Asphalt Self-Healing Effect Based On StressControlled Release Microcapsules

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Traditional stress-controlled release microcapsules used for asphalt self-healing suffer from poor strength, low thermal stability, and inconsistent release rates, limiting their practical application. This study proposes the design of high-strength, thermally stable stress-controlled release microcapsules to enhance asphalt's self-healing performance. By using high-performance polymer materials as the shell and employing the solution impregnation method for microcapsule synthesis, the proposed microcapsules exhibit improved stability in high-temperature environments. The shell thickness, core content, and preparation conditions such as temperature, pH, and solvent selection are optimized to achieve precise control over the release rate and amount. Customizable microcapsules are developed to meet varying self-healing needs. These microcapsules are uniformly dispersed in the asphalt matrix through heating and stirring, ensuring an even distribution for effective self-healing. Experimental verification under different stress conditions confirms their stress-controlled release capabilities and crack-healing performance. Results demonstrate a crack closure degree of 0.87 at a stress frequency of 6 Hz, a compressive strength recovery rate of 0.82, and a repair time of 14 minutes. The microcapsules achieve a release rate accuracy between 0.90 and 0.97 across the stress frequency range, providing superior control over the healing agent release. This research offers a promising solution for improving asphalt durability.

Keywords: Stress Controlled Release Microcapsules; Asphalt Materials; Asphalt Self-Healing; Self-Healing Effect; Release Rate

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1. Introduction

Asphalt is a key material for road construction. Long-term exposure to external stress and high-temperature environments can easily cause microcracks, resulting in performance degradation. With the in-depth research on self-healing materials, asphalt self-healing technology combined with stress-controlled release microcapsules has gradually attracted attention. This type of microcapsule can release repair agents when cracks are generated, repair damaged areas, and extend the material's service life [1, 2]. Optimizing microcapsule design and achieving precisely, controlled release under different environments is an important research direction for improving the self-healing ability of asphalt.

In the application of asphalt self-healing technology, the design of traditional microcapsules faces the problem of controlling the release rate and amount. Existing microcapsules mainly release repair agents through shell rupture to repair cracks. Still, the strength and stability of the shell material are insufficient, and it is difficult for microcapsules to maintain stable release performance under high temperatures and external forces [3, 4]. The release amount of these microcapsules is uneven and uncontrollable during storage, and the repair effect in practical applications is not ideal. In complex stress environments, the effectiveness of microcapsules is particularly limited. Traditional methods mostly rely on macro-control of ambient temperature or Time, and it is difficult to adjust the release behavior in real Time according to the actual stress state, resulting in uneven material repair effects and failure to meet the needs of efficient and adaptive self-healing [5, 6].

There are many problems in the preparation process of microcapsules. The existing preparation methods have a relatively rough control over the shell thickness, material selection and type of inclusions of microcapsules, making it difficult to accurately control the performance of microcapsules [7, 8]. Some studies have attempted to improve the self-healing effect of microcapsules by changing the composition of microcapsules, but there is a lack of effective stress regulation mechanism. The release behavior of microcapsules under complex stress fields is still unstable, and the predictability and repeatability of the crack repair process are poor [9, 10]. This limitation makes the reliability of traditional microcapsules in the face of environmental factors such as high temperature and stress a great challenge, reducing its application prospects in asphalt repair.

With growing infrastructure maintenance demands, traditional repair methods lack flexibility and efficiency, making it difficult to meet diverse road environment requirements. This study designs a stress-controlled release microcapsule to enhance asphalt's self-healing ability, ensuring precise and efficient crack repair under varying stress and high-temperature conditions. Unlike conventional microcapsules, which struggle with controlled release, the proposed design dynamically adjusts the release rate and amount of repair agents based on crack severity and environmental factors. Using high-strength, thermally stable polymer materials for the shell, the microcapsules maintain stability under extreme conditions, overcoming the limitations of traditional designs. By optimizing shell thickness and core content, an adaptive controlled-release mechanism is achieved. Additionally, uniform dispersion within the asphalt matrix ensures consistent performance. These innovations improve asphalt durability, offering a flexible, efficient self-healing solution for road maintenance. The use of microcapsule technology, that release healing chemicals when stress is sensed, unites materials science, chemical engineering, and mechanical engineering in this work. Asphalt's mechanical behavior and material qualities are enhanced as well by this multidisciplinary approach. Additionally, the self-healing asphalt serves to promote sustainability by prolonging the life of roads, lowering the need for repairs, and lessening the environmental effect of road maintenance. From a financial standpoint, it reduces traffic interruptions and repair expenses. The study presents a novel approach that might revolutionize infrastructure maintenance by improving road durability, enabling autonomous fracture repair, and developing the field of self-healing materials. This research contributes to advancing asphalt self-healing technology, promoting its practical application in infrastructure development.

1.1. Related Work

Scholars have extensively studied asphalt self-healing materials, with many focusing on microcapsule-based approaches. Microcapsules, introduced through solution impregnation, have demonstrated crack repair effectiveness [11, 12]. Additionally, bio-based spores encapsulating regeneration agents enhance asphalt elasticity and self-healing properties via vacuum encapsulation [13]. Temperature-controlled release mechanisms have also been explored [14, 15]. However, challenges such as poor thermal stability and uncontrolled release rates persist, limiting their practical application under extreme conditions. Further research is needed to address these limitations.

Traditional microcapsule self-healing asphalt materials face limitations in thermal stability, mechanical strength, and precise release control. Researchers have improved microcapsules by using high-strength polymer shells, enhancing durability in high-temperature environments [16, 17]. Li X developed polydopamine composite microcapsules with silica modification, increasing hardness, elasticity, and substrate compatibility [18]. Adjusting shell thickness and content type has enabled controlled release, but challenges remain in achieving precise dosage control and uniform dispersion [19, 20]. This study introduces stress-controlled release microcapsules to optimize self-healing efficiency, ensuring accurate release rates and amounts. The approach enhances asphalt durability, addressing gaps in existing methods and advancing self-healing asphalt technology.

The Warm-Mix-Asphalt (WMA) and stress-controlled release microcapsules aligns well as it improves durability of the asphalt. WMA's improved rutting resistance and lower resilient modulus which provide a flexible foundation, while microcapsules activate under stress to release healing agents, preventing damage. This synergy offers environmental benefits, reduces maintenance needs, and extends asphalt lifespan by enhancing its ability to self-heal under varying traffic and temperature conditions. The evaluation of physical properties like resilient modulus (deformation under repeated loading) and rutting (resistance to deformation under traffic loads) in warm asphalt mixtures are emphasized. The focus here is on assessing the performance of asphalt mixtures under specific conditions, such as those found in Iraq [21].

The method of strengthening recycled concrete aggregate (RCA) mixtures with waste alumina to improve the mechanical qualities of asphalt. Based on the study, adding alumina substantially enhances the binder concentration and overall strength of the asphalt, increasing its resilience to stress. In addition to encouraging environmentally friendly road building methods, this strengthens the asphalt's structural integrity, producing more durable and long-lasting combinations that need less maintenance. Nanotechnology is being used in order to combat asphaltic pavement rutting, with a recent study showing the effectiveness of industrial carbon nanotubes (CNT) as a strengthening additive. Four dosages of CNT were added to two bitumen grades, 40/50 and 60/70 [22, 23].

2. Materials and methods

2.1. Microcapsule Design and Synthesis

2.1.1. Selection and Regulation of microcapsule shell materials

Under high-temperature application conditions, the shell strength and durability of the microcapsule structure are enhanced, focusing on the use of polymer materials with high strength and excellent thermal stability to construct the shell of the microcapsule. These selected polymers can effectively withstand high-temperature environments and keep the microcapsule structure intact.

Thermal stability is the primary consideration in selecting shell materials. Polyester and polyurethane series polymers have excellent thermal stability and mechanical strength properties and are currently ideal shell material options. Finely controlling the molecular structure of these polymers can enhance their stable performance under high-temperature conditions to a certain extent. These key temperature points of the selected materials must be significantly higher than the actual use temperature of asphalt so that the shell material does not lose its necessary rigid support during high-temperature operations. The heat resistance of polyester materials and the structural stability of polyurethane materials allow them to maintain good shape and performance in the temperature environment where asphalt is located.

The solution immersion method is used to achieve the thickness regulation of the shell, the polymer solution into the main material, the control of the solution concentration and immersion time to adjust the thickness of the shell, the solution concentration and immersion time have a significant impact on the thickness of the shell, the following formula can describe the relationship between them:

$$d = r \cdot t = \left(\frac{k \cdot C}{\eta}\right) \cdot t \tag{1}$$

r is the shell deposition rate, k is a constant, and η is the viscosity of the solution. By precisely controlling the solution concentration and immersion time, the thickness of the shell can be precisely adjusted.

The shell material also adds a cross-linking agent to enhance the strength of the microcapsule and physical or chemical cross-linking is used to improve the structural strength of the material. The crosslinking agent's selection and concentration control also affect the microcapsule shell's overall performance. The crosslinking reaction increases the crosslinking degree of the polymer chain, improves the thermal stability and high-temperature resistance of the shell, and effectively enhances the service life of the microcapsule to a certain extent; the thermal stability and strength of the shell material are shown in Table 1.

2.1.2. Selection and Regulation of mMicrocapsule Contents

The Selection of microcapsule contents and their compatibility with shell materials directly affect the functionality and application effect of microcapsules. The contents of stress-controlled release microcapsules must be able to self-heal and repair and must also work effectively under specific stress and temperature environments. The study ensures that they can effectively perform self-healing functions in asphalt by accurately selecting the type and concentration of the contents. The study selected a thermosetting repair agent with good fluidity and reactivity to give the stability and functionality of the contents. The repair agent can flow quickly and repair the cracks when the microcapsule is broken. The inclusions' type highly depends on their compatibility with the shell material. The interaction between the polymer shell and the inclusions has a certain influence on the microcapsules' overall stability and release performance. Using polyurethane and polyester composite materials as inclusion carriers effectively improves the stability of the inclusions and the bonding strength with the shell. Table 2 shows the effect of inclusion concentration on the self-healing performance of microcapsules.

In Table 2, Crack Healing Time (hours) is referenced as the time it takes for the crack to heal after treatment, with different repair agent concentrations listed. For example, at 10% repair agent concentration, the crack healing time is 6 hours. The concentration control of the inclusions mainly relies on the solution impregnation method, and the concentration of the repair agent is changed to achieve the content adjustment of the microcapsule. The change of the content concentration affects the structural integrity

Table 1. Thermal stability and strength of shell materials.

Shell Material Type	Glass Transition Temperature	Melting Point	Tensile Strength (MPa)	Maximum Operating Temperature (°C)
Polyester Material	120°C	240°C	45	250°C
Polyurethane Material	80°C	210°C	50	230°C
Polyacrylic Material	90°C	180°C	42	200°C

Table 2. Effect of inclusion concentration on the self-healing performance of microcapsules.

Repair Agent Concentration (%)	Crack Healing Time (hours)	Crack Closure (%)	Recovery Strength (MPa)
10	6	70	25
20	5	80	30
30	4	85	32
40	3	90	34

of the microcapsule and also affects its self-healing ability. Too high or too low a concentration can led to an abnormal release rate and affect the repair effect. It is very important to adjust the content concentration accurately.

Experiments also verified the interfacial bonding strength and release characteristics of the microcapsule contents and shell. By changing the solvent and pH value of the contents, the solubility of the contents was optimized so that they could be quickly released after the microcapsule ruptured and react with the cracks in the asphalt to repair them. The Selection and concentration of the repair agent and its compatibility with the shell are key factors in designing efficient microcapsules. The Regulation of the above two aspects, the Selection of shell materials, and the design of inclusions can ensure the stability and efficient self-healing effect of the microcapsules in high-temperature environments, laying the foundation for subsequent research on stress-controlled release mechanisms.

Fig. 1 shows the crack repair process of microcapsules under stress, emphasizing the stability of microcapsules and the effectiveness of repair agents in high-temperature environments, realizing the self-healing function of asphalt. This structural design ensures the long-term effectiveness and efficient self-healing ability of microcapsules in asphalt, significantly improving the service life and anti-wear performance.

2.2. Regulation of Microcapsule Release Characteristics

The preparation process, temperature, pH value, and solvent selection of microcapsules can be changed to adjust their release rate and amount; microcapsules of different specifications can be designed to meet asphalt's different self-healing requirements.

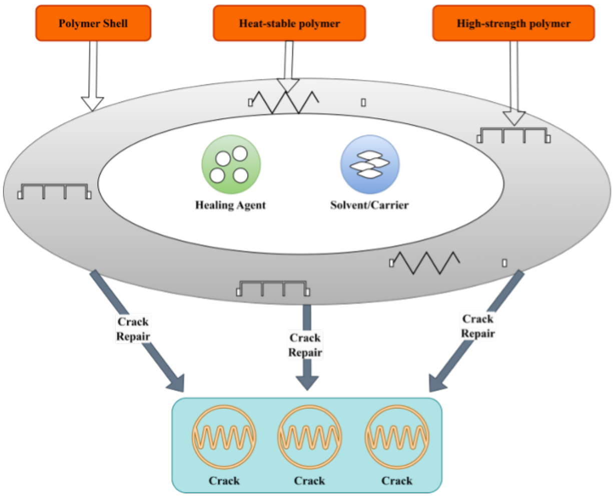


Fig. 1. Microcapsule structure and function.

2.2.1. *Regulation of microcapsule release rate*

The choice of solvent is a key factor. The polarity and solubility of the solvent have a significant effect on the structure of the microcapsule shell. The use of low-polarity solvents can make the polymer shell structure more compact; on the contrary, high-polarity solvents tend to enhance the solubility of the polymer, resulting in more pores in the microcapsule shell, thereby accelerating the release process of the repair agent. To quantitatively describe the release rate of the microcapsule, it can use a specific mathematical formula to estimate it.

$$\frac{dQ}{dt} = k \cdot (C_{\text{in}} - C_{\text{out}}) \cdot A \tag{2}$$

$\frac{dQ}{dt}$ represents the repair dose released by the microcapsule per unit time, k is the release rate constant, C_{in} is the content concentration, C_{out} is the external environment concentration, and A is the surface area of the microcapsule. Adjusting the temperature, pH value and solvent selection can regulate the release rate constant and achieve precise control of the release characteristics of the microcapsules.

2.2.2. *Regulation of the release amount of microcapsules*

Both immersion time and pH play key roles in controlling the performance of microcapsules for asphalt self-healing. Immersion time affects the thickness of the microcapsule shell, with longer times leading to thicker shells that enhance mechanical strength and thermal stability, providing better protection for the repair agent and improving the microcapsule's effectiveness under stress. Additionally, the pH of the environment influences the solubility of the repair agent; a lower pH (around 4) accelerates the degradation of the shell, causing faster release of the repair agent, while a neutral pH stabilizes the shell, resulting in a slower and more controlled release. These adjustments allow for the fine-tuning of microcapsule behavior to optimize crack repair in asphalt under varying conditions. The effect of pH adjustment on the release of microcapsules is also significant. The solubility characteristics of the shell material and the contents of the microcapsules are different at different pH values. When the pH value is adjusted to the microcapsule shell material's degradation critical value, the shell's solubility can increase sharply, and the release amount can increase accordingly. When the pH value is 4, the degradation rate of the shell material is significantly accelerated, and the release amount of the repair agent increases significantly; in a relatively neutral pH environment, the shell is relatively stable, and the release amount is relatively low. Table 3 shows the effect of pH adjustment on the microcapsule shell.

The release number of microcapsules can also be quantitatively described using the following formula:

$$Q = M_{\max} \cdot \left(1 - e^{-k \cdot t}\right) \tag{3}$$

Q represents the repair dose released by the microcapsules, $M_{\max}$ represents the maximum release amount, and t represents the Time. Adjusting the temperature, pH value, and solvent selection can affect the maximum release amount, accurately control the release number of microcapsules, and meet the repair needs of different asphalt self-healing processes.

The above process regulation can accurately control the release rate of microcapsules and adjust their release amount under different environmental conditions to optimize the self-healing performance of asphalt. The strategy of precisely controlling the release characteristics can design microcapsules of different specifications according to actual needs and maximize their effectiveness under different stress conditions.

2.3. Composite of Microcapsules and Asphalt

2.3.1. *Uniform dispersion of microcapsules in asphalt*

The microcapsules are evenly dispersed in the asphalt matrix by combining high-speed stirring and ultrasonic treatment. High-speed stirring can accelerate the mixing of microcapsules and asphalt, effectively breaking the surface tension of the asphalt matrix and evenly dispersing the microcapsules in the asphalt; ultrasonic treatment enhances the dispersibility of microcapsules through the vibration of high-frequency sound waves and avoids the agglomeration of microcapsules in the asphalt matrix; This method allows the microcapsules to be distributed in the asphalt at a uniform density, which can play the greatest role in the subsequent self-healing process.

The uniform distribution of microcapsules in asphalt is very important for the subsequent self-healing process, allowing the microcapsules to quickly release the repair agent when cracks occur, achieving more efficient crack repair; the uniform distribution of microcapsules in asphalt can be quantified using the following formula:

$$D = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{|x_i - \mu|}{\sigma} \right) \tag{4}$$

D is the distribution uniformity, n is the number of samples, x_i is the position of the i th microcapsule, μ is the uniform distribution center of the microcapsule, and σ is the standard deviation. This formula can evaluate the distribution uniformity of microcapsules in the asphalt matrix to ensure that it meets the design requirements.

2.3.2. *Optimization of the self-healing performance of microcapsule composite asphalt*

The self-healing performance of composite asphalt materials is also closely related to external environmental conditions such as temperature and stress. The fluidity of asphalt is enhanced at higher temperatures, which is conducive to the release of the repair agent in the microcapsules; changes in stress can also directly affect the release behavior of the microcapsules. Simulating different stress conditions can effectively evaluate the self-healing ability of composite asphalt. This process enables the microcapsules to release the repair agent according to the design requirements under stress conditions, optimizing the self-healing performance of asphalt; the self-healing performance of microcapsule composite asphalt can be quantified using the following formula:

$$R = \frac{S_{\text{recovered}}}{S_{\text{initial}}} \tag{5}$$

The optimization of the above composite process can improve the dispersibility of microcapsules in the asphalt matrix and enhance asphalt's self-healing performance. Finely

Table 3. Effect of pH Adjustment on the Microcapsule Shell.

pH Value	Polymer Solution Concentration (%)	Shell Stability (hours)	Shell Dissolution Rate (mg/min)
4	10	4	0.075
5.5	10	8	0.028
7	10	8	0.022
9	10	6	0.035

controlling the composite process of microcapsules can enable asphalt to quickly release repair agents when cracks occur during use, achieve efficient self-healing effects, and extend the service life of asphalt materials.

2.4. Verification of Stress-Controlled Release Mechanism

In the experiment, different tensile or compressive stresses were applied to study microcapsules' rupture and repair process under stress. Changes in stress can affect the rupture mechanism of the microcapsule shell and the release rate of the internal repair substance. The microcapsule's crack healing behavior is manifested as changes in crack closure under different stress conditions. The crack length and healing process can be monitored in real Time.

The crack healing process is quantified using the key indicator of crack closure, which is calculated by the following formula:

$$\text{Crack Closure} = \frac{\text{Crack Length After Healing}}{\text{Initial Crack Length}} \tag{6}$$

Taking into account the change in the release rate of microcapsules under stress, the compression effect of stress on the microcapsule shell is used here to control the way and intensity of stress application to meet different self-healing needs. The repair time and repair effect under different stresses is compared to verify the stress-controlled release mechanism of microcapsules. The following formula can describe the change in release rate:

$$\dot{m} = k((g/s)/Pa) \cdot \sigma^n \tag{7}$$

$\dot{m}$ is the release rate of the repair substance. The release rate under different stresses is calculated to obtain the response characteristics of the microcapsules under stress and verify the effectiveness of its stress-controlled release mechanism.

These experimental methods can verify the self-healing ability of microcapsules under different stress conditions and provide a reliable experimental basis for their practical application. σ is the applied stress (Pa).k is a constant that depends on the units of release rate and stress. n is an exponent that describes the relationship between release rate and stress and is dimensionless.

2.5. Experimental Methodology for Stress Testing

The experimental methodology for stress tests involves designing microcapsules with strong, thermally stable polymer shells and fluid repair agents. The microcapsules are synthesized using the solution impregnation method, with the shell thickness controlled by adjusting solution concentration and immersion time. To simulate real-world conditions, tensile and compressive stresses are applied to the asphalt samples at varying frequencies. Crack healing effectiveness is evaluated by monitoring crack closure, strength recovery, and repair time.

The release rate of repair agents is measured under stress conditions, and the results demonstrate that the microcapsules outperform traditional ones in crack healing, strength recovery, and faster repair times. The release rate is precisely controlled, ensuring effective agent release when needed. These experiments validate the performance of the microcapsules, showing their enhanced ability to self-heal asphalt under stress conditions, making them suitable for practical applications in road maintenance.

3. Results and discussion

3.1. Method Effect Evaluation

3.1.1. Shell Thickness Analysis and Distribution Uniformity Evaluation of Microcapsules in Asphalt Matrix

Fig. 2 how shell thickness, soaking duration, and solution concentration relate to the creation of microcapsules. The thickness of the shell rises with increasing soaking time and solution concentration. This suggests that a thicker shell is produced by accelerating the deposition of shell components with a longer immersion period and a higher concentration. The plot highlights how crucial it is to maximize these two variables in order to regulate the microcapsule's strength and thermal stability. Manufacturers can customize the shell thickness for particular applications by varying both parameters, guaranteeing the performance and efficiency that are needed.

Table 4 shows the evaluation of the distribution uniformity of microcapsules in the asphalt matrix under different stirring conditions. By adjusting the stirring speed and stirring Time, the distribution uniformity of microcap-

Table 4. Evaluation of the uniformity of microcapsule distribution in asphalt matrix.

Treatment Method	Microcapsule Distribution Uniformity	Stirring Speed (rpm)	Stirring Time (min)	Standard Deviation
Low-speed stirring, Short Time	0.85	200	10	0.03
High-speed stirring, Short Time	0.92	600	10	0.02
Low-speed stirring, Long Time	0.88	200	30	0.05
High-speed stirring, Long Time	0.95	600	30	0.01

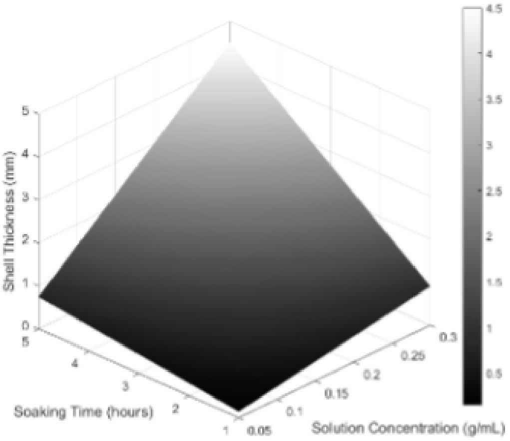


Fig. 2. Shell thickness analysis.

sules reached the optimal value of 0.95 under high speed and long stirring conditions, and the minimum standard deviation was 0.01, indicating that the distribution of microcapsules in the asphalt was more uniform; Under the conditions of low-speed stirring or short-time stirring, the distribution uniformity of microcapsules is low and the standard deviation is large, indicating that the dispersion of microcapsules in asphalt is poor. These results show that appropriate stirring speed and Time are crucial for the uniform distribution of microcapsules and help improve the self-healing properties of asphalt.

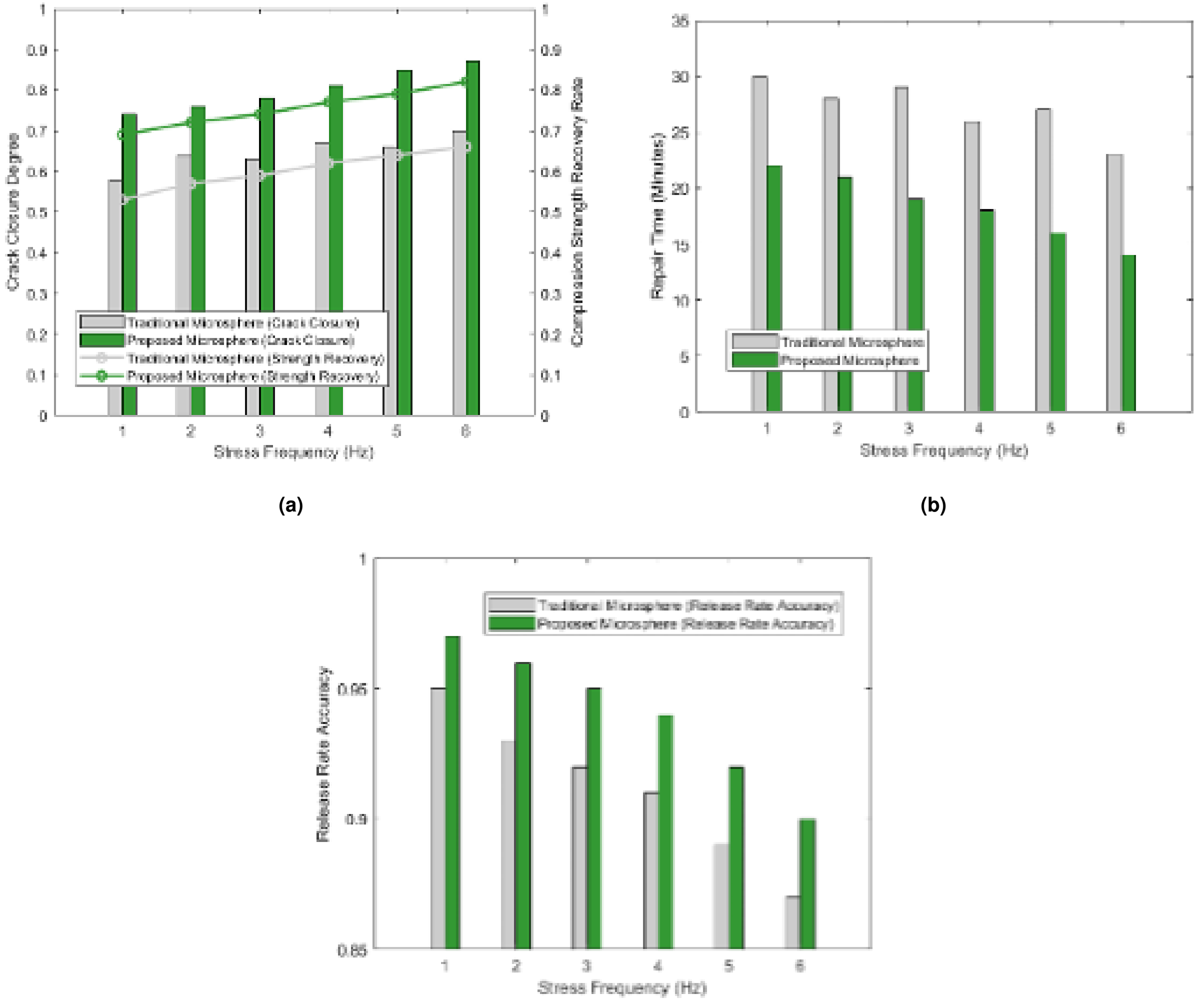
3.2. Self-healing Effect Evaluation Indicators

The evaluation indexes of the self-healing effect mainly include three aspects: crack closure degree, compressive strength recovery rate and repair Time. Crack closure degree is used to quantify the degree of crack healing, compare the length of the crack after healing with the initial crack length, and evaluate the repair ability of microcapsules in the self-healing process. The compressive strength recovery rate reflects the recovery of the compressive properties of the asphalt sample after microcapsule repair and embodies the material's ability to recover its mechanical properties; the repair time is the Time required for the microcapsules to achieve effective repair, which can measure its repair speed. These indicators are used to compare the performance of traditional stress-controlled release microcapsules and the microcapsules proposed in this paper under different stress frequencies, and the self-healing effect of the microcapsules is comprehensively evaluated to reveal their advantages and potential application value in improving the self-healing properties of asphalt.

Fig. 3(a) compares traditional microcapsules' crack closure rate and compressive strength recovery rate and the microcapsules proposed in this paper under six different stress frequencies. The bars at each stress frequency point represent the crack closure of the traditional microcapsules and the microcapsules in this paper, respectively, and the broken lines represent the compressive strength recovery rates of the two microcapsules. The crack closure of the traditional microcapsules fluctuates and is relatively low, while the microcapsules in this paper show a relatively stable and gradually increasing crack closure at each frequency. At a stress frequency of 6 Hz, the crack closure degree of the microcapsules in this paper is 0.87, significantly better than that of traditional microcapsules. Regarding compressive strength recovery rate, the recovery rate of the microcapsules in this paper is higher than that of traditional microcapsules at each frequency point, which is 0.82 at a stress frequency of 6 Hz. This appears to represent the percentage of crack closure after healing, though the specific experimental conditions or formula used to calculate this degree.

The data clearly show the significant advantages of the microcapsules in this paper in crack repair and strength recovery, proving that they have better self-healing effects under high-stress conditions.

Fig. 3(b) shows the repair time of traditional stress-controlled release microcapsules and those proposed in this paper under six different stress frequencies. Each frequency point corresponds to two columns, representing the repair time of traditional microcapsules and those proposed in this paper. The data show a certain fluctuation. The repair time of traditional microcapsules shows a certain volatility with increased stress frequency. The repair time of the microcapsules in this paper is shorter overall. The repair time is 14 minutes at a frequency of 6 Hz, which is shorter, indi-



(a) (b) (c)

Fig. 3. (a) Comparison of crack closure rate and strength recovery rate of different stress-controlled release microcapsules2. (b) Comparison of the repair time of different stress-controlled release microcapsules. (c) Comparison of release rate accuracy of controlled-release microcapsules at different stress frequencies

cating better self-healing performance. The microcapsules in this paper can cope with stresses of different frequencies more efficiently and have stronger adaptability and faster repair speed. Traditional microcapsules for asphalt self-healing face issues like poor thermal stability, weak mechanical strength, and inconsistent release. Advanced methods like nanomaterials enhance asphalt's strength, durability, and healing efficiency but are costly and hard to integrate. Bio-based systems offer environmental benefits and better compatibility with asphalt but struggle with extreme conditions. Self-healing bitumen blends provide an integrated solution with lower maintenance costs but lack precise control over healing. Combining these methods could optimize asphalt self-healing performance.

3.3. Evaluation of Release Rate Accuracy

The release rate of microcapsules under different stress frequencies was determined experimentally, the deviation between the actual release rate and the designed target rate was calculated, and the rate control accuracy of microcapsules under different environments was quantified.

Fig. 3(c) shows the release rate accuracy comparison between traditional and microcapsules proposed in this paper at six different stress frequencies. The release rate accuracy of traditional microcapsules gradually decreases with the increase of stress frequency, from 0.95 to 0.87. The control ability is weakened under a high-frequency stress environment, which is related to the stress response ability of microcapsule materials. The microcapsules proposed in this paper show more stable and higher release rate accuracy in the entire stress frequency range, between 0.90 and 0.97, and can still maintain high accuracy under high-frequency conditions. The microcapsules in this paper can more accurately control the release rate, effectively improve its self-healing performance in complex stress environments, and demonstrate its potential and advantages in practical applications.

3.4. Stress Application to Microcapsules

In order to simulate actual asphalt conditions, stress was given to the microcapsules in the experiments using both compressive and tensile forces. There were fluctuations in the frequency of the cyclic application of the stress. As an example, the microcapsules achieved an 87% crack closure rate at a frequency of 6 Hz, healing cracks in 14 minutes. The ability of the microcapsules to release the healing substance in an adaptable manner under various stress situations was demonstrated by the direct relationship between the repair agent's release rate and the frequency and intensity of the applied stress. In dynamic environmental conditions, this stress-controlled release mechanism is essential for enhancing asphalt's self-healing capabilities.

High material prices and intricate production procedures are involved in the economic and scalability elements of producing microcapsules for asphalt self-healing. Process optimization, material consistency, and specialized equipment are necessary for scaling up. Despite the high upfront expenditures, the investment may be recovered over time by lower maintenance costs. Microcapsule integration into current asphalt manufacturing, regulatory compliance, and market acceptance are necessary to facilitate large-scale implementation. For the technology to be practical for broad adoption, certain obstacles must be overcome.

4. Conclusions

This paper designs and synthesizes high-strength, thermally stable stress-controlled release microcapsules, applies them to asphalt self-healing research and has achieved important results. By precisely controlling the shell thickness, content type and preparation process of the microcapsules, the research successfully improved the stability and strength of the microcapsules in high-temperature environments and solved the performance degradation problem of traditional microcapsules under storage and high-temperature conditions. The release rate and number of microcapsules are finely regulated to meet the diverse needs of asphalt self-repair; the microcapsules are combined with the asphalt matrix, and the uniform distribution is ensured by heating and stirring to greatly enhance the self-repair ability of asphalt. In the stress-regulated release mechanism test, microcapsules can accurately release repair agents under different stress environments, effectively promoting the self-repair of asphalt cracks. The evaluation results of the self-repair effect show that the microcapsules developed in this study are superior to traditional microcapsules in terms of crack closure degree, compressive strength recovery ratio and repair efficiency, highlighting its obvious advantages in improving the self-repair performance of asphalt. The evaluation of the release rate accuracy also further verifies the rate control stability of microcapsules under different conditions, laying a solid foundation for its practical application.

The stress-regulated microcapsule technology enhances asphalt self-repair, overcoming current challenges. Future advancements in microcapsule design and preparation can expand their potential in road maintenance and high-performance materials.

References

[1] P. Wan, S. Wu, Q. Liu, et al., (2022) *"Recent advances in calcium alginate hydrogels encapsulating rejuvenator for asphalt self-healing"* **Journal of Road Engineering** *2*(3): 181–220.

[2] Y. Y. Wang and Y. Q. Tan, (2023) *"Preparation, with graphene, of novel biomimetic self-healing microcapsules with high thermal stability and conductivity"* **Frontiers of Structural and Civil Engineering** ***17***(8): 1188–1198. DOI: https://doi.org/10.1007/s11709-023-0027-5.

[3] J. Norambuena-Contreras, J. L. Concha, G. Valdes-Vidal, et al., (2024) *"Optimised biopolymer-based capsules for enhancing the mechanical and self-healing properties of asphalt mixtures"* **Materials and Structures** ***57***(10): 1–21. DOI: https://doi.org/10.1617/s11527-024-02508-6.

[4] X. Qiu, W. Cheng, W. Xu, et al., (2022) *"Fatigue evolution characteristic and self-healing behaviour of asphalt binders"* **International Journal of Pavement Engineering** ***23***(5): 1459–1470. DOI: https://doi.org/10.1080/10298436.2020.1806277.

[5] M. Hu, D. Sun, T. Lu, et al., (2020) *"Laboratory investigation of the adhesion and self-healing properties of high-viscosity modified asphalt binders"* **Transportation Research Record** ***2674***(1): 307–318. DOI: https://doi.org/10.1177/03611981209029.

[6] S. Inozemtcev, E. Korolev, and T. Do, (2023) *"Intrinsic self-healing potential of asphalt concrete"* **Magazine of Civil Engineering *123***(7): 95–104. DOI: 10.34910/MCE.123.8.

[7] P. Cheng, Z. Zhang, Z. Yang, et al., (2022) *"Evaluation of self-healing performance and mechanism analysis of nano-montmorillonite-modified asphalt"* **International Journal of Pavement Research and Technology *15***(4): 876–888. DOI: https://doi.org/10.1007/s42947-021-00059-5.

[8] C. Shi, R. Luo, H. Liu, et al., (2022) *"Evaluation of self-healing characteristics of asphalt materials by intermittent loading tests"* **Road Materials and Pavement Design *23***(11): 2684–2696. DOI: https://doi.org/10.1080/14680629.2021.1978525.

[9] Y. Li, R. Gu, L. Lyu, et al., (2024) *"Tracking the Aging-Induced Evolution in Self-Healing Capacities of Asphalt Binder: Microstructure and Rheology Analysis"* **Langmuir *40***(49): 26179–26192. DOI: https://pubs.acs.org/doi/epdf/10.1021/acs.langmuir.4c03687.

[10] J. L. Concha, L. E. Arteaga-Pérez, E. Alpizar-Reyes, et al., (2023) *"Effect of rejuvenating oil type on the synthesis and properties of alginate-based polynuclear capsules for asphalt self-healing"* **Road Materials and Pavement Design *24***(7): 1669–1694. DOI: https://doi.org/10.1080/14680629.2022.2092026.

[11] J. Norambuena-Contreras, L. E. Arteaga-Pérez, J. L. Concha, et al., (2021) *"Pyrolytic oil from waste tyres as a promising encapsulated rejuvenator for the extrinsic self-healing of bituminous materials"* **Road Materials and Pavement Design *22***(sup1): S117–S133. DOI: https://doi.org/10.1080/14680629.2021.1907216.

[12] Y. Wang, R. Zhai, B. Sun, et al., (2022) *"Microcapsule synthesis and evaluation on fatigue and healing of microcapsule-based asphalt by the entropy and TOPSIS method"* **International Journal of Pavement Engineering *23***(13): 4610–4621. DOI: https://doi.org/10.1080/10298436.2021.1968395.

[13] E. Alpizar-Reyes, J. L. Concha, F. J. Martín-Martínez, et al., (2022) *"Biobased spore microcapsules for asphalt self-healing"* **ACS Applied Materials & Interfaces *14***(27): 31296–31311. DOI: https://pubs.acs.org/doi/abs/10.1021/acsami.2c07301.

[14] W. Mamo, A. Ambaye, A. Beshir, et al., (2025) *"Comprehensive review of the recent advancements in self-healing asphalt utilizing nanotechnology"* **Ethiopian Journal of Science and Sustainable Development *12***(1): 16–27. DOI: https://www.ajol.info/index.php/ejssd/article/view/285893.

[15] D. Grossegger, A. Garcia, and G. Airey, (2022) *"The composition of the material phase responsible for the self-healing of macro-cracks in asphalt mortar beams"* **Road Materials and Pavement Design *23***(3): 656–665. DOI: https://doi.org/10.1080/14680629.2020.1842793.

[16] R. Barbaz-Isfahani, S. Saber-Samandari, and M. Salehi, (2023) *"Experimental and numerical research on healing performance of reinforced microcapsule-based self-healing polymers using nanoparticles"* **Journal of Reinforced Plastics and Composites *42***(3-4): 95–109. DOI: https://doi.org/10.1177/07316844221102945.

[17] J. Sun, Y. Li, B. Liao, et al., (2024) *"Development and performance evaluation of bioenzyme-responsive temporary plugging materials"* **Advances in Geo-Energy Research *11***(1): 20–28. DOI: https://ager.yandypress.com/index.php/2207-9963/article/view/327.

[18] X. Li, J. Wang, X. Li, et al., (2024) *"Compatibility of high strength silica-modified microcapsules modified with polydopamine in elastomer substrates"* **Polymer Composites *45***(2): 1250–1265. DOI: https://doi.org/10.1002/pc.27850.

[19] A. Teimouri, R. Barbaz Isfahani, S. Saber-Samandari, et al., (2022) *"Experimental and numerical investigation on the effect of core-shell microcapsule sizes on mechanical properties of microcapsule-based polymers"* **Journal of Composite Materials *56***(18): 2879–2894. DOI: https://doi.org/10.1177/00219983221107831.

[20] S. S. Chaudhari, N. G. Patil, and P. A. Mahanwar, (2024) *"A review on microencapsulated phase change materials in building materials"* **Journal of Coatings Technology and Research *21***(1): 173–198. DOI: https://doi.org/10.1007/s11998-023-00814-2.

[21] M. M. Hilal and M. Y. Fattah, (2022) *"Evaluation of Resilient Modulus and Rutting for Warm Asphalt Mixtures: A Local Study in Iraq"* **Applied Science *12***: 12841. DOI: 10.3390/app122412841.

[22] M. Q. Ismael, H. H. Joni, and M. Y. Fattah, (2022) *"Neural Network Modeling of Rutting Performance for Sustainable Asphalt Mixtures Modified by Industrial Waste Alumina"* **Ain Shams Engineering Journal**: DOI: 10.1016/j.asej.2022.101972.

[23] M. Q. Ismael, M. Y. Fattah, and A. F. Jasim, (2021) *"Improving the Rutting Resistance of Asphalt Pavement Modified with the Carbon Nanotubes Additive"* **Ain Shams Engineering Journal**: DOI: 10.1016/j.asej.2021.02.038.