

Analysis of fire resistance of ethylene-vinyl acetate polymer calcium sulfoaluminate cement mortars

Research Article

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Abstract: This research focuses on enhancing the fire resistance of cement mortars by incorporating ethylene-vinyl acetate (EVA) polymer. It aims to assess how EVA improves the mortar's performance when exposed to high temperatures and fire. The expected benefits include increased durability and enhanced safety under fire conditions through polymer modification. To investigate this, calcium sulfoaluminate cement mortars with varying EVA contents were subjected to direct fire exposure up to 700°C, following a detailed experimental plan to analyze their thermomechanical behavior after testing. The findings reveal that some samples experienced explosive reactions upon exposure to fire. Notably, the incorporation of EVA significantly enhanced both compressive and flexural strengths after direct fire exposure, with mortars containing 2 and 3% EVA achieving impressive compressive strengths of 11.55 and 13.82 MPa, respectively; the flexural strength peaked at approximately 4.5 MPa with 3% EVA. Thermal analyses indicated pronounced improvements in insulation properties for EVA concentrations between 1 and 3%, evidenced by reduced thermal conductivity and increased specific heat, highlighting the energy efficiency of these modified mortars, a vital consideration for sustainable construction. Additionally, mercury intrusion porosimetry testing showed that the optimal porosity of 29.92% was achieved with 1% EVA, while further increases to 2 and 3% led to diminishing returns. Thus, determining the optimal percentage of EVA is essential, as EVA modifications present a promising and sustainable alternative to conventional practices in cement mortars.

Keywords: Cement mortar • Fire resistance • Calcium sulfoaluminate cement • EVA polymer

1. Introduction

To extend the service lifespan of civil infrastructure, such as roads and pipeline construction, repair work is essential [1,2]. Recently, polymer-modified calcium sulfoaluminate cement (PMCSAC) mortar has gained significant attention due to its advantages, including high early strength, low alkalinity, and superior performance compared to conventional ordinary Portland cement (OPC) mortar [3,4]. As a result, it has been extensively utilized for repair work in various building constructions [5–7]. Due to the high-quality characteristics of PMCSAC mortar, including excellent early strength, water resistance, good bonding to the substrate concrete, and improved resistance to chemical attacks, it is

widely utilized in infrastructures such as external wall insulation mortars, bridges, and self-leveling mortars in various applications [8,9]. Furthermore, when compared to OPC mortar, PMCSAC mortar demonstrates superior performance when repairing reinforcing concrete structures [5,10–12]. Nevertheless, selecting the appropriate mortar repair material can be quite challenging, primarily due to the limited availability of experimental results concerning the safety and fire resistance of polymer mortar [13,14]. There is growing concern regarding the increasing use of PMCSAC mortar in construction, particularly relating to its fire resistance. This concern stems from the understanding that PMCSAC mortar is known for its combustibility and potential for deterioration, which can lead to de-bonding from the substrate concrete at elevated temperatures [15–17]. It is more urgent than ever to explore the failure mechanisms

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of PMCSAC mortar after exposure to direct fire. This urgency arises from the presence of combustible organic polymers, which are vulnerable during fire situations. Additionally, there are insufficient data on this topic. Recent research studies have primarily focused on the design of PMCSAC mortar, as well as its mechanical properties, bonding characteristics, and durability both before and after the repair process [9,18]. Published studies indicate that cement-based compounds can disintegrate when exposed to direct fire, and this is mainly due to two reasons. First, there is the uneven thermal expansion between the cement matrix and the aggregates, which is caused by the thermo mechanical process. Second, the porous network of the material can accumulate high pressures during such exposure [19,20]. Despite research on reinforced cement mortars under fire, no studies specifically examine ethylene-vinyl acetate (EVA)-modified mortars subjected to direct fire testing. Existing work shows that EVA enhances the mechanical strength by up to 33% but degrades significantly above 200°C, with strength dropping 78–80%. Comparative analyses highlight EVA's superior fire resistance versus other polymers, yet higher polymer content raises combustion risks, underscoring the need for focused investigation [21]. Consequently, this research study seeks to address the lack of understanding regarding how the incorporation of EVA polymer into calcium sulfoaluminate cement (CSAC) and exposure to direct fire influences the performance of mortars. During a fire event, cement mortar acts as an inert material that primarily absorbs a portion of the generated heat, while other substances may emit gases and heat, among other effects. Thus, it is crucial to examine the effects of fire on the EVA polymer CSAC mortars explored in this research. This analysis aims to evaluate the viability of using EVA polymer to enhance their performance concerning their response to fire conditions.

2. Materials and methods

2.1 Materials

The materials employed in carrying out the experimental development associated with this research are as follows.

- CSAC 42.5 (Appendix 1), which was provided by Sishui Zhonglian Cement Group Co., Ltd in China, was utilized in compliance with the GB/T 20976-2007 standards [22].
- In the experiment, standard fine sand was utilized, as specified by the Chinese standard GB/T 17671-1999 [23].
- This experiment used tap water that complies with the water quality guidelines established in the Chinese standard GB 50164-2011 for concrete casting [24].
- The research team utilized rubber powder consisting of an EVA composition of 30/10. In this designation, the 30 indicates that the vinyl acetate content is 30%. The EVA was applied in its unprocessed form, requiring no further treatment.
- No additional substances were incorporated.

The mixture ratio of the mixed samples of different EVA PMCSACs is shown in Table 1.

2.2 Preparing test specimens

This research followed the Chinese standard GB/T 17671-2021 to prepare the samples measuring 40 mm × 40 mm × 160 mm for the intended purpose [25]. A total of six samples were produced for each group, and the average measurements are presented in this study. Following the casting process, the samples were cured at a temperature of 20 ± 2°C with controlled relative humidity of 95%. The EVA rubber powder PMCSAC repair mortar was poured into beam molds of 40 mm × 40 mm × 160 mm (Figure 1). After a curing period of 24 h, the specimens were de-molded and placed in a controlled environment for standard curing over a duration of 28 days.

2.2.1 Direct fire exposure

After a curing period of 28 days, the samples were subjected to oven drying until the weight variation reached 1 g over a duration of 2 h, in accordance with the European standard EN 480-5 [26]. The fire test was conducted following the UNE-EN 1363-1:2012, UNE-EN 1363-2:2000, UNE-EN 1365-4:2000, and ISO R-834 standards [27–30]. For the direct fire test, the ISO R-834 standard was implemented, which specified a calorific potential of 40 kg of wood per square meter (kg/m²),

Number of samples	CSAC (g)	Sand (g)	EVA content (%)	Water (g)	Water reducer (%)
A	450	1,350	0	225	0.5
B	450	1,350	1.0	225	0.4
C	450	1,350	2.0	225	0.3
D	450	1,350	3.0	225	0.2

Table 1. Mixing of the EVA PMCSAC mortar samples.



Figure 1. Preparation and curing of EVA PMCSAC mortar specimens.

representing the average calorific value encountered in fire conditions. The 40 mm × 40 mm × 160 mm specimens were placed horizontally on a 1 m² steel grill, ensuring that all sides were in direct contact with the flames (Figure 2). Six specimens from each sample were arranged on the grill to ensure each compound was represented in the area farthest from the fire, the innermost area, and the intermediate area. Combustion was initiated by spraying pinewood with gasoline. The test lasted for 1 h, during which temperature measurements were taken at three points on the surface of the specimens every 5 min, using a compact infrared thermometer, model Testo 845. Following 1 h of exposure to fire, the samples were allowed to cool gradually on the grill. Additionally, thermal images were captured at various intervals throughout the testing procedure.

3. Testing parameters

3.1 Ultrasonic pulse velocity (UPV) testing

UPV testing is a crucial non-destructive evaluation technique used to determine the quality of mortar. This

method involves transmitting ultrasonic waves through the mortar and measuring the time it takes for these waves to pass through the material. After exposing the mortar to direct fire, engineers can utilize UPV testing to evaluate how fire affects the material and to detect any potential issues. This research work followed the ASTM C1060-18 procedures and guidelines for UPV testing of mortar [31].

3.2 Flexural strength and compressive strength

The flexural and compressive strength tests were conducted in accordance with the ASTM C109 standard [32]. Specimens measuring 40 mm × 40 mm × 150 mm were placed under a vertical three-point loading arrangement at a rate of 50 N/s until failure occurred. Subsequently, half beams measuring 40 mm × 40 mm × 80 mm were utilized for the compressive strength tests, where a load of 2,400 N ± 200 was applied until the specimens fractured.

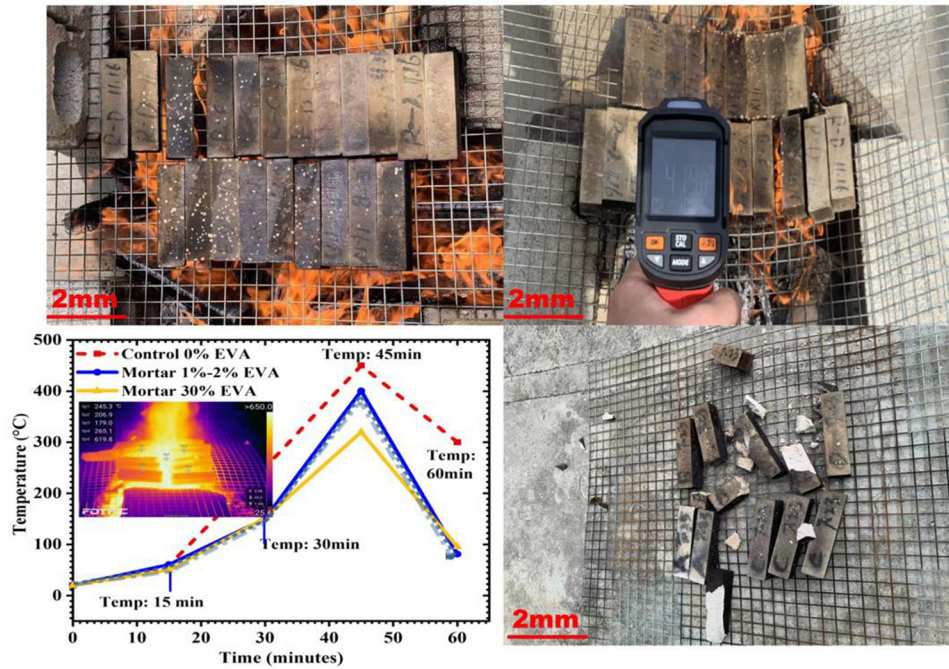


Figure 2. Thermographic images of the start of the fire. Resistance to direct fire test and temperature were measured using an infrared thermometer.

3.3 Thermal conductivity

Thermal conductivity was assessed utilizing the Hot Disk device, in compliance with the Chinese standard GB/T 20219-2015 [33]. This technique utilizes a guarded hot plate system, which facilitates a consistent heat flow through the material sample. By evaluating the temperature variation across the sample and the heat flux that moves through it, the thermal characteristics were determined.

3.4 Micromorphology analysis

Utilizing scanning electron microscopy (SEM) to analyze the microstructure of the mortar after direct fire exposure could provide detailed insights into the effects of EVA on the binder phase and overall material performance. This test helps in assessing whether the polymer contributed to any significant changes in pore structure, density, and bonding behavior, which are crucial factors influencing the mechanical properties and fire resistance of the mortar. The analysis of the microstructure of mortar through SEM following fire exposure was conducted in accordance with the guidelines established in the ASTM C1723-16 standard, which outlines practices for the preparation of concrete and mortar samples for testing [34].

3.5 Pore structure analysis

This research utilized two methods to analyze the pore structure of the EVA PMCSAC mortars: **Method (a)** involved water absorption testing, which evaluated the water absorption capacity of the mortars after direct exposure to fire, according to the Chinese standard GB/T 3183-2017 [35]. This testing is crucial as high temperatures can alter the microstructure and consequently affect these properties. **Method (b)** comprised mercury intrusion porosimetry (MIP), which was performed according to ASTM B922 [36] to characterize the porosity and pore size distribution in the samples. For this analysis, small square specimens with dimensions of 10 ± 1 mm were created by crushing the material, and the samples were dried according to established protocols prior to the MIP examination.

4. Results and discussion

4.1 UPV

The results of the UPV testing support the hypothesis that incorporating EVA into PMCSAC mortars enhances their

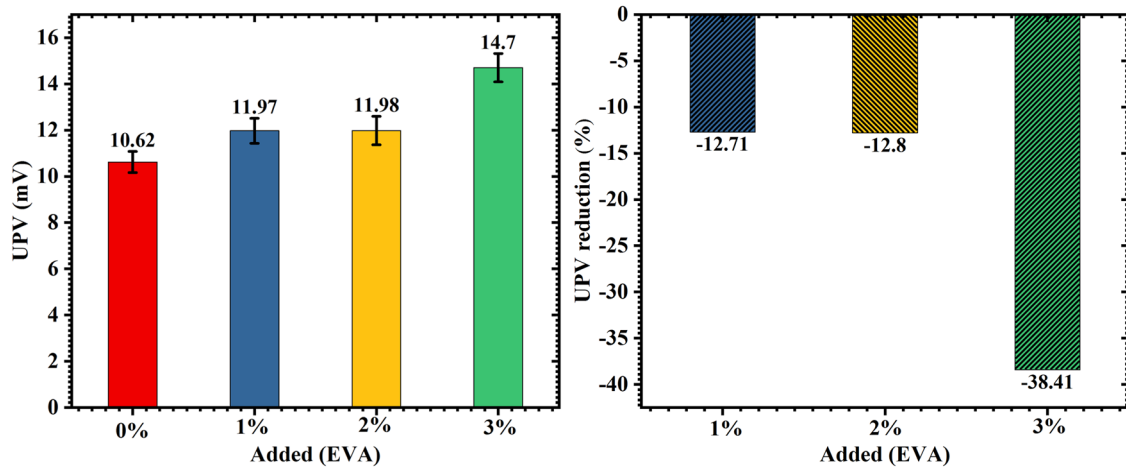


Figure 3. UPV values of EVA PMCSAC mortars.

overall structural integrity (Figure 3). The control sample, which contained 0% EVA, demonstrated an average UPV value of 10.62 mV, indicative of its baseline mechanical performance. When 1% EVA was added, the average UPV increased by 11.97%, reflecting improved material cohesion and density. Further additions of EVA revealed even more notable enhancements; with 2% EVA, the average UPV rose by 11.985%, and with 3% EVA, it reached an increase of 14.7%. These findings are aligned with prior research, which indicates that the UPV serves as an effective non-destructive testing method to evaluate the quality and durability of concrete materials [37]. For instance, studies have shown that enhanced UPV readings directly correlate with improved binding, lower porosity, and greater compressive strength, reinforcing the advantages of incorporating polymers into cementitious systems [38]. The progressive increase in UPV values with higher EVA concentrations not only underscores the effectiveness of the polymer modification but also suggests that optimal EVA incorporation can lead to cement-based composites with superior performance characteristics, making them more suitable for structural applications in demanding environments.

4.2 Flexural and compressive strength

The analysis of the flexural and compressive strength of EVA PMCSAC mortar reveals significant trends upon the addition of varying percentages of EVA (0, 1, 2, and 3%) after direct exposure to fire for 1 h (Table 2).

According to recent research, the incorporation of EVA polymer enhances the performance of the mortar, especially in terms of compressive strength [39]. For instance, when compared to the control group (0% EVA), the addition of 1% EVA resulted in decreased compressive strength, with the mean value dropping to approximately 0.82 MPa. However, with further increases to 2 and 3% EVA, the compressive strength improved to 11.55 and 13.82 MPa, respectively, indicating that a moderate EVA concentration plays a beneficial role in mitigating heat-induced degradation (Figure 4). The flexural strength, which is also critical for structural applications, showed similar trends, with optimal strength values being achieved at 3% EVA, where it reached approximately 4.5 MPa. Recent studies corroborate these findings, emphasizing that EVA's gasification and decomposition processes contribute to improved thermal resistance, thereby enhancing the mechanical performance of mortars under fire conditions [40,41]. This evidence suggests that while low percentages of EVA may weaken the structural integrity post-fire exposure, higher concentrations effectively strengthen both compressive and flexural capacities, making them suitable for applications requiring enhanced thermal resilience.

4.3 Thermal conductivity

The analysis of thermal properties in EVA PMCSAC mortar reveals significant trends related to the incorporation of EVA as a modifier. The control sample, containing 0% EVA,

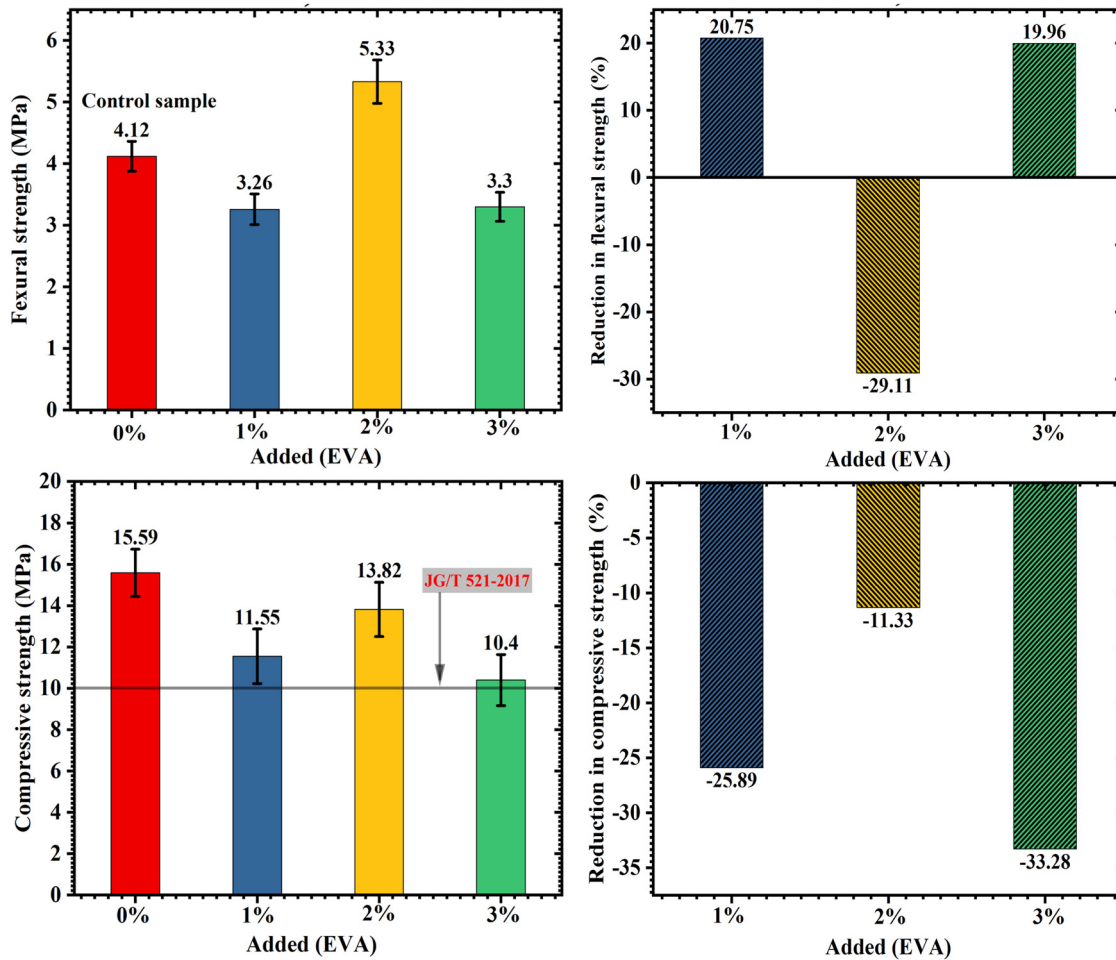


Figure 4. Flexural and compressive strength of the EVA PMCSAC mortars after direct fire exposure.

exhibited thermal conductivity at 1.62, thermal diffusivity of 1.26, and specific heat of 1.28. With the addition of 1% EVA, thermal conductivity decreased significantly to 1.32, while thermal diffusivity and specific heat displayed lower values of 0.89 and 1.46, respectively (Figure 5). This trend continues with 2% EVA, where the thermal conductivity further decreases to 1.05 alongside thermal diffusivity of 0.67 and specific heat of 1.56. With 3% EVA, the thermal conductivity remains relatively low at 1.08, with thermal diffusivity at 0.68 and a specific heat of 1.58. These results suggest that the incorporation of EVA improves the thermal insulation properties of the PMCSAC mortar, as corroborated by previous studies demonstrating that EVA enhances the overall thermal performance of cement-based materials by reducing thermal conductivity and improving energy efficiency [42,43]. Additionally, the observed increase in specific heat indicates that the EVA-modified samples may retain heat more effectively, a

characteristic that is advantageous for energy-efficient building applications [44]. The data indicate that even small percentages of EVA can substantially influence thermal properties, providing a pathway for developing advanced cementitious composites with improved thermal insulation capabilities.

4.4 Pore structure analysis

4.4.1 Method A: water saturation

The examination of saturated absorption in EVA PMCSAC mortar reveals critical insights regarding the effects of EVA content and the type of water used during testing. As indicated in the findings, the figures illustrate in Figure 6, the changes in saturated absorption for EVA PMCSAC mortar variants prepared with 0, 1, 2, and 3%

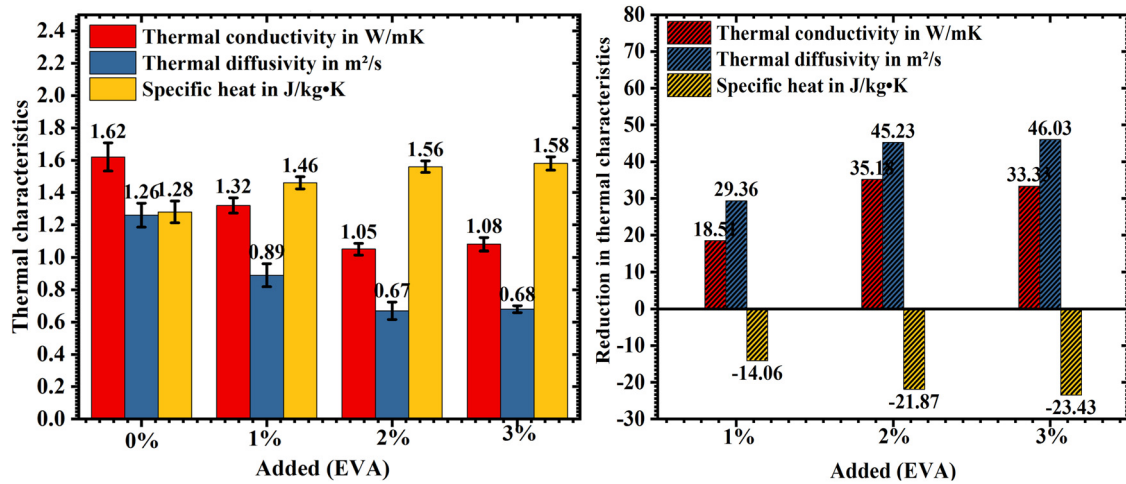


Figure 5. Thermal characteristics of the EVA PMCSAC mortars.

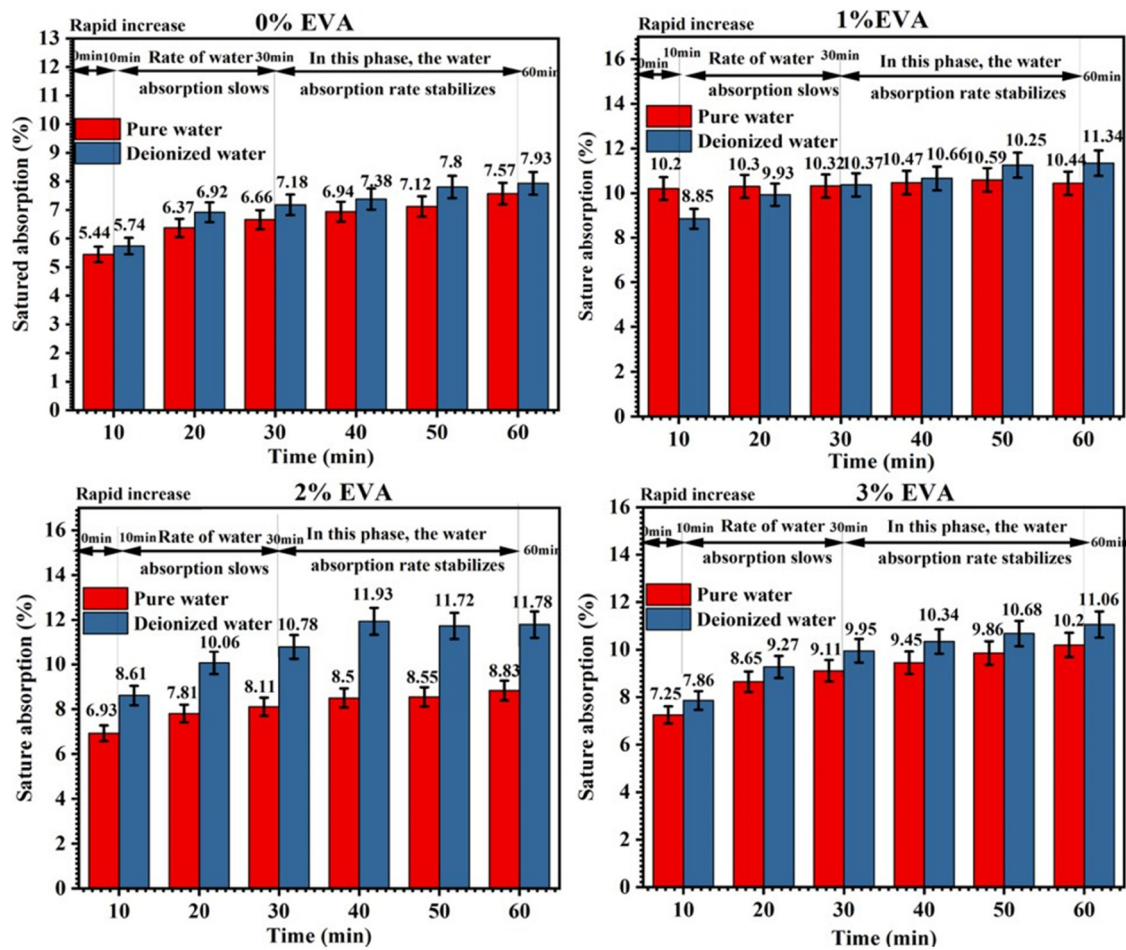


Figure 6. Water saturation of the EVA PMCSAC after direct fire exposure.

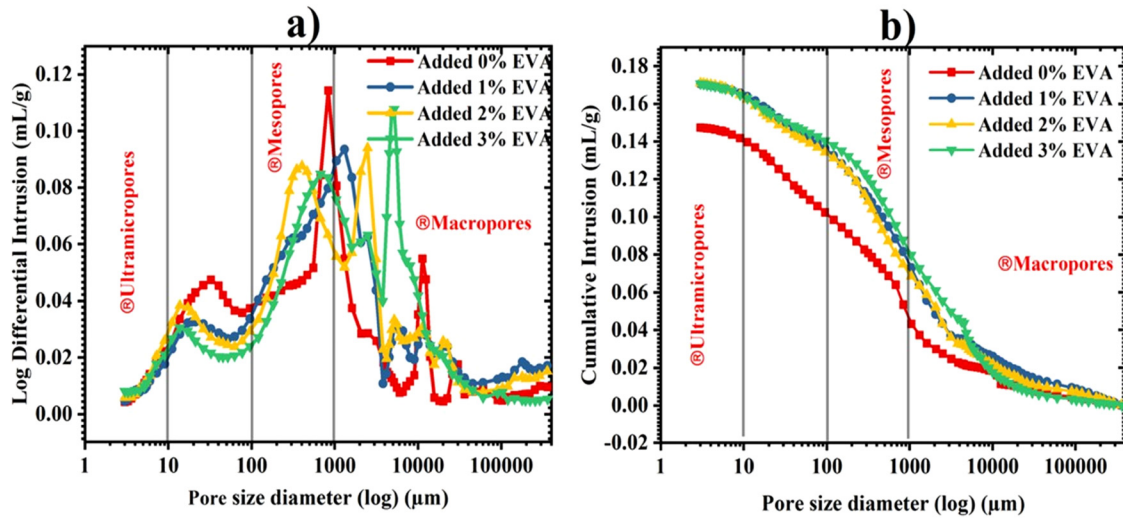


Figure 7. (a) Log differential intrusion volume in mL/g and (b) the cumulative intrusion volume.

EVA after exposure to direct fire, highlighting two types of water – pure water and deionized water. Notably, throughout all concentrations of EVA, saturated absorption metrics are significantly elevated when deionized water is employed in comparison to pure water. For example, the case with 0% EVA shows that the saturated absorption after 60 min using deionized water is approximately 7.93%, while that using pure water is around 6.92%, marking an increase of roughly 14.6%. This discrepancy can be attributed to the impurity levels in pure water, such as dissolved salts and minerals, which can chemically interact with the cement matrix [45]. These interactions can adversely affect the cement's capacity to absorb water efficiently [46]. Previous research supports the notion that the ionic composition of water can either enhance or weaken the hydration process of binders, which directly impacts the material properties of the mortar [47]. Moreover, the introduction of EVA into the cement matrix generally correlates with reduced saturated absorption levels, implying the material's function as a water repellent agent. It has been indicated that the incorporation of polymer additives like EVA can significantly reduce water absorption due to their hydrophilic and hydrophobic balance, enhancing the durability of cement-based materials [48]. Nonetheless, this water-repellent effect appears to be less pronounced when deionized water is utilized, as evidenced by the reduced difference in saturated absorption between the two water types at higher EVA content levels of 3%. Additionally, these findings pose important implications for mortar's long-term resilience against environmental stressors such as freeze–thaw cycles and sulfate attacks, challenges known to significantly compromise

cement durability. As noted in existing literature, materials with high water absorption rates are more vulnerable to deterioration from freeze–thaw cycles [49]. This analysis emphasizes the pivotal role of water quality in determining the saturated absorption characteristics of EVA PMCSAC mortar. The findings underscore that employing deionized water enhances water absorption, possibly compromising the mortar's resilience against various degradation phenomena. At the same time, the effectiveness of added EVA in conferring water repellency may be less evident in scenarios utilizing deionized water for testing.

4.4.2 Method B: MIP testing

Figure 7 presents the pore size distribution of EVA PMCSAC mortar samples subjected to varying proportions of EVA after exposure to direct fire. The differential intrusion data (Figure 7a) reveal a noticeable shift in the peak pore size toward larger diameters as the EVA content increases. This phenomenon supports findings from published literature, which indicate that EVA incorporation can promote the formation of larger pores within the mortar matrix [50]. Additionally, the cumulative intrusion data (Figure 7b) strengthen this assertion, exhibiting a heightened cumulative intrusion volume at larger pore sizes in samples with increased EVA content. Such results align with previous studies, wherein similar polymer additions were shown to enhance porosity in cementitious materials [51]. This trend underscores the implication of EVA addition for practical applications, suggesting that a more porous structure may influence the mechanical and

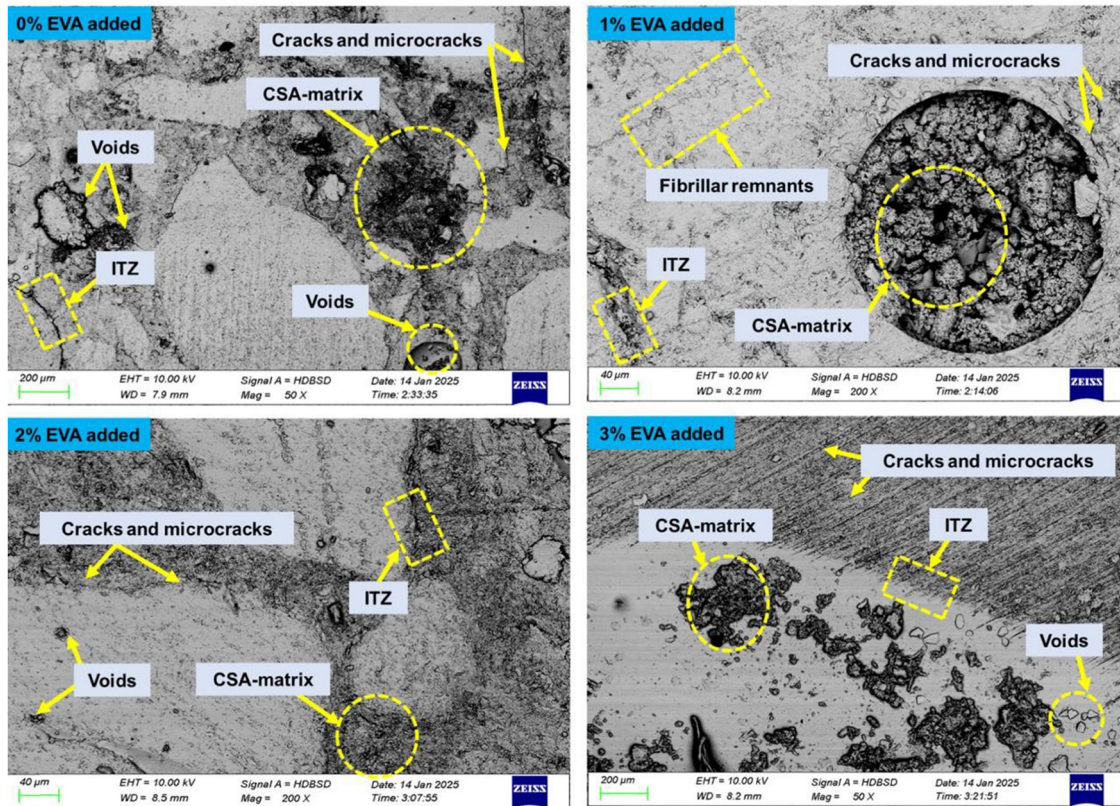


Figure 8. SEM observations of different EVA PMCSAC mortars.

thermal properties of the mortar, potentially improving its performance during high-temperature conditions. The ability to engineer porosity in construction materials can lead to enhanced thermal insulation and reduced weight, ultimately contributing to more efficient building systems [52].

The statistical analysis of the porosity results reveals a notable shift in the characteristics of EVA PMCSAC mortar in response to varying concentrations of EVA after direct fire exposure. The average porosity values were recorded as 26.80% for the 0% EVA mixture, increasing to 29.92%

with 1% EVA, and relatively stable at 29.54 and 29.37% for the 2 and 3% EVA mixtures, respectively (Table 3). The standard deviation for these groups was found to be statistically significant, with a significance level (p -value) below 0.05, indicating a reliable difference in porosity associated with the EVA modifications. These results align with the previously published studies, which illustrate the correlation between polymer modifications and enhanced structural characteristics in cementitious materials [53]. The implications of these findings are critical; they suggest that while the initial improvement (1% EVA) enhances

Sample group	Mean compressive strength	Std. Dev. compressive	Confidence interval	Mean flexural strength	Std. Dev. flexural	Flexural confidence interval
0% EVA (Control, Sample A)	15.2585	2.2574	(12.9605, 17.5565)	4.228	0.5764	(3.663, 4.793)
1% EVA (Sample B)	11.8875	2.7735	(9.5886, 14.1864)	3.2668	0.1638	(3.2516, 3.2804)
2% EVA (Sample C)	13.1567	3.2475	(10.4839, 15.8295)	5.6865	0.8920	(4.6680, 6.7040)
3% EVA (Sample D)	10.7400	3.3218	(8.0790, 13.4010)	3.3040	0.2213	(3.2281, 3.3799)

Table 2. Compressive and flexural strength analysis of EVA-enhanced CSAC mortars following direct fire exposure.

Group	Average values parameters			
	Total intrusion volume (mL/g)	Total pore area (m ² /g)	Median pore diameter (nm)	Tortuosity (%)
0% EVA added	0.147	10.87	13.22	3.00
1% EVA added	0.170	9.26	13.36	3.48
2% EVA added	0.171	10.69	11.36	17.20
3% EVA added	0.170	9.39	10.36	3.72

Table 3. Summary of the MIP testing of EVA PMCSAC mortars.

porosity moderately, higher concentrations do not yield further benefits, underlining the necessity for optimal EVA ratios in applications where fire resistance and structural integrity are paramount. Thus, careful consideration of EVA content can lead to improved performance in construction materials subjected to high-temperature environments.

4.5 SEM analysis

The analysis of EVA PMCSAC mortar with varying percentages of EVA reveals an intriguing relationship between EVA content and the material's microstructural integrity when subjected to direct fire exposure (Figure 8). In the PMCSAC without EVA, the densification and homogeneity of the hydrated cement phases are evident; however, thermal stress has led to the formation of microcracks, particularly in the interfacial transition zone (ITZ). The introduction of 1% EVA shows a slightly heterogeneous microstructure, with cracks that are similarly induced by thermal stresses; importantly, the ITZ remains relatively well-defined despite showing signs of microstructural damage. At 2 and 3% EVA, the EVA PMCSAC mortar continues to exhibit a heterogeneous phase distribution with visible microcracking under thermal stress, suggesting that even as EVA is introduced, its protective effects are somewhat limited. The unmodified CSA mortar exhibits severe cracks and voids, highlighting its brittleness under thermal stress. With 2 and 3% EVA additions, the PMCSAC mortar shows a heterogeneous phase distribution and persistent microcracking, indicating that while EVA reduces crack propagation, bridges gaps, and strengthens the microstructure, its protective effects remain limited under high temperatures. Although higher EVA content (3%) significantly improves fire resistance compared to unmodified mortar, the structural integrity is not fully reinforced, as microcracks still form. This suggests that EVA enhances certain properties under normal conditions but may not sufficiently ensure long-term durability in fire-prone

environments, raising concerns about the safety and performance of these composites in extreme thermal exposure.

5. Conclusion

This study investigates the EVA PMCSAC cement with varying percentages of EVA added, specifically examining its effects on samples subjected to direct fire exposure. The investigation utilized non-destructive testing, mechanical property assessments, and microstructure analysis. The following conclusions can be drawn:

- (1) The UPV testing on EVA PMCSAC mortars, prepared with varying concentrations of EVA, clearly demonstrate that the inclusion of EVA enhances the material's structural integrity. The significant increases in UPV values, particularly at 2 and 3% EVA concentrations, indicate improved cohesion and durability. Importantly, these findings align with the standards set forth in IS 1905, which outline the necessary tests to assess the strength and quality of masonry mortars.
- (2) The study demonstrates that incorporating EVA polymer into PMCSAC mortar significantly enhances its compressive and flexural strengths after direct fire exposure. Mortars with 2 and 3% EVA exhibited remarkable compressive strengths of 11.5541 and 13.8234 MPa, respectively, alongside a flexural strength peak of approximately 4.5 MPa at 3% EVA. These results suggest that the mortar meets relevant standards for enhanced thermal resistance, in particular ASTM C348 for flexural strength, underscoring the potential of EVA-modified mortars in fire-prone applications.
- (3) Thermal analysis shows EVA-modified PMCSAC mortar improves insulation, especially at 1–3% EVA, with lower thermal conductivity and higher specific heat. This enhances energy efficiency for sustainable construction. The results comply with ANSI A118.15, confirming high-performance thermal properties for energy-efficient building applications.

- (4) MIP testing of EVA-modified mortar shows 1% EVA yields optimal porosity (29.92%), while 2 and 3% reduce effectiveness. With a *p*-value inferior to 0.05, results meet fire-resistance standards, improving thermal and structural performance. Optimizing EVA content aligns with ASTM C150, ensuring efficiency in high-temperature applications.
- (5) SEM analysis of EVA-modified PMCSAC mortar reveals that lower EVA percentages reduce microcracking under fire but fail to meet ASTM E119 fire resistance standards. High temperatures still cause significant damage, raising concerns for fire-prone areas. Caution is advised when using EVA-PMCSAC in construction.

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Author contributions

The authors of this study declare the following contributions: Zihao Li: Data collection and analysis. Fengzhen Yang and Zihao Li conducted the data collection and performed all statistical analyses necessary for the interpretation of the results. Jean Jacques Kouadjo Tchekwagep: Conceptualization and methodology of the research. Jean Jacques Kouadjo Tchekwagep was responsible for the design of the study, including the theoretical framework and the research questions. Shifeng Huang and Shoude Wang: Drafting and editing of the manuscript. Shifeng Huang was primarily involved in drafting the initial manuscript and revising it for important intellectual content. Herve Kouamo Tchakouté and Ning Ding: Supervision and project administration, oversaw the research process and managed the logistics throughout the project. All authors have read and approved the final manuscript and agree to be accountable for the integrity and accuracy of the work.

Conflict of interest statement

The authors declare no conflict of interest.

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Appendix 1 CSA chemical and physical characteristics

CSA chemical and physical composition

Oxide	SiO ₂	Al ₂ O ₂	Fe ₂ O ₃	MgO	SO ₃	Na ₂ O	K ₂ O	Cao	Specific gravity
Compositions									(g/cm ³) 3.1
Weight (%)	7.5	35	1.5	—	15.5	—	—	41.0	
Mineralogical phase composition	C ₂ S	C ₄ A ₃ \$		C ₁₁ A ₇ F	CaSO ₄	Fluor- elpasolite		Others	Specific surface (m ² /kg)
Weight (%)	18	60		4.4	9.9	4.5		3.2	450