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# A New Transient Method to Measure Thermal Conductivity of Asphalt


## Abstract

The modern market of testing equipment provides new alternatives in choosing the most suitable and effective method to measure thermal properties of any material. C-Therm Technologies offers a new solution with respect to measuring thermal properties of asphalt concrete materials. The C-Therm TCi Thermal Property Analyzer allows determining accurate values for thermal conductivity and thermal effusivity of asphalt concrete without extensive sample preparation or damage to the sample. This technique has clear advantages over other existing techniques, one of which is the capability to test asphalt materials in situ. Laboratory testing was done for two types of asphalt concrete samples: lightweight and normal weight. A comparison analysis with other existing test methods demonstrated the applicability of C-Therm TCi System to asphalt concretes.


## Background

Asphalt concrete is generally considered to have three main structural elements: aggregates, bitumen (binder) and the contact layer between them. In addition to these components, it is necessary to the include air and moisture which fills capillary porous spaces. Each of these elements has its effect on thermal properties of the system known as asphalt concrete. The bitumen molecules are known to consist of weak chemical bonds that change easily with temperature. This partially explains the viscoelastic behaviour of asphalt concrete pavements (Mrawira and Luca 2002).

The mechanical behaviour of asphalt concrete is highly temperature dependant. Asphalt concrete tends to expand with increasing temperature and contracts with decreasing temperature (Xu and Solaimanian 2008). It is relatively “soft” at high temperatures and susceptible to rutting under the traffic, whereas it is brittle at low temperatures resulting in thermal cracking. As a result, pavement deterioration is aggravated in countries such as Canada with wide annual temperature swings(Fig.1).

A material’s thermal properties (thermal conductivity, thermal diffusivity, heat capacity) has a significant effect on the distribution and variation of temperature in a body. Modeling the time – temperature relationship of any solid such as asphalt concrete requires thermal properties as inputs. The ability to predict the thermal properties in pavement structures has generally been a major concern in seasonal frost areas. A variety of factors can influence the thermal properties during thawing such as solar radiation, snow cover, precipitation and embankment vegetation.


**Figure 1 –** Cracks from excessive pavement contraction.

The thermal properties of asphalt materials have been studied for many years. Although the literature on measurement techniques of thermal properties of pavement materials is extensive: ASTM C177, ASTM C518, ASTM C1045; steady-state methods have obvious limitations (Tan et al. 1992, Tan et al. 1997). Traditional steady-state methods are inconvenient due to the time (usually several hours) required to obtain a measurement and their restricted size of testing samples. More advanced, transient-state methods have been proposed and tested on asphalt pavements (Kavianpour and Beck 1977, Highter and Wall 1984, Beck and Al-Araji 1974).

Various laboratory testing apparatuses exist for determining the thermal properties of solids. Usually these tests are conducted at a range of temperatures, and the temperature for each test must be controlled carefully due to the high dependency of asphalt concrete properties on temperature. Generally, it is required for the specimen to reach a stable test temperature which can be time consuming and  yield indaquate precision.

A fast, simple and accurate method of analysis for thermal properties is highly desirable. This paper presents such a method, the modified transient plane source (MTPS) technique, that is simple to use and offers real-world in-situ measurement capability in characterizing the impact of changing environmental conditions on the thermal properties of the material. Measurement of the thermal properties of asphaltic pavement in its in-situ condition is important because of the unknown effects of moisture and aging under service conditions.

## Thermal Test Methods Device Description

There is a wide variety of methods and techniques to measure thermal conductivity, each suitable for a limited range of materials, depending on the thermal properties and the temperature of the medium. Generally speaking, the testing methods for determination of thermal properties of any material can be divided into two groups: steady-state and transient-state methods. The main difference between these two methods is that steady-state requires the specimen to reach a stable test temperature. This is time consuming. Transient-state methods perform a measurement during the process of heating up or cooling down. Measurements can be done quickly. Figure 2 shows the classification of some common methods and their descriptions.

The guarded–hot plate method is probably the most common steady-state method. Obvious limitations of steady-state methods include the requirement that flat slab specimens have a thickness not exceeding one third of the length of the metered region (to ensure one-dimensional heat flow). It is very difficult to prepare a specimen with such dimensions from laboratory-compacted asphalt mix briquettes or field cores of in-situ pavements. Other disadvantages include the need to accurately measure the applied heat flux (Tan et al. 1992) and the long time required to reach the equilibrium state, especially given the low-conductivity values involved (Tan et al 1992 and Tan et al. 1997). Despite the noted disadvantages of steady-state methods for measuring thermal conductivity, quite accurate results can be obtained by testing non-homogeneous solids with moderate conductivity (Mrawira and Luca 2002).

In contrast to steady-state procedures, transient methods can determine the thermal conductivity of solid materials like asphalt concrete quicker. Other advantages include the possibility of measuring only one face of a large specimen, and the feasibility of testing in situ pavements.

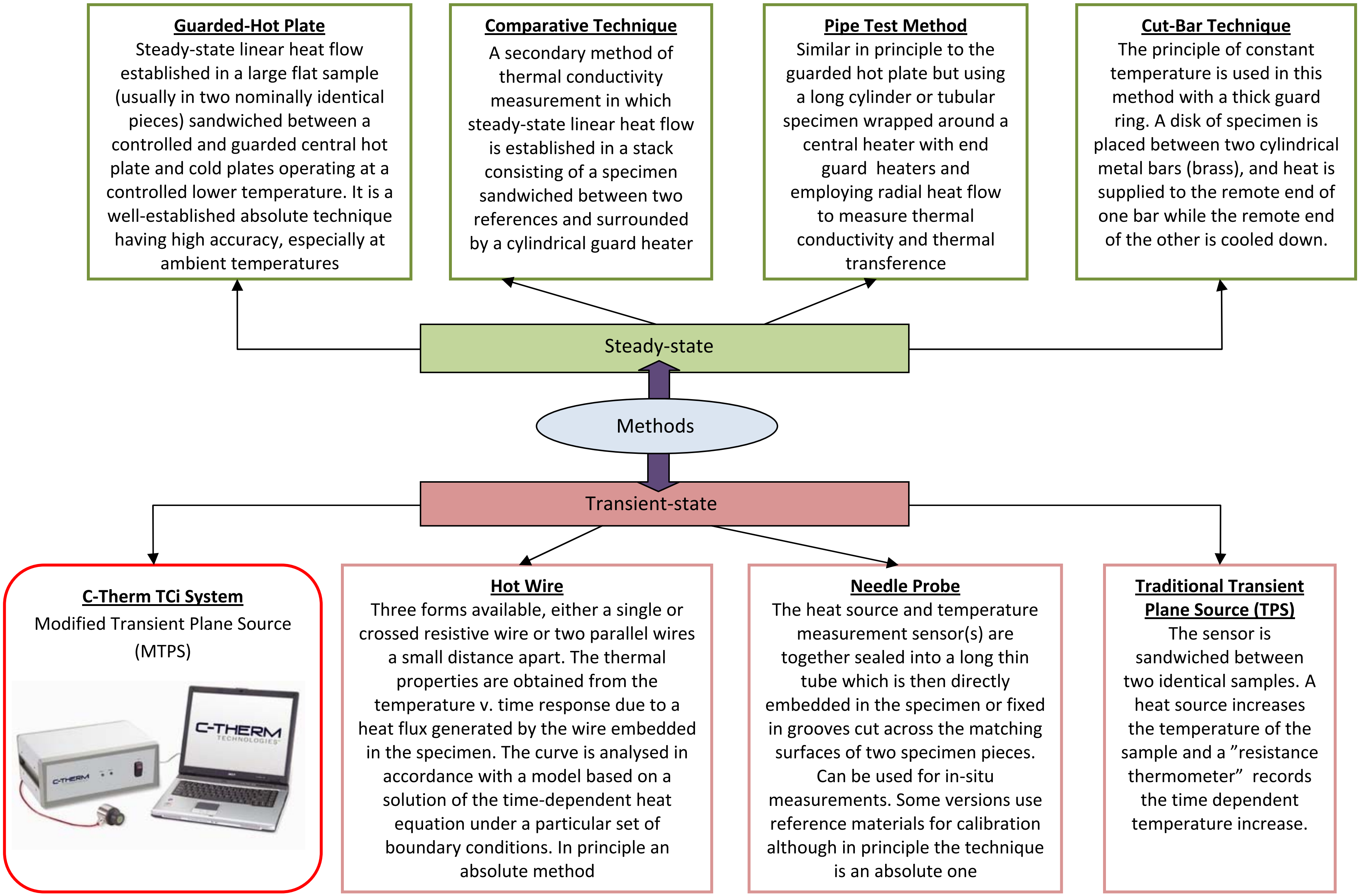



**Figure 2 –** Common methods for determining thermal conductivity of solids.

A new technique, the modified transient plane source (MTPS) technique employed by the C-Therm TCi Thermal Conductivity Analyzer, was used in this study to measure the thermal conductivity and the thermal effusivity of asphalt concrete. This highly accurate technique is based on the transient plane source (TPS) method. The primary difference between the *traditional* and *modified* transient plane source techniques is that the modified offers a single-side interface compared to the double-sided interface requirements of the traditional version.

The MTPS technique has many advantages in comparison to other available testing methods such as guarded hot plate, hot wire or hot probe. The non-invasive nature of the C-Therm TCi's MTPS sensors allows testing of materials of any size in-situ or in laboratories without destruction of the specimen. Moreover, testing can be done in seconds with consistent and accurate results.

The operational principle of the C-Therm TCi system is the following:

1. The system is comprised of a one-sided interfacial sensor, controller electronics and computer software (Fig. 3a).
2. The sensor (Fig.3b) has a central heater/sensor element in the shape of a spiral surrounded by a guard ring which generates heat in addition to the spiral heater. Thus, approximating a one-dimensional heat flow from the sensor into the material under test in contact with the sensor.
3. The voltage drop on the spiral heater is measured before and during the transient. The voltage data is then translated into the effusivity value of the tested material.
4. The conductivity is calculated from the slope of the voltage data. (For more detailed information on the TCi visit www.ctherm.com/TCi.)

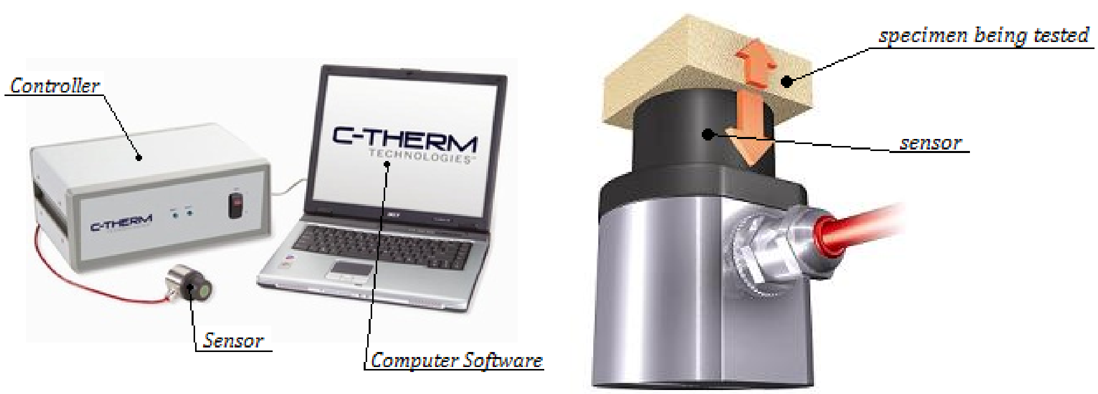



**Figure 3** – C-Therm TCi thermal conductivity analyzer: (a) C-Therm TCi system; (b) Sensor in use.

Basically, the sensor is a one-sided, interfacial heat reflectance device that applies a constant current heat source to the sample. The sample is heated by approximately 1-3°C during the testing. The sample absorbs some of the heat depending on its thermal conductivity, and the rest causes a temperature rise at the sensor interface. The rate of the increase in temperature at the sensor surface is inversely proportional to the ability of the sample to transfer heat. Thermal conductivity and effusivity are measured directly, providing a detailed overview of the thermal nature of the sample material.

## Laboratory Testing

The main purpose of this paper was to demonstrate that C-Therm TCi system is applicable to test asphalt materials and provide a comparison to other existing methods. Table 1 presents comparative qualities of the methods that were used in this study to determine thermal conductivities of the asphalt specimens.

**Table 1** – Comparison of C-Therm TCi System to other test methods.

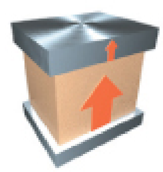
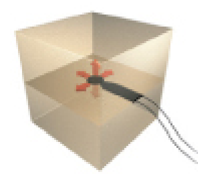
| Methods | **C-Therm TCi (Modified Transient Plane Source - MTPS)** | **Traditional Guarded Hot Plate** | **Traditional Transient Plane Source (TPS)** |
|---|---|---|---|
| | Transient-State | Steady-State | Transient-State |
| Illustration of the main measuring element |  |  |  |
| Sample preparation | Easiest of the methods described – no extensive sample preparation required. (Limited to application of a couple of drops of contact agent employed in optimizing contact with sample material.) | Extensive, sample must conform to very specific geometrical requirements. (Contact agent may be used as well in optimizing contact with sample materials.) | Some sample preparation required. Technique requires two homogeneous samples that must each be well-graded in preparing two smooth surface areas in "sandwiching" the double-sided sensor interface |
| Sample Configuration | Any shape with a minimum size of 17 mm | Two identical samples of specific sample geometry. (Actual sample size may vary: typically 150mm and 600mm sq) | Two identical samples, well-polished with a minimum size of 25x25mm |
| Testing Time | Seconds | Hours | Minutes |
| k-range | 0-100 W/m·K | 0-2 W/m·K | 0-100 W/m·K |
| Temperature Range | -50 – 200°C | -20 – 200°C | -100 – 1000°C |
| Materials Testing Capabilities | Solids, Liquids, Powders, Pastes | Solids | Solids, Liquids |

Table 1 lists the three testing methods used for determining the thermal conductivity of the asphalt concrete samples: guarded-hot plate, traditional transient plane source and C-Therm TCi system (modified transient plane source).

The guarded-hot plate device, available at the University of New Brunswick, requires the preparation of two identical specimens of the size 100x100x20 mm; thermal paste was applied on the specimens to insure a good contact with the heater.

The traditional transient plane source (TPS) tester also requires two identical samples which were ground until the contact between the specimens and the sensor is reached. Due to limitations of the traditional commercial TPS instrumentation - it is not possible to use contact agents between the sensor and the specimens in improving the contact. Therefore, greater sample preparation is necessary to obtain accurate results in preparing the surface of the samples with the TPS device.

Two types of asphalt concrete were tested: lightweight (LW) and normal weight (NW) hot mix asphalt (Fig.4). The specimens of LW asphalt concrete were tested using the guarded-hot plate and C-Therm TCi systems, whereas NW asphalt concrete specimens were tested with the transient plane source method and the newer modified transient plane source method as employed by the C-Therm TCi system.

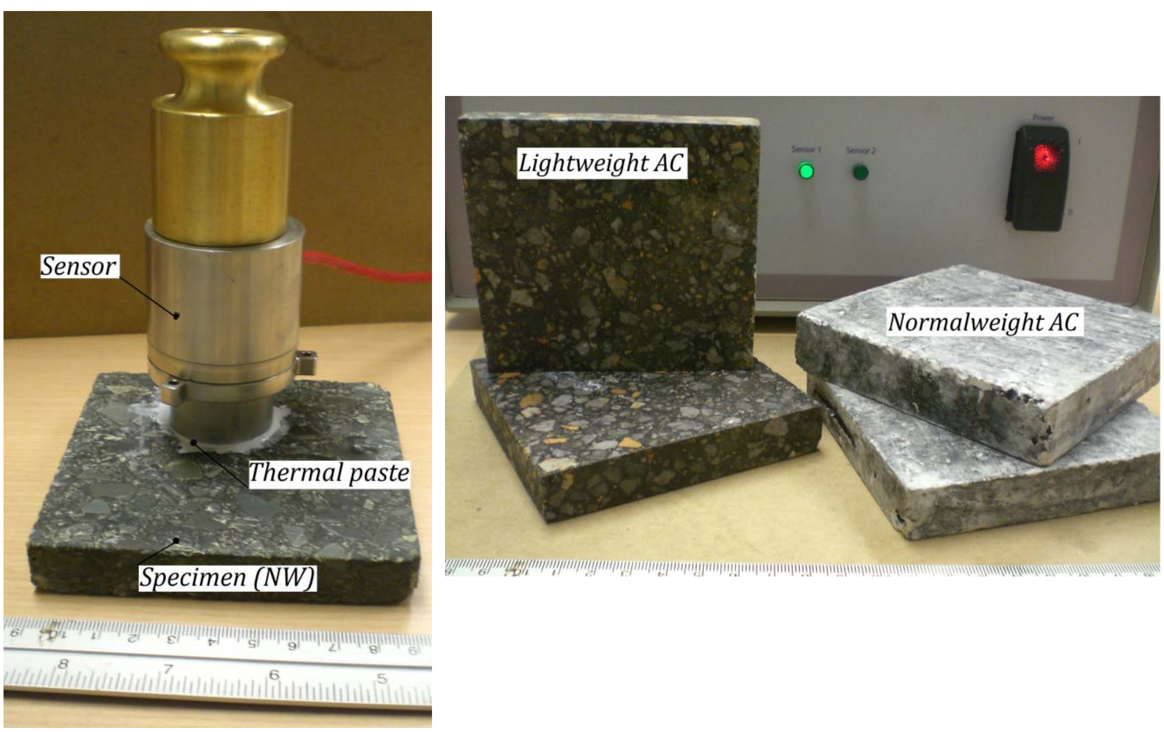



**Figure 4 –** Specimens of lightweight and normal weight asphalt concrete.

The advantage of the C-Therm TCi system's MTPS method is that the size or the shape of a specimen is not important. The measurement time is also very short. In optimizing sensor/sample contact and negating the impact of contact resistance, a thermal paste was applied to the surface of the specimen beneath the sensor in addressing surface unevenness.

## Results

The results for the thermal conductivity of LW and NW asphalt concrete obtained from three methods are presented in Table 2. The values for LW asphalt specimens using GHP method were obtained by Khan and Mrawira (2008).

**Table 2** – Test results obtained from Modified Transient Plane Source (C-Therm TCi system), Guarded Hot Plate and Transient Plane Source testing methods.

| Specimen | Bulk density, kg/m$^3$ | C-Therm TCi Modified Transient Plane Source (MTPS) | | Guarded Hot Plate (GHP) | | Traditional Transient Plane Source (TPS) | |
|---|---|---|---|---|---|---|---|
| | | k, W/m·K | RSD*, % | k, W/m·K | RSD, % | k, W/m·K | RSD**, % |
| LW1 | 1686 | 0.841 | 2.62 | 0.845 | n/a | - | - |
| LW2 | 1587 | 0.786 | 3.24 | 0.785 | n/a | - | - |
| NW1 | 2585 | 2.124 | 3.12 | - | - | 2.008 | 1.12 |
| NW2 | 2459 | 2.206 | 2.07 | - | - | 2.187 | 1.16 |

*RSD of five measurements across six different locations.
**RSD of five measurements at the same location.

The results obtained from C-Therm TCi system (MTSP) show a good correlation with values obtained using the other methods. Sample results for LW1, LW2 and NW2 provide a better than 1% agreement. Sample results for NW1 differed by approximately 6% which likely due to positional bias of where the TPS sensor was located in relation to the multiple sample locations tested with the MTPS sesnor. The traditional TPS measures the thermal conductivity at one location of both specimens at the same time in averaging the result, whereas C-Therm TCi's MTPS technique determines thermal conductivity at any location of one specimen at a time. Because the specimen of asphalt mix is not uniform, thermal conductivity varies across the specimen. The Relative Standard Deviation (RSD) of the MTPS technique results are thus indicative of the sample's heterogeneity as measurements were taken in six different locations per sample in offering additional insight as to the sample's material properties. In testing more homogeneous samples , the RSD drops dramatically, even when measuring at multiple locations. The precision of the MTPS technique is better than 1%.

## Conclusions

Three methods to determine thermal conductivity of asphalt concrete were compared. The C-Therm TCi System, using a modified transient plane source method, is suitable and offers some significant advantages for measuring thermal conductivity of asphalt materials due to its versatility, speed and accuracy.

The values of thermal conductivity for lightweight asphalt concrete obtained using C-Therm TCi System agree well with those obtained from the guarded-hot plate tester, presently considered to be the most accurate testing method. The normal weight asphalt specimens were also tested using a traditional Transient Plane Source method and the results were compared to the data obtained from C-Therm TCi System. The thermal conductivity varies for different locations of the specimen due to the heterogeneity of asphalt concrete but still agreed well with the TPS system.

The C-Therm TCi System was shown to be applicable for asphalt concrete materials and presents some significant advantage over other traditional techniques in offering faster test times, more versatile sample configurations/interface and minimal sample preparation requirements. It additionally offers the potential to be configured as an easily transportable system with the unique ability for in situ testing.

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