its INSTITUTE OF TRANSPORTATION STUDIES
Technology Transfer Program
TECHNICAL TOPICS

The Role of Compaction in the Fatigue Resistance of Asphalt Pavements

by Larry Santucci, LTAP Field Engineer, TTP and Pavement Specialist, Pavement Research Center, UC Berkeley

The Technology Transfer Program is the continuing education arm of UC Berkeley's Institute of Transportation Studies. Our mission is to bridge University of California research with contemporary transportation practice by facilitating the transfer of knowledge and skills from university research to applications in the planning, design, construction, operation and maintenance of efficient and effective state-of-the-art transportation systems.

The Pavement Research Center at UC Berkeley has been advancing pavement technical knowledge for nearly 50 years. The Center has led the way for many important discoveries in the field of pavement design including the development of elements of Superpave mix design technology through the Strategic Highway Research Program (SHRP). Currently the Center is conducting large scale accelerated vehicle testing of pavement structures in partnership with Caltrans, the South African Council of Scientific and Industrial Research, and Dynatest USA. A key role of the Center is the training of pavement engineering personnel. Through the Technology Transfer Program, the Center can provide a link between innovative developments in technology and practical engineering applications.

Background

Fatigue or load associated cracking was identified in the Strategic Highway Research Program (SHRP) as one of the primary distress mechanisms affecting the long term performance of asphalt pavements. The other two major distress conditions are permanent deformation (rutting) and low temperature cracking. Fatigue cracking generally starts as a series of short longitudinal cracks in areas subjected to repeated wheel loadings. With additional traffic, the number of cracks increase and interconnect into a typical "alligator" crack pattern (Figure 1).

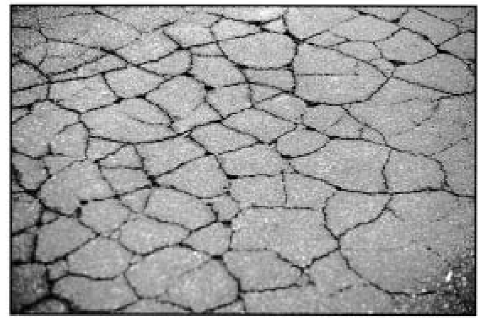


Figure 1: Chicken wire/alligator pattern cracking typical in fatigue cracking

In an asphalt pavement structure under load, the highest tensile stresses normally occur on the underside of the asphalt treated layer, as shown in Figure 2. In some circumstances, the tensile stresses can be higher on the

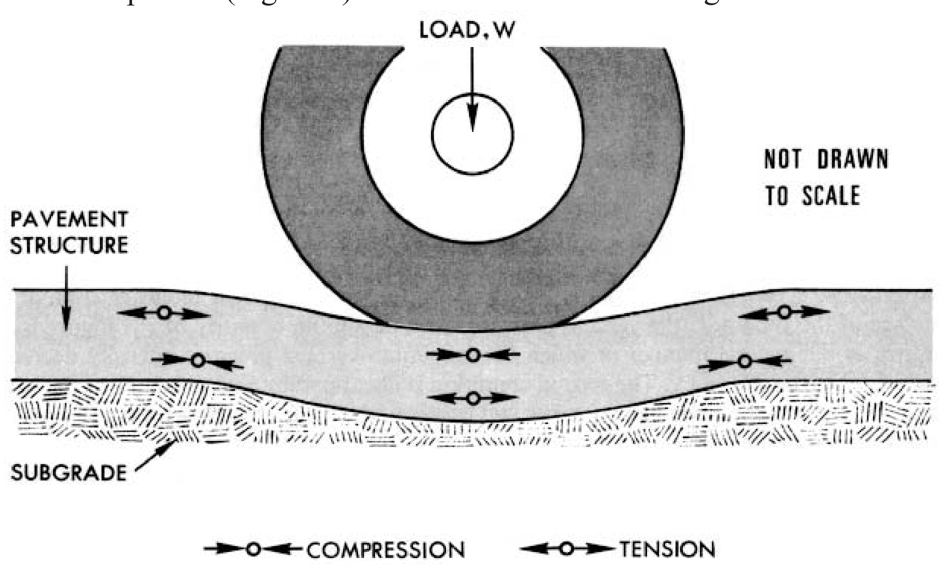


Figure 2: Pavement deflection results in tensile and compressive stresses in pavement structure.

pavement surface next to the wheel load but this is generally the exception rather than the rule. Fatigue cracks initiate in these high tensile stress zones and then gradually propagate through the asphalt treated layer of the pavement. One way to reduce the potential for fatigue cracking is to simply make the asphalt pavement thicker to reduce the magnitude of the tensile stresses. However, it costs money to build pavements thicker. Hence, the challenge becomes how to build more cost effective pavements that are fatigue resistant.

Laboratory Fatigue Testing

Numerous researchers have studied the fatigue behavior of dense graded asphalt mixes in the laboratory. Sample configurations have included rectangular beams tested in flexure, trapezoidal beams

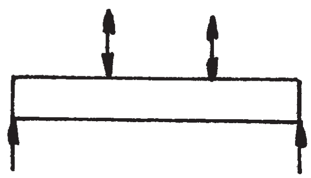
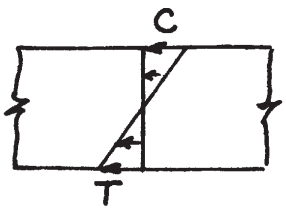
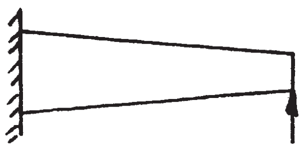
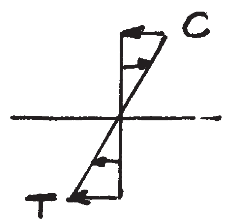
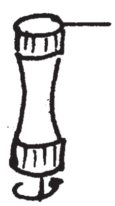
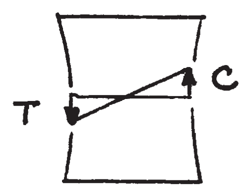
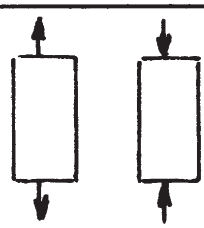
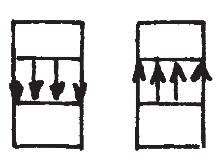
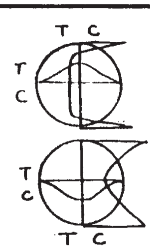
Test	Loading Configuration	Stress Distribution	State of Stress	Does failure occur in a Uniform Bending Moment or Tensile Stress Zone?
Third Point Flexure			Flexural	Yes
Cantilever			Flexural	No
Rotating Cantilever			Torsional	Yes
Axial			Uniaxial	Yes
Diametral		Horiz Vert 	Biaxial	No

Figure 3. Examples of laboratory fatigue test conditions

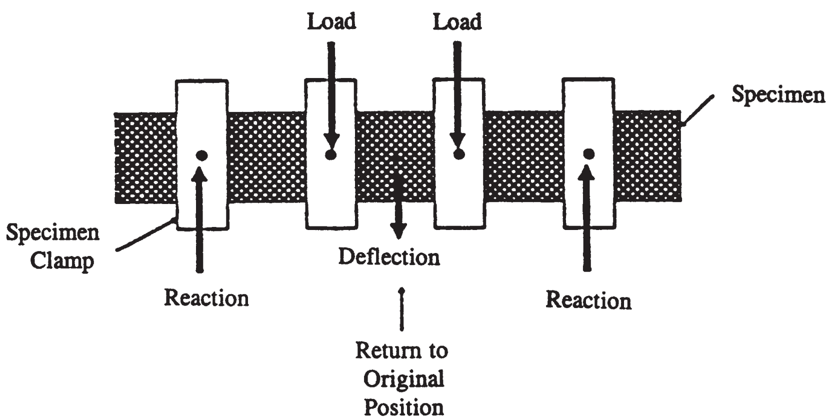


Figure 4. Schematic of third-point loading fatigue test apparatus

loaded as a cantilever, necked-down cylinders tested in rotation, cylinders tested axially, and cores set on edge and loaded diametrically. Examples of these loading configurations are illustrated in Figure 3. The most widely used and fundamentally sound of these test methods is the third-point flexure test depicted schematically in Figure 4. Fatigue results from these tests can be expressed in the general form:

$$N = a\left(\frac{1}{\epsilon_t}\right)^b$$

where: N = number of load applications to failure;
ϵ_t = tensile strain; and
a, b = mix specific coefficients determined by test.

Typical examples of beam fatigue test results are shown in Figure 5 for different test temperatures.

Factors Affecting Fatigue

The stiffness of an asphalt mix plays a major role in the fatigue resistance of an asphalt pavement. Just as with increasing pavement thickness, a higher mix stiffness reduces the tensile stresses at the bottom of the asphalt treated layer and the likelihood of crack initiation. Experimental results verify this observation for asphalt pavements greater than 10 cm (4 in.) in thickness. Higher mix stiffness can result from the use of a harder asphalt, a lower pavement temperature, or a denser (better compacted) mix. However, for thin asphalt pavements (less than 10 cm) or pavements subjected to high deflection (weak subgrade), a less stiff or more flexible mix will produce a more fatigue resistant pavement. Polymer or rubber modified asphalts may help provide the more resilient characteristics desired in this situation. Therefore, strength and resilience are both important characteristics of a fatigue resistant asphalt pavement.

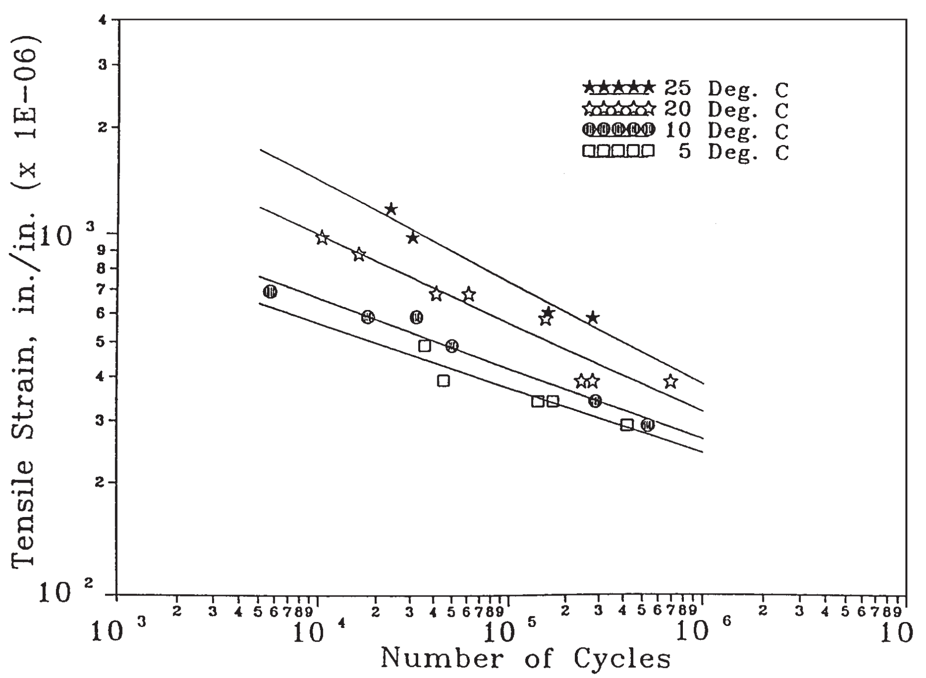


Figure 5. Strain-versus-fatigue relations for different temperatures

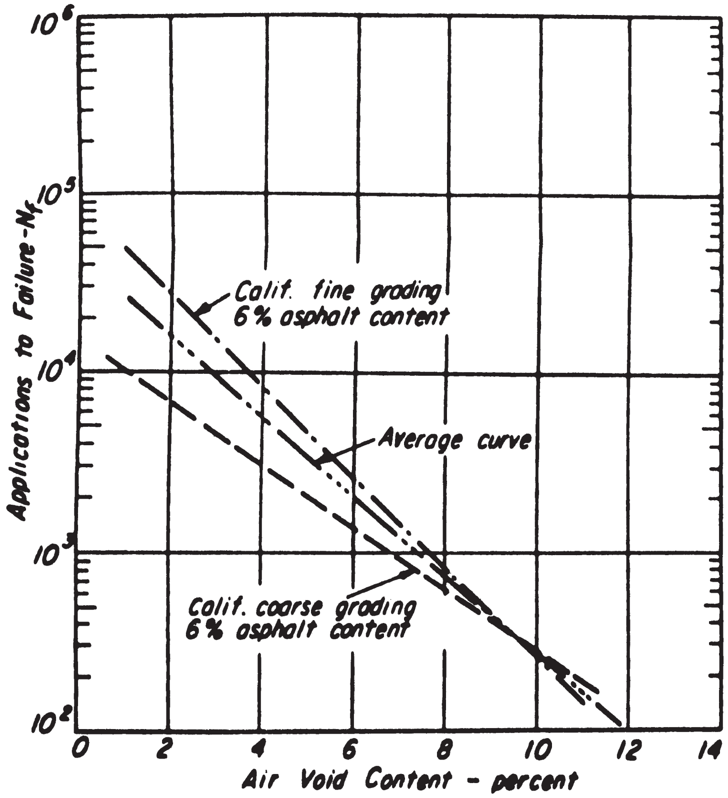


Figure 6. Influence of air void content on fatigue performance

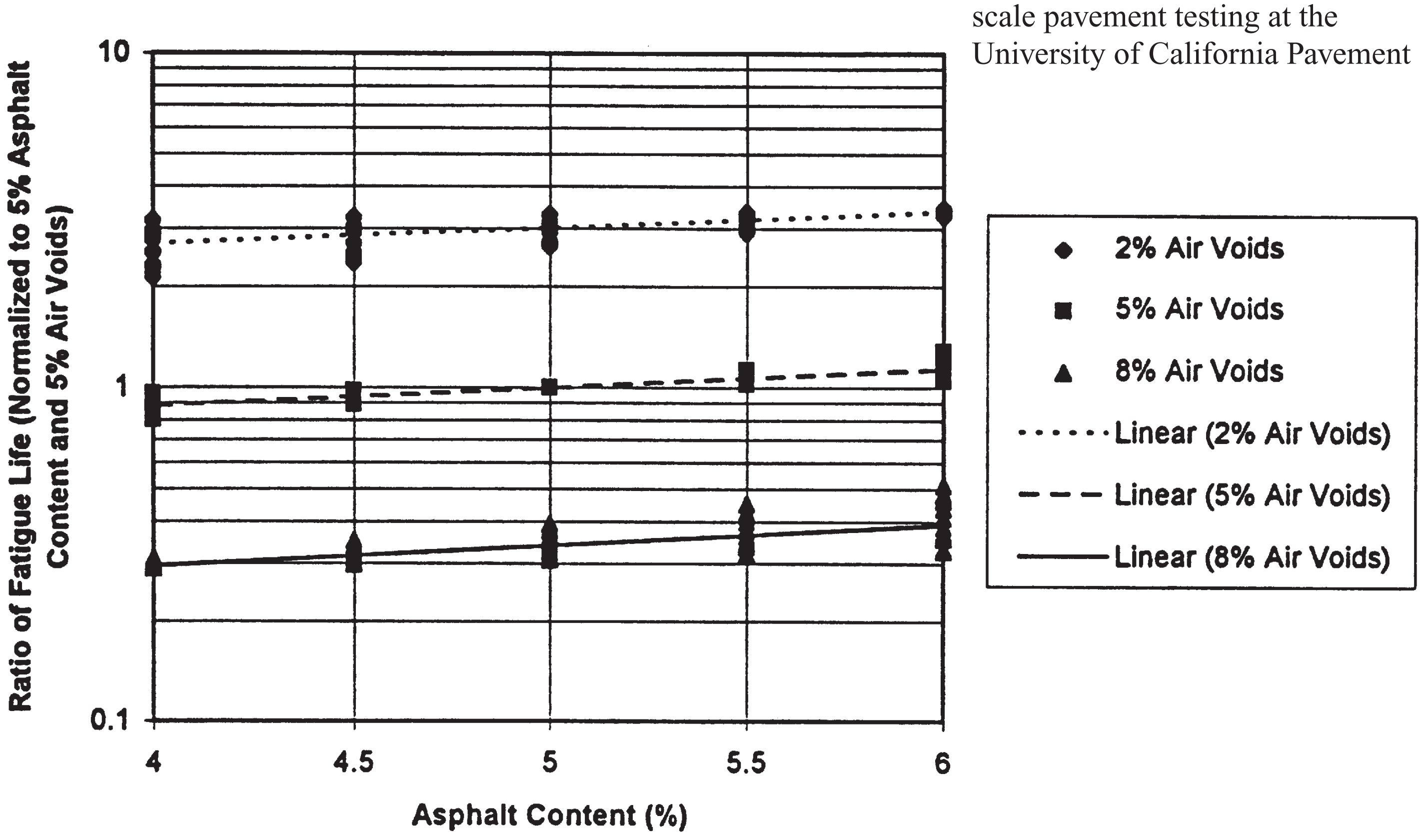
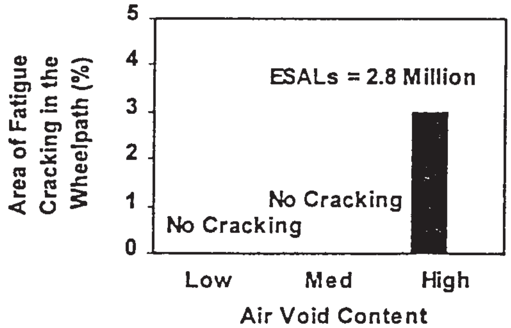


Figure 7. Effect of asphalt and air-void contents on simulated, fatigue-life ratio for 270 mix-pavement combinations

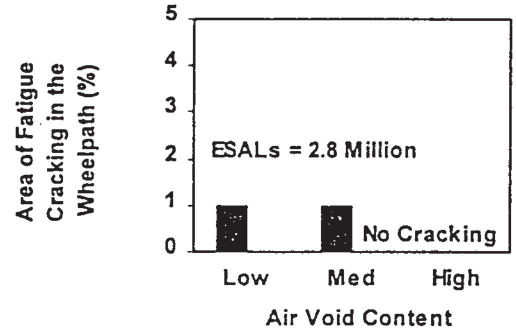
Air Void Effects

One mix characteristic that has a major effect on the fatigue resistance of dense graded asphalt pavement structures, regardless of pavement thickness, is air void content. Laboratory test results, shown in Figure 6, suggest that fatigue life can be improved an order of magnitude (10 times) by reducing air void content from 10% to 5%. This finding certainly passes the “test of reasonableness”. In metal fatigue, for example, applications to failure are reduced as the number of impurities (stress concentration points) increase. Similarly, in an asphalt mix, air voids act as stress concentration points and are the likely place where cracks begin.

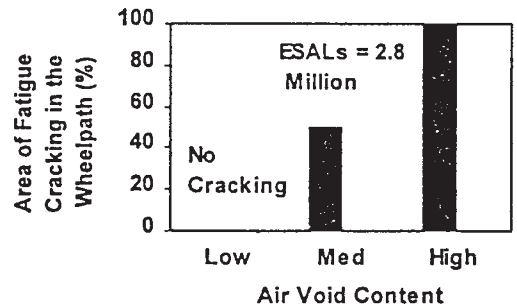
The effect of void content on fatigue life has been verified in full scale pavement testing at the University of California Pavement



Fine gradation at optimum asphalt binder content



Fine plus gradation at optimum asphalt binder content



Coarse gradation at optimum asphalt binder content

Figure 8. Effect of in-place air void content on fatigue cracking at WesTrack.

Research Center and at WesTrack. Using multilayer elastic computer analysis, simulations of pavement performance for 270 different mix-pavement structure combinations were conducted to determine the effect of asphalt and air void contents on fatigue behavior. Figure 7 shows that about a 3-fold increase in fatigue life can be expected when asphalt mix void content drops from 8% to 5%. The very significant effect of air void content on fatigue life was demonstrated further by the estimation of truck wheel loadings (ESALs) under accelerated pavement testing with a heavy vehicle simulator (HVS) at the Pavement Research Center. The number of load applications to failure for a full scale asphalt pavement section which contained 4.4% air voids in the bottom 76 mm lift and 7.8% air voids in the top 74 mm lift was estimated at 2.9 times that of an asphalt pavement section with 8.0 % air voids throughout.

Actual applications of load from the HVS on the pavement section with 4.4% voids in the bottom lift and 7.8 % voids in the top lift resulted in 112,200,000 ESALs to fatigue failure.

Preliminary results from WesTrack reinforce the findings from the HVS tests and analysis. WesTrack is a $14 million accelerated pavement test facility located in the state of Nevada approximately 100 km (62 miles) southwest of Reno.

One of the main objectives of the WesTrack project is to evaluate the impact on performance of deviations in materials and construction properties such as asphalt content, aggregate gradations, and in-place air void content. In an interim report on WesTrack performance by Dr. Jon Epps of the University of Nevada, Reno, fatigue cracking is shown to generally increase with increasing in-place air void content at optimum asphalt content (Figure 8). This trend occurs for both fine and coarse graded mixes.

Simulated HVS ESALs for:	
HVS conditions with standard mix (4.4% AV bottom lift, 7.8% AV top lift, and 5% AC): full friction interface	HVS conditions with standard mix (8% AV and 5% AC): full friction interface
52,951,000	18,133,000

As-measured average relative compaction (%)	As-measured standard deviation of relative compaction (%)		
	< 1.2	1.2 to 1.9	> 1.9
98.9 to 99.0	15	10	0
98.7 to 98.8	10	10	0
98.5 to 98.6	10	5	0
98.3 to 98.4	10	5	0
98.1 to 98.2	5	5	-5
97.9 to 98.0	5	0	-5
97.7 to 97.8	5	0	-10
97.5 to 97.6	0	-5	-10
97.3 to 97.4	0	-5	-15
97.1 to 97.2	0	-10	-20
96.9 to 97.0	0	-15	-20
96.7 to 96.8	0	-15	-25
96.5 to 96.6	0	-20	-25
96.3 to 96.4	0	-20	-30
96.1 to 96.2	-20	-25	-30
95.9 to 96.0	-20	-25	-35

Note: Bonuses are positive and penalties are negative

Table 1. Recommended contractor pay factors for relative compaction. (Percentage of future rehabilitation costs in current-year dollars.)

Practical Implications

Given this information from laboratory and accelerated pavement testing, what adjustments can be made in practice to realize improved pavement performance? Highway agencies, such as Caltrans, that call for a minimum 95-96% compaction in the field relative to laboratory compaction, are allowing up to approximately 8-10% air voids in the finished pavement. Attaining a minimum relative compaction of 98% would drop the in-place air void content to approximately 5-7%. Based on our earlier observations, this could mean a 3-fold increase in pavement fatigue life. Pavements that are failing by fatigue in 7 years should last for over 20 years with a little additional effort during placement.

One additional comment is necessary during our discussion of compaction. While most agencies use relative compaction as a target density requirement, there is a growing trend to compare field compaction to a fixed single mix measurement, such as maximum theoretical density. This approach would seem much less confusing and would identify a clear target rather than an allowable range. For example, a 95% field compaction based on maximum theoretical density would produce a 5% in-place air void mix. A 95% relative compaction could produce a mix with anywhere from 8% to 10% voids because of the range of voids or minimum voids requirement in the laboratory design mix.

Construction Incentives

In order to encourage a paving contractor to construct pavements having decidedly superior performance compared to pavements that simply meet minimum specification requirements, pay incentives should be seriously considered. This approach focuses primarily on the economic impact to the highway agency. It assumes that a penalty for inferior construction should be the added cost to the highway agency. It also assumes that any bonus for superior construction should be no greater than the added savings to the highway agency. These agency costs/ savings are normally associated with subsequent pavement rehabilitation. Inferior construction hastens future rehabilitation and its cost while superior construction reduces these costs largely by deferring future rehabilitation. Other related costs, such as the costs associated with traffic delays during rehabilitation, need to be considered.

Table 1 provides an example of how a bonus/penalty incentive for relative compaction might work. In this case, for a standard deviation in the range of 1.2 to 1.9 and a target relative compaction of 98%, a bonus of 10% is suggested if the contractor attains a relative compaction of 99% and a penalty of 15% is imposed if only 97% relative compaction is reached. A lower standard deviation for relative compaction results in a greater opportunity for bonus as well as less severe penalties. Combining a pay incentive factor for relative compaction with other critical mix properties, such as asphalt content and pavement thickness, can help assure the construction of a superior performing pavement.

Related Benefits

Aside from the improved fatigue performance of dense graded asphalt pavements expected with better compaction and a reduction in air void content, there are other benefits that can be realized. Moisture damage of asphalt pavements is a serious problem. Pavements with 8-10% voids allow moisture into the mix but are not open enough for the moisture to readily leave. The presence of moisture tends to reduce the stiffness of the asphalt mix as well as create the opportunity for stripping of the asphalt from the aggregate. This, in combination with repeated wheel loadings, can accelerate pavement deterioration. By reducing the air void content and a related property, permeability, of the mix, moisture damage can be minimized. A lower void content mix will also be less susceptible to oxidative hardening or “aging”.

Recommendations

In summary, it appears from extensive laboratory testing and the analysis of full scale pavement test section results that the fatigue resistance of dense graded asphalt pavements can be significantly improved by reducing the in-place air void content of asphalt mixes. An estimated 3-fold increase in fatigue life is possible with a reduction in void content from 8% to 5%. Reduced moisture damage and oxidation are added benefits that can be realized with the use of lower air void mixes. In focusing on air void content as a critical performance measure, it is suggested that field compaction be measured in terms of maximum theoretical density rather than relative to some laboratory compactive effort so that a clear target value can be established. Contractor pay incentives, combining such mix properties as air void content, asphalt content, and pavement thickness, seem to be an excellent way to encourage the construction of superior performing pavements.

References

Monismith, C. L., K. E. Secor, and E. W. Blackmer, *Asphalt Mixture Behavior in Repeated Flexure*, Proceedings, Association of Asphalt Paving Technologists, Charleston, S. C., Vol. 30, February, 1961, pp 188-222.

Tangello, S. C. S. Rao, J. Craus, J. A. Deacon, and C. L. Monismith, *Summary Report on Fatigue Response of Asphalt Mixtures*, Strategic Highway Research Program Report No. SHRP-A/IR-90-011, Institute of Transportation Studies, University of California, Berkeley, February, 1990, 147 pp.

Deacon, J. A., A. A. Tayebali, J. Coplantz, F. N. Finn, and C. L. Monismith, *Fatigue Response of Asphalt-Aggregate Mixes Part III—Mix Design and Analysis,* Strategic Highway Research Program Report No. SHRP-A-404, National Research Council, Washington, D. C., 1994.

Harvey, J. T., J. A. Deacon, B. Tsai, and C. L. Monismith, *Fatigue Performance of Asphalt Concrete Mixes and Its Relationship to Asphalt Concrete Performance in California*, Asphalt Research Program, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley, October, 1995, 189 pp.

Deacon, J. A., C. L. Monismith, and J. T. Harvey, *Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs*, TM-UCB-CAL/APT-97-1, Pavement Research Center, CAL/APT Program, Institute of Transportation Studies, University of California, Berkeley, April 1997, 46 pp.

Harvey, J. T., T. Hoover, N. F. Coetzee, W. A. Nokes, and F. C. Rust, *Caltrans Accelerated Pavement Test (CAL/APT) Program—Test Results; 1994-1997*, Paper prepared for AAPT Symposium on Accelerated Pavement Testing, Boston, MA, March 16-18, 1998, 40 pp.

Epps, J. A., *WesTrack Full Scale Test Track: Interim Findings*, internal report, College of Engineering, University of Nevada, Reno, Fall, 1997, 18 pp.