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ARTICLE

Sustainable Asphalt Concrete Containing RAP and Coal Gangue Aggregate: Performance, Costs, and Environmental Impact

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ABSTRACT

The shortage of natural aggregates is becoming a severe problem in the pavement industry globally. To address this issue, in this study, an effort was made to use reclaimed asphalt pavement (RAP) and coal gangue (CG) as coarse and fine aggregate, respectively for producing the hot mix asphalt (HMA). As the replacement of natural aggregate, there were seven types of HMA containing 20% and 40% RAP coarse aggregate content, and 10% and 25% CG fine aggregate content were designed and prepared. In addition, Marshall Stability test, rutting resistance test, immersion Marshall test, freezing-thaw splitting test, moisture-induced sensitivity test, and low-temperature semicircle bending test were conducted. The results show that the properties of the asphalt mixture containing both RAP and CG meet the Chinese specification through it is slightly lower than the virgin asphalt mixture. Furthermore, the addition of 40% RAP coarse aggregate and 25% CG fine aggregate to asphalt mixes can significantly reduce manufacturing costs, energy consumption, and CO_2 emissions by 29.4%, 19.8%, and 21.9%, respectively, compared to the virgin asphalt mixture. The finding of this study contributes to current knowledge by investigating the feasibility of jointly using the RAP and CG in asphalt mixture, which could be interested by both industry and academic society.

KEYWORDS

Reclaimed asphalt pavements (RAP); coal gangue (CG); mechanical properties; cost analysis; environmental impact

1 Introduction

After the most stringent *Environmental Protection Law of the People's Republic of China* in history was issued by Chinese authorities, the exploitation of natural stone is strictly restricted, leading to an estimated over 60% capacity reduction. Consequently, in some parts of the country, for example, Jiangxi Province, the price of natural aggregate has nearly tripled in the past five years. This dilemma is intensively reported in Australia, Japan, Hong Kong, and South Africa, and so on [1–4]. Therefore, to mitigate the impact of aggregate shortages, sustainable solutions should be implemented by using waste materials. The waste materials, such as RAP, CG, crumb rubber, steel slag, and recycled concrete, have been successfully used in the pavement industry [5–9].

RAP, including aged asphalt binder and aggregates, is a mixture produced from asphalt pavement rehabilitation and reconstruction [10]. Incorporating the RAP into HMA can produce economical and environmentally recycled hot-mix asphalt (RHMA) mixture [11], and many countries have widely used RHMA in the pavement industry. Such as, in Europe, the percentage of 47% available RAP was used in hot or warm mix asphalt applications, and approximately 22 million tonnes were used in other applications; in the US, it is estimated that approximately 84% RAP was used in asphalt applications [12]; meanwhile, the recycling rate in Japan, Australia, and Sweden exceeds 80% [13]. In China, it is estimated that only 30% of RAP are reused for producing RHMA. Meanwhile, the need for natural aggregate in China was continuously increasing in recent years, and there is an urgent need to use other waste materials to replace natural aggregate. Previous studies have indicated that the feasibility of using various waste materials to make recycled asphalt mixtures. Mansour et al. [14] reported that the RAP and steel slag aggregates into the warm mix asphalt (WMA) mixture could improve the dynamic creep and indirect tensile fatigue of asphalt mixture compared with the conventional WMA. Erdem et al. [15] investigated the mechanical properties of asphalt mixture containing RAP and waste precast concrete as aggregate, and found that it can be used in non-structural applications. Purohit et al. [16] explored the use of RAP and recycled concrete aggregates (RCA) in asphalt mixture, evaluating the performance of asphalt mixture containing RAP and RCA by using Marshall and moisture susceptibility test, and indicating an advantage over the conventional mixes. Ramos et al. [17] reported the asphalt mixture containing copper slag (CS) and RAP, and indicated that asphalt mixes stability improved with ranges from 45% to 55% of recycled material. Therefore, to reduce the consumption of natural aggregates, it is necessary to further explore the possibility of replacing natural aggregates with other wastes materials to produce RHMA, and expand the waste types.

CG is a waste material generated during coal mining and washing, with the production of coal, more and more landfills will be needed to stack CG, which will lead to water and soil pollution and disrupt ecological cycles [18]. At present, utilization way for CG is diversified in pavement industry, such as coal gangue powder (CGP) [19], fine and coarse CG [20], Modarres et al. [19,20] indicated that the performance of HMA containing CGP or its ash was improved by comparing with limestone and zeolite, which has nearly similar mechanical properties to ordinary Portland cement. Liu et al. [21] reported the moisture stability of emulsified asphalt mixture can be improved by adding coal gangue, and the strength of the mixture is formed by the joint action of emulsified asphalt and coal gangue according to the microscopic analysis. Xiong et al. [22] evaluated the durability properties of the asphalt mixture containing coal waste ash as a partial replacement of cement. Amouzadeh et al. [23] evaluated the mechanical properties of emulsified cold recycled mixtures containing cement kiln dust (CKD) and coal waste ash (CWA) by Marshall Stability, indirect tensile strength, and moisture susceptibility tests. Yang et al. [24] indicated that coal gangue aggregate can meet the specifications except for the content of the Flat and Elongate particles, and the performance of asphalt mixture containing coal gangue as coarse aggregate has the equivalent with limestone mixture, and the properties of HMA could be guaranteed.

Previous studies have indicated that the RAP or CG can be used in asphalt mixture to produce the sustainable asphalt mixture. However, it still requires large amounts of virgin aggregate, which is not acceptable in China due to the shortage of aggregates. Therefore, this study innovatively proposes the concept of integrated utilization of multiple waste materials to produce asphalt mixture to reduce the dependence on virgin aggregates. In addition, asphalt mixture containing RAP or CG with acceptable properties, however, there are few studies on asphalt mixtures containing RAP and CG. Thus, the main objective of this study is to demonstrate the feasibility of the design idea that sustainable asphalt concrete containing RAP and CG waste materials as aggregates in asphalt mixture.

This study is organized as follows. Section 2 tests the material properties, introduce the experimental designs and the process of the specimen making; then, it explains the optimum asphalt content and the test methods of mechanical performance for the asphalt mixture. Section 3 displays the experimental data and then analyzes the obtained data to develop conclusions. Finally, the conclusions of this study are summarized in Section 4. The results of this study contribute to the popularization and application of asphalt mixture containing RAP and CG, and providing a new idea for using different waste materials together in the pavement field. The framework of this study can be summarized and illustrated in Fig. 1.

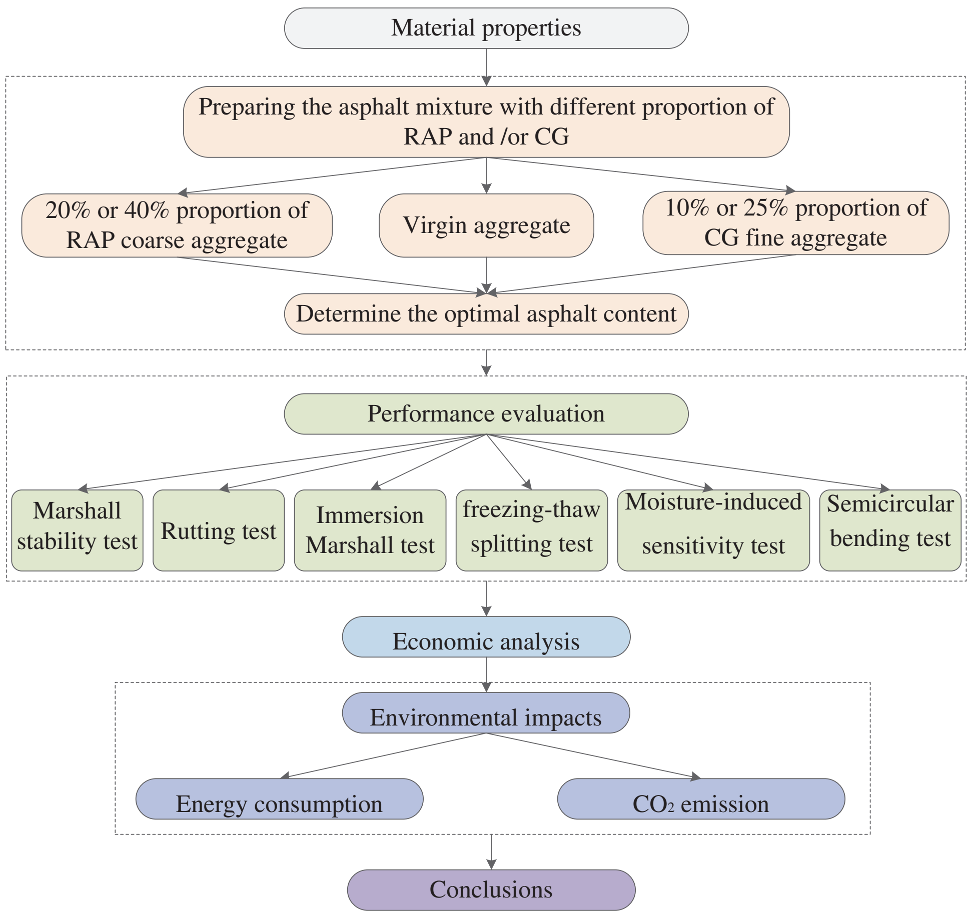

Figure 1: The frame work of this study

2 Materials and Methods

2.1 Raw Materials

2.1.1 Asphalt Binder

SBS (Styrene-Butadiene-Styrene)-modified asphalt binder was used in the study. According to the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering* (JTG E20-2011) [25], the physical properties are listed in Table 1, which meets the requirement of the *Technical Specifications for Construction of Highway Asphalt Pavements* (JTG F40-2017) [26].

Table 1: Physical properties of SBS-modified asphalt

Test items	Requirement	Results	Test method
Penetration (25°C, 0.1 mm)	40–60	45.3	T 0604
Softening point (°C)	≥60	81.4	T 0606
Ductility (5°C, cm)	≥20	34.5	T 0605
Specific gravity (g/cm^3)	-	1.028	T 0603
Flashing point (°C)	≥230	285	T 0611

2.1.2 Aggregates

In this study, limestone (LS) and CG are produced in Shanggao county and Wannian County of Jiangxi Province, respectively. For each LS and CG aggregate source was given in Fig. 2a, Shanggao county has 1350 square kilometers, and the local aggregate is mainly CG aggregate that is shown in Fig. 2b, with a great shortage of LS aggregate. However, Wannian county is the closest LS source to Shanggao, and the distance between them is about 220 km, thus, it is very meaningful to carry out the study of CG utilization by considering the transportation cost.

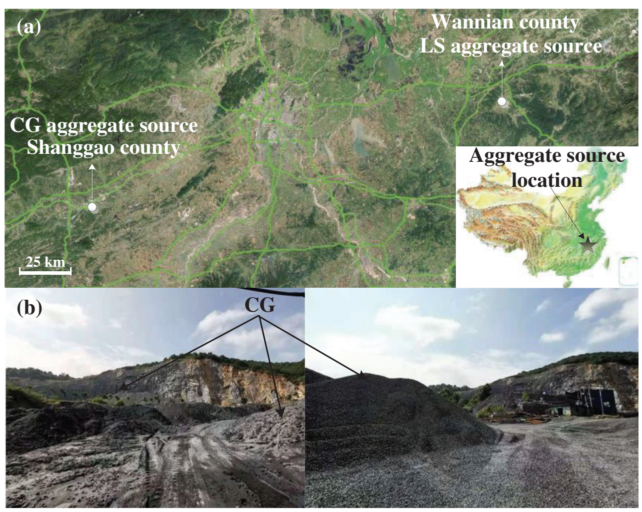

Figure 2: Aggregate source (a) aggregate source location. (b) CG mine

The aggregate of LS (Fig. 3a) and CG (Fig. 3b) was sieved multiple specifications, and the CG with particle size less than 4.75 mm was used in this study. Meanwhile, both LS and CG were tested following the *Testing Methods of Aggregate for Highway Engineering* (JTG E42-2005) [27], and its performance is listed in Table 2, which satisfied the requirement of the specifications JTG F40-2017 [26]. Additionally, the mineral compositions and morphology of both LS and CG were determined by X-ray diffraction (XRD) and scanning electron microscope (SEM) are shown in Figs. 4 and 5. Fig. 4 revealed that the main mineral compositions of CG were $CaCO_3$, SiO_2, $CaSO_4$, and CaO, and the limestone was $CaCO_3$. The morphology of LS was more coarse compared with the CG according to Fig. 5.

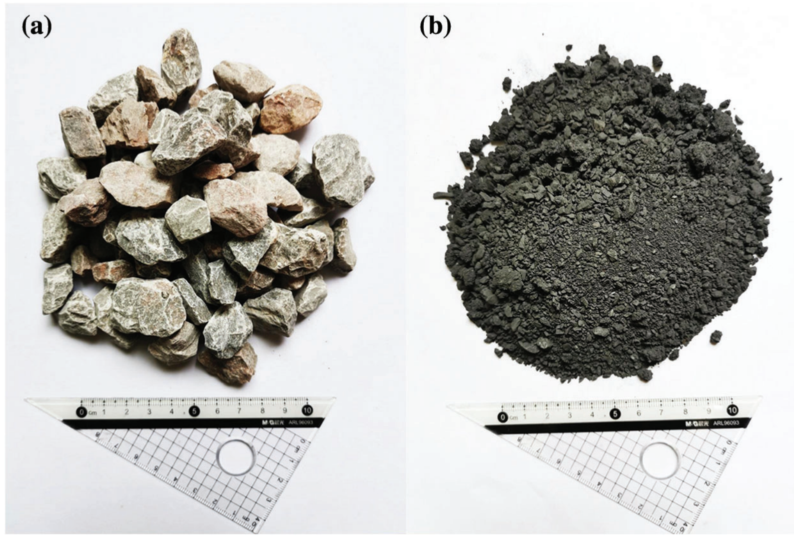

Figure 3: Aggregate characteristics (a) LS. (b) CG

Table 2: Physical properties of LS and CG aggregates

Aggregate type	Test items	Requirement	Results	Test method
Coarse LS aggregate	Specific gravity	≥2.5	2.703	T 0304
	Flakiness and elongation particles (%)	≤18	13.7	T 0312
	Crushing value (%)	≤28	11.4	T 0316
	Los Angeles abrasion (%)	≤30	18	T 0317
	Water absorption (%)	≤3.0	0.8	T 0304
Fine LS aggregate	Specific gravity	≥2.5	2.718	T 0328
	Sand equivalent (%)	≥60	75.3	T 0334
Fine CG aggregate	Specific gravity	≥2.5	2.711	T 0328
	Sand equivalent (%)	≥60	63.2	T 0334
Filler	Specific gravity	≥2.5	2.732	T 0328

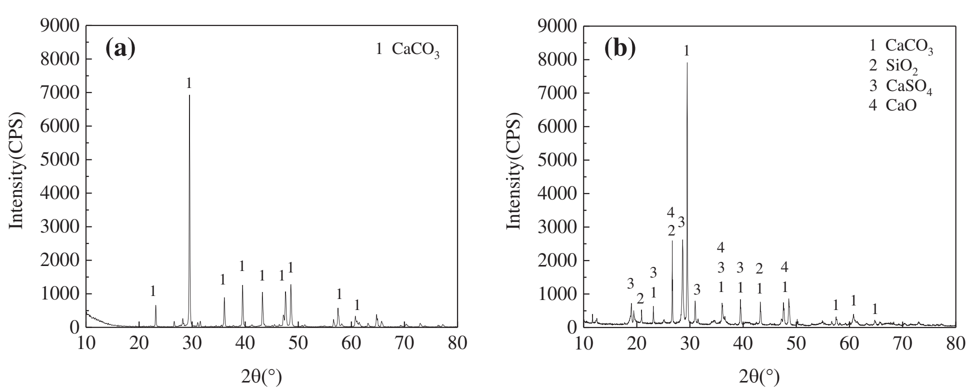

Figure 4: XRD test results (a) LS (b) CG

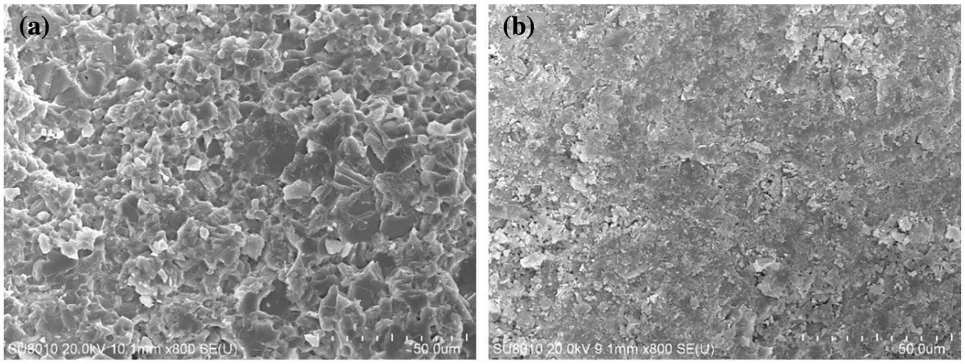

Figure 5: SEM test results (a) LS (b) CG

2.1.3 RAP

RAP milled from the Sanming section of Fuzhou-Yinchuan expressway located in Sanming, Fujian Province, China; After crushing and sieving, the RAP with 12–20 mm size was used as coarse aggregate. The aggregates and aged binder in the RAP were separated by dissolving the RAP in trichloroethylene solution according to JTG E20-2011 using an automatic extractor produced by Changji Co., Ltd. (China). The gradation of RAP (12–20 mm) was determined according to JTG E42-2005 [27], and the result is shown in Fig. 6. Meanwhile, the asphalt content of RAP (12–20 mm) was 3.25%. The aged asphalt was extracted from Trichloroethylene solvent that dissolving the RAP according to JTG E20-2011 [25] using an automatic rotary vacuum evaporator produced by Buchi, Ltd. (Switzerland), and the performances of aged asphalt and aggregate that extracted from RAP are listed in Table 3.

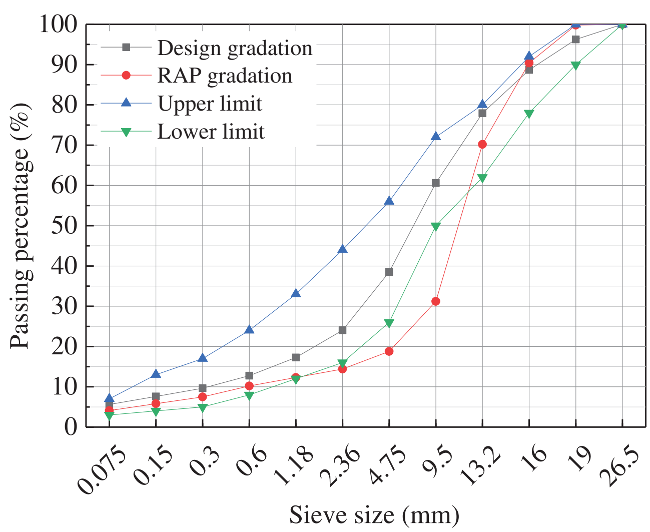

Figure 6: Gradation of the aggregates for designed asphalt mixture

2.2 Mixture Design

The target aggregate gradation of asphalt mixture containing RAP, CG, and virgin aggregate is shown in Fig. 6, whose nominal maximum aggregate size is 19 mm. Meanwhile, the aggregate proportion of various materials in RHMA is given in Fig. 7, and the size of virgin aggregate, RAP, and CG are 0−26.5 mm, 12~20 mm, and 0–4.75 mm, respectively. In addition, the proportion of different aggregates is the weight of the specimen, and all mixtures used the same gradation. The optimum asphalt contents (OAC) of mixtures

(Fig. 7) were determined using the standard Marshall design method according to ASTM D-6927 [28], and the 4% air void was used to determine the optimum asphalt content.

Table 3: Physical properties of RAP

Materials	Test items	Results	Test method
Binder in RAP	Penetration at 25°C (0.1 mm)	28.5	T 0604
	Softening point (°C)	70.7	T 0606
	Ductility at 15°C (cm)	19.2	T 0605
	Dynamic viscosity 60°C (Pa·s)	2980	T 0619
Coarse aggregate in RAP	Crushing value (%)	10.2	T 0316
	Flakiness and elongation particles (%)	13.4	T 0312
	Specific gravity	2.701	T 0304
Fine aggregate in RAP	Specific gravity	2.686	T 0328

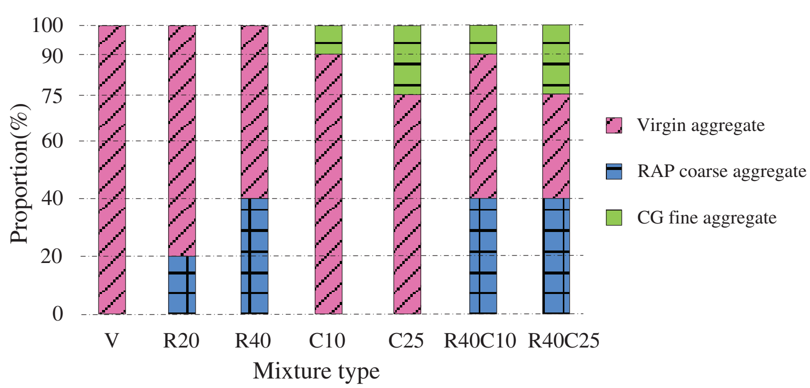

Figure 7: Combinations of different aggregates of asphalt mixtures

2.3 Sample Preparation and Optimum Asphalt Content

The procedures for preparing RHMA are shown in Fig. 8. Firstly, LS, CG fine aggregate, and filler were placed in an oven at 190°C for at least 2 h before the mixing, and the asphalt binder was separately heated to the mixing temperature for 160°C. Meanwhile, RAP coarse aggregate was placed in the oven at 130°C for 2 h to avoid further age based on the NCHRP recommendation [29], and the mixing and compaction temperature was selected at 165°C and 155°C, respectively. During mixing, the LS, CG fine aggregate, or RAP coarse aggregate was first mixed for 60 s; then, the virgin asphalt binder was added for another 60 s; lastly, the mineral powder made from different ratios of LS and CG was added for 60 s of mixing. Afterward, compacting the asphalt mixture of different design schemes into the specimen using a Marshall compaction tester produced by Changji Co., Ltd. (China), and the optimum asphalt content results of different experimental designs schemes are listed in Table 4.

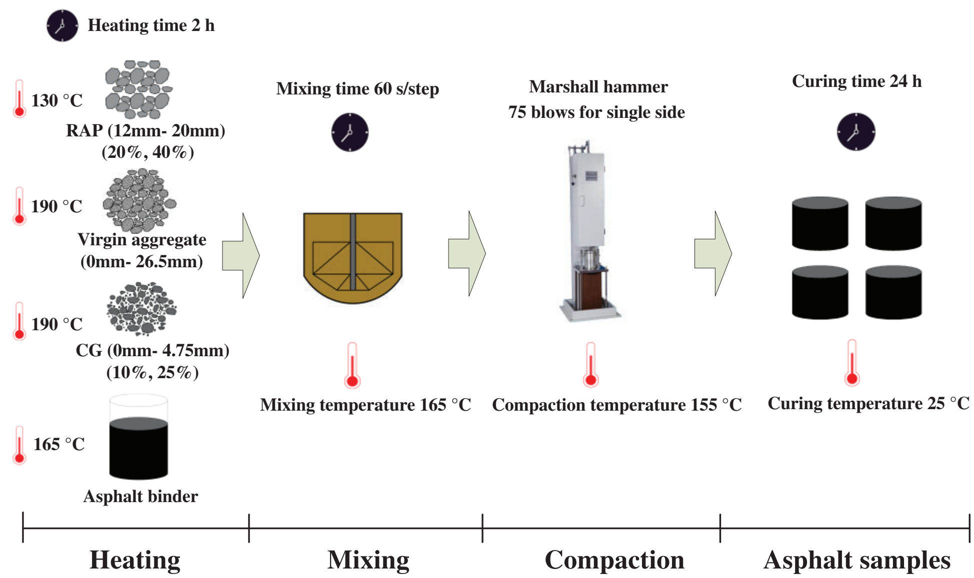

Figure 8: Preparation and compaction of the asphalt mixture

Table 4: The percentages of bitumen in asphalt mixes

Mixtures	Proportions	Optimum asphalt content (%)	Newly added virgin asphalt content (%)
V	-	4.35	4.35
R20	20% RAP	4.61	3.97
R40	40% RAP	4.88	3.60
C10	10% CG	4.32	4.32
C25	25% CG	4.00	4.00
R40C10	40% RAP + 10% CG	4.79	3.51
R40C25	40% RAP + 25% CG	4.63	3.35

2.4 Experimental Methods

2.4.1 Marshall Stability Test

To determine the mechanical character of prepared asphalt mixtures, the Marshall Stability and flow were measured according to JTG E20-2011, specimens of 100 mm diameter and 63.5 mm in height were tested under a loading rate of 50 mm/min at 60°C. Besides, the Marshall quotient (MQ) that defined as the ratio of stability to flow was calculated according to Eq. (2). MQ can also be an evaluation index of the rutting resistance of materials [30].

$$MQ = \frac{MS}{FL} \tag{1}$$

where MQ is the Marshall quotient of Marshall specimen, kN/mm; MS is the stability of Marshall specimen, kN; and FL is the flow of Marshall specimen, mm.

2.4.2 Rutting Resistance Test

The high-temperature performance of mixes was determined by using a dynamic stability index, which can be calculated using Eq. (2). In addition, three rutting samples (300 mm * 300 mm * 50 mm) of mixes were produced for the different design schemes, separately, and the rutting test was carried out according to JTG E20-2011.

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \tag{2}$$

where DS refers to the dynamic stability of mixes, cycles/mm; t_1 means 45 min; t_2 means 60 min; N is the rotation speed of the wheel, 42 rpm/min; d_1 is the rutting depth at t_1, mm; and d_2 is the rutting depth at t_2, mm.

2.4.3 Moisture Sensitivity Test

One of the most critical performances of asphalt pavement is its durability under the moisture environment. In this study, the immersion Marshall test, freezing-thaw splitting test, and moisture-induced sensitivity test were used to evaluate the moisture sensitivity of asphalt mixtures. For conducting the above test, six samples for each test were made and equally divided into unconditioned and conditioned groups, and then the test was conducted.

The immersion Marshall test was conducted according to JTG E20-2011, and the Marshall Stability ratio was then calculated using Eq. (3).

$$MSR = \frac{Ms}{Md} \times 100 \tag{3}$$

where MSR is the Marshall Stability ratio, %; Ms refers to the average stability of conditioned specimens which were placed into the water bath for 24 h at 60°C, kN; Md refers to the average stability of conditioned specimens which were placed into the water bath for 30 min at 60°C, kN.

The freezing-thaw splitting test was performed following JTG E20-2011, and the tensile strength and freeze-thaw splitting tensile strength ratio were calculated according to Eqs. (4) and (5), respectively.

$$TS = \frac{0.006287P_T}{h} \tag{4}$$

where TS refers to tensile strength, MPs; P_T refers to the maximal loading pressure, N; and h refers to the height of specimens, mm.

$$TSR_{ft} = \frac{TS_{con-ft}}{TS_{uncon}} \times 100 \tag{5}$$

where TSR_{ft} refers to freeze-thaw splitting tensile strength ratio, %; TS_{con-ft} refers to the average tensile strength of conditioned specimens which were vacuumed at 0.9 MPa for 15 min, then transferred into the bath for 24 h at 60°C, and finally, the tensile strength was tested after 2 h in the water bath at 25°C, MPa; TS_{uncon} refers to the average tensile strength of unconditioned specimens which placed into the water bath for 2 h at 25°C, MPa.

The moisture-induced sensitivity test (MIST) was performed following JTG E20-2011, and the tensile strength and splitting tensile strength ratio for MIST were calculated according to Eqs. (4) and (6), respectively.

$$TSR_{mis} = \frac{TS_{con-mis}}{TS_{uncon}} \times 100 \tag{6}$$

where TSR_{mis} refers to splitting tensile strength ratio of moisture-induced sensitivity, %; $TS_{con-mis}$ refers to the average tensile strength of conditioned specimens which were placed into the bath of 60°C for 3500 cycles at 276 kPa, using a MIST produced by Changji Co., Ltd. (China), MPa.

2.4.4 Low Temperature Cracking Resistance

Fracture characteristic of asphalt mixtures is one of the critical criteria which impact the performance of durable for designed pavement, and the SCB test is proven to be the most effective test method [31,32]. Hence, the low-temperature characteristic of asphalt mixtures containing RAP, CG, and virgin aggregate, in this study, was evaluated using the SCB test, and the low-temperature characteristic of different design schemes was compared. The thickness and width of specimens are designed 25 mm and 150 mm, respectively, and then the notch with 2 mm width and 15 mm length was cut at the center of the above specimen. Therefore, the fracture characteristic of asphalt specimens was determined according to JTG E20-2011 using a universal testing machine under the monotonical load rate of 0.06 mm/min at −10°C. The fracture energy (Gf), considering the homogeneity of materials and linear elastic fracture mechanics (LEFM), was selected as the main criterion to estimate the low-temperature performance of asphalt mixtures. The fracture energy means the energy demanded crack propagation, and the impacts of different types of materials can be effectively characterized in this method [33]. In this research, the fracture energy (G_f) was calculated using Eqs. (7) and (8), respectively.

$$G_f = \frac{w_0}{A_{lig}} \tag{7}$$

$$A_{lig} = \left(\frac{D}{2} - a\right) \times t \tag{8}$$

where G_f refers to the fracture energy, J/m^2; $w_0 = \int Pdu$ refers to the fracture work, N·m; P refers to the applied load, N; u refers to average load line displacement, m; A_{lig} refers to the ligament area [34], m^2; D refers to the diameter of the Specimen, m; a refers to the length of the notch, m; and t refers to the thickness of the Specimen, m.

3 Experiment Result and Discussion

3.1 Mechanical Properties

3.1.1 Marshall Stability Test

The stability of asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate is shown in Fig. 9. Comparatively, the stability of asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate was lower than the virgin asphalt mixture, and the stability of mixture containing RAP coarse aggregate decreases with the content of RAP increases, which is unconformity with the results of previous studies [14]. On the other hand, the trend of stability for asphalt mixture containing CG fine aggregate was increased with the content of CG increase. The stability of asphalt mixtures containing 40% RAP coarse aggregate and 25% CG fine aggregate was 11.33% lower than that of virgin asphalt mixture. Moreover, despite the stability of the asphalt mixture containing RAP and/or CG was decreased by comparing with virgin asphalt mixture, the Marshall Stability is still higher than 8 kN, which meets the strength requirements of the related specification JTG F40-2017 [26]. Similarly, the flow does not exceed 4 mm under the different proportions of RAP and/or CG, and the flow is still within the range of specification JTG F40-2017 [26].

Fig. 10 presented the MQ results of the mixtures, and the MQ of asphalt mixture containing RAP coarse aggregate and/or CG fine aggregate was lower than that of virgin asphalt mixture. In addition, it can be seen that the MQ of the asphalt mixture containing RAP coarse aggregate was decreased with RAP addition, while that of asphalt mixtures containing CG fine aggregate was increased with CG addition. Besides, the MQ of asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate was 8.76% lower than that of virgin asphalt mixture. In general, the MQ values for the asphalt mixture containing RAP coarse aggregate and/or CG fine aggregate are greater than 4.0 kN/mm, and the asphalt mixture has a high ability to resist deformation.

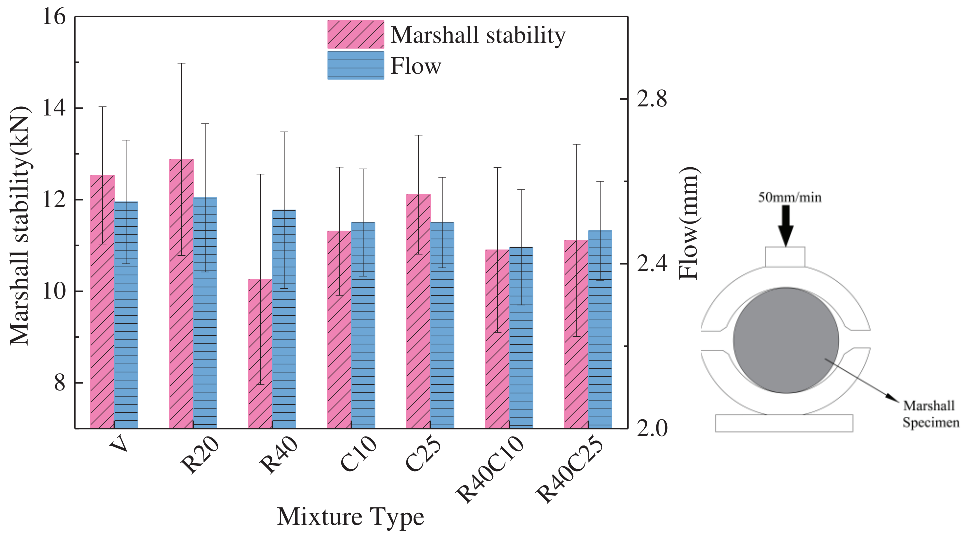

Figure 9: The results of Marshall Stability and flow for different mixture types

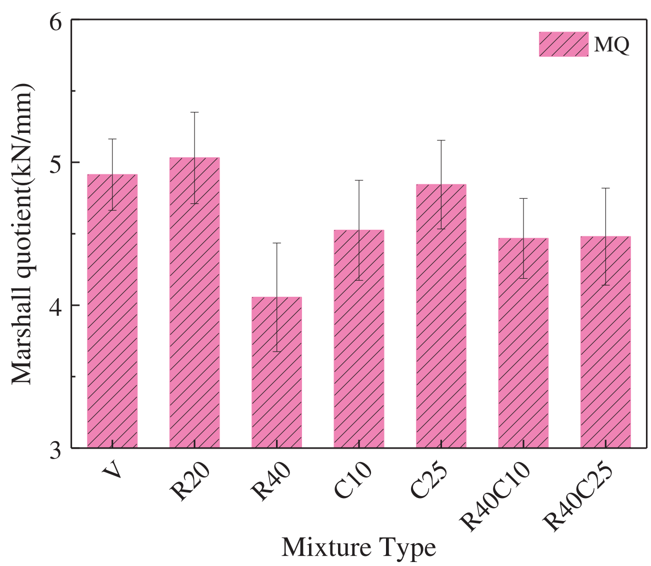

Figure 10: The results of Marshall quotient for different mixture types

3.1.2 Rutting Resistance Test

One of the most critical characteristics of asphalt pavement is its rut resistance at high-temperature. According to Fig. 11, the RAP coarse aggregate and/or CG fine aggregate addition to the asphalt mixture decrease the dynamic stability compared with the virgin asphalt mixture, and the performance of high-temperature rut resistance for the asphalt mixture becomes worse. In addition, results indicated that adding CG fine aggregate into asphalt mixtures containing RAP coarse aggregate improves the dynamic stability, and the trend of dynamic stability for asphalt mixtures was increased and then decrease with the content of RAP coarse aggregate increase by comparing virgin asphalt mixture, however, the trend for asphalt mixtures containing CG fine aggregate was increased with CG addition. Besides, the dynamic stability of the asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate was 9.4% lower than those of virgin asphalt mixture. Even though the RAP and CG are reduced the dynamic stability of the asphalt mixture, the values of dynamic stability for asphalt mixtures are still higher than 2800 cycles/mm, which meets the requirements in the specification of JTG F40-2017 [26].

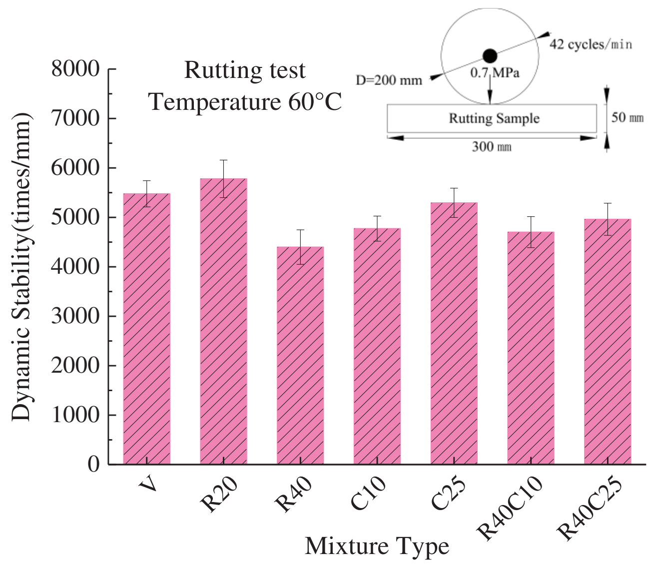

Figure 11: The results of dynamic stability for different mixture types

3.1.3 Moisture Sensitivity Test

Fig. 12 presents the stability of the conditioned and unconditioned specimens and the MSR values for different mixtures. The stability of the conditioned specimens was lower than that of unconditioned specimens for different mixtures. In addition, incorporating RAP coarse aggregate and/or CG fine aggregate into asphalt mixture increases the MSR values compared to the virgin asphalt mixture, and the largest growth rates of MSR values were achieved at 40% RAP coarse aggregate or 25% CG fine aggregate, reaching 7.59% and 15.59%, respectively. Furthermore, adding 40% RAP coarse aggregate and 25% CG fine aggregate increases the MSR value by about 12.68% compared to the virgin asphalt mixture. Moreover, the MSR of asphalt mixtures with RAP coarse aggregate and/or CG fine aggregate was higher than 85% that meets the requirements of the related specification JTG F40-2017 [26].

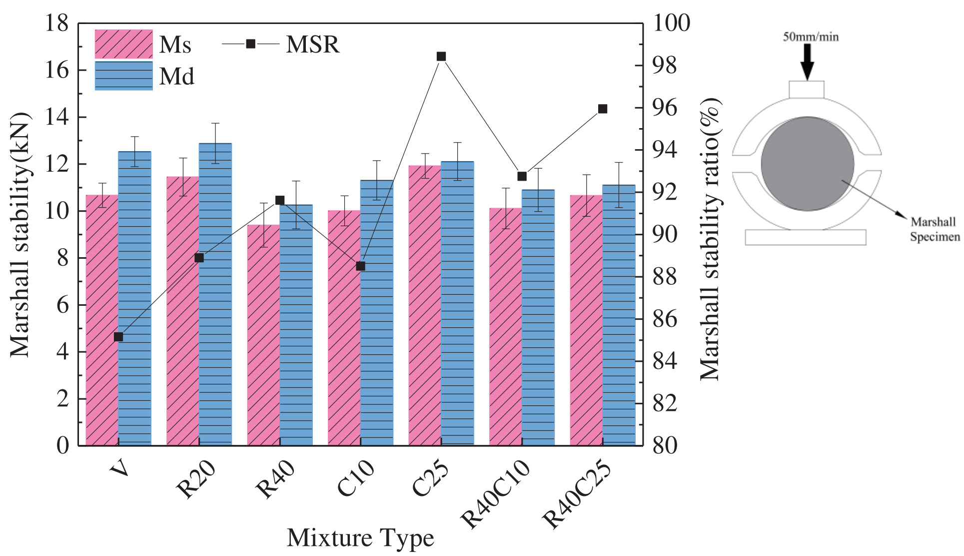

Figure 12: The results of the immersion Marshall test of different asphalt mixtures

The results of the ITS and the TSR_{ft} values for different asphalt mixtures are shown in Fig. 13. Incorporating RAP coarse aggregate increases the TS_{uncon} of asphalt mixtures compared with virgin asphalt mixture; however, the addition of CG fine aggregate will have the opposite effect. In addition, the TS_{con-ft} values of the asphalt mixtures were lower than those of TS_{uncon}, indicating that the specimens were damaged by the freeze-thaw effect. Referring to the results of Fig. 13, incorporating RAP coarse aggregate in asphalt mixture decreases the TSR_{ft} values of specimens for R20 and R40, and the decreases TSR_{ft} value of R40 was higher than that of R20. However, the trend of TSR_{ft} values of asphalt mixtures mixed with CG fine aggregate was the opposite. The maximum values of TSR_{ft} were relevant to C25 followed by R40C25, C10, V, R20, R40C10, and R40 with the TSR_{ft} values of 89.2%, 87.3%, 86.0%, 85.1%, 83.6%, 83.5%, and 80.6%, respectively, and the TSR_{ft} values of different asphalt mixture types were greater than 80%, indicating that the proposed asphalt mixtures have acceptable moisture susceptibility [26].

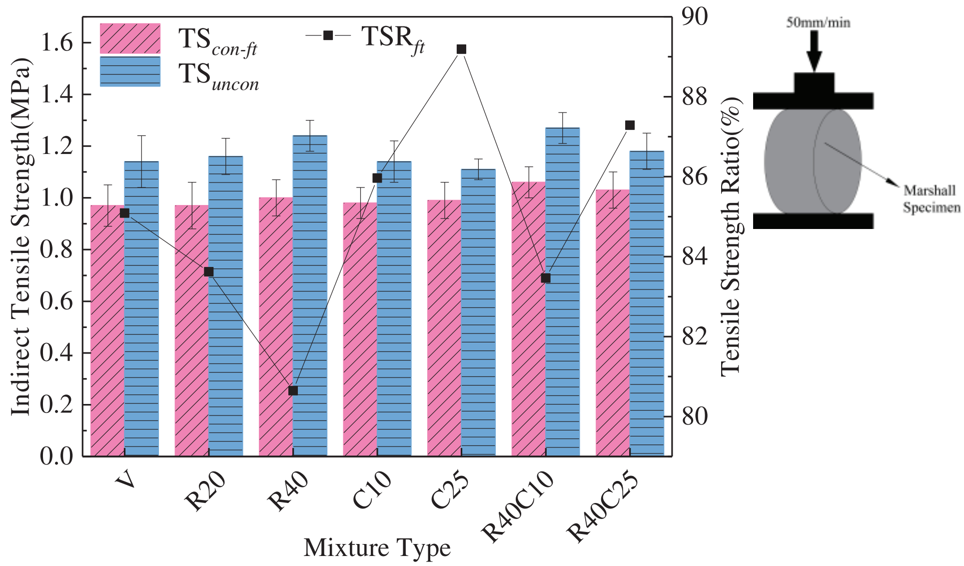

Figure 13: The results of the freezing-thaw splitting test of different asphalt mixtures

The results of the MIST are shown in Fig. 14. Adding RAP coarse aggregate to the asphalt mixtures significantly reduces the TSR_{mis} values compared with the virgin asphalt mixture; however, the TSR_{mis} values of asphalt mixtures increase with the addition of CG fine aggregate. In addition, the maximum values of TSR_{mis} were relevant to R40C25 followed by C25, C10, V, R40C10, R20, and R40 with the TSR_{mis} values of 94.1%, 91.9%, 88.6%, 86.8%, 86.6%, 83.6%, and 81.5%, respectively, and the results of MIST analysis are consistent with the results of the freezing-thaw splitting test.

In general, the results of the immersion Marshall test, freezing-thaw splitting test, and MIST show that the CG enhances the resistance to moisture damage, and the changes are mainly because CG contains $CaSO_4$ compared with LS, which endows CG to be more alkaline; thus, CG can bond closer with asphalt binder than LS, causing the asphalt mixture containing CG fine aggregate better moisture resistance [7]. In addition, the RAP coarse aggregate increases the MSR values in the immersion Marshall test, and the trend can be attributed to the coated aggregates of RAP with hard binder leading to the lower capability of water to penetrate the aggregate-binder bonding interface [35,36]; however, decreasing the values of TSR_{ft} and TSR_{mis} in the freezing-thaw splitting test and MIST, respectively. This trend can be attributed to higher stress and strain concentration in asphalt mixture containing a high percentage of RAP under the freezing or hydrodynamic pressure environment, which aggravates the internal damage of the asphalt mixture structure [35,36]. Thus, adding CG fine aggregate in the asphalt mixes can improve the moisture sensitivity, and the asphalt mixture containing RAP coarse aggregate was more easily damaged by hydrodynamic pressure and freezing-thaw cycle.

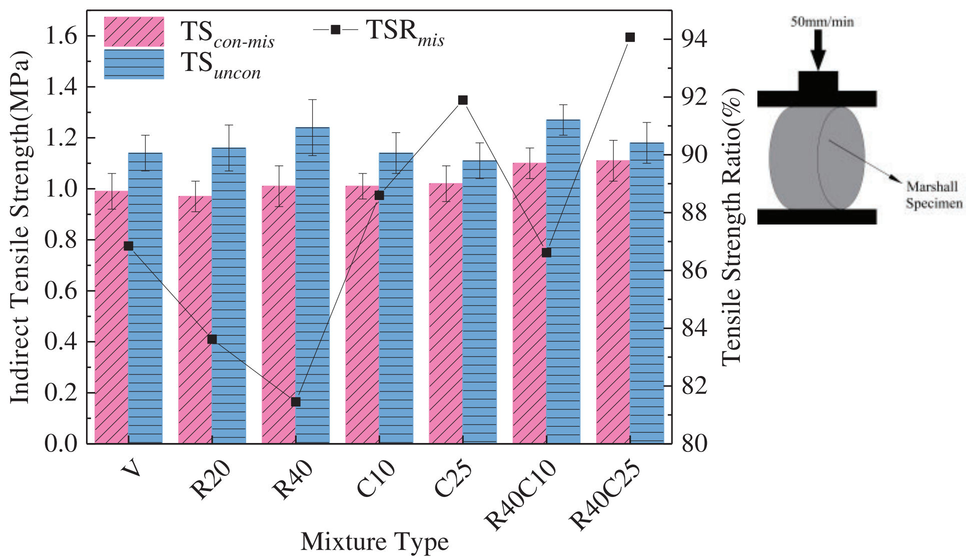

Figure 14: The results of the MIST of different asphalt mixtures

3.1.4 Cracking Resistance at Low Temperature

The results of the SCB test are illustrated in Fig. 15. The fracture energy of asphalt mixture containing RAP coarse aggregate decreased significantly with the addition of RAP compared with virgin asphalt mixture, and the reduction in fracture energy of asphalt mixtures containing 20% and 40% RAP coarse aggregate was 13.6% and 24.4%, respectively. As a matter of fact, RAP mixtures are fragile, and it may be the reason for fracture energy reduction. In addition, the fracture energy for the asphalt mixture containing CG fine aggregate shows a slightly increasing trend, and adding 10% and 25% CG fine aggregate in the mixtures increases the fracture energy by 4.2% and 9.7%, respectively, compared to virgin asphalt mixture. This can be related to the adhesion that CG can bond closer with asphalt binder than LS [35,36]. Furthermore, the fracture energy for asphalt mixture containing 40% RAP coarse aggregate was also improved by using CG fine aggregate, and the change of fracture energy of asphalt mixture containing 40% RAP becomes obvious as the content of CG fine aggregate reaches 25%, and the fracture energy increased for about 13.3% by comparing with the 40% RAP asphalt mixture. In addition, fracture energy for the asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate was 14.4% lower than that of virgin asphalt mixture. Moreover, concerning the fracture energy of the asphalt mixture, the methods of limit the content of RAP and use the high-performance rejuvenator should be adopted in the process of recycled asphalt mixture design, which was proved by Ziari et al. [37].

3.1.5 Mechanical Properties Analysis

The mechanical properties results of asphalt mixtures are illustrated via a radar chart, as shown in Fig. 16. By observing the radar chart, three conclusions can be drawn. First, the deformation resistance (MS, MQ, and DS), moisture damage resistance (MSR, TSR_{ft}, and TSR_{mis}), and low temperature cracking resistance (G_f) of the asphalt mixtures decreased with the increase of RAP coarse aggregate content. Compared with the virgin asphalt mixture, the asphalt mixture containing 40% RAP coarse aggregate showed greater attenuation of deformation resistance and low-temperature crack resistance, indicating that RAP coarse aggregate was detrimental to the mechanical properties of the asphalt mixture. Second, incorporating CG fine aggregate to asphalt mixture can improve the moisture damage resistance and low temperature cracking resistance compared with the virgin asphalt mixture, and there is no significant change in their deformation resistance. Therefore, CG fine aggregate can play a beneficial role in the mechanical properties of asphalt mixture. Third, the addition of 25% CG fine aggregate into the asphalt mixture containing 40% RAP coarse aggregate improved its performance, which was between that of asphalt mixture containing 40% RAP coarse aggregate and virgin asphalt mixture. Thus, CG fine aggregate can improve the performance of asphalt mixes containing RAP. Overall, the above mechanical properties results indicate that it is feasible to produce asphalt mixes with high waste material content by using 40% RAP coarse aggregate and 20% CG fine aggregate.

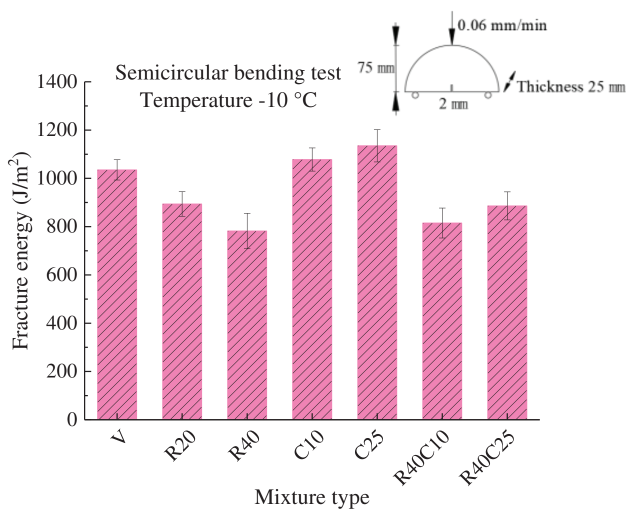

Figure 15: The results of the SCB test of different asphalt mixtures

3.2 Economic Analysis

3.2.1 Calculation Method of Economic Analysis of Asphalt Mixture

The economic benefit is one of the most crucial criteria to design the material composition of the asphalt mixture. Considering the gap between limited construction materials and maintenance funds, the government and enterprises have been investigated new methods to reduce the consumption of virgin aggregate and asphalt binder, and the asphalt mixture containing RAP and waste materials has been attracted attention in recent years [38]. In this study, asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate are designed, and the production process of making these asphalt mixtures by conventional equipment. In addition, the manufacturing cost of the asphalt mixture was calculated according to Eq. (9).

$$C_S = \sum_{i=1}^{n} c_i \times w_i + C_P + C_T + C_O \quad (9)$$

where C_S refers to the total cost of one-ton asphalt mixture, USD/Ton; c_i refers to the material production cost of asphalt mixture such as aggregate production, RAP processing, and binder production, USD/Ton. w_i refers to the proportion of RAP, asphalt binder, and LS virgin aggregate in one-ton asphalt mixture, %; C_P refers to the cost of plant production of asphalt mixture, USD/Ton; C_T refers to the cost of material transportation, USD/Ton; and C_O refers to the other cost of asphalt mixture such as RAP processing, USD/Ton.

Considering the cost composition of each part of the asphalt mixture, in this study, only the costs of materials, plant production, and RAP processing are considered. Furthermore, the unit price of materials and the processing price of asphalt mixture, etc., are listed in Table 5, which was summarized from the previous study [12,37].

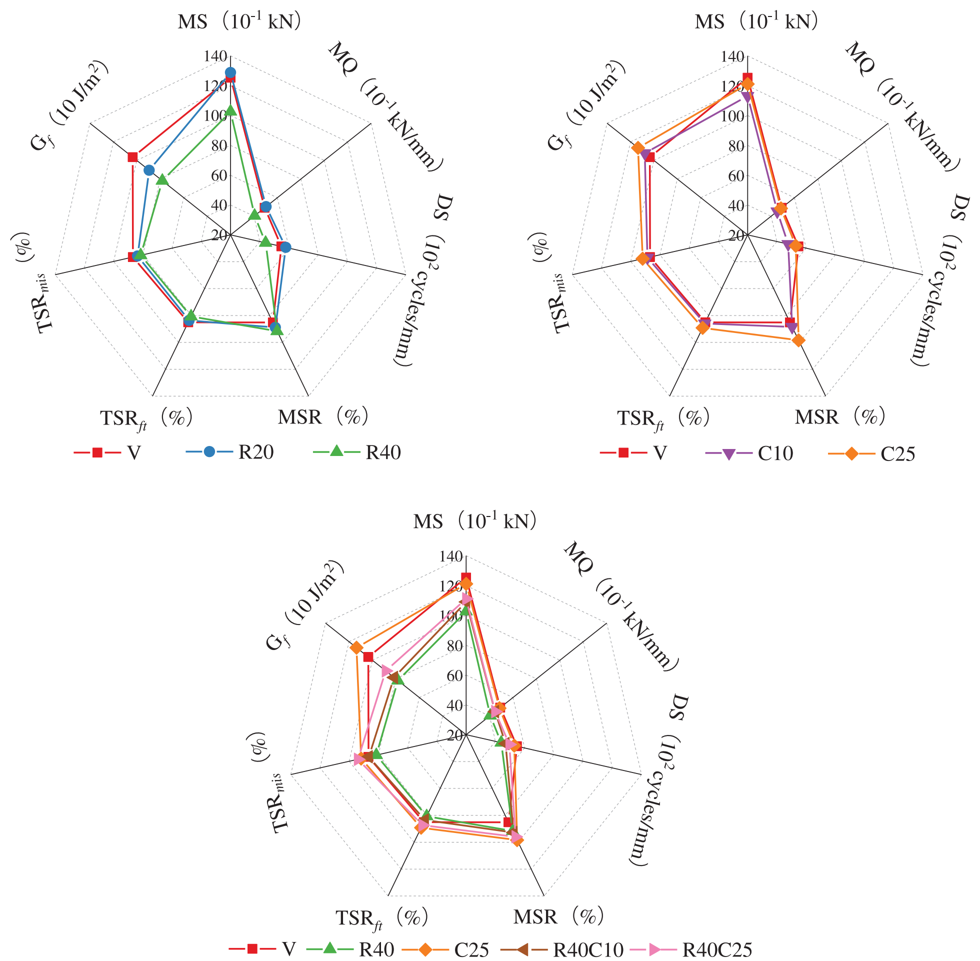

Figure 16: Results of mechanical properties for different asphalt mixtures

Table 5: The unit price of materials and the processing price for producing asphalt mixture

Materials and process	Unit price (USD ($)/Ton)	Source of data
Aggregate production	19.8	[12]
RAP processing	3.3	[12]
Binder production	704	[12]
Plant production	12	[39]

3.2.2 Calculation Results

According to Table 5 and Eq. (9), the manufacturing price of seven types of asphalt mixtures is shown in Fig. 17. Concerning the cost results of the analysis, the manufacturing price of asphalt mixture containing

RAP coarse aggregate and/or CG fine aggregate is lower than that of the virgin asphalt mixture, and the level of production cost reduction for R20, R40, C10, C25, R40C10, and R40C25 approximately is 9.5%, 18.9%, 3.4%, 11.6%, 22.9%, and 29.4%, respectively, which is comparing with the V. Therefore, asphalt mixtures included in the waste materials are more economical than the virgin asphalt mixture, and the production cost is obviously reduced by increasing the content of RAP. Clearly, the asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate is the cheapest cost, and this mixture descends the production cost from 61.56 USD/Ton to 43.49 USD/Ton by comparing the virgin asphalt mixture, and the level of cost reduction approximately is 29.4%. In addition, the cost of aggregate production significantly reduced with the content of the RAP increase; however, the cost of binder production slightly reduced with the content of RAP or CG increase. Furthermore, if the cost that comes from the binder and the aggregate rises, the benefit of using high RAP or other waste materials will only increase.

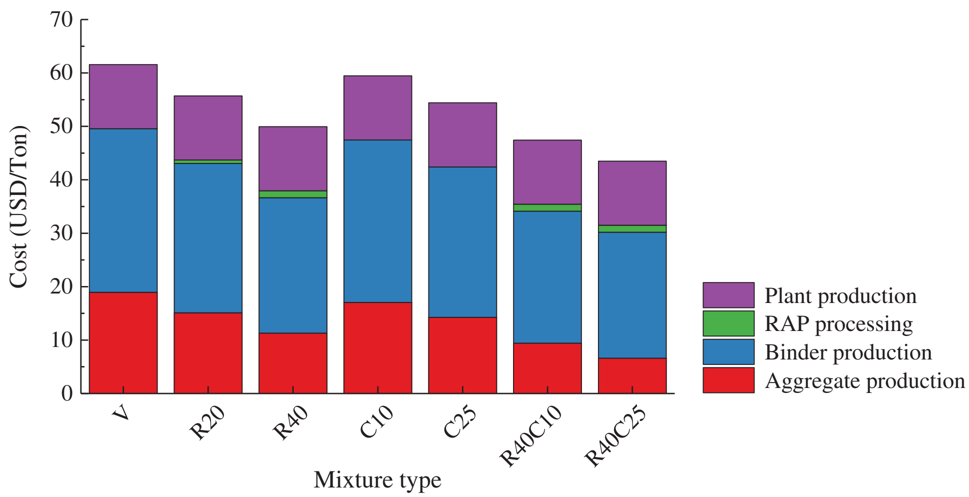

Figure 17: The production cost of designed asphalt mixtures

3.3 Environmental Impacts

3.3.1 Calculation Method of Environmental Impacts of Asphalt Mixture

Currently, the construction, maintenance, and rehabilitation of roads need a massive volume of materials and a large amount of non-renewable resources are used, causing a lot of energy consumption and dangerous gas to be emitted during these processes. Therefore, how to reduce the negative impact of the pavement industry has been received wide attention. As mentioned in the introduction, the waste materials such as RAP and CG are using in the pavement industry to reduces the exploitation of non-renewable resources and the landfills for the waste materials. To quantitatively evaluate the environmental benefits of studied asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate, the energy consumption and the CO_2 emissions of the asphalt mixture are calculated by using Eqs. (10) and (11), respectively.

$$Q_S = \sum_{i=1}^{n} w_i q_i + Q_P + Q_T + Q_O \tag{10}$$

where Q_S refers to the energy consumption of one-ton asphalt mixture, MJ/Ton; q_i refers to the material production energy consumption of asphalt mixture such as aggregate production, RAP processing, and binder production, MJ/Ton. w_i refers to the proportion of RAP, asphalt binder, and LS virgin aggregate in one-ton asphalt mixture, %; Q_P refers to the energy consumption of plant production of asphalt mixture, MJ/Ton; Q_T refers to the energy consumption of material transportation, MJ/Ton; and Q_O refers to the other energy consumption of asphalt mixture such as RAP processing, MJ/Ton.

$$E_S = \sum_{i=1}^{n} w_i e_i + E_P + E_T + E_O \tag{11}$$

where E_S refers to the CO_2 emissions of one-ton asphalt mixture, Kg/Ton; e_i refers to the material production CO_2 emissions of asphalt mixture such as aggregate production, RAP processing, and binder production, Kg/Ton. w_i refers to the proportion of RAP, asphalt binder, and LS virgin aggregate in one-ton asphalt mixture, %; E_P refers to the CO_2 emissions of plant production of asphalt mixture, Kg/Ton; E_T refers to the CO_2 emissions of material transportation, Kg/Ton; and E_O refers to the other CO_2 emissions of asphalt mixture such as RAP processing, Kg/Ton.

In this study, the energy consumption and CO_2 emissions for each part of asphalt mixtures used in this calculation are given in Table 6. During the process of calculation, the milling of old pavement, the transportation of RAP, and the laying of pavement was not considered, however, the transport distance for the virgin aggregate, asphalt binder, which was obtained from project research, is designed to be 200 and 100 km, respectively.

Table 6: Energy consumption and the CO_2 emissions for asphalt mixtures production

Process	Energy consumption (MJ/Ton)	Source of data	CO_2 emissions (Kg/Ton)	Source of data
Aggregate production	54.0	[40]	10	[41]
RAP processing	16.5	[12]	4	[12]
Binder production	1749	[12]	285	[41]
Plant production	275	[12]	22	[41]
Transport	0.9 MJ/Ton-km	[41]	0.06	[41]

3.3.2 Calculation Results

According to the statistical results of Tab. 6 and the calculation formula of Eqs. (10) and (11), the energy consumption and the CO_2 emissions for asphalt mixtures containing RAP and/or CG are shown in Figs. 18 and 19, respectively.

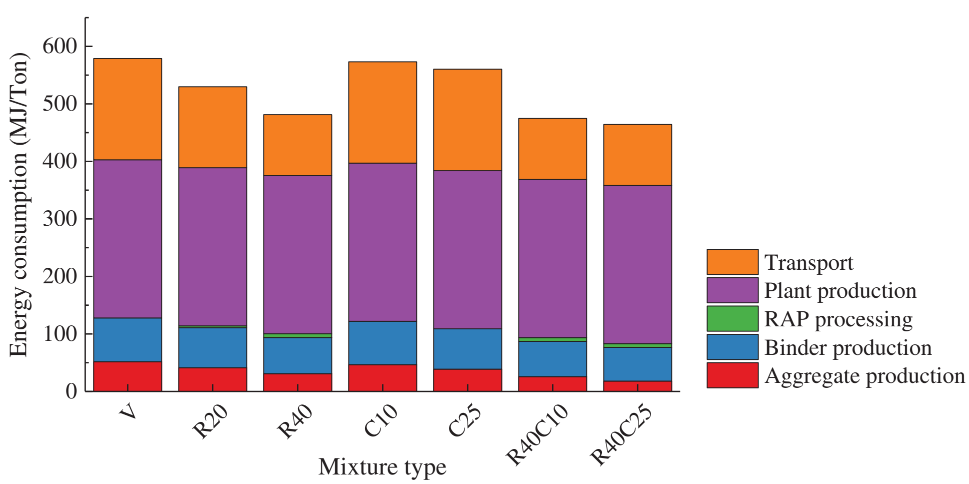

Figure 18: The energy consumption of the studied mixtures

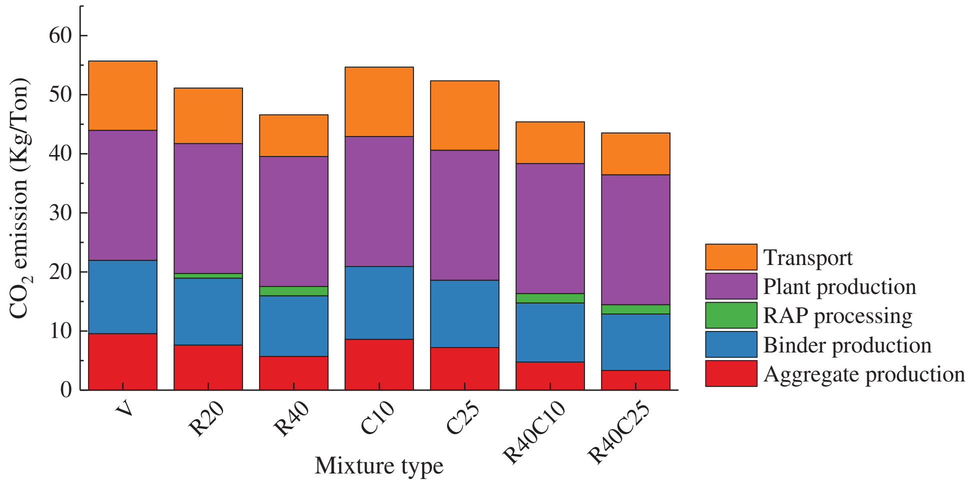

Figure 19: The CO_2 emission of the studied mixtures

Fig. 18 provides the information about the needed energy consumption to produce one ton of asphalt mixtures, it can be seen that the asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate could reduce the energy consumption compared with the virgin asphalt mixture, and the RAP decreased more significantly. Comparing the mixture types of R20, R40, C10, C25, R40C10, and R40C25 with V, the level of reduce the needed energy for asphalt mixtures production is 8.5%, 16.9%, 1.0%, 3.2%, 18.0%, and 19.8%, respectively. Obviously, the asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate have the lowest energy consumption. A more detailed look at the calculation results of Fig. 18, which reveals that the highest energy consumption in the asphalt mixtures production is the process of plant production, and the energy consumption of RAP processing or aggregate production is the lowest. In addition, the transport and the aggregate production energy consumption are significantly reduced as the content of RAP increases, thus, the amount of energy can be decreased in case of using the asphalt mixture with the RAP and controlling the transport distance of the materials such as aggregate, asphalt binder, and RAP. By considering the asphalt mixture production in the world, the benefits of saving energy by adding waste materials into asphalt mixtures would be more prominent.

Regarding the results of Fig. 19, the trend of CO_2 emission of asphalt mixtures production is approximately the same as the trend of energy consumption. In the same way, by increasing the proportion of RAP coarse aggregate and/or CG fine aggregate into the asphalt mixture, the amount of CO_2 emission is reduced during the asphalt mixture production process, and the addition of the RAP coarse aggregate in the asphalt mixture could significantly reduce the CO_2 emission than that of CG fine aggregate. In addition, the CO_2 emission of asphalt mixture that including the RAP coarse aggregate and CG fine aggregate is lowest, and this amount of CO_2 emission is lower than that of virgin asphalt mixture. Comparing the mixture types of R20, R40, C10, C25, R40C10, and R40C25 with V, the reduce ratio of CO_2 emission for asphalt mixtures production is 8.2%, 16.3%, 1.9%, 6.0%, 18.5%, and 21.9%, respectively. Besides, the CO_2 emission of the plant production process is far higher than the process of aggregate production, by increasing the proportion of RAP coarse aggregate in the asphalt mixture, the CO_2 emission of aggregate production and transport drops remarkably. In other words, using the RAP coarse aggregate and the CG fine aggregate in the asphalt mixtures could reduce the amounts of CO_2 emission because of the production of asphalt binder and aggregate need to emit CO_2, and the transportation of materials and asphalt binder also needs to generate CO_2 emission. Hence, by utilizing asphalt mixture containing RAP coarse aggregate and CG fine aggregate in pavement application, the amount of mentioned CO_2 emission could be prevented. Besides, improving production equipment and reducing production energy consumption is also a way to reduce CO_2 emissions.

4 Conclusion

The objectives of this study are to scrutinize the feasibility of manufacturing sustainable asphalt mixtures containing RAP coarse aggregate and/or CG fine aggregate. To achieve the mentioned purpose, the mechanical performance is investigated by Marshall Stability test, rutting resistance test, moisture sensitivity test, and semicircle bending test at low temperature, and the economic and environmental benefits are also estimated. Based on the results presented in this paper, the following conclusions can be made for this study:

Substituting the virgin aggregates with RAP coarse aggregates and CG fine aggregates will slightly lower the Marshall Stability, MQ, and dynamic stability of asphalt mixture compared with virgin asphalt mixture, and those properties decrease as the content of RAP increase, but the trend of CG is opposite. By incorporating CG fine aggregate in asphalt mixture to improve the moisture susceptibility compared with virgin asphalt mixture, and the moisture susceptibility index of MSR is improved by adding RAP, but its effect on TSRft and TSRmis is reversed. The low temperature cracking resistance is reduced as the content of the RAP increase, but CG fine aggregate can improve this property. In addition, the Marshall Stability, MQ, dynamic stability and fracture energy of the asphalt mixture containing 40% RAP coarse aggregate and 25% CG fine aggregate are 11.33%, 8.76%, 9.4%, and 14.4% lower than that of virgin asphalt mixture, respectively. Furthermore, adding 40% RAP coarse aggregate and 25% CG fine aggregate into asphalt mixture increases the MSR, TSR_{ft}, and TSR_{mis} value by 12.68%, 2.2%, and 7.3%, respectively, compared to the virgin asphalt mixture. In general, the mechanical performances of asphalt mixture containing RAP coarse aggregate and CG fine aggregate are slightly lower than virgin asphalt mixture, which is acceptable.

Comparing with virgin asphalt mixture, the asphalt mixture containing RAP coarse aggregate and CG fine aggregate has favorable economic and environmental benefits. The manufacturing cost, energy consumption, and CO_2 emission of asphalt mixture can be decreased by 29.4%, 19.8%, and 21.9%, respectively, in case of replacing virgin aggregates with 40% RAP coarse aggregate and 25% CG fine aggregate.

The properties of the asphalt mixture containing RAP coarse aggregate and CG fine aggregate meet the Chinese specification through it is slightly lower than the virgin asphalt mixture. However, the mechanisms that cause changes in the properties of asphalt mixture are not clear, which needs to be further studied.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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