Influence of microcapsules on self-healing performance and road performance of dense-graded asphalt mixture

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Abstract. Asphalt mixture containing microcapsules has a certain self-healing ability, which can prolong the service life of asphalt pavement. In order to study the self-healing performance and road performance of asphalt mixtures containing microcapsules, the intermittent fatigue test and split test were used to study the effect of microcapsule content on self-healing performance, and the road performance of the mixture with different microcapsule content was studied. The results show that with the increase of the amount of microcapsules, the intermittent fatigue life and SHSR of asphalt mixtures containing microcapsules increased first and then decreased, and reached the maximum when the amount of microcapsules was 6%. The low-temperature bending strain of the mixture increased, while the dynamic stability (DS) and TSR decreased. Considering the change law of self-healing performance and road performance, the recommended content range of microcapsules was 4%-6%.

1. Introduction
Cracks are among the most common issues in asphalt pavement [1]. Initially, independent microcracks gradually expand under the coupling of temperature and traffic loads. If no effective measures are taken, the expanded cracks become top-down or bottom-up cracks with unfavourable effects on the service level and lifetime of the pavement. Moreover, under the scouring effects of high-pressure water, cracks eventually induce problems in the pavement such as loosening [2]. Studies have shown that asphalt mixtures have self-healing capability at higher temperatures under no traffic load [3-5]. However, cracks cannot be repaired adequately by only this self-healing ability, because asphalt pavement is exposed to a complex natural environment including high or low temperatures and significant traffic loading during transportation periods. Several technologies have been invented to promote the self-healing capability of asphalt mixtures. Microcapsule-blended asphalt mixtures have recently emerged as promising solutions to repair cracked asphalt pavements [6-7].

The microcapsules can break and release a rejuvenator which automatically repairs cracks, thus inhibiting crack development and decreasing their depths; thereby, microcapsules improve the service level and service lifetime of asphalt pavement. Self-healing microcapsules are broadly categorised into three main groups: encapsulation [8-12], expansive agent-mineral admixtures [13-14], and bacteria. An ideal self-healing system senses the damage and consequently triggers the release of the healing agent. An integral part of the self-healing process is the supply of necessary materials with self-healing properties to the host material, i.e. asphalt concrete, when needed. The effectiveness of the self-healing
process largely depends on managing the dispensing of the self-healing materials to ensure that release corresponds with cracking.

The rapid and scientific evaluation of the self-healing capability of asphalt mixtures is an important topic studied both domestically and abroad. Booil and Reynaldo [15] proposed using the dissipation rate of creep strain energy to evaluate the self-healing rate of fatigue damage. Pronk [16, 17] established a model of self-healing for evaluating asphalt mixtures by using the dissipation energy. However, the dissipation energy does not permit intuitive evaluation and its calculation process is complicated. Bazin et al. [18] and Qiu et al. [19] both proposed using the ratio of tensile strengths of the healed versus original asphalt mixtures to evaluate the self-healing performance of asphalt mixtures through direct tensile testing. However, the data obtained from this method was discrete and unlike the actual mechanical state. Other researchers [20-22] have used the intermittent fatigue life to evaluate the self-healing performance of asphalt mixtures, while Chai et al. [23] used the split test and the fatigue strength test to evaluate the self-healing effect.

Regarding the self-healing effects of microcapsules in asphalt mixtures, Grant [24] reported that the temperature critically affected the fatigue damage of asphalt mixtures, and that the self-healing rate of asphalt at 15 °C is more thrice that at 10 °C. Kim, Little, & Lytton [25] studied the influence of chemical components in the asphalt on the self-healing performance of the asphalt mixture. Yang, Gong, & Wang [26] stated that cracks in asphalt mixtures were partially self-healed without external loading over sufficient time intervals. Su and Schlangen [27] reported that the size and thickness of the microcapsules were critical in determining the self-healing performance of an asphalt mixture. Research conducted by Huang et al. [20] indicated that the fatigue self-healing efficiency of rubber asphalt mixtures was proportional to the time of self-healing and the asphalt dosage, which was inversely proportional to the strain, damage, and porosity. Research conducted by Dong et al. [21] reported that fatigue self-healing showed a good correlation with porosity and gradation. Norambuena-Contreras and Garcia [28] evaluated the effects of microwave and induction heating on the self-healing of asphalt mixtures.

Incorporating microcapsules has a significant impact on the self-healing performance and road performance of asphalt mixtures. Most relevant studies focus on self-healing performance, while the road performance of microcapsule asphalt mixtures has not been studied in detail. To fill the research gap, this paper used the ratio of intermittent fatigue times and split healing strength to evaluate the self-healing performance of microcapsule asphalt mixtures, and comprehensively studied the influence of microcapsule content on the self-healing performance and road performance of asphalt mixtures containing microcapsules. The optimal range of microcapsule content is recommended, which provides a powerful reference for the optimization design of microcapsule asphalt mixture.

2. Materials

2.1 Raw materials

The microcapsules were prepared by adsorption method. The microcapsules were composed of capsule core, capsule wall and wrapping material. The capsule core was an asphalt regenerant, the capsule wall was porous expanded perlite, and the wrapping material was diluted with epoxy resin, epoxy curing agent, epoxy and liquid dispersant. The preparation steps are as follows: (1) Put the porous expanded perlite into the asphalt regenerant to fully soak, and then let it stand for 24 hours. (2) Add the wrapping material to the container in proportion, and stir with a glass rod for 2-3 min to a uniform state; (3) Put the porous expanded perlite after absorbing the regenerant into the wrapping material and stir for 2-3 min; (4) Add the solid dispersing material (cement) into the container, mix and uniformly form microcapsule particles; (5) Use a 0.3mm screen to disperse the microcapsule particles, spray water and cure to obtain the microcapsules. The mass fractions of wrapping materials are 40.5%, 13.1%, and 46.4% respectively.
Matrix 90# asphalt and SBS modified asphalt were used in the test, and the performance is shown in Table 1. Limestone is also used in the asphalt mixture. The test shows that the crush value and the polish value are 15.8% and 43.5%, respectively.

Table 1. Experimental Results of Asphalt

| Asphalt type     | Penetration /0.1mm | Ductility /cm | Viscosity (Pa.s) | Softening Point/°C | Rotating film heating test |
|------------------|--------------------|---------------|------------------|--------------------|----------------------------|
| 90# matrix       | 90                 | 116.0         | 279              | 47.5               | -0.06                      |
| SBS modified     | 65                 | 32.8          | 2.6              | 87.5               | 0.23                       |

Remarks: The test temperature for the ductility of the matrix and SBS modified asphalt are 10°C and 5°C, respectively. The viscosity of the base asphalt is 60°C dynamic viscosity, and the viscosity of SBS modified asphalt is 135°C Brookfield viscosity.

2.2 Mixtures
Two kinds of asphalt mixtures are used for testing and analysis, namely AC-13 (matrix 90#) and AC-13 (SBS asphalt). The technical indicators of the mixture are shown in Table 2.

Table 2. Marshall Parameters of asphalt mixtures.

| Mixture | Asphalt type     | Optimal asphalt content (%) | Bulk relative density | Volume of air voids (%) | Voids in mineral aggregate (%) | Void filled in asphalt (%) | Marshall stability (kN) |
|---------|------------------|----------------------------|-----------------------|-------------------------|-------------------------------|---------------------------|-------------------------|
| AC-13   | matrix 90#       | 4.9                        | 2.429                 | 3.5                     | 14.0                          | 74.8                      | 8.9                     |
|         | SBS modified     | 5.2                        | 2.438                 | 3.6                     | 13.9                          | 74.1                      | 12.4                    |

3. Methodology

3.1 Self-healing performance test

3.1.1 Intermittent fatigue
Dong et al. [21] reported that the intermittent fatigue life could correspond to the self-healing ability of an asphalt mixture. When traditional continuous loading is replaced by intermittent loading, the asphalt mixture can heal in times between loading and show improved fatigue life. In the experiment here, the three-point-bending fatigue test with an MTS 810 apparatus was performed on beam specimens with the size of 25 mm × 30 mm × 250 mm. The stress control mode was selected and the key loading parameters were set as follows: stress ratio of 0.4, test temperature of 15 °C, and loading frequency of 10 Hz. Unlike continuous loading, the intermittent loading was divided into three stages. Firstly, continuous loading was applied until the specimen experienced fatigue fracture; the fatigue life \( N_1 \) was recorded. Secondly, another intact specimen was fatigue-tested for \( N_1/3 \) loading cycles before being moved to an oven at 45 ± 1 °C and cured for 12 h. Thirdly, the cured specimen was continuously loaded until it experienced damage; the remainder fatigue life \( N_2 \) was then recorded. The total intermittent fatigue life \( N \) was evaluated according to Equation (1). Greater values of \( N \) correspond to better self-healing effects.

\[
N=N_1/3+N_2
\]

3.1.2 Splitting healing strength ratio
The self-healing effect of an asphalt mixture can be characterised by the splitting healing strength ratio (SHSR) [29]. Firstly, the splitting strength \( S_1 \) of the asphalt mixture was tested at 5 °C. The specimen
was then moved to an oven at 45 ± 1 °C and cured for 48 h. The cured specimen was then moved to an oven at 6 °C and held for 6 h. Finally, the splitting healing strength $S_2$ was tested at 5 °C. The SHSR was calculated according to Equation (2). Greater SHSR values indicate better self-healing effects.

$$SHSR = \frac{S_2}{S_1} \times 100\%$$

(2)

3.2 Road performance test

3.2.1 Dynamic stability

The dynamic stability (DS) was tested by loaded wheel testers (LWTs) and used to evaluate the high-temperature performances of the asphalt mixtures. The testing conditions were as follows: testing temperature of 60 °C, wheel pressure of 0.7 MPa, testing time of 60 min, and loading rate of 43 times/min. The deformation at 60 min $D_{60}$ was recorded and the DS was calculated by Equation (3) [30]:

$$DS = \frac{(d_2 - t_1)}{d_1} \times N \times C_1C_2$$

(3)

where: DS has units of times per millimetre, $d_1$ is the deformation at $t_1 = 45$ min (mm), $d_2$ is the deflection at $t_1 = 60$ min (mm), N is the rolling speed of the test wheel (usually 43 times/min), and $C_1$ and $C_2$ are coefficients indicating the machine and specimen types, respectively.

3.2.2 Low-temperature bending strain

The low-temperature bending strain ($\varepsilon_B$) can be used to evaluate the resistance to low-temperature cracking of an asphalt mixture. The MTS system was used to test $\varepsilon_B$ under testing conditions as follows: testing temperature of −10 °C and loading rate of 50 mm/min. Specimen failure is determined as the point at which the specimen’s bending strength is maximised. The $\varepsilon_B$ at failure can be calculated using Equation (4) [30].

$$\varepsilon_B = \frac{6hd}{L^2}$$

(4)

where: $b$ is the width of the specimen at the mid-span section (mm); $h$ is the height of the specimen at the mid-span section (mm); $L$ is the span of the specimen (mm); and $d$ is the mid-span deflection at failure (mm).

3.2.3 TSR

The tensile strength ratio (TSR) is an indicator evaluating the water stability of asphalt mixtures. In the TSR testing method, eight specimens of 101.6 mm in diameter × 63.5 mm in length were fabricated with 50 cycles of two-face compaction. The four group 1 specimens were first saturated under 97.33 kPa vacuum conditions for 15 min before placement in sealed plastic bags containing approximately 10 mL water and refrigeration at the constant temperature of −18 °C for 16 h. The specimens were then removed from the plastic bags and placed in a 60 °C water bath for 24 h. Then, specimens of both groups 1 and 2 are immersed in 25 °C water baths for 2 h and tested to obtain their tensile strengths. The formula used for the calculation of TSR is listed as Equation (5) [30].

$$TSR = \left(\frac{ITS_1}{ITS_0}\right) \times 100$$

(5)

where: TSR is measured as a percentage and $ITS_0$ and $ITS_1$ are the tensile strengths without and with the freeze-thaw cycle (MPa).
4 Results and discussions

4.1 Effect of self-healing microcapsules on self-healing performance of asphalt mixture

Two typical pavement structure types, AC-13 and SMA-13, were used to evaluate the self-healing performance of the microcapsule mixture, and five content levels of 0, 2%, 4%, 6%, and 8% were designed to study the effect of microcapsules on the self-healing performance of asphalt mixtures.

4.1.1 Intermittent fatigue
Figure 1 shows the results of the intermittent fatigue test of asphalt mixtures. It can be seen that the intermittent fatigue life of the two types of asphalt mixtures increases first and then decreases with the increase in the amount of microcapsules. When the microcapsule content is 6%, the intermittent fatigue life of the asphalt mixture is the largest. The maximum intermittent fatigue life of AC-13 asphalt mixture is 8950 times, which is 72.1% higher than that of asphalt mixture without microcapsules, and 9741 times for SMA-13 asphalt mixture, which is 64.6% higher than that of asphalt mixtures without microcapsules. In the case of intermittent loading, the microcapsules can play a role in repairing and improve the fatigue performance of the asphalt mixture to a certain extent. We can define the appropriate microcapsule content range for intermittent fatigue life to be 4%~8%.

The repair effect of microcapsules in AC-type asphalt mixtures is better than that of SMA-type asphalt mixtures. This is because most of the load is borne by the coarse aggregate in the skeleton dense structure asphalt mixture, the capsules and other fine aggregates only play the role of filling the voids, and the effective load borne by them is small and insensitive to external loads. However, in a suspended compact structure, the capsule bears part of the load and is more sensitive to external loads, and can reach the destruction threshold when the mixture is destroyed.

4.1.2 Splitting healing strength ratio
Figure 2 shows the results of the crack splitting strength test of the mixture. It can be seen that the splitting strength of the mixture under the two types of structures has a certain degree of recovery. The crack healing strength ratios of AC-13 asphalt mixture without and with 6% microcapsules were 34.7% and 43.2%, respectively. The recovery effect of the mixture with embedded microcapsules is better, which is 7.5% higher than that of the asphalt mixture without embedded microcapsules. For the SMA-13 asphalt mixture, the crack healing strength ratios of no and 6% microcapsules are 29.2% and 32.9%, respectively. The recovery of the microcapsule-embedded mixture is 3.7% higher than that of the microcapsule-free mixture. At the same time, it can be seen that the healing effect of the microcapsules in the AC-13 structure mixture is slightly better than that of the SMA-13 type, which shows a consistent trend with the fatigue results. We can define the appropriate microcapsule content range for the split healing strength ratio to be 4%~8%.

| Figure 1. Intermittent fatigue life of asphalt mixture containing microcapsules | Figure 2. SHSR of asphalt mixture containing microcapsules |
4.2 Effect of self-healing microcapsules on road performance of asphalt mixture

The study designed five content levels of 0, 2%, 4%, 6%, and 8% to study the influence of microcapsules on the dynamic stability (high temperature stability), low temperature bending strain (low temperature crack resistance) and Freeze-thaw splitting TSR (water stability) of asphalt mixtures.

4.2.1 Dynamic stability

According to the "Technical Specification for Construction of Highway Asphalt Pavements" (JTG F40-2004), the dynamic stability of the asphalt mixture was tested. The test results are shown in Figure 3. It can be seen that with the increase of the microcapsule content, the dynamic stability of the mixture decreases. When the mixing amount is 0%~4%, the addition of microcapsules does not significantly reduce the dynamic stability; when the mixing amount is 4%~6%, the dynamic stability has a relatively obvious decline, indicating that the high temperature stability has a greater tendency to weaken; When the content exceeds 6%, the dynamic stability decreases rapidly, and the high temperature stability sharply decreases. When the content is 8%, it can no longer meet the requirements of the "Code". This is because the high temperature performance of the asphalt mixture is related to the aggregation angle. The microcapsules are spherical, which reduces the frictional resistance of the aggregates in the asphalt mixture. Therefore, as the content of microcapsules increases, the high-temperature stability decreases. From the data, we choose a roughly appropriate range of microcapsule content of 0-6%.

4.2.2 Low–temperature bending strain

The results of low-temperature bending strain of asphalt mixture are shown in Figure 4. It can be seen that as the output of microcapsules increases, the bending strain value gradually increases. As the content of microcapsules increases from 0 to 8%, the low-temperature bending strain increases by 27.8%. It shows that the addition of microcapsules can enhance the low-temperature crack resistance of the mixture to a certain extent. The reasons are analyzed as follows: First, the addition of microcapsules increases the percentage of fine aggregates in the mixture, resulting in a decrease in the stiffness modulus of the mixture; second, the texture of the microcapsules is relatively soft and has weak deformability, which is different from the properties of mineral aggregate. Therefore, the low-temperature deformation ability of the asphalt mixture with microcapsules is relatively enhanced, which will also result in the enhancement of low-temperature crack resistance. We can define the suitable microcapsule content range for low temperature anti-cracking performance as 0%~8%.

4.2.3 TSR

The TSR result of the asphalt mixture is shown in Figure 5. It can be seen that with the increase of the content of microcapsules in the asphalt mixture, the freeze-thaw splitting TSR gradually decreases, which means that the water stability performance becomes worse with the increase of the content. Studies have shown that the water stability of asphalt mixtures is related to the binding of asphalt and mineral aggregates. Because the surface roughness and angle of the microcapsules are lower than that of mineral aggregates, the adhesion of asphalt and microcapsules is weaker than that of natural aggregates. Therefore, when the microcapsules are incorporated into the asphalt mixture, the TSR decreases. According to the standard requirement, TSR should meet no less than 75%, so the reasonable range of microcapsule output is 0-7%.
5. Conclusion
(1) The influence of the amount of microcapsules on the self-healing performance of asphalt mixtures was studied. With the increase of the amount of microcapsules, the intermittent fatigue life and SHSR showed a trend of first increasing and then decreasing, reaching the maximum when the content is 6%.
(2) The study revealed the influence of microcapsule content on the high temperature stability, low temperature crack resistance and water stability of asphalt mixture. As the amount of microcapsules increased, the low-temperature bending strain of the mixture increased, while the dynamic stability (DS) and TSR decreased.
(3) Integrating the self-healing performance and road performance of the mixture with the change of the microcapsule content, the recommended microcapsule content is 4%-6%.

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Reference
[1] Miao S J, Chen S S. Disease analysis and maintenance of highway asphalt pavement [J]. Jiangxi Building Materials, 2021(02):147-148.
[2] Ji X P, Yang Z G, Zhou Z H, Zhang Y L, Lei Y Z. Evaluation method for self-healing performance of dense gradation asphalt mixture [J]. Journal of Highway and Transport, 2018,
[3] Wu D Y, Meure S, Solomon D. Self-healing polymeric materials: A review of recent developments [J]. Progress in Polymer Science, 2008, 33(5):479-522.

[4] Sun, D.Q., Zhang, L.W., & Liang, G. Research progress on self-healing behavior of asphalt concrete fatigue damage (1) self-healing behavioral mechanism and characterization [J]. Petroleum Asphalt, 2011, 25(5), 7–11.

[5] Lv, Q., Huang, W.D., Zhu, X.Y., & Xiao, F.P. On the investigation of self–healing behavior of bitumen and its influencing factors [J]. Materials and Design, 2017, 117, 7–17.

[6] Garcia, Á, Schlangen, E., van de Ven, M., & Sierra-Bertrán, G. Preparation of capsules containing rejuvenators for their use in asphalt concrete [J]. Journal of Hazardous Materials, 2010, 184, 603–611.

[7] Su, J.F., & Schlangen, E. Synthesis and physicochemical properties of high compact microcapsules containing rejuvenator applied in asphalt [J]. Chemical Engineering Journal, 2012, 198–199, 289–300.

[8] Brown, E.N., Kesseler, M.R., Sottos, N.R., & White, S.R. In situ poly (urea-formaldehyde) microencapsulation of dicyclopentadiene [J]. Journal of Microencapsulation, 20(6), 2003, 719–730.

[9] Samadzadeh, M., Hatami, S., Peikari, M., Kasiriha, S.M., & Ashrafi, A. A review of self-healing coatings based on micro/nanocapsules [J]. Progress in Organic Coatings, 2010, 68(3), 159–164.

[10] Shirzad, S., Hassan, M.M., Aguirre, M.A., Mohammad, L.A., & Daly, W.H. Evaluation of sunflower oil as a rejuvenator and its microencapsulation as a healing agent [J]. Journal of Materials in Civil Engineering, 2016, 28(11), 040161161–9.

[11] Li, R., Zhou, T.S., & Pei, J.Z. Design, preparation and properties of microcapsules containing rejuvenator for asphalt [J]. Construction and Building Materials, 2015, 99, 143–149.

[12] Su, J.F., Schlangen, E., & Wang, Y.Y. Investigation the self-healing mechanism of aged bitumen using microcapsules containing rejuvenator [J]. Construction and Building Materials, 2015, 85, 49–56.

[13] Garcia, Á. Schlangen, E., & van de Ven, M. Properties of capsules containing rejuvenators for their use in asphalt concrete [J]. Fuel, 2011, 90, 583–591.

[14] Garcia, Á, Austin, C.J., & Jelfs, J. Mechanical properties of asphalt mixture containing sunflower oil capsules [J]. Journal of Cleaner Production, 2016, 118, 124–132.

[15] Boool, K., & Reynaldo, R. Evaluation of Healing Property of Asphalt Mixtures [J]. Transportation Research Record Journal of the Transportation Research Board, 2006, 1970(1970):84-91.

[16] Pronk A C. Partial Healing — A New Approach for the Damage Process during Fatigue Testing of Asphalt Specimen[C]// R Lytton Symposium on Mechanics of Flexible Pavements. 2006.

[17] Pronk, A.C. PH Model in 4PB Test with Rest Periods [J]. Road Materials and Pavement Design, 2009, 10, 417–426.

[18] Bazin, P., & Saunier, B. Deformability, Fatigue and Healing Properties of Asphalt Mixes [J]. Proceedings of the Second International Conference on the Structural Design of Asphalt Pavements. 1967, 553-569.

[19] Qiu, J., van de Ven, M.F.C., Wu, S., Yu, J., & Molenaar, A.A.A. Investigating the self-healing capability of bituminous binders [J]. Road Material and Pavement Design, 2009, 10(2), 81–94.

[20] Huang, M., Wang, X., & Huang, W.D. Analysis of influencing factors self-healing of fatigue performance of asphalt rubber mixture [J]. China Journal of Highway and Transport, 2013, 26(4), 16–22.

[21] Dong, R.K, Zheng, M., Huang, W.D., & Huang, M. Fatigue performance comparison of various kinds of asphalt mixtures with self-healing compensation considered [J]. China Journal of Highway and Transport, 2015, 28(5), 87–92.

[22] Garcia, A. Self-healing of open cracks in asphalt mastic [J]. Fuel, 2012, 93, 264–272.
[23] Chai, Z.Q., Zheng, Y., & Zhao, H.D. Performance evaluation of self-repairing capsules embedded in asphalt mixture [J]. Transportation Science & Technology, 2016, 93, 163–165.

[24] Grant, T. P. Determination of asphalt mixture healing rate using the superpave indirect tensile test [D]. University of Florida, Gainesville, FL, USA. 2001.

[25] Kim, Y.R., Little, D.N., & Lytton, R.L. Fatigue and healing characterization of asphalt mixtures [J]. Journal of Materials in Civil Engineering, 2003, 15, 75–83.

[26] Yang, J., Gong, M., & Wang, Z. Multiscale research progress of fatigue and self-healing properties of asphalt mixtures [J]. China Science Paper, 2013, 8(5), 435–440.

[27] Su, J.F., Schlangen, E., & Qiu, J. Design and construction of microcapsules containing rejuvenator for asphalt [J]. Power Technology, 2013, 235(2), 563–571.

[28] Norambuena-Contreras, J., & Garcia, A. Self-healing of asphalt mixture by microwave and induction heating [J]. Materials and Design, 2016, 106, 404–414.

[29] Yang, Z.G. Development and performance evaluation of crack self-healing microcapsule asphalt mixture [D]. Chang’an University, Xi’an, China. 2017.

[30] RIOH. Standard test methods of bitumen and bituminous mixtures for highway engineering (JTJ 052–2000) [S]. Beijing: China Communications Press. 2000.