite its many advantages.

Description of the Developed Method: An In-Depth Approach to Thermal Characterization via Electric Excitation

The characterization of the thermophysical properties of materials is a crucial step in understanding their behavior under real-world conditions, especially in fields like construction, industry, and materials science. Among the various experimental methods available, the approach based on electric excitation has proven to be particularly effective for measuring thermophysical properties such as thermal conductivity. This method involves applying a constant thermal flux to a material assumed to be homogeneous and recording the temperature at a specific point within the material over time. The goal is to extract reliable thermophysical data based on the mathematical relationship between temperature and thermal flux, taking into account Fourier's law of heat conduction.

2. Sample Preparation: Sandwiching the Material

The first step of this method involves carefully preparing the sample to be studied. The sample is placed in a specialized setup designed to create a controlled thermal environment. It is sandwiched between two conductive materials or heating plates, which are intended to ensure that the thermal flux is evenly distributed throughout the material. Precision in this step is crucial, as any non-uniform distribution of heat could skew the thermal conductivity measurements, leading to

unreliable results. Additionally, the material under study should be assumed to be homogeneous and thermally balanced at the outset, meaning its initial temperature should be uniform across the entire sample. This setup creates a controlled thermal gradient across the material, which is fundamental for observing temperature changes over time and determining the material's thermal properties. The choice of sandwich material should also account for its own thermal properties, to avoid interfering with the results obtained from the material being tested.

3. Exposure to Thermal Flux: The Heating Phase

Once the sample is in place, the next step is to subject both sides of the material to a constant thermal flux. This phase, known as "heating time" or *time_{heat}*, is crucial for establishing a steady temperature variation throughout the material. The applied thermal flux raises the temperature, which gradually propagates across the material. This phase must be carefully monitored, as the heating time needs to be long enough for the material to reach a measurable thermal response but not too long to prevent errors due to transient thermal effects or excessive heating at the edges.

The duration of the heating phase is calculated based on the specific characteristics of the sample, aiming to maximize the accuracy of the measurements while respecting the thermal limits of the material under test.

4. Data Centralization: Using the Data Acquisition System

A key component of this method is the use of a data acquisition system. This electronic system collects, stores, and analyzes real-time temperature data during the experiment. It is equipped with highly sensitive thermal sensors, often thermocouples or resistance probes, placed on the surface of the sample to measure temperature variations in response to the thermal excitation. High-frequency data acquisition with great accuracy is essential, as even small temperature changes can significantly impact the final results.

The data recorded by the acquisition system can be visualized in real-time, allowing researchers to track the material's thermal behavior and ensure the experiment is progressing as planned. This system also offers flexibility in adjusting experimental parameters, such as the heating duration or the precision of the data recording intervals, depending on the preliminary results observed during the experiment.

5. Recording Temperature Variations: Precision of Time Step

The next step involves recording temperature variations

with a precise time step. The time step, which defines the frequency at which temperature is measured, must be selected to optimize the accuracy of the recordings without unnecessarily increasing the volume of data to be processed. A time step that is too long might miss rapid temperature changes, while a time step that is too short could result in an overwhelming amount of data, complicating the analysis.

The choice of time step depends on several factors, including the total duration of the experiment, the thermal conductivity of the material, and the sensitivity of the sensors. In general, temperature recordings must be frequent enough to capture the subtle thermal variations of the material while being spaced out sufficiently to simplify the data analysis. This step is essential because the relationship between the recorded temperature and the material's thermal conductivity is determined by solving thermal equations that account for the temporal data.

6. Data Analysis: Calculation of Thermophysical Properties

Once the data has been collected, the final step involves analyzing the temperature variations to calculate the material's thermophysical properties, particularly its thermal conductivity. By applying Fourier's law of heat conduction, which relates the variation in temperature to the variation in thermal flux, the thermal conductivity of the material can be determined from the obtained temperature data.

The analysis also involves taking into account the boundary conditions of the experiment, such as the initial temperatures, the characteristics of the thermal flux, and the geometric properties of the system. Once these elements are integrated into a mathematical model, the thermal conductivity can be determined with high accuracy. This method is particularly useful for characterizing materials in real-world configurations, where materials are often heterogeneous or exposed to variable environmental conditions.

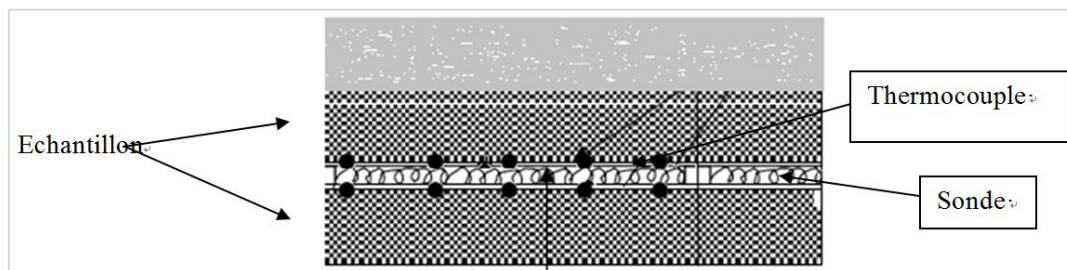


Figure 1. Hybrid Hot Rod Method.

The heat equation in cylindrical coordinates for the problem is written as:

$$\left(\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r,t)}{\partial r} \right) = \frac{1}{a} \frac{\partial T(r,t)}{\partial t} \quad (1)$$

The analytical solution of the heat equation, taking into account the boundary conditions, becomes:

$$T(r,t) - T_o = \frac{Q}{4\pi\lambda} \left[\ln\left(\frac{4_{at}}{r_o^2}\right) + \frac{r_o^2}{4_{at}} + \dots \right] \quad (2)$$

When time tends to infinity, the general solution of the heat equation becomes:

$$T(r,t) - T_o = \frac{Q}{4\pi\lambda} \ln(t) + \frac{Q}{4\pi\lambda} \ln\left(\frac{4a}{r_o^2 C}\right) \quad (3)$$

The development of an experimental protocol that uses an insulated box, a temperature recording system, and a heating element allows for the measurement and characterization of the thermal properties of building materials, including stone, under controlled conditions. This protocol aims to simulate

the effects of temperature on materials by measuring their ability to store and release heat. The insulated box is used to minimize thermal exchanges with the outside environment, allowing the analysis to focus on the material being tested. Inside this box, a heating element provides a stable heat source, simulating the temperature variations a material may experience in a building.

Temperature sensors, connected to a recording system, measure the material's temperature at different time intervals, offering a detailed view of how the material reacts to this heat. This setup generates precise data on the material's thermal characteristics, such as its thermal conductivity and specific heat capacity. Once the data is collected, it is analyzed to determine the thermal inertia and heat absorption capacity of the tested material.

This protocol can be adapted for testing various types of stones, assessing their energy efficiency in conditions that replicate those encountered in real buildings. By recording temperature at different points of the material and analyzing the heat variations over time, parameters such as thermal conductivity and thermal diffusivity can be calculated. These are essential metrics for evaluating the potential of a material

to regulate the thermal environment within buildings.

This type of experimental protocol, providing reliable and comparable data, is key to developing more energy-efficient and sustainable building materials.

Water Absorption and Thermal Characterization of Building Materials: Experimental Protocol and Results

Water absorption is defined as the maximum amount of water a rock can absorb. For the measurements, we used the protocol. The sample is first dried in an oven at 110°C for 24 hours, after which we measure its initial mass (M_0). The sample is then immediately submerged in distilled water for 8 hours until saturation is reached. We then measure its mass (M_s). The absorption percentage is calculated using the fol-

lowing method:

The measurements show that the salt stone has an absorption rate of 12%. We place the probe (heating wire) with a thickness of 2mm between the two blocks of the sample. To maintain constant temperature at the boundaries, we insulate the edges of the sample with 10cm thick fiberglass. A thermal flux is then injected into both blocks using a Metrix device, and a Type K thermocouple, positioned between the wire turns, measures the temperature on the face of each block. The measurement time interval is set to 1 second. A central acquisition system (Agilent32) records the temperature variations from the thermocouple.

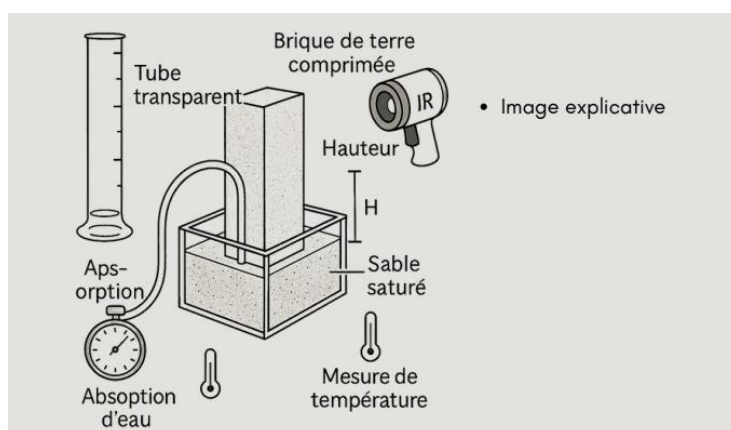


Figure 2. Materials and Equipment Use.

The selection of the heating power is based on an iterative method to determine the appropriate thermal power to inject. The methodology we used involves varying the voltage and current in such a way that the temperature difference for each experiment is greater than or equal to 10°C.

An important point regarding the preparation of the samples concerns the moisture content of the sample. In fact, the

material is stored in the open air of the laboratory, meaning that moisture can be absorbed by the pores, potentially skewing thermal conductivity measurements. To address this, we place the sample in a convection oven at 60°C for 24 hours before each measurement. Before and after each heating cycle, we measure the sample's mass to determine its moisture content.



Figure 3. Drying of the Samples in an Experiment.

Another important point is that the thermal conditions are kept constant throughout each experiment. A temperature and humidity recorder is placed in the laboratory to precisely measure the ambient humidity and temperature. To also maintain constant boundary conditions, we place the sample holder in an enclosure insulated with thermal insulation (fiberglass).

For the thermal conductivity measurements, we used a material (porous stone) widely used in construction materials in the region. Thermally, the porosity of this material has direct consequences on the apparent thermal conductivity. Indeed, the material's low density (1600 kg/m^3) and high porosity limit the heat transfer through its solid matrix.

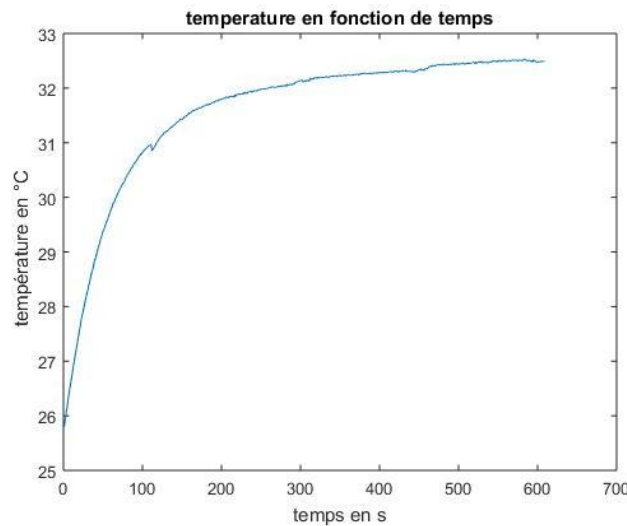


Figure 4. Temperature Variation Over Time During the Experiment.

Figure 4 clearly shows that the temperature of the sample changes over time. The sample is subjected to thermal flux for a period of 10 minutes. After analyzing this figure, we see that the temperature range is divided into two phases:

- 1) Phase 1: The temperature increases slowly, with a difference of 1 to 2°C. The sensitivity analysis of the heat equation model shows that the thermal inertia of the heating wire plays a significant role in this phase. Indeed,
- 2) Phase 2: The temperature increase follows an exponential growth. The temperature difference exceeds 10°C. This variation depends greatly on the nature of the material and its moisture content.

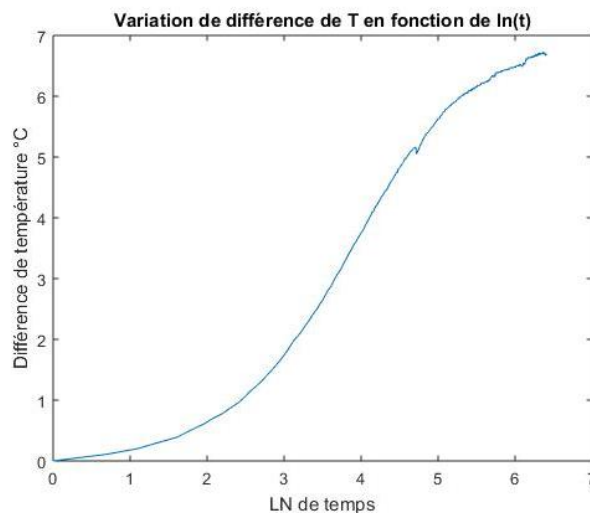


Figure 5. Temperature Difference ($T(t)-T_0$) as a Function of Logarithmic Time.

Figure 5 illustrates the variation of the temperature difference ($T(t)-T_0$) as a function of the logarithm of time. The analysis of this profile shows that this function is a straight line, ranging from long times (120s to 600s). It should be noted that beyond 600s, a change in direction occurs, as the heat transfer is limited by the thermal boundaries of the system.

Figure 6: Temperature Difference vs. Logarithmic Time

The response of the temperature after 120 seconds becomes linear. Linear regression allows us to determine the thermal conductivity value based on the input parameters, namely the length of the heating wire (4.4 cm) and the injected heating

power (0.28×0.66 W).

$$T(t) = A1 \ln(t) + B1$$

Where A1 is the slope.

After linear regression, we obtain the thermal conductivity value of 0.4587 W/m·K.

The characterization method we developed allows us to compare our results with those obtained using another method, namely the hot plate method. The table below shows the results obtained:

Table 1. Apparent Thermal Conductivity Obtained.

Method Used	Developed Method	Hot Plate Method
Thermal Conductivity (W/m·K)	0.4587	0.44

The difference in thermal conductivity between the two methods is quite small. However, further comparison with other characterization methods is needed. In fact, the two methods are based on different approaches. The hot plate method uses a steady-state approach, whereas the developed method relies on a transient excitation. This transient regime can lead to significant differences between the measurements and the actual thermal conductivity value.

7. Conclusions and Discussions

The measurement of thermal conductivity in construction materials is a critical step in assessing their thermal performance for practical applications, such as the design of energy-efficient buildings. In our laboratory, we have developed a thermophysical characterization method that enables efficient and cost-effective measurement of thermal conductivity. This method is based on a simple yet robust principle, involving temperature and heat flux measurements under controlled conditions. It proves particularly suitable for a wide range of materials, from stones to synthetic insulators, offering flexibility for various applications. One of the main advantages of this approach is its ease of use, allowing even novice researchers to obtain reliable results with minimal investment in expensive equipment.

A key feature of our method lies in its simplicity of implementation. Unlike more complex techniques such as the hot-plate method or steady-state temperature measurement, our approach does not require sophisticated systems or lengthy, costly experimental processes. Instead, we have designed a protocol that uses readily available devices, such as thermocouples and controlled heat sources, to record temperature varia-

tions in the material under study. By utilizing a reliable data acquisition system, results are obtained quickly, enabling efficient analysis of the thermophysical properties of the materials. This ease of execution, combined with its precision, makes this method a valuable tool for researchers and engineers seeking to evaluate the thermal performance of materials in realistic conditions without the need for costly infrastructure.

However, while this method is already effective, there are areas for improvement to further enhance its accuracy and ability to characterize a broader range of materials under varying conditions. For instance, the introduction of high-resolution temperature sensors and the optimization of the measurement protocol to reduce errors caused by external disturbances or sample preparation inconsistencies could refine the method. Additionally, the development of a more sophisticated mathematical model that incorporates transient thermal effects and the specific properties of materials would provide a more accurate estimation of thermal conductivity under real-use conditions. This ongoing development work is crucial to ensure that our measurement method remains competitive and applicable within the research and construction industries, where demands for energy efficiency continue to rise.

Conflicts of Interest

The authors declare no conflicts of interest.

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