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Thermal Conductivity of Mineral Wool Materials Partially Saturated by Water[1]

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The thermal conductivity of several types of mineral wool-based materials, namely, materials with hydrophobic admixtures, hydrophilic admixtures, and without any admixtures are measured as a function of moisture content from the dry state to the partially water saturated state. An impulse technique is employed for the measurements using both surface and needle probes. The data are analyzed using the Bruggeman effective media concept for different shapes of inclusions and Wiener's basic formulas. It is found that for most materials, the experimental data for thermal conductivity in the range of low moisture content are close to the lower Wiener's bound but in the range of higher moisture content the data are close to the upper Wiener's bound.

KEY WORDS: Bruggeman effective media concept; mineral wool; moisture content; thermal conductivity; Wiener's bounds.

1. INTRODUCTION

Thermal properties of mineral wool-based materials appear to be of particular importance for their practical applications because the majority of them are used in the form of thermal insulation boards. Every catalog list of any material producer of mineral wool contains thermal conductivity, sometimes also specific heat capacity, but they normally give only single characteristic values. The dependence of the thermal conductivity of common mineral wool on temperature, which is required, for instance, for

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pipe insulations, was reported in Refs. 1–4. The dependence of the thermal conductivity of mineral wool boards on moisture content was presented in Ref. 5. The effect of natural convection on heat transfer in mineral wool was studied in Ref. 6, and the radiative behavior of mineral wool was studied in Refs. 7 and 8. Theoretical considerations on combined heat transfer in mineral wool were published in Refs. 9 and 10.

Many mineral wool products are provided with hydrophobic substances because the presence of water in the material is undesirable for the majority of applications. The main argument for hydrophobization is that the presence of water in mineral wool increases its thermal conductivity several times, which leads to the loss of thermal insulation properties. Hydrophilic additives are seldom used in mineral wool products. However, this kind of material has good potential for application, for instance, in interior thermal insulation systems.

The different treatment of mineral wool fibers in both cases mentioned above leads to different conditions for the appearance of water in the material. Hydrophobization leads to repulsion of liquid water from the fibers, which is expected to result in the appearance of water drops in the porous system. On the other hand, hydrophilic admixtures bond water molecules on the fiber surface so that the presence of liquid water in the porous space is limited. Therefore, the dependence of thermal properties on moisture content will probably be different for materials with hydrophobic and hydrophilic admixtures and the knowledge gained from the behavior of one type of material cannot be interchanged with the other.

In this paper, the dependence of the thermal conductivity on moisture content is studied for several types of mineral wool-based materials, namely, materials with hydrophobic admixtures, hydrophilic admixtures, and without any admixtures. The primary aim of this study is a better understanding of the effect of water location in the porous system on thermal properties of the studied materials. Therefore, the experimental data are analyzed using a homogenization technique.

2. EXPERIMENTAL METHODS

The thermal conductivity as the main parameter of heat transport was determined using the commercial device ISOMET 104 (Applied Precision, Ltd.). ISOMET 104 is a multifunctional instrument for measuring the thermal conductivity, thermal diffusivity, and volumetric heat capacity. It is equipped with various types of optional probes; needle probes are for porous, fibrous, or soft materials, and surface probes are suitable for hard materials. The measurement is based on the analysis of the temperature response of the analyzed material to heat flow impulses. The heat

flow is induced by electrical heating using a resistor heater having direct thermal contact with the surface of the sample. The measurements in this paper were done as a function of moisture content; both needle and surface probes were applied for the sake of comparison. Within the moistening process, the samples were put in contact with a damp sponge for different time intervals. The higher moisture content in the samples was reached by immersion of the samples into distilled water. The moisture content was determined by a gravimetric method.

3. HOMOGENIZATION TECHNIQUES

The determination of the moisture-dependent thermal conductivity was carried out using homogenization techniques as well. In terms of homogenization, a porous material can be considered as a mixture of three phases, namely, solid, liquid, and gaseous phases. For materials on the basis of the mineral wool studied in this work, the solid phase is represented by basalt fibers, the liquid phase by water, and the gaseous phase by air. For the case of the dry material, only the solid and gaseous phases are considered. The volumetric fraction of air in the porous body is given by the measured total open porosity. For the case of penetration of water, part of the porous space is filled with water. For the evaluation of the thermal conductivity of the whole material, the thermal conductivities of the particular constituents forming the porous body must be known. The values of the thermal conductivity of basalt, water, and air used in this paper were taken from the CRC Handbook of Chemistry and Physics [11].

In this work, three Bruggeman-type homogenization formulas [12] were employed. The first of them, the original one, was proposed for spherical inclusions, the second assumes acicular orientation of inclusions, and the third was derived for their board orientation. The applied mixing formulas are described, respectively, as

$$\lambda_{\text{eff}} = \lambda_{\text{M}} + \sum f_{\text{j}}(\lambda_{\text{j}} - \lambda_{\text{M}}) \frac{3\lambda_{\text{eff}}}{2\lambda_{\text{eff}} + \lambda_{\text{j}}}, \tag{1}$$

$$\lambda_{\text{eff}} = \lambda_{\text{M}} + \sum f_{\text{j}}(\lambda_{\text{j}} - \lambda_{\text{M}}) \frac{5\lambda_{\text{eff}} + \lambda_{\text{j}}}{3\lambda_{\text{eff}} + 3\lambda_{\text{j}}}, \tag{2}$$

$$\lambda_{\text{eff}} = \lambda_{\text{M}} + \sum f_{\text{j}}(\lambda_{\text{j}} - \lambda_{\text{M}}) \frac{2\lambda_{\text{j}} + \lambda_{\text{eff}}}{3\lambda_{\text{j}}}, \tag{3}$$

where λ_{eff} is the thermal conductivity of the studied material, λ_{M} is the thermal conductivity of the solid phase (basalt, $3.0\,\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)), f_{j} is the

volumetric fraction of air or water, and λ_j is the thermal conductivity of air ($0.026\,W{\cdot}m^{-1}{\cdot}K^{-1}$) or water ($0.6\,W{\cdot}m^{-1}{\cdot}K^{-1}$).

At first, the mixing formulas were applied for the evaluation of the thermal conductivity of dry materials. After that, the thermal conductivity of particular materials was assessed as a function of moisture content.

For the verification of obtained results, Wiener's lower and upper bounds [13] were used which are given in the following relations, respectively:

$$\lambda_{\text{eff}} = \frac{1}{\frac{f_1}{\lambda_1} + \frac{f_2}{\lambda_2} + \frac{f_3}{\lambda_3}}, \tag{4}$$

$$\lambda_{\text{eff}} = f_1\lambda_1 + f_2\lambda_2 + f_3\lambda_3, \tag{5}$$

where λ_{eff} is the thermal conductivity of the studied material, f_1–f_3 are the volumetric fractions of the particular constituents of the porous body, and λ_1–λ_3 are the thermal conductivities of the constituents.

4. MATERIALS AND SAMPLES

Mineral wool materials, analyzed in this paper, were produced specifically for testing purposes by Rockwool CZ, Inc. Basic characteristics of the mineral wool materials concerning the type of admixture and bulk density are given in Table I. All materials had fibers parallel to the board surface.

The specimens were cut from the material boards delivered by the producer. The size of the specimens for the determination of thermal conductivity was $50\,mm \times 50\,mm \times 20$ to 50 mm. This specimen's size was chosen with reference to the measuring method and applied sensors. Five specimens of each particular material were used for each measurement.

Table I. Basic Characteristics of Mineral Wool Materials

Material	Type of admixture	Total open porosity (%)	Bulk density ($kg{\cdot}m^{-3}$)
CNL	Hydrophobic	88	270
CNR	Hydrophobic	87	110
TCR	No admixture	91	90
STR	No admixture	94	120
INH	Hydrophilic	93	210
INS	Hydrophilic	96	90

A part of the specimens was partially saturated by water. They were left under water for a specified time, then water and vapor-proof insulated by a plastic foil, and after that, water was allowed to distribute uniformly in the specimens for 1 week.

5. RESULTS AND DISCUSSION

The results of thermal conductivity measurements using both needle and surface probes are summarized in Figs. 1 and 2. The thermal conductivity of dry materials and materials with a moisture content within the hygroscopic range was practically dependent on only the bulk density. Materials with a bulk density of approximately $100\,\mathrm{kg\cdot m^{-3}}$ achieved λ values of about $0.04\,\mathrm{W\cdot m^{-1}\cdot K^{-1}}$, and those with a bulk density above $200\,\mathrm{kg\cdot m^{-3}}$ had values a little higher, around $0.05\,\mathrm{W\cdot m^{-1}\cdot K^{-1}}$. This is in good agreement with reference data (see e.g., Ref. 1). In the hygroscopic moisture range ($w < 0.01$), the data obtained by both needle and surface probes differed only within the error range of the measuring method.

The thermal conductivity data obtained for specimens with a moisture content in the overhygroscopic range exhibited much higher differences between the particular materials and particular probes.

For the hydrophilic materials denoted by the producer as INH and INS (see Table I), the differences between data obtained by needle and surface probes showed systematic differences. The surface probe always gave higher λ values. For an explanation of this behavior it is necessary

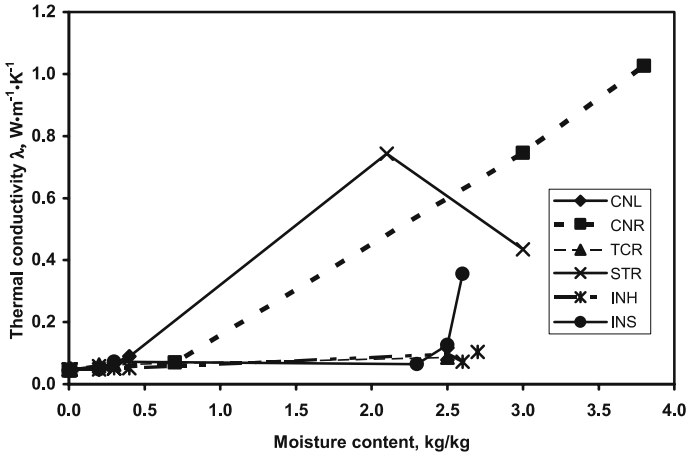

Fig. 1. Dependence of experimentally determined thermal conductivity of mineral wool materials on moisture content in the direction along the fibers, i.e., using the needle probe.

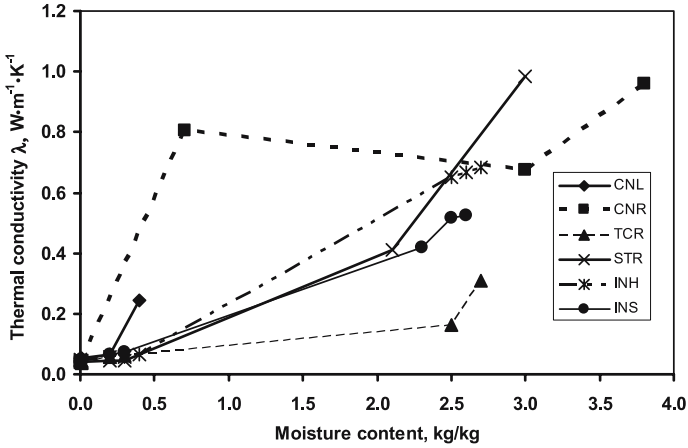

Fig. 2. Dependence of experimentally determined thermal conductivity of mineral wool materials on moisture content in the direction perpendicular to the fibers, i.e., using the surface probe.

to take into account that the surface probe measures the thermal conductivity in the direction perpendicular to the fibers while the needle probe in the direction along the fibers. For the hydrophilic mineral wool materials, water is localized on the surface of the fibers. Therefore, a surface probe can achieve contact with the material over its whole surface. On the other hand, a needle probe crosses the fibers and some parts of the probe are still in contact with the remaining air in the material. Thus, the character of differences in data obtained by both type of probes seems to be logical. It should be noted in this respect that for a thermal insulation material, the thermal properties in the direction across the board that are commonly applied for determination of the thermal resistance of the board are of greater importance than its properties along the board that could only be utilized in two-dimensional (2-D) calculations. Therefore, in standard building-physics related calculations, the data obtained using the surface probe are to be used.

Looking at the results from a quantitative point of view, for the material INH the surface-probe λ values for the highest moisture content are slightly higher and for INS slightly lower than the thermal conductivity of water ($0.60\,W{\cdot}m^{-1}{\cdot}K^{-1}$ at 20°C, see Ref. 11). This again seems to be a logical result. The higher bulk density material INH contains a higher amount of fibers per unit volume, and it can be assumed that most of the voids are full of water. So, the final thermal conductivity should be somewhere between the thermal conductivity of water and

basalt ($3.0\,W\cdot m^{-1}\cdot K^{-1}$, see Ref. 11). The lighter material INS containing a smaller amount of fibers per unit volume certainly retained more air voids than INH even in the layer close to the material surface. These voids then resulted in lower measured λ values.

The thermal conductivity data of hydrophobic materials and materials without any admixtures in the overhygroscopic range exhibited differences that appeared random. The results obtained with the surface probe were sometimes higher, sometimes lower than those with the needle probe. In some cases, the λ values even decreased with increasing moisture content (for instance, the material denoted by the producer as CNR, see Table I). This corresponds to the presumed character of the water distribution in this type of materials. The hydrophobization prevents water from direct contact with fibers, and even the mineral fibers without any surface treatment have a very low wettability. Therefore, water in the material is presented mostly in the form of droplets that can be distributed in a random way.

In a quantitative sense the worse contact of water with fibers has led, for hydrophobic materials and materials without any admixtures in some cases, to an increase of the thermal conductivity (CNR and STR, see Table I) to about $1.0\,W\cdot m^{-1}\cdot K^{-1}$. This was possibly due to the effect of the higher thermal conductivity of basalt. On the other hand, the thermal conductivity of TCR and CNL (see Table I) was lower, down to about $0.30\,W\cdot m^{-1}\cdot K^{-1}$. This was presumably due to the effect of the remaining air in the voids.

The thermal conductivity vs. moisture content relationships calculated using three Bruggeman-type mixing formulas and two Wiener's formulas are presented for each studied material and for both needle and surface probes in Figs. 3–14, where w [m^3/m^3] is the volumetric moisture content.

Looking at the results from the point of view of Wiener's bounds, we could see that the measured data for the materials CNL, TCR, INH and INS met them well, but the data for CNR and STR were out of these bounds for substantial parts of the $\lambda(w)$ functions. This basically confirms the assumptions on the consequences of water location in the particular types of materials given above. However, the bulk density of mineral wool materials appeared to be also an important parameter because CNR and STR had lower bulk densities than CNL and TCR which contained the same type of fiber treatment. The most probable reason for this finding was that higher-density materials had a more rigid structure and the presence of water did not lead to substantial deformation while for the lower-density materials with hydrophobic admixtures and without admixtures the dimensions of the specimens changed significantly after penetration of a higher amount of water.

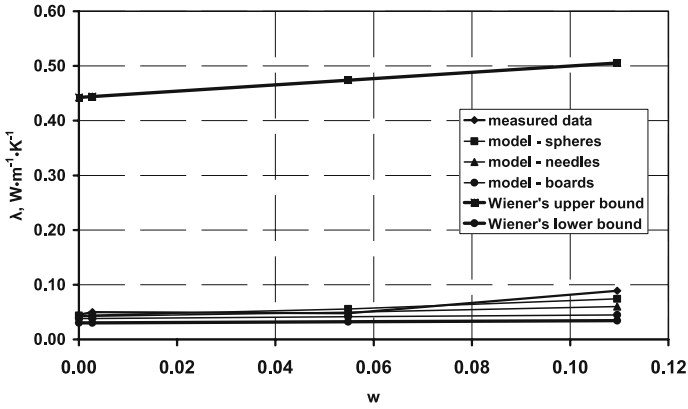

Fig. 3. Dependence of thermal conductivity of CNL on moisture content measured by the needle probe and calculated by mixing formulas.

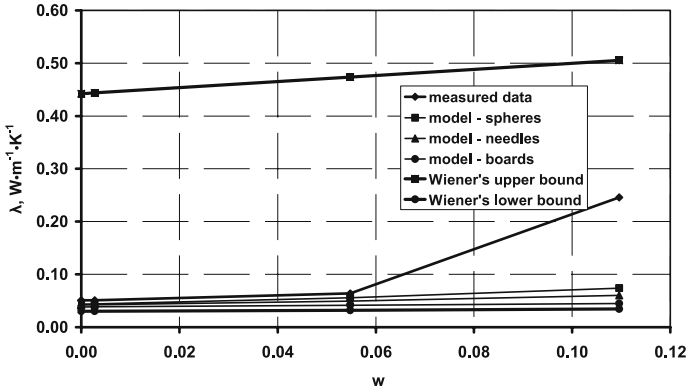

Fig. 4. Dependence of thermal conductivity of CNL on moisture content measured by the surface probe and calculated by mixing formulas.

The analysis of the results from the point of view of the effect of moisture content on the agreement between the experimental and calculated data showed that the experimental and calculated values of thermal conductivity of all investigated materials in a dry state corresponded well for both sensors and all three Bruggeman-type formulas. The observed differences between the particular models were very small, especially taking into account the measuring error of the employed device which could be estimated as $\pm 10\%$. The experimental results determined by the needle probe were also very close to the lower Wiener bound. The same good

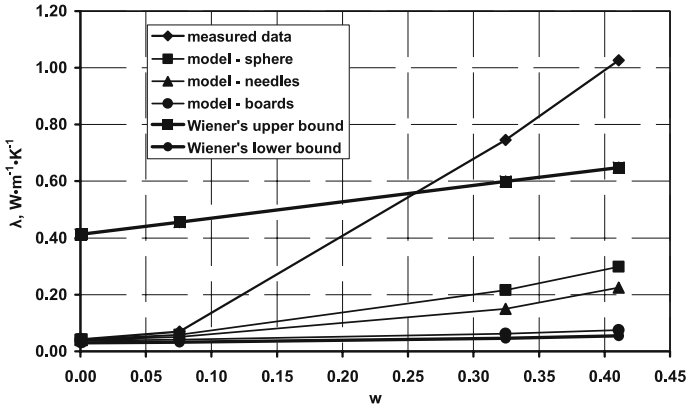

Fig. 5. Dependence of thermal conductivity of CNR on moisture content measured by the needle probe and calculated by mixing formulas.

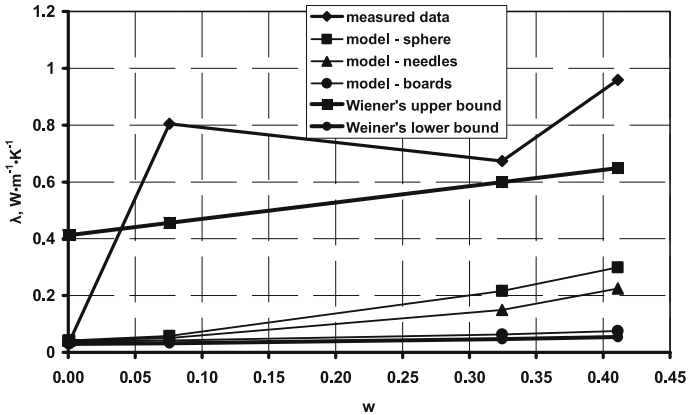

Fig. 6. Dependence of thermal conductivity of CNR on moisture content measured by the surface probe and calculated by mixing formulas.

agreement was also obtained for a lower content of water in the materials, typically up to $0.05\,m^3/m^3$.

On the other hand, the agreement between experimental and calculated thermal conductivities determined for a high moisture content differed significantly for different types of materials and different probes. For the hydrophilic materials INH and INS the data obtained by needle probes were close to the lower Wiener's bound and the data measured by the surface probe were close to the upper Wiener's bound. This was in qualitative agreement with the presumed effect of water localized on the

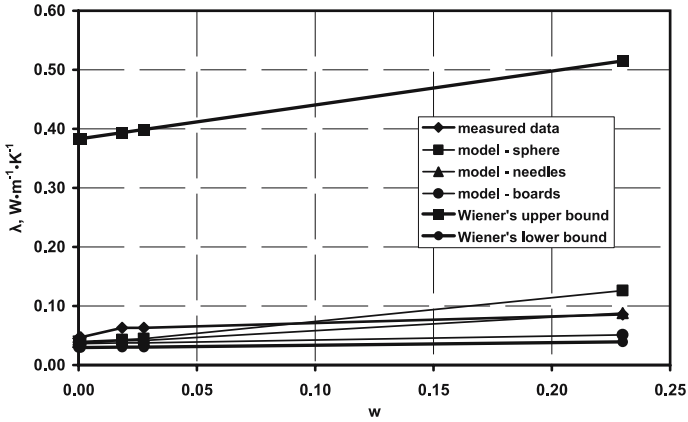

Fig. 7. Dependence of thermal conductivity of TCR on moisture content measured by the needle probe and calculated by mixing formulas.

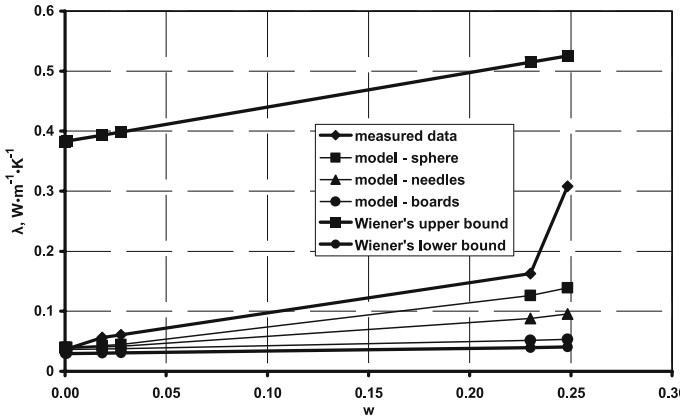

Fig. 8. Dependence of thermal conductivity of TCR on moisture content measured by surface probe and calculated by mixing formulas.

fiber surface in this type of material. For the dense hydrophobic material CNL and for the material TCR without any admixture, all data were close to the lower Wiener's bound which was clearly due to the lower volume fractions of water. The lower density hydrophobic material CNR and the material STR without any admixtures generally followed the trend observed for INH and INS, but the thermal conductivities exceeded the upper Wiener's bound as was analyzed before.

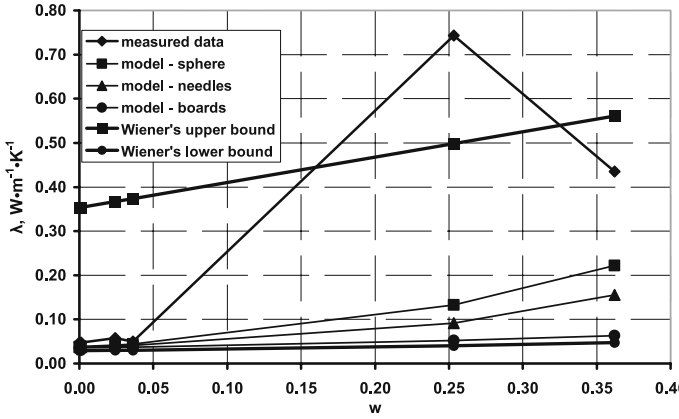

Fig. 9. Dependence of thermal conductivity of STR on moisture content measured by the needle probe and calculated by mixing formulas.

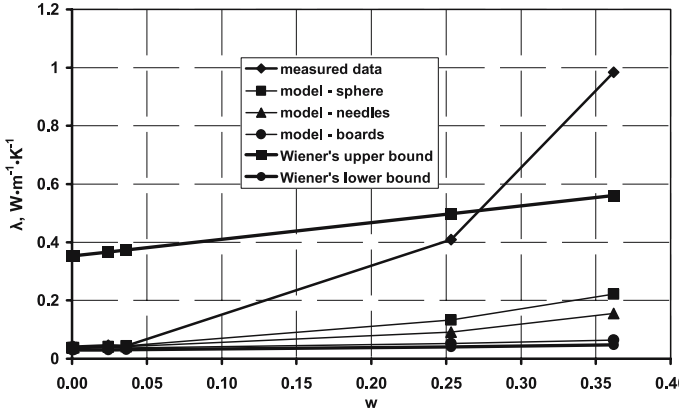

Fig. 10. Dependence of thermal conductivity of STR on moisture content measured by the surface probe and calculated by mixing formulas.

6. CONCLUSIONS

The results of measurements and calculations of the thermal conductivity of six different types of mineral wool materials over a wide range of moisture content in this paper have shown that the application of homogenization techniques can provide useful estimates of measured data even for some of these highly inhomogeneous materials, particularly those with hydrophilic admixtures. However, a unified formula could not be found for the whole range of moisture content studied. For most materials, the

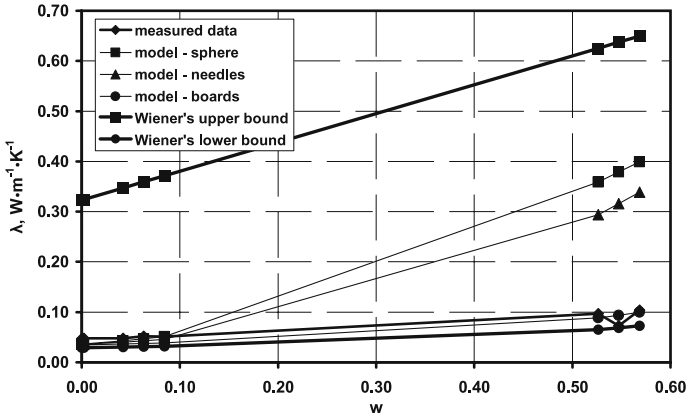

Fig. 11. Dependence of thermal conductivity of INH on moisture content measured by the needle probe and calculated by mixing formulas.

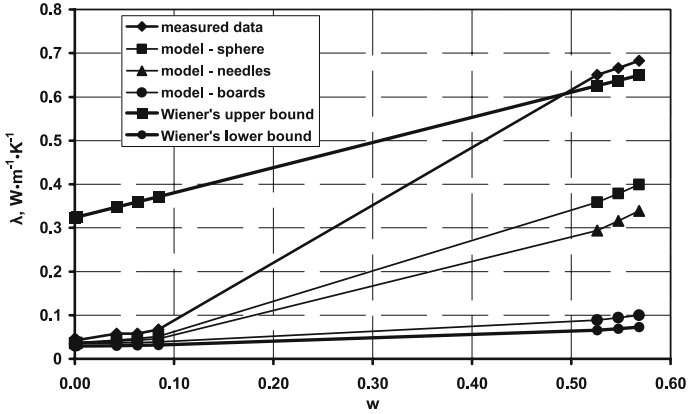

Fig. 12. Dependence of thermal conductivity of INH on moisture content measured by the surface probe and calculated by mixing formulas.

experimental data for thermal conductivity in the range of low moisture content were close to the lower Wiener's bound but in the range of high moisture content close to water saturation the data were close to the upper Wiener's bound. The use of Bruggeman-type formulas, which proved useful in a variety of previous applications, was not a successful solution in our case, and there is an open question if utilization of more sophisticated mixing formulas would lead to better results. Another question is the suitability of the impulse method for measurement of the thermal conductivity of hydrophobic mineral wool materials since some of the data exceeded

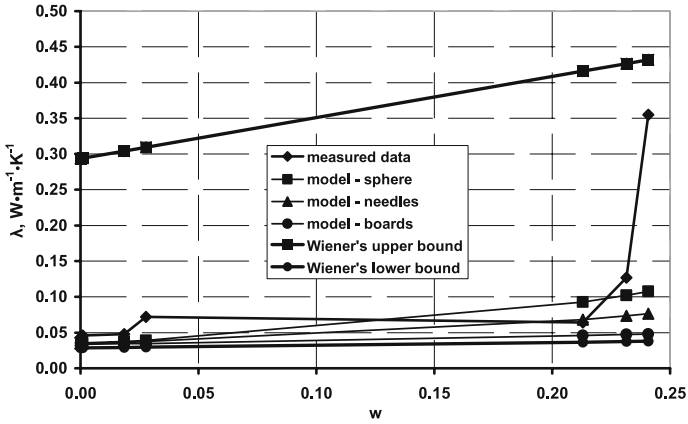

Fig. 13. Dependence of thermal conductivity of INS on moisture content measured by the needle probe and calculated by mixing formulas.

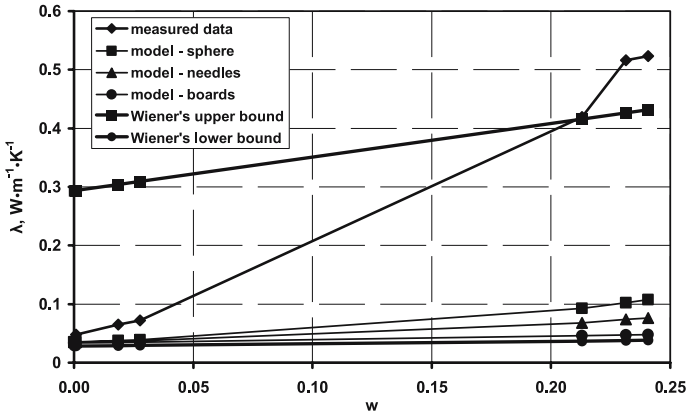

Fig. 14. Dependence of thermal conductivity of INS on moisture measured by the surface probe and calculated by mixing formulas.

Wiener's upper bound. Perhaps, the standard guarded hot-plate method could be a more successful choice in this case despite the possible problems with water redistribution due to temperature gradients.

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