

Design of dense gap-graded friction course mixture

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Abstract: The design procedure of a dense gap-graded friction course (DGGFC) with coarse aggregate void filling method is presented. Testing results show that a DGGFC mixture possesses a dense stone-matrix structure, good stability and almost the same texture depth as stone matrix asphalt (SMA). It also has a coarse and even surface after paving and has no separation during construction. It is durable and impermeable. It balances and improves the inherent inconsistency of asphalt mixture between the large texture depth for skid resistance and the impermeability for durability. The actual application in the Nanning-Liuzhou Expressway also shows that the performance of the DGGFC is as excellent as that of SMA, while the DGGFC mixture is cheaper than SMA. The DGGFC mixture is good for wearing course of pavement. Further research on DGGFC can be helpful for improving the surface skid resistance, prolonging the life-span period and reducing the construction costs of asphalt pavement.

Key words: dense gap-graded friction course (DGGFC); coarse aggregate void filling method; dense stone-matrix structure; pavement performance

Since 1990's, highway construction in China has developed rapidly. Now, the total kilometrage of expressways in China ranks No. 2 in the world. However, there are still some problems in the procedures of superhighway development. One of them is the premature destruction of the friction courses of asphalt pavement. Some pavements even encounter the problem of raveling/delamination within two or three years after construction because of the AK graded mixtures used with high voids in total mixture (VTM) for expressway friction courses to achieve high microtexture. Surveys^[1] show that high VTM is actually one of the main causes of the premature destruction of expressways. It can be expected that the life of a permeable pavement will be shorter than that of an impermeable pavement, due to the deterioration of mixture through water and air infiltration, and the subsequent stripping, oxidation and hardening of binder. So the new technical specifications^[1] for the construction of highway asphalt pavements, issued by the Ministry of Communications of the People's Republic of China in 2004, annulled the AK series gradations and introduced the stone matrix asphalt (SMA) gradations and open-graded friction course (OGFC) gradations. SMA mixtures have coarse aggregate (retained on 4.75 mm sieve) skeletons with stone-on-stone contact to minimize rutting^[2], have high microtexture, and they are dense, impermeable and durable. SMA mixtures have satisfactory performance but they are more expensive than normal mixtures because of their high asphalt content (from 6.0% to 7.0%) and the adding of fiber. OGFC has been applied since the 1950's in several states of the United States to improve the surface frictional resistance of asphalt pavements^[3]. OGFC improves the wet weather driving conditions by allowing the water to drain through its porous structure away from the roadway. The improved surface drainage reduces hydroplaning, reduces splash and spray behind vehicles, improves wet pavement friction and surface reflectivity. It also reduces traffic noise. But it has high VTM and is not durable. The new generation of OGFC^[3] with fiber and high stiffness binder improves its durability performance, but it is still not as durable as dense graded mixtures yet.

It seems that good design is the key to improving the performance of friction course mixtures. There is a need to develop an advanced design procedure for the friction courses to improve the performance of friction course mixtures. A new design procedure using coarse aggregate void filling methods for new material-dense-graded friction course (DGGFC) mixture design is presented in this paper.

1 Design Procedure of DGGFC Asphalt Mixture

1.1 Selection of raw materials

The first step in the DGGFC mixture design is to select suitable materials. Materials required by DGGFC in-

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clude aggregates, asphalt binders and fillers. Guidance for suitable aggregates can be obtained from recommendations for SMA^[1,4]. In this research, diabase aggregates from Chongzuo in Guangxi Province are applied, and the coarse aggregate is defined as the aggregate fraction retained on the 4.75 mm sieve. The aggregates’ preliminary technical parameters are listed in Tab. 1 and Tab. 2.

Tab. 1 Technical parameters of coarse aggregates

Index	Requirement ^[1,4]	Measured data	Measuring standard
Crushing value/%	≤26	12.2	T0316—2000
L. A. abrasion/%	≤28	12.1	T0317—2000
Impact value/%		11.3	T0322—2000
Polished stone value	≥42	58	T0321—94
Water absorption/%	≤2.0	1.6	T0304—2000

Tab. 2 Measured data of physical parameters of aggregates

Aggregates	10 to 15 mm crushed stone	5 to 10 mm crushed stone	0 to 3 mm stone chip	Filler(limestone)
Bulk specific gravity	2.516	2.478		
Apparent specific gravity	2.645	2.624	2.657	2.754
Sand equivalent/%			78	
Passing 16 mm sieve/%	100			
Passing 13.2 mm sieve/%	74.0	100		
Passing 9.5 mm sieve/%	13.2	98.7		
Passing 4.75 mm sieve/%	0.5	15.8	100	
Passing 2.36 mm sieve/%	0.1	1.6	94	
Passing 1.18 mm sieve/%	0.1	0.2	64	
Passing 0.6 mm sieve/%	0.1	0.2	44	
Passing 0.3 mm sieve/%	0.1	0.2	29	100
Passing 0.15 mm sieve/%	0.1	0.2	16	98.7
Passing 0.075 mm sieve/%	0.1	0.2	8.7	88.2

The binder selection should be based on factors such as environment, traffic, and expected functional performance of DGGFC. High stiffness binders, such as PG 76-xx, made of polymers, are recommended^[3] for hot climates or cold climates with freeze-thaw cycles, medium to high volume traffic conditions, and mixes with high air void contents (in excess of 22%). Styrene-butadiene-styrene (SBS) modified bitumen is applied in this study to reduce rutting. The technical parameters of the SBS polymer-modified asphalt binder are listed in Tab. 3.

Tab.3 Related indices of SBS polymer-modified asphalt binder

	Item	Value	Requirement ^[1,5]
Original modified asphalt cement	Penetration at 25 °C/0.1 mm	55	30 to 60
	Penetration index (PI)	0.23	≥0
	Ductility at 5 °C/cm	56.6	≥20
	Softening point (R&B)/°C	82.0	≥60
	Elastic recovery, 25 °C/%	90.0	≥75
	Separation test, softening point difference, 48 h/°C	2.0	≤2.5
	Specific gravity	1.027	
	DSR, $G^* / \sin \delta$, @ 10 rad/s, 76 °C/kPa	1.89	> 1.0
RTFOT residue, 163 °C, 85 min	Mass change/%	0.1	≤1.0
	Penetration Ratio/%	94.6	≥75
	Ductility at 5 °C/cm	20.0	≥15
	DSR, $G^* / \sin \delta$, @ 10 rad/s, 76 °C/kPa	2.23	> 2.2
RTFOT + PAV	DSR, $G^* \sin \delta$, @ 10 rad/s, 28 °C/kPa	2 254	≤5 000
	S/MPa	288	< 300
	Creep stiffness, @ 60 s, -12 °C $m(\text{slope})$	0.378	≥0.3

1.2 Mineral material gradation design of DGGFC

The coarse aggregate void filling (CAVF)^[6-8] method is used for DGGFC mineral material gradations design. The idea behind the CAVF is to make the coarse aggregate (retained on a 4.75 mm sieve) form stone-on-stone contact skeletons, while the fillers, the fine-aggregate and binder properly fill the void in the coarse aggregate (VCA), viz. :

The volume of void in the coarse aggregate = the volume of (fine aggregate + filler + binder) +
the volume of VTM

The CAVF assumes that : ① The granule of the fine-aggregate fraction does not interfere with the stone-on-stone contact skeletons of the coarse-aggregate fraction; ② Mastic formed by the fine-aggregate, filler and binder also does not interfere with the stone-on-stone contact skeletons of the coarse-aggregate.

When using the CAVF to design the DGGFC mixture, 4% VTM is ideal. Try to select a single size of coarse aggregate to form stone-on-stone contact skeletons. The more the single size of the coarse aggregate, the higher the microtexture and the more even surface the DGGFC pavement achieves. And try to select fine aggregates passing 2.36 mm sieve size to form a gap-grade gradation to avoid the interference of granule of fine aggregate fraction.

According to the above analysis, the volume relationship among every part of the DGGFC is shown as

$$q_c + q_f + q_p = 100 \quad (1)$$

$$\frac{q_c}{100\rho_{sc}}(V_{DRC} - V_{vs}) = \frac{q_f}{\rho_{tf}} + \frac{q_p}{\rho_{tp}} + \frac{q_a}{\rho_a} \quad (2)$$

where q_c is the percent coarse aggregate of the total mineral aggregate by weight; q_f is the percent fine aggregate of the total mineral aggregate by weight; q_p is the percent filler of the total mineral aggregate by weight; q_a is the percent asphalt aggregate ratio by weight; V_{DRC} is the percent dry-rodded voids in the coarse aggregate; V_{vs} is the percent air void in bituminous mixtures, 4% is ideal to DGGFC mixtures; ρ_{sc} is the specific gravity of the coarse aggregate fraction in the dry-rodded condition; ρ_{tf} is the combined apparent specific gravity of the fine aggregate; ρ_{tp} is the apparent specific gravity of the filler; ρ_a is the specific gravity of binder.

In this study, 10 to 15 mm crushed diabase is blended with 5 to 10 mm crushed diabase with a proportion of 2:1 to be used as a coarse aggregate framework of 13.2 mm nominal maximum aggregate size (NMAS) DGGFC (DGGFC-13) mixture. The testing value of ρ_{sc} of the blend is 1.488, and the testing value of dry-rodded void in the coarse aggregate V_{DRC} is 41.08%. 0 to 3 mm crushed diabase chip is used as fine aggregate of the DGGFC-13 mixture. To form a gap-graded gradation, no 3 to 5 mm crushed diabase is used. 6% limestone filler of the total mineral aggregate by weight is also used in the DGGFC-13 mixture. Assume an empirical percentage of asphalt aggregate ratio by weight $q_a = 5.0$, percentage of air void in bituminous mixtures $V_{vs} = 4$. Then, according to Eqs. (1) and (2), $q_c = 67.8$, and $q_f = 26.2$. Then, the composite gradation of the DGGFC-13 is determined. The composite gradation and grading requirements of the DGGFC-13 and 13.2 mm NMAS SMA (SMA-13) gradation recommended by the specifications^[1,4] are shown in Tab. 4.

Tab. 4 Composite gradation and grading requirements of DGGFC-13 and SMA-13

		16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
	Sieve size/mm										
	DGGFC-13 composite gradation	100	88.2	60.5	36.0	31.1	23.0	17.6	13.6	10.1	7.6
Percent passing	DGGFC-13 grading requirements	100	75 to 100	45 to 75	32 to 43	27 to 37	18 to 29	13 to 24	11 to 18	8 to 14	7 to 12
	SMA-13 gradation ^[1,4]	100	95	62.5	27	20.5	19	16	13	12	10

Based on Tab. 4, we can find that although DGGFC-13 and SMA-13 gradation are both found in the dense framework structure, DGGFC-13 needs more fine aggregates than SMA-13 in order to fill the voids in the coarse aggregate, while it needs less binder, less filler and no fiber. That is the reason why DGGFC mixtures are cheaper than SMA mixtures.

1.3 Determination of optimum asphalt aggregate ratio

We use the design gradation to prepare DGGFC-13 mixtures at five asphalt aggregate ratios which are in increments of 0.5%, one after another. Then the mixtures are compacted using 50 bellows of Marshall hammer. Finally, the Marshall test is conducted and the void in the coarse aggregate for each compacted mixture (V_{mix}) is determined. The test results are listed in Tab. 5.

To form a framework structure, the compacted mixtures should meet the requirements for V_{mix} ($V_{mix} < V_{DRC}$)^[2]. Based on Tab. 5, DGGFC-13 blended with asphalt aggregate in ratios of 4.0% to 5.3% meets the requirements for V_{mix} and has coarse aggregate stone-on-stone contacts. DGGFC-13 blended with asphalt aggregate in a ratio of 5.2% meets the aim V_v requirements of 4.0%. So we can conclude that the primary optimum asphalt aggregate ratio of DGGFC-13 is 5.2%.

Tab.5 Marshall test results for DGGFC-13 mixtures

Item	Asphalt aggregate ratio/%					Requirement ^[1]
	4.0	4.5	5.0	5.5	6.0	
Bulk specific gravity of compacted mixtures G_{mb}	2.309	2.317	2.325	2.321	2.318	
Theoretical maximum specific gravity	2.458	2.442	2.426	2.411	2.396	
Void in mineral aggregate $V_{MA}/\%$	14.8	15.0	15.2	15.7	16.3	≥ 14.0
Volume of air voids $V_V/\%$	6.1	5.1	4.2	3.7	3.2	4 to 6
Void filled with asphalt $V_{FA}/\%$	59.2	65.8	69.4	73.9	78.2	65 to 75
Marshall stability/kN	9.73	11.11	14.45	13.35	9.31	≥ 8.0
Flow value/0.1 mm	35.0	34.4	30.5	34.0	39.7	15 to 40
Void in coarse aggregate of asphalt mixture $V_{mix}/\%$	40.56	40.65	40.72	41.11	41.46	

1.4 Check on the optimum asphalt aggregate ratio

We use the design gradation to prepare DGGFC-13 mixtures at the primary optimum asphalt aggregate ratio of 5.2%. Then we prepare specimens for Marshall tests, rut tests, etc. Finally, we conduct Marshall tests, rut tests, abrasion tests and moisture susceptibility tests. A summary of all the test results are shown in Tab.6 and Tab.7.

Tab.6 Summary of Marshall test results for the optimum asphalt content checking

Asphalt aggregate ratio/%	Bulk specific gravity of compacted mixture	$V_{MA}/\%$	$V_V/\%$	$V_{FA}/\%$	Marshall stability/kN	Flow value/0.1mm	$V_{mix}/\%$
5.2	2.322	15.4	4.0	73.8	13.86	31	40.91

Tab.7 Summary of the other test results for the optimum asphalt content checking

Item	Abrasion loss/%	Residue Marshall stability ratio/%	Tensile strength ratio $R_{TS}/\%$	Dynamic stability S_D (times \cdot mm ⁻¹)
Requirement ^[1,4]	≤ 15	> 80	> 80	$> 3\,000$
Test results	3.1	91.9	90.2	4\,200

Based on Tab.6 and Tab.7, DGGFC-13 blended with an asphalt aggregate ratio of 5.2% meets the requirement for V_{mix} and the aim V_V requirement of 4.0%, and has stone-on-stone contact. It can be finally concluded that the optimum asphalt aggregate ratio of DGGFC-13 is 5.2%.

2 Construction Trial and Comparison to SMA

In the Nanning-Liuzhou Expressway Overlay Project, a 2 cm thick stress-absorbing membrane interlayer (SAMI) was placed firstly on the original Portland cement concrete pavement to retard and prevent the reflecting crack, then a 6 cm thick dense gap-graded modified asphalt mixture was placed, and finally a 4 cm thick DGGFC-13 was placed.

The application rate of tack coat is about 0.2 to 0.4 L/m². The DGGFC-13 course is prone to cooling because it is only 4 cm thick, as indicated in the contract plans. It is recommended that three vibratory rollers be used to insure timely compaction. The rollers should run slowly and follow the asphalt pavers tightly with high frequency and low amplitude of vibration to enhance the efficiency of compaction. The recommended temperatures under which DGGFC asphalt mixtures are produced, placed and compacted are shown in Tab.8.

Tab.8 Recommended producing and placing temperatures of DGGFC asphalt mixtures

Working phase	Aggregate	SBS-modified asphalt	Producing	Placing	Compacting start	Compacting finished
Temperature/ $^{\circ}$ C	185 to 190	175 to 185	180 to 190	> 165	> 155	> 110

Traffic shall not be allowed on the DGGFC at least during the first hour after the final rolling operations have been completed. Traffic on completed pavement too soon may result in flushing.

To make a comparison, 2 km of SMA-13 pavement was constructed at the same time. A series of tests were conducted during/after the construction of the DGGFC and SMA pavement. Testing results are shown in Tab.9.

Tab.9 Properties of DGGFC and SMA pavement

Pavement	Abrasion loss/%	Residue Marshall stability ratio/%	Tensile strength ratio $R_{TS}/\%$	Dynamic stability S_D /(times \cdot mm ⁻¹)	Mean texture depth/mm	Permeability/(mL \cdot min ⁻¹)
DGGFC-13 pavement	3.1	91.9	90.2	4\,200	0.92	53.1
SMA-13 pavement	4.0	89.2	90.5	4\,150	1.0	62.5

As we can see in Tab. 9, DGGFC-13 pavement's properties are almost the same as the SMA-13 pavement's. It has good stability and almost the same texture depth as the SMA, and it has coarse and even surface after paving and has no separation during construction. It is durable and not permeable, and it is excellent for wearing course of pavement.

3 Conclusion

The design procedure for the DGGFC with the coarse aggregate void filling method presented in this paper is simple and effective. According to this procedure, the DGGFC is dense-gap graded, consumes the same quantity of bitumen and filler as that required by normal dense mixtures, while it uses no fiber. Testing results show that DGGFC gradations have coarse aggregate skeletons with stone-on-stone contact to minimize rutting, have no separation during construction, and have even and high microtexture after placing. They are durable and impermeable. The actual application also shows that the DGGFC mixture is as excellent as the SMA, but it is cheaper than the SMA. The DGGFC mixtures have good performance. Further research on the DGGFC would be helpful for improving the surface skid resistance, prolonging the life-span period and reducing the construction costs of asphalt pavement.

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密断级配抗滑层沥青混合料设计

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摘要:介绍了应用主骨架空隙填充法进行密断级配抗滑层(DGGFC)沥青混合料配合比设计的全过程,并对其各项性能进行了试验研究. 试验结果表明:根据这一方法所设计的 DGGFC 沥青混合料属于骨架密实结构,具有良好的路用性能和表面功能,施工不离析,密实不透水,高温稳定性和耐久性好,表面均匀,具有较大的构造深度,很好地改善了表面抗滑层混合料表面构造和密实耐久性之间的矛盾. 实际应用表明, DGGFC 沥青混合料几乎达到 SMA 的使用效果,而其造价比 SMA 低,可作为高速公路和高等级沥青路面表面磨耗层. 开展 DGGFC 沥青混合料的研究和推广对于降低工程造价、改善表面抗滑性能和延长路面使用寿命具有现实意义.

关键词:密断级配抗滑层;主骨架空隙填充法;骨架密实结构;路用性能

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