Observations, Analysis, and Prediction of Asphalt Cracking

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ABSTRACT: The various causes/categories of pavement cracking and generalized criteria for identification of potential deficiencies are presented in conjunction with case histories that relate to investigations of pavement distress. Asphalt binder properties, such as viscosity and penetration are shown to relate well with thermal and combined thermal/load stress conditions. Although slightly more involved testing procedures are required, criteria have been developed for different yearly ESALS to identify a paving mixture's resistance to top-down cracking. Dissipated creep strain energy parameters are obtained from indirect tension tests to define an energy ratio for separating cracked from uncracked pavements. It is difficult to interpret Falling Weight Deflectometer (FWD) data from cracked pavements unless special procedures are followed. At high pavement temperatures the influence of cracks will diminish and allow for improved determination of moduli for underlying pavement layers and foundation/subgrade soils. These analyses are enhanced when asphalt viscosity relationships with resilient moduli are used to assign E_1 values for backcalculation. Relationships or procedures for estimation of any pavement layer or subgrade modulus are very beneficial in simplifying the interpretation or backcalculation of other layer moduli. Where possible, laboratory test parameters that relate directly to the behavior of paving mixtures should be integrated in the design and performance models for asphalt pavements. Realistic, multiple/simplified, methods for design and/or evaluation of pavement performance are desirable over one specific approach since comparable results are an indication of reliability.

KEY WORDS: Cracking, asphalt concrete pavements, low temperature, top down cracking, laboratory and field testing.

1 INTRODUCTION

Asphalt concrete pavements are often called "flexible pavements" because the soft asphalt binder in the paving mixture will often tolerate greater strains and deformation than "rigid" Portland Cement Concrete (PCC) pavements. However, aggregate gradation, excessive fines, lack of sufficient asphalt, and age hardening of the asphalt binder can embrittle the material making it comparable to a PCC pavement, particularly at low temperature. In this brittle condition, asphalt mixtures will crack at stress levels similar to those in PCC (e.g., creep failure when stresses are approximately 65%).

Hypothetically, a well designed and constructed pavement should only deteriorate due to wear of its surface by the combined effects of traffic and climate (temperature, rain, snow, etc.). Unfortunately, variations in subgrade soils, moisture conditions and paving materials can contribute to a critical condition that results in pavement cracking. Subgrades involving water sensitive soils (e.g., silts, silty sands, etc.) are especially prone to high compressibility and loss in shear strength. A lack of embankment height, high water table, and poor surface/subsurface drainage can produce extensive pavement cracking. However, Falling Weight Deflectometer (FWD) tests on thick, stiff, pavements over organic soils have shown that maximum deflections appeared excessive but pavement stresses were relatively low and no cracking developed.

A low water table (e.g., 3 m below the surface of the pavement) would often be considered adequate to minimize subsurface moisture damage. In one case silty soils with high capillary rise increased the moisture content of the granular base by 6 to 7 percent resulting in cracking of the asphalt concrete pavement. The high compressibility of silty soils allow for exudation of moisture when subjected to repeated stress from heavy vehicles.

The ensuing presentation provides information relating to 1) factors affecting age hardening and cracking, 2) thermal transverse cracking, 3) effect of binder properties on cracking, 4) analyses and modeling of combined load and thermal stresses, 5) crack and airfield pavement analyses, 6) analysis of pavement cracking resulting from water infiltration, and 7) top-down surface cracking. Additional more detailed information can be acquired from the cited references.

2 FACTORS AFFECTING AGE HARDENING AND CRACKING

Pavement cracking is generally categorized according to the observed crack pattern. Sometimes it is possible to infer the cause of cracking from the location and pattern of cracks but detailed (forensic) investigations are usually required to pinpoint the exact conditions and causes that contributed to crack development in the pavement. In general, pavement stiffness is primarily influenced by subgrade support and foundation conditions that often initiate pavement failure. The characteristics of soils and subsurface moisture conditions are key to the behavior of the granular base and asphalt concrete pavement layers. However, even under ideal in situ foundation conditions an asphalt pavement can exhibit distress and various forms of cracking.

2.1 Short Term

Age hardening, both long and short term (Page, Murphy, Ruth and Roque 1985), has a major effect on the crack resistance of asphalt paving mixtures. The use of an asphalt having a low flash point or containing light ends may produce a loss in volatiles with a substantial increase in binder viscosity and asphalt mixture stiffness. When paving mixtures contain excessively absorptive aggregates it may be difficult to control asphalt hot mix plant operations to produce a uniform, quality, paving mixture. Other than the influence of moisture on flushing of asphalt and fines, there is a tendency to use high drum temperatures to maintain production rather than to increase retention time in the drum mixer. Some high flash point asphalts may withstand exposure to these excessively high temperatures but often volatiles are lost and the asphalt binder is severely damaged.

On one Florida paving project the mixture was so severely damaged that five months later transverse thermal cracking developed with spacings between cracks of one to three meters. Indirect tension tests of pavement cores revealed a very brittle condition at 10C, similar to Portland Cement Concrete (PCC).

2.2 Long Term

Long term aging can be considered as a function of mixture permeability, binder properties, asphalt film thickness and in situ pavement temperature. Excessive air void contents (> 7%)

implies excessive permeability and greater potential for abnormal age hardening. Inadequate binder content compaction, or aggregate gradation are the most common causes for early cracking and poor longevity. A continuous aggregate gradation without any gap grading or excessive amounts retained on any sieve size will provide better mixture properties.

An investigation of rutted pavement at the intersection of two-four lane divided highways developed block cracking in the gore adjacent to the left turn lane that was not exposed to traffic. High air voids and accelerated age hardening produced cracking within about two years after paving. However, pavement cracking is not always detrimental to rideability (roughness) or service life. One pavement exhibited about three longitudinal cracks with transverse cracks forming block cracking without any noticeable change in ride or crack pattern over ten years. This was attributed to good surface and subsurface drainage with a deep, non-detectable water table.

Compaction with rolling equipment may be adversely affected by lift thickness relative to the effective maximum size of the aggregate. Until more recently, a constructed pavement layer thickness that was twice the maximum aggregate size was considered adequate. This concept has changed and now lift thicknesses of 3 to 4 times the maximum size of aggregate are being used. This is beneficial from the standpoint of greater heat retention in colder weather, greater aggregate mobility (strain) to facilitate compaction, improved longevity, and structural behavior. A 3.2 mile long test road with 14 different mixtures was constructed with layer thicknesses exceeding five times the maximum aggregate size demonstrated the benefits of using a greater ratio (Ruth and Schaub 1966).

Film thickness may be more important than air void content from the standpoint of aging. Several investigations into cracked pavements revealed that sand asphalt mixtures with 15± percent air voids hardened excessively even though the permeability was very low and it was covered by asphalt concrete. Furthermore, thicker asphalt films coating a good aggregate gradation can provide greater failure strain energy to resist cracking.

Climatic zones result in different high pavement temperatures which have a marked effect on long term aging. Comparison of pavements indicated that the clear atmospheric conditions and high solar radiation in Arizona produced about three times the amount of long term age hardening as found in Florida (Guan and Ruth 1990). Note that ultraviolet radiations affect only exposed surfaces. Roof top exposure of pavement cores and laboratory specimens over 6 months produced accelerated hardening as compared to the pavement. The reduced time to achieve the same binder viscosity as in the pavement was found to be proportional to the exposed surface area.

3 THERMAL TRANSVERSE CRACKING

Cold weather transverse cracking of pavements is commonly referred to as “thermal cracking.” Thermal cracking analyses and predictive models have generally neglected the effect of vehicular load induced stresses. The results of research involving the thermal cooling of a test pit pavement with dynamic applications of a dual tire were reported by Ruth, Hardee, and Roque 1988. It was observed that a fast rate of cooling produced a rippling effect similar to warping/curling in PCC pavement. The wave length or distance of lift-off increased at lower temperatures and with a greater rate of cooling. Load induced tensile stresses in the asphalt pavement layer increased accordingly. Studies in Connecticut and South Africa confirmed the rippling effect.

Data from 21 test pavements were analyzed to determine the cause of thermal cracking in Quebec, Canada (Keyser and Ruth 1984). Asphalts recovered by the Abson method from 6 to 9 year old test roads were evaluated to determine the penetration and other binder properties. Transverse (thermal) cracks were counted over each 3 km test section. Six categories of traffic, light to heavy, were established to characterize each section. Analysis of the data revealed an excellent relationship between the number of transverse cracks and the recovered asphalt penetration for light to medium, level 1 through 3, traffic. This relationship, illustrated in Figure 1, indicated that essentially no cracking was observed with penetrations of about 90 but the number of cracks increased exponentially with lower penetration values. The amount of cracking appeared to be more severe when the pen was less than 35 with light to medium traffic.

The relationship for the heavy traffic {level 4-6} test sections was not as definitive. The interactive effects of stresses resulting from truck tires and thermal stress shifted the relation upward as shown in Figure 1. Observations in Florida and South Africa {RSA} suggest that a pen of 30 to 35 related to initiation of pavement cracking. Obviously softer, higher pen penetration binders that resist age hardening, are beneficial in reducing the potential and severity of pavement cracking. For example, the access road to the Hydro-Quebec power generating facility near James Bay was constructed using a 300 - 400 pen asphalt cement. Except for isolated failures associated with ice lenses {palsas] in the subgrade, the pavement performed very well with minimal cracking, even though there was heavy truck traffic.

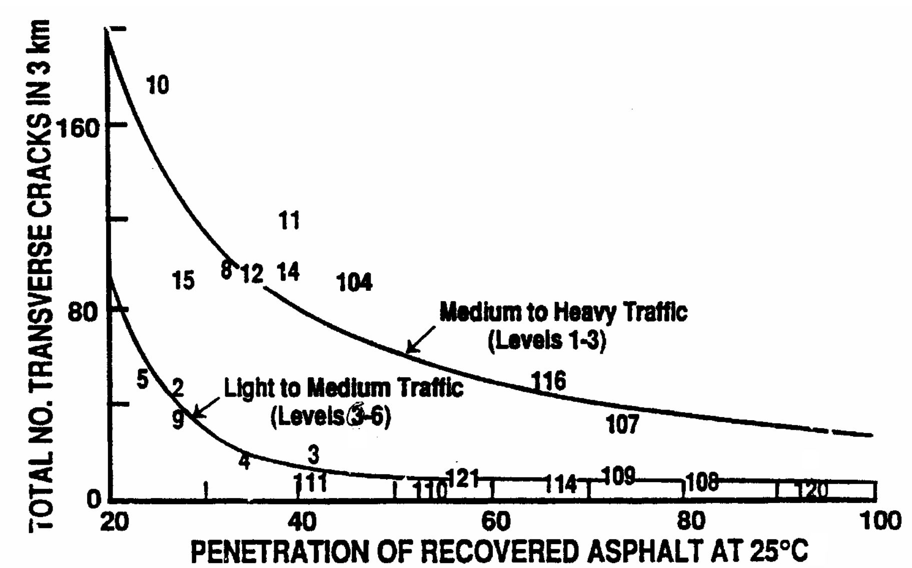

Figure 1: Effect of penetration and traffic on transverse cracking.

4 EFFECT OF BINDER PROPERTIES ON CRACKING

Properly designed pavements develop fatigue, block, thermal, etc. cracking primarily as the result of low temperature properties of the binder. The wheel loads and thermal cooling rates impose stress/strain conditions that can exceed those provided by the binder and aggregate in the pavement layer. For simplicity, low temperature behavior may be considered as primarily related to binder properties even though the aggregate contributes substantially to the mixture's resistance to cracking.

Performance Grade (PG) test methods and specifications were developed for the purpose of improving our ability to characterize asphalts, particularly at low temperature. Until recently, the effect of the rate of cooling was not considered as being a crucial factor. This is best illustrated by comparing the relatively slow cooling rate for pavements in the far north (e.g., James Bay) with those in lower latitudes with desert climates (e.g., Arizona). Arizona has greater age hardening and substantially more thermal change cycles than in the far north.

Asphalts selected for these environments are very different in consistency due to emphasis on low versus high temperature conditions.

At present there is concern that PG grades do not adequately define the properties of polymer modified asphalt binders. This problem is directly attributed to the shear susceptibility (complex flow) changes as type of bitumen or test temperatures are changed. Some air blown and polymer modified asphalts tend to exhibit non-newtonian behavior at high in-service pavement temperatures. These binders provide less change in shear susceptibility than other ashpalts as the temperature is reduced. Also, they tend to resist oxidation and age hardening to a greater degree.

It has been observed that some shear susceptible asphalts exhibit a gradual change in volumetric contraction. This makes determination of the glass transition temperature more difficult but more tolerant to rapid cooling and fracture at low temperatures. As an example, an 85-100 pen. air blown asphalt from a naphthenic crude had a Tg that was 10C lower than an 85-100 pen. straight-run California valley asphalt. Furthermore, throughout a large range in temperatures, the air blown asphalt mixtures retained much better properties than mixtures prepared with the other asphalt. Complex flow for the air blown asphalt ranged between 0.86 and 0.58 whereas it was 1.00 to 0.35 for the straight-run asphalt which abruptly changed from 0.64 to 0.35 after a 5C reduction in temperature.

It is the authors' belief that Herbert Schweyer's rheological characterization using the Burger's model with a feedback of complex flow provides the only true appraisal of viscosity and stiffness throughout a wide temperature range (Tia and Ruth 1985). His application of the log constant power (η_j; where j = 100 watts/m^3) versus Log K makes it feasible to define viscosity-temperature relationships and to establish power law trends with mixture properties.

Critical viscosity criterion at 45C, as developed in Australia, was converted to constant power (η_j) and combined with the Florida criterion for 25C to establish a relationship for cracking. Figure 2 compares this trend with data from cracked and uncracked airfield and highway pavements. Keep in mind that the climatic conditions are somewhat similar. It may not be realistic to use this relationship to define cracking where rates of cooling and/or wheel load stresses are considerably different.

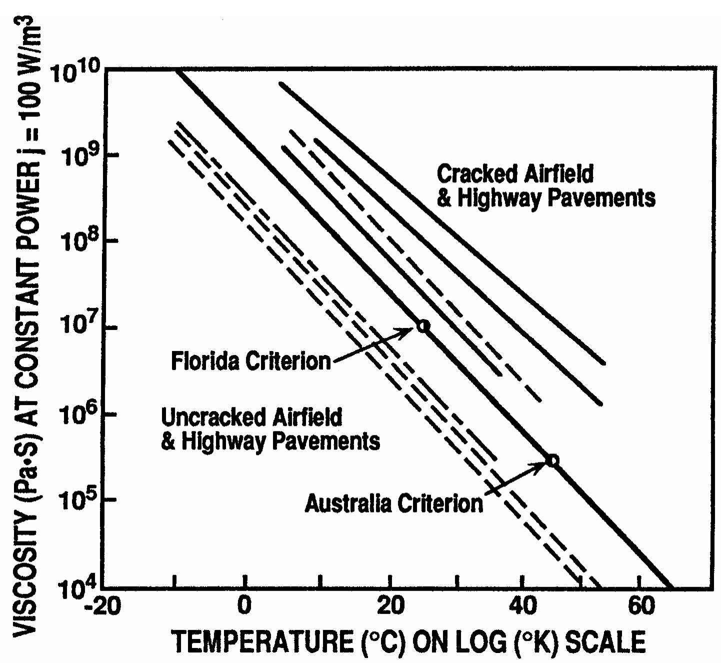

Figure 2: Critical viscosity - temperature concept for temperature climates.

The Schweyer constant power viscosity was evaluated for six different asphalts used in construction of the Pennsylvania D.O.T., Elk County, test road (Ruth, Schweyer, Davis, and Maxfield 1977). Two of the six test sections developed extensive transverse cracking in January, four months after construction. The temperature susceptible propane derived asphalts used in these two sections exhibited severe changes in shear susceptibility as the temperature was reduced, producing very high viscosity and stiffness. Even without aging the original asphalt properties clearly identified cracking potential. The rate of cooling was extremely high at the time these pavement sections cracked.

5 ANALYSES AND MODELING OF COMBINED LOAD AND THERMAL STRESS

A methodology has been developed for evaluation and rehabilitation of pavements (Guan, Ruth, and Roque 1991). This method was dependent upon establishment of criteria to define the "critical condition" at which the pavement may crack. What is a critical condition? It is any combination of materials, environment, and loading characteristics that produce stresses, strains, or energy equivalent to those required for fracture of the asphalt pavement.

The key elements used to establish the properties of the asphalt mixture in the pavement include:

Asphalt: constant power viscosity (η_j) vs. temperature (°C)

Prediction of Asphalt Properties using:

Mix Viscosity: η_{mix} vs. η_j

Static Modulus: E_S vs. η_{mix}

Dynamic Modulus: E_D vs. η_j

Also, the prediction of fracture parameters were determined for use in the assessment of the pavement's potential for cracking (Ruth, Guan, and Tia 1992).

Indirect tension tests performed at different temperatures were used to establish the maximum tensile strength. Florida and the Penn D.O.T., Elk County, test road mixtures had essentially the same failure stress (2760 to 2930 kPa). A value of 2760 kPa was selected to typify stress at failure. Similarly, the failure strain and fracture energy were determined using constant stress and dynamic indirect tests. The relationship between resilient modulus (E_1) for mixtures and the constant power viscosity (η_j) was established as shown in Figure 3.

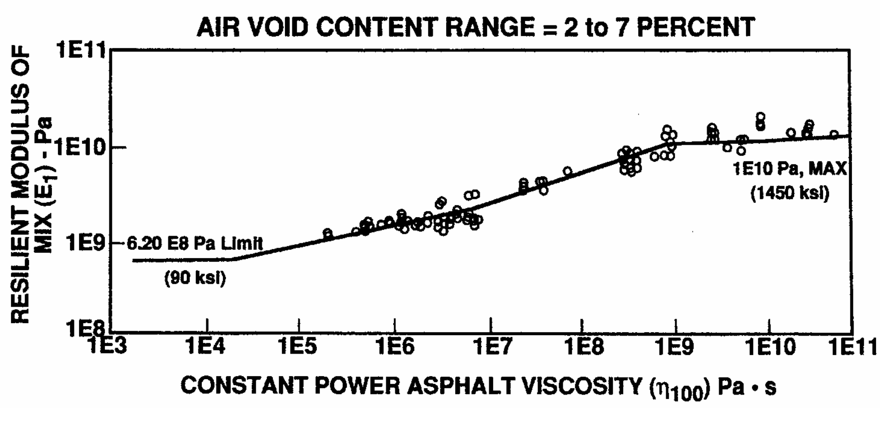

Figure 3: Asphalt viscosity prediction of E_1 for mix.

This simplified the analysis of Falling Weight Deflectometer data since E_1 could be inserted into elastic layer analyses for determination of E_2, E_3, and E_4 (Badu-Tweneboah, Manzione, Ruth, and Miley 1988). Asphalts recovered from pavement cores were used to determine η_j and predict E_1 of the in situ asphalt pavement and provide input for thermal and/or load analyses at different temperatures (Ruth, Guan, and Tia 1992). This approach was successfully used in the evaluation of airfield and highway pavements.

6 CRACKED AIRFIELD PAVEMENT ANALYSES

An airport taxiway in the Florida panhandle developed fairly extensive cracking. Upon detailed investigation of the asphalt concrete pavement, it was found to have a sand asphalt base which undoubtedly contributed to the observed cracks in the pavement (Manzione 1989). Cores were taken and tested to obtain the necessary parameters for input into the prediction of failure parameters. Similarly, cores were evaluated for stress, strain, and energy for fracture. The penetration values of recovered asphalts ranged from one for the sand asphalt base to 23 for the asphalt concrete wearing surface. Attempts to test cores at temperatures below about 45C failed because of the brittle nature of the sand asphalt base. Also, FWD tests were inconclusive since pavement cracks induced considerable variability in the measured response. Consequently, pavement temperatures were monitored and FWD test performed when the pavement temperature was sufficiently high enough to minimize the effect of cracks and reduce the stiffness of the sand asphalt base to simulate an uncracked base condition. Recovered asphalt viscosity and the high temperature FWD pavement data were then used to predict cracking under typical load and cooling condition. Since pavement response at high temperature was basically not affected by pavement cracking, the assumption was made it simulated the pavement in its uncracked condition but with the highly aged asphalt binders. Figures 4 and 5 illustrate the relationships for E_1 and E_2 versus η_j for different levels of cracking.

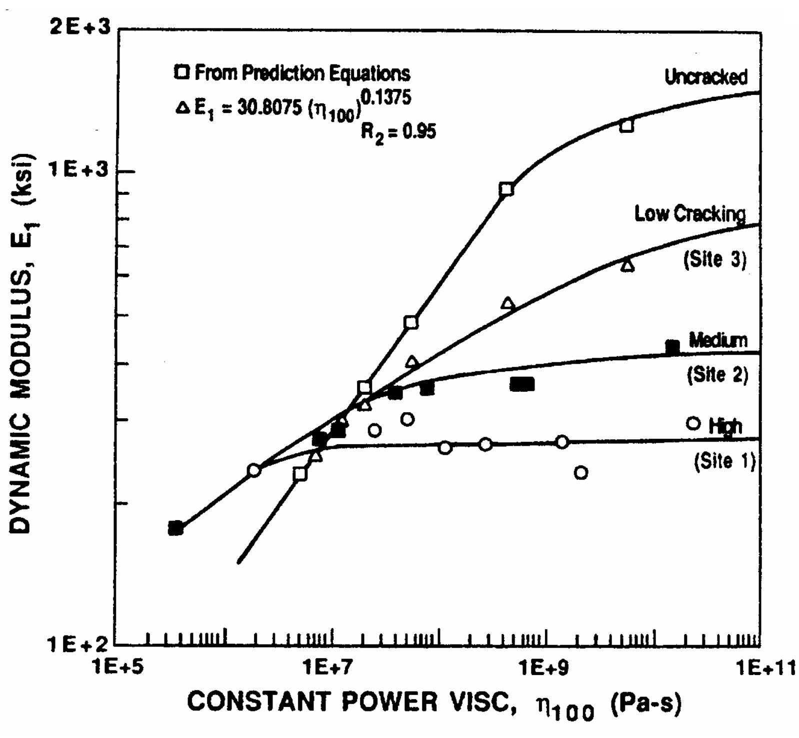

Figure 4: E_1 as a function of η_{100} for cracked and uncracked pavements.

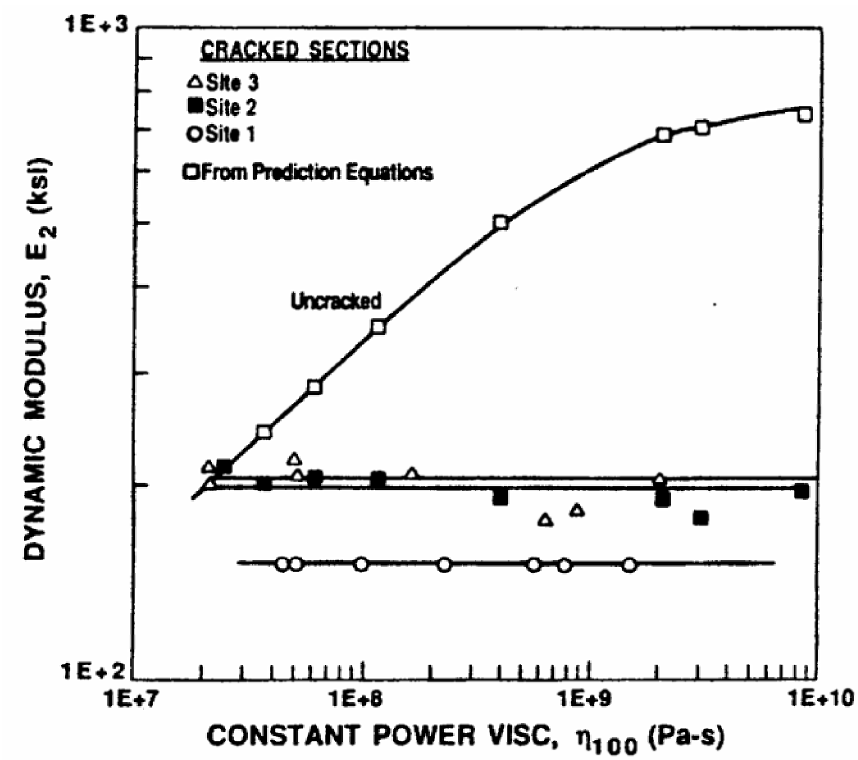

Figure 5: E_2 as a function of η_{100} for cracked and uncracked pavements.

7 ANALYSIS OF PAVEMENT CRACKING RESULTING FROM WATER INFILTRATION

Occasionally conventional construction methods can result in early failure of pavements. In one case, after construction of a pavement in South Florida, heavy rains produced extensive ponding of water at the edge of the pavement just prior to spreading of a soil wind-row for shoulder dressing. This impediment to surface drainage allowed water to seep downward from the pavement edge and into the underlying base course and subgrade. Upon detection of cracking, an investigation was conducted using FWD and data sufficient for analysis of stress and fracture energy ratio (Roque and Ruth 1990). The analysis performed using an approximation of in-service pavement temperature gave a stress ratio of 0.87 (2400 kPa) and an FE close to 1.00. An uncracked segment of pavement had a FE ratio of 0.55. It was predicted that this section of the pavement would fail. Three months later cracks were observed in the pavement.

8 TOP-DOWN SURFACE CRACKING

Crack growth rate parameters were determined from indirect tension tests of dissipated energy and stiffness (Roque, Zhang, and Sankar 1998). Subsequent research has revealed that dissipated or failure strain energy relates to the potential for top-down surface cracking. This form of cracking appears on high stiffness pavements (e.g., interstate highways). It became evident when trucks stopped using bias-ply tires and installed radials which produce high shear and lateral tensile stresses within the upper 25 mm of the pavement.

Subsequent research has resulted in the development of a performance based mixture specification based on dissipated creep strain energy (Roque, Birgisson, Drakos, and Dietrich 2004) as presented below:

Traffic ESALS/year × 1000	Minimum Energy Ratio
< 250	1.0
< 500	1.3
< 1000	1.95

The Energy Ratio is defined as follows:

$$ER = DCSE_f / DCSE_{min}$$

Where, $DCSE_f$ is the dissipated creep strain energy threshold of the mixture, and $DCSE_{min}$ is the minimum creep strain energy required to minimize the potential for cracking.

A total of 22 Florida pavements and three in Pennsylvania were evaluated using ER. The ER criteria correctly identified the cracked and uncracked pavements.

The gradation of the aggregate blend and asphalt film thickness has a noticeable effect upon creep strain and stress at failure. Power law gradation characterization factors (slope and intercept) were found to relate very well with the properties of paving mixtures (Ruth, Roque, and Nukunya 2003). Consequently, it seems logical that criteria can be established for selection of aggregate gradations that will meet FE requirements to minimize and/or eliminate top-down surface cracking of asphalt pavements.

9 SUMMARY AND CONCLUSIONS

The design or rehabilitation of pavements to minimize or eliminate cracking probably depends more on the selection of materials, design of the mix, and the adequacy of construction than thickness design. Materials characterization needs to identify parameters that can be used in pavement design to effectively prevent cracking. To accomplish this goal, it is essential that in situ conditions are properly determined. For example, minimum pavement temperature, rate of cooling, wheel load stresses, etc. should be based on what constitutes the most critical conditions over a ten or twenty year period rather that use an average, so called "typical value."

Low temperature cracking may be predicted using penetration, viscosity or energy ratio. Unfortunately, age hardening is the least tangible parameter in the prediction of future pavement performance. Consequently, local or regional experience or historic data need to be used to select the proper parameters. Even wheel loads are often underestimated by assuming load limits prevail.

In consideration of the information presented in this paper, it appears feasible to develop a simple, but comprehensive system that will interact key parameters in relationships to minimize thermal, fatigue, block, and top-down cracking in asphalt pavements.

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