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THERMAL CONDUCTIVITY OF GYPSUM PLASTERBOARDS

At ambient temperature and exposed to fire

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INTRODUCTION

One of the more complicated thermal properties to calculate for gypsum plasterboard is the thermal conductivity. The thermal conductivity is important because it plays an important role in the fire behaviour of gypsum plasterboards. Plasterboard often protects steel structures of buildings, because it conducts heat slowly and absorbs the heat of the fire by its volumetric enthalpy. This paper will focus on the first role.

The thermal conductivity becomes more complicated for porous media, which consist of different phases. Kaviany (1995) points out that the heat conduction through fully saturated matrix depends on the structure of the matrix and the thermal conductivity of each phase. The same principle applies for any heterogeneous material. One of the most difficult aspects of the analysis of heat conduction through a porous medium is the structural modelling. The thermal conductivity of the solid phase is generally larger then that of the fluid, the manner in which the solid is interconnected influences the conduction. Plasterboard consists of a solid phase and water/air mix in the voids. The thermal conductivity of the voids depends strongly on the amount of moisture (absorbed water) in the voids, since the thermal conductivity of water is 23 times the thermal conductivity of air.

This article will try to solve this problem partly by assuming that gypsum plasterboards can be assumed to be a three-phase system consisting of two different two-phase systems. This concept is applied to various types of gypsum/limestone plasterboards. The models are validated by comparing the results of the models with experiments. Based on these results and models conclusions are drawn in regard to the amount of absorbed water.

Finally the concept of thermal conductivity is applied on gypsum plasterboards under fire.

1 TWO-PHASE SYSTEMS

This section will focus on the description of thermal conductivity for two phase systems (fluid-solid). For these systems, several equations have been suggested during the last two centuries. Côte and Konrad (2008) point out that heat conduction through a two-phase porous media depends on the thermal conductivity as well as the structure of the solid matrix. In terms of thermal behaviour, the structure of the solid matrix determines the contact resistance and the continuity of the solid phase (Kaviany, 1995). Hamilton and Crosser (1962) showed theoretically that the thermal conductivity of particle packings decrease with increasing sphericity of particles. This effect was also noticed by Johansen (1975) and Côté and Konrad (2005) in air-saturated geomaterials where the thermal conductivity of natural particle packing (rounded/sub-rounded particles) were systematically lower than those of crushed particle packings (angular/sub-angular particles). A possible reason for this effect could be found in the smaller contact areas among the spherical particles compared to the more angular particles. Since the amount of contact area is related to the possible amount of solid-solid conductivity, which is always more than solid-fluid conductivity.

Within this article two equations are used, which take into account the structure of the solid. The first equation was introduced by Hadley (1986). This equation uses a so called mixture factor, which depends on the sphericity of the particles and the ratio of the thermal conductivity of the different phases. Another possibility is to describe the thermal conductivity with method of Zehner and Schlünder (1972). Zehner and Schlünder take into account the shape of the particles and therefore their surface connectivity. For the description of the form of the particle the factor C is used. These values are for particles which can be freely move in/through the matrix. In the case of a gypsum core there are a high number of so-called solid-phase bridges. This higher connectivity leads to a higher conductivity compared to a system with the same void fraction but with lower connectivity. For such systems with high number of solid-phase bridges, a C-value of 5 is proposed (Zehner and Schlünder, 1970).

2 THEORY VERSUS EXPERIMENTAL DATA

This section describes the experimental data on thermal conductivity of gypsum plasterboards found in literature, which are used to compare with the results of the theoretical equations. This experimental data is often found together with a description of the apparent density and chemical composition. Both these parameters are important in order to predict the thermal conductivity of plasterboards. The density is important because it is closely related to the void fraction of plasterboards. As can be seen in the previous section, the void fraction is one of the main parameters for the calculation of the thermal conductivity. The chemical composition of gypsum plasterboards influences the thermal conductivity of the solid phase within the board.

Table 1 shows values which are presented in literature. The experimental data is compared with the equations of the previous section. For this comparison the thermal conductivity of the solid needs to be known. Since the solid phase of gypsum plasterboards consist of several phases, the thermal conductivity of the solid phases has to be calculated. There are different calculation methods available for thermal conductivity of the composite solid.

Table 1. Experimental values of gypsum plasterboards as describes in literature

Source	**Apparent density** ρ_e [kg/m^3]	**Composition** % $m_{C\bar{S}H_2}$ [kg/kg]	% $\mathrm{m}_{\mathrm{C\bar{C}}}$ [kg/kg]	% $\mathrm{m}_{\mathrm{M\bar{C}}}$ [kg/kg]	**$\mathbf{k}_{\mathbf{meas}}$** [W/(m K)]
Wullschlager (2008)	810	81	9.5		0.28
Ang and Wang (2004)	836.4				
Grazi Wakali (2007)	810	81	9.5		0.28
Mehaffey (1994) 1	732				0.25
Mehaffey (1994) 2	648				0.24
Clancy (2001)					0.18
Sultan (1996)	698				0.25
Thomas (2002)					0.25
Ghazi Wakali (2008) 1	735	80.9	12.3		0.28
Ghazi Wakali (2008) 2	840	62.2	32.3		0.30
Ghazi Wakali (2008) 3	740	76.5	4.2	4.7	0.23
Ghazi Wakali (2008) 4	870	98			0.32

The geometric mean (eq. (1)) is a type of average, which indicates the central tendency or typical value of a set of numbers, and is often used for exponential data. As it is the most realistic model, it is used for the calculation of the solid thermal conductivity. Côté and

Konrad (2005) recommend this geometric method for the calculation of the thermal conductivity of dry soil. The method uses the volume-based composition. This equation reads;

$$k_s = \prod k_i^{\delta_i}, \qquad (1)$$

with k_i is the thermal conductivity of i^{th} phase and δ_i the volume fraction of i^{th} solid phase. Table 4 shows the results of the thermal conductivity of the solid phase based on eq. (1), the chemical composition from Table 1 and properties from Table 2.

Table 2. Thermal conductivities and specific density

Substance	**Thermal conductivity** [W/(m K)]	**Specific density** [kg/m^3]
$CaSO_4 \cdot 2H_2O$	1.255	2310
$CaCO_3$	3.58	2720
$MgCO_3$	5.83	2990
H_2O	0.60	1000
Air (dry)	0.026	1.3

Table 3. The solid thermal conductivity for the solid phase only based on the geometric method and the solid composition

	Solid thermal conductivity [W/(m K)]
Wullschlager (2008)	1.38
Mehaffey (1994) 1	1.26
Mehaffey (1994) 2	1.26
Sultan (1996)	1.26
Grazi Wakali (2008) 1	1.42
Grazi Wakali (2008) 2	1.72
Grazi Wakali (2008) 3	1.40
Grazi Wakali (2008) 4	1.26

Next, the two-phase conductivities are computed based on the expressions from Section 1 and the calculated solid thermal conductivities from Table 3. The results of these computations are presented in Table 4.

Table 4. Results of different theoretical equations for the dry thermal conductivity

	k_{meas}	**Zehner and Schlünder (1972)**
Wullschlager (2008)	0.28	0.171
Wullschlager (2008)	0.28	0.165
Wullschlager (2008)	0.28	0.167
Mehaffey (1994) 1	0.25	0.145
Mehaffey (1994) 2	0.24	0.126
Sultan (1996)	0.25	0.137
Grazi Wakali et al (2008) 1	0.28	0.152
Grazi Wakali et al (2008) 1	0.28	0.146
Grazi Wakali et al (2008) 1	0.28	0.149
Grazi Wakali et al (2008) 2	0.30	0.189
Grazi Wakali et al (2008) 2	0.30	0.175
Grazi Wakali et al (2008) 2	0.30	0.181
Grazi Wakali et al (2008) 3	0.23	0.154
Grazi Wakali et al (2008) 3	0.23	0.147
Grazi Wakali et al (2008) 3	0.23	0.149
Grazi Wakali et al (2008) 4	0.32	0.181

The best results were obtained with Zehner and Schlünder with C = 5 [1]. The obtained value from the equation of Zehner and Schlünder (1972) are too low compared to the results obtained from experiments. This could be the result of the current assumption that the voids

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[1] A comparison of more equations and the experimental data can be found in De Korte and Brouwers (2009).

are filled with dry air, while in reality the fluid in the voids is usually moistured. Building materials, like gypsum plasterboards, are porous media in which moisture transfer occurs in both the vapor/gas and liquid phase. Bouguerra (1999) points out that the thermal conductivity is strongly influenced by the moisture content migrating through porous material. Since the thermal conductivity of water vapour is similar to the thermal conductivity of air there will no clear difference. But the thermal conductivity of liquid water is 23 times the thermal conductivity which will lead to clear difference. The next section will focus on the effect of moisture on the thermal conductivity of the gypsum plasterboards.

3 THREE-PHASE SYSTEM

This section will focus on the calculation of the thermal conductivity of a solid porous medium with a mixture of a liquid (water) and a gas (dry air) in the voids. Somerton et al. (1973) have derived the following equation for porous medium filled by a mixture of two fluids

$$k_e = k_g + \sqrt{s_l}(k_l - k_g) \quad . \tag{2}$$

Here k_g is the effective thermal conductivity of the porous medium filled with dry air, k_l is the effective thermal conductivity of the porous medium filled with water and s_l is the water saturation in the voids. Both k_g and k_l can be calculated with the equations for two-phase effective conductivity given in Section 2, with k_{air} and k_{water} as the k_f respectively.

Here, this method proposed by Somerton et al. (1973) is used to derive the amount of water needed to comply with the thermal conductivity as measured in the literature. During this derivation the effect of the moisture on density needs to be taken into account. A higher moisture content means a lower dry mass, so lower dry density. The dry density, in turn, is related to the void fraction of the material. So the density, void fraction and moisture content are all interrelated.

Table 5 shows the results of both the Zehner & Schlünder equation The sorbed water values are all in line with values from literature. Ang and Wang (2004) also give a moisture content of 3% m/m. This value is furthermore mentioned by Thomas (2002), Belmiloudi and Le Meur (2005). Therefore one can conclude that all three equations are close to the values from literature.

Table 5. Water content derived to match the experimental value

	Zehner & Schlünder C=5
Wullschlager (2007)	2.08 %
Mehaffey (1994) 1	2.32 %
Mehaffey (1994) 2	3.42 %
Sultan (1996)	2.95 %
Ghazi Wakali (2008) 1	3.37 %
Ghazi Wakali (2008) 2	1.72 %
Ghazi Wakali (2008) 3	1.78 %
Ghazi Wakali (2008) 4	3.24 %

4 APPLICATION TO THERMAL CONDUCTIVITY DURING FIRE

In the previous sections the thermal conductivity at ambient temperatures were analysed. In this section, the developed method is used for the determination of the thermal conductivity during fire, i.e. for elevated temperatures.

The thermal conductivities can be computed as the composition of the system is known for all temperatures. The decomposition process is described in more detail in de Korte and Brouwers (2009). Figure 1 shows the comparison of the results of the three-phase system with the experimental results of Mehaffey (1994). The used gypsum plasterboard of Mehaffey (1994) has a density of 732 kg/m^3 and consists of 100% gypsum. The thermal conductivity is simulated with the Zehner and Schlünder equation with a shape-factor (C) of 5 and an initial moisture content of 2.8% on the gypsum mass is used. This is based on the result from Section 3. The equation of Zehner and Schlünder is used because it depends on a few parameters. Furthermore the thermal conductivities of the solid and fluid phases are assumed to be equal to the data in Table 2, so the thermal conductivities are assumed to be constant, i.e. not a function of temperature. Also the thermal expansion of the solids is ignored. Upon heating, the solids expand, which reduces the void fraction.

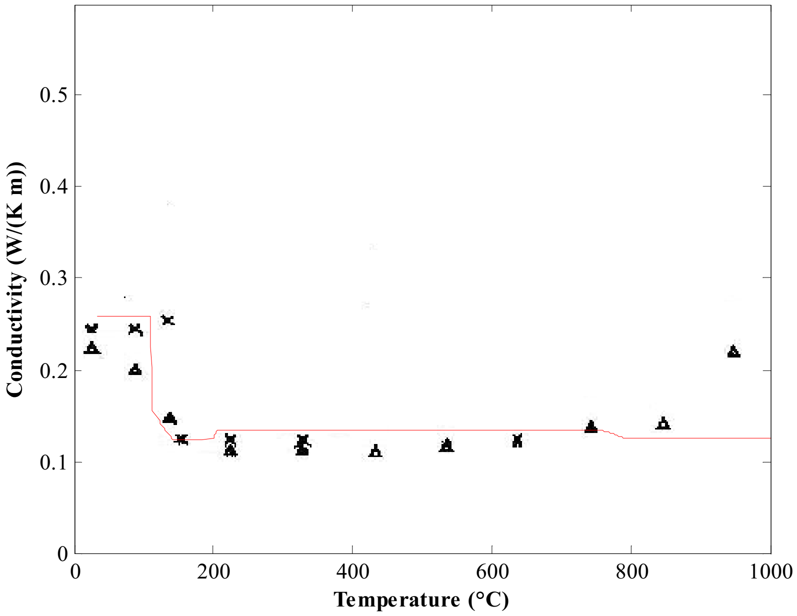

Fig. 1. Simulated thermal conductivity according to the proposed model (thin line) and experimental thermal conductivity (Mehaffey, 1994).

Notwithstanding these and other simplifications, it can be seen from Figure 1 that the simulated value have a good fit with the experimental value obtained from literature. The raise in thermal conductivity beyond 850°C in the experiments is probably caused by shrinkage cracks in the material. Due to cracks the air flows through the cracks more easy, increasing the apparent thermal conductivity. Obviously, this system change is not dealt with by the present model.

5 SUMMARY/CONCLUSION

The thermal conductivity of gypsum plasterboard up to a temperature of 105°C can be described best by a three-phase system as first introduced by Somerton et al (1973). This method requires information about the thermal conductivities which are provided by two-phase systems and the saturation of the voids. The two two-phase systems govern the cases with no saturation and full saturation of the voids.

For the two-phase system the Zehner and Schlünder equation met shape-factor of 5 yields good results. Furthermore, a moisture content of 2.8 % on plasterboard mass appears to be needed to explain the thermal conductivity of the board.

Using this moisture content of 2.8%, and the equations of Zehner and Schlünder with C=5 and Somerton, measured values for the thermal conductivity of several plasterboards from literature up to 105°C can be predicted excellently. This amount of moisture content is in line with the values reported in literature, and here it appears to depend only on the gypsum content of the solid phase. For more elevated temperatures, the two-phase equations (air/solid) also proves to be useful, when one takes account of the appropriate changes in the type of solid (dehydration, decarbonation) and volume (void fraction).

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