Factors in Joint Seal Design

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Recent theoretical and experimental investigations have helped to explain the behavior of one-phase (solid) extension-compression type joint and crack sealants and have revealed their limitations. If a one-phase, constant volume sealant has to go through a tension cycle, two situations are possible: (a) if the sealant is elastic with no permanent deformation and stress relaxation, long-term stress on the bond interface coupled with imperfections in the bond and water effects can result in adhesion failure of the seal; or (b) if the sealant undergoes permanent deformation (accompanied by stress relaxation), the stresses on the bond may become small (or negligible), but the shape of the sealant is distorted. This again may result in inability of a sealant to perform its function.

It is apparent that a seal which can retain its shape and not place any tensile stress on the contact surface between the sealant and the joint would be more effective, at least theoretically. Recent field research has indicated that at least one type of precompressed elastic sealant which is in compression all the time promises to serve longer than tension-compression sealants when relatively large joint width variations are expected. Poured-in-place tension-compression sealants are expected to perform well in joints with quite small cyclic variations in width. Cracks can also be sealed with such sealants.

•JOINTS AND cracks are usually undesirable discontinuities induced by man or nature in a highway riding surface. Because these discontinuities are generally the weakest links in a pavement (including bridges), they are often subject to more rapid deterioration. In an attempt to protect the joint (or crack) and the area surrounding it from artificial and natural damages, the joints (and cracks) are often filled with other materials which act as protectives against the ingress of liquids and solids.

In 1953 a summary on sealants and fillers was published (5). The basic concepts discussed in this publication are still valid today. Since that time several papers have been published on the subject, and with the 1964 HRB symposium on joint sealing problems, new theories and experiences have been added to the sealing field. The purpose of this paper is to discuss some of the theoretical and practical developments and to outline possible future efforts in joint and crack sealing, with main emphasis on sealants.

FACTORS AFFECTING PERFORMANCE OF A SEAL

Success in sealing joints and cracks depends on many variables, some of which are difficult to evaluate and control. The major factors influencing the performance of a

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seal are (a) characteristics of the joint (or crack) to be sealed (including properties of the pavement material); (b) properties of the sealant to be used; (c) properties and condition of the sealant-joint (or crack) interface; (d) quality of workmanship; and (e) type of service to which the sealed joint is subjected. There may be other factors operating under certain circumstances. For instance, the effectiveness of a filler strip supporting a sealant may be important in some cases.

CHARACTERISTICS OF JOINTS AND CRACKS

A joint or crack can be characterized by its geometric shape, the changes in joint dimensions, and the materials forming the joint (or crack).

Types of Joints and Cracks

Although many types of joints and cracks can be listed if differences in details are emphasized (2, 3, 10, 20, 26, 27, 30), only a few basic types will be mentioned here. Once they can be effectively sealed, the others will not present much difficulty. The basic (difficult to seal) types of openings which are found on road surfaces are contraction joints (pavement), expansion joints (pavement), expansion joints in bridges, and cracks in any surface. A simplified cross-section of the four types of openings is given in Figure 1. The first three are introduced during construction; the last one (crack) usually is not a discontinuity planned by the designer.

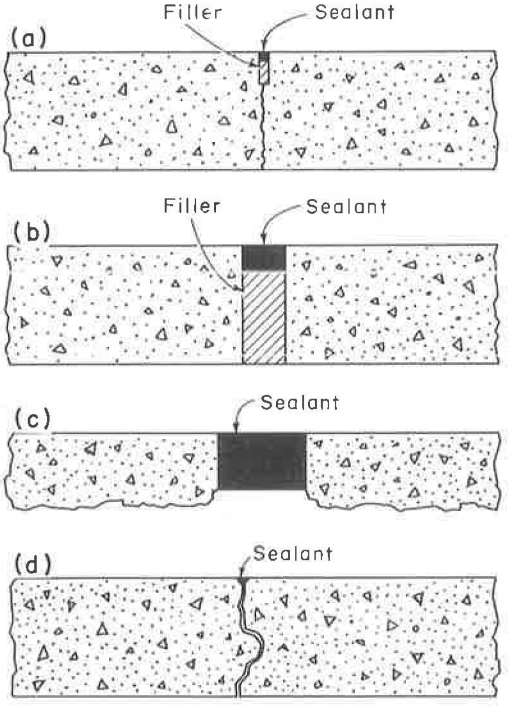

Figure 1. Important types of discontinuities in pavement surfaces: (a) contraction joint (pavement) often 0.1 to 0.5 in. wide; (b) expansion joint (pavement), often 0.5 to 1 in. wide; (c) bridge joint, often 0.5 to several inches wide; and (d) crack, often hair to ½ in. wide.

Factors Affecting Joint (and Crack) Movements

All four types of openings are subjected to various environmental and service effects, causing horizontal and vertical movements in the slabs at the joints (or cracks). Data on vertical joint movements are lacking. Measurements taken in Massachusetts on more than 100 expansions in two locations showed the maximum relative vertical movement to be about 0.07 in., with an average around 0.01 in. The measurements were made under a 20,000-lb axle load, early in the morning when slabs were warped up.

In the case of expansion joints with 1-in. wide openings and average horizontal joint width variation of about 0.20 in. in Massachusetts, the 0.01-in. shear strain is 5 percent of the tension strain in the sealant. Therefore, the vertical deflections of pavements with expansion joints similar to Massachusetts do not seem to be very important in sealant performance. A somewhat similar reasoning can be applied to bridge joints (3). Not much is known about vertical movements of cracks and contraction joints.

Horizontal joint movement is another factor to consider when designing a joint seal. It is known that joint closing and opening depend on many factors and, therefore, the calculations are often omitted. The many field measurements available on joint movements show that in sound concrete the temperature effects are the most prominent. Thus, for instance, if the amount of joint opening per 10 F is plotted against the slab length, a straight-line relationship is indicated as shown in Figure 2. The top curve is based on unrestricted expansion and contraction of the concrete slab, using a thermal coefficient of expansion equal to 0.000006 per degree F. The middle curve was obtained by plotting the maximum joint width variations from two Michigan test roads (3) and adding data from Massachusetts and other states. The lowest curve was obtained by plotting "overall average data" for all kinds of joints in New Jersey (3). Even though local variations in different regions and projects will be present, Figure 2 may be of practical use for estimating the amount of joint opening in portland cement concrete pavements.

With cracks, the problem is slightly more complicated. If there is no reinforcement in a cracked portland cement concrete slab, the cyclic crack width variations can be approximated from Figure 2. In the case of bituminous concrete pavement, it is difficult to obtain reliable values for variations in crack width because the material is not elastic. The average thermal coefficient of expansion between 0 and 80 F is about four times higher than that of portland cement concrete (no friction case).

To summarize, the upper part of the joint which is going to receive the sealant is usually rectangular in cross-section and, in the case of road surface joints, the variations in width can be predicted. The cross-section of cracks is varied, and there are problems in introducing the sealant in the crack and predicting how much the crack will open. Effect of vertical movements on joint seals may be negligible in wide joints but needs further study.

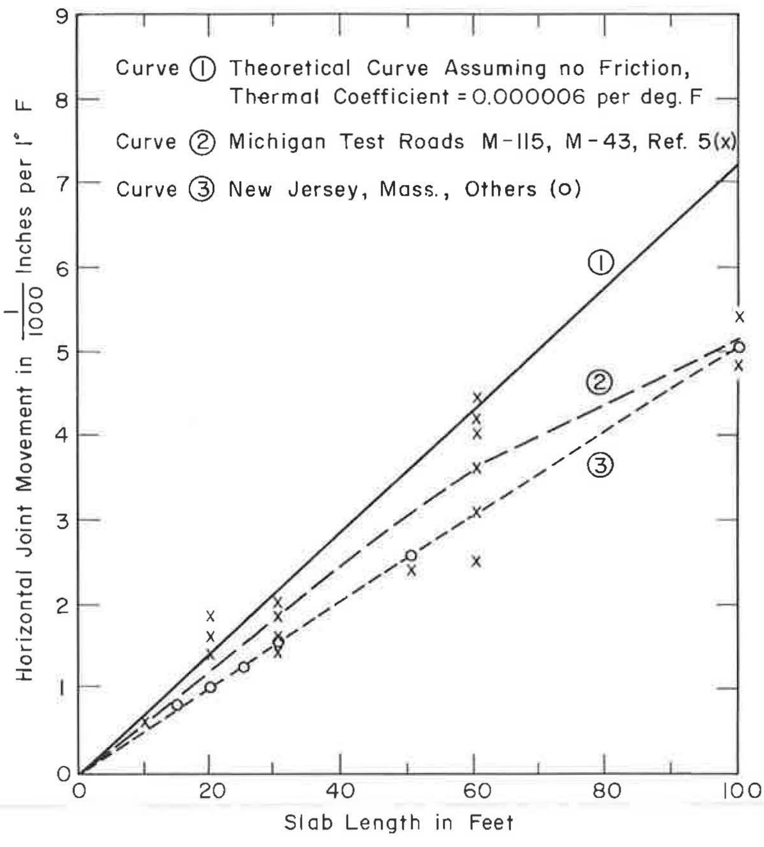

Figure 2. Joint spacing and movement.

PROPERTIES OF SEALANT TO BE USED

It is apparent from the cross-section of a joint (or crack) in a pavement that the plug of the sealant placed in the joint will be similar to a short single-span bridge fixed (glued) to two abutments which move back and forth in opposite directions with temperature changes. In addition, the two joint ends (abutments) may have considerable movement in the vertical direction due to wheel loads (joint deflections). To design a bridge for such conditions is obviously not an easy task.

The closing and widening of a joint (or crack) causes strains in the sealant. These strains can be predicted for one-phase (solid) compounds which do not change their volume while in the joint (29).

For sealants, in general, three distinct stress-strain cases can exist:

1. The sealant is sometimes in tension and at other times in compression (stress reversals);
2. The sealant is always in compression; and
3. The sealant is always in tension.

The first case is the most common in present road joints (and cracks) and, therefore, is discussed in more detail.

Stress Reversal Case

If a joint or crack is sealed with a one-phase (solid) sealant in warm weather while the joints (or cracks) are at their minimum width, the sealant will first undergo a slow tension cycle as the slabs gradually cool down (fall and winter) and then a compression

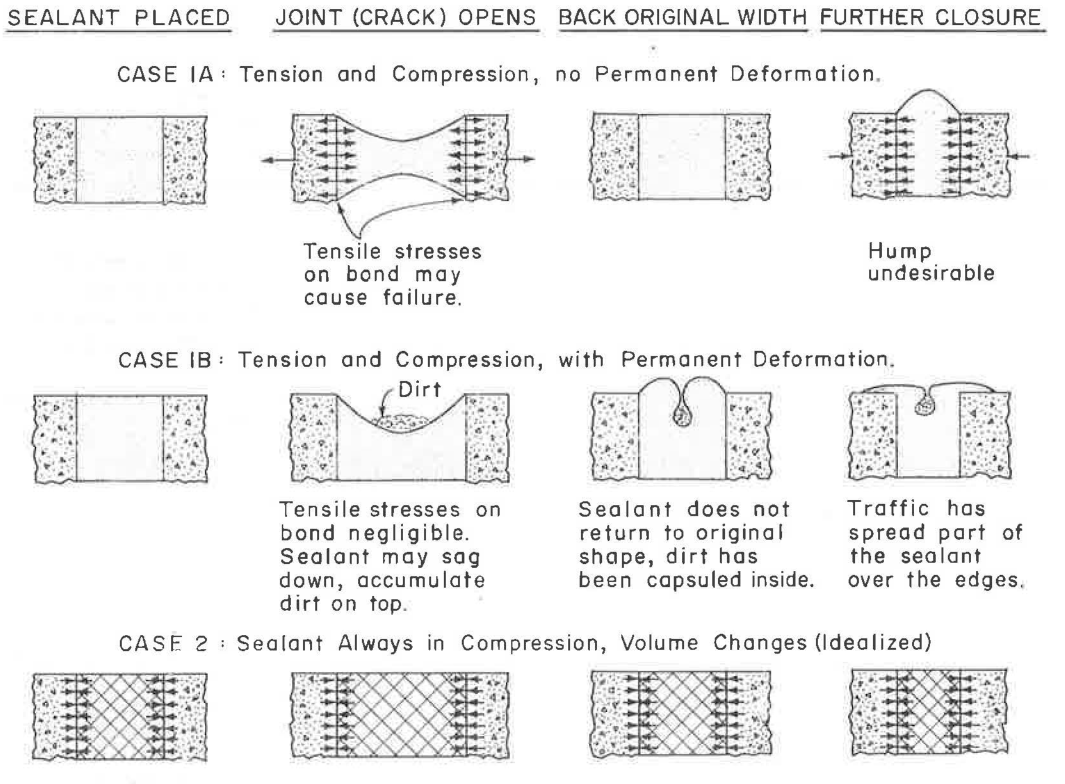

Figure 3. Conventional tension-compression sealants compared with compression-type sealants (uniform support underneath).

cycle during the second half of the service year (spring and summer). Superimposed on this long extension-compression cycle are daily variations of joint width.

In the analogy of a bridge span glued to abutments which move back and forth, it is apparent that a material spanning the joint will be strained. Depending on the type of sealant used, this strain may be recoverable or nonrecoverable (Fig. 3). Assume the abutments have moved apart and extended the sealant. This is followed by a compression cycle. If the strain of the sealant is recoverable, the sealant plug will return to its original shape and the "bridge" will continue to serve. If the stretched-out sealant is not able to recover from the tensile strain, it will lose its shape during the compression cycle and buckle (sag) down (or up) in the joint. If this sag is excessive, the "bridge" may be considered as failed (3).

In the case in which the sealant fully recovers its shape after an extension-compression cycle, the permanence of the bond between the sealant and the joint wall needs more attention because of the elastic property of stress proportionality with strain. Such a sealant at the end of the extension cycle will have a steady stress on the bond and, due to imperfections in this adhesive bond or due to service influences, the sealant can peel away from the joint interface.

From the foregoing brief discussion, it is apparent that both purely elastic sealants and those which exhibit permanent deformation under strain in service may fail when stress reversals are present (tension and compression) and the amount of joint movement is relatively large. This has been observed in the field. Many joints (and cracks) sealed in the past with the sealants alternating through compressive and tensile stress-strain cycles, have shown adhesion failures and distortion in the sealant shape (3, 7, 18, 19, 27). The changes in shape of the sealant have often been unpredictable and difficult to control even when a good filler support was present (8).

It must be emphasized that in cases where the variations in joint and crack width are relatively small and the sealant has a good support, many sealants may serve well even under stress reversals.

Compression Case

In this case, the sealant would be placed in a joint so that it is always in compression, no matter what the season. Only a material which exhibits complete strain recovery can be suggested for a compression-type sealant. A sealant exhibiting permanent deformation and stress relaxation will flow and change its shape while the joint is closing. It will be in tension as the joint opens to its maximum width (if the sealant is adhering to the joint walls).

The main advantage of a compression-type sealant is that it does not impose any significant stresses on the bond or contact interfaces between the sealant and the joint. The sealant is placed in a joint while compressed so that at all times during the closing and opening of the joint, only compressive stress is present in the material (7).

Besides having the ability to recover, a sealant should change its shape as the width of the joint varies so that there is no objectionable protuberance of the sealant above the pavement surface (hump) and no deep curve-in below the surface of the slabs (causing progressive accumulation of solid matter). This can be achieved in various ways, for example, by introducing gas (air) into the sealant plug to make it compressible so that it can follow the volume of the joint.

Tension Case

Pretensioning a sealant before placing it in a joint and holding it in tension is difficult and impractical in road joints. The situation is similar to the first (tension) part of the stress reversal case.

PROPERTIES AND CONDITION OF SEALANT-JOINT INTERFACE

A sealed joint can be compared to a combination of two concrete blocks glued together with a thick layer of adhesive (sealant). If the two blocks are pulled apart until failure takes place, this failure can occur in (a) the adhesive itself (the sealant fails in cohesion); (b) the adhesive-adherend (block) interface; or (c) the adherend (block). In the field, one of the most frequent failures in joint seals has been along the adhesive-adherend interface (bond failures) in spite of the fact that laboratory bond-ductility tests have shown no signs of weakness in adhesion. If there is a true bond between the polymer (sealant) and the concrete block, the sealant should fail in cohesion rather than in adhesion.

There are several explanations of the large number of bond failures. The most common are as follows:

1. Laboratory bond test blocks are carefully prepared. On the road, the surfaces of the adherend (concrete) are not clean but contain fine solid particles, moisture and possibly other adsorbed matter. It is difficult, if not impossible, sometimes uniformly to clean and prepare the surfaces of the adherend to receive the adhesive (sealant). Therefore, built-in bond weaknesses are present from the very beginning.
2. Portland cement concrete paste and mortar contains pores (or voids), part of which frequently contain water. The water can also migrate to the bond interface and affect it. This may be especially destructive during freezing when quite high pore pressures can exist if any part of the concrete gets saturated with water which will convert to ice. Such pressures would also be developed at the bond interface, possibly causing spotty separations between the sealant and the concrete.
3. Numerous load applications accompanied by vertical movements of the slabs and abrasive action of the tires, especially after sanding, can also contribute to at least a localized bond separation.
4. During the joint widening cycle, the sealant and the bond interface are in tension all the time unless complete stress relaxation takes place in the sealant.

From this it is apparent why so many joint seals which have undergone tensile stress cycles have failed in adhesion. This loss of bond is often a long-term phenomenon.

If a satisfactory sealant can be developed which, during the extension cycle, does not build up tensile stress at the bond interface, adhesion failures should be less frequent. Such a sealant would have to be placed in a joint which opens a relatively small amount and also gives good support to the sealant (using a filler below). This type of sealant has to be used for crack sealing in bituminous concrete. If a sealant without the ability for stress relaxation during the extension period is placed in a crack in bituminous concrete, the bituminous concrete itself may fail in tension, thus creating a new crack nearby.

Sealing cracks in portland cement concrete or bituminous concrete is a frustrating undertaking. Adhesion is a problem, and also the proper width-to-depth ratio often is almost impossible to maintain. The cracks have irregular alignment and width. In narrow areas, the sealant does not penetrate the crack; in wider areas it goes down too deep. One remedy for this is to use a grooving machine and widen the whole crack to a certain width, thus obtaining a uniform width crack with a freshly cut exposed surface to receive the sealant (27).

A special case in crack sealing is that of reflection cracks which are found in bituminous concrete surfacings over portland cement concrete slabs. The most critical areas are usually the transverse joints where the cracks close and open as the slabs expand and contract, causing relatively large variations in the crack width. Using present methods, such cracks have to be resealed every one to three years (27). Reflection cracks may be avoided by sawing grooves in the bituminous resurfacing before the cracks have appeared. The sawed openings are then filled with a sealant (30).

OTHER FACTORS OF INFLUENCE

In addition to the joint-sealant properties, there are other factors which may influence the performance of the seal:

1. Conditions During Placement. —Although sealing sounds like a simple operation, the skill and patience of those responsible for placing the sealant are very important. There is a difference between a sealed joint and a filled joint.

2. Service Conditions. —The length of service expected from a sealant will depend on the amount of traffic on the road and the environmental conditions to which the sealed joint is exposed. Also, a tight seal is more desirable for highly traveled roads (many load repetitions) to protect the support from weakening effects of water.

SUMMARY

1. Concepts of quantitative analysis have entered the joint sealing field. It is possible to predict (or design for) a tensile strain in a solid-type rectangular cross-section sealant plug under varied conditions.
2. Theoretical calculations and practical experiences, however, show that for large joint width variations, the strains (and stresses) in the solid-type seal are high and frequently result in failures. Bond failures are especially numerous.
3. Compression-type (two-phase) sealants show promise theoretically and in practice. Their prime advantage is that adhesive bond is not needed.
4. Poured-in-place solid-type sealants with stress reversals while in service may be used in joints which induce low strains in the seal. Also, all cracks are to be sealed with such sealants.

RECOMMENDATIONS

There are several problems which need attention, including:

1. Performance criteria and evaluation tests for compression type and tension-compression sealants;
2. Adhesion problems in poured one-phase sealants used in joints and cracks;
3. Field measurements of vertical joint movements;
4. Effects of shear stresses and strains on sealants in pavement joints and cracks; and
5. Possible methods and materials for sealing irregular cracks.

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