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Research on the Rubber-Asphalt Mixtures Based on GTM Design Method

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Abstract: In order to investigate gradations and the pavement performance of rubber-asphalt mixtures, the GTM (Gyratory Testing Machine), which is a gyratory compaction molding method for rubber-asphalt mixture design, was used for the first time in China. Based on this method, continuous-gradation and three types of gap-gradation mixtures with different through-rates of 4.75*mm* were examined systematically. Without considering the volume parameters, the optimum asphalt content was identified according to the physical and mechanical parameters, including the GSI (gyratory stability index) and GSF (gyratory safety factor). The rubber-asphalt mixtures with different gradations and molding modes were expanded linearly considering the parameters mentioned above. The results indicate that dense-graded rubber-asphalt mixtures can be used based on the GTM design method. Through a comprehensive evaluation on the pavement performance, it is concluded that the GTM design method is more appropriate for dense-grade rubber-asphalt mixtures and that pavement performance with the GTM design method is superior to that of the gap-grade mixtures.

Key words: *GTM; Linear expansion; Pavement performance; Rubber-asphalt mixture.*

Preface

The molding mode and design indicators are the basic concepts in asphalt mixture design. They directly determine the optimum asphalt content and gradation, as well as the on-site compaction-control standards, and ultimately, they determine the performance of the asphalt mixture. However, the ensuring that asphalt mixtures have excellent pavement performance requires that the molding mode and the design indicators be scientific. In other words, the molding method must simulate the field-compaction conditions well, and the design indicators must reflect the stress-strain state accurately under the actual traffic loads. The Marshall Design mixture method with a hitting molding mold is the most widely used. However, the existing research results demonstrate that there are large gaps between the Marshall Design indicators and the pavement performance. In addition, engineering practice can also prove that the Marshall Design method has some limitations and has difficulty modeling the features of modern heavy traffic loads.

Based on the discussion above, the GTM (Gyratory Testing Machine) integrates characteristics such as compacting, rubbing, and shearing. It can simulate the actual stress-strain situation in field-compaction, and it can also compact the asphalt mixtures to the ideal dense situation in accordance with the real pavement temperature and traffic loads [1]. Therefore, evaluating the gradation and the pavement performance of the rubber-asphalt mixtures systematically based on the GTM design method should have important practical applications.

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Principle of the GTM Design Method

The GTM compaction instrument designs the asphalt mixtures by using the stress-strain characteristics through a scientific analysis method. During the specimen molding process, the vertical pressure is determined according to the real pressure that the tire imposes on the pavement. Meanwhile, the compaction power is varied throughout the formation process, and the limit equilibrium state is set to the terminal conditions, which reflect the physical and mechanical properties of different asphalt mixtures [1].

The design target of the GTM compaction method is to prevent the final excessive plastic deformation. In the process of specimen molding, the stress-strain data can be automatically collected, and the GTM can illustrate changes in the anti-shearing strength. The strain of the sample is characterized by the size of the gyration angle, and the anti-shearing strength is derived from the wheel pressure by calculation [1]. The final plastic deformation of the compacted sample is characterized by the GSI (gyratory stability index), which is the ratio between the gyration angle at the end of the experiment and the minimum gyration angle during the compaction process; it is used to characterize the samples' plastic deformation. Therefore, the GTM design method uses the GSI to identify the optimum asphalt content, which effectively connects the optimum asphalt content with its mechanical properties. In addition, GTM can also provide the anti-shearing strength when the sample is compacted to the limit equilibrium state. We can obtain the GSF (gyratory safety factor) easily by calculation. The GSF is the ratio between the anti-shearing stress when the sample is compacted to the limit equilibrium state and that when the mixture is required to bear traffic loads. It can characterize the sample's anti-shearing effect under the traffic loads.

Physical and Mechanical Properties of Raw Materials

Table 1. Rubber Asphalt Test Data Performance.

Test Items		Units	Results	Methods
Kinematic Viscosity(175°C)		Pa.s	1.863	T 0625
Penetration (25°C,100*g*, 5s)		0.1*mm*	57	T 0604
Softening Point (Ring and Ball Method)		°C	59	T 0606
Elastic Recovery(25°C)		%	75	T 0662
Ductility(5°C, 5*cm*/min)		*cm*	15	T 0605
Segregation(48hr,the Difference of Softening Points)		°C	4.3	T 0661
Residues after TFOT*	Mass Losing	%	-0.27	T 0609
	Penetration Ratio	%	81	T 0604
	Ductility(5°C, 5*cm*/min)	*cm*	7	T 0605

*TFOT: Thin Film Oven Test.

Table 2. Coarse-Aggregate Test Data Performance.

Test Items	Units	Results	Methods
Crushing Index	%	13.4	T 0316
Abrasion Loss	%	14.2	T 0317
Water Absorption	%	1.2	T 0304
Adhesion to Bitumen	level	5	T 0616
Content of Flat Long and Thin Particle	%	9.1	T 0312

The rubber-asphalt used in the experiment was provided by the Tianjin Haitai Technology Development Limited Corporation and it includes 20% rubber powder particles from recycled waste tires. "Technical specification of waste tire rubber powder modified asphalt pavement in Tianjin" guided the performance testing conducted in this paper. Based on the analysis of existing research results, kinematic viscosity (175°C), penetration, the softening point, and elastic recovery (25°C) are the key controlling indicators. The specific experimental results are shown in Table 1.

In order to improve the water stability of the rubber-asphalt mixtures, the experiment used basalt aggregate that is larger than 4.75*mm* and a limestone aggregate that is smaller than 4.75*mm*; the limestone powder was treated as the mineral powder. The major physical and mechanical properties of the coarse-aggregate are shown in Table 2.

Design Scheme for Selecting Gradations

The experiments mainly investigate the gap-graded mixture and make a detailed comparison among the dense-graded gradations. Based on the GTM design method, the optimum gradation for the rubber-asphalt mixtures is comprehensively identified based mainly on the mechanical indicators and pavement performance and not the volume index. The application effect of continuous gradation was also evaluated at the same time.

In order to reduce the restraint that the mold imposed on the mixtures, the fine-asphalt mixture was used for this research. Although 2.36*mm* was the sieve size used to discriminate the coarse aggregate and the fine aggregate, in the coarse aggregate with gap gradation, the real role of the skeleton was the part of the aggregate that is larger than 4.75*mm*, and the 4.75*mm* passing size is the key indicator to select the coarse gap-graded gradation [2]. Therefore, in combination with the existing research on rubber-asphalt mixtures [3-6], the 0.075*mm* passing size of the gap gradation is fixed at 5%,

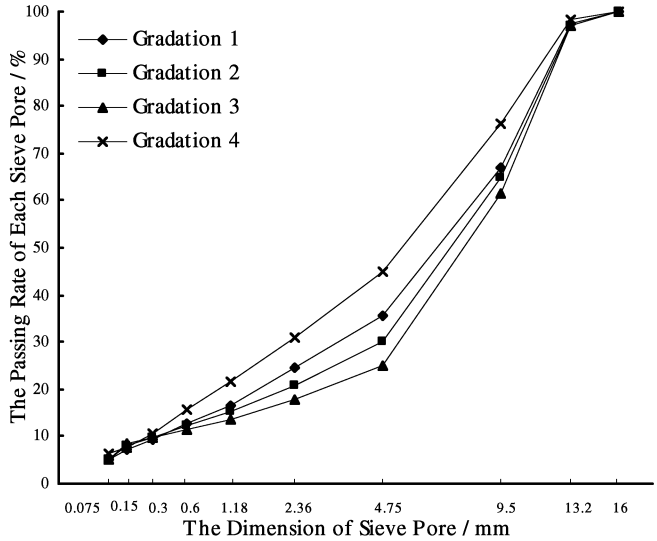

Fig. 1. Selected Gradation Trends.

and the 4.75*mm* passing size is at 25, 30, and 35%, respectively. Meanwhile, in order to provide space for the rubber powder particles in the rubber-asphalt, the 4.75*mm* passing size was reduced and the voids among the coarse aggregate increased appropriately in the design process of the dense gradation. The specific gradations selected are shown in Fig. 1.

Mix Design

The GTM design method identifies the optimum asphalt content by its physical and mechanical parameters, such as the stability index, GSI, and the safety factor, GSF. Without considering the air void, the saturation, and other volumetric properties can effectively circumvent the non-uniformity of the calculation of rubber-asphalt mixture volumetric properties [6]. The research results [7] illustrate that when GSI ≤ 1.10, or GSF ≥ 1.30, the pavement would not have a rutting or that the rutting depth is so small that it can be considered negligible.

In view of the high viscosity of the rubber-asphalt, the experimental conditions of the molding mode are controlled as follows: aggregate heating temperature 200-205°C, rubber-asphalt heating temperature 180-185°C, mixing temperature 190-195°C, and molding temperature 170-175°C, while the GTM vertical pressure is set to 0.8*MPa,* the initial mechanical angle is set to 1.4 degrees, and the limit equilibrium state control mode is adopted.

According to the conditions mentioned above, four different groups of asphalt-aggregate mixes (ratios) were studied for the selected gradations, and the samples were made with the GTM. Fig. 2 illustrates the changing regularity of the bulk volume relative density of the samples and the GTM mechanical parameters for the asphalt-aggregate ratios.

As seen in Fig. 2, the stability index, GSI, that characterizes the plastic deformation of the asphalt mixtures increases as the asphalt-aggregate ratio increases. However, the GSF, which characterizes the anti-shearing strength of the asphalt mixtures, initially increases with the asphalt-aggregate ratio and then decreases. In the case of Gradation 1, when the asphalt-aggregate ratio is greater

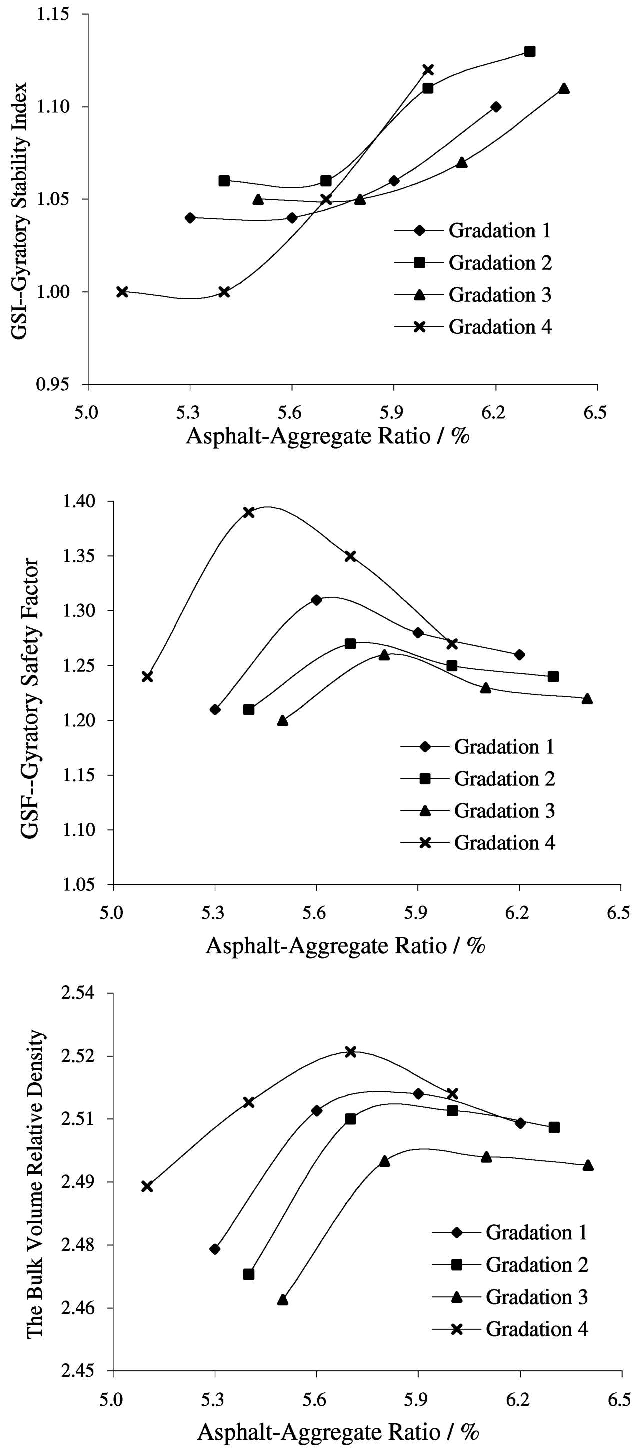

Fig. 2. Changing Regularity of the Mechanical Parameters and Density of the GTM Samples with the Asphalt-Aggregate Ratios.

than 5.6%, GSI increases significantly. The rapid increase illustrates that the asphalt content is excessive at this time, and the plastic deformation of the specimen is too large. In addition, when the asphalt-aggregate ratio is 5.6%, GSF reaches its highest value, and when the asphalt-aggregate ratio is greater than 5.6%, GSF drops with increases in the asphalt-aggregate ratio. This indicates that the anti-shearing strength of the specimen reaches its maximum at this time. Considering the mechanical parameters and the changing bulk volume density of the samples, the optimum asphalt content for Gradation 1 is identified as 5.6%. Similarly, the optimum asphalt contents for Gradation 2, 3, and 4 are 5.7, 5.8, and 5.4%, respectively.

As seen in Fig. 2, for Gradation 4, GSI is smaller and GSF is larger than those of other gradations, based on the optimum asphalt content for each condition. This indicates that, by means of the GTM molding method, the continuous-graded mixtures have minimum plastic deformation and maximum anti-shearing strength.

Linear Expansion

In order to evaluate the influence of the swelling action and the flexibility of the rubber powder particles, asphalt was imposed on the samples based on the GTM molding mode, especially for the continuous-graded gradation. The samples were rotationally molded; their heights were measured at different times, which can be used to calculate and analyze the linear expansion of the samples and to indirectly determine their influence on the different gradations from the macro level. On this basis, Marshall's double-sided 75-hit method was used to mold the samples in accordance with each gradation for comparison, and their linear expansion ratios were measured in the same way to understand the influence of the molding mode on such an expansion phenomenon.

The linear expansion characteristics of the samples with different gradations and molding modes over time are shown in Fig. 3, and the linear expansion ratios are shown in Table 3, in which the linear expansion ratio is the ratio of the height variation to the initial height.

As seen from Fig. 3 and Table 3, the following results are observed:

1. For different molding modes, there is a certain amount of linear expansion for all the samples of the rubber-asphalt mixtures; for the same kind of molding mode, the linear expansion rate of the gap-graded samples is smaller than that of the dense- graded samples, and within the test range, the more coarse the gradation is, the smaller the linear expansion rate;
2. The molding mode has significant influence on the linear expansion of the rubber-asphalt mixtures; for different molding modes, the linear expansion rate with the same gradation varies; by comparison with the Marshall molding mode, the linear expansion rate with the GTM molding mode is smaller, and that of the dense-graded is even less than that of Gradation 1 and 2 with the Marshall molding mode.

The experimental results show that, regardless of the molding mode used and compared with the dense-graded, the gap-graded mixtures have more space for the unreacted rubber powder particles in the rubber-asphalt to fill. As a result, the powder particles interfere less with the existing structure, and the linear expansion ratios are smaller. Meanwhile, compared with the traditional Marshall molding mode, using the GTM gyratory compaction molding method causes the powder particles to be distributed more uniformly with the moving rubber-asphalt, and it should be easier to fill the space of the coarse aggregate fully and with a more stable position as well. During the shearing and rubbing, which lasted for more than 40 minutes, the deformation of the powder particles stabilized, and the deformation recovery slowed as well. Thus, the rubber powder particles

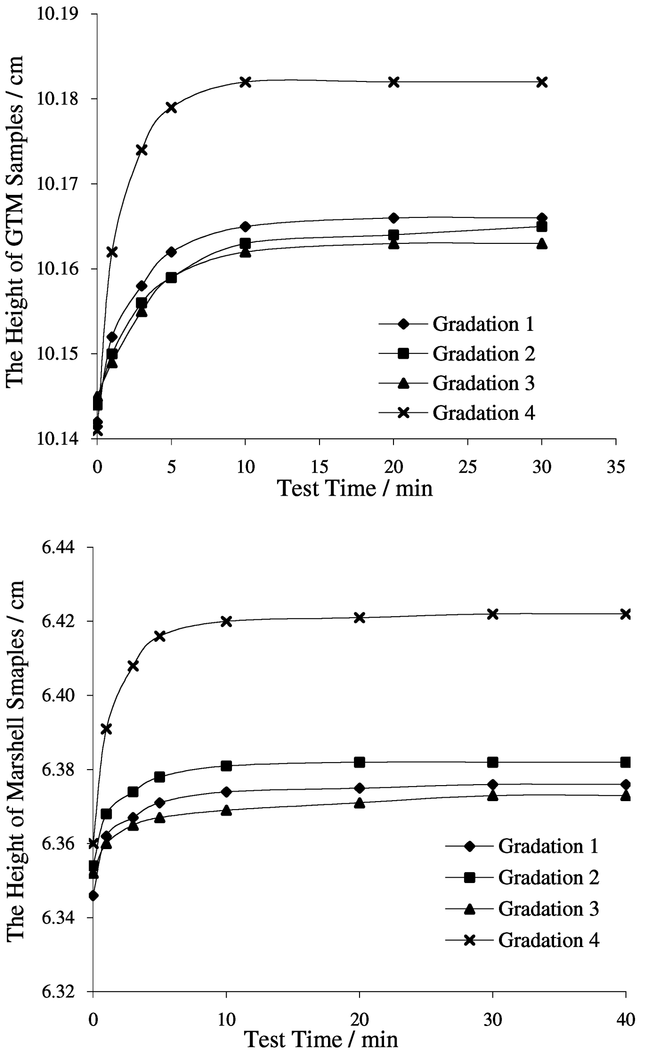

Fig. 3. Linear Expansion with Different Gradations and Molding Modes over Time.

Table 3. Linear Expansion Ratios with Different Gradations and Molding Modes.

Gradation		Linear Expansion Ratio（%）	
		GTM Molding Mode	Marshall Molding Mode
1	$P_{4.75}$=35%	0.24	0.47
2	$P_{4.75}$=30%	0.21	0.43
3	$P_{4.75}$=25%	0.18	0.33
4	Continuous	0.4	0.97

have less influence on the original gradation, and the linear expansion ratios are smaller.

As can be seen from the experimental results, the linear expansion ratios of the specimens with the dense grade are quite small when using the GTM molding mode [6]. Furthermore, in such cases, there will be no changes in the air voids, the voids in mineral aggregate, the saturation or other volumetric properties of the rubber-asphalt mixtures. Thus, the unreacted rubber powder particles in the rubber-asphalt would have little influence on the original structure. Consequently, based on the GTM design method, the dense-graded mixtures can be adopted for the rubber-asphalt mixtures.

Table 4. Rutting Test Results for the Rubber-Asphalt Mixtures with Different Gradations.

Items	Gradation 1 $P_{4.75}$=35%	Gradation 2 $P_{4.75}$=30%	Gradation 3 $P_{4.75}$=25%	Gradation 4 Continuous
Dynamic Stability (times/*mm*)	3,626	3,218	2,642	4,039
Relative Deformation (%)	2.8	3.1	3.8	2.4

Table 5. Density of the Rubber-Asphalt Mixtures under Different Molding Conditions.

Items	Gradation 1 $P_{4.75}$=35%	Gradation 2 $P_{4.75}$=30%	Gradation 3 $P_{4.75}$=25%	Gradation 4 Continuous
Density GTM Samples (g/cm^3)	2.511	2.506	2.496	2.521
Density Platy Samples (g/cm^3)	2.441	2.426	2.394	2.511
Density Ratio(%)	97.2	96.8	95.9	99.6

Analysis and Discussion on Pavement Performance

High-Temperature Performance

Platy samples were fabricated in accordance with the optimum asphalt content determined by the GTM design method, and rutting tests were conducted to analyze the rutting resistance performance of different-gradation rubber-asphalt mixtures at high temperatures. The Rolling Frequency is fixed at 50 cycles, which is determined by the GTM compaction power and the on-site compaction condition. The results of the rutting tests are shown in Table 4. The relative deformation is defined as the ratio of the final deformation depth after the test to the depth before the test.

As can be seen from Table 4, the high-temperature performance of the dense-graded is much better, not only in terms of the dynamic stability, but also the relative deformation index, when using the GTM design method. Furthermore, the dynamic stability and the relative deformation are consistent in the evaluation of the high-temperature performance of the rubber-asphalt mixtures. For the gap-graded mixes, the high-temperature performance is optimum when the 4.75*mm* passing rate is 35%. It is not reasonable to evaluate the high-temperature performance of the rubber-asphalt mixtures, and the relative deformation index is a more scientific method of describing the performance [3, 8]. In view of the importance of the high-temperature performance for the asphalt mixtures, two controlling indexes are proposed: the dynamic stability and relative deformation, with the latter as the primary target. A related study [9] indicates that the relative deformation index for the rubber-asphalt mixtures should be controlled within 3% under heavy traffic.

Generally speaking, the rutting resistance performance of the dense-graded mixtures is worse than that of the gap-graded mixtures. However, with the GTM design method, the rutting resistance performance of the dense-graded mixture is much better than that of the gap-graded. This is mainly because the coarse gap-graded mixtures have more coarse aggregates. Compared with the 5 *cm*-thick testing mold, the compaction effect is relatively small with the same compaction power. In addition, the 0.075*mm* passing rate of the gap-gradation is only 5%. Thus, the dust content is so little that

Table 6. Freeze-Thaw Split Test Results of for the Rubber-Asphalt Mixtures with Different Gradations.

Items	Gradation 1 $P_{4.75}$=35%	Gradation 2 $P_{4.75}$=30%	Gradation 3 $P_{4.75}$=25%	Gradation4 Continuous
Splitting Strength (*MPa*)	1.18	1.13	0.98	1.21
Cycled Splitting Strength (*MPa*)	1.02	0.94	0.80	1.07
Freeze-Thaw Split Strength Ratio (%)	86.6	83.6	81.7	88.3

the skeleton gaps among the coarse aggregate cannot be fully filled, which would lead to easier compaction.

The interpretations above can be proven by the experimental results shown in Table 5. Under the rolling number determined by the experiments, the density of the gap-graded samples is only 97% of that of the GTM gyratory molding samples, while the comparative data of the dense-graded give a value of 99.6%, which illustrates that the dense-graded mixtures are more easily compacted under the same compaction effort. Additionally, for the gap-graded rubber-asphalt mixtures, the density of the plate samples becomes larger as the 4.75*mm* passing rate increases within the test range. This indicates that the coarser the gradation is, the more easily the skeleton gaps among the coarse aggregate can be filled, i.e., the smaller the porosity. This can explain the regularity with which the high-temperature performance varies with the passing rate of 4.75*mm*.

Water Stability Performance

The freeze-thaw split tests are used to evaluate the water stability performance of the rubber-asphalt mixtures. The GTM molding samples were cut according to the size of the standard Marshall's samples tested previously. The results are shown in Table 6.

The experimental results shown in Table 6 illustrate that the freeze-thaw splitting strength ratios of the dense-graded rubber-asphalt mixtures are better than those of the gap-graded rubber-asphalt mixtures. In addition, for the gap-graded mixtures, the index is closely related to the 4.75*mm* passing rate. The greater the 4.75*mm* passing rate is, the greater the fine aggregate content and the greater the freeze-thaw splitting strength. This is mainly because, with the GTM design method and throughout the test range, the greater the 4.75*mm* passing rate is, the higher the density and the smaller the porosity. Therefore, it is difficult for water to penetrate the samples and weaken the mixtures. Thus, the freeze-thaw residual strength ratio is greater under the same condition.

Low-Temperature Performance

The platy samples with the round-crushed (50 times rolling back and forth) molding method were cut into specimen beams with a size of 30 × 35 × 250*mm* for the bending failure tests. Under the temperature of -10±0.5°C, the bending failure tests were performed according to MTS-810. The bending failure strain is treated as the evaluation index for the low-temperature performance of the rubber-asphalt mixtures. The results are shown in Table 7.

Table 7. Bending Failure Test Results for the Rubber-Asphalt Mixtures with Different Gradations.

Items	Gradation 1 $P_{4.75}$=35%	Gradation 2 $P_{4.75}$=30%	Gradation 3 $P_{4.75}$=25%	Gradation 4 Continuous
Bending Failure Strain ($m\varepsilon$)	2,892	2,210	1,872	3,461

Table 8. Results of Slip Resistant Tests for the Rubber-Asphalt Mixtures Different Gradations.

Items	Gradation 1 $P_{4.75}$=35%	Gradation 2 $P_{4.75}$=30%	Gradation 3 $P_{4.75}$=25%	Gradation 4 Continuous
Friction Graph Pendulum Value (BPN*)	63	68	77	57
Texture Depth (*mm*)	0.89	0.96	1.02	0.65

*BPN: British Pendulum Number

As can be seen from Table 7, the bending failure strains of the dense-graded rubber-asphalt mixtures are greater than those of the gap-graded rubber-asphalt mixtures. Moreover, for the gap gradation, the coarser the gradation is, the smaller the bending failure strain will be. This is primarily because the stress is transferred by the mineral aggregate particles during the bending failure process. As the crack transfers, the crack distance and energy consumption increase because of the numerous fine particles and cement. Therefore, the finer the gradation is, the greater the rupture strains. In addition, for the dense-graded mixtures, the mixtures are more flexible because they are encapsulated more uniformly and tightly by the rubber-asphalt, which is also why they have higher failure strain and better low-temperature performance.

Anti-Skid Performance

During the course of the experiment, British pendulum number (BPN) and the texture depth of the platy samples with different gradation rubber-asphalt mixtures were measured. This was used to evaluate the anti-skid performance. The experimental results are shown in Table 8.

As can be seen from Table 8, the anti-skid performance of the dense-graded rubber-asphalt mixtures is the worst. For the gap-graded mixes, the skid resistance is obviously related to the 4.75*mm* passing rate, which specifically illustrates that the greater the 4.75*mm* passing rate, the more fine aggregate content will be included, the smaller the BPN and the texture depth are, and the smaller the skid resistance is.

Impermeability

During the course of the experiments, the water permeability coefficient of the platy specimens with different gradations was measured, and the experimental results illustrate that the rubber-asphalt mixtures of each gradation are generally impermeable.

Conclusions

Based on the GTM design method, studies on dense-graded and gap-graded rubber-asphalt mixtures were carried out, and with data analysis and comparison with their linear expansibility and pavement performance, several conclusions can be drawn:

1. Based on the GTM design method, the rubber-asphalt mixtures can adopt dense gradation, and the rubber powder particles will not affect the original grading structure.
2. Based on the GTM design method, the dense-graded rubber-asphalt mixtures have excellent pavement performance and are better than those of the rubber-asphalt mixtures with coarse gap-graded mixtures.
3. Considering the pavement performance and construction, it is proposed that the dense-graded mixture should be adopted in engineering practice, while the coarse aggregate content should be increased moderately in order to enhance the anti-skid performance. If using the coarse gap-graded aggregate, the 4.75*mm* passing rate should be controlled at about 35%.
4. The GTM design method is more suitable for the design of dense-graded rubber-asphalt mixtures.

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