EVALUATION OF PAVEMENT PERFORMANCE ON TAIWAN FREEWAY'S NETWORK USING SUPERPAVE SYSTEM

Jian-Neng Wang
Assistant Professor
Department of Civil Engineering
Chien-Hsin Institute of Technology
2F,68, Ln 422, Sec 2, Chung-Shan E Rd
Chungli 320, Taiwan
FAX: 011-886-3-466-4628
E-mail:wangjn@cc.ncu.edu.tw

Tsair-Yi Luo
Assistant Engineer
Design Division
Taiwan Area National Expressway
Engineering Bureau,
5F,1, Ln 1, Sec 3, Ho-Ping E Rd
Taipei 106, Taiwan
FAX: 011-886-2-2701-8891
E-mail:tyluo@ms.taneeb.gov.tw

Abstract: This paper presents the evaluation of pavement performance on Taiwan's freeway network using the Superpave system. Rutting is the principal pavement distress plaguing Taiwan's Freeway pavements. Two Superpave mixtures and the Taiwan Freeway Mixture (TFM) were compared on both volumetric and mechanical properties. Volumetric analyses of specimens showed the TFM mixture hardly meets the Superpave requirements. This mix contains less than 1 percent air voids at the number of gyrations for initial compaction. This strongly suggests that the TFM mixture might be highly prone to rutting. These three mixtures were tested using the Superpave Shear Tester for conducting FSCH and RSCH tests. The relative permanent deformation of the TFM mix is about five times as larger as those of the two Superpave mixes. The TFM mix has the lowest complex shear modulus and the highest phase angle among the three mixes in the high temperature and frequency situation.

1. INTRODUCTION

Successful design of Hot Mix Asphalt (HMA) is crucial in Taiwan because more than 96 percent of Taiwan's freeway network has been constructed with HMA. Based on information obtained from the material testing laboratory of the Taiwan Area National Expressway Engineering Bureau (TANEEB), permanent deformation (rutting) is the principal pavement distress plaguing HMA pavements. The type of rutting does not belong to a pavement structure problem but results from accumulated deformations in the asphalt layers. It typically occurs in hot weather in conjunction with heavy traffic conditions. The moisture damage problem is also a concern since the TFM mix is produced using siliceous materials without any treatment.

By 1998, more than 400 HMA pavements in the United States have been designed according to the Superpave (Superior Performing Asphalt Pavements) mix design method and analysis. The excellent performance of virtually all these pavements indicates that the Superpave system has high potential for producing superior-performing pavement structures. This research focused on the application of Superpave technology to produce Superpave mixtures. The volumetric and mechanical performance properties of the Superpave and the TFM mixes were compared to help solve the rutting problem.

2. BACKGROUND

In Taiwan, an old version of the Marshall mix design method is currently used to design asphalt mixtures. Asphalt binders are usually classified and selected according to the penetration grading system. The asphalt binders, 85-100 and 60-70 pen, are generally used for northern and southern freeway's pavements, respectively. Aggregates are blended to meet local Taiwan gradation requirements (TANEEB 1996). Figure 1 shows the gradations of seven plant mixes used on Taiwan freeway's network.

Superpave was the principal product of the Strategic Highway Research Program (SHRP). SHRP consisted of a 5-year, $50-million asphalt research project. It was established by U.S. Congress in 1987. Superpave consists of two major parts: the Superpave asphalt binder analysis and the Superpave asphalt mixture design and analysis. It is considered to be a superior system for grading asphalt binders, selecting aggregate materials, conducting asphalt mixture design, and predicting pavement performance. Table 1 shows the comparison of the Superpave and Taiwan mix design systems.

3. EXPERIMENTAL PROGRAM

The research approach for comparing the performance properties of the Superpave mixtures with those of a simulated Taiwan freeway's mixture was aimed at the following:

- volumetric property
- mechanical property

The same basic set of materials were used in the design of those mixtures. All mixtures evaluated utilized aggregate with a 19 mm nominal maximum size because it is less costly and represents the most common nominal size for dense-graded wearing courses in Taiwan. All of the laboratory tests were conducted in the South Central Superpave Center in the USA.

4. VOLUMETRIC TESTING AND ANALYSIS

Based on the standard Superpave mix design procedure (Kennedy *et al.* 1994; McGennis *et al.* 1995), the major steps are the following: (1) selection of materials, (2) selection of a design aggregate structure, (3) selection of a design asphalt content, and (4) evaluation of moisture sensitivity of the design mixture. The project site was assumed to be located at the Southern Cross-Island expressway. The traffic volume was in excess of 30 million ESALs (Equivalent Single Axle Loads) and the layer in question is within the upper 100 mm of the pavement. The design traffic speed is 90-100 km/hour and a minimum 98% reliability for binder selection was used.

4.1 Material Selection

The selection of asphalt binder and aggregates was considered based on information of the project site such as pavement temperatures, traffic volume etc. According to the estimated air temperatures of the project site, the closest standard grade for asphalt binder that would meet these temperature requirements was a PG 58-22. Since the traffic volume exceeds 30 million ESALs, the high temperature grade of the asphalt binder needs to be increased one grade; therefore, the final selection was a PG 64-22. A PG 64-22 binder means that the binder must meet high temperature physical property requirements at least up to 64° C and low temperature physical property at least down to -22° C. One of Taiwan asphalt binders, 60-70 pen, was classified as a PG 58-16 and compared with a PG 64-22 binder used in this study. Table 2 shows the binder test results.

The sample of Taiwan aggregates was reported to be a crushed, sized river deposit composed primarily of sandstone with small amounts of quartz, granite, and basalt. Through observation of the mineralogy, gradations, and specific gravities of Taiwan aggregates, a sandstone deposit, produced in Texas, was used as the substitute in this study. For the consensus property, the coarse aggregates have the value of about 2% Flat and Elongated Particles (FEP), which are largely cubical with practically 100 percent crushed faces as determined by the Coarse Aggregate Angularity (CAA) test. For the Fine Aggregate Angularity (FAA) test, the manufactured sand exhibits a high value at 48.4 percent and its sand equivalent value is 83 percent. For the source properties, the values for soundness (5-cycle magnesium sulfate) and Los Angeles abrasion tests are 15 and 26 percent, respectively. The above information displays the sandstone materials meet the Superpave aggregate requirements for traffic level more than 30 million ESALs. The test results of Taiwan aggregates and the sandstone aggregates are shown in Table 3.

4.2 Aggregate Structure

The selection of a design aggregate structure is one of the major features of the Superpave mix design method. A typical Taiwan freeway's gradation and five Superpave gradations were used for the selection of aggregate structures of mixtures (in Table 4) These six aggregate structures satisfied the Superpave gradation requirements and were selected as the design aggregate structure candidates. However, the aggregate structure candidates must meet the Superpave volumetric requirements by means of the Superpave Gyratory Compactor (SGC) to determine whether or not they can become the design aggregate structures.

The target values for laboratory mixing and compaction temperature were determined as 152° and 143° C using the Brookfield rotational viscometer following the method in ASTM D4402. Based on the specific gravity of selected aggregates, the trial asphalt binder content was calculated to be 4.5 percent by mass of total mix. According to the traffic and air temperature conditions (traffic level >30 million ESALs and air temperature < 39° C), the number of gyrations for initial cpmpaction, design compaction, and maximum compaction were recommended by SHRP as $N_{initial}$ = 9 gyrations, N_{design} = 126 gyrations, and $N_{maximum}$ = 204 gyrations (McGennis *et al.* 1995). The relationship among N_{design}, $N_{initial}$, and $N_{maximum}$ are shown below:

$$Log_{10}(N_{maximum}) = 1.10 \times Log_{10}(N_{design}) \qquad (1)$$
$$Log_{10}(N_{initial}) = 0.45 \times Log_{10}(N_{design}) \qquad (2)$$

The Taiwan freeway's gradation did not meet the Superpave volumetric requirements. However, it was also used for comparative analysis. The two Superpave gradations, SM1 and SM2, are the only aggregate structures meeting the Superpave volumetric requirements. These three selected gradations are shown in Figure 2.

4.3 Analysis of Volumetric Properties of Asphalt Mixtures

After the design aggregate structure has been determined, the selection of a design asphalt content is obtained based on the SGC specimens with 4 percent air voids. An estimated asphalt binder content to achieve 4% air voids (96% G_{mm} at N_{design}) is determined using Superpave formula (McGennis *et al.* 1995).

The TFM mixture has the Taiwan freeway's gradation with the design asphalt content obtained using the old-version Marshall mix design method. The volumetric performance properties of these mixtures (SM1, SM2, and TFM) are shown in Table 5. VMA, VFA, air voids, and dust proportion are very important to asphalt mixtures since they significantly affect their durability and stability (Asphalt Institute 1993). Assuming that the TFM mixture represents the mixture currently used on freeway's pavements, this suggests that many current Taiwan mixtures would not be considered suitable under the Superpave system since the TFM mixture failed to meet all but one (dust proportion) of the Superpave volumetric requirements, and the air void content at N_{design} was extremely low (0.6 percent). This mix could possibly become a plastic mixture because of the high value (99.7 percent) of % G_{mm} at $N_{maximum}$. The SM1 and SM2 mixtures were then compared using the mechanical property testing with the TFM mixture. Compaction Slopes *(CS)* are calculated as the slope of the densification (%G_{mm}) versus the gyration number ($N_{maximum}$ and $N_{initial}$) curves on a log-log scale. The TFM mixture has the lowest compaction slope (3.62) compared with those of the Superpave mixtures (SM1: 9.39, SM2: 8.41). The Superpave mixtures exhibit relatively steep compaction slopes and low values for %G_{mm} at $N_{initial}$ are indicative of having well-developed aggregate structure or internal resistance to densification.

4.4 Evaluation of Moisture Susceptibility

The evaluation of moisture susceptibility of the design mix is the last step for conducting the Superpave mix design procedures. ASTM D1075 (immersion-compression test) or Marshall-immersion procedure is used in Taiwan mix design practice to evaluate the moisture susceptibility of asphalt mixtures, while the Superpave system uses AASHTO T283 (modified Lottman procedure). AASHTO T283, as reported by Asphalt Institute (1987 and 1993), is a better procedure than either ASTM D1075 or Marshall-immersion procedure because these two methods failed to effectively predict the moisture susceptibility of the mixtures. In this study, only AASHTO T283 was used to evaluate the moisture susceptibility. Since the same basic set of materials were used, the SM1 and SM2 mixes were evaluated. The results of all moisture susceptibility testing showed that neither of the Superpave mixtures meet the minimum indirect Tensile Stress Ratio (TSR) requirement (80% minimum). The Project staff treated the asphalt binder with 1.0 percent Perma-Tac 99 and Kling Beta 2550 by mass of binder and repeated the AASHTO T283 tests. Based upon observation of failing and passing TSR values the Kling Beta 2500 was a more effective liquid anti-stripping agent to overcome the moisture damage problem of the sandstone aggregate than Perma-Tac 99. The results are shown in Table 6. This was somewhat expected since siliceous materials have been known to exhibit stripping, as reported by Kennedy *et al.* (1983).

5. MECHANICAL PROPERTIES TESTING AND ANALYSIS

The Superpave performance test results are designed to be input into SHRP performance models to predict the pavement distresses. Unfortunately, the existing SHRP performance models do not provide reasonable performance prediction (Witczak *et al.* 1998). Although the SHRP performance models require some corrections, modifications and enhancements, the output of the Superpave Performance tests can be used to calculate mechanical properties of asphalt mixtures, such as relative cumulative strain and mixture stiffness (Wang 1998; Anderson *et al.* 1999). The Superpave Shear Tester (SST) is used to perform nearly all of the load-related performance tests. Rutting is the major distress plaguing the freeway's network in Taiwan; therefore, the Frequency Sweep Test at Constant Height (FSCH) and the Repeated Shear Test at Constant Height (RSCH) were selected for the analysis of these asphalt mixtures. The background for the SST test procedures was reported by May and McGennis (1996).

5.1 Test Parameters

The test parameters for the mechanical performance tests are described in this section. The FSCH test, testing was conducted at 4°, 20°, and 40° C. These are the normal temperatures used for a Superpave complete mix analysis (ESALs > 10^7). The RSCH testing was conducted at T_{max} = 56° C, which was calculated to simulate actual pavement temperature on project site at a depth of 50 mm. The temperature value for a depth of 20 mm could be converted to surface temperature with several empirical formula by Solaimanian and Kennedy (1993). Three specimens were prepared for each mix at any test temperature in FSCH and RSCH tests. This experiment used the air void tolerance recommended by May and McGennis (1996), which is applied as 7.0 percent ± 0.5 percent.

5.2 Discussion of Mechanical Property Test Results

Frequency Sweep Test at Constant Height

The relationship between the complex shear modulus and frequency at 4°, 20°, and 40° C is shown from Figures 3 to 5. The complex shear modulus increases as test temperature decreases. An asphalt mixture typically has higher complex shear moduli at higher frequencies and lower temperatures. The complex shear moduli of all three mixtures are similar at all test temperatures. However, the complex shear moduli of the TFM mixture at 40° C in conjunction with low frequencies (0.01, 0.02, 0.05, and 0.1 Hz) are almost constant. This can be further studied whether or not the binder-aggregate interaction plays an important role.

Phase angle variations with different frequencies and test temperatures are shown from Figures 6 to 8. At lower frequencies and higher test temperatures, the phase angle increased for each mix. The high frequency and low temperature caused the asphalt mixtures to behave like elastic materials. The shape of the phase angle-frequency curve is binder-type dependent, reported by Zhang and Huber (1996). The shape of the phase angle-frequency curve for all mixtures are almost the same, since the same asphalt binder was used to produce these mixtures. However, the phase angle for all mixtures tested at 40° C are independent of frequency and their values vary significantly especially at 0.01 Hz. It is believed that the aggregate skeleton plays a very important role at high temperature where stone-on-stone contact is important to resist rutting.

The m value is defined as the slope of the complex shear modulus versus frequency curve on a log-log scale. In SHRP permanent deformation material models (Lytton *et al.* 1993) assumes that the m value is dependent on temperature but independent of stress state. However, Figure 9 shows that m values for these three mixes vary not only with different temperatures but also different frequencies.

Table 7 shows some results of the complex shear moduli and phase angles and the compaction slopes for theses three mixes. The complex shear modulus and phase angle at 10 Hz ($G^*_{@10Hz}$ and $\delta_{@10Hz}$) were selected for the comparison since they represent the shear stiffness and phase angle of a mix at a frequency simulating freeway traffic (Anderson *et al.* 1999). The complex shear modulus of each mix is not proportional to the corresponding compaction slope. TFM has the lowest $G^*_{@10Hz}$ and the highest $\delta_{@10Hz}$ among these three mixes; thus the TFM mix is anticipated to be more susceptible to permanent deformation than the SM1 and SM2.

Repeated Shear Test at Constant Height

The results of cumulative (permanent) shear strain versus number of cycles for the SM1, SM2 and TFM mixtures are in Figure 10. Sousa and Solaimanian (1995) established the linear relationship between predicted rut depth and the permanent shear strain and the estimate of converting load cycles to traffic level (ESALs) have been established as follows:

$$Predicted\ Rut\ Depth\ (mm) = 279.4 * Permanent\ Shear\ Strain \quad (3)$$
$$Predicted\ ESALs = 10^{\{[Log\ (load\ cycles) + 4.36]/1.24\}} \quad (4)$$

The predicted rut depth of the TFM mixture was 24.4 mm when the cumulative shear strain reached 5 percent after 3200 cycles. The final estimated rut depths for both the Superpave SM1 and SM2 mixtures are 4.53 and 4.54 mm, respectively. In SHRP A-005 contract, the permanent deformation model (Lytton *et al.* 1993) is the following:

$$Log\ \gamma_P(N) = Log\ \gamma_P 1 + S\ Log\ N \quad (5)$$

where $\gamma_P(N)$ *is* the permanent shear strain to the repetitions (N), $\gamma_P 1$ is the intercept and S represents the slope. In addition, a regression analysis was conducted using the SHRP A-005 permanent deformation models. These results are shown in Table 8. It is obvious that the TFM mix has the largest permanent strain and slope (S) among these three mixes. Although the maximum permanent strain of the SM1 is almost the same as that of the SM2, these two mixes have different slopes and intercepts. Based on these results, Equation *(5)* exhibits good correlation between the permanent strain and the number of cycles. However, this model does not take tertiary rutting into account (Witczak *et al.* 1998).

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be drawn from the test results:

1. The TFM mixture exhibited a low air void content at N_{design} (0.6 percent). This low air void content strongly suggests that the Taiwan freeway's mix might be highly prone to rutting.
2. The asphalt binders used on Taiwan freeway's network are recommended to select according to the pavement temperatures, traffic speed, traffic volume, and design reliability. Furthermore, most of Taiwan aggregates belong to siliceous materials and if the freeway's mixture produced using these materials without any treatment, it is susceptible to moisture damage.
3. The TFM mixture has the lowest compaction slope compared with those of these two Superpave mixtures. Therefore, this gradation is not a well-developed aggregate structure or internal resistance to densification.
4. For withstanding permanent deformation, the ability of the TFM mixture was found not as much as those of the Superpave mixes. This was based on the results of the following mechanical property tests:
   (1). FSCH results: The TFM mixture possessed lower complex shear moduli and higher phase angles at high frequency (10 Hz) in conjunction with high temperature (40^{o} C). It is not as stiff as the mixtures SM1 and SM2 and its elastic component is too small in the high-frequency-and-temperature situation.
   (2). RSCH results: The cumulative shear strain and predicted rut depth of the TFM mixture were about five times as large as those of the mixtures SM1 and SM2.
5. The general concept of the Superpave system is being implemented extensively in the USA. It is recommended Taiwan roadway authorities might initiate one or more demonstration projects using the Superpave system to gain a more intimate understanding of its use to minimize or control pavement distress problem.

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REFERENCES

Anderson, R.W., Bukowski, J.R. and Tuner, P.A. (1999) Evaluating asphalt mixtures using Superpave performance tests. Preprint, 78th TRB Annual Meeting, Washington, DC.

Asphalt Institute. (1987) **Causes and Prevention of Stripping in Asphalt Pavements ES-10**. Asphalt Institute, College Park, Maryland.

Asphalt Institute. (1993) **Mix Design Method for Asphalt Concrete and Other Types MS-2**. Asphalt Institute, Lexington, Kentucky.

Lytton, R.L., Uzan, J., Fernando, E.G., Roque, R., Hiltunen, D., and Stoffels, S.M. (1993) Development and validation of performance prediction models and specifications for asphalt binders and paving mixtures. Report No. SHRP-A-357, Strategic Highway Research Program, National Research Council, Washington, DC.

Kennedy, T.W., McGennis, R.B., and Roberts, F.L. (1983) Investigation of moisture damage to asphalt concrete and the effect on field performance - a case study. **Transportation Research Record 911**, TRB, Washington, DC, 158-165.

Kennedy, T.W., Huber G.A., Harrigan, E., Cominsky, R.J., Hughes, C.S., Quintus, H.V., and Moulthrop, J.S. (1994) Superior performing asphalt pavements (Superpave):the product of the SHRP asphalt research program. Report No. SHRP-A-410, Strategic Highway Research Program, National Research Council, Washington, DC.

May, R.W., and McGennis, R.B. (1996) **Superpave Asphalt Mixture Analysis: Advanced Course**. National Asphalt Training Center II. FHWA, Office of Technology Application and Asphalt Institute Research Center, Lexington, Kentucky.

McGennis, R.B., Anderson, R.M., Kennedy, T.W., and Solaimanian, M. (1995) Background of Superpave asphalt mixture design and analysis. Report No. FHWA-SA-95-003, Asphalt Institute, Lexington, Kentucky.

Solaimanian, M. and Kennedy, T.W. (1993) Predicting maximum pavement surface temperature using maximum air temperature and hourly solar radiation. **Transportation Research Record 1417**, TRB, Washington, DC, 1-11.

Sousa, J.B. and Solaimanian, M. (1995) Abridged procedure to determine permanent deformation of asphalt concrete pavements. **Transportation Research Record 1448**, TRB, Washington, DC, 25-33.

Taiwan Area National Expressway Engineering Bureau. (1996) **Construction Standard Specifications and Technology Provisions**. TANEEB, Taipei, Taiwan.

Wang, J-N. (1998) **Evaluation of Hot Mix Asphalt Pavement Performance for Taiwan's Freeway Network Using the Superpave System.** Ph.D. Dissertation, The University of Texas at Austin, Austin, Texas.

Witczak, M.W., Von Quintus, H.L., and Schwartz, C.W. (1998) Superpave support and performance models management: evaluation of the SHRP performance models system. University of Maryland, College Park, Maryland.

Zhang, X. and Huber, G. (1996) Effect of asphalt binder on pavement performance: an investigation using the Superpave mix system. **Proc., Association of Asphalt Paving Technologists**, Volume 65.

Table 1. Comparison of the Superpave and Taiwan Mix Design Systems

Subsystem	Superpave System	Taiwan System
Asphalt Binder	Performance-graded binder specification based on pavement temperatures, traffic condition and design reliability	Penetration-graded system 85-100 and 60-70 used in the northern and southern regions
Aggregate	Properties related to traffic volume and depth Consensus and source properties	No fine and coarse aggregate tests, No standard method for FEP test
Selection of Design Aggregate Structure (Gradation)	Use of 0.45 power chart with gradation limits and restricted zone. Min. of three trial blends to obtain the design aggregate structure	Use of required grading envelopes the average of upper and lower limits to be the Job-Mix formula
Laboratory Compaction	Superpave gyratory compactor Measurement of densification Diagnose of tender mixtures Gyratory compactive effort specified for traffic and average design high air temperatures	Marshall compaction Impact-type compaction 75 blows per face for freeway design
Selection of Design Asphalt Content	Compacted SGC specimens: estimated binder content, $\pm 0.5\%$, and $+1.0\%$ Design asphalt binder content based on 4 percent air voids	At least 5 trial binder contents Selection of the design asphalt content at the average of 4% air voids, max. density, and max. stability
Volumetric Properties	Extensive volumetric mix property • Dust proportion • $\%G_{mm}$ @ $N_{initial}$ • $\%G_{mm}$ @ $N_{maximum}$	No VFA requirement Same min. VMA value for any max. nominal aggregate size
Mix Design Level	Without mix analysis if $ESALs \leq 10^6$ Intermediate mix analysis if $10^6 < ESALs \leq 10^7$ Complete mix analysis if $ESALs > 10^7$	Old-version Marshall mix design method, heavy traffic condition: freeways and expressways ($ESALS > 10^6$)
Moisture Susceptibility	Modified Lottman Procedure (AASHTO T283)	Immersion-Compression Test, (ASTM D1075) or Marshall-immersion procedure

Table 2. Binder Requirements and Test Results

Test	Property	PG 64-22	Taiwan 60-70 pen	Criteria
		Original Binder		
RV	135° C	0.440 Pa-s	0.500 Pa-s	3 Ps-s max.
RV	165° C	0.104 Pa-s	0.201 Pa-s	n/a
DSR	G*/sin δ @ 64° C	1.288 kPa	1.701 kPa	1.0 kPa min.
DSR	G*/sin δ @ 70° C	0.605 kPa	0.500 kPa	1.0 kPa min.
		RTFO-aged Binder		
Mass Loss	n/a	0.04% gain	0.09% loss	1.00% max.
DSR	G*/sin δ @ 64° C	2.340 kPa	2.140 kPa	2.2 kPa min.
DSR	G*/sin δ @ 70° C	1.023 kPa	n/a	2.2 kPa min.
		PAV-aged Binder		
DSR	G* sin δ @ 22° C	3083 kPa	5284 kPa	5000 kPa max.
DSR	G* sin δ @ 25° C	1946 kPa	3423 kPa	5000 kPa max.
BBR	Stiffness @ -22° C	190 Mpa	236 Mpa	300 MPa max
BBR	m-value @ -22° C	0.333	0.308	0.300 min.

Table 3. Aggregate Requirements and Test Results

Property	Taiwan Aggregates		Substitutes		Criteria
	Coarse	Mnf. Sand	Coarse	Mnf. Sand	
Coarse Ang.	99/94 %	n/a	100/100 %	n/a	100/100 % min.
Fine Ang.	n/a	48%	n/a	48%	45% min.
Thin/Elongated	0.4%	2.0%	2.4%	2.4%	10% max.
Sand Equivalent	n/a	74&77%	n/a	83%	45 min.
Toughness-	21&25%	n/a	26%	n/a	35~45% max.
Soundness (Mg)	n/a	n/a	15%	15%	10~20% max.
Soundness (Na)	4.9&0.4%	2.9&2.9%	n/a	n/a	10~20% max.
Combined G_{sb}	2.56~2.59	2.520	2.61~2.62	2.630	n/a

Table 4. Gradation Information for Six Trial Blends

Sieve Size		Percent Passing					
US Units	SI, mm	SM1	SM2	SM3	SM4	SM5	TFM
1	25	100.0	100.0	100.0	100.0	100.0	100
¾	19	94.3	97.6	96.2	97.0	90.4	97
½	12.5	88.7	89.5	92.4	93.0	81.1	80
3/8	9.5	76.6	77.7	77.6	80.0	71.3	71
No. 4	4.75	44.2	45.0	38.1	57.0	45.8	54
No. 8	2.36	27.0	32.0	22.9	40.0	28.3	39
No. 16	1.18	16.0	22.5	13.9	31.0	16.6	29
No. 30	0.6	10.1	15.0	9.2	25.0	10.1	22
No. 50	0.3	7.0	7.9	6.7	19.0	6.8	16
No. 100	0.15	4.8	4.1	5.0	12.0	4.3	10
No. 200	0.075	3.2	3.5	3.5	6.0	2.7	4.5

Table 5. Summary of Mix Design Properties

Superpave Mix Design Property	SM1 Gradation	SM2 Gradation	TFM Gradation	Criteria (Superpave)
Mix Design Method	Superpave	Superpave	Marshall	
% Asphalt	5.5	4.7	5.5	n/a
% Air Voids	4.0	4.0	0.6	4.0 %
VMA, %	15.0	13.8	12.7	13.0% min
VFA, %	73.3	70.0	95.7	65.0-75.0 %
$\%G_{mm}$ @ N_{ini}, %	84.9	86.5	94.3	89.0% max
$\%G_{mm}$ @ N_{max}, %	97.7	97.0	99.7	98.0% max
Dust Proportion	0.6	0.8	1.2	0.6-1.2
Compact Slope	9.39	8.41	3.62	n/a

Table 6. AASHTO T283 Test Results

	SM1						SM2					
Property	w/o		PT 99		KB 2550		w/o		PT 99		KB 2550	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
TS, kPa	710	503	692	541	577	548	861	524	870	653	770	704
TSR, %	70.8		78.2		95.0		60.9		75.0		91.5	

Note: TS:(Indirect)Tensile Strength; TSR: (Indirect) Tensile Strength Ratio; w/o: without anti-stripping agent; PT 99: Perma-Tac 99; and KB 2500: Kling Beta 2550

Table 7. Properties of Mixes obtained form FSCH and SGC

		FSCH						SGC
Mix	AC, %	$G^*_{@10Hz}$, kPa			$\delta_{@10Hz}$, Degree			Compaction Slope
		4° C	20° C	40° C	4° C	20° C	40° C	*CS*
SM1	5.5	3914591	1513694	176635	14.6	30.0	62.0	9.39
SM2	4.7	4029200	2026753	254067	14.4	28.9	59.5	8.41
TFM	5.4	3208114	1603081	124545	12.5	27.1	67.1	3.62

Table 8. Properties of Mixes Obtained from RSCH

	RSCH @T_{max}=56° C							
Mix	Test Results		Sousa's Equations		SHRP Model (A-005)			
	Max. Permanent Strain	No. of Cycle	Predicted Rut Depth	Predicted ESALs	Slope S	Interception log (γ_p1)	R^2	S_e
SM1	0.0164	5000	4.556 mm	3155217	0.1160	2.2176	0.7771	0.08555
SM2	0.01626	5000	4.544 mm	3155217	0.2447	2.6675	0.9753	0.03366
TFM	0.087335	3200	24.40 mm	2200231	0.3181	2.1202	0.9644	0.05934

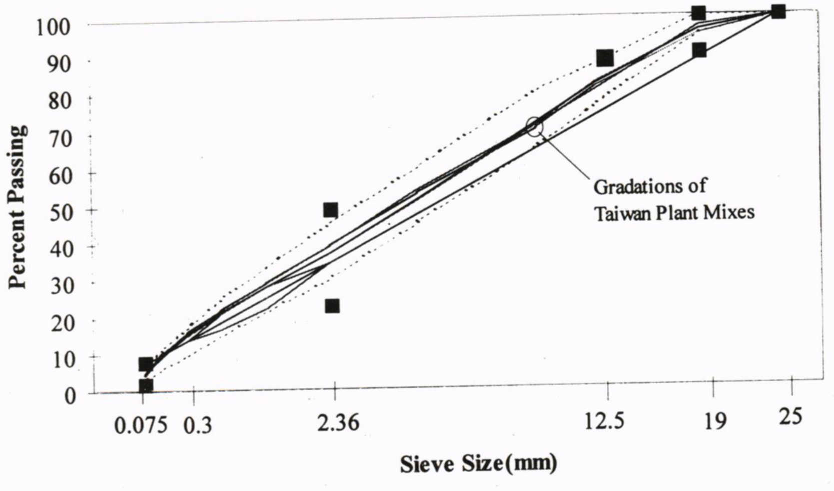

Figure 1. Gradations for 7 Plant mixes

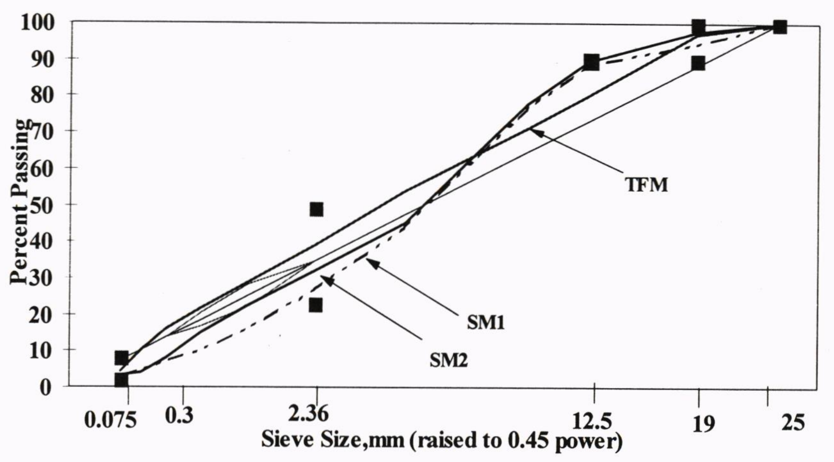

Figure 2. Gradations for Three Selected Mixes

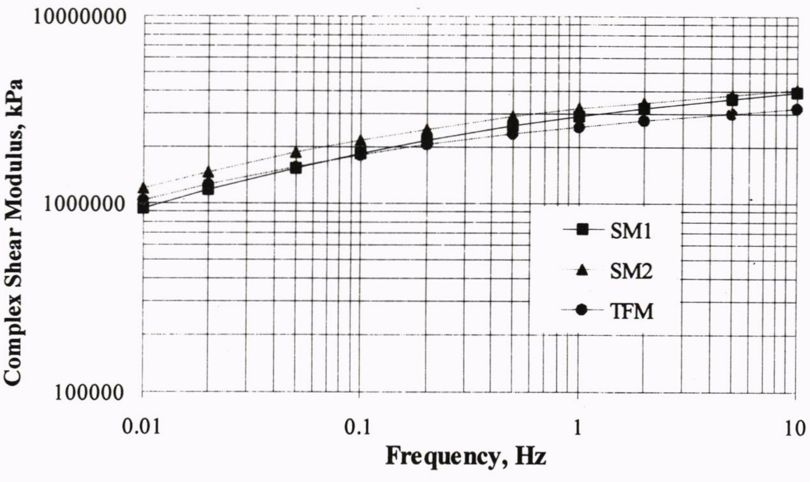

Figure 3. Complex Shear Modulus versus Frequency (4° C)

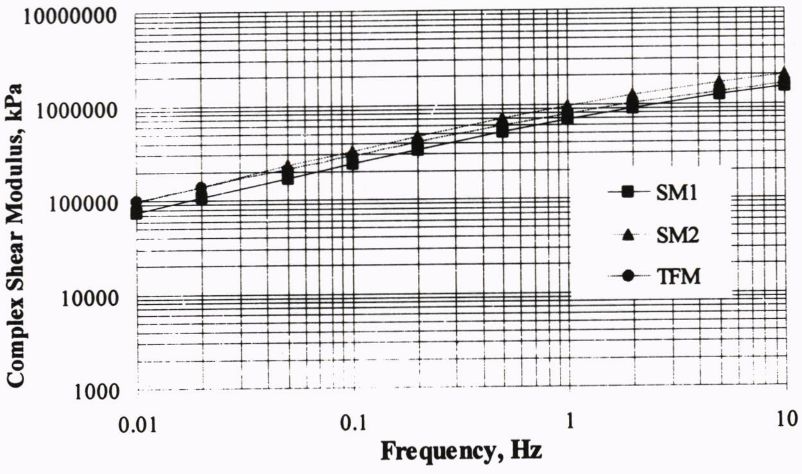

Figure 4. Complex Shear Modulus versus Frequency (20° C)

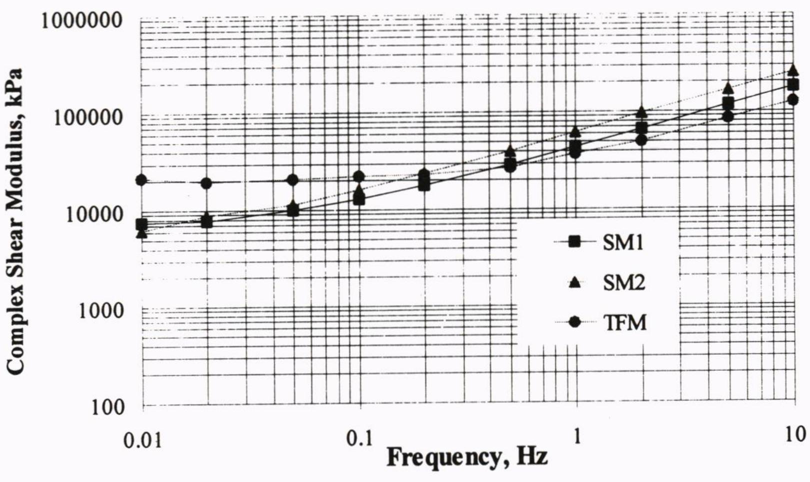

Figure 5. Complex Shear Modulus versus Frequency (40° C)

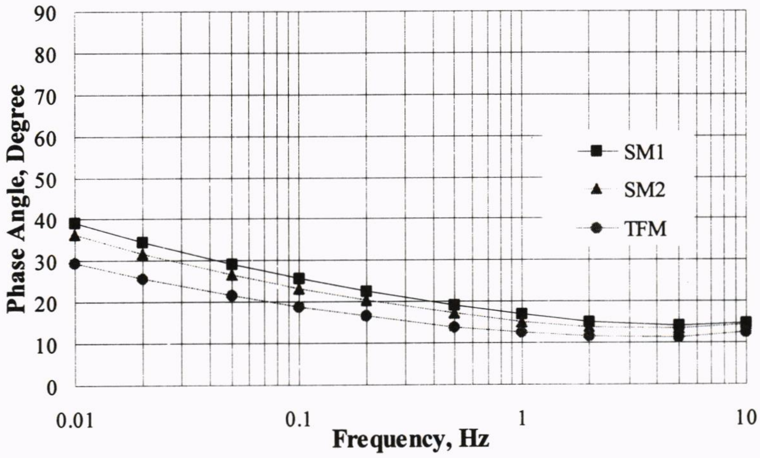

Figure 6. Phase Angle versus Frequency (4° C)

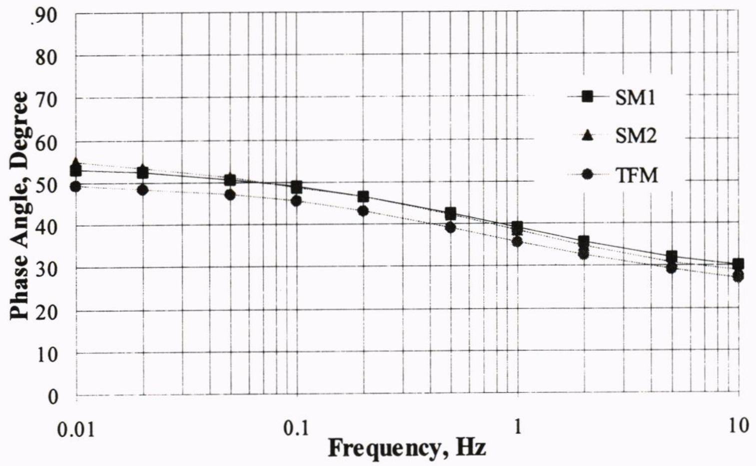

Figure 7. Phase Angle versus Frequency (20° C)

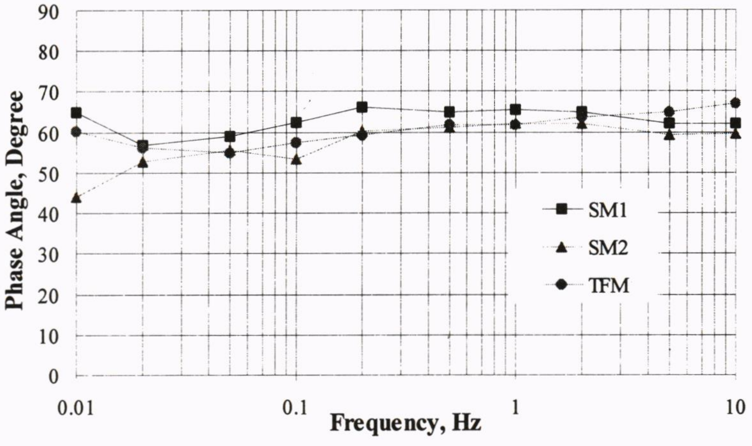

Figure 8. Phase Angle versus Frequency (40° C)

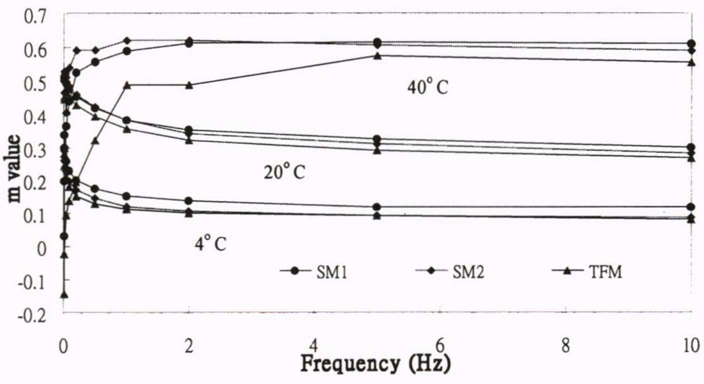

Figure 9. m versus Frequency at Different Temperatures

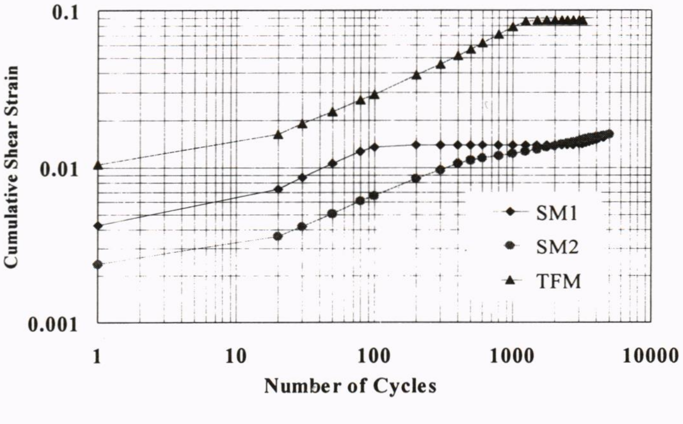

Figure 10. Cumulative Shear Strain versus Number of Cycles