MECHANISM OF REDUCING ROAD/TIRE NOISE WITH DIFFERENT NMAS ASPHALT MIXTURE

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ABSTRACT

The main objective of this research is to analyze the relationship between the Nominal Maximum Article Size (NMAS) and Road/Tire noise based on bitumen mixture visco-elastic behavior. The dynamic complex modulus test, static compressive resilient modulus test, dynamic compressive resilient modulus test are employed to evaluate the visco-elastic behavior of mixtures, and standing wave tube method is employed to measure the noise absorption effect of mixtures. Five bitumen mixtures with various NMAS are measured under multiple frequency level and temperature. Shown as test results, Under same air void level, the phase angle show increasing trend with the decreasing of NMAS, Generally, the hypothesis has been proved by other studies that the more viscous, the smaller road/tire noise. So the bitumen mixture with small NMAS potentially produced lower road/tire noise.

Keywords: nominal maximum aggregate size, road/tire noise, phase angle, SPT

1. Introduction

As a sustainable and environment friendly pavement technique, the quiet pavement is potential one in the future, in the past decade years, many researchers have involved it. The results illustrate that The Nominal Maximum Article Size (NMAS) is one of the most important factors for pavement road/tire noise. In general, open graded bitumen pavement with small aggregate size has good potential for reducing noise. (Robert.B., Roger L.W., 2005, Keith H.,2004). And there will be as much as 14dBA differences between the noisiest and quietest pavement under similar traffic conditions. Former researches indicate that the recommended value of NMAS will range from 4 to 6mm for light traffic and 6-10mm for heavy traffic (Nilsson, R., Nordlander, J., Sliwa, N.,2005). And this conclusion has been verified by the results measured in 68 roads in Europe and more than 200 roads in UA (Paul.R.D., 2002). European highway agencies have found that the proper selection of the pavement surface can be an appropriate noise abatement procedure. Specifically, they have identified that a low noise road surface can be built at the same time considering safety, durability and cost using one of the following approaches:(Douglas I. H, Robert S. J and Christopher N., 2004)

1. A surface with a smooth surface texture using small maximum size aggregate.
2. A porous surface, such as an open-graded friction course (OGFC) with a high air void content.
3. A pavement-wearing surface with an inherent low stiffness at the tire-pavement interface.

On the other hand, the mechanism of noise reduction is also researched, especially the relationship between the visco-elastic characteristic and noise reduction effect of bitumen mixture. Such as the dynamic modulus, phase angle etal. parameters which reflect the visco-elastic characteristic of mixture. Krishna P. B. (2008) Used Simple Performance Tester (SPT) to measure and analyze the dynamic modulus and phase angle, achieved the relationship between dynamic modulus and phase angle and the noise reduction effect, the results illustrated that the larger viscosity the better noise reduction effect.

2. Objective and Scope

The visco-elastic behaviour and the NMAS are the two main influence factors for road/tire noise, but more researches focus on the relationships between NMAS and road/tire noise, Actually, The visco-elastic behaviour of bitumen mixture has direct correlation with Road/Tire noise, and require to research deeply. So in this study, visco-elastic behaviour for different NMAS bitumen mixtures are measured, as well as the acoustic response of each mixtures are measured, the relationships between these two are investigated.

In this project, The NMAS of mixture is 4.75mm、7.2mm、9.5mm、13.2mm and 16mm respectively, Denominate as SAC-X, shown in Tab.2. The binder is same. And the target air void of mixture is 5% uniformly, under this requirement, the corresponding bitumen /aggregate ratio (the mass ratio of bitumen and aggregate) and bulk gravity of mixtures mean values are measured and shown in Tab.3.

Tab. 2 Gradations for test

	Passing rate (%)											
Sieve(mm)	19	16	13.2	9.5	7.2	4.7	2.36	1.1	0.6	0.3	0.1	0.07
SAC-16	100	97.5	80.9	58.8	44.9	30.0	23.5	18.4	14.5	11.4	8.9	7.0
SAC-13		100	97.5	66.7	48.5	30.0	23.5	18.4	14.5	11.4	8.9	7.0
SAC-10			100	97.5	60.8	30.0	24.0	19.2	15.5	12.4	10.0	8.0
SAC-7.2				100	97.5	62.8	30.0	23.6	18.6	14.6	11.5	9.0
SAC-4.75					100	97.5	30.0	24.1	19.4	15.6	12.5	10.0

Tab.3 Bitumen/ aggregate ratio and bulk gravity of various bitumen mixture

Mixture	Air Voids	Bitumen Aggregate Ratio (%)	Bulk Gravity （g/cm^3）
SAC-16	5%	4.31	2.4798
SAC-13.2	5%	4.84	2.4564
SAC-10	5%	5.19	2.4529
SAC-7.2	5%	5.03	2.4395
SAC-4.75	5%	8	2.3625

Here, three tests methodologies are employed to analyze the visco-elastic behaviour. Refer to Dynamic complex modulus, static resilient modulus and Dynamic resilient modulus test.

1) Dynamic complex modulus testing is completed by Simple Performance Tester(SPT). The character indexes of dynamic complex modulus curve and phase angle curve are collected. The samples are prepared as design volumetric criterion column with 150mm height, 100mm diameter, 6 replicates for each test.

2) Static resilient modulus and Dynamic resilient modulus. is completed by Material Test System(MTS)-810, The samples are prepared as design volumetric criterion column with 100mm height, 100mm diameter, 6 replicates for each test.

On the other hand, for acoustic test, The standing wave tube methodology is employed, the noise reduction coefficient is the selected index, and the dimension of specimen is also 100mm height, 100mm diameter.

3. Testing and data analysis

3.1 SPT Testing and Master Curve of Dynamic Modulus and Phase Angle

Base on the test data of dynamic complex modulus and phase angle, Master curve is constructed using the principle of time-temperature superposition. First a standard reference temperature is selected, then data at various temperatures are shifted with respect to time until the curves merge into a single smooth function.

Previous studies indicate that dynamic complex modulus master curve is referenced as the Sigmoid model, and phase angle master curve is referenced as the GaussAMP model, as formula 3 and 4.

$$\log(|E^*|) = \delta + \frac{\alpha}{1+e^{\beta-\gamma\cdot\log\omega_r}} \qquad (3)$$

Where: ω_γ -loading frequency under reference temperature, Hz; β,γ are parameters describing shape of Sigmoid curve; δ -logarithm of minimum value of dynamic modulus; $\delta+\alpha$ -logarithm of maximum value of dynamic modulus;

$$\varphi = \varphi_0 + A\cdot e^{-\frac{(\log\omega_r-\omega_c)^2}{2w^2}} \qquad (4)$$

Where: φ -phase angle; ω_γ -loading frequency under reference temperature, Hz; ω_c -loading frequency corresponding to peak value of phase angle master curve;

3.2 Static Compressive Resilient Modulus Test (SCRMT)

In the USCRMT, the loading model is multi-level load. For each level, loading rate is 200N/min. It maintains 60 seconds when reaching load level, and the deformation l_1^a is noted. Then unload with same loading rate is to zero, keep 30 seconds and the deformation l_2^a is noted. So, the $\Delta l^a = l_1^a - l_2^a$ is considered the resilient deformation of this loading level. Therefore, the static compressive resilient modulus (SCRM) of mixes can be drawn by Formula 5.

$$E_a = \frac{N_a}{\Delta l^a} \times \frac{l}{S} \qquad (5)$$

where: E_a - USCRM of mixes under loading a, MPa; N_a -loading level at loading a, N; Δl^a -static compressive resilient deformation of test specimen at loading a, mm; l -height of test specimen, mm; S -cross-section area of test specimen, mm2.

In order to improve the reliability, at least 6 replicated specimens are required. The abnormal values are deleted in accordance with 3 times standard deviation, afterwards, the average and coefficient of variation can be calculated; The representatives can be reached in 95% probability (Formula 6).

$$E_{a,0.95}=\overline{E_a}\times(1-1.645\times Cv) \qquad (6)$$

Where: $E_{0.95}$ -representative modulus in 95% confidence level, MPa; $\overline{E}$ -average of modulus, MPa; Cv -coefficient of variation.

3.3 Dynamic Compressive Resilient Modulus Test (DCRMT)and Calculation of Area of Hysteretic Curve

DCRMT also adopted multi-level repeated loading mode. Havesine wave loading is forced at 10Hz. 200 cycles continuous loadings are included in each level. The stress amplitude and relevant strain amplitude are continuously collected within the last 10 cycle, and the average value can be calculated. The dynamic compressive resilient modulus (DCRM) can be followed by Formula 7.

$$E_d=\frac{\sigma_0}{\varepsilon_0} \qquad (7)$$

Where: E_d - UDCRM of mixes under loading σ_0, MPa; σ_0 -stress amplitude, MPa; ε_0 -strain amplitude.

The loading level of UDCRMT is identical with that of USCRMT. And same data analysis and calculation method are employed.

3.4 Standing Wave Tube Method and Noise Absorption Coefficient Calculation

The maximum and minimum of acoustic pressure are measure by standing wave tube, the ratio to maximum and minimum is defined standing wave ratio, The standing wave ratio is the noise absorption coefficient under certain frequency and can be measured during testing directly, shown in the formula 2.

$$a=\frac{4S}{(S+1)^2} \qquad (2)$$

where：

a—noise absorption coefficient；

S—standing wave ratio；

The mean of noise absorption coefficient of material at 250Hz、500Hz、1000Hz and 2000Hz is defined as noise reduction coefficient (NRC).

4. Test Results Analysis

4.1 Results of Standing Wave Tube Testing

The noise absorption coefficient of 5 various NMAS mixtures are listed at Tab.4. And the corresponding NRC are listed too.

Tab.4 Noise absorption coefficient of various NMAS mixtures

Frequency（Hz）	200	250	400	500	630	800	1000	1250	1600	2000	NRC
SAC-4.75	0.13	0.09	0.09	0.13	0.14	0.29	0.88	0.41	0.46	0.14	0.310
SAC-7.2	0.12	0.09	0.10	0.13	0.13	0.23	0.69	0.53	0.43	0.28	0.296
SAC-10	0.12	0.10	0.09	0.07	0.12	0.40	0.49	0.30	0.27	0.19	0.214
SAC-13	0.10	0.07	0.09	0.04	0.11	0.24	0.57	0.60	0.60	0.13	0.199
SAC-16	0.05	0.05	0.07	0.08	0.18	0.66	0.35	0.12	0.19	0.15	0.158

AS results show, when the mixtures have same air voids, the NRC increases with the decreasing of mixture NMAS, so the decreasing of NMAS is effective for noise reduction. This result is consistent with the former research.

Next, we discuss the relationships between the visco-elastic parameters that measured by various method and the NRC.

4.2 Static Compressive Resilient Modulus and NRC

The static resilient modulus value of 5 mixtures are listed in Tab.5. Results show that the static resilient modulus decrease with the smaller NMAS. Since the Modulus is a reflect of material hardness, so we assume that the modulus decreasing will result in road/tire noise reduction. Actually, the relationship curve of static resilient modulus and NRC Shown as Fig.1. proves that the NRC will increase with the decreasing of modulus, and the correlation coefficient reaches 0.97.

Table 5 Static Compressive resilient modulus (1MPa loading interval)

	Samples	Average (MPa)	Standard deviation	Variability coefficient	Representative Value (MPa)
SAC-4.75	6	481.8	8.4	1.75%	464.9
SAC-7.2	6	512.3	19.3	3.76%	473.8
SAC-10	6	518.5	14.6	2.81%	489.3
SAC-13	6	526.2	11.9	2.27%	502.3
SAC-16	6	540.2	8.3	1.55%	523.5

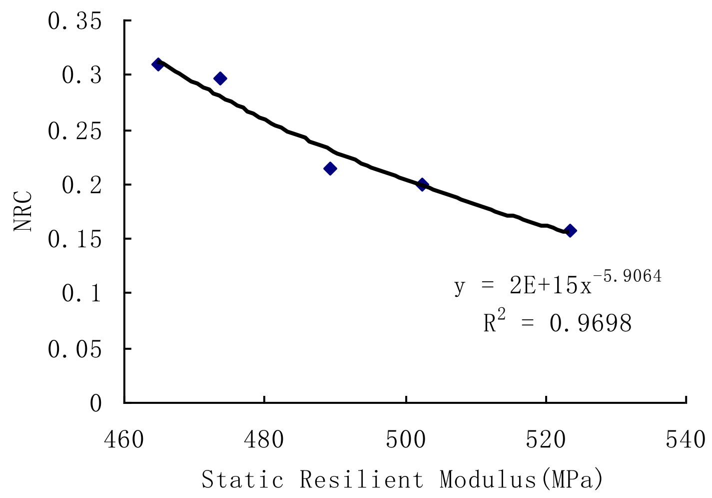

Figure 1 Curve of NRC versus Static compressive resilient modulus

4.3 Results of dynamic compressive Resilient Modulus

On the other hand, we see the dynamic resilient modulus, the changing rule is opposite to static resilient modulus. The dynamic resilient modulus will decrease with the increasing of NMAS. (Tab. 6)

Tab.6 Testing result of dynamic compressive resilient modulus (1.0 MPa loading level)

NMAS (mm)	Dynamic Compressive Modulus (MPa)				Area of hysteretic curve (N.mm)			
	sample	Average (MPa)	Variability coefficient	Respective value (MPa)	sample	Average (MPa)	Variability coefficient	Respective value (MPa)
4.75	7	1065	2.11%	1019.9	7	190	1.20%	185
7.2	7	1096	3.56%	1018.4	7	190	2.13%	182
9.5	7	1044	3.44%	972.4	7	192	2.40%	183
13.2	7	1054	3.05%	989.7	7	188	4.06%	173
16	7	1015	2.99%	954.6	7	167	2.45%	159

The essential difference between static and dynamic modulus test is the loading mode and the loading time. The dynamic modulus reflect the elastic character on the other hand the static modulus testing loading time is longer and in this process, the viscosity proportion of material will increase. This is one reason that appear various rule between dynamic and static modulus test.

Results of area of hysteretic curve calculation shows, with the increasing of NMAS, the area of hysteretic curve decrease (Table 5). Especially, the mixtures with 13.2mm and 16mm NMAS, the area of hysteretic curve decrease remarkably. At same loading level, the area hysteretic curve increasing reflect the viscosity increasing. The viscosity of mixture will increase with the decreasing of NMAS, and the noise reduction effect is good, the NRC is large.

4.4 The result of SPT test

The dynamic modulus and phase angle master curve parameters are listed in Tab. 7.

Table 7 Parameters of Dynamic modulus and Phase angle master curve

NMAS (mm)		4.75	7.2	9.5	13.2	16
Dynamic modulus master curve	δ	0.839	1.872	1.623	1.303	1.089
	$\delta+\alpha$	4.110	4.311	4.247	4.252	4.232
	Β	-0.61	-0.30	-0.48	-0.71	-0.77
	Γ	0.649	0.704	0.734	0.699	0.723
Phase angle master curve	$\varphi_{\max}$	42.1	39.7	41.2	42.5	46.7
	ω_c	-0.8742	-0.9038	-1.0384	-1.3241	-1.3788
	w	2.6445	2.3826	2.6054	2.5617	2.5524

δ is the minimum of dynamic complex modulus, this parameter is reflection of the performance of mixture on high temperature or low frequency. Shown in results that the δ will decrease with the increasing of NMAS except 4.75mm, this means the flexibility of mixture increase. And this rule is contrary with static resilient modulus test.

$\delta+\alpha$ is the maximum of dynamic complex modulus, this parameter is reflection of the performance of mixture on low temperature or high frequency. The results show that, the $\delta+\alpha$ will wave with the increasing of NMAS, This is considered because of the same bitumen, and same proportion of aggregate.

$\varphi_{\max}$ is the maximum of phase angle, this parameter is a reflection of maximum viscous behavior. The results show that, the $\varphi_{\max}$ will increase with the increasing of NMAS except 4.75mm. This rule is consistent with the minimum of master curve of dynamic modulus.

ω_c is the corresponding frequency that appear $\varphi_{\max}$. The results show that, with the increasing of NMAS, the ω_c will decrease. And the decreasing of ω_c illustrates the increasing of mixture elastic. These all are reflection of visco-elastic behavior of mixtures, and have relation with the noise absorption behavior.

5. Conclusions

Results indicate that the noise reduction effect of different NMAS are determined by visco-elastic character basically. Generally speaking, with the same rule of aggregate proportion, the viscosity increase with the decreasing of NMAS, and the noise reduction effect improve.

In this paper, three test methods are used to evaluate the visco-elastic character and the corresponding noise absorption effect are analyzed, the conclusions are:

1. The standing wave tube results show, with the decreasing of NMAS, under same air voids, the noise absorption coefficient will increase, namely the noise reduction effect increase.
2. Shown as static resilient modulus testing results, with the decreasing of NMAS, the resilient modulus will decrease. Base on testing principle, the static resilient modulus reflect the visco-elastic character, and with the decreasing of modulus the viscosity of mixture will increase. And the decreasing of modulus has good relationship with noise reduction coefficient.
3. The two parameters dynamic resilient modulus and the area of hysteretic curve are analyzed through dynamic resilient modulus. The former is reflection of elastic character of mixture, and the latter is reflection of viscosity. The result shows that with the decreasing of NMAS, the elastic modulus increase, and the area of hysteretic curve increase. The increasing of area of hysteretic curve illustrate the increasing of viscosity, this is consistent with the rule of noise absorption coefficient.
4. SPT test is another evaluation method to evaluate the dynamic character of mixture, and the testing results are correlative with not only the NMAS, but also the gradation and binder performance. Thus, when the binder is same, the visco-elastic character appears complexity. but see from the frequency that corresponding to maximum of phase angle, the rules are that when the NMAS decrease, the frequency will increase, and this point indicate that the viscosity of the mixture increase, this behavior has some consistent with noise absorption coefficient.

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