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Experimental investigation of the fire resistance of multi-layer drywall systems incorporating Vacuum Insulation Panels and Phase Change Materials

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ABSTRACT

This paper studies the fire resistance of innovative high thermally insulated multilayer drywall assemblies incorporating conventional insulation materials, Phase Change Materials (PCMs) and Vacuum Insulation Panels (VIPs). An experimental study was developed and implemented into two directions. In the first direction, four different multilayer drywall configurations were subjected to fire temperatures up to 900 °C from one side, while the other side was at ambient conditions. Each configuration consisted of a gypsum board with PCMs (PCM-GB), a standard gypsum board (S-GB), an Expanded Polystyrene (EPS) layer, a thermal insulation render containing EPS (TIR) and an insulation layer located between the PCM-GB and the S-GB. A different insulation layer was used for each configuration: cavity (no insulation), EPS, mineral wool (MW) (both conventional insulation materials) and Vacuum Insulation Panels (VIP) (super insulation material). In the second direction, Differential Scanning Calorimetry (DSC) measurements, at inert (nitrogen) and oxidized (air) environments, were performed for all the utilized materials.

DSC results indicated that at temperatures up to 200 °C, the gypsum boards (both PCM-GB and S-GB) act as fire retardants because of the dehydration process. The paraffin and PMMA components of the PCM started to evaporate and oxidize at temperatures higher than 200 °C and up to 500 °C. The resin binder of the mineral wool started to volatilize and oxidize at 265 °C, while at 500 °C the mineral wool started to melt. The volatilization of the EPS started at 275 °C, while the full volatilization and oxidation took place at the temperature range between 420 °C and 550 °C. The chemically bound water of the TIR dehydrated at the temperature range between 50 °C and 200 °C, while the EPS contained in the TIR behaved similar as the EPS sample. Finally, the cellulose fibers contained in the VIP volatilized and oxidized at the temperature range between 320 °C and 480 °C.

Furnace results confirmed the fire resistance behavior of the gypsum boards indicated by the dehydration "plateau". The wall assembly with the EPS layer found to behave similar to the assembly with the cavity due to the fact that the EPS melted at temperatures near 200 °C. The wall assembly with the mineral wool delayed the temperature rise until 500 °C where it started to melt. The VIP layer found to significantly delay the penetration of the heat through the drywall configuration when compared to the other configurations. According to the failure criteria regarding excessive temperature rise on the ambient facing side of the wall, the VIP layer was found to increase the time-to-failure by approximately 68%, with respect to the assembly with the cavity. On the other hand, the respective time increase for the conventional insulation materials was 2% and 19% for the EPS and the MW, respectively.

1. Introduction

In the last two decades, the need for sustainable buildings that minimize the consumption of raw materials and energy [1] has gradually shifted the focus of the building sector towards lightweight constructions and nearly Zero Energy Buildings (nZEB). Lightweight multi-level buildings based on Dry Wall Systems (DWS) provide a safe, fast and long lasting solution to housing, particularly in high risk areas, such as highly seismic areas [2,3]. On the other hand, the presence of low density materials and thin envelopes in the lightweight buildings reduces the thermal efficiency (low thermal mass and low insulation) of the buildings. The latter, creates a number of new challenges for the design of

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Nomenclature

Abbreviations

DSC	Differential Scanning Calorimetry
DWS	Dry Wall System
EPS	Expanded Polystyrene
MW	Mineral Wool
nZEB	Nearly Zero Energy Building
PCM	Phase Change Materials
PCM-GB	Gypsum board with Phase Change Materials
PFP	Passive Fire Protection
S-GB	Standard gypsum board
SIM	Super Insulation Material
TES	Thermal Energy Storage
TIR	Thermal Insulation Render
VIP	Vacuum Insulation Panel

lightweight buildings. An attractive solution to this challenge appears to be the efficient integration of Phase Change Materials (PCMs) and Super Insulation Materials (SIM) in the lightweight building envelope [4]. The PCMs, due to their high amount of latent heat, utilized for thermal energy storage in building elements, are able to cope with thermal and electricity peak loads [5]. The SIMs, due to their very low thermal conductivity, provide efficient wall insulation solutions, as well as efficient solutions to thermal bridging effects [6]. Hence, the incorporation of PCMs and SIMs in DWS can lead to sustainable and thermally efficient lightweight constructions.

Thermal Energy Storage (TES) in general and PCMs in particular, have been a research topic for the last 20 years. TES is an area of international interest dealing with energy saving, efficient and rational use of available resources [7–12]. It provides solutions in very specific areas: time delay and available power between production or availability of energy and its consumption in receiving systems (solar energy, cogeneration, etc.); security of energy supply (hospitals, computer centers, etc.); thermal inertia and thermal protection of the buildings. The thermal inertia and thermal protection are the areas where the PCMs have achieved a relatively high market penetration. Applications include, among others, their incorporation in the core of building materials. Particularly in the building sector, PCMs have been successfully integrated in the building fabric either by directly incorporating PCM microcapsules into commonly used building materials, such as in concrete, gypsum boards and natural stones [13–15] or by using separate layers of shape stabilized PCMs in wall assemblies [16]. The utilization of PCMs could lead to reduction of power requirements of the heating and cooling equipment commonly used to secure continuous energy supply. In the building context, the incorporation of PCMs into the core of building materials is intended to increase the thermal storage capacity of the building element [17]. The technology takes advantage of the latent heat of the PCM during the solid–liquid change of state to stabilize the temperature of the material and reduce the heat losses/gains from the building to the environment [18,19]. However, PCMs are usually mixtures of hydrocarbon molecules, which at temperatures higher than 200 °C evaporate. The gas mixture produced is flammable and may affect the fire endurance of the building element [20].

SIMs and particularly the Vacuum Insulation Panels (VIP) have been developed in the last decade, mainly for use in appliances, such as refrigerators and deep-freezers [21,22]. The reason hereto is the significantly low thermal conductivity (5–7 mW/(m K)), a factor of five to eight times better than the conventional insulation materials (≥ 30 mW/(m K)) [23]. In the frame of building constructions, VIPs enable thin and highly insulation constructions to be realized for walls, floors and roofs. The motivation for examining the SIMs in buildings comes mainly from the difficulties involved in renovation, aesthetic considerations, as well as from the necessity to reduce the overall energy consumption of the buildings. The latter is accomplished by increasing the thermal resistance of the envelope's walls, as well as by reducing the effect of thermal bridges introduced when materials with higher thermal conductivity (e.g. steel studs) break through or partially break through a layer with higher thermal resistance (i.e. lower thermal conductivity) creating pathways of lower thermal resistance causing increased heat losses [24–26]. VIPs consist of inorganic compounds and thus, it is expected that they would enhance the fire resistance of a wall configuration. To the authors' knowledge, there is not any research found in the literature on the fire behavior of VIPs.

Fire protection in the building technology is still extremely topical, especially due to the increase of the legislation and fire standard restrictions [27,28]. Dry wall systems (e.g. gypsum boards, cement boards etc.) are the most common systems used in lightweight steel skeleton buildings as Passive Fire Protection (PFP) systems for the steel structure (e.g. frames, studs etc.) [29]. This is due to the fact that they have very good fire behavior, associated with the water contained in their crystal structure, which is evaporated under fire conditions absorbing significant heat quantities from the fire and thus, delaying the heat penetration through the assembly [30–32].

The objective of the current work is to study for the first time the fire resistance of innovative and high thermally insulated wall assemblies in terms of energy storage and super insulation capabilities. The examined combinations of multilayer assemblies can find direct application in drywall construction due to their exceptionally good thermal insulation properties and relatively low thickness. An experimental study was developed and implemented, where "small-scale" furnace tests, as well as DSC measurements were performed in order to deeply analyze the fire resistance of the examined configurations. Within the furnace tests, four different multi-layer drywall configurations incorporating PCMs, VIPs and conventional insulation materials (mineral wool and expanded polystyrene) were subjected to fire temperatures up to 900 °C from one side, while the other side was at ambient conditions. Additional DSC measurements for all the components of the examined assemblies were performed in order to assess their thermal degradation at temperatures up to 600 °C. The main innovation of this work is owed to the study of the fire behavior of VIPs and PCMs, the interaction between different building materials that form a wall assembly under fire conditions and to the provision of experimental data in order to calibrate and validate dedicated fire numerical models.

2. Experimental study

The overall experimental strategy followed two directions. Firstly, the chemical reactivity of the examined materials under inert and oxidized conditions was examined by performing DSC measurements. Secondly, "small-scale" furnace experiments were performed, in which multi-layer configurations, composed of different building materials, were positioned in front of a high temperature radiation furnace. The temperature evolution at different positions through the configurations was recorded, and together