STUDY ON SMA MIXTURE BY ORTHOGONAL EXPERIMENTAL DESIGN METHOD

Dang Van Thanh[1], Pham Van Tinh[2]
[1,2]*Vietnam National University of Forestry*

SUMMARY

Stone Matrix Asphalt (SMA) is a new type of asphalt concrete which has been applying in many countries over the world for highway building. This is a kind of hot asphalt created by mixture of plastic mastic that fills pores of interrupted gradation macadam formed according to the Macadam principle. By orthogonal experimental design method and asphalt concrete experiments in laboratory such as Marshall stability test, Residual stability test and Rutting test, this study evaluates the impact of several factors of material composition including asphalt content factors, fiber content and mineral filler content to the basic features of SMA mixture used in pavement construction presented in this paper. Research results indicate that the influence of these factors on the basic features of SMA mixture is clearly noticeable. The study also recommends the optimal values of asphalt content, fiber content and mineral filler content used for SMA-16 mixture, in turn of 6.2%; 0.30% and 10.5%, respectively.

Keywords: Marshall stability, orthogonal experiments, residual stability, rutting, SMA mixture.

I. INTRODUCTION

Stone Matrix Asphalt (SMA) is a type of gap-graded hot asphalt, which relies on stone-on-stone contact to resist deformation; which is made up of asphalt, fiber stabilizer, mineral filler, and less fine aggregate consisting of mastic asphalt binder; this mixture fills in the gaps of the coarse aggregate skeleton gradation in the formation of SMA (Ibrahim M. Asi, 2006). SMA has a strong permanent deformation resistance capacity, is capable of resisting deformation in high temperatures, and can also significantly improve the water stability of the mixture; it also has positive performance features such as good phydroplaning resistance, anti-aging capability, and resistance to fissure in low temperature, consequently extending the life of the pavement[2]. In recent years, the application of SMA has been widely increasing. The characteristics of the composition of SMA, mix optimization, and its road performance improvements have received considerable attention from the researchers. However, asphalt is a composite material, using different constituent materials lead to different properties of SMA mixture; the specific performance requirements also vary depending on the climate conditions in different countries. Therefore, prior to SMA mixture usage, its characteristics and indicators need to be investigated. In certain construction conditions, constituent materials of SMA mixture and their volume fractions or contents are particularly important. Material factors can be divided into types of materials and content of materials. With each specific conditions, types of selected materials were fixed, only the material content can be controlled. When the ratio of the material compositions change this would greatly affect essential performances of SMA mixture. So far, there have been many authors also studied on SMA (Ge Liang, 2010), however, there is not studies to mention the simultaneously influence of multiple factors about the material composition to the SMA performances. By orthogonal experimental design method (Zheng Shaohua, Jiang Fenghua ed, 2003) and asphalt concrete experiments in laboratory such as Marshall stability test, soaked Marshall and rutting test. This study evaluates the influence of three factors on the composition of manufacturing constituent materials including asphalt content factor (L), fiber content factor (X) and mineral filler content factor (K) to the basic performances of SMA mixture; and introduce methodology of components design of SMA mixture used in pavement construction.

II. RESEARCH METHODOLOGY

2.1. Materials

The study was performed with SMA-16 mixture made from the material composition as follows:

Asphalt was used styrene butadiene styrene polymer (SBS) modified asphalt, made in China with a penetration of 67 mm (at 25°C), ductility of 95.2 cm (at 5°C) and softening point of 76.5°C.

Aggregate and mineral filler: Aggregate used crushed basalt mineral, with a specific gravity of 2.84 g/cm^3 and maximal size of 16mm; mineral filler used limestone type, with a specific gravity of 2.78 g/cm^3, with 87.7% by mass smaller than 0.075 mm. The passing quality percentage of aggregates and mineral filler is shown in Table 1.

Table 1. Passing quality percentage of mineral aggregate (%)

Sieve size (mm)	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Crushed stone (10-20mm)	100	88.9	29.0	0.7	0.1	0					
Crushed stone (5-10mm)			100	98.8	0.2	0.1	0				
Crushed stone (3-5mm)				100	70.5	0.2	0				
Fine aggregate (< 3mm)					100	90.3	63.0	35.9	21.9	11.2	5.7
Mineral filler									100	96.6	87.7

Fiber: Using lignin fiber that is made from Chinese. This fiber is less than 6mm long, fibre diameter 46 μm, with a density of 1.6 g/cm^3. Figure 1 shows the picture of this fiber.

All physical and mechanical properties of the materials are checked and proven to satisfy standard requirements (JTG F40-2004, 2004; JTJ 052-2000, 2000).

Figure 1. Picture of lignin fiber

2.2. Methods

2.2.1. Orthogonal experimental method

To evaluate the influence of these factors and performances of SMA, we use the orthogonal experimental design method. The method studies the influence of many factors in experiments. Based on methods of scientifical experiment, orthogonal method has advantages in minimizing numbers of experiments, in order to reduce time and cost for doing experiments. In fact, this method is very efficient, fast and economical. The order for the design and analysis of experimental results according to the orthogonal experiment method can be divided into three steps: experimental plans design, perform experiment and analysis of experimental results.

2.2.2. Orthogonal experimental design

Many factors affect the properties and performance of SMA that divided into three groups: material, disgn and construction factors. If all materials that form this mixture are qualified and mineral aggregate gradation is according to the standard requirements, three design factors are: Asphalt content (L) which is the percentage ratio of asphalt to mineral aggregate (coarse aggregate, fine aggregate and mineral filler); Fiber content (X) which is the percentage ratio of lignin fiber to mineral aggregate; and Filler content (K) which is the percentage ratio of mineral filler to mineral aggregate.

For studying the effect of the three factors mentioned above, based on the guidance on the norms (JTG F40-2004, 2004; JTJ 052-2000, 2000) and refer to some research results, four levels of each factor are selected. Table 2 indicates the orthogonal test factors and levels.

Table 2. Selected levels of three factors

Levels	Factor		
	Asphalt content L (%)	Fiber content X (%)	Filler - content K (%)
1	5.8	0.28	9
2	6.2	0.32	10
3	6.6	0.36	11
4	7.0	0.40	12

Based on the results of the mineral aggregate sieving test and SMA-16 gradation requirements (JTG F40-2004, 2004), the combined ratio of mineral materials obtained as follows: 10 - 20 crushed stone ratio is 57%, 5 - 10 crushed stone ratio is 18%, 3 - 5 crushed stone ratio is 5%, and fine aggregate and mineral filler is 20%. Corresponding to four different fine aggregate and mineral filler ratios there are four SMA-16 mineral aggregate gradations as shown in Table 3.

Table 3. SMA-16 gradation requirements and four aggregate gradations

Sieve size (mm)	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Gradation 1	100	95.1	81.9	53.7	25.3	18.2	15.8	13.4	11.3	9.9	8.6
Gradation 2	100	95.1	81.9	53.7	25.3	18.4	16.2	14.0	12.1	10.8	9.4
Gradation 3	100	95.1	81.9	53.7	25.3	18.6	16.5	14.6	12.9	11.6	10.2
Gradation 4	100	95.1	81.9	53.7	25.3	18.7	16.9	15.2	13.7	12.5	11.0
upper limit	100	100	85	65	32	24	22	18	15	14	12
lower limit	100	90	65	45	20	15	14	12	10	9	8

Table 3 shows that all four-level specifications meet SMA-16 gradation requirements (JTG F40-2004, 2004); the difference is due to the amount of fine aggregate and mineral filler. Orthogonal experiment method (Zheng Shaohua, Jiang Fenghua ed, 2003) is used to design sixteen experimental groups of Marshall test. The specific orthogonal experiment scheme is shown in Table 4.

2.2.3. Marshall test

For the Marshall test (JTJ 052-2000, 2000), four specimens for each group were manufactured following Marshall standard (101.6 mm in diameter and 63.5 ± 1.3 mm in height). Each specimen was compacted with 75 pens per side then was left in the mold and maintained in a period of 48 hours.

After 48 hours, the sample will be removed from the mold and tested will be tested to determine the bulk specific gravity (G_{mb}), Marshall stability (MS - Marshall stability at 60^0C, 30 min water immersion), Marshall flow value (FL), air void (AV), voids in mineral aggregate (VMA) and voids filled asphalt (VFA). Figure 2 shows photographs of samples and experiment equipment.

a) Samples is soaking in constant temperature pool b) Samples and Marshall experiment

Figure 2. The photographs of samples and experiment equipment

2.2.4. Water stability test

Residual stability test[6] was used to evaluate the water stability of the SMA mixture. The experiment is also done by the Marshall machines with two sample groups: (i) Marshall experiments for the normal specimen group, and (ii) the other sample group was soaked in water for 48 hours. Water Stability is assessed through Residual stability indicators which is determined as the formula 01:

$$MS_0 = \frac{MS_2}{MS_1} \times 100,\% \qquad (1)$$

Where: MS_2 is Marshall stability at 60^oC, after 48h water immersion; MS_1 is Marshall stability at 60^oC, 30min water immersion and MS_0 is residual stability at 60^oC, after 48h water immersion.

2.2.5. High temperature stability test

To evaluate the high temperature stability of the SMA mixture, the Rutting test was conducted. The wheel tracking test was utilized to measure rutting resistance of the specimens. The square slab specimen with 300 mm long, 300 mm wide and 50 mm thick. The experiment was performed on rutting test equipment, which is shown in Figure 3.

a) Equipment is connected computer

b) Samples in rutting test equipment

Figure 3. Samples and rutting test equipment

The samples was immersed in dry atmosphere at 60 ± 0.5°C for 5 to 24 hours; subsequently a wheel pressure of 0.7 MPa ± 0.05MPa was applied onto the specimen; the traveling speed of the wheel was 42 ± 1cycles/min; the wheel was loaded to test for 60 minutes. High temperature stability is assessed by dynamic stability (DS), it is determined as formula 2 (JTJ 052-2000, 2000):

$$DS = \frac{42 \times 15}{d_{60} - d_{45}} \qquad (2)$$

Where: DS is the dynamic stability (cycle/mm); d_{60} and d_{45} is the rutting depth (mm) at 60min and 45min; 42 is the speed (cycle/min) and 15 is the time difference (min).

III. RESULTS AND DISCUSSION

3.1. Orthogonal experimental results

Table 4. Marshall orthogonal test results

TT	L (%)	X (%)	K (%)	G_{mb}	MS (kN)	V_a (%)	VMA (%)	VFA (%)
1	1(5.8)	1(0.28)	1(9)	2.42	8.58	5.48	18.50	69.73
2	1	2(0.32)	2(10)	2.42	8.87	5.51	18.57	69.60
3	1	3(0.36)	3(11)	2.41	8.81	6.13	19.15	67.13
4	1	4(0.4)	4(12)	2.40	8.49	6.19	19.26	66.89
5	2(6.2)	1	2	2.44	10.19	4.21	18.16	76.30
6	2	2	3	2.44	10.85	4.44	18.40	75.25
7	2	3	4	2.43	9.40	4.58	18.57	74.62
8	2	4	1	2.44	8.99	4.44	18.50	75.24
9	3(6.6)	1	3	2.44	9.20	3.82	18.56	78.98
10	3	2	4	2.43	9.10	4.03	18.79	78.00
11	3	3	1	2.43	7.98	4.10	18.90	77.71
12	3	4	2	2.44	8.26	3.81	18.61	79.00
13	4(7.0)	1	4	2.43	8.72	3.81	19.28	79.85
14	4	2	1	2.43	7.78	3.67	19.22	80.45
15	4	3	2	2.43	8.00	3.65	19.24	80.51
16	4	4	3	2.42	8.47	3.88	19.49	79.48
Requirement (JTJ 052-2000, 2000)					≥ 6	3 - 4.5	≥ 16.5	70 - 85

Based on designed orthogonal experiment plan and experimental procedures the study determines: bulk specific gravity (G_{mb}), Marshall stability (MS), Marshall flow value

(FL), air void (VV), voids in mineral aggregate (VMA) and voids filled asphalt (VFA). The test results are shown in Table 4.

3.2. Optimal scheme analysis

From the results of experiments conducted orthogonal analysis, the results analysis are obtained in Table 5 and Table 6.

Table 5. F values of the variance analysis of Marshall indexes

Factor	G_{mb}	MS	V_a	VMA	VFA	$F_{0.05}$	$F_{0.01}$
L	64.27	9.16	335.44	70.88	628.20	2.800	4.220
X	9.60	2.96	7.14	14.42	7.67	2.800	4.220
K	10.78	2.13	9.62	10.76	10.25	2.800	4.220

(Note: $F_{0.05}$ - significant at 95% probability; $F_{0.01}$ - significant at 99% probability).

Table 6. Results of general equilibrium analysis

Indicator	Parametric analysis	L (%)	X (%)	K (%)
Specific gravity - G_{mb}	K_1	38.614	38.927	38.882
	K_2	38.980	38.884	38.931
	K_3	38.968	38.794	38.815
	K_4	38.841	38.798	38.775
	The variance S	0.0054	0.0008	0.0009
	Optimal scheme		L2X1F2	
Marshall stability - MS	K_1	138.990	142.990	137.060
	K_2	157.680	150.090	141.230
	K_3	138.140	136.770	149.310
	K_4	131.870	136.830	139.080
	The variance S	23.2502	7.5046	5.4077
	Optimal scheme		L2X2F3	
Air void - V_a	K_1	93.231	69.258	70.742
	K_2	70.710	70.600	68.722
	K_3	63.031	73.859	73.081
	K_4	60.046	73.301	74.473
	The variance S	42.2206	0.8993	1.2108
	Optimal scheme		L4X1F2	
Voids in mineral aggregate - VMA	K_1	301.916	297.998	300.462
	K_2	294.523	299.925	298.292
	K_3	299.454	303.437	302.425
	K_4	308.892	303.425	303.607
	The variance S	6.7066	1.3645	1.0184
	Optimal scheme		L4X3F4	
Voids filled with asphalt - VFA	K_1	1093.433	1219.425	1212.538
	K_2	1205.618	1213.250	1221.635
	K_3	1254.799	1199.889	1203.412
	K_4	1281.158	1202.444	1197.422
	The variance S	1291.9541	15.7815	21.0737
	Optimal scheme		L4X1F2	

As can be seen from Table 5: all three factors have significant influence on the Marshall indexes of SMA; of these three ratios, asphalt content has the most significant influence. Only the F value corresponding to the influence of filler content on Marshall Stability is smaller than the value of $F_{0.05}$, other values are also greater. This suggests that, influence of asphalt content and fiber content to Marshall indexes are very clear; with respect to filler content, except that influence to Marshall stability is not clear, the other indexes are significantly influenced.

From Table 4, exception of Air void and Voids filled with asphalt when asphalt content less than 6.2% is not satisfactory, when asphalt content from 5.8% to 7.0% all other indexes of SMA are satisfactory. Therefore, the selection of optimal values of plastic content, fiber content and filler content are mainly based on the consideration of Air void; Voids filled asphalt is satisfactory or not; and Marshall stability is big or small.

From test results can be seen, when asphalt content from 6.2% to 7.0% both of Air void and Voids filled asphalt are satisfactory; Marshall stability is biggest when asphalt content is of 6.2%. Therefore, selection the optimum asphalt content value of 6.2% is very reasonable, ensuring not only economical but also technical properties.

Based on Air void and Voids filled with asphalt from test result analysis on Table 6, fiber content of 0.28% is reasonable. Based on Marshall stability the reasonable fiber content is of 0.32%. When asphalt content of 6.2%, fiber content of 0.28% and 0,32% then Air void and Voids filled asphalt are satisfactory. Therefore, the average value of 0.30% can be selected as the optimal fiber content.

Table 6 also shows that the reasonable filler content is 10%. When filler content is 11%, the Marshall stability is biggest. From test results show that when asphalt content is 6.2% and filler-aggregate ratio is 10% or 11%, Air void and Voids filled with asphalt are both satisfactory. Accordingly, the average value (10,5%) can be chosen as the optimal filler content. These optimal values are also within the limits as some previously published studies on SMA.

3.3. Checking the basic properties of SMA

The combined analysis results, material components selection for manufacturing SMA-16 is shown in Table 7.

Table 7. Results of selected material component for manufactured SMA-16

L, %	X, %	K, %	Crushed stone (10 - 20 mm)	Crushed stone (5 - 10 mm)	Crushed stone (3 - 5 mm)	Fine aggregate (< 3 mm)
6.2	3.0	10.5	57	18	5	9.5

With manufactured material components as in Table 7, the sample groups for Marshall test, Residual stability test and Rutting test are manufactured to check the reliability of the results of orthogonal analysis. The checking results are shown in Table 8.

Table 8. Checking results of SMA-16 samples

Indicator	G_{mb}	MS (kN)	VV (%)	VMA (%)	VFA (%)	MS_0 (%)	DS (cycle/mm)
Measurement results	2.437	10.09	4.07	18.34	76.85	83.35	6790
Request (JTG F40-2004, 2004)	-	≥ 6	3～4.5	≥ 16.5	70～85	≥ 80	≥ 3000

Table 8 shows that, all of Marshall stability (MS), Residual stability (MS_0) and Dynamic stability (DS) are satisfied; in which, Dynamic stability is twice greater than required showing that the component alternatives is very reliable.

IV. CONCLUSION

Taking SMA-16 mixture as an object of research, this paper analyzes the influence of asphalt content, fiber content and filler content to mixture properties and design component. The study results showed: only the influence of filler content to Marshall Stability is not clear; the effect of asphalt content, fiber content and filler content to Marshall indexes are very clear. When design and construction of SMA need to pay considerable attention to the asphalt content and fiber content. When using the same manufactured material of SMA-16 mixture the optimal value of asphalt content, fiber content and filler content are in turn of 6.2%; 3.0% and 10.5%, respectively. However, this result is consistent with the material and climatic conditions of northern China area; In other areas, especially in the hot and humid climate as Vietnam, when designing and executing SMA also need to check these optimal values.

Through examination of basic SMA properties showing that the selected results of material composition according to experimental methods and orthogonal analysis are completely ensure reliability.

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NGHIÊN CỨU HỖN HỢP SMA
BẰNG PHƯƠNG PHÁP THIẾT KẾ THÍ NGHIỆM TRỰC GIAO

Đặng Văn Thanh[1], Phạm Văn Tỉnh[2]
[1,2]*Trường Đại học Lâm nghiệp*

TÓM TẮT

Mát tít nhựa đá dăm (SMA) là loại bê tông nhựa kiểu mới đã và đang được nghiên cứu ứng dụng ở nhiều nước trên thế giới trong việc xây dựng mặt đường ô tô. Đây là loại bê tông nhựa nóng, được tạo thành từ hỗn hợp mát tít nhựa lấp đầy lỗ rỗng của đá dăm cấp phối gián đoạn được hình thành theo nguyên lý Macadam (đá chèn đá). Bằng phương pháp thiết kế thí nghiệm trực giao và các thí nghiệm bê tông nhựa trong phòng, trong đó nổi bật là các thí nghiệm: Marshall, Marshall ngâm nước, Lún vệt bánh xe - nghiên cứu đánh giá sự ảnh hưởng của một số yếu tố thuộc về thành phần vật liệu chế tạo, bao gồm: hàm lượng nhựa, hàm lượng sợi và hàm lượng bột khoáng đến các tính năng cơ bản của hỗn hợp SMA dùng xây dựng mặt đường ô tô đã được trình bày trong bài báo này. Kết quả nghiên cứu chỉ ra rằng, sự ảnh hưởng của ba yếu tố này đến các tính năng cơ bản của hỗn hợp SMA là rất rõ rệt. Nghiên cứu cũng đã đề xuất được trị số tối ưu của hàm lượng nhựa, hàm lượng sợi và hàm lượng bột khoáng dùng cho hỗn hợp SMA-16 lần lượt là: 6,2%; 0,30% và 10,5%.

Từ khóa: Độ ổn định còn lại, độ ổn định Marshall, hỗn hợp SMA, lún vệt bánh xe, thí nghiệm trực giao.

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