

# Deterioration of Bonding Performance of OPC-SAC Binary System Pavement Repair Materials under Extreme High Temperatures

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**Abstract:** In recent years, amid intensified global climate change, extreme high temperatures severely damage cement pavements in China. Studying how OPC-SAC affects the bonding performance of pavement repair materials under such conditions is crucial for improving road quality, durability, and adaptability to extreme climates. To promote polymer cement-based materials in building repair and renovation, this study focuses on extreme high temperatures' impact on the OPC-SAC binary system—SAC has fast early strength development and excellent mechanical properties, while OPC develops strength steadily, with good late-stage strength and wear resistance; their blended system, distinct from traditional ones, is a cement-based repair material with excellent and stable early performance. The study tested different proportions of this system, compared different temperatures and heat treatment durations, and explored their influence on the material's physical and bonding properties; results show that after 3 days of heat treatment, the sample's flexural strength is around 2.0 MPa at room temperature, peaks at approximately 3.8 MPa at 60 °C (with the strongest cement mortar bonding), and all samples' bonding strength weakens at 80 °C.

**Keywords:** Ordinary Portland Cement-Sulphoaluminate Cement (OPC-SAC); Extreme High Temperature; Material Performance Deterioration

## 1. Introduction

With the global climate warming, extreme high-temperature weather events have become increasingly frequent and severe. As a typical case, the pavement surface temperature in Chongqing can reach up to 80°C in summer.

This extreme environment poses enormous challenges to transportation infrastructure such as roads and bridges, and the stability of pavement material performance, which is directly related to the service life of roads and driving safety, has become increasingly prominent. During the long-term service of concrete structures, they are prone to damage due to the combined effects of various internal and external factors. Therefore, concrete repair technology has always been one of the core issues concerned by the industry [1-6]. As the current mainstream pavement repair material, Ordinary Portland Cement-Sulphoaluminate Cement (OPC-SAC) based composite material is widely used due to its excellent workability, bond strength and wear resistance. However, this material is prone to performance degradation such as strength reduction and increased deformation in high-temperature environments, that seriously threatens the service safety and service life of pavements. At present, domestic and foreign studies on OPC-SAC based repair materials have formed a multi-dimensional exploration system.

Domestic research focuses on this composite material, centering on mix ratio optimization, performance regulation and environmental adaptability: in terms of mix ratio optimization, Ma et al. [7] carried out OPC-SAC compounding tests in the range of 0~100% (in 10% increments), and screened the optimal mix ratio based on setting time, fluidity and strength; Shi &Liu [8] further pointed out that the composite cementitious performance is optimal when the SAC content is 15%, and rapid repair mortar can be prepared by adding fibers and other components. In terms of the influence of environmental factors, Li et al. [9] research revealed the key role of curing temperature, specifying that although the increase of SAC content can accelerate hydration and promote strength development, the temperature

exceeding 35°C will lead to the decomposition of hydration products, resulting in the decrease of strength and expansibility. In terms of mineral admixture regulation, Ren et al. [10] found that the compounding of fly ash and slag at a mass ratio of 1:2 can reduce the hydration heat release of OPC-SAC, prolong the setting time and increase the fluidity; although it will slightly reduce the compressive strength, it can significantly improve the bond strength; Ding et al. [11] also systematically explored the overall influence of mineral admixtures on the performance of this composite system.

Foreign studies focus on the component optimization and nano-modification of OPC-SAC materials: Wang et al. [12] proposed that increasing the ratio of active components A:B, reducing the water-binder ratio and adding fine aggregates can enhance the impermeability and structural performance of the material; some components can reduce self-shrinkage, while nano-silica (NS) and silica fume will increase the shrinkage rate, and the pore structure of the repair material is better. The research of Li et al. [13] showed that controlling the particle size and content of silicon nanoparticles can improve the performance of the OPC-SAC system; Cao et al. [14] further found that nano-materials can reduce the sulfuric acid degradation rate of this composite material (especially when used as a repair material), thus improving its performance. Comprehensive domestic and foreign studies show that the OPC-SAC based composite system has become the preferred material for concrete pavement repair due to its advantages such as rapid hardening and stable late-stage strength development. However, this system still has obvious shortcomings: with the increase of SAC content, the hydration reaction accelerates, leading to the shortening of setting time; moreover, in extreme high-temperature environments (such as surface temperature of 80°C), the material is prone to problems such as strength reduction and increased deformation, and the degradation law and influence mechanism of its bond performance under high temperature are still lack of systematic research. In view of this, this paper tests the physical properties and flexural strength (characterizing the bond performance) of the OPC-SAC system under different temperatures and heat treatment durations, and systematically analyzes the influence law of extreme high temperature on the performance of the system. It aims to

provide theoretical support for the selection of cement pavement repair materials in extreme high-temperature areas, promote the development of scientific theory of pavement repair materials, improve the quality and safety of pavement maintenance projects, and contribute to the research and application of environmentally friendly and sustainable pavement materials.

## 2. Experiment

### 2.1 Experimental Materials

Materials and Experimental Process Ordinary Portland Cement (OPC, Grade 42.5R) was used, meeting all requirements of GB 175-2023 Common Portland Cement. Sulphoaluminate Cement (SAC) of Grade 42.5 was adopted, complying with all criteria in GB/T 37125-2018 Sulphoaluminate Cement. Medium sand was used as fine aggregate, meeting the requirements of GB/T 14684-2022 Standard for Sand for Construction. The test water was tap water from Chongqing, in line with the specifications of GB/T 18916.62-2022 Water Intake Quota - Part 62: Cement. In addition, there were 48 residual samples of OPC-SAC cement mortar specimens. First, prepare the materials required for the experiment and fabricate the necessary samples. After different heat treatments, tests were conducted to measure the apparent density, water absorption, flexural strength, and mass loss of the samples at different temperatures. Through these tests, the influence of extreme high-temperature environments on the bond performance of OPC-SAC pavement repair materials was determined.

### 2.2 Experimental Method

- Prepare the materials and experimental tools required for the experiment: sand, water, balance, mortar mixer, Ordinary Portland Cement (OPC), Sulphoaluminate Cement (SAC).
- Prepare the experimental cement according to the customized ratio (OPC: SAC = 4:1).
- Cure the specimens for 28 days (curing temperature: 20±2°C, humidity: ≥95%).
- Conduct periodic performance tests: under extreme high temperatures (60°C-80°C) with 3-day and 7-day heat treatments, perform performance tests on the samples, record the test results, and observe the variation law of performance (including the apparent density,

flexural strength, mass loss, and mass before and after heat treatment of the cement specimens).

e. Analyze the data to study the influence of extreme high-temperature environments on the bond performance of OPC-SAC pavement repair materials. (As shown in table1)

**Table 1. Experimental Materials**

Experimental materials	Formula	Group 1 Dosage
Sulphoaluminate Cement (SAC)	Group 1 Blank Sample requires	90g
Ordinary Portland Cement (OPC)	450g of cement (OPC:SAC = 4:1)	360g
medium sand as fine aggregate	None	1350g
test water	None	225g

### 3. Results and Analysis

#### 3.1 The Effect of Temperature on Flexural Strength

From the perspective of strength variation law, for the OPC-SAC binary system pavement repair materials subjected to 3-day and 7-day heat treatments, the response of their flexural strength to temperature shows significant differences with distinct characteristics at each stage. An in-depth analysis of the mechanism reveals that the strength variation trend is jointly determined by the activity of the material's hydration process and the dual effects of high temperature. Specifically, for the material with 3-day heat treatment, as the temperature gradually rises from room temperature to 60°C, its flexural strength presents a rapid and significant upward trend. For example, from room temperature to 60°C, the strength may continuously climb from around the initial 2.0 MPa, eventually reaching a peak of approximately 3.8 MPa at 60°C—the highest peak among the two materials—and the strength increase during the upward phase exceeds 80%. However, when the temperature exceeds 60°C, the strength turns to enter a rapid downward channel. For instance, when the temperature rises to 70°C, the strength decreased to approximately 2.9 MPa; by 80°C, it further decreases to about 2.2 MPa, a decline of nearly 42% compared with the peak strength, yet it is still higher than the strength of the material with 7-day heat treatment at the same temperature. In contrast, the strength peak of the material with

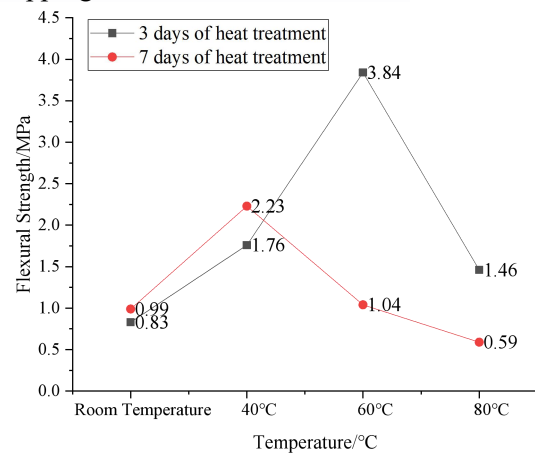
7-day heat treatment appears earlier, arriving at 40°C, and the peak strength is only about 2.2 MPa, far lower than that of the material with 3-day heat treatment. During the upward phase from room temperature to 40°C, the strength increase is slight, possibly rising slowly from around 1.8 MPa to 2.2 MPa with an increase of less than 23%. After the peak, the strength shows a continuous and stable downward trend without an obvious plateau. When the temperature rises from 40°C to 60°C, the strength may drop to around 1.5 MPa; when the temperature reaches 80°C, it has plummeted to approximately 0.6 MPa, a decrease of up to 73% compared with its own peak strength, making it the material with the lowest strength at 80°C among the two.

From the perspective of action mechanism, the variation of the material's flexural strength is essentially the result of the trade-off between the "promoting effect of temperature on hydration reaction" and the "destructive effect of high temperature on material structure", while the duration of heat treatment determines the balance of strength between these two effects. Among them, the promoting effect of temperature on hydration reaction is the core reason for strength increase. The hydration reaction of OPC (Ordinary Portland Cement) requires appropriate temperature and moisture; elevated temperature provides more energy for the hydration reaction, accelerating the reaction between active minerals such as  $C_3S$  (tricalcium silicate) and  $C_2S$  (dicalcium silicate) with water, and generating more cementitious products such as C-S-H gel (calcium silicate hydrate gel) and  $Ca(OH)_2$  (calcium hydroxide). These cementitious products fill the internal pores of the material, enhance the bonding force between aggregates and the cementitious matrix, and thereby improve the overall flexural strength of the material. For the material with 3-day heat treatment, due to the short heat treatment duration, the hydration process of OPC is still in a relatively active stage with a large amount of unreacted active minerals, so the promoting effect of temperature rise on hydration reaction is more prominent, leading to a more obvious strength increase and a higher peak strength. When the temperature exceeds the peak temperature, the destructive effect of high temperature gradually dominates, which is the key factor for strength decline. High temperature causes strength reduction mainly

through two pathways: on one hand, rapid moisture evaporation—excessively high temperature accelerates the evaporation of free water and bound water inside the material, which not only terminates the hydration reaction prematurely due to "water shortage" resulting in insufficient production of cementitious products, but also leaves a large number of micro-pores and even micro-cracks inside the material, damaging its compactness; on the other hand, microstructural deterioration—prolonged high temperature may cause the deterioration of the internal microstructure of the material, for example, C-S-H gel may undergo dehydration shrinkage, leading to weakened bonding force between gel particles, and meanwhile, the thermal stress generated by high temperature may cause interfacial debonding between aggregates and the cementitious matrix, weakening the inter-particle bonding force and ultimately resulting in a significant drop in flexural strength. In addition, as a key variable in the action mechanism, the duration of heat treatment has a significant impact on the strength variation of the two materials. For the material with 7-day heat treatment, due to the longer heat treatment duration, the early hydration reaction has been basically completed, and the amount of unreacted OPC active minerals has decreased significantly. When the temperature rises subsequently, the strength gain brought by "temperature-promoted hydration" is very limited. At this time, the destructive effect of high temperature on the material structure surpasses the hydration-promoting effect earlier, so the strength peak appears earlier with a lower peak strength. Meanwhile, since the structure formed by early hydration has been relatively stable, the damages caused by high temperature such as micro-cracks and moisture loss are more likely to accumulate, leading to a continuous strength decline with a larger amplitude after the peak.

As shown in Figure 1, for the OPC-SAC binary system pavement repair material with 3-day heat treatment, the flexural strength first increases significantly with the rise of temperature, reaches a peak (about 3.8 MPa) at around 60°C, and then decreases rapidly as the temperature continues to rise; while for the material with 7-day heat treatment, its flexural strength first reaches a relatively small peak (about 2.2 MPa) at around 40°C with the increase of temperature, and then shows an overall downward trend,

dropping to about 0.6 MPa at 80°C.



**Figure 1. Variation of Flexural Strength under Different Temperatures**

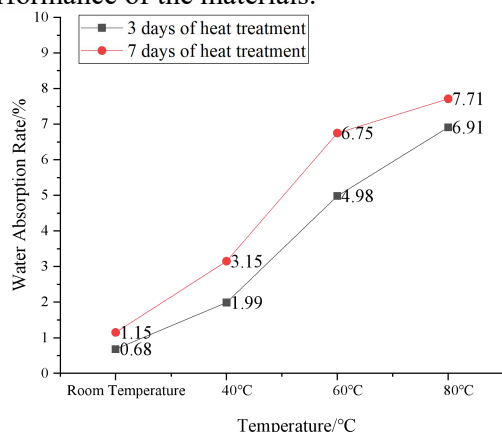
Within a certain temperature range, the increase in temperature can promote the hydration reaction of OPC, generating more cementitious products to enhance the internal bonding effect of the material, thus increasing the flexural strength. This is more obvious in the material with 3-day heat treatment, because its hydration process may still be in a relatively active stage, making the promoting effect of temperature more prominent. However, when the temperature is too high (exceeding the peak temperature), on one hand, excessively high temperature will accelerate the evaporation of moisture, which may lead to insufficient hydration reaction and even the appearance of micro-cracks; on the other hand, high temperature may cause the deterioration of the internal microstructure of the material, such as causing phase transformation or weakening the inter-particle bonding force, thereby reducing the flexural strength. For the material with 7-day heat treatment, due to the longer heat treatment duration, most of the early hydration reaction has been carried out, and the strength gain brought by the promotion of hydration when the temperature rises subsequently is limited, while the destructive effect of high temperature on the structure dominates earlier, so the strength peak appears earlier and the subsequent decline is more continuous.

### 3.2 The Effect of Temperature on Water Absorption Rate

From the test data in Figure 2, it can be intuitively observed that as the temperature gradually increases from room temperature to 80°C, the water absorption rate of the OPC-SAC



binary system pavement repair materials subjected to 3-day and 7-day heat treatments both shows a remarkably significant upward trend. Moreover, at any identical temperature, the water absorption rate of the material with 7-day heat treatment is consistently higher than that of the material with only 3-day heat treatment, and the difference between the two does not show an obvious narrowing trend as the temperature rises—this clearly reflects the synergistic effect of temperature and heat treatment duration on the water absorption performance of the materials.



**Figure 2. Variation of Water Absorption Rate under Different Temperatures**

The occurrence of this phenomenon needs to be comprehensively analyzed from two aspects: temperature-driven microstructure changes and the rules of structure formation and water penetration dominated by heat treatment duration. As the ambient temperature rises, the thermal motion rate of various molecules inside the material increases sharply. This intense thermal motion not only exerts an "expansion effect" on inherent defects in the material such as pre-existing micropores and microcracks—promoting an increase in pore size, further extension and interconnection of microcracks, and the formation of more unobstructed water penetration channels—but also may disrupt the stable state of hydration products inside the material. This disruption triggers micro-expansion of some hydration products or local structural dissociation, thereby inducing new micropores and microcracks within the material. These microstructure changes significantly increase the contact area between water and the material's interior, providing more paths and space for water infiltration, diffusion, and storage. As a result, water can enter the material more quickly and

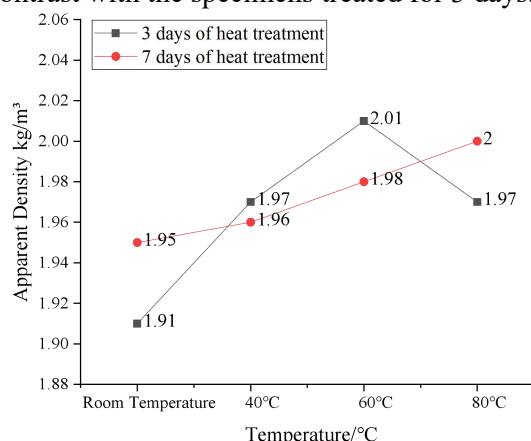
deeply, directly leading to a significant rise in the material's water absorption rate with increasing temperature.

The difference in heat treatment duration further amplifies the difference in water absorption rate at the same temperature from two dimensions: the material's own structural characteristics and the adequacy of water penetration. For the material with 7-day heat treatment, the longer heat treatment cycle plays a crucial role in its hydration and solidification process. Although the hydration reaction over 7 days is relatively more sufficient, differences in the formation rate and accumulation mode of hydration products may lead to the formation of a relatively looser microstructure. For example, the arrangement of hydrated crystal particles may not be dense enough, with larger gaps between crystals, or cementitious substances may be unevenly distributed during hardening, forming local pore-enriched areas. This loose structure itself has stronger water absorption and storage capacity. At the same time, the 7-day heat treatment duration also provides abundant time for water penetration—far exceeding the 3-day duration. Water penetration inside the material is a gradual process: under the 3-day short-term treatment, water can only penetrate into the material's surface and near-surface pores, and it is difficult to fill the tiny or closed pores in the deep interior. In contrast, under the 7-day long-term treatment, water has sufficient time to gradually penetrate and diffuse to every corner of the material's interior, including those extremely small, deeply located closed or semi-closed pores. This further enhances the material's overall water absorption capacity. Therefore, at the same temperature, the material with 7-day heat treatment exhibits a higher water absorption rate due to its looser microstructure and more adequate water penetration.

### 3.3 The Effect of Temperature on Apparent Density

From the test results in Figure 3, it can be clearly observed that the apparent density of the OPC-SAC binary system pavement repair material exhibits a significant differential law with temperature variation, and this law is closely related to the heat treatment duration. For the specimens subjected to 3-day heat treatment, their apparent density shows a "first increases and then decreases" characteristic as

the temperature gradually rises from 20°C: it reaches a density peak when the temperature rises to around 60°C, and the density at this point is significantly higher than that under the initial condition of 20°C. When the temperature continues to rise above 60°C, the apparent density gradually decreases accordingly, and by 80°C, it has fallen back to a level close to or even lower than that in some low-temperature ranges. In contrast, the apparent density of the specimens subjected to 7-day heat treatment does not fluctuate with increasing temperature, but always maintains a sustained upward trend. Throughout the entire temperature range from 20°C to 80°C, the density increases steadily with temperature, and no peak or downward inflection point is observed—forming a sharp contrast with the specimens treated for 3 days.



**Figure 3. Variation of Apparent Density under Different Temperatures**

The essence of this differential variation law lies in the fact that temperature and heat treatment duration affect the internal water content of the material through a coupled effect, thereby regulating the hydration reaction process and microstructural evolution, and ultimately dominating the variation trend of apparent density. As a key indicator reflecting the mass per unit volume of the material, the change in apparent density is directly related to the internal pore structure of the material, the filling state of hydration products, and the water content.

For the specimens with 3-day heat treatment, due to the short heat treatment cycle, the amount of moisture loss inside the material is small, and the initial water content is relatively sufficient. In the early stage of temperature rise (in the range of 20°C to 60°C), the increase in temperature becomes the dominant factor promoting the hydration reaction: elevated

temperature accelerates the thermal motion rate of cement particles and water molecules, prompting the incompletely hydrated OPC and SAC particles to further react with internal water, generating more hydration products (such as C-S-H gel, ettringite, etc.). These newly formed hydration products continuously fill the tiny pores and cracks inside the material, making the internal structure of the material increasingly dense and increasing the content of substances per unit volume—thus driving the apparent density to rise continuously until it reaches the peak state of structural densification at around 60°C. When the temperature exceeds 60°C, the influence mechanism undergoes a fundamental change: excessively high temperature leads to accelerated evaporation of internal moisture in the material, resulting in excessive loss. This not only hinders the hydration reaction due to "water shortage" (preventing the continuous generation of sufficient hydration products to fill the structure) but also causes the formation of new pore channels inside the material due to the rapid loss of moisture. Additionally, high temperature may induce micro-expansion or local dissociation of some early hydration products (such as the unstable ettringite phase), leading to further development and connection of the internal pore structure and a decrease in material compactness. Ultimately, the apparent density shows an obvious downward trend with increasing temperature.

For the specimens with 7-day heat treatment, the longer heat treatment cycle allows them to undergo sufficient moisture evaporation before temperature rise, resulting in an initial water content significantly lower than that of the 3-day heat-treated specimens. During the temperature rise process, although temperature also promotes the hydration reaction, the mode of moisture affecting the material structure is completely different: on one hand, the low initial water content limits the extent of moisture loss during temperature rise, avoiding the "excessive water loss" problem observed in the 3-day specimens. On the other hand, the 7-day long heat treatment has enabled the material to complete most of the early hydration reaction, and the internal structural skeleton has basically taken shape and tends to be stable. When the temperature rises subsequently, the remaining small amount of water participates in the late-stage hydration under the drive of high

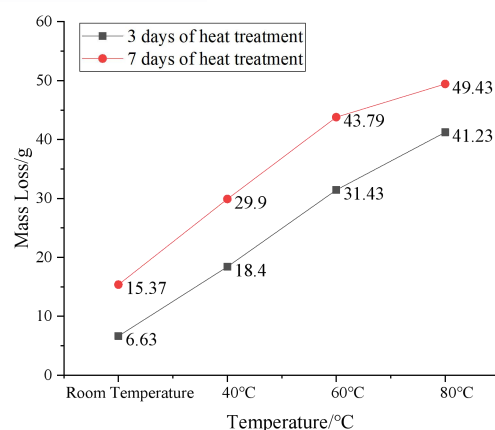
temperature, and the generated hydration products mainly perform refined filling of the tiny pores inside the structure. At the same time, the temperature rise may promote further compaction and adjustment of the incompletely dense structure inside the material, leading to a gradual increase in density per unit volume. Furthermore, the thermal stability of the material is improved after long-term heat treatment, and phenomena such as rapid pore expansion or hydration product decomposition are less likely to occur under high temperature. Therefore, the apparent density can maintain a sustained upward trend with increasing temperature.

It is worth noting that this variation law of apparent density does not exist in isolation; it has an intrinsic correlation with the deterioration mechanisms of key mechanical properties of the material, such as bonding performance and compressive strength. The increase or decrease in material compactness directly affects its interface bonding capacity and structural integrity, and the regulation law of temperature and heat treatment duration on density also provides an important basis for the performance optimization of OPC-SAC pavement repair materials under extreme high-temperature environments. For example, the density stability of the material under extreme high temperature can be improved by adjusting the initial water content of the material and optimizing the heat treatment process, thereby enhancing its service performance.

### 3.4 The Effect of Temperature on Mass Loss

From the test data in Figure 4, it can be clearly observed that the mass loss law of the OPC-SAC binary system pavement repair material exhibits a significant correlation with ambient temperature and heat treatment duration. Regardless of whether the specimens undergo 3-day or 7-day heat treatment, their mass loss under different temperature environments shows a consistent "temperature dependence"—the higher the temperature, the more severe the mass loss. Specifically, under room temperature (around 20°C), both types of specimens have the smallest mass loss and the highest mass retention rate. As the temperature gradually rises to 40°C and 60°C, the mass loss increases sequentially; when the temperature reaches the extreme high of 80°C, the mass loss peaks, showing a significant increase compared to the

loss under room temperature. Meanwhile, under the same temperature environment, the difference in heat treatment duration also leads to an obvious distinction in mass loss: the mass loss of specimens subjected to 7-day heat treatment is generally higher than that of specimens with only 3-day heat treatment, and this difference is more prominent in the high-temperature range (60°C~80°C), reflecting the synergistic intensifying effect of heat treatment duration and temperature on the material's mass loss.



**Figure 4. The Effect of Temperature on Mass Loss**

The core driving factor behind this mass loss law is moisture evaporation: during the heat treatment process of the material, the physically adsorbed water and chemically bound water inside will gradually dissipate with the increase in temperature and the extension of treatment duration, and the main source of mass loss is precisely the evaporation of this moisture. For the specimens with 7-day heat treatment, due to the longer duration of thermal action, the amount of moisture lost in the initial stage is much greater than that of the 3-day heat-treated specimens, resulting in an inherently lower internal water content. When exposed to the same temperature environment, the remaining moisture in the 7-day specimens is more likely to further evaporate under the drive of high temperature; moreover, long-term heat treatment may make the internal pore structure of the material more conducive to moisture escape, thus leading to more significant mass loss.

At the same time, the test results also indicate that heat treatment duration has a crucial impact on the bond strength of OPC-SAC repair materials, and this impact has a complex interactive effect with temperature. In the stage of short heat treatment duration (within 3 days),

as the heat treatment duration increases, the bond strength of the material shows a continuous increasing trend. This is because within a reasonable range of heat treatment duration, the extension of time provides a guarantee for the sufficient progress of the hydration reaction: the OPC and SAC cementitious systems, with the participation of water, gradually complete the hydration and hardening process of cement particles, continuously generating hydration products such as C-S-H gel and ettringite. These hydration products not only fill the internal pores of the material to improve the compactness of its own structure but also form a strong bonding effect at the repair interface—through physical interlocking and chemical bonding, they tightly connect the repair material with the original concrete matrix, thereby promoting the continuous improvement of bond strength.

However, when the heat treatment duration is extended to 7 days (i.e., exceeding the reasonable range), the variation trend of bond strength reverses, showing an obvious weakening trend with the increase in temperature. This is attributed to the deterioration of the material's internal structure under the combined action of excessively long heat treatment and high temperature: on one hand, the long-term high-temperature environment will damage the stability of hydration products; some early-generated hydration products (such as the unstable ettringite phase) may decompose or undergo crystal transformation under the action of sustained high temperature, leading to looseness and dissociation of the originally dense hydration product structure, and thus a simultaneous decrease in the material's own strength and interface bonding capacity. On the other hand, excessively long heat treatment will cause excessive evaporation of moisture inside the material; the massive loss of moisture will form numerous micro-pores and cracks inside the material, and these micro-defects will become weak areas prone to stress concentration. When the material bears external forces or the interface is stressed, cracks tend to propagate along these areas, thereby significantly weakening the bond strength.

The above variation laws of mass loss and bond strength profoundly reveal the regulation mechanism of temperature and heat treatment duration on the performance of OPC-SAC repair

materials, and this law is closely related to the deterioration process of the material's overall performance—the structural loosening caused by moisture changes, as reflected by mass loss, is precisely an important inducement for the decline of mechanical properties such as bond strength. This finding also provides a key technical basis for pavement repair projects in extreme high-temperature areas: in practical applications, it is necessary to accurately control the heat treatment duration of the repair material based on the maximum surface temperature of the project site. While ensuring the sufficient progress of the hydration reaction to form sufficient strength, it is necessary to avoid material structure deterioration caused by excessively long heat treatment duration or high temperature, thereby realizing the effective regulation and optimization of the repair material's performance under extreme high-temperature environments.

#### 4. Conclusion

This study investigates the effects of different heat treatment durations on the physical properties and bond performance (characterized by flexural strength) of the OPC-SAC binary system pavement repair material under extreme high temperatures. The following conclusions are drawn:

The flexural strength is significantly affected by the coupling effect of temperature and heat treatment duration: For the material with 3-day heat treatment, the flexural strength first increases with rising temperature, reaches a peak of approximately 3.8 MPa at around 60°C, and then decreases rapidly. For the material with 7-day heat treatment, the flexural strength only shows a relatively small peak of about 2.2 MPa at around 40°C, followed by an overall downward trend, dropping to approximately 0.6 MPa at 80°C. In the early stage of temperature rise, the hydration reaction of OPC can be promoted to enhance the bonding effect; however, excessively high temperature or overly long heat treatment duration will lead to strength reduction due to moisture loss, microstructural deterioration, and other factors.

The water absorption rate shows an obvious upward trend with increasing temperature, and at the same temperature, the water absorption rate of the material with 7-day heat treatment is higher than that of the material with 3-day heat treatment. This is because the increase in



temperature intensifies the development of pores and microcracks inside the material, providing more channels for water infiltration; meanwhile, a longer heat treatment duration tends to make the material form a more water-absorbent microstructure or allows water to penetrate more fully into the material interior.

The variation of apparent density differs with heat treatment duration: The apparent density of the specimens with 3-day heat treatment first increases with rising temperature, reaches a peak at around 60°C, and then decreases gradually. The apparent density of the specimens with 7-day heat treatment increases continuously with rising temperature. This law is closely related to the coupled regulation of temperature and heat treatment duration on the material's water content and the degree of hydration reaction.

The mass loss increases significantly with rising temperature, and at the same temperature, the mass loss of the specimens with 7-day heat treatment is much greater than that of the specimens with 3-day heat treatment. This is because both the increase in temperature and overly long heat treatment duration accelerate the evaporation and loss of moisture.

In conclusion, temperature and heat treatment duration cause performance deterioration by coupling to affect the material's water content and the degree of hydration reaction. In the early stage of temperature rise, the hydration reaction of OPC can be promoted to enhance the bonding effect; however, excessively high temperature or overly long heat treatment duration will lead to strength reduction due to moisture loss, microstructural deterioration, etc. A longer heat treatment duration tends to make the material form a more water-absorbent microstructure or allows water to penetrate more fully, while accelerating moisture evaporation to increase mass loss; moreover, the variation of apparent density is also closely related to the material's water content and the degree of hydration reaction regulated by the coupling of temperature and heat treatment duration. When applying this repair material in extreme high-temperature areas, the heat treatment duration should be reasonably controlled based on the maximum surface temperature to optimize performance. Specifically, cities with summer surface temperatures  $\geq 60^{\circ}\text{C}$  are recommended to use the OPC-SAC system with 3-day heat treatment, so as to utilize its

advantage of maintaining relatively high flexural strength even at higher temperatures; cities with annual surface temperatures  $< 40^{\circ}\text{C}$  are recommended to use this system with 7-day heat treatment, which can adapt to longer heat treatment duration while ensuring certain performance.

This study deeply reveals the coupled influence mechanism of temperature and heat treatment duration on the multiple properties of the OPC-SAC binary system pavement repair material, provides solid theoretical support for the selection of cement pavement repair materials in extreme high-temperature areas, and has important practical guiding significance for improving the durability and reliability of pavement repair projects in such areas.

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