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Thermal Conductivity of Saturated Samples Using the Hot-Disk Technique

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Abstract:- The HOT DISK technique is used to measure the thermal conductivity of dry and saturated samples of building materials at room temperature. This technique is also known as transient plane source technique (TPS). The technique uses a resistive heater pattern (TPS element) that is cut from a thin sheet of metal and covered on both sides with thin layers of an insulating material. The TPS element/sensor is used as both heat source and temperature sensor. Regarding measurements of saturated (wet) samples this technique has several advantages such as the short measuring time and the small temperature rise (few degrees) across the sample. These two advantages will prevent a non-uniform moisture distribution that may arise when a high temperature difference across the wet samples is maintained for a long time. Another advantage, the shape of TPS-element being flat and thin leads to a substantial reduction in contact resistance between the sample and the sensor. More details about the HOT DISK technique and its major characteristics will be discussed. The investigated samples are of different types of building materials with various water absorbing abilities. The thermal conductivity was measured both at dry and 40% by weight-wet conditions.

Keywords: Transient technique, Hot Disk, thermal conductivity, wetting effect, building materials.

1 Introduction

The reliability of a specific method to measure thermal properties is given by several factors, such as the speed of operation, the required accuracy and performance under various environmental conditions, the physical nature of material, and the geometry of the available sample. However, in most methods the main concern is to obtain a controlled heat flow in a prescribed direction, such that the actual boundary conditions in the experiment agree with those assumed in the theory.

The transient methods are a class of methods for measurements of thermal properties of materials. The principle of these methods is simple. The sample is initially kept at thermal equilibrium. Then a small disturbance is applied on the sample in a form of a short heating pulse. The change in temperature is monitored at one or more points during the time of measurement.

Most laboratory measurements of thermal conductivity have been performed using conventional steady-state techniques such as "the divided bar apparatus" Sass et al. [1]. These techniques involve the simultaneous measurements of steady state heat flux and temperature gradient through test samples "in the form of bars" for which the solution to the differential equation of heat conduction is readily available.

According to Woodside and Hessmer [2], thermal conductivity measurements using steady-state techniques may have several drawbacks. For example, besides the long time required (several minutes) to attain equilibrium, in most of the cases, there will be edge or end effects that may increase due to lack of good thermal insulation at the sample boundaries. Moreover, if any moisture is present in the sample, a non-uniform moisture distribution may arise when the temperature difference across the sample is maintained for a long time. This may lead to conductivity measurements that depend upon the sample size and the magnitude of the applied temperature difference

In contrast to steady-state techniques, transient techniques are fast (seconds) and therefore, in spite of their drawbacks, are less likely to produce non-uniform saturation distribution in the case of partially saturated samples, see for example, Middleton [3].

In this work, the HOT-DISK technique Gustafsson [4], is used to perform measurements of thermal conductivity of dry and partially saturated solid samples. This technique has an additional advantage of using a flat thin sensor which makes it more suitable to substantially reduce the contact resistance between the sample and the sensor, more details are given in the text The traditional masonry construction of a typical old Middle Eastern building is based on concrete-backed stone masonry made of limestone bricks joined by mortar forming the outer walls of the building envelope. The locally produced building materials during 1970's were used in the construction of buildings such as houses, schools, hospitals ...etc.. These materials were limited to the basic construction simple units of the building envelope such as bricks, tiles, cement plasters, mortar and ground soils without any insulation components. Therefore, the study of thermal contributions of wall thickness, orientation, thermal conductivity, and orientation of the building are crucial parameters in the thermal performance of a building envelope [5]. Furthermore, due to the seasonal climate variations the effective thermal capacitance, the time constant, and the thermal delay of temperature variations through building elements are also important parameters characterizing the dynamic thermal behaviour of building envelope [6]. In addition, the variations in the properties of row materials, methods of processing and workmanship, make testing of the finished products an essential to the designers [7]. Many buildings were built without having technical data on building materials which made them very unpleasant to occupants during both hot and cold seasons. Technical data such as thermal conductivity values as well as the assessment of moisture effect within the structures are essential for the calculations of thermal loads on buildings.

The objective of this work is to report the thermal conductivity values under dry and wet conditions of the locally produced Middle Eastern building materials used in the construction of a typical building envelope and give suggestions to improve the thermal performance of the envelope.

2 The Technique

The HOT-DISK technique has been used several times to report thermal conductivity measurements over a wide range of temperatures [4, 8-10]. A full complete description of the experimental capability regarding precision/accuracy and reproducibility of the measured data of various applications is given elsewhere [9]. The main features and the principles of this technique are discussed below. The TPS technique uses a resistive heater pattern (TPS element) that is cut from a thin sheet of metal (Ni) and covered on both sides with thin layers of an insulating (kapton) material. The conducting pattern of the TPS element/sensor has the shape of spiral strips as shown in Fig.1. This element/sensor is used as both heat source and temperature sensor, i.e. in similar manner as the wire in the transient hot-wire method.

To insure good thermal contact, in the experimental arrangement the sensor is clamped between the sample halves that consist of two identical disc-shaped pieces, each having a diameter in the range of (10-7 cm) and a thickness in the range of (2-2.5 cm.), for more details see the sample characteristics section. The experiment is performed by recording the voltage/resistance variations over the TPS-element, while its temperature is slightly raised (by few degrees) by a constant electrical current pulse. The time-dependent resistance of the TPS element during the transient recording can be expressed, in first approximation, as

$$R(t) = R_0 [\, 1 + \alpha\, \Delta T(t) \,] \qquad (1)$$

where R_0 (≈5 Ω at room temperature [9]) is the resistance of the TPS element before the transient recording has been initiated, α is the temperature coefficient of resistance (TCR) for the TPS element (TCR ≈ 4.0 x 10^{-3} K^{-1} at room temperature ≈ 298 K), and $\Delta T(t)$ is the time-dependent temperature increase of the TPS element, Fig.1 shows atypical temperature increase of about 1 K. The theory of the method is based on a three-dimensional heat flow inside the sample. The samples were large enough so that they can be regarded as infinite medium provided that the time of the transient recording is ended before the thermal wave reaches the boundaries of the sample and produces edge effects. It should be pointed out, that the total time of the transient event is proportional to the square of the overall dimension of the conduction pattern or the distance from the conducting pattern to the nearest free surface of the sample. This is evident from the expression for the probing depth [4, 9] $\Delta_p = \beta(t_{max}\kappa)^{1/2}$, where t_{max} is the total of the recording, κ is the thermal diffusivity of the sample and β is a constant which related to the experimental accuracy. The probing depth and the sample size are intimately connected in the sense that the shortest distance from any point on the TPS element to the nearest point on any of the free surface of the sample must always exceed the probing depth. To achieve high accuracy in our measurements, a β-value of 1.42 seems to define reasonably well the probing depth of our samples.

The assessment of the temperature increase $\Delta T(t)$ in the heater depends on several factors such as the power output in the TPS element, the design parameters of the sensor, and the thermal transport properties of the surrounding sample. For a disk-shaped sensor, the thermal conductivity and diffusivity can be obtained from $\Delta T(t)$ that is given by the following equation [4].

$$\Delta T(\tau) = P_O\,(\pi^{3/2}\, a\, \lambda)^{-1} D(\tau) \qquad (2)$$

Here P_O is the total output power, λ is the thermal conductivity of the sample, and a is the radius of the sensor. $D(\tau)$ is the theoretical expression of the time dependent temperature increase, which describes the conducting pattern of a disk-shaped sensor, assuming that the disk consists of a number m of concentric ring sources[10] and given by:

$$D(\tau) = [m(m+1)]^{-2} \int_0^{\tau} d\sigma\, \sigma^{-2} \left[\sum_{l=1}^{m} l \sum_{k=1}^{m} k \exp\left(\frac{-(l^2+k^2)}{4m^2\sigma^2} \right) I_0 \left(\frac{l\,k}{2m^2\sigma^2} \right) \right] \qquad (3)$$

For convenience, the mean temperature change of the sensor is defined in terms of the non-dimensional variable τ, where $\tau = (\kappa t/a^2)^{1/2}$ or $\tau = (t/\theta)^{1/2}$, t is the time measured from the start of the transient heating, $\theta = a^2/\kappa$ is the characteristic time,. Fitting the experimental values of $\Delta T(t)$ from equation.(1) to the theoretical values of $\Delta T(\tau)$ in equation (2) will yield all desired information.

It was previously mentioned the tool of estimating the probing depth, insures that the heat will not reach the outer boundary of the sample which resembles the basis of three-dimensional heat flow model. Furthermore, the short measuring times (seconds) and small temperature gradient across the sample will prevent a non-uniform saturation distribution (thermo-migration phenomena) in the case of partially saturated samples.

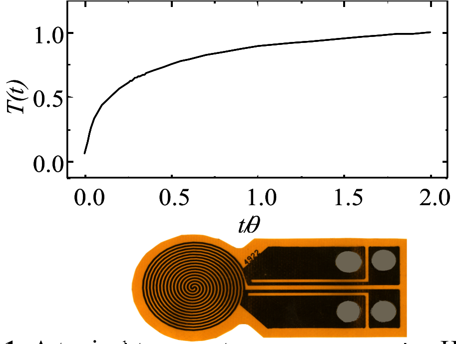

Figure. 1: A typical temperature response and a. HOT-DISK sensor

The influence of the insulting layer, the heat capacity of the sensor and the contact resistance (possible presence of air pockets between the sensing element and the sample) are all dealt with by deleting a few number of experimental points at the beginning of the transient recording.

The number of the deleted points is decided by looking at the difference graph. It is a graph that illustrates the difference between the experimental and theoretical temperature values (ΔT_{exp} - ΔT_{theo}) versus the measured experimental points/measuring time. By excluding the initial part of the measurement The influence of the insulting layer, the heat capacity of the sensor and the contact resistance (possible presence of air pockets between the sensing element and the sample) are all dealt with by deleting a few number of experimental points at the beginning of the transient recording. The data, stemming from the heat transport through the protective layer, the influence of contact resistance is avoided [8]. All of these measures will substantially reduce the possible errors that may result either due to the specific geometry or due to the physical nature of the available sample.

3 Characteristics of the samples

The bricks are excavated from two major rock mines used as a supply of solid building bricks. The soil is a mix of clay (mud) and sand used to fill the spacing between the solid ground and the tiles covering the floor of buildings. Three different samples were investigated, two from soft and hard bricks and one from a ground soft soil, each consists of two different disc-shaped pieces with diameter in the range of 7-10 cm and a thickness in the range of 2-2.5 cm.. Two schemes are followed to prepare the samples. The first one is by cutting the sample pieces from the bricks, as it has been done for the soft and hard bricks samples. The second scheme is by making disc-shaped pieces from powders of the basic constituents of the ground soft soil used in flooring the houses. The disc-shaped pieces were made by using a 7 cm disc-shaped die with a uni-axial load ranging from 15 to 17 tons. The samples have an average apparent densities ranging from 390-1485 kg/m^3. These values were calculated using the dimensions (volume) and masses of the individual samples.

A characterizing parameter such as porosity can be estimated, using the following formula:

$r = 1- (\rho_{ave}/ \rho_{cal})$ where ρ_{ave} is the average apparent density of the sample pieces, and ρ_{cal} is the calculated density based on the atomic weights of the constituting atoms and the dimensions of the unit cell [11]. However, these samples contain micro-voids and composed from large diversity of its individual constitutes (compounds and elements) and it was not possible to estimate the porosities of the samples. In general, the estimated porosity values should be proportional to the apparent densities shown in table I, below which gives the detailed parameters characterizing the samples.

Table I. Characteristics of the investigated samples

The Sample	Hard bricks	Soft bricks	Soft Soil
Diameter (m)	0.050	0.051	0.070
Thickness (m)	0.020	0.025	0.018
Density (kg m^{-3})	1985	1444	0390

The assessment of moisture effect was carried by washing the samples with water until they are saturated up to 40 percent by weight then thermal conductivity measurements were preformed and compared with the corresponding dry samples measurements. Before the experiment is preformed the samples must be arranged properly, see the previous section. There are two aspects to be considered in this arrangement. Firstly, we should insure a good thermal contact between the sensor and the sample pieces, which is done by clamping the TPS element between the sample halves via a screw arrangement. Secondly, in some cases it might be necessary to place (guarding) the sample pieces and the sensor arrangement inside a metallic cylinder in order to protect the sample from the external radiation or/and to achieve a homogeneous temperature distribution around the sample. A typical arrangement of the sample in the sample holder and the guarding_cylinder are shown in Fig.2.

Figure2. The sample arrangement and the metallic cylinder used for guarding

4 Results and discussion

The mean values of λ of several runs are given in Table II for both dry and 40% by weight wet conditions. The samples were isotropic and have similar thermal conductivity profiles with higher values for higher densities as expected. The accuracy of these measurements is within 3-5%. It should be pointed out that the accuracy in evaluation of the theoretical expression $D(\tau)$ that involves an integral of product of special functions[4], was affected by the natural behavior of the product of these functions which altered the stability of the results within very small values of τ (less than 0.1). However, this problem appears only for samples that have a very large characteristic time or extremely low diffusivity, i.e. samples with slow response to thermal perturbation. Our samples were evaluated for τ values greater than 0.3 and the accuracy deviations were within 2% of the reported λ values. A remarkable increase in the mean conductivity values due to moisture effect have been observed, see the last column in Table

II. This increase is more pronounced in the soft samples which can be explained as follows:

The thermal conductivity indicates the measure of the ease by which heat is transferred across the material. It depends on the density, porosity of the material and its water content. According to the thermal insulation handbook [12], the moisture has considerable effect on the conductivity of the materials, owing to the fact that liquid water has thermal conductivity which 25 times greater than that of air. However, due to the complexity related to moisture content, which associated with several factors such as mode of heat transfer (sensible and/or latent), the moisture location, arrangement of moisture in the building blocks etc. Such factors have a considerable effect on the measured heat conduction. Because of the complexity, there are no tables that can state that for a given percentage of moisture in the material there will be a certain percentage increase in its conductivity. The only certain statement which can be made is that moisture in the liquid phase will increase the conductivity, which is in exact agreement with our measurements. The insulating value of most materials is greatly reduced by the presence of free water. It is generally agreed that the durability of masonry depends primarily on its resistance to the penetration of moisture into the body of masonry. The source of this moisture may be wind-driven rains, foggy weather conditions, or relatively high outside temperature which creates high humidity.

Table II The apparent densities and the mean values of λ in dry and 40% wt moisture

The Sample	Hard bricks	Soft bricks	Soft Soil
Density (kg m^{-3})	1985	1444	0390
λ_{dry} (W m^{-1} k^{-1})	1.533	0.751	0.455
λ_{wet} (W m^{-1} k^{-1})	1.847	1.239	1.228
$\{(\lambda_{wet} - \lambda_{dry}) / \lambda_{dry}\}$ x 100	20%	65%	170%

Differences in humidity between inside and out side air will cause vapor flow within the wall (depending on the degree of porosity) and it may condense within the wall under certain temperature conditions. On the other hand when wall surface temperatures are substantially below air temperatures, condensation may occur on the wall surface. Thus, the increase of λ_{wet} is associated with decease in the density or increase in the relative porosity of the samples. Hard bricks have compact and dense structure. If the walls are pores to the extend that it will allow vapor migration, the temperature eventually will reaches its dew point, at which location it will condense. As a result water will travel on toward the low temperature side and in the worst case; it might solidify into ice if the temperature reaches the freezing point, leading to uncomfortable environment inside the buildings. According to our data, the hard bricks value has the lowest percent increase , however, the absolute mean values for all samples, in both dry and wet conditions, are relatively high. Therefore, insulation and/or vapor barriers are required for such buildings. Adding insulation on the walls will damp temperature fluctuations inside the space and provide better comfort and prevent moisture condensation within the wall and surfaces..

5 Conclusion

The HOT-DISK technique is used to investigate the effect of wetting on thermal conductivity of three locally produced building materials. The technique has main dual advantage of short measuring time and small temperature gradient to prevent thermo-migration phenomena through saturated (wet) samples. The investigated materials were used in the construction of a typical building envelope and they have similar thermal conductivity profiles with higher values for the high density samples. The hard bricks value has the lowest percent increase; however, the absolute mean values for all samples, in both dry and wet conditions, are relatively high. .

A remarkable increase in the mean conductivity values due to moisture effect have been observed, particularly, in the soft samples. The increase of λ_{wet} is associated with decease in the density or increase in the relative porosity of the samples which might lead to vapor migration through the walls. It should be noted that measurements made by laboratory test may not be truly indicative of the properties of the materials in service and aging effects on dimensional stability (ability to retain size and shape) should be anticipated. Furthermore, other factors such as the location and extreme weather conditions, proportion of glassed areas and whether the building is only cooled or heated and cooled are to be presented in future article investigating the thermal loads in such buildings.

Furthermore, that there are some constraints imposed upon using this technique, such a limited number of samples, and limiting the analysis to room temperature data. Such constraints may introduce a degree of uncertainty in the conclusion. However, there is a tendency of a good agreement between the measured thermal conductivity values and apparent densities. Furthermore, in this attempt of comparison we have applied this technique for these three samples, just to examine the ability of the technique to probe the effect of moisture on building materials and the possibilities of correlation between the densities and thermal conductivities of such materials. Further work is planned to investigate larger number of samples with wider absorbing properties.

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