Structural Requirements of Bituminous Paving Mixtures

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Bituminous paving mixtures are used as surface or base layers in a pavement structure to distribute stresses caused by loading and to protect the underlying unbound layers from the effects of water. To adequately perform both of these functions over the pavement design life, the mixture must also withstand the effects of air and water, resist permanent deformation, and resist cracking caused by loading and the environment.

Many factors affect the ability of a bituminous paving mixture to meet these structural requirements. Mixture design, construction practices, properties of component materials, and the use of additives all play important roles in the resulting structural characteristics of a pavement. It is also important to recognize the interaction between mixture design and pavement design to arrive at the most cost-effective solutions.

Although great strides have been made in understanding the behavior of bituminous mixtures and the factors that affect their performance, much work remains. The following sections provide a summary of some of the principal issues and challenges associated with the design and production of bituminous mixtures that can meet the ever-increasing structural needs of modern pavements.

CHALLENGES AND OPPORTUNITIES

The asphalt pavement community faces important challenges that will continue to develop in the near future. These challenges include

- Changes in the properties of component materials, primarily in the availability of modifiers and manufacturing processes that can be used to assist in engineering the bituminous mixture, but also in the availability of good sources of the two main components—asphalt and aggregate;
- Increased severity of the conditions under which bituminous mixtures are expected to perform, primarily greater tire contact stresses, loads, and load repetitions, including changes resulting from advancements in tire technology;
- Increased need to reduce the adverse environmental impacts of bituminous mixture production and paving and to increase the reuse of materials from existing pavements and other sources; and
- More restrictive constraints on the time frames and production requirements of pavement rehabilitation and reconstruction operations, especially in urban areas, where traffic delay is an important issue.

At the same time, the knowledge and technology available to address these challenges are improving. The behavior of bituminous mixtures under traffic and environmental conditions is highly complex, especially when compared with other materials, such as steel or hydraulic cement concrete. Application of basic knowledge from other fields, primarily mechanics of materials and statistics, is improving the understanding of the mechanisms that determine the performance of bituminous mixtures in the pavement structure. Basic engineering research on the properties of asphalt, aggregate, and additives and their effects on specific distress mechanisms has significantly contributed to the ability of engineers to develop materials that will perform well under specific environmental and traffic conditions. Much of this progress has been possible through continuing and dramatic reductions in computing costs and improvements in laboratory testing technology.

The challenges are formidable, and the implementation of improved technology must outpace the increase in performance requirements for bituminous mixtures and flexible pavement structures driven by changes in traffic and availability of new materials. Engineers must work to improve cost efficiency and environmental compatibility of asphalt paving technology while preserving the pavement infrastructure, and not merely struggle to maintain the status quo.

STRUCTURAL REQUIREMENTS

To perform satisfactorily in pavement systems, bituminous mixtures should exhibit (*a*) ability to distribute stresses; (*b*) stability when resisting permanent deformation; (*c*) resistance to cracking; and (*d*) resistance to freeze-thaw and moisture damage. Numerous factors and associated properties affect a bituminous mixture's ability to meet these structural requirements:

- Factors:
  - Binder characteristics;
  - Aggregate characteristics;
  - Additives;
  - Temperature;
  - Moisture;
  - Loading history (e.g., loading and rest times, loading rate, load level);
  - Aging characteristics;
  - Stress state; and
  - Compaction method.
- Properties:
  - Stiffness,
  - Rheological properties,
  - Permanent deformation properties, and
  - Cracking properties.

These factors are related to materials, environment, load, and construction. The state of knowledge of selected structural requirements and related properties and issues, as well as the direction of future research on these topics, are discussed in the following sections.

Stiffness

Bituminous mixture stiffness must be determined to evaluate both the load-induced and thermal stress and strain distribution in asphalt pavements. Stiffness has also been used as an indicator of mixture quality for pavement and mixture design and to evaluate damage and age-hardening trends of bituminous mixtures in both the laboratory and the field. However, the determination of practical and reliable methods to determine bituminous mixture stiffness remains a challenge, as does the proper use of stiffness in the evaluation and design of bituminous mixtures and pavements.

Part of the challenge rests on the dependence of bituminous mixture stiffness on temperature, time or frequency of loading, and stress state. In addition, there are numerous definitions of stiffness, including dynamic modulus, resilient modulus, bulk modulus, shear modulus, and creep compliance, which all depend on these factors and even on the test method used in their determination. Different moduli are also determined from nondestructive field tests, in which the value determined depends on the characteristics of the load and the model used to represent the pavement system.

Much work remains in evaluating the relevance of stiffness as a measure of mixture quality and its relation to pavement performance. Higher stiffness mixtures reduce load-induced stresses to underlying layers, but increase both load-induced and thermal stresses in the bituminous mixture. In addition, higher stiffness can be achieved by changing any of the following: mixture gradation, asphalt content, compaction, filler content, and binder type, including additives. Therefore, the effect of increased stiffness on performance depends on how it is achieved and at what cost. Clearly a great deal of work lies ahead in the determination and use of bituminous mixture stiffness for the design of bituminous mixtures and pavements.

Stability

Stability can be simply described as the ability of the bituminous mixture to resist excessive permanent deformation. Bituminous mixtures are typically designed for stability, if for no other distress mechanism, because stability problems typically occur within a few years or even months or weeks after construction. Stability problems often require complete removal and replacement of the rutted mixture—an expensive undertaking. Premature cracking, although costly over the life-cycle of the pavement, does not present the same type of safety problem and typically occurs later in the life of the pavement. In addition, the useful life of a cracked pavement can often be prolonged by maintenance.

Principal factors affecting the stability of bituminous mixtures include the following:

- Magnitude, frequency, pressure, and speed of loading;
- Temperature;
- Aggregate gradation, shape, and texture;
- Binder type and amount; and
- Construction variables such as compaction, quality control, and segregation.

Important issues related to stability that need to be addressed include the following:

- Quantification of the key factors known to affect mixture stability.
- Development of tests and analysis procedures for predicting mixture stability in the laboratory during design and in the laboratory and the field during construction.
- Development of models for evaluating mixture stability and predicting performance. These models will require (*a*) development of statistical relationships between mixture components, test results, or both, and observed performance in the field, and (*b*) development of mechanistic models of material behavior. The latter requires development of appropriate constitutive relationships for asphalt concrete at elevated temperatures that capture the viscoelastic and elasto-plastic components of its behavior.

- Conversion of new knowledge and tools into construction practices, technical understanding, and products—such as new testing machines, procedures, specifications, materials, and software—to be used by the practicing asphalt paving technologist.

Resistance to Cracking

Cracking of the bituminous mixture layer in pavement structures can be classified in four categories according to cause of the cracking: fatigue cracking, thermal cracking, reflection cracking in overlays, and construction-related cracking. The first three are significantly influenced by the characteristics of the bituminous paving mixture and are discussed in the following sections.

Fatigue Cracking

Fatigue cracks are caused by repeated traffic loading. Recent work has indicated that fatigue cracks start as microcracks (crack initiation phase) that later propagate, densify, and coalesce to form macrocracks (crack propagation phase) as the mixture is subjected to tensile stresses, shear stresses, or a combination of both. Recent work has indicated that fatigue cracks can start at the bottom or at the top of the bituminous surface layer, depending on the structural characteristics of the pavement. The actual contact stress distribution under truck tires has also been found to play a major role in the location and development of fatigue cracks. In addition, the importance of the effect of healing and interfacial properties between asphalt and aggregate on the rate of crack development has been more clearly identified in recent years.

This improved understanding of the mechanisms of fatigue cracking is leading to improved mixture tests and materials and pavement models to predict the field performance of bituminous mixtures more reliably. Recognizing that both crack initiation and propagation processes are directly related to stress-strain fields in bituminous layers, researchers recently have focused on developing constitutive relationships that can describe the hysteretic behavior of bituminous mixtures under realistic traffic conditions composed of multiple load levels and random rest periods. A reliable constitutive model must be capable of accounting for effects of temperature, loading rate and time, rest periods, aging, and multilevel loads. The complex interaction of these variables warrants the need for viscoelasticity, damage mechanics, and fracture mechanics in developing reliable constitutive models. For the component materials specifications, these models have an advantage over empirical models because their fundamental nature provides links between component materials' properties and mixture performance.

It is expected that significant developments and contributions will continue in the area of fatigue cracking in the coming years. Once mechanisms of failure are more adequately defined, a significant amount of work will be required to quantify the effects of different factors on fatigue resistance. This work will lead to improved design procedures and specifications for bituminous mixtures.

Thermal Cracking

Some researchers have attributed the development of two types of thermal cracks to two different environmental conditions: (*a*) low-temperature cracking caused by a single drop to an extremely low temperature and (*b*) fatigue cracking caused by multiple cycles of temperature change with thermal stresses below the tensile strength of the mixture. These cracks normally start from the pavement surface, where the temperature is the lowest and exhibits the greatest fluctuations.

Because bituminous binders are significantly weaker in tension than aggregate and are affected by temperature change to a much greater degree, binder properties alone have been used to control thermal cracking in the past. Recent research suggests that mixture testing and analysis may be necessary to distinguish mixture resistance to thermal cracking, especially for modified binders. The indirect tension test and thermal stress restrained specimen test (TSRST) have been the primary test methods used to evaluate the thermal cracking performance of bituminous mixtures, and future research will focus on more advanced interpretations of measurements from these tests.

Reflection Cracking in Overlays

Reflection cracks result from vertical and horizontal movement of discontinuities in underlying layers caused by wheel loads and by thermal expansion and contraction. A thin stress-absorbing layer over the existing layer has been used to retard crack propagation in bituminous overlays, but vastly different performance has been reported in field studies.

Because of complex stress and strain fields caused by both vertical and horizontal movements in the supporting layer, laboratory characterization of reflection cracking resistance is difficult. Therefore, a significant level of research is expected to focus on reflection cracking in the next several years. This research will involve (*a*) development of a testing apparatus that can simulate the complex stress-strain fields in bituminous mixtures caused by simultaneous vertical and horizontal movements of underlying layers; (*b*) improvement in analysis methods; and (*c*) development of additive materials and systems to retard cracking in overlays.

Durability

Durability of a bituminous mixture is defined as its resistance to weathering and the abrasive action of traffic. This definition includes changes in mixture properties resulting from hardening of the asphalt caused by exposure in air, degradation or disintegration of the aggregate caused by traffic or freeze-thaw effects, and the action of water and water vapor. This action of water and water vapor may cause moisture damage, including a reduction in mixture stiffness, stripping of the binder from the aggregate, and further hardening of the binder resulting from exposure of new binder film surfaces as water soluble oxidation products are removed.

Durability is desirable in mixtures to ensure that structural requirements are met throughout the life of the pavement, but the measurement and evaluation of this property is not as straightforward as the evaluation of the effects of load on mixture response. In assessing durability, a mixture is subjected to environmental conditioning, and a mixture property associated with load-related or environmental distress is measured before and after the conditioning process. These processes may include (*a*) a variety of moisture-conditioning procedures to accelerate the damaging effects of water or (*b*) oven aging to simulate short-term aging or short- and long-term aging during mixing, construction, and service.

To preclude damage due to the effects of air and water, a durable mixture has a high binder content, dense aggregate gradation, and low air void content. Greater binder contents promote durability by decreasing the permeability of the mixture to air and water and increasing the binder film thickness on aggregate particles, thus reducing the effects of hardening. Low permeability also results from mixtures with dense aggregate gradations and proper compaction to a minimum air void content that does not sacrifice stability. The damaging effects of moisture may also be mitigated through the use of hard asphalt or hydrated lime or liquid antistrip agents.

A sufficient amount of a hard binder is also required for a durable mixture to ensure adequate resistance to the abrasive forces of traffic. Abrasion characteristics of the aggregate in the mixture must also be considered in the assessment of durability. Future research will likely focus on the ongoing search for reliable laboratory test methods that assess mixture durability and correlate well with field performance.

EVALUATION OF MIXTURES TO MEET STRUCTURAL REQUIREMENTS

The development of reliable and practical approaches to evaluate a bituminous mixture's ability to meet structural requirements remains a major challenge. A variety of tools is needed to evaluate mixtures during hot-mix asphalt production, including simple yet effective tests for use in specifications and for mixture optimization during design; even simpler, process-oriented tests for quality control during production; and more sophisticated tests to determine fundamental properties to ensure that mixtures will meet a minimum standard of performance when used in a pavement system.

Myriad laboratory testing systems have been proposed to evaluate a mixture's resistance to cracking and rutting, but none has been generally accepted or even verified to work for the variety of aggregates, binders, mixture types, environments, and loading conditions encountered in the hot-mix asphalt industry. In addition, each testing system has advantages and disadvantages in applicability, cost, and level of complexity. There are several categories of mixture evaluation tests, including torture tests (or physical analogs), simple strength tests, tests to determine permanent deformation characteristics, and tests to determine fundamental properties. Examples of torture tests include those that use rolling wheel devices and the repeated simple shear test for rutting, fatigue tests for load-associated cracking, and TSRST for thermal cracking. Accelerated pavement testing facilities are full-scale torture tests that are gaining popularity. Simple strength tests include Marshall and Hveem stability, shear strength from the gyratory testing machine, confined or unconfined compressive strength, and indirect tensile strength. Torture tests and simple strength tests (except those of the gyratory testing machine) are limited: for a given specimen, tests can be performed at only one condition of load, temperature, and compaction level. Therefore, the proper selection of test conditions and representation of the stress states in the actual pavement are critical to their success.

The measurement of fundamental mixture properties offers the advantage of being able to represent a variety of loading and environmental conditions through numerical modeling. Rapid developments in instrumentation and computer capabilities continue to make this measurement a more viable approach for mixture evaluation. However, identification and verification of the most appropriate constitutive models for bituminous mixtures is a major challenge. Bituminous mixture behavior is highly complex: its response to stress can be elastic, viscous, plastic, or dilatant, and may also include microdamage and fracture. Furthermore, behavior is dependent on stress state, temperature, and boundary conditions to which the material is subjected, either in the laboratory or in the field. Changes in properties resulting from the effects of aging and moisture sensitivity further complicate mixture behavior and its evaluation.

One of the major challenges for developing proper methods for bituminous mixture evaluation is to sort out the effects of all these complexities and arrive at a more complete understanding of bituminous mixture behavior. This understanding can then be used to identify simple yet effective approaches to design, specify, and control mixtures with suitable structural characteristics.