Research on the Impact of Recycled Asphalt Mixture on Road Performance Based on New Thermal Recycling

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Abstract. Different binder content to RAP Regeneration SBS modified asphalt mixture for road performance to SBS modified asphalt (I-D type) as an index, determine the optimum dose of new heat regenerating agent and different RAP regeneration, and prepared different recycled asphalt, which have differences in RAP content. The performance of recycled asphalt mixture with different RAP content was evaluated by freeze-thaw splitting test, Rut test and Low temperature trabecular bending test. The correlation between RAP content and pavement performance was analyzed by grey system correlation analysis method. According to the experimental verification results, it can be known that increasing the content of RAP material can improve the high-temperature performance of reclaimed asphalt, but will result in a qualitative decrease in low-temperature performance and water temperature, but the above-mentioned performance can reach the required level. Shows that new heat regenerators play a role in the road performance of RAP materials, and for the RAP material utilization ratio of more than 50%, as for the gray correlation analysis, it can be found that there is a close correlation between the low-temperature performance of recycled asphalt mixture and the content of RAP material. The low temperature cracking resistance of asphalt mixtures will change significantly due to the slight changes in RAP materials.

Keywords: New Heat Regenerator, RAP Content, Road Performance, Grey Correlation Degree.

1. Introduction
With the renovation, transformation and expansion of a large number of high-grade highway asphalt pavements in my country, a large amount of RAP materials are randomly piled up and wasted, which not only causes a waste of resources, but the carcinogen benzene contained in the asphalt also causes a certain extent to the surrounding residents. The health problems of the above, the idea of recycling RAP materials came into being [1-3]. Adding a regenerate to realize the regeneration of aging asphalt has the characteristics of convenient construction and excellent road performance. The commonly used regenerant uses aromatic oil as the base oil, but the aromatic oil contains a large amount of carcinogens such as benzene and toluene. In order to take into account environmental issues and workers’ health issues, the aromatic oil regenerant is gradually eliminated by the market [4-6].

According to the four-component theory of asphalt, Asphalt is a mixture, mainly composed of some saturated chemical substances, aromatic components, asphaltenes and gums. From the analysis
of the microstructure of asphalt, the molecular interactions between various compounds in asphalt can be found. Asphalt performance, In order to well reflect the regeneration mechanism of regenerated asphalt, a self-made thermal regenerant with excellent performance based on light oil was made and named as YZSJ-I type regenerant [7, 8]. It passed a series of macro performance tests. After verifying the performance of the reclaimed asphalt binder with the micro-mechanism analysis test, the road performance of the mixture is verified through the road performance test of the mixture. The grey correlation analysis method is used to analyze the correlation between RAP material parameters and road performance [9-12]. The research results can provide references for the popularization and application of recycled asphalt mixtures prepared from light oil regenerants.

2. Test Materials and Methods

2.1. RAP Material and Asphalt
The RAP material is selected from the SBS modified asphalt concrete surface pavement milling material from a highway in Chongqing that has been in service for more than 5 years. The asphalt content and aggregate gradation of the RAP material are determined by the extraction and screening method. The actual test results show that the content of old asphalt reaches 4.9%, for detailed aggregate screening qualification rate, please refer to Table 1 below. The new asphalt adopts the ID type SBS modified asphalt produced by Maoming Petrochemical, and the aging SBS modified asphalt is prepared through the RTFOT test. The performance of the asphalt before and after aging meets the requirements of JTG F40-2004 As required by Article 4.6.2, the basic performance of asphalt is shown in Table 2.

Table 1. RAP screening results

| Project                     | 16.0 | 13.2 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
|-----------------------------|------|------|------|------|------|------|------|------|------|-------|
| Old road mixture            | 100  | 94.6 | 79.8 | 45.2 | 29.9 | 22.3 | 19.2 | 14.5 | 10.5 | 4.6   |
| AC-13 specification range   | 100  | 90-100| 68-85| 38-68| 24-50| 15-38| 10-28| 7-20 | 5-15 | 4-8   |

Table 2. Performance indicators for asphalt

| Asphalt type                        | 25°C Penetration (0.1mm) | 5°C Ductility (mm) | Softening Point (°C) |
|-------------------------------------|--------------------------|-------------------|----------------------|
| New SBS modified asphalt            | Penetration ≥65%          | Softening Point ≥75°C |
| RTFOT asphalt after aging           | 40.4                      | >200              | 75.4                 |
| As-is asphalt technical indicators are required | 40–60                    | ≥60               |                      |
| RTFOT or TFOT aging asphalt         | Penetration ratio ≥65%    | RTFOT ≥72.3%      | ≥150                |
| requirements indicators             |                          |                   |                      |

2.2. Regenerating Agent and Recycled Asphalt
The regeneration agent developed in this paper is mainly made of base oil, high viscosity modifier, plasticizer, antioxidant and ultraviolet absorber. Among them, the base oil is 32# white oil produced by Jinan Tianfang Company, the plasticizer is 117-81-7# DOP plasticizer produced by Jiangsu Wenru Chemical, and the antioxidant is Zhengzhou Poly The BASF 1010 type antioxidant produced by Li Chemical, the UV absorber selected is the UV-531 and PT-HVA type high-viscosity modifier produced by Guangdong Luwei New Material Technology Co., Ltd., and it has passed the three major indicators of asphalt and rotating film oven Wait for experiment to find the best blending ratio and production process of regenerant.
With the help of Design-Expert software, the response surface design method which is used to conduct multi-factor and multi-level calculation and analysis, and finally determine the formula of the regenerant: base oil: plasticizer=7:3, 0.438% antioxidant, 0.308% ultraviolet absorber, 1.711% high viscosity modifier, and the formulated regenerant is named YZSJ-I type regenerant [13].

Refer to the following steps for the principle of regenerant production process flow: After the base oil and the plasticizer are weighed in a 7:3 ratio, the mixed solution of the two is manually stirred for 20 minutes, then put it in a constant temperature oil bath for heat preservation, which was using high-speed scissors. Stirring and shearing the material through the shearing machine. In order to ensure the solubility of the anti-aging agent, the heat preservation temperature of the oil bath is set to 160°C, and the cutting speed of the high-speed shearing machine is 5000r/min. Add antioxidants, ultraviolet absorbers and high Viscosity modifier, in order to ensure that the anti-aging agent can be uniformly dispersed in the regenerating agent, Use a small amount of times, and then the YZSJ-I type regenerating agent is made after continuous shearing and stirring for 40 minutes.

The self-made YZSJ-I type regenerating agent is used to make different content of recycled asphalt, and the macro performance test of recycled asphalt proves that the optimal content of the regenerating agent is 5%. For detailed test results, see Table 3 below.

### Table 3. Performance indicators of recycled asphalt

| Index              | As-is SBS asphalt | Agin g SBS asphalt | 2% YZSJ-I Regenerative agent | 4% YZSJ-I Regenerative agent | 5% YZSJ-I Regenerative agent | 6% YZSJ-I Regenerative agent | 8% YZSJ-I Regenerative agent |
|--------------------|------------------|--------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 25°C Penetration(0.1 mm) | 55.9             | 40.4               | 52.5                        | 61.8                        | 70.1                        | 80.7                        | 111.7                       |
| 5°C Ductility(mm)    | 372              | 230                | 257                         | 308                         | 374                         | 423                         | 505                         |
| Softening Point(°C) | 75.8             | 75.4               | 70.1                        | 66.8                        | 66.2                        | 64.5                        | 63.4                        |

3. Performance of Hot Recycled Mixture

3.1. Marshall Test

The aggregate gradation used in this experiment is AC-13 gradation, the content of RAP material changes from 30%-50% every 10%, and see Table 4 for the grading ratio of hot recycled mixture mineral material. During the test the mixing amount of regenerant is 5%, the control group uses SBS modified asphalt mixture without any RAP material. For detailed test results, see Table 5 below.

### Table 4. Ratio of mineral aggregate of hot recycled asphalt mixture with different RAP content

| RAP doping (%) | 0    | 30   | 40   | 50   | JTGF40 requirements |
|----------------|------|------|------|------|---------------------|
|                | 16   | 13.2 | 9.5  | 4.75 | 2.36                |
| Pass the mass percentage of the following perforations (mm)/% | 0.18 | 0.36 | 0.72 | 1.44 | 2.88               |
| 100            | 95.4 | 94.7 | 95.1 | 96.2 | 90-100              |
| 90-100         | 68.5 | 75.3 | 77.4 | 77.9 | 68-85               |
| 68-85          | 38.6 | 48.4 | 49.5 | 45.1 | 38-68               |
| 38-68          | 24-50| 37.2 | 49.5 | 45.1 | 24-50               |
| 24-50          | 15-38| 37.9 | 49.5 | 45.1 | 15-38               |
| 15-38          | 10-28| 37.4 | 49.5 | 45.1 | 10-28               |
| 10-28          | 7-20 | 37.4 | 49.5 | 45.1 | 7-20                |
| 7-20           | 5-15 | 37.4 | 49.5 | 45.1 | 5-15                |
| 5-15           | 4-8  | 37.4 | 49.5 | 45.1 | 4-8                 |
According to Table 5, compared with recycled asphalt mixture and SBS improved asphalt, the former is relatively low in theoretical density, stability and sample density, but the porosity and flow value have increased. The stability difference between% of recycled asphalt mixture and SBS modified asphalt mixture is only within 1KN, and the Marshall test results of the recycled asphalt mixtures in various amounts meet the requirements of Article 5.3.3 of JTG F40-2004.

### 3.2. High Temperature Stability

Through the rutting test, the influence of RAP content on the high-temperature performance of the hot-recycled asphalt mixture was comprehensively evaluated in terms of the dynamic stability and rutting deformation of the asphalt pavement. For detailed test results, see Table 6 below.

#### Table 6. High temperature performance index of recycled asphalt mixtures

| RAP doping /% | Dynamic stability / (num/mm) | Rut deformation /mm |
|---------------|------------------------------|---------------------|
| 30            | 4345                         | 2.234               |
| 40            | 4846                         | 2.127               |
| 50            | 5575                         | 1.904               |
| SBS modified asphalt mixture | 4145                         | 2.357               |

It can be seen from Table 6 that regardless of the amount of RAP material, the dynamic stability of the recycled asphalt mixture is greater than that of the SBS modified asphalt mixture, while the change trend of rutting deformation is just the opposite. The minimum dynamic stability of the material is 4345 times/mm, which is much higher than the 2800 times/mm specified in JTG F40-2004, and hot recycled asphalt has more advantages in high temperature performance than SBS modified asphalt mixture. When the content of RAP material in hot recycled asphalt increases from 30% to 50%, the dynamic stability of hot recycled asphalt mixture will be further improved, and the improvement range will reach 4.8% to 34.5%, and the rutting deformation is reduced by 5.22%~19.22%. This shows that increasing the content of RAP material can significantly improve the recycled asphalt The high-temperature performance of the mixture, analyze the reason, this may be because the RAP material is wrapped in the aged asphalt, and the aged asphalt has a lot of heavy components. The viscosity increases after the new and old asphalt is mixed, which makes the recycled asphalt mixture resistant to plasticity The increased capacity makes the hot recycled asphalt mixture have good high temperature stability.

### 3.3. Low Temperature Crack Resistance

Low temperature trabecular bending test was done, the influence of the RAP content on the low-temperature crack resistance of the hot-recycled asphalt mixture was comprehensively evaluated from the flexural tensile failure strength and maximum failure strain of the asphalt mixture. For detailed test results, see Table 7 below.
Table 7. Low temperature performance index of recycled asphalt mixtures

| RAP doping /% | Bending strength /MPa | Maximum failure strain /με |
|--------------|-----------------------|---------------------------|
| 30           | 12.16                 | 3558.96                   |
| 40           | 10.92                 | 3117.28                   |
| 50           | 8.93                  | 2864.01                   |
| SBS modified asphalt mixture | 13.88 | 3924.45 |

It can be seen from Table 7 that the flexural tensile failure strength and maximum failure strain of all asphalt mixtures decrease with the increase of RAP material content. Increase RAP content, the corresponding low temperature performance will show a downward trend. But the minimum value of its maximum failure strain is 2864.01, which still meets the requirement of 2500με specified in JTG F40-2004; If the content of RAP material contained in thermally regenerated asphalt is increased from 30% at the beginning to 50%, hot recycled asphalt The bending tensile failure strength of the mixture is reduced by 12.39%-35.66%, and the maximum failure strain is reduced by 9.31%-27.02%, indicating that the increase of the RAP content has a certain negative impact on the low temperature performance of the hot recycled asphalt mixture. Analyze the reason, this may be due to the increase in the amount of RAP material, the uneven miscibility between the new and old asphalt increases, resulting in a decrease in the crack resistance of the asphalt mixture. Therefore, compared with the SBS modified asphalt mixture, the RAP content of the hot reclaimed asphalt will increase from 30% to 50%, There should be restrictions. For the self-made light oil regenerant used in this article, the best content is set at 50%.

3.4. Water Stability
Through the freeze-thaw splitting test, the influence of the RAP content on the water stability of the hot-recycled asphalt mixture was comprehensively evaluated from the aspects of splitting strength and freeze-thaw splitting strength ratio. For detailed test results, see Table 8 below.

Table 8. Water stability index of recycled asphalt mixture

| RAP doping /% | Splitting strength /MPa | TSR/% |
|--------------|------------------------|-------|
| 30           | 1.331                  | 90.50 |
| 40           | 1.267                  | 90.13 |
| 50           | 1.178                  | 89.97 |
| SBS modified asphalt mixture | 1.427 | 94.07 |

According to the data in the table, it can be known that when the amount of RAP material is increased, the splitting strength and freeze-thaw splitting strength ratio of all asphalt mixtures continue to decrease, indicating that the water stability of recycled asphalt mixtures gradually decreases with the increase of RAP material content. The minimum value of TSR is 89.97%, it can also meet the basic requirements of road construction. Compare this material with SBS modified asphalt mixture, it can be found that when the RAP content is increased from 30% to 50% In this case, splitting strength attenuation 6.73% ~ 17.45%, and the TSR reduction range is 3.57%--4.36%. It can be seen that the increase in RAP content has a negative impact on the qualitative water temperature of the asphalt mixture. Analysis The reason may be that as the amount of RAP material increases, the unevenness of asphalt mixture mixing also increases, and the uniformity of miscibility between the new and old asphalt decreases. The water stability of the asphalt mixture will change. Therefore, in order to ensure the material water temperature qualitativeness. The amount of RAP usage needs to be controlled. If it is the preparation of light oil regenerant, the best dosage is 50%.
4. Grey Relational Analysis

4.1. Basic Principles and Steps

4.1.1. Fundamental. The gray correlation analysis method is the gray system theory proposed by Professor Deng Julong in 1982. It provides a statistical analysis method to describe the advantages and disadvantages of the relationship between factors. The basic idea of gray correlation analysis is based on the data series of factors, using mathematical methods to study the geometric correspondence between factors, after analyzing and comparing geometric shapes, it is believed that the closer the geometric shapes are, the closer the development trend is, and the higher the degree of correlation [14, 15].

4.1.2. Step. Set the variable from the reference sequence, and compare the number of variable columns before and after the arrangement:

\[ X_i = \{X_i(k)\} = 1,2, \cdots n \]
\[ X_0 = \{X_0(k)\} = 1,2, \cdots n \]

(1)

(2)

Use the mean value method to non-dimensionlize the sequence for calculation and analysis:

\[ Y_0 = \{Y_0(k)\} = \{X_0(k) / \bar{X}_0\} = 1,2, \cdots n \]
\[ Y_i = \{Y_i(k)\} = \{X_i(k) / \bar{X}_i\} = 1,2, \cdots n \]

(3)

(4)

The correlation coefficient of reference sequence and comparison sequence at time k:

\[ \varepsilon_i(k) = \frac{\min_j \min_k |Y_0(k) - Y_j(k)| + \varepsilon \max_j \max_k |Y_0(k) - Y_j(k)|}{|Y_0(k) - Y_i(k)| + \varepsilon \max_j \max_k |Y_0(k) - Y_j(k)|} \]

In the formula, the value of \( \varepsilon \) is between 0-1, usually 0.5.

Grey correlation calculation result:

\[ \gamma_i = \frac{1}{n} \sum_{k=1}^{n} \varepsilon_i(k) \]

(5)

(6)

In the formula, \( \gamma_i \) is the degree of correlation between the comparison sequence \( X_i \) and the reference sequence \( X_0 \). The larger the value of \( \gamma_i \), the closer the development trend of \( X_i \) and \( X_0 \), and the closer the correlation degree between the both.

4.2. Grey Correlation Analysis of RAP Content and Road Performance of Mixture

In this paper, the RAP material content is used as a comparative series, research and analysis of performance parameters such as maximum failure strain, stability, tensile failure strength and yield strength, split strength and split strength ratio are used as the reference series. The gray correlation analysis is carried out on the RAP material content and the road performance of the mixture. The specific analysis results can be found in Table 9 to Table 11 below.

It can be seen from Table 9-11 that the RAP content has the most significant impact on the high temperature performance of the mixture, according to the aforementioned analysis and research, it can be known that the increase of RAP can promote the high temperature characteristics of the mixture. This article mainly explores the amount of RAP material has an adverse effect on the road performance, therefore, the discussion is limited to water stability and low temperature performance.
The calculation shows that the amount of RAP material has the most significant effect on the maximum failure strain of the mixture, followed by freezing. Therefore, when regenerating light oil regenerants, research should focus on low temperature properties of the mix, but for affecting the stability of the water can not be ignored. Data analysis shows that the content of RAP The correlation between the maximum failure strain and the freeze-thaw splitting strength ratio is not much different. This may be because the bonding performance of the new and old asphalt in the recycled asphalt mixture is mainly reflected in the water damage resistance of the mixture, while the RAP content The increase in slag affects the contact area of new and old asphalt, therefore, in cold and rainy areas, the amount of RAP material in the recycled asphalt mixture should be carefully considered.

### Table 9. Raw series of blends

| Project | SBS asphalt mixture | 30% asphalt mixture | 40% mixed asphalt mixture | 50% mixed asphalt mixture |
|---------|---------------------|---------------------|--------------------------|--------------------------|
| X01     | 4145                | 4345                | 4846                     | 5575                     |
| X02     | 2.357               | 2.234               | 2.127                    | 1.904                    |
| X03     | 13.88               | 12.16               | 10.92                    | 8.93                     |
| X04     | 3924.45             | 3558.96             | 3117.28                  | 2864.01                  |
| X05     | 1.427               | 1.331               | 1.267                    | 1.178                    |
| X06     | 94.07               | 90.5                | 90.13                    | 89.97                    |
| X1      | 0                   | 0.3                 | 0.4                      | 0.5                      |

### Table 10. Average series

| Project | SBS asphalt mixture | 30% asphalt mixture | 40% mixed asphalt mixture | 50% mixed asphalt mixture |
|---------|---------------------|---------------------|--------------------------|--------------------------|
| Y01     | 0.876738406         | 0.919041828         | 1.025011898              | 1.179207868              |
| Y02     | 1.093481791         | 1.036418464         | 0.98677801               | 0.883321735              |
| Y03     | 1.20984964          | 1.05992591          | 0.95184136               | 0.77838309               |
| Y04     | 1.165848478         | 1.057271235         | 0.926059994              | 0.850820293              |
| Y05     | 1.097059389         | 1.023255814         | 0.974053431              | 0.90561367               |
| Y06     | 1.031837003         | 0.992678312         | 0.988619848              | 0.986864837              |
| Y1      | 0                   | 1                   | 1.333333333              | 1.666666667              |

### Table 11. Grey correlation analysis

| Project | SBS asphalt mixture | 30% asphalt mixture | 40% mixed asphalt mixture | 50% mixed asphalt mixture | Correlation |
|---------|---------------------|---------------------|--------------------------|--------------------------|-------------|
| ε011    | 0.394893446         | 1                   | 0.695505406              | 0.560932889              | 0.662832935 |
| ε021    | 0.355536699         | 1                   | 0.65281745              | 0.438437391              | 0.611697885 |
| ε031    | 0.366354467         | 1                   | 0.674005891              | 0.445249793              | 0.621402538 |
| ε041    | 0.366082721         | 1                   | 0.646533064              | 0.45768439              | 0.617575044 |
| ε051    | 0.347465545         | 1                   | 0.6298518                | 0.436622474              | 0.603484955 |
| ε061    | 0.338063853         | 1                   | 0.607972046              | 0.437594123              | 0.595907505 |

### 5. Conclusion

In this paper, a new type of thermal regenerating agent is independently prepared, and the optimal content of the regenerating agent is determined to be 5% through related tests of asphalt cement. Using a new type of regenerant to prepare recycled asphalt mixtures with different dosages and conduct road performance tests, according to the results, it can be found that in the process of increasing the use of RAP materials, the high temperature resistance of the mixture will be significantly improved, but it will significantly affect its water stability and low temperature resistance characteristics. However, all test verification parameters can meet the target level. By comparison of
the data analysis, based on the self-made new thermal regenerator in this article, RAP optimal amount of material was 50%.

Through the gray correlation analysis of the RAP content and the road performance of the asphalt mixture, analysis found to affect low temperature performance of RAP feed Volume of Mixture most significant, followed by water stability. So, for the low temperature and rainy areas, it should be considered carefully the amount of RAP material in the recycled asphalt mixture.

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References
[1] Wang, B. (2020) “Application of Local Heat Regeneration Technology in Highway Construction” Asphalt Pavement China Highway, (12):98-99.
[2] Shan, K., Li, D. D., Li, Q., Yuan, Q. H., Fan, X. (2019) “Hot Regeneration Technology and Mechanism of Highway Old Asphalt Pavement Material”, Functional materials, 50(10):10110-10114.
[3] Wang, X. L., Hu, L., Huang, X. M. (2019) “A Study on the Key Technology of Mixing Heat Regeneration in Asphalt Pavement Plant”, Journal of China & Foreign Highway, 39(01):210-214.
[4] Zhang, C. B. (2006) “A Study on the Technology of Mixing Heat Regeneration in Asphalt Concrete Plant”, Chang’an University. (in Chinese)
[5] Zhang, W. H. (2014) “A Study on Heat Regeneration Technology in Asphalt Pavement Plant”, Chang’an University. (in Chinese)
[6] Yang, P. (2015) “A Stuy on Heat Recycling in Asphalt Pavement Plant”, Changsha University of Technology. (in Chinese)
[7] Zhou, Z. G., Yang, Y. P., Zhang, Q. P., Gao, H. Y. (2020) “Regenerative behavior of regenerator on old asphalt”, Journal of Traffic and Transportation Engineering 11(06):10-16.
[8] Zhou, Y., He, C., Li, Q., Wen, G. X., Li, K., Wu, C. F. (2019) “Preparation and Performance Evaluation of Basic Regeneration”, Highway, (05):236-242.
[9] He, D. P., Yu, Z. X. (2020) “The influence of SBS and SBR modified asphalt on the performance of warm recycled asphalt mixture”, New Chemical Materials, (08):254-257 262.
[10] Ma, F., Li, Y., B., Fu, Z., Han, W. H., Zhang, C. (2020) “A Study on the Properties of Composite Fiber Asphalt Mixer”, Journal of Henan Polytechnic University (Natural Science), (01):157-163.
[11] Zhang, X. F., Zhu, J. C., Wu, C. F., Luo, P., Liu, K. F. (2020) “A study on the properties of wood tar-based recycled asphalt and mixture”, New Building Material, (05):145-149 154.
[12] Wang, Z. J., Fu, Q. L., Huang, L.g, Wei J. G., Wang, L. Y. (2020) “Effect of waste oil regenerator on the performance of warm-mixed recycled asphalt mixture”, Journal of China & Foreign Highway, (02):184-191.
[13] Liu, C. H., Liao, M. J., Liu, L., Liu, J. Y. (2019) “Study on the Content of Nano TiO_2/Nanometer MMT/SBR Composite Modified Asphalt”, Journal of Changsha University of Science and Technology: Natural Science, 16(04):1-7.
[14] Li, L. P., Feng, J., Yu, J. (2018) “Grey Correlation Analysis of Composition and and Properties of Warm Mix Asphalt”, Highway Engineering 40(04):24-27.
[15] Zuo, F., Ye, F., Song, Q. Q. (2017) “The influence of RAP content on the performance of recycled asphalt mixture”, Journal of Jilin University (Engineering and Technology Edition), 50(04):1403-1410.