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Aging Properties of HMB15 with Varying Binder Film Thicknesses

(Sifat Penuaan HMB15 dengan Ketebalan Filem Perekat yang Berubah)

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ABSTRACT

In order to cope with the ever-increasing traffic loading and to minimise the cost of road construction and maintenance, several road trials of high modulus base (HMB) materials containing a 15 penetration grade bitumen (known as HMB15) have been carried out in the UK since 1990s. It has been showed that, although HMB15 behaved in a similar way to conventional dense bitumen Macadam with a cost saving of approximately 25%, its long-term durability (aging and moisture damage) is still a major concern of researchers as considerable deteriorations have been commonly observed during the ongoing investigations on cored samples from the sites (either with or without traffic loading). The aim of this paper was to quantitatively show the relationship between aging properties of HMB15 and its binder film thickness (binder content), so that an optimum binder content could be determined. In order to achieve this, 5 groups of cylindrical HMB15 specimens with different binder contents (3.5%, 4%, 4.5%, 5% and 5.5%) were fabricated and subjected to SHRP long-term oven aging test (at 85^{o}C for 5 days), their mechanical properties both before and after aging simulation were tested using indirect tensile stiffness modulus (ITSM) tests. In addition, binders were recovered at different aging stages and their rheological characteristics were investigated with dynamic shear rheometer (DSR) tests. Based on these, aging indices of different groups were calculated and their mathematical relationship with binder film thicknesses was regressed. The results showed that the aging properties of HMB15 mixtures were significantly affected by their binder film thicknesses. However, regression analysis between aging indices and binder film thicknesses indicated that, as the binder film becomes thicker than 9.5 μm, the change of aging indices with film thicknesses becomes minor and therefore, a film thickness of approximately 9.5 μm was recommended for HMB15 mixtures.

Keywords: Aging; DSR; film thickness; HMB15; ITSM

ABSTRAK

Dalam usaha untuk berdepan dengan beban trafik yang semakin meningkat dan mengurangkan kos pembinaan jalan serta penyelenggaraan, beberapa percubaan pembinaan jalan raya daripada bahan tapak modulus tinggi (HMB) yang mengandungi bitumen bergred penembusan 15 (dikenali sebagai HMB15) telah dijalankan di UK sejak tahun 1990-an. Ia telah menunjukkan bahawa, walaupun HMB15 mempunyai ciri yang sama dengan jalan konvensional asfalt berbitumen padat dengan penjimatan kos kira-kira 25%, ketahanan jangka panjang (jangka hayat dan kerosakan akibat kelembapan) masih membimbangkan penyelidik kerana kerosakan yang agak besar telah biasa dilihat semasa siasatan dijalankan ke atas sampel yang dibuang dari tapak kerja (dengan atau tanpa muatan lalu lintas). Tujuan kajian ini dijalankan adalah untuk mengkaji hubungan kuantitatif antara sifat penuaan HMB15 dan ketebalan filem pengikat (pengikat kandungan), supaya kandungan bitumen yang optimum dapat ditentukan. Bagi mencapai matlamat ini, lima kumpulan HMB15 spesimen silinder dengan kandungan pengikat yang berbeza (3.5%, 4%, 4.5%, 5% dan 5.5%) telah direka dan tertakluk kepada SHRP ujian ketuhar penuaan jangka panjang pada (85^{o}C selama 5 hari), sifat-sifat mekanik mereka sebelum dan selepas simulasi penuaan telah diuji dengan menggunakan ujian kekukuhan tegangan tidak langsung modulus (ITSM). Di samping itu, pengikat pulih pada peringkat usia yang berbeza dan ciri-ciri reologi mereka dikaji dengan reometer ricih dinamik (DSR). Berdasarkan ini, penuaan indeks kumpulan-kumpulan yang berbeza telah dikira dan hubungan matematik dengan filem pengikat ketebalan telah mengurang. Keputusan menunjukkan bahawa sifat penuaan HMB15 campuran ini secara ketara dipengaruhi oleh ketebalan filem pengikat. Walau bagaimanapun, analisis regresi antara indeks penuaan dan ketebalan filem pengikat menunjukkan bahawa, apabila filem pengikat menjadi tebal daripada 9.5 μm, perubahan penuaan indeks dengan ketebalan filem menjadi kecil dan dengan itu, ketebalan filem kira-kira 9.5 μm disyorkan untuk HMB15 campuran.

Kata kunci: DSR; HMB15; ITSM; ketebalan filem; penuaan

Introduction

Since 1990s, there has been a general trend in the UK to use progressively stiffer base materials in pavement construction, driven by the need to cope with the ever-increasing traffic loading and to minimise the road construction and maintenance cost (Read & Whiteoak 2003). Initial road trials of high msodulus base (referred to as HMB) materials containing a 15 Penetration bitumen (10/20 paving grade), known as HMB15, were undertaken in the UK at five sites (Nunn & Smith 1997). It has been showed that, although HMB15 behaved in a similar way to conventional dense bitumen Macadam with a cost saving of approximately 25%, its long-term durability (aging and moisture damage) is still a major concern of researchers as considerable deteriorations have been commonly observed during the ongoing investigations on cored samples from the sites (either with or without traffic loading).

It is commonly accepted that thicker binder film (higher binder content) can effectively prevent asphalt mixtures from age hardening and therefore, ensure reasonable durability of the asphalt mixtures (Kandhal & Chakraborty 1996). On the other hand, because the cost of the binder always constitutes the major part of the total expenditure of a pavement project, a thicker bitumen film thickness will significantly increase the road construction cost. Many efforts have been made by researchers to keep the binder content to a minimum while satisfying specification criteria (Campen et al. 1959; Goode & Lufsey 1965; Kandhal & Chakraborty 1996; Kandhal et al. 1998; Kumar & Goetz 1977).

Campen et al. (1959) investigated the influence of voids, surface area and film thickness on the durability of dense grade asphalt mixtures. It was pointed out that thicker binder films produced flexible and durable mixtures, while thin films produced brittle asphalt mixtures, which tended to crack excessively, retarded pavement performance and reduced its service life. According to their analysis, film thicknesses of the most desirable asphalt mixtures usually ranged from 6 to 8 microns.

Goode and Lufsey (1965) presented the relationships among voids, permeability, film thickness and asphalt hardening. The hardening of the asphalt binder was expressed as a function of air voids, film thickness, temperature and time in their study. In order to avoid the implication that all aggregate particles had the same thickness of binder coating, the authors introduced a new concept named 'bitumen index', which was defined as pounds of binder per square foot of aggregate surface area. Based on this concept, they concluded that a minimum bitumen index of 0.00123, which corresponds to a value of 6 μm of average film thickness, could be set as a control in the asphalt mixture design.

Kumar and Goetz (1977) studied bitumen age hardening as related to the mixture permeability and bitumen film thickness. They stated that the best way for predicting the hardening resistance of bitumen in a single-sized asphalt paving mixture was to calculate the ratio of the film thickness factor to permeability. However, at the design value of 4% air voids, which is common for most dense graded asphalt paving mixtures, the effects of permeability of the mix was determined to be insignificant.

Kandhal and Chakraborty (1996) also did some investigations to quantify the relationship between various binder film thicknesses and the ageing characteristics of asphalt mixtures. For the asphalt mixtures with 8% void content, a binder film thickness of 9-10 microns was recommended by the authors, below which the ageing rate of both the asphalt mixture and the bitumen in the mixture would accelerate significantly. Kandhal et al. (1998) reviewed the VMA requirements in Superpave and suggested that a minimum average binder film thickness of 8 microns be used instead of the minimum VMA requirements.

The above studies have greatly improved our understanding on the relationship between ageing properties of common asphalt mixtures and their binder film thicknesses, voids and permeability. However, there have been limited research to quantify the effects of binder film thicknesses on ageing properties of HMB mixtures. In this study, five groups of cylindrical HMB15 specimens with different binder contents (3.5%, 4%, 4.5%, 5% and 5.5%) were fabricated and subjected to SHRP long-term oven aging test (at 85°C for 5 days), their mechanical properties both before and after aging simulation were tested using indirect tensile stiffness modulus (ITSM) tests. In addition, binders were recovered at different aging stages and their rheological characteristics were investigated with dynamic shear rheometer (DSR) tests. Based on these, aging indices of different groups were calculated and their mathematical relationship with binder film thicknesses was regressed.

Materials and Testing Programmes

Materials

The bitumen used in this study was a very hard bitumen with a penetration of 15 dmm. The aggregate used was granite. The aggregate batching details are given in Table 1 and graphically compared against the 28 mm DBM base specification (BS 4987-1 2001) in Figure 1. Asphalt slabs (305 mm × 305 mm × 100 mm), with five different binder contents: 3.5%, 4%, 4.5%, 5% and 5.5% (by mass), were compacted using a roller compactor. After compaction, five cylindrical specimens were cored from each slab and then cut to target height. The design details of the specimen are as follows; height: 60 mm, diameter: 100 mm and target void content: 8%.

Testing Programmes

After specimen coring, the bitumen from the off cuts was recovered and subjected to DSR testing. The stiffness of each specimen was tested using the ITSM test both before and after the specimen was aged in a forced draft oven for

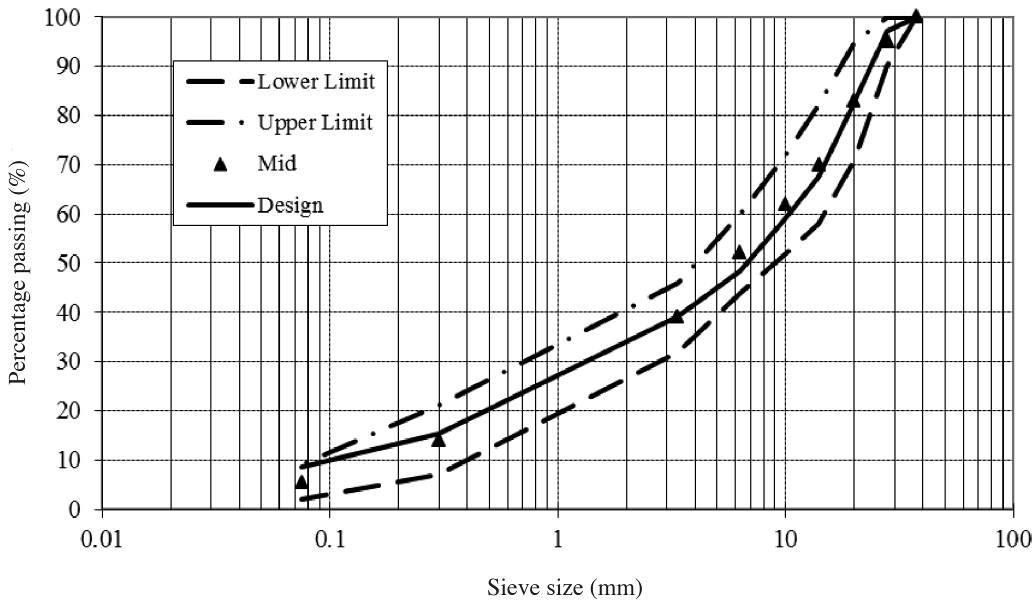


FIGURE 1. Gradation of granite aggregate

TABLE 1. Batching details for the granite

Material	Percentage	Sieve size (mm)								
		37.5	28	20	14	10	6.3	3.35	0.3	0.075
28 mm	20	100	85.28	20.51	2.41	1.01	0.75	0.74	0.61	0.35
20 mm	11	100	100	87.5	8.96	1.4	1.1	0.93	0.6	0.3
14 mm	11	100	100	100	73.65	12.34	1.03	0.82	0.56	0.29
10 mm	10	100	100	100	100	95.39	20.02	6.03	2.66	2.12
6 mm	10	100	100	100	100	100	82.5	17.77	4.69	2.9
Dust	35	100	100	100	100	100	99.8	95.47	32.4	13.6
Filler	3	100	100	100	100	100	100	100	100	100
Total	100									

5 days at 85°C (SHRP long-term oven aging condition). Finally, one representative specimen from each slab was selected for bitumen recovery and DSR testing.

PRELIMINARY WORK

AIR VOID CHECK

The aim of this study was to quantify the relationship between hardening properties of asphalt mixtures and the binder contents (film thickness). Therefore, it is extremely important to keep the air voids of specimens from different groups at a similar level. After the asphalt specimens were fabricated, their air void contents were tested using the sealed specimen method from the standard EN 12697-6:2003. Table 2 shows the void content for each asphalt specimen of the group containing 4.5% binder. It can be seen that the air void within the compacted slab is not homogeneous. In addition, the average air void content for each group was found to be different from each other. Therefore, special attentions should be paid during the results analysis.

THEORETICAL FILM THICKNESS CALCULATION

The theoretical average film thicknesses for specimens from different groups were calculated using the method developed by Campen et al. (1959). Based on the batching and gradation details for the aggregate (as shown in Table 1 and Figure 1), the surface area factor for the aggregates used was calculated and presented in Table 3.

With the calculated total surface area factor for the aggregate used in this study, the film thicknesses for the mixtures with different binder contents were calculated with the following equation (Read & Whiteoak 2003):

$$T_f = \frac{b}{100-b} \times \frac{1}{\rho} \times \frac{1}{\alpha},$$

TABLE 2. The void contents of asphalt specimens with 4.5% binder content

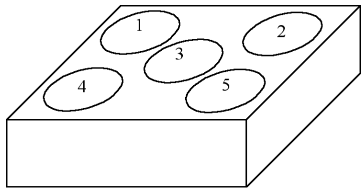
Binder content	No.	Void content	Layout of specimens
4.5%	C1	9.43%	
	C2	9.65%	
	C3	7.39%	
	C4	8.69%	
	C5	9.55%	

TABLE 3. The calculation of the surface area factor for Campen's method

Sieve size (mm)	Surface area factor (m^2/kg)	%	Calculated SAF (m^2/kg)
>4.75	0.41	55%	0.2255
2.36	0.82	9%	0.0738
1.18	1.64	6%	0.0984
0.6	2.87	8%	0.2296
0.3	6.14	6%	0.3684
0.15	12.29	4%	0.4916
0.075	32.77	12%	3.9324
			$\Sigma = 5.4179$

where T_f is bitumen film thickness (m); ρ is density of bitumen (kg/m^3); α is surface area factor (m^2/kg) and b is bitumen content (in %). The calculated binder film thicknesses for specimens with 3.5, 4, 4.5, 5 and 5.5% binder contents are: 6.56, 7.54, 8.53, 9.52 and 10.53 μm.

RESULTS AND DISCUSSION

ITSM RESULTS ANALYSIS

As stated above, the indirect tensile stiffness modulus (ITSM) of each specimen at 20°C was measured both before and after SHRP long-term aging. However, it should be noted that, due to the variation of average air void contents among different groups, the average stiffness of each group may not be very reliable in the analysis of binder film thickness effects on the bitumen aging, since the samples were not aged with the same level of void content. In order to eliminate the influence of air void content, plots of stiffness vs void content were made for each group; a trend line for the relationship between the stiffness and void content was added to each group before (BA) and after aging (AA). Figure 2 shows the plot for the group with 4.5% binder content. Based on the stiffness vs air void content figures, a theoretical stiffness for each group was calculated at a void content of 8%. Comparison was made between the average and the theoretically predicted stiffness (at 8% air void content) of each group and the aging indices expressed by them (Table 4).

The relationship between the film thickness and stiffness values before and after oven aging is presented in Figure 3. From this figure, a marked similarity between the curves obtained before and after aging can be observed for both the average result and the predicted result. In addition, it can be seen that, because of the differences in the air void content among different groups, the relationship between the average stiffness result and binder film thickness is not as regular as that between the predicted stiffness and binder film thickness. Therefore, the following analysis and discussion are mainly based on the predicted data.

From the predicted results in Figure 3, it can be seen that the amount of stiffness increased due to the aging reduces as the film thickness becomes thicker, which indicates that the influence of aging on the mixture stiffness is reduced in the specimens with higher binder contents. In addition, a quadratic polynomial regression was used to quantify the relationship between the asphalt stiffness and its binder film thickness. The relationships for materials in this study are presented as follows:

Before long-term oven aging:

$$S_{ba} = 109.68T^2 - 2701.3T + 24017$$
$$R^2 = 0.9858,$$

where S_{ba} is asphalt stiffness at 20°C and 8% air void content before aging (MPa) and T is film thickness (μm).

After long-term oven aging:

$$S_{aa} = 178.63T^2 - 4512T + 36439$$
$$R^2 = 0.9999,$$

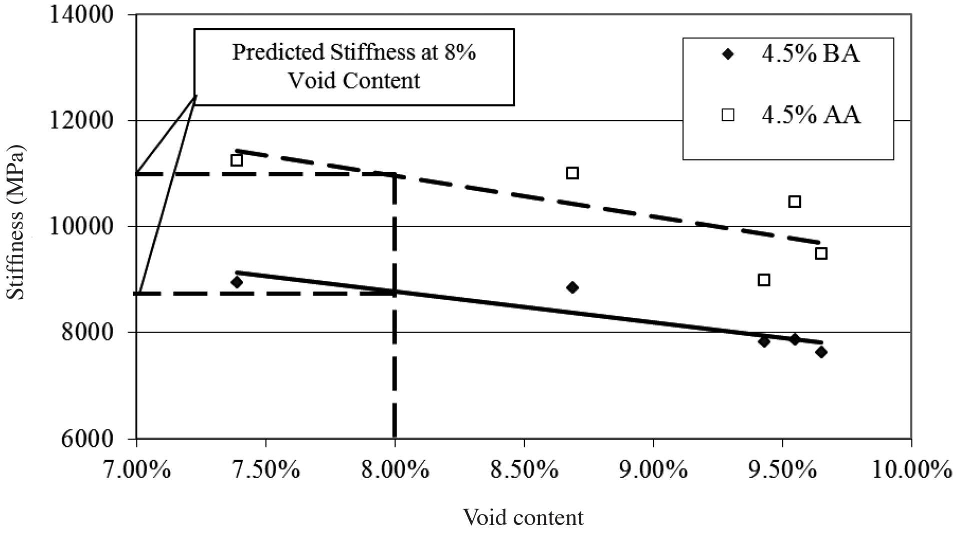


FIGURE 2. ITSM results for specimens with 4.5% binder content

TABLE 4. Average and predicted stiffness of each group before and after aging

Film thickness (μm)	Average results			Predicted results		
	Stiffness BA (MPa)	Stiffness AA (MPa)	Aging index	Stiffness BA (MPa)	Stiffness AA (MPa)	Aging index
6.56	9008	11472	1.27	10926	14543	1.33
7.54	9707	12141	1.25	10125	12538	1.24
8.53	8227	10239	1.24	8776	10965	1.25
9.52	7952	9368	1.17	8243	9689	1.18
10.53	7719	8673	1.12	7763	8725	1.12

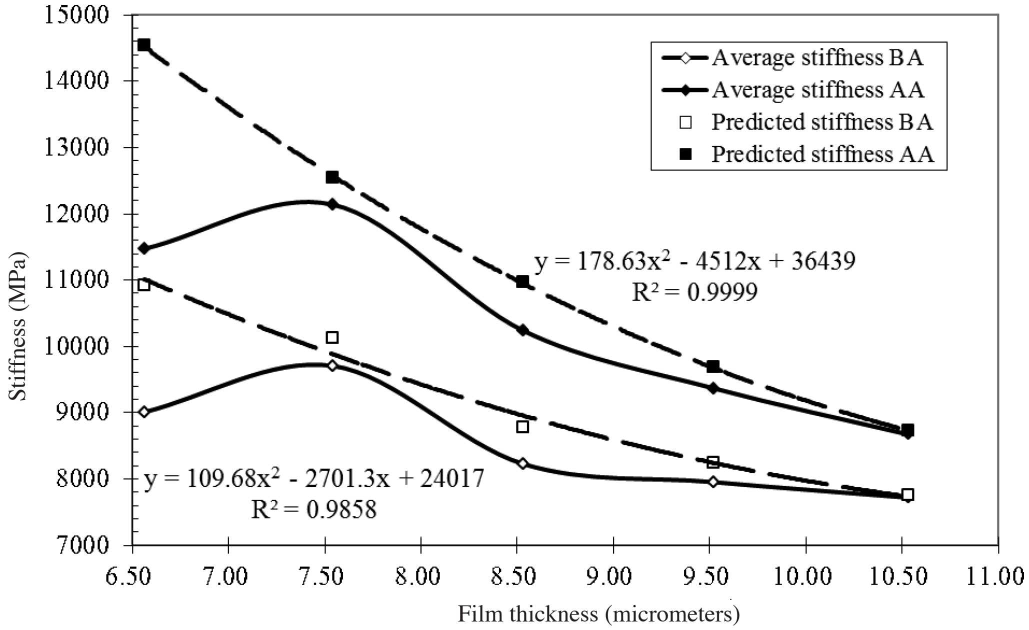


FIGURE 3. Plot of asphalt stiffness (at 20°C) vs film thickness

where S_{aa} is asphalt stiffness at 20°C and 8% air void content before aging (MPa).

In order to illustrate the influence of aging on the mixture stiffness more clearly, the aging index in terms of the asphalt stiffness (at 8% void content) was plotted against the film thickness in Figure 4. It can be seen clearly that the aging index decreases gradually as the binder film thickness increases, which indicated that asphalt mixtures with thicker binder films (higher binder content) are more resistant to age hardening. A linear regression gives an acceptable model for this relationship as follows:

$$I_s = -0.0484T + 1.6371$$
$$R^2 = 0.9248,$$

where I_s is aging index expressed by asphalt stiffness at 20°C and 8% air void content.

DSR ANALYSIS

In order to study the influence of aging on the binder properties, binder recovery and DSR testing were applied to the specimens with different binder contents both before and after aging simulation. As stated above, bitumen recovered from the offcut part of the compacted slab was used as the binder before aging and bitumen recovered from representative specimen of each group (the one with an air void content closest to 8%) was used as the binder after aging.

Dynamic mechanical analysis (DMA) was performed on the binders using a Bohlin Gemini 200 DSR machine. The DSR tests reported in this paper were performed under controlled-strain loading conditions using frequency sweeps between 0.1 and 10 Hz at temperatures between 0 and 70°C. The tests between 0 and 45°C were undertaken with a 8 mm diameter – 2 mm gap, parallel plate testing geometry and from 25 to 70°C with a 25 mm diameter – 1 mm gap geometry. The strain amplitude for all tests was confined within the linear viscoelastic response of the binders. The strain limits for 8 mm and 25 mm geometries in this study were selected at 0.15 and 0.25%, respectively.

The DSR results for binders from different groups, both before and after aging, have been presented as complex modulus (G^*) master curves (with a reference temperature of 25°C), as shown in Figures 5 and 6. As expected, the complex modulus decreased with increasing bitumen film thickness (binder content). This finding indicated that the presence of thicker films of bituminous binder in the asphalt paving mixtures minimizes aging of bitumen. In addition, from Figure 5, it can be seen that, although the asphalt mixtures in this study have not been subjected to any short-term oven aging simulation, the binders recovered from slab offcuts show significant difference in their stiffness (G^*); this means that age hardening has already occurred in the bitumen during the material preparation and slab compaction. Furthermore, the amount of bitumen stiffness increase is highly dependant on the binder content (film thickness) of the asphalt mixture.

In order to show the influence of bitumen film thickness on the bitumen aging more quantitatively, the complex moduli at 60°C and 0.4 Hz for binders at different aging stages were selected and used in aging index calculations, as shown in Table 5. Accordingly, the aging indices in terms of bitumen complex modulus were graphically summarized in Figure 7. From this figure, it

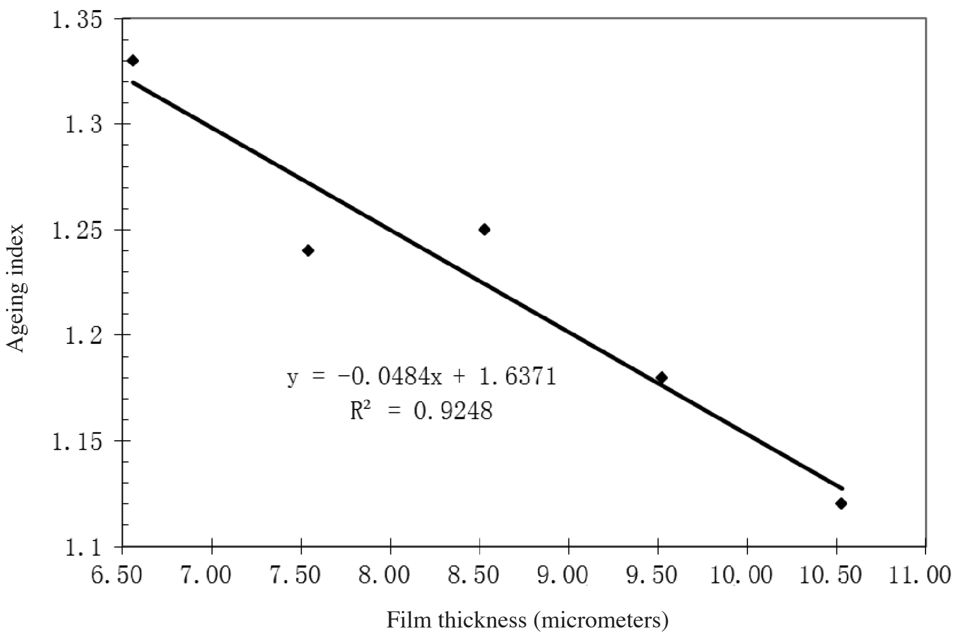


FIGURE 4. Plot of aging index expressed by asphalt stiffness (at 20°C and 8% of air void content) vs film thickness

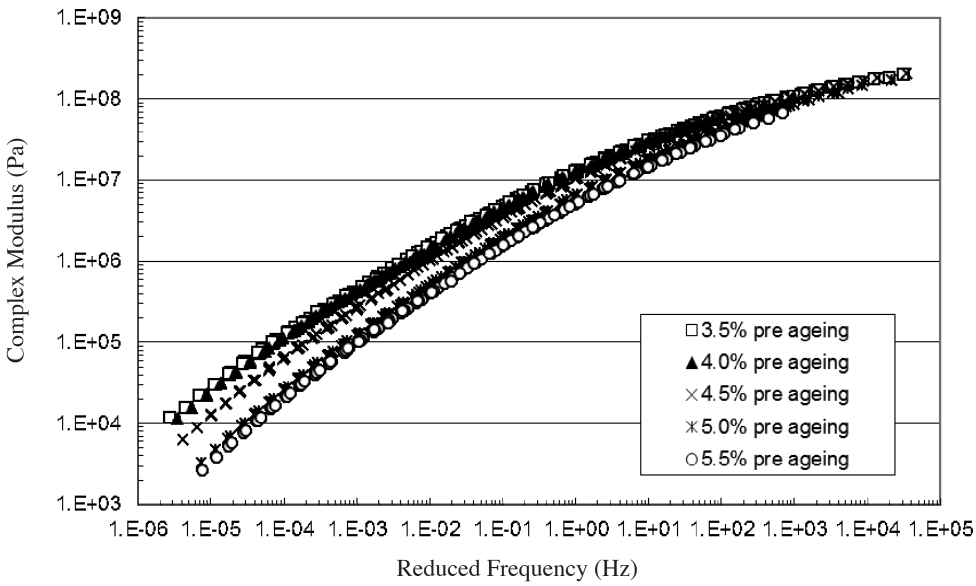


FIGURE 5. Complex modulus master curves for binders before aging (with a reference temperature of 25°C)

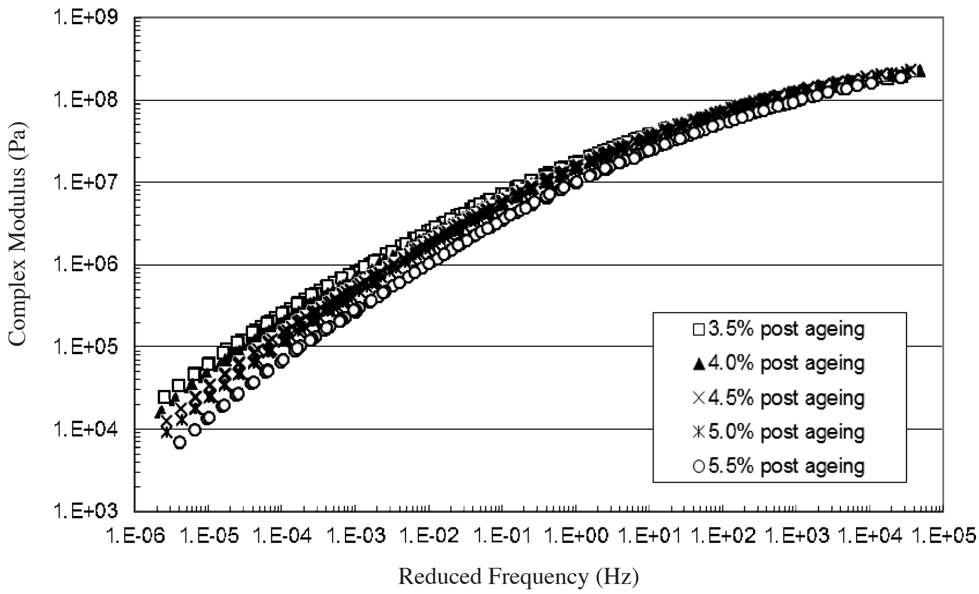


FIGURE 6. Complex modulus master curves for binders after aging (with a reference temperature of 25°C)

TABLE 5. Aging index calculation for binders at different aging stages

Film thickness (μm)	Complex modulus at 60°C and 0.4 Hz (Pa)			Aging index	
	Virgin binder	BA[a]	AA[b]	BA	AA
6.56	11480	98150	204350	8.55	17.80
7.54		103100	153990	8.98	13.41
8.53		61731	113720	5.38	9.91
9.52		35023	86117	3.05	7.50
10.53		29089	65750	2.53	5.73

[a] Before artificial aging, but after compaction
[b] After artificial aging

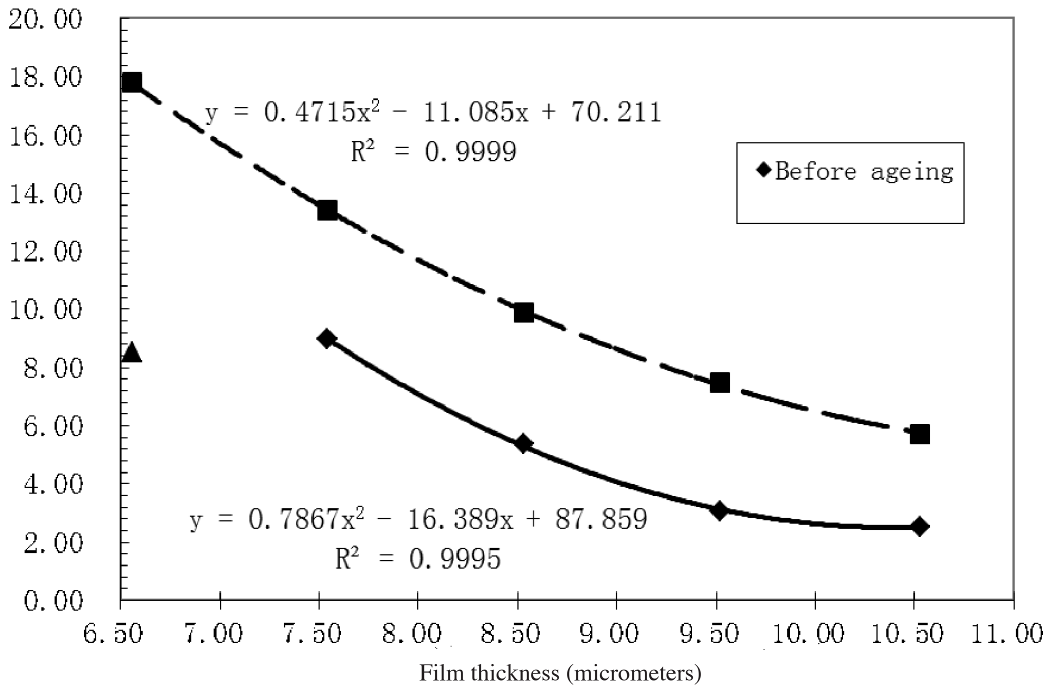


FIGURE 7. Plot of aging index expressed by complex modulus (at 60°C and 0.4 Hz) versus film thickness

can be seen that the aging index increased consistently as the bitumen film thickness decreased, which indicated that a thinner binder film in asphalt mixtures can result in stronger age hardening to the bitumen. It can also be observed that the fitted curves for the data both before and after aging become flatten when binder film thickness was more than 9.5 μm, which indicated that the film thickness has a decreasing effect on the aging properties of the bitumen when the asphalt mixtures have a relatively high binder content (thicker binder film). The result is in good agreement with the work done by Kandhal and Chakraborty (1996), although different binders were used in these two studies.

Two quadratic polynomial models were obtained from regression analysis for the relationship between aging index (in terms of complex modulus) and binder film thickness both before and after aging.

Before long term oven aging:

$$I_{ba} = 0.7867T^2 - 16.389T + 87.859$$
$$R^2 = 0.9248,$$

where I_{ba} is aging index in terms of complex modulus (60°C, 0.4 Hz) before aging.

After long term oven aging:

$$I_{aa} = -0.4715T^2 - 11.08T + 70.211$$
$$R^2 = 0.9999,$$

where I_{aa} is aging index in terms of complex modulus (60°C, 0.4 Hz) after aging.

CONCLUSIONS

Several conclusions can be drawn as follows: the binder content (film thickness) in HMB15 can significantly influenced the aging of bituminous material. With the same aging time, asphalt mixtures with thinner binder film can be affected by age hardening more strongly and binders recovered from these mixtures have much higher stiffness; as the binder film thickness increased, its influence on the aging properties of both the asphalt mixtures and bitumen binders becomes smaller and stabilised, which means that with thicker binder films, the aging of bituminous materials will be less sensitive to the changes in film thickness; based on the regression analysis, there was a strong relationship between the aging indices (expressed by G^* of recovered binders) and bitumen film thicknesses and an optimum bitumen film thickness of approximately 9.5 μm was chosen for the HMB15 mixtures.

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