SHRP-A/WP-90-008

Hypotheses and Models Employed in the SHRP Asphalt Research Program

Thomas W. Kennedy
Ronald J. Cominsky

The University of Texas at Austin
Asphalt Research Program
8701 N. Mopac Boulevard, Suite 450
Austin, Texas 78759-8345

Edward T. Harrigan
Rita B. Leahy

Strategic Highway Research Program
818 Connecticut Avenue, N.W.
Washington, DC 20006

Strategic Highway Research Program
National Research Council
Washington DC 1990

Acknowledgments

We wish to acknowledge the extensive use of the technical proposals, work plans and reports provided by the following SHRP Asphalt Program Contractors in preparing this working paper: Contracts A-002A, A-003A, A-003B, A-004 and A-005.

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

Contents

1

Introduction

The purpose of this report is to present for open examination the hypotheses (in some instances termed "models") employed in the SHRP Asphalt Program (hereinafter termed the "asphalt program") to structure the individual reseazch components. These hypotheses present the researchers' views expressed in their contract proposals, work plans, working papers, quarterly and interim reports, etc. of how asphalt properties affect performance; how the interaction of asphalt with aggregate modulates those effects; and how test methods and predictive models may be formulated to truly measure and estimate the influence of materials properties on the ultimate performance of asphalt pavements.

To be genuinely valuable, hypotheses must be dynamic, that is, they must change and evolve as research results become available. After all, research is conducted to test hypotheses; blind adherence to any hypothesis, no matter how cherished by the research community, in the face of contradictory results stifles the research process and attempts to fit reality, in the form of reasonable, reliable research data, to some preconceived notion of what reality should be. Thus, the hypotheses presented here should be expected to change and sharpen in successive strategic plans as research results become available. At the end of the program in 1993, a core of empirically tested and proven hypotheses will remain that can be incorporated into a consistent theory to explain how asphalt properties influence pavement performance.

In practical terms, this theory will be expressed through the two principal products of the SHRP asphalt program, performance-based specifications for asphalt binders and asphalt-aggregate mixtures, and their supporting test methods and protocols, that address six principal pavement performance factors, viz. fatigue cracking, permanent deformation, low-temperature cracking, aging, water sensitivity and adhesion. These specifications are discussed in more detail in chapters 3 and 5 of the companion volume to this report, *The SHRP Asphalt Research Program: 1990 Strategic Plan*ning Document (SHRP-A/WP-90-007); it is in support of their development that the hypotheses examined in this report have been formulated.

A principal objective of the research efforts in contracts A-003A and A-005 is the accelerated validation of the candidate relationships between asphalt binder properties and the performance of asphalt-aggregate mixtures and field pavements. The mechanics of this vitally-important validation process, which will determine the requirements and limits contained in the specifications, are described more fully in chapter 4 of report SHRP-A/WP-90-007 and are only alluded to here. The chapters of this report dealing with contracts A-003A and A-005 will concentrate on hypotheses proposed in those studies for development of, respectively, performance-related test methods for mixture analysis systems and prediction models to link mix design with pavement design.

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 May 1986 *Strategic Highway Research Program Research Plans, Final Report.* 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 have been 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 this report. Figure 1.1 presents the strategy employed with the asphalt program to achieve its key products, the performance-based specifications for asphalt binders and asphalt-aggregate mixtures, in terms of a graphical time line. A full discussion of this strategy is presented in chapter 2 of report SHRP-A/WP-90-007.

2

Coordination, Technical Direction and Specification Development- SHRP Contract A-001

Coordination is an essential requirement between all of the SHRP tasks and contracts to assure continuity, productivity and continual progress to achieve the two performance-based specifications. SHRP Contract A-001 is responsible for the technical direction, leadership and coordination of the asphalt program, and for the development of the performance-based specification for asphalt binders.

Materials Reference Library

The magnitude of the asphalt program requires major endeavors through broad and complex research efforts. For this total research effort to be both meaningful and effective, all the asphalt research contracts must have access to and use the same materials in their studies. Therefore, the A-001 contractor developed and operates a Materials Reference Library (MRL) containing sufficient quantities of asphalts and aggregates for use by the asphalt research contractors through the entire 5½-year program.

Asphalt Selection Process

The basic premise of the selection process for the asphalts included in the MRL was that the performance of asphalt pavements is directly influenced by the physicochemical properties of asphalt cement. Thus, asphalt cements were deliberately chosen to create an MRL containing currently available asphalt cements representing a wide range of field performance histories, crude oil sources, refinery practices, and physical and chemical properties. Figure 2.1 is a summary of the perceived relationships between asphalt physical and chemical properties and pavement performance that were employed

Asphalt Cement Characteristics	Pavement Distress Factors				
	Thermal Cracking	Fatigue Cracking	Permanent Deformation	Adhesion and Water Sensitivity	Aging
Vanadium / Nickel Ratio	M	V	M	M	V
Sulfur Content	V	M	O	O	S
Temperature Susceptibility	V	M	V	O	M
Nitrogen Content	O	V	O	V	O

Significance of Effects on Performance

Very Significant	V
Significant	S
Minor Significance	M
No Significance	O

Figure 2.1 Perceived relationship of asphalt cement properties to pavement performance.

in the overall asphalt selection process. Thirty-two asphalt cements have been selected, sampled and stored in the MRL. Figure 2.2 illustrates the geographic distribution of the refineries producing the asphalts sampled.

Eight of the asphalts were selected as having sufficiently diverse performance histories, chemical and physical properties to warrant their being designated as the core or common asphalts in the asphalt program. The core asphalts are to be tested by in every experiment in the asphalt program to permit a systematic analysis and correlation of the data obtained in the various contracts and parts of the program.

Aggregate Selection Process

A similar approach was employed in the selection of the aggregates for inclusion in the MRL. The aggregates were chosen based on known chemical, physical, geologic and petrographic properties as these properties relate to perceived performance in asphalt-aggregate mixtures. Eleven aggregates were selected and Figure 2.3 illustrates the geographic distribution of the aggregates.

Performance-Based Specifications Concepts

Keeping with the concept of the asphalt program as a product development and implementation (marketing) process, product concepts must first be envisioned and then these concepts advanced towards production. SHRP Contract A-001 is responsible for the ongoing conceptualization and continued development of the performance-based specification for asphalt binder. As discussed in chapter 8, SHRP Contract A-006, working as an extension of A-001, is responsible for the conceptualization and development of the performance-based specification for asphalt-aggregate mixtures.

Preliminary working concepts of the final performance-based asphalt binder specification and the performance-based specification for asphalt-aggregate mixtures have already been developed by SHRP contract A-001 and have evolved as work has progressed. These preliminary working concepts were formulated to help guide, focus and coordinate the efforts of the various asphalt program contractors toward the final product. As the research progresses during the next three years and new information is developed, or novel or unsuspected findings occur, the hypotheses specifications will continue to evolve from these early working concepts to SHRP's final proposed specifications and support products readily adaptable for use by state highway agencies. The specific details of the current hypothesis specifications for asphalt and asphalt-aggregate mixtures are provided in chapter 5 of companion report SHRP-A/WP-90-007.

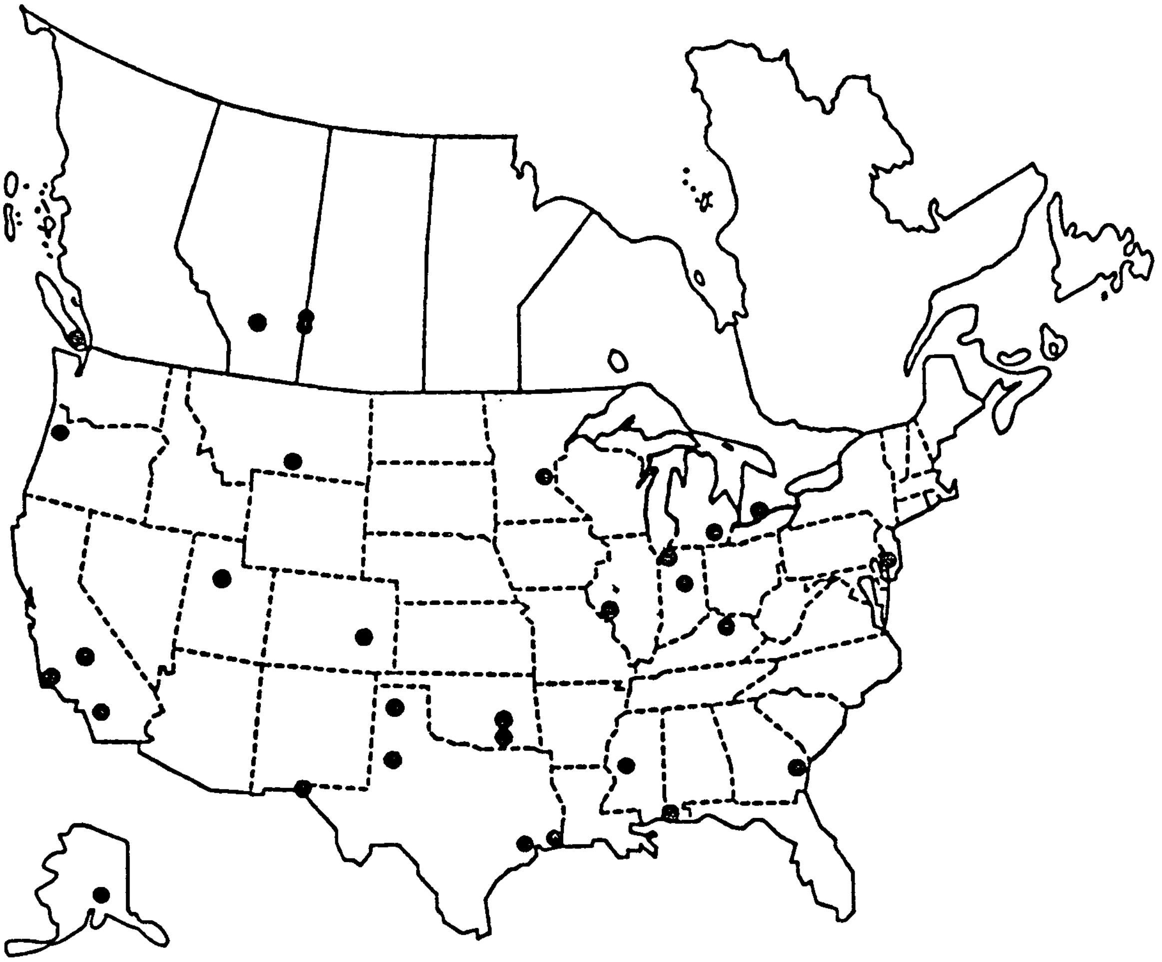

Figure 2.2 Geographical distribution of asphalts sampled for inclusion in Materials Reference Library.

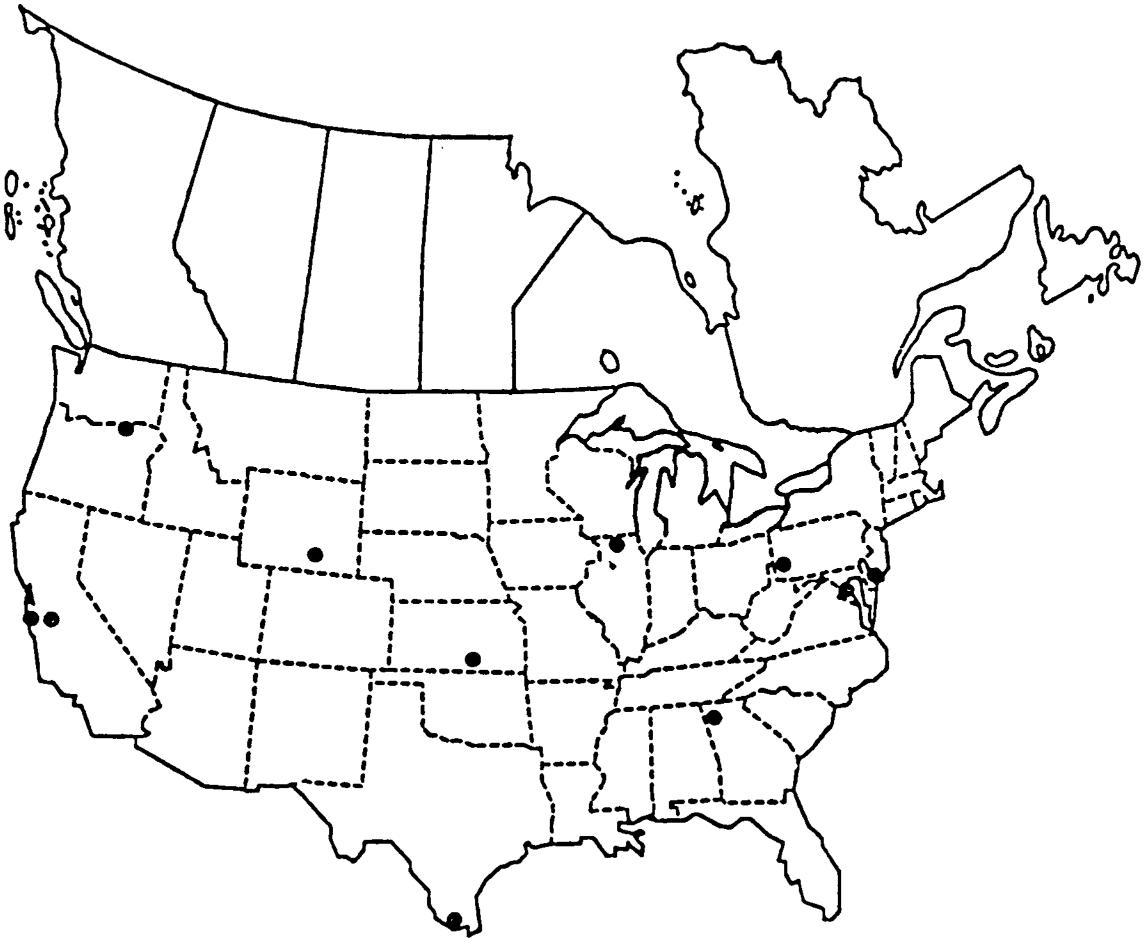

Figure 2.3 Geographical distribution of aggregates sampled for inclusion in Materials Reference Library.

3

Binder Characterization and Evaluation - SHRP Contract A-002A

SHRP Contract A-002A is the basis for the conceptualization and development of the asphalt binder performance-based specification and the source for much of research data needed to conceptualize the specification.

The objective of the research effort in Contract A-002A is to improve upon the understanding of the fundamental physicochemical properties of asphalt that influence pavement performance, so that a rational basis can be formulated for the development of a specification that is more closely tied to superior performance of the binder in an asphalt pavement.

The work is divided into three major tasks:

- Task 1.1 Asphalt Chemical Composition.

The research effort in this task will identify and quantify the chemical, compositional factors in asphalt that significantly influence its important physical properties and the performance of asphalt-aggregate systems.

- Task 1.2 Asphalt Physical Properties.

The research work in this task will develop new and improved techniques for measuring the physical properties of asphalt.

- Task 2.1 Testing and Measuring System for Asphalt With or Without Modification.

This research approach will develop standardized test methods for asphalt or modified asphalt which will satisfy requirements of AASHTO, the state highway agencies and ASTM, and which can be employed to specify and accept binders for use with performance-based specifications.

The model or working hypothesis of asphalt that is being investigated is shown schematically in figure 3.1.

Chemical Composition and Model Conceptualization

The chemical composition of a material such as asphalt essentially determines its physical (rheological) properties. In order to be able to predict with reasonable accuracy the changes in fundamental engineering properties over time of mixtures of asphalts with various aggregates by means of a limited number of rapid, inexpensive physical tests, perhaps supplemented by a few chemical tests, the fundamental basis for each test must be known as well as the sensitivity of physical properties to chemical composition.

A working model has been developed to provide this information figure 3.2. The model envisions aromatic, high molecular weight, core molecules dispersed in a medium of relatively, low-molecular weight molecules. The dispersed phase is viewed as being peptized by adsorbed aromatic molecules lower in molecular weight than the core materials and which are soluble in the dispersing medium. The core materials are considered as asphaltene micelles, the peptizing agents as resins and the dispersing medium as oils (maltenes).

The working hypothesis of asphalt structure which explains rheological behavior states that the phase consisting of relatively aliphatic, non-polar molecules that are low in heteroatoms disperses the micellar structures of asphaltene-like molecules. These asphaltene-like molecules are aromatic, polar and contain heteroatom functional groups. Many are polyfunctional and are capable of associating or agglomerating into molecular networks. The size of the micelles may vary widely, and their shape may tend to be more similar to a trunk and branches than to spheres.

The hypothesis characterizes chemical composition by classifying asphalts into sol-like or gel-like categories. In the extreme case of the sol, no micellar structures would be present and any such asphalt would be a true solution. However, all asphalts exhibit micellar structures to varying degrees. Some asphalts demonstrate an observable amount of micellar structures but they are small in size and number and are well dispersed. Such asphalts exhibit Newtonian rheological behavior (i.e., the shearing stress is proportional to the rate of flow or shear rate) down to fairly low service temperatures.

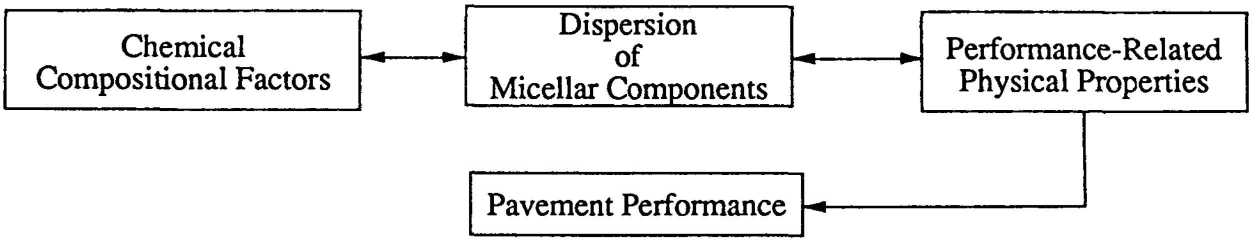

Figure 3.1 SHRP contract A-002A working model for asphalt research.

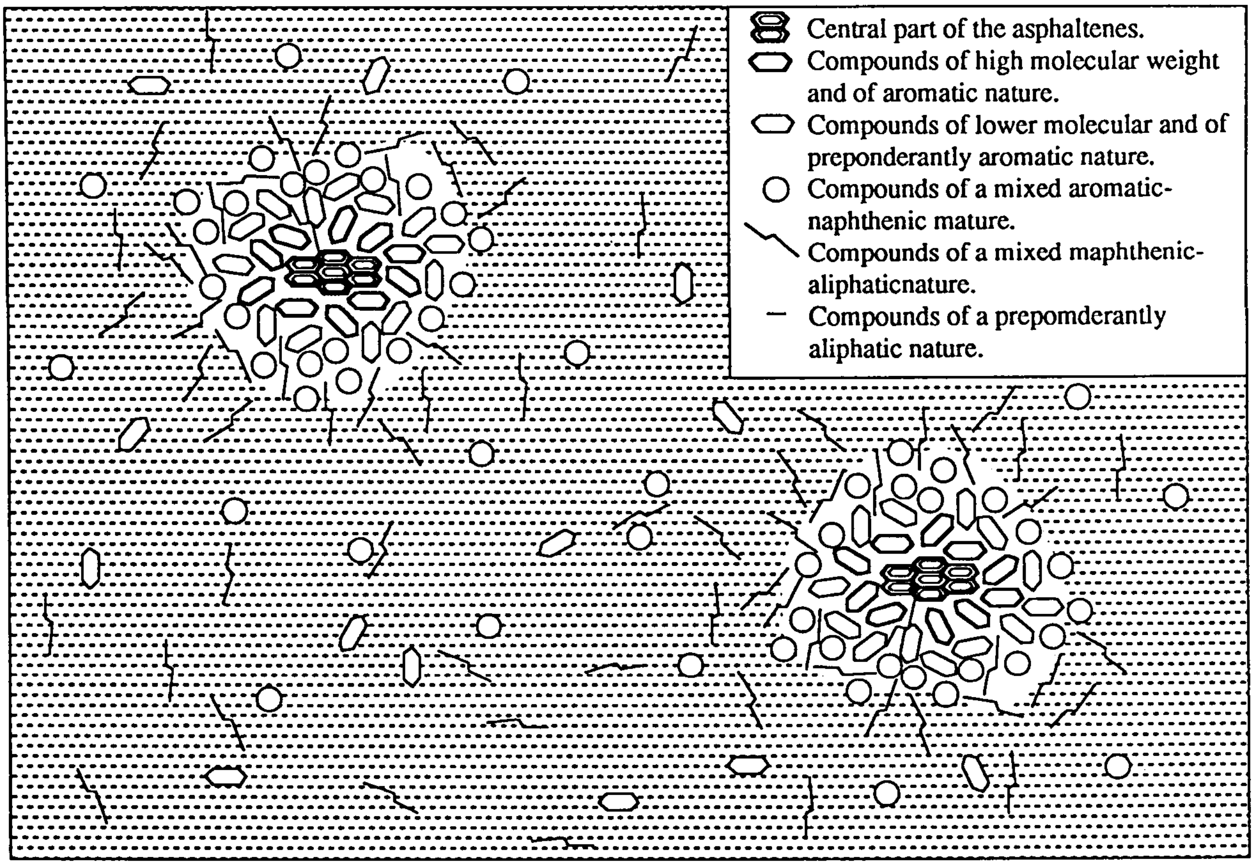

Figure 3.2 Schematic representation of peptized asphaltene micelles.

Other asphalts exhibit substantial amounts of large micelles that are poorly dispersed and are capable of forming three-dimensional networks of asphaltene micelles within the asphalts. These asphalts exhibit pronounced non-Newtonian behavior, particularly at low service temperatures.

Whatever their composition, the micellar structures formed by asphaltene-like molecules are themselves capable of agglomerating by chemical association or bonding into three-dimensional networks. These networks, and the micellar structures themselves, are broken up by heat and shear stress. The three-dimensional structuring is suppressed by an effective solvent phase but promoted by an ineffective one. *From this model, it follows that those chemical variables which influence asphalt physical (rheological) properties to the greatest degree are those which are most responsible for the structuring and dispersal of the micelle system.*

Thus, the focus of the research is on the separation of asphalts into chemically distinct fractions. These fractions will be used primarily to more completely characterize asphalt and to determine how the different chemical functionalities in these unique fractions influence the physical (rheological) properties of the asphalt and its performance in pavements.

The asphalts are separated into five chemically distinct factors -- neutral, weak acid, strong acid, weak base and strong base -- by ion exchange chromatography (IEC). Assuming from the proposed model that asphalts are composed of micellar structures dispersed in a non-polar solvent phase, then the non-polar, neutral fraction comprises the solvent phase. The highly polar, strong acid and (to a lesser degree) base fractions principally form the micellar phase. Consequently, the relative amounts of neutral and polar fractions in an asphalt and the details of their composition should be reflected in the asphalt's physicochemical properties and, ultimately, in its performance in a pavement.

Results to date suggest that the strong acid fraction, which typically comprises 15 to 25 weight percent of an asphalt compared with 50 to 60 weight percent for the neutral fraction, is highly aromatic, has the highest apparent molecular weight and is rich in polar, polyfunctional groups containing oxygen, nitrogen and sulfur. Results demonstrate that the strong acid fraction is the viscosity-building component in the asphalt and, significantly, is the fraction that controls its temperature susceptibility. Data also suggest that the strong acid fraction governs adhesion and water sensitivity through the interaction of the polar functional groups and aromatic ring structures with aggregate surfaces.

Specific molecular entities in the strong acid fraction are also hypothesized to link together into an elastic network, the details of whose structure will affect the response of the asphalt to the load and thermally-induced stresses that cause low-temperature and fatigue cracking in pavements. Aging of the asphalt, while comprising the oxidation of molecular species in both the neutral and polar fractions, appears to have a significant effect on asphalt performance mainly through changes that occur in the strong acid fraction.

Relationships between chemical composition and physical (rheological) properties based on chemical fractions isolated from the asphalts are being verified by studies in which specific chemical fractions are recombined with other fractions or with whole asphalts and the resulting chemical and physical properties of the recombined materials are measured. Suitable physical and rheological properties are determined on the asphalts and asphalt blends to demonstrate the effects of the chemical fractions on the asphalt properties.

By means of this process, identification and definition of the chemical factors are made that influence asphalt physical properties, particularly rheological, fracture and complex flow properties at various temperatures, and its performance in pavements. This process then logically flows towards the development of performance-based specifications for asphalt binders and of performance-related tests based upon chemical and corresponding physical properties.

Performance-Related Physical Properties of Asphalts

The selection of the most appropriate physical properties that merit characterization is driven by the modes of distress (permanent deformation, fatigue cracking, thermal cracking, aging, moisture sensitivity and adhesion) encountered during the service life of the pavement. The behavioral modes that relate to the distress factors are envisioned to be rheology (stiffness), fracture, stress-strain characterization, tensile strength, asphalt-aggregate adhesion (disbonding) and oxidative hardening. The physical property data must be developed from correlation with chemical, compositional properties since asphalt chemical structures vary with temperature and applied stress, and therefore so do their apparent molecular weights. Consequently, the general approach is to employ the concepts of physical chemistry, tempered with engineering judgment, by considering the physical (rheological) properties of asphalts as being directly related to their chemical properties, neither of which are considered independent of each other. This approach is shown schematically in figure 3.3.

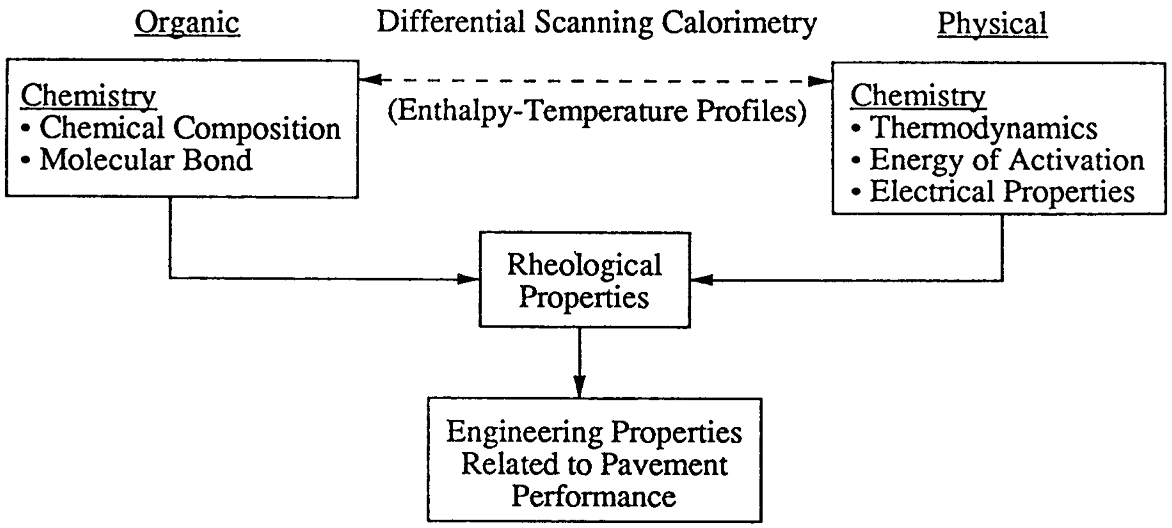

Figure 3.3 Relationship of asphalt organic and physical chemistry to asphalt physical properties as they relate to performance.

Rheologically, a Newtonian asphalt is a material that exhibits a constant ratio between stress and rate of strain. A non-Newtonian asphalt does not exhibit a constant ratio but depends on the imposed rate of shear strain. The rheological behavior of asphalt can be explained in chemical terms by the molecular association which occurs; i.e. the bonding energy by which the asphaltene micelles are held together (hydrogen bonding, π-π interactions, etc.). Significant changes in asphaltene micelle structure will be accompanied by enthalpy changes. Significant changes in enthalpy at the same temperatures at which asphalt rheology changes from a Newtonian to a non-Newtonian material would support the hypothesis that rheological properties are dependent upon the details of the intermolecular bonding.

In addition, asphalt generally behaves partially like a solid and partially like a liquid over a wide temperature range which includes the in-service temperature range. Such behavior is described as viscoelastic and implies that the rheological functions depend on the loading time of the external force. Under simple shearing at ambient temperatures, most asphalts exhibit complex flow or non-Newtonian behavior. The viscoelastic and complex rheological behavior of asphalt can also be explained in chemical terms by the molecular association which occurs. Mechanical deformation (e.g., shear flow) can break or alter the intermolecular structure. The resistance to flow changes with the change in microstructure, resulting in a shear-rate-dependent viscosity. Therefore, shear susceptibility (complex flow) and temperature susceptibility (stiffness properties) are hypothesized as being reflective of component interactions of asphalts.

A conceptual response surface model has been developed considering the variation of asphalt stiffness with time, temperature and loading (figure 3.4). Each of the pavement distress factors would progress at different rates depending on the asphalt's rheological properties. The three-dimensional response surface model is beingadvanced to describe the stress-strain response as a function of loading time and temperature. Ideally asphalts will show no substantial difference early in their pavement life (shown as the time axis in figure 3.5). As the asphalt ages and is subjected to loading distresses, fatigue and thermal cracking become more apparent. Subsequent additional aging or loading would develop permanent deformation (rutting).

The measured physical properties must be related to the distress modes. They should be fundamental properties expressed in terms of stress, strain, or other fundamental engineering units and should relate phenomenologically to the chemical composition of the asphalt cement, the asphalt-aggregate system, and systematically to the pavement structural design and performance.

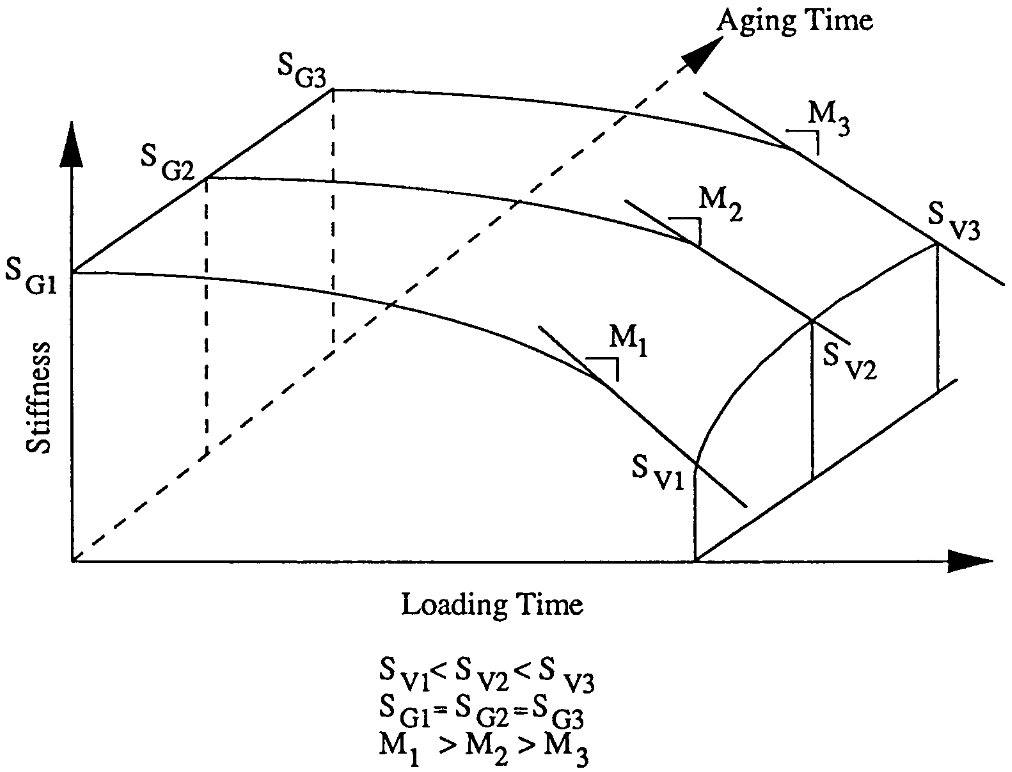

Figure 3.4 Conceptual response surface considering asphalt stiffness, time temperature and loading.

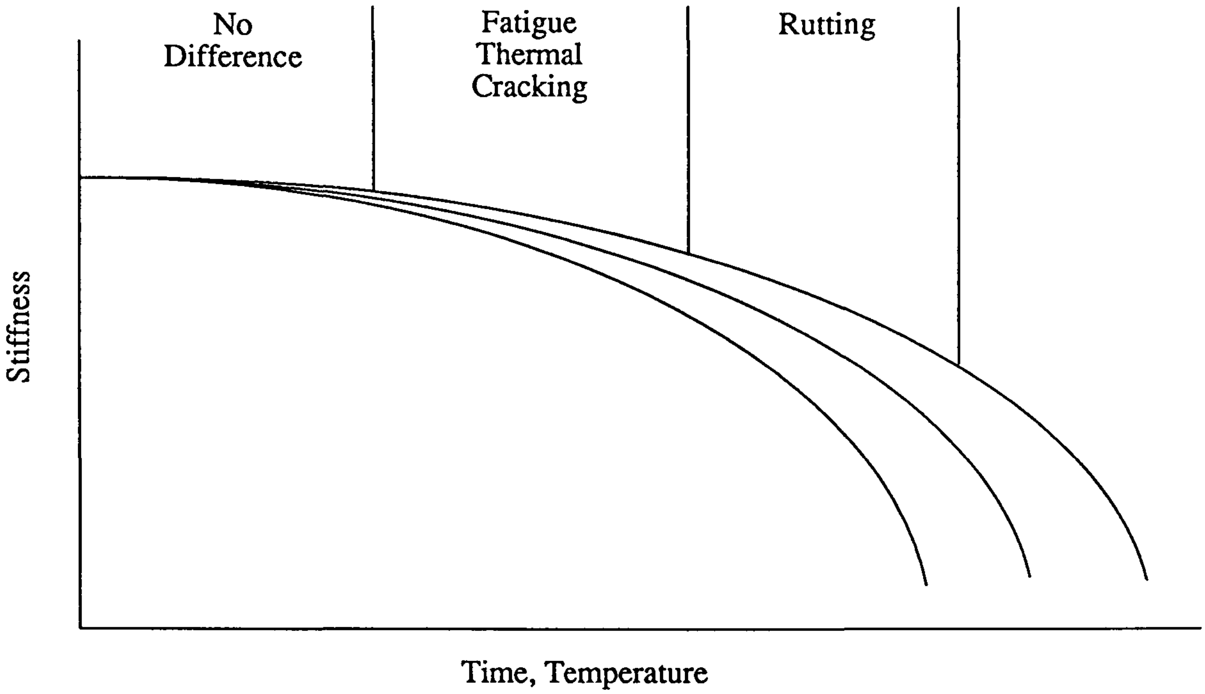

Figure 3.5 Pavement distress factors related to rheological properties.

Testing and Measuring Systems for Asphalt

The comprehensive test methods used for chemical analysis and physical determinations are considered as "bench-mark" tests. These bench-mark tests are considered the ultimate methods and employ the state-of-the-art technology. They obviously include complex procedures, require expensive and complicated equipment, demand complicated data analysis and require highly-trained technicians.

Simplified versions of the bench-mark tests suitable for standardization and implementation by the state highway agencies will be developed. The bench-mark test procedure will be used to validate the acceptability of the simplified technique, since it serves the purpose of providing target values by which the more routine specification tests can be judged.

In the case of sophisticated chemical tests, surrogate physical tests will be developed to mimic the physicochemical parameters being evaluated. These physical tests will yield results in fundamental engineering units (stress and strain) to provide a sound link between standardized tests and field performance. Some chemical tests may also prove suitable for incorporation in routine specifications.

4

Asphalt Modification - SHRP Contract A-004

Asphalt cements with optimum properties may not be obtainable from all crude oils by conventional refining processes or blending practices because of inherent variability in the characteristics of the crude oils. Many of these crude oils may be deficient in some chemical constituents or physical properties that affect the pavement performance of the asphalt. Asphalt modification may prove to be the best means for correcting asphalt deficiencies and producing binders with preferred pavement performance properties from a wide variety of crude oils.

Chemical Composition and Model Conceptualization

The working hypotheses employed in the area of modified binders are quite similar conceptually to those discussed for unmodified asphalts. One is the identification of the molecular forces which are responsible for the creation and control (formation of stable micelles) of the sol-gel parameters in the modified asphalts. Figure 4.1 illustrates the working concept or model to control sol-gel relationships. This reaction chemistry approach is being pursued by categorizing the types of chemical reactions with respect to chemical mechanisms and activation energy requirements. The types of reactions being considered are addition, substitution, elimination, electrolytic and fragmentation.

As previously discussed with unmodified asphalts, the sol-gel model views paraffins as the sol and asphaltenes and polar aromatics as the gel. The sol-gel character of the asphalt will be modified by the removal of the asphaltenes and the addition, substitution, elimination, etc. of the polar functionalities. Studies are being advanced on the pH dependent behavior of the chemical functionalities in acidic and basic environments. This work is being performed on the MRL core asphalts.

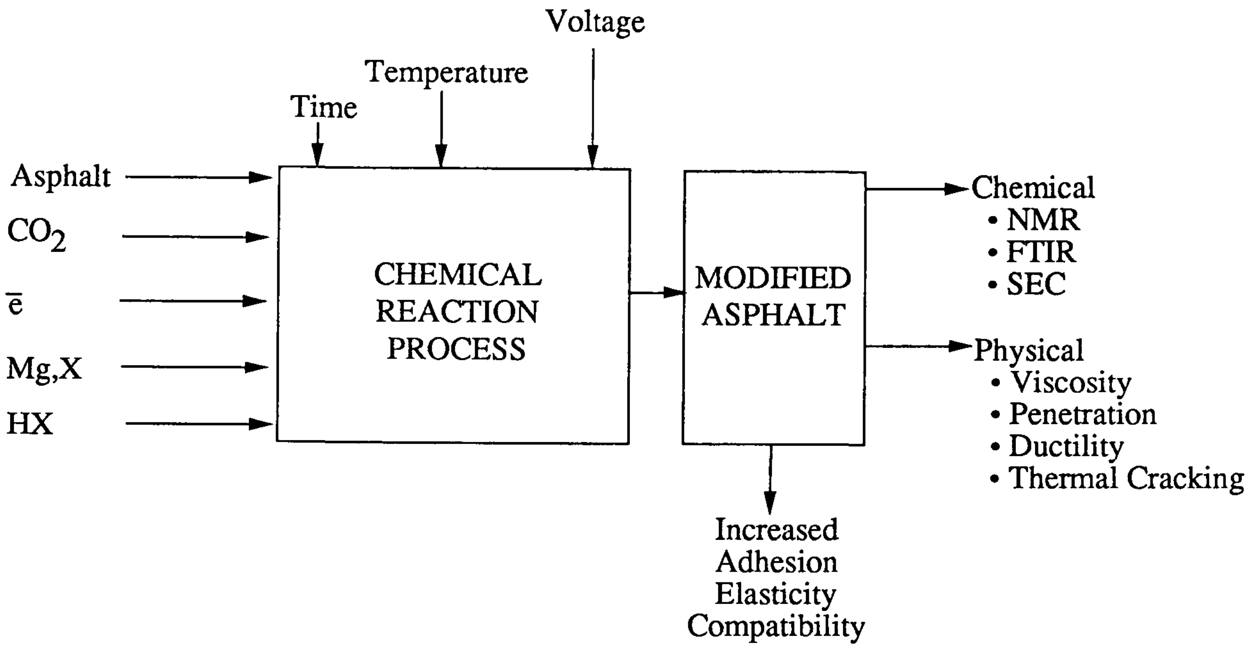

Figure 4.1 Conceptual model to control sol-gel relationships.

Asphalt does not have the chemical gel point in the sol-gel transition which is characteristic of polymers. The characteristic inflection point of the viscosity-temperature curve which is unique to polymers is not present in the viscoelastic behavior of asphalt. Consequently, modified asphalts with varying polarity and phase compatibility are being prepared and the resultant variations in sol-gel behavior are being compared to unmodified asphalts.

Elastic Network

A working concept is being advanced for investigating the molecular forces which produce an elastic network (entanglement) within modified asphalts. Figure 4.2 illustrates schematically the approach being pursued. Theoretically, extensive branching of the asphalt molecules will decrease viscosity at low temperatures due to molecular motion of the functional end groups which are active at low temperatures. Also, theoretically, extensive branching will increase viscosity at high temperatures and will introduce significant entanglement.

Asphalts are being modified by different strategies intended to create an elastic network. Known elastomeric polymers are being used for base-line comparisons and characterizations to create a better understanding of the development of the elastic network in both modified and unmodified asphalts. This approach should provide a fundamental understanding of how a brittle asphalt can be modified to increase elasticity and thus minimize cracking and subsequent accelerated aging.

Performance-Related Physical Properties of Modified Asphalts

For each of the working hypotheses previously discussed in this and the previous chapter, various separation schemes or techniques similar to those for unmodified asphalts (nuclear magnetic resonance, quantitative infrared analysis, size exclusion chromatography, etc.) are used for the chemical evaluation procedures and characterization. These analyses may prove to be more complex than desirable for routine use by state highway agencies; however, they will provide an improved understanding of the asphalt modification in terms of fundamental engineering units for which more simplified or routine surrogate-type laboratory tests could be developed.

Accordingly, practical, standardizable tests that are applicable to both modified and unmodified asphalts will be developed. Modified asphalts, however, may pose some

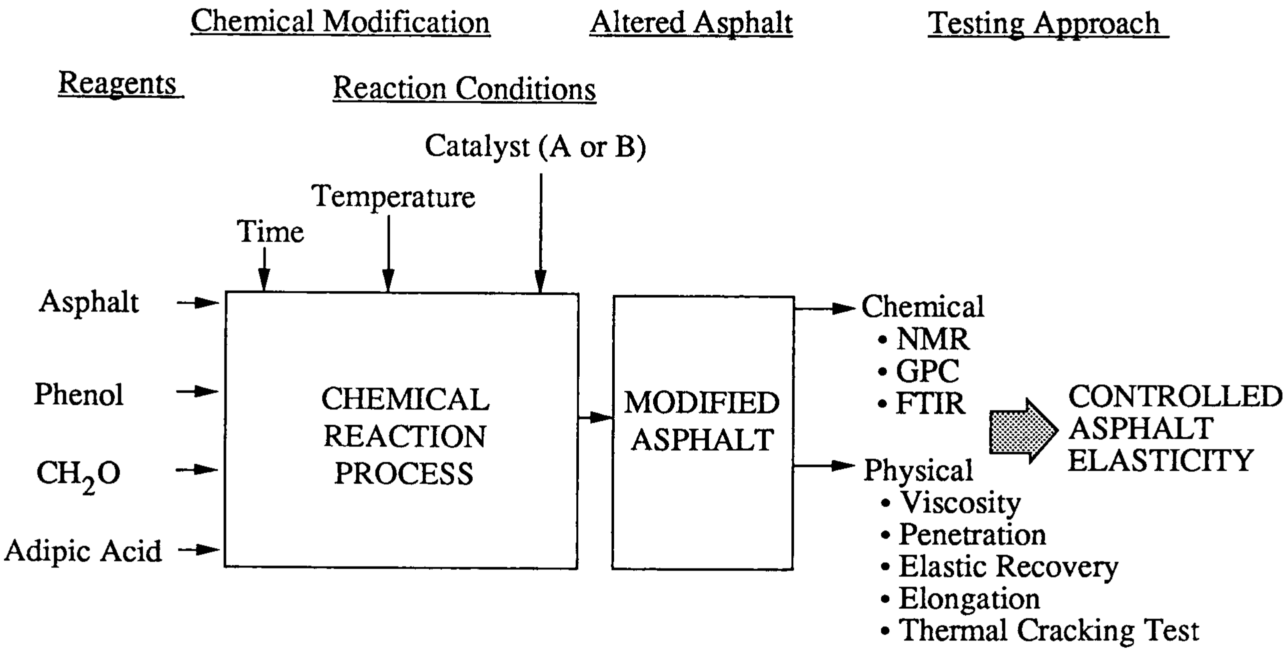

Figure 4.2 Model to evaluate asphalt elastic network.

special characterization problems. For example, asphalts may contain a polymer-molecular network that requires a certain level of strain before it affects stiffness, thus necessitating different test conditions than required for unmodified asphalts. The selection and measurement of performance-related physical properties may require special consideration for modified asphalts. The test development approach, however, is focused on the chemical and physical characterization, in fundamental engineering units, of the six pavement performance factors presented in chapter 1.

Close interaction and cooperation are required between SHRP's A-002A and A-004 contractors. The tests identified for unmodified asphalts will be employed with modified asphalts if feasible. The objective, however, is to distinguish between those tests which simply characterize the presence of modifiers in asphalt from those which provide results that reflect the influence of the modifiers on the pavement performance factors. Key to this philosophy are tests and procedures that will identify the fundamental mechanisms for modification techniques to enhance pavement performance beyond that supplied by unmodified asphalts.

A modification method for enhancing asphalt properties in one area may severely affect the asphalt's performance in another. For example, oxidants used to solve permanent deformation problems at high temperatures might cause unacceptable brittleness at low temperatures. Therefore, characterization of the rheology of the modified asphalt over a large temperature and frequency range will be conducted as needed to evaluate the impact of the modification method on the overall asphalt performance. This approach, which is similar to that discussed for unmodified asphalts, will establish the region (boundaries) of linear stress-strain behavior in the non-linear region if this region is determined to be applicable to service behavior. It will characterize the Newtonian and non-Newtonian flow behavior of modified asphalt by providing information related to shear susceptibility, complex flow and activation energy of flow from which the fundamental mechanisms controlling modified asphalt rheology can be deduced. As with the unmodified asphalts, the comprehensive test methods will be used as "bench-mark" tests to verify the acceptability of the simpler techniques employed in the physical tests, yielding fundamental engineering parameters (stress and strain) linked to pavement structural design and performance.

5

Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption -- SHRP Contract A-003B

An essential property of unmodified or modified asphalt is the ability to adhere properly to an aggregate surface. This adherence or bonding is essential to the performance of a pavement. There is a lack of understanding of the fundamental chemistry and physics of these paving material components because of the past reliance on tests which primarily use physical properties of asphalt and asphalt mixes that cannot be derived from a fundamental engineering analysis of their behavior as a means of classification. No relationship has been developed between these "non-fundamental" physical properties and the interfacial chemistry of the component materials.

Bonding between asphalt and aggregates is dependent upon both the chemical and physical properties of the asphalt and the aggregate. There is a need to develop better methods to measure asphalt-aggregate interactions and apply these techniques for improving asphalt-aggregate mix characteristics. From a physical chemistry viewpoint, what occurs at the molecular level in the region of the asphalt-aggregate interface influences the macroscopic performance of the pavement as observed by such properties as tenderness, embrittlement, cracking, water stripping, etc. From a materials engineering design view point, the adhesive bonding between the asphalt and aggregate should not be much stronger than the cohesive bonding within the asphalt or fracture within the asphalt may result. Likewise, the cohesive bond strength within the asphalt should not be much stronger than the adhesive bonding between the asphalt and aggregate, or fracture will occur within the asphalt-aggregate interface.

Fracture of any type is detrimental to pavement service life due to moisture infiltration and its attendant problems (freeze/thaw action, stripping, raveling, etc.). Once a better understanding of the asphalt-aggregate interaction is acquired, the information can be used to effectively match asphalts and aggregates, design more effective and longer lasting modifiers and to ultimately achieve better pavement performance.

SHRP Contract A-003B is tasked with providing fundamental information on the chemical nature of the asphalt-aggregate bond; the chemistry and morphology of the aggregate; aggregate-induced asphalt chemistry such as structuring of the interphase region which encompasses the asphalt in the transitional region between the interface and the bulk asphalt; and the changes in asphalt chemistry due to selective absorption/adsorption caused by absorption of asphalt into the aggregate. These fundamental results, in turn, will provide a direct link between the asphalt-aggregate chemistry and the pavement performance properties in terms of fundamental engineering properties produced by accelerated laboratory test procedures.

Chemical Composition and Model Conceptualization

The model being investigated considers interactions between the asphalt and aggregate surfaces occurring in three zones. These zones include an absorbed region, an interface region and an interphase region (figure 5.1).

Molecules absorbed within the pores of the aggregate constitute the absorbed region. Those molecules attached directly to the aggregate surface are considered as the interface region. Molecules that are structured near the interface but not attached to the aggregate surface are considered as the interphase region. The bulk of the asphalt lies beyond the interphase region.

Molecular structuring, which is often induced by aggregate chemistry, occurs in the asphalt at the interface and in the interphase regions. This structuring is hypothesized as having a definite effect on the chemistry of the asphalt-aggregate mixture and subsequently on the pavement performance characteristics.

Asphalt absorbed within the pore space of the aggregate may have differing chemical and physical properties as compared to the bulk asphalt. This difference can be caused by selective absorption effects wherein chemical segregation of the asphalt constituents occurs during the absorption process. In other words, selective absorption of the highly polar molecules leads to a situation in which the absorbed asphalt has a substantially different composition than the asphalt film. Larger molecular species such as asphaltenes and resins are preferentially left in the asphalt film. The net result of such selective absorption is that the actual effective asphalt film binding the aggregate together has a composition, and properties, which are different from the bulk asphalt.

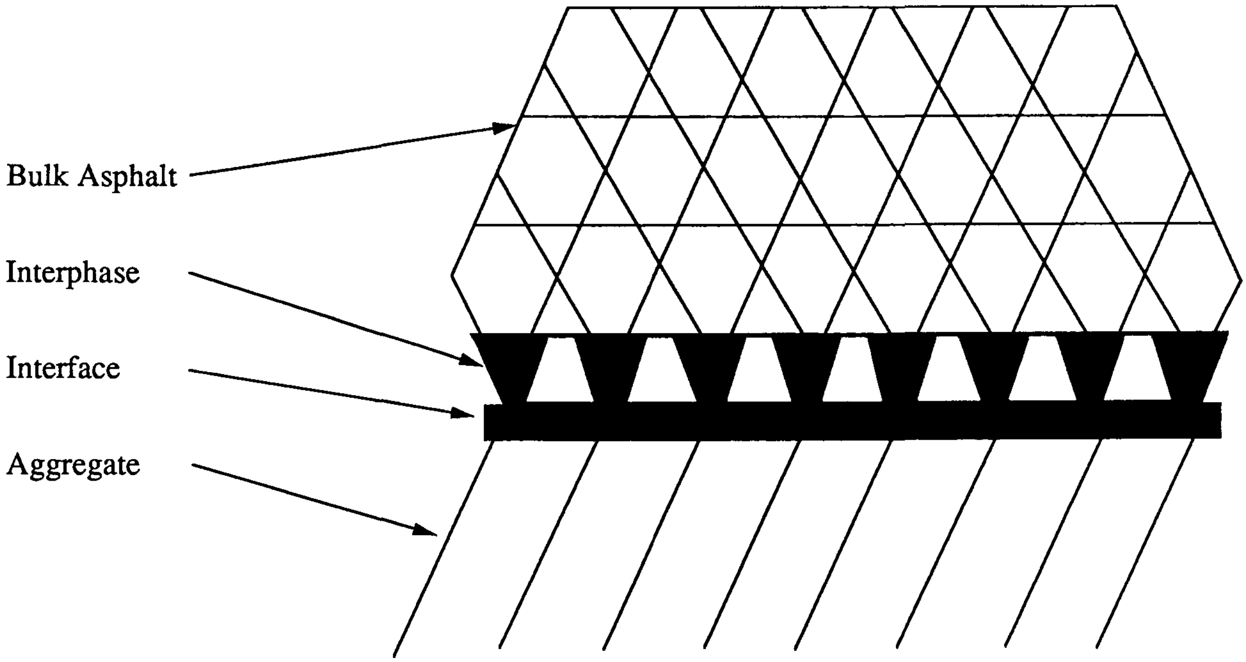

Figure 5.1 Asphalt-aggregate model illustrating interphase and interface regions.

Adhesion -- Chemistry of the Interface and Interphase

A chemical model (figure 5.2) is being advanced on the basis of the findings from research examining adhesion at the interface and the effect of adhesion on the interphase.

The model views asphalt as being a complex mixture of polar and nonpolar organic compounds having a wide molecular weight range. The individual molecules have increased mobility with increased temperatures and tend to align as fixed, relatively immobile structures at decreased temperatures. The model suggests that polar organic molecules bind to polar sites on the aggregate surface to form an interface between the asphalt and aggregate, the interface perhaps having a chemical composition different from that of the bulk asphalt. The model also suggests that an interphase region of polarizable molecules develops from the interface and extends as far as 100 microns into the bulk asphalt. The composition of the polarizable interphase molecules may also be different from that of the bulk asphalt. The research is designed to test the model to determine whether or not

(1) specific, identifiable, organic compound types are involved with bonding at the interface;

(2) specific organic compound types are found in the interphase region;

(3) specific organic compound types appear in the interface or interphase regions as a result of aging; or

(4) chemical modification agents improve asphalt/aggregate bonding by changing the composition of the interface or interphase regions.

The conceptual model considers whether aggregate pretreatment procedures may be used to make mix behavior independent of intrinsic aggregate surface properties.

The experimental approaches to understanding the chemistry of the asphalt-aggregate bonding will involve research on both selected model compounds as well as asphalts. Elucidation of the chemistry of the asphalt-aggregate interfacial bond using model asphalt functionalities will involve measurement of their adsorption on moist and dry aggregates both individually and competitively. Their sensitivity to moisture will be ascertained as well as their propensity for desorption in the presence of water. In addition, the energy of adsorption and desorption of specific functionalities on both moist and dry aggregates will be obtained by thermal desorption of a variety of model functionalities. The influence of both commercial and chemically synthesized

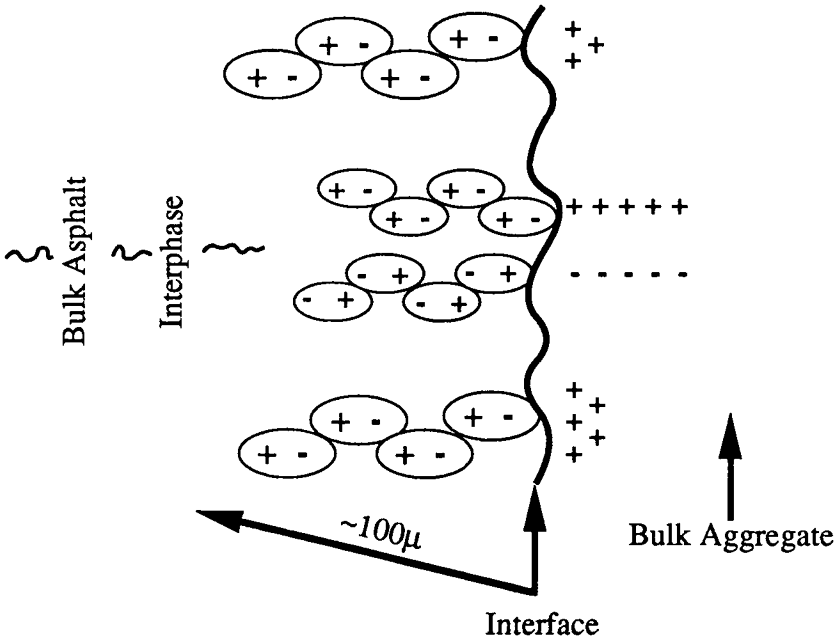

Figure 5.2 Proposed model of the asphalt-aggregate interface.

antistripping agents and aggregate modification agents on the nature of functionality adsorption and its sensitivity to desorption by water will also be evaluated. This research will provide both qualitative and quantitative data on the adsorption/desorption behavior of functionalities present in asphalt on actual well-characterized aggregates and should constitute a significant advancement of knowledge.

The chemistry and morphology of the aggregate is examined to issess the fundamental importance of aggregate surface properties and its chemistry and morphology in establishing a strong asphalt-aggregate bond. The modification of aggregate surface properties via simple and inexpensive surface pretreatment to strengthen the asphalt-aggregate bond is also being examined. Inferential measurement techniques will be used here as well as more direct measurement techniques for gauging interfacial bonding energies (or strengths). More directly, microcalorimetry will be used to measure heat of wetting/immersion (bonding energy).

The more fundamental studies must be done in concert with the asphalt-aggregate mix studies in order to: (1) determine differences in basic aggregate properties (e.g. streaming potential or zeta potential) and composition/morphology for characterization purposes and (2) relate aggregate properties (and combinations thereof) to differences in bonding strength and performance. The manner in which the structured region affects mix characteristics will also be determined. The techniques employed represent approaches that will define the chemistry and physical properties of the interphase region.

Absorption -- Physical Mechanism and Chemistry of Absorbed Asphalt

The hypothesis established to describe absorption of asphalt into porous aggregates considers both the physical mechanisms involved as well as the chemical effects on the asphalt.

Physical Mechanisms

The modeling of the absorption of asphalt by porous aggregates is very complex. It is based upon three fundamental physical principles involving the flow of a liquid into a porous medium. These principles are:

1. A materials balance for the liquid;

2. An expression of the relation between pressure drop and flow rate for flow in

a porous medium by Darcy's Law; and

3. The derivation of the driving force for absorption from capillary pressure, i.e. the pressure differential across a curved fluid interface.

Using these three principles, a mathematical description of asphalt absorption have been developed that expresses the absorption characteristics of a specific asphalt-aggregate system in terms of a dimensionless variable analogous to the Reynolds number employed to describe the flow of liquid through a pipe. In the case of absorption, the dimensionless variable might be a reduced time variable by which the rates of absorption of various asphalt-aggregate systems could be compared directly without requiring a detailed knowledge of the underlying physical quantities.

The dimensionless variable could be made up of various combinations of asphalt and aggregate properties including factors such as: the viscosity and surface tension of the asphalt; the size, shape and pore radius of the aggregate; the contact angle of the asphalt wetting the aggregate; and perhaps even a factor that accounts for the twisting and turning of the pores in the aggregate.

This hypothesis is being tested by a careful examination of the absorption versus time behavior of a variety of pure liquids and asphalts in contact with porous media including well-defined synthetic aggregates as well as a selection of natural aggregates of widely-varying absorption characteristics obtained from the Materials Reference Library.

Chemical Effects

The hypothesis established to examine the chemical effects of absorption models the selective absorption of specific asphalt components in the aggregate and the implications of such phenomena with respect to adhesion and the durability of the asphalt-aggregate bond.

Analogous to the model established to study adhesion, three distinct regimes can be defined for an asphalt in contact with an absorptive aggregate, viz., absorbed asphalt located inside of the porous aggregate; nonabsorbed asphalt in close proximity to the aggregate but not absorbed inside; and bulk asphalt that is not in contact with aggregate in any respect (figure 5.3).

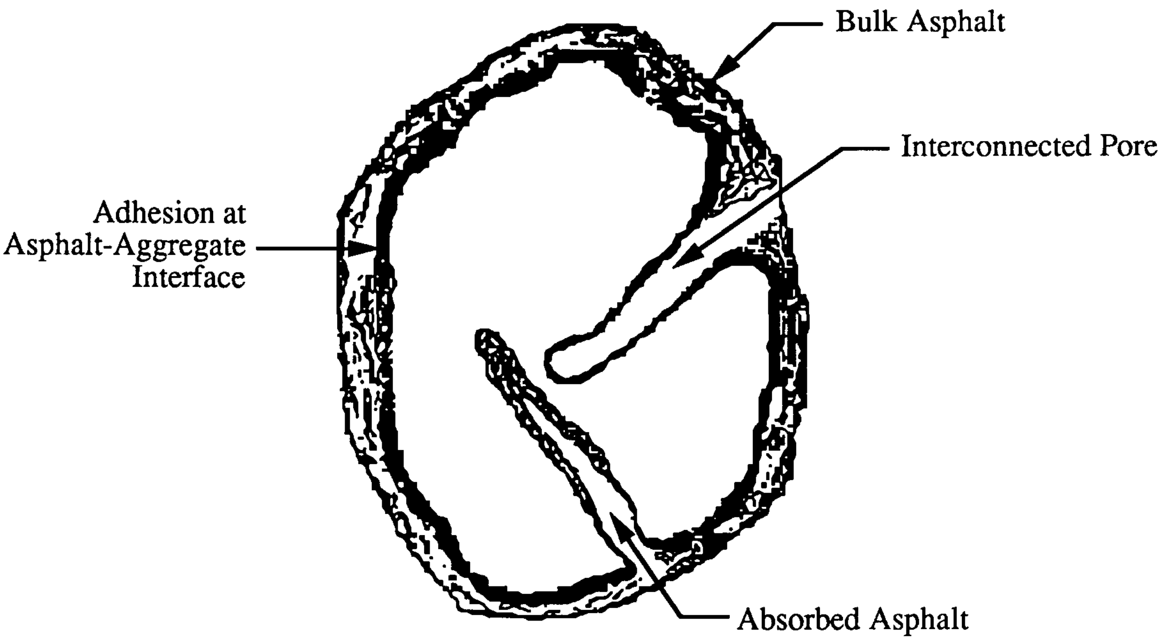

Figure 5.3 The basic model proposed for absorption.

Like chromatographic media, porous aggregates are expected to selectively absorb asphalt components on the basis of both their relative sizes and their chemical affinities for the aggregate constituents. These two factors may also strongly interact in any given set of circumstances. Selective absorption of asphalt components that create favorable bonding interactions with the aggregate can reduce the efficacy of the asphalt binder and decrease its performance. On the other hand, the selective absorption of asphalt components that ordinarily hinder adhesion or deter asphalt-aggregate bonding might increase performance by promoting the adherence of strongly binding components to the aggregate.

The hypothesis will be tested experimentally by in three principal ways. First, asphalts enriched with model compounds of different polarity and size will be absorbed onto a variety of aggregates of differing porosity and chemical composition to determine whether particular compounds and/or functional groups are favored in absorption. Second, the effect of widely varying molecular size distributions in asphalt upon the their absorption will be examined. Third, an attempt will be made to determine differences in the chemical makeup between the absorbed, nonabsorbed and bulk asphalts recovered from contact with absorptive aggregates.

Performance-Related Test Methods to Measure Asphalt-Aggregate Interactions

The physical properties selected for measurement must be related to the pavement distress modes. The physical properties should be fundamental properties expressed in terms of stress, strain, or other fundamental engineering units and should relate phenomenologically to the asphalt chemical composition, asphalt-aggregate system, and systematically be related to the pavement structural design and performance.

The approach pursued in contract A-003B is similar to efforts ongoing in A-002A and A-004 in that the rheological properties (viscoelastic, complex behavior) will be explained in chemical terms by molecular association. Mechanical deformation (e.g. shear flow) will be hypothesized as breaking or altering the intermolecular structure. The more complex chemical and physical tests will be substituted by simpler techniques. The more comprehensive tests will be employed as "bench-marks" and are considered as the ultimate, "gold standard" methods. These will be employed to verify the acceptability of the simplified techniques by providing target values. These simplified physical tests are designed to provide engineering units (stress/strain) and a fundamentally sound link between standardized tests and field performance.

6

Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures - SHRP Contract A-003A

Initially the asphalt program began with an intensive laboratory investigation (SHRP Contract A-002A) to relate the chemical and physical properties of asphalt to the behavior of asphalt mixes and pavement performance. Subsequent research support activities directly related to the asphalt were developed in SHRP Contracts A-083B and A-004.

The impact of these properties, however, cannot be assessed through analyses of the asphalt alone. Long-term performance of pavements is a function of the properties of the asphalt and aggregate components, and of their complex interactions (chemical and physical) when combined in the paving mix.

The performance of asphalts, therefore, must be considered and tested in a mixture context. Tests developed for this purpose are valuable tools to improve mix designs that are based directly on performance-based fundamental engineering parameters and to improve construction quality control.

SHRP Contract A-003A is considered as a cornerstone contract of the asphalt program since it provides the foundation upon which accelerated performance-related tests will be developed for asphalt-aggregate systems. These accelerated tests should allow successful simulation of various construction and service conditions. The fundamental knowledge of mix performance and material component interaction obtained in this research is of critical importance for the successful completion of SHRP Contracts A-005 and A-006. Findings from SHRP Contract A-003A will provide the majority of the research data needed to conceptualize and develop the performance-based specification for asphalt-aggregate mixtures.

Objectives and General Research Approach

The objectives of this key research effort are to develop (1) methods to analyze asphalt-aggregate interactions which significantly affect pavement performance; (2) accelerated, standardizable performance-related tests for asphalt-aggregate systems that successfully model construction and service conditions; and (3) a database derived from laboratory investigations that can be used to validate the asphalt chemical and physical characteristics significant to the performance of asphalt paving mixtures.

Initially, these techniques would be used to extend and validate the results obtained by SHRP Contracts A-002A, A-003B and A-004, by determining their relationship to the performance of asphalt paving mixtures. At a later stage, the focus will be placed upon the development of test methods suitable for standardization to estimate probable field performance of modified and unmodified asphalt-aggregate mixtures. The concept of validation as it applies to the research conducted in contract A-003A is presented in detail in chapter 4 of the companion report SHRP-A/WP-90-007. The following discussion concentrates on the A-003A activities related to test method development to support the performance-based specification for asphalt-aggregate mixtures.

There are test methods and procedures in general use today which can be used for the design of asphalt-aggregate mixtures, notably the Marshall and Hveem design procedures, but they all have serious shortcomings. Specifically, these design procedures are limited in most part to the establishment of a "design asphalt content" for an asphalt-aggregate mix which may or may not perform satisfactorily in terms of adequate stability and durability for the purpose as established from empirical observations. Moreover, these test methods define engineering properties in "non-fundamental" units of "stability," "durability" or "flexibility" on laboratory-fabricated specimens of questionable validity as they are not necessarily realistic reproductions of field pavements compacted by construction equipment and subsequently rubber-tire traffic.

This situation can be corrected and improved by giving consideration to the following essential elements:

1. Develop theoretically sound and reliable test methods and procedures for laboratory-fabricated, binder-aggregate mixtures which can be standardized and proven to be reproducible and will

a. truly characterize their significant and fundamental engineering properties (stress, strain,etc.) related to aging, water sensitivity, fatigue, permanent deformation and thermal cracking;

b. be capable of predicting their performance under the variety of field conditions of loading and environmental exposure generally encountered by in-service pavements; and

c. be practical, efficient, and relatively affordable for use in laboratory facilities of user agencies, materials suppliers and contractor.

2. Consider not only the impact of the research results on advancing the understanding of the behavior of asphalt-aggregate mixtures but also of the entire pavement system with which the asphalt-aggregate system must interact, i.e., as a structural unit through its strength parameters.

3. Extend, define, and complement the results of ongoing research within SHRP, NCHRP and FHWA.

Therefore, as part of the overall test method development, it is essential to produce realistic laboratory-fabricated test specimens in whatever form (e.g., cylinders, beams) necessary to obtain test measurements in fundamental engineering units from and in a manner essentially identical to the response of test specimens taken from field pavements at any given state of traffic and environmental exposure.

The ultimate result is planned to be the development of an entirely new approach for the design of asphalt-aggregate mixtures (SHRP Contract A-006) which will be sensitive to asphalt properties and which can be used to simulate the role of asphalt mixtures under a wide range of in-service conditions.

Model Conceptualization and Validation of Binder Effects on Performance

Several approaches were considered in developing the working models. These included the following:

1. Relate existing test methods to pavement performance by analyzing information in the literature including results of test roads and field studies.

2. Emphasize the need for a new approach involving tests and test results that

can be used for modeling the responses of an asphalt concrete pavement to traffic and climate-induced loads.

3. Utilize laboratory procedures which could simulate field conditions, similar to the approach which is under development by the Laboratoire Centrel des Ponts et Chausses (LCPC) of France.

After evaluating each of the three possibilities, it was decided to incorporate all three in the program. However, emphasis would be placed on the second approach. Accordingly, a working model was formulated which would:

1. Include an extensive search and evaluation of the literature with emphasis on those studies which included field performance data for asphalt pavements. In reviewing the literature, an effort would be made to obtain both qualitative and quantitative data which could help identify the properties of asphalt that influence performance.

2. Include development of a new set of tests, recognizing that existing test methods (Hveem, Marshall) are not acceptable since they cannot be used with existing analytical procedures to estimate mixture response to load (stress, strain, and deformation) and environment including the effects of aging and moisture. This new set of tests would provide results in fundamental engineering units, thus permitting them to be used with analytical methodology. Selection of the tests for development would be guided by an extensive evaluation of the existing literature as well and would include any information relating the laboratory tests to field performance.

3. Include provision for prototype testing such as controlled accelerated test facilities.

Working Hypotheses for Pavement Performance Factors

A key objective of SHRP Contract A-003A is to develop accelerated, standardizable test methods yielding results in fundamental engineering units that may be employed to estimate probable pavement performance. The common link between the laboratory findings from the modified asphalt and unmodified asphalt research and field performance of the paving mixtures is the measurable fundamental engineering properties (stress, strain, etc.). These fundamental properties are identified by well-defined tests which to a large extent should mimic in-service conditions (materials, environment, traffic loading).

The following working hypotheses were established based on the concepts of measurable fundamental engineering properties pertaining to pavement performance and related distress factors.

Fatigue Cracking

The working hypothesis for fatigue in asphalt-aggregate systems is that there is a unique relationship between stress or strain and number of cycles to failure. Prior attempts to develop accelerated test methods have not been completely successful in that "shift factors" are required to convert lab data to field performance. Innovative techniques such as strain energy concepts and fracture mechanics are being explored to address these shortcomings.

Cracking results from a tensile stress or strain (less than the fracture stress or strain-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. The relationships are dependent on the temperature and mode of loading and must be established by some form of repetitive load testing.

Cracking may also result from repetitive stress (strain) applications when either the total energy or the strain energy of distortion reaches some limiting value regardless of the mode of loading to which the specimen is subjected. Figure 6.1 presents the approach being used to test this working hypothesis.

Permanent Deformation

Permanent deformation (rutting) in an asphalt concrete layer may be caused by a 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 rutting; the repeated application of these stresses under conditions of comparatively low mix stiffness are responsible for the accumulation of the permanent deformations in the form of ruts at the pavement surface.

Test methods which duplicate the stress states in the upper portion of the asphalt-bound pavement layer have the potential to define the propensity of a particular asphalt concrete to rut under repeated trafficking. In particular equipment with the capability

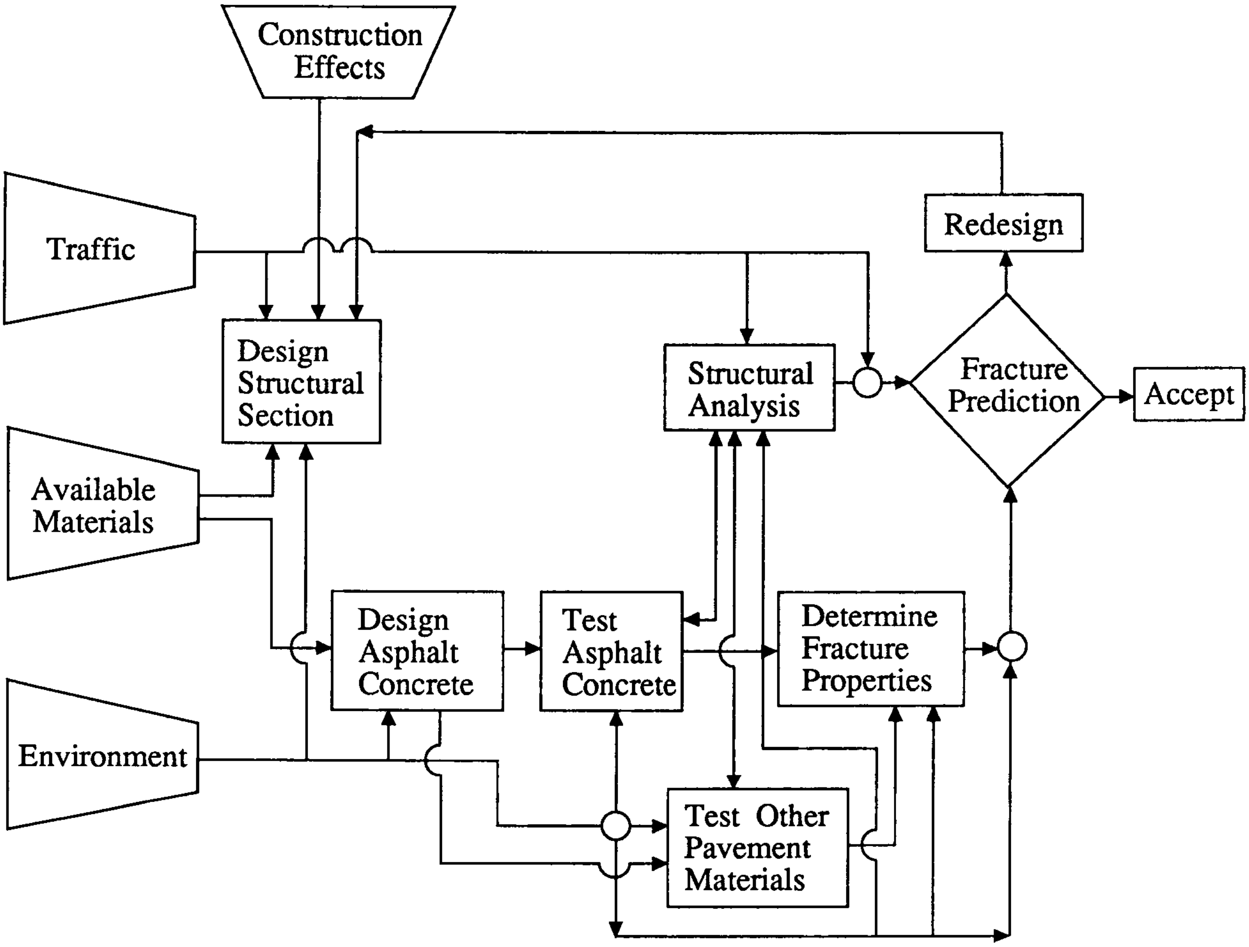

Figure 6.1 Working concept for fracture analysis related to fatigue properties.

of directly applying shear stresses should be utilized. Figure 6.2 illustrates the approach being pursued to test this working hypothesis.

Thermal Cracking

Two hypotheses are being tested for the thermal cracking study. With respect to low temperature cracking, the hypothesis is that as the temperature drops to an extremely low value and when the tensile stress is equal to the tensile strength at that temperature, a microcrack develops at the surface of the pavement. The crack then propagates through the depth of the layer when subjected to additional thermal cycles. Figure 6.3 shows the relationship of tensile stress to tensile strength concept. The second hypothesis is that thermal fatigue cracking occurs when temperatures cycle above the level required for low temperature cracking even though the stress in the pavement is typically far below the strength of the mixture at that temperature. Consequently, failure does not occur immediately, but develops over a period of time similar to the time required for fatigue cracking associated with traffic load induced strains in the asphalt concrete pavement layer.

Aging

The working hypothesis for aging of asphalt-aggregate mixtures is that two major effects dominate. They are:

1. Loss of volatile components in the construction phase (short term aging); and

2. Progressive oxidation of the in-place mixture in the field (long term aging).

Other factors may contribute to aging. In particular, molecular structuring may occur over a long period of time resulting in steric hardening. Actinic light, primarily in the ultraviolet range also has an effect, particularly in desert-like climates.

Aging results in hardening (stiffening) of the mixture which will result in a change in performance of the mixture. This may be beneficial since a stiffer mixture will have improved load distribution properties and will be more resistant to permanent deformation. However, aging may also result in embrittlement (increased tendency to

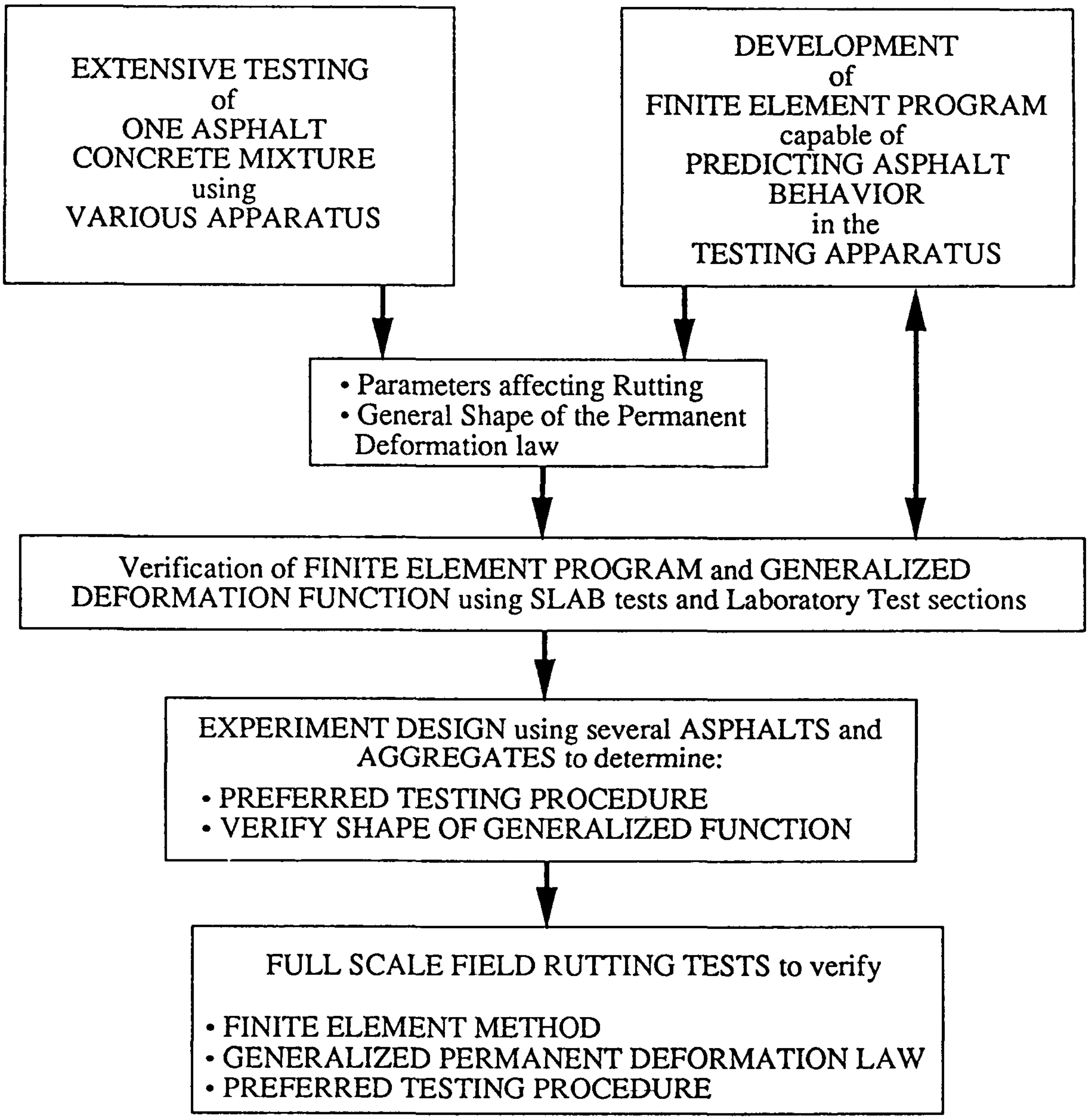

Figure 6.2 Working concept for developing test for evaluation permanent deformation.

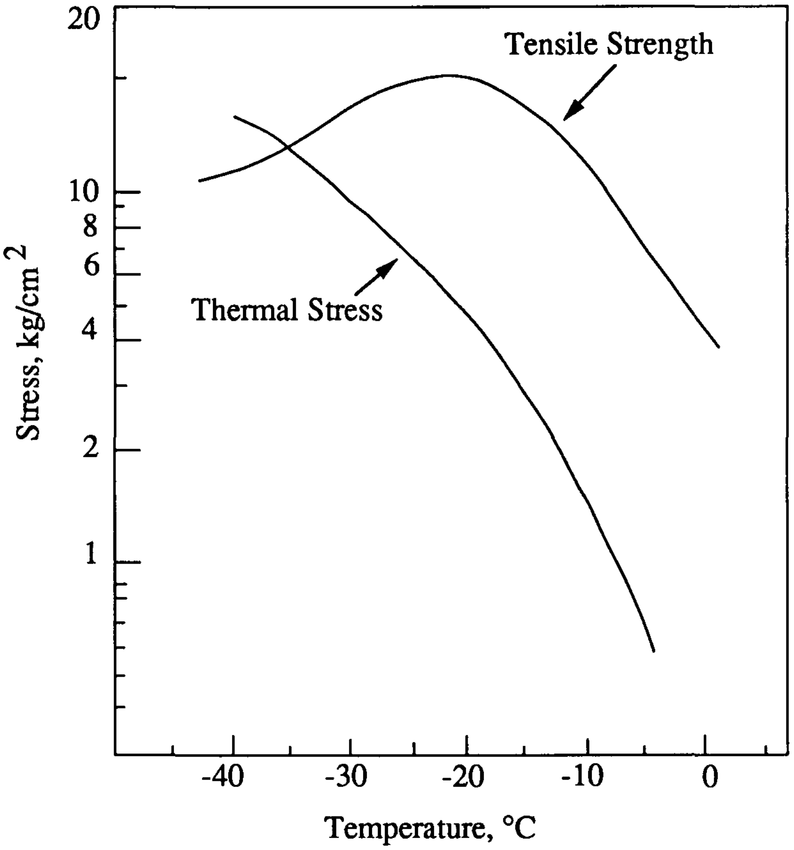

Figure 6.3 Relationship of tensile stress to tensile strength concept.

crack) and loss of durability in terms of wear resistance and moisture susceptibility.

Development of a laboratory method or methods to simulate aging will concentrate on reproducing the two dominant effects, i.e., volatilization and oxidation.

Clearly, the level of temperature will play a part in the extent of volatilization, but it will also affect the extent of oxidation, and it is thought that for a particular temperature there will be a threshold level of aging. The rate at which aging occurs will be accelerated by increasing the concentration of oxygen. Figure 6.4 shows the possible interaction of temperature and oxidation aging.

Water Sensitivity

The working hypothesis for water sensitivity of asphalt-aggregate mixtures is aimed at controlling the air void content because existing mixture design and construction practice tend to create an air void system that may be the major cause of moisture-related damage.

Figure 6.5 shows that for most asphalt concrete mixtures, the strength or modulus (such as M_R) will be reduced as much as 50% when wet or "conditioned" by water. The amount of M_R loss depends upon the amount and nature of the voids. At less than 4 percent voids, the mixture is virtually impermeable to water, so is essentially unaffected. Region A-B in figure 6.5 is where designers often design and try to construct pavements. Region B-C is where the pavement is constructed, with higher voids. As the voids increase to D and beyond, the M_R becomes less affected by water because the mixture is free draining.

The region B-C in figure 6.5 can be called "Pessimum" void content because it represents the opposite of optimum. "Pessimum" voids actually represent both a quantitative (amount of voids) and qualitative (size, distribution, interconnection) concept as they affect the behavior and performance of pavements.

The laboratory research being developed to test the hypothesis includes the development and use of a modified triaxial cell. For a given specimen, several factors can be varied and monitored by measuring M_R. These factors include: temperature (hot, cold, freeze); water condition (dry, moist, saturated); permeability (which may be a better measure than air void content); and loading (traffic).

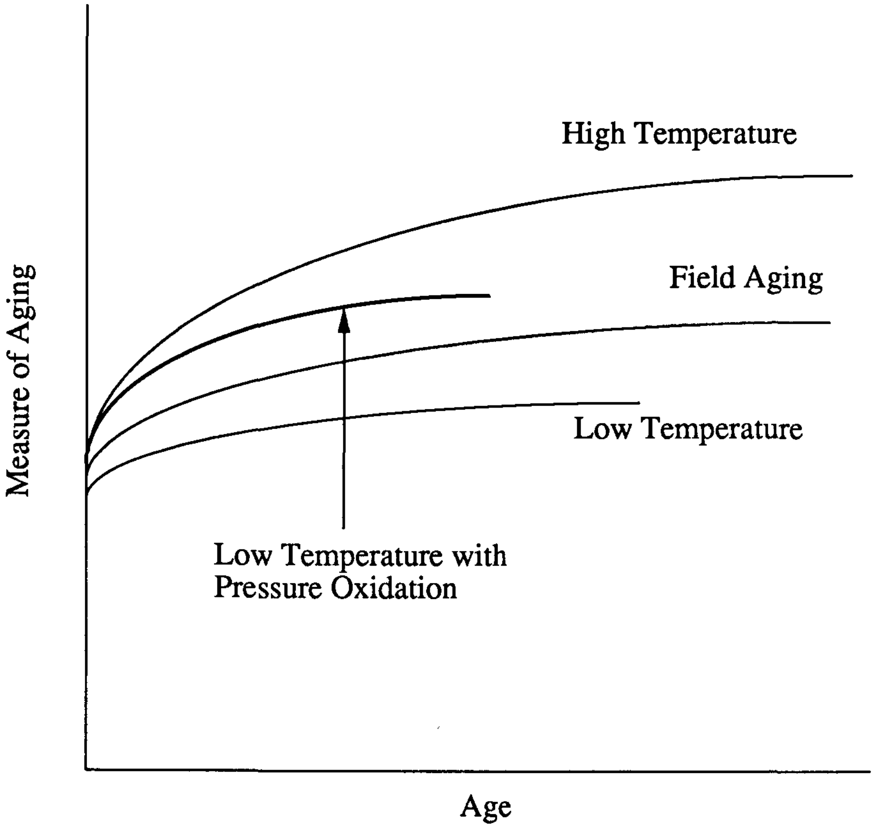

Figure 6.4 Possible interaction of temperature and oxidation on aging.

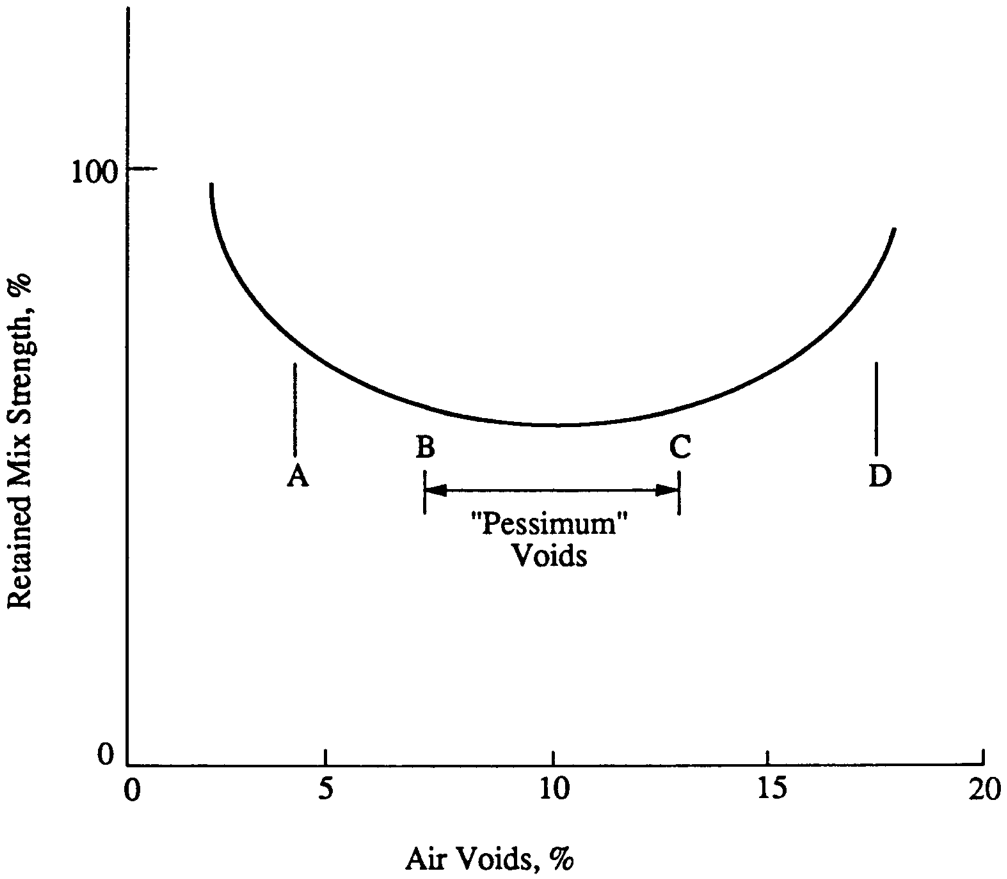

Figure 6.5 Concept of "Pessimum Voids" as related to retained asphalt concrete mix strength and percent air voids.

7

Performance Models and Validation of Test Results - SHRP Contract A-005

The second-stage validation (see the discussion in chapter 4 of the companion report SHRP-A/WP-90-007) of important relationships between asphalt properties and field performance could be accomplished through a long-term investigation of the performance of controlled field experiments. This approach, however, would require an estimated twenty or more years of investigation, and would be inconsistent with SHRP's objective of rapid development of recommended performance-based specifications for asphalt. Therefore, research project A-005 is mainly organized to accelerate the validation process through a correlation of the relationships between asphalt properties and field performance, and the predictive performance models expressing these relationships, with in-place field performance data, by employing statistical data treatment, judgment and interpretation in place of long-term performance analysis. The success of this project is vital to the success of the entire SHRP asphalt program.

Contract A-005 also has the goal of developing performance models capable of capitalizing upon the data obtained from the SHRP Long-Term Pavement Performance (LTPP) General Pavement Studies (GPS) and upon other data available from state highway agencies, FHWA, and industry and accelerated field tests such as conducted at the Pennsylvania State University test track or the FHWA's Accelerated Loading Facility (ALF). These models will be needed to estimate pavement performance factors, account successfully and realistically for the effects of load-related and non-load related factors on the performance of these asphalt concrete pavements, and anticipate the effect of new demands that will be made on the pavements built in the future.

Thus, it is essential to the success of this research to formulate relationships between asphalt, mix properties, and field performance in a manner that realistically accounts for the effects of traffic loads, the environment, pavement structure, and construction variables. The approach must be accomplished with the strategic view in mind that both traffic loads and construction variables will certainly change in the future. Concepts for development of these performance models are discussed below.

General Research Approach

Pavement performance models are commonly classified as empirical, mechanistic or mechanistic-empirical. Because of the complexity of pavement structures, there are no purely mechanistic models of pavement performance. Instead, the primary response of a mechanistic model (deflection, stress, or strain) must be related empirically to some measurable form of distress. This is a mechanistic-empirical model which is an extremely efficient method of extrapolating current observations into future conditions, and will be the principal method used in this research.

An empirical model is an attempt to form a statistical relation between causal factors and their effects in the absence of an understanding of the physical principles that are involved. While commonly being very useful, such models have the same limitations as do all statistical methods, the principal one being that their validity is limited to the inference space from which it was drawn. The most appropriate way to use empirical models in this research will be in the materials property relationships to be developed from laboratory tests.

SHRP anticipates that performance prediction models which satisfy the objectives of the asphalt program research will make use of all of these model types. Figure 7.1 in conjunction with the information in table 7.1 provides an example model for load-related fatigue cracking. Relation No. 1 in figure 7.1 indicates that there are several types of relations that have been developed between the properties of asphalt and aggregates and the properties of the aggregate-asphalt mixture. Some of these relations are purely empirical and others are mechanistic-empirical. The same comment applies to fatigue properties, some of which are empirical and others, which are based upon fracture mechanics, are mechanistic-empirical. The relations between these fatigue properties, the primary responses which are predicted mechanistically by the layered pavement model, and the amount of field fatigue cracking is a purely empirical relation, relation No. 4. The overall model illustrated in figure 7.1 is termed a "mechanistic-empirical model" but it is made up of a number of sub-models that are themselves mechanistic, empirical, or mechanistic-empirical. The same can be said for models of the other types of distress of interest to this project.

SHRP Contract A-005 has special interest in three materials characteristics of asphalt-aggregate mixtures: aging, adhesion, and water sensitivity. The relationship of these characteristics to field performance must be viewed as affecting one or both of the materials relations in figure 7.1, namely Relation No. 1 and Relation No. 2. It is important to understand this distinction at the beginning of this research. A direct

Table 7.1 Explanation of Relation Number Identified in Fatigue Model

Relation Number	Type of Relation	Composed of Relations Among Listed Properties
1	Asphalt-Aggregate Mixture (e.g., Stiffness, Creep, Tensile Stength) Empirical Coefficients	Asphalt Binder Aggregate Stress Moisture Temperature Internal Damage (e.g., Aging, Adhesion, Water Sensitivity)
2	Material Damage (e.g. Fatigue, Permanent Deformation, Low Temperature Cracking) Empirical Coefficients	Asphalt-Aggregate Mixture Layer Thickness
3	Mechanistic Response	Asphalt-Aggregate Mixture Moduli of other Layers Loads, Temperature, Moisture Primary Response (e.g., Stress, Strain, Deflection)
4	Performance Empirical Coefficients	Mechanistic Response Material Damage

empirical relation does not and should not exist between the distress a pavement develops and the materials characteristics which are known to accelerate or diminish the rate of appearance of that distress, such as aging, adhesion, and water sensitivity.

Thus, when models of fatigue, permanent deformation, and low temperature cracking are developed, they will be in reality like the overall model relation shown in figure 7.1. On the other hand, when models of aging, adhesion, and water sensitivity are developed, they will model relations such as No. 1 or No. 2 in figure 7.1.

These types of relations will be developed by laboratory testing, and will be altered by field observations only after a sound empirical Relation No. 4 has been developed. The success of SHRP Contract A-005 depends upon: (1) making these distinctions clear at the outset; (2) having sound Relations No. 1, 2, and 4 developed between the properties of virgin asphalts and field performance in Project A-002A and A-003A; and (3) altering these relationships in a systematic way using field measurements of distress and laboratory tests on materials which have been in service and subject to the effects traffic and environment as well as of aging, water sensitivity, and variable adhesion properties. This process will be assisted measurably by selecting as part of the experiment design as many pavement sections as possible for which the virgin asphalts are available.

Overall, these models will demonstrate not only how successful and cost-effective performance-based specifications can be developed, but also the cost-effectiveness of the SHRP-directed efforts in asphalt and long term pavement performance.

Model Conceptualization

Pavement performance is influenced by so many variables that a comprehensive approach becomes necessary in order to identify all the significant factors as well as the important interactions. An ideal comprehensive framework for evaluating pavement performance is presented in figure 7.2. The framework recognizes that a variety of factors related to the environment, pavement materials, traffic, design, and construction, individually and interactively influence the performance of a pavement section with time or with increasing axle load applications. Consequently, models for estimating the effects of these factors will have to be considered in the development of a set of algorithms for evaluating flexible pavement performance. These models will be used in conjunction with pavement structural response and distress models to establish criteria for developing performance-related specifications.

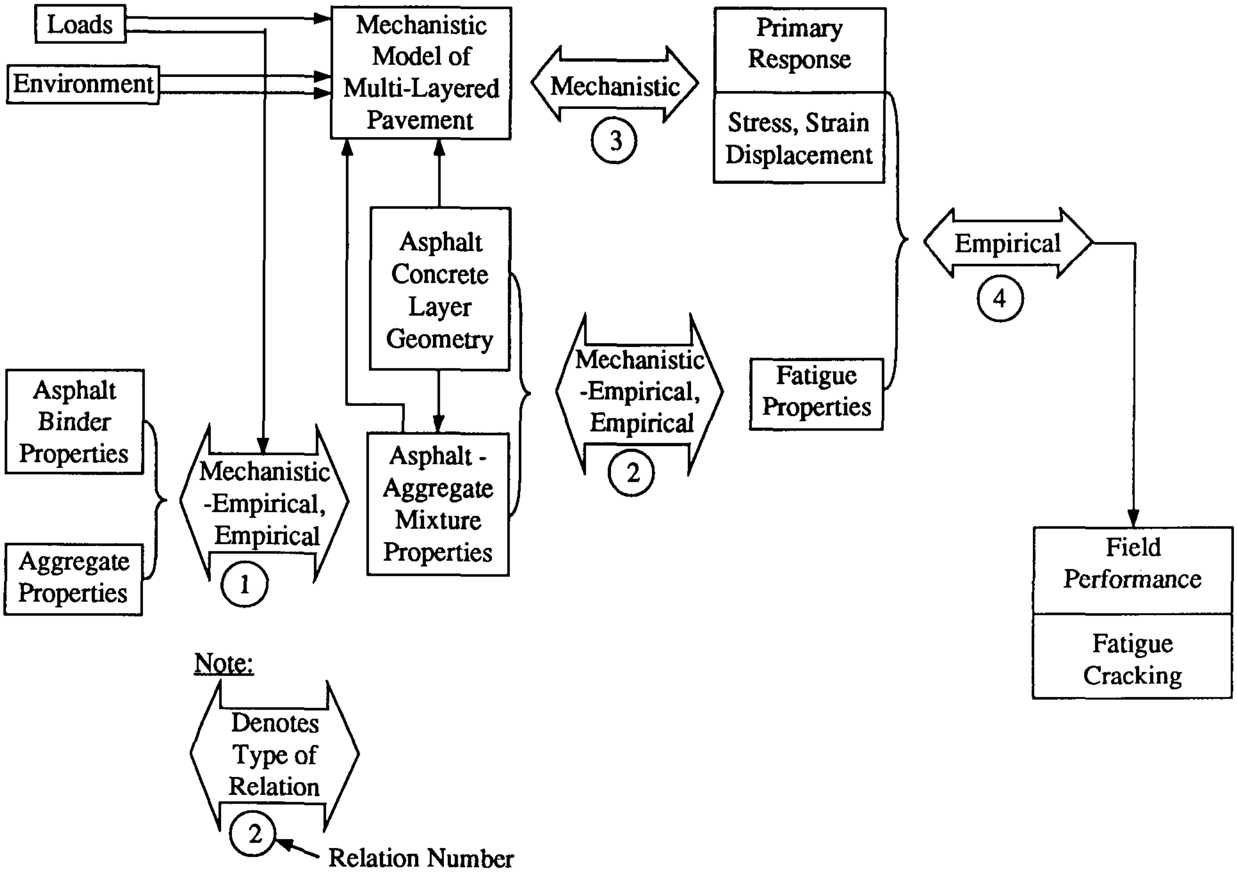

Figure 7.1 Illustration of the types of relations involved in a load-related pavement performance prediction model considering fatigue cracking.

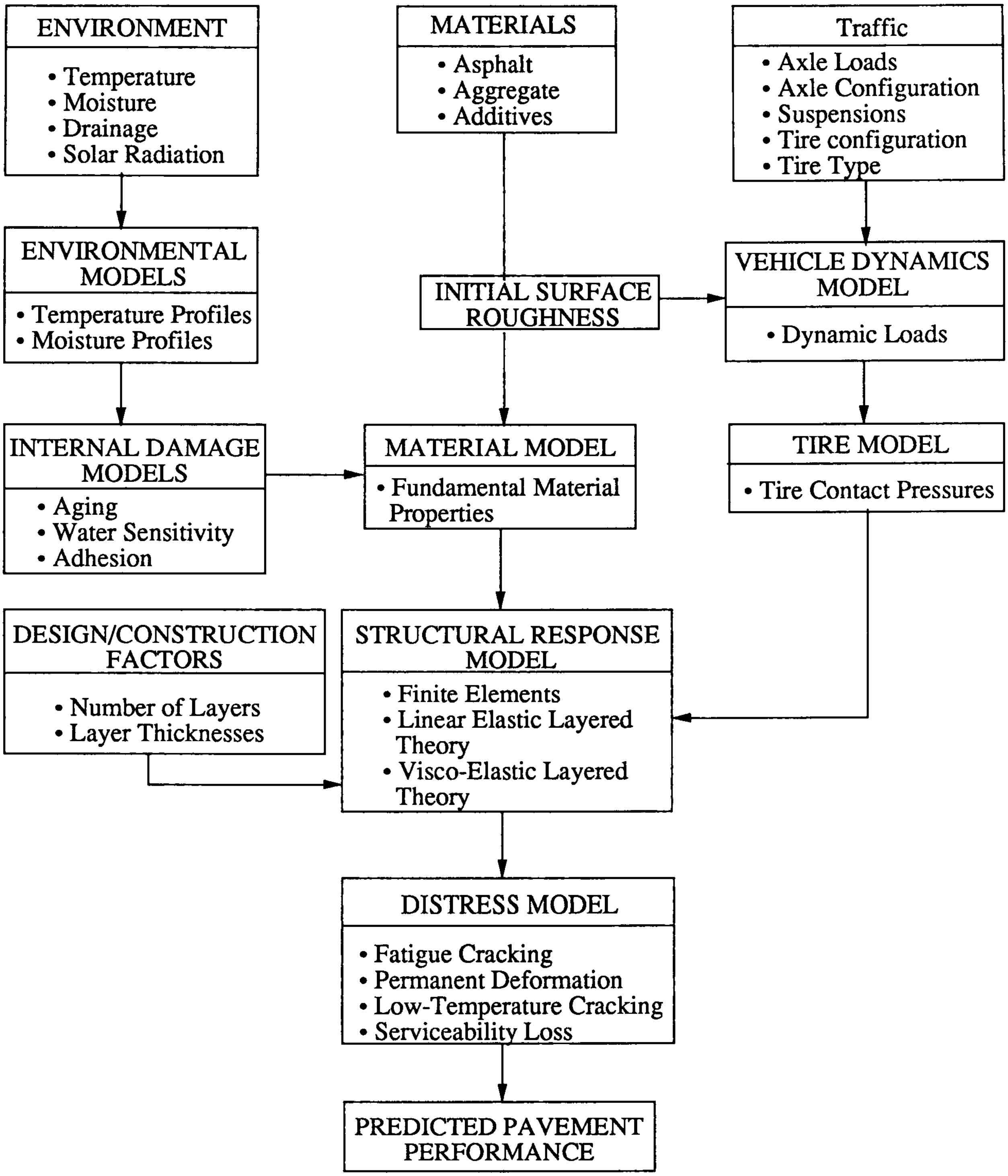

Figure 7.2 Ideal framework for pavement performance evaluation.

The framework is based on a stepwise procedure wherein the various models are applied in sequence. Consequently, the accuracy of the predictions from any one model will affect the accuracy of the predictions from subsequent models. For example, errors due to simplifying assumptions made in one model will systematically show up in the predictions from subsequent models, with the errors from all models accumulating and distorting the final performance estimates. This indicates that the models to be selected must be realistic and be state-of-the-art to minimize the compounding of errors that can occur.

SHRP Contract A-005 will review available models that can serve as elements of the framework shown in figure 7.2. This synthesis will draw significantly from the results of on-going SHRP contracts, particularly SHRP contracts A-002A and A-003A, and the FHWA study on *Development of Performance-Related Specifications for Asphalt Concrete: Phase II.*

Performance-Related Material Property Test Models

SHRP contracts A-002A and A-003A are developing (1) relationships between asphalt properties and pavement performance and (2) performance prediction models which may use asphalt-aggregate system properties. SHRP Contract A-005 will first validate these relationships and models, and will then develop procedures for adjusting and calibrating these relationships and models.

There are several opportunities for validation of relation-ships and models in the A-005 research. The most desirable way of developing relations and models is to define the basic form of the model theoretically and then use statistics to find the values of coefficients. Figure 7.3 depicts some of these opportunities shown by the arrows connecting the boxes. The results of materials tests will be made in SHRP Contracts A-002A, A-003A and possibly A-003B, and will be analyzed using appropriate materials property relationships. These relationships will be incorporated into the performance prediction models. The analysis should produce materials properties and "empirical coefficients", both of which are to be programmed into the performance prediction models as dimensioned variables. The coefficients derived from the laboratory tests will be incorporated into the programs as data blocks which will make it a simple matter to adjust and update them based upon matching field data with values predicted by the performance prediction models.

In developing the models, it is important to recognize that there are twelve mechanistic properties of a material from which all other properties may be derived:

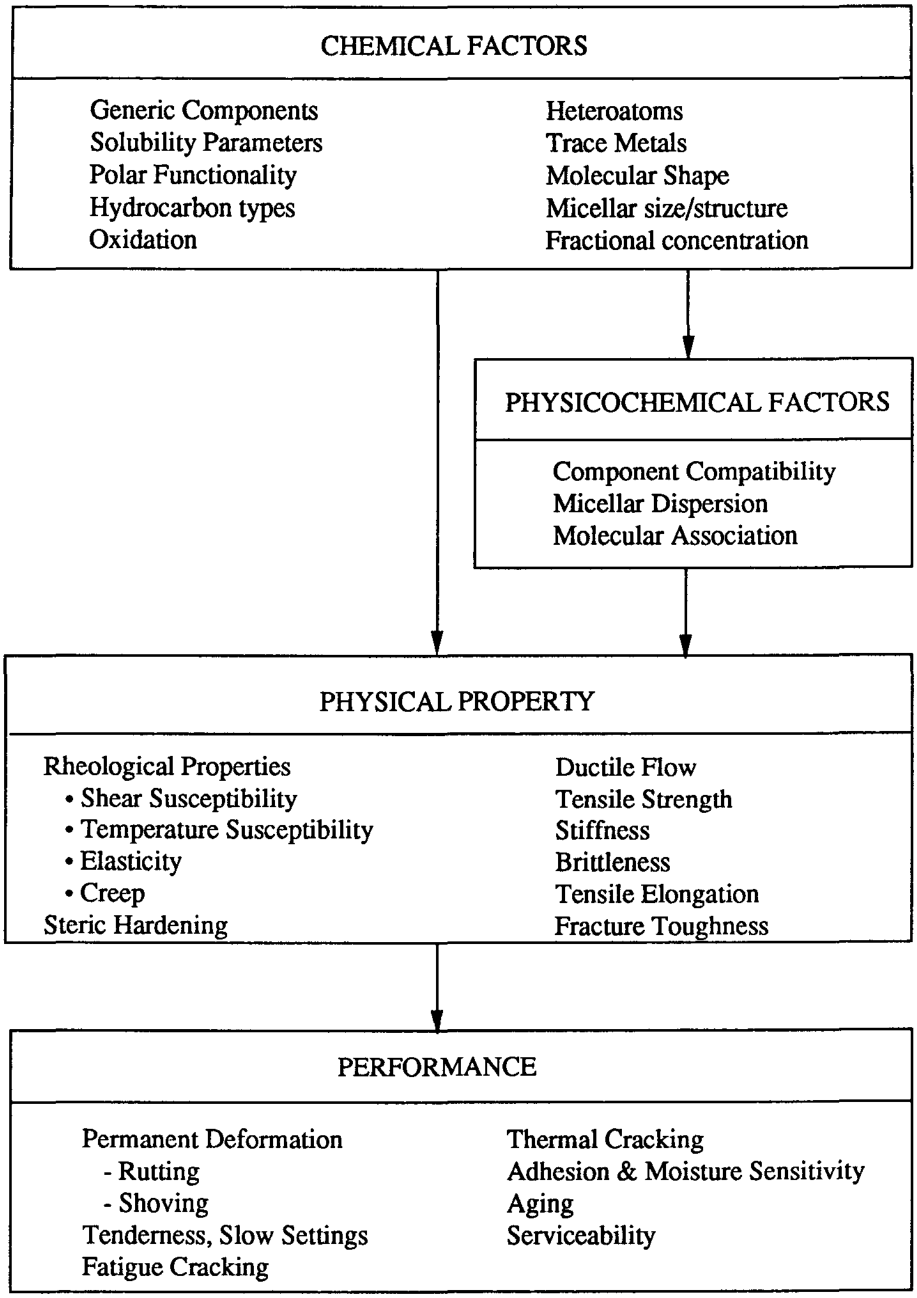

Figure 7.3 Selection of possible relationship opportunities.

1. Bulk Compression: stiffness, strength, and change of stiffness and strength with time and temperature.

2. Bulk Tension: stiffness, strength, and change of stiffness and strength with time and temperature.

3. Temperature Shear: stiffness, strength, and change of stiffness and strength with time and temperature.

All of these properties are illustrated in figure 7.4. Real materials do not follow the straight lines indicated in the figure but instead, transition from one to another. However, for the purposes of the interpretation of the data generated by the various research activities, it is essential to maintain a clear picture of the twelve properties.

Considering fatigue cracking models, the only tests needed to completely characterize the fatigue properties, K_1 and K_2, are the tensile stiffness, strength, and creep tests (which are directly related to the tensile relaxation tests). Permanent deformation properties, alpha and gnu, can be derived from the compressive creep and stiffness tests. The low-temperature cracking properties that govern the behavior of an asphalt-aggregate mix are the tensile fracture properties which, once again, may be derived from the tensile stiffness, strength, and creep (or relaxation) tests at low temperatures.

If these tests can determine the fatigue, permanent deformation, and low-temperature cracking properties of mixes, it is possible that they can also determine the effect of aging, adhesion, and water sensitivity. Aging acts to increase all stiffness properties, to increase compressive strength and decrease the tensile and shear strength, and to flatten the relaxation (or creep) curves.

Their translation into practical terms for use in predictive models must be in the effects they have on the twelve mechanistic properties. Because adhesion is a surface phenomenon and water sensitivity is a bulk phenomenon, this provides a simple and straight-forward way of distinguishing them in their test properties. Adhesion will affect the ability of a mix to withstand or resist shear and bulk tensile stresses, but will not affect the bulk compression properties. Water sensitivity will affect all of the properties by decreasing the stiffness(and strength and steepening the relaxation (or creep) curves.

Representing the mechanistic properties of aging is complicated somewhat by the fact that some part of aging is reversible (steric hardening) by the application of kneading loads (i.e., loads which induce shearing stresses) while another part is irreversible (oxidative hardening).

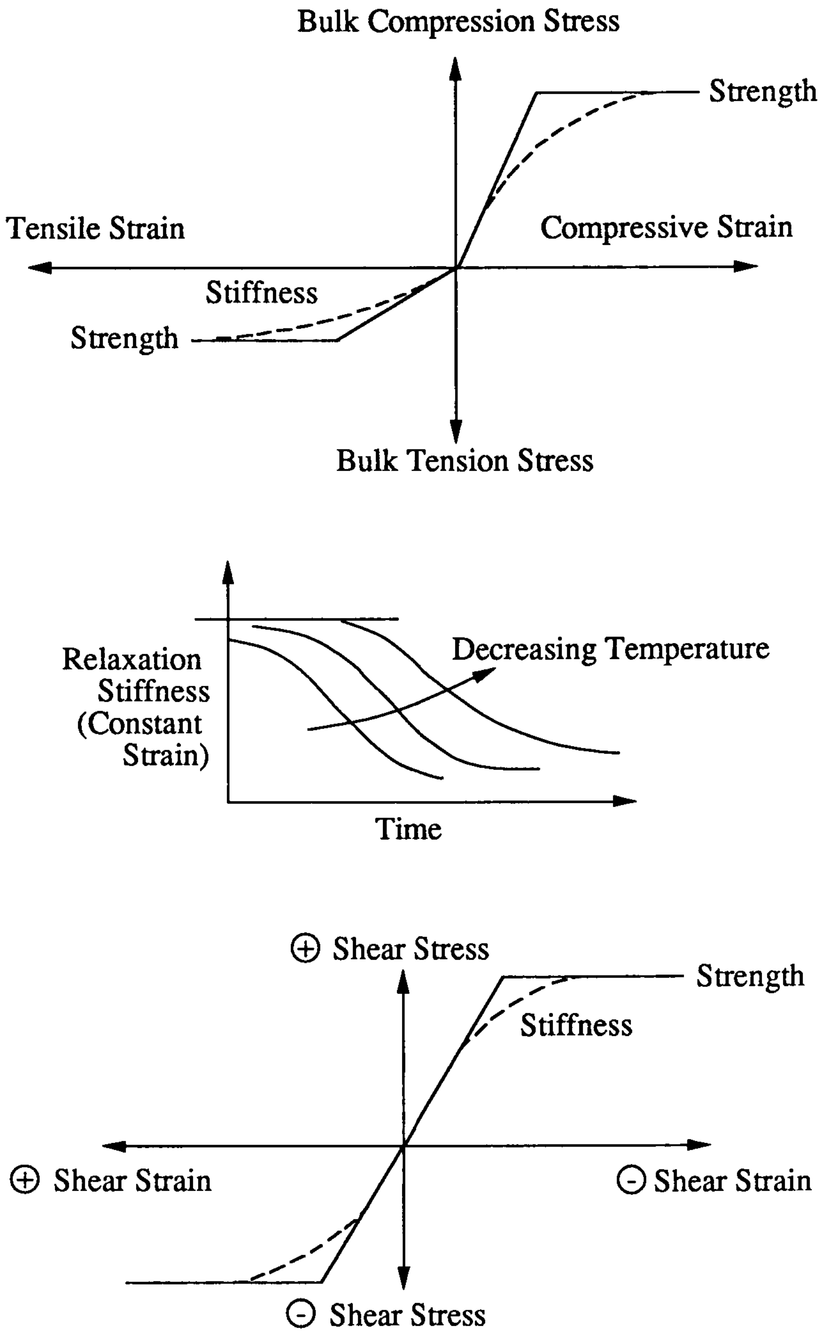

Figure 7.4 The twelve basic mechanistic materials properties.

The facts summarized above are a complete catalog of the effects of these "internal damage" mechanisms on the mechanistic properties of an asphalt-aggregate mix.

Sensitivity Matrices for Performance Models

A sensitivity matrix for selected load-related and non-load related pavement performance prediction models will be developed. Sensitivity coefficients will be determined for each type of distress and each coefficient to form the sensitivity matrix. The coefficients in each relation with empirical coefficients will be stored in a data block. Weights between 0 and 1 will be provided for each coefficient and each relation (Nos. 1, 2, and 4 shown in figure 7.1) within the model, and a subroutine will be provided to invert the sensitivity matrix products. Subroutines will be provided to perform the automated search for a new set of coefficients and to substitute the new values into the coefficient data block, prepared for the next set of calculations by the performance model. Another subroutine will be set up to determine automatically the percent difference between the calculated and observed distress (the residual vector) either for a single pavement or any specified number of pavements.

The sensitivity matrix approach, used together with full distress data obtained from pavement sections, will be used to adjust the model coefficients. The resulting coefficients will be the ones reported.

Sensitivity Matrices for Materials and Performance Relations

Sensitivity matrices will be developed for each of the relations within each pavement performance prediction model in order to permit an independent, automated adjustment of the coefficients within each of those relations. A separate microcomputer program will be developed for each relation to invert the sensitivity matrix product, update the residual vector, and compute the next set of coefficients. Relations encompass all of the models of the different material properties included in the relation. Take, for example, Relation No. 1 (figure 7.1) for asphalt-aggregate Mixture properties.

This "relation" encompasses <u>several</u> models of asphalt-aggregate mixture properties including those for stiffness, creep compliance (tensile and compressive), tensile strength, and so on; one model for each property, and each model having its own set of empirical coefficients.

A sensitivity matrix can be constructed for <u>each</u> material property in this Relation No. 1, and an automated procedure can be set up to permit engineering judgment to weight the sensitivity coefficients, invert the sensitivity matrix product, update the residual vector, and calculate a new set of coefficients. In this case, the residual vector will be the percent difference between a predicted material property (such as tensile strength) and a measured one. The coefficients may be adjusted iteratively until the prediction matches the measured within acceptable limits.

This procedure will be used to adjust the coefficients of the material models in Relations No. 1 and No. 2 (figure 7.1) using the data from laboratory tests conducted in contract A-005 and contracts A-002A and A-003A. The resulting coefficients will be the ones reported.

8

Performance-Based Specifications for Asphalt-Aggregate Mixtures - SHRP Contract A-006

A Conceptual Framework for a Performance-Based Specification for Asphalt-Aggregate Mixtures

NCHRP Contract 10-26(A) has provided a framework for development of performance-related specifications for hot-mix asphalt concrete; this framework will play a principal role in the development of working concepts for and the final form and content of the specification. Figure 8.1 presents the conceptual framework. Several assumptions were made in the development of this conceptual framework:

1.The basic element in the framework is the relationship between pavement performance and environmental, structural, material, and construction variables. The relationships are not specified but may include those in the new AASHTO design guide (2) or any other valid relationships between pavement performance and environmental, structural, material, and construction variables.

2.The same performance relationships can be used to evaluate the initial pavement design and to assess the costs associated with nonconformance with materials and construction (M&C) specifications.

3.The framework requires a statistically based acceptance plan and payment schedule. Process control is considered the responsibility of the contractor and is an inherent part of the specification. Furthermore, the framework places the responsibility for quality control with the contractor rather than with the user agency.

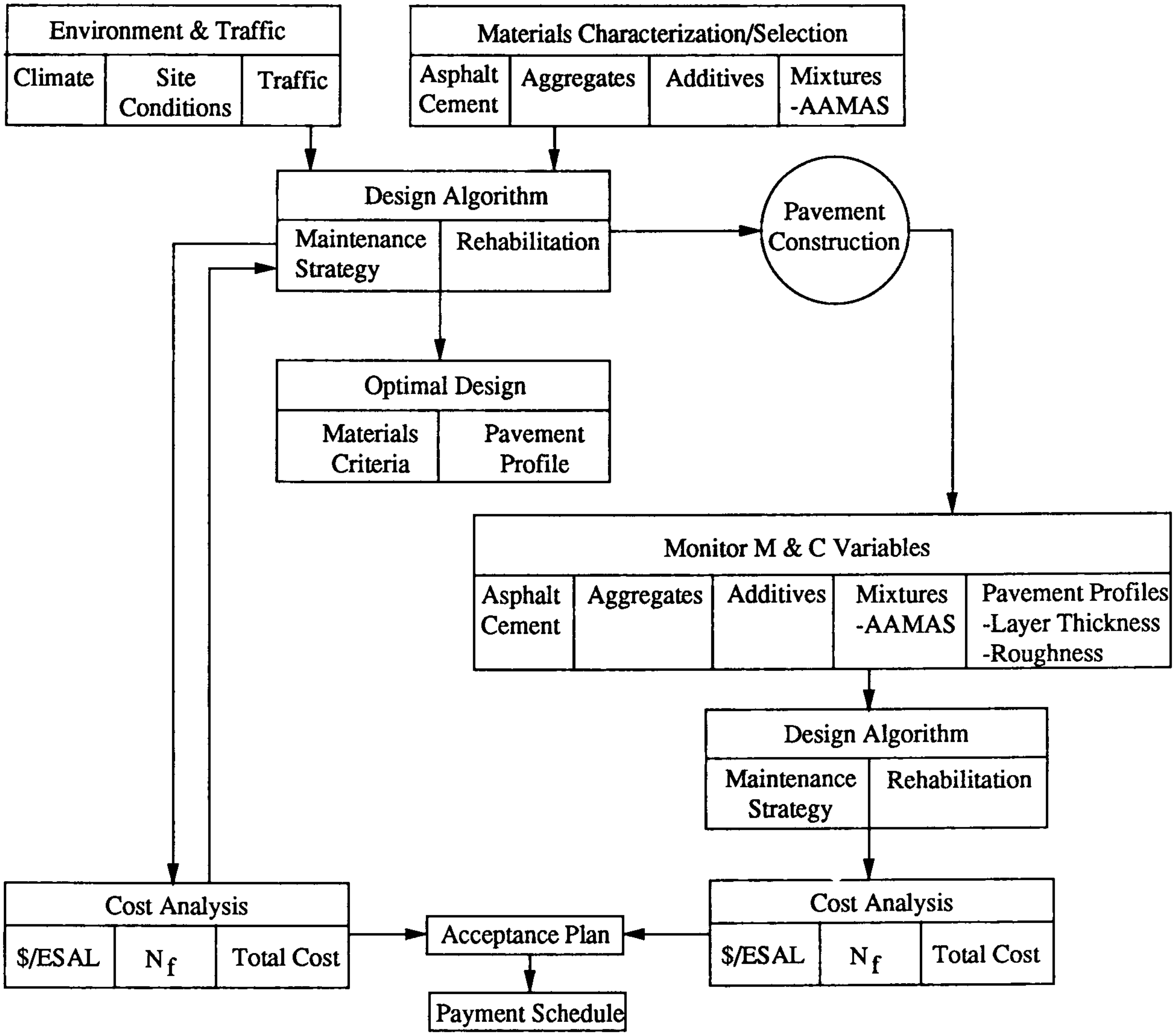

Figure 8.1 Conceptual framework for a performanced-based specification.

4. Pavement performance can be quantified in terms of functional performance or structural performance. Performance is measured by evaluating pavement condition indicators such as roughness, skid resistance, and cracking.

5. For payment purposes, performance is expressed in terms of life-cycle costs. This provides a common denominator for equating life-cycle costs with the penalties assessed for M&C specification noncompliance. Life-cycle costs include the cost of construction, maintenance, and user costs.

The conceptual framework in figure 8.1 considers the various factors in the pavement engineering process. The basic element in the framework is an algorithm for pavement design. This algorithm embodies the relationships between pavement performance and various inputs to the design process, e.g., environment-, traffic-, and materials-related variables. Factors associated with environmental and traffic conditions are beyond the control of the pavement engineer, the materials supplier, or the contractor and will be referred to as uncontrolled factors.

Materials-related variables, on the other hand, are controlled factors and are the primary interest in this study. Examples of such factors are the asphalt content, the gradation of the aggregates, and the compaction of the asphalt concrete mat. Material response characteristics, e.g., mix stiffness, are either measured in the laboratory or estimated from established relationships between certain material response characteristics and properties of the basic mixture components. Such relationships are expected to be embodied in the Asphalt-Aggregate Mixture Analysis System (AAMAS) currently being developed as part of NCHRP Project 9-6 and in the SHRP mixture analysis system (MAS) that will form an integral part of the performance-based specification for asphalt-aggregate mixtures.

Obviously, many of the elements proposed in the framework (figure 8.1) are not yet fully developed. This is particularly true with regard to models that relate pavement performance to material properties. The Strategic Highway Research Program (SHRP) and, in particular, the Special Pavement Studies (SPS) envisioned in the Long Term Pavement Performance Program (LTPP), offer an excellent opportunity to develop many of the missing links in the conceptual framework.

A Specific Working Concept for the SHRP Mixture Specification

While the research conducted in this contract does not lend itself to the development of working hypotheses to guide the work, a working concept or model of the performance-based specification will be developed early in the study utilizing the general principles discussed in the previous section. This model will consider the philosophies, hypotheses and rationale involved with the envisioned specification limits for mix properties measured by anticipated test methods, for the full range of design considerations for the asphalt-aggregate mixture. An initial concept based upon the work already accomplished in contract A-003A is discussed in chapter 5 of companion report SHRP-A/WP-90-007 and will serve as the starting point for further conceptualization in contract A-006.

The performance-based properties of the asphalt binder that are significant to the performance-based specification for asphalt-aggregate mixtures will be isolated. Pertinent findings and information from contract A-005 related to the identification and validation of important asphalt binder and asphalt-aggregate mixture properties, and the recommended ranges of those properties that significantly affect the performance of the pavement, will be identified.

This information will be employed to form an effective system with which to select and proportion the materials associated with an asphalt-aggregate mixture so that it:

- will be tolerant to a wide range of mixing temperatures without damaging the asphalt and adversely affecting its desirable mixing and placing characteristics or its long-term performance in-service;
- will not be affected adversely by the chemical and physical properties of the aggregate used in the mixture;
- will provide the needed adhesion in the mixture;
- will be resistant to bleeding and flushing of asphalt at high temperatures;
- will be resistant to the adverse effects of asphalt aging;
- will produce a flexible mixture at all surface temperatures; and
- will produce a mixture that will be resistant to fatigue cracking, permanent deformation (rutting) and low-temperature cracking for the projected traffic loads and environmental conditions.

Conceptually, the performance-based specification will incorporate a mix analysis system; performance-related, accelerated test methods; a modifier evaluation protocol; and specification tolerances for the specified properties measured by these tests, so that a mixture will be consistently produced with the following characteristics related to design considerations:

- Resistant to creep and permanent deformation (i.e., rutting).
- Resistant to repeated bending stresses and strains (i.e., fatigue).
- Resistant to low-temperature cracking (i.e., thermal cracking).
- Resistant to aging in-service at relatively high air voids (i.e., long-term durability).
- Resistant to the effects of moisture and water (i.e., water sensitivity).
- Compactible over a wide temperature range.

In summary, the performance-based specification for asphalt-aggregate mixture is conceived as based upon a set of validated relationships between (modified and unmodified) asphalt binder properties, asphalt-aggregate mixture properties and field (pavement) performance that establish acceptable responses for fatigue cracking, permanent deformation (rutting), low-temperature cracking, aging, adhesion, and water sensitivity.

The performance-based specification will allow selection of an optimal job-mix formula that will provide for satisfactory pavement performance and accommodate a wide variety of environment, construction and traffic loading conditions encountered in the United States and Canada. In addition, it will provide a structured method for estimating the probable effects of off-specification paving mixes on near- and long-term pavement performance. The actual specification information, related tests, and a mix analysis system will be developed in appropriate AASHTO and ASTM format to ensure their ready consideration by the AASHTO Subcommittee on Materials and appropriate ASTM subcommittees.