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Fire Safety of Steel Wall Systems Using Enhanced Plasterboards

Abstract

Fire safety design is important to eliminate the loss of property and lives during fire events. Gypsum plasterboard is widely used as a fire safety material in the building industry all over the world. It contains gypsum (CaSO4.2H2O) and Calcium Carbonate (CaCO3) and most importantly free and chemically bound water in its crystal structure. The dehydration of the gypsum and the decomposition of Calcium Carbonate absorb heat, which gives the gypsum plasterboard fire resistant qualities. Currently plasterboard manufacturers use additives such as vermiculite to overcome shrinkage of gypsum core and glass fibre to bridge shrinkage cracks and enhance the integrity of board during calcination and after the loss of paper facings in fires. Past research has also attempted to reduce the thermal conductivity of plasterboards using fillers. However, no research has been undertaken to enhance the specific heat of plasterboard and the points of dehydration using chemical additives and fillers. Hence detailed experimental studies of powdered samples of plasterboard mixed with chemical additives and fillers in varying proportions were conducted. These tests showed the enhancement of specific heat of plasterboard. Numerical models were also developed to investigate the thermal performance of enhanced plasterboards under standard fire conditions. The results showed that the use of these enhanced plasterboards in steel wall systems can significantly improve their fire performance. This paper presents the details of this research and the results that can be used to enhance the fire safety of steel wall systems commonly used in buildings.

Keywords: Fire safety, Steel wall systems, Enhanced plasterboards, Chemical additives, Fillers, Thermal performance, Standard fire conditions.

1. Introduction

In recent times, LSF wall and floor systems are increasingly used in low-rise and multi-storey buildings, but without a full understanding of their fire performance. Currently LSF wall and floor systems are made of cold-formed thin-walled steel lipped channel sections and gypsum plasterboards. Under fire conditions, cold-formed thin-walled steel stud and joist sections heat up quickly resulting in fast reduction in their strength and stiffness. Therefore they are commonly used in structural wall and floor systems with plasterboard linings on both sides used as fire protection (see Figure 1).

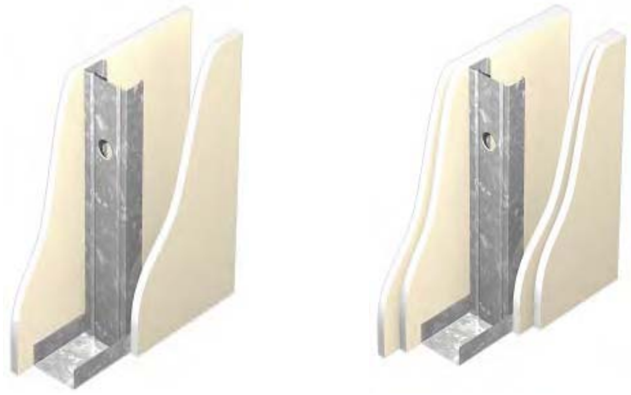


Figure 1: LSF wall systems with gypsum plasterboard lining

Cavity insulated LSF walls are regularly used for the purpose of climate control in exterior and party walls and acoustic benefits. However, they are also required to be fire rated. Hence many researchers investigated the fire resistance ratings of LSF wall systems with different types of insulations in the wall cavities. Sultan (1995) found that when rockwool was used as cavity insulation the fire resistance rating increased by 54% over the non-insulated wall assemblies. Kodur and Sultan (2001) found that LSF wall assemblies without insulation provides higher fire resistance compared to cavity insulated LSF wall assemblies. Feng et al. (2003) found that the thermal performance of steel channel wall panels was not affected by the type of insulation and that the thermal performance of wall panels improved with the use of cavity insulation. In summary, past research has provided varying results about the benefits of cavity insulation to the fire rating of LSF wall systems. Kolarkar and Mahendran (2008) developed a new composite LSF wall panel system in which a thin insulation layer was used externally between plasterboards instead of the conventional cavity insulation located within the stud space. Since the new composite LSF wall panels have an external insulation layer between the plasterboards, they also provide climate control and acoustic benefits. Kolarkar and Mahendran (2008) found that composite LSF wall panels provided a better quality thermal envelope than the cavity insulated LSF wall panels. However, the use of such composite panels is considered expensive due to the complicated installation process and higher labour cost. This research therefore aims to use alternative methods based on enhanced plasterboards to develop LSF wall systems with increased fire rating.

Many research studies have investigated the thermal behaviour of conventional gypsum plasterboards, mostly under a standard fire (time-temperature) curve. Limited research has been undertaken on thermal behaviour of enhanced plasterboards. The dehydration of gypsum associated with the decomposition of calcium carbonate absorb heat, giving the plasterboard its fire protection qualities. However, the fire protection qualities of gypsum plasterboards have not been improved much despite their use for many years. Keerthan and Mahendran (2010) found that currently available Australian plasterboards showed that calcination is associated with two dehydration reactions at 100 to 150^{o}C and 150 to 200ºC, respectively, and resolved the contradictions among past researches. They have improved the understanding of the thermal performance of conventional Australian plasterboards under standard fire conditions including their thermal properties as a function of temperature, and developed validated thermal numerical models for plasterboards and LSF wall systems (Keerthan and Mahendran, 2012).

The 16mm standard plasterboard currently used in construction only provides 60 minutes of fire protection (non-load bearing LSF wall). When wall designs require increased fire resistance rating, multiple plasterboards are used to increase the fire resistance rating (FRR). By improving the specific heat capacity and reducing the thermal conductivity of the gypsum plasterboard, its fire rating could be increased to negate the need for additional plasterboards. The chemical composition of the gypsum plasterboard could be modified through the addition of chemical additives and fillers to improve the thermal properties of plasterboard. Figure 2 demonstrates the time-temperature profiles of standard and enhanced plasterboards under standard fires.

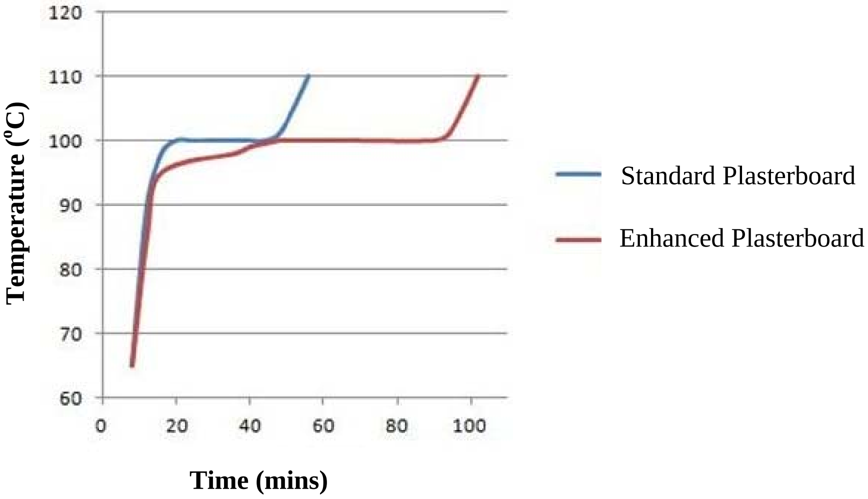


Figure 2: Time-temperature profiles of standard and enhanced plasterboards

Plasterboard manufacturers use additives such as vermiculite to overcome shrinkage of gypsum core and glass fibre to bridge shrinkage cracks and enhance the integrity of board during calcination and after the loss of paper facings in fires. Attempts were made to reduce the thermal conductivity of plasterboard using fillers (Baux et al., 2008 and Baspinar et al., 2011). However, no research has been undertaken to enhance the specific heat and the points of dehydration using chemical additives and fillers. Thirty specific heat and density tests of powdered samples of plasterboard mixed with chemical additives and fillers in varying proportions were conducted. In this research, finite element (FE) models of enhanced plasterboards were also developed to simulate their thermal behaviour under standard fire conditions using SAFIR. Measured thermal properties of enhanced plasterboard were used in these FE models. This paper presents the details of experimental and numerical studies into the thermal performance of enhanced plasterboards and the results that can be used to enhance the fire safety of steel wall systems commonly used in buildings.

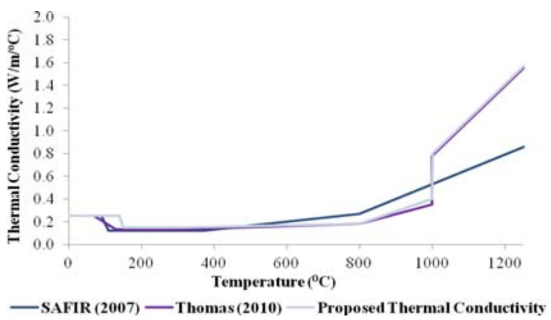
2. Thermal properties of standard plasterboard

In order to develop suitable finite element models of Australian gypsum plasterboard, thermal properties of gypsum plasterboard were summarized based on a series of experimental results (Keerthan and Mahendran, 2011) and past research (Cooper, 1997; Thomas, 2010). Figure 3(a) shows the proposed thermal conductivity of gypsum plasterboard. In order to include the effect of ablation, the thermal conductivity of plasterboard was modified to 0.80 W/m/K at 1000ºC.

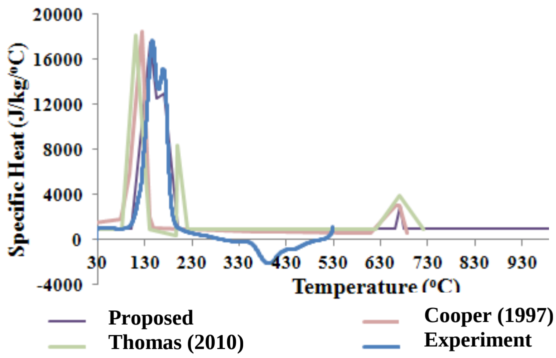
Past research showed some discrepancy in relation to the second dehydration reaction. However, it is concluded that the first and second dehydrations occur at 100 to 150ºC and 150 to 200ºC, respectively, based on our experiments (Keerthan and Mahendran, 2012). Figure 3(b) also shows the proposed specific heat values as a function of temperature and compares them with test and other researchers' specific heat values (Cooper, 1997; Thomas, 2010) while Figure 3(c) shows the relative density values as a function of temperature and compares them with test and other researchers' relative density values (Cooper, 1997; Thomas, 2010). Further details of the proposed thermal properties of plasterboards are given in Keerthan and Mahendran (2012). The specific volumetric enthalpy of gypsum plasterboard is given by the area under the specific heat multiplied by the density versus temperature curve as shown in Equation (1).

$$E(T) = \int_{T_A}^{T} C_P(T)\rho(T)dT \qquad (1)$$

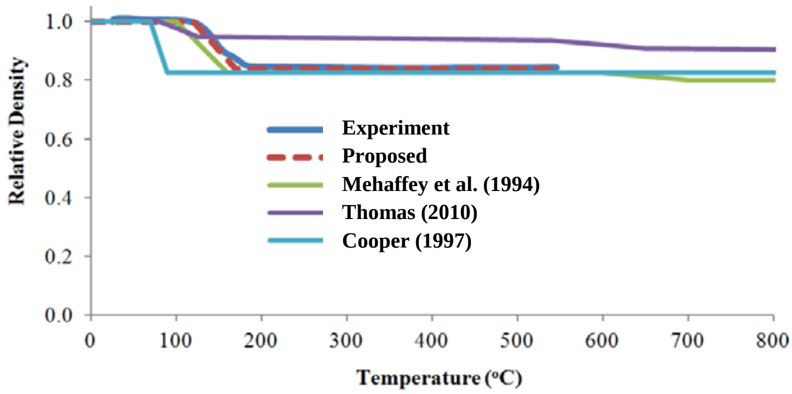
where E(T) is the specific volumetric enthalpy in J/m^3 at temperature T, Cp(T) is the specific heat (J/(kgºC)) and ρ(T) is the density (kg/m^3) at temperature T, and T_A is the ambient temperature. Keerthan and Mahendran (2012) recommended a convective coefficient (h) of 25 W/m^2/K for the exposed side of plasterboard and 10 W/m^2/K for its unexposed side. They recommended 0.9 as emissivity of plasterboard for both exposed and unexposed surfaces. When the proposed thermal properties were used as input to SAFIR, the time-temperature profiles agreed well with Kolarkar's (2010) fire test results.



(a) Thermal conductivity



(b) Specific heat



(c) Relative density

Figure 3: Proposed thermal properties of standard plasterboard (Keerthan and Mahendran, 2012)

3. Thermal properties of enhanced gypsum plasterboard

3.1 Literature review

In order to enhance the fire resistant rating (FRR) of gypsum plasterboard, past researches have investigated the effects of fillers and additives on the thermal properties of gypsum plasterboard. Baux et al. (2008) investigated the effects of silica based filler on the thermal and mechanical properties of gypsum-based panels. They also investigated the effects of silica filler on shrinkage and cracking caused during the dehydration of gypsum. Figure 4 shows the thermal conductivity of gypsum board as a function of the filler content. The results show that adding the filler dramatically decreases the thermal conductivity.

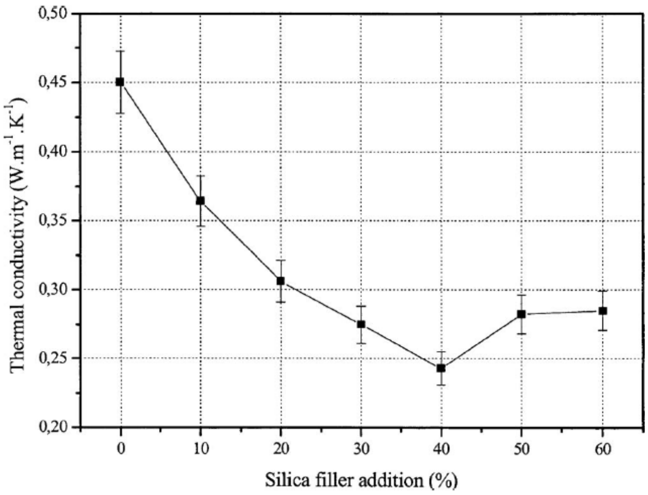


Figure 4: Thermal conductivity versus Silica filler addition (Baux et al., 2008)

Figure 5 shows the time-temperature profile of 40 mm gypsum panel (Temperature measured 30mm from the exposed face of the gypsum panel). Baux et al. (2008) observed that the time-temperature profile consisted of three stages when there was no filler addition and four stages when the silica fume was present (see Figure 5). The exposed side of the panels after fire tests is shown in Figure 5 (Baux et al., 2008).

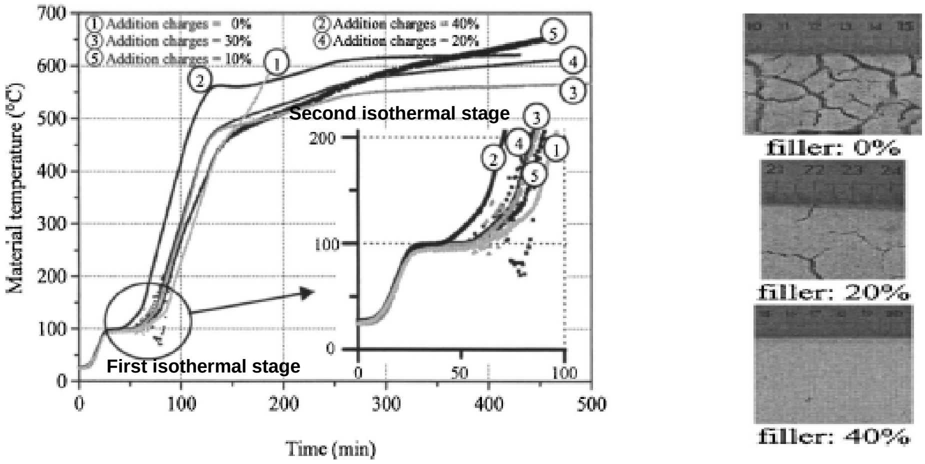


Figure 5: Time-temperature profile of 40 mm gypsum panel (Baux et al., 2008)

Baux et al. (2008) found that the length of first isothermal stage depends on the gypsum amount. They found that the shrinkage induced by the dehydration increases the heat flow through the panels and consequently increases the temperature of the unexposed side.

The two first stages of gypsum panels with silica fume are similar to those of the gypsum panels without filler. The length of the first isothermal stage depends on the filler amount. Addition of fillers (silica fume) decreases the specific heat of gypsum. The second isothermal stage at 600^{O}C is not induced by another phase change (see Figure 5). It is due to the stabilization of the heat flow activated by thermal conduction and convection (Baux et al., 2008).

Baux et al. (2008) found that adding small amounts of silica filler to the plaster gives the following advantages. The propagation of the microcracks related to the dehydration of gypsum is blocked. The compressive strength increases as the density decreases and the thermal conductivity is reduced. One drawback is the reduction of specific heat capacity due to the substitution of gypsum by silica fume. Baux et al. (2008) found that the use of aluminosilicate fillers is promising above 1000°C.

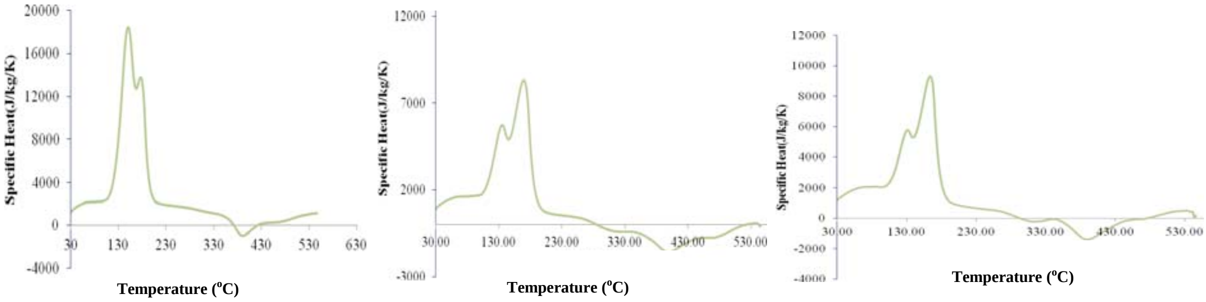
Baspinar and Kahraman (2011) found that addition of expanded silica gel granules to hardened gypsum decreased the bulk density of product significantly without any significant loss in compressive strength. They also found that Macroporous foam like structure of expanded silica gels decreased the thermal conductivity of hardened gypsum at around 61.3%. High temperature durability of the hardened gypsum product was also improved when the expanded silica gel granules were added. They concluded that expansion of silica gel is a controllable process and its addition to gypsum product improves many properties. Table 1 shows the results of thermal and mechanical test results. It shows that adding the silica gel dramatically decreases the thermal conductivity of gypsum.

Table 1: Properties of gypsum-expanded silica gel samples (Baspinar and Kahraman 2011)

Name of the series Expanded silica gel (wt.%)	G0 0% (control series)	GS5 5%	GS10 10%	GS15 15%
Water absorption	22.98	21.88	21.59	17.91
Apparent porosity (%)	30.07	24.13	21.68	Not measured
Bulk density (g cm^{-3})	1.31	1.10	1.01	0.89[a]
Compressive strength (MPa)	3.21	3.09	2.73	2.38
Flexural strength (MPa)	2,51	2.16	1.86	1.14
Ultrasonic wave Velocity (m sn^{-1})	4760	5750	6620	7190
Calculated ultrasonic Young modulus (GPa)	29.68	36.24	44.26	46.01
Thermal conductivity (W/m K)	0.31	0.25	0.21	0.16

3.2 Thermal properties of enhanced plasterboards

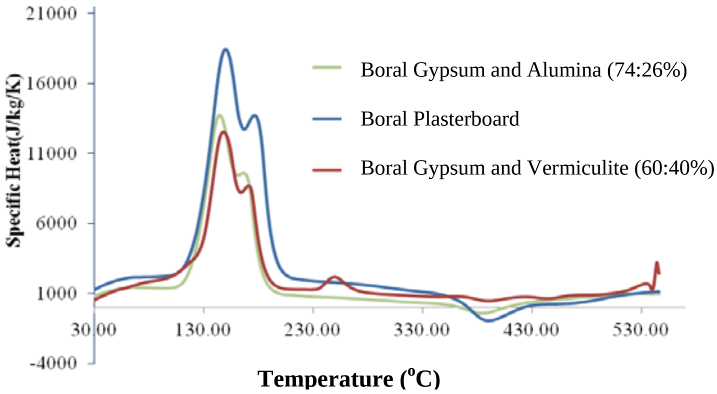
The thermal properties of conventional/standard plasterboards (Boral, CSR and Knauf) were measured (see Figure 6), which showed that Boral Firestop plasterboard's thermal properties are superior to those of other conventional plasterboards. Hence only the Boral Firestop plasterboard was considered in this research to further enhance the thermal properties.



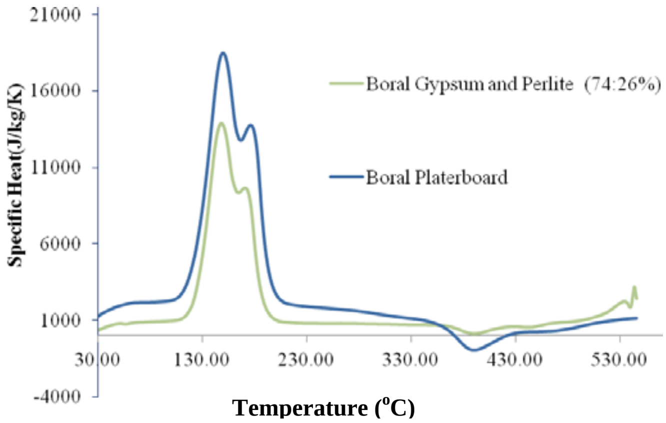
(a) Boral Plasterboard *(b) CSR Plasterboard* *(c) Knauf Plasterboard*

Figure 6: Specific heat of different types of Australian plasterboard

Thirty specific heat and density tests of powdered samples of plasterboard mixed with chemical additives and fillers in varying proportions were conducted using differential scanning calorimetry (DSC) and thermo-gravimetric analysis (TG) to determine suitable combinations that improve thermal properties.

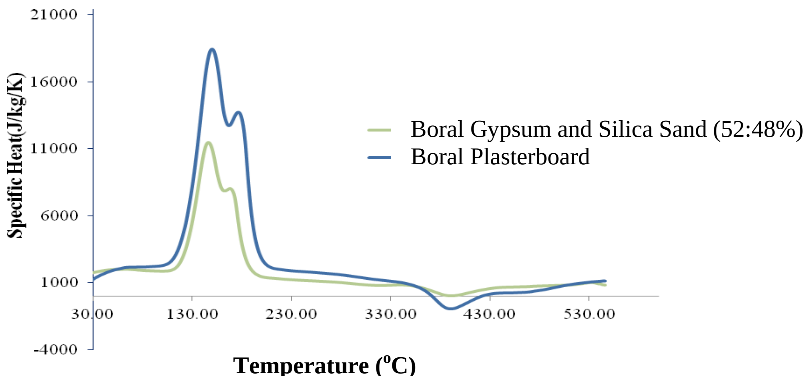


(a) Alumina and Vermiculite



(b) Perlite

Figure 7: Effect of chemical additives on the specific heat of plasterboard



(c) Silica sand

Figure 7: Effect of chemical additives on the specific heat of plasterboard

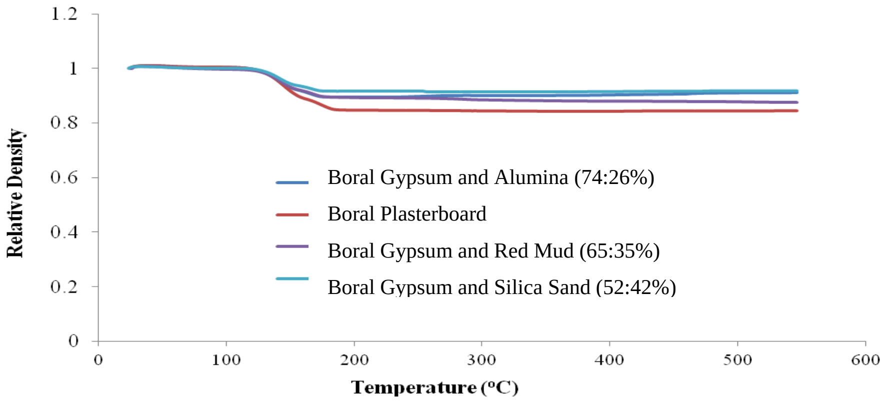


Figure 8: Effect of chemical additives on the relative density of plasterboard

Initially chemical additives and fillers such as Perlite, Alumina, Silica Sand, Calcium Silicate and Vermiculite were considered. Figures 7(a) to (c) show the effects of using them on the specific heat of the gypsum plasterboard while Figure 8 shows the effects on the relative density of the gypsum plasterboard. Figure 7 shows that chemical additives and fillers such as Vermiculite, Alumina, Perlite and Silica sand reduce the specific heat of the plasterboard, and this is not desirable although Vermiculite produced a third peak at approximately 260°C. Figure 8 shows that adding Vermiculite, Alumina, Red Mud and Silica sand increase the relative density of plasterboard, which is useful. These chemical additives and fillers will also reduce the shrinkage induced by the dehydration and reduce the heat flow through the panels. Overall, the use of Perlite, Alumina, Silica Sand, Calcium Silicate, Red Mud and Vermiculite is not likely to produce significant improvements to the thermal performance of plasterboards.

In the second stage of our tests two chemical additives that are by-products of industrial waste were attempted. Figure 9 shows that the use of these chemical additives (A and B) are able to enhance the specific heat of plasterboard with four peaks and increased the enthalpy of plasterboard. During heating, the relative density of plasterboard reduces slightly (Figure 10) and therefore the specific volumetric enthalpy given by the area under the specific heat multiplied by the density versus temperature is the most important parameter governing its thermal performance. By increasing the enthalpy and reducing the thermal conductivity, fire resistant qualities of plasterboards can be significantly improved. Test results in Figure 9 show the presence of four peaks instead of two observed for standard plasterboards and the resulting enhancement of enthalpy by 35%. Its thermal conductivity is reduced from 0.25 to 0.1 after two peaks. Hence four peaks will lead to further reduction in thermal conductivity (0.05). However, thermal conductivity of standard plasterboard was used in our numerical studies conservatively.

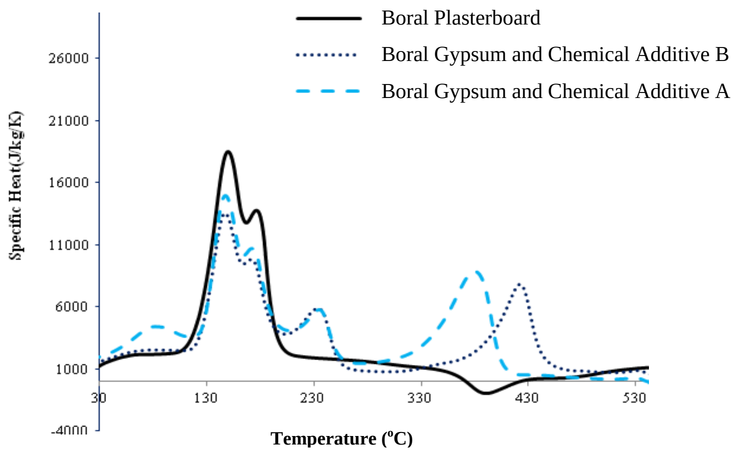


Figure 9: Effect of chemical additives A and B on the specific heat of plasterboard

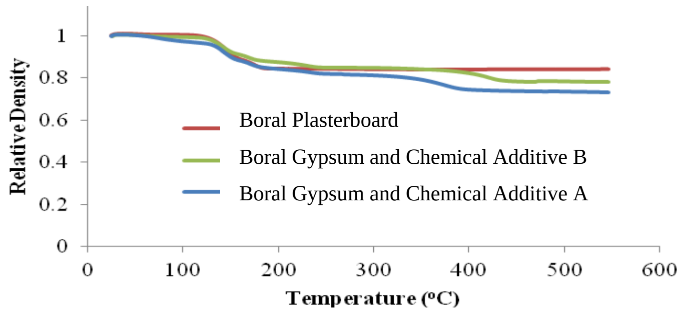


Figure 10: Effect of chemical additive B and Red Mud on the relative density of plasterboard

It was found that Boral gypsum with chemical additive A provided the higher specific heat capacity and resulting enhancement of enthalpy by 35%. Hence the measured thermal properties of Boral gypsum with chemical additive A were used in numerical studies.

4. Numerical studies of the thermal behaviour of load bearing LSF wall panels with enhanced plasterboards

4.1 General

This section presents the details of the numerical studies into the thermal behaviour of the load bearing LSF walls with enhanced plasterboards and their results. Recently many numerical heat transfer models have been developed (Alfawakhiri, 2001; Franssen, 2005). There are also many general finite element packages that can be used for thermal analyses. The finite element model employed in this study to predict the thermal behaviour of load bearing LSF wall panels with enhanced plasterboards was based on SAFIR (Franssen, 2005). SAFIR is a special purpose finite element program for the analysis of structures under ambient and elevated temperature conditions. In this research the GID software was used to create the input file for the models as well as analysing the model output results.

4.2 Thermal boundary conditions and material properties

The heat flux at the boundary will be calculated from the temperature of the fire curve T_g and the temperature on the surface T_s according to Equation (2).

$$q = h(T_g - T_s) + \sigma\varepsilon(T_g^4 - T_s^4) \qquad (2)$$

where q is the total heat flux, ε is the relative emissivity, σ is the Stefan–Boltzmann constant (5.67E−08W/m^2/K^4), T_g and T_s are the gas and surface temperatures, respectively. For fire exposure to the standard cellulosic curve, T_g = 345log(8t+1)+20. Convective heat transfer coefficient (h) is approximately 25 W/m^{2}K on the fire exposed side, and it is 10 W/m^{2}K on the unexposed side. Emissivity of 0.9 was used for both exposed and unexposed surfaces. Default thermal properties (specific heat and thermal conductivity) for both Type X and Type C gypsum plasterboards within SAFIR are based on Cooper's (1997) research. However, the measured thermal properties of enhanced plasterboard in Section 3.2 were used in this research (Boral gypsum with chemical additive A). Since the thermal conductivity of enhanced plasterboard was not measured, thermal conductivity of standard plasterboard was used in numerical studies conservatively. Figure 11 shows the finite element models of LSF wall with two enhanced plasterboards on each side. Here three voids were created to transfer the heat through radiation and convection. Elements surrounding an internal void were assigned in the counter clockwise direction.

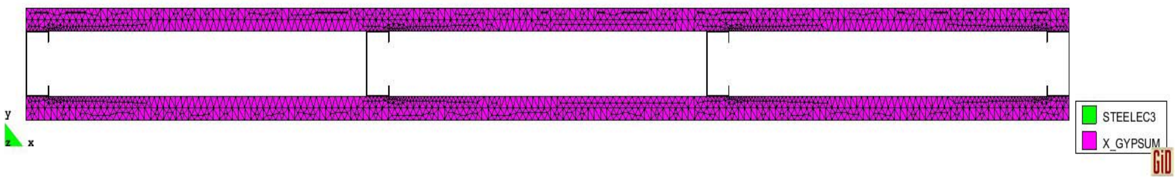


Figure 11: Finite element modelling of LSF wall panel

It is necessary to validate the developed finite element models for the thermal analyses of standard and enhanced plasterboards and load bearing LSF walls with enhanced plasterboards. This was achieved by comparing the time-temperature profiles with the corresponding fire test results of standard plasterboard and load bearing LSF walls with standard plasterboards (Kolarkar, 2010). Hence validated finite element models can be used for the thermal analyses of load bearing LSF walls with enhanced plasterboards. Details of the validated thermal finite element models are given in Keerthan and Mahendran (2012).

To demonstrate the improved thermal performance and associated high FRR, the validated thermal FE model developed in Keerthan and Mahendran (2012) was used with the measured thermal properties of enhanced plasterboards to predict the time-temperature curves in LSF walls. Failure time (FRR) of load bearing LSF wall with two 16 mm standard plasterboard is 111 mins for a load ratio of 0.2. Figure 12 shows that the LSF wall steel stud temperatures [hot (HF) & cold (CF) flanges, web] are considerably reduced in comparison to standard plasterboards under standard fires. This means that the failure time (FRR) increases from 111 to 146 mins based on the limiting temperature of 500ºC when enhanced plasterboards are used, ie. 32% increase. Figure 13 shows the temperature distributions of LSF walls with two 16 mm enhanced plasterboards under standard fire conditions.

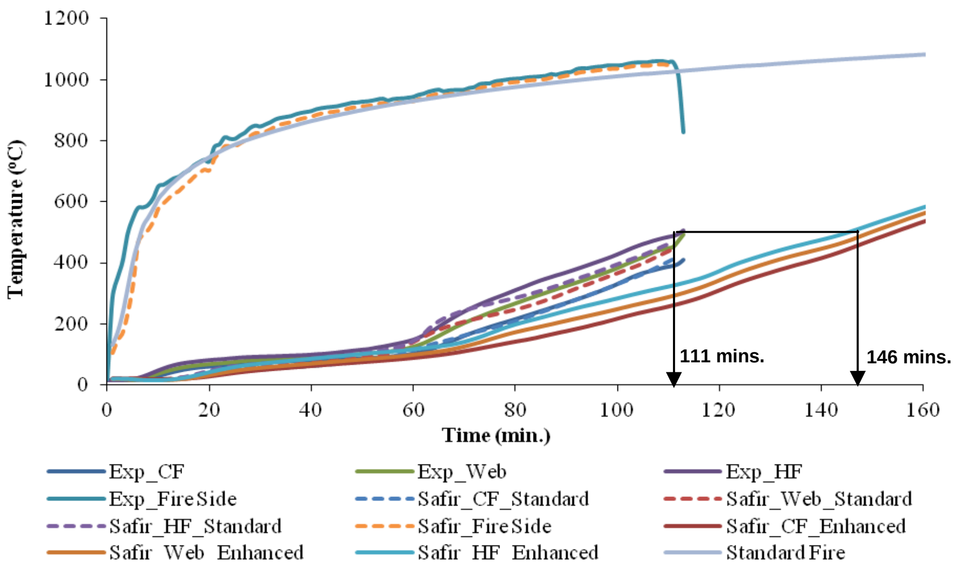
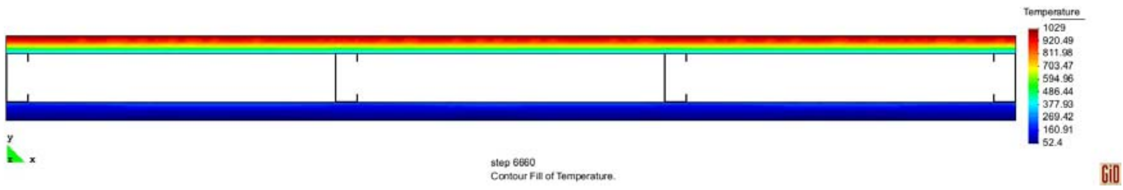
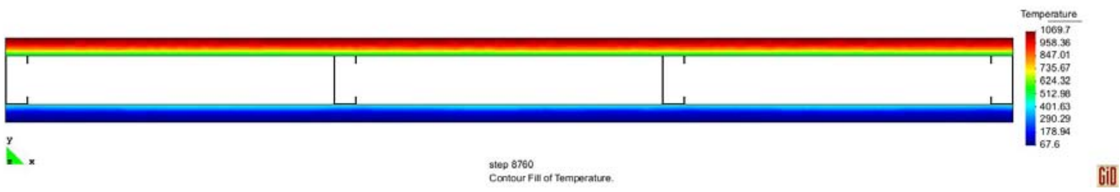


Figure 12: Time-temperature profiles of LSF wall with two 16 mm enhanced plasterboards



(a) 111 minutes



(b) 146 minutes

Figure 13: Temperature distributions of LSF walls with two 16 mm enhanced plasterboard under standard fire conditions

5. Conclusions

This paper has presented the effects of using chemical additives and fillers on the thermal performance of gypsum plasterboard. It was found that the use of suitable chemical additives is able to enhance the specific heat of plasterboard with four peaks and increased area under the curve (Enthalpy). Numerical models were also developed to investigate the thermal performance of load bearing LSF walls with enhanced plasterboards under standard fire conditions. The results showed that enhanced plasterboards can be used with LSF walls to significantly improve their fire resistance rating.

6. Acknowledgements

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