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Fire performance of bio-based PCM lined LSF wall

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Abstract

Light gauge steel framed (LSF) wall systems are made of cold-formed steel studs lined with different types of wallboards. Increased demand for LSF wall systems has led to researchers focusing on improving their fire performance. Moreover, the thermal mass of LSF wall systems is not adequate compared to conventional wall systems, resulting in poor thermal performance. Thermal energy storage techniques can be used to increase the thermal mass of wall systems. Phase change materials (PCM) could be used due to their high thermal storage capacity, which can increase the thermal mass of LSF wall systems. PCM absorbs or loses energy and undergoes a phase transition from solid to liquid or liquid to solid, respectively, which helps to maintain the indoor thermal comfort level. Nevertheless, few organic PCM could increase the fuel load during the fire. Fire performance of LSF wall systems enhanced with PCM has not been investigated. Therefore, this study is aimed at investigating the fire performance of LSF wall systems enhanced with bio-based PCM under standard fire conditions. Fire rated gypsum plasterboards were used as lining in LSF wall systems. Findings reveal that higher fire resistance was obtained for LSF wall systems, lined with the bio-based PCM liners. This paper presents the fire test results of LSF wall systems made of fire rated gypsum plasterboards and lined with or without bio-based PCMs.

1. Introduction

Light gauge steel framed (LSF) wall systems are widely used as load bearing or non-load bearing elements in the emerging lightweight cold-formed steel construction. They are made of cold-formed steel (CFS) studs and tracks, and lined with different types of wallboards. Various types of wallboards are introduced and used with LSF walls due to their improved thermal and physical properties for the purposes of thermal comfort, fire resistance, impact resistance, sound insulation and moisture resistance. Gypsum plasterboard, fibre cement board, phase change materials incorporated plasterboards, magnesium oxide board and magnesium sulphate boards are some of them currently used in LSF wall construction. Thermal mass and fire resistance are the most important design parameters for LSF wall systems. However, LSF wall systems are being used in many countries but without a full understanding of the knowledge of these parameters. Failures of steel studs occur in load bearing LSF walls exposed to fire due to the deterioration in mechanical properties of CFS at elevated temperatures [1]. Such failures are delayed by fire protective wallboards and fire rated gypsum plasterboards are commonly used in LSF wall systems for this purpose. Fire resistance of load bearing elements is measured as Fire Resistance Level (FRL) in minutes under three failure criteria, structural adequacy, integrity and insulation as given in AS 1530.4 [2]. Structural adequacy is the ability of an element to withstand a load while integrity is the ability to resist flames and hot gases from the fire side to the ambient side during fire. Insulation failure is the ability of the ambient side during fire to maintain the temperature below a specified limit, which is 140 °C on average or 180 °C at any point (maximum temperature of the surface) above the initial room temperature. Many researchers have focused on developing LSF wall systems with adequate fire resistance with commonly used LSF wall systems [3-9].

LSF wall systems have lower thermal mass compared to conventional wall systems and thus exhibit poor thermal performance. This affects the indoor thermal comfort level of buildings and creates fluctuations during seasonal variations. Thermal energy storage techniques can be used to avoid indoor temperature fluctuations by increasing the thermal mass of wall systems. Phase change materials (PCM) with high latent heat storage capacities can be used as thermal energy storage materials in buildings [10]. PCM absorb or lose considerable energy and undergo a phase transition from solid to liquid or liquid to solid. They melt during daytime and solidify at night times due to the phase transition, and thus help to maintain the indoor thermal comfort level. Commonly, organic microencapsulated

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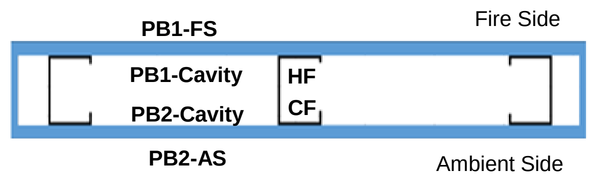
paraffin PCM is used in building products. However, the organic paraffin PCM being a flammable material increases the flammability of these products and affects their fire performance [11-13]. Further, LSF wall systems made of plasterboards added with PCM (PCM-plasterboards) show reduced fire resistance compared to LSF wall systems made of conventional fire resistive plasterboards [14]. Instead, bio-based PCM materials can be adopted in buildings due to their relatively high ignition resistance and significantly less flammability compared to paraffin-based PCMs [15, 16]. These bio-based PCMs are mostly made of fatty acid oil esters and are capable of actively performing thousands of cycles. They are capable of absorbing and releasing a larger amount of heat, similar to organic paraffin PCMs [15]. Further, they help in reducing indoor heat stress with improved occupant health caused by the increased thermal discomfort in high energy efficient buildings in hot days and heatwave periods [17]. Therefore, bio-based PCM liners could be used with commonly used gypsum plasterboards to improve the thermal mass of LSF wall systems. However, their fire performance is unknown.

This research investigated the fire performance of thermal mass improved LSF wall made of commonly used gypsum plasterboard and micro-encapsulated bio-based PCM liners and compared with the LSF walls made of commonly used conventional fire resistive gypsum plasterboards under standard fire conditions using small-scale fire tests. The insulation based failure times of all the LSF walls were measured and compared to identify the best performing LSF wall system. This paper presents the details of the above-mentioned fire tests and the results.

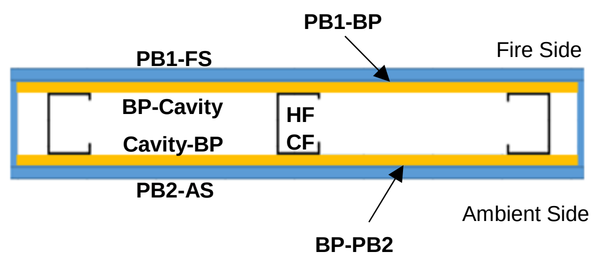
2. Experimental study

Fire tests were conducted on two non-load bearing LSF wall systems of 1.4 m width and 1.2 m height to investigate their fire performance when exposed to the standard time-temperature curve according to AS 1530.4 [2]. Both test specimens were lined with single layer of 16 mm thick plasterboards on both sides. But one of them was first lined with bio-based PCM lining on the inside of both sides (Figure 1). Bio-based PCM is filled in 9 mm thick pockets of a thinner flexible mat. The stud and track arrangement used in LSF wall systems was made of 0.95 mm thick tracks and 0.75 mm studs made of G550 steel (minimum yield strength of 550 MPa). The dimensions of studs and tracks were 90×36×7×0.75 mm and 92×40×0.95 mm, respectively. Studs were located inside the tracks at 450 mm spacing and D-type flat head self-drilling screws of 16 mm length were used to fasten them.

Single layer of gypsum plasterboard was used on both sides of the wall. Each board layer consisted of three pieces, 1200×1200 mm, 1200×100 mm and 1200×100 mm. The 1200×1200 mm board was placed in the centre and fastened to all three studs. The two small boards (1200×100 mm) were placed on the right and left sides of the larger board and connected to both top and bottom tracks. Small boards were used to increase the wall panel width to 1400 mm, which helped in fixing the panels to the furnace.



(a) Fire Test-1



(b) Fire Test-2

Note: PB1-Fire side plasterboard, PB2-Ambient side plasterboard, FS-Fire side, AS-Ambient side, BP-Bio-based PCM liner, HF-Stud hot flange, CF-Stud cold flange

Figure 1. Fire test specimen details

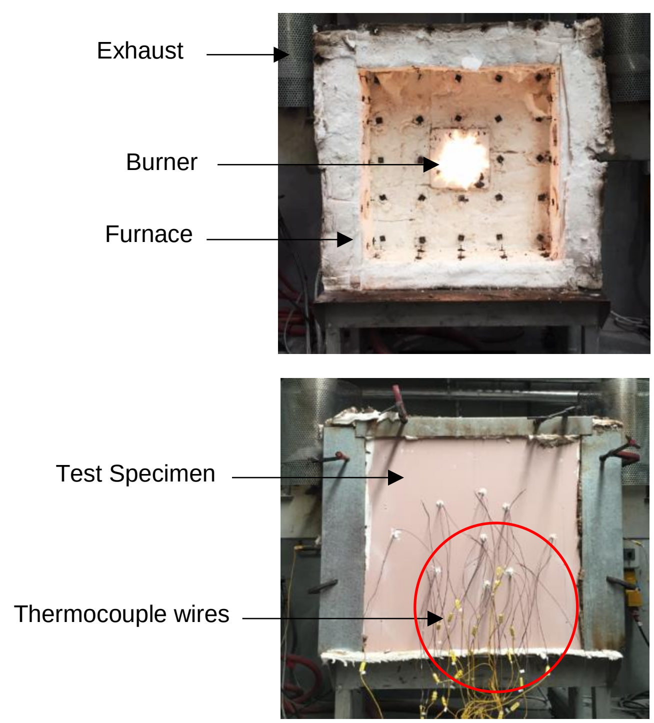


Figure 2. Fire test set-up

Wallboards were screw fastened only to studs and not to tracks using bulge head self-drilling screws of 36 mm length. The joints on the board layer were filled with two layers of plaster joint filler compound with sealing paper tape placed between them. The bio-based PCM layer was of 1000×1000 mm, which was placed in the center to cover the fire exposed area of the furnace. Further, the holes, which were used to take the thermocouples to the ambient side, were made in a pattern so that they did not create any leakages on the PCM pockets. K-type thermocouple wires were used to measure the temperature variations of test specimens during the fire tests. Small-scale fire tests were conducted using a gas furnace with thermocouple wires connected to a data logger to record the fire test data (Figure 2). The external gas supply of the furnace was terminated, when any of the ambient side thermocouples recorded a temperature exceeding the average or maximum insulation failure temperature.

3. Test observations

Fire Test-1

Initially, smoke started after 30 s from the commencement of the fire test, which reduced after 5 min and was visible again at 7 and 25 min. Smoke was due to the burning of paper on both sides of the plasterboards. Water drops were visible on the top of the furnace and on the floor below the furnace after 11 min and again from 28 to 48 min. Dripping of water from the test wall was caused by the dehydration of gypsum plasterboard. Discolouration of ambient side plasterboard commenced at 84 min and the board fully turned dark at around 133 min (Figure 3). The test was stopped at 143 min, when the average temperature of the ambient side was nearly 200 °C.

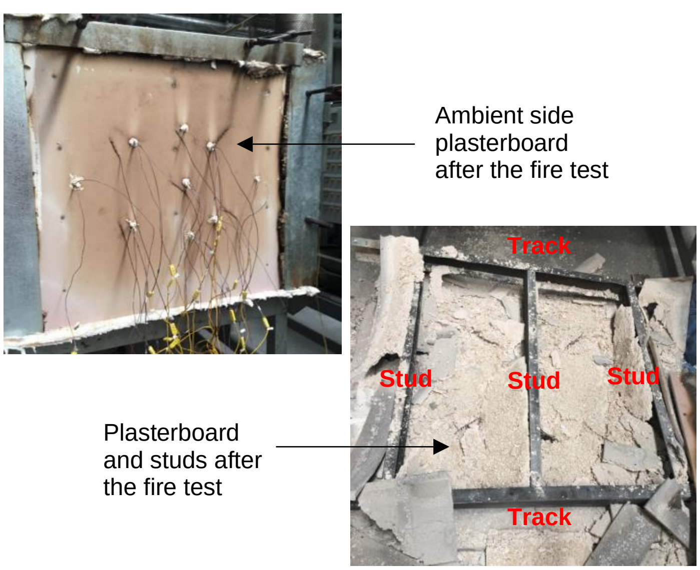


Figure 3. Test specimen 1 – after the fire test

Fire Test-2

Initially, smoke was seen after 1 min due to the burning of paper on the fire side and reduced at around 10 min. Again, smoke started at 25 min and continued throughout the test. This is due to the burning of paper on the board surfaces and burning of evaporated PCM from the board. Dripping of PCM was initially seen on the floor from the right side bottom corner of the test specimen at 26 min. Initial dripping was a thick white liquid droplet and later the colour turned to light greenish grey/sage after the dripping volume increased. Dripping of PCM rate increased at 31 min with an increment in grey smoke. The average temperature of the melted PCM on the floor was around 330 °C. Thick white liquid drops were seen on the floor below the left corner of the specimen at 40 min (Figure 4), which might be due to the melting of poly film. However, the spill stopped within a minute at the left-hand corner. Spill continued on the right bottom corner until 50 min and then the flow rate reduced. Again, the spill was increased at 55 min and the smoke also increased at 60 min. This might be due to the melting of the second PCM layer, which was on the ambient side.

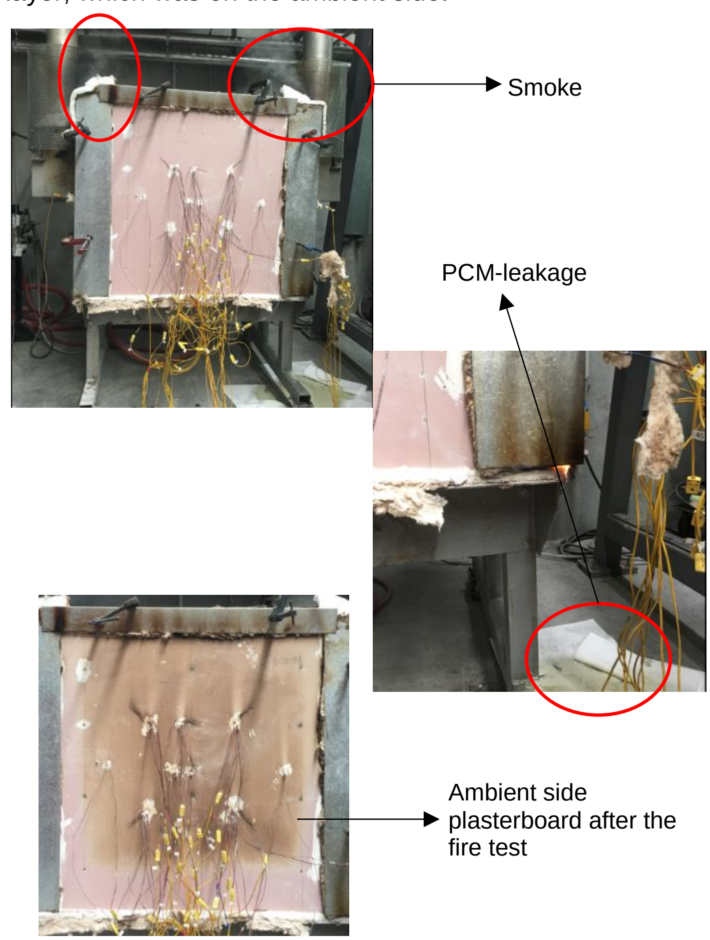


Figure 4. Test specimen 2 – during and after the fire test

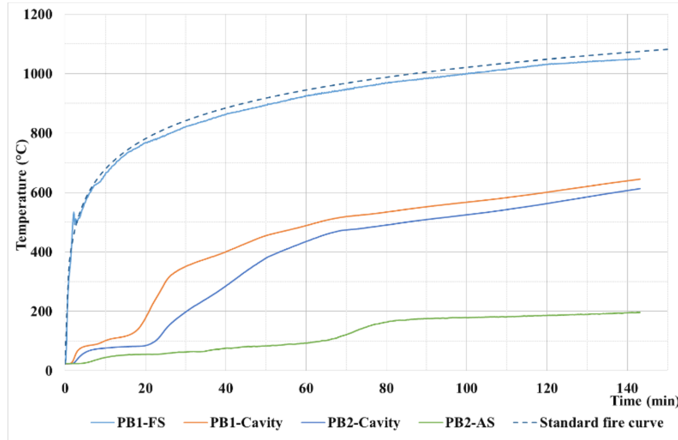
A spill of the creamy textured liquid stopped at 75 min. Water drops were visible on the plasterboard surface at 66 min. This might be due to the dehydration of the ambient side plasterboard. Further, water drops were seen on the floor below the furnace at 71 min (no creaminess or dark colours and drops dried after some time). Discolouration started on the ambient side gypsum plasterboard at 87 min. The test was terminated at 115 min when the maximum insulation failure temperature was reached. A flame was seen at 116 min on the right side bottom corner of the specimen, where melted PCM leaked. The flame was observed through the exhaust after 122 min. Significant colour change (light brown to dark brown) was seen on the ambient side plasterboard, which stayed brisk with no cracks.

4. Fire test results

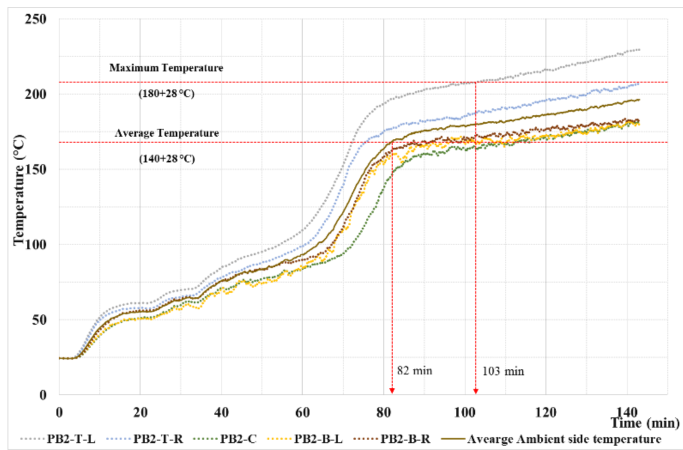
Fire Test-1

Figure 5 (a) shows the average time-temperature profiles measured on the wallboards of Test specimen 1 lined with single layer of gypsum plasterboard on both sides (PB1 and PB2). Fire side temperature of the test had a maximum deviation of 20 °C from the standard fire curve, which is below the acceptable limit specified in AS 1530.4 [2]. Initially, the temperatures of all plasterboard layers were maintained at a constant value less than 100 °C for a certain period of time, which is due to the dehydration of gypsum plasterboard. Time taken to reach 100 °C was 10, 22 and 65 min for PB1-Cavity, PB2-Cavity, and PB2-AS, respectively. This is similar to the observations of Ariyanayagam and Mahendran [3]. Sudden increments were observed in the plasterboard temperatures after the dehydration process. Further, the temperature gradient for PB1-Cavity and PB2-Cavity reduced after 60 min and continued to have constant deviation until the end of the test. Maximum fire side temperature of 1050 °C was reached at 143 min.

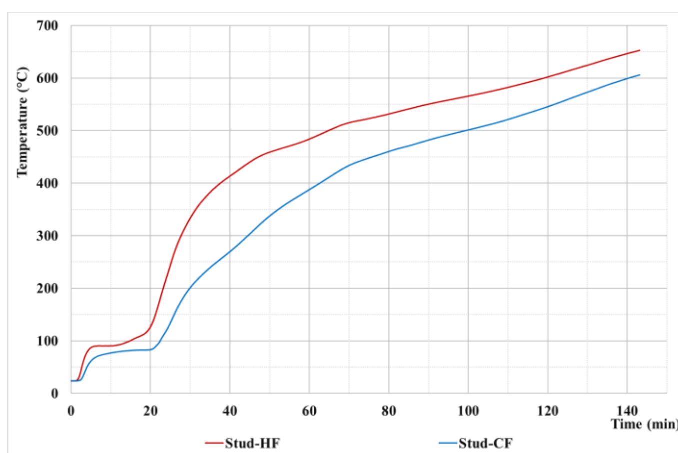
The measured individual thermocouple readings and the average temperatures on the ambient side plasterboard (PB 2) are shown in
Figure (b). Average insulation failure temperature limit of 168 °C was observed at 82 min (initial ambient temperature was 28 °C) whereas the maximum insulation failure temperature limit of 208 °C was observed after 103 min. However, the test was continued until 140 min.
Figure (c) shows the average stud time-temperature profiles of hot flange (HF) and cold flange (CF). The maximum temperature of 650 °C on HF was reached at 143 min. The maximum deviation of 160 °C was seen between the HF and CF temperatures after 40 min.



(a) Average gypsum plasterboard temperatures



(b) Ambient side thermocouple readings/ gypsum plasterboard (PB2) temperatures



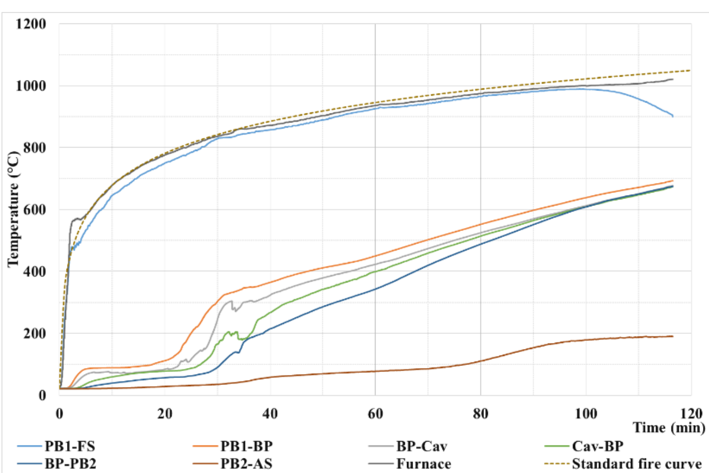
(c) Average stud (HF & CF) temperatures

Figure 5. Fire test results of Test specimen 1

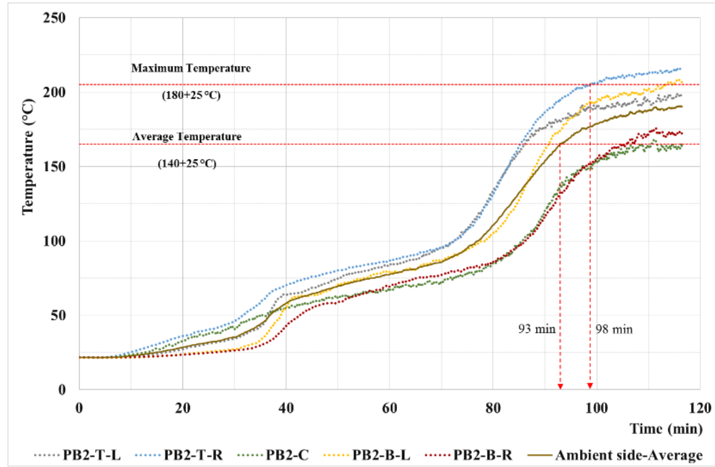
Fire Test-2

Figure 66 (a) shows the average time-temperature profiles measured on the wallboards of Test specimen 2 lined with single layer of gypsum plasterboard on the exterior and bio-based PCM mat placed on the interior. Fire side temperature of the test agreed well with the standard fire curve and was within the limit specified in AS 1530.4 [2]. Initially, the temperatures of all gypsum plasterboard surfaces and the bio-based PCM mat surfaces were maintained at a constant value, less than 100 °C for a certain period of time due to the dehydration process of gypsum plasterboard and the heat absorption capacity of PCM. Sudden increments with fluctuations are observed in the temperature on both sides of the bio-based PCM mat lined on fire and ambient sides. This might be due to the melting of PCM. Further, the gradients of the temperatures of surfaces (PB1-Cavity and PB2-Cavity) reduced after 40 min and converged at the end of the test. At this time, the air temperature in the cavity and, the temperature between the PCM mat and gypsum plasterboard were the same, which might be due to the melting of the poly film mat. Time taken to reach 100 °C was 17, 23, 27, 31 and 77 min for PB1-BP, BP-Cavity, Cavity-BP, BP-PB2 and PB2-AS, respectively. The maximum fireside temperature of 1010 °C was reached at 116 min.

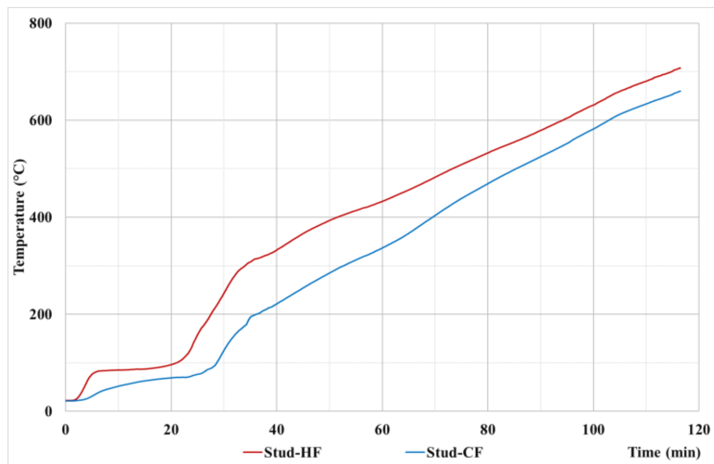
Figure 66 (b) shows the individual thermocouple readings and the average temperature of the ambient side of Test specimen 2, measured on gypsum plasterboard (PB2). Average and maximum insulation failure temperatures of 165 and 205 °C were observed at 93 and 95 min (the initial ambient temperature was 25 °C) and the test was terminated at 116 min. Figure 66 (c) shows the average stud time-temperature profile of hot flange (HF) and cold flange (CF) of Test specimen 2. The maximum temperature of 710 °C on HF was reached at 116 min. The maximum difference between HF and CF temperatures was 110 °C at 45 min.



(a) Average gypsum plasterboard and bio-based PCM surface temperatures



(b) Ambient side thermocouple readings/gypsum plasterboard (PB2) temperatures



(c) Average stud (HF & CF) temperatures

Figure 6. Fire test results of Test specimen 2

5. Discussion and Conclusions

This paper has presented the details of an experimental investigation on the fire performance of LSF walls lined with gypsum plasterboards with and without bio-based PCM mats. These experimental investigations are based on small-scale fire tests exposed to the standard fire time-temperature curve. LSF wall lined with gypsum plasterboard only, performed without any cracking and discolouration at higher temperatures. LSF wall lined with gypsum plasterboard and bio-based PCM mat also performed without any cracking and discolouration at higher temperatures.

The LSF wall lined with only gypsum plasterboards performed with an average insulation failure time of 82 min.

The use of bio-based PCM mats in the LSF wall lined with gypsum plasterboards increased the fire resistance level by 11 min from 82 min to 93 min based on the average insulation failure temperature limit. These results reveal that the bio-based PCM mat used within the LSF wall lined with external gypsum plasterboard linings can improve the thermal mass and does not reduce its fire resistance.

In the previously conducted fire tests on paraffin-based PCM added plasterboards revealed that PCM provided additional fuel to the wall system, indicating a potentially high reduction in the fire resistance of PCM incorporated plasterboards [14]. Thermal property test results showed that the PCM-plasterboard has a very high mass loss of 40% at elevated temperatures due to dehydration and evaporation of PCM, compared to the 23% mass loss caused by dehydration in gypsum plasterboard. These results indicate a reduced fire resistance of PCM-plasterboards. However, PCM absorb or lose considerable energy and undergo a phase transition from solid to liquid or liquid to solid and help to maintain the indoor thermal comfort level at room temperatures. Bio-based PCM mainly comprises of derivatives of fatty acids, fatty alcohols, esters, emulsifiers, thickening agents and proprietary cross-linkers. Further, these bio-based PCMs can absorb, store and release a larger amount of heat, similar to organic paraffin PCMs [15-17]. This study has shown that the use of bio-based PCM mat together with external gypsum plasterboard lining increased the insulation based fire resistance time of LSF wall. Further, the measured time-temperature profiles of studs indicate that the structural adequacy based fire resistance time could also be increased with the use of bio-based PCM mat.

6. Acknowledgments

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