The technology of warm mix asphalt for use in the pavement structure of undersea tunnel

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ABSTRACT: According to the pavement environmental features and traffic characteristics of Qing-Huang undersea tunnel, the article has developed systematic study on the design of the pavement structure and materials. This paper has established a mechanics analysis model for undersea tunnel to Analyze the effect on the Pavement Structural Stress which caused by the inter-layer bonding conditions. By the study on the rheological properties of modified asphalt and pavement performance of its warm mix asphalt, this paper puts forward material technical index and pavement design method which is suitable for warm mix asphalt pavement of undersea tunnel.

KEY WORDS：Warm mix asphalt, pavement structure, undersea tunnel technical index, pavement design method.

1 INTRODUCTION

Tunnel is a throat of the highway communication, it has an important role to control the communication. The condition of the tunnel pavement has plays a greater impact on the road safety and driving comfort. Climatic conditions, traffic conditions and subgrade support conditions of undersea Tunnel is different from the normal road surface, has its own peculiarities. In order to ensure the durability and good service property, the pavement structure should have excellent slip resistance, sound absorption and oil flame retardant; Good water stability and corrosion of salt; excellent structural durability; Maintain a good environment for the construction.

2 PERFORMANCE TEST OF ASPHALT BINDER AND ITS MIXTURE

The WAM (warm mix asphalt mixture) Technology is now available to decrease HMA(hot mix asphalt mixture) production temperature by 15℃to over 50℃. These relatively new processes and products use various mechanical and chemical means to reduce the shear resistance of the mixture at construction temperatures while maintaining or improving pavement performance.The technology achieves a smoke-free operation and greatly improves the construction environment, then can ensure the construction quality.

2.1 Performance Test of Asphalt Binder

The SHRP PG (Performance gradation) of asphalt binder is related with the average 7d maximum design temperature and the minimum design temperature of the pavement. In this paper, respectively take the SBS modified bitumen and SBS modified asphalt mix which was added Evotherm^{TM}-DAT warm agent as example to put to the test of conventional indicators and SHRP PG.

2.1.1 Low-temperature Performance

（1）Ductility test

Table1: Ductility test of asphalt binder

item	SBS modified asphalt	SBS modified asphalt+Evotherm^{TM}
5℃ductility	24	34.0
10℃ductility	59	69.0
RTFOT		
5℃ductility	15.5	19

As can be seen from the above test results, after adding EvothermTM, whether it is 5 ℃ductility or 10 ℃ ductility and whether it is original sample or the sample treated after RTFOT, the ductility of binder has a certain degree of increases. It shows that the low-temperature ductility of asphalt binder has been improved after adding EvothermTM, which is beneficial to low-temperature performance of asphalt mixture.

（2）The test of bending creep stiffness modulus(BBR)

It can be seen from the test result, the stiffness modulus of the SBS modified asphalt which was added Evotherm^{TM} agent is closed to SBS modified asphalt which did not added, but the value of the slope m values were somewhat lower. It's indicating that the low-temperature deformation properties of the asphalt produced a certain amount of weakening after Evotherm^{TM} agent added. However it is still within the same SHRP PG, belongs to the same PGxx-22.

Table 2: Asphalt Binder bending creep stiffness test（BBR)

condition of experiment	Item	Asphalt type	
		SBS modified	SBS odified+ Evotherm^{TM}
After PAV （-6℃）	Creep stiffness modulus G*	50.7	85
	m values	0.44	0.419
After PAV （-12℃）	Creep stiffness modulus G*	141	141
	m values	0.354	0.327
After PAV （-18℃）	Creep stiffness modulus G*	314	320
	m values	0.282	0.257

2.1.2 High-temperature performance

In this paper, using Dynamic Shear Rheometer (DSR) to analysis the rutting factor (G */sin δ) and the fatigue factors (G *. sin δ), to evaluate the effect on the high-temperature properties of asphalt binder which caused by the Evotherm^{TM} agent and to evaluate the changes in the aging factor. The asphalt binder including SBS modified bitumen before and after aging, and the SBS modified bitumen which was added Evotherm^{TM} agent.

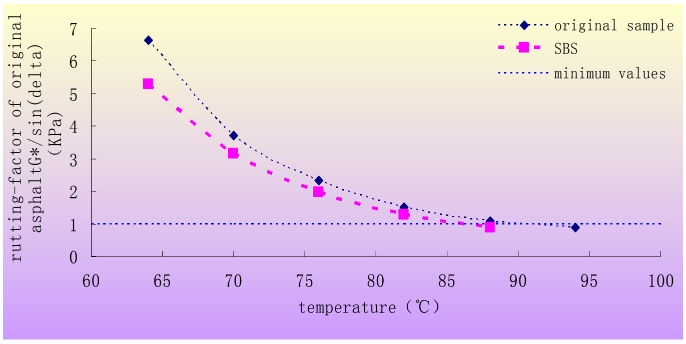

Figure1：Rutting-factor of original asphalt $G^*/\sin\delta$

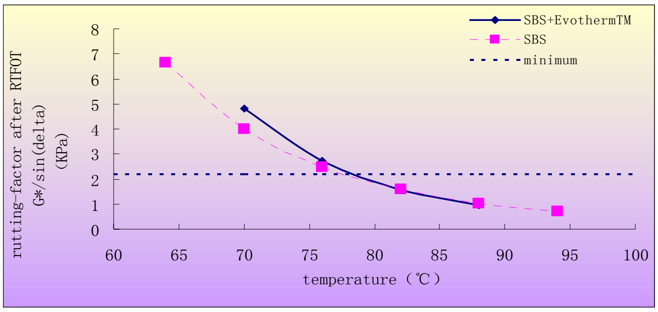

Figure 2: Rutting-factor of asphalt after RTFOT G*/sinδ

As is shown in figure 2, the high-temperature rating of the SBS modified asphalt which be added the EvothermTM agent is the same as the original SBS modified, both belongs to PG76-xx. the rutting-factor of the SBS modified asphalt which was added the EvothermTM agent is higher than the SBS modified asphalt at the temperature of 76℃, its shows that the anti-rutting capacity of the asphalt added the EvothermTM agent is Slightly better than the SBS modified asphalt.

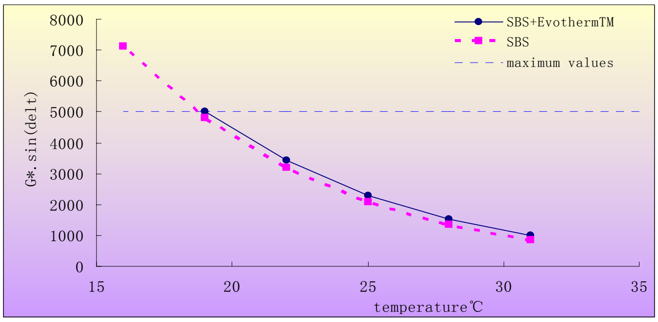

Figure 3: fatigue factor of asphalt binder

Table 3: Fatigue factor of asphalt binder

Binder type	Temperature,℃	fatigue factor sinδ.G*,Kpa
SBS+Evotherm^{TM}	19.1	5000
SBS	18.7	5000

By SHRP PG, the SBS modified asphalt with the same classification performance of the SBS modified asphalt added Evotherm^{TM} agent are part of PG 76-22.

As can be seen from the analysis on the high and low temperature performance of asphalt, the high-temperature performance of asphalt has increased after adding Evotherm^{TM} agent, the changes in the rate of stiffness of SBS modified asphalt added Evotherm^{TM} agent is slightly lower than original SBS modified Asphalt, that is, m value is smaller, but little impact. And the SBS modified asphalt cement added Evotherm^{TM} low-temperature ductility is larger than the original asphalt cement. It shows that its low-temperature Anti-cracking performance is good.

It can be seen that the Evotherm^{TM} has little effect on the low temperature performance of Asphalt Binder, but it improves the high-temperature performance of Asphalt Binder

2.2 Test of Asphalt Mixture

2.2.1 the determination of mixing and rolling temperature for WAM

In this paper, study on the high and low temperature performance and dynamic modulus of asphalt mixture, as to SMA10，for an example. Under the optimum asphalt content in accordance with the different mixing and compaction temperature to experiment on the hot mix asphalt and WAM, and according voidage to determine the mixing and compaction temperatures, test results as shown in the table4.

Table4: SMA10 mixing and compaction performance test

Temperature，℃	115	125	130	135	140	160	170
The voidage of SMA10，%	6.8	5.9	5.5	5.1	5	4.6	4
The voidage of WAM SMA10，%	5.8	4.3	4.3	4.1	3.9		

To ensure the voidage of SMA10 around 4%, the discharge temperature of WAM SMA10 only requires 140 ℃, thus the mixing and rolling temperature of WAM can reduce 30 ℃ around than HMA (the temperature usually at 170 ℃).

2.2.2 Performance test of asphalt mixture

High and low temperature performance test results of WAM as shown in the table 5.

Table5：Performance test of asphalt mixture

Item	SMA-10		
	Technical requirement	SBS modified asphalt	SBS modified asphalt +evotherm
TSR,%	>80	89	92.6
Stability	>6	10.2	9.6
trabecular low temperature bending strain,$\mu\varepsilon$	>2800	3860	3585
Dynamic stability（times/mm）60℃,0.7MPa	>2800	4815	5165
Drainage Test,%	<0.1	0.03	0.02
Cantabro Test,%,<15	<15	2.5	3.1

2.2.3 Hamburg wheel-tracking rut test

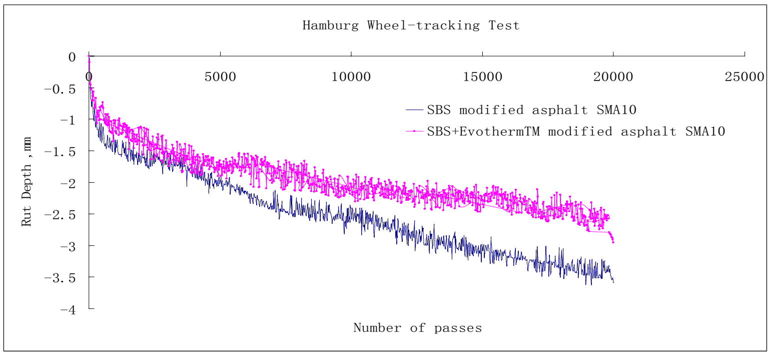

Figure4：Deformation curve of WAM SMA10 added Evotherm^{TM} and HMA SMA10

Table6：Hamburg wheel rut test results

Item	Mixture type	Deformation of recording sites	the deformation after10000times rolling ,mm	the deformation after20000times rolling ,mm	stripping point （times/mm）
SBS modified asphalt	SMA-10	the mean value of 3 and 9 point	2.685	3.59	NO
SBS+Evotherm^{TM} modified asphalt	SMA-10	the mean value of 3 and 9 point	2.01	2.95	NO

The WAM SMA10 Hamburg wheel rut test performance is good, it does not appear stripping point within the specified rolling times and its deformation is less than the HMA SMA10, and the deformation is smaller after 20000 rolling times.

All these show that its water sensitivity and anti-rutting performance is better than HMA SMA-10, is fully capable to meet the high-temperature and water stability.

3 MECHANICAL ANALYSIS OF PAVEMENT STRUCTURE

The strength of the base and subgrade inside the tunnel is higher, which causes the stress under the pavement be the compressive stress, and the deflection of the composite pavement surface smaller. Thus the checking indicators of the tensile stress under the pavement and the deflection index of pavement design be unavailable for the composite pavement design inside tunnel.

The good bonding condition between the asphalt layer and the CRCP is the assurance for the pavement quality, Interlaminar shear stress and bond strength is of important factors for the bonded status between layers. The interlaminar shear stress and the thickness of the pavement structure have a close relationship. To ensure the shear stress underside of the asphalt pavement less than the shear strength between layers is a sufficient condition to maintain the status of bonding condition between layers. On the other hand, the micro-crack in the surface of CRCP will be expand under the repeated load, in this cases, the stress near the crack will be increased. In order to ensure the tunnel road driving quality, it needs to consider the extension of the cracks in CRCP under the special environment and the load inside tunnel, and the Asphalt layer thickness impact on the extended performance of the cracks.

In this paper, to consider comprehensively the environmental conditions, traffic conditions, the base conditions and the structural characteristic of the CRCP+AC composite pavement inside undersea tunnel. Intending to take into account the two directions to consider the parameters impact on the asphalt layer thickness inside the tunnel：one is to ensure the shear strength between the cement concrete layer and the asphalt concrete layer meet the traffic requirements; the other is to ensure non-occurrence of unstable crack extension.

In this paper, using 8-node structure to analysis element, that is solid 45. Reinforcement ratio is controlled by the temperature and humidity changes. In this paper, according the character of the undersea tunnel pavement, Determined by calculating the ratio of reinforcement was 0.65%. To investigate the previously paved CRCP, found that the transverse crack spacing is usually between 1.0 ~ 2.5m; To calculate by finite element, found that when the rear axle loads on the same sides of the edge of transverse cracks, the critical stress value is maximum. Finite element model as shown in Figure5.

The tire contact pressure is 0.7MPa, Horizontal Force coefficient is the mean value of emergency braking force coefficient and the normal moving, taken as 0.35.

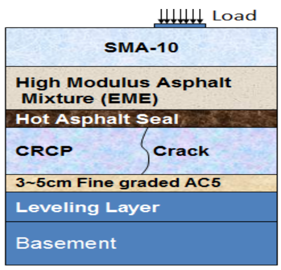

Figure5: Mechanical calculation model

Table7：Parameter used for finite element analysis

	modulus（MPa）						Poisson ratio μ
	5℃	10℃	20℃	30℃	40℃	50℃	
SMA10	4943	4368	3213	2124	1187	491	0.3
EME0/14	12750	8997	3941	1400	461	238	0.3
AC5	5000	3255	1149	352	223	121	0.3
Concrete slab	30000						0.2
Steel bar	200000						0.3
Leveling layer	15000						0.25
Roadbed	5000						0.25

Table8： Shear stress between the asphalt layer and CRCP

Asphalt pavement thickness, cm		6	8	10	12	15
shear stress ,MPa	Horizontal force coefficient, 0.35	0.292	0.276	0.252	0.243	0.239
	Horizontal force coefficient, 0.5	0.312	0.297	0.273	0.264	0.259

As can be seen from table 8, the interlaminar shear stress is decreases with the increase of the asphalt pavement thickness. When it reaches a certain thickness, the shear stress drop slowed down. The interlaminar shear stress results shown in table9.

Table9: shear strength of the bonding layer

temperature（℃）	25℃	35℃	45℃	55℃
Hot SBS modified asphalt seal coat	1.16	0.57	0.35	0.28

As can be seen from table 9, the shear strength between the asphalt layer and the CRCP dropped significantly with the temperature increase. However, taking into account the temperature changes inside the tunnel relatively small and the maximum temperature only about 50℃, we can determine the minimum thickness of the asphalt layer is no less than 9cm through the interlaminar shear stress calculation.

The shear stress is the main factor to cause the slip-type crack. Based on the fracture criterion of the maximum circumferential tensile stress, the conditions of crack unstable extended As shown in Equation (1)

$$K^* = \cos\tfrac{\theta^*}{2}\left[K_{\mathrm{I}}\cos^2(\tfrac{\theta^*}{2}) - \tfrac{3}{2}K_{\mathrm{II}}\sin\theta^*\right] \geq K_{IC} \qquad (1)$$

K^*:composite Stress Intensity Factor; θ^*: the crack propagation angle; K_I: open-type crack Stress Intensity Factor; K_{II}: slip-type crack Stress Intensity Factor; K_{IC}: fracture toughness of the material shear-type cracks

There is a large number of cracks in the CRCP, the concrete slab will produce constringency when Ambient temperature to reduce. This constringency will be restricted by the friction between overlying asphalt layer, CRCP and leveling layer, then will produce stress between these layers. The longer the CRCP The more strongly the displacement Trends of the end, the stress under the asphalt layer will also be greater. In order to make the calculate results have a certain universality, to take the length of the CRCP is 2m. According to the climatic and environmental conditions of the undersea tunnel, take the maximum temperature gradient is 40℃, the uniaxial load is 100kn and the horizontal force coefficient is 0.3.

As can be seen from the table 10, the crack cause a large KI in the asphalt pavement, to increase the thickness of the asphalt layer help to reduce the value of the crack tip stress intensity factor.

Table10: stress intensity factor at the crack

Thickness of the layer ,cm	6	8	10	12
K_{I} ,kn/cm^2	0.9654	0.8652	0.7689	0.7248
K_{II} ,kn/cm2	0.03764	0.03564	0.03329	0.03189

Composite stress intensity factor as shown in the table11, according to the fracture toughness KIC generally around 0.7, in order to ensure that composite asphalt pavement does not occur Reflective cracking damage, the thickness of the asphalt layer should not be less than 10cm.

Table11:composite stress intensity factor

Thickness of asphalt layer（cm）	6	8	10	12
Composite stress intensity factor K*（kn/cm^2)	0.9681	0.8681	0.7218	0.6876

In this paper, to separately calculate the asphalt layer shear stress in the state of continuous layer, interlayer adhesion, as well as a state of interlayer slip, and to calculate the fatigue life of the pavement structure. As shown in table12.

Table 12: asphalt pavement stress and fatigue life

Interlayer bonding state	Asphalt layer shear stress	Tensile stress under the asphalt layer	Fatigue life of asphalt layers
continuation	0.298	0.01367	4.1×10^{13}
Adhesion	0.319	0.1211	8.8×10^{8}
smooth	0.338	0.2268	9.5×10^{7}

When the bonding condition between the Composite Pavement Layers change from fully continuous and conditional continuous to discontinuous state, the maximum shear stress in the asphalt pavement Constantly increasing, but the increase range is not large. This shows that the bond condition between layers have little influence on the maximum shear stress.

It can be seen that the attenuation of the bonding between layers will lead to life dramatically reduced. The maximum water depth of The Qing-Huang undersea tunnel is 42 meter and the maximum longitudinal gradient is 4%. Finally, through experimental studies and mechanical analysis to determine the pavement structure is 4cmSMA10+6cm HMA(EME)+Hot Asphalt Seal+22cm CRCP+3cm Fine Grade AC5+20cmLeveling Layer+ Basement .

In this pavement structure project, The warm mix technology can reduce dust emissions and improve the construction environment without loss of compaction. The SMA wearing surface can achieve anti-rutting, anti-sliding, sound absorption and durability function layer. The high modulus asphalt concrete has good anti-fatigue properties, Watertight performance and excellent Resistance to permanent deformation properties. CRCP has the performance of high intensity, durability and good structure integrity.

Fine graded AC5 has the properties of more asphalt content, smaller porosity and fine-graded. This asphalt mixture has anti-cracking performance under low temperature, good anti-fatigue properties. This asphalt mixture has good watertight properties, it is beneficial to block the passage of groundwater upwelling, avoid the moisture vitiate the bonding layers and avoid the corrosion of the steel bars. The Leveling effect of fine-graded AC5 is very good and this asphalt mixture has excellent anti-rutting properties.

4 SUMMARY

(1) The performance of EvothermTM technology based WAM is not worse than HMA, and it high temperature stability and water stability is superior to HMA.

(2) to the composite pavement structure inside the tunnel, to increase the thickness of the asphalt layers is beneficial to reduce the shear stress between asphalt layer and CRCP then can extend the pavement life.

(3) the thickness of the asphalt pavement inside Qing-Huang undersea tunnel should not be less than 10cm.

(4) the asphalt mixture design of composite pavement inside the undersea tunnel can controlled by the shear stress index.

(5) to composite asphalt pavement, the bonding condition between the asphalt layer and CRCP have remarkable impact, in order to extend the pavement life, pavement structural layer should have good inter laminar bond strength and better ability to maintain the bond between layers.

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