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Evaluation of feasibility and performance of foamed Fire-Resistant coating materials

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ABSTRACT

A preliminary study found high-performance cement mortar, geopolymer mortar, and magnesium phosphate cement mortar (MPCM) have the potential as new fire-resistant materials. In this study, foam was added to these three fire-resistant materials to further improve their rheological, mechanical, and fire-resistant performance and reduce costs. Systematic design and experimental programs were conducted. The results showed the addition of foam enhanced workability, adhesiveness, and fire resistance, allowing the materials to withstand higher temperatures and further delay heat transfer. A mixture of 70% MPCM and 30% foam was identified as the optimum design, which could withstand 1000 °C with low heat transfer rates.

1. Introduction

In the past few decades, the United States has experienced a high frequency of wildfires, leading to the loss of approximately one million homes within fire perimeters in the western region between 1990 and 2015 [1,2]. To prevent such losses, there is a need to evaluate and improve the fire resistance of structures. One potential solution is to use fire-resistant coating materials, such as lightweight materials, bio-based materials, ceramics, innovative materials, fibers, nanomaterials, responsive materials, polymers, plastics, and packaging materials [3].

A recent study developed and validated three fire-resistant materials, i.e., high-performance cement mortar (HPCM), geopolymer mortar (GPM), and magnesium phosphate cement mortar (MPCM) [4]. HPCM is primarily composed of chemically inert components such as sand and cement. As a result, it exhibits good non-combustible properties. It was found that the viscosity, workability, slip resistance, cohesiveness, and adhesiveness of HPCM could be further improved by adding chemical admixtures, such as superplasticizers, viscosity-modifying admixtures (VMA), and accelerator. GPM, on the other hand, is formulated using an alkaline solution and solid aluminosilicate. MPCM is derived from the reactions between phosphate and magnesium oxide. It sets quickly and exhibits high early-age strength. The previous study found that these materials exhibited adequate fire resistance, workability, and adhesion as coating materials. Among the three coating materials, MPCM had the best fire-resistant properties of the three materials, remaining crack-free at temperatures up to 1000 °C [4].

On the other hand, researchers have demonstrated that foamed materials have superior fire resistance to conventional materials due to their low unit weights and high air contents [5]. Foamed mortar, for example, was created with a foaming agent by entrapping a large number of finely divided air bubbles through either a pre-foaming or a mixed foaming process [6]. The selected foaming agent produced a uniform distribution of unconnected pores. Since air is an ideal insulation material, the air voids in the foamed mixtures could provide additional heat insulation and fire resistance [7]. The effectiveness of resisting fire in the foamed mortar varies with its mixture proportions, compositions, and constituents. In general, its fire resistance effectiveness proportionally increases as the foam content increases. Other than fire resistance, foamed mortar has been found to offer many advantages over conventional mortar, including good workability [8,9], thermal insulation [10], freeze/thaw stability, and low cost [7,11,12]. In recent years, foamed concrete has also been used as a fire-resistant construction material. The development of protein-hydrolyzation-based foaming agents and foam-generating equipment has improved the stability of the foam, allowing foamed concrete to be manufactured for structural applications [7]. Tests have shown that foamed concrete does not spall or explode when subjected to high-energy flames, unlike normal concrete [13,14]. Likewise, increasing the foam content and decreasing the density of the concrete can increase the fire resistance in foamed concrete. For example, concrete with densities of 950 kg/m^3 and 1200 kg/m^3 can withstand fire for 3.5 h and 2 h, respectively. Additionally, foamed concrete with a density of 400 kg/m^3 has been found to have a

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rate of resistance to fire three times lower than that with a dry density of 150 kg/m^3 [7,15]. Foamed concrete's excellent fire resistance is attributed to its textural surface and porous microstructure. The microstructure allows the material to become relatively homogeneous compared with conventional concrete [7,16,17].

The objective of this study was to further explore the potential of using foaming techniques in the developed coating materials, i.e., HPCM, GPM, and MPCM, to create novel fire-resistant materials, namely F-HPCM, F-GPM, and F-MPCM. The study aimed to determine the optimum foam content for each material and identify the most effective material by evaluating their workability, adhesion to structures, and fire resistance. The research was conducted with systematic laboratory tests on various parameters, such as flow value, compressive strength, setting time, slip resistance, cohesiveness, adhesiveness, thermal conductivity, and fire resistance, to assess the materials' feasibility and performance.

2. Experimental program

2.1. Design s of foam mixes

In this study, Missouri River sand was utilized for all three materials. The fineness modulus of sand was 2.46. HPCM was prepared using Type I Portland cement and several admixtures, including superplasticizer, viscosity modifying admixture (VMA), and accelerator. The VMA was added to increase the viscosity of fresh cement mortar, prevent bleeding and segregation issues, and stabilize air bubbles [18]. GPM was created using a combination of Class F fly ash, sand, and an alkaline activator composed of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). For the MPCM mortar, dead burned magnesium oxide (MgO), potassium dihydrogen phosphate (KH_2PO_4), borax ($Na_2B_4O_7 \cdot 10H_2O$), and sand were mixed together. Borax was used as a retarder to slow down the rapid setting process.

To determine the optimum foam content for each material, different amounts of foam (0%, 10%, 30%, and 50% measured by total mixture volume) were added to HPCM, GPM, and MPCM. The original non-foamed surface-bonded fire-resistant materials were used as the control group. As a result, foamed coating materials were developed, known as F-HPCM, F-GPM, and F-MPCM, respectively. The mixed proportion of the F-HPCM, F-GPM, and F-MPCM were displayed in Tables 1–3.

2.2. Foam production and mixture specimen fabrication

Foam generation was achieved using Aerlite™ foaming agent and a foam stabilizer. The foam stabilizer was added due to its high surface activity to decrease the surface tension of the liquid and improve foam stability. A mix of foaming agent, foam stabilizer, and water was poured into a container (Figure 1), and the 'solution-in hose' was immersed. Once all hoses were connected, the foam generator machine was started, and the solution began flowing from the 'foam-out hose.' Adjusting the 'bypass valve' allowed for consistent foam discharge, and a foam quality test was conducted to ensure that the foam density fell within the recommended range (about 50 kg/m^3). The required volume (as indicated in Table 1) was measured and added to the mixture in the subsequent step.

For F-HPCM and F-MPCM, all other ingredients were mixed for 5 min before adding the foam. Once the foam was added, the mixtures were stirred for another 5 min and then transferred into the molds with a slight vibration to ensure complete filling. As for F-GPM, sodium silicate and NaOH were mixed for three minutes, then combined with fly ash and sand. The foam was added and stirred for another five minutes before being placed in the mold.

Table 2
Mix proportions of the F-GPM.

Mix	Fly ash (g)	Sand (g)	Water (g)	Sodium silicate (g)	sodium hydroxide (g)	Foam (cm^3)
0% F-GPM	1000	2000	91	75	266	0
10% F-GPM	1000	2000	91	75	266	283
30% F-GPM	1000	2000	91	75	266	849
50% F-GPM	1000	2000	91	75	266	1415

2.3. Testing methods

Feasibility tests were conducted (i.e., flow value, compressive strength, setting time, slip resistance, cohesiveness, adhesiveness, and thermal conductivity) to determine the optimum foam content of each material. Furthermore, materials with optimum foam contents were tested for fire resistance. Table 4 provides a summary of all testing methods used in this study.

The testing procedures of the flow table, setting time, spray test (i.e., slip resistance, cohesiveness, and adhesiveness), and compression strength tests were consistent with the methodology used in the previous study [4]. The spray test evaluated the coating materials' slip resistance, cohesiveness, and adhesiveness. As shown in Figure 2, a compressed air sprayer was used to spray fresh mortar onto the vertically positioned wood pad. The mortar was sprayed from left to right while a camera continuously recorded the entire process and one minute following the spraying. The spray test is crucial in determining the fresh quality of the coating material and assessing its slip resistance, cohesiveness, and adhesiveness.

The slip resistance of the coating material was determined by calculating the spray area expansion ratio, which was based on the area of mortar sprayed on the wood pad at different moments [4]. MATLAB algorithms were used to count the number of pixels and determine the area of the sprayed mortar. The area extension ratio was then calculated by comparing the mortared area at various times to the area at 0 s. A higher area extension ratio indicates lower slip resistance. Current specifications do not have specific requirements for slip resistance, but a spray area expansion ratio of less than 2 at 60 s and less than 1.4 at 10 s was used as a criterion based on testing and application experience [4]. The criterion of less than two at 60 s assumed that the coating material should not lose more than 50% of its thickness within one minute.

To evaluate the cohesiveness of the mortars, the buildup thickness was measured using the volume of fresh mortar retained on the wood pad [4]. A minimum buildup thickness of 2.5 mm was deemed necessary to ensure sufficient cohesion [24]. Adhesiveness was assessed by the rebound value, representing the proportion of fallen mortar to the total sprayed mortar [25]. As there are no specific requirements for adhesiveness in current specifications, a rebound value of less than 30% was considered optimal for satisfactory applicability based on construction

Table 1
Mix proportions of the F-HPCM.

Mix	Cement (g)	Sand (g)	Water (g)	Superplasticizer (g)	Accelerator (g)	VMA (g)	Foam (cm^3)
0% F-HPCM	1000	2000	365	7	17	1	0
10% F-HPCM	1000	2000	365	7	17	1	260
30% F-HPCM	1000	2000	365	7	17	1	780
50% F-HPCM	1000	2000	365	7	17	1	1300

Table 3
Mix proportions of the F-MPCM.

Mix	Magnesium (g)	Phosphate (g)	Sand (g)	Water (g)	Borax (g)	Foam (cm^3)
0% F-MPCM	1000	502	3004	390	122	0
10% F-MPCM	1000	502	3004	390	122	171
30% F-MPCM	1000	502	3004	390	122	513
50% F-MPCM	1000	502	3004	390	122	855

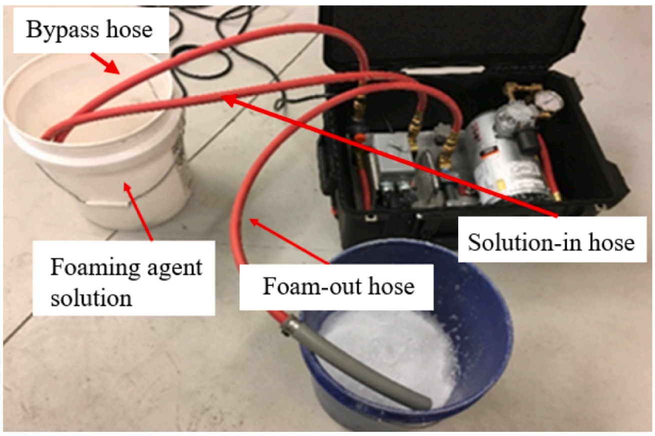


Fig. 1. Foam stabilizer and foam generator set up.

Table 4
Summary of testing methods.

Testing methods	Specifications	Parameter	Requirements
Flow table	ASTM C230 [19]	Flow table spread	Between 65% and 120% [4]
Setting time	ASTM C403 [20]	Setting time	Between 10 min [4] and 10 h [21]
Compressive strength	ASTM C109 [22]	Compressive strength	Greater than 9 Mpa [23]
Slip resistance	N/A	Spray area expansion ratio	Less than 2 at 60 s Less than 1.4 at 10 s [4]
Cohesiveness	N/A	Buildup thickness	Greater than 2.5 mm [24]
Adhesiveness	N/A	Rebound value	Less than 30% [4]
Thermal conductivity	N/A	Thermal conductivity	N/A
Fire resistance	N/A	Maximum ambient temperature	N/A

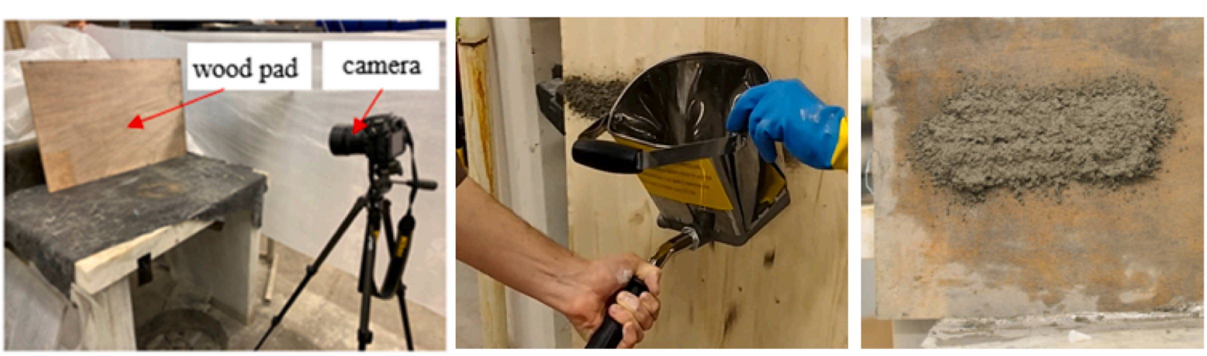
*N/A = not applicable.

experience [4].

In addition to fresh properties, a compressive strength test was conducted. Cubic specimens with standardized dimensions (2 × 2 × 2 in.) were prepared for the compressive strength tests. The specimens were then subjected to curing stages of 1, 3, and 7 days to evaluate their compressive strength. The measurement of compressive strength is necessary for assessing the structural integrity of coating materials. The relationship between the foam content and the compressive strength was also investigated in this study. The relationship was used to determine the optimum foam content.

The thermal conductivity of the coating materials was also measured in this study. Coating material with low thermal conductivity can form a good heat insulation layer. In this study, the thermal conductivity test employed cubic specimens (2 × 2 × 2 in.) to conduct the compressive strength tests. The Transient Plane Source (TPS) method was used to measure thermal conductivity, which involves using a transiently heated plane sensor (the Kapton insulated sensor 5501) and the Hot Disk Thermal Constants Analyzer. The Kapton sensor was placed between two square-shaped specimens to ensure good thermal contact, and voltage variations over the sensor were recorded. At the same time, its temperature was slightly raised by a constant electrical current pulse [26]. The temperature increase was typically less than 2 °C.

Monitoring fire resistance temperature is a widely used method for evaluating the fire resistance of coating materials. The measured temperature data under laboratory-simulated firing conditions can provide insights into several key factors, such as temperature changing rate, maximum temperature before failure, and duration of high temperature exposure. In this study, the fire resistance test was conducted to assess the fire resistance of materials with optimum foam contents. Standard cylinders (4 in. in diameter and 8 in. in height) were fabricated and cured for seven days, and they were exposed to high temperatures in a ventilated furnace. Optical fiber sensors were embedded along the centerline of the specimens to monitor temperature changes inside them. The temperature–time relationship and crack images of samples exposed to different temperatures were analyzed to evaluate their fire resistance.



(a) (b) (c)

Fig. 2. Evaluation of slip resistance, cohesiveness, and adhesiveness (a) equipment set up; (b) spray testing; (c) sprayed coating [4].

3. Results and discussion

3.1. Flow value

The study used flow table tests to assess the workability of the coating materials. The results, as shown in Figure 3, indicate that the flow value of each type of mortar increases with foam content increase. This trend implies that the mortar becomes more workable with more foam incorporated. Increased foam content also raises the water content, which further enhances workability. F-GPM has a higher flow value than the other mortars at the same foam content level. According to ASTM C230, a flow value of 65%-120% is acceptable for workability. It was determined that F-HPCM with all levels of foam content (0%-50%) met this requirement. The foam content should not exceed 10% for F-GPM to ensure workability. For F-MPCM, foam can be added up to 30% while still meeting the workability requirement.

3.2. Compressive strength

Figure 4 illustrates the compressive strength of the coating materials. As shown in Figure 4, the strength of the materials decreases as the foam content increases. Because the merging of bubbles as foam content increases leads to larger voids, reducing the strength of the materials [27,28]. Additionally, the uneven pore size distribution that arises due to high foam content can cause stress concentration in tiny pores when loads are applied, thus further decreasing the strength of the materials [28]. F-HPCM has the highest compressive strength among the three materials at low foam contents (less than or equal to 10%). However, its strength drops dramatically at higher foam contents (greater than or equal to 30%). F-GPM has the highest strength at high foam contents. The strength requirement for coating materials is 9 MPa at 7 days [23]. Based on the test results, all three materials with 0–30% foam met the strength requirements, but mortars with 50% foam did not.

3.3. Setting time

Figure 5 illustrates the setting time of each material, revealing that adding foam prolongs the setting process for all three materials. A linear relationship is observed between foam content and setting time. The trend is due to the low gas permeability and high water retention of foam, which hinders the hydration process [29]. F-HPCM exhibits the longest setting time, followed by F-GPM and F-MPCM. To ensure sufficient operation time and acceptable setting duration, it is recommended that the final setting time of the mortar be between 10 min and 10 h [4]. In this study, all three materials meet the setting time requirement.

3.4. Slip resistance, cohesiveness, and adhesiveness from spray test

The spray testing assessed three essential properties of coating materials: slip resistance, cohesiveness, and adhesiveness. Figures 6, 7, and 8 display the slip resistance, cohesiveness, and adhesiveness test results. Figure 6 indicates that the area expansion ratio was utilized to evaluate the slip resistance of the mortars. The area expansion ratio measures how fast the mortar flows after spraying onto a vertical wood surface. Therefore, a steeper slope on the curve indicates a faster expansion ratio of the material, indicating a lower slip resistance. Generally, the area expansion ratio increases as the foam content increases. The 0% F-HPCM and 0% F-GPM have a constant ratio of 1, which means they adhere firmly to the wood pad. After 60 s, some materials flowed beyond the wood pad area and were not measured. As a surface coating material, the expansion ratio must be less than 1.4 at 10 s to meet the requirement [4]. Therefore, only 50% F-HPCM and 50% F-MPCM failed to meet the need.

The results of the build-up thickness analysis are presented in Figure 7, which shows that an increase in foam content reduces the build-up thickness of the mortar, resulting in decreased cohesiveness. The reduced cohesiveness at high foam content is likely due to the high water content in foam. Additionally, F-HPCM and F-MPCM show higher build-up thickness than F-GPM at all foam content levels. However, the differences in build-up thickness among the three materials are insignificant. According to the standard, the minimum build-up thickness should be 2.5 mm [24]. All three non-foamed materials meet this requirement. Among the foamed mortars, only 10% F-HPCM, 30% F-HPCM, 10% F-GPM, 10% F-MPCM, and 30% F-MPCM meet the requirement.

The adhesiveness of the coating materials is indicated qualitatively by the rebound value, which is calculated by dividing the falling mass percentage by the sprayed material's total mass. Figure 8 shows that as the foam content increases, the rebound value of all three materials decreases. F-HPCM has the lowest rebound values, followed by F-GPM and F-MPCM, indicating that F-HPCM exhibits the highest adhesiveness. All materials have rebound values below 30%, meeting minimum adhesiveness requirements.

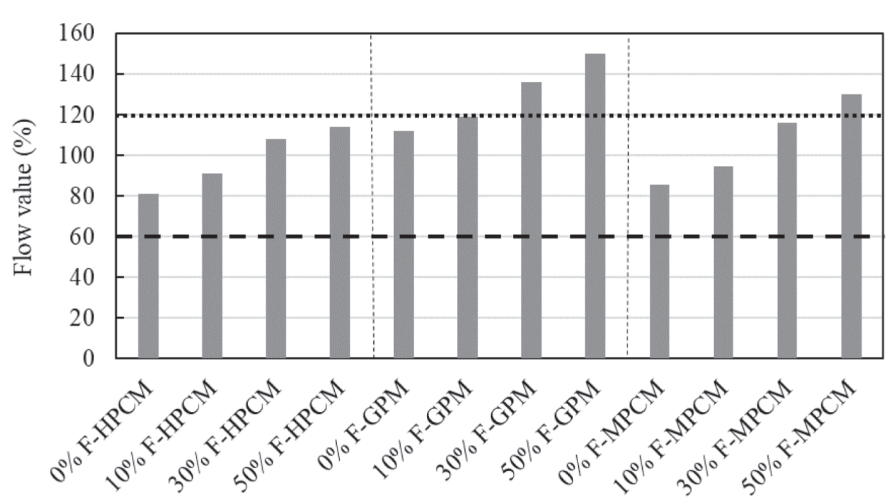


Fig. 3. Flow value of different materials.

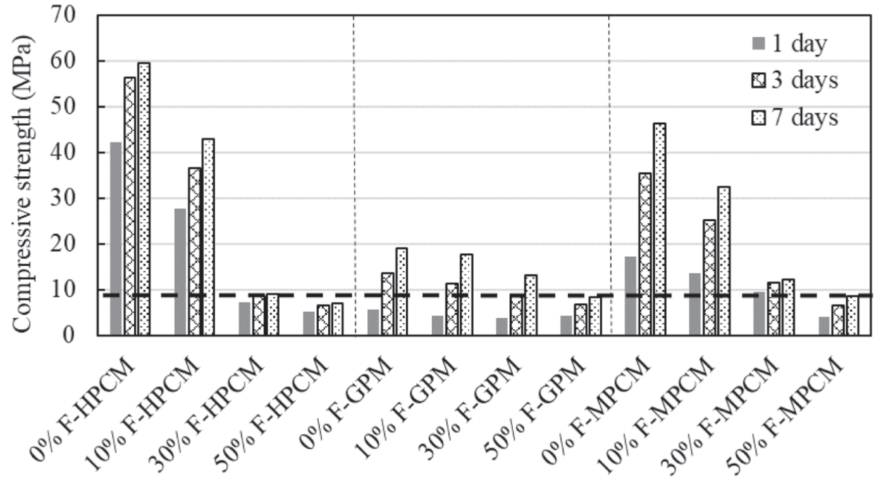


Fig. 4. Compressive strength of each material.

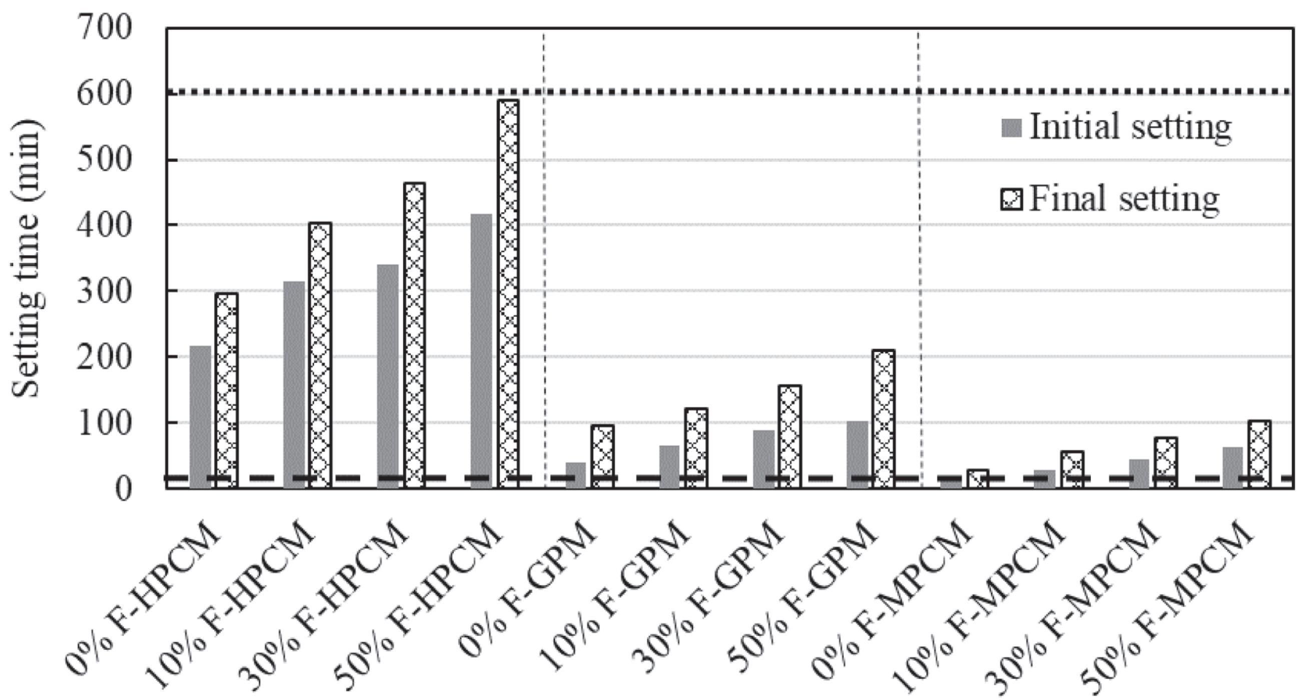


Fig. 5. Setting time of different materials.

3.5. Summary of the feasibility tests

Table 5 presents a summary of the feasibility tests on foamed coating materials. The results indicate that F-HPCM and F-MPCM can accommodate foam up to 30%, while F-GPM can only accommodate 10%. Based on these results, further testing was conducted on the materials that passed the feasibility test to evaluate their thermal behavior and fire resistance.

3.6. Thermal conductivity

Thermal conductivity is an important parameter for coating materials because it directly affects the heat transfer rate between the external heat source and the underlying structure. The thermal conductivity of porous materials is normally affected by their constituent phases, i.e., the void phase and the solid phase [30]. In the case of foamed mortar, the solid phase is a complex multi-phase composite with porosity, moisture, and continuous hydration, all impacting thermal conductivity [31,32]. The coatings with low thermal conductivities will provide benefits in three aspects, including heat insulation, temperature reduction, and enhanced fire protection.

Figure 9 depicts the relationship between thermal conductivities and foam contents of the three potential fire-resistance coating materials. As can be seen, the thermal conductivity of the foamed material decreases as the foam content increases. This trend can be attributed to the fact that air, a poor heat conductor, occupies the void phase. Therefore, as

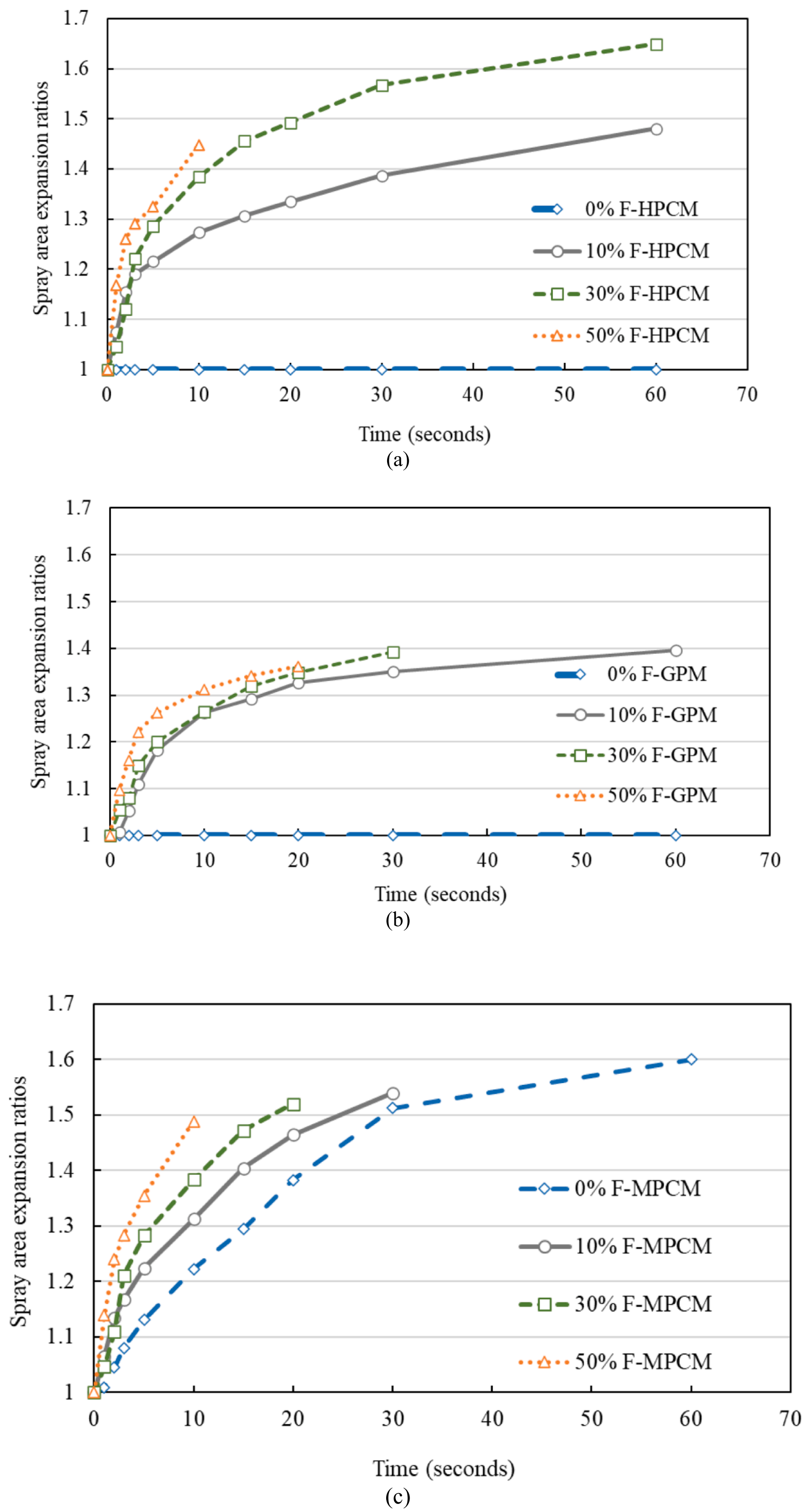


Fig. 6. Spray area expansion ratio of different materials (a) F-HPCM, (b) F-GPM, (c) F-MPCM.

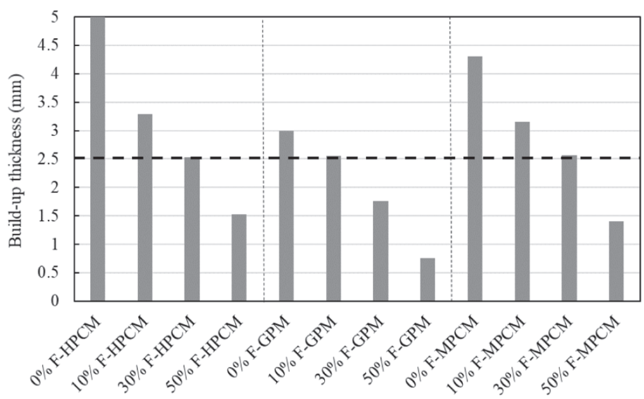


Fig. 7. Build-up thickness ratios of different materials.

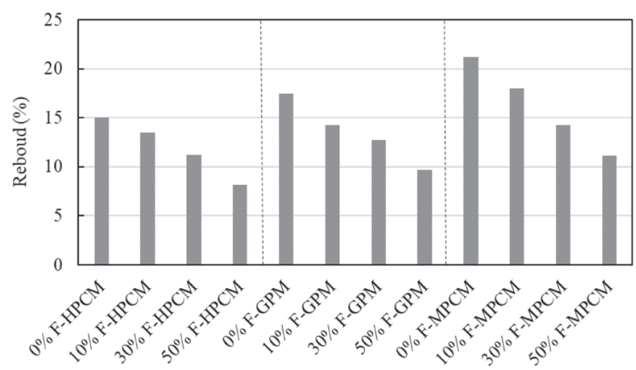


Fig. 8. The rebound of different materials.

the air content increases, the overall thermal conductivity decreases. The thermal conductivity of 0% F-HPCM is approximately equal to that of 10% F-GPM. The thermal conductivities of F-HPCM with 0%~50% foam content range from 0.47 and 1.67 W/mK for different foam contents. Similarly, the thermal conductivities of F-GPM and F-MPCM with 0% – 50% foam content range from 0.83 to 1.82 W/mK and from 0.75 to 1.78 W/mK, respectively. As shown in Figure 9, 10% F-HPCM has a similar thermal conductivity of 50% F-GPM, and 30% F-HPCM has a similar thermal conductivity of 50% F-MPCM. Compared with the F-GPM and F-MPCM, the F-HPCM has lower thermal conductivity; thus, considered as an ideal thermal insulation material. The 50% F-HPCM has the lowest thermal conductivity, which is approximately only half of the value of 50% F-GPM and two-thirds of the value of 50% F-MPCM.

3.7. Fire resistance temperature monitoring

Temperature monitoring is the most direct method to evaluate the fire resistance of coating materials. By measuring and analyzing the temperature changes during a fire, researchers and engineers can assess the performance of coatings in terms of their ability to withstand elevated temperatures and protect the underlying substrates. Temperature monitoring typically involves placing temperature sensors at critical locations on or near the coated surface. These sensors are designed to measure the temperature at specific points or continuously throughout the fire test. The collected data is then analyzed to evaluate the coating's performance.

Figure 10 illustrates the fire resistance temperature monitoring of selected specimens of F-HPCM, F-GPM, and F-MPCM. In the fire resistance tests, six specimens (i.e., 0% F-HPCM, 0% F-GPM, 0% F-MPCM, 30% F-HPCM, 10% F-GPM, and 30% F-MPCM) were subjected to increasing ambient temperatures, and the temperatures within the specimens were recorded using optic fibers. At an ambient temperature of 670 °C (after 65 min), the optic fiber signal from the 0% F-HPCM specimen was lost due to damage. At that point, the temperature inside the specimen had already reached 501 °C. Based on the data presented in Figure 10, it can be observed that the temperature inside the 0% F-HPCM specimen reached 501 °C twenty minutes after the ambient temperature had reached 670 °C. Moreover, when the ambient temperature exceeded 770 °C, the 30% F-HPCM specimen failed at 591 °C. The critical temperature thresholds represent specific limits at which the fire resistance of the coatings may be compromised. Notably, the lowest critical temperature threshold is observed for 0% F-HPCM, which is 501 °C. 10% F-HPCM follows this at 591 °C, and then 0% F-GPM at 920 °C. On the other hand, the remaining three materials, namely 10% F-GPM, 0% F-MPCM, and 30% F-MPCM, exhibited integrity throughout the test, with their temperature thresholds surpassing 908 °C, 915 °C, and 889 °C, respectively. The results show that the foamed mateials have a lower heat transfer rate than their non-foamed counterparts. Therefore, it can be inferred that incorporating foam in materials improves their fire resistance and reduces the heat transfer rate. At the 0% foam content level, it is evident that HPCM exhibits the lowest heat transfer rate, followed by MPCM, and then GPM. These findings align with the results obtained from the thermal conductivity tests, further validating their consistency.

Figure 11 shows surface cracks on the cylindrical specimens after optic fiber damage during the tests. The changes in specimen appearance, such as cracking and color changes, can also indicate fire resistance. The non-foamed specimens, 0% F-GPM and 0% F-HPCM, showed obvious cracks, while the foamed material specimens remained visually intact. This is because foamed materials have high penetrability and greater moisture movement, which leads to higher fire resistance. Based on the test results, 0% F-MPCM, 30% F-MPCM, and 10% F-GPM are suitable fire-resistant coating materials, with 30% F-MPCM exhibiting the highest level of fire resistance.

Table 5
Summary of the feasibility tests.

Coating Mortar	Foam Content	Flow Value	Compressive Strength	Setting Time	Slip Resistance	Cohesive-ness	Adhesive-ness	Summary
F-HPCM	0%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	10%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	30%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	50%	Pass	Fail	Pass	Fail	Fail	Pass	Fail
F-GPM	0%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	10%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	30%	Fail	Pass	Pass	Pass	Fail	Pass	Fail
	50%	Fail	Fail	Pass	Pass	Fail	Pass	Fail
F-MPCM	0%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	10%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	30%	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	50%	Fail	Fail	Pass	Fail	Fail	Pass	Fail

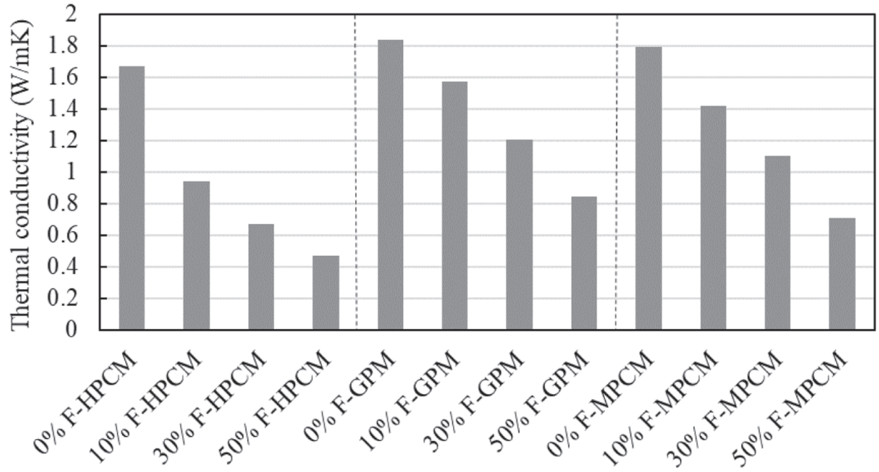


Fig. 9. Thermal conductivity of different materials.

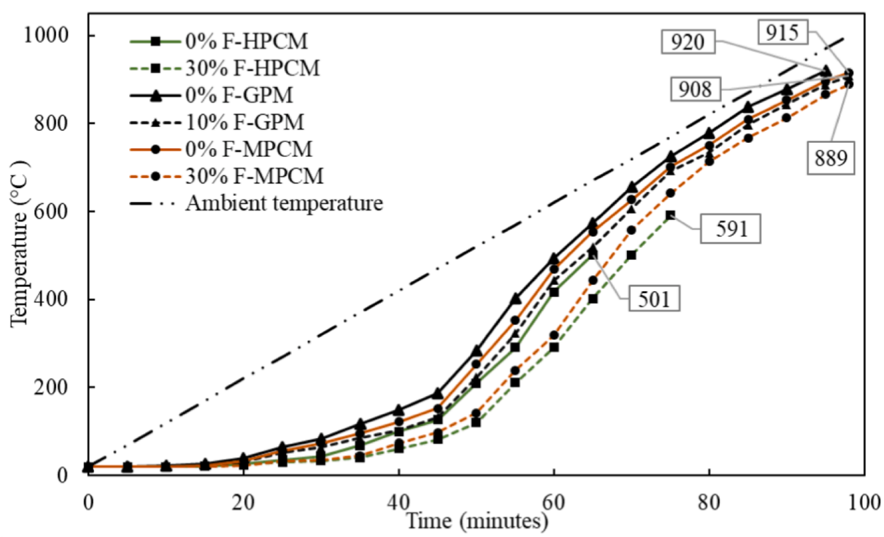


Fig. 10. Temperature vs. time diagram recorded during heat transfer test.

4. Conclusion and recommendations

In this study, novel fire-resistant coating materials were developed, namely F-HPCM, F-GPM, and F-MPCM mortars. Various tests were conducted to evaluate the feasibility and performance of these materials. Feasibility tests such as flow table, setting time, compressive strength, and spraying were carried out. The results showed increased foam content led to increased flow value, setting time, and adhesiveness, while compressive strength, slip resistance, and cohesiveness decreased. Furthermore, the thermal conductivity tests indicated that increased foam content improved thermal insulation. Based on the feasibility test results and the requirements, the maximum foam contents were found to be 30%, 10%, and 30% for F-HPCM, F-GPM, and F-MPCM, respectively.

Subsequently, fire resistance tests were then conducted on the selected foamed mortars and their non-foamed control materials. The results revealed that foamed materials could withstand higher ambient temperatures and have a lower heat transfer rate than non-foamed materials. The 0% and 30% F-HPCM failed at ambient temperatures of 670 ℃ and 770 ℃, respectively. On the other hand, both F-GPM and F-MPCM, with or without foam, could withstand ambient temperatures up to 1000 °C. Moreover, non-foamed F-GPM and F-HPCM specimens showed cracks after heating, while their foamed materials remained visually intact. This suggests that incorporating foam into a material can increase fire resistance by improving penetrability and moisture movement. Based on the fire resistance results, the 30% F-MPCM is an ideal fire-resistant coating material due to its relatively low heat transfer rate and ability to withstand high ambient temperatures (up to 1000 °C).

To further enhance the practical applications of F-HPCM, F-GPM, and F-MPCM as fire-resistant coating materials, future studies will focus on validating their performance under outdoor conditions, including exposure to ultraviolet light, condensation, and rainwater. Adhesion tests will also evaluate their compatibility with various structural surfaces. To better understand the mechanism of fire resistance of different materials or foam contents, additional assessment methods will be employed, such as measuring residual strength and analyzing changes in chemical compositions and microstructure following exposure to high temperatures. These efforts will provide a more comprehensive understanding of the properties and behaviors of foamed materials such as fire-resistant coatings and help identify further improvements and applications in the field of fire protection.

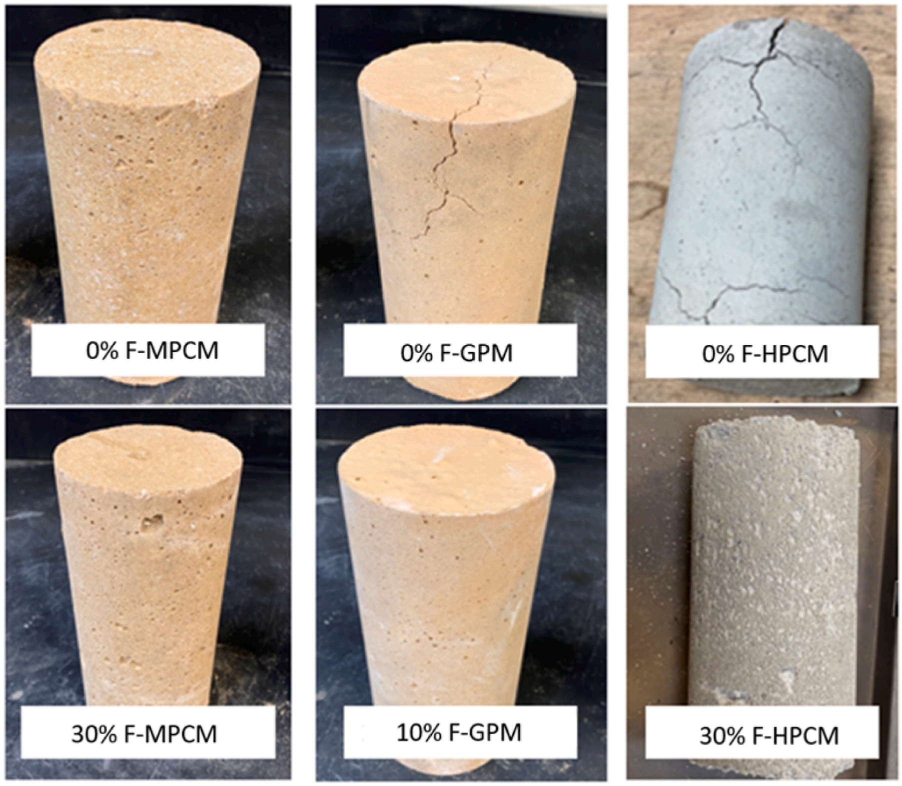


Fig. 11. Representative image of cracking.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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