DEVELOPMENT OF ASPHALT BINDER SPECIFICATION BASED ON DISSIPATED ENERGY

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Abstract: Traditional binder specifications including penetration and viscosity are basically empirical in nature. Although the recent development from the Strategic Highway Research Program (SHRP) provides insights as to the fundamental properties of asphalt binders, no agreements have been reached on the proper parameter to govern pavement performance. This paper was to derive the theoretical background of dissipated energy and to demonstrate its relevance through experiment works. Specifications for different class of roadway were presented based upon field and laboratory works. Results indicated that the dissipated energy corresponded well with pavement rutting and cracking, while SHRP parameters led to weak prediction on pavement performance. Practical recommendations were made to improve current systems to provide adequate grading parameters, thus enhancing pavement performance. The results of this study can help pavement engineers to better select asphalt binder based upon climate and traffic.

1. INTRODUCTION

Asphalt cements have historically been graded by two empirical tests: penetration and viscosity. These tests were developed in the early 1900's, using experiences with asphalt pavements. Empirical tests work well as long as all of the conditions at the time of the test remain unchanged. Unfortunately, this is not true for our asphalt pavements today. Penetration and viscosity tests were developed in an era of less traffic and lower tire loadings. Trucks of yesteryear were limited to about 32,660 kg (72,000 lb.), and rode on bias ply tires with tire pressures of 1066 kg/cm^2 (75 psi). Today, truck weights exceed 36,290 kg (80,000 lb.), and radial tires are inflated to 1778 kg/cm^2 (125 psi). A 10% increase in truck weight may not seem significant, but it results in a 40% increase in stresses applied to the pavement. These factors, along with the dramatic increase in the numbers of trucks traveling on the highway system today, resulting in rutting and premature failure on asphalt pavements.

Penetration measures the depth of a sewing needle into a sample of asphalt at 25°C. Viscosity measures the time required for asphalt to flow through a calibrated glass tube at 60°C. These two tests are measured at only one temperature, which do not give any indication how the material will perform at the wide range of temperatures the roadway will experience. In addition, various crude oils produce asphalts with widely different properties. Many contractors discovered this fact during the oil crisis of the 1970's, when refiners used whatever crude was available. Asphalts produced from different crudes may meet the penetration and viscosity specifications of a given grade, but perform quite differently during construction and on the road.

Asphalt pavements account for more than 96 percent of all paved highways in Taiwan, and annual expenditures for asphalt pavements top NT$10 billion. The pavement coverage is approximate 32 million m^2 in Taiwan, but about one third of its total coverage needs to be rehabilitated annually (MOTC 1997). In addition, the price to maintain the pavement just above its serviceable level gradually increases and becomes enormous. Among many factors affecting pavement performance, it is believed that one of the main reasons attributing pavement failures is asphalt binders. Conventional binder specifications have been used in highway agencies for decades without properly correlating to pavement performance. With increase in budget each year, apparently money spent on constructing pavement does not have its dollar value returned. If the service life of asphalt pavements can be designed to last longer, a nation could stand to reap substantial benefits.

It is obvious the previous empirical specifications did not relate directly to asphalt binder performance in our pavements. The Strategic Highway Research Program (SHRP) sponsored $50 million of research on asphalt binders to relate the specifications to actual pavement performance. The outcome of the SHRP project was termed as Superpvae, initiated from the Superior Performance Asphalt Pavements. The new Performance Grade (PG) asphalt binder specifications measures physical properties of the material throughout its temperature range. PG graded asphalt binders are graded according to the climatic conditions they will endure in the roadway. A PG 64-22 will perform from a high pavement temperature of 64°C to a low pavement temperature of -22°C.(Anderson, Kennedy 1992; Bahia, Anderson 1995)

In spite of Superpave's efforts on relating asphalt's properties to pavement performance, the binder specification still inherits several shortcomings. The parameters used to judge asphalt binders are not well explained theoretically, thus, causing confusions among highway agencies. This specification has never been thoroughly validated before its release to the public. Recent reports showed speculation on the accuracy and appropriateness of Superpave's binder specifications (Reese 1997; Zhang 1997). The study had three objectives: (1) to develop the fundamental-sound concept for materials that will outperform and outlast the pavements being constructed today; (2) to investigate why some pavements perform well, while others do not; and (3) to give highway engineers the tools they need to design asphalt pavements that will perform better under different temperature and heavy traffic loads.

2. MODEL DEVELOPMENT

When pavements are subjected to traffic loading, asphalt is assumed to be under a sinusoidal strain. Since asphalt is a linear viscoelastic material, it is shown as follows:

$$\varepsilon = \varepsilon_0 \cdot \sin(\omega t) \quad \text{(Eq. 1)}$$

$$\sigma = \sigma_0 \cdot \sin(\omega t+\delta) \quad \text{(Eq. 2)}$$

The storage modulus and the loss modulus can be expressed as follows:

$$G' = (\sigma_0/\varepsilon_0) \cdot \cos(\delta) \quad \text{(Eq. 3)}$$
$$G'' = (\sigma_0/\varepsilon_0) \cdot \sin(\delta) \quad \text{(Eq. 4)}$$

In case of a linear viscoelastic response, the rheological behavior of asphalt can be expressed by energy dissipated per cycle, W_d. Under dynamic loading conditions asphalt can be characterized as follows:

$$\begin{aligned} W_d &= \int \sigma \, d\varepsilon = \int_0^{2\pi/\omega} \sigma \frac{d\varepsilon}{dt} dt \\ &= \omega \varepsilon_0^2 \int_0^{2\pi/\omega} [G' \sin(\omega t)\cos(\omega t) + G'' \cos(\omega t)] \, dt \\ &= \pi \, G'' \varepsilon_0^2 \end{aligned} \quad \text{(Eq. 5)}$$

However, in the development of Superpave specification, W_d was derived and put in the form as follows:

$$W_d = \pi \cdot \sigma_0 \cdot \varepsilon \cdot \sin \delta \quad \text{(Eq 6)}$$

2.1 Rutting Criteria

Superpave assumed rutting to be a stress-controlled cyclic loading phenomenon. A parameter, G*/sin δ, was proposed to control rutting. To reduce rutting, G*/sin δ should be minimized. This means that G*/sin δ should be maximized to control permanent deformation. Superpave, thus, used the parameter, G*/sin δ, to rank the rutting susceptibility of pavements. Asphalt properties needs to be measured on the original binder at average 7-day maximum pavement temperature and at a frequency of 10 rad/sec.

Experiences have, however, been not very positive regarding the G*/sin δ parameter. Some complications have arisen as validation work continues. Most laboratory and field studies reflect ambiguous correlations between the rutting parameter, G*/sin δ, measured by the Dynamic Shear Rheometer (DSR) and rutting for any given mix design (Claxton *et al.* 1996; Stastna *et al.* 1997; Oliver, Tredrea 1998). Long Term Pavement Performance (LTPP) studies are continuing to perfect the air-to-pavement temperature algorithms at high summertime temperatures. Results to date do not suggest that any serious problems exist in the current system. One important issue not yet resolved is the question of "grade bumping" to stiffer binders based on traffic speed and load (Chen 1996).

It is argued in this study that the assumption of the stress-controlled mode for representing permanent deformation in Superpave may not reflect the actual situation of pavement rutting. The frequency at 10 rad/sec may not specifically refer to the corresponding traffic speed inducing deformation. Researchers were speculative as to the adequacy of using the parameter, G*/sin δ, to predict pavement rutting (Claxton *et al.* 1996; Stastna *et al.* 1997). As derived in equation (5), the mechanism of asphalts of contributing to rutting is directly related to the dissipated energy, W_d, regardless the mode of tests. The more W_d, the more energy dissipated in pavement deformation. Hence, it would be appropriate to limit the W_d

value. In other words, under the same temperature and loading frequency, asphalts with lower W_d values are expected to better resist rutting.

2.2 Fatigue Cracking Criteria

Highly oxidized asphalts may perform well in low strain environments, but may crack severely in fatigue when pavement strains are large. Elastomeric polymers, on the other hand, would appear to offer the greatest economic benefit in higher strain environments along with benefit in low strain environments. This complicates the grade selection issue because both modification techniques (oxidizing and polymer modification) can be used to extend the temperature range to meet current PG specifications. Both modification methods could be used to make the same PG 76-22, but their relative performance in fatigue will vary greatly depending upon the strains developed during loading of the pavement structure.

The Superpave specification stipulates that fatigue cracking is primarily due to repeated loading on the pavement surface, and a strain-controlled (ε) phenomenon is assumed (Anderson, Kennedy 1992; Bahia, Anderson 1995). To prevent fatigue cracking, the parameter, $G^* \cdot \sin\delta$, is recommended in Superpave to be minimized to control fatigue cracking. Superpave, thus, uses $G^* \cdot \sin\delta$ measured on the PAV-aged residue at an intermediate pavement temperature and at a frequency of 10 rad/sec to rank the fatigue cracking susceptibility of asphalts.

Because of its inherited assumptions, $G^* \cdot \sin\delta$ may not be a good indicator for evaluating fatigue cracking. When pavements subjected to traffic loading, part of external work from traffic loading is recovered in elastic rebound of pavement, and the remaining work is dissipated as results of fatigue cracking. The more energy dissipates the more likely pavements would crack. The dissipated energy, W_d, represented by equation (5) seems to be more in line with pavement cracking. It has nothing to do with whether the test is run under a strain-controlled mode or not. Unsatisfactory results on using $G^* \cdot \sin\delta$ to predict the pavement cracking have been reported (Leahy *et al.* 1994; Reese 1997).

3. MATERIALS AND TEST METHODS

3.1 Asphalt Binders

Three different kinds of asphalt binders manufactured by the Chinese Petroleum Corporation in Taiwan were selected for this study. These asphalts as shown in Table 1 represented a wide range of practical usage for pavement construction in Taiwan. The conventional tests including penetration, soft point and viscosity are empirical in nature, and the performance models based on these tests have been considered to be speculative (Leahy *et al.* 1994).

Table 1. Asphalts Used in This Study

Code	Grade	Soft. Point °C	Penetration 25°C, 0.1mm	Viscosity 60°C, poise	Viscosity 135°C, cSt
A	85/100 pen	48	98	1029	289
B	60/70 pen	52	64	1992	569
C	40/50 pen	49	47	3862	543

3.2 Asphalt-Aggregate Mixes

Only one type of crushed limestone was selected for the research so that differences in rutting and fatigue cracking behavior were attributed only to the asphalt binders used. This dense mix as shown in Table 2 was typical of mixtures used on high-volume highways in Taiwan. Mix designs were developed following the 75-blow Marshall procedures currently employed by the highway authority. A grading of 19-mm maximum aggregates was mixed with an optimum binder content of 5.4 percent and an air void of 4.7 percent.

Table 2. Asphalt Mixture Gradation

Sieve	1"	3/4"	3/8"	#4	#8	#30	#50	#100	#200
Passing %	100	90	70	56	42	24	18	11	4

3.3 Dynamic Shear Rheometer (DSR)

The DSR, a CSR-500 model, was used to characterize viscoelastic behavior of asphalt binders. It measured the complex shear modulus (G*) and phase angle (δ) of asphalt binders by subjecting a small sample of binder to oscillatory shear stress. G* is a measure of the total resistance of a material to deformation when repeatedly sheared. δ is an indicator of the relative amount of recoverable and non-recoverable deformation. Two measurements for each asphalt were obtained over a range of frequencies to determine the time dependency of the asphalt binder. Asphalt was sandwiched between the oscillating spindle and the fixed steel plate. The DSR measured G* and δ by measuring the strain response of the specimen to a fixed torque. The normal procedure was to deposit a molten sample of a binder on the heated rotor and raised the plate so that a 2-mm binder film was formed before testing. Asphalt was tested at 60°C for rutting and 20°C for fatigue cracking. A computer was used with the DSR to control test temperatures and record test results. By measuring G* and δ, the DSR provided a complete picture of the behavior of asphalt at pavement service temperatures.

3.4 Aging Tests

Two types of aging tests were performed in this study: thin-film oven test (RTFOT) and pressure aging vessel (PAV). The former one was used to simulate the early oxidation of asphalt in the pugmill according to ASTM D2872. The RTFOT involved a moving film of asphalt material heated in an oven for 75 minutes at 163°C. The PAV developed by Superpave was to age asphalt in the laboratory to simulate the severe aging that occurs after the binder has served many years in a pavement. The PAV apparatus consisted of the pressure aging vessel and temperature chamber. A cylinder of dry, clean compressed air provided air pressure with a pressure regulator, release valve. In this study a 2.1 MPa pressure of air gas was applied to asphalts conditioned at 100°C for 20 hours.

3.5 Wheel Tracking Test

A wheel tracking tester was used to evaluate a mixture's susceptibility to permanent deformation in the Asphalt Laboratory at the National Cheng-Kung University. This equipment is similar to the Hamburg Wheel-Tracking Device, which was shown to be one of adequate accelerated wheel test devices used to simulate the effect of traffic on pavements (Williams, Stuart 1998). Mixture samples of different binders were carefully controlled to have the same binder content, air void content, gradation and aggregate type as used in the field. To predict rutting, a series of experimental tests were performed at the mean highest weekly average temperature as proposed by Superpave, which was set at 60°C under dry conditions. A smooth solid-steel track travelling at a speed of 1.44 km/hr was used. Rut depths were measured at every 200 wheel pass on 300mm x 300mm x 70mm samples trafficking by a tire pressure of 540 kPa (80 psi).

Two rutting parameters were measured from the wheel tracking test: total rut depth and normalized rut rate. The total rut depth was the rut depth at the end of the test, i.e., after 8000 passes. The normalized rut rate was the rate of increase in rut depth (0.01mm/cycle) between 4000 and 8000 loading passes. The normalized rut rate was considered to be a more reliable indicator of permanent deformation because it is less likely to be affected by the initial compacting "errors."

4. RESULTS AND DISCUSSIONS

4.1 Binder Properties

Since the low-temperature cracking is not a concern in Taiwan, the Superpave PG grading is only based on unaged, RTFOT and PAV asphalts tested by the dynamic shear rheometer (DSR) in this study. Asphalt B (Pen 60/70) was expected to be classified as higher grade (i.e., PG 64-xx) than the asphalt A (Pen 85/100). Examination of Table 3 showed that asphalt B is stiffer at all temperatures than asphalt A; however, asphalt B barely failed the RTFOT residue stiffness requirement ($G^*/\sin\delta > 2.2$ kPa) at 64°C with a value of 2.14 kPa. The physical properties of asphalts A and B belonged to the upper and lower limits of a PG 58 grade respectively. Although both asphalts A and B were graded the same (PG 58-xx) at high temperatures, they may perform differently for rutting.

Asphalt C passed both rutting requirements at 67°C. However, tests conducted at the Federal Highway Administration WesTrack test facility in Nevada in 1997 indicated that premature rutting and permanent deformation of Superpave test sections may have sent out the wrong signals to those highway departments and contractors considering laying down the Superpave mix. The major cause of early rutting of the reconstructed test sections was a combination of a coarse-graded mixture with high optimum asphalt content (5.7%) and low binder stiffness (PG 64-22).

By comparing the southern region of Taiwan where high pavement temperature (>60°C) and heavy traffic (>3x10^7 ESAL) occur, experiences showed that a higher grade will be needed. Current Superpave grades exist a big gap between PG 64-xx and PG 70-xx. To be on the safe side of pavement distresses, a PG 67 grade was recommended in the study to meet the specific requirements of Taiwan climatic and traffic. Asphalt C, graded as PG 67-xx, appeared to be the better selection of binders that can be used in the southern Taiwan. As a matter of fact, some highway agencies even try to use a PG 70-xx asphalt cement for conditions in southern Taiwan. Cautions should, however, pay to the possible of fatigue cracking. More research is needed to investigate this matter. Asphalts A and B were recommended to apply to the northern and middle regions of Taiwan respectively, where temperature in summer is relatively mild. .

Table 3. PG-Graded Asphalts Used in Taiwan

Test	Property	Asphalt A	Asphalt B	Asphalt C	Superpave Spec.
rotational viscosity, unaged	viscosity @135°C	0.34 Pa-s	0.48 Pa-s	0.52 Pa-s	3 Pa-s, max.
dynamic shear, unaged, 10 rad/sec	G*/sinδ				1.00 kPa, min.
	@58°C	1.12 kPa	2.47 kPa	3.51 kPa	
	@64°C	0.67 kPa	1.23 kPa	1.51 kPa	
	@67°C	-	0.81 kPa	1.12 kPa	
	@70°C	-	0.47 kPa	0.82 kPa	
RTFOT, mass loss		0.08%	0.09%	0.07%	1.00%, max.
Dynamic shear, RTFOT, 10 rad/sec	G*/sinδ				2.20 kPa, min.
	@58°C	2.45 kPa	4.71 kPa	-	
	@64°C	1.21 kPa	2.02 kPa	3.29 kPa	
	@67°C	-	-	2.29 kPa	
	@70°C			1.67 kPa	
Dynamic shear, PAV, 10 rad/sec	G*·sinδ				5000 kPa, max.
	@16°C	6512 kPa	9812 kPa	-	
	@19°C	3872 kPa	6932 kPa	6893 kPa	
	@22°C	2496 kPa	5325 kPa	4512 kPa	
	@25°C	-	3512 kPa	-	
PG Grade		PG 58-xx	PG 58-xx	PG 67-xx	

Questions were raised concerning the similarities of asphalt cement having the same grades. For example, would two sources of PG 64-22 be expected to have similar performance? The belief is that the source of the asphalt cement and the way the asphalt cement is produced will affect its performance (Goodrich 1988; King *et al.* 1992). A PG 64-22 that is a neat asphalt cement will likely perform differently than a PG 64-22 that is a modified binder. The type of modification will also have an effect, i.e., modified by SBS or EVA. While we conveniently assume that the performance of all PG 64-22 asphalt is the same, it doesn't appear that this is true.

The original SHRP research was based on conventional asphalts, and the PG specs may not be able to distinguish between the performance of various modification techniques that achieve the same grade. Research is continuing in this area, but in the interim, many agencies are specifying polymer modifiers that have a history of excellent performance. The complexity of the issue has led some agencies to add a polymer-specific identifier test to insure polymer modification. For example, maximum phase angle and elastic recovery ratio requirements were used as specification parameters.

The new PG grading system is a major improvement over the traditional systems. There were some concerns the binder testing may take too long for quality control (QC) at the refinery. It is expected that after some experience with testing of Superpave binders technicians will be able to run one or two consistency tests for QC. For example, the dynamic shear rheometer (DSR) test is reasonably fast and should be able to use it for consistency. As compared to the old systems (i.e, penetration and viscosity), a significant amount of time can be saved when conducting the specified tests.

According to refiners, controlling the properties of the binders will take much more effort than it did with the old system. Some work is needed by refineries to predict the PG grades that can be produced from given crudes. Years of experience have resulted in a number of methods that can be used to predict viscosity or penetration values that could be obtained from crude sources. This experience is not yet available for Superpave binders. Polymers can be used to modify asphalt cements to meet certain grades. Some agencies may use polymers to meet certain PG grades, while others require that polymers be used to meet these PG grades. Again, the feeling is that the PG grade is important, but the way in which the PG grade is achieved is also important.

With Superpave, asphalt binder is now an engineered product and is no longer a by-product of the refining operation. This should result in improved performance, and in some cases will result in increased costs. However, binder equipment is significantly more expensive than that used prior to Superpave, and there have been some reliability problems with much of the equipment. PG binder selections may lead to increased use of modified binders and, therefore, changes in production and placement, including increased temperatures. Personnel need to be properly trained before being qualified to run the Superpave tests.

4.2 Wheel Tracking Test Results

The Superpave binder specification was based on traffic speeds of 80-100 km/hr while the wheel tracking test traveled at 1.44 km/hr (Bahia, Anderson 1995). It was reasoned that the slow speed of the wheel tracking would make the subjected pavements too severe. Figure 1 showed that the relationship between rutting rate and G*/sinδ at 10 rad/sec is not very good with a coefficient of determination (R^2) value of 0.46. Asphalt binder is rather frequency-dependent. In this study the DSR frequency corresponding to the pavement and mixture tests was chosen at 10 rad/sec being equivalent to 80 km/hr. In order to make the comparison at the same loading rate, asphalts should be tested at a frequency of 0.18 rad/sec (corresponding to the track speed 1.44 km/hr) under temperature 60°C. However, the closest frequency of loading that could be obtained experimentally was 0.6 rad/sec. The improvement of using parameter G*/sinδ to predict rutting rate was indicated in Figure 2 in which the R^2 value is 0.57. The correlation was improved by the change in loading frequency, but the parameter G*/sinδ was found to be not very reliable to predict pavement rutting. This finding is in good agreement with other researchers (Leahy *et al.* 1994; Claxton *et al* 1996).

Because of some highway agencies' concerns, it was proposed to reduce the G*/sin δ on RTFO material from 2.2 to 1.75 for modified binders. This proposal was written based on data which showed polymer-modified asphalts exhibiting a lower ratio of RTFO's G*/sin δ to original's G*/sin δ. It also possible to use phase angle to indirectly specify polymer-modified binders. For example, reports indicated to use phase angle as one of several criteria for polymer modified asphalt binders: 77 degrees maximum for SBR, and 82 degrees maximum for SBS type polymers.

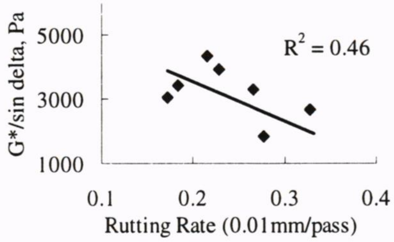

Figure 1. Rutting Rate and G*/sin δ at 10 rad/sec from Wheel Tracking Test

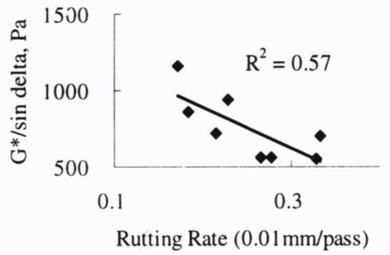

Figure 2. Rutting Rate and G*/sin δ at 0.6 rad/sec from Wheel Tracking Test

Figure 3 showed a better relationship between rutting and the dissipated energy (W_d) with a R^2 equal to 0.72. The proposed parameter, i.e., W_d, appeared to be a better indicator for predicting the rutting rate than G*/sinδ at the same loading rate. Decreasing W_d confirms the direction of decreased permanent deformation; thus, a minimum W_d value needs to be set to prevent rutting. The implication is that, if the W_d value exceeds this limit, the binder would provide acceptable resistance to permanent deformation in asphalt mixes whereas binders with lower W_d value may contribute less to rutting.

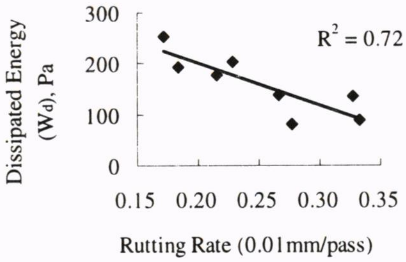

Figure 3. Rutting Rate and Dissipated Energy at 0.6 rad/sec from Wheel Tracking Test

4.3 In-Situ Rutting Evaluation

The plot of Superpave's G*/sinδ versus rutting depth was shown in Figure 4 with a poor R^2 value of 0.44. The SHRP researchers had based their specification on the presumption that the binder's inverse shear loss compliance plays an eminent role in preventing rutting (Bahia, Anderson 1995). The SHRP assumptions of stress-controlled mode and 10 rad/sec frequency may not be representative for the in-situ rutting. It is important to determine the viscous behavior of asphalt binders under the same traffic speed to predict permanent deformation in pavements. Average speed of traffic was conservatively set at 40 km/hr in the primary highway because of traffic congestion. The corresponding frequency for traffic speed 40 km/hr was set at 5 rad/sec.

It should be noted that there is nothing magical about PG graded asphalt binders. They simply represent the asphalts we have used in the past and they are specified in a new way; thus, there are new grades available to handle higher temperatures and heavier traffic. PG asphalts give us a new tool to insure our asphalt pavements last longer and perform better. However, data from the WesTrack test facility in Nevada showed that a combination of a coarse-graded mixture with high optimum asphalt content (5.7%) and low binder stiffness (PG 64-22) can lead to premature rutting. Parameters used to specify asphalt need more revisions to make them reflect the regional conditions.

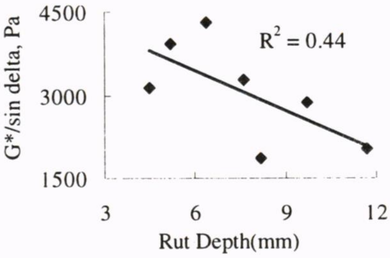

Figure 4. In-situ Rutting Depth and G*/sinδ at 10 rad/sec

This study proposed using the dissipated energy, W_d, as a measure for the ability of the binder to resist permanent deformation. The dissipated energy with a corresponding frequency 5 rad/sec tested for asphalt was then plotted against the rut depth as shown in Figure 5. The R^2 value of 0.68 implied that W_d can reasonably well predict the in-situ rutting. Significant improvements in the rut resistance were observed when W_d become less. Therefore, a minimum value of dissipated energy, W_d, needs to be set for evaluating pavement rutting. This approach combined the linear viscoelastic properties of the binder in one parameter via the dissipated energy. It also accounts for the rate dependence of the material functions because W_d is time dependent as shown equation (5). Recommendations were also made regarding how to avoid early rutting with similar mixes in the future. It is considered to increase the binder two grades for design ESAL's greater than 10,000,000.

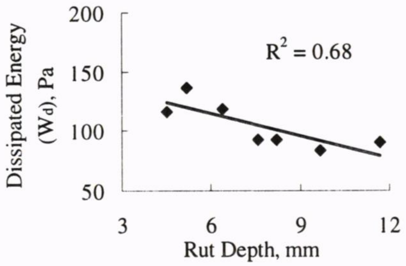

Figure 5. In-situ Rutting Depth and Dissipated Energy at 5 rad/sec

4.4 In-Situ Fatigue Cracking Evaluation

The fatigue parameter, G*·sin δ, has not been validated, and continues to be questioned by several asphalt mixture researchers. The parameter is important since badly fatigued pavements must be removed and replaced. Data showed that highly oxidized asphalts may perform very well in very low strain environments, but may crack severely in fatigue when pavement strains are large. Use of the parameter G*·sin δ to control fatigue cracking was based in part on the controlled-strain fatigue tests as results of SHRP research efforts (Bahia, Anderson 1995). This study indicated in Figure 6 that fatigue cracking observed from in-situ pavement is a poorly-correlated function of the asphalt parameter G*/sin δ with a R^2 value equal to 0.49. Other researchers also showed that the parameter G*/sin δ cannot well predict pavement cracking (Leahy *et al.* 1994; Reese 1997).

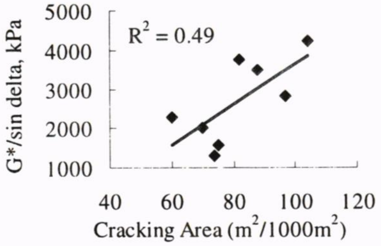

Figure 6. In-situ Fatigue Cracking and G*/sinδ at 10 rad/sec

As shown in Figure 7, the dissipated energy, W_d, seemed to be a good indicator for predicting fatigue cracking with a R^2 of 0.80. Research reports by other investigators showed that dissipated energy is related to the fatigue response of asphalt-aggregate mixes (Leahy *et al.* 1994; Zhang 1997). It appeared logical to use the binder's W_d as the parameter to control pavement cracking since fatigue life is attributable to cracking in the binder phase of the mix. Assuming a strain-controlled mode as suggested in the Superpave cannot control fatigue response in a pavement structure. Dissipated energy is independent of the mode of testing, i.e., stress-controlled versus strain-controlled; thus, W_d is more representative. This study, thus, proposed that a maximum value of W_d be set for evaluating pavement cracking.

Elastomeric polymers would appear to offer the greater economic benefit in higher strain environments along with benefit in low strain environments. This complicates the grade selection issue because both modification techniques (oxidizing and polymer modification) can be used to extend the temperature range to meet current PG specifications. Both modification methods could be used to make the same PG 76-22, but their relative performance in fatigue will vary greatly depending upon the strains developed during loading of the pavement structure. The complexity of the issue has led some agencies to add a polymer-specific identifier test to some grades to insure polymer modification. For example, some agencies using a DSR maximum phase angle requirement; others are specifying a elastic recovery test; and specifying 5 percent SBS or 3 percent SBR modifier.

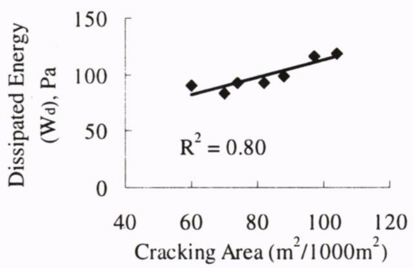

Figure 7. In-situ Fatigue Cracking and Dissipated Energy at 5 rad/sec

5. CONCLUSIONS AND RECOMMENDATIONS

The current Superpave system provides an excellent modular framework for necessary corrections and future enhancements. The performance prediction parameters for load-associated distress included in the existing system, however, function improperly. Substantial corrections and enhancements to the load-associated rutting and fatigue systems are necessary to make these parameters reliable for general use. Examination of asphalt data from the dynamic shear rheometer suggested that another PG 67-xx grade be introduced in Superpave binder specification for the different climatic conditions. The wide temperature gap existing in the Superpave specification can be improved by inserting middle grades in between. The parameters defined in the Superpave binder specification were shown to be insufficient for predicting pavement rutting and fatigue cracking. In order to investigate the effects of linear viscoelastic properties of asphalt binders on pavement performance, samples have to be tested at the same temperature and frequency experienced on pavements. Based on the theoretical derivation, the approach of dissipated energy, W_d, was proposed as a fundamental indicator for pavement distresses in Taiwan. Both results of the wheel tracking test and the in-situ pavement study clearly demonstrated tits superior capability to distinguish the behavior of permanent deformation and cracking of asphalt pavements. This study has shown that there existed a reasonably good relationship between W_d and pavement rutting and cracking. Other contributing factors including mix characteristic and pavement structure need to be further investigated to determine the effects of asphalt mixtures on pavement performance. Attention should be also paid to apply the results to other mixtures that are different from this study.

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