ON THE ASSESSMENT OF THE THERMAL CONDUCTIVITY OF GRANULAR MATERIALS

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ABSTRACT
This paper presents the results of a comprehensive laboratory study on the thermal conductivity of dense and broadly graded coarse granular materials used in pavement base-course layers. Materials were selected from 8 quarries along the axis of St-Lawrence River to include a variety of samples of different geological origins. Nearly 200 tests were performed in a thermal conductivity cell using Pyrex heat flux meters to characterise the relationships between the thermal conductivity of unfrozen and frozen samples and the water/ice content and the effect of mineralogy on the thermal conductivity of solid particles of each of the selected quarries. An improved model using the geometric mean method to compute the thermal conductivity for the solid particles and for the saturated materials, a modified form of the geometric mean method to predict the thermal the thermal conductivity of dry materials and its porosity, and empirical relationships to assess the relative thermal conductivity of unfrozen and frozen granular materials is presented.

RÉSUMÉ
Cet article présente les résultats d'une étude en laboratoire sur la conductivité thermique des matériaux granulaires denses à granulométries étalées utilisés en fondations routières. Les matériaux ont été sélectionnés dans 8 carrières sur l'axe du fleuve St-Laurent pour inclure une variété d'échantillon de différentes origines minéralogiques. Près de 160 essais ont été menés dans une cellule de conductivité thermique utilisant des fluxmètres thermiques en Pyrex afin de caractériser la relation entre la conductivité thermique d'échantillons non gelés et gelés et la teneur en eau/glace ainsi que l'effet de la minéralogie sur la conductivité thermique des particules solides de chaque carrière. On propose un modèle amélioré utilisant la méthode de la moyenne géométrique pour prédire la conductivité thermique des matériaux saturés, une forme modifiée de la méthode de la moyenne géométrique pour prédire la conductivité thermique des matériaux secs et des relations empiriques pour déterminer la relation en la conductivité thermique relative des matériaux non gelés et gelés.

1. INTRODUCTION

Heat transfer and frost action analyses in pavements require the knowledge of the thermal properties of each layer of the pavement structure including materials or subgrade soils. Among the various thermal properties, the thermal conductivity is one of the most important input parameter in heat transfer modelling. It is well known that the thermal conductivity of a soil is strongly influenced by its density and water content owing to contrasting values of its basic components. For instance, the thermal conductivity of solid particles generally varies from 1 to 5 W/m°C, while that of water, ice and air are respectively equal to 0.6 W/m°C, 2.24 W/m°C and 0.024 W/m°C. Moreover, several other factors such as grain mineralogy and fabric need also to be considered.

In the last decades, many studies were conducted to quantify the effects of these factors on the thermal conductivity, k, of soils. Theoretical models were developed for the calculation of the thermal conductivity of dry soils (Smith 1942) and moist soils (Mickley 1951; DeVries 1963). Empirical models were also developed to fit experimental data for unfrozen and frozen moist soils (Kersten 1949; Van Rooyen and Winterkorn 1959; Johansen 1975).

As pointed out by Côté and Konrad (2003), mass transfer characteristics of granular materials typical in pavement base-course and sub-base layers were not systematically studied in the past. Unfortunately, the same applies to heat transfer characteristics of these granular materials. Thus, there is a lack of experimental data to develop reliable empirical models for the prediction of thermal conductivity of coarse-grained soils. These materials are broadly graded with typical grain sizes ranging from 0 to 20 mm and are compacted to dry densities ranging from 1800 up to 2350 kg/m³. The fabric of soils, which refers to as the size and the arrangement of particles as well as the pore space distribution (Mitchell 1993), has an undisputable influence on the thermal conductivity of soils (Kersten, 1949, Van Rooyen and Winterkorn 1957, Johansen 1975, Farouki 1981, Mitchel 1993). It is thus expected that prediction of the thermal conductivity of compacted coarse grained materials should be different from the well documented sands and fine grained soils.

The objectives of this paper are to characterise the thermal conductivity of dense granular materials and to develop a new empirical model adapted to these materials. The paper presents first the experimental setup for the measurement of thermal conductivity using Pyrex heat flux meters developed for the purpose of this study. Experimental results of measurements for unfrozen and frozen granular materials are reported. A new empirical model using the concept of relative thermal conductivity is subsequently proposed for the prediction of thermal conductivity of these materials. The new model is tested with a set of data from Kersten (1949) for crushed rocks similar to the materials used in this study. Finally, the paper describes a step by step methodology for the assessment of thermal conductivity of coarse granular materials.

2. EXPERIMENTAL PROGRAM

2.1 Experimental setup

Figure 1 shows the experimental setup used in this study. It comprises a thermal conductivity cell surrounded by an insulated and temperature controlled box that is placed inside a large cold room maintained at a constant temperature of about 4°C below the average temperature used in the test cell. Granular materials are compacted into a cylindrical PVC mould with an inside diameter and height of 101.6 mm and 75 mm, respectively. The sample and the mould are placed between two Pyrex disks of 101.6 mm in diameter and of 30 mm high. Each Pyrex disk is instrumented with two thermistors embedded in the center, at a few tenths of millimetres from the each faces. The temperatures at the top and bottom of this three layer system are maintained constant with two independent heat exchangers (Figure 1) in order to create a vertical heat flow through both the sample and the Pyrex disks. The sample and the Pyrex disks are tightly surrounded with a 50 mm thick polystyrene jacket in order to reduce radial heat losses. The ambient temperature of the insulated box is maintained equal to the mean value of the temperatures applied at both extremities of the Pyrex disks.

The heat flux in the thermal conductivity cell is measured through the Pyrex disks (Corning® Pyrex 7740) as the thermal conductivity of this standardized borosilicate glass is known (Powell et al. 1966) and as temperature is measured at each end of both Pyrex disks. The thermal conductivity of the Pyrex 7740 varies little with temperature, at -20°C, the thermal conductivity is 1.015 W/m°C, while it is 1,09 W/m°C at 20°C and it can be assessed from the relationship given by Powell et al. (1966).

The temperatures of the top and bottom of each Pyrex heat flux meters are recorded every fifteen minutes through an acquisition system and plotted as a function of time. When temperatures become constant with time, steady state heat flow is reached. The thermal gradients in the Pyrex disks are readily determined knowing the distance between the center of each thermistor for both disks and the temperature measurements. The thermal gradient in the sample is determined from the Pyrex/sample interface temperatures which are extrapolated from the thermistors measurements in both Pyrex disks. The thermal conductivity of the tested sample is approximated as:

$$k = \frac{q_{uf} + q_{lf}}{2} \frac{\Delta h}{\Delta T} = \frac{\left(k_{uf} \frac{\Delta T_{uf}}{\Delta h_{uf}} + k_{lf} \frac{\Delta T_{lf}}{\Delta h_{lf}} \right) \times \frac{\Delta h}{\Delta T}}{2} \quad [1]$$

where k is the thermal conductivity (W/m°C), q is the heat flux (W/m²), the subscripts $_{uf}$ and $_{lf}$ refer to the upper heat flux meter and the lower heat flux meter, respectively, Δh is the distance between two temperature measurements (m) and ΔT is the temperature difference (°C).

2.2 Materials tested

The main focus of this study was to establish reliable data of thermal conductivity of unfrozen and frozen granular materials that are used in pavements as base and sub-base courses and to develop a thermal conductivity model adapted for these materials. These materials are referred to as MG-20 and MG-112, respectively in the specifications of the Ministry of Transportations of Quebec (MTQ). The grain size distribution of MG-20 is shown in Figure 2 by the dark shaded area limited by the full lines while that of MG-112 is represented by the diagonal hatches and dotted lines. The materials studied herein had a maximum grain size of 20 mm.

The materials were selected from 8 different quarries along the axis of St-Lawrence River to include a variety of samples with different geological origins in order to characterise the influence of mineralogy on thermal conductivity. The materials studied were all crushed rocks : a) a basalt from St-Joseph-de-Beauce which is located about 50 km south of Quebec City; b) a dolostone from St-Eustache at about 15 km north-west of Montreal; c) a granite A from Quebec City (Valcartier), d) another granite B from Quebec City (Lac-St-Charles); e) a limestone from St-Marc-des-Carrières at about 50 km west of Quebec City; f) a quartzite from Rimouski; g) a sandstone from St-Anaclet which is 20 km east of Rimouski; and finally, h) a syenite from Mont-St-Hilaire located at about 60 km east of Montreal. The characteristics of each material tested herein are given in table 1.

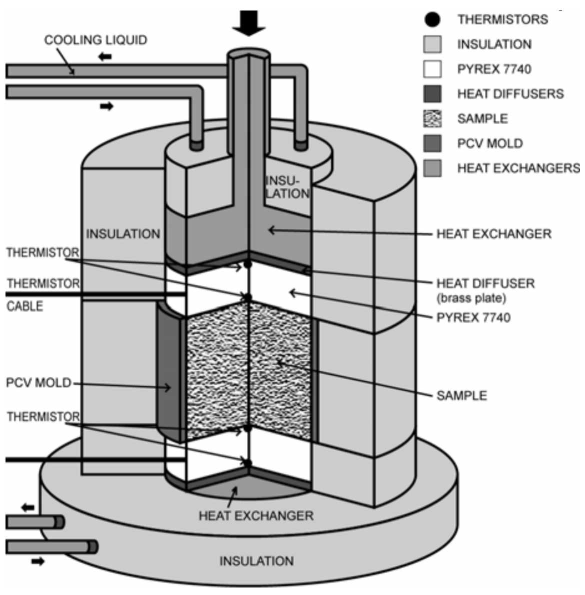

Figure 1. Thermal conductivity cell.

Table 1. Mass-volume properties of the materials tested and testing program.

Material	Location	ρ_s [kg/m³]	ρ_d [kg/m³]	n	range of w [%]	number of tests unfrozen	number of tests frozen	number of tests rock cylinders
Basalt	St-Joseph-de-Bauce	2950	2231	0.244	0.27 – 7.91	4	4	2
			2274	0.229	0.12 – 4.88	4	4	
Dolostone	St-Eusatche	2850	2405	0.156	0.04 – 5.66	4	4	2
GraniteA	Valcartier	2750	2104	0.235	0.17 – 4.84	4	4	2
			2191	0.203	0.16 – 4.73	4	4	
			2265	0.176	0.16 – 2.98	3	3	
			2051	0.254	0.16 – 4.73	4	4	
			1921	0.301	0.02 – 7.65	6	6	
			1834	0.333	0.09 – 7.66	6	6	
			2204	0.199	0.12 – 5.90	7	7	
			2261	0.178	0.12 – 5.37	6	6	
GraniteB	Lac-St-Charles	2650	1854	0.300	0.00 – 8.80	4	4	2
Limestone	St-Marc-des-Carrières	2670	2313	0.134	0.10 – 5.40	6	6	2
			2320	0.131	0.13 – 5.60	4	4	
Quartzite	Rimouski	2650	2263	0.146	0.41 – 5.43	4	4	2
			1904	0.282	0.01	1	1	
			1706	0.356	0.08	1	1	
			1545	0.417	0.11	1	1	
Sandstone	St-Anaclet	2670	2276	0.148	0.15 – 5.70	4	4	2
			1886	0.294	0.03	1	1	
			1720	0.347	0.00	1	1	
Syenite	Mont-St-Hilaire	2730	2323	0.149	0.12 – 5.49	4	4	2
			2254	0.175	0.46	1	1	
			2004	0.266	0.14	1	1	
			1792	0.344	0.06	1	1	
					Total number of tests :	190		

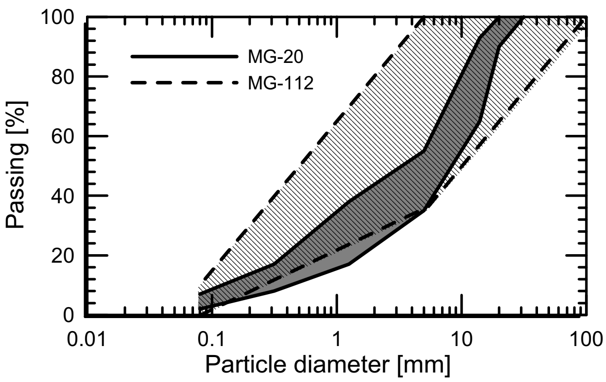

Figure 2. Grain size distribution for base and sub-base materials.

3. EXPERIMENTAL RESULTS

3.1 Thermal conductivity of solid particles, k_s

The thermal conductivity of each rock cylinder, presented in table 3, is the mean of two measurements made at a mean temperature of about 5°C and -5 °C. Typical variations of less than 5% were observed between the values obtained at both temperatures. The thermal conductivity of solid rock varied from 1.6 W/m°C for the syenite sample to 5.0 W/m°C for the quartzite sample. Intermediate values of 2.2, 2.3, 2.6, 3.3 and 3.4 W/m°C were obtained for basalt, limestone, granite A and B, dolostone and sandstone, respectively. Results are grouped in table 2.

3.2 Thermal conductivity of compacted granular materials

The bulk results of the thermal conductivity measurements are shown as a function of water content by weight in Figure 3 for unfrozen compacted granular materials and as a function of ice content by weight in Figure 4 for the frozen state. As anticipated, the thermal conductivity has a general tendency to increase with water content as water/ice is a much better heat conductor than air. This is schematically shown by the dotted trend lines. For example, at water contents of 0.4, 1.3, 3.8 and 5.4%, the quartzite sample displayed thermal conductivities of 1.67, 2.25, 3.26 and 3.56 W/m°C respectively in the unfrozen state and values of 1.67, 2.23, 3.35 and 4.32 W/m°C in the frozen state. These data also reveal that at water contents higher than 2% the thermal conductivity of the materials in the frozen state is higher than that for the unfrozen state, which is consistent with the fact that ice has a thermal conductivity almost four times higher than water.

Results also show that materials with solid particles having high thermal conductivity (table 2) display higher bulk thermal conductivity as it is the case for the quartzite materials. This study also revealed that for a constant value of k_s (graniteA materials) the highest thermal conductivities were obtained for the lower porosities, which is consistent with data from the literature.

4. DEVELOPMENT OF AN IMPROVED MODEL FOR GRANULAR MATERIALS

Farouki (1981, 1982) evaluated many theoretical and empirical models for the computation of thermal conductivity of soils. In general, the model proposed by Johansen (1975) for fine grained soils and sands gave the bests results in the widest range of soils and degree of saturation. This model is based on the relative thermal conductivity concept which is expressed as:

$$k_r = \frac{k - k_{dry}}{k_{sat} - k_{dry}} \qquad [2]$$

where k_r is the relative thermal conductivity, k is the actual thermal conductivity, k_{sat} and k_{dry} are the thermal conductivity for saturated and dry soils. Empirical equations between k_r and S_r should satisfy both conditions of eq [3]:

$$\begin{aligned} S_r = 0 \;&:\; k = k_{dry} \;\Rightarrow\; k_r = 0 \\ S_r = 1 \;&:\; k = k_{sat} \;\Rightarrow\; k_r = 1 \end{aligned} \qquad [3]$$

Improvements to Johansen's model are thus proposed in order to adapt it to dense and broadly graded granular materials. An existing method for the determination of the thermal conductivity of saturated soils and solid particles that considers the complete mineralogy is reviewed. A new relationship between k_{dry} and n is proposed. Also, mathematical equations that relate k_r to S_r which fully satisfy the conditions given by eq. [3] are developed for unfrozen and frozen granular materials.

Table 2. Thermal conductivity of solids particles for the materials tested.

Materials	k_s (W/m°C)
Basalt	2.2
Dolostone	3.3
Granite A	2.6
Granite B	2.6
Limestone	2.3
Quartzite	5.0
Sandstone	3.4
Syenite	1.6

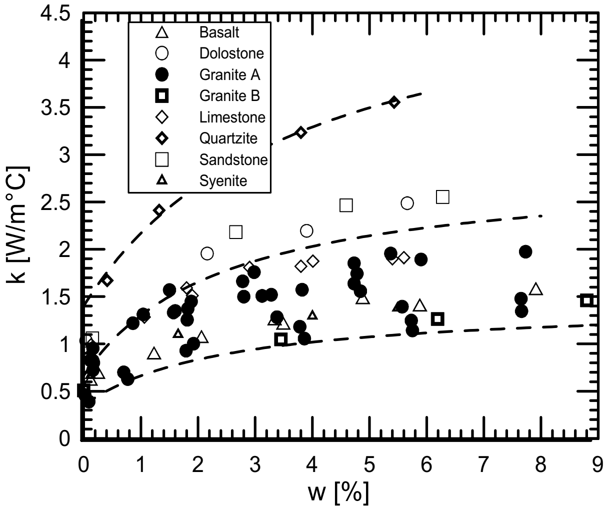

Figure 3. Thermal conductivity for unfrozen granular materials as a function of water content.

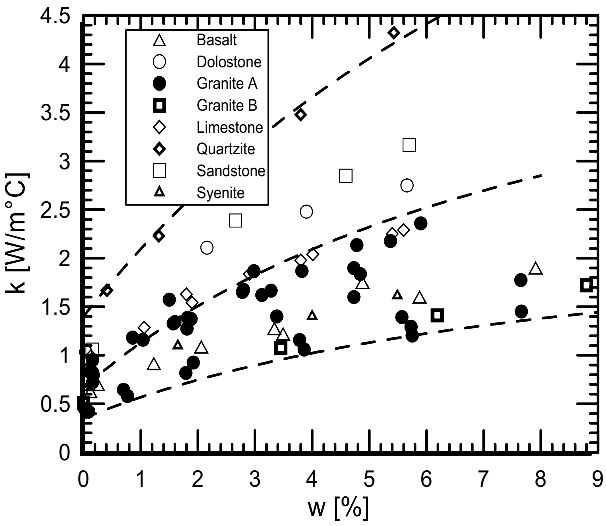

Figure 4. Thermal conductivity for frozen granular materials as a function of water content.

4.1 Thermal conductivity of saturated materials

To compute the thermal conductivity of the saturated soil, Johansen (1975) proposed to use the well accepted method of the geometric mean given in eq. [4]. It is noted that this equation gives satisfying results when the ratio of the thermal conductivity of the solid particles and the water (or the ice) is lower than 10.

$$k_{sat(u)} = k_s^{1-n_u} \times k_w^{n_u} \quad T \geq 0°C$$
$$k_{sat(f)} = k_s^{1-n_f} \times k_i^{n_f} \quad T < 0°C \qquad [4]$$

where k_s, k_w and k_i are thermal conductivity of the solid particles, the water (0.6 W/m°C) and the ice (2.24 W/m°C) respectively, n_u and n_f are the porosity of unfrozen and frozen soil. Both can be computed using:

$$n_f \approx n_u = n = 1 - \rho_d / \rho_s \qquad [5]$$

where ρ_d is the dry density and ρ_s, the density of solid particles (kg/m³).

The thermal conductivity of solid particles can be obtained from various sources as many authors have provided average values (Andersland and Anderson 1978, Birch and Clark 1940, Goguel 1975, Johnston 1981, Jumikis 1977, Missenard 1965 and Sass et al. 1971). It can also be computed from the mineralogical composition using a generalised form of the geometric mean method and the values for various minerals as measured by Horai (1971).

$$k_s = \prod_{j=1}^{z} k_{mj}^{x_j} \rightarrow \text{with} \sum_{j=1}^{z} x_j = 1 \qquad [6]$$

where the symbol Π represent the product of the thermal conductivity of the minerals k_m raised to the power of their volumetric proportion x, the sum of the volumetric proportion of the minerals is equal to 1. Eq. [6] gives the best results when the thermal conductivity of each mineral does not contrast by more than one order of magnitude.

4.2 Thermal conductivity of dry materials, k_{dry}

Thermal conductivity measurements were made on samples dried in the oven at a temperature of 105 °C for 24 hours. Since most of the samples still contained small amounts of water (0% < S_r < 2.3%), the thermal conductivity at dry state was extrapolated from the k – S_r relationships for each sample as indicated in Figure 5 by the left hand arrow. The theoretical value of thermal conductivity at the saturated state (eq. [4]) was also used to improve curve fitting.

The k_{dry} values are shown in Figure 6 where four distinct relationships are obtained; one for the quartzite materials (k_s = 5.0 W/m°C), one for the sandstone and the dolostone materials (k_s = 3.4 and 3.3 W/m°C), one for the basalt, the limestone, the granite A and the granite B (k_s = 2.2 to 2.6 W/m°C) and one for the syenite materials (k_s = 1.6 W/m°C). The fairly good correlations obtained between k_{dry} values and n confirm the high sensitivity of thermal conductivity of dry materials to variations in porosity observed by Smith (1942) and Johansen (1975).

From the four general correlations obtained in Figure 6, it can also be concluded that mineralogical composition plays an important role on the thermal conductivity of dry crushed rock. For example, at a porosity of 0.15, the thermal conductivity of dry syenite (k_s = 1.6 W/m°C) is equal to 0.64 W/m°C, that of dry sandstone (k_s = 3.4 W/m°C) is equal to 1.1 W/m°C and that of quartzite (k_s = 5.0 W/m°C) is equal to 1.4 W/m°C). However, this effect tends to decrease with increasing porosity, and values of thermal conductivity seem to converge for porosity of about 0.4. It is noted that Smith (1942) and Johansen (1975) did not observe significant mineralogical effects on the thermal conductivity of dry crushed rocks and fragmented soils with porosities ranging from 0.3 to 0.7.

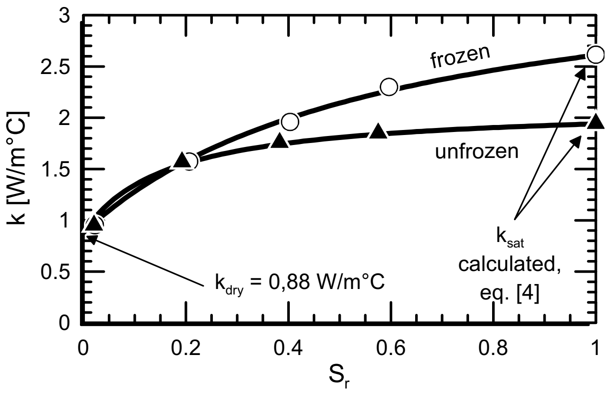

Figure 5. Determination of k_{dry}.

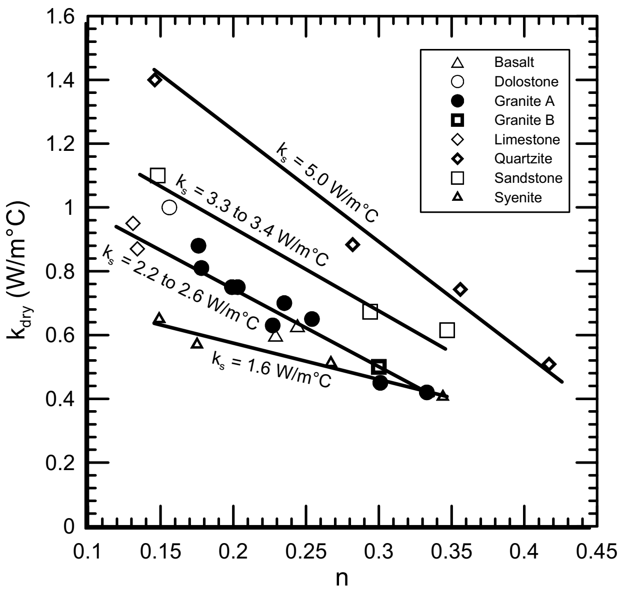

Figure 6. k_{dry} – n relationships.

The thermal conductivity of dry crushed rocks can be obtained using a modified form of the geometric mean method was thus developed as expressed by eq. [7] where α and β were set to 0.59 and 0.73 to fit experimental data:

$$k_{dry} = k_s^{\left((1-n)^{\alpha}\right)} \times k_a^{\left(n^{\beta}\right)} \qquad [7]$$

This modified form of the geometric mean method is consistent with physical limits of thermal conductivity for material combination as it will lead to the thermal conductivity of solid particles (k_s) for porosity equal to 0 and to the thermal conductivity of air (k_a) for porosity equal to 1. Calculated values of k_{dry} using eq. [7] for the materials of this study are generally within ± 20 % of error compared to measured values.

4.3 Relative thermal conductivity k_r

The relative thermal conductivity (eq. [2]) was computed for each sample using the thermal conductivities in the saturated state derived from eq. [4] and in the dry state as extrapolated from the k – S_r relationships. The results are presented in Figure 7 for the unfrozen state and in Figure 8 for the frozen state. Similar to Johansen (1975), the relative thermal conductivity can be related to the degree of saturation to obtain single relationships for the frozen state and for the unfrozen state. Simple mathematical equations that satisfy the conditions of eq. [3] are proposed to express the relative thermal conductivity of unfrozen granular materials, eq. [8], and frozen materials, eq. [9], as functions of the degree of saturation. It is noted that these equations fit most of the experimental data within a range of relative thermal conductivity of ± 0.1 as outlined by the thinner lines in Figure 7 and 8.

$$k_{ru} = \frac{4.7 S_{ru}}{1 + 3.7 S_{ru}} \qquad [8]$$

$$k_{rf} = \frac{1.8 S_{rf}}{1 + 0.8 S_{rf}} \qquad [9]$$

where S_{ru} and S_{rf} are the degree of saturation of unfrozen and frozen soils which can be computed as:

$$S_{rf} \approx S_{ru} = S_r = \frac{w \rho_d}{n \rho_w} \qquad [10]$$

4.4 Evaluation of the model

More than 150 experimental data measured by Kersten (1949) were compared to values computed using the proposed model. These data were obtained for gravels: Chena River gravel (32 test results), and coarse sands: Fairbanks sand (34 tests results), crushed quartz (34 test results), crushed feldspar (24 test results), crushed trap rock (16 test results) and crushed granite (18 test results). The proportion of grains over 2 mm in size was equal to 85% for the Chena River gravel and ranged from 15 to 30% for the coarse sands compared to proportions

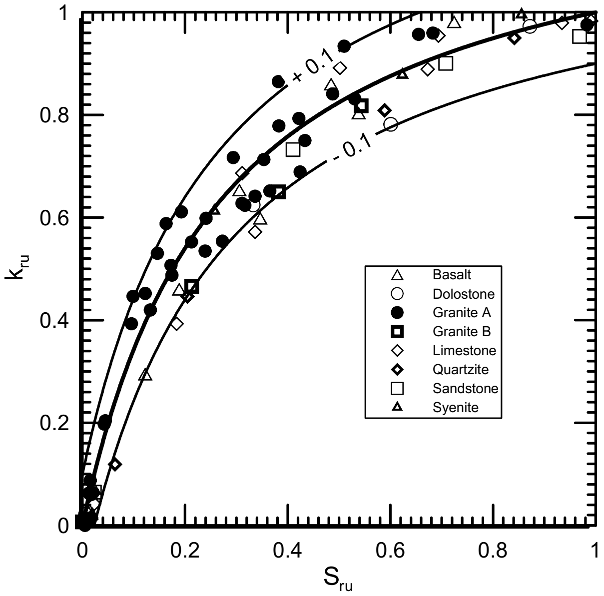

Figure 7. Relative thermal conductivity of unfrozen granular materials.

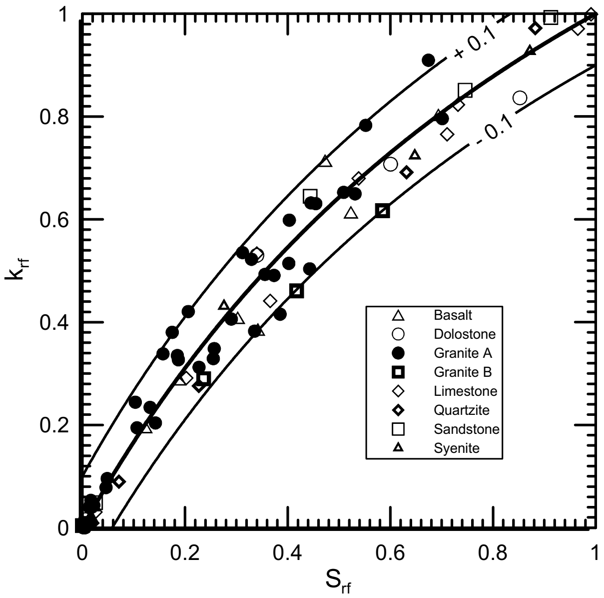

Figure 8. Relative thermal conductivity of frozen granular materials.

between 20 to 75% for the materials studied herein. The samples were tested in the unfrozen and the frozen states at the compaction water content only, resulting in nearly 80 different samples with porosity ranging from 0.21 to 0.45 with degrees of saturation from 0 to 70%. No tests were made to determine the thermal conductivity of the solid particles but complete mineralogical compositions were established, making it possible to estimate the k_s

values using eq. [6] and the thermal conductivities of minerals from Horai (1971).

Comparative results of computed thermal conductivity using the proposed model with the experimental data from this study and from Kersten (1949) are shown in Figure 9 and Figure 10 for unfrozen and frozen state, respectively. The parameters $k_{sat(u)(f)}$, k_{dry} and k_{ru} and k_{rf} were computed using eqs [4], [7], [8] and [9] respectively.

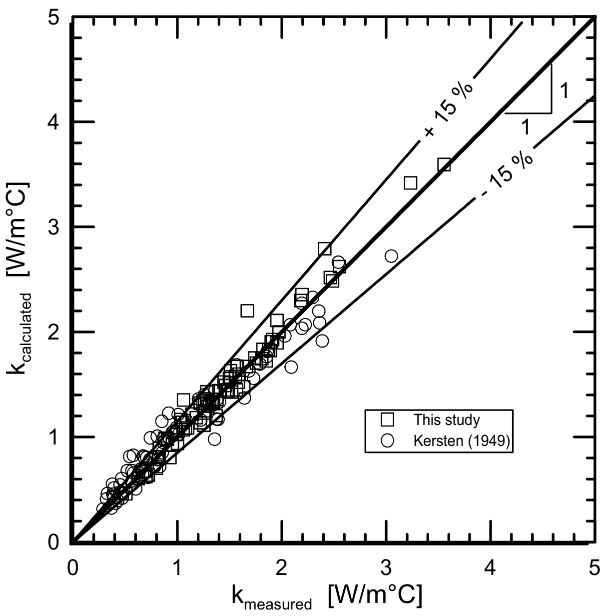

Figure 9. Predicted thermal conductivity of unfrozen granular materials using the proposed model.

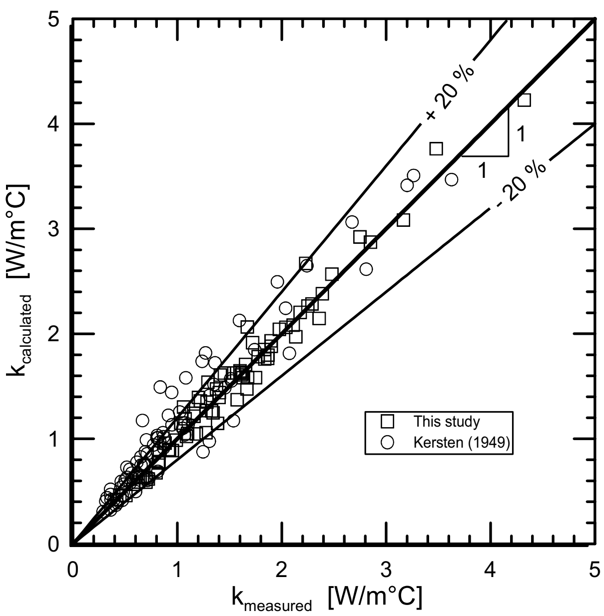

Figure10.Predicted thermal conductivity of frozengranular materials using the proposed model.

As anticipated, the improved model accurately predicts the thermal conductivity for the materials of this study with differences from the experimental data less than 10% for the unfrozen state and less than 15% for the frozen state. The model also provided fairly good predictions for Kersten's coarse sands and gravels with errors generally less than 15% for the unfrozen and generally less than 20%. These larger but acceptable differences from an engineering point of view probably reflect the differences in fabric between Kersten's materials and the ones studied here.

5. ASSESSMENT OF THE THERMAL CONDUCTIVITY OF GRANULAR MATERIALS

The thermal conductivity of granular materials can be assessed with the relationships developed in this paper using eq. [1] rewritten as:

$$k = (k_{sat} - k_{dry}) \times k_r + k_{dry} \quad [11]$$

The thermal conductivity at the saturated state k_{sat} is computed using the well accepted geometric mean method as given by eq. [4]. The thermal conductivity of the solid particles k_s can obtained from average values as found in Andersland and Anderson (1978), Birch and Clark (1940), Goguel (1975), Johnston (1981), Jumikis (1977), Missenard (1965) and Sass et al. (1971) or it can be computed using eq. [6] together with the values for different minerals as measured by Horai (1971). The thermal conductivity at dry state can be assessed using eq. [7] which is a modified form of the geometric mean method with fitting parameters α and β being equal to 0.59 and 0.73 for the materials tested in this paper. The relative thermal conductivity k_r can be computed using eqs [8] and [9].

Figure 11 schematically summarises the thermal conductivity model.

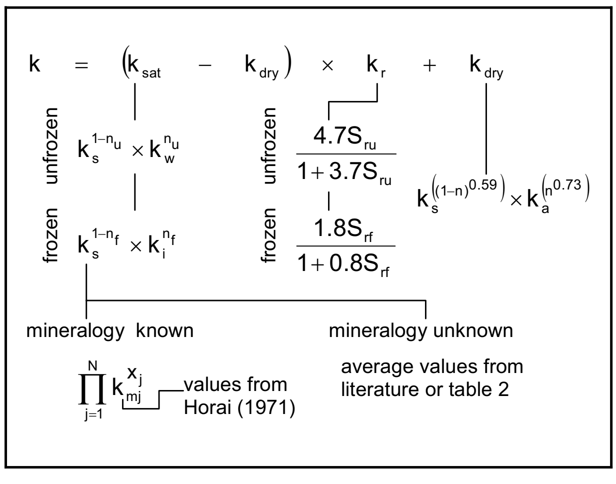

Figure 11. Method for the assessment of the thermal conductivity of granular materials.

6. CONCLUSION

A comprehensive laboratory study of the thermal conductivity of dense and broadly graded granular materials was conducted on materials selected from 8 quarries along the axis of St-Lawrence River. Nearly 200 tests on unfrozen and frozen compacted granular samples and solid rock cylinders were performed in a thermal conductivity cell using Pyrex heat flux meters. As anticipated, the experimental results indicated that the thermal conductivity is strongly influenced by water content, porosity of the samples and mineralogy of the solid particles of the materials.

A model is proposed for the prediction of the thermal conductivity of granular materials.

The model developed in this study relies on:

1. the porosity, the degree of saturation and the mineralogy of granular materials;
2. the geometric mean model for the computation of the thermal conductivity of solid particles and for the saturated granular materials in the unfrozen and frozen states;
3. a modified form of the geometric mean model for the computation of the thermal conductivity of dry granular materials which respect the physical limits of thermal conductivity for the full range of porosity ($n = 0 : k_{dry} = k_s$ and $n = 1 : k_{dry} = k_a$) ;
4. two simple relationships between the relative thermal conductivity and the degree of saturation for granular materials in the unfrozen and the frozen states.

The new model was put to the test with more than 150 data available from Kersten (1949) for gravels and coarse sands. The predicted values generally agreed with the measured ones within errors less than 15% for unfrozen materials and less than 20% for frozen samples.

7. ACKNOWLEDGEMENTS

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