

BEHAVIOR OF ASPHALT-RUBBER BINDERS FOR DIFFERENT RUBBER PARTICLES SIZE

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The addition of polymers and by product waste materials to straight asphalt has shown improvement of binder's properties. In this research, the rubber powder by which the waste tire of the passenger motorcar smashed with the freezing-method is added to the straight asphalt 60/80. Rubber 0.2mm, 0.4mm, 0.6mm, 0.8mm and 1.2mm, respectively, was mixed with asphalt at a rate of 15% by total weight. The viscosities measured with a rotation viscometer, Complex Shear Modulus ($|G^*|$), phase angle (δ) and softening point temperatures evaluated the behavior at high temperatures. The flexural creep stiffness and slope of response evaluated the behavior at low temperatures. The improvements on binder properties after rubber addition showed the same magnitude despite the difference of rubber size.

Key Words : asphalt-rubber, rubber, rutting, fatigue cracking, elasticity

1. INTRODUCTION

The increasing amount of scrap tires has become a serious environmental problem. In Japan, the amount of discarded tires reached 103 million in 2004¹⁾. These tires when disposed at inadequate places are in danger of fire and if this occurs, the air and the underground water can be polluted.

A literature review shows that scrap tires can be used in whole form, in small pieces or as ground particles. Their use in whole form takes place at power plants to produce energy, whereas, the small pieces can be used for vehicles mudguards or padding. The finer/ground particles of rubber may be mixed with asphalt, acting as an asphalt modifier^{2, 3)}.

Scrap tires can be smashed in small particles using an ambient grinding, cryogenic grinding or wet grinding. The ambient grinding method is performed at ambient temperatures using grinders and screens to size the material and remove any residual steel and fiber. The material resultant from this process presents a very rough surface texture, what improves the reaction with asphalt cements. The cryogenic grinding consists to cool the tires with liquid nitrogen and then these cooled tires can be quite easily seized in a similar way used for ambient grinding. The rubber powder resultant presents a very smooth

surface texture what makes it less reactive with asphalt cements when compared with the ambient grinding process. The wet grinding method uses a coarse rubber powder in wet slurry. This slurry is then smashed between grinding stone. This process produces a finer material than that obtained from ambient grinding, but it still retains a rough surface texture, showing in this way a very thorough reaction with asphalt cements⁴⁾.

This paper presents an analysis performed for Japanese asphalt-rubber binders considering different sizes of rubber particles. The study aimed to evaluate the behavior of Japanese rubber modified binders considering the local materials (straight asphalt and rubber powder) available to use. Rubber powder 0.2mm, 0.4mm, 0.6mm, 0.8mm and 1.2mm was mixed separately with straight asphalt 60/80 (grade of penetration) at a rate of 15% by total asphalt-rubber weight. The softening point temperatures, Complex Shear Modulus ($|G^*|$) and Phase angle (δ), as well as the viscosity measured with a rotation viscometer evaluated the behavior at high temperatures. At intermediate temperatures the $|G^*|$ and δ were studied, whereas the flexural creep stiffness and the slope of response analyzed the behavior at low temperatures.

2. ASPHALT-RUBBER BINDERS

Two methods have been used to mix asphalt and rubber powder. The first method, called “dry process”, consists to blend rubber particles with aggregate for a short period of time before mixing straight asphalt with them. The second method, known as “wet process” consists to mix asphalt and rubber for a longer period of time, before mixing the aggregates. In this way, the properties of asphalt-rubber binder can be measured and controlled during the production of asphalt mixtures. Several researches developed, especially in USA, show the addition of rubber powder to straight asphalt is accomplished at high temperatures. In Arizona, for instance, the Arizona State Highway recommends blending asphalt and rubber for 60 minutes at 175°C, whereas in California the blending temperature may range between 175°C to 190°C during 45 minutes. On the other hand, the Florida State Highway advises blending temperatures ranging from 150°C to 175°C for 10 to 45 minutes. Along the time of reaction, rubber particles tend to swell, the interparticles distance is reduced and the viscosity of asphalt-rubber binder is increased²⁾.

The swelling of rubber powder is not a chemical reaction since these rubber particles do not melt into the asphalt binder. The reaction is similar to a compressed, hard, dry sponge being placed in a water bath. As the sponge absorbs the water, it swells and softens. The swelling of rubber powder is due to the absorption of asphalt components. Rubber particles absorb aromatic oils from the asphalt binder into the rubber chains, which are the key components of the natural and synthetic rubber. Natural rubber provides elastic properties while synthetic rubber improves the thermal stability properties. The reacted particles become tacky and develop adhesive properties. Furthermore, the viscosity of asphalt-rubber binder is increased, as the amount of aromatic oils to lubricate the binder is reduced³⁾.

This investigation performed previously several tests so as to determine the best rate of rubber addition when using respectively, different particles size. The results published elsewhere^{5, 6, 7, 8)}, showed the addition of 15% of rubber produced the best properties for almost tests accomplished. On the other hand, the temperature of 180°C, for a mechanical mixing time of 30 minutes presented the best viscosities and binder's workability.

3. MATERIALS AND MIXING PROCESS

This evaluation used straight asphalt 60/80 (grade of penetration), whose physical characteristics are

presented in **Table 1**. Rubber powder from passenger car tires showed the chemical components described in **Table 2**. A sieve analysis for rubber particles showed the gradation presented in **Table 3**.

The wet process method was used to mix asphalt and rubber powder. The addition of rubber powder to asphalt was accomplished at 180°C±1°C, using a mechanical mixer for a rotation speed of 250RPM. When the rubber addition finished, the mechanical mixing continued for 30 minutes at 660RPM. After that, the binder resultant was kept in oven for one hour at 180°C±1°C to perform the binder digestion.

4. LABORATORY FINDINGS

This study evaluated original and short-term aged (oxidized) modified binders. The short-term aging tries to simulate the binder oxidation that takes place during the plant mixing and compaction services in the field. The following sections will mention the short-term aging just as “aging”, for short. The Rolling-Thin Film Oven (RTFO) machine oxidized straight asphalt and rubber 0.4mm, respectively, during 85 minutes at 163°C. Modified binders using rubber 0.2mm, 0.6mm, 0.8mm and 1.2mm, respectively, were blown out of bottles during the RTFO aging process, being left a little binder after the period of oxidation. In this way, the Thin-Film Oven (TFO) machine, running for five hours at 163°C was used to oxidize these modified binders and overcome the inconvenience aforementioned.

(1) Softening point test

This experiment determines the temperature at which an asphalt cement cannot support the weight of a steel ball and starts flowing. In this way, is possible to establish the temperature at which a phase change occurs in the asphalt cement⁹⁾. The temperature is read when a standard metal ball passes through a standard ring, previously filled with asphalt binder, and touches a reference plate, after displacing 25.4 mm¹⁰⁾.

As illustrates **Fig. 1**, after mixing rubber powder to straight asphalt, the softening point temperatures became bigger proving an increase of binder's resistance to rutting. Further, considering the effect of rubber size, it can be seen that for all sizes analyzed, the temperatures presented the same order of magnitude, before and after aging.

(2) Viscosity test

The viscosity requirement aims to insure that the material can be pumped and mixed with aggregate. The

Table 1. Physical characteristics of straight asphalt

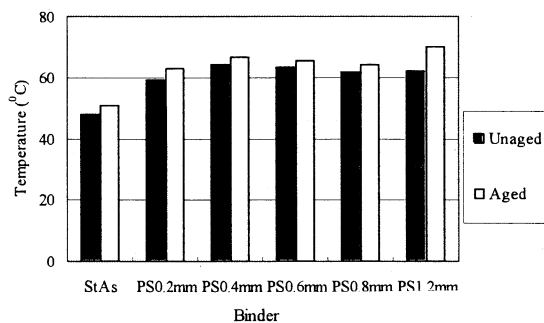
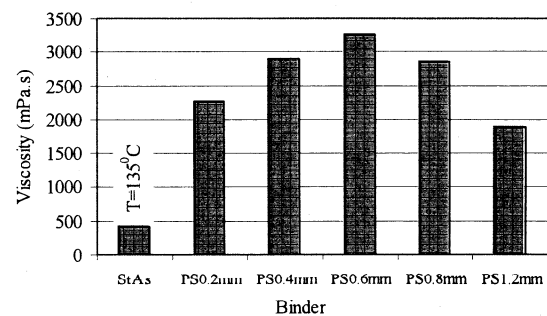
Physical Characteristic	
Penetration at 25°C	70dmm
Penetration at 4°C	22dmm
Softening point	46.8°C
Flash point	339°C
Ductility	bigger than 100cm

Table 2. Rubber powder chemical components

Component	
Acetone extract	8.6%
Ash	4.8%
Natural rubber	43.59%
Styrene Butadiene Rubber (SBR)	13.31%
Specific gravity	1.13

Table 3. Rubber gradation for passenger car tires (PS)

Sieve opening (mm)	Percent passing				
	0.2mm	0.4mm	0.6mm	0.8mm	1.2mm
2.36	100.00	100.00	100.00	100.00	100.00
1.18	100.00	99.50	100.00	99.79	63.96
0.85	-----	----	----	64.41	----
0.60	100.00	97.40	69.07	31.57	26.39
0.425	98.42	68.80	27.40	14.04	13.35
0.30	91.80	24.10	9.75	5.39	6.28
0.25	77.61	13.00	6.07	3.07	3.90
0.15	20.14	1.25	0.36	0.36	0.97
0.075	0.67	0.03	0.00	0.32	0.13
Pan	0.00	0.00	0.00	0.00	0.00

**Fig. 1** Softening point temperatures before and after aging**Fig. 2** The viscosity when adding rubber powder to the straight asphalt

apparent viscosity of asphalt binders can be determined using a rotation viscometer. The viscosity is measured through the torque required to rotate a spindle plunged into hot asphalt at a constant rotational speed¹¹⁾.

This study determined the viscosities only for original binders at 175°C and after one hour of digestion. The viscosities at 30, 60 and 90 seconds were registered and the average calculated¹²⁾. It was found that (Figure 2), as the size of particles increase and considering their swelling after mixing with asphalt,

they develop higher friction contact and the viscosity tends to become higher, improving the consistency of modified binders. Such enhancement presented a maximum value for binders using particles 0.6mm, decreasing from this point on. The authors performed further studies^{13, 14)} and observed that rubber particles bigger than 0.4mm require bigger times of digestion so as to absorb the aromatic oils from asphalt and then, swell and increase the viscosity. Despite this, after one hour of digestion, all rubber modified binders presented acceptable viscosities and good workability.

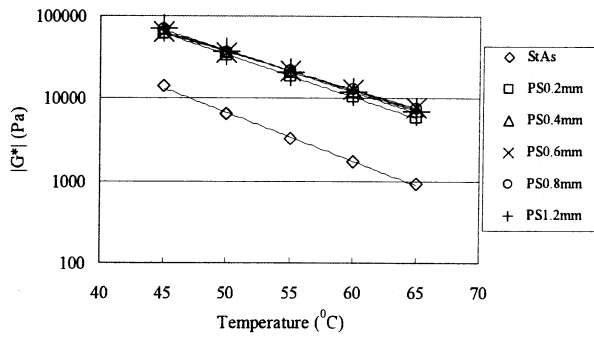


Fig. 3 $|G^*|$ values at high temperatures before aging

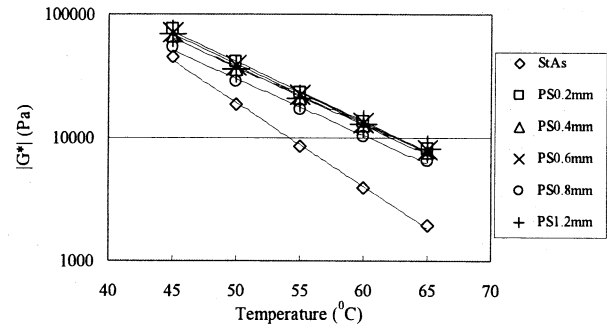


Fig. 4 $|G^*|$ values at high temperatures after aging

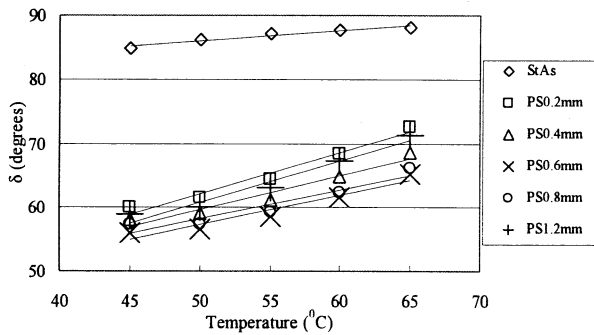


Fig. 5 Phase angle (δ) at high temperatures before aging

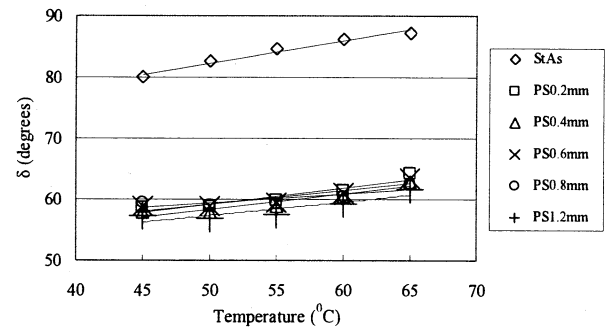


Fig. 6 Phase angle (δ) at high temperatures after aging

(3) Dynamic Shearing

This test is performed by the Dynamic Shear Rheometer (DSR) machine and evaluates the unaged, short-term aged and long-term aged asphalt binders. The viscous and elastic behavior of asphalt binders can be determined at high and at intermediate service temperatures. The DSR measures the Complex Shear Modulus ($|G^*|$) and phase angle (δ) of asphalt binders at the desired temperature and frequency of loading.

The Complex Shear Modulus ($|G^*|$) is the ratio of maximum shear stress ($\tau_{\max}$) to maximum shear strain ($\gamma_{\max}$), and it represents the total resistance of the binder to deformation when repeatedly sheared⁹. The time lag between the applied stress and the resulting strain is the phase angle (δ). A perfectly elastic material will present instant response to an applied stress, so the time lag or phase angle (δ) is zero. When viscous liquids like hot asphalt binder are tested, the time lag is large and the phase angle (δ) approaches 90 degrees.

At high temperatures, the behavior of binders was evaluated from 45°C to 65°C, considering increments of 5°C between these values. The DSR machine used a parallel plate configuration. The plates measured 25mm diameter and the gap between the lower and the upper plate was determined as 2.5 times the respective size of rubber particles. All tests were performed considering a 12% constant strain and ran at a frequency of 1.59Hz.

Comparing straight asphalt and modified binders (Fig. 3), the addition of rubber powder increased the $|G^*|$ values before aging. So, the resistance to permanent deformation improved. Even when the temperature grow and the $|G^*|$ values became smaller; the difference of magnitude among straight asphalt and modified binders did not change. Further, despite the difference of rubber size, the $|G^*|$ values showed the same order of magnitude. After aging (Fig. 4), modified and unmodified binders showed similar values at 45°C. However, increasing the temperature, straight asphalt showed a higher tendency to reduce the $|G^*|$ and as a result of this, higher reduction on it's resistance to rutting. In this way, straight asphalt presented higher temperature susceptibility after oxidation. Besides, analyzing Figs. 3 and 4, it could be seen that modified binders presented similar $|G^*|$ values before and after aging. This may be resultant from the antioxidant components present in the tire compounds. In addition, modified binders presented values with the same order of magnitude, despite the difference of rubber size.

Considering the phase angle (δ) (Fig. 5), when the temperature increased, the δ values tended to become bigger for both types of binder. Modified binders showed higher susceptibility to temperature change, presenting a higher decrease of phase angles as the

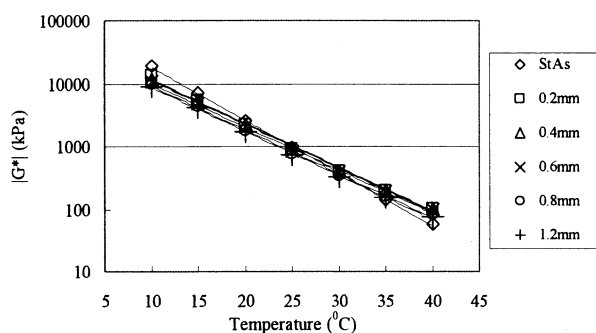


Fig. 7 $|G^*|$ values at intermediate temperatures before aging

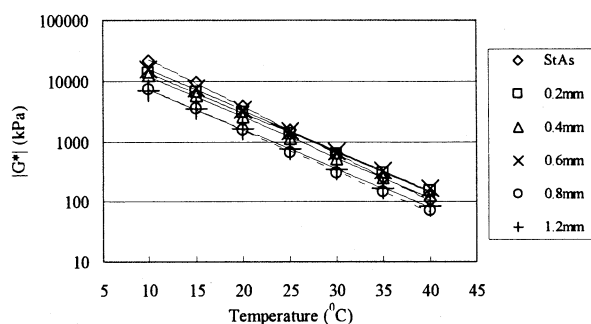


Fig. 8 $|G^*|$ values at intermediate temperatures after aging

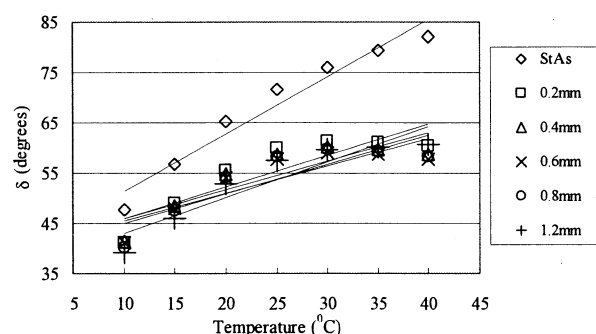


Fig. 9 Phase angle (δ) at intermediate temperatures before aging

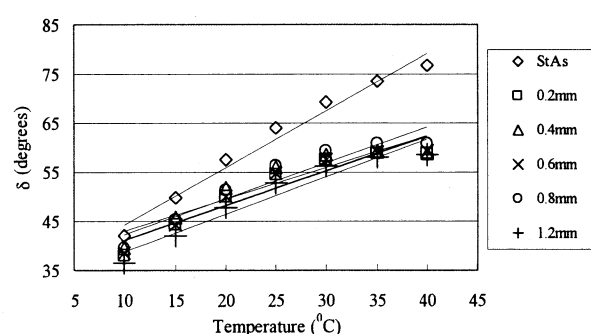


Fig. 10 Phase angle (δ) at intermediate temperatures after aging

temperature grew. However, such growth was lower for binders using rubber 0.6mm and 0.8mm. On the other hand, comparing straight asphalt and modified binders separately at every temperature, the last ones presented lower absolute values showing individually, a higher elasticity at every temperature.

After aging (Fig. 6), modified binders presented lower δ values than that measured for straight asphalt. In this way, the elastic properties enhanced. Further, despite the difference of rubber size, the phase angles presented the same order of magnitude for modified binders. Moreover, comparing Figs. 5 and 6, it's observed that modified binders showed lower δ values and then lower stiffening, probably as a result of the presence of antioxidants in rubber compounds. In addition, the temperature susceptibility of modified binders was also reduced.

At intermediate temperatures, the evaluation of binders took place for temperatures varying between 10°C and 40°C, considering increments of 5°C between these values. The DSR machine used a parallel plate configuration. The plates measured 8mm diameter and the gap between the lower and the upper plate was determined as 2.5 times the respective size of rubber particles. All tests were performed considering 1% constant strain and ran at a frequency of 1.59Hz. As shows Fig. 7, before oxidation, for modified and unmodified binders, the

$|G^*|$ increased when the temperature became lower. At 40°C, the $|G^*|$ values for modified binders presented little higher values than that measured for straight asphalt. However, decreasing the temperature, a reverse tendency took place, and as a result of this, at 10°C modified binders presented lower $|G^*|$ values. In this way, the resistance to deformation of asphalt-rubber binders decreased, thus improving the resistance to fatigue cracking. Further, modified binders showed similar behavior despite the difference of rubber size.

After oxidation (Fig. 8), as the temperature decreased, the $|G^*|$ values became bigger for both types of binder. However, the addition of rubber powder reduced the $|G^*|$ compared with that measured for straight asphalt, enhancing the resistance to fatigue cracking. This fact was more remarkable for binders using bigger particles of rubber (0.8mm and 1.2mm, respectively). Comparing Figs. 7 and 8, the $|G^*|$ for straight asphalt increased a little after oxidation, whereas, modified binders showed similar or smaller $|G^*|$ values after aging. Therefore, the oxidative effect was reduced after rubber addition.

Considering the phase angle (δ), for unaged binders (Fig. 9), it was observed that as the temperature became smaller, the δ values decreased for both types of binder. So, the elastic properties

improved. Such improvement was more important for modified binders whose phase angles presented lower values compared with that for straight asphalt. In addition, the phase angles for modified binders showed values with the same order of magnitude despite the difference of rubber size. Analyzing the tendency of phase angles from 40°C to 10°C, it's seen that straight asphalt showed higher susceptibility to temperature change.

After aging (**Fig. 10**), the phase angles decreased for both types of binder as the temperature dropped. Therefore, the elastic properties enhanced. Besides, at 10°C, straight asphalt and modified binders presented similar behavior. However, modified binders proved little lower δ values, and so a little higher elasticity. Further, the phase angles for modified binders showed values with the same order of magnitude, despite the difference of rubber size. Again, straight asphalt presented higher susceptibility to temperature change, whereas modified binders showed behavior similar to that observed before aging.

(4) Flexural Creep Stiffness

The tendency of asphalt binders to develop thermal cracking at low service temperatures can be determined using the Bending Beam Rheometer (BBR) machine. Thermal cracking of asphalt concrete pavements results when the temperature drops rapidly at cold temperatures. As the pavement contracts, stresses begin to build up within the pavement layers. If the contraction occurs very rapidly, the stresses can eventually exceed the stress relaxation ability of the asphalt concrete pavement. As a result of this, the pavement develops cracking as a way to relieve the stresses. Thermal cracking can result from one thermal cycle when a critically low temperature is encountered, or from thermal cycling where the temperature cycles up and down, but always remains above the critical low temperature. Cracking caused by a single thermal cycle is related to the asphalt binder stiffness at the temperature at which cracking occurs. This temperature is called as the limiting stiffness temperature, and is defined as the pavement service temperature at which a certain stiffness value is reached after a specified loading time⁹⁾.

The Bending Beam Rheometer (BBR) measures the midpoint deflection of a simply supported prismatic beam of asphalt binder that is subjected to a constant load applied to the midpoint of the beam. A test beam is placed in a controlled temperature fluid bath and loaded with a constant load for 240 seconds. The test load ($980 \pm 50 \text{ mN}$) and the midpoint deflection of the beam are monitored versus time

using a computerized data acquisition¹¹⁾.

The maximum bending stress at the midpoint of the beam is calculated from its dimensions, span length, and load applied to the beam for loading times of 8, 15, 30, 60, 120 and 240 seconds. The maximum bending strain is calculated for the same loading times from its dimensions and respective deflection. The stiffness (S) of the beam for the loading times specified above is calculated through the quotient between the stress and the maximum strain. The stiffness (S) is then plotted versus the log of time. The longer the load is left on the sample, the deformation increases, and as a result of this the stiffness (S) decreases with time. According to the Superpave specification two parameters should be analyzed, the stiffness (S) at 60 seconds and the slope of the tangent line at this point (called "m-value")¹¹⁾.

In this study, the flexural creep stiffness of modified and unmodified binders was performed from -30°C to -10°C, at increments of 5°C between these values. According to **Fig. 11**, the lowest the temperature, the lowest the stiffness measured for modified binders compared to straight asphalt. In this way, the addition of rubber enhanced the resistance to thermal cracking and such benefit seemed to become more significant as the temperature decreased. Moreover, the performance of modified binders was similar despite the difference of rubber size. Besides, modified binders showed lower susceptibility to temperature change.

After oxidation (**Fig. 12**), the behavior of aged binders showed the same tendency observed before aging. So, the stiffness of modified binders decreased and the resistance to thermal cracking improved mixing rubber powder to straight asphalt. Further, after oxidation, modified binders mixing respectively rubber 0.4mm, 0.8mm and 1.2mm tended to present slightly lower stiffness values when the temperature dropped. Again, modified binders presented lower susceptibility to temperature change.

The analysis of slopes of response before oxidation (**Fig. 13**) showed decreasing values as the temperature became smaller. Further, at -10°C, the slope of response was little higher for straight asphalt, however, dropping the temperature, a reverse tendency could be observed and as a result of this, at -30°C, modified binders showed little higher m-values. However, the absolute values of slopes of response at this temperature are so small that the gain aforementioned probably will not contribute to relax the thermal stress fast enough to prevent cracking. Further, despite the difference of rubber size, the slopes of response for modified binders showed

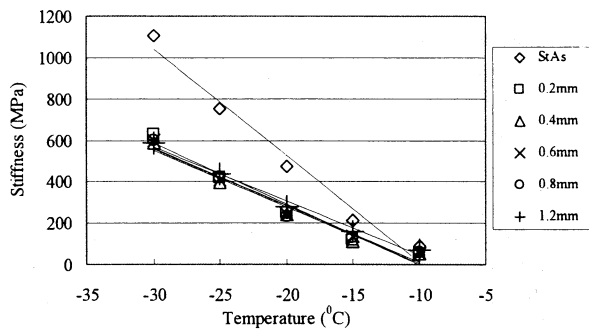


Fig. 11 Stiffness at low temperatures before aging

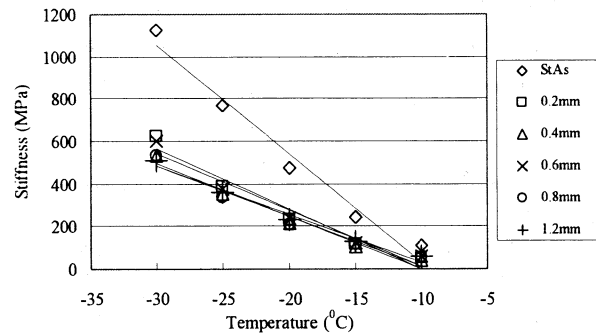


Fig. 12 Stiffness at low temperatures after aging

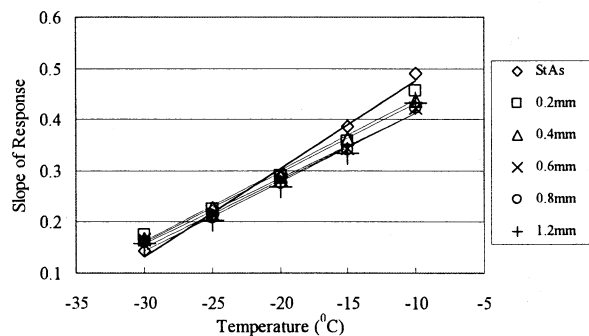


Fig. 13 Slope of response at low temperatures before aging

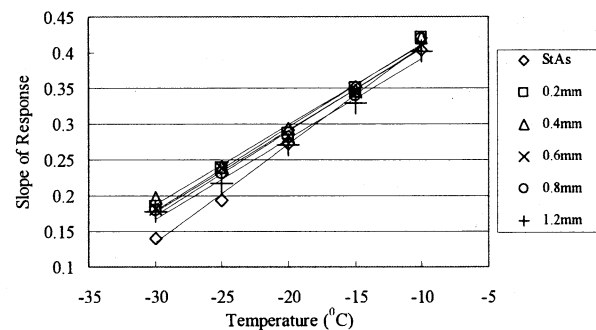


Fig. 14 Slope of response at low temperatures after aging

values with the same order of magnitude.

After aging (Fig. 14), for modified and unmodified binders, the slopes of response became smaller when the temperature dropped. So, the ability to relieve the thermal stresses by asphalt flow decreased, raising the propensity of thermal cracking. Moreover, comparing both types of binder, as the temperature became smaller, straight asphalt tended to produce lower m -values at lower temperatures.

Even though the m -values for modified binders at lower temperatures are higher than that measured for straight asphalt, probably they are not big enough to relieve the thermal stresses. On the other hand, despite the difference of rubber size, the slopes of response for modified binders showed values with the same order of magnitude. Once more, modified binders proved better behavior to temperature susceptibility change.

5. CONCLUSIONS

This paper presented a comparative analysis among straight asphalt and asphalt-rubber binders mixing respectively rubber particles with different size. Rubber powder 0.2mm, 0.4mm, 0.6mm, 0.8mm and 1.2mm were mixed separately to straight asphalt 60/80 (grade of penetration) at a rate of 15% of total

asphalt-rubber weight. Conventional and Superpave tests evaluated the behavior of such binders at high, at intermediate and at low temperatures. It was found that:

- ✓ At high temperatures, before and after aging, the addition of rubber powder to straight asphalt increased the softening point temperatures and the $|G^*|$ values, whereas the phase angles showed lower values than that measured for straight asphalt. Thus, the resistance to permanent deformation improved.
- ✓ At intermediate temperatures, before and after oxidation, modified binders presented lower $|G^*|$ values and phase angles, improving the resistance to fatigue cracking.
- ✓ Before and after aging, the lowest the temperature, the lowest the stiffness measured for modified binders compared with straight asphalt. Therefore, the addition of rubber enhanced the resistance to thermal cracking and such benefit seemed to become more significant at lower temperatures.
- ✓ The addition of rubber powder showed improvements of asphalt properties, but such kind of enhancement presented the same order of magnitude despite the different size of rubber particles used.

- ✓ The influence of size of rubber particles was more remarkable when measuring the viscosities with a rotation viscometer.

ACKNOWLEDGMENTS: This study was supported by the aid of Japan Asphalt Rubber Research Group. This paper was supported financially by Chuo University as one of the 2005 Research Projects for Promotion of Advanced Research at Graduate School. The main author also acknowledges the financial support provided by Japan International Cooperation Agency (JICA).

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ゴム粉のサイズの違いによるアスファルトラバーバインダの特性に関する検討

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ストレートアスファルトにポリマーや他産業廃棄物を加えることによりバインダの特性が改良されることが分かっている。本研究は、ストレートアスファルトに一般車用の廃タイヤのゴム粉を混合した際のアスファルトバインダの挙動に関する検討である。アスファルトの全重量に対し15%の割合で0.2mm, 0.4mm, 0.6mm, 0.8mm, 1.2mmのサイズのゴム粉をそれぞれ混入した。高温時において、回転粘度計で測定した粘性、複素せん断係数 ($|G^*|$)、位相角 (δ)、軟化点の挙動を検討し、さらに、低温時におけるたわみクリープスティフネスや応力リラクゼーションの挙動も検討した。ゴム粉のサイズによる違いはあるものの、ゴム粉を混入することによりバインダの特性は改良されることを示した。