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Research paper

The recycling of construction waste asphalt mixes – study case

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Abstract: Construction waste (CW) has become one of the main factors exacerbating regional environmental damage, and how to recycle and utilize CW as a resource is also a key focus of future urban construction in China. Although CW has good application effects in highway construction, its service life is still a factor that affects its promotion. Currently, CW is mostly concrete waste, so it is integrated with asphalt mixtures to prepare new types of recycled asphalt, extending the service life of asphalt roads, reducing construction costs and environmental damage. The experimental results show that the optimal asphalt to aggregate ratio of Recycled Concrete Aggregate (RCA) asphalt mixtures is between 4% and 5%. The road performance of four asphalt mixtures with different RCA contents meets the standard, and two RCA mixtures have better performance than traditional asphalt. When subjected to 150 cycles of temperature humidity coupling, the fatigue life of five different asphalt mixtures decreased, and the fatigue damage was in a rapid growth stage. The fatigue life of traditional mixtures decreases more than 1.3 times faster than that of CW asphalt mixtures. There are two types of CW asphalt mixtures that can still maintain good fatigue performance under different temperature and humidity coupling effects, which can effectively extend the service life of traditional asphalt pavement. RCA asphalt mixture has better adhesion performance, effectively alleviating the fracture impact of aggregate rigidity.

Keywords: asphalt mixes, big data analysis, construction waste, renewable aggregates, road performance

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1. Introduction

Construction waste (CW) is a collective name for waste such as slag, waste concrete and broken masonry generated during the construction or demolition of various types of buildings, pipelines, etc. With the speed and high-quality development of China's urban construction, CW has always maintained a high output, but China's comprehensive utilization of CW is insufficient, resulting in excessive economic cost losses [1–3]. At present, the total production of CW in China reaches more than 30% of urban waste, but the utilization rate of CW is less than 5%. With the continuous development of China's highway construction, the total mileage of highways opened to traffic in China has exceeded 140,000 km. Roads can generally be divided into concrete roads and asphalt roads. Although asphalt roads have low noise, easy maintenance and other characteristics, but the service life of asphalt roads is the biggest drawback [4–6]. Because of the relative lack of asphalt resources in China, the direct use of traditional asphalt or improved asphalt mixed with other materials still requires a lot of mining of natural aggregates, leading to serious ecological damage and also cannot effectively extend the service life of asphalt roads [7–9]. Therefore, the study mixed RCA from CW into asphalt mixes, tested and analyzed the chemical composition, mechanical properties and other basic indexes of CW, modified the initial gradation of asphalt mixes, and reconstructed asphalt pavements while ensuring no degradation of road performance. Due to the inclusion of RCA and scientific proportioning of asphalt materials and regenerating agents, it has the advantages of lower economic cost, environmental pollution and shorter construction time compared with other asphalt pavement renovation technologies, and can effectively extend the service life of asphalt roads. Overall, improving the utilization rate of waste recycling is of great significance to the resource utilization efficiency of engineering construction, rapid economic development, and social benefits. Meanwhile, scientifically conducting fatigue life prediction of asphalt pavement can provide important experimental data for highway maintenance in China.

2. Literature review

How to effectively recycle CW is a topic that has been studied by scholars around the world, and CW can be reused as recycled resources after sorting, crushing or rejecting. Three types of pretreatment methods were designed to recycle the residues, reduce their toxicity and improve their performance. The results show that the studied residues can be used for the preparation of construction materials after treatment, which can improve the mechanical and chemical properties of the residues. Not only can the economic losses in the construction process be reduced, but also the environmental benefits can be effectively improved [10]. Song et al. [11] on the other hand, prepared rhodolite, a mineral that can be used as an adsorbent for the removal of methylene blue, by treating CW using alkali fusion hydrothermal synthesis after analyzing the CW composition. The experimental results show that the treated and synthesized rhodochrosite has a typical crystal structure and good regeneration and recycling ability, which is a novel approach compared to other recycling methods. Jakub et al. [12] mixed CW with recycled rubber to prepare a recycled cement composite. After analyzing the mixing ratio as well as the waste composition, the optimal cement mixing ratio was determined. The experimental results showthat the new recycled cement material can meet the construction requirements in all properties and can be used as a way to dispose of CW. Chernavin et al. [13] then used CW as a binder for concrete as well as recycled aggregates to make recyclable concrete. The experimental results show that the concrete incorporating CW waste-related materials outperform the conventional concrete in compressive and tensile strengths compared to the concrete with natural fillers, and can well be used as an alternative to conventional concrete in specific buildings. Chen et al. [14] used solid waste such as CW as a raw material to prepare efficient adsorbent materials, which enabled the extraction of crude tellurium from photovoltaic waste. It was shown that this adsorbent material facilitates the effective transport of tellurium ions to the interior of the adsorbent and the controlled process provides an effective method to prepare functional adsorbents using CW as a raw material for tellurium extraction.

At present, how to effectively improve the road performance of asphalt mixtures and reduce the economic cost of asphalt mixtures is also a key research direction for domestic and foreign scholars. Quan et al. [15] reduced the traffic noise hazards of pavements by improving asphalt mixture preparation parameters, and incorporated crumb rubber into asphalt mixtures to optimize the mixture gradation. The experimental results indicated that with the increase of crumb rubber content, the damping ratio of mixed aggregates gradually increased; It is beneficial to improve the damping performance and toughness, and the rational use will be of positive significance to promote the green development of highway construction and the harmless treatment of waste resources. Zhang et al. [16], to improve the low-temperature crack resistance of permeable asphalt mixes, steel slag of different volumes was substituted. The experimental results showed that the physical and chemical adsorption between steel slag and asphalt formed an asphalt orientation layer, which enhanced the cohesion of the mixture and effectively improved the low temperature crack resistance of traditional asphalt mixes (TAM). Xia et al. [17] added CFR to TAM to suppress tunnel fires in which the asphalt pavement burns to produce large amounts of toxic, carcinogenic and harmful black smoke, causing serious pollution problem. The test results showed that the composition of combustion residues of CFR asphalt mixes was significantly reduced compared with that of asphalt mixes, which is of great importance in fire safety.

In summary, in urban construction, CW is recycled in road facilities, but it is more often used in concrete preparation and production of recycled adsorption materials for other minerals. The application of RCA from CW is incomplete. And the application of CW in asphalt mixes is not enough research, and asphalt mix performance research is more for short-term road time long fire, anti-cracking. Long-term asphalt safety research is insufficient. Therefore, the study of the part of CW that can be used as recycled aggregate, performance analysis and as a substitute for natural aggregates mixed with asphalt matrix to prepare renewable asphalt mixes to solve the problem of excessive urban CW.

3. Modification of regenerated asphalt

3.1. The proportioning of recycled asphalt mixture

Road transportation is one of the necessary conditions for the economic and social development of the country and the region. While infrastructure construction and various construction facilities are being developed, a large amount of natural resources are put into production and use. At present, the construction waste recycled aggregates in the eastern region of China are mainly divided into brick and recycled soil-basedaggregates (RSA) and RCA. The basic flow of the study to prepare RCA recycled asphalt mixes by mixing RCA into asphalt is shown in Fig. 1.

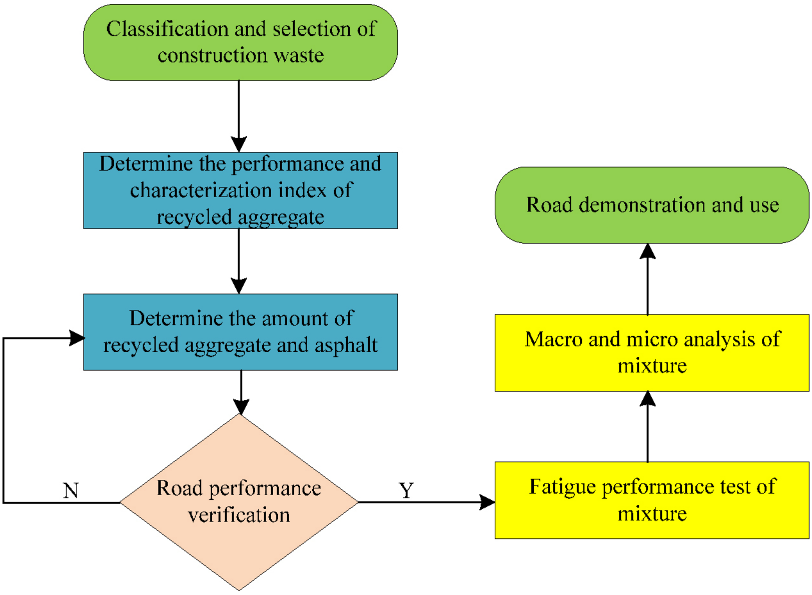


Fig. 1. Preparation of recycled asphalt mixture

Figure 1 shows the basic preparation of recycled asphalt mixture. After analyzing the basic properties and characterization indexes of recycled aggregates in CW, the RCA material and the optimal amount of asphalt for asphalt mixture are determined, and then the basic performance of the mixture is verified by road performance. Among them, the mechanical properties of RCA in CW are too different from natural aggregates, which will directly affect the road performance of recycled asphalt mixes, so the mechanical properties of RCA compared to natural aggregates need to be calculated. The mass change rate of each grade of coarse and fine aggregates before and after incorporating RCA and mixing is calculated by Eq. (3.1).

$$K_n = \frac{Z_n - G_i}{Z_n} \times 100\% \tag{3.1}$$

In Eq. (3.1), K_n is the rate of change of aggregate mass for different grades; Z_n is the percentage of mass before mixing; G_i is the percentage of mass after mixing. When K_n is less than 0, it means that the mass of aggregate increases after mixing. The calculation of corrected mass ratio for each grade of aggregate is shown in Eq. (3.2).

$$T_n = \frac{Z_n^2}{\sum_{t=1}^{n} G_i} \times 100\% \tag{3.2}$$

In Eq. (3.2), T_n is the mass ratio of each grade after correction. Since there is an obvious density difference between RCA and natural aggregates, the synthetic density difference should also be considered in the mix ratio design, and the difference calculation is shown in Eq. (3.3).

$$\gamma_h = \frac{P_x \gamma_{RCA}(\gamma_{RCA} + \gamma_t)}{\gamma_t} + \frac{P_x \gamma_t(\gamma_{RCA} + \gamma_t)}{\gamma_t} + P_v \gamma_t \tag{3.3}$$

In Eq. (3.3), γ_h is the synthetic density of mixed aggregates; P_x is the percentage of coarse aggregates; P_v is the percentage of fine aggregates; γ_{RCA} is the density of RCA aggregates in the corresponding grade, and γ_t is the density of natural aggregates. In RCA asphalt mixes, the optimum asphalt dosage is calculated by Marshall method, and the equation for calculating the mass of RAC materials in each grade and sample is shown in Eq. (3.4).

$$m_{i,RCA} = M \times P_{i,RCA} \times (1 + P_{\alpha i,RCA}) \tag{3.4}$$

In Eq. (3.4), M is the total mass of the mineral in the sample; $P_{i,RCA}$ is the blending ratio of RCA in different grades in the gradation composition, and $P_{\alpha i,RCA}$ is the oil to stone ratio in the RCA material in different grades. Therefore, the total mass of asphalt required for the specimens in the sample can be calculated from Eq. (3.5).

$$m_a = M \times P_b \tag{3.5}$$

In Eq. (3.5), P_b is the oil-to-rock ratio of each test piece. And the calculation for the RCA mass of RCA mixture in each grade is calculated as in Eq. (3.6).

$$m_{i,R} = m_{i,RCA} \times \frac{P_{\alpha i,RCA}}{1 + P_{\alpha i,RCA}} \tag{3.6}$$

In the mixing, the regenerant mass also needs to be changed, and the calculation for the regenerant mass is shown in Eq. (3.7).

$$m_r = P_r \times \sum m_{i,R} \tag{3.7}$$

In Eq. (3.7), P_r is the proportion of regenerant dosing, so the required mass of new asphalt in each specimen has Eq. (3.8) to calculate.

$$m_{new} = m_a - m_r - \sum m_{i,R} \tag{3.8}$$

3.2. Calculation and study of fatigue performance of RCA recycled asphalt

When calculating the fatigue performance of asphalt mixtures, the temperature field of asphalt pavement should be predicted first, and theoretical and statistical analysis methods are commonly used to predict that. Since theoretical analysis is based on the basic principles of meteorology and thermal science to establish the temperature field prediction model, there is a complex operation and complicated data input in the prediction. So the study chooses the statistical analysis method based on regression analysis to predict the pavement temperature field. The study

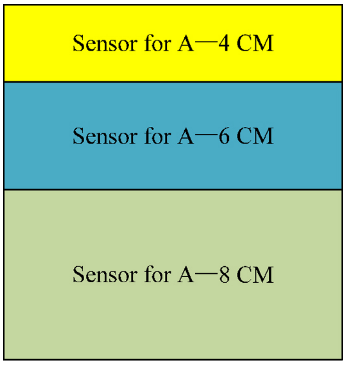


Fig. 2. Schematic diagram of pavement embedding

chose to bury the temperature sensor in the surface layer paving stage of an urban asphalt pavement in the eastern region of China, and the burial depth schematic diagram is shown in Fig. 2.

In Fig. 2, a schematic diagram of the temperature sensors is shown, and three groups of sensors are placed, where group A, group B and and group Csensors are separately laid in the upper, middle and lower layer of the pavement with a burial depth of 4 cm, 6 cm and 8 cm. After the data obtained from the temperature sensors and analyzed, it was determined that the most influential environmental factors in the pavement temperature field were the air temperature and solar radiation. So the prediction model of the asphalt pavement temperature field was calculated as shown in Eq. (3.9).

$$T_P = P_1 + P_2 T_{a5} + P_3 Q_5^2 + P_4 H T_a + P_5 H Q + P_6 H + P_7 H^2 + P_8 H^3 + P_9 Q_m \tag{3.9}$$

In Eq. (3.9), T_P is the temperature at a location on the pavement in the test area. T_a represents the current temperature; T_{a5} is the average temperature of 5 hours before the current temperature; Q is the current solar radiation intensity; Q_5 is the average solar radiation intensity in 5 hours; H is the pavement depth; Q_m is the average monthly temperature of the study area in the calendar year; P_1 to P_8 are the regression coefficients of the area correction factor, and P_9 is the study area correction factor. The calculating for the annual fatigue equivalent temperature in the study area is shown in Eq. (3.10).

$$T_{yf} = T_{yslow} + 1.79 T_{ys} - 2.83 e^{-0.138Z} \tag{3.10}$$

In Eq. (3.10), T_{ys} is the annual average road surface temperature; T_{yslow} is the annual minimum road surface temperature, and Z is the pavement depth. In Eq. (3.9) and Eq. (3.10), the solving process of Eq. (3.9) and Eq. (3.10) is carried out based on genetic algorithm. Genetic algorithm is used to find the global optimal and reduce the fuzziness of the solution. And in different RCA content, the asphalt mixture under different temperature coupling need to explore the fatigue performance decay law and the mechanism, where the residual fatigue life calculation as shown in Eq. (3.11).

$$P_c = \frac{P_n}{P_w} \times 100\% \tag{3.11}$$

In Eq. (3.11), P_n is the number of residual fatigue life of asphalt mixture when the temperature and humidity coupling is$n$ times, and P_w is the number of fatigue life of asphalt mixture without temperature and humidity coupling. The fatigue expressionof RCA asphalt mixture is shown in Eq. (3.12).

$$N = a \times x^b \tag{3.12}$$

In Eq. (3.12), N is the fatigue life; x is the number of temperature and humidity coupling; a and b are the fatigue characteristic parameters.

The quality of the nonlinear model is determined by cross-validation and performance measures, which evaluate the predictive power and robustness of the model through the determination coefficient and mean square error.

Stress control mode was used to test the fatigue performance. The influence of traffic load on pavement is simulated by applying variable cyclic load, and the influence of traffic load on asphalt mixture is observed. Within each cycle, the length and width of the load will remain the same, and the only thing that changes is the vertical stress applied to the mixture. The controlled stress is the vertical stress acting on the mixture, precisely applied by the fatigue testing machine.

4. RCA recycled asphalt performance verification and empirical analysis

4.1. Performance verification of RCA recycled asphalt

In the performance verification of RCA recycled asphalt mixture, the characteristics of aggregate, the tensile fatigue resistance under different stresses and different temperature and humidity coupling, and the microscopic morphology were analyzed. All index tests, data analysis and performance tests in the study were carried out according to the corresponding industry standards, and standard Marshall specimens were used in the tests in accordance with JTG/E20-2019 “Test Regulations for Asphalt and Asphalt Mixtures for Highway Engineering”. A large amount of raw data is collected and analyzed, including the production of construction waste in different geographical locations and climatic conditions, the physical and chemical properties of recycled aggregates, and the road performance of asphalt mixtures. Using random forest, neural network, support vector machine and other complex algorithms, these data are analyzed in depth. At the same time, the weight analysis and prediction of several parameters which affect the pavement performance of asphalt mixture are carried out by using regression model.

In the study of reclaimed asphalt modification, Eq. (3.1) is used to calculate the water absorption rate of reclaimed aggregate. Eq. (3.2) and Eq. (3.3) are used to calculate the Los Angeles abrasion rate and crushing value of the recycled aggregate, respectively, and Eq. (3.4) is used to calculate the apparent relative density of the polymer. Eq. (3.5) and Eq. (3.6) are used to calibrate the mass ratio of the recycled mixture to ensure material consistency.

The traditional asphalt mixture (TAM) from a certain area in eastern China was compared with RCA recycled asphalt mixed with different aggregate proportion. The basic indexes of different asphalt mixtures are shown in Table 1.

Table 1. 5 basic indexes of asphalt mixture

No. of mixture	CARD (g/cm^3)	RDS (g/cm^3)	OAC (%)	AS (%)
TAM	2.67	2.54	4.3	67.4
R1	2.77	2.68	5.0	68.2
R2	2.74	2.57	5.1	70.3
R3	2.72	2.53	5.0	70.1
R4	2.68	2.54	5.0	69.2
Technical requirement	–	–	3–6	65–75

In Table 1, TAM is the traditional asphalt mixture, and R1 to R4 are asphalt mixtures with different RCA contents. CARD is the synthetic apparent relative density, analyzing the density of the mixed aggregate. RDS is the relative volume density of synthetic wool, which analyzes the internal structural compactness of the mixture. OAC represents the optimal ratio of oil to stone and analyzes the strength and durability of the mixture. AS refers to the saturation of asphalt, reflecting the waterproof performance of the mixture. Among them, the optimal oil-to-rock ratio of TAM and four RCA asphalt mixes were between 4% and 5%. synthetic apparent relative density of R1 to R4 were 2.77, 2.74, 2.72, 2.68, synthetic gross volume relative density were 2.68, 2.57, 2.53, 2.54, and asphalt saturation were 68.2, 70.3, 70.1, 69.2, respectively. The experimental results after fatigue life testing of the five asphalt mixtures are shown in Table 2.

In Table 2, the best initial fatigue performance of the five materials was TAM at different stresses when no coupling action was carried out, compared to other RCA asphalt mixes by a factor of more than 1.2. The initial fatigue performance of TAM reached 23732 at 0.2 stress, 5435 at 0.3 stress, and 1329 at 0.4 stress. The best fatigue performance of R1 was achieved when 150 coupling actions were carried out, 11216 under 0.2 stress, 2635 under 0.3 stress and 624 under 0.4 stress, while the fatigue life of the five asphalt mixtures decreased significantly with the increasing number of temperature and humidity coupling actions. The fatigue life of the five asphalt mixtures under different stresses were within 10000 when the service life of 10 years. Among them, the asphalt mixes with the highest fatigue life under different stresses were all R1, reaching 9514, 2217, 524. After comprehensive analysis to rank the fatigue life, the best fatigue life was R1, followed by R2, and R4 had the lowest fatigue life.

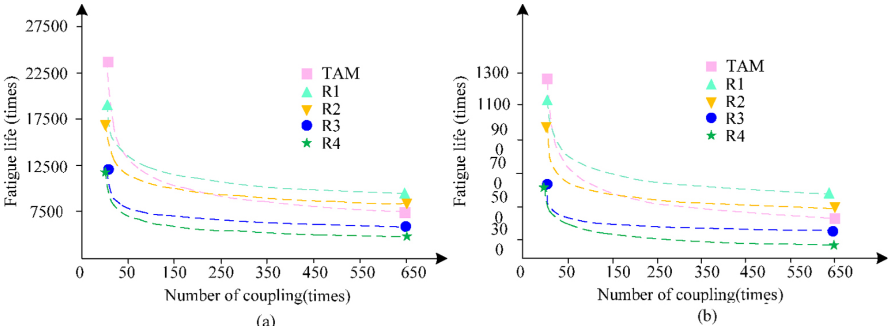
4.2. RCA recycled asphalt characterization and service life study

The fatigue life regression curves of asphalt mixture samples under different stress ratio levels are shown in Fig. 3.

Figure 3 shows the fatigue life regression curves of different asphalt mixes under different stresses, in which there is a large difference between the fatigue life and the number of coupling actions under different stresses due to the placement ratio of the aggregates and the fact that TAM is a natural aggregate [18, 19]. When the regression curve decreased more slowly, it reflected that the fatigue life of the mix was less sensitive to the effect of coupling, and the

Table 2. Fatigue performance test results of different asphalt mixtures

Temperature and humidity coupling action times (times)	**No. of mixture**	**Stress level**		
		0.2	**0.3**	**0.4**
0	TAM	23732	5435	1329
	R1	18986	4196	1082
	R2	16842	3823	977
	R3	11793	2629	637
	R4	11757	2751	612
150	TAM	9289	2174	548
	R1	11216	2635	624
	R2	9879	2242	573
	R3	6717	1478	417
	R4	5763	1354	294
650	TAM	8348	1953	434
	R1	9514	2217	524
	R2	8377	1919	486
	R3	6149	1352	350
	R4	5116	1156	292



(a) (b)

Fig. 3. Regression curve of fatigue life of asphalt mixture: (a) 0.2 Stress level, (4) 0.4 Stress level

fatigue performance decayed more slowly under the coupling action. And TAM asphalt in the absence of coupling effect of fatigue resistance effect was better, mixed with RCA material in the asphalt mixture, R1 mixture and R2 mixture of the initial fatigue resistance performance was the most excellent. Combined with the fatigue characteristics, although the natural aggregate based mixes have superior initial fatigue resistance, the fatigue performance declines fastest after being put into service, due to the existence of the crushing of recycled aggregates themselves, resulting in lower initial fatigue performance than TAM asphalt mixes. R2 asphalt mixes are the least sensitive to the coupling effect and achieve the highest integrated fatigue life.

Figure 4 shows the correlation analysis between the synthetic properties of the mix and the fatigue characteristic parameters. The relative density of synthetic wool volume and the apparent relative density were strongly correlated with parameter a (Pearson coefficient $\geqslant 0.9$), while the only significant correlation of synthetic brick-mixture content was parameter b. No aggregate property index is highly correlated with both a and b parameters. The initial fatigue resistance of asphalt mixture (parameter a) increases with the increase of aggregate bulk density and apparent relative density, and the fatigue decay rate of asphalt mixture (parameter b) decreases with the increase of brick-concrete content under long-term temperature and humidity environment.

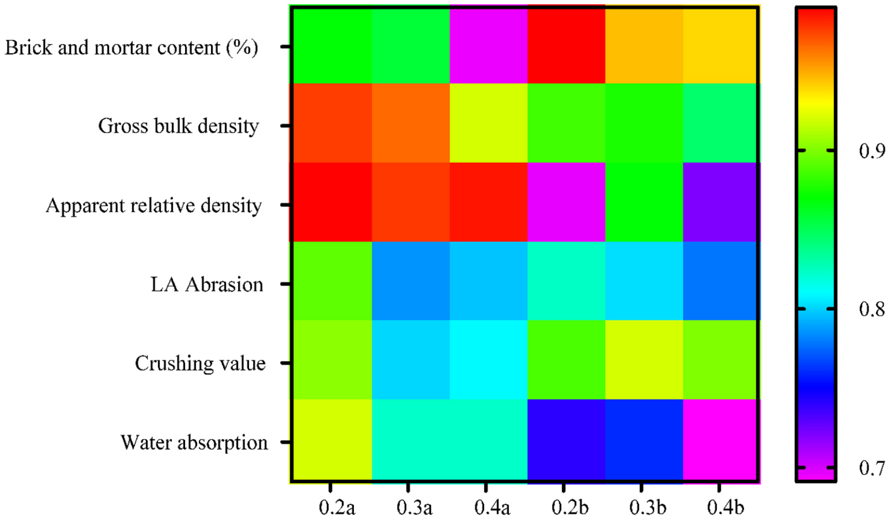


Fig. 4. Correlation analysis of aggregate synthesis characteristics and fatigue characteristic parameters

Figure 5 shows the element distribution of the asphalt mixture in RCA material, RCA asphalt mixture has better adhesion compared with the traditional asphalt mixture. And the recycled aggregate of RCA has the property of porous surface layer, which can absorb asphalt and form asphalt layer, protect the overall structure of asphalt, relieve the rupture impact of aggregate rigidity, and improve the fatigue resistance of RCA mix under the action of temperature and moisture coupling. Fig. 6 shows the fatigue cracking of the improved material.

Figure 6 shows the analysis results of element distribution after big data analysis. After big data analysis, the theoretical model obtained is applied to the actual recycled aggregate, and the change of its microscopic morphology and element distribution can verify the correctness and practicability of the model.

It can be seen from Fig. 6 that the overall fatigue cracking cross-section is symmetrical and the cracking cracks are smooth. In general, the coefficient of each parameter represents the degree of influence of the parameter on the pavement performance of asphalt mixture, and the model test shows that the parameter has statistical significance. The predicted results of the model are in good agreement with the actual observed values, and the residual distribution of the model satisfies the assumption of normality and independence, which indicates that the model selection and setting are reasonable.

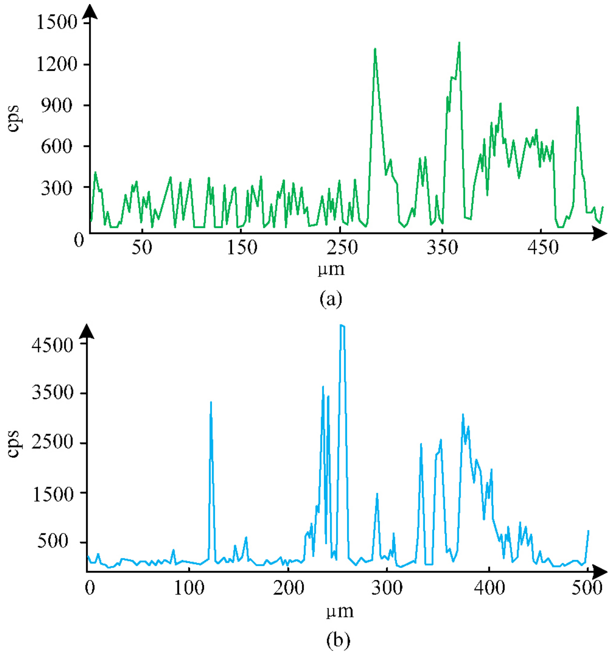


Fig. 5. Energy spectrum curve of mixture: (a) C content, (b) Si content

Fig. 6. Physical image of fatigue cracking: (a) Symmetric fatigue cracking of asphalt mixture, (b) Fatigue cracking cross section

5. Conclusions

China's infrastructure is gradually improving, and old facilities and buildings are being gradually eliminated. In the production, a large amount of natural resources are put into manufacturing and production, but this process is also accompanied by the generation of a large amount of urban CW and solid waste. Improper disposal of CW and debris can consume excessive human resources and economic costs, as well as cause great damage to the global environment. Therefore, CW is screened and incorporated into asphalt mixtures as recycled aggregates and used in transportation road infrastructure. The experimental results showed that the optimum oil to stone ratio of RCA asphalt mixes were between 4% and 5%, and the asphalt saturation reached 68.2, 70.3, 70.1, and 69.2, respectively. The road performance of the four different RCA content asphalt mixes met the specification standards, and the R1 mixes and R2 mixes had the best performance. The fatigue life of the five different asphalt mixtures decreased when the temperature and humidity coupling was within 150 times, and the fatigue damage was in the rapid growth stage. The fatigue life of TAM mixture decreased more than 1.3 times of that of RCA mixture. RCA mixture has excellent initial fatigue resistance when applied to asphalt pavement, strong overall transition zone integrity, stronger water damage and low temperature resistance compared to TAM mixture. RCA asphalt mixture has better adhesion performance and effectively alleviates the fracture impact of aggregate rigidity. However, this study only focuses on fatigue experiments on asphalt pavements in the eastern region of China. In the future, fatigue performance of asphalt pavements under multi climate conditions can be conducted for too long, and more recycled aggregate samples can be used to enrich the data volume of aggregate properties.

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