Investigation of Aging Effect on Rheological Properties of Asphalt Binder in RAP Contained Mixture Design Process

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ABSTRACT

There are several methods determining an appropriate performance grade of virgin binder, which is referred as design binder, in RAP contained bituminous mixture design process. However, difficulties have been experienced in utilizing the methods in the field application in Korea, because SHRP binder test, the key tests to determine a design binder, requires well-trained personnel, high price equipment, and time consuming process. Thus, the study investigated the relationship among the binder aging level, RAP contents, and rheological properties of binder. The study results provide mix designer with a simple method in selecting an appropriate grade of virgin binder.

1. INTORDUCTION

Typical RAP contained HMA mix design procedure blends aged binder with an appropriate grade of virgin binder to soften aged binder. An appropriate grade of virgin binder, which is referred as "Design Binder," is determined based on the RAP contents and RAP binder properties.

Recently, Kandhal and Foo reported study results concerning RAP contents and design binder in RAP contained mixture mix design process. The study concluded that less than 15% of RAP use, a virgin binder, which is selected based on the performance temperature, is same as a design binder. In this situation, RAP is regarded as black rock. Between 16% and 25% RAP use, the virgin binder grade should be decreased by one increment in both of high and low performance grade. More than 26% RAP use, RAP binder properties should be analyzed to construct a blending chart which can suggests an appropriate amount and performance grade of virgin binder (1). There are several types of blending charts which determine a design binder when more than 26% RAP is to be used. Kandhal and Mallick suggested a blending chart which is based on binder's viscosity at 60℃. This method evaluates the viscosity of both

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virgin and RAP binder at 60℃ and plots the results on rectangular coordination system. Finally the design binder is determined at a design viscosity (2). Similar method has been constructed utilizing Dynamic Shear Rheometer (DSR). This method uses the $G^*/\sin\delta$ values at high performance temperature in lieu of viscosity at 60℃ (3). Kandhal and Foo developed iso-stiffness curve method. This method performs DSR test on varying RAP content. Iso-stiffness curve is constructed on which all the $G^*/\sin\delta$ values have 1.00kPa at high performance temperature based on the original-DSR test results. Similarly, iso-stiffness curve for short-term aged and long-term aged binder are constructed on which all the $G^*/\sin\delta$ and $G^*\times\sin\delta$ values have 2.20kPa and 5MPa at high and intermediate performance temperature respectively (4). Recently, McDaniel and Anderson presented the "critical temperature" concept which determines the appropriate high and low performance grade temperature of virgin binder when above 26% of RAP is used. This method determines a temperature at which the $G^*/\sin\delta$ value is 1.00kPa. This temperature is called high critical temperature. In similar pattern, medium critical temperature and low critical temperature are determined based on PAV-DSR test and Bending Beam Rheometer (BBR) test respectively (5).

Binder's rheological property, as well as RAP contents, is another major variable to be considered in RAP contained mixture design. However, it is difficult to identify RAP binder's rheological properties because most RAP stock pile consist of various RAP sources, i.e., gradations, binder contents, aging levels, and so on (6). Thus, RAP properties are capricious during the HMA manufacturing process. To determine an appropriate performance grade of virgin binder (design binder), the aging level of RAP binder should be considered because aging level plays an important role in binder's rheological properties. Many studies have been reported concerning aging effect on binder's rheological properties. It is well known that there are six factors affecting asphalt aging, i.e., oxidation, volatilization, polymerization, thixotropy, syneresis, and separation. However, one of the major factors affecting asphalt aging has been reported as oxidation (7). Further study identified two major group types, ketones and sulfoxides which are generated from asphalt oxidation hardening process (8, 9). The mechanism and interrelationships of ketones and sulfoxides between asphalt oxidation has been investigated that ketones have a much greater effect on viscosity increase than sulfoxides (10). Huang et al. performed a study to investigate the effect of hydrated lime on aging characteristics of binder. It is observed that the elastic response increases more rapidly than viscous response decrease during the Dynamic Shear Rheometer (DSR) test (11). Said reported the aging effect on the in-situ stiffness modulus of Hot Mix Asphalt (HMA) layer that stiffness modulus increases dramatically during the 1^{st} year after construction. The research results imply that the aging level of binder in RAP varies by performance life, consequently the stiffness modulus varies by performance life (12).

As described above, numerous studies have been conducted to aid a guideline or a method to utilize RAP in the Hot Mix Asphalt (HMA). However, difficulties have been experienced in utilizing above mentioned methods in the HMA manufacturing plants, because it is hard to identify the rheological properties of RAP binder due to the heterogeneity of RAP binder's aging levels, and because SHRP binder test, which is essential tests to determine the design binder, requires well-trained personnel, high price equipment, and time consuming process. Thus, the study investigated a relationship among the binder aging level, RAP contents, and rheological properties of binder in order to provide a mix designer with a simple method in selecting a design binder.

2. EXPERIMENTAL DESIGN

To facilitate the experiments, RAP binders have been prepared using the laboratory aging equipment, i.e., Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV). The laboratory aging process utilized a virgin binder of PG64-22, which has been aged into three levels in accordance with the Superpave aging concepts; short-term aging, mid-term aging and long-term aging. It is noted that "mid-term aging" concept has been introduced in this study that asphalt binder has been aged utilizing RTFO with exposure time of 270 minutes instead of 85 minutes at the same air flow rate and temperature as short-term aging process. 270 minutes are determined based on the $G^*/\sin\delta$@64℃ value (see Table 1) which lies in the middle of $G^*/\sin\delta$@64℃ value of short-term aged binder and long-term aged binder. The properties of laboratory aged binders are described in Table 1. To quantify the binder aging levels, the study introduced Binder Aging Level Index (BALI) as shown in equation 1 through equation 4, which describes aging level of non-aged binder, short-term aged binder, mid-term aged binder, and long-term aged binder respectively. Using BALI values are convenient to analyze the binder properties with respect to aging level and also manipulative to categorize aging level of any field binder because binder aging levels are expressed into a certain numeric numbers. Table 1 shows BALIs for each binder aging levels.

$$BALI_{ORG} = \frac{G^*/\sin\delta@\text{Original DSR} - G^*/\sin\delta@\text{Original DSR}}{G^*/\sin\delta@\text{Original DSR}} \qquad \text{(Equation 1)}$$

$$BALI_{SHORT} = \frac{G^*/\sin\delta@\text{RTFO DSR} - G^*/\sin\delta@\text{Original DSR}}{G^*/\sin\delta@\text{Original DSR}} \qquad \text{(Equation 2)}$$

$$BALI_{MID} = \frac{BALI_{SHORT} + BALI_{LONG}}{2} \qquad \text{(Equation 3)}$$

$$BALI_{LONG} = \frac{G^*/\sin\delta@\text{PAV DSR} - G^*/\sin\delta@\text{Original DSR}}{G^*/\sin\delta@\text{Original DSR}} \qquad \text{(Equation 4)}$$

Three types of virgin binders, PG58-22, PG64-22, and PG64-12, have been used in this study. The selected virgin binders are mostly used for bituminous pavements in Korea. The varying percentages of laboratory aged binders have been blended with selected virgin binders, i.e., 15, 25, 50, and 100%. Then, penetration test, DSR test, and BBR test were performed for the experimental design binders.

Table 1. Summary of Aged Binders Properties

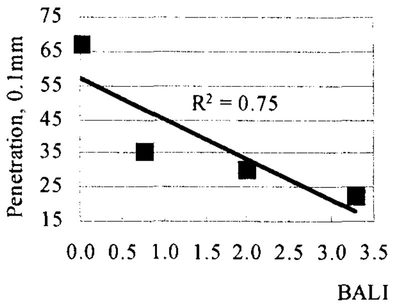
Test \ Aging	Original	Short-Term	Mid-Term	Long-Term
Penetration (0.1mm)	67.5	35.5	30.4	22.6
G*/sinδ@64℃ (kPa)	1.41	2.49	4.23	6.04
G*/sinδ@70℃ (kPa)	0.68	1.99	2.76	3.62
G*sinδ@25℃ (kPa)		5006	5395	5911
S-value@-18℃ (MPa)	336.1	326.0	339.7	382.8
m-value@-18℃	0.28	0.15	0.37	0.29
S-value@-12℃ (MPa)		157.4	238.6	238.1
m-value@-12℃		0.40	0.44	0.36
Binder Aging Level Index	0	0.77	2.00	3.28

Note: G*/sinδ@64℃ for original asphalt binder = 1.41, BALI = 0

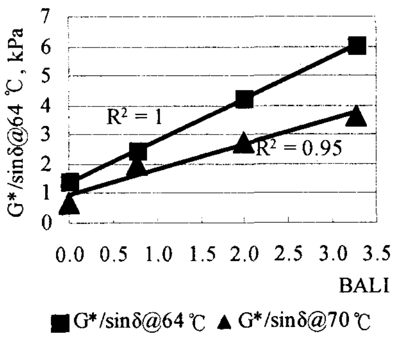
3. RESULTS AND DISCUSSION

3.1 Validation of Binder Aging Level Index (BALI)

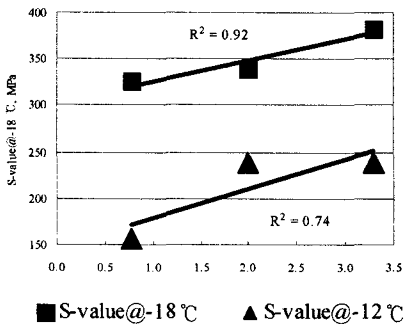
Figure 1a through Figure 1d show the binder property changes with respect to the BALI changes. Figure 1a shows that penetration decrease as BALI increase but the relationship is weak between them (R^2 =0.75). Figure 1b shows that G*/sinδ values increase as BALI increases with approximately perfect linear relationship (R^2 = 1 and 0.95). Figure 1b also shows that G*/sinδ@64℃ values increase more rapidly than those of G*/sinδ@70℃. The results implies that aging effect is more sensitive on G*/sinδ value at the lower temperature. Aging effect, therefore, should be significantly considered at the lower performance temperature area. Figure 1c shows that stiffness increase as BALI increase with fair relationship (R^2 = 0.92 and 0.74). The results are not explainable but m-value has no pattern with binder aging effect as shown in Figure 1d. Thus, the BBR test was excluded in the following study. Based on the test results shown in Figure 1, G*/sinδ has been selected as the parameter which describes binder aging level.



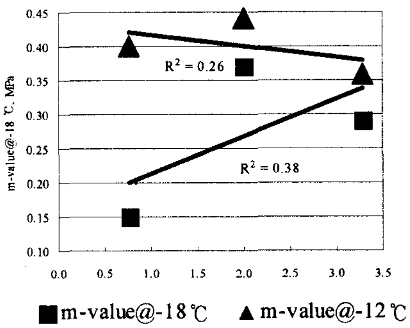
<Figure 1a> Penetration versus BALI



<Figure 1b> G*/sinδ versus BALI



<Figure 1c> S-Value versus BALI

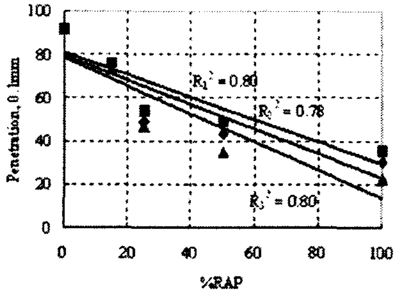


<Figure 1d> m-Value versus BALI

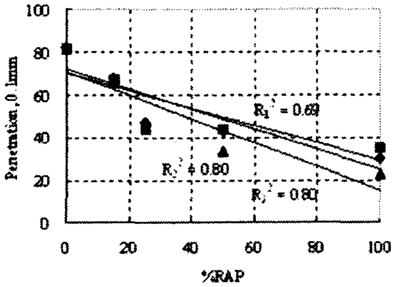
Figure 1. Binder Properties Change versus Binder Aging Level Index

3.2 Penetration Test

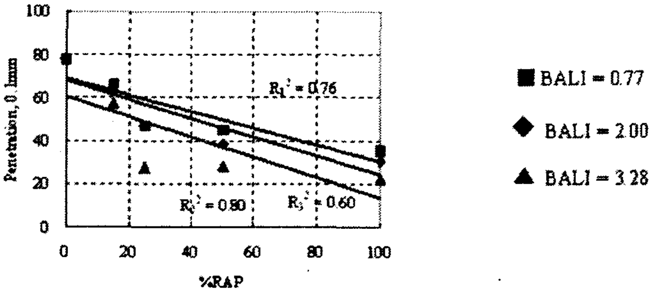
The study investigated penetration changes versus RAP content change with varying binder aging levels. Varying percentage of RAP have been blended with virgin binders; PG58-22, PG64-22, and PG64-16 shown in Figure 2a through Figure 2c respectively. It is observed that as BALI and %RAP increase, penetration decrease. It is also observed that as the penetration value of virgin binder and BALI increase, penetration value decrease more rapidly. Thus, it is concluded that the binders having higher penetration value are more susceptible to aging in terms of penetration test.



<Figure 2a> Penetration versus %RAP for PG58-22



<Figure 2b> Penetration versus %RAP for PG64-22



<Figure 2c> Penetration versus %RAP for PG64-16

Figure 2. Penetration changes versus varying RAP contents with varying BALI blended with virgin binder, PG58-22, PG64-22, and PG64-16

3.3 Dynamic Shear Rheometer Test

The study investigated G*/Sinδ changes versus RAP content change with varying binder aging levels. Varying percentage of RAP have been blended with virgin binders; PG58-22, PG64-22, and PG64-16. It is observed that as %RAP increase, G*/Sinδ increase as expected. Figure 3 illustrates the G*/Sinδ increasing rate with respect to the virgin binder performance grades, penetration values, and BALIs. According to Figure 3, it is found that penetration values have no effect on the G*/Sinδ increasing rate neither performance grade of virgin binder does. However, it is observed that as the BALI increase, the G*/Sinδ values increase more rapidly. Thus, binder aging level should be carefully considered in determining design binder's high performance temperature. The more detailed considerations are discussed in the followings.

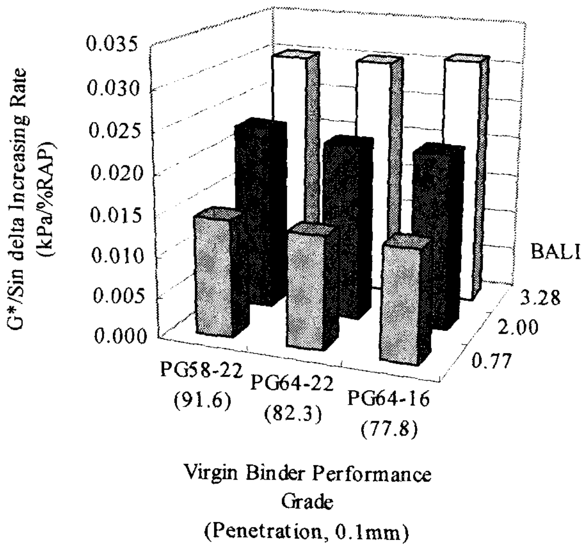
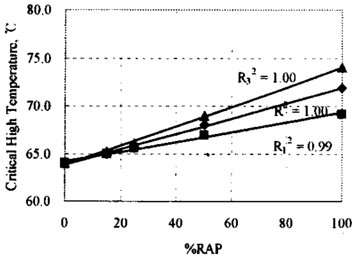


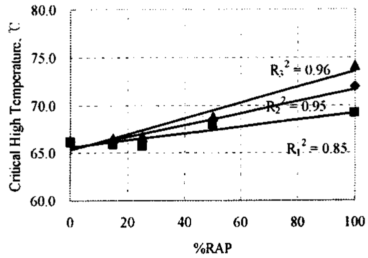
Figure 3. G*/Sinδ increasing rate with varying performance grades, penetration values, and BALIs

3.4 Critical High Performance Temperature, Tc(High)

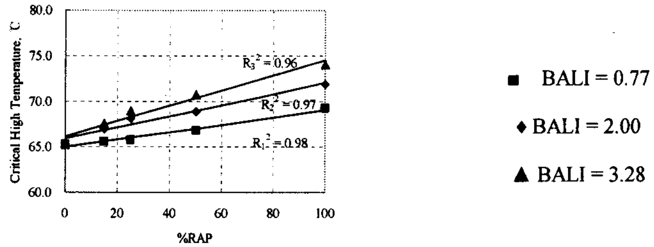
The study investigated Critical high temperature changes versus RAP content change with varying binder aging levels as shown in Figure 4a through Figure 4c. It is observed that as BALI increase, Critical high temperature increase more rapidly. Figure 5 illustrates the Critical high temperature increasing rate with respect to the virgin binder performance grades, penetration values, and BALIs. As shown in Figure 5, it is found that penetration values have no effect on the critical high temperature increasing rate.



<Figure 4a> Tc(High) versus %RAP for PG58-22



<Figure 4b> Tc(High) versus %RAP for PG64-22



<Figure 4c> Tc(High)versus %RAP for PG64-16

Figure 4. Critical high temperature changes versus varying RAP contents with varying BALI blended with virgin binder, PG58-22, PG64-22, and PG64-16

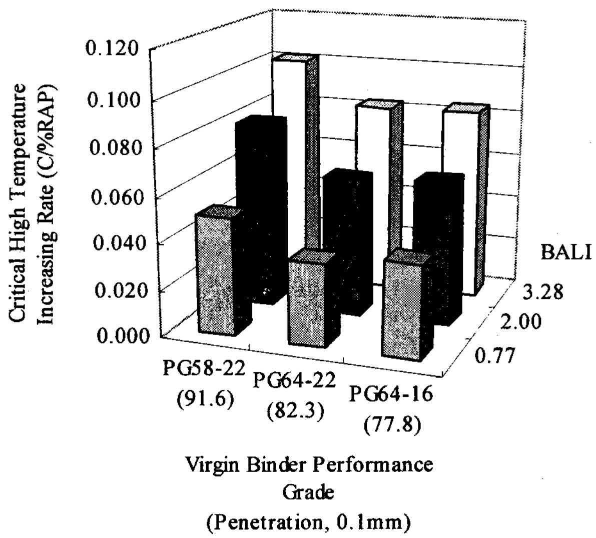


Figure 5. Critical high temperature increasing rate with varying performance grades, penetration values, and BALIs

4. CONCLUSIONS AND RECOMMENDATIONS

It is observed that Binder Aging Level Index (BALI) is a good parameter on the base of SHRP binder test results. Thus, BALI could be applicable when classify the field RAP into a certain aging level categories. However, careful cautions should be taken because the study covered only limited range of binder grades. Thus, further study is recommended to investigate wide range of virgin binder' performance grades and wide range of binder aging level. Especially, it will be more practical if the field RAP binders having wide range of aging levels are to be investigated in the future study. Even though the study is limited to a specific condition, it is found that virgin binders having higher penetration value are more susceptible to the aging effect. It is also found that G*/Sinδ increase more rapidly as BALI increases.

It is observed that from Figure 4 that the high critical temperature of aged binders having BALI=0.77 are less than 70℃. Thus, the aging effect of aged binders having BALI=0.77 is negligible in 64℃ high performance temperature region. However, the aging effect of aged binders having BALI=2.00 is negligible only when they are used less than 50 percent. Similarly, the aging effect of aged binders having BALI=3.28 is negligible only when they are used less than 50 percent at 64℃ high performance temperature region.

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