Designing Asphalt Pavements for Extreme Climates

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Three test sections were placed in the Arizona low desert in 1992 to test the use of the West Coast Asphalt Cement PBA-7 desert specification. After a short hot spell the material exhibited significant rutting compared with the conventional AC-40. The binders and mixes were characterized using performance-related test techniques that were developed within the Strategic Highway Research Program (SHRP). The results indicated that the PBA-7 binder was much more susceptible to permanent deformation in marginal mixes than a conventional AC-40. However, both the rheological characterization of the binder and repetitive creep on the appropriate SHRP PG grade indicated superior performance over both traditional binders both at high and low temperatures and over the PBA-7 at high temperatures.

The extremely high temperatures of the southwestern United States present a unique challenge for hot mix asphalt (HMA) pavements and can lead to accelerated aging of the asphalt binder. Reese and Predoehl observed that the viscosity of the base asphalt may increase by a factor of 40 within 2 to 4 years (*1*). This aging causes the pavement to embrittle and consequently to fatigue crack (*2*). In some cases the effect can be so serious that the pavements may need to be resurfaced within 2 to 5 years because of severe alligator cracking. On the other hand the high pavement temperatures of up to 170°F coupled with high traffic loading may result in premature failure due to rutting. Consequently, the major issue under these climatic conditions is to balance durability versus rut resistance, as shown in Figure 1. Depending on the quality of the HMA and the structural design, a window of acceptable performance may not exist for conventional unmodified asphalts.

To overcome these problems, Caltrans developed an experimental polymer-modified asphalt (PMA) grade, which was placed on the Needles test section in the Mojave Desert. The performance of the test sections was monitored and compared with a straight AR4000 and a more conventional PMA. After 4 years the experimental grade showed essentially no fatigue cracking and a much lesser degree of aging than the control sections (*1*). Thus, this experimental system appeared to offer an opportunity to balance rut resistance and durability in a comprehensive manner (see "ideal asphalt" in Figure 1). On the basis of this experience the West Coast User Producer Conference (WCUP) adopted a desert specification that was descriptive of the material used in Needles test sections into their performance-based asphalt cement specification (PBA) as a PBA-7 (Table 1).

In this paper we will discuss the results of test sections that were placed in early 1992 on I-10 about 50 mi west of Phoenix, Arizona, near Tonopah. In this test section a PBA-7 was compared with a conventional AC-40 and another PMA. The field performance data will be compared with SHRP binder tests and performance-related mix testing, specifically high-temperature repetitive creep.

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CONSTRUCTION OF THE TONOPAH TEST SECTION

To test the pavement performance value of the PBA-7 grade of asphalt, an Interstate overlay project near Tonopah, Arizona, approximately 55 mi west of Phoenix, was selected and several test sections built. The project was 4.72 mi (7.87 km) long and in a hot desert climate. The project selected, Tonopah (FIR-10-2 (141), consisted of a 3-in. (76.2-mm) full-width overlay with an AC-40 base mix. On top of the overlay, an open-graded ½-in. (12.7-mm) finishing course was placed on the driving (high traffic lane) and passing lanes. The PBA-7 test sections consisted of two ½-mi (0.83-km) overlay test sections, built back to back from Mileposts 90 to 91 in both the eastbound and westbound directions. The test section overlays covered both the high traffic travel lane and the right distress lane. The passing lane and median shoulder were overlaid with the AC-40 base mix. Before overlaying, the existing badly cracked and rutted pavement was milled to a depth of 4 in. (101.6 mm) in the high traffic driving lane and 3 in. (76.2 mm) in the passing lane. The milled trenches were inlaid with AC-40 base mix.

Project construction started in March 1992. Before construction, mix design testing was conducted by the contractor's materials consulting laboratory, the Arizona Department of Transportation (ADOT), the PBA-7 supplier, and Shell. Results of this mix design testing indicated that the PBA-7 mix could be tender and prone to rutting. The Marshall stability of the AC-40 base mix was 3,106 which exceeded the minimum required value of 3,000. The PBA-7 mix Marshall stability was 1,867. Repetitive creep testing carried out at Shell indicated the chance of hot-weather rutting. It was decided to build the PBA-7 test sections with 0.5 percent less asphalt to help improve the stability.

Construction occurred on March 25 and 26, 1992. The PBA-7 mix was very tender, and it was allowed to cure for a considerable time before traffic was allowed on it. The westbound section needed a 6-hr traffic-free period, and the eastbound section needed an overnight traffic-free period to allow the mix to cure.

BINDER RHEOLOGY

Recent research has shown that the major contributions to rut resistance and fatigue resistance come from the mix properties (*3*). However, estimates made within the SHRP contract put the binder

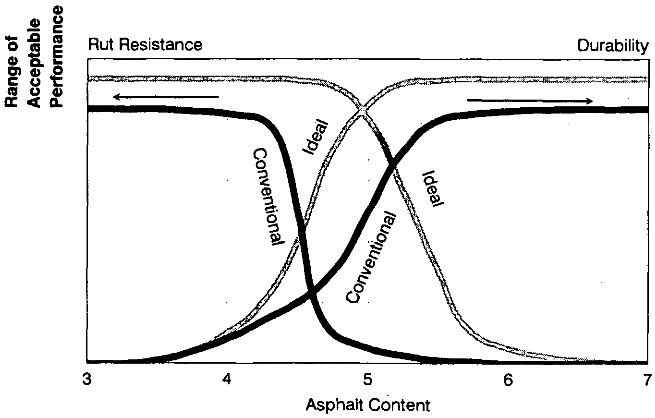

FIGURE 1 Durability versus rut resistance.

contribution at about 20 to 40 percent. This has been substantiated by wheel tracking experiments (*4*) and fatigue experiments (*5*), which showed significantly different performance levels in the same mix when different binders were used. These differences have also been found to be mirrored in field performance evaluations (*1,6*). The SHRP researchers had also based the SHRP performance grade asphalt cement specification on the presumption that the binder plays an important role in preventing rutting (*7*). They proposed using the inverse shear loss compliance, $1/J''$ (see Equation 1), as a measure of the ability of the binder to resist permanent deformation. This is a novel and intriguing approach because it captures both the stiffness and elastic behavior of the binder in one parameter via the complex modulus, G^*, and the phase angle. It also accounts for the rate dependency of the material functions because the moduli are a function of the angular velocity.

$$1/J'' = \frac{(G^*)^2}{G''} \frac{G^*}{\sin\delta} \quad (1)$$

In the case of an ideally elastic material the phase angle is 0, and hence $1/J''$ is infinite. In this case no permanent deformation should occur. Consequently, in an ideally viscous material the phase angle is 90 degrees and $1/J''$ is proportional to the viscosity of the binder. In fact, most straight unmodified asphalts have purely viscous behavior at elevated temperatures (T > 60°C) (*8,9*). The larger $1/J''$, the better the binder should be in mitigating permanent deformation. The rut resistance is considered to be a function of this parameter, as indicated in Equation 2. To ensure a certain rut resistance, the final SHRP specification calls for a minimum value of $1/J''$ of 2.2 kPa (RTFO residue) at 10 rad/sec.

$$\text{rut rate} = f\left(\frac{1}{J''_\omega}\right) \quad (2)$$

The three binders that were used in Tonopah were rheologically characterized at ADOT using a Rheometrics RAA, and $1/J''$ was measured over a relatively wide temperature range to determine whether the three binders met the SHRP specification requirements and to determine how the three materials ranked in performance. The results are given in Table 2. At the temperature of 70°C that the SHRP specification calls for, none of the binders placed meet the 2.2-kPa requirement. However, the PBA-7 material has a value of $1/J''$ of 0.9 kPa, which is only 40 percent of the minimum value required by the SHRP specification. This is in traditional terms equivalent to placing an AC-16 where an AC-40 was called for. Consequently, one would not expect the material to exhibit good rut resistance in marginal mixes. With regard to rut resistance, one would expect the following relative ranking according to $1/J''$:

AC-40 > PMA6/7 > PBA-7

As previously mentioned, the intent of the PBA-7 specification was to obtain fatigue-resistant binders. From the dissipated energy concept (*10*) it follows that in the case of a strain-controlled pavement structure the fatigue resistance should be a function of the loss modulus, G'' [i.e., the softer and more elastic a material the less prone it should be to fail because of fatigue cracking (*11*)]. However, this ranking by G'' will only hold true in the very same mix with the very same structural design and foundation. One cannot obtain any correlation when comparing different pavements' fatigue performances on the basis of the binders' G''. In this case the situation becomes significantly more complicated, and viscoelastic pavement analysis programs such as PACE are required to obtain fatigue resistance predictions (*12*). The SHRP binder specification calls for a maximum value of 5 MPa for G'' at a 34°C after rolling thin film oven (RTFO) and subsequent pressure aging vessel (PAV) aging for a PG70-10, which should have been placed in this climatic region according to the SHRP binder specification and SUPERPAVE (*13*). The G'' values are shown for two of the three test binders in Table 2. The PBA-7 and the PMA6/7 exhibit relatively small values of G'' and, therefore, the materials are expected to exhibit excellent fatigue resistance compared with the AC-40. The relative performance would probably be even more in favor of the PMA after a few years of aging in the field (*2*). With regard to fatigue resistance we obtained the following relative ranking: PBA-7 > AC-40.

MIX RHEOLOGY

Current research has shown that the Marshall stability test does not capture the true performance of HMA (*9*). This is especially true for ground tire rubber or polymer-modified systems, which tend to exhibit pronounced elastic recoil. The most widely accepted performance-related method to evaluate the rut resistance of mixes is the repetitive creep test. In this test a specimen is subjected to a pulse load and then allowed to relax. The load period can be chosen to best fit the loading conditions in the field [i.e., if the loading is slow (e.g., slow-moving truck) a long load is applied and if the load application is fast (transient traffic) a load pulse a short duration is applied (*9*)]. As previously mentioned, the pulse is followed by a relaxation time, which allows the material to recover elastically. This is of special importance for modified mixes, which may exhibit elastic recovery in excess of 90 percent (*14*). The relative performance of the mixes in preventing rutting is measured using the strain accumulation rate in the linear range, ϵ'. The strain accumulation rates of the three mixes are given in Table 2. (The testing was carried out on mix that went through the hot mix plant and not on virgin materials.) As predicted by the binder rheology, the AC-40 performs the best, followed by the PMA6/7. The PBA-7 exhibits about a five times

TABLE 1 WCUP PBA-7 Desert Specification

PBA-7	Binder Test	AASHTO Test Method	Very Hot Climate $T_- > -10F$ $T_+ > 100F$
High Ambient Temperature Mix Stability	Absolute Viscosity @ 140F, P		
	Original Binder	T-202	
	RTFO Binder	T-202	1100+
Consistency During Construction.			
	Kinematic Viscosity @ 275F, cSt		3000+
- Pumpability	Original Binder	T-201	
- Mix Tenderness	RTFO Binder	T-201	
Hardening During Hot Mix Paving Operation	Absolute Viscosity Ratio μ_{RTFO}/μ_{ORG}		
			2000-
			275+
			4.0-
Severe Climate Aging.	Pen @ 77F (100g, 5s), dmm CATOD Residue	T-49	30+
Severe Climate Aging.	Ductility @ 77F (5cm/min), cm CATOD Residue	T-51	40+
Severe Climate Aging.	Absolute Viscosity @ 140F, P CATOD Residue	T-202	50,000-
Safe Handling.	Flash Point (COC), F Original Binder	T-48	450+
Environmental Impact.	Mass Loss after RTFO, %	T-240	Report
Asphalt Binder Purity.	Solubility in Trichlorethylene, % Original Binder	T-44	
			Report
Asphalt Cement Internal Compatibility.	Ductility @ 77F (5cm/min), cm RTFO Binder	T-51	
			75+

TABLE 2 Rheological Properties of the Binders Used in the Tonopah Test Sections

Rut Resistance of the Binder	1/J", KPa @60C	1/J", KPa @70C	
AC-40			
Org.	6.5	1.3	
RTFO	14.8	4.2	
Extracted[1]	58.6	11.7	
PMA 6/7			
Org.	1.2	0.5	
RTFO	2.1	0.7	
Extracted[1]	3.2	1.1	
PBA-7			
Org.	1.7	0.7	
RTFO	2.1	0.9	
Extracted[1]	2.8	0.9	
Fatigue Resitance of the Binder	**G", MPA @ 10 C**	**G", MPA @ 20 C**	**G", MPA @ 30 C**
AC-40			
Org.	8.7	2.25	0.38
RTFO	7.5	2.54	0.58
Extracted[1]	25.8	----	----
PBA 7			
RTFO	5.8	0.55	0.069
Extracted	15.7	2.82 (@17.8 C)	----
'. in/in/cycle @ 60 C			
AC-40			
PMA 6/7	4.5		
PBA-7	5.8		
	25		

[1] Interpolated value.

TABLE 3 Air Temperatures Measured in Tonopah, Arizona, During Time Period in Which Pavement Rutted and the Hot Spell in June 1990

Date, July 1992	T_{max}, F	T_{min}, F	Date, June 1990	T_{max}, F	T_{min}, F
9	105	79	19	107	69
10	105	72	20	111	71
11	101	75	21	111	70
12	104	72	22	110	76
13	106	76	23	112	79
14	109	72	24	112	80
15	113	74	25	118	85
16	112	75	26	121	83
17	109	75	27	115	76
18	109	82	28.	115	84
19	106	82	29	106	87
20	106	79	30	111	87
Average	107	76	Average	113	79

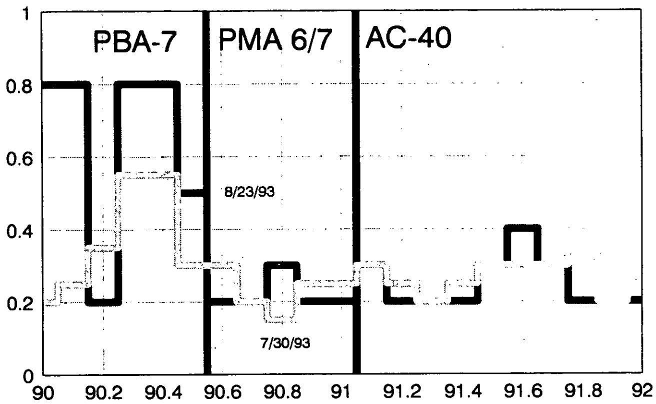

FIGURE 2 Rut depths in the various test sections.

higher strain accumulation rate, which indicates that this mix will not perform well in preventing permanent deformation.

FIELD PERFORMANCE

After construction, the test sections were closely observed. In June 1992 the daily high temperatures were consistently higher than 100°F (38°C). Starting about June 16, 1992, the air temperature reached and subsequently exceeded 109°F (43°C) as indicated in Table 3. On June 22, 1992, significant rutting was observed in both the eastbound and westbound PBA-7 test sections. Rutting continued to worsen during the summer. The measured rut depths for the eastbound lane are shown for all test section in Figure 2 (the results are randomly replicated in the westbound lane). The average number of ESALs in the high traffic lane is approximately 1,550,000 per year. During the first measurement period (April 1992 to August 1992) the high traffic lane experienced about 644,000 ESALs. In the subsequent measurement period (August 1992 to August 1993) the pavement was trafficked by another 1,550,000 ESALs. However, in fall 1992, maintenance removed the high side portions of the rut. Consequently, the measured rut depths in the second period would have been even higher. Subsequent to this, it was agreed that the high traffic lane would be removed and replaced with the next construction project scheduled for summer 1993.

PAVEMENT TEMPERATURE

To properly evaluate the performance of the binders and mixes used in this test section, it is important to have information on the pavement temperature. In this case we used both the "simple" SHRP temperature depth approximation, which is a part of SUPERPAVE, and a sophisticated heat flux finite element program (HiRoad) (*15*) to calculate the temperature depth profiles on the basis of the 12 hottest days during which the rutting occurred. The air temperatures are given in Table 3. The calculated pavement temperatures of the hottest day are given in Table 4. The analysis shows a clear discrepancy between the SHRP method and the finite element program. This probably stems from the fact that the SHRP algorithm cannot take the heat history into account and therefore will underpredict the absolute highs. Nonetheless the results clearly show that the binder needs to exhibit good rut resistance up to pavement temperatures of 150°F to 160°F (65.6°C to 71°C). Historical data indicate that to rule out premature rutting it would be best to have a material that will perform up to temperatures as high as 170°F (77°C) to cover extreme hot spells, as experienced during June 1990 (Tables 3 and 4). Consequently, the binder should probably meet a PG76 or even a PG82 grade to perform in the Arizona low desert. Where slow or standing traffic is prevalent, even higher PG grades would be required to mitigate permanent deformation.

TABLE 4 Calculated Temperature Depth Profiles for Tonopah, Arizona (Temperature Data Are for Hottest Case During Respective Periods)

Depth, in	HiRoad, 7/92	SUPER-PAVE, 7/92	HiRoad, 6/90	SUPER-PAVE, 6/90
surface	160	150	171	155.5
1	150	141.5	164	146.5
2	144	134.5	155.5	139.5
4	131.5	125	142.5	129.5

COMPARISON OF CONVENTIONAL BINDERS WITH SHRP BINDERS

To evaluate whether the proposed SHRP binders will help mitigate permanent deformation, a PG76-10 was formulated. The binder was rheologically characterized and its rut resistance evaluated using repetitive creep. The mix testing was carried out with the same mix design and aggregate that was used in the Tonopah test road. The results of the rheological characterization and the strain accumulation rates are given in Table 5. The mix containing the

TABLE 5 Rheological Characteristics of a PG76-10 Binder Formulated for Repetitive Creep Testing in Tonopah Mix

Property	Spec Limit	PG76-10 Binder
Original Binder		
1/J", KPa @ 76 C	1.00+	1.37
RTFO Binder		
1/J", KPa @ 76 C	2.20+	2.24
PAV Residue, T_{PAV} =110 C		
G", MPa @ 34 C	5.00-	2.33
S(60s), MPa @ 0 C	300-	159
m-value @ 0 C	0.30+	0.37
r', μin/in/cycle	---	2.2

PG76-10 clearly outperforms all the materials used in the Tonopah test road by a wide margin. It is worth noting that the mix of the PG76-10 has only half the strain accumulation rate of the AC-40 (ϵ' = 2.2 μin./in./cycle versus 4.5 μin./in./cycle). The most astounding fact is that the strain accumulation rate in the linear range is about 10 smaller than that of the PBA-7. Thus, this binder specification appears to provide a material that can resist thermal cracking and fatigue cracking without becoming unnecessarily soft at elevated temperatures.

CONCLUSIONS

1. The PBA-7 evaluated tended to be relatively tender and required significantly more attention during placement than conventional asphalts or even standard PMAs. In fact, the traffic could not be released on the PBA-7 pavement for more than 12 hr to prevent immediate rutting of the fresh pavement.

2. The PBA-7 specification provides binders with excellent aging and fatigue cracking resistance. However, the material does not provide good rut resistance and can lead to catastrophic failure when used with average to mediocre mixes. In excellent mixes it can, however, perform well.

3. The PG76-10 binder resulted in a mix that combined good cracking resistance with superior rut resistance. The repetitive creep data appear to substantiate the SHRP findings and lead us to believe that the PG76-10 provides a binder with a better balance of properties than the PBA-7 binder.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Materials.