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INSULATION MATERIALS IN MASONRY BLOCK CAVITIES – DOES THIS HELP FIRE RESISTANCE RATING - FINITE ELEMENT STUDY

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ABSTRACT

The effect of fire temperatures on concrete masonry has been an area of interest over the years. The performance of concrete masonry during a fire has been concluded to be excellent because of its non-combustible nature, exceptional thermal properties, and stability. Hollow blocks with vertically oriented cavities are widely used in order to reduce heat flow through a wall. However, heat transfer predominantly by radiation and convection through the cavities is of major concern, as the hot gases in the cavities travels upward and increase the heat flow in the blocks. This gives rise to the need to further improve the fire resistance of concrete masonry blocks through the use of a lightweight insulating materials placed in the cavities. This study involves the use of alternative approach to study the thermal behaviour of normal weight concrete masonry walls with gypsum and polystyrene materials as fillers in the block cells. A finite element thermal analysis was conducted using ABAQUS CAE 14 on hollow concrete masonry blocks. The results obtained were compared with the air-filled masonry walls. All the walls failed due to the 180 °C insulation failure criteria. The walls with gypsum and polystyrene inserts had improved fire resisting properties than those with air-filled cavities. They improved the fire resistance of masonry concrete blocks by an additional 48mins.

KEYWORDS: *concrete masonry, fire, gypsum, heat transfer, insulation, modelling*

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INTRODUCTION

Over the years, critical events like the collapse of the World Trade Center towers within 1 hour and 42 minutes on September 11th in Manhattan have led to the increasing interest in the behavior of building materials and structures in a fire. This incident caused over billions of dollars in infrastructure and property damage, 2996 deaths and more than 6000 injured [1]. The behaviour of concrete masonry walls in a fire is largely influenced by the mechanical and thermal properties. At elevated temperatures, the cement paste in concrete undergoes an endothermic reaction. This phase assists in limiting the temperature rise in the fire-exposed concrete. This is why the performance of concrete masonry walls during elevated temperatures is deemed excellent. Hollow blocks are widely used in the building industry because they are lightweight, easy to install and cost-effective. When the hollow blocks are stacked in a running bond pattern, the heat transfer via conduction, convection and radiation takes a longer route. Regardless of this, the heat transfer via radiation and convection through the cell cavities is still a major concern [2]. When concrete masonry wall is heated, the hot gases in the cavities travel upwards, and increase the heat flow in the blocks. This eventually causes failure to occur in the cell cavities.

Nowadays, the convectional masonry wall requires additional thermal insulation to increase its thermal resistance. This can be added in the block mix or as cell fillers in the hollow blocks. Both methods have a significant positive effect on the thermal resistance of masonry blocks, however, the blocks filled in have a better thermal resistance than those block mixed [3]. This is due to the elimination of the effect of radiation and convection, by having the cavities filled. Al-Hadhrami *et al*. [3] in their research concluded that for blocks filled with insulating materials, the type of insulation used is significant. This is because of the chemical compositions of the insulation materials, allowing them to react differently in fire. Insulating materials are lightweight, poor conductors of heat, and have a low thermal conductivity. They can be organic or inorganic materials. [4]. Organic insulation materials can be gotten from renewable materials and natural vegetation e.g., polystyrene, flax wool, etc. while inorganic insulation materials can be gotten from non-renewable materials e.g., mineral wool, perlite, gypsum etc. [4]. Organic insulation materials have better thermal insulating properties, although they are highly flammable, and expensive [5]. Inorganic insulations on the other hand have a lesser thermal insulating property but are inexpensive. They are able to resist moisture and fire better [4], and for this reason, they are preferred in construction. When compared to organic insulation materials, inorganic materials have a greater density. This may not always be desirable, but the thickness needs to be increased to match a certain level of thermal insulation.

For the purpose of this research, gypsum and polystyrene were the chosen insulation materials. Gypsum is a highly porous material that contains about 21% by weight of chemically bound moisture in its crystals. Evaporation of the moisture in gypsum occurs in a double stage, at two different peaks points. The first peak point of moisture loss takes place at 100 °C, where gypsum loses about 75% of its moisture [6]. The other 25% of its moisture is lost during the second stage of moisture loss. Research conducted in the past do not all agree on the second peak point for moisture loss to occurs. Sultan [6] reported a second peak at 670 °C but Mehaffey *et al*. [7] only went as far as 200 °C in their experiment, and so no peak point was recorded. During moisture loss, the free and chemically bound water is released into the pores, resulting in an increased pore pressure. This process of water release and evaporation is known as calcination of gypsum. The heat absorbed by gypsum at elevated temperatures does not cause temperature increase [8]. This property of gypsum makes it of interest in fire protection. Heat transfer through gypsum occurs via conduction, convection, and radiation. Gypsum plaster boards subjected to elevated temperatures are susceptible to cracks, but not large enough to pose a problem [8]. These cracks only widen when cooling begins.

Polystyrene used as insulation can be of various forms, with expanded polystyrene (EPS) and extruded polystyrene (XPS) being the most common forms. They all have a closed cell form making them good insulating materials. They are able to keep heat in or out of structures. When polystyrene was used as a cell filler, it showed a 30% decrease in the thermal conductivity of the assembly [9]. Another research conducted using polystyrene bars as cell fillers showed a 36% reduction in the heat transfer rate [10]. Past research on the impact of moisture and temperature on the thermal conductivity of EPS showed that as a result of its impermeable nature, the thermal conductivity increases as the moisture and temperature increases [11], but decreases when density increases [12].

Al-Hadhrami *et al*. [3] also highlighted another method of further improving the thermal resistance of a wall assembly through the use of insulating mortar as opposed to using conventional mortar [3]. Insulating mortar showed a 23 – 46 % increase in the thermal resistance of the walls [3]. With the use of insulating mortar, the tendency of the mortar joints to act as thermal bridges are eliminated. These insulating mortars consists of a cementitious binder, water, and lightweight aggregate such as expanded perlite, polystyrene particles (PP), and vitrified microsphere [13].

The aim of the current study is to analyse the effects on the fire resistance of assemblies when the cell cavities are filled with insulating materials. A numerical investigation was conducted using gypsum and polystyrene as cell fillers.

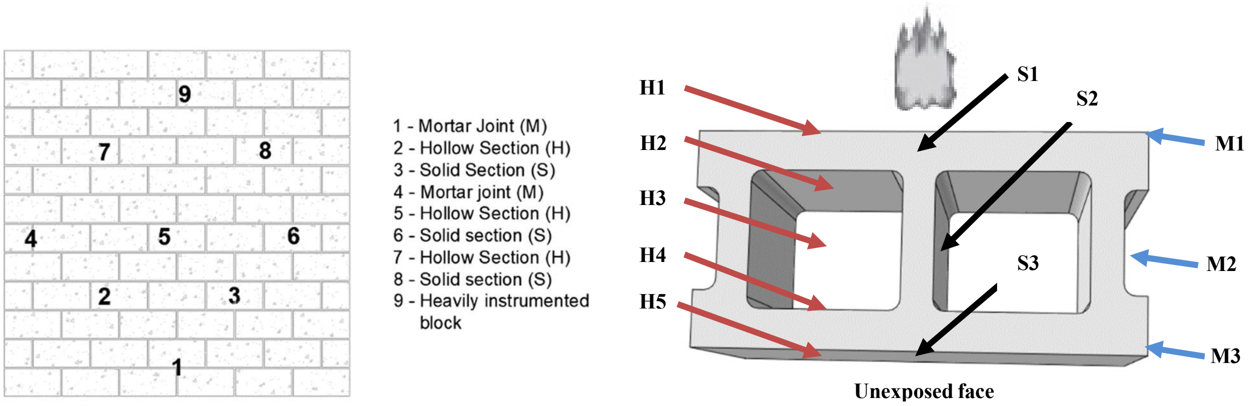
Fire resistance

The most common approach to assessing the fire resistance of a building element or assemblages is by using the full-scale fire resistance test. In Canada, this test is done according to the CAN/ULC-S101. It is a time consuming and expensive approach. The test makes use of a standard fire curve, that in reality, does not clearly depict a real fire but works as a good approximation to creating standards and determining failure times or modes of building elements. Depending on the building element in question, there are three (3) failure criteria for fire resistance testing: Insulation, stability, and integrity. During a test, when any of these criterions are reached, failure is assumed, and the test is terminated. Building elements like load-bearing walls, floors, beams, or columns fail to meet the stability criterion, when they can no longer support the loads for which they were designed for, resulting in a collapse. Building elements such as partitions, floor etc. fail to meet the integrity criterion, if cracks develop, allowing the passage of smoke or hot gases through the walls. Building elements like non-loadbearing walls fail by insulation when the temperature on the unexposed face of the wall exceeds an average increase of 140 ºC or 180 ºC on a single point. Few factors primarily control the fire resistance of a concrete masonry wall. They include cement type, aggregate type, thermal capacity, moisture content and thermal conductivity of the concrete. These factors determine the extent of heat transfer through the concrete masonry, from the exposed face of the block to the unexposed face.

EXPERIMENTAL SETUP

Full-scale fire resistance test was conducted on a non-loadbearing wall 2.8 m wide and 3.2 m high. The wall was exposed to the CAN/ULC-S101 standard fire to investigate the thermal behaviour of the wall. It was constructed using a 15 MPa, standard 20 cm normal weight concrete hollow masonry blocks (390 x 190 x 190 mm) bonded together with a 10 mm general-purpose Type S concave mortar joint. The mortar was a cement-based one with a strength of 12.5 MPa. To monitor the heat transfer rate through the walls, from the exposed side of the wall to the unexposed side of the wall, Type K thermocouples were placed at unique locations on both sides of the wall. These Type K thermocouples are the most common types, with a wide temperature range of −200 ºC to +1350 ºC. As illustrated in Figure 1*a,* thermocouples were placed on the unexposed side of the wall at locations 1 to 9 in accordance with CAN/ULC-S101. The block located at position #9 was heavily instrumented to further study the heat transfer through the block. This block was chosen because of its location high up on the wall, as it is assumed that hot gases travel vertically upwards, leaving the top region of the wall hotter than the lower region. For this, 11 other thermocouples were placed at unique locations as illustrated in Figure 1*b*. Thermocouples H1-H5 measured temperatures along the hollow cell, thermocouples S1-S3 measured temperatures along the solid webs while thermocouples M1-M3 measured temperatures along the mortar. However, for the purpose of this research, the thermocouples of interest were H5, S3 and M3 on the unexposed face of the wall. To validate the thermocouple readings, a thermal imagining camera was also used to visually monitor the temperature distribution of the wall.

The insulation failure criterion was chosen and thermocouples on the unexposed face were used to monitor the temperatures until an average increase of 140 ºC or 180 ºC on a single point was reached, after which the test was terminated.



a) b)

Figure 1: Thermocouple locations: (a) Full wall; (b) Highly instrumented block

Finite element model setup

The time consuming and expensive nature of the standard fire test calls for the use of a numerical approach to analyse an insulated masonry wall exposed to a fire. For this approach, ABAQUS finite element analysis software package was adopted because it allows its users full control of model configurations, element type, meshes, boundary conditions, etc. The masonry units (corner blocks, middle blocks, half block, head joint, and bed joint) were modeled as individual parts with their respective local coordinate systems. They were coupled in the assembly module as independent instances of parts relative to each other in a global coordinate system. For the heat transfer analysis, the density (ρ), specific heat capacity (Cp), and thermal conductivity (k), were specified.

The presence of moisture during heating has vast effects on the outcome of the test and so should be taken into consideration. The heat transfer in the cavities negatively impacts the fire resistance of the masonry block, but the moisture plays a role in diminishing the heat transfer effects by causing a plateau [14]. Energy is required for water to heat up and for vaporization to occur. Since this energy is directly related to the specific heat, the specific heat values around 100 °C were increased to consider the effects of moisture.

To consider the effect of conduction in ABAQUS, a surface-to-surface interaction module was defined for the units in contact. The blocks were assigned master surfaces while the mortar was assigned slave surface, with a thermal conductance property of 0.8 W/mK. Convection and radiation which are the predominant modes of heat transfer, were accounted for in the heat transfer step. In the experimental test, the thermocouples on the unexposed side of the wall had insulating pads over them that reduced the effect of heat radiating to the environment. As such, the effects of convection and radiation were only accounted for on the exposed face of the wall and the cavities. The combined effects of convection and radiation on the exposed side of the wall were incorporated in the standard fire equation in a user subroutine DFLUX file. The DFLUX (Distributed Flux) file was used to apply the non uniformly distributed heat flux to the exposed face of the wall while the combined effects of convection and radiation in the hollow cavities were applied in ABAQUS by manually selecting the hollow surfaces.

For the finite element analysis, only a sub model was considered. Sub-modelling allows for a more detailed analysis of a specific section of the global model. This approach is less time consuming and is useful when the aim is to obtain an accurate, detailed solution using smaller meshes. Sample models (a single concrete masonry block, a 2-course wall, and a 3-course wall) were analyzed with a uniform mesh density. The area under the graphs was compared to determine how close the results were to each other. The result showed that the analysis of a single block is a poor approximation to a 1-course wall, with over 5% and 7% error in the hollow cells and webs, respectively. Whereas the 1 and 2-course wall showed a 1% and 0% error in the hollow cells and webs. For the finite element analysis, a 2-course wall was used as the sub model.

Model validation

To correctly validate the model, a parametric study was conducted on the surface emissivity, convective heat transfer and on the mesh sensitivity. For surface emissivity, a range of values were modelled with, and compared to the experimental results: 0.94 was found to be the most optimal. For the convective heat transfer, single non-temperature dependent h (W/m^{2}K) values and temperature dependent h values were modelled with. The results were compared with the experimental results and the temperature dependent h values were found to be the most optimal. Mesh sensitivity was conducted using various mesh grades as illustrated in Table 1. The choice of the mesh used for the rest of the analysis was dependent on the accuracy, and computational time. The 'Fine' mesh density was adopted because it was within the acceptable 5 percentile, gave a close result to the experimental result, and also had a reasonable computational time.

Table 1: Mesh optimization

Mesh statistics	Extra coarse	coarse	Normal	Fine	Extra fine
Number of elements	1849	3388	9425	25,731	199,866
CPU time (hr)	0.4	0.73	2.28	7.07	81
Hollow cell % error	-	1.48	5.51	**3.43**	4.35
Web % error	-	8.85	4.94	**3.48**	5.26

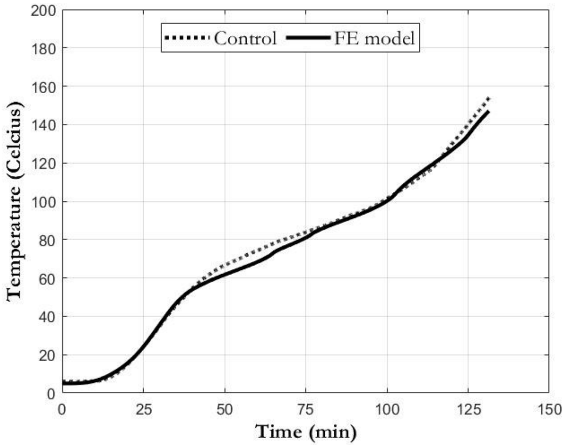


Figure 2: Average temperature profile on the unexposed face of the wall.

The average temperature profile on the unexposed face of the wall is illustrated in Figure 2. The graph represents a comparison between the control wall and the validated numeral model. The finite element model closely imitates the experimental result, but for a slight discrepancy between 60 ºC - 80 ºC and towards the end of the test. This is due to the simplification done on the finite element model.

After the finite element model was validated, insulating materials were modelled as inserts in the cavities. The two (2) inserts considered were: fire-rated gypsum, and polystyrene. The properties of each inserts as summarized in Table 2, were obtained from already existing literature [10] [15]. With these, two walls were modelled and analyzed to investigate the effect of insulating fillers on the fire resistance of concrete masonry walls.

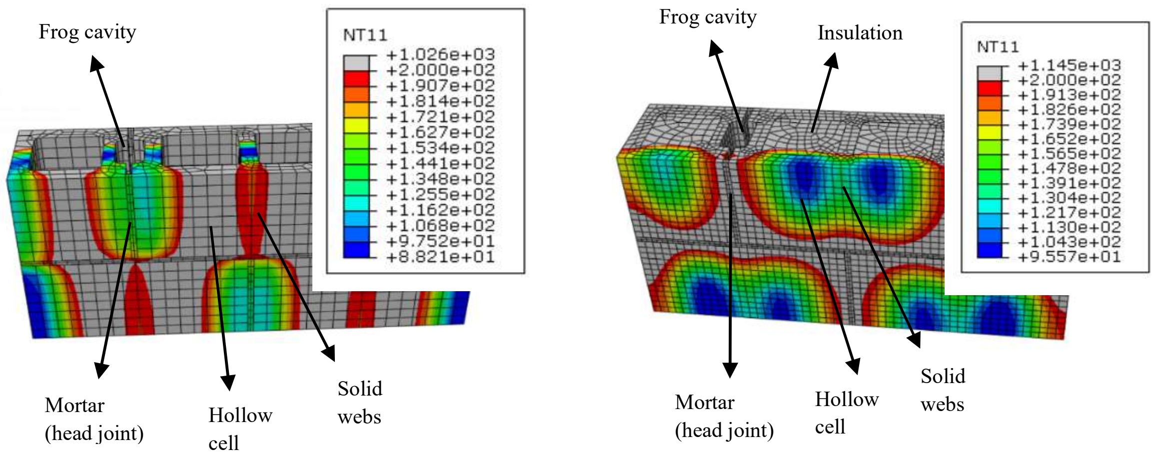
Table 2: Insulation properties.

	Gypsum [15]	**Polystyrene** [10]
Density (kg/m^3)	810	28
Specific heat (J/kgk)	1000	1800
Thermal conductivity (W/mk)	0.28	0.033

With the addition of the inserts in the cells, surface-to-surface interaction between the hollow cavity and the inserts were considered. The effects of radiation and conduction were only considered in the frog cavities alone. The results from the analysis were compared with the validated numerical model without any inserts to determine the improvement of the fire resistance of concrete masonry walls.

RESULT AND DISCUSSION.

The anisotropic nature of concrete masonry walls due to the joints and hollow cavities cause the temperature on the unexposed face of the wall to differ from point to point. The three (3) distinct locations investigated on the unexposed surface were – the hollow cells (H5), the solids webs (S3) and the mortar (M3). The nodal temperature distribution through the uninsulated and insulated walls are illustrated in Figure 3. The contour shows the temperature variation across the models at 200 °C, from the greatest temperature (grey contour) to the least temperature (blue contour) on the unexposed face. The coolest regions on the air-filled cavity wall, as illustrated in Figure 3*a*, was along the wall ends with temperatures between 88 °C - 97 °C. On the other hand, the coolest regions on the insulated cavity wall, as illustrated in Figure 3*b*, was along the center of the cell cavity with temperatures between 95 °C - 113 °C.



a) **b)**

Figure 3: Nodal temperature distribution °C (NT11): a) Uninsulated wall; b) Insulated wall.

The temperature profile of the air-filled cavity walls is illustrated in Figure 4. The hollow cell (H5) recorded the highest temperature as a result of the buoyant convective air in the cavities. The mortar – head joint (M3) was comparatively hotter than the webs (S3) at the start of the analysis but went through a plateau phase that allowed it cool while the webs continued to heat up.

On the other hand, for walls filled with gypsum and polystyrene, the temperature profile as illustrated in Figure 5 indicates that the mortars (M3) – head joint recorded the highest temperatures while the hollow cells (H5) recorded the least temperatures because of the insulating materials replacing the buoyant air. These inserts completely eliminated the effect of radiation and convection in the cells and significantly reduced the rate of the heat transfer to hollow cells. By having the cells filled, heat transfer occurred by conductions which is generally a much slower process. However, this was not the case for the frog cavities as the convective air still present in these cavities caused the head joints to heat up quicker, regardless of its moisture content of the mortars.

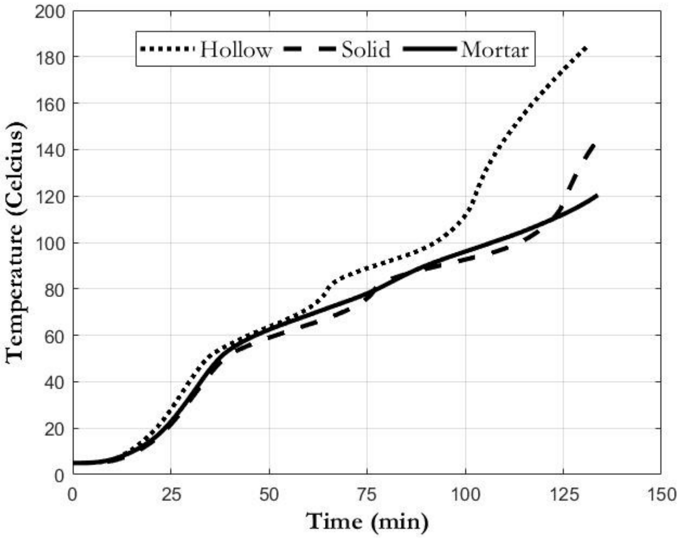


Figure 4: Temperature profile on the unexposed face for an uninsulated wall.

From Figure 5 below, it is evident that Gypsum is a better insulating material than Polystyrene, but only by a small margin. This is partly due to its calcination that significantly slows down heat transmission. The webs (S3) and the Hollow cells (H5) of both insulated walls follow a close and similar pattern from the start of the test to about 70 ºC. At this temperature and beyond, gypsum and polystyrene are able to absorb and store heat without causing an increase in temperature, as a result of their moisture contained in gypsum and closed cell form of polysyterne. This gives the hollow cells enough time to plateau while the webs continue to rise until the test is terminated after a 180 ºC rise. At the time of termination, the hollow cells recorded an average temperature of about 100 ºC, while the webs recorded an average temperature of about 110 ºC. Both areas did not fail during the test and could have gone on for longer if the mortar did not fail sooner. There was a huge temperature gap between the conduction dominant areas and the convection and radiation dominate areas. This proved that the main modes of heat transfer through a block is via convection and radiation. It is also worth noting that the mortars (gypsumM and polystyreneM) also follow a similar pattern from the start of the test to about 70 ºC after which there is a noticeable change in the temperature rise with time. This shows that even though the mortars are the hottest region where failure would occur, the type of insulation used in the cell cavities could also be a factor to be considered. However, since this change was only about 2%, it was be considered insignificant.

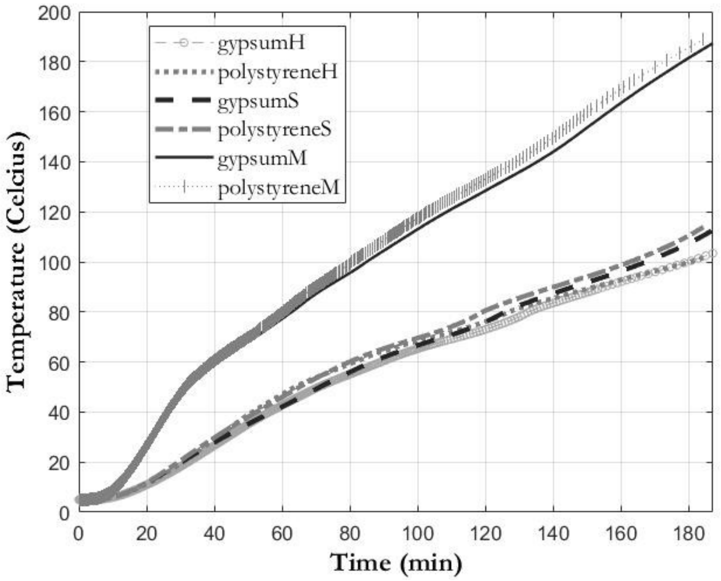


Figure 5: Temperature profile on the unexposed face for an insulated wall.

All three walls (air filled cavity wall, gypsum wall, polystyrene wall) failed due to the 180 °C insulation failure criteria. The wall without inserts failed at the hollow cells after 2.25 hrs, while the polystyrene and gypsum filled walls failed after 3 hrs.

CONCLUSION

The finite element model developed was able to accurately depict the heat transfer mechanism through the concrete masonry wall. Past research has shown that the cavity convection in hollow masonry blocks is a phenomenon that cannot be ignored. As a way to reduce the convection currents, gypsum and polystyrene were used as inserts in the cell cavities. Gypsum proved to have a better thermal insulating property than polystyrene. This is attributed to gypsums ability to resist fire or heat better as an inorganic material. The moisture content contained in gypsum also played a major role in ensuring the heat transfer process was not hastened. The inserts significantly suppressed the in-cavity convective air thereby improving the fire resistance of the concrete masonry wall. In using gypsum, the fire resistance rating increased by 35% while polystyrene improved the fire resistance rating by 31%. Thus, it can be inferred that insulating materials, whether organic or inorganic perform a fine job at improving the fire resistance rating of hollow concrete blocks in elevated temperatures.

LIMITATIONS

Some limitations to this study are highlighted below:

- There were no experimental tests conducted on concrete masonry walls with insulations in the cell cavities, to further verify the finite element model developed.
- This experiment and analysis were conducted on normal weight concrete blocks.

- The mechanical properties of concrete masonry were not considered for the heat transfer analysis.
- The finite element model was simplified by increasing the specific heat capacity within the temperature range of moisture loss.
- Cost analysis of using gypsum filled block or polystyrene filled blocks were not considered.

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