have performed satisfactorily. With the exception of one section on the first contract in Region 10, there have been virtually no failures in bond adhesion, material cohesion, or extrusion. It would appear that rigorous inspection with regard to field application is the key to successful performance.

(Editor's note: A rigorous specification is currently in force and is working well in Region 10 in New York State. A copy of the specifications is available from the author.)

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Materials and Methods for Sealing Cracks in Asphalt Concrete Pavements

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ABSTRACT

In recent years significant advances in both materials and methods for sealing cracks in asphalt concrete pavements have been made. Crack sealing has been transformed from a poorly performing and many times ineffective fill-in type of maintenance task to a viable and cost-effective preventive maintenance technique that can extend the life expectancy of roadways. Many aspects of the maintenance technique of sealing cracks in asphalt concrete pavements are examined herein. The subject is covered by qualitatively examining the cracking mechanism and the consequences of not maintaining adequately sealed cracks. The influences of climatic conditions and traffic on crack formation and subsequent movements are discussed. Physical characteristics of sealant materials required for application and acceptable performance are discussed, as well as testing methods for determining these characteristics. Physical properties and specification conformance of materials that are currently used as crack sealants are presented. Advantages and disadvantages of two basic types of sealant application configurations are discussed along with equipment and application methods that are used in crack sealing.

Asphalt concrete highways comprise approximately 1.9 million miles or 93 percent of the surfaced roadways in the United States, with portland cement concrete roadways comprising the remaining 7 percent (1). Asphalt concrete roadways range in type from low traffic volume seal-coated roads and subdivision streets to high traffic volume full-depth asphalt concrete Interstate highways. The majority of asphalt concrete roadways are at least several years old and are exhibiting cracking of varying types and extents.

Crack sealing in asphalt concrete pavements is thought by many to be an ineffective, low-priority pavement maintenance task that is performed only after other pavement maintenance activities such as overlays, seal coats, and fog seals are completed, and only if time, budgets, and manpower are sufficient. Because of this belief, cracks in many miles of highways are not sealed each year, which results in accelerating pavement deterioration because of intrusion of moisture and increased oxidation of the pavement binder.

Significant strides in both sealing materials and techniques for sealing cracks have been made during the past decade. Crack sealing is no longer a slow and ineffective task. With currently available materials and equipment, crack sealing has advanced from being a low-priority maintenance task to being a viable and effective preventive maintenance technique that can greatly increase the life expectancy of asphalt concrete highways.

Many aspects of crack sealing technology for asphalt concrete pavements are presented and discussed in this paper. The subject is covered by examining crack formation, types, movements, and growth. Properties of sealant materials, testing methods, and specifications are summarized. In addition, sealant application techniques and equipment used for sealing cracks are discussed.

CRACKING IN ASPHALT CONCRETE PAVEMENTS

Crack Formation

Asphalt concrete pavement systems are typically composed of a compacted subgrade, a granular base course, and an asphalt concrete surfacing layer. In contrast to rigid portland cement concrete pavements, asphalt pavements are designed as flexible systems that can deform without cracking when subjected to vehicle loadings, contraction and expansion due to thermal effects, or subgrade movements and changes in volume (2). Various factors can influence the degree of flexibility of asphalt pavements, including ambient temperature, aggregate characteristics, asphalt cement stiffness, temperature susceptibility of the asphalt cement, asphalt content of the mixture, and degree of compaction. Each of these factors can have a significant effect on pavement stiffness and flexibility. However, asphalt cement stiffness and temperature susceptibility characteristics are of special interest with respect to pavement cracking.

Recent research has indicated that the viscosity of asphalt cement in service can increase by as much as ten- to fifty-fold in 4 years because of aging effects from oxidation (3). The rate and magnitude of aging is related to many factors, including degree of mixture compaction, source of asphalt cement, aggregate absorptive characteristics and climate (3). With very old pavements, recovered asphalt cement viscosities at 140°F of 500,000 poise and greater are common, which indicate that viscosity can increase because of long-term in-service aging by as much as 125 times (assuming an initial viscosity at 140°F of 4,000 poise).

Asphalt concrete pavements that contain asphalt cement that has aged significantly are not as flexible as when originally constructed because of the increased stiffness of the asphalt cement. The increased pavement stiffness results in a pavement that has a lessened ability to redistribute stresses caused by thermal deformation or other loading effects. Cracking then occurs when the pavement is subjected to heavy traffic loadings, cold temperatures, rapid temperature decreases, or subgrade movements.

Considerable research on the influences of asphalt concrete mixture and component properties on crack formation has been performed (4-10). The majority of these studies has determined that several mixture properties can influence crack formation; however, properties of the asphalt cement have been found to have the most significant effect. In general, stiffer grade asphalt cements result in increased cracking at low temperatures. In addition, asphalt cements with high degrees of temperature susceptibility, as indicated by penetration index (PI) or pen-vis number (PVN), have been found to have a greater cracking potential than asphalts with lower degrees of temperature susceptibility.

Cracking Types and Occurrences

Several different types of cracking may occur in asphalt concrete pavements as the pavement ages. Most cracking can be classified as either temperature or fatigue related (2,11). Reflective cracking of underlying cracks through newly constructed asphalt concrete overlays is another common type of cracking.

Thermal Cracking

Thermal-related cracking appears as both transverse and longitudinal cracks and results from the inability of the asphalt concrete to redistribute horizontal tensile stresses that develop along the length and width of the pavement as ambient temperature decreases. In properly designed and constructed pavements, transverse cracking, which extends the full pavement width and at large spacings (greater than 100 ft), is usually the first type of cracking to occur. As the pavement ages and the asphalt cement stiffens, transverse cracks appear at lesser spacings and may be present in old pavements at spacings of less than 10 ft (12).

Longitudinal thermal-related cracking occurs when the pavement stiffness is such that thermally induced stresses in the transverse direction cannot be adequately distributed by the pavement. Cracking generally appears as a single crack near the center of the pavement width for two-lane pavements, or at a spacing of approximately 10 to 15 ft for wider pavements. Thermal-related transverse cracking tends to appear in most pavements within 1 to 3 years, whereas longitudinal cracking begins at a somewhat later age.

Fatigue Cracking

Fatigue or alligator cracking is generally caused by the inability of the pavement to redistribute stresses resulting from vertical deformations caused by traffic loadings or base or subgrade failure. Fatigue cracks generally appear in a rather close block-type pattern spaced at between 4 and 12 in. Cracking is many times localized and present where poor drainage, inadequate base thickness, or poor compaction of the base or subgrade was attained. Fatigue cracking may also be prevalent in heavily traveled vehicle wheelpaths.

In properly designed and constructed pavements, fatigue cracking appears in wheelpaths as the pavement nears the end of its design life. However, fatigue-type cracking can occur within a short time following pavement construction in areas in which construction deficiencies or overloading occur. Following periods of wet weather, fatigue cracking can also appear adjacent to open thermal cracks because of the weakening effect of surface moisture intrusion into base and subgrade layers through the open cracks.

Reflective Cracking

Reflective cracking in asphalt concrete overlays is caused by transference of horizontal or vertical movements of discontinuities in underlying pavement materials into a localized area of the overlay (13). Cracking then results when the ability of the asphalt concrete overlay to adjust to these movements is exceeded. Typical cases of reflective cracking at overlays include

1. Cracking above joints in portland cement concrete due to localized horizontal movement induced by thermal expansion and contraction of the concrete at the joint (reflective cracking may also result from vertical movements of faulted slabs at joints);
2. Cracking above cracks in portland cement concrete pavements due to horizontal or differential vertical movement of the slab sections;
3. Cracking above transverse and longitudinal thermal cracks in asphalt concrete pavements due to localized horizontal movement resulting from thermal effects or localized differential vertical faulting-type movements resulting from vehicle loadings; and
4. Cracking above fatigued areas in asphalt concrete pavements due to localized differential vertical movements at the fatigued area.

Reflective cracking of asphalt concrete overlays and its prevention are major concerns when resurfacing old pavements because reflective cracking can greatly reduce the useful life of overlays.

Crack Movements

Cracks in asphalt concrete pavements can experience movements in both horizontal and vertical directions (2). As previously discussed, horizontal movements result from thermal expansion and contraction of the pavement. Horizontal movements of transverse cracks in a full-depth asphalt concrete pavement of as much as 0.4 in. have been observed in Kansas from summer to winter (note that data are from correspondence with Glenn Koontz, materials engineer, August 10, 1983). Larger movements are common in colder areas. These thermally induced movements mainly occur on a seasonal rather than a daily basis (14). Even though air temperatures may change significantly during a 24-hr period, pavement temperature variations are small because of the heat-retention effects of the base and subgrade below the pavement surface. On a seasonal basis, however, the subgrade and therefore the total pavement system experience significant temperature changes. In general, cracks are open their widest in the winter and are narrowest in the summer.

The magnitude of horizontal, thermally induced movement at cracks is dependent on the spacing between cracks in much the same way as thermal movements at joints in portland cement concrete pavements depend on joint spacing (14). In general, cracks that are widely spaced may experience greater horizontal movement than closely spaced cracks. Another observation is that transverse thermal cracks may not experience uniform movement or, in other words, some thermal cracks may experience large movements while adjacent cracks move only slightly. Thermal cracks generally experience greater horizontal movement than fatigue cracks because of their greater spacing. Reflective cracks in an asphalt concrete overlay on a jointed portland cement concrete pavement will tend to move horizontally with seasonal temperature variations in a manner similar to the underlying joint.

Differential vertical movement at cracks may result from moving vehicle loadings because the crack creates a discontinuous pavement surface structure that can have reduced load transfer capabilities. The reduction in load transfer capacity depends on the width of the crack. Load transfer will be the least when the crack is widest (in the winter) and greatest when the crack is narrowest (in the summer). Reduction or loss of load transfer capacity in a pavement at a crack may result in differential vertical movements when loaded. If underlying base and subgrade layers are saturated with moisture, differential vertical movements may be greater because of the weakening effect of moisture.

Crack Growth

In some cases cracks have been observed to grow or widen with time (data from Glenn Koontz). This is especially true with thermal transverse and longitudinal cracks. Crack growth is hypothesized to occur as a result of three possible mechanisms.

First, when a hairline crack (in the summer) opens during the winter because of thermal contraction, it can become partially filled with debris. When the pavement warms, expansion is restricted by the debris and expansive stresses are relieved through either flow and yielding of the warmed asphalt concrete, warping of the pavement, or spalling at the crack. The crack that was originally hairline or very narrow may then be as wide as 0.5 in. During the second winter the pavement contracts, which again widens the crack. The open crack then is blocked by additional noncompressibles that once again restrict pavement expansion in warm weather, resulting in an even wider crack the following summer. This cycling continues each year and the crack widens by approximately the amount of pavement contraction that occurs at the crack each year.

The second possible widening mechanism comes from the observation that cracks that are not blocked with noncompressibles may not completely return to their original summer width after a winter contraction cycle (data from Glenn Koontz). A possible explanation is that during the pavement expansion cycles the pavement is warmed, which significantly reduces its stiffness. During the expansive cycle, frictional restraining forces between the asphalt concrete and the base may be of sufficient magnitude to cause yielding and viscous flow in the asphalt concrete so that the crack does not completely return to its original width.

The third possible widening mechanism is that of noncompressibles being plowed into the bottom of the crack from the base or subgrade when the crack closes as the pavement warms and expands. Many times, especially when milling asphalt pavements during recycling operations, it is noted that cracks may widen toward the bottom of the asphalt concrete layer, which may support this hypothesis. Crack widening at the bottom of the pavement may also be due to stripping in the asphalt concrete caused by water entry at the crack.

Consequences of Inadequately Sealed Cracks

When cracks in asphalt concrete pavements are not maintained and are left unsealed, deterioration of the pavement immediately adjacent to the cracks is hastened. There are three ways that deterioration can occur. First, the faces of the cracks are exposed to the environment, and the binder at the exposed crack faces begins to oxidize and harden more quickly than if the pavement was not cracked. The increased stiffening of the binder then can result in raveling and further deterioration of the asphalt concrete at the crack face, thus widening the crack.

The second major type of deterioration caused by inadequately sealed cracks consists of water entry through the crack into the base and subgrade of the pavement. The presence of excess water in the pavement base or subgrade tends to reduce both the compressive and shear strengths of these structural layers in areas immediately below and adjacent to the crack. Because the base and subgrade are weakened in the presence of excess moisture, deflections of the pavement surface may increase when loaded, thus promoting further cracking and deterioration (11). If water entry continues, eventually fatigue-type cracking and potholes may occur.

The third type of deterioration, which can occur when cracks are not adequately sealed, is entrance of noncompressibles into the crack, which restricts crack closure during warm weather, as previously discussed. The noncompressibles may also cause compressive stresses at the crack faces, resulting in spalling and loosening of the asphalt concrete. In some cases, with highly oxidized pavements, the stresses resulting from noncompressibles are relieved by heaving of the pavement near the crack, resulting in bumps.

An additional effect of improperly sealed cracks is that crack growth is not controlled or restricted due to the entrance of noncompressibles, as previously discussed.

When cracks in asphalt concrete pavements are adequately sealed and maintained, crack growth is lessened because of the rejection of surface noncompressibles, and pavement life is increased because of minimizing deterioration caused by entrance of surface water into the underlying base and subgrade.

SEALANT MATERIALS

Required Properties for Acceptable Performance

For a material to perform adequately as an asphalt concrete crack sealant, it must have sufficient flexibility throughout the range of temperature encountered in service to remain bonded to the crack faces. The general requirements of ASTM D3405, "Joint Sealants, Hot-Poured, for Concrete and Asphalt Pavements" (15), are typical of those required for adequate performance of a crack sealant as follows:

> The joint sealant shall be composed of a mixture of materials that will form a resilient and adhesive compound capable of effectively sealing joints and cracks in concrete and asphaltic pavements against the infiltration of moisture and foreign material throughout repeated cycles of expansion and contraction with temperature changes, and that will not, at ambient temperatures, flow from the joint or be picked up by vehicle tires. The material shall be capable of being brought to a uniform pouring consistency suitable for completely filling the joints without inclusion of large air holes or discontinuities and without damage to the material. It shall remain relatively unchanged in application characteristics for at least six hours at the recommended pouring temperature in the field.

These general requirements may be separated into nine specific characteristics that are important in roadway sealants:

1. Ability to be easily and properly placed in a crack through application equipment,
2. Adequate adhesion to remain bonded to the asphalt concrete crack faces,
3. Adequate resistance to softening and flow at high in-service pavement temperatures so that the sealant will not flow from the crack and therefore prevent tracking,
4. Adequate flexibility and extensibility to remain bonded to crack faces when extended at low in-service temperatures,
5. Sufficient elasticity to restrict the entrance of noncompressible materials into the crack,
6. Sufficient pot life at application temperatures for application of the total amount of prepared material,
7. Resistance to degradation from weather to ensure long in-service life of the sealant,
8. Compatibility with asphalt concrete, and
9. Low cure time to permit opening to traffic as soon as possible after application.

Testing Methods

Many testing methods that are applicable to sealants for cracks in asphalt concrete pavements are contained in testing specifications for portland cement concrete joint sealant materials. Testing specifications for concrete joint sealant materials contained in the ASTM standards (15) that are applicable are

ASTM Specification No.	Title
D1191	Standard Methods of Testing Concrete Joint Sealers
D3407	Standard Methods of Testing Joint Sealants, Hot-Poured, for Concrete and Asphalt Pavements
D3408	Standard Methods of Testing Joint Sealants, Hot-Poured, Elastomeric-Type for Portland Cement Concrete Pavements

In addition, several other standard and nonstandard tests can be used to determine crack sealant properties. A list of properties that should be determined for asphalt concrete crack sealants and testing methods that can be used to determine these properties is given in Table 1.

The following is a brief discussion of testing applicability and the mechanics of performing testing for determining various sealant properties.

Application Characteristics

The application temperature viscosity of a sealant can be determined effectively by using a Brookfield viscometer and testing at the application temperature. Sealants with an application temperature viscosity less than approximately 70 poise are self-leveling when applied, generally pump easily, and can penetrate cracks less than 0.375 in. wide. Sealants with viscosities at application temperatures greater than approximately 70 poise are generally not self-leveling and may not penetrate narrow cracks.

TABLE 1 Testing Methods to Determine Sealant Properties

Property	Testing Methods	ASTM Specification No.
Application characteristics	Brookfield viscosity at application temperature	D3236
Adhesion	Low temperature bond	D1191, D3407, D3408
High temperature softening resistance	Flow Softening point	D1191, D3407 D36, D2398
Flexibility and extensibility at low temperatures	Low temperature bond Mandrel bend Ductility at 39.2°F	D1191, D3407, D3408 —[a] D113
Elasticity	Resilience	D3407, D3408
Pot life	Extended heating	D3407
Weathering resistance	Weatherometer	G23, G53
Cure time	—[b]	—[b]
Compatibility	Compatibility test	D3407

[a]A nonstandardized test used by several state agencies.

[b]A general characteristic of the type of material being used. Hot-pour materials generally cure when cooled to ambient pavement temperature (1 hr), whereas cold-pour solvent-based and emulsified materials take longer and may require several days to several weeks to cure to a nontracking condition.

Adhesion

Adhesion, as well as low temperature flexibility characteristics of sealants, may be determined by using the bond test as specified in ASTM D1191, D3407, or D3408. The test consists of pouring sealant between two concrete blocks, trimming the excess, extending the blocks at 0.125 in. per hour a specified distance at low temperature, and then allowing the blocks to return to their original spacing at ambient temperature. This extension and return sequence is then repeated a specified number of times. To pass the test, there must not be any adhesive or cohesive failure greater than 0.25 in. deep at the sealant block interface or within the sealant. The bond test in ASTM D1191 uses 1-in.-thick specimens that are extended 50 percent at 0°F for five cycles, whereas ASTM D3407 specifies 0.5-in.-thick specimens extended 50 percent at -20°F for three cycles, which is a more difficult test than D1191.

High Temperature Softening Resistance

The resistance of sealant to softening at high in-service pavement temperatures needs to be determined to guard against possible tracking by vehicles and flow of the sealant from the crack. Surface temperatures of asphalt concrete pavement can commonly be as high as 150° to 190°F on bright sunny summer days. The flow test, in accordance with ASTM D1191 or D3407, can aid in determining high temperature softening resistance. The test consists of casting a 3.2-mm-thick x 40-mm x 60-mm sample of the sealant on a tin plate, which is then placed in an oven at 140°F on a 75-degree angle for 5 hr. The amount of sag of the specimen during this time is measured in millimeters. Paving grade asphalt cements will generally flow in excess of 50 mm within 1 hr, whereas acceptable crack sealants flow much less. The maximum flow for ASTM D1190 sealant is 5 mm in 5 hr, and for D3405 sealant it is 3 mm in 5 hr.

The ring and ball softening point test (ASTM D36 or D2398) can also be used as an indication of high temperature softening resistance. To resist in-service tracking, the sealant softening point should be at least 20°F higher than the maximum expected pavement surface temperature.

Low Temperature Flexibility and Extensibility

The flexibility and extensibility of sealant materials at low service temperatures may be determined in conjunction with adhesive characteristics by using the low temperature bond test in accordance with ASTM D1191, D3407, or D3408, as previously discussed. A simple nonstandard test that can be used to determine low temperature flexibility characteristics is the mandrel bend test. The test consists of casting a 0.125-in. thick x 1-in. wide x 4-in. long sample of the sealant, conditioning at a specified low temperature, and then bending over a 1-in.-diameter mandrel 90 degrees at a uniform rate in 10 sec. A passing test is one in which the sample does not crack. Common testing temperatures used by several specifying agencies are 0° and 10°F. Ductility at 1 cm/min at 39.2°F also provides an indication of the degree of low temperature extensibility of a sealant material.

Elasticity

The elastic characteristics of a sealant may be determined by using the resilience test as specified in ASTM D3407 or D3408. The test is conducted by using a 6-oz. tin sample of sealant and a standard penetrometer with a ball penetration device instead of the penetration needle. Basically the test measures the amount that the ball penetration device rebounds after being forced into the sealant sample; it is expressed as a percentage. Pavement grade asphalt cement generally is nonelastic in this test and has a resilience between 0 and -50 percent, whereas concrete joint sealants may have resiliences as high as 90 percent. Sealants with resiliences in excess of approximately 40 to 50 percent generally have adequate ability to reject noncompressible materials from the sealed crack. Sealants with high degrees of elasticity, as indicated by high resilience values, tend to be relatively strong materials that may be prone to pull-off types of failures when poor bonding conditions exist.

Pot Life

Sealant materials must have sufficient pot life during application to permit acceptable preparation and application of the entire batch of prepared material. For hot-pour-type sealants, pot life may be determined by using extended heating (for example, 6 to 8 hr) at application temperatures in an indirect heated melting unit and testing the material before and after the extended heating period to determine changes in physical characteristics caused by the heating period.

Resistance to Weathering

Weathering resistance of sealant may be qualitatively evaluated by testing in a carbon arc or ultraviolet-type weatherometer unit (ASTM G23 or G53). The sealant material is evaluated visually and qualitatively after exposure for hardening, embrittlement, cracking, shrinkage, blistering, and so forth.

Compatibility with Asphalt Concrete

Sealant materials for use in asphalt concrete must be compatible with the asphalt concrete. Compatibility can be determined by using the asphalt compatibility test specified in ASTM D3407. This test consists of sawing a 0.5-in.-wide by 0.75-in.-deep groove along the diameter of a compacted asphalt concrete specimen (Marshall or Hveem), filling the groove with sealant, and then placing it in an oven at 140°F for 72 hr. After removing from the oven, the specimen is examined for incompatibilities, which may consist of bubbling, blistering, or formation of an oil-like exudate. Asphalt-based sealants are generally compatible with asphalt concrete, whereas tar-based sealants may not be.

Available Sealant Materials

A wide range of materials with varying properties are currently used to seal cracks in asphalt concrete pavements. The majority of these materials can be grouped into three basic classifications based on their physical characteristics and degree of temperature susceptibility modification: unmodified asphalts, asphalt-rubber, and polymer-modified asphalt.

A listing of several typical physical properties of an unmodified asphalt that meets requirements of ASTM D3405 is given in Table 2. Cone penetration data from Table 2 as a function of temperature are plotted in Figure 1. From Figure 1, differences in the slopes of the plots, which indicate different temperature susceptibilities, can be noted. In addition, from Table 2 differences in resilience and thus elasticity of the materials are noted.

Unmodified Asphalt

This classification includes various grades of asphalt cement, emulsified asphalts, cutback asphalts, and asphalts that contain various types of mineral or fibrous fillers. Common specifications for these materials are as follows:

Material	Specifications
Asphalt cement	ASTM D3381, D946, D312 AASHTO M226, M20
Emulsified asphalts	ASTM D977, D2397 AASHTO M140, M208
Cutback asphalts	ASTM D2027, D2028 AASHTO M82, M81
Filled asphalts	Various state highway department specifications

As a class, unmodified asphalts have a high degree of temperature susceptibility. At low pavement service temperatures (approximately 0°F), unmodified asphalts are very stiff and brittle, whereas at high pavement service temperatures (approximately 140° to 160°F), they are very soft and

TABLE 2 Typical Physical Properties of AC-10 Asphalt, Asphalt Rubber, and Polymer-Modified Asphalt

Property	Test Specification	AC-10 Asphalt Cement	Asphalt-Rubber	ASTM D3405 Polymer-Modified Asphalt
Cone penetration, 150 g, 5 sec (dmm)				
0°F		9	14	20
77°F	ASTM D1191	130	60	75
140°F		>300	220	130
Resilience, 77°F (%)	ASTM D3407	−30	40	70
Flow, 140°F, 5 hr (mm)	ASTM D3407	>50[a]	10	1
Softening point (°F)	ASTM D36	115	170	190
Bond, 0°F, 1 in., 50% extension	ASTM D1191	Fail	Pass	Pass
Bond, −20°F, 0.5 in., 50% extension	ASTM D3407	Fail	Fail	Pass

[a]In 1 hr.

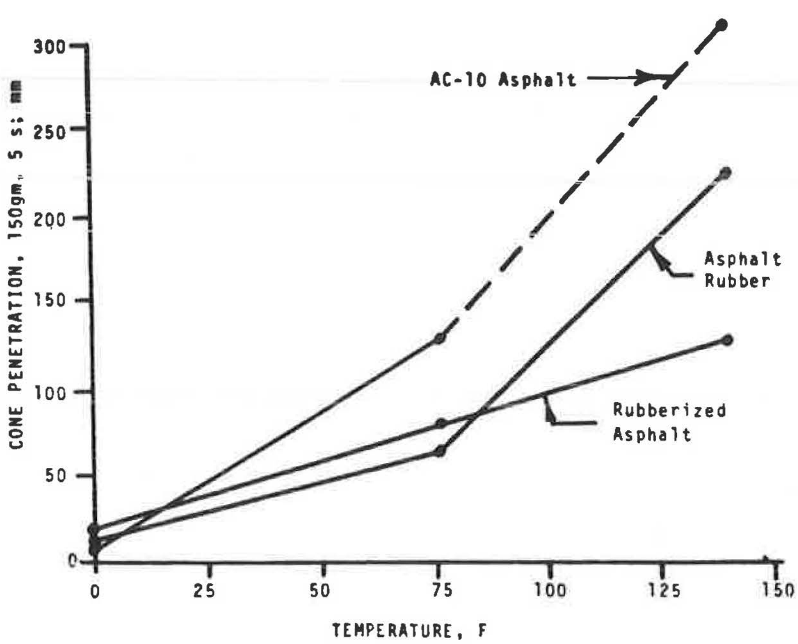

FIGURE 1 Cone penetration for sealant materials at 0°, 77°, and 140°F.

semifluid. In addition, unmodified asphalts have little or even negative resilience values, as indicated in Table 2. Generally, the useful life as a sealant of an unmodified asphalt is less than 1 year.

Unmodified asphalts are the least expensive type of material currently in use, costing approximately $0.08 to $0.15 per pound. Because of their high degree of temperature susceptibility when compared with other sealant materials, unmodified asphalt sealants tend to experience tracking in warm weather and may crack easily in cold weather. Because of their low degree of elasticity, unmodified asphalts will permit penetration of noncompressible materials into sealed cracks.

Asphalt-Rubber

Asphalt-rubber is a mixture of paving grade asphalt cement and between 15 and 30 percent granulated reclaimed crumb rubber particles. When the asphalt and rubber are heated to approximately 350°F, a reaction between the two occurs. The rubber particles absorb fractions of the asphalt, which results in swelling, and the rubber may partially dissolve in the asphalt (16,17). The degree of reaction is dependent on the physical and chemical characteristics of the asphalt and rubber as well as reaction temperature and time period (18). Reacted asphalt-rubber has radically different properties than the base asphalt cement or unreacted blends of asphalt and rubber. The reacted asphalt-rubber has a much higher viscosity and greater elasticity than the unreacted material and also has a lower degree of temperature susceptibility, as evidenced by greater high temperature stiffness and lesser low temperature brittleness (this can be noted in Figure 1). The asphalt-rubber reaction has been studied extensively and reported in the literature (16-18). In addition, much effort has been placed in studying properties in the laboratory of reacted asphalt-rubber materials (16-19). In most of this work, however, asphalt-rubber was studied for use in stress-absorbing membranes, interlayers, and waterproofing membranes, and not as a crack sealant material.

Specifications currently in use for asphalt-rubber sealants generally specify the grade(s) of asphalt cement that may be used, the percent and type of rubber, and the gradation of rubber. Several agencies specify additional requirements at low and high in-service temperatures, which provide an indication of the degree of temperature susceptibility modification achieved. These additional requirements may be a mandrel bend test at low temperature, ring and ball softening point, and 39.2°F ductility. Also, the Asphalt Rubber Producers Group has developed a guide specification for asphalt-rubber sealant materials (20).

As a class, asphalt-rubber sealants have improved temperature susceptibility characteristics and higher elasticity than the unmodified asphalt sealants. Properly formulated asphalt-rubber sealants can provide an effective and lasting seal for many types of cracks in asphalt concrete pavements in all but the coldest of climates. Working transverse thermal cracks in cold climates, which are sealed with asphalt-rubber, may separate when the pavement contracts in the winter. Asphalt-rubber sealants currently in use are more expensive than unmodified asphalt sealants and cost approximately $0.20 to $0.30 per pound.

Polymer-Modified Asphalts

Polymer-modified asphalt hot-poured sealant materials are compounded with asphalt cements, plasticizers, and various types of polymers and other ingredients to provide sealant materials with a high degree of temperature susceptibility modification, and thus greatly improved performance when compared with unmodified asphalt sealants. Polymer-modified asphalt sealant materials can be formulated to be capable of high degrees of extension at low service temperatures, while having softening points in excess of 200°F, which will minimize tracking in even extremely hot climates. In addition, polymer modification can impart high degrees of elasticity if desired. These materials are commonly used as joint sealants in portland cement concrete pavements; however, they can perform extremely well as crack sealants in asphalt concrete when appropriately installed.

Various standard concrete joint sealant specifications are currently used to specify these types of materials and include ASTM D1190, D3405 and AASHTO M173. In addition, several modifications to these specifications are used by various state agencies to provide improved performance. It is important to note when specifying asphalt crack sealing materials using concrete joint sealant specifications, that the sealant material must be compatible with asphalt concrete, as indicated by the ASTM D3407 compatibility test procedure. The physical requirements for various polymer-modified asphalt sealant specifications are given in Table 3. From the limits in Table 3 and the test data in Table 2, improvements in properties can be noted for polymer-modified asphalt as compared with unmodified asphalts and asphalt-rubber sealants.

Polymer-modified asphalt sealant materials are excellent long-lasting crack sealing materials in nearly all climates and conditions. The cost of these materials varies widely (from approximately $0.30 to $0.70 per pound), depending on the specific type of material.

TABLE 3 Polymer-Modified Asphalt Specification Requirements

Property	ASTM D1190, AASHTO M173	State-Modified M173	ASTM D3405	State Low-Modulus D3405
Cone penetration (dmm)				
77°F	90[a]	50-90	90[a]	110-150
0°F	–	–	–	40[b]
Flow, 140°F (mm)	5[a]	5,10[a]	3[a]	3[a]
Resilience, 77°F (%)	–	25[b]	60[b]	60[b]
Bond	0°F, 50%, 5 cycles	0°F, 100%, 5 cycles	−20°F, 50%, 3 cycles	−20°F, 100%, 3 cycles
Ductility, 77°F (cm)	–	35, 40, 50[b]	–	35[b]
Prolonged heating (hr)	–	6	6	6
Tensile adhesion (%)				
77°F	–	–	–	600[b]
−20°F	–	–	–	300[b]

[a]Maximum.
[b]Minimum.

SEALANT AND USE APPLICATION

Proper use and application of sealing materials to cracks in asphalt concrete pavements is essential for optimum performance and maximum life of the seal. Factors that need to be considered when sealing cracks include seal geometry, expected crack movement, crack cleaning techniques and equipment, and sealant application techniques and equipment.

Seal Geometry

Two basic seal geometries can be used when sealing cracks. The first is commonly called an overband or band-aid configuration, and the second is called a sealant reservoir. Each of these geometries has inherent advantages and disadvantages in different sealing situations.

Band-Aid Configuration

The band-aid type of sealant configuration consists of applying a 3- to 4-in. width of sealant approximately 0.125 to 0.25 in. in thickness on top of the crack on the cleaned pavement surface, as shown in Figure 2. The advantage of sealing cracks with this geometry is mainly ease and quickness of application. The band-aid type of configuration is attained by pumping sealant over the crack and then leveling with a wiping or "squeegee" operation.

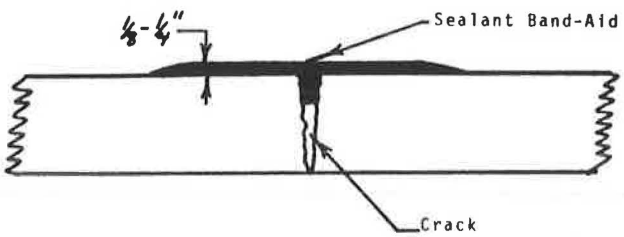

FIGURE 2 Band-aid sealant application configuration.

Several disadvantages of this type of geometry exist. First, a pavement sealed in this manner is unsightly because of the wide dark bands of sealant. Second, the sealant material is on top of the pavement and is exposed to abrasion from vehicle tires that can wear it away soon after application. In cold climates, snowplow operations can dislodge the sealant. The third disadvantage is that when working thermal cracks are sealed in this manner, the sealant is subjected to relatively large and localized tensile strains immediately above the crack, which can promote early failure. For a sealant to perform well in this situation, it must be capable of large extensions at low temperatures. In addition, the sealant must have sufficient high in-service temperature stiffness to resist pickup and tracking by vehicle tires.

Sealant Reservoir

The sealant reservoir type of configuration consists of a widened crack in a rectangular shape cut approximately 0.5 in. wide and 1 in. deep in the pavement surface. The crack is then filled to surface level with sealant, as shown in Figure 3. The reservoir can be efficiently cut with commercially available sawing and routing equipment designed specifically for this purpose.

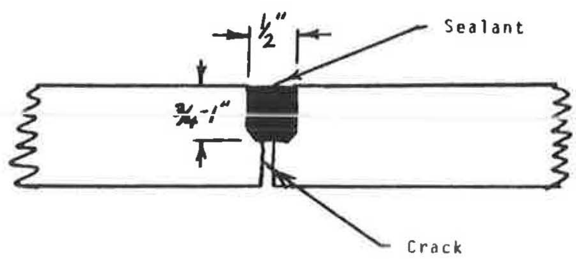

FIGURE 3 Sealant reservoir application configuration.

Crack sealing using a sealing reservoir type configuration has several advantages. First, the sealant is applied only to surface level, resulting in a neat appearance when compared with the band-aid configuration. Second, the sealant is not on top of the pavement surface, and therefore it is not directly exposed to abrasion by vehicle tires. The crack widening operation also cleans the crack faces, which provides intact surfaces for the sealant to adhere to. Another advantage when compared with the band-aid configuration is that the sealant is subjected to a lesser amount of strain when the pavement contracts in cold weather because of the increased width of the sealant. In very cold areas where large crack movements are expected, a v-shaped reservoir, which is between 0.25 and 0.375 in. deep at the center and 1.5 to 2 in. wide, can provide improved performances when compared with a standard widened reservoir. This type of reservoir may also be cut with commercially available equipment.

The main disadvantage of using the sealant reservoir geometry is that the widening operation is an extra step and an added cost. With commercially available equipment, an operator can widen between approximately 4,000 and 8,000 linear feet of cracks (depending on asphalt concrete characteristics) in an 8-hr shift at a total cost of between $0.05 and $0.08 per foot.

Crack Preparation Methods

In order for sealant material to adhere appropriately to the pavement and to ensure maximum sealant life, the crack must be prepared in a manner that provides intact bonding surfaces that are free of moisture, dust, loose aggregate, or other contaminants. Various methods and equipment types can be used to clean cracks. Many times several of the following cleaning methods need to be used to adequately prepare the cracks for sealing.

Compressed Air

Compressed air at a minimum of approximately 80 psi can be used to remove relatively loose debris, dust, and slight amounts of moisture from cracks. For dry cracks that are relatively clean and at least 0.5 in. wide, use of compressed air may be the only cleaning operation required before sealing.

Low Pressure-High Volume Air

Low pressure-high volume air flows can be used to clean cracks and can be provided by several pieces of commercially available equipment. In contrast to use of an air compressor, the low pressure-high volume air blowing devices are smaller and more portable. These devices can adequately clean many cracks of loose debris, dust, and slight amounts of moisture.

Wire Brushing

A power wire brushing operation can aid in cleaning and removing relatively loose deteriorated asphalt concrete from cracks and can greatly improve the adhesion of the sealant in the pavement. Several different devices are available commercially.

Crack Widening

Crack widening is performed when sealing relatively narrow cracks (less than 0.375 in. wide) using the sealant reservoir geometry or when the faces of the crack are deteriorated to the point that they must be cut back to provide intact asphalt concrete. Following crack widening, the crack should be cleaned with an air-blowing operation or wire brushing before sealing.

Hot Compressed Air

Devices are commercially available that receive compressed air from an air compressor, heat the air, and then direct the air to the crack. These devices can remove loose debris and dust from cracks, as well as dry out and remove excess moisture before sealing, which can aid in extending the sealing season in cold or damp weather. An added benefit of the hot compressed air cleaning operation is warming the pavement, thus promoting an improved seal with hot-pour sealants.

Application of Sealants

Two basic sealant classifications with respect to mode of application exist: cold pour and hot pour. Cold-pour sealants, as the name implies, are applied by pouring at ambient temperatures. Cold-pour sealants cure or set up as the fluidizing medium, generally either hydrocarbon solvent or water, evaporates. Many times cold-pour-type sealants require sanding immediately following application to prevent tracking.

Hot-pour-type crack sealants must be melted and then heated to the manufacturers' recommended application temperature before being applied to ensure development of maximum adhesion and to provide appropriate sealant consistency for penetration into cracks. Many sealant materials may degrade if overheated; therefore sealants should not be heated in excess of the manufacturers' recommended safe heating temperature. Several different types of equipment can be used to melt and apply hot-pour crack sealing materials.

Melter Applicator Units

A sealant melter applicator unit is a device specifically designed to efficiently melt and then apply hot-pour-type pavement sealant materials. Most commercially available units also have an agitation system that assures uniform temperature and consistency of the sealant at application. Melter applicator units generally are constructed in a tank-within-a-tank type of configuration, in which sealant is melted in the inner tank and the space between the tank shells is filled with a heated heat-transfer medium (generally heat-transfer oil) that provides indirect heating. Indirect heating is necessary for many types of sealant to guard against localized overheating and possible sealant degradation. Sealant at the proper application temperature is generally applied to the crack through a pump-fed applicator wand and nozzle. It is important that the melter applicator unit being used is capable of safely heating the sealant to the proper application temperature. Several currently available melter applicator units can be used to melt and apply as much as 5,000 to 8,000 lb of sealant (approximately 15,000 to 24,000 ft of cracks) in an 8-hr day.

Pour Pots

Sealant may also be applied through hand-operated gravity feed pour pots. For hot-pour sealants, the sealant first is melted in a kettle, and then the pour pot is filled. The pour pot is then used to apply the sealant. Pour pots cannot efficiently apply sealants that are of high viscosity at application temperatures. Pour pots may also be used to apply some types of cold-pour unmodified asphalt sealants such as emulsified sealants.

Crack Sealing Cases

Many types of cracks in asphalt concrete pavements in several different situations should be sealed to ensure maximum pavement life. Crack sealing, if performed adequately and soon after crack development, can be an economical and effective preventive maintenance technique. In addition, crack sealing can be performed along with other types of pavement maintenance and rehabilitation functions.

Transverse and Longitudinal Thermal Cracks

Thermal cracks should receive the highest priority when sealing cracks because they occur before the pavement has significantly deteriorated. It is important that these cracks be sealed with a sealant and in a manner and configuration that will assure that the seal can adjust to various crack widths as the pavement contracts and expands. Sealing thermal cracks soon after development will aid in limiting crack growth and minimize moisture-related deterioration while extending the life of the pavement.

Fatigue Cracks

Sections of pavements that experience fatigue cracking have failed structurally. Therefore, sealing fatigue cracks will not increase pavement life to the extent that sealing transverse cracks will. Sealing fatigue-type cracks, however, aids in retarding further deterioration by minimizing moisture intrusion; therefore the useful life of deteriorated pavement areas can be increased by extending the time to reconstruction.

Reflective Cracking

Reflective cracking in asphalt concrete overlays may appear within a year after construction of the overlay. Sealing of reflective cracks, especially reflected thermal-related cracks, will aid in ensuring that the overlay does not prematurely deteriorate and provides useful service throughout its design life. Sealing cracks in the pavement surface that is being overlaid will also aid in minimizing deterioration by preventing moisture from reaching the base and subgrade. When milling old pavements, crack sealing should be considered after completion of milling operations before construction of an overlay.

Shoulder Joints

Although joints between portland cement concrete pavements and asphalt concrete shoulders are not cracks in asphalt concrete pavements, the need exists for sealing this joint. Maintaining an adequate seal in shoulder joints aids in minimizing deteriorations of the asphalt concrete shoulders as well as along the edges of the concrete pavement. Sealant material used to seal shoulder joints should be capable of conforming to varying joint widths that can occur as shoulders settle and move.

SUMMARY

The many aspects of the maintenance technique of sealing cracks in asphalt concrete pavements are examined. The mechanism of cracking, crack movement, and consequences of not sealing cracks are discussed. In addition, properties and specifications for sealant materials and application techniques are covered. In summary, several specific statements are presented.

1. Cracking is a normal occurrence in asphalt concrete pavements and occurs mainly because of aging of the binder and loading of the pavement.
2. If cracks are not effectively sealed, pavement deterioration is hastened because of the detrimental effects of moisture intrusion into the pavement structural system.
3. Cracks in asphalt concrete pavements may experience significant movement from summer to winter. Therefore it is essential that the crack sealant material be capable of extending and flexing at low ambient temperatures so that it can maintain the seal as the pavement moves.
4. Several different types of sealant materials are currently used for crack sealing. The properties, effectiveness, and life expectancy of these materials vary widely.
5. Two basic types of sealant geometries (band-aid and widened reservoir) are currently in use; each has advantages and disadvantages in specific situations.
6. Equipment specifically designed for high production crack sealing is currently available.
7. With available materials, equipment, and techniques, crack sealing in asphalt concrete pavements today is a lasting and cost-effective preventive maintenance function that can extend the useful life of asphalt concrete pavements.

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