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# Drywall Thermal Properties Exposed to High Temperatures and Fire Condition

J. Norgaard[a], M. A. Othuman Mydin[b*]

[a]*Architectural and Environmental Engineering Department, 301E Dean Keeton St. STOP C1700 Austin, Texas 78712-1056 USA*
[b]*School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia*

*Corresponding author: azree@usm.my

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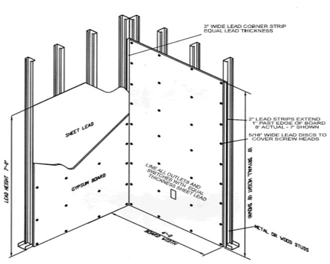
**Graphical abstract**




**Abstract**

Drywall is a widespread fire barrier used in house and general building construction. Drywall partitions and ceiling membranes are possibly the most common fire resistant construction approach employed in an extensive range of building types. The utilization of drywall board as prime fire protection of light-flame wood or steel construction is ubiquitous. Drywall 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 drywall 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 will presents the properties of drywall board which will includes the assemblies and standard fire tests and the thermal properties of drywall in general and includes suggested properties of drywall by different researchers. Drywall boards shrink and crack at high temperatures, and this leads to collapse of parts of the drywall boards in fire. Fall-off of gypsum in fire affects the fire resistance of the assembly considerably, and cannot be overlooked when evaluating the fire resistance of drywall assemblies.

*Keywords*: Drywall board; thermal properties; conductivity; high temperatures; ablation

**Abstrak**

Dinding gypsum adalah bahan penghalang kebakaran meluas yang digunakan di dalam pembinaan perumahan dan bangunan. Dinding sekatan gypsum dan membran siling adalah di antara kaedah atau pendekatan ketahanan api paling biasa dipraktikkan untuk pelbagai jenis bangunan. Penggunaan dinding gypsum sebagai perlindungan kebakaran utama untuk kayu yang mudah bakar atau pembinaan berasaskan keluli telahpun wujud sejak sekian lama. Sistem berasaskan dinding gypsum adalah antara sistem yang digunakan secara meluas pada masa sekarang sebagai dinding atau siling dan ia terutamanya digunakan sebagai bahan lapisan dalam pembinaan ringan, yang merupakan teknik yang cekap dan efektif dari segi kos dalam menyediakan pemasangan pembahagi yang fleksibel di dalam bangunan komersil dan kediaman. Ketebalan lapisan dinding gypsum dan konfigurasi bingkai adalah fleksibel untuk di ubah bagi memenuhi keperluan tertentu bagi keperluan kebakaran. Penggunaan sistem ini juga semakin meningkat pada saat dan ketika ini dan ada permintaan untuk diperbanyakkan penyelidikan berkenaan sifat dan kebolehan bahan ini. Kertas kerja ini akan membincangkan berkenaan sifat-sifat dinding gypsum termasuk kaedah pemasangan dan ujian kebakaran standard dan kebolehan terma dinding gypsum secara umum dan termasuk sifat-sifat atau kebolehan dinding gypsum yang telah dicadangkan oleh penyelidik-penyelidik yang berbeza. Dinding gypsum akan mengecut dan mengalami keretakan pada suhu yang tinggi, dan ini akan membawa kepada keruntuhan bahagian-bahagian tertentu pada dinding gypsum dalam api. Tahap kejatuhan gypsum dalam api memberi kesan ketahanan api dari aspek pemasangan sistem ini secara total, dan ianya tidak boleh diabaikan apabila menilai ketahanan api sistem ini.

*Kata kunci:* Dinding gypsum; sifat terma; konduktiviti; suhu tinggi



## ■1.0 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. For a performance-based design approach, it is significant to distinguish when wall assemblies collapse and when their effectiveness as a smoke and flame barrier is compromised due to drywall board shrinkage and cracking [1]. At present, there is limited or no experimental data and information regarding the behaviour, performance and failure mechanisms of drywall board wall assemblies under realistic fire conditions are accessible; this significantly impedes the utilization of performance-based design approaches in the current design method. It should be pointed out that devoid of physical information and data of actual failure properties, it is unfeasible to envisage the time to failure of the drywall board wall assembly during fire condition using the current procedures. Such information is critical to determine safe egress times from buildings and provide guidance to fire fighters entering a building [2].

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. Drywall 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 Figure 1. Such walling systems consist of steel studs or wood studs with one or two drywall 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 [3].

Drywall 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, drywall board systems are also used in other outsized building types [4]. 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 drywall board. At the stairs and elevator shafts, fire separation partitions consisted of steel stud and drywall board assemblies where the drywall board became detached during the destruction [4].

Each board is composed of a non-combustible drywall core with paper-laminated surfaces which provide tensile strength to the lining. Drywall 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 [5].

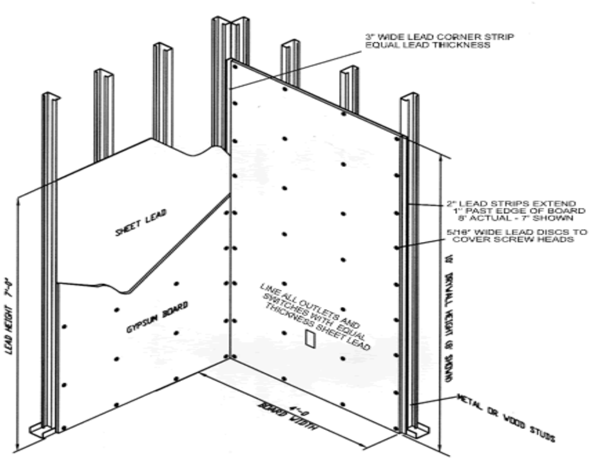



**Figure 1** A typical drywall board wall assembly

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

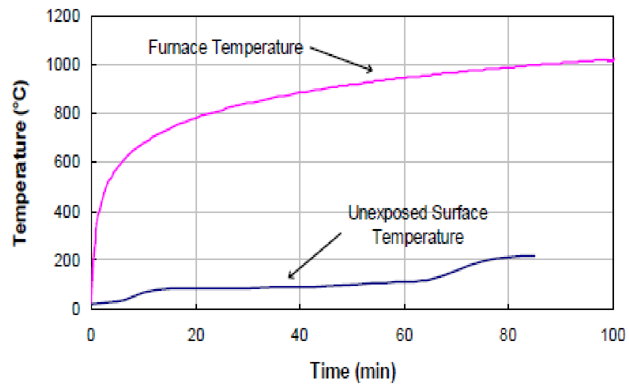



**Figure 2** Temperature development on the unexposed side of a drywall board with 25mm thickness subjected to a standard cellulosic fire

## 2.0 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 [6]

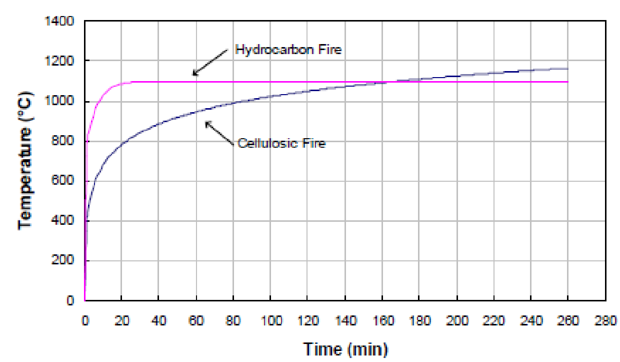



**Figure 3** Time-temperature curves for standard fires according to BS476 [7]

In a standard fire test, the elements of interest are subjected to increasing temperatures governed by a specified temperature-time relationship [7]. 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 [4]. Hydrocarbon fires are more likely to occur in petrochemical industry. The two fire curves are plotted in Figure 3. As can be seen from the plots, hydrocarbon fire has a steep initial temperature rise to 1100°C, simulating fast reaction of hydrocarbons [8].

## ■3.0 HEAT TRANSFER IN DRYWALL ASSEMBLIES

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

- Path 1: Heat transfer from the furnace (fire) to the exposed side of drywall is by convection and radiation, with radiation being the more dominating.
- Path 2: Heat transfer through drywall is by conduction. However, as drywall is a porous material, heat transfer through drywall 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 drywall 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 [4]. 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 drywall is one of the main objectives of this research.
- Path 3: Heat transfer from the cavity side of the exposed drywall to the cavity gas is by convection and radiation.
- Path 4: Heat transfer from the cavity gas to the cavity side of the unexposed drywall is again by convection and radiation.
- Path 4: Heat transfer through the unexposed drywall is by conduction.
- Path 5: Heat transfer from the unexposed drywall to ambient environment is by convection and radiation, with convection dominating at lower temperatures [6].

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 [6].

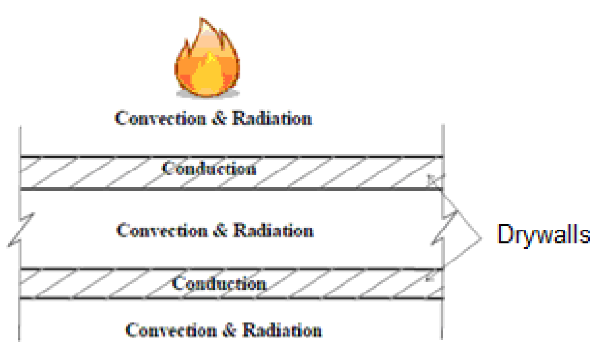



**Figure 4** Heat transfer modes through drywall board assemblies

## ■4.0 DRYWALL BOARD THERMAL PROPERTIES AT HIGH TEMPERATURES

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

### 4.1 Specific Heat

The specific heat of drywall at different temperatures has been investigated by several researchers (Figure 5). Having known water dissociates from drywall 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.

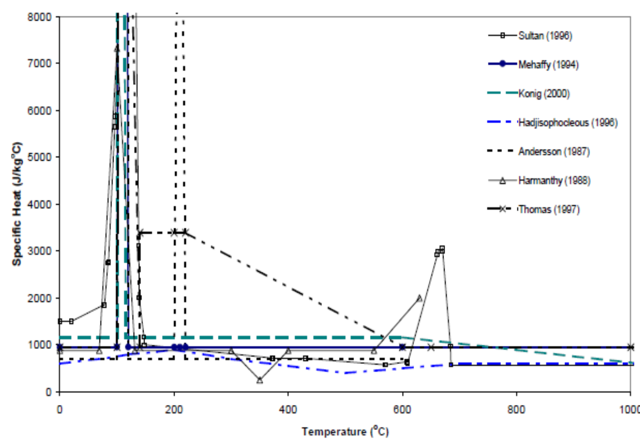



**Figure 5** Specific heat of drywall boards according to various researchers [4,9]

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 [10]. 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 [11].

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 [11]. 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 drywall).

Mehaffey *et al.* measured specific heat up to 200°C, thus no second peak was observed. Sultan 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 [4]. 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, 0.95 kJ/kg.°C by Mehaffey *et al.* and taken as 0.7 kJ/kg.°C by Andersson and Jansson.

Since specific heat of drywall 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 [9].

### 4.2 Density

Mehaffey *et al.* used thermogravimetric analysis (TGA) at a scanning rate of was 20°C/min to determine the changes in mass of 10-30 mg specimens of drywall (Type X) with temperature [12]. The result is demonstrated in Figure 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 (0.75x21%=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.

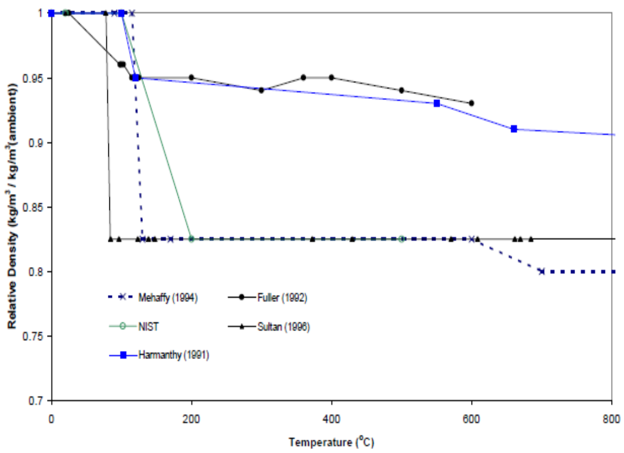



**Figure 6** Density of drywall board relative to ambient density, versus temperature [4,9]

Mehaffey *et al.* report the initial density of the 15.9mm Type X drywall board as 648 kg/m$^3$ [12]. However, the density of the drywall core of different drywall boards at ambient condition varies from type to type and also from different manufacturers. A study by Thomas *at al* on a large number of Type X drywall board samples shows that the density of 12.5mm and 15.8mm boards varies largely both within and between manufacturers [9]. 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 drywall is quite complicated due to the effects of moisture and radiation in the pores [6]. Drywall 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. Figure 7 shows thermal conductivity of drywall versus temperature given by a few studies [8]. The symbols represent measured values and the lines represent modified curves used in models to provide good calibration between numerical and experimental results. 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 [11]. Their results for thermal conductivity of drywall 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 *at al*'s who used the TC-31 thermal conductivity meter [12].

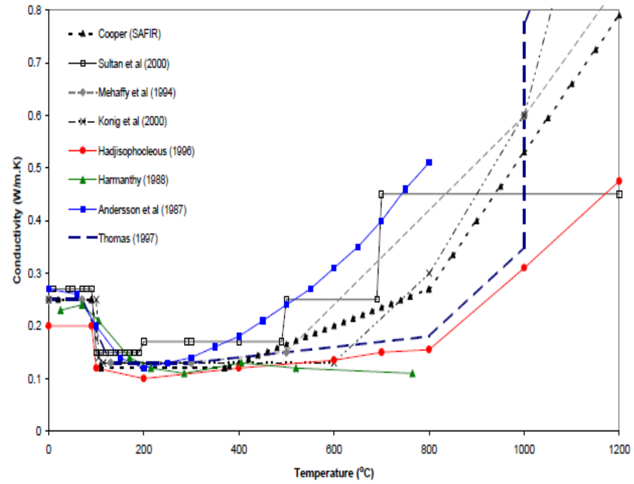



**Figure 7** Thermal conductivity of drywall board versus temperature [4,9]

Thomas (2002) mentions that the significant increase in thermal conductivity of drywall at temperatures above 800°C is to allow for the opening of cracks and ablation of drywall, since the testing method used by Mehaffey *at al* prevents the cracks from opening up in the board [9]. It can also cover accelerated radiations in the voids at high temperatures: As mentioned before, heat transfers through the pores of drywall is 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 [9].

## 4.4 Specific Volumetric Entalpy

The enthalpy of drywall 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, Figure 8 shows that the inconsistencies present in the reported values of specific heat in Figure 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) [9,11]. Values reported by Mehaffy *et al.* 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 [12]. The thermal properties of drywall board used in the study by Konig *et al.* (2000) were based upon those measured by Mehaffy *et al.* (1994), which is indicated by similar enthalpy curves [13]. Sultan (1996) based his enthalpy curve upon the properties of Type C drywall board, which are present in the default thermal properties of drywall board in the SAFIR software [6]. 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 [10].

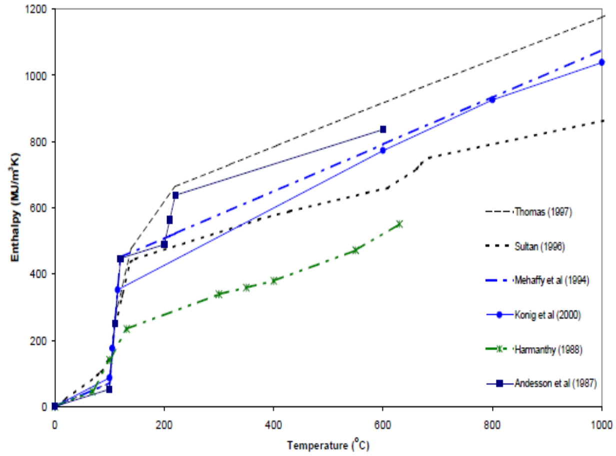



**Figure 8** Comparative enthalpy of drywall board from various sources [4,9]

## 4.5 Linear Expansion

Figure 9 shows the shrinkage of drywall board and drywall core against temperature according to NRCC (National Research Council of Canada). When subjected to high temperatures, drywall core experiences significant shrinkage. In addition, at temperature range of about 200-350°C the paper laminates on the sides of drywall core burn off. Thus the thickness of the board (drywall and paper) is also reduced [6]. 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 [9].

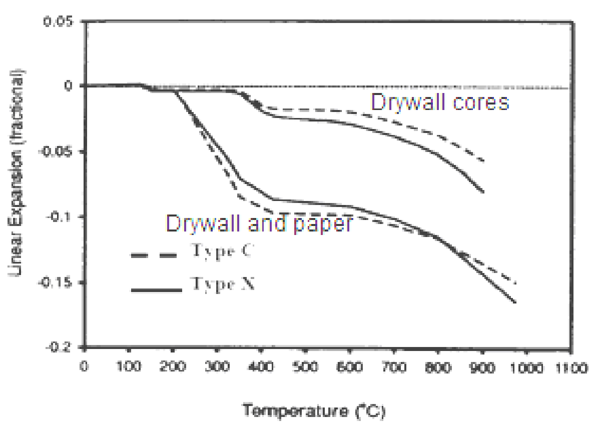



**Figure 9** Linear expansion of drywall as a function of temperature [12]

Vermiculite, a natural mineral, is commonly used as an additive to the drywall core to mitigate the effect of shrinkage. Vermiculite expands with the application of heat, partly offsets the contraction of drywall and therefore enhances the performance of the system in fire [11]. Glass fibre is also a reinforcing agent which bridges shrinkage cracks and attempts to sustain the integrity of drywall board during calcinations [12,14].

## 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 drywall loses water and turns into calcium sulphate anhydrite, which falls off the unaltered substrate [13]. 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 drywall board and 1000°C for fibre reinforced board [9]. 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 [6]. Nevertheless, since ablation occurs at high temperatures, its effect would be small

## 4.7 Relative Emissivity and Coefficient of Convection of Drywall Board

The emissivity of the exposed drywall board should be dependent on the state of the thermal degradation of its surface [15]. However, the difficulty is 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 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/m2.K for the convective coefficient of the exposed drywall surface and a value of 12 W/m2.K for the unexposed surface [15]. 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 [16].

## 4.8 Chemical Reaction at High Temperatures

The core material of drywall is a porous solid composed mainly of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a naturally occurring mineral. The occurrence of the water molecules is a key feature in establishing the fire resistance properties of drywall. When the drywall being heated, crystalline gypsum dehydrates and water is liberated, characteristically in two separate, reversible chemical reactions [17]:

$$CaSO_4 \cdot 2H_2O + Q \leftrightarrow CaSO_4 \cdot (1/2)H_2O + (3/2)H_2O \quad (1)$$

$$CaSO_4 \cdot (1/2)H_2O + Q \leftrightarrow CaSO_4 + (1/2)H_2O \quad (2)$$

Both of these dehydration reactions are endothermic and usually take place at temperatures between 125 and 225°C. It was also found that the reduced pinhole size resulted in a slow removal of the dehydration product from the pan and guide to a clear distinction between the two dehydration reactions. In addition to two dehydration reactions, a third exothermic reaction occurs at a temperature of around 400°C, in which the molecular structure of the soluble crystal reorganizes itself into a lower insoluble energy state (hexagonal to orthorhombic):

$$CaSO4(sol) \rightarrow CaSO4(insol) + Q \quad (3)$$

## ■5.0 CONCLUSION

This paper has provided a review of relevant literature on fire resistance of drywall systems, focusing on the determination of drywall 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 drywall from different investigators and there is a need to develop a method to help manufacturers to extract relevant specific thermal properties of their specific drywall 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 modeling should be those which give calculation results in agreement with experimental results of temperature developments in drywall. This will often require an iterative process, therefore, the closer the thermal properties of drywall to their actual values are used in numerical analysis, the better the agreement between numerical and experimental results.

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