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The SHRP Asphalt Research Program: 1990 Strategic Planning Document

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Contents

1

Introduction

The SHRP Asphalt Research Program passes its midpoint in 1990. This presents an appropriate occasion to evaluate its progress and examine restructuring which may be needed to achieve the program's goals within the time and money available.

This report documents the strategic plan for the remainder of the program which ends on March 31, 1993. In this respect it is reemphasized here that the entire program is focused on delivering two main products:

the Asphalt Binder Specification; and

the Asphalt Aggregate Mixture Specification including an Asphalt-Aggregate Mixture Analysis System (AAMAS).

Both specifications will also include the necessary supporting tests. Those activities which do not contribute to the development of these specifications must be curtailed (figure 1.1). Additionally, it may be periodically necessary to refocus the research efforts.

This report attempts to concisely describe the SHRP asphalt research program, with emphasis on defining its goals and explaining how the program has been structured to achieve these goals. Effort has also been made to illustrate the methods of data analysis which are and must be used, in particular the rather freeform, intuitive approach employed for interpretation and synthesis to achieve specific products when rigorous mathematical methods are ineffective.

The report is also intended to serve as a resource for the midterm 1990 assessment of the SHRP asphalt research program which will be conducted in August 1990. In that regard, it presents possible options for the restructuring of the program to most effectively and efficiently attain its goals and objectives within the time and money constraints established at its outset.

Finally, SHRP is a product-oriented R&D program; its goal is the development of performance-based specifications and associated test methods and devices. The establishment of concurrent implementation strategies for these products, integral with the research program itself, is explored in this working paper. This includes a very preliminary discussion of the economic issues, data and analysis methods needed to guide the implementation activities toward the most cost-effective ends.

In succeeding chapters the following topics are discussed in detail: Chapter 2 - evolution and organization of the program; Chapter 3 - research products; Chapter 4 -

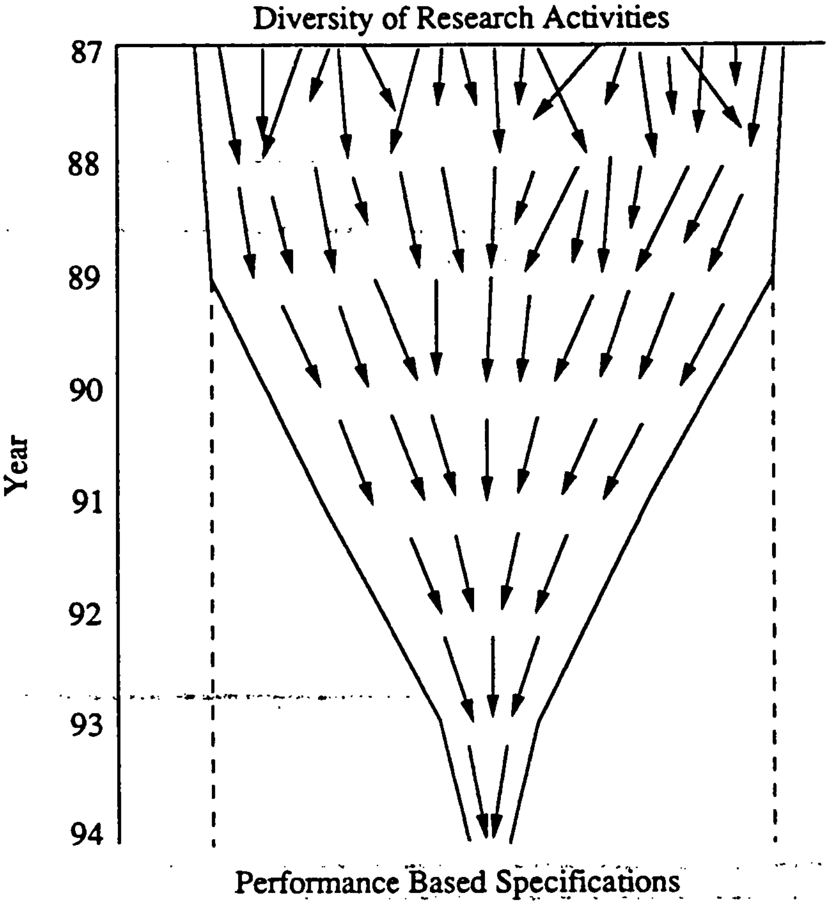


Figure 1.1 Focus of research activities.

experimental design and data analysis; Chapter 5 - performance based specifications for asphalt binder and asphalt-aggregate mixes; Chapter 6 - economic analysis to assess product viability; and Chapter 7 - product implementation.

2

Evolution, Organization and Strategy of the Research Program

This chapter is organized to present a brief review of the development of the SHRP Asphalt Research Program and a more detailed discussion of how the program is organized to achieve its principal products, performance-based specifications for asphalt binders and asphalt-aggregate mixtures.

Program History and Evolution

The emphasis and need for specification development in the SHRP Asphalt Program originated in TRB Special Report 202, *America's Highways: Accelerating the Search for Innovation*, the so-called "Blue Book," that presented the conclusions and recommendations of the Strategic Transportation Research Study (STRS). The objective of the asphalt research program was stated as follows:

> "To improve pavement performance through a research program that will provide increased understanding of the chemical and physical properties of asphalt cements and asphalt concretes. The research results would be used to develop *specifications, tests*, ... needed to achieve and control *the pavement performance desired*."

This emphasis was reinforced and further defined in the May 1986 TRB report titled *Strategic Highway Research Program Research Plans*, the so-called "Brown Book," in which it was stated (page TRA 1-11) that a specific constraint or guideline for the asphalt program was that "... the final product will be *performance-based specifications for asphalt*, with or without modification, and *the development of an asphalt-aggregate mixture analysis system* (AAMAS)."

Moreover, this report described (page TRA 1-14) Project 1-4 of the research program, titled "Preparation of Performance Based Specifications for Asphalt and Asphalt-Aggregate Systems" that would be composed of two tasks, one to develop the asphalt specification and one to develop the AAMAS.

Finally, the SHRP Executive Committee in 1987 approved *A Contracting Plan For SHRP Asphalt Research*. This contracting plan is the "gold standard" strategic plan for the SHRP asphalt program and takes precedence over the earlier research plans when issues of proper technical direction arise. The contracting plan combined the multiplicity of tasks identified in the 1986 research plan into a coordinated, manageable structure of six main contracts (since expanded to nine with the further division of the original contracts A-002 and A-003). The contracting plan assigned the responsibility to develop the performance-based asphalt binder specification to contract A-001 and the performance-based specification for AAMAS to contract A-006.

In the 3 years since the establishment of the contracting plan, the asphalt research program has been put into action by the award of nine major research contracts and 15 supporting studies. Yet the goals of the program remain substantially unchanged from those originally articulated in the "Blue Book," Special Report 202. Both specifications are still required to be performance-based; the ramification of this terminology is discussed in more detail in the following paragraphs.

Furthermore, the primacy of the development of the asphalt binder specification that was established in Special Report 202 over the study of the behavior of asphalt-aggregate mixtures and the development of a mixture specification is unchanged. To quote the 1987 contracting plan on this point:

> "In the asphalt area, the original report, America's Highways: Accelerating the Search for Innovation, clearly put the dominant focus on asphalt binders. Subsequent discussions by the AASHTO Task Force, the AASHTO Select Committee on Research, and the National Research Council's SHRP Executive Committee have reinforced this initial vision, placing the primary emphasis on research to improve asphalt binders."

While the goal of the SHRP asphalt program is the successful delivery of both specifications, this primacy of emphasis on the asphalt binder specification must be clearly recognized when issues of technical direction and allocation of resources are decided. Thus, the focus of technical efforts and resources must be to ensure the delivery of the asphalt binder specification, even at the expense of successfully completing work on the asphalt-aggregate mixture specification and its mix analysis system.

Two subtle but important changes to the research and contracting plans have evolved in the interim through an ongoing dialogue among those in the highway community who have taken part in the development, conduct, management and oversight of the program.

1. The term "asphalt" has been broadened to "asphalt binder" in order to recognize the fact that the specification will encompass modified binders as well as unmodified asphalt cements.
2. The concept of a specification for an asphalt-aggregate mixture analysis system (AAMAS) has changed to one for asphalt-aggregate mixtures which includes a mixture analysis system, mixing and compaction procedures and accelerated test methods.

In both cases, the material or mixture properties needed to obtain satisfactory pavement performance with respect to permanent deformation, fatigue cracking, low temperature cracking, adhesion, moisture sensitivity and aging will be specified.

In this scheme, the mixture analysis system itself does not represent a specification *per se*, rather it supports the mixture specification as a protocol for use in designing mixtures that will achieve the required performance levels. This change also reflects the fact that much fundamental work on development of a mixture analysis system has already been accomplished through NCHRP Project 9-6(1). It is envisioned that the SHRP mixture specification development will incorporate and evolve from the NCHRP AAMAS results to yield a robust, well-validated mix analysis system (MAS).

At this midpoint of the asphalt program, there is a renewed need to examine program objectives and anticipated products and to decide whether additional changes are warranted to more closely tailor the research tasks to the attainment of performance-based specifications. Specific recommendations are needed with respect to the following:

> 1) curtailment of current tasks and work elements that no longer appear to adequately support the program objectives, and
>
> 2) addition or restructuring of tasks or work elements to exploit technical breakthroughs and assure delivery of the primary products.

These recommendations for the second half of the asphalt program will be a key goal of the SHRP Summer Workshop, to be held in Denver, Colorado in August 1990.

Program Organization

To accomplish the development of the performance-based specification products, the SHRP asphalt research program is organized into seven main asphalt research contracts. These contracts were formed in the April 1987 *Contracting Plan For SHRP Asphalt Research* from the tasks presented in the Strategic Highway Research Program Research Plans, Final Report (NCHRP, 1986). The resulting contracts are:

- A-001 -- "Improved Asphaltic Materials, Experiment Design, Coordination and Control of Experimental Materials,"
- A-002A -- "Binder Characterization and Evaluation,"
- A-003A -- "Performance Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures,"
- A-003B -- "Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption,"
- A-004 -- "Asphalt Modification,"

- A-005 -- "Performance Models and Validation of Test Results,"
- A-006 -- "Performance-Based Specifications for Asphalt-Aggregate Mixtures."

These seven contracts are critically placed in the asphalt program to provide necessary fundamental findings and applied research support for the evolution of the performance-based specifications and related products.

Two other major contracts, viz. A-002B, "Novel Approaches for Investigating Asphalt Binders," and A-002C, "Nuclear Magnetic Resonance (NMR) Investigation of Asphalt," support main contract A-002A. In addition, 15 relatively small A-IIR (Asphalt Independent, Innovative Research) contracts were let to support contracts A-002A, A-003A and A-003B.

All SHRP contracts must be viewed as components of the overall asphalt research program rather than as self-contained or stand-alone studies since their success will be measured solely by how well they contribute the specific, well-defined results needed for the development of the performance-based specifications.

The important hypotheses and models employed in each of the main contracts to organize the research are discussed in detailed form in the companion report (Kennedy et al., 1990) to this one.

Present Program Strategy

The overall strategy of the program, the mission of the individual contracts and the integration of the individual contract efforts and results in the asphalt program are discussed below.

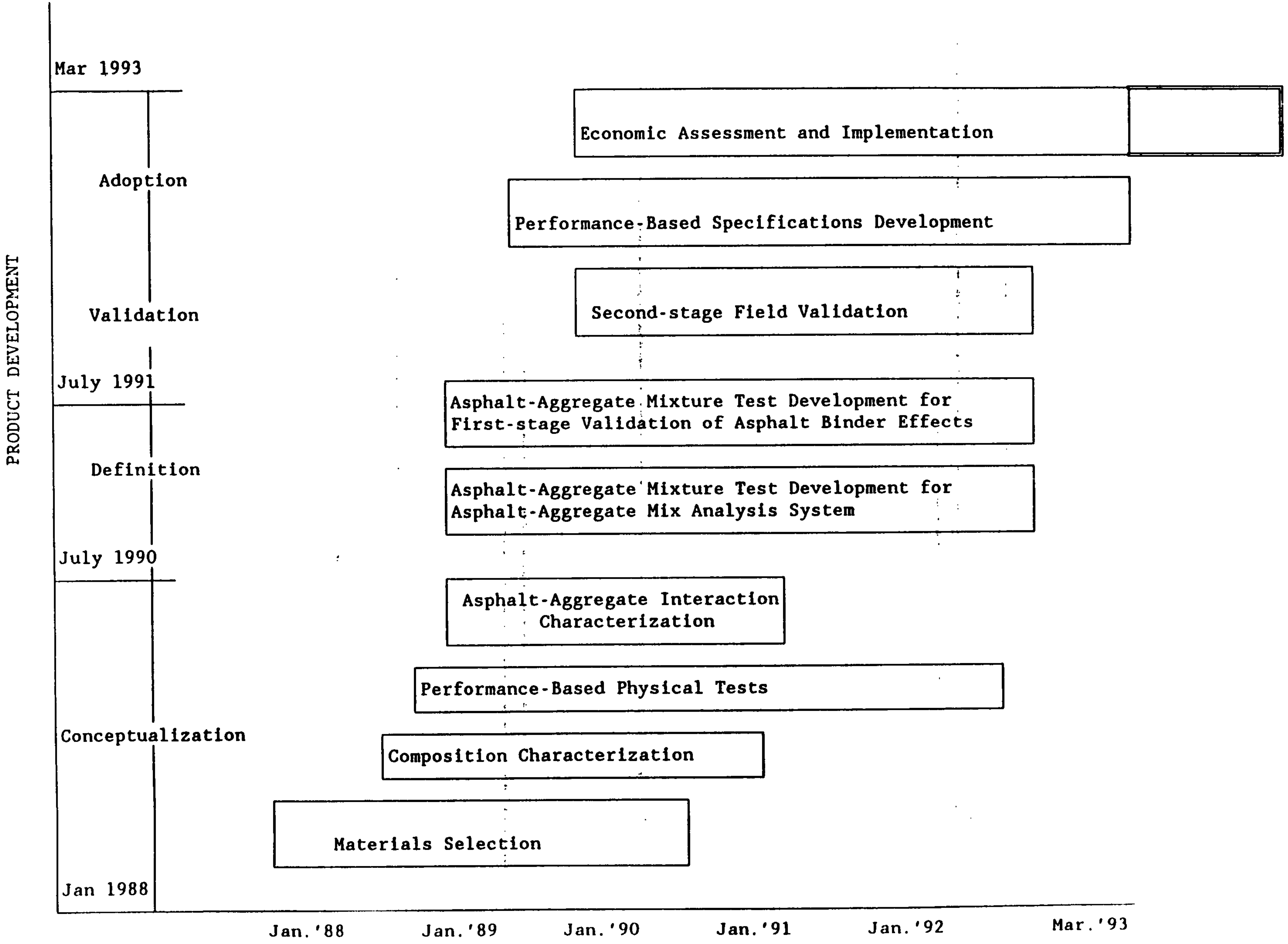
Overall Strategy

Figure 2.1 presents the strategy employed within the SHRP Asphalt Program to achieve its key products, performance-based specifications for asphalt binders and asphalt-aggregate mixtures, in terms of a graphical time-line. The strategy is planned to provide the necessary fundamental research findings and applied research support needed for the development and implementation of the specifications within the limited time period allowed for completion of SHRP.

In the first phase of the program (**Conceptualization**), candidate physicochemical properties of asphalt binders and mechanical and structural properties of asphalt-aggregate mixtures that affect pavement performance will be identified and defined.

In the second phase (**Definition**), the effect of important asphalt binder properties will be validated in asphalt-aggregate mixtures primarily through the use of highly simulative laboratory test methods and, to a lesser degree, full-scale, accelerated

Figure 2.1. Strategy to Achieve Key Products



pavement testing (the first-stage validation process described in chapter 4). Concurrently, accelerated, standardizable test methods suitable for support of the binder and mixture specifications and for inclusion in the asphalt-aggregate mixture analysis system will be developed.

In the third phase (**Validation**), field performance data will be employed to complete the validation of those binder and mixture properties judged to have an important effect on pavement performance (the second-stage validation described in chapter 4).

In the fourth and final phase (**Adoption**), the binder and mixture specifications will be formed with those properties which the validation process has demonstrated have a major, significant effect on pavement performance, and their implementation will be begun.

A third-stage validation process will occur after the completion of the SHRP asphalt research program through the use of a Specific Pavement Study (SPS-9) in the SHRP Long Term Pavement Performance (LTPP) program which will be constructed beginning in 1992 to validate specific asphalt research program results.

Contract Missions

Each main contract has a definite mission established by the 1987 Contracting Plan in support of the overall program strategy. The specific missions are as follows:

> Contract A-002A: Identify the chemical and physical properties of asphalt binder believed to influence the performance of asphalt-aggregate pavement systems. Refine into test methods those chemical and physical characterization processes that appear to offer the most practical basis for specification testing in terms of: correlation between binder properties, mixture performance and pavement performance established by contracts A-003A and A-005; reliability; cost; ease of use; and other features of the tests themselves.
>
> Contract A-003A: Validate in asphalt-aggregate mixtures the candidate relationships identified in contract A-002A (and to a lesser extent, A-003B and A-004) between the physical and chemical properties of asphalt binder and asphalt pavement performance (first-stage validation). Develop standardizable, accelerated test methods for asphalt-aggregate mixtures that may be employed in a mixture analysis system to support a performance-based specification for mixtures.
>
> Contract A-003B: Develop a fundamental understanding of the chemistry of the asphalt-aggregate bond and how it affects adhesion and water sensitivity. Develop a fundamental understanding of the mechanical and chemical basis of asphalt absorption into highly porous aggregates. Prepare reliable, practical test methods that measure asphalt-aggregate adhesion, water sensitivity and absorption and estimate their effects on pavement performance.

Contract A-004: Adapt as necessary performance-related test methods for binders and mixtures to permit their use with the full range of modified systems. Explore innovative refinery processes to enhance the performance of modified asphalt binders. Develop a modifier evaluation protocol to permit evaluation and selection of modified binder systems that remedy specific pavement performance gaps.

Contract A-005: Validate relationships between asphalt binder and asphalt-aggregate mixture properties and pavement performance (second-stage validation). Establish, on the basis of documented field performance data, criteria, limits and requirements that may be used for asphalt binder and asphalt-aggregate mixture specifications. Develop performance prediction models incorporating the properties of asphalt binders and asphalt-aggregate mixtures.

Contracts A-001 and A-006: Prepare model, performance-based specifications for asphalt binders and asphalt-aggregate mixtures, respectively, using the validated results of contracts A-002A, A-003A, A-003B, A-004 and A-005.

Integration of Each Contract Component In the General Strategy

Figures 2.2 and 2.3 present the general strategy discussed previously from an alternative perspective. The contribution of each contract component of the SHRP Asphalt Program to the development of the key products, performance-based specifications for asphalt binder and asphalt-aggregate mixtures, is defined.

A Performance-Based Specification for Asphalt Binders

The development of the binder specification (figure 2.2) is founded upon the identification and quantification in contracts A-002A and A-003B of candidate compositional (or chemical) properties that significantly affect pavement performance. Additionally, the effect of these compositional properties on the physical behavior of the asphalt binder is measured, and both chemical and physical test methods for the asphalt binder that can support a performance-based specification are developed. Contract A-004 evaluates whether these test methods can be utilized with modified binder systems; if not, changes to the test methods or, less preferably, new test methods are provided to accommodate the presence of the modifiers.

In contract A-003A, highly simulative laboratory tests are employed to validate the effect of the candidate binder properties on the performance of asphalt-aggregate mixtures (refer to the fuller discussion of first-stage validation in chapter 4).

Binder properties which are shown to have a significant influence on mixture performance are correlated in contract A-005 with various types of field data to directly validate their influence on pavement performance; limits and/or ranges of the properties are determined (see the discussion of second-stage validation in chapter 4).

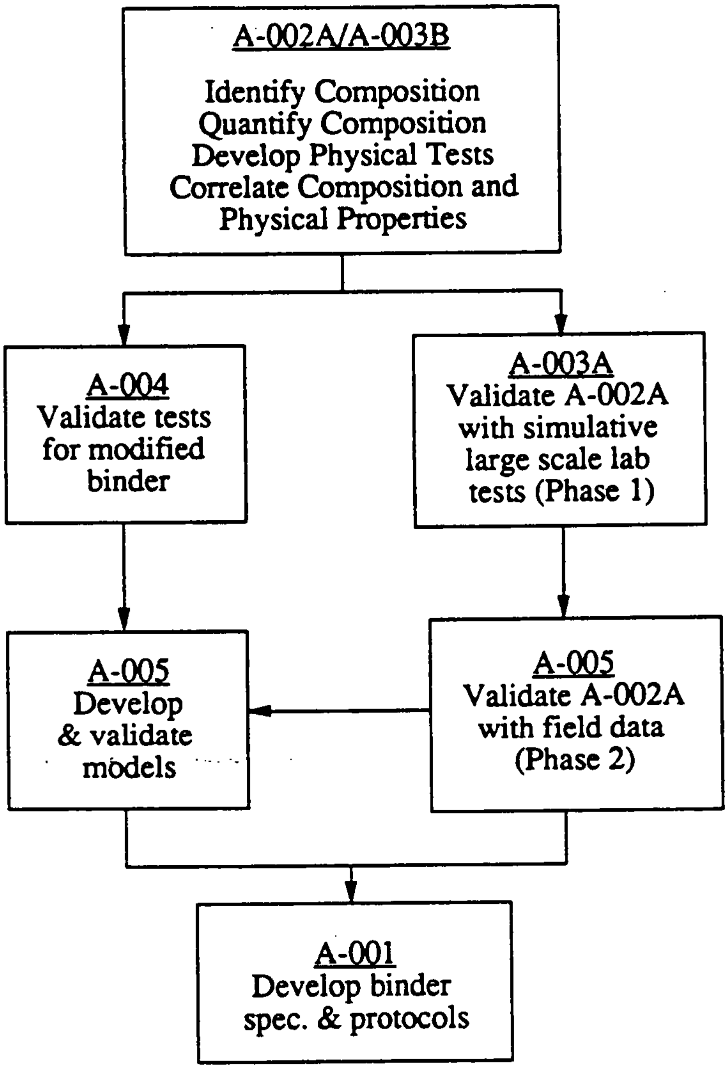


Figure 2.2 Strategy to achieve performance-based asphalt binder specification.

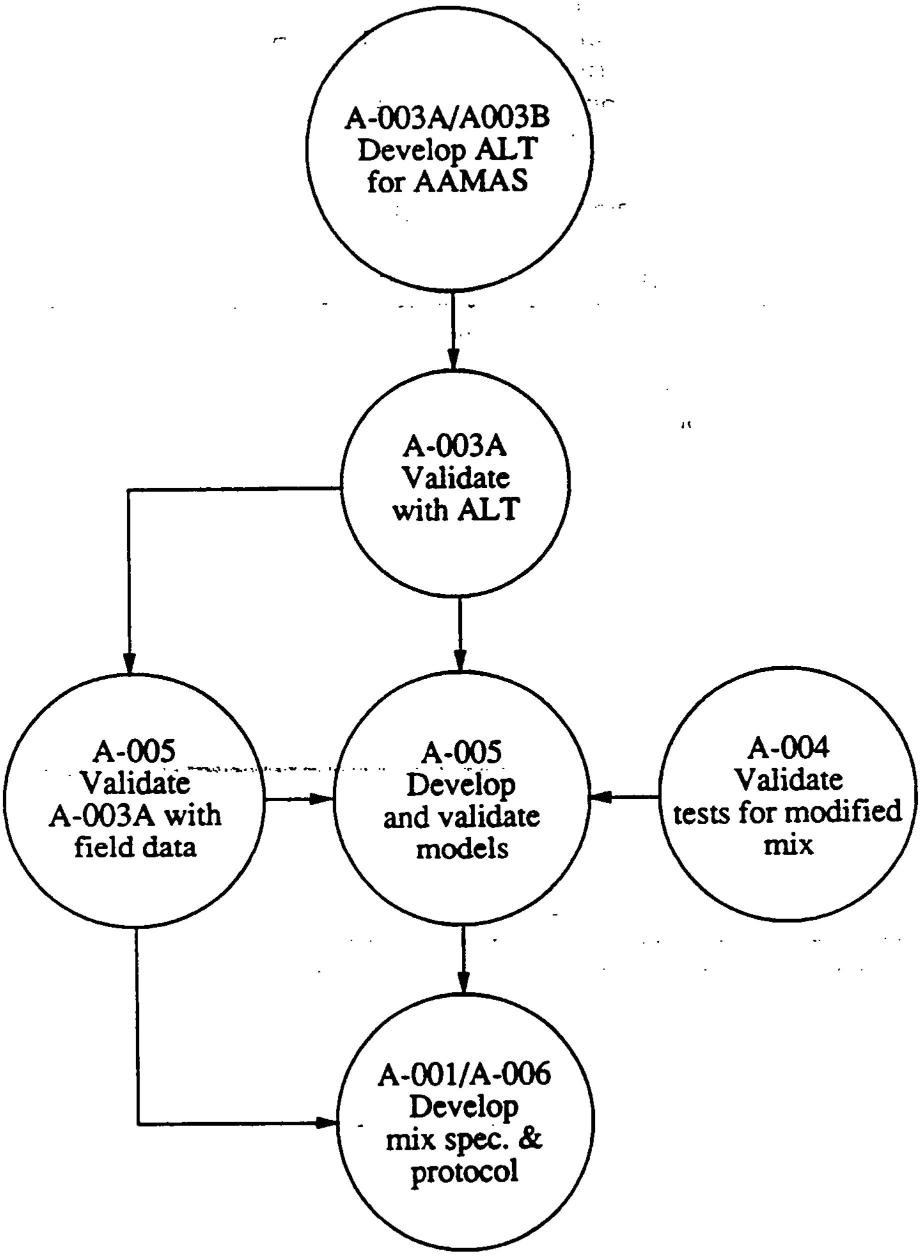


Figure 2.3 Strategy to achieve performance-based asphalt-aggregate mixture specification.

Finally, the validated binder properties and their limits or ranges are incorporated in contract A-001 into a performance-based asphalt binder specification supported by the necessary test methods and conditioning protocols.

Performance-Based Specification for Asphalt-Aggregate Mixtures

Figure 2.3 is a flow chart for the development of the mixture specification. While this work is in many respects highly interrelated with the work on the binder specification, it is presented separately to emphasize that the program 1) is aimed at the binder specification first, the mixture specification a close, but distinct, second, and 2) is structured to assure the timely, successful development of the binder specification even if other key products, including the mixture specification, must be sacrificed to accomplish it. **It should be noted that the trade off is not the binder specification versus the mixture specification because the program is organized and committed to delivering both specifications. If the program, however, is designed to deliver both specifications by focusing on the mixture specification, the trade off becomes both versus none; this is unacceptable.**

Asphalt-aggregate mixture properties that strongly influence pavement performance are identified and quantified in contract A-003A and correlated in contract A-005 with various types of field data to validate their influence on pavement performance; limits and/or ranges of the properties are determined.

Accelerated laboratory tests (ALT) that measure the mixture properties in performance-related, fundamental engineering units that may be directly employed in mathematical models for predicting pavement performance are being developed in contracts A-003A and A-003B. Results from the ALTs are correlated in contract A-003A with those from the simulative laboratory methods employed in the first-stage validation process discussed in the previous section to validate their ultimate use in the mixture specification and its supporting mixture analysis system.

The applicability of the ALTs to modified systems is evaluated in contract A-004; changes to the test methods or, less preferably, new test methods are provided to accommodate the presence of the modifiers if the need is identified. A modifier evaluation protocol is being developed to determine if a modifier system is needed to enhance specific mixture properties to meet stringent performance requirements.

Contract A-005 also develops and validates mathematical models that predict pavement performance on the basis of material (binder and mixture) properties, traffic loads, structural factors and environmental conditions. These models may be useful for indirectly validating relationships between mixture properties and pavement performance; they are more generally employed to estimate how the durability and serviceability of pavements are affected by variations in material properties, construction parameters, traffic loads, etc.

Finally, the validated binder properties and their limits or ranges are incorporated in contracts A-001 and A-006 into a performance-based asphalt-aggregate mixture specification supported by the necessary standardizable, accelerated test methods, conditioning protocols, mixture analysis system and modifier evaluation protocol.

3

Products of the Research Program

Introduction

An important and distinctive feature of the Strategic Highway Research Program is its organization to yield hard, specific products in a form amenable to immediate implementation. While the sheer volume of research under way in SHRP will also yield dividends in terms of information, data and reports eminently useful to the highway research community in the future, acquisition of these "soft" products is of minor importance to the program except insofar as they facilitate product development.

This commitment to product development is especially prominent in the SHRP Asphalt Research Program where the program will not be judged successful unless it provides the highway community with the two previously mentioned specific products, viz. performance-based specifications for asphalt binders and for asphalt-aggregate mixtures, in a form ready for immediate implementation. It is also mandatory that a significant and meaningful portion of this implementation be accomplished before the program ends in 1993.

The Principal Products: Performance-Based Specifications

A performance-based specification may be defined as the limits and requirements developed from an extensive database related to pavement performance factors that can be defined quantitatively. These factors must be quantified by standard and, in some cases, accelerated performance-based tests by means of well-established performance prediction models which have been validated by correlation with in-place field performance data.

Distinguishing Features of the Specifications

The distinguishing feature of such specifications is that they allow the rational selection of materials to achieve performance levels required by the present and projected traffic loading and environmental exposure of the pavement. Present specifications for asphalt cement, e.g. AASHTO M 20, Penetration Graded Asphalt Cement and M 226, Viscosity Graded Asphalt Cement, do not meet this requirement. Specifications for asphalt-aggregate mixtures do not exist *per se*; rather, mixture specifications tend to reflect limits derived from local experience related to what has provided adequate pavement performance in the past. Additionally, almost all specifications for modified binders and mixtures are specialized to fit the particular modifiers under consideration and yield little objective information about their performance.

Performance-based specifications, however, should not necessarily be considered more restrictive than current specifications. On the contrary, by specifying performance levels rather than arbitrary material properties or test responses, performance-based specifications may actually allow the engineer more latitude in the selection and combination of materials than at present.

The SHRP asphalt program is designed to develop specifications that address six pavement performance factors: viz., permanent deformation (rutting); fatigue cracking; low-temperature (thermal) cracking; moisture sensitivity; aging; and adhesion. Conceptually, it is envisioned that an engineer will be able to define the requirements of a new or rehabilitated asphalt pavement in terms of attaining satisfactory levels of serviceability in each of these areas for present and projected traffic loads and environmental conditions.

For example, for an urban freeway in a desert or semi-arid climate, the main concern might be control of permanent deformation due to the combination of high temperatures and heavy traffic, and to a lesser extent, fatigue cracking due to the heavy repeated loads. Aging of the asphalt binder due to the combination of high temperature and the prevalent sunlight would also need to be considered since the hardening would tend to increase fatigue and thermal cracking, but minimize permanent deformation.

On the other hand, in designing a pavement on a rural primary route in the upper Midwest, the primary concern might be the control of low-temperature cracking, as a result of the prevailing climatic conditions, and to a lesser degree, long term permanent deformation and fatigue cracking as traffic volume increases. Additionally, in this example, moisture sensitivity would be the principal conditioning factor that must be taken into account.

In either of these situations, present specifications for asphalt binders and asphalt-aggregate mixtures are of little help in controlling, preventing or predicting distress. Selection of a specific viscosity or penetration grade of asphalt cement allows only a limited response to the requirements of controlling permanent deformation or low-temperature cracking. Often, the control of one of these distress types leads to a heightened susceptibility to the other. Moreover, no present asphalt binder specification addresses long-term aging, moisture sensitivity, fatigue cracking or, most fundamentally, adhesion.

At present, asphalt-aggregate mixture properties are not specified in the usual sense of that term. The sole purpose of the Marshall and Hveem *mix design methods* is to determine acceptable asphalt contents for paving mixes. Mixture properties such as stability, flow and void content obtained from these methods have only an intuitive link with pavement performance. It is not possible, for example, to specify a minimum Marshall stability that will eliminate the possibility of rutting on a high volume, urban freeway in a hot, dry climate.

Nor is it possible to specify an acceptable Hveem stability that will prevent rutting on a rural primary highway on the basis of projected traffic volume 10 years in the future. State highway agencies often employ standard mixes with well-defined asphalt contents and aggregate gradations for specific applications such as base and surface courses, but there is generally no known, rational relationship between the properties of these mixtures and their expected performance.

This lack of credible performance-based specifications for asphalt binders and asphalt-aggregate mixtures hinders the highway engineer in another important way. Consider that design guidelines very often employ pavement structural thickness as a means of controlling material response to load and environmentally induced stresses. The union of true performance-based specifications for asphalt binders and asphalt-aggregate mixtures with pavement design guidelines, especially the improved ones to be developed from the SHRP Long Term Pavement Performance (LTPP) program, will allow the investment in materials for pavement construction or rehabilitation to be minimized without sacrificing needed performance. This may be done by judiciously balancing binder and mixture performance with pavement thickness to achieve optimum, robust performance at the least cost. This topic is discussed in much greater detail in chapter 6.

The first step is to select an asphalt binder whose properties, insofar as possible, ensure the required minimum performance level. The SHRP asphalt program is founded on the premise that asphalt pavement performance is significantly influenced by the properties of the asphalt binder. Therefore, to design a pavement to provide the performance dictated by its present and future "environment," first consideration must be given to selecting an asphalt binder whose properties, insofar as possible, ensure the required minimum performance levels.

Once the influence of the asphalt binder on performance is defined, the effect of its combination with aggregate must be considered. In certain cases, the locally-available aggregates may detract from the performance-based response of the binder, necessitating a change in aggregate or asphalt binder. There is also the possibility, however, that certain aggregates may actually enhance binder performance, allowing the engineer wider latitude in materials selection or pavement thickness.

In any case, the mixture specification should be viewed as modulating the binder response in each performance area. The availability of both specifications allows a range of material selection options to be considered for any particular paving project. In the authors' judgement, neither specification will be as useful alone as when used in unison with the other specification and ultimately with structural design procedures.

In the most basic terms, a specification is simply a table of property limits that, taken together, define the required behavior of a material or combination of materials under prospective conditions of use. However, all specifications, and in particular the performance-based specifications under development in the SHRP asphalt program, also must provide standard test methods and protocols for their use that measure the specified performance factors. In this respect, the performance-based specifications for asphalt binders and asphalt-aggregate mixtures differ significantly.

Supporting Performance-Related Tests

The performance-based specification for asphalt binders is conceived to incorporate a suite of tests that principally measure physical and chemical properties of the binders, which will have been validated as directly influencing the six pavement performance factors. Insofar as possible, only fundamental properties of the asphalt binder will be selected, i.e. those properties which affect performance and whose effect may be explained and estimated from a theoretical treatment of the underlying physical and chemical behavior of the material at the molecular or microscopic levels. Test methods which measure asphalt binder behavior purely on the basis of correlation with mixture and pavement performance will be used only when fundamental measures prove inadequate.

For example, the ductility of a briquette of asphalt cement, as measured by the test machine specified in AASHTO standard method T 51, provides an experiential estimate of asphalt performance for which no sound theoretical basis exists. Viscosity, by comparison, is a fundamental measurement that has been empirically related to pavement performance factors. The influence of viscosity on pavement performance is also susceptible to analysis by the use of thermodynamics and consideration of the detailed molecular structure of the constituent asphalt molecules and their atomic, molecular and colloidal-scale interactions although such a theoretical treatment has not yet been completely accomplished, mainly due to a lack of pertinent chemical data.

Similarly, the performance-based specification for asphalt-aggregate mixtures will be based upon fundamental engineering properties of the mixture from which reasonable estimates of pavement performance can be computed. The laboratory test methods that are employed must measure the true stress-strain relationships or other performance-related properties on an accelerated basis so that the degree of permanent deformation, fatigue cracking and low-temperature cracking in actual pavements may be realistically gauged and compared to estimates derived from a theoretical analyses of these related factors.

An example of a fundamental engineering property is tensile strength. One explanation of low-temperature cracking suggests that as the pavement temperature drops, thermal stress increases until it is equal to the tensile strength of the pavement. At that temperature, a microcrack develops which subsequently propagates throughout the pavement layers.

An accelerated test method that permits the development of this thermal stress to be simulated with an asphalt-aggregate mixture in a realistic specimen configuration would be suitable for a performance-based specification. It would furnish a measurement of the temperature at which the thermal stress exceeds the tensile strength and yield a fundamental engineering property of the mixture that may be compared to values theoretically derived from an analysis of the pavement distress mechanism.

By comparison, the characteristic stability value for an asphalt-aggregate mixture obtained from the Marshall mix design method, although commonly employed as an estimate of the stability or rutting resistance of an asphalt pavement mixture, is not a fundamental engineering property and in reality is not a measure of the rutting resistance of the mixture. The test method employed for its measurement induces a complex stress pattern in the laboratory Marshall specimen that is uncharacteristic of the stresses actually experienced in a pavement. Moreover, no theoretical analysis has proven capable of directly relating Marshall stability values to expected pavement performance. Indeed, Foster (1984) has pointed out that the limiting stability values "specified" in the Marshall design method (Asphalt Institute, 1988) for different categories of pavements and traffic volumes were empirically determined more than 40 years ago by a comparison of laboratory data with the observed degree of distress experienced by a small number of test pavements.

It is important to point out here that while supporting test methods that yield measurements in fundamental scientific and engineering units should be favored for performance-based specification, the test methods employed in the validation of the effect of asphalt binder properties on asphalt-aggregate mixture performance need not meet this requirement. Indeed, it may be strongly argued that this validation process principally requires test methods that are highly simulative of field conditions. A good example is the use of a wheel tracking test to validate the predicted effect of asphalt binder properties on the rutting behavior of asphalt-aggregate mixtures.

Conditioning Protocols

In addition to the test methods, the performance-based specification must include or, more specifically, be supported by, methods or protocols for the conditioning of specimens to simulate environmental effects. These protocols must be developed through examination of the fundamental effects involved, and must address the molecular mechanisms involved in the interaction of asphalt with oxygen and moisture, and its interaction with aggregate in the form of adhesion and absorption.

The performance-based specification for asphalt-aggregate mixtures will require methods or protocols for 1) mixing and compaction of laboratory mixture specimens that realistically simulate the effects of field operations; 2) the combination of materials to obtain a job mix formula that provides the required performance levels; and 3) the evaluation and selection of modifiers or modification techniques when it is determined that unmodified mixtures cannot meet the performance demands present in project. These represent a <u>mix analysis system</u> (MAS) that, together with the performance-based specifications itself and the accelerated test methods, allow an informed selection and combination of materials to achieve the performance levels required of the pavement.

Summary

The important features of the two specifications that will be the primary products of the SHRP asphalt program are as follows:

1) *they are performance-based* - their use allows the present and future performance of the pavement to be closely estimated;

2) *they are readily implementable* - the development of supporting test methods and conditioning schemes considers, as much as is possible, the need for simplicity, reasonable time required for testing, good precision and accuracy, and affordable equipment cost;

3) *they employ fundamental properties* - wherever possible, the effects of materials on performance are susceptible to theoretical analysis using underlying chemical, physical and engineering principles; and

4) *they allow an informed pavement design selection* - used in concert with improved pavement design guidelines, the pavement layer design options that will yield the necessary performance at the least cost may be identified.

Since the implementation of these specifications will require their adoption by the state highway agencies and standard-setting organizations such as AASHTO and ASTM, the final report for the SHRP asphalt program will include the following:

1) the specifications;
2) the supporting test methods, mix analysis system and modifier evaluation protocol;
3) all necessary precision and bias data; and
4) the field pavement data and analysis that validate the limits and requirements included in the specifications.

The Other Products: Methods, Models and Materials

As a product-oriented research program, the SHRP asphalt program is required to yield many "hard" products that will benefit the state highway agencies by improving efficiency, reducing costs and enhancing the effectiveness of their operations. More than 40 potential products of this type have already been identified, exclusive of the two performance-based specifications, under development in the program.

While the major monetary savings realized from the SHRP asphalt program will come from the deployment on the performance-based specifications above, many new, secondary products of the types described here will also result in significant savings, directly or through improved efficiency of operation.

These secondary products may be categorized as follows:

- Standard Test Methods;
- Performance Models;

- Quantifiable Material Characterization;
- Models Relating Asphalt Chemistry, Physical Properties and Performance;
- New Test Devices; and
- New Materials.

Some of the test methods and devices will be available for cooperative testing early in 1990.

Standard Test Methods

As discussed in the last section, each specification will require a specialized standard test method and/or conditioning scheme to address each of the six performance factors. Additionally, the asphalt program will provide a wide complement of ancillary test methods intended for both routine laboratory use and complex research applications. Several illustrative examples may be given in each category.

An improved, routine asphalt extraction and recovery procedure will be developed that minimizes the effects of solvent on recovered asphalt binder properties as well as the environmental and safety hazards associated with the use of organic solvents inherent in existing procedures. An accurate, rapid method to measure asphalt absorption in porous aggregates will fill a need now addressed mainly by non-standard, rudimentary procedures employed by several states.

Asphalt core tomography provides an example of a research technique evolving from the program. Computerized axial tomography (CAT scan) is being applied to asphalt concrete specimens with the goal of examining changes in internal structure, such as the size and distribution of air voids and the orientation of aggregate particles, caused by application of static and dynamic loads. Several improved methods for separation and analysis of asphalt binder components are also being developed.

Performance Models

Performance models permit the effect of asphalt binder and asphalt-aggregate mixture properties on the pavement performance and serviceability to be predicted. They employ a variety of computational methods as well as mechanistic and/or empirical linkages between properties and performance. These models must account in a comprehensive and realistic manner for the effects of material properties, as well as for external factors such as environmental, construction-related and traffic loading effects.

The principal purpose for performance model development in the SHRP asphalt research program is to assist in the validation of performance-related asphalt binder properties by correlation with actual field pavement data. However, emphasis will be placed upon producing models in the form of "user-friendly" software packages for personal computers so that state highway agencies can easily evaluate combinations of mixture and pavement design options with respect to pavement serviceability and performance.

Moreover, this software, used together with the performance-based specifications, will allow the effect of variations in the job mix formula caused by plant operations, changes in materials, laydown operations, etc. on pavement serviceability to be estimated.

Quantifiable Materials Characterization for Use in Pavement Design

As discussed above, SHRP presents a unique opportunity to incorporate quantifiable mixture design factors in the selection of an overall pavement design strategy through the provision of performance-based specifications for asphalt binders and asphalt-aggregate mixtures.

Ideally, a pavement design, i.e. the choice of a cost-effective, efficient combination of structural layers, should be grounded in an intimate knowledge of the performance characteristics of the materials employed. Rather than employ structural numbers derived empirically from evaluation of a limited number of field pavements without any consideration of the actual materials employed, pavement performance goals can be defined and an iterative process utilized to reach a balance of mix design and structural design considerations that will achieve these goals.

This approach allows the engineer to weigh the practical effects of different alternatives that may arise. For example,

> *Is the higher initial cost of employing select materials offset by savings in maintenance and rehabilitation costs over the life cycle of the pavement? or, for the materials employed in the construction project, is the incremental first cost represented by a thicker pavement layer justified by the predicted savings accrued from better long term performance?*

The answers to these questions require an integrated design system where quantitative performance characteristics may be allocated between the pavement structure and the pavement materials to achieve the best solution within the available funding and design constraints. The SHRP asphalt program will provide the materials characterization necessary to link with structural characterization developed by the SHRP LTPP program.

Models That Describe the Effect of Asphalt Chemistry on Physical Properties and Performance

Central to the effort to develop a performance-based specification for asphalt binders is the concept or hypothesis that the chemical and physical properties of the asphalt binder determine, to an important degree, the level of performance achieved by the asphalt pavement.

Physical properties, in particular rheological properties, present the best opportunity for development of binder specification requirements because they are directly susceptible to expression in terms of the expected engineering behavior of the asphalt-aggregate mixture and the pavement itself. However, asphalt physical properties are themselves direct consequences of the chemical composition of the asphalt and especially of the interactions that occur between its constituent molecules.

Formulation and verification of a model of the structure of asphalt that reconciles the extensive volume of chemical and physical data coming out of the SHRP asphalt program are not merely an interesting intellectual exercise. Rather, a model that describes in a comprehensive, coherent manner how the elemental, molecular and microscopic makeup of the asphalt determines its physical properties, and ultimately its performance in a pavement, is an essential tool for binder specification development, and for the ongoing evaluation of the potential effects of changes in crude oil sources, refining processes and modification techniques.

Historically, asphalt has been modelled as a stable colloid with micelles dispersed in an oily medium (Petersen, 1984). Asphaltenes, that portion of the asphalt virtually insoluble in all hydrocarbon solvents, have long been associated with the dispersed or micelle phase. The ability of the oily phase to maintain the dispersion of the highly associated asphaltene components has been taken as a determinant of the rheological characteristics of the asphalt binder.

In order to verify this model, the size of the micelles; the molecular basis and strength of the associative and dispersing forces operating to maintain the stability of the colloid; the change in chemical composition of the two phases with variations in crude oil sources and refining processes; and effect of time and environment on the colloid are important questions among many that will have to be answered through an ongoing analysis and reconciliation of the experimental results.

Whether in fact this model is actually the most reasonable or most compatible with the experimental results is still open to question, and certainly other models will be proposed. What is certain is that a unified model for asphalt chemistry and structure and their effects on physical properties and performance that will guide specification development must evolve from the SHRP asphalt program.

Another essential model is that of the chemistry of the asphalt-aggregate bond. This model will seek to explain how the chemical composition of the bulk asphalt binder is perturbed by interaction with the aggregate surface in bond formation and how the strength and integrity of the bond is affected by the action of oxygen and moisture. A rational, consistent model of this type will allow prescreening of asphalt-aggregate pairs to identify potential problems as well as permit the informed development of strategies and materials to reduce moisture sensitivity and stripping.

New Test Devices

New test methods will require in many instances new test devices. These devices will be configured to measure fundamental physical and chemical properties of the asphalt binder and fundamental engineering properties of asphalt-aggregate mixtures.

As a general rule, when several competing designs are available for a particular test device, the design offering the most attractive combination of cost, simplicity and ease of use will be selected, even if some small sacrifice in the achievement of measurements in fundamental engineering units is entailed. When the new devices are unavoidably more complex and sophisticated than analogous instruments in present use, modular, computer-based control and analysis systems will be employed to facilitate their use in routine laboratory operations.

In cases where chemical measurements are required to support aspects of the asphalt binder specification, the test devices will be designed so that measurements may be made by personnel without extensive proficiency in chemical laboratory and instrumental techniques. One useful model in this regard is the medical diagnostic testing field where the use of computer-based instruments and prepackaged, premeasured chemical reagents allows technician-level personnel to perform complex test procedures in a rapid, routine manner.

New Materials

At present, the authors feel that the new materials coming from the SHRP asphalt research program will be limited to modifiers that enhance specific performance characteristics of asphalt binders and, to a lesser extent, aggregates.

The concept for the asphalt binder specification, discussed in more detail in Chapter 5, foresees several multi-grade performance levels in which petroleum produced by the same or slightly modified current processes satisfies all but the most stringent set of requirements. At that level, major modifications or the use of modifiers would be required, but the base stock would still essentially be conventional petroleum asphalt.

It is anticipated that some variation in the operating parameters (e.g. temperature and pressure) of the refining processes employed currently to produce paving asphalts may be required to meet the criteria in a new performance-based specification; however, it is unlikely that major changes or limitations on refinery operations would be necessary or desirable.

The crude oil sources employed for asphalt production are significantly more important than the refining processes used in the United States and Canada for asphalt production in determining the ultimate performance of the asphalt cements. It is possible that the use of certain crude oils now available may be incompatible with the requirements of a performance-based specification. Such a change in the refiners' latitude to choose crude oils would, of course, would probably spur an increase in the cost of the asphalt binder.

A main thrust of new materials development in the SHRP asphalt program is in the area of chemical modification of asphalt in the refinery. This is considered high-risk, a speculative venture where, however, the potential payoff may be substantial if the work succeeds.

Asphalt modification through chemical reaction explores the possibility of enhancing the performance characteristics of the asphalt through the action of reagents such as nitric acid, bromine, chlorine, phenol, etc. in refinery-scale operations. This line of investigation is founded on a consideration of the effects of well-known, organic addition, substitution and elimination reactions using asphalt as the substrate.

Aggregate modification will also be explored. Emphasis is being placed upon aggregate coatings which control absorption, enhance asphalt adhesion and reduce the moisture sensitivity of asphalt-aggregate mixtures.

4

Validation and the Treatment and Analysis of Research Data

Introduction

A central problem of the SHRP asphalt research program is to discover how best to translate the large volumes of research results generated by 24 contractors into a coherent set of performance-based specifications.

In this chapter the validation, data handling and analysis methods employed to address this problem will be briefly described. These range from conventional, well-defined statistical analysis methods to freeform, intuitive techniques for drawing conclusions from sets of data of differing quality and completeness.

The analytical process may be viewed as a pyramid (figure 4.1) with the validated, performance-based specifications at the pinnacle. Individual experiments conducted in each of the contracts form the base; these experiments are required to be designed using sound statistical methods.

Higher up on the pyramid, research results from all the different experiments in the program are evaluated and combined in different ways in order to select a consistent set of relationships between material properties and performance that may be suitable as a basis for specifications. Although all of these data sets will have been developed from statistically-designed experiments, their precision, accuracy and quality will vary because of the inevitable uncertainties inherent in the various experiments.

Finally, at the highest level of the pyramid is the validation process that occurs in two stages in contracts A-003A and A-005. Relationships that have been selected on the basis of an analysis of laboratory results as most promising for use in performance-based specifications must be tested against field data. Ideally, this validation process would be conducted with well-controlled, long-term field experiments such as those incorporated in the LTPP Specific Pavement Study (SPS) series.

The tight schedule for the SHRP asphalt research program, which requires that the specifications be available within 5 $^1/_2$ years of the initiation of the research program, precludes complete reliance upon a long-term program such as LTPP. Rather, the best-available information, running the gamut from reliable data from controlled field experiments to personal observations by experienced engineers, will have to be identified, assessed and combined in an accelerated validation process in order to reach the pinnacle of the pyramid on time.

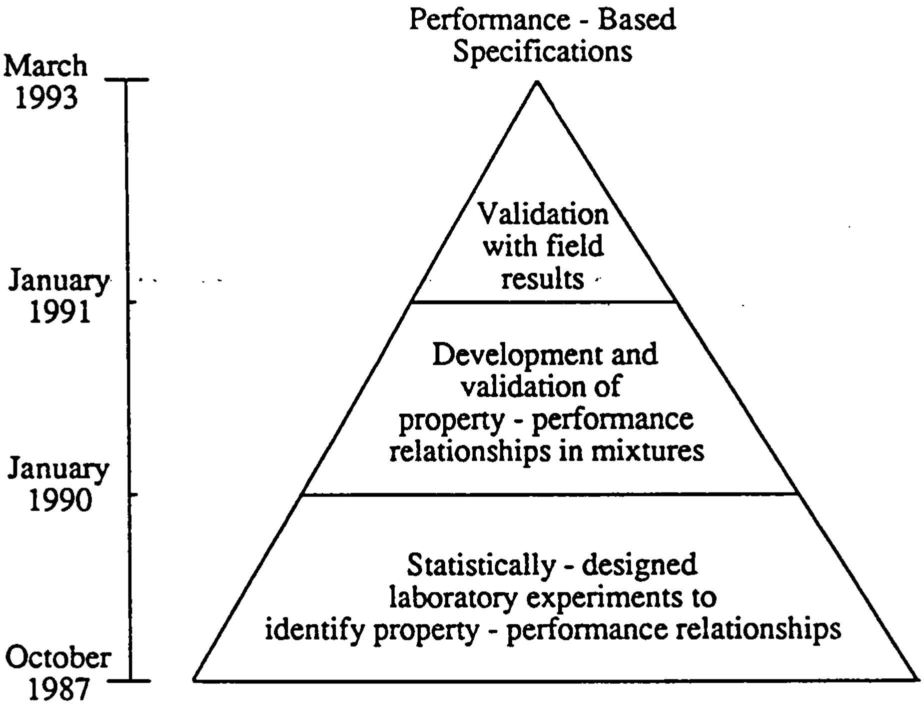


Figure 4.1 The data treatment pyramid.

Each level of the pyramid requires a different set of analytical techniques and assumptions. At each stage in the process, a different mix of deductive and inductive reasoning may be needed. What is most important, therefore, to the ultimate acceptance of the products of the program, especially the performance-based specifications, is that all the analytical methods, assumptions, presumption, intuitions, etc. employed to reach them be openly presented for all to examine and judge.

The following sections address in more detail the ideas discussed in this introduction.

The Concept of Validation

The successful development of performance-based specifications for asphalt binders and asphalt-aggregate mixtures requires the validation of binder and mixture properties identified as important determinants of pavement performance. Validation is defined here as confirmation of probable relationships between the properties of materials, viz. asphalt binders and asphalt-aggregate mixtures, and pavement performance through their correlation with measured characteristics of actual field pavements.

First-Stage Validation

The discussion in chapter 3 established that validation of the asphalt program results is a two-stage process coordinated between contracts A-003A and A-005. The first stage (contract A-003A) will confirm that variation of asphalt binder properties identified as probable, significant determinants of pavement performance causes reasonable, meaningful changes in the relevant performance characteristics of asphalt-aggregate mixtures.

For example, if the elemental nitrogen content of the asphalt binder were to be hypothetically identified as an important determinant of water sensitivity in asphalt pavements, then the water sensitivity of asphalt-aggregate mixtures prepared with asphalt binders exhibiting a wide range of nitrogen contents should vary in a corresponding manner.

Obviously, for the binder property to be useful for specification purposes, its variation must cause a large enough change in the mixture property to discriminate real differences from the experimental variation of the test method. To extend the hypothetical example from the last paragraph, if a 100 percent change in the nitrogen content of the binder, for example, from three to six mass percent, caused only a one percent variation in the water sensitivity of the mixture using a test method that has an experimental precision of ± 2 percent, then nitrogen content probably would be of little practical use as a requirement in an asphalt binder specification.

Second-Stage Validation

The second stage of the validation (contract A-005) establishes the degree of correlation between the asphalt binder properties shown to significantly affect performance-related characteristics of asphalt-aggregate mixtures and relevant field pavement performance parameters, and provides data upon which to set the specification limits for the relevant properties selected to control performance. Using another hypothetical example, if a laboratory wheel tracking test demonstrated that the stiffness of the asphalt binder significantly influenced rut depth in compacted laboratory specimens, the variation of the binder stiffness in actual pavements would then be compared with measured pavement rut depths to determine if the laboratory correspondence carried over into field behavior.

In simplest terms then, validation is based upon mathematical correlation between pairs of measured properties. In practice, the laboratory validation process is the most straightforward since, with due care, the experiment may be designed so that the only independent variable is the asphalt binder property. This requires close attention to compaction of the mixture specimens, temperature control, control of applied load and its frequency, aggregate gradation, etc. The experiment design must also provide a mechanism to identify other binder or mixture properties that might confound the correlation. For example, if more than one chemical property of the asphalt binder could affect its water sensitivity, the experiment design would have to enable the individual effects of the two properties to be measured separately.

The validation of binder properties with field data is much more complex and problematical. Pavement performance is affected not only by materials behavior, but also by a myriad of internal and external factors such as compaction, subgrade condition, drainage, pavement structure, traffic volume and mix, and environment. The validation must encompass a statistically-sound sample of pavements in which the effect of the relevant binder property can be isolated from all these complicating factors. This will not be an easy task even with a full complement of specimens and performance data available from the LTPP GPS and SPS experiments.

The Need For Statistically-Sound Experiment Designs

The basis for a successful validation process is the use of statistically-sound experiment designs. All major contracts in the SHRP asphalt research program are required to establish statistically-sound designs for all major experiments in the research. The justification for this requirement and suggested techniques for establishing these designs are contained in Antle (1989), which is summarized in the following.

For the SHRP asphalt program to be successful, mechanisms must exist that permit all the researchers to merge, correlate and draw statistically valid inferences from the data collected from the various studies. Moreover, an objective means must be available with which to quantitatively judge the "goodness" and reasonableness of each research result.

These requirements are satisfied in two ways. First, all research agencies participating in the program employ the same materials, essentially 32 asphalt cements and 11 aggregates contained in the Materials Reference Library (MRL) (Cominsky et al., 1989). Thus, the confusion, prevalent in the past, that arises from attempts to draw conclusions from data sets produced by the analysis of differing materials with unknown characteristics and behavior should be eliminated. Inherent in the MRL selection process is the assumption, qualified by recourse to historical performance data as well as the informed scientific judgment of the selection panel, that the 32 MRL asphalts span the range of performance expected from the full set of asphalts available now and in the future in the United States and Canada.

Second, the research studies in the asphalt program are organized as experiments selected to test hypotheses and accomplished according to basic statistical procedures and sound experiment designs. The experiments must be designed to validate relationships among test variables, to calibrate and validate test procedures and equipment, and to establish specification variables or criteria. These designs are distinguished by a minimum of four attributes:

1) independent replication of procedures and processes to provide an accurate estimate of experimental error;
2) use of randomization to avoid biases caused by the order of measurement;
3) use of blocking and control variables to eliminate extraneous sources of error; and
4) use of blind samples wherever possible.

The use of statistically-sound experiment designs assures that all research results, principally measures of asphalt, aggregate and asphalt-aggregate mixture properties, have an appropriate measure of uncertainty. Usually, a 95% confidence interval will be constructed for the true parameter value, expressed as $X \pm E$ where X is the mean and E is the half width of the 95% confidence interval. It also assures that relationships identified between two properties are physically reasonable, rather than arbitrary, empirical correlations obtained by the use of computational methods such as least-squares fitting.

In summary, the validation at the core of the SHRP asphalt program is founded upon a series of well-designed experiments that produce research results whose experimental uncertainties are clearly defined. The relative value of relationships established among experimental parameters may be judged in terms of their physical reasonableness as well as their degree of correlation. Thus, at this stage of the program the value or goodness of all the experimental results can be compared by the use of a uniform measure of uncertainty. Moreover, the uncertainty resulting from a merging of data sets from different experiments can be gauged quantitatively.

The Need For Both Deductive and Inductive Reasoning in the Validation Process

The validation process has been previously discussed as a two stage process during the SHRP asphalt program (a third stage is planned subsequent to 1993 as SPS-9 in the LTPP), involving distinct correlations of binder properties with laboratory mixture and field pavement data. The experiments described in the last section are expected to identify important relationships between asphalt binder properties and predicted field performance and to provide the first-stage laboratory validation that these relationships translate into significant variation in the corresponding properties of asphalt-aggregate mixtures. These properties ultimately will be incorporated into performance-based specifications for binders and mixtures.

The larger and more difficult question is then how to demonstrate that the binder property is truly predictive of field performance. To this point, the binder property has only been correlated with a mixture property, and such a correlation in itself does not prove that the binder property is predictive and useful for specification purposes.

The second stage of the validation process consists of a mathematical correlation of the candidate binder and mixture properties with performance data gathered from both full-scale pavement test facilities such as the FHWA Accelerated Load Facility (ALF) and in-situ field pavements studies, typified by the SHRP LTPP General and Specific Pavement Study (GPS and SPS) pavement sections.

The first stage of the validation process may be looked upon as an inductive process since it does not provide *conclusive* grounds for the truth of the conclusion that relationships exist between binder properties and pavement performance, but rather affords some support for it. The second stage of the process, however, is a deductive process in that it provides conclusive grounds for this conclusion.

For example, if hypothetically the tensile strength of the asphalt binder is shown to have a significant effect on the fracture strength of the asphalt-aggregate mixture, then strong support, but not conclusive proof, of an important relationship between the low-temperature cracking behavior of field pavements and the tensile strength of the binder has been demonstrated.

The second stage of the validation process by contrast, relies upon the correlation of binder and mixture properties with actual field performance to demonstrate the soundness of the inferred relationships between properties and performance. If a significant, positive correlation is found, for example, between the occurrence of thermal cracking in pavements and the tensile strength of the asphalt binder, the ability to predict pavement performance by measuring this asphalt property may be judged to have been proven conclusively with a certitude that can never be achieved using only laboratory results.

In practical terms, the strength of the correlation and the ultimate predictive value of the binder or mixture property will be tempered by several factors including the number of particular instances (field pavement sections) utilized in the validation and the degree to which the field pavement sections represent controlled experiments. The use of performance data from SHRP LTPP SPS sections would be preferred to data from GPS sections since the SPS sections are being constructed as controlled experiments. Either would probably be preferable to data gathered from a random assembly of uncontrolled field pavement sections.

Moreover, the possibility must be recognized that if insufficient field data are available from existing pavements, performance data from other sources will also have to be employed, e.g. historical projects that have been extensively described in the literature, interviews with experienced materials engineers who can provide information concerning asphalt properties and pavement performance, etc. While confidence in the conclusion reached from this data might be lessened, the process employed to reach the conclusion would be unchanged.

In summary, the validation in the laboratory of candidate properties for incorporation in performance-based specifications is principally an inductive process. It is aided by the existence of complete data sets from well-designed, controlled experiments, but cannot conclusively prove perceived relationships to pavement performance.

By contrast, the conclusive selection of the final suite of properties actually used in the specifications and their limits requires a deductive validation process that may, however, employ a mix of statistical data treatment, judgement, interpretation and intuition to compensate for a lack of long-term performance analysis and the possible need to employ incomplete or poor quality performance data. These factors will influence the strength of the conclusions reached in the validation process.

The Treatment Of Chaotic Data

Chaotic data may be defined as a body of research results of varying origin, quality and statistical soundness that must be used together to reach a specific research goal. In the SHRP asphalt program, a wide variety of quantitative data must be employed along with qualitative judgments, intuitions, etc. to develop performance-based specifications. If each specification is to be organized around the six performance factors (permanent deformation, fatigue cracking, low-temperature cracking, aging, water sensitivity, and adhesion), it is likely that confidence in certain limits and requirements in the specification will be greater than in others, perhaps by a large degree, because of the chaotic nature of the data employed in its development.

In spite of extensive coordination, use of standardized reference materials, and other actions to ensure consistency, the chaotic nature of the SHRP asphalt research data will increase as the program proceeds from identification of candidate predictive binder properties through their validation with asphalt-aggregate mixture properties to their validation with field data and incorporation into specifications. Therefore, while exacting statistical treatment of the data is required almost unanimously in the early stages of the program (the bottom level of the pyramid in figure 4.1), this will be less possible in succeeding levels, in particular in the field (second stage) validation process.

In assembling the specifications, when the available data are not completely susceptible to established statistical methods of analysis, the intuition and engineering and scientific judgement of the research team will be strongly relied upon to pick and choose between confusing or even contradictory results and successfully reach the program goals.

For example, suppose insufficient field data are available to validate a candidate relationship between the tensile strength of the asphalt binder and the predicted incidence of low-temperature cracking in pavements by standard statistical methods. How might a practical specification for low-temperature cracking be developed in the time period available to SHRP?

In lieu of a statistical correlation of data sets, the research team might first examine the mixture test method itself, estimating how well it simulates the stress-strain patterns induced in a pavement by dramatic temperature changes. Next, it might reevaluate the laboratory experiments that correlated binder tensile strength with mixture fracture strength, perhaps expanding the data set with additional asphalts and aggregates, in order to gauge how significant the response of the mixture property for the maximum variation in the binder property would be in terms of actual pavement behavior.

Finally, if the variation was indeed judged to be significant, the team would have to settle upon the recommended specification limits for both the binder and mixture properties, recognizing that the relationship of the binder and mixture properties to pavement performance in this instance was only strongly supported, not proven conclusively. This decision could be assisted by an evaluation of the mixture response data or perhaps by use of a mechanistic-empirical performance model to estimate satisfactory limits; these tentative limits would be open to revision as long-term performance data from the LTPP became available[1]. If, on the other hand, the variation did not appear to be significant, different candidate properties and their effect on mixture properties would have to be examined.

In summary, it is anticipated that the information needed to set SHRP's performance-based specifications will include some gaps and data with variable degrees of experimental uncertainty in the data sets. This means, particularly in the second-stage field validation process, SHRP must use qualitative and historical results that cannot be fully controlled. The chaotic nature of the supporting data will require the balanced application of well-defined statistical analysis methods in combination with more intuitive, interpretative techniques that rely upon the scientific and engineering judgement of the researchers, to develop the two performance-based specifications and other products of the program by its March 31, 1993 completion date.

Clearly, the acceptance of the specification limits and requirements by the highway community will be predicated upon a clear, open presentation of the analytical processes employed to reach them, and the underlying premisses, assumptions, judgments, intuitions, etc. utilized to deal with the unevenness and uncertainties in the research results. In particular, open evaluation of data, i.e. whether they are founded upon field validated or only laboratory mixture-validated relationships, will be absolutely

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[1] Any performance-based specification developed in the SHRP asphalt program will be subject to revision as long-term field performance data become available from the LTPP. One of the purposes of developing performance models in contract A-005 is to facilitate the updating of the specifications by user agencies.

essential. When either type of validation is incomplete, special efforts must be taken to ensure that the judgments that are made are balanced and representative of the widest possible cross section of scientific opinion.

The Employment of Simulative Test Methods and Test Methods Yielding Results In Fundamental Engineering Units

As discussed in detail in report SHRP-A/IR-90-013, the performance-based specifications developed in the SHRP asphalt program should insofar as possible be based upon fundamental properties of the asphalt binder and asphalt-aggregate mixtures, i.e. those material properties whose effect on performance may be explained and estimated from a theoretical treatment of underlying physical principles.

Whenever feasible, only fundamental properties should be employed in development of specification limits and requirements. The use of simulative laboratory or non-fundamental field data to validate how these properties relate to performance will probably be required. In the first stage laboratory validation, simulative test methods such as a wheel tracking test may be quite useful and appropriate for confirming the effect of asphalt binder properties on mixture performance, e.g. rutting. Correlation may be accomplished successfully although these simulative test methods would not be suitable for use in predicting pavement performance by input of the test results into computational performance models.

Similarly in the second stage field validation process, quantities such as rut depth and transverse crack length per unit pavement area, which we will term "end-result field data," must be viewed as necessary indicators of the corresponding pavement performance factors (for this example, permanent deformation and low-temperature cracking), and used in the validation process to correlate pavement performance with material properties, although a detailed explanation of how traffic and environmental stresses cause these responses is incomplete.

Ideally, an analysis based upon underlying physical principles that quantitatively define how distress is manifested as a pavement structure responds over time to dynamic and static load-induced stresses should be used in developing performance-based materials specifications. This analysis would provide an uninterrupted, fundamental linkage between these properties and pavement performance. The effect of the material property upon the response of the pavement to externally-induced stresses could be calculated, and then the development of specific types of pavement distress in response to the corresponding strains would be estimated. Both the former and the latter are goals of the SHRP asphalt research program (specifically contracts A-003A and A-005), but realistically the information needed to link pavement response to pavement distress may not be completely available within time frame allotted for the initial specification development.

Since it is not possible to predict using fundamental mixture properties the degree of permanent deformation caused by any particular combination of traffic loading and environmental factors, end-result field data such as rut depths must be correlated with fundamentally-derived material and mixture properties in deciding upon the limits and requirements for the material properties incorporated in the performance-based specifications.

This reliance upon data from simulative test methods and end-result field data in the validation stage of the specification development and the necessity for refinement of the specifications as more LTPP program results become available must be clearly recognized by the state highway agencies, standard-setting organizations such as AASHTO and ASTM, asphalt producers, contractors and others responsible for their adoption and use. At the same time, the prohibition against utilizing test methods such as Marshall stability, that neither adequately simulate field performance nor yield results in fundamental engineering units, in the validation, development and definition of the specifications must be scrupulously observed.

The Assessment of the Relative Quality of Different Data Sets

Any research result derived from a statistically-sound experiment design will have a measure of uncertainty (a quantitative confidence interval) associated with it by which its comparative quality may be assessed. This will apply to most, if not all, of the results used in the identification, development and first-stage validation of asphalt binder property-pavement performance relationships. Standard mathematical methods can then be applied to estimate the uncertainty in the verified relationships.

In the second stage of the validation process, a mix of results with both quantitative and qualitative uncertainties will likely be employed. At a minimum, only test methods with defined precision and bias statements should be used in this process to measure material, mixture, and pavement response properties, such as deflection. Since precision and bias statements are derived from a statistical measure of <u>inherent</u> experimental error, an ongoing quality assurance effort is required to assess whether extraneous factors are affecting the caliber of these results.

The use of end-result field data in the validation process (for example, pavement rut depths or crack lengths per unit area) complicates the problem of estimating uncertainties in the experimental data. Standard distress classification and measurement techniques must be used, and multiple, independent measurements made on each pavement section in order that the precision of the measurements can be calculated. Quality control of these field measurements is especially important because the uncertainty inherent in the measurement process is expected to be large to begin with; poor experimental technique in taking the measurements could render the data essentially worthless.

If use must be made of historical results and/or qualitative, anecdotal information (e.g. interviews with experienced materials and pavement engineers), stringent quality control of the data will be of overriding importance. Essentially, the researchers will be required to <u>assign</u> a conservative estimate of uncertainty to this type of data, and this can be accomplished only after a thorough examination and expert assessment of the validity of the information. Obviously, the employment of substantial amounts of this type of data would reduce confidence (in the statistical sense) in the specification limits and requirements developed from them because of the large uncertainties involved.

In summary, a vigorous, independent quality assessment of all the data sets employed in the development of the performance-based specifications is necessary to assure that the limits and requirements of the specifications realistically reflect uncertainties due to both experimental error and the mixed use of quantitative and qualitative information.

5

Performance-Based Specifications

The principal and primary goals of the SHRP asphalt research program are to develop performance-based specifications for asphalt binders and asphalt-aggregate mixtures. These specifications will allow the engineer to select an asphalt binder on the basis of the performance level required of the pavement under the present and predicted traffic and environmental conditions. Both modified and unmodified binders are to be covered by these two unified specifications that incorporate a protocol for determining when and what type of modification may be needed to meet required performance standards. However, it is unlikely that a binder will be specified that can act as a complete panacea for poor pavement design or construction practice.

The performance-based specifications will be based on a set of validated relationships between asphalt binder properties, mixture properties and field (pavement) performance that establish acceptable response ranges to control fatigue cracking, permanent deformation (rutting), low-temperature cracking, aging, adhesion, and water sensitivity. Present specifications assure the producer and user that the asphalt binder will respond in a predictable, consistent manner during hot-mix production and laydown operations. However, no minimum level of pavement performance is warranted, or even intended, in any but a peripheral sense.

An Asphalt Binder Specification

An initial working concept of the performance-based asphalt binder specification was developed in May 1989 to guide and coordinate the many components of the asphalt program (figures 5.1 and 5.2). It was anticipated that this initial concept would be periodically updated, fleshed out with specific information and adjusted, as necessary, to exploit new or unexpected results. In essence, it was to serve as a definitive goal for the entire program and continually to evolve until the final specification is achieved. Additionally, this evolving binder specification will serve as a focal point for interaction and information exchange with the user-producer groups and others within the asphalt industry involved in implementation activities within the SHRP asphalt program.

It is anticipated that the asphalt binder specification generally will employ physical properties as surrogates for significant chemical, or compositional, factors that influence pavement performance. Moreover, the binder specification will allow the engineer to match materials to several levels of pavement service and to tailor the choice of asphalt binder to eliminate or minimize specific distresses.

"Strawman"
Specification for Asphalt Binders
Graded at (0°C 32°F) and 80°C (176°F) for aged binders

Property	Asphalt Binder Grade											
	AB 21-$\overline{20}$	AB 30-$\overline{20}$	AB 40-$\overline{20}$	AB 11-$\overline{10}$	AB 15-$\overline{10}$	AB 20-$\overline{10}$	AB 6-$\overline{5}$	AB 7.5-$\overline{5}$	AB 10-$\overline{5}$	AB 3-$\overline{2.5}$	AB 4-$\overline{2.5}$	AB -5-$\overline{2.5}$
Rheology Index*, 0°C (32°F)	2100±210	3000±300	4000±400	1100±110	1500±150	2000±200	600±60	750±75	1000±100	300±30	400±40	500±50
Rheology Index*, 80°C (176°F)	$\overline{2000}$±200			$\overline{1000}$±100			$\overline{500}$±50			$\overline{250}$±25		
Nitrogen Factor**	a ± for all grades											
Acid Factor**, max	b for all grades											
Healing Factor***, min	c for all grades											
Viscosity, 135°C (275°F) Cs, max	600 for all grades											
Flash Index, °C (F) min	d(d')			e(e')			f(f')			g(g')		

* Related to low temperature cracking and permanent deformation. Test is conducted on aged binders. Binders are aged using low temperature, high oxygen pressure test simulating 5 years of service life.
** Nitrogen factor and acid factor are related to moisture damage and are optional for regions without moisture damage problems or if the asphalt is modified. A surrogate test on the asphalt mixture can be substituted.
*** Related to fatigue cracking.

Figure 5.1 Example of SHRP asphalt binder specification 1A.

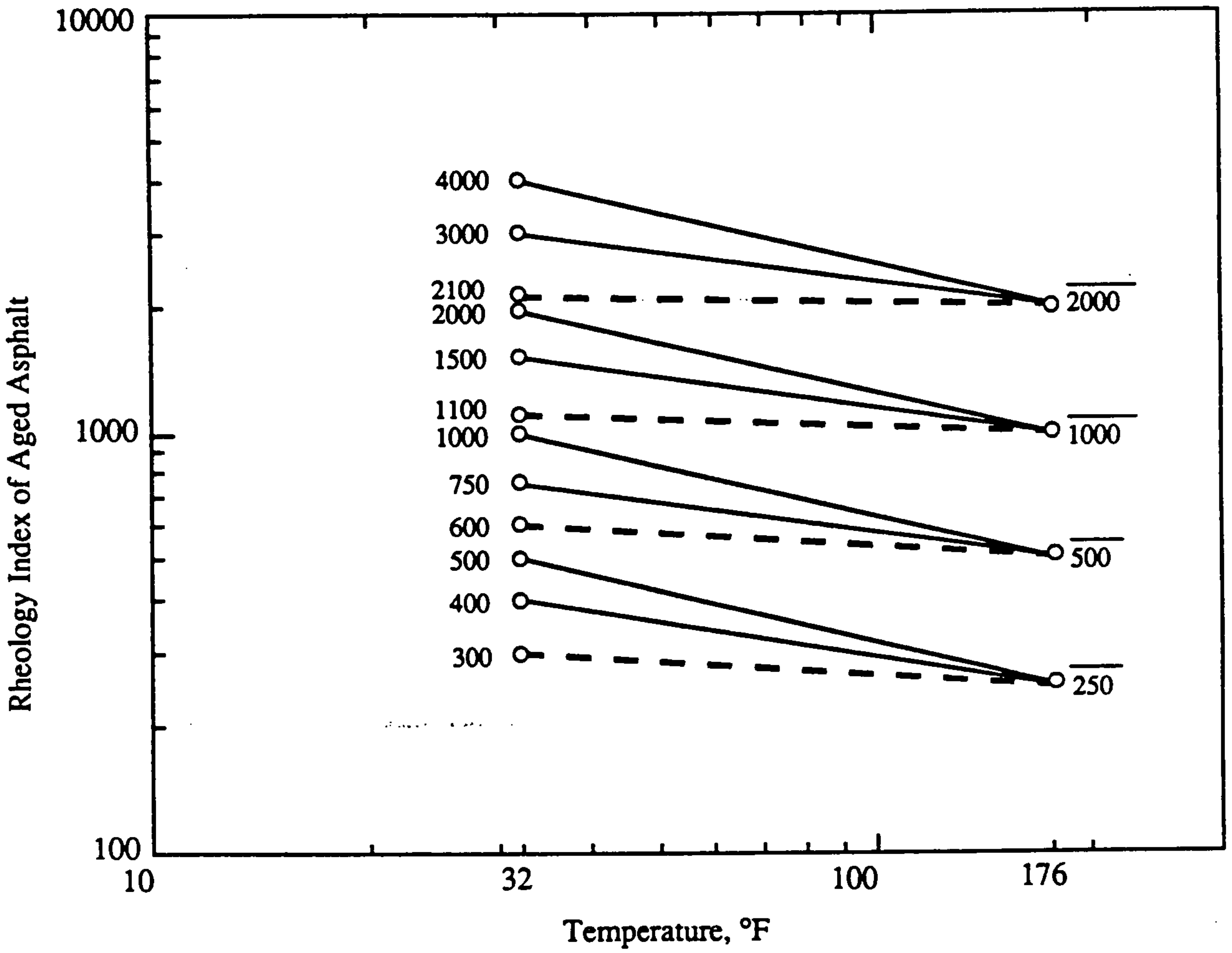


Figure 5.2 Hypothetical relationship between Rheology Index and Temperature for the proposed asphalt binder grades (specification 1A).

Initial Draft Binder Specification

In the initial working concept, grading was based upon the properties of the asphalt binder aged to simulate a specific pavement service period of nominally 5 years. It is a bimodal system; that is, it was based upon rational performance indices established for both low temperature (32°F) and high temperature (176°F) pavement service. Thus, a precise grade could be selected to accommodate the need to control low-temperature cracking, rutting, or both in a particular construction project. In addition, it addressed certain aspects of fatigue cracking.

However, fatigue cracking was primarily controlled by specifying a minimum value of a microcrack healing index that measures the ability of the asphalt binder to chemically bridge and repair fatigue and low temperature cracks.

Water sensitivity was controlled by the use of an index based directly upon chemical composition factors linked with this phenomenon, e.g., a nitrogen factor or an (organic) acid factor. These indices also served as a measure of adhesion. It was noted that a surrogate physical test developed by one of the SHRP contracts might be ultimately employed in place of these compositional characteristics.

The specification also included requirements related to the behavior of the asphalt binder during hot mix production and pavement construction. A minimum flash index (which may or may not be the current flash point) was specified as a safety factor; an aging index employing a test procedure that simulates the effect of hot mix production (as opposed to the long-term aging accounted for in the grading system itself) also was included as a requirement. A maximum viscosity value at (135°C) was specified for all grades to ensure that the bindez is adequately fluid for hot mix production and construction, thus addressing the practical aspects of constructability.

This initial draft spmcification brought a reality to the SHRP asphalt program, focused the research on the final products, and served as a catalyst for development of input from the user-producer community was well as the researchers. As a result, this initial koncept continued to evolve and has led to a second generation concept discussed next.

Second Generation Draft Asphalt Binder Specification

A second generation draft specification evolved based on the developments and findings of the asphalt research program and technical comments provided by users and producers to date. The general form of the specification is shown in figures 5.3 and 5.4. The major changes relate to specifying tests for the various characteristics contained in the original specification and the preliminary identification of environmental conditions related to performance. It is emphasized that these tests and the details of the specification are subject to change and continuing refinement.

	Aged Asphalt Binder Grades											
	AB $\overline{1}$-			AB $\overline{2}$-			AB $\overline{3}$-			AB $\overline{4}$-		
	1	2	3	1	2	3	1	2	3	1	2	3
Highest mean monthly temperature °F	<80			80 - 90			90 - 100			>100		
Lowest anticipated temperature °F	<-20	-10 to -20	>-10	<-20	-10 to -20	>-10	<-20	-10 to -20	>-10	<-20	-10 to -20	>-10
Temperature Dependency												
Low Temperature Cracking												
Low temperature stiffness at -10°F, psi (Bending Beam Test, SHRP B001)												
Permanent Deformation												
Dynamic stiffness at 140°F (Indentation Test, SHRP B002), psi												
Fatigue Cracking												
Cycles to failure at 77°F (Bending Beam Fatigue Test, SHRP B003), min												
Healing index at 77°F (Microcrack Healing Test, SHRP B004), min												
Aging												
Mass change, (TFOT or RTFOT, AASHTO Test) max, %												
Low temperature stiffness SHRP B001 at -10°F max, psi												
After POV aging (POV Aging Test, SHRP B005) at temperature of, °F	120	120	120	140	140	140	160	160	160	180	180	180
Water Sensitivity												
Bond strength at 90°F (Blister Test, SHRP B006), min, psi												
Adhesion												
Bond strength at 32°F (Modified Blister Test, SHRP B006M), min, psi												
Constructability												
Kinematic viscosity at 275°F test (ASTM D2170), max, cS_T	1500			1500			1500			1500		
Safety												
Flash point (COC Flash Point, ASTM D92), max, °F	450			450			450			450		

Figure 5.3 Example of SHRP asphalt binder specification 2.

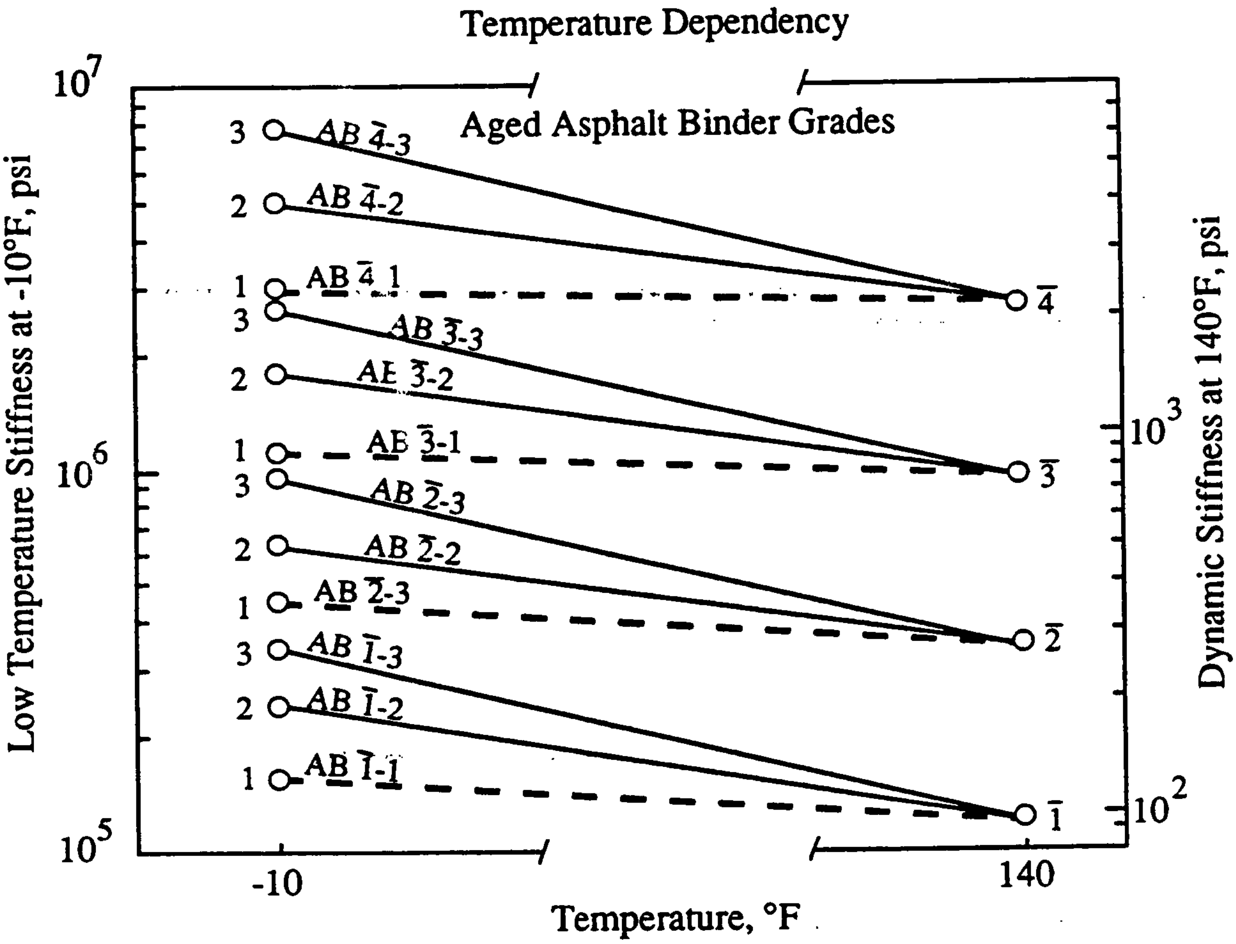


Figure 5.4 Hypothetical relationship between stiffness and temperature for the proposed asphalt binder grades (specification 2).

Environmental Conditions

Input from the asphalt user-producer community has identified preliminary temperature regimes that are related to pavement performance. These are shown in figure 5.3.

Low Temperature Cracking and Permanent Deformation

The low and high temperature performance indices will be measured using two different tests which yield fundamental properties related to low temperature cracking and permanent deformation (rutting). As shown, figure 5.4 is similar to the original concept of temperature dependent properties (figure 5.2). However, the lines now represent a series of binders which have different rheology measured by different tests at different temperatures.

1. Direct tension test

The direct tension test is conducted at a constant rate of deformation to fracture using a single "dog bone" shaped specimen. The load and tensile deformation at fracture and an energy to fracture are recorded. The test is conducted in a self-contained stand-alone device that includes automatic, computer controlled operation, data acquisition and temperature control. The test results characterize the strain tolerance of asphalt cement or modified asphalt binder.

2. Low temperature bending beam test

The bending beam test tests provides a direct measurement of the low temperature creep stiffness of the asphalt binder. As such, it is a replacement for nomographic methods used to predict low-temperature stiffness from measurements made at temperatures of 77°F or higher. The test involves a simply supported beam (5 in x 0.5 in x 0.25 in) loaded in flexure with a constant center point load. The time dependent deflection is measured and used to calculate the time dependent stiffness modulus. Low temperature cracking can be controlled by specifying a maximum binder stiffness less than the specification value, as measured by the bending beam test conducted at the minimum anticipated pavement temperature, be less than the specification value.

3. Indentation test

At the higher service temperatures, the ability of the asphalt binder, particularly modified binders, to resist plastic or non-recoverable shear deformation is critical to pavement performance related to rutting and shoving under load. The indentation test, currently in the early stages of development, applies a repeated shear stress to the test specimen and the accumulated, non-recoverable deformation is recorded. By measuring these non-recoverable shear strains, which are directly related to the shear strains produced by repetitive, dynamic traffic loadings, it will be possible to specify values of dynamic stiffness to regulate the permanent deformation characteristics of the asphalt binder.

Fatigue Cracking

The fatigue characteristics are evaluated using the bending beam fatigue test and the microcrack healing test.

1. Bending Beam Fatigue test

The bending beam fatigue test involves the repeated application of a load to a simply-supported beam (5 in x 0.5 in x 0.25 in) and the measurement of the number of load applications required to produce failure. The test can be conducted by applying a constant repeated load (controlled stress applicable to thick pavements) or a load that causes the applied strain to remain constant (controlled strain applicable to thin pavements).

2. Microcrack Healing test

The microcrack healing test measures the microcrack healing potential of asphalt cement. The test involves the uniaxial loading of a fully-supported notched beam composed of asphalt cement and fine aggregate (-30). The notch is located in the center of the beam to control the location of crack growth. The applied uniaxial load is large enough to propagate the crack at the notch. Additionally three replicate rest periods of 5, 10, 20 and 40 minutes are introduced at the beginning, middle and end of the loading sequence.

The healing index is the ratio of the difference of the energies required to propagate the crack after and before the rest period to the energy required to propagate the crack after the rest period.

Aging

Aging is subdivided into the changes which occur during construction (short term) and the changes which occur during the service life of the pavement (long term). The grading system proposed for the asphalt binders involves short term aging followed by long term aging to simulate a 5-year service life.

1. TFOT or RTFOT (Short Term)

It is anticipated that the aging characteristics of the asphalt cement will be evaluated using the current Rolling Then Film Oven Test (RTFOT) AASHTO T240 or Thin Film Oven Test (TFOT) AASHTO T179. While improvements could be made, it is not felt that this is a critical problem and thus the effort required is not justified at this time. Work subsequent to the SHRP research program may need to consider this question.

It is anticipated that the aging of modified binders will require the development of new test procedures (Contract A-004). These may also be unchanged from the current AASHTO and ASTM procedures.

2. POV Test (Long Term)

The pressure oxygen vessel (POV) will be used to simulate long term oxidative aging which occurs subsequent to construction. The test involves exposing the asphalt to oxygen at elevated pressures (300 psi or less) at the maximum anticipated pavement pressure. Currently the test involves a stainless steel pressure vessel and utilizes oxygen at a pressure of 300 psi, but it is anticipated that the final procedure will utilize air at a lower pressure.

Water Sensitivity

The water sensitivity of the binder will be measured by the blister test which provides a direct measurement of the adhesion force between the asphalt binder and aggregate surface. As shown in figure 5.5, a film of asphalt binder is placed on the aggregate surface and is then pressurized to determine the force required to separate the binder from the aggregate. The aggregate at the interface can be saturated to provide an estimate of the wet adhesive strength and the effect of saturation. The test may be conducted statically or with a repeated loading to simulate the action of traffic loadings. By specifying a minimum allowable strength, the asphalt-aggregate adhesion in the presence of water can be insured and the effects of moisture damage minimized.

Adhesion

Adhesion of the binder to dry aggregate can also be measured by the blister test, possibly by using an inert gas or a non-polar liquid. It is anticipated, however, that such a test may produce a cohesion failure rather than an adhesion failure, indicating that adhesion failures are primarily associated with moisture.

Constructability

This is controlled by a maximum viscosity at 275°F as measured by the present AASHTO and ASTM procedures. A maximum viscosity of 1500 cSt is specified to insure that the binder can be pumped and mixed with the aggregate.

It is also recommended that the viscosity be measured at 140°F and 275°F to allow the mixing and compaction temperatures to be estimated.

Safety

This is controlled by specification of a minimum flash point as measured by the current AASHTO or ASTM procedures. It is not anticipated that a new test will be developed or emerge from the SHRP asphalt program.

An Asphalt-Aggregate Mixture Specification

Essentially, there are no existing mixture specifications that address performance.

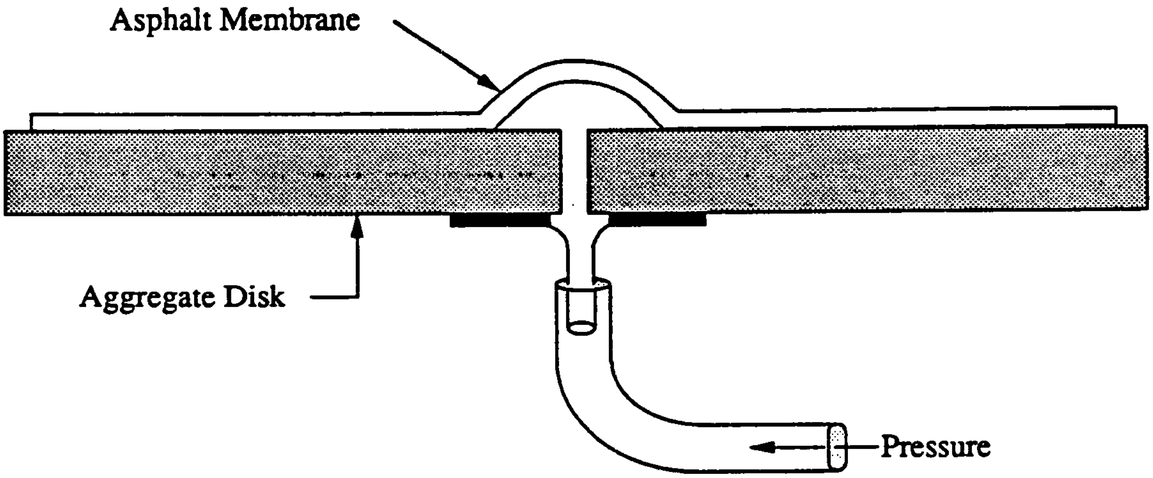

BLISTER TEST

Figure 5.5 Schematic representation of blister test apparatus.

Thus, it is necessary for the SHRP Asphalt Program to develop a performance based asphalt mixture specification and the supporting tests and protocol; while all of the contracts will provide input in varying degrees to this effort, the actual development is the responsibility of contracts A-001 and A-006.

In addition to the results of these contracts, it will be necessary to consider the findings and input from the other related projects, such as the NCHRP 9-6(1) AAMAS study, NCHRP 10-26A Performance-Related specification study, NCHRP 1-26 study of Mechanistic Structural Analysis Procedures, and the FHWA study for Development of Performance-Related specifications.

Initial Draft Asphalt Mixture Specification

As with the binder specification, a preliminary asphalt-aggregate mixture specification concept was developed in an effort to focus the research efforts, to generate input from users and producers, and to bring a sense of reality to the end products of the SHRP asphalt research program.

Like the asphalt binder specification, the mixture specification must be performance-based and be applicable to mixtures utilizing either unmodified or modified binders. It must consider the six performance factors of low temperature cracking, permanent deformation (rutting), fatigue, water sensitivity, aging and adhesion in conjunction with the effects of environmental conditions and traffic.

Attention must also be given to fatigue cracking of both thick (> 6 inches) and thin (< 2 inches) asphalt pavements and possibly to rutting of thick pavements and of thin overlays on very rigid bases.

Figure 5.6 is a first draft of the performance-based mixture specification. While it is premature to establish values, it is not premature to begin identifying tests and environmental conditions.

Environmental Conditions

Initially, the four environmental conditions defined by SHRP LTPP have been included. These four environmental regions (Fig 5.6) are as follows:

A Wet - Freeze;
B Wet - No Freeze;
C Dry - Freeze; and
D Dry - No Freeze.

As the specification evolves and is adopted by the states, they may wish to further subdivide the regions and refine mixture specifications to satisfy these environmental conditions. For example, figure 5.7 illustrates an alternative breakout with nine climate zones.

Climatic Zone	Wet-No Freeze				Dry-No Freeze				Wet-Freeze				Dry-Freeze			
Highest mean monthly temperature, °F	90 - 100		>100		90 - 100		>100		<80		80 - 90		<80		80 - 90	
Lowest anticipated temperature, °F	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10	-10 to -20	>-10
Traffic Level [1]	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
Low Temperature Cracking Stress at cracking, psi Temperature at cracking, °F (Thermal Stress-Restrained Tensile Test, SHRP M001)																
Thermally Induced Fatigue Cracking Cycles to failure, Nf (Thermal Stress-Restrained Tensile Test, SHRP M001)																
Permanent Deformation Strain/cycle at 104°F (Triaxial Compression-Repeated Shear Stress Test, SHRP M002)																
Fatigue Cracking Cycles to failure at 68°F, Nf (Beam Fatigue Test, SHRP M003)																
Short Term Aging Stiffness aging index (Mixture Rolling Thin Film Oven Test, SHRP M004)																
Long Term Aging Stiffness aging index (POV Aging Test, SHRP M005)																
Water Sensitivity Minimum retained stiffness, psi (Repeated Load-Triaxial Water Conditioning Test, SHRP M006)																

[1] L: $<10^4$; M: $10^4 - 10^7$; H: $>10^7$ design EALs

Figure 5.6 Example of SHRP asphalt-aggregate mixture specification 1.

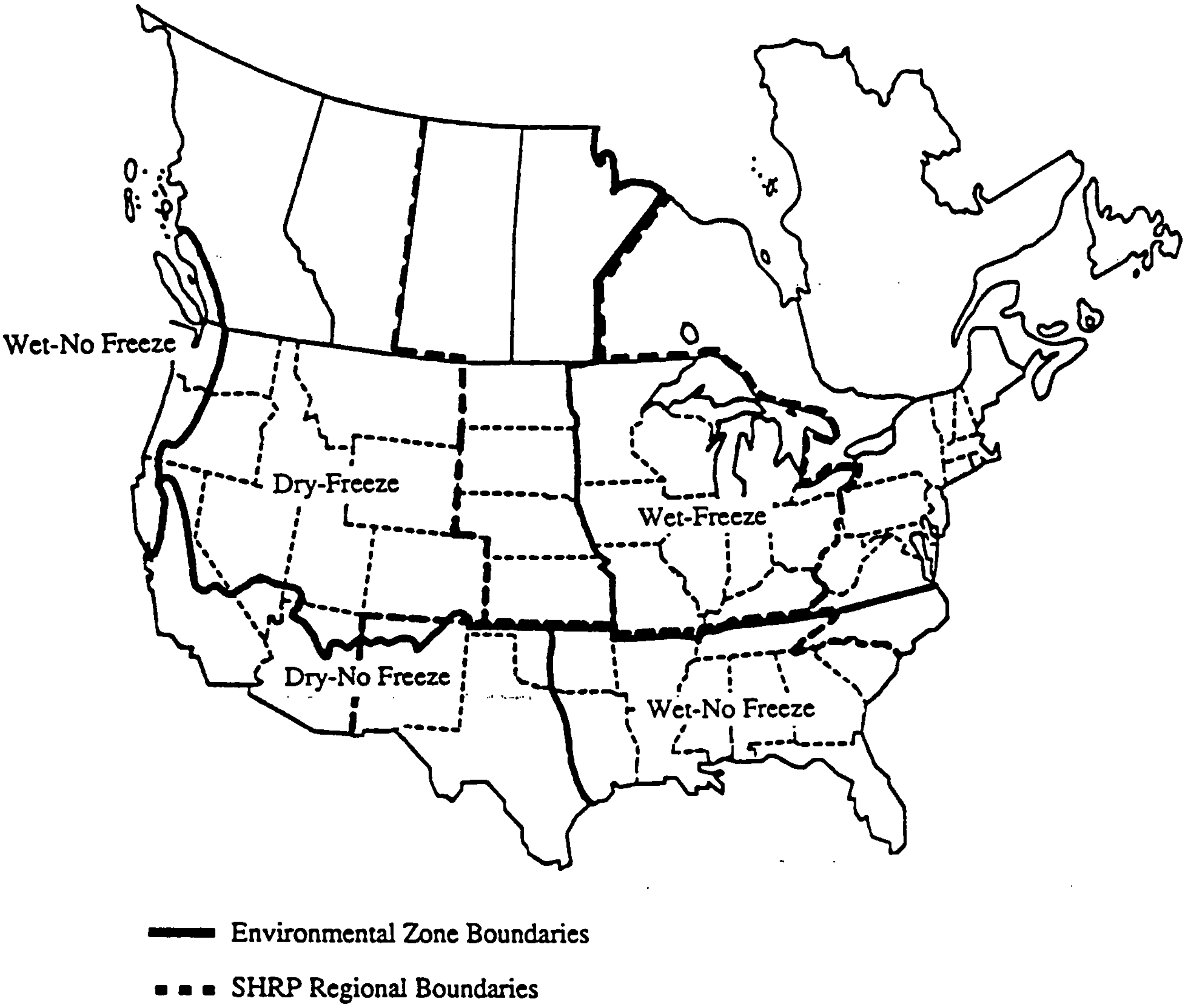


Figure 5.7 Example possible climatic zone breadkout employed with mixture specification 1.

Traffic Conditions

A minimum number of these traffic levels has been included in the initial specification. Again, as the results of contract A-005 become available it may be necessary, desirable and possible to specify other traffic conditions and to consider the possible interaction between traffic and environment. The current traffic ranges in terms of 18 kip EALs are as follows: (1) LIGHT, $<10^4$; (2) MEDIUM, 10^4 to 10^7; and (3) HEAVY, $>10^7$.

Mixture Conditioning Procedures

Procedures have been identified to simulate aging and water sensitivity of the mixtures.

Aging

Two aging tests or procedures will be utilized. The first will simulate the aging which occurs during plant mixing and construction, and the second simulates the aging that occurs during the first five years of service subsequent to construction.

1. Mixture Rolling Thin Film Oven Test

The aging that occurs during mixing and construction will probably be simulated by using a modification of the rolling thin film oven test. This modification involves placing a cylinder containing loose asphalt mixture on the shaft of the rotating element and subjecting the mixture to a specified time and temperature.

A second possibility originally suggested by the NCHRP AAMAS research is the use of a forced draft oven in which the loose mixture is subjected to a temperature of 275°F for 4 hours.

2. Pressure Vessel Test

The aging of the mixture during long-term service (5 to 10 years) will be simulated by using a high pressure vessel in which the loose mixture is placed in a pressure vessel containing air or oxygen at an elevated temperature or a temperature equal to the highest mean monthly pavement temperature.

The backup or secondary method involves the AAMAS procedure using a forced draft oven in which the mixture is subjected to a temperature of 140°F for 48 hours, followed by 225°F for 120 hours.

Moisture Sensitivity

A single moisture sensitivity condition procedure will be utilized. This test procedure involves subjecting the specimen to pressure, moisture and elevated temperature. The test apparatus is a triaxial compression type cell. A minimum acceptable retained stiffness or tensile strength will be specified. Additionally, permeability measurements may be required.

Performance Related Tests

Modular accelerated laboratory tests and test parameters that relate to field performance will be utilized in the specification. These procedures and properties must consider the three basic modes of distress: permanent deformation (rutting), cold temperature cracking, and fatigue cracking.

Permanent Deformation

Confined Axial Compression-Shear Test

The test method utilized to evaluate and control permanent deformation is the confined axial compression-shear test. This test involves cylindrical specimens (4 or 6 inches in diameter; 2.5 or 3.5 inches high) which are subjected to a confining pressure. During test the specimen is subjected to a vertical axial stress and to a repeated shear stress. The shear stress is applied for 1000 cycles and the accumulation of permanent strain is measured.

Low Temperature Cracking

Two forms of low temperature cracking must be considered. These two forms involve (1) a single drop in temperature which causes the tensile stresses to exceed the tensile strength (figure 5.8) and (2) cyclic temperature changes which result in thermal fatigue.

Both types of behavior may be measured using a restrained specimen-low temperature tensile test in which the temperature is 1) dropped rapidly through a wide range or 2) cycled repeatedly through an appropriate temperature range until cracking occurs. The beam specimen is restrained by clamping its ends to prevent movement.

Fatigue Cracking

The specification must consider both modes of testing: controlled stress which simulates thick asphalt layers and controlled strain which simulates thin layers. Thus, the tests utilized must be able to simulate both conditions. Although it is premature to make a judgment concerning the final selection, the following is offered based on the best information available.

A possible test is the bending beam test or a axial push-pull test. A third possibility is the combination of two or more test procedures which would be a surrogate procedure for fatigue.

1. Bending Beam Test

The test would be conducted on beam specimens (1.5 in x 1.5 in x 15 in or 3 in x 3 in x 15 in). Testing would involve a third point loading using a sinusoidal load pulse at a relative high load frequency (e.g. 20 Hz). Testing would be conducted to failure or to a specified number of load repetitions (e.g. 50,000) at which time measurements would be

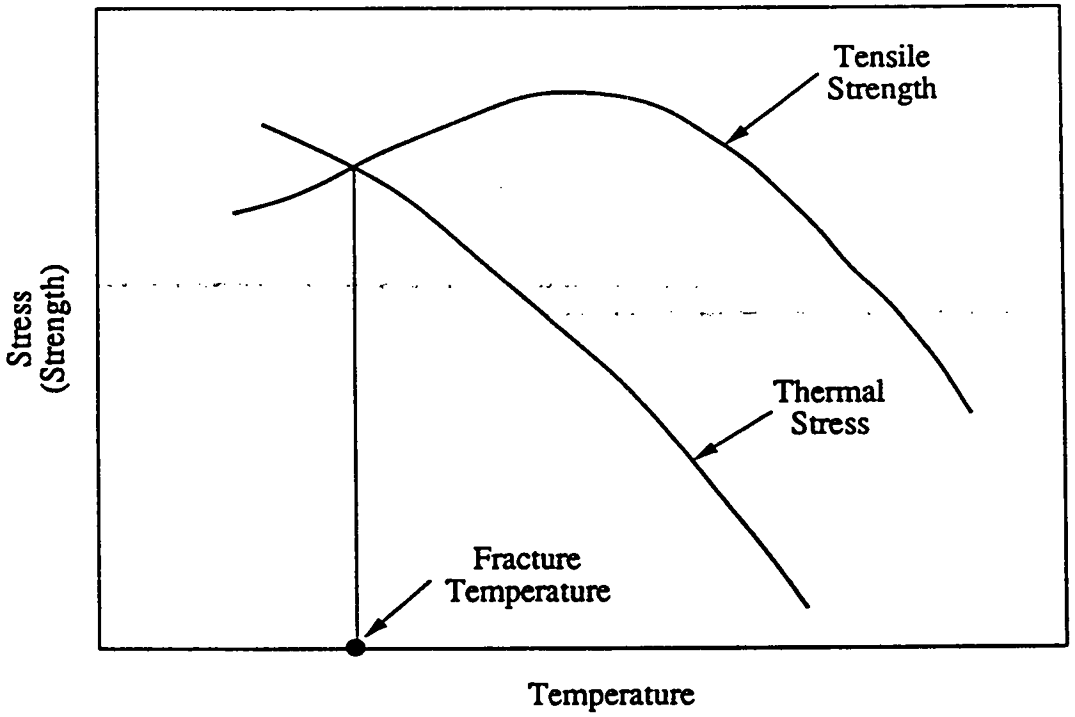


Figure 5.8 Stress versus temperature relationships involved in low-temperature cracking.

made to allow stiffness and strain to be estimated and relative to the fatigue characteristics of the mixture. Test parameter alternatives currently being considered are as described below.

1. Subject beam to strain level of 500 x 10 $^{-6}$ in/in at 68°F; N $\geq$ 5000 repetitions; would require approximately 50 minutes of testing at 100 repetitions per minute (0.1 s loading time, 0.5 s rest period).

2. Subject beam to strain level of 400 x 10 $^{-6}$ in/in at 68°F, N $\geq$ 50,000 repetitions; would require 45 minutes of testing at a frequency of 20 Hz.

2. Tensile Compression Fatigue Test

This test involves a cylindrical specimen with a reduced central portion diameter to ensure fracture in the central region rather than at or near the platens. An alternating axial tensile-compressive load pulse without rest periods is applied until fracture occurs. Under a constant applied stress the strain will continue to increase with time. Thus, the fatigue characteristics can be defined in terms of the applied stress or the initial strain.

3. Combined Tests

The third approach is to use a combination of two or more tests as a surrogate test procedure for fatigue. While this procedure does not measure the fatigue characteristics directly, it does provide meaningful information which relates to the fatigue behavior of the mixtures.

Stiffness Measurement

A specification must consider the determination of dynamic modulus and phase angle over a range of frequencies (0.01 Hz to 20 Hz) and temperatures (0°C to 60°C). These tests would be performed using prismatic or cylindrical specimens under confined pressure.

All of the above tests will be related and correlated with short term or accelerated-simulated field performance and ultimately with long term pavement performance as part of the LTPP program.

Aggregate Requirements

Although the SHRP program is not focused on the role of the aggregate, it is recognized that the quality of the aggregate is important and significantly influences adhesion and absorption (A-003B). It is also recognized that the gradation is extremely important. Thus, the mixture specification will contain requirements related to the aggregate. For example, the following requirements for voids in the mineral aggregate and gradation are included.

Voids in the Mineral Aggregate (VMA)

The initial specification utilizes the currently accepted VMA requirements specified by The Asphalt Institute (figure 5.9). It is anticipated however that these values, which are based on the bulk specific gravity of the aggregate, will be modified and ultimately based on the effective specific gravity of the aggregate.

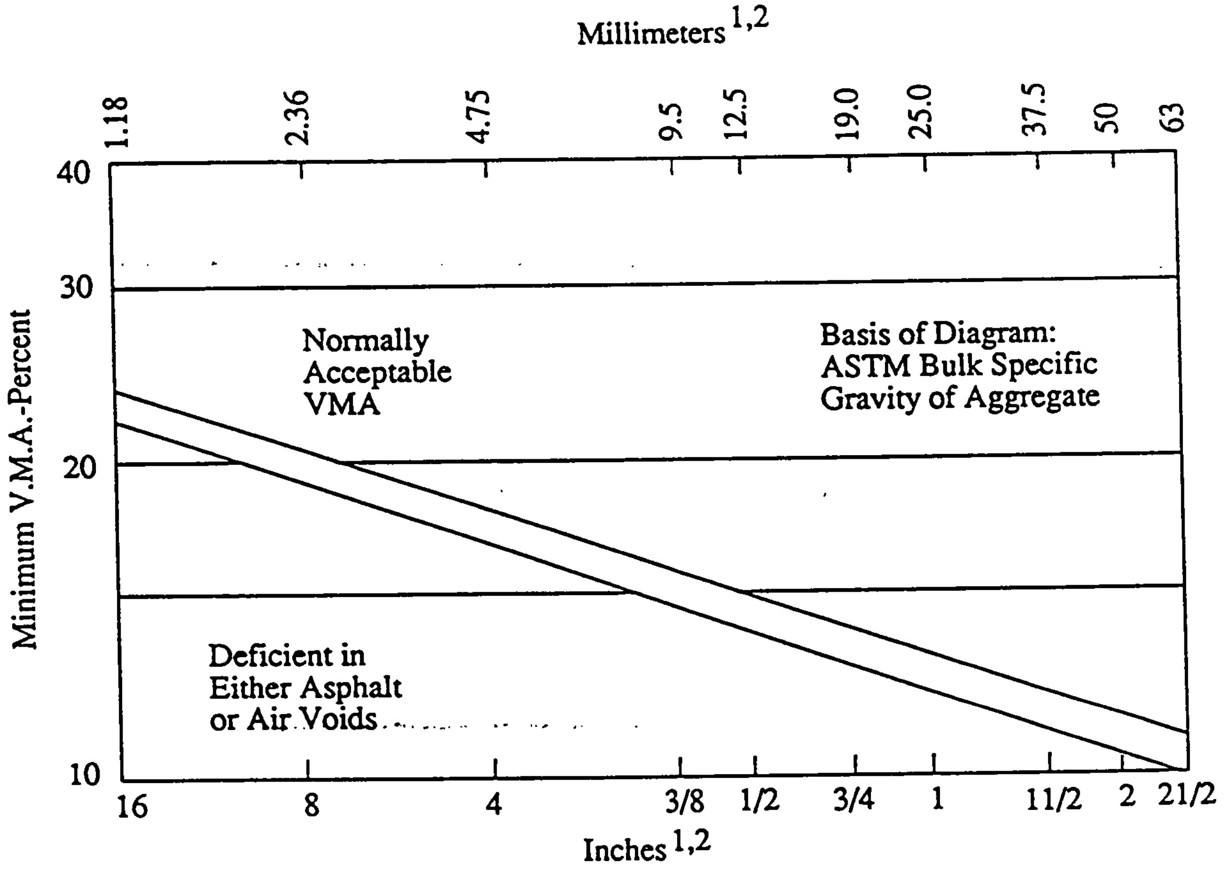
Gradation

The specification for the gradation of the aggregate is controlled by VMA requirements as well as the 0.45 power relationship and the hatched zone shown in figure 5.10. The basic premise is that the gradation of the aggregate will be acceptable if the gradation relationship does not enter or cross the hatched zone and that VMA requirements are satisfied. Thus, the aggregate specification may be above or below the 0.45 power curve and should involve a relatively smooth curve connecting the nominal maximum aggregate size and the amount of minus 200 material.

Constructability

Recommended plant temperatures should be able to produce an asphalt binder viscosity that will allow efficient coating of the aggregate. Similarly, the compaction should occur at a binder viscosity that allows ready compaction of the aggregate.

The temperatures needed for mixing and compaction may be estimated from a viscosity temperature relationship and correspond to viscosities of 1.8 and 2.8 stokes, respectively. In no case should the compaction occur at mixture temperatures below about 175°F.

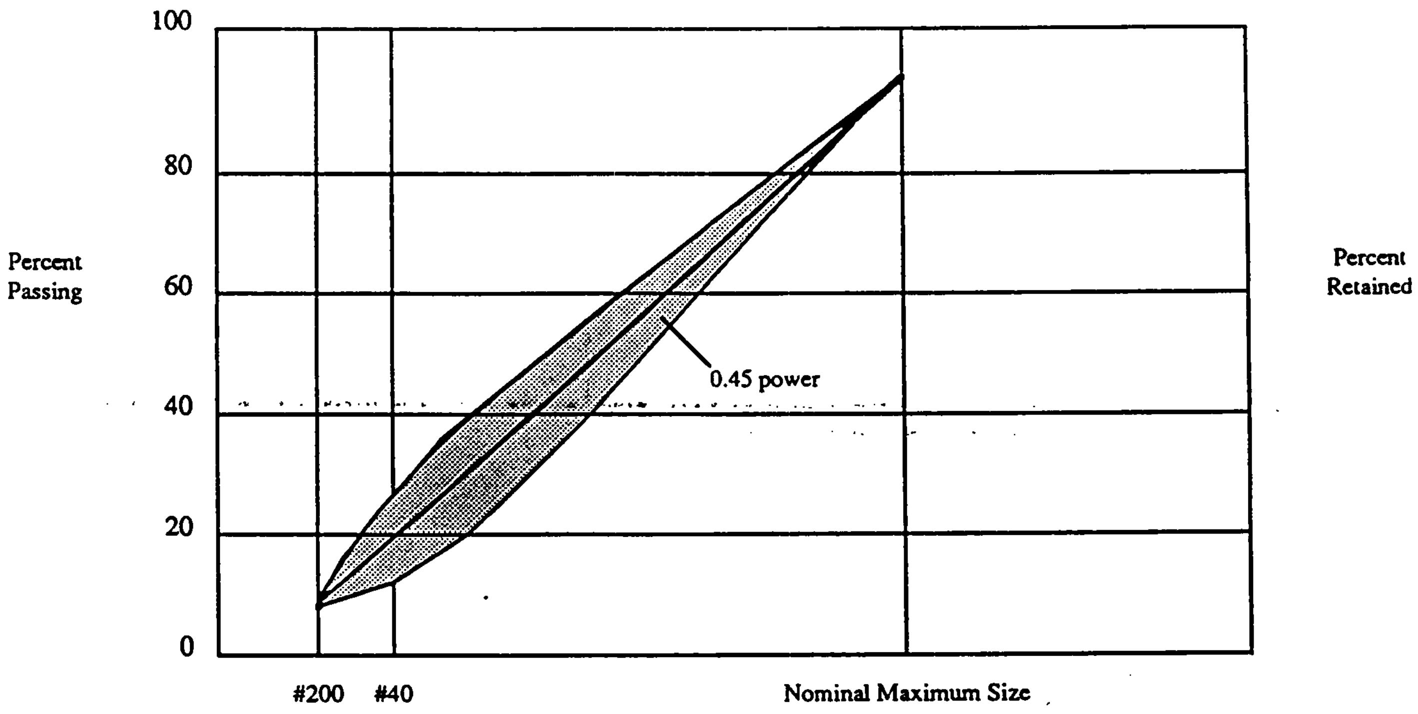


[1] Standard Specifications for Wire Cloth Seives for Testing Purposes, ASTM Designation EII (AASHTO Designation M92).

[2] For processed aggregate, the nominal maximum particle size is the largest sieve size listed in the applicable specification upon which any material is retained.

[3] Mixtures in the 1% tolerance band shall be permitted only when experience indicates that the mixture will perform satisfactorily and when all other criteria are met.

Figure 5.9. Minimum percent voids in the mineral aggregates (from Asphalt Institute Manual MS-2).



Sieve Sizes Raised to 0.45 Power
Note: Gradation curve should not cross or enter shaded zone.

Figure 5.10 Aggregate gradation specification plotted on 0.45 power chart.

6

Economic Analysis of Product Impacts on the Highway Community

Performance-based specifications for asphalt binders and asphalt-aggregate mixtures will have profound economic impacts on the public agencies and private organizations involved in supplying the materials, and in constructing and monitoring asphalt pavements. In this chapter, a preliminary discussion is presented of the scope of these impacts in the following areas: the system-wide supply and demand equation for asphalt cement; the engineering and costs for individual projects; the reduction of financial risk to all parties involved in highway construction, operation and maintenance; and the overall budgeting process for highway construction and maintenance. *The content is intended to stimulate discussion of this important topic and lay groundwork for more sophisticated economic analyses that will be made during the next year by specialists in each area.*

System Economics: Potential Changes in the Supply and Demand Equation for Asphalt Suppliers

It is well recognized that different crude oils inherently contain different quantities of asphalt. Different crude oils also require different refining process conditions for the separation of an asphalt.

Historically, the price of asphalt has been viewed to a large degree as an economic loss to the refinery and is "shored up" by the higher value of the lighter products. Asphalt is generally viewed as a major product of small refineries but only a small part of the production of many large refineries. For example, refineries with less than 10,000 barrels per day of crude oil capacity yield 7 percent asphalt production (Holbrook, 1985). On the other hand, larger refineries yield only 2 percent asphalt production (Holbrook, 1985).

To understand the functioning of the refinery market economy, one must first recognize that there are five fundamental questions to which this economy must respond (McConnell et. al, 1990). The questions are as follows:

1. **How much** is to be produced? At what level and to what degree should available resources be utilized in the production process?

2. **What** is to be produced? What collection of products and services will best satisfy society's petroleum demand?

3. **How** is that output to be produced? How should production be organized? What firms should do the producing and what productive techniques should be utilized?

4. **Who** is to receive the refinery product output? In particular, how should the output of the economy be shared by individual consumers?

5. Can the system **adapt** to change? Can the system negotiate appropriate adjustments in response to changes in consumer demands, resource supplies, and technology?

An Economic Basis for Product Slate

Given the refiners' products and resource prices established by competing buyers and sellers in both the product and resource markets, how would a refinery economy decide the types and quantities of goods to be produced? Remembering that refinery businesses are motivated to seek profits and avoid losses, it can be generalized that those refinery products that can be produced at a profit will be produced and those whose production entails a loss will not. What determines profits or the lack of them? Two things:

1. the total revenue generated by product sales and

2. the total production costs.

Both total revenue and total costs are price-times-quantity figures. (McConnell et. al, 1990). Total revenue is determined by multiplying product price by the quantity of the product sold. Total costs are determined by multiplying the price of each resource used by the amount employed and summing the cost of each.

Refinery Economic Costs and Profits

To say that those refinery products which can be produced will be produced and those which cannot is only an accurate generalization if the meaning of refinery economic costs is clearly understood. To grasp the full meaning of costs, the refinery business should be thought of as a business represented by an organizational chart, that is, a business "on paper," distinct and apart from capital, raw materials, labor and entrepreneurial ability which make it a going concern (McConnell et. al, 1990). To become an actual producing refinery, this "on paper" business must secure all four types of resources.

Refinery economic costs are the payments that must be made to secure and retain the needed amounts of these resources. The per unit(size of these costs will be determined by supply and demand conditions in the refinery resource market. The point to emphasize is that ----like land, labor, and capital ---- entrepreneurial ability is a scarce resource and consequently has a price tag on it (McConnell et.al, 1990). Costs therefore must include not only refinery wage and salary payments to labor, and interest and rental payments for capital and land, but also payments for the entrepreneurial skill required to organize and combine the other resources in the production of some petroleum commodity. The cost payment for these contributions by the entrepreneur is called a **normal profit** (McConnell et.al, 1990). Hence, a refinery product should be produced only when total revenue is sufficient to pay wage, interest, rental, and normal profit costs. Now if total revenues from the sale of a refinery product exceed all production costs, including a normal profit, the remainder would accrue to the entrepreneur as the risk taker and organizing force in the going concern. This return above all costs is called a **pure**, or **economic, profit**. It is not an economic cost, because it need not be realized for the refinery business to acquire and retain entrepreneurial ability.

Traditional Refinery Economics Approach

Refineries, as a result of the changing economies, have modified their processes to meet changing market conditions and also to meet changing crude oil availability. The increasing price of crude oil and resulting petroleum products has made residual heating oil, for example, uneconomical as compared with coal and natural gas (Holbrook, 1985).

Crude oil quality is also changing. A variety of different gravities of crude oil is available in the world. Right now the crude oil processed in the United States is about 60 percent light and 40 percent heavy (Holbrook, 1985). The known reserves of heavy crude oils in the world are generally found in Venezuela, Mexico, and a number of other countries. Crude oil discoveries are generally heavy. As a result, it is predicted that by 1990 there will be a dramatic switch from light to heavy crude oils. That means more residuum available to convert to asphalt (Holbrook, 1985).

Price of crude oil certainly has an effect on availability and what the refinery is going to process. In the past, the light crude oils have sold at a premium. With the recent decline in price of the light crude oils and the simultaneous increase in the price of the residuum, demand for heavier crude oil has increased. This trend is expected to continue in the foreseeable future. Consequently there are many factors that must be considered in the analysis of refinery economics (Holbrook, 1985). However, asphalt production in the majority of the cases is not viewed as an economically attractive market commodity for several reasons: (a) the market volume is viewed as small and satisfactorily supplied by current production; (b) asphalt prices are low and crude oil prices are high (asphalt should recover at least the costs of the crude oils); and (c) asphalt traditionally competes with the so-called light products, and the economics are determined by the selling price of the products produced.

Future Potential Asphalt Market Economics

Refinery economists frequently indicate that asphalt prices must increase in order to insure product viability. They further hypothesize that refinery operations must recover crude oil costs from asphalt in the market economy, or more of them are going to cease asphalt production in the future.

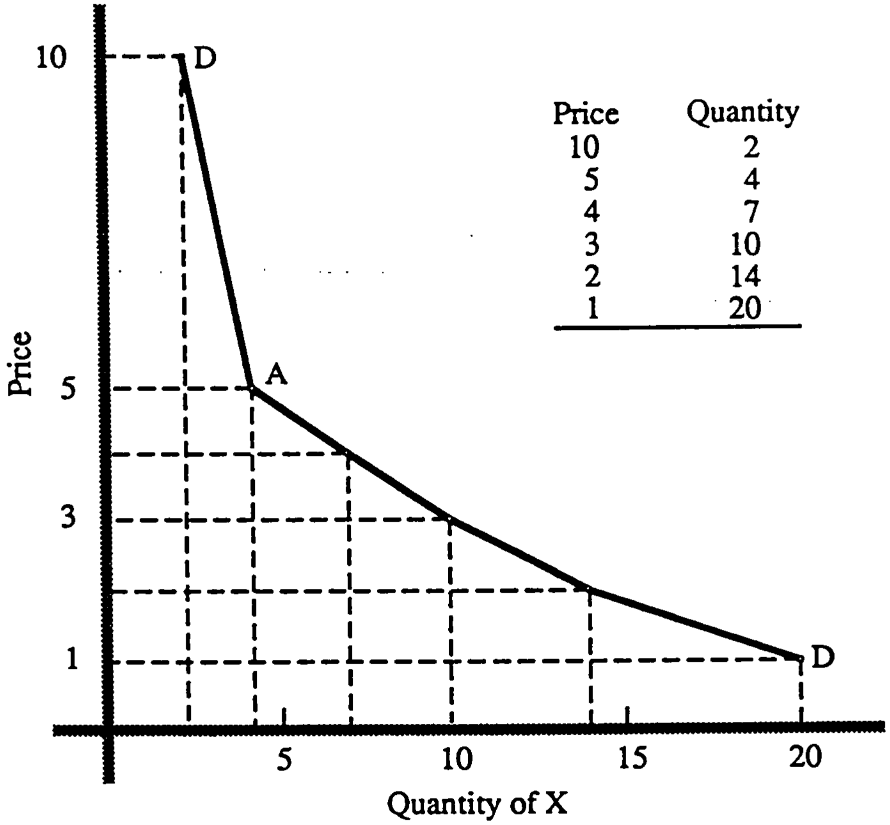
In short, refineries have traditionally viewed asphalt market economics from the supply side. But the consumer demand for a specific product quality will also affect the economic equation also. Figure 6.1 illustrates conceptually the demand equation term (Ward, 1967). By measuring horizontally from the vertical axis to the point on the graph, the product quantity is determined. Similarly, by measuring vertically from the horizontal axis, the price is found at which the quantity is bought. Thus, point A in the diagram corresponds to the second row in the table indicating that at a price of $5 the consumers are prepared to buy a total of four units. Furthermore, the producer will recover the same dollar value if selling 2 units for $10 or 20 units for $1.

Figure 6.2 shows the superposition of the supply graphics (curve SS) onto the demand graph (curve DD). Conceptually, as with the demand, the supply can be represented on a diagram, and a smooth curve drawn to represent the points that determine price-and-quantity pairs (Ward, 1967). At Point B in Figure 6.2, the two curves intersect. At this point, the total amount the consumer is willing to buy at the price of three dollars just equals the total amount the consumer is willing to sell at that price. If the market can move to that point, everyone will be satisfied -- that is, everyone who is willing to pay the price or accept it will be able to make economic deals in the market.

Of course, there is one obvious difference between the supply and demand curves: demand slopes downward to the right while supply slopes upward to the right. It seems reasonable that this should be so. When the price is lower, the consumer can afford more. When the price is higher, the consumer will be more selective in purchases, but may be willing to obtain the commodity if the quality is enhanced. Herein lies the potential for the future growth of the asphalt market.

The SHRP performance-based specifications for asphalt binders will identify acceptable response range limits to control fatigue cracking, permanent deformation, thermal cracking, aging, adhesion and water sensitivity. These specifications will allow the design engineer to select an asphalt binder (modified or unmodified) based on the required pavement performance level, given the expected traffic and environmental conditions.

SHRP envisions that these performance-based specifications will provide for significant increases in pavement service life, with attendant decreases in maintenance and rehabilitation costs. Although initial or first costs for the asphalt binder may be higher, when amortized over the extended life of the pavement, this may result in a more economically attractive engineering investment strategy. Consequently, the demand for such asphalt binders should significantly increase.



Price	Quantity
10	2
5	4
4	7
3	10
2	14
1	20

Figure 6.1 Graphical concept of commodity demand.

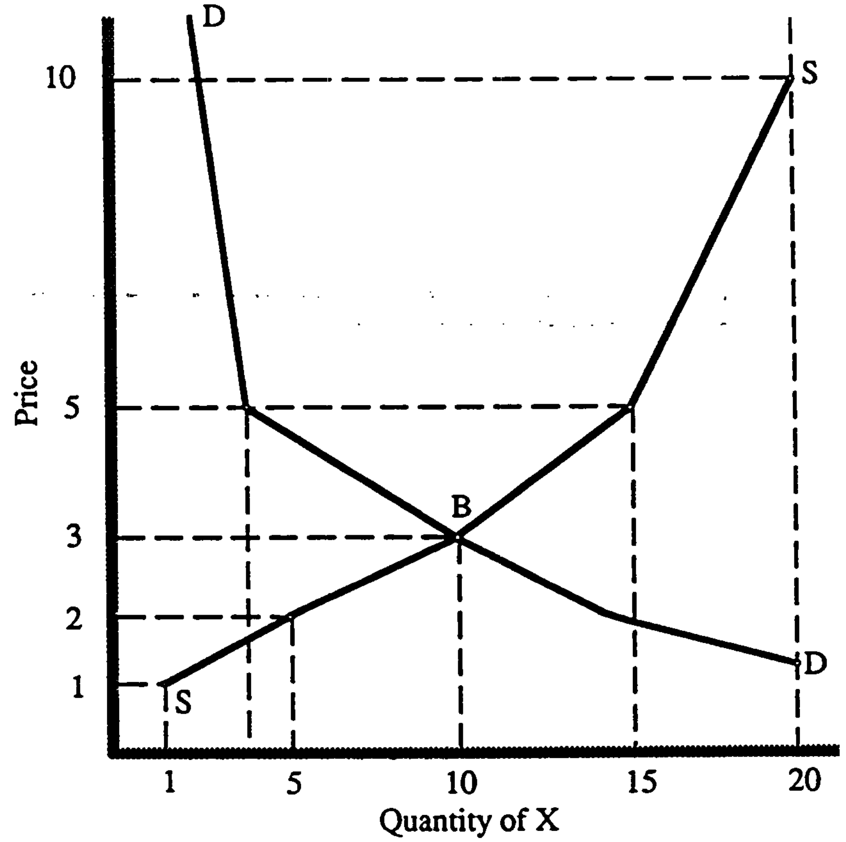


Figure 6.2 Graphical concepts of commodity demand and supply.

From the supply side, the refineries might then view asphalt as a specific marketable commodity (entrepreneurial ability), based both on the potential higher selling price and the increased demand, that will compete with the lighter petroleum products. The quality of the asphalt, in terms of superior performance in relation to specific pavement distress factors, should be accompanied by a price increase. Obviously, the stability of this increase will be established by marketplace competition. As the refining industry expands its production, new firms, attracted by these above-normal profits, will emerge.

The entry of new firms, however, should be a self-limiting process. As new firms enter the asphalt market, the supply should increase relative to demand. This may lower the market price to the end that economic profits will, in time, be possibly "competed" away. The supply and demand situation prevailing when economic profits become zero or minor will determine the total amount of asphalt produced. At this point, the asphalt refinery industry will maintain its "equilibrium size" until a change in the asphalt demand or supply disturbs that equilibrium.

However, if the asphalt market as viewed by the refineries for the performance-based asphalt binders is less than favorable, then they would not be attracted and view the market as a declining industry economically. At this point, other entrepreneurs such as those in the modifier industry would compete in this asphalt marketplace based on their viewpoint of an expanding industry and above-normal profits created by increased consumer demand.

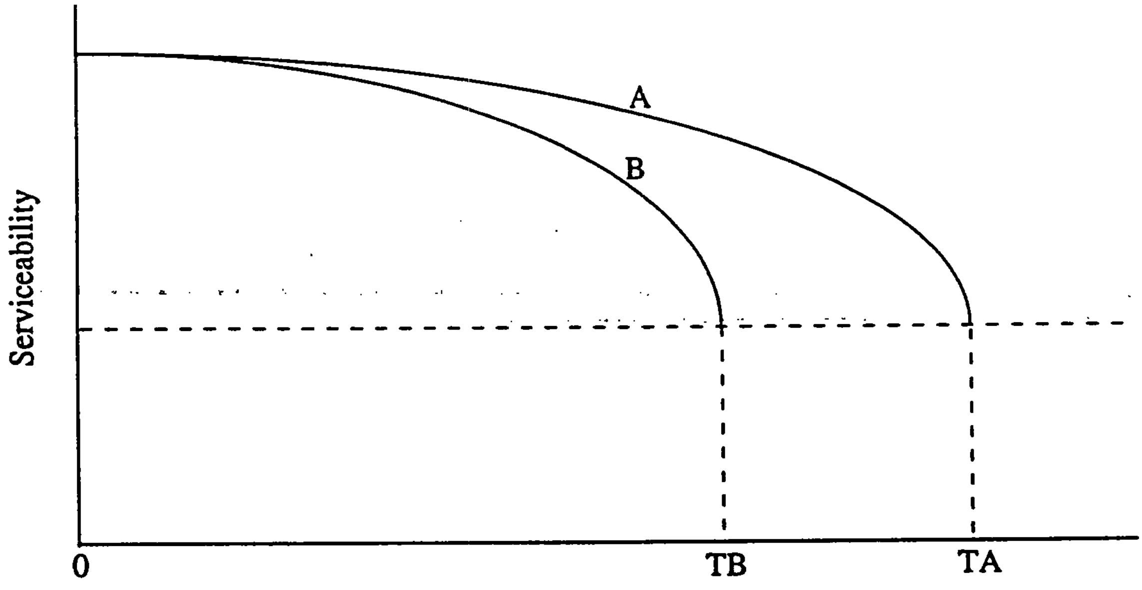
Either way, the demand placed on the marketplace for "quality" asphalt binders should provide suppliers of this material through supply market competition. Eventually this competition could possibly reach an equilibrium size and initial asphalt binder costs will also equilibrate.

Project Economics

Specifications which allow for enhanced binder properties or (the use of additives) may increase significantly the cost of binder systems and thus the mixtures and pavements produced with these binders. To justify this expense, it is necessary to improve performance, reduce maintenance and rehabilitation, or sufficiently extend the pavement life to offset the increased material cost.

General Approach

Pavement performance is usually defined as the trend in serviceability with increasing number of axle load application{ or time as shown in Figure 6.3. While serviceability indicates how well a pavement is serving its intended function of carrying traffic, it is generally described by a pavement condition index which quantifies the condition of a pavement section with respect to distress at the specified point in time (Penn(DOT, April 1985).



Number of Load Applications or Time

Figure 6.3 Typical performance relationships involving serviceability with time.

These pavement condition indicators normally involve or relate to the following:

a. cracking (fatigue, thermal, shrinkage);
b. permanent deformation (shoving, rutting);
c. serviceability (roughness);
d. skid resistance;
e. ravelling;
f. moisture damage; and
g. wear resistance.

All of these charactmristics are influenced by environmental, structural, material, and construction variables. Thus, the basic element required is an algorithm or model which can relate these variables to the pavement condition indicators with time or more specifically to pavement performance.

Models

Models relating materials and mixture properties to performance will be focused on the asphalt binder and its interaction with aggregate. Figure 6.4 provides a framework for relating asphalt cement specifications to predicted pavement performance and for evaluating the economic effectiveness of such specifications. The evaluation of performance-based specifications involves a stepwise procedure consisting of the following main elements:

1) a model that relates specification criteria for asphalt cement to fundamental response variables such as viscosity and bitumen stiffness;

2) a system for performing the mixture design and for relating the proportions of asphalt and aggregate in the mix to fundamental mixture response variables;

3) a pavement structural analysis algorithm; and

4) a performance prediction algorithm.

The key element in the framework is the algorithm for predicting the trend of a pavement condition indicator as a function of time or load applications. The framework established is general and accommodates performance models that are based on structural criteria (e.g., cracking, permanent deformation), user oriented criteria (e.g., roughness, skid resistance), and durability criteria (e.g., raveling, moisture damage, wear resistance). It is recognized that the importance of the various pavement condition indicators can vary with the user agency, making it imperative to develop a framework that is useful for a wide range of performance models.

Numerous models are available for predicting pavement performance in terms of various condition indicators. Most currently available models relate material response such as resilient modulus, fatigue, or creep properties to predicted long-term performance, as evidenced by trends in cracking or rutting. In addition, considerable laboratory research has been conducted to identify models that relate mixture parameters (e.g., voids, asphalt content, aggregate absorption, etc) to material response such as resilient modulus or fatigue parameters. Unfortunately, there are few, if any, models that directly relate mixture parameters to performance. Therefore, the relationship between mixture parameters and pavement performance will have to be evaluated using procedures such as the stepwise procedures illustrated in Figure 6.4.

The performance models can be categorized according to the methodology by which they were developed (i.e., empirical, mechanistic-empirical, mechanistic) or according to the prediction methodology followed (i.e., the model predicts the time and number of load applications to a predefined failure condition, or the model predicts the trend in a pavement condition indicator with time or load applications).

The models for predicting fundamental response variables for asphalt cement and for the asphalt-aggregate mixture will be developed in SHRP contracts A-002A and A-003A, respectively. Validation of these predictive models and test results will be performed by SHRP contract A-005.

The performance prediction algorithm will allow the evaluation of the relationship between asphalt specification criteria and pavement performance. The choice of specification criteria will be aided by the performance model. Logically, the specification criteria selected must be those that significantly influence the performance predictions. In addition, the performance prediction algorithm will influence the selection of other models such as those relating specification criteria to fundamental response variables for the asphalt cement; models for determining fundamental response variables for the asphalt concrete mix; and models for analyzing pavement structural response.

Engineering Economics

The methodology for evaluating the economic effectiveness of performance-based asphalt specifications will involve life-cycle cost analyses. It is recognized that higher initial construction costs may be associated with the new specifications. However, the expected improvements in pavement performance should justify the implementation of performance-based asphalt specifications. The evaluation of life-cycle costs provides a vehicle for attaching monetary values to performance predictions for a variety of pavement design alternatives.

Life-cycle costs include costs associated with initial construction (or reconstruction), routine maintenance, rehabilitation, user operation, user delay, and salvage value (NCHRP, 1985). Future costs are discounted according to a specified interest rate so that cost comparisons can be made on the basis of value at a particular point in time. Costs are considered over a designated analysis period, which can vary in length depending upon the specific conditions being analyzed. By comparing the life-cycle costs associated with various design alternatives, the economic effectiveness of implementing new performance-based specifications for a particular set of conditions

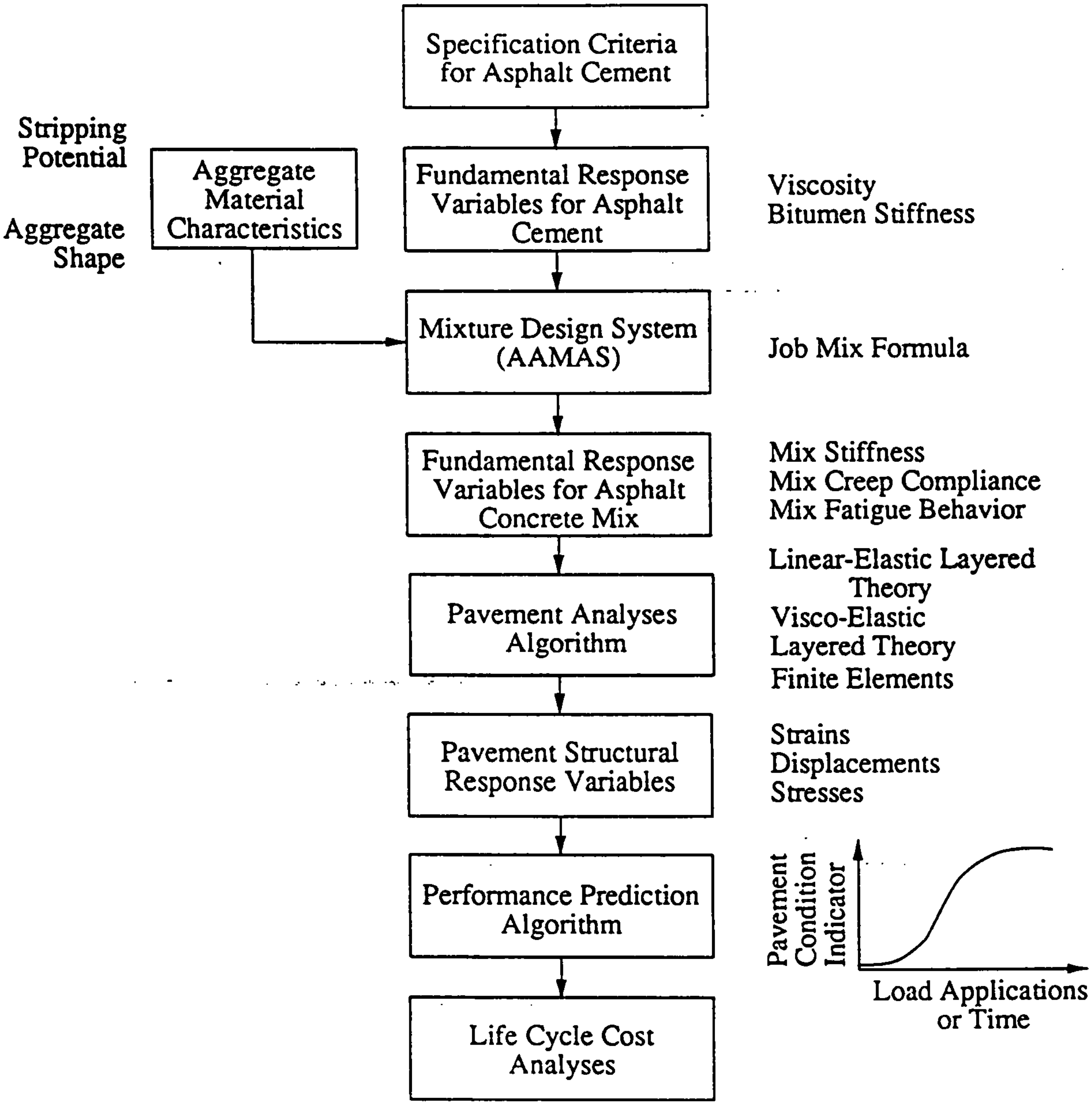


Figure 6.4 Conceptual framework for relating asphalt properties to performance.

can be evaluated.

Although life-cycle costing for pavements is not a new concept, it has not been widely utilized by state highway agencies (NCHRP, 1985). The reason most often cited for not using these analyses is the lack of certain input information related to user costs, interest rates, or the time value of money, and the inflation rate. Others question the appropriate methodology for integrating these factors into the life-cycle cost analysis.

This procedure, however, provides an effective means for analyzing all potential alternatives. Moreover, many agencies have based their selection exclusively on initial cost, without consideration of the future costs related to pavement performance. For long-term investments, such as for pavements, the initial or first cost is not the most critical issue. Life-cycle costs are dependent on the following: the projected performance or life of the various identified alternatives; the pavement type, design life, and cost of future maintenance and/or rehabilitation activities; the length of analysis period; and interest rates; etc. These must all be integrated into a procedure that will ensure the lowest life-cycle cost for a given design alternative.

The approach taken will be as follows:

(1) Estimate the increased first costs associated with the new performance-based asphalt specifications or the use of modifiers and the performance-based specification for the unmodified or modified asphalt-aggregate mixtures.

(2) Relate quantified specification values of asphalt and mixture characteristics to pavement performance using algorithms or models developed by the A-005 contractor.

(3) Estimate changes in maintenance, rehabilitation, or user costs based on the predicted performance and service life.

(4) Conduct life-cycle cost analyses using average annual cost, present worth, rate of return or benefit-cost ratios.

(5) Determine the economic impact of the proposed specification changes or use of modifiers.

For life-cycle analysis of pavements, mathematical models are needed to estimate the rate of pavement deterioration associated with each design alternative or rehabilitation strategy (Penn DOT, April 1985). Performance of a given strategy can then be predicted under future traffic conditions for a specific environment. These mathematical models define the damage functions which vary with pavement types and performance variables.

These damage functions are extremely important in developing life-cycle analysis methodology because they are used to predict future pavement condition. Table 6.1 presents a list of performance variables for which different investigators have tried to develop empirical models (Penn DOT, April 1985). It is evident that some of these models are unique for a specific pavement type.

Commonly used performance indicators are based on roughness, some form of distress such as fatigue and thermal cracking or permanent deformation. These models make it possible to quantify the performance and expected life using different design strategies by computing the time to reach a user-specified limiting value of each variable. This in turn helps to compute costs associated with each strategy during its life-cycle analysis. Figure 6.5 illustrates the comparison of different strategies over the service life of asphalt pavements (Penn DOT, March 1986).

Sensitivity Analysis

A sensitivity analysis will be used in the life-cycle cost analysis to determine the effect that a variable may have on the cost. Specifically, a sensitivity analysis is used to determine the absolute (or relative) change in the criterion variable as a result of an absolute (or relative) change in the predictor variable (NCHRP, 1985). In this instance the predictor variables might include any or all of the following: structural design; material properties; pavement distresses; and some measure of pavement condition. It may also be helpful in identifying various design options that may need to be considered in greater detail and variables that require additional information. A sensitivity analysis is generally more effective in the design stage of a pavement and should be a normal part of an economic analysis.

In the process of selecting a pavement design alternative, the designer may be uncertain as to the outcome because of inadequate input data, initial assumptions, accuracy of estimates, or any combination of the preceding. The critical questions in a life-cycle cost analysis are the following: "(1) How sensitive are the results of the analysis to variations in these stochastic parameters? (2) Will these variations tend to justify the selection of an alternative not currently being considered? (3) How much variation in a given parameter is required to shift the decision to select alternative B rather than alternative A?" The basic purposes of a sensitivity analysis are to determine how sensitive the outputs from the life-cycle cost analysis are to variations in certain inputs and to evaluate the risk and uncertainty associated with a selected alternative. This allows the designer to determine the probability of selecting the wrong alternative.

Risk exists as a result of the stochastic nature of the input variables, but can be considered in the analysis to determine its effect on costs (NCHRP, 1985). Pavement design itself involves a degree of risk in that a certain probability exists that a pavement will not reach its design life. Decisions are generally based on calculated risks, which means gambling on the chances that the future will be as predicted by educated judgments. Decisions that are made with the full realization of the uncertainties assume that the future may not be the same as planned and the designer knows the

Table 6.1 List of performance variables to be considered in developing damage functions

FLEXIBLE PAVEMENTS

- Present Serviceability Index
- Rut Depth
- Cracking
  - Linear
  - Fatigue
- Roughness
- Raveling
- Potholes

OVERLAID FLEXIBLE PAVEMENTS

- Cracking
  - Transverse
  - Longitudinal
  - Multiple
  - Alligator
- Patching
- Roughness
- Serviceability Loss
- Rutting

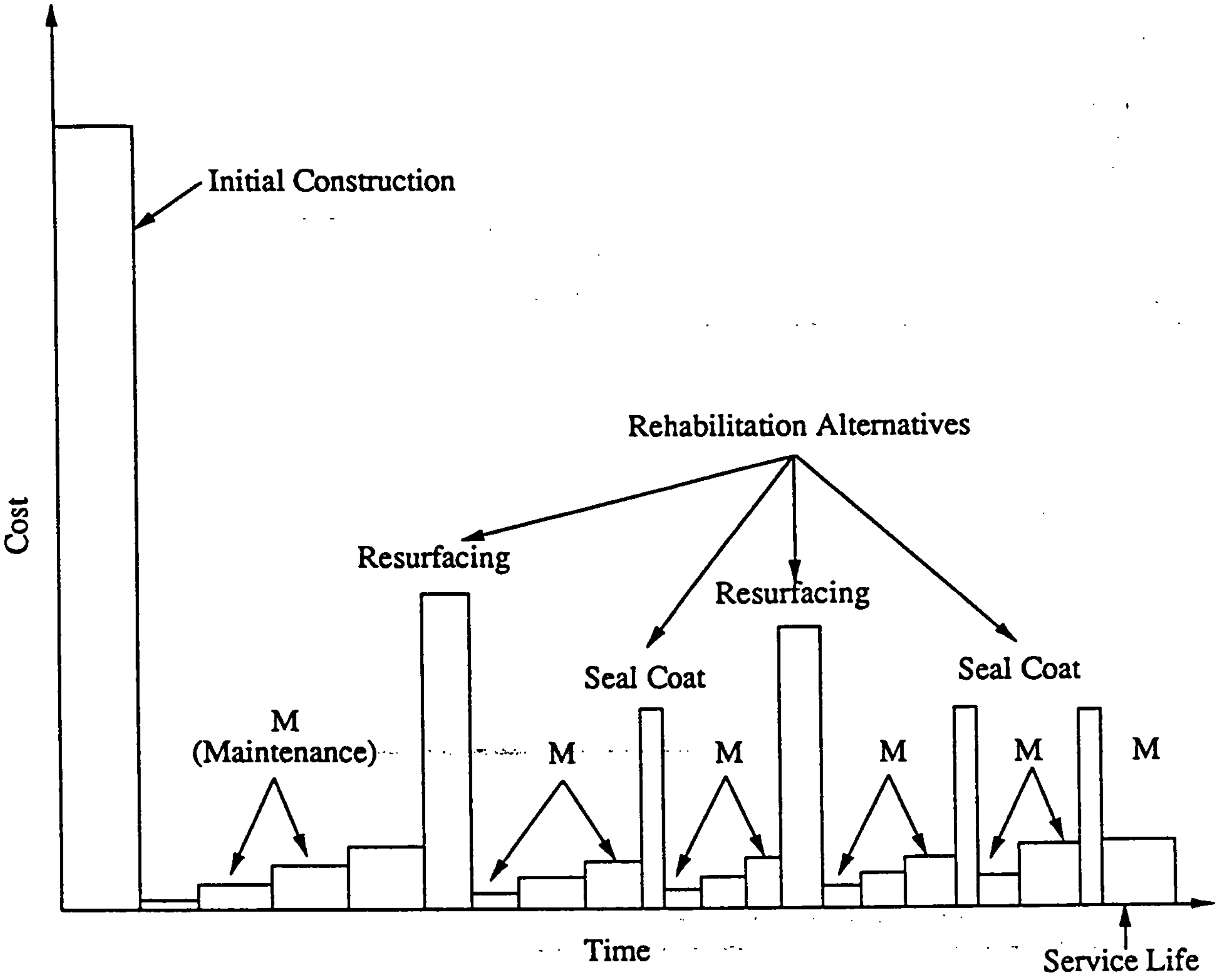


Figure 6.5 Comparison of different strategies over the service life of asphalt pavements.

effect that any variation may have on the predicted results.

The economic analysis for any paving project is, by necessity, based on the uncertainty of the future and on predictions of performance that often are inaccurate. Accordingly, the measurement of any economic costs and benefits implicitly includes probability judgments (NCHRP, 1985). The basic components of input and output prices and quantities in an economic analysis seldom represent definite events in that they could be described by single values. It is, therefore, desirable for an economic analysis to take into consideration the range of possible variations in the values of the basic components and hence the extent of the uncertainty associated with the outcome. It is possible to generate performance prediction curves (Figure 6.6) for dealing with treatment of uncertainties.

Minimizing Producer and User Risks

As discussed in Chapter 2, the SHRP asphalt program is founded on the intuitive concept that, first and foremost, asphalt pavement performance is significantly influenced by the properties of the asphalt binder. Therefore, to design a pavement to provide the performance dictated by its present and future "environment", consideration first must be given to selecting an asphalt binder with properties that, insofar as possible, ensure the required minimum performance levels.

Once the influence of the asphalt binder on performance is defined, the effect of its combination with aggregate is to be considered. The mixture specification is viewed by SHRP as modulating the binder response in each performance area. The availability of both specifications allows a range of material selection options to be considered for any particular paving project.

These procedures will require new equipment, new materials (i.e., asphalt and aggregate modifiers), and more broadened training related to understanding of the relationship of material characterization as related to pavement design and resultant performance. All these parameters will impact the state highway agencies' initial costs pertaining to their financial investment in the adoption of the asphalt program products. However, the results of the SHRP Asphalt Program research efforts should increase substantially the service life of asphalt concrete pavements due to the better understanding and definition of the component materials, design and performance factors. The initial investment amortized over the entire pavement life should reflect a reduction in the frequency and magnitude of future maintenance and rehabilitation costs. In other words, it will be more economically attractive to invest in first-cost dollars today extended over a longer service life, than to invest in future dollars to maintain that same pavement that did not provide its estimated service life. The financial risks to the SHA will be greatly minimized, since the range of material and performance factors are more accurately defined in the specifications.

The producers' financial risks are also envisioned to be reduced since clearly there will be competition in a market established by performance-based specifications. The two main thrusts of materials development in the SHRP asphalt program are the

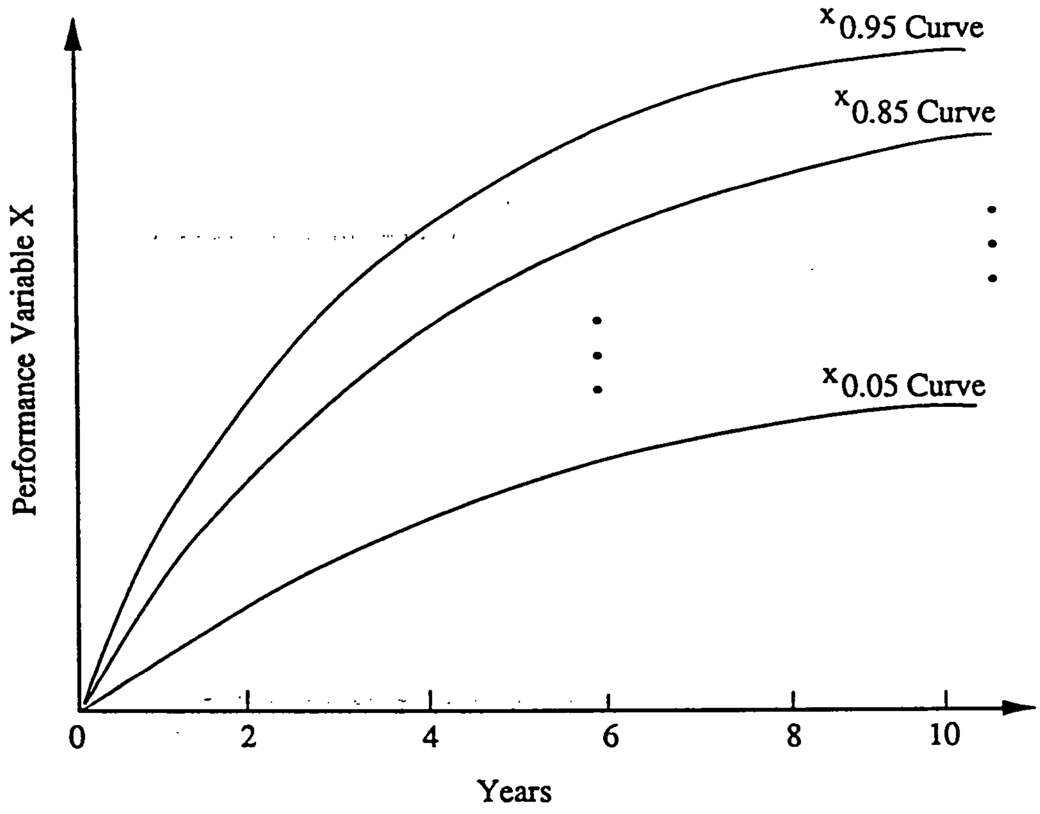


Figure 6.6 Treatment of uncertainties in performance prediction.

development of a consistent asphalt and the chemical modification of asphalt in the refinery. The refinery will have an understanding that through application of refinery-scale separation and blending techniques it has an opportunity to compete for the asphalt market related to performance. However, if modification is required, the physical and chemical response of a consistent asphalt to diverse modifiers will be well defined. The refiner could take advantage of this knowledge or another industry (i.e., modifier groups) could supply the modified asphalt. The less speculation related to the manufacture of a performance-based specification material, the less the producers' financial risk. Ultimately, this reduction in risk will be reflected in a stabilizing of material costs.

The contractors, on the other hand, should be able to cost the project from bid to construction in a consistent manner. The selection of materials, mix design and pavement design will be founded on the same fundamental engineering properties. The specifications should eliminate the arbitrary selection of materials and mix design which in turn should reduce the contractors' financial risks due to speculation related to the SHA specifications. This process should provide for more uniform costs reflected by the contractors' bids. In addition, the state highway agencies should reap additional benefits related to substantial reduction of materials and construction claims.

Summary: Strategic Plans and Supportive Budget Forecasting

State highway agencies are continually confronted with budget and fiscal constraints related to highway construction and maintenance activities. Prudent investment of the taxpayers' dollars in these activities is a primary concern. Consequently, many state highway agencies have developed strategic plans for future construction (new and rehabilitation) and maintenance. Many states have developed strategic plans employing some form of pavement management system whereby each year a specific number of highway miles is scheduled for construction and maintenance. By such a process, highway budgets are rationally developed and allocated. Ideally, all existing mileage would be upgraded cyclically within a designated number of years.

However, when asphalt pavements fail prematurely and require immediate attention it drains the fiscal year's budget and delays, or possibly cancels, previously scheduled construction and maintenance activities. Such unscheduled delays wreak havoc with the budget planning process and ultimately increase the taxpayers' future costs.

Realistically, pavement service life involves a degree of risk in that a certain probability exists that a pavement will not reach its design life. Service "life" is broadly defined as a period during which pavement condition remains satisfactory or relatively better than the condition at the time of rehabilitation. Although a small percentage of the risk is derived from poor or improper construction practices, the majority is due to the lack of proper material characterization linking quantifiable, fundamental physicochemical and engineering properties of the asphalt binder and the asphalt-aggregate mixture to the structural design of the pavement layers.

SHRP anticipates that the quantified properties included in the performance-based specifications for both binders and mixtures will markedly improve performance and substantially reduce maintenance and rehabilitation costs. Moreover, it is expected that through a better understanding and definition of the design and performance factors of the component materials, the service life of asphalt pavements will substantially increase and premature pavement failure will be greatly reduced. This will allow rational planning and more stable, projected highway budget estimates associated with these plans by the state highway agencies.

7

Strategy for Implementation of the SHRP Asphalt Program Products

Introduction

The implementation of the SHRP asphalt products cannot be accomplished completely within the time and resources available to the program. However, a significant and meaningful portion of the implementation must be accomplished prior to the end of the SHRP asphalt program. Thus, there are a number of necessary actions that must be carried out concurrently with the research to assure successful, timely implementation of the products in the post-SHRP period. This *implementation strategy* is described in this chapter.

At its most elemental level, implementation is simply the effective dissemination of information on the products of the asphalt research program to the users and producers; this type of passive, one-way activity, although necessary to alert a wide audience to the SHRP products, is not sufficient to achieve their complete, effective implementation. It is critically important that the overall strategy and execution of the implementation process actively involve the users and producers in defining the most practical, readily adoptable form for the products. This involvement must be interactive with the researchers so that the products of the program represent the best possible mix of the following characteristics: reliance on sound engineering and scientific principles; well-planned and documented validation; simplicity; ease of use; reasonable cost and impact on current operations; and excellent precision and accuracy.

Any implementation strategy must recognize the fact that there is a natural, human reluctance to change from the "tried and true" materials and techniques of the past to the new and unfamiliar. Indeed, this tendency serves the important purpose of minimizing costly errors that may arise from the ill-conceived and uninformed adoption of new technology. The successful implementation strategy, then, must involve the users, producers and researchers in an open, three-way dialogue to identify and assess the positive and negative impacts of new products on the users and producers and guide their development in such a way that the benefits are enhanced and the disadvantages minimized.

In the particular case of the products of the SHRP asphalt program, the implementation strategy must also take account of the fact that the information presented in the form of new material specifications is, for the most part, of an interim nature, since a 5 year research and development program is not sufficient for a complete validation process requiring the monitoring of the long-term performance of controlled, well-characterized field test sections. Thus, both the research and implementation strategies must provide specific tools and techniques to continue the validation process and incorporate new results in the specifications.

Of particular importance is the need to integrate the implementation into the fabric of the research from a very early stage of the program. This requires information flow to the various users and producers through both presentations to various interested groups at national, regional, state and local meetings and, more importantly, the establishment of meaningful routes for two-way dialogue with user and producer groups throughout the country. This will help satisfy the real need to guide the research to readily-implementable products by fostering a continual, active assessment of their utility and practicality by those who will use and produce them. This process ideally will also make the products so familiar to the highway community that any reluctance to change will disappear long before the research is completed, to be replaced by an enthusiasm to employ products whose advantages over previous technology are clear and whose drawbacks have been minimized by the involvement of the users and producers from the earliest stage of their development.

In summary, the implementation strategy for the products of the SHRP asphalt research program during the course of the SHRP asphalt research program itself will rely upon three main approaches (figure 7.1):

1) *information sharing* to familiarize the highway community with the scope and progress of the product development, especially of the two model specifications, the mix analysis system and the supporting test methods;

2) *establishment of interactive mechanisms* for the ongoing, substantive participation of users and producers in the process of product definition and development; and

3) *development of marketing plans* for well-defined, implementable products.

To be effective, all three techniques must begin at an early stage of the research. This strategy will set the stage for similar post-SHRP interactive implementation activities conducted to complete the accomplishment of the marketing plans developed for the SHRP products; and to further refine and calibrate the performance-based specifications with LTPP pavement performance data and experience gained through their routine use.

Finally, to aid in overcoming some of the anticipated problems in the implementation of such a large and complex program area, an Implementation Expert Task Group has been established in the SHRP asphalt program. This task group will be made up of recognized representatives of the relevant user and producer agencies and organizations who can both provide information to their respective agencies

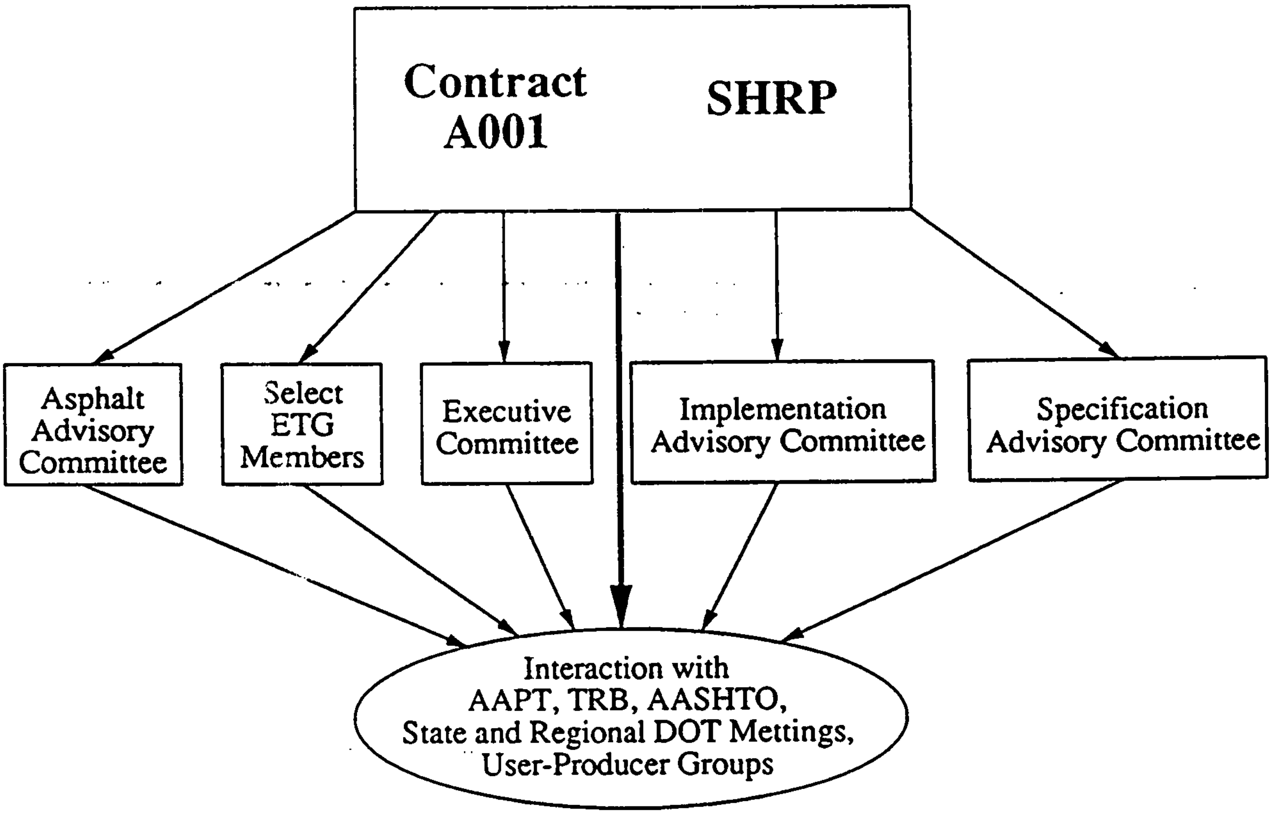


Figure 7.1 Continuous implementation approach.

throughout the five-year research program and advise SHRP on the development of interactive mechanisms and definition and marketing of products of the program.

Information Sharing

In terms of relative importance, this first approach is the least important of the three. Although it lacks an effective means for dialogue, information sharing, when done well, does present the opportunity to inform a wide audience of the progress of the program and the ongoing definition of the products. Moreover, it is very helpful in preparing target audiences to participate in the interactive implementation activities discussed in the next section. The various stratagems discussed here may be employed to advantage in information dissemination.

Updates of Ongoing Research

Involvement and interest by major industry groups can be encouraged through periodic distribution of information and research findings beginning at the earliest stages of the program.

To specifically meet this objective for the SHRP asphalt program, the following tasks are being performed.

a. Provide information for SHRP Focus. Up-to-date information on current studies is being provided for Focus, the monthly SHRP newsletter.

b. Provide information and articles for various trade publications. These articles provide information on current activities, proposed research direction, and anticipated products.

c. Provide updates to various user and producer groups and to the FHWA. These updates are being presented by A-001 and SHRP staff to the various trade and technical meetings held through the end of the program (figure 7.1).

d. Provide updates and information to AASHTO and ASTM committees. This information is invaluable in facilitating the smooth adoption of the asphalt program specifications as standards by these national, standard-setting organizations.

e. Provide information to SHRP for other presentations. Information is being provided for presentation to special groups (e.g., Congressional committees and AASHTO committees).

Develop Information Packages

To ensure that information developed by the research effort will be shared most effectively, information packages using the findings of the asphalt program are being developed and a significant information transfer activity conducted to ensure that the user and producer groups are anticipating the findings and recommendations and are receptive to their adoption and use. These information packages incorporate data and results from all aspects of the program with special attention to implementable findings.

Each organization has individuals at different levels with different perceptions of a new technology. If information is to be shared effectively, these functional classes of individuals must be identified and their specific informational needs, uses, and deficiencies determined. Specific tools that have shown to be effective for the sharing of information with each user level must be identified so that each group will be addressed at the appropriate level of technical detail.

Technology sharing (or transfer) can be broken into two types, "vertical" and "horizontal." Vertical transfer takes place when a process or product is implemented and becomes recognized as "state of the art" in the system. Horizontal transfer is the process by which a technology from one application is adapted to a different application. Generally, SHRP will rely upon the vertical transfer process.

Since implementation is the end product of effective technology transfer, the media tools chosen to make up the appropriate program must be able to impact every level of user. There are a number of tools available to combine into an effective system of information sharing for the SHRP asphalt program.

a. Presentations. Presentations given to professional and trade societies or at other progressional meetings can result in an estimated time for transfer of one to three years. The effectiveness depends largely on the size and type of audience and the effectiveness of the speaker.

b. Visits. Personal visits between implementation team members and users can shorten the estimated time of technology transfer to six months to two years. Visits also allow for interaction on a personal basis and can influence the user more than pesentations.

c. Courses. Another tool for transferring knowledge is through short courses, seminars, and schools. The time of transfer is estimated to be a few days to one year. This should not be confused with general training courses. Instead, these courses are much more specific and are conducted in greater detail. Several are currently forecast for very specialized topics in the SHRP asphalt program.

d. Audio-Visual. This type of tool is reflected in the use of films, packaged slide presentations and television, using either video tape or closed circuit. The effectiveness of this media alone does not appear to be quantitatively known. However, the quality of this type of product is a major factor in its effectiveness.

An optimum information sharing program must utilize several of these available tools to provide an effective technology transfer system for the type of user involved.

Establishment of Interactive Mechanisms

At this juncture in the SHRP asphalt program, two main interactive mechanisms have been identified to promote implementation of SHRP products through the direct involvement of the highway community in their development, viz. *user-producer groups and cooperative test programs*. Using these mechanisms for implementation, new products are not seen as "imposed" on the highway community, rather the entire community shares the responsibility for their development and acceptance becomes a foregone conclusion for those products that meet the test of utility and practicality.

User-Producer Groups

Essential to the development of satisfactory specifications is their continuous review and evaluation by users and producers within the asphalt industry and the highway community during the development process itself. The objective of this effort is to allow all interested and affected parties to have input during the development of the specifications, allowing the specifications to benefit from industry input and insuring that there will be minimal "surprises" to the producers and users at the conclusion of the asphalt program in 1993. Thus, implementation will proceed concurrently with and integral to the research and development process that leads to the finished specifications.

The interactive mechanism chosen to foster this continuous evaluation is the development of working relationships with various groups of users and producers and standard-setting organizations such as AASHTO and ASTM. As shown in figure 7.1, these groups and organizations involve producers of asphalt and modifiers, hot-mix contractors, and user agencies (states, cities, counties and FHWA).

To date, a strong and effective relationships involving the binder specification has been established with the West Coast User-Producer Group which is working with the A-001 contractor staff and will continue to provide interaction and input during the next 3 years. Working relationships have also been initiated with Midcontinent, East Coast and Gulf Coast user-producer groups, with relevant committees in the AASHTO and ASTM organizations, and with the Asphalt Institute. Additionally, steps have been taken to establish user-producer groups specialized toward modifiers and construction activities. The latter will utilize the efforts of the National Asphalt Paving Association (NAPA) and selected state paving associations.

While it would be ideal to have and interact with a single user-producer group with national scope, the diversity of interests, materials sources and environments throughout the United States makes this impractical. Moreover, the size and diversity of interests represented by such a group would make it extremely difficult to establish the coherent, two-way flow of information needed to develop and implement the specifications. Thus, initial efforts are concentrated upon working with smaller groups with unified, well-defined interests and needs.

Cooperative Testing Programs

Cooperative test programs will be employed by all of the contractors in the SHRP asphalt program to "shake down" and fine tune prospective test methods, test devices and protocols and establish their precision and reliability. There is no better way to measure the clarity and effectiveness of a new test method or pinpoint operational problems with a new test device than to conduct an interlaboratory test program involving organizations that will be called upon to routinely use them if they become "standards."

It is very important that the cooperative test programs rely principally on the participation of laboratories operated by user agencies, asphalt refiners, hot-mix contractors and other "front line" organizations. While the involvement of research agencies and consulting laboratories is desirable, these should represent a minority of the participating organizations.

Large-scale, cooperative test programs foster implementation by promoting wide dissemination of detailed information on new products and by demonstrating their benefits to the highway community through "hands on" use early in the development process. Moreover, this firsthand involvement encourages acceptance of new products by giving the user and producer agencies an early, continuing identification with the products and their success or failure.

Development of Marketing Plans

The first two implementation approaches discussed here, *information sharing* and the *establishment of interactive mechanisms* for the participation of users and producers, are principally designed to promote "real world" feedback into the product development process. They operate from the premise that new products that are already familiar to their target audience and, more importantly, in whose development process the target audience has played a substantive role, will be more easily implemented into routine, everyday use as specifications, test methods, construction materials, etc.

The third implementation approach, the *development of marketing plans*, shifts ahead from product development to the definition of the most promising mechanisms to accomplish implementation of specific products. Information sharing and interactive mechanisms can smooth the way for product acceptance, but a precise plan is still needed for each product, or at least each class of products, to successfully "sell" the product to the target audience.

If the implementation strategy presented here has been followed up to this point, then as is stated in the Federal Highway Administration's 1990 *Marketing Highway Technology and Programs*:

> "The result will be a customer base that has participated in the development of a product and is waiting for its completion, rather than one that has to be "sold" a product which they neither know or care about."

At this point, well-tailored marketing plans that "...effectively reach potential users and convince them to adopt the product..." (Federal Highway Administration) must be in place. Marketing plans extend the implementation strategy into the post-SHRP period and thus must be crafted to both accommodate and take advantage of the specialized resources and personnel available to organizations such as AASHTO, TRB, FHWA and ASTM to "close the sale" without the benefit of ready access to the SHRP staff or research teams.

A seven-step marketing process, which encompasses the development and execution of marketing plans for each designated, high-priority SHRP product, is discussed briefly below; the reader is referred to the above-mentioned Federal Highway Administration report for a fuller exposition. Certainly, in many instances steps may be eliminated or telescoped together to improve marketing efficiency and product delivery time, but the general flow of activity would remain the same.

Of course, for most R&D organizations, the development of marketing plans is a continual, ongoing process. SHRP's operation must differ from those of other, similar organizations because SHRP has a finite life and will be producing a "cresting wave" of new products late in its operating term. This means that the marketing process must also be concentrated into a short time frame, and that the organizations that will be responsible for the marketing after the end of SHRP must be brought into the process at a early stage. If this is not done, there is a strong possibility that the marketing process will falter or fail regardless of the degree to which information sharing and user-producer interaction in the development process were successful.

1. Conduct Product Assessment

In this step, potential products from the SHRP asphalt program are identified, primarily by the researchers and the SHRP staff, and evaluated in terms of how well they may satisfy specific operational needs. The evaluation would also include at least a rough estimate of the probable economic impact of the products on both users and producers and a determination of the most likely routes to market.

This step affords a ranking of the various products in terms of their likelihood of implementation, based on a balance of factors such as the followig: fulfillment of existing needs; cost; technical reliability and complexity; competition with existing technology; and probable routes to market. Ideally, it permits the allocation of finite implementation resources to those products whose implementation has a high probability of success.

2. Perform Market Analysis

Once implementable products have been identified, a market analysis is conducted to identify the probable users and assess potential obstacles to the adoption of each product.

These issues are addressed in fairly specific terms, by considering the following: the geographic location of the target audience; the size of the target audience; the organizational level at which a decision to use the product would be made; and any special skill or resources dictated by product use; etc.

An effort must also be made to fully explore the advantages that would accrue to the target audience through the use of the product; this should attempt to estimate its positive economic impact compared to any high production costs or increased first costs of use.

At the conclusion of this step, those potential products which have a low probability of success, either because of their cost or technical complexity or because they fail to provide a clear-cut benefit to a well-defined target audience, would be assigned a low priority in the remainder of the process.

3. Perform Product Analysis

In conjunction with the market analysis, a product analysis is also desirable, at least for those products judged to be "winners." This would cover an initial estimate of the costs and benefits to the user of adopting the product, or at least a plan for obtaining this information as part of the overall marketing effort.

It would also be necessary to analyze how the product matches the user's perceived needs and whether its adoption would require substantial changes in operations, training, facilities, etc.

Finally, the specific resources needed to manufacture and distribute the product must be quantified. While this may be fairly straightforward for a product such as a new test device, it could prove very complex to accomplish for a new specification for asphalt cements since the economic impact on many industries and users agencies must be assessed.

4. Evaluate Marketable Products

This step essentially will allow a midcourse review of the marketing process, distinguishing those products which would require more detailed market and product analyses. For those products for which adequate analyses are in place, marketing strategies (or in other terms, routes to implementation) would be determined and the mix of organizations needed to accomplish the marketing identified. It is possible that at this point a decision would be made to limit the implementation of certain products to information sharing only.

5. Perform Additional Market and Product Analyses

For certain high priority products, for example, performance-based specifications for asphalt binder and asphalt-aggregate mixtures, expanded analyses may be necessary. These analyses, probably best conducted by professionals in the areas of economics and marketing, will focus upon obtaining detailed estimates of costs and benefits to users and producers; the types of resources needed to successfully market the product; and the capital requirements and profit margins needed by industry to assure its ready production.

6. Prioritize Products and Allocate Resources

Based upon the detailed market and product analyses and an examination of the resources available for marketing, a decision must be made on what priority to assign to products for marketing activities. This decision is moot for certain products; the performance-based specifications developed in the SHRP asphalt program are its principal products and it is a foregone conclusion that they will be marketed vigorously.

The asphalt program will produce many dozens of other products, of the types discussed in report SHRP-A/IR-90-013, that will all have to be prioritized in this step. Certain test methods and test devices that directly support the specifications will have to receive a "bye" into the marketing process, but the ultimate utility of many other test methods, test devices, new materials, computer software, etc. will need to be weighed and a decision made upon which to allocate the finite resources available for marketing.

7. Develop Marketing Plans

A marketing plan will be developed for each product designated for marketing. In form, a marketing plan is a formal document that sets out in detail the actions, schedule, resources and budget for marketing a product such that it is readily made available by producers and accepted into routine operational service by its target audience of users. For our purposes here, the exact form of the marketing plan is not important, but a very useful format is presented in appendix A of the Federal Highway Administration report *Marketing Highway Technology and Programs*.

Those products which have been identified as requiring intensive marketing efforts may require the assistance of a professional marketing specialist to develop a comprehensive plan. It is envisioned that while a specific plan would be developed for each high priority product, "generic" or "standard" marketing plans for classes of lower priority products may be sufficient.

8
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9

Glossary of Terms

ACCELERATED LABORATORY TESTS (ALT). Laboratory tests specifically designed and developed to simulate pavement performance-related properties.

ADHESION. Molecular attraction or bonding exerted between the surfaces in contact between asphalt and aggregate.

AGING. Chemical and physical phenomena resulting from the loss of volatile components (short term) from the asphalt and progressive oxidation of the in-place asphalt-aggregate mixture in the field (long term) resulting in hardening (stiffening) of the asphaltic material.

ALGORITHM. A step-by-step procedure for solving a problem. Specifically, a procedure for solving a mathematical problem in a finite number of steps that frequently involves repetition of an operation.

ALTERNATIVES. Different courses of action or systems that will satisfy objectives and goals.

AMORTIZE. An economics term indicating the process of extinguishment of a debt over a specified period of time.

ANALYSIS PERIOD. The time period used for comparing design alternatives. An analysis period may contain several maintenance and rehabilitation activities during the life-cycle of the pavement being evaluated. It is sometimes referred to as the economic life, which is that period over which an investment is considered for satisfying a particular need.

ASPHALT-AGGREGATE MIXTURE ANALYSIS SYSTEM (AAMAS). A systematic mix design process employing a specific mix procedure, compaction method and performance-related, accelerated laboratory tests to provide for the selection of an optimal job-mix formula that meets performance-based specifications requirements.

BOND STRENGTH. Force of molecular attraction either within a material (e.g. asphalt) or between two different materials (e.g. asphalt and aggregate).

CHAOTIC DATA. A body of research results of varying origin, quality and statistical soundness that must be used together to reach a specific research goal.

COMPOSITIONAL PROPERTIES. Those properties of an asphalt which through chemical analysis are observed to be directly related to chemical activity or reaction processes (e.g. molecular attraction, association or combination).

CONDITIONING PROTOCOLS. Prescribed procedures for conditioning the test sample and established conventions governing the strict adherence to correct testing practices.

CONFIDENCE INTERVAL. The statistical interval within which measured values are estimated to be contained with a specified probability.

CORRELATION PROCESS. A statistical procedure for determining the degree of relationship between variables, which seeks to determine how well specific models describe or explain the relationship between the variables.

DEDUCTIVE REASONING. The derivation of a conclusion by inference in which the conclusion about the particulars follows necessarily from a set of logical premises (e.g. the conclusive selection of a final suite of properties based on positive correlation found between asphalt binder and mixture properties with actual field performance).

DESIGN LIFE. The length of time (in years) for which a pavement facility is being designed, including programmed rehabilitation. At the end of this period, the physical life of the facility is considered to be ended, i.e., the pavement structure has deteriorated to a point where total reconstruction would be necessary.

ECONOMIC PROFIT. The remainder value from total revenues from sale of a product or service after subtracting all production or business costs.

END-RESULT FIELD DATA. In-place pavement performance data related to a distress factor obtained by some specified measurement process (e.g. pavement rut depths or crack lengths per unit area).

ENGINEERING ECONOMICS. Technique that allows the assessment of proposed engineering alternatives on the basis of considering their engineering consequences over time.

FATIGUE. The tendency of a material (e.g. asphalt binder or mix) to fail (crack development) under repeated stress or strain application. Cracking results from tensile stresses or strains (less than the fracture stresses or strains-at-break under one load application) at a specific number of stress or strain applications, the number of load applications being larger as the magnitude of the stress or strain is smaller.

FIRST-STAGE VALIDATION. Confirmation by SHRP Contract A-003A that variation of asphalt binder properties identified by SHRP Contracts A-002A and A-004 as probable, significant determinants of pavement performances causes reasonable, meaningful changes in the relevant performance characteristics of asphalt-aggregate mixtures. This validation process employs the use of inductive reasoning since this process does not provide conclusive grounds for the truth of the conclusion that relationships exist between binder properties and pavement performance, but rather affords support for it.

FUNDAMENTAL PROPERTIES. Those properties of the asphalt binder or mix which affect pavement performance and whose effect may be explained and estimated from a theoretical treatment of the underlying chemical or physical behavior of the material at the molecular or microscopic levels.

For example, viscosity is a fundamental property of an asphalt binder since the influence of viscosity on pavement performance is susceptible to analysis by use of thermodynamics and consideration of detailed molecular structure of the constituent asphalt molecules and their atomic, molecular and colloidal-scale interactions.

Tensile strength is a fundamental property of a mix since the influence of tensile strength on pavement performance may be analyzed by measuring the increase in tensile stresses with the lowering of pavement temperature. At some low temperature value the tensile stresses equal the tensile strength of the mix and at that temperature a microcrack develops which subsequently propagates through the mix.

FUNDAMENTAL TEST METHODS. Test methods the results of which are suitable for use in performance prediction models for predicting thermal cracking, permanent deformation, fatigue, etc. These tests are statistically correlated and validated with actual field performance data and have validated precision and accuracy statements associated with them.

GENERAL PAVEMENT STUDIES (GPS). Existing in-service pavement sections that have a suitable range of characteristics to develop a national data base that will provide the needed data to meet the objectives of the Long-Term Pavement Performance (LTPP) Program.

HARD PRODUCTS. Those products of the SHRP Asphalt Research Program that will directly benefit the state highway agencies by improving efficiency, reducing costs and enhancing the effectiveness of their operations (e.g. performance-based specifications, quantifiable material characterization, new test devices, new materials, etc.).

HEALING INDEX. An index developed from the healing test procedure which quantifies the ability of asphalt to resist crack propagation, and flexurally and thermally induced fatigue by relaxation and healing of microcracks within the process zone or damage zone.

HYPOTHESES. Tentative theories or suppositions provisionally adopted to explain certain experimental facts and to guide in the investigation of others.

INDUCTIVE REASONING. Inference of a generalized conclusion supported by a particular set of data or circumstances. For example, tensile strength of asphalt binder may be shown to have a significant effect in the laboratory on the fracture strength of the asphalt-aggregate mixture, then strong support, but not conclusive proof, of an important relationship between low-temperature cracking behavior of field pavements and the tensile strength of the binder has been demonstrated.

INITIAL or FIRST COSTS. Costs associated with initial development of a facility, including project costs (fees, real estate, site, etc.) as well as construction costs.

LIFE-CYCLE COSTS. Economic cost assessment of an item; area, system or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars.

MAINTENANCE. Anything done to the pavement after original construction until complete reconstruction, excluding shoulders and bridges. It includes pavement rehabilitation.

MARKET ANALYSIS. An objective review of a product's supply and demand to identify the probable users and assess potential obstacles to the adoption of the product.

MARKETING PLANS. A formal document that sets out in detail the actions, schedule, resources and budget for marketing a product such that it is readily made available by producers and accepted into routine operational service by its audience of users.

MATERIALS REFERENCE LIBRARY (MRL). Facilities for storing sufficient quantities of selected asphalts, modifiers, and aggregates which will be used throughout the SHRP Asphalt Research Program and possibly by future asphalt research efforts. The materials were selected by SHRP so that all SHRP asphalt researchers would have access to and use of the same materials in their studies. The materials represent currently available materials representing a wide range of performance histories, sources, production practices and physical and chemical properties.

MODIFICATION PROCESS. Procedures for altering refinery practice producing an asphalt or adding a modifying agent to the produced asphalt to enhance the asphalt's ability to minimize pavement performance distress factors.

MOISTURE SENSITIVITY. A distress factor manifested by inclusion or intrusion of water or moisture vapor in the asphalt pavement layer. Damage results by loss of adhesion between the asphalt and aggregate and by loss of cohesion in the asphalt binder matrix.

NORMAL PROFIT. An economics term referring to the entrepreneur's return. This is the minimum return or payment necessary to retain the entrepreneur in some specific line of production.

PAVEMENT MANAGEMENT SYSTEM. A set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time.

PAVEMENT PERFORMANCE. Measure of accumulated service provided by a facility; i.e., the adequacy with which it fulfills its purpose based on all indicators or measurement types.

PAVEMENT SERVICEABILITY. The ability of a pavement to serve high-speed, high volume traffic at any given time.

PERFORMANCE-BASED SPECIFICATIONS. Specification limits and requirements developed from an extensive data base related to the types of pavement performance factors that can be defined quantitatively as measured by accelerated, standardized tests using well-established performance prediction models validated by correlation with in-place field pavement data.

PERFORMANCE-BASED SPECIFICATION LIMITS. Tolerances established for satisfactory pavement performance factors developed from statistical procedures and well-established and validated performance prediction models representing the full range of mixture design considerations.

PERFORMANCE INDICATORS. Measures of the condition of an existing pavement section at a particular point in time. When considered collectively, such indicators (i.e., fatigue, permanent deformation, thermal cracking, etc.) provide an estimate of the current overall adequacy of a particular pavement and identify deficiencies which can lead to accelerated deterioration of pavement condition.

PERFORMANCE PREDICTION MODELS. Mathematical procedures developed for predicting pavement performance criteria using laboratory test results from validated tests which are statistically correlated to actual, in-place field performance data.

PERFORMANCE-RELATED TESTS. Those tests developed intuitively to evaluate asphalt binders and mixes that individually or interactively have an influence on pavement performance but are not necessarily correlated and validated with actual field performance data. A performance-based test is correlated and validated with actual field performance data.

PERMANENT DEFORMATION (RUTTING). Combination of densification (volume change) and shear deformation (plastic deformation without volume change). Shear deformations resulting from high shear stresses are the primary cause of this permanent deformation. The repeated application of these stresses under conditions of comparatively low mix stiffness are responsible for the accumulation of permanent deformations in the form of ruts at the pavement surface.

PHYSICAL PROPERTIES. Those properties of an asphalt binder and mixture that can be measured by mechanical processes (e.g. the rheological properties of asphalt; the stiffness and thermal properties of asphalt-aggregate mixture).

PHYSICOCHEMICAL. A term used in chemistry to emphasize the interrelationship of the physical and chemical properties of a material such as asphalt binder.

QUANTIFIABLE MATERIAL CHARACTERIZATION. Those chemical and physical properties of an asphalt binder or asphalt-aggregate mixture that are directly validated with field performance (e.g. tensile strength of asphalt-aggregate mixture to low-temperature cracking in the field; or, oxidation of the asphalt binder to thermal cracking in the field).

RECONSTRUCTION. The complete rebuilding or replacement of a pavement structure.

REHABILITATION. The work undertaken to extend the service of an existing facility. This work comprises placement of additional surfacing material and/or other work necessary to return an existing roadway, including shoulders, to a condition of structural or functional adequacy.

RHEOLOGICAL PROPERTIES. Those properties of an asphalt binder dealing with the ability to flow or deformation.

RISK. Conditions that exist when each alternative will lead to one of a set of possible outcomes and there is a known probability of each outcome.

SECOND-STAGE VALIDATION. The correlation of binder and mixture properties with actual field performance to demonstrate the soundness of the inferred relationships between properties and performance. This validation process employs the use of deductive reasoning and provides data upon which to set the performance-based specification limits for the relevant properties selected to control performance.

SENSITIVITY ANALYSIS. A technique to assess the relative effect a change in the input variable(s) has on the resulting output.

SIMULATIVE TEST METHODS. Test methods using devices that enable the operator to represent under laboratory test conditions phenomena likely to occur in actual field performance.

SOFT PRODUCTS. Products such as information, data and reports which may be eminently useful to the highway research community in the future but are not directly related to the state highway agencies by improving efficiency, reducing costs and enhancing the effectiveness of operations.

SPECIFIC PAVEMENT STUDIES (SPS). Provisions for study of specific design and construction features using specifically constructed sections for the Long-Term Pavement Performance Program (LTPP). The highway sections are specifically designed and constructed through a cooperative effort with interested state highway agencies, frequently with the test sections collocated to ensure the same subgrade, climate and traffic.

STANDARD TEST METHOD. Well-established reference test methods preferably developed to measure fundamental chemical, physical and engineering properties. These tests are related phenomenologically to the asphalt binder or asphalt-aggregate mixture and systematically to the pavement structural design and performance.

STATISTICALLY-DESIGNED EXPERIMENT. Factorial designs or other approved statistical designs established for evaluating the effects of various independent variables, and their interactions, on a dependent variable of interest.

STOCHASTIC. Conditions involving a random variable, chance or probability.

STRUCTURAL NUMBER. An index number used by the design engineer derived from an analysis of traffic, roadbed soil conditions, and regional factor which may be converted to thickness of flexible pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer of the pavement structure.

SUPPLY AND DEMAND. An economics term employed in market analysis whereby the supply of a product and the demand of that product are viewed simultaneously to establish pricing trends and future market expansion and declines for that product.

THERMAL CRACKING. A pavement distress factor manifested by either low-temperature cracking when the temperature drops and the tensile stress is equal to tensile strength at that temperature and a microcrack develops; or, thermal fatigue cracking resulting from temperature cycles at higher temperatures resulting in failure or crack development over a period of time due to thermally induced strains.

TIME VALUE OF MONEY. Recognition that all organizations have limited resources (finances, people, facilities, equipment) and that the commitment of these to a project precludes their use for any other investment. Whether internal resources are used, or borrowed ones are used, the interest that these resources could produce is a cost to the project.

USER COSTS. Those costs that are accumulated by the user of a pavement facility. In a life-cycle cost analysis, these could be in the form of delay costs or change in vehicle operating costs.

VALIDATION. Confirmation of the probable relationships between the properties of materials (e.g. asphalt binders and asphalt-aggregate mixtures) and pavement performance through their correlation with measured characteristics of actual field pavements.

<u>WORKING CONCEPT</u>. Abstract ideas of research procedures, tests and specification format generalized from historical data or preliminary research findings. The concept is initially formulated to be refuted with future research data. Eventually a prototype would evolve supported by validated research data.