SHRP-A/UWP-91-508

Factors Influencing Mix Setting Characteristics and Tests to Predict Mix Setting Characteristics

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Strategic Highway Research Program
National Research Council
Washington, DC 1994

SHRP-A/UWP-91-508
Contract A-003B
Product No.: 1012

Program Manager: *Edward T. Harrigan*
Project Manager: *Ian Jamieson*
Production Editor: *Marsha Barrett*
Program Area Secretary: *Juliet Narsiah*

February 1991
Reprint March 1994

key words:
absorptive aggregate
aggregate
asphalt
mix-setting characteristics
slow-setting mixes
steric hardening
tenderness

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50/NAP/394

Acknowledgments

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.

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OBJECTIVE

The principal objective of this literature review is to survey published information and cite references pertaining to the various asphalt, aggregate and other mix properties that influence the setting characteristics of the mix, and to identify the various tests that are used to measure these mix characteristics. Some of the more specific objectives of this review deal with the following areas:

1. To survey the role absorptive aggregates have in influencing the mix-setting characteristics.

2. To survey the role of basic asphalt and aggregate properties in mix-setting characteristics.

3. To identify the effect of steric hardening (structuring) on mix-setting characteristics.

4. To survey both the laboratory and field tests presently used in measuring mix-setting characteristics.

Finally, based on a critical analysis of the literature reviewed, this document attempts to identify potential research avenues in developing laboratory tests for evaluating mix-setting characteristics associated with absorptive aggregates and the effect of these characteristics on moisture susceptibility.

DESCRIPTION OF PROBLEM

Mixes which shove extensively under steel wheel rollers, do not densify, or are tender to any type of distortion, are defined as "slow setting." Tender pavements have been described in several ways. Some of the more common descriptions have been *(1)*:

1. The mix is difficult to roll.
2. Specified density cannot be achieved.
3. The pavement ruts under load after completion of construction.
4. The pavement is soft after completion and will displace under the heel of a shoe.
5. A pavement "shoves" under traffic, sometimes months after construction.
6. A pavement "slips" under traffic, usually fairly soon after construction.
7. A pavement "scuffs" under power steering or severe braking action.
8. A pavement indents under a punching load.

Some of the conditions described as "tender pavements" are actually other kinds of distresses. It would also appear that not all of the conditions associated with tender pavements are attributable to the same causes, although there are some things that may be common to all of them. Certainly some of the conditions listed above are closely related and will in fact contribute to pavement tenderness. Pavement behavior concerning rolling and density has always been related to a tender pavement even though all mixes that are difficult to compact do not necessarily result in tender pavements.

It is now generally accepted by researchers that there are two distinctly different types of behavior that are commonly attributed to "tender pavement mixes." One type is when tenderness is exhibited during construction in that the mix is characterized by being easily overstressed during compaction; that is, shoving under steel wheel rollers or resisting compaction at normal temperatures. (A mix is said to be overstressed when rolling [compactive effort] causes a drop in its degree of compaction [i.e. lower density]).

The other type of behavior is when slow setting occurs after construction. This is characterized by plastic deformation or scuffing within a few weeks after construction, particularly during periods of hot weather. Frequently, both types of these behaviors are exhibited by the same material.

The causes of tender pavements have been as varied as the description of the associated problems themselves *(6)*.

PROBABLE CAUSES OF TENDER PAVEMENTS

1. Incorrect mix design.

2. Too much middle-sized sand in the mix. (Stated another way: there is a hump in the grading curve for the material passing the No. 4 sieve.)

3. Insufficient amounts of material passing the No. 200 sieve.

4. The grade of asphalt used in the mix was too soft. Another way of saying this is that the viscosity of the asphalt used in the mix was too low.

5. The ambient temperature was too high.

6. Density of the completed pavement was insufficient. There are a number of factors that may contribute to this.

7. Moisture in the mix.

TENDERNESS DURING CONSTRUCTION

Tenderness of an asphalt concrete mixture during construction refers to a mixture that will not densify properly at normal compaction temperatures using conventional equipment. The mixture may shove excessively under steel wheel rollers or leave depressions behind pneumatic rollers. This problem normally results from a lack of interparticle friction or shear strength such as that brought about by aggregate properties including smooth, rounded particles, high sand content, small top size, low filler content, and so on. Where aggregate problems already exist, the problem will be compounded by an asphalt of high temperature susceptibility. Such an asphalt may meet specifications at 140°F; however, at 275°F the viscosity may be sufficiently low to reduce the shear resistance of the asphalt paving mixture. A mixture of this type may be accommodated by lowering the compaction temperature. Low plant temperatures, particularly with drum mix plants, can contribute to this type of problem by reducing the asphalt hardening that normally occurs in the plant. One may also consider a harder grade of the asphalt or the addition of filler such as limestone screenings, lime, or cement to reduce the tenderness during construction. Difficulty in compacting a tender mix is a result of overstressing the mix. This problem can sometimes be accommodated by using pneumatic rollers with reduced tire pressure.

TENDERNESS AFTER CONSTRUCTION

Tenderness of an asphalt concrete mixture after construction usually disappears within a few weeks and is most likely caused by a slow setting asphalt. This mixture may also be tender (difficult to compact) during construction. The resulting pavement will scuff and deform under point loads or shear forces for a few days or weeks but will eventually "set up" and may then be expected to perform quite well. The use of slow-setting asphalts may cause this problem. These types of asphalts are not necessarily highly temperature susceptible and thus may be more difficult to accommodate than those that are highly temperature susceptible. The addition of filler such as lime, cement, or limestone screenings may help provide some stability to this mixture during the compaction and setting stages. If tenderness after construction is not asphalt-related, it is probably due to lack of adequate densification during the conventional compaction process. This problem may be diminished by continued rolling of the finished pavement using pneumatic rollers during the hottest part of the day.

IDENTIFYING TENDER MIXES

It is desirable to identify tender mixes prior to the start of construction so materials and/or design parameters may be altered. Mixtures which contain one or more of the following characteristics should be suspect:

1. Large proportions of sand sizes.
2. Small quantities of minus No. 20 material.
3. Small maximum size aggregate.
4. Smooth, rounded aggregates.
5. Asphalts that are highly temperature susceptible.
6. Slow-setting asphalts.
7. Less than anticipated hardening during hot mixing.
8. High fluids content.

The development of mixture testing techniques to identify tender mixes prior to construction has been attempted (8). Ideally, the field engineer would like to recognize that a mixture will be difficult to compact and/or will be slow setting after construction prior to placing the mix in the field. Two possible approaches are proposed to assist the field engineer in recognizing tender mixes prior to placement. The first approach uses the collective field experience of engineers to identify those material mixtures and construction factors which contribute to tender mixtures. The second approach uses laboratory tests and associated criteria for identification of mixtures that are likely to be tender during placement.

CONDITIONS CONTRIBUTING TO TENDERNESS

Interestingly, complaints about "tender" or "slow-setting" asphalt pavements have always occurred at about the same time of the year, from about the first part of July through about the middle of September, regardless of location *(2)*. At this time of year ambient temperatures are high. Because "tender" pavements have been rarely reported to occur in cool weather, it is obvious that one of the conditions that must be responsible for this type of distress is hot weather. A paper presented in 1963 by Hveem, Zube and Skog noted that no tenderness problems occurred when ambient temperatures were below 80°F *(2)*.

A second condition that almost invariably has been noted in tests of tender pavements is relatively low mix density. Rarely has a mix that has been compacted to a high density in a pavement exhibited tenderness. On the other hand, some mixes compacted to a relatively low density have not exhibited tender characteristics. In addition, a mix that has a tendency to exhibit tenderness has been frequently difficult to densify. It appears, then, that tender pavements have usually been characterized as having a low mix density in the compacted mix, although having a low density may not necessarily result in a tender pavement being tender *(2)*. (One should bear in mind that many factors may contribute to a pavement having a low density, and not all of them will necessarily contribute to the mix being tender.)

A third condition that appears to be common to tender mixes has to do with the aggregate gradation. In almost every thoroughly investigated instance of tenderness, there was an excess of middle-sized sand fraction in the aggregate fraction passing a No. 4 sieve.

The maximum in the grading curve caused by excess sand appears at different sieve fractions in the minus No. 4 and plus No. 100 sieve range, but it seems to be most significant when the maximum occurs near a No. 30 sieve size *(3,4)*. When this aberration in the grading curve occurs, it nearly always is accompanied by a relatively low amount of aggregate passing a No. 200 sieve.

A fourth condition usually noted is that tenderness in a mix is likely to be more severe when the asphalt used has a low viscosity *(3)*. In other words, a harder or more viscous asphalt in a given mix will tend to reduce the occurrence of tenderness. The viscosity of the asphalt alone may not be the only consideration; the amount and kind of material passing a No. 200 sieve must be taken into account in conjunction with the asphalt viscosity. These factors probably contribute to altering the "mass viscosity" of a mix and its cohesive strength, and as a result, these factors may affect the resistance of a mix to both punching shear loads as well as horizontal shear forces.

A fifth condition causing pavement tenderness to manifest itself as a problem is the critical load *(1)*. Normally the average rolling load of a vehicle wheel is not critical. A high-intensity unit stress (such as that developed under the steel wheel of a truck trailer parking dolly, a woman's high-heeled shoe having a small cross-sectional area at the heel, or the legs of tables or benches having a small contact area) may cause holes to be punched in a pavement. Severe horizontal shear forces --- such as those developed under standing tires by power steering turns, severe braking, or a rolling wheel, or rapid acceleration, or spinning of a wheel--may also cause scuffing of a pavement surface.

A characteristic of a tender pavement is that its tenderness shows up during or immediately after construction and normally disappears as a problem within two weeks to two months. Rarely does a tenderness complaint about a pavement continue after this period of time *(11)*. Similarly, a tenderness complaint is practically rarely heard concerning a pavement that is six months old or older. Reasons given by different researchers for this also vary, but probably the principal reason is that the pavement toughens with a little age and some traffic. The toughness may increase because of some oxidation of the asphalt on the pavement surface. The kneading action of pneumatic tires tends to knit the surface particles of the pavement more closely, resulting in a higher tensile strength at the surface, thus developing an increased resistance to horizontal shearing forces *(1)*. It should also be noted that usually after a tender pavement has been allowed to age for a couple of months and the tenderness is no longer observed, the weather conditions also have become more moderate and ambient temperatures have decreased. And thus, one of the major contributing factors to the pavement tenderness, a high ambient temperature, is also gone.

EFFECT OF AGGREGATE ON TENDERNESS

One of the two main ingredients in a mix is the aggregate, which plays a significant part in pavement tenderness. A principal requirement of a "good" mix is a high resistance to internal shear deformation *(6)*. The aggregate provides this resistance which is manifested in the difficulty that develops for one particle to slide past another when a load is applied. This resistance, due to the aggregate, is a function of the surface texture of the aggregate particles. In other words, the particles develop frictional resistance when they come in contact with each other. A mix composed of a very rough-textured aggregate rarely has any tenderness problems. A rough aggregate surface texture can be natural, or it may be created by exposing new aggregate surfaces by crushing the aggregate. A rough texture does not, however, always result simply from crushing. The aggregate must have natural characteristics for providing a rough texture; otherwise, crushing does little to improve aggregate roughness *(1)*. For example, crushing may improve the roughness of a polished stream-bed or glacial gravel. Generally, rounded, polished aggregates tend to contribute more to a mix being tender than do angular, rough-textured aggregates. This holds true for the entire gradation of the mix, especially the portion passing the No. 4 sieve.

Probably the most important single factor contributing to tenderness is gradation of the aggregate. Particularly, the amount of dust, or the aggregate passing the No. 200 sieve, is significant. This portion of the aggregate bridges with the asphalt and, thereby, makes a major contribution to mix cohesion *(4)*. A high degree of cohesion results in a high mix tensile strength, or toughness, which is necessary at the pavement surface to resist horizontal shearing forces. There have also been some limited indications that the gradation of the filler passing the No. 200 sieve, as well as the amount, affect mix toughness. More study in this area is necessary over a range of aggregate types.

Improper aggregate gradation alone may not cause tenderness in a mix. However, it can cause mix tenderness if other important contributing factors are present at the same time. Conversely, a tenderness problem in the mix can be completely corrected in some cases by appropriately adjusting the aggregate gradation.

ROLE OF ABSORPTIVE AGGREGATES ON MIX-SETTING CHARACTERISTICS

Tender mixes have been observed to occur when low-absorptive aggregates as well as high-absorptive aggregates are used. Often, the use of a highly absorptive aggregate increases the propensity of a mix to be tender, especially if the rate of absorption is slow. Since additional asphalt must be used to account for eventual asphalt absorption, the mix is temporarily <u>overasphalted</u> and, therefore tender.

Absorption of asphalt by paving aggregate is an important factor that affects the quantity of asphalt present on the surface of the aggregate and that is available as a binder, and consequently affects the mix-setting characteristics. The nature and amount of absorption directly influence both design and durability of an asphalt paving mixture by having an effect on the mix density, chemical composition of asphalt (when selective asphalt absorption occurs), and on the quantity of "available" asphalt between aggregates. Further, highly absorptive aggregates are more difficult to dry completely compared to low absorptive aggregates because of their higher internal surface areas. Incomplete drying results in moisture being in the absorptive aggregate pores. This trapped moisture can influence mix-setting properties. It interferes with the penetration of the asphalt into the aggregate pores. Also, the moisture vaporizes and tries to escape through the asphalt film during setting, causing disturbances in the steric hardening (structuring) and lowering the apparent viscosity of asphalt film. Both of these factors influence the mix tenderness. More needs to be understood about the role that moisture entrained in the pores of absorptive aggregates plays in the steric hardening of the film of asphalt between the aggregate surface and the bulk asphalt and the degree to which this is reflected in mix-setting characteristics.

The results of asphalt absorption may be any combination of the following (any one of which could lead to the failure of the paving mixture) (14).

1. If there is selective absorption, the asphalt may change its physical, rheological, and chemical properties to such an extent that it may behave differently as a film than in bulk.

2. A thin film, which will be more susceptible to stress and weathering.

3. Not enough binder, which causes the mix to be more susceptible to water action.

4. Incorrectly calculated percent voids, which may lead to percent voids being filled with bitumen or voids in the compacted mineral aggregate. Incorrect voids calculation may result in mixtures lacking durability or future stability.

The most common method of attempting to deal with absorptive aggregates is to increase the content of the mix; this solves the problem sometimes. Another novel technique experimented with in some instances is pretreatment of the aggregate prior to mixing with the asphalt. Different types of pretreatment solutions have been experimented with, including silane, polymer solutions, and organic as well as inorganic coating solutions. Although some results indicate that pretreatment not only reduces asphalt absorption but also aids in stronger bonding, additional research data are required, particularly regarding feasibility, before any deductions can be made.

Although researchers have attempted formulating correlations between asphalt absorption and mineral composition, porosity, pore and size distribution, water absorption, kerosene absorption and oil absorption, little data exist relating asphalt absorption to mix-setting characteristics.

EFFECT OF ASPHALT ON TENDERNESS

The asphalt cement in the pavement mix is the second major ingredient. Many researchers have blamed asphalt for most of the tenderness problems that are encountered. However, asphalt can only contribute to pavement tenderness when one or more of several other critical contributing factors are present *(5)*. These factors are critical load, high ambient temperatures, low mix density, high middle-sized sand content, and low filler content, as previously discussed *(6)*. Asphalt type does not normally influence pavement setting rate or tenderness unless the mixes have low stability or are insufficiently compacted. Limited data indicate that mixture tenderness is somewhat dependent upon asphaltene content of the asphalt. Tenderness is amplified when the anticipated hot plant hardening of the asphalt is not achieved and when asphalts with a low asphaltene content are used. Well-designed mixes with high internal friction and cohesion characteristics are relatively indifferent to asphalt type, with respect to the density achieved during compaction.

An important factor in the resistance to tenderness is the cohesion developed in the mix. This is directly related to the filler content and the asphalt in the mix. The two combined materials compose the binder that holds the more coarse aggregate particles together in the mix and provide tensile strength *(5)*. A higher viscosity asphalt tends to be more effective in this respect and can be influential in reducing tenderness, particularly if the filler content in the mix is low. It should be kept in mind, however, that a mix tends to become less durable (that is, more brittle) with an excessively hard (high viscosity) asphalt and a high filler content.

In selecting the grade of asphalt and the filler content in the mix design, one must exercise care in producing a mix which is not tender in its early life (first two months) and yet is durable over the long span of its service life.

EFFECT OF STERIC HARDENING ON TENDERNESS

The relation of mix-setting characteristics to steric hardening (or asphalt structuring) is not well understood, but is known to be related. Viscosity of heavy fractions like asphalt is known to correlate with chemical composition of the fractions. Intermolecular self-association, thus, should have a direct association with the viscosity. There is sufficient evidence that polymerization (joining together of many small molecules to make a large molecule) may occur during oxidation in pavements (15, 16, 17). Further, at high temperatures, such as those encountered in a hot mix plant or a thin film oven test, the hardening may be more related to increasing the polarity of the asphaltenes and other materials in the asphalt which contain oxygen, sulfur, and nitrogen. These polar materials orient and associate together, being bound by Van der Waals' forces and hydrogen bonds.

The effect of steric hardening or molecular structuring within the asphalt cement as a function of time is apparent by the changes in viscoelastic properties observed between the original and thermally treated "control" sample. Steric hardening is a thermally reversible phenomenon. These types of measurements where viscoelastic properties of thermally treated asphalts are monitored as a function of time provide useful information relating to the setting characteristics of the mix.

Cracking and rutting tendencies in asphaltic pavements should relate to differences in viscoelastic behavior of asphalt cements. Applications of these concepts has led to the development of a procedure which has successfully correlated rheological properties of asphalt and aggregate-asphalt mixtures to tender and slow setting problems experienced in roadways.

EFFECT OF MIX TEMPERATURE ON TENDERNESS

A factor that has contributed substantially to the tenderness problem in the recent past has been the trend toward lower mix temperatures *(12)*. Even though the trend is considered beneficial from many standpoints, it results in less hardening of the asphalt during the mixing process and thus produces a softer (less viscous) asphalt residue in the mix. In turn, this usually results in a mix with a low degree of cohesion (or tensile strength), which contributes to mix tenderness. Lower mix temperatures occur usually in both thick lift construction, which requires a low mix temperature for placing and compacting, and in mixes produced in dryer-drum plants.

EFFECT OF MOISTURE ON TENDERNESS

As a corollary to lower mix temperatures, which reduces the propensity for mix to be tender, higher moisture content in the mix becomes increasingly significant; moisture in a hot mix tends to act as a lubricant *(12)*. This may be helpful in the compaction process, but it may also reduce the viscosity of the binder (asphalt plus filler) and thus reduce cohesion in the mix. (The moisture content of a mix is probably most important when the mix is at a higher ambient temperature and tends to become less important as the mix ambient temperature becomes cooler.)

EFFECT OF CONSTRUCTION ON TENDERNESS

The aspect of construction that probably bears most significantly upon pavement tenderness is compaction. A mix that has been brought to a suitable density rarely exhibits tenderness characteristics *(6)*. To achieve an adequate density, two things must occur. First, compaction process must distribute the aggregate particles in the mix into a sufficiently small volume to develop the required density. Secondly, the binder (asphalt plus filler) must hold the aggregate particles in that volume. As mentioned earlier, a tender pavement usually occurs when the compacted mix density is low; but a low mix density does not necessarily result in a tender pavement.

In order for an asphalt mix to be adequately densified, proper compactive pressure must be applied to a layer of mix that is satisfactorily confined *(7)*. Confinement of the mix is provided by the base on which the mix is being compacted, the surface of the compacting device and the combination of stability and cohesion of the mix being compacted. Ideally, movement of particles in the mix should be downward only, although this rarely occurs. Some horizontal movement takes place under most compaction procedures. Every effort, however, should be made to hold this movement to a minimum. Little densification is achieved with horizontal movement of the mix particles, and in fact decompaction can occur *(7)*. It is incumbent upon the construction engineer from the standpoint of proper selection and use of equipment, compaction procedure, and mix design, to produce a satisfactory density in the pavement.

A mix that may produce a tender pavement usually exhibits borderline stability. One must not use a roller that produces stresses in the mix greater than the mix can tolerate without horizontal movement. With steel-wheel rollers, the horizontal movement of concern is in the direction of rolling; with pneumatic-tire rollers, the movement of concern is transverse to the direction of rolling. The controlling factors with steel rollers are gross weight and wheel diameter *(13)*. With pneumatic-tire rollers, the factors will be gross weight and tire pressure. In both cases, the unit contact pressures are what must be controlled.

LABORATORY TESTS TO IDENTIFY SLOW-SETTING MIXES

Button and Epps *(8, 18)* investigated a number of laboratory tests to identify tender mixtures. These tests included:

1. Resilient modulus of mixtures,
2. Indirect tensile strength of mixtures,
3. Marshall stability,
4. Hveem stability,
5. Asphalt temperature susceptibility (as defined by several parameters),
6. Asphalt consistency versus time relationship (viscosity and penetration),
7. Asphaltene content,
8. Asphaltene setting test *(9)*, and
9. Gel permeation chromatography (GPC)*(10)*.

Performance-related tests were performed on three sample groups: (1) selected asphalts, (2) mixtures obtained from field projects and (3) laboratory prepared mixtures. The results from these tests indicated that three mix properties were the most useful in identifying potentially tender mixtures in the laboratory: (1) resilient modulus, (2) indirect tensile strength, and (3) the asphaltene content of the asphalt cement.

Criteria for each of these tests are presented by Button and Epps (8). On the basis of the project results, it was suggested that the indirect tensile test and/or the resilient modulus test be performed on laboratory-mixed and laboratory-compacted samples, using a criterion developed and following specific conditions:

1. Gyratory compaction (modified or standard).
2. Air void content at standard or higher.
3. Test temperature of 104°F or 77°F.
4. Load duration of 0.1 sec for resilient modulus test.
5. Sample age of 90 minutes or 24 hours.

Ideally, a mathematical, or statistical, relationship could be developed between mix performance in terms of indirect tensile strength and resilient modulus measurements and each of the aforementioned mixture and construction variables that have been reported to have a significant influence on mix tenderness. Each of these variables would be properly "weighted" to indicate its relative influence on tender mix development. A sufficiently large data base would be necessary before such a reliable equation could be developed. Further, a large and continuous research effort would be needed to develop such an equation.

CONCLUSIONS

Although the literature review does identify certain mechanisms and associated asphalt and aggregate properties that are responsible for mix-setting properties, more fundamental studies are needed to ascertain, for example, the role that structuring plays and the role that fines have in enhancing stiffness and offsetting tenderness. Some of the specific areas that need more focused attention for future research are:

a) **Role of Absorptive Aggregate Properties in Mix-Setting Characteristics**
Here, the effect of porosity, pore size, and surface charge of aggregate on mix-setting properties could be investigated.

b) **Role of Asphalt Properties in Mix-Setting Characteristics**
Fundamental physical and chemical properties, including absorption induced asphalt properties and structuring need to be examined further.

c) **Laboratory Tests to Identify Mix-Setting Characteristics**
Simplified methods for individual or lumped measurement (eg., tensile strength, resilient modulus) of factors/properties that affect mix-setting should be identified.

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