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GYPSUM BOARD THERMAL PROPERTIES EXPOSED TO HIGH TEMPERATURE AND FIRE CONDITION

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Abstract. Gypsum board is a widespread fire barrier used in house and general building construction. Gypsum board partitions and ceiling membranes are possibly the most common fire resistant construction approach employed in an extensive range of building types. The utilization of gypsum board as prime fire protection of light-flame wood or steel construction is ubiquitous. Gypsum board based systems are among those now broadly used, as walls or ceilings and it is principally employed as lining material in light-weight construction, which is a competent and cost effective technique of providing flexible partitioning assemblies in commercial and residential buildings. The thickness of the gypsum board lining and the configuration of the framing can be flexibly changed to meet specified fire performance requirements. The use of such systems is increasing every day and there demands to be more research on their properties and behaviour. This paper presents the properties of gypsum board which include the assemblies and standard fire tests and the thermal properties of gypsum in general and includes suggested properties of gypsum by different researchers.

Key words: gypsum board; thermal properties; conductivity; high temperatures; ablation.

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1. Introduction

Fire resistant barriers play significant role in maintaining building integrity and reducing the spread of fire from the room of origin to neighbouring compartments. Building codes usually necessitate compartments within a building to be detached by continuous fire rated barriers, such as drywall construction. Drywall construction is an efficient and cost effective method of achieving a flexible partition assembly within a commercial or residential building. Gypsum boards are mainly used as sheet material lining in light-weight constructions, namely Light Steel Framing (LSF) and Light Timber Framing (LTF). A typical wall assembly of drywall construction is shown in Fig. 1. Such walling systems consist of steel studs or wood studs with one or two gypsum boards fixed to each side of the studs. The cavity between the boards are filled with insulation layers or left empty. The insulation materials commonly used in the cavity are glass fibre, rock wool and cellulose fibre.

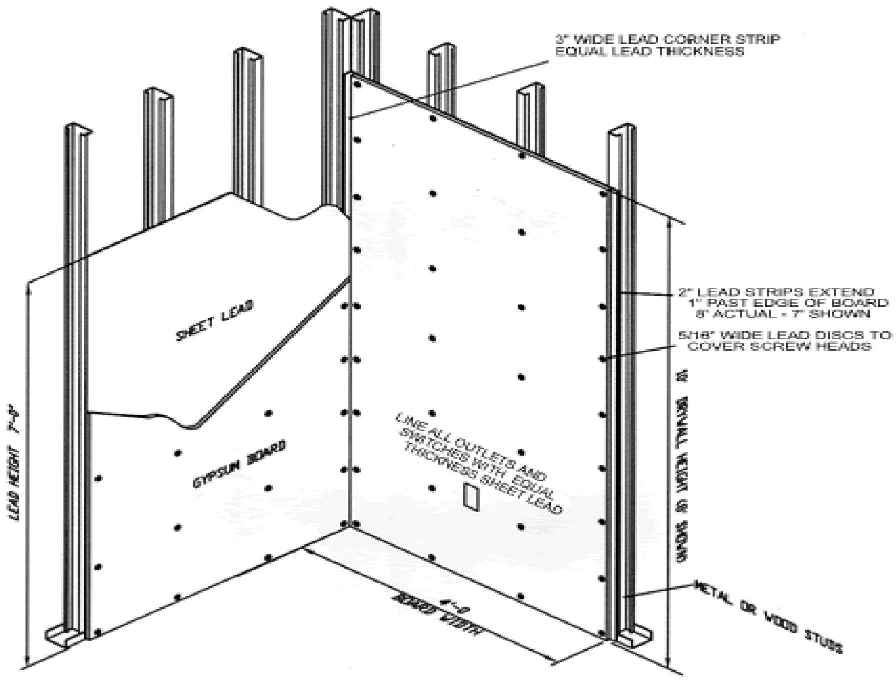

Fig. 1 – A typical gypsum board wall assembly.

Gypsum board partitions and ceiling membranes are possibly the most common fire resistant construction approach employed in an extensive range of building types. Very familiar in light frame construction allied with single and multi-family housing, gypsum board systems are also used in other outsized building types. The fire resistance of the World Trade Centre buildings brought new awareness to the present approaches to designing fire resistance throughout the world and has highlighted the role played by gypsum board. At the stairs and elevator shafts, fire separation partitions consisted of steel stud and gypsum board assemblies, where the gypsum board became detached during the destruction.

Each board is composed of a non-combustible gypsum core with paper-laminated surfaces which provide tensile strength to the lining. Gypsum contains chemically bound water and a small amount of free water, which play a key role in the performance of the assembly at elevated temperatures.

During a fire, when gypsum board is heated up to about 100°C, a great amount of heat is absorbed to drive off water. This process therefore delays the development of temperature rise through gypsum until the entire board is dehydrated. The consequent temperature plateau is the basis of gypsum board systems fire resistance as shown in Fig. 2.

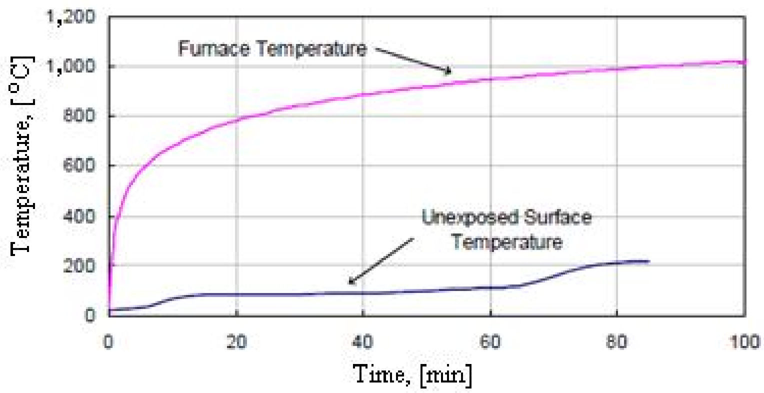

Fig. 2 – Temperature development on the unexposed side of a gypsum board with 25 mm thickness subjected to a standard cellulosic fire.

2. Fire Resistance

In order to recognize fire resistance of a system, building codes and regulations rely on standard fire test procedures. Fire resistance is then defined as the duration for which a fire protection system can endure a standard fire test until it reaches failure criteria. Failure is considered as loss of either fire separating function or load bearing function and categorized as insulation (excessive temperature rise on the unexposed surface), integrity (fire spread through fissures and openings) and stability (structural collapse) criteria.

In a standard fire test, the elements of interest are subjected to increasing temperatures governed by a specified temperature *vs.* time relationship (BS476, 1987). It should be noted that standard fire curves are attempts to classify construction elements, although they might not represent fire scenarios in real world. In general building uses, the cellulosic fire condition is applied. Hydrocarbon fires are more likely to occur in petrochemical industry. The two fire curves are plotted in Fig. 3. As can be seen from the plots, hydrocarbon fire has a steep initial temperature rise to 1,100°C, simulating fast reaction of hydrocarbons.

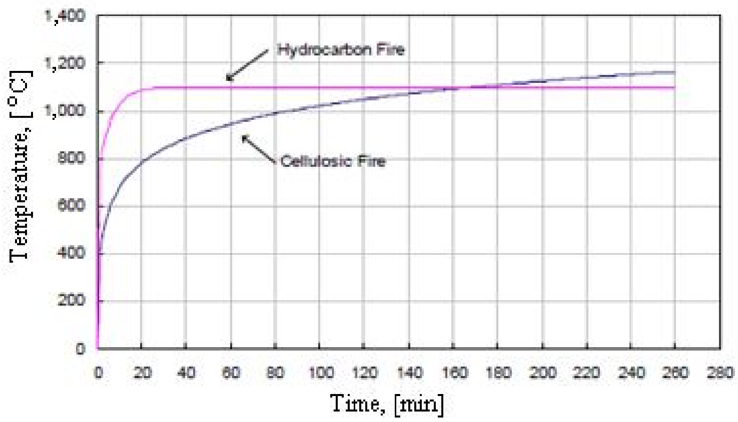

Fig. 3 – Time *vs.* temperature curves for standard fires according to BS476 (1987).

3. Heat Transfer in Gypsum Board Assemblies

Heat transfer through gypsum board assembly is a combination of all three modes of conduction, convection and radiation (Fig. 4) as below:

a) P a t h 1. Heat transfer from the furnace (fire) to the exposed side of gypsum is by convection and radiation, with radiation being the more dominating.

b) P a t h 2. Heat transfer through gypsum is by conduction. However, as gypsum is a porous material, heat transfer through gypsum is a combination of all three modes: conduction through the solid and convection and radiation through the pores. Therefore thermal conductivity of porous materials like gypsum is an empirical factor that helps to describe the combined heat transfer based on Fourier law (conduction), and it might be called *the effective thermal conductivity*. This effective thermal conductivity can be affected by many factors, such as temperature, density, moisture content and porosity of the material. Such sensitivity then describes the diverse data reported by several research studies directed towards the determination of the effective conductivity of these materials. Developing a method to quantify the effective thermal conductivity of gypsum is one of the main objectives of this research.

c) P a t h 3. Heat transfer from the cavity side of the exposed gypsum to the cavity gas is by convection and radiation.

d) P a t h 4. Heat transfer from the cavity gas to the cavity side of the unexposed gypsum is again by convection and radiation.

e) P a t h 4. Heat transfer through the unexposed gypsum is by conduction.

f) P a t h 5. Heat transfer from the unexposed gypsum to ambient environment is by convection and radiation, with convection dominating at lower temperatures.

It should be noted that in insulated assemblies, the insulation materials also contribute to heat transfer through the system. However, their change in volume should be considered in the analysis, since they burn away easily after a certain temperature is reached (depending on the material used).

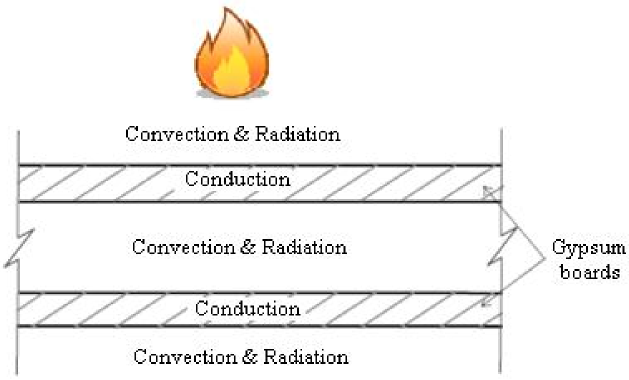

Fig. 4 – Heat transfer modes through gypsum board assemblies.

In a standard fire test, the elements of interest are subjected to increasing temperatures governed by a specified temperature *vs.* time relationship (BS476, 1987). It should be noted that standard fire curves are attempts to classify construction elements, although they might not represent fire scenarios in real world. In general building uses, the cellulosic fire condition is applied. Hydrocarbon fires are more likely to occur in petrochemical industry. The two fire curves are plotted in Fig. 3. As can be seen from the plots, hydrocarbon fire has a steep initial temperature rise to 1,100°C, simulating fast reaction of hydrocarbons.

4. Gypsum Board Thermal Properties at High Temperatures

The key material in drywall construction which provides the fire resistance is gypsum. Therefore it is important to study thermal and material properties of gypsum. This section first describes some of gypsum's main thermal properties as studied by various researchers.

3.1. Specific Heat

The specific heat of gypsum at different temperatures has been investigated by several researchers (Fig. 5). Having known water dissociates from gypsum in two phases, it is not surprising that specific heat experiences two peaks. The results from different studies agree well on the first peak (corresponding to the first reaction) to occur at about 100°C. However, there is inconsistency on the temperature at which the second reaction takes place as well as the value of the peaks.

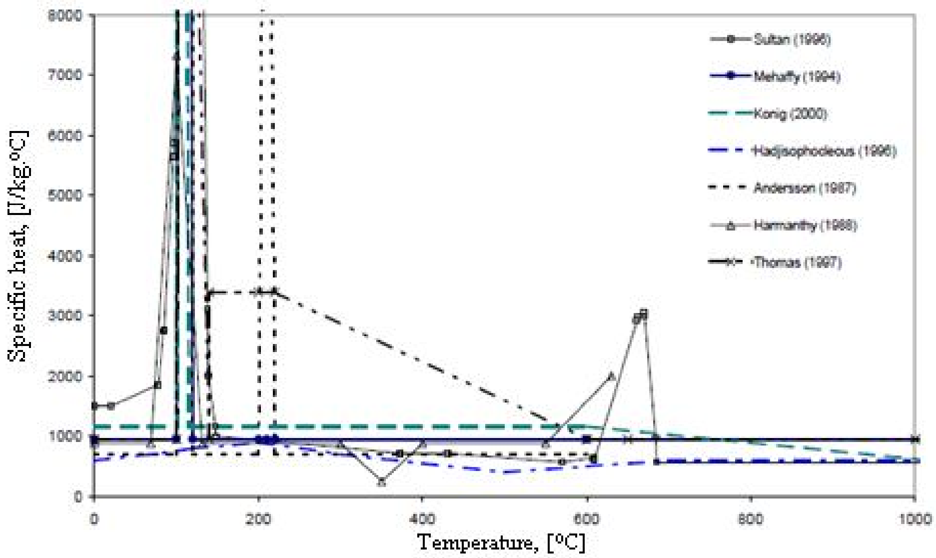

Fig. 5 – Specific heat of gypsum boards according to various researchers.

Harmathy (1998) reports a peak of 7.32 kJ/kg.°C at 100°C and although he does not give measurements over 630°C, his results shows a peak of 2 kJ/kg.°C at this temperature which indicates the second reaction. Andersson and Jansson (1987) provide peak values of 52.2 kJ/kg.°C and 19.2 kJ/kg.°C at 110°C and 210°C, respectively.

Mehaffey *et al*. (1994) first conditioned the specimens at 40°C for 24 hours in an attempt to drive off free moisture and then used a differential scanning calorimeter at two scanning rates of 2°C/min and 20°C/min. The results showed a peak of 29 kJ/kg.°C at 95°C when the slower scanning rate was used, and a peak of 14 kJ/kg.°C at 140°C when the faster scanning rate was employed, while the area under both peaks was about 500 kJ/kg, corresponding closely to the values in section **2.5.1** (100 + 356 = 456 kJ per kg of gypsum).

Mehaffy *et al*. (1994) measured specific heat up to 200°C, thus no second peak was observed. Sultan (1996) reports the first peak of 18.5 kJ/kg.°C occurring at 125°C and the second peak of 3.07 kJ/kg.°C at 670°C. The specific heat at ambient temperature is the base value when no reaction occurs. This base value is reported to be 0.88 kJ/kg.°C by Harmathy (1988), 0.95 kJ/kg.°C by Mehaffey *et al*. (1987) and taken as 0.7 kJ/kg.°C by Andersson and Jansson.

Since specific heat of gypsum shows sharp peaks, in some finite element modelling, the use of enthalpy is preferred to separate values for specific heat and density to avoid numerical instability (Thomas, 2002).

4.2. Density

Mehaffey *et al*. (1994) used thermogravimetric analysis (TGA) at a scanning rate of 20°C/min to determine the changes in mass of 10...30 mg specimens of gypsum (Type X) with temperature. The results are represented in Fig. 6. As can be seen, between 100°C to 160°C about 17.5% of the initial mass is lost, which indicates the first dehydration reaction and the release of water of crystallization (0.75 × 21% = 15.75%) as well as the evaporation of the free water (less than 3%). They also noticed a mass loss at 650°C which corresponds to the second dehydration reaction.

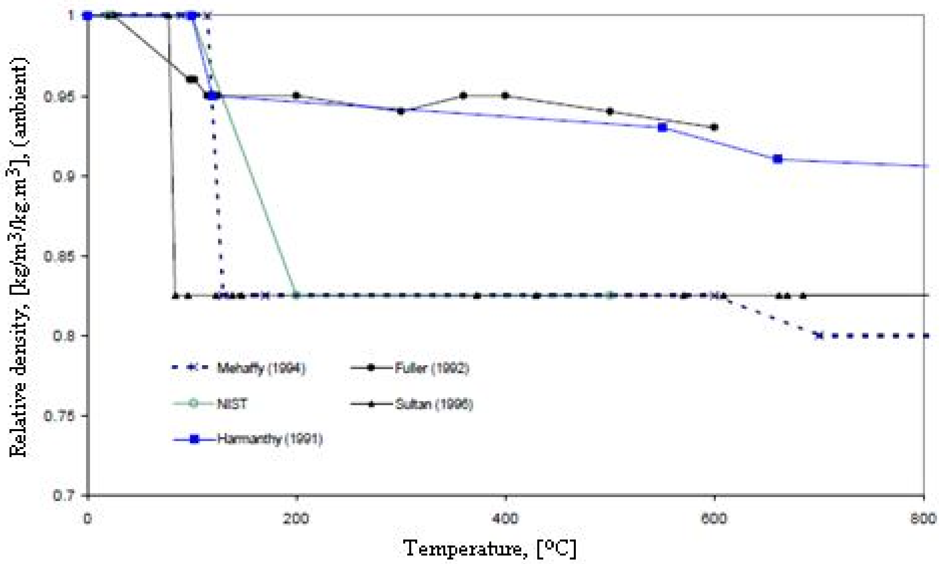

Fig. 6 – Density of gypsum board relative to ambient density, *versus* temperature.

Mehaffey *et al*. (1994) report the initial density of the 15.9 mm Type X gypsum board as 648 kg/m^3. However, the density of the gypsum core of different gypsum boards at ambient condition varies from type to type and also from different manufacturers. A study by Thomas *et al*. (2002) on a large number of Type X gypsum board samples shows that the density of 12.5 mm and 15.8 mm boards varies largely both within and between manufacturers. The mean value of the densities ranges from 687 kg/m^3 to 811 kg/m^3.

4.3. Thermal Conductivity

The determination of the thermal conductivity of gypsum is quite complicated due to the effects of moisture and radiation in the pores. Gypsum from different sources or manufacturers varies, in microstructure, and methods employed to measure its thermal conductivity also differ. As a result the values reported by different studied vary widely (especially at temperatures above 500°C); nevertheless follow a similar trend. Fig. 7 shows thermal conductivity of gypsum *versus* temperature given by a few studies. The symbols represent measured values and the lines represent modified curves used in models to provide good calibration between numerical and experimental results.

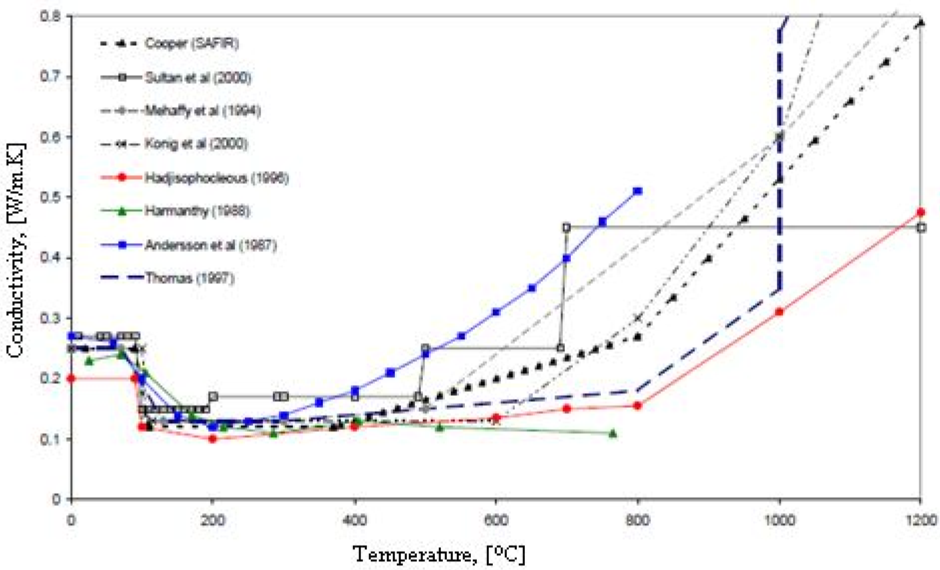

Fig. 7 – Thermal conductivity of gypsum *versus* temperature.

Andersson and Jansson (1987) used the Transient Hot Strip (THS) method which measures the resistance of a metal strip embedded in the material and derives the thermal conductivity of the material. Their results for thermal conductivity of gypsum is quite isolated compared to others. Harmathy (1988) used a variable state scanning technique with relatively small temperature gradients. His results are very much in agreement with Mehaffey *et al.*'s (1994) who used the TC-31 thermal conductivity meter.

Thomas (2002) mentions that the significant increase in thermal conductivity of gypsum at temperatures above 800°C is to allow for the opening of cracks and ablation of gypsum, since the testing method used by Mehaffey *et al*. prevents the cracks from opening up in the board. It can also cover accelerated radiations in the voids at high temperatures: As mentioned before, heat transfers through the pores of gypsum is realized by convection and radiation. At high temperatures water is migrated from pores and the radiation through pores becomes significant (since it is proportional to temperature to the power three), which highly improves the heat transfer.

4.4. Specific Volumetric Entalpy

The enthalpy of gypsum board is given by the area under the specific heat multiplied by the density *versus* temperature curve. Although there is still a certain degree of variation between different studies, Fig. 8 shows that the inconsistencies present in the reported values of specific heat in Fig. 5 are smoothed by the summation of area under the respective curves. Thomas (1997) used a smoothed version of his calculated enthalpy curve, which was based upon the findings of Andersson *et al*. (1987). Values reported by Mehaffy *et al*., (1994) are similar to Andersson and Janssen.s values, except they exclude the second step rise in enthalpy due to the second dehydration reaction at approximately 210°C.

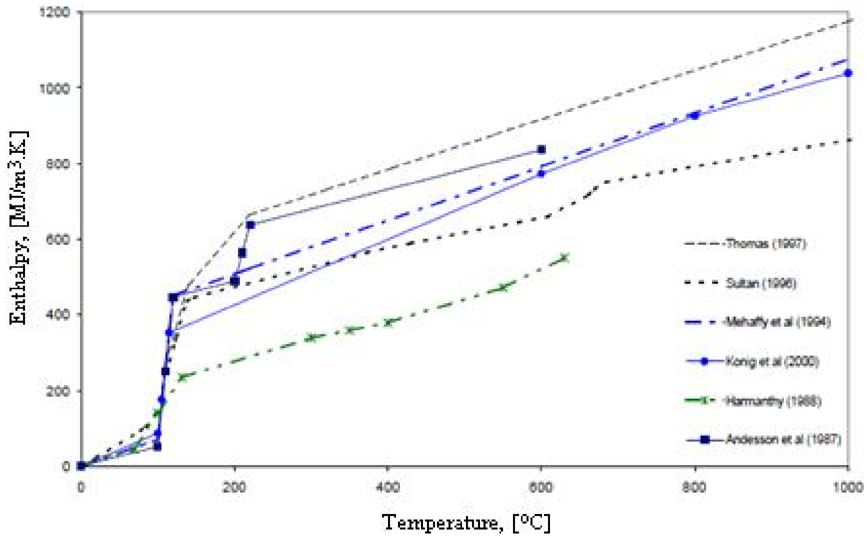

Fig. 8 – Comparative enthalpy of gypsum board from various sources.

The thermal properties of gypsum board used in the study performed by Konig *et al*. (2000) were based upon those measured by Mehaffy *et al*. (1994), which is indicated by similar enthalpy curves. Sultan (1996) based his enthalpy curve upon the properties of Type C gypsum board, which are present in the default thermal properties of gypsum board in the SAFIR software. The second peak in the specific heat values reported by Sultan give rise to the step in the enthalpy curve at approximately 600°C. The values of Harmanthy (1988) are significantly lower than those of other studies, due to the low reported peak in the specific heat curve at 100°C.

4.5. Linear Expansion

Fig. 9 shows the shrinkage of gypsum board and gypsum core *versus* temperature according to NRCC (National Research Council of Canada). When subjected to high temperatures, gypsum core experiences significantly shrinkage. In addition, at temperature range of about 200°...350°C the paper laminates on the sides of gypsum core burn off. Thus the thickness of the board (gypsum and paper) is also reduced. This significant reduction needs to be considered when modelling the structure, since it will eventually cause the formation of cracks as well as the opening of the joints. Both these effects might hugely influence the heat transfer through the system.

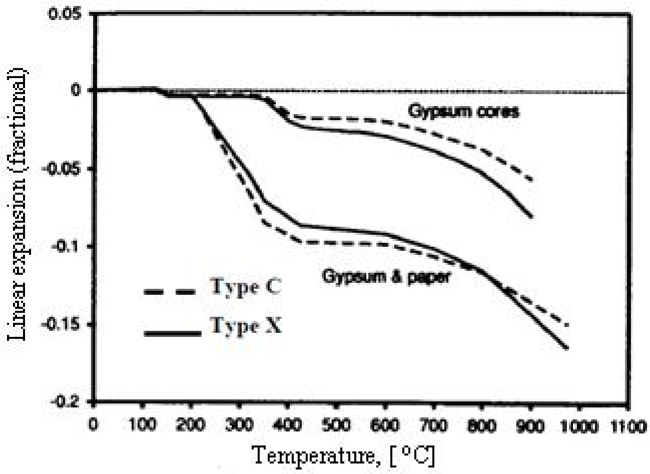

Fig. 9 – Contraction of gypsum as a function of temperature (Mehaffey *et al*., 1994).

Vermiculite, a natural mineral, is commonly used as an additive to the gypsum core to mitigate the effect of shrinkage. Vermiculite expands with the application of heat, partly offsets the contraction of gypsum and therefore enhances the performance of the system in fire. Glass fibre is also a reinforcing agent which bridges shrinkage cracks and attempts to sustain the integrity of gypsum board during calcinations (Gerlich, 1995).

4.6. Ablation

Given sufficient time under heat or exposure to fire, some materials undergo physical and chemical changes, which results in bonding reduction of the material and removal of successive thin layers from its surface. This process is referred to as *ablation*. With rising temperatures the exposed surface of gypsum loses water and turns into calcium sulphate anhydrite, which falls off the unaltered substrate. As heat penetrates through the thickness, more material transforms to anhydrite powder and consecutive layers are shed. Using glass fibre reinforcements delays the ablation of the exposed surface Thomas (2002) observed ablation at about 700°C for normal gypsum board and 1,000°C for fibre reinforced board. It is also worth noting that ablation is of greater importance for thin boards compared to thick ones, as a larger proportion of the material is shed off.

To include ablation in numerical analysis, one can simulate the reduction in thickness of the material, however, it is more convenient to modify thermal conductivity value (increase the value at high temperatures) to allow for the effects of ablation. Nevertheless, since ablation occurs at high temperatures, its effect would be small

4.7. Relative Emissivity and Coefficient of Convection of Gypsum Board

The emissivity of the exposed gypsum board should be dependent on the state of the thermal degradation of its surface (Clancy, 1999). However, the difficulty consists in determining the evolution of surface emissivity with temperature. In SAFIR a relative emissivity coefficient is used to represent the surface emissivity of the board at all temperatures.

Clancy (1999) found that results from modelling were insensitive to surface emissivity values in the range of 0.6...0.9. Clancy adopted a low value of 2 $W/m^2.K$ for the convective coefficient of the exposed gypsum surface and a value of 12 $W/m^2.K$ for the unexposed surface. He states that although there are substantial differences given by various researchers, these variations are not expected to significantly affect the time of failure due to the dominance of radiant heat transfer over convective

5. Conclusions

This paper has provided a review of relevant literature on fire resistance of gypsum systems, focusing on the determination of gypsum thermal properties. There exist quite a large number of studies on this subject, each considering some aspects of the problem, which verifies the breadth of the matter and ongoing demand for more accurate and efficient approaches.

It is clear that there are large discrepancies in results of thermal properties of gypsum from different investigators and there is a need to develop a method to help manufacturers to extract relevant specific thermal properties of their specific gypsum products. These thermal properties can then be implemented in numerical models to generate results to evaluate the effectiveness of different new products before committing great resources to expensive full scale fire testing, which is the current practice. Since these properties are mainly to be used in numerical modelling, they do not need to represent the precise actual values.

Provided the numerical analysis procedure is correct, the thermal property values used in numerical modelling should be those which give calculation results in agreement with experimental results of temperature developments in gypsum. This will often require an iterative process, therefore, the closer the thermal properties of gypsum to their actual values are used in numerical analysis, the better the agreement between numerical and experimental results.

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PROPRIETĂŢILE TERMICE ALE PANOURILOR DE RIGIPS SUPUSE ACŢIUNII TEMPERATURILOR RIDICATE ŞI A FOCULUI

(Rezumat)

Panourile de rigips sunt folosite în mod frecvent în construcţiile de uz general şi a celor cu destinaţie clădiri de locuit ca o barieră împotriva focului. Pereţii despărţitori şi tavanele din rigips sunt cea mai folosită metodă de împiedicare sau diminuare a efectelor focului asupra unei structuri. Utilizarea panourilor din rigips ca metodă principală de protecţie a structurilor din lemn sau a celor de oţel este foarte des întâlnită. Mai mult decât atât, panourile de rigips sunt folosite cu succes şi ca elemente de partiţionare interioară atât a clădirilor cu destinaţie comercială cât şi a celor de locuit. Grosimea panourilor de rigips cât şi configuraţia cadrelor metalice de prindere a acestora pot fi modificate astfel încât să satisfacă o multitudine de cerinţe. Având în vedere folosirea tot mai frecventă a unor asemenea panouri în construcţii se impune o cercetare mai amănunţită a proprietăţilor mecanice sau de altă natură precum şi a comportamentului acestora la diferite solicitări. Se prezintă o sinteză a proprietăţilor termice ale panourilor de rigips precum şi comportamentul acestora la acţiunea focului folosind metode de testare standardizate..