Deterioration Mechanism of EVA-Modified OPC-SAC Pavement Repair Materials under Extremely High Temperatures

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Abstract: Rising infrastructure demands push cement-based repair materials to their limits. Hot-patch scenarios subject OPC-SAC blends to wide temperature swings that disturb hydration, destabilise hydrates, and resulting in micro-cracking, reduced toughness, and increased maintenance demands. We prepared EVA-latex modified OPC-SAC, exposed it to 20–80°C, and tracked property evolution. At 23°C, EVA cut flexural/ compressive strength by 25.9%/31.5%. From 23°C to 80°C, compared to the plain blend, the reduction in flexural strength of the modified composite stabilized at high temperatures (after an initial complex variation), while the compressive strength increased 5.79% higher than the control group, demonstrating EVA's stabilizing effect under extremely high temperatures.

Keywords: Extremely High Temperatures; EVA Modifier; OPC-SAC Binary System; Performance Degradation

1. Introduction

The increasing frequency of extreme heat events, driven by global climate change, poses severe challenges to critical infrastructure systems, including roads and bridges. The long-term performance of concrete, a primary construction material, is inherently susceptible to degradation from synergistic environmental and mechanical stressors. Consequently, developing advanced and durable repair methodologies for concrete structures remains a paramount and persistent focus within civil engineering research [1-3]. Composites based on Ordinary Portland Cement (OPC) and Sulfoaluminate Cement (SAC) represent the predominant strategy for rapid repair, capitalizing on their fast-setting nature, high early strength, and ease of application [4]. Ethylene-vinyl acetate copolymer (EVA) has the advantages of wear resistance, impact resistance, water resistance, light weight, and environmental friendliness. It can be blended and modified with cementitious materials to improve heat resistance [5]. However, the performance of EVA-modified OPC-SAC composites is susceptible to significant deterioration under elevated temperatures, posing substantial challenges to the structural integrity and service life of pavement systems. A comprehensive investigation into the high-temperature degradation behavior of these materials and the underlying environmental interaction mechanisms is therefore imperative. Such research holds profound significance: it not only advances the fundamental understanding of structure-property relationships in cementitious composites but also enables the development of precision repair strategies for enhanced durability and operational safety. Moreover, these insights provide the scientific foundation for designing sustainable pavement materials with reduced ecological footprint, aligning with global initiatives for green infrastructure development.

Ma [6] systematically investigated the OPC-SAC binary system by preparing mixtures with SAC substitution levels from 0% to 100% in graded increments of 10%. They evaluated key performance indicators, such as setting time, to identify the optimal formulation and benchmark it against pure OPC, thereby providing a critical foundation for the application of OPC-SAC composite systems. Li [7] developed a steam-free, early-strength concrete by employing a blend of OPC and low-alkali SAC. Their research demonstrated that mixtures with SAC contents between 10% and 25% exhibited superior workability. These formulations achieved a compressive strength of ≥15 MPa within 10 hours and surpassed 36 MPa after 28 days of curing. Shi [8] reported that an increase in SAC content was positively correlated with an accelerated hydration rate and a consequently shortened setting time. Notably, they observed that when the ambient temperature exceeded 35°C, the primary hydration products underwent subsequent decomposition, leading to a marked decline in both mechanical strength and expansion performance in the long term. Based on comprehensive rheological and FTIR analyses, Yan [9] concluded that an EVA content exceeding 4% yields high-temperature performance metrics superior to those of SBS-modified asphalt. Their study further highlighted a marked enhancement in storage stability with EVA modification. Li [10] employing dynamic shear rheometer (DSR) tests, corroborated that EVA modification effectively reduces the temperature susceptibility of asphalt, with this effect exhibiting a monotonic improvement with increasing EVA content. Collectively, these findings establish a robust theoretical and experimental foundation for the application of EVA-modified cementitious systems in high-temperature environments.

The performance degradation of EVA-modified ordinary Portland cement-calcium sulfoaluminate cement (OPC-SAC) composites for pavement repair is governed by a complex synergy between their intrinsic chemical formulation, the ensuing microstructural architecture, and the severity of external environmental stressors. A systematic investigation into their failure mechanisms under extreme high-temperature conditions is therefore imperative, serving a multifaceted and critical purpose. From a fundamental science standpoint, such research is essential for deciphering the intricate structure-property-performance relationships and elucidating the synergistic, multi-factorial degradation pathways. This deep mechanistic understanding is a prerequisite for advancing predictive theoretical models and guiding the rational design of next-generation materials. From an applied engineering perspective, the insights garnered are instrumental in informing evidence-based material selection and optimizing construction methodologies. This knowledge directly translates to enhanced in-service durability, structural resilience, and long-term safety of pavement infrastructure, thereby reducing premature failure. Furthermore, from an environmental sustainability dimension, this line of inquiry supports the development of eco-efficient repair solutions. By extending service life and minimizing the frequency of rehabilitation, it contributes significantly to reducing the life-cycle ecological footprint and resource consumption of maintenance operations. In conclusion, this research domain is not only pivotal for safeguarding transportation infrastructure—directly impacting road safety and functional longevity—but also carries profound implications for driving technological innovation and promoting sustainable construction practices, solidifying its status as a field of paramount scientific and societal merit.

This investigation utilized a mortar system formulated from an OPC-SAC binary cementitious matrix modified with EVA copolymer emulsion. Prismatic specimens (40 mm × 40 mm × 160 mm) were fabricated under controlled laboratory conditions (20°C ± 2°C, RH $\geq$ 95%) and subjected to standard curing for 28 days. Following initial curing, the specimens underwent accelerated thermal aging through 7-day exposure to graded temperature regimes (80°C, 60°C, 40°C, and ambient temperature). A multi-scale characterization protocol was implemented to assess the composites' physico-mechanical performance, macrostructural integrity, and microstructural evolution. The experimental results were further contextualized within practical road rehabilitation scenarios to evaluate the material's durability metrics, service reliability, and environmental footprint throughout its lifecycle under high-temperature service conditions. This integrated approach aims to establish a scientifically-grounded framework for developing rapid pavement repair solutions in extreme climate regions.

2. Experiment

2.1 Materials

(1) OPC: Grade 42.5R OPC, complying with all requirements of the Chinese National Standard GB 175-2007 for 'Common Portland Cement', was used.

(2) SAC: Grade 42.5 SAC, conforming to the Chinese National Standard GB/T 20472-2006 for 'Sulfoaluminate Cement', was employed.

(3) Aggregate (Sand): Standard fine sand meeting the specifications for building sand according to Chinese Standard GB/T 14684-2001 was utilized.

(4) EVA: A vinyl acetate-ethylene co-polymer

emulsion (commercial designation: 705) was used as the modifier. Its key properties are a solid content of approximately 50% (calculated from the provided mass of 108g for the solid component, implying a total emulsion mass of ~216g for a 50% solid content), a viscosity ranging from 1500 to 2500 mPa·s, and a pH value between 4 and 6.

(5) Water: Tap water from the Chongqing municipal supply, which satisfies the requirements stipulated in the Chinese Standard JGJ 63-2006 for 'Water for Concrete', was used for all mixtures.

2.2 Method

The flowchart of the experimental procedure is shown in Figure 1.

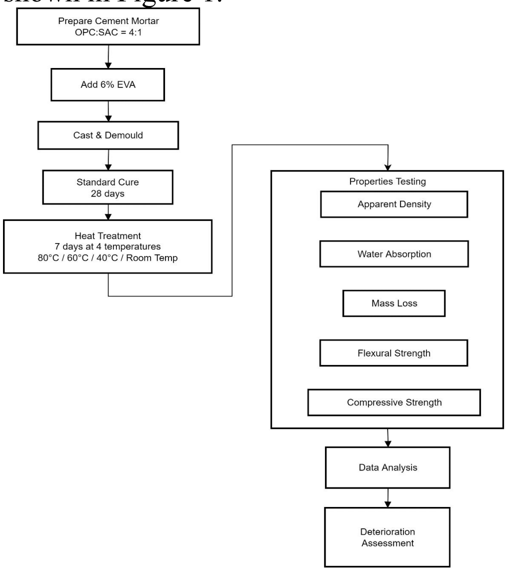

Figure 1. Flowchart of the Experimental Procedure

3. Research Results and Analysis

3.1 EVA in OPC-SAC Modified Systems

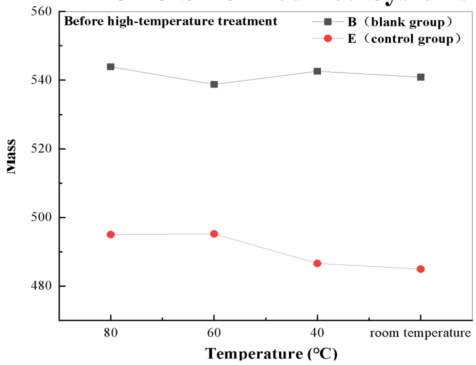

Figure 2. Changes in Mass of OPC-SAC Composites with and without EVA Modification under Different Temperatures

As shown in Figure 2, the temperature affected mass loss trends similarly in both the control and modified groups; however, the control group consistently demonstrated higher residual mass across all temperature levels (80°C, 60°C, 40°C, and ambient), with specific differences measured at 9%, 8%, 10%, and 10%, respectively. This confirms that the incorporation of EVA systematically reduces the mass of the OPC-SAC composite by an average of 9.4%. The underlying mechanisms may involve the lower density of EVA reducing the overall composite density, potential interface defects arising from incompatibility between EVA and the cement matrix, chemical interactions between EVA and hydration products that alter microstructure, volatilization of residual components from the emulsion, and process-induced variations affecting material compactness.

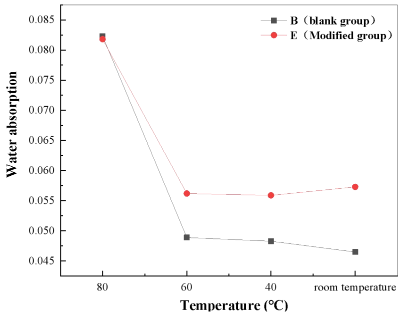

Figure 3. Changes in Water Absorption Rate of OPC-SAC Composites with and without EVA Modification under Different Temperatures

In Figure 3, experimental data indicate that water absorption remained relatively stable from ambient temperature up to 60°C, with the control group consistently exhibiting lower values than the modified group. Within this range, the modified group showed increases in water absorption of 14.9%, 15.6%, and 23.6% at 60°C, 40°C, and ambient temperature, respectively, demonstrating that the EVA modifier significantly enhances the hydrophilicity of the OPC-SAC composite. In contrast, at 80°C, the water absorption of the modified group was only 0.66% lower than that of the control, suggesting a negligible effect of EVA under such high-temperature conditions. This is likely due to microstructural alterations induced by EVA, which affect water molecule diffusion and adsorption. At lower temperatures (ambient to 60°C), the inherent hydrophilicity of EVA, its interaction with OPC-SAC forming hydrophilic groups, interfacial effects, and the material's own water-absorbing properties collectively contribute to elevated absorption. However, at elevated temperatures approaching 80°C, thermal-induced changes in EVA's properties likely diminish its hydrophilic characteristics, thereby neutralizing its impact on water absorption.

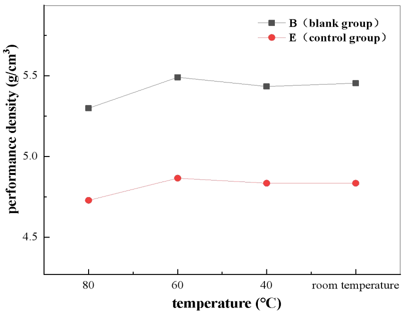

Figure 4. Changes in Apparent Density of OPC-SAC Composites with and without EVA Modification under Different Temperatures

As shown in Figure 4, while temperature exerted minimal influence on the apparent density of both the control and EVA-modified groups, the modified group consistently exhibited lower values across all tested temperatures. Specifically, at 80°C, 60°C, 40°C, and ambient temperature, the apparent density of the modified group was 10.76%, 11.38%, 11.03%, and 11.35% lower than that of the control group, respectively. This consistent reduction, averaging approximately 11%, confirms that the incorporation of EVA significantly decreases the apparent density of the OPC-SAC composite under identical processing conditions. The observed density reduction may be attributed to distinct microstructural characteristics: the control group likely possesses a more compact particle arrangement, smaller and more uniform particles, lower porosity, and consequently a greater mass per unit volume. In contrast, the processing methods and EVA addition in the modified group potentially increase interparticle voids, introduce larger or irregular particles, and elevate overall porosity, thereby reducing mass per unit volume. Furthermore, the specialized processing and EVA incorporation may alter the internal architecture and particle characteristics. At the same time, adjustments in manufacturing parameters could further compromise material compactness, collectively contributing to the reduction in apparent density.

As shown in Figure 5, a consistent reduction in the flexural strength of the EVA-modified group compared to the control group across all tested temperatures, with decreases of 10.4% at 80°C, 10% at 60°C, 14.6% at 40°C, and 25.9% at ambient temperature. This indicates that the incorporation of EVA exerts a detrimental effect on the flexural strength of the OPC-SAC composite, with the degree of degradation gradually diminishing as temperature increases and stabilizing beyond a certain threshold. Repeated experiments consistently confirmed that EVA incorporation compromises the flexural capacity of OPC-SAC, rendering it more susceptible to failure under bending stress.

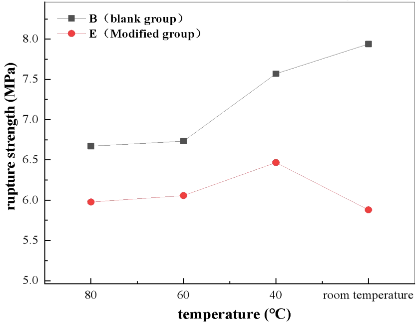

Figure 5. Changes in Flexural Strength of OPC-SAC Composites with and without EVA Modification under Different Temperatures

The observed strength reduction can be attributed to several interrelated mechanisms. First, the inherent mismatch in mechanical properties between the elastic EVA polymer and the rigid OPC-SAC matrix promotes phase separation and microstructural heterogeneity. This heterogeneity leads to uneven stress distribution at the interfaces, facilitating crack initiation and propagation under load. Second, the interfacial bonding strength between EVA and the cementitious matrix plays a critical role. Inadequate adhesion impedes efficient stress transfer across the interface, creating zones of weakness that compromise the structural integrity of the composite. Furthermore, insufficient chemical interaction or bonding at the interface directly undermines the composite's mechanical performance. Finally, the dispersion state of EVA within the matrix is crucial. Poor dispersion can result in localized EVA agglomeration, acting as stress concentration sites that become potential failure origins. Processing parameters such as insufficient mixing, inadequate curing, or incomplete hydration further exacerbate these issues, collectively contributing to the diminished flexural strength.

As shown in Figure 6, a temperature-dependent influence of EVA modification on the compressive strength of OPC-SAC composites. At ambient temperature, the compressive strength of the EVA-modified specimen decreased by 31.5% compared to the control group, with reductions of 26.43% at 40°C and 7.4% at 60°C. In contrast, at 80°C, the modified specimen exhibited a 5.79% increase in compressive strength. These results indicate that while the EVA modifier reduces the compressive strength of OPC-SAC from ambient temperature up to 60°C, the compressive strength of the modified specimens shows a continuous upward trend with increasing temperature, whereas that of the control group declines steadily. A crossover point exists at which the compressive strengths of the two groups converge; beyond this temperature, the modified specimens demonstrate progressively enhanced performance, as evidenced by the 5.79% improvement at 80°C.

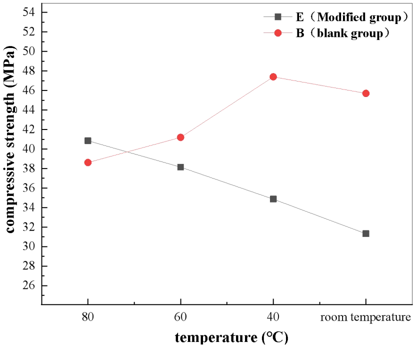

Figure 6. Changes in Compressive Strength of OPC-SAC Composites with and without EVA Modification under Different Temperatures

The observed behavior can be explained by the thermomechanical response of EVA and its interaction with the cementitious matrix. At lower temperatures (ambient to 60°C), the thermoplastic EVA modifier remains inadequately softened, limiting its ability to effectively fill pores and microcracks. Moreover, the weak interfacial bonding between EVA and the OPC-SAC matrix further compromises compressive strength. Under elevated temperatures, however, the thermal stability of EVA is enhanced, enabling it to contribute more effectively to load-bearing capacity. Concurrently, the control specimens undergo structural weakening due to moisture evaporation and thermal expansion. Additionally, the volatile components released by EVA pyrolysis at high temperatures may help reduce pore pressure, while its physical filling effect becomes more pronounced, collectively contributing to the improved compressive performance.

3.2 The Influence of Temperature on the Modification of EVA with OPC-SAC

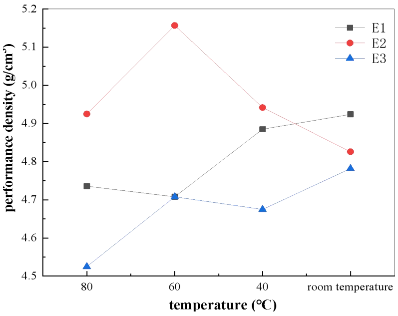

Figure 7. Mechanistic Interpretation of Apparent Density Stability with Temperature

As shown in Figure 7, the apparent density of EVA-modified OPC-SAC materials remains relatively stable under temperature changes from multiple perspectives. First, in terms of molecular structure stability: EVA, as a thermoplastic elastomer, has a stable molecular chain structure at room temperature and does not change significantly with temperature; the Portland cement component in OPC-SAC also has a relatively stable molecular structure at room or slightly elevated temperatures, since significant hydration reactions require higher temperatures (ranging from tens to hundreds of degrees Celsius). Second, the thermal expansion coefficient shows low sensitivity: the thermal expansion coefficient of the EVA and OPC-SAC composite material may be low, resulting in small volume changes under temperature variations, so the apparent density of the material does not change significantly. Third, in terms of microstructural consistency: if EVA is uniformly dispersed in OPC-SAC with good interfacial bonding, the microstructure is consistent, and under temperature changes, the two interact to jointly resist volume changes, maintaining stable apparent density. Fourth, moisture stability within the temperature range: OPC-SAC is a cement-based material containing internal moisture. If the experimental temperature range is reasonably designed to avoid moisture evaporation or condensation intervals, the influence of moisture on apparent density can be ignored.

As shown in Figure 8, the temperature significantly influences the flexural strength of EVA-modified OPC-SAC composites: from room temperature to 40°C, the flexural strength gradually increases; from 40°C to 60°C, it gradually decreases; and from 60°C to 80°C, the strength change is negligible, remaining comparable to that at room temperature.

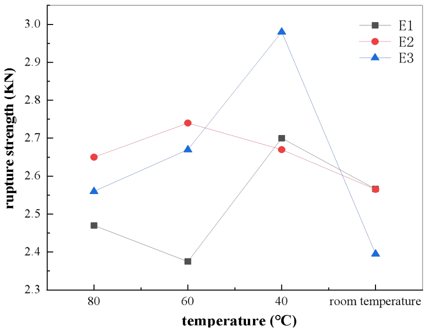

Figure 8. The Influence of Temperature on Flexural Strength of EVA-Modified OPC-SAC Composites

This trend demonstrates that as temperature rises, the flexural strength slightly increases within the room temperature to 40°C range, slightly decreases between 40°C and 60°C, and stabilizes from 60°C to 80°C, showing minimal deviation from the strength at room temperature.

The underlying mechanisms can be attributed to the following factors: The vinyl acetate (VA) content in EVA influences its thermal properties, where higher VA content generally enhances softness and toughness, potentially improving flexural strength at lower temperatures. However, phase transitions of the VA component at specific temperatures may alter physical properties, explaining the strength reduction observed between 40°C and 60°C. At lower temperatures, the EVA modifier improves interfacial bonding with OPC-SAC, thereby enhancing flexural strength, whereas elevated temperatures weaken this interfacial adhesion, leading to strength degradation. Additionally, the physical cross-linking formed by EVA within OPC-SAC enhances cohesion at lower temperatures but weakens between 40°C and 60°C. Concurrently, thermal expansion-induced microstructural changes further contribute to the variations in flexural strength.

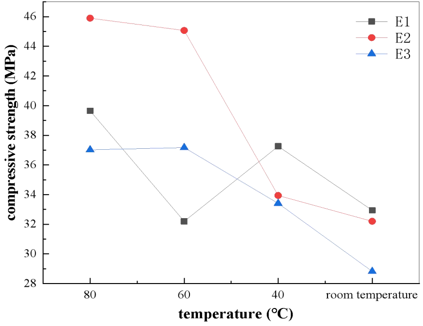

Figure 9. The Influence of Temperature on Compressive Strength of EVA-Modified OPC-SAC Composites

As shown in Figure 9, a significant enhancement in the compressive strength of EVA-modified OPC-SAC composites with increasing temperature, demonstrating that the EVA modifier effectively improves the compressive performance of OPC-SAC under extreme high-temperature conditions.

This improvement can be attributed to several key mechanisms. As a thermoplastic material, EVA exhibits increased molecular chain mobility at elevated temperatures, enabling it to flow and fill pores and microcracks more effectively, thereby forming a more homogeneous and compact microstructure that enhances compressive strength. Concurrently, elevated temperatures may promote the formation of additional physical cross-linking structures within the EVA phase, reinforcing the overall stability of the composite material. The improved interfacial bonding between EVA and the OPC-SAC matrix at high temperatures strengthens adhesion, facilitating more efficient stress transfer and distribution across the interface. Furthermore, the inherent flame-retardant and thermal insulation properties of EVA may help protect the OPC-SAC matrix from thermal degradation, thereby preserving its structural integrity and performance under high-temperature exposure.

4. Conclusion

The introduction of EVA copolymer into the OPC-SAC composite system induced an average mass reduction of 9.4%, with the modified specimens maintaining consistently lower mass values (8-10% reduction) compared to the control group across the entire temperature spectrum (20, 40, 60, and 80°C). Correspondingly, the apparent density exhibited an average decrease of 11%, demonstrating negligible temperature dependence within the investigated range. Water absorption characteristics revealed a substantial 23.6% increase at ambient temperature relative to the control; however, this enhancement exhibited progressive attenuation with elevating temperature, ultimately approaching parity with the control specimens at 80°C.

The mechanical performance evaluation uncovered distinctive thermal-dependent behavior. The flexural strength degradation showed a pronounced recovery trend, with the reduction magnitude decreasing from 25.9% at ambient temperature to approximately 10% at 80°C. More significantly, the compressive strength manifested a remarkable transition from impairment to enhancement: the strength reduction progressively narrowed from 31.5% to 7.4% across the 20-60°C interval, culminating in a 5.79% performance improvement over the control at 80°C. This phenomenon indicates a fundamental shift in EVA's role within the composite system, transitioning from a performance-inhibiting factor to a performance-enhancing component under elevated temperature conditions.

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