

A Structural Approach to Sealing Joints in Concrete

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•SEALING OF joints in concrete pavement often is termed an art. Whether this designation dignifies or belittles the process, its implications are scarcely reassuring to highway engineering which strives for performance based on definitive appraisal of cause and effect. Shortcomings in existing practice are documented too well to require recitation, except to observe that the incidence of random failure should not be unexpected since the solid-fill technique is analogous to plugging an enlarging hole with an undersized cork. Accomplishment of such a feat assuredly demands a high order of ingenuity. I submit that technical effort based on such an approach, or simply in pursuit of tradition, might better have been directed toward clearer definition of the problem and a more effective solution.

SCOPE

Although the principles developed herein may have broader application, this paper is concerned chiefly with the sealing of joints which gap substantially with contraction and expansion of the joined sections of pavement. The basic requirement is that of fully occupying at least the uppermost portion of a changing rectangular section whose width may vary in ratio of 1:2. One of the more obvious ways to occupy such a space is to fill it with a volume-variable composition such as sponge rubber. Attempts to use foam latex appear to have been unsuccessful, due to its inability to prevent gravel and other foreign matter from becoming imbedded and trapped within the joint space.

DEFINITION OF THE PROBLEM

Instead of using the slot as a mold, we may approach the subject as a structural engineering problem, that is, to provide a bridge between two concrete abutments. Unlike ordinary bridges it should be capable of doubling its shortest length and returning in repetitive cycles. In addition, it is desirable that level top surface continuity be developed across the span. Since the exposed surface is subject to abrasion and to a variety of hazards, it should be as durable as possible. And finally, having defined the structure as a bridge, let us attempt to endow it with structural capability.

STRESS

Since this is to be a designed structure, we must first determine which of the several stress-strain principles to use: compression, tension or stress reversal. The individual cases for these three approaches have been outlined definitively by Tons (1) and indicate that tensioning the seal, whether constantly or intermittently, invites trouble. There are five links in each tension chain: the centrally positioned sealant, its bond to each of the abutment surfaces, and the supporting sections of concrete. Sufficient weakness in any one of these may cause failure. It is significant that as the span widens, the sealant is more demanding of its anchorage, not only because of the distention but also because of its increasing modulus of elasticity as temperatures fall. Except for such relaxation as may be tolerated in certain stress-reversible sealants, the demanding factors in a tensioned system thus tend to compound rather than to alleviate. The

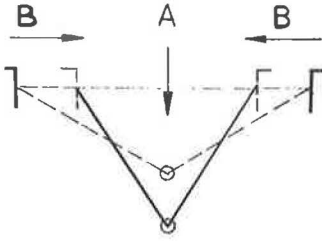


Figure 1. Hinged lever principle.

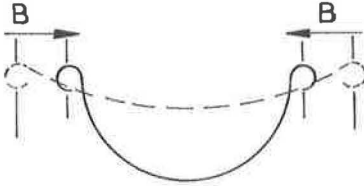


Figure 2. Spring principle.

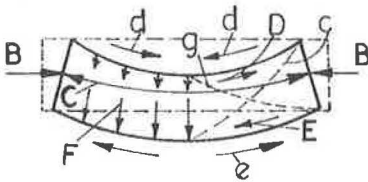


Figure 3. Elastomeric spring principle.

spiraling of such factors, the marginal security of tensionable anchorage to and/or within the supporting concrete abutments, the skill demanded in execution and the many precautions which must be observed in both slotting and filling, as well as imponderables such as vapor pockets in the sealant and undetectable fracturing within the concrete, certainly dictate that any approach involving chain tension should be questioned and that compression must be given serious consideration. Although stress reversal is a compromise intended to relieve the two extremes, it is incompatible with stress dependence in a structured element. It will be ruled out of consideration for this reason and because it involves chain tensioning in the more dutiful portion of its cycle.

DESIGN PRINCIPLES

Since we have set out to design a structural element, defined it as a bridge, determined that it should be compression principled and made of durable material(s), or compositions which are not necessarily volume variable, the first problem becomes one of finding means whereby the excess of filling material may be displaced as the gap diminishes in width. Instead of resorting simply to horizontal or accordion-like collapsibility, we should attempt to develop complementary vertical motion in the central portion of the structure.

One mechanism which behaves in this manner is a hinged lever arrangement pivoting against the concrete abutments, coupling the oppositely inclined sine and cosine functions of a fixed-length hypotenuse. This principle is illustrated in Figure 1, in which concrete abutments support symmetrically positioned levers which are pivotable against the abutments. This causes downward motion (A) of the hinged ends of the two levers in the vertical center plane as the abutments move inward (B), thus steepening the inclination of the levers. The areas of the two symmetrical triangles illustrated are equal when the sides are inclined 30° and 60° , respectively. Thus, if the shallow triangle were filled with a suitably deformable composition, the excess of fill would have been displaced downward as the gap diminished and the top level would be unchanged.

Similar motion is developed by substituting a spring element for the hinged lever arrangement (Fig. 2). In this example, however, the area included within the narrower half circle is greater than that of the broader but shallow arc segment. This is fortunate since the sidewall pivots must be positioned below the top surface of the pavement and, therefore, greater deepening displacement is needed to allow for the reducing volume in this upper area as the joint narrows.

Figure 3 illustrates development of the spring principle in an elastomeric substance. When a rectangular rubber block is squeezed horizontally (B), the initial pressure is applied slightly above the plane of force-balance and the block deflects downward. A square-ended eraser resembling the illustration and manipulated between thumb and forefinger will demonstrate this eloquently, and much can be learned by observation of its behavior under compressive load. First, the upper or concave section tends to

shorten (d) and the lower or convex section to lengthen (e); the ends of the block tilt inward as the arced deflection progresses. Thus in direct consequence of being arcedly deflected (for the moment eliminating the effect of the external force which so positioned it) the sections are oppositely deformed arc-longitudinally, the upper being in compressive stress (D) and the lower in tension (E). Since the ends of the illustrated rubber block are free to pivot about their centers, these normal stresses maximize at the vertical center plane and diminish outward, inversely opposed by shear in angular deformation. The ends of the block thus tilt inward in equilibrated compromise between vertical and radial inclination. A graphic explanation of the same phenomenon would indicate tensiled lengthening of the upwardly inclined diagonal (c) and compressioned shortening of the opposite diagonal (g) as shown in the right half section.

Since the deformation characteristics of rubber and rubber-like elastomers are conspicuously omnidirectional, making their application to the subject purpose practical, lateral deformation also becomes significant. Because of longitudinal deformation and the normal or primary stresses above identified, quasi-radial-vertical lines of secondary stress (F) develop within the deflected section. These lines of force exhibit graded stress reversal between inner and outer termini, any given point being stressed oppositely and proportionally to the primary stress and at right angles to it except as influenced by angular deformation and shear.

The stress pattern within elastomeric structures of the types herein suggested is sufficiently complex that illustration is difficult. It will be apparent, however, that all internal stresses resulting from arced deflection compound to restore the block to its original rectangular shape, and that each contributes to opposing the external force (B); their combined force is illustrated by the arced line of compressive stress (C). This outward force is strictly horizontal and should be so indicated. It is shown as arced in the figure merely by artistic license to emphasize the similarity between the elastomeric element and the spring leaf segment of Figure 2.

Figure 4 develops the elastomeric spring concept into a designed form in which a center-notched superstructure has been added to the rectangular block of Figure 3, and the ends of its body section have been sloped outward from the vertical as indicated in the phantom figure. Because its compressive resistance is thus imbalanced, the elastic structure deflects downward (A) as it opposes the incoming horizontal force (B) even as the extended outboard corners are first contacted. When deflected to the solid-lined position with its top surface level, the center notch is closed and its top corners are abutted. This is its maximum design width; in this position it becomes a stably stressed structure capable of fully occupying the upper portion of a joint in concrete and constituting a bridge which may provide level surface continuity between joined sections of pavement.

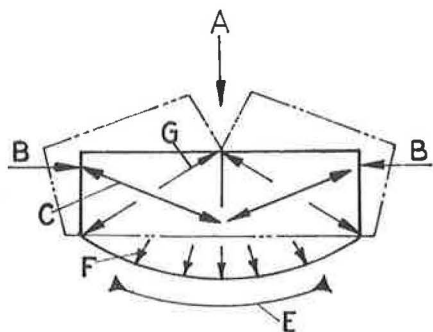


Figure 4. Elastomeric spring with center-notched superstructure.

When so compressed, lines of force (C, E, F) similar to those of Figure 3 defectively equilibrate the structure against the support (B), and the compression (D) of the inner arc of the deflected rectangular block here is combined with the dominant compressive stress (C). Due to the addition of the top-filling superstructure and the occupancy in compression of the total upper area, cross-diagonal secondary lines of compressive force (G) begin to develop at their respective termini in opposite corners. Although such lines of stress centrally are tensioned by the dominant or primary compression (C), lateral displacement contributes by impaction to the terminal compressive force (G).

As the structure is compressed further and its central portion is lowered in increasing deformation and shear, the designated secondary force (G) increases and the line of primary force (C) moves parallelly

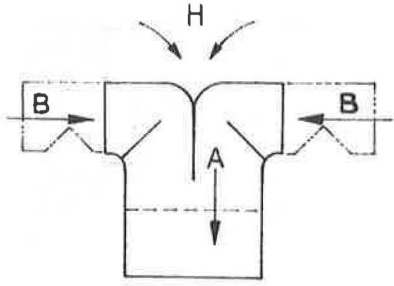


Figure 5. Rolling gland principle with strain relief.

Figure 5 illustrates the rolling gland principle (H) which harmoniously combines the inward (B) and downward (A) movements of the top surfaces, which are transitioned between horizontal and vertical planes by recycling as the joint closes and opens. Although certain of the elements described in four previous examples may be alternative, the rolling gland principle of interplanar transition is incorporated in all of the designs herein illustrated or discussed.

In Figure 5, the elastomer is relieved of leveraged concentrations of stress which may be potentially destructive in loss of its stress memory. This principle also may be applied to the solution of specific behavioral problems such as that of top corner withdrawal occasioned by the lengthening diagonal. By notching the lower section of the structure adjacent to its supporting corners, compression relief is provided the inwardly bending moment, thus relieving the pivot-supported distention which previously had caused intolerable lengthening of the (then arced) diagonal. Although oversimplified in Figure 5, the notch simply closes as the gland rolls together, permitting the end faces to remain upright instead of tilting inward. This arc segmental relief, mentally superimposed on Figure 4, interferes little with the indicated lines of force (C, E, F, G) and thus affects only minimally the insert's load-bearing capability. Center notching the superstructure in Figure 4 also provides arc segmental relief and facilitates transition into the rolling gland, which, in effect, is initiated when the structure is first deflected.

CLASSIFICATION

The development of sealing inserts based on the principles thus far described falls readily into three groups, each separably identifiable by Figures 1, 2 and 3. These are the levered insert, the spring-supported and the elastomeric block.

SOLID PROTOTYPE (GROUP III)

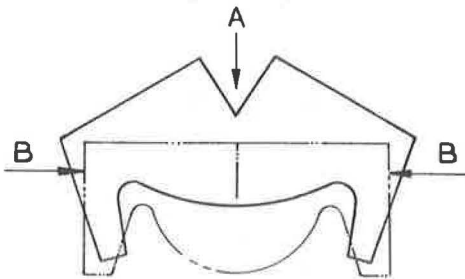


Figure 6. Prototype of solid elastomeric insert.

downward; its original outboard position tends to be drawn inward as a terminus of its lengthening diagonal (c). This phenomenon is demonstrated clearly by the inwardly sloping ends of the deflected rubber block as shown in Figure 3. By oppositely sloping the ends of the modified structure, thus providing an excess diagonal, terminal compression has been maintained at the extreme corners in the maximum design width position illustrated. Although additional impaction might be tolerated, withdrawal of the top corners would tend only to be delayed rather than prevented. One remedy for such malfunction is shown Figure 5.

Figure 6 shows the form of a sealing insert based on the elastomeric spring principle of Figure 3 and developed in accordance with Figures 4 and 5. This may be considered the prototype of the elastomeric block insert (Group III). The main figure indicates its shape as originally formed, and the phantom figure its profile when compressively (B) positioned at its maximum design width. Figure 7 illustrates its positioning in a concrete joint gapped medially within the insert's design range. The insert is ledge supported and its top surface is flush with the adjoining concrete.

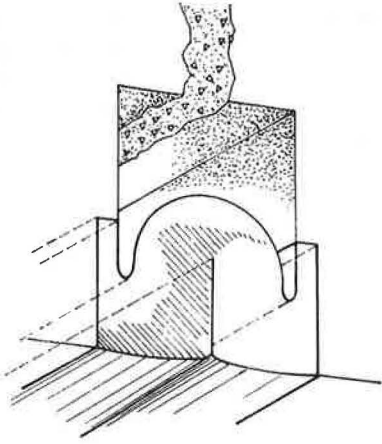


Figure 7. Solid insert installed in medianly gapped joint.

Errata - Fig. 7 is upside down

Installation of this type of insert requires the use of compressive force which may be applied by a pattern of rollers, the leading pair compressing its width followed by downward force which seats the insert. Although ledge support is ideal with respect to structure and certainty of installed depth, the complications of developing such ledges in concrete could preclude their use. Alternatively, it will be recognized that such an insert possesses considerable compressive capability and that supplemental means may be used if needed to assure anchorage.

TUBULAR JOINT

Figure 9 shows a similarly patterned insert formed in a broad, relatively shallow tubular section, which becomes inversely proportioned when maximally compressed as shown in Figure 10. Here it is installed in a saw-slotted groove, beneath which the contractionally broken sections of the concrete keyingly abut each other. By connecting the lower outboard corners of the sealing insert, thereby making it tubular in section, compressible installation is greatly simplified over that of the original form shown in Figure 6, in which the tubular insert is positionable by rolling or depressing it directly into place.

LUBRICATION AND ANCHORAGE

Lubrication facilitates this method of insertion and minimizes abrasion of wall-contacting surfaces, both concrete and

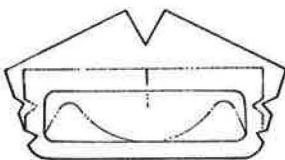


Figure 9. Tubular prototype.

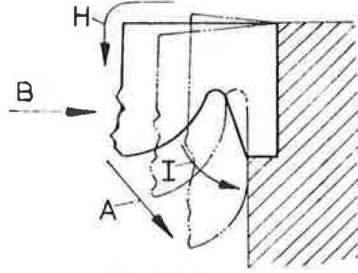


Figure 8. Progressive positioning of half section of solid insert.

Figure 8 shows a half section of the same insert of the same maximum width as is phantom in Figure 6, and indicates its changing form as it is compressed progressively to its median and then to its minimum design width. The directional arrows (A, B, H, I) indicate motion relative to its slab-contacting edge.

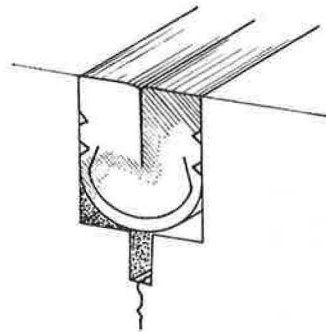


Figure 10. Tubular insert positioned in closed joint.

insert. Lubrication may comprise either a fugitive substance or a bonding element pocketed in grooves formed in the sidewalls of the insert, thus keying the interface by providing bead-formed support ledges. Mechanical keying may also be developed in this type of installation by temporarily and shallowly incorporating an evaporable solvent or a fugitive plasticizer into the outer surface of the elastomer, thus permitting stress-relaxed imaging of the opposing concrete surface and ultimate restoration of its original physical properties. Combinational means including both bonding and keying may be employed advantageously; either method may involve partial attack on the polymeric composition whether it be deformable or rigid.

RETAINERS

The assembly shown in Figure 11 also is designed for simple depressible installation achieved by containment of the sealing insert within a metal or rigid plastic clip shaped to be insertable into the prepared slot and weakened along its centerline, permitting separation when sufficiently stressed. Initial deflection of the sealing insert under downward force (A) narrows the top of the assembly and reduces its included angle, thus dropping it a little deeper into the slot and improving its wedging advantage. Continuing downward force (A'), now borne by the top edges of the retaining clip, wedges the assembly deeper, fulcrums the sides against the concrete abutments, fractures the clip along its weakened centerline and parallels its two segments, permitting the compressed assembly to be pushed without obstruction into final position flush with the top surface of the pavement.

Whereas a resilient surface under compression has measurable capacity to seal the interface against water intrusion, interposition of a rigid element demands sealing, which may be done concomitant with adhesional anchorage. Figure 11 shows external recesses (which coincidentally form internal support ledges for the elastomeric insert) in which a hardenable or semihardenable sealing composition may be pocketed to form keying beads against the concrete, as in the like-purposed treatment suggested in Figures 9 and 10.

Figure 12 shows a modified form of retainer for the same type of sealing insert, positioned in a joint which is almost closed. The retainer comprises opposed F-shaped extrusions, depthed so as to bottom supportably in the slot, with the top sections inwardly overhanging the insert. Thus, the retainer rigidly cantilevers a portion of the gap and thereby reduces the variable complementary portion spanned by the elastomer.

The insert's tolerance for this type of inclosure is perhaps best explained by re-

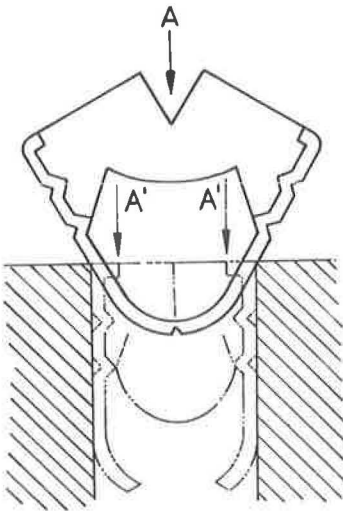


Figure 11. Clip retainer assembly.

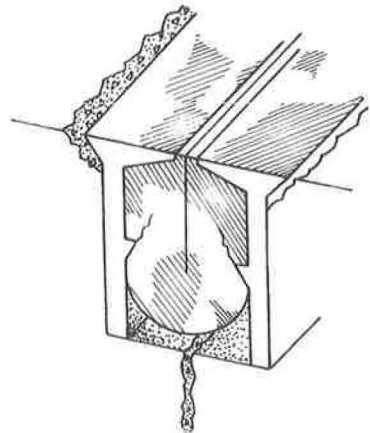


Figure 12. Cantilevered retainer assembly installed in spalled joint.

ference to the rolling gland principle (H) as illustrated in Figure 5, from which it will be evident that the outboard portions of the top surface demand no change as the gland rolls inward. It further will be apparent that deformable occupancy of the upper outboard area is nonessential to the mechanical behavior of the insert, and it will be recalled that withdrawal from this area indeed presented a serious problem until it was relieved by pivotal arc segmental relief.

Another advantage gained by cantilevering concerns control of level top surface in the closed joint. Characteristic behavior is indicated in Figure 8, wherein the top surface of the insert tends to depress at its median width and to rise when minimally gapped. Although final compression contributes to bulging by maximizing perpendicular displacement, in addition to which volume considerations are inescapable, the described phenomenon is explainable in linear terms. When interpreting behavior as a system of levers it will be apparent that these relative motions are imperfectly complementary since they mirror the $\sin:\cos$ factor, which crosses unity at 45° . A comparable relationship also occurs between the depth of an arced segment and its half chord. Although the tendency of the insert to overfill a closed joint seemingly is incontrovertible, it may be controlled or prevented by use of a cantilevered retainer.

A further justification for the use of retainers concerns the problem of coping with imperfections in slot formation. One example is that of raveling in the sawing of the joint. Although width imperfections may not necessarily be grievous when flowable sealants are employed, they could seriously affect the performance of a precision insert of which maximal demand is made and in which the design specification did not permit allowance for such variation. In the case of more serious defects such as chipping or spalling, installation of a structured element likely would require some sort of retainer. Such a case is suggested by Figure 12, where the void could be filled with sealant or other suitable material.

LEVERED INSERT (GROUP I)

Figure 13 shows the fabricated form of a levered insert, based on the principles suggested by Figure 1, and its shaping when compressed in the narrowing joint. The insert comprises an elastomeric superstructure bonded to a rigid base which instead of being hinged is weakened at its centerline so as to bend along the line and to fracture when further stressed. Separation of the levers permits bottom spread and provides additional space into

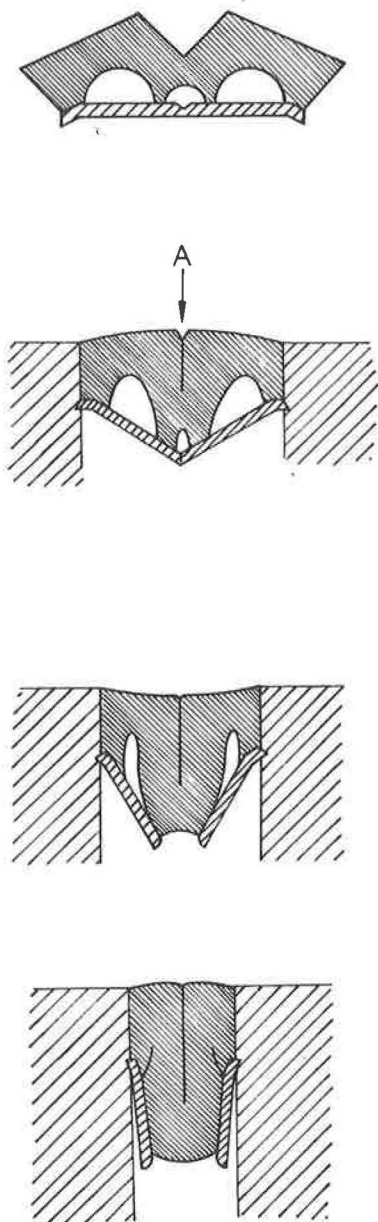


Figure 13. Levered insert with collapsible voids.

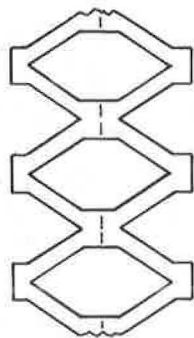


Figure 14. Expanded strip for levered insert.

which the central portion of the elastomer may depress. It also develops a compound levering motion which leans toward improvement in linear behavior at the vertical centerplane and thus favorably affects deflection of the top surface.

The elastomeric superstructure contains voids capable of occupancy by the elastomer, permitting collapsibility into a volume of space less than that originally occupied and giving the insert a wider range of operational width than otherwise would be practicable without resort to a volume-variable composition. The use of such voids extends the second principle of Figure 5 concerning relief of severe concentrations of stress and development of mechanical behavior patterns, permitting the use of somewhat tougher and higher-modulus elastomers.

The levered insert is installed simply by application of downward force to the proper depth where the sharp corners of the levers, whether cut square or shaped in the manner indicated, pivot in the supporting concrete sidewalls. Overcentering makes vertical withdrawal or suction removal of this insert mechanically impossible except by use of a tool designed for the purpose. The lever-like baseplates may be either rigid plastic or metal; the latter has greater capacity to develop pivotal grooves in the supporting concrete. This is not of particular significance except that when the joint is maximally spread and the insert minimally stressed, traffic-applied downward force might reseat the insert at a lower level.

There are also problems of bonding combinational elements, some of them simple and others complex. In the event that a particular combination is difficult or costly, it is a relatively simple matter to provide mechanical interlocking, e.g., by perforating the baseplate longitudinally and extruding the elastomer keyably in place.

There is also the problem (at least theoretical) of differential coefficients of expansion, especially when considering materials with significant linear distensibility. Lateral corrugation or spaced ribbing can prevent accumulation of such forces. The troublesome element can be segmented or, if it must be continuous, slotted relief may be provided alternately from opposite edges. Such solutions are applicable not only to the baseplates of the levered insert but also to the retaining clip shown in Figure 11. By contributing to flexibility, such expansion relief in this latter instance could facilitate its rollable installation.

Another approach, specially adaptable to the levered insert, is the use of a longitudinally expanded strip as illustrated in Figure 14, with which may be incorporated mechanical keying by extrusion envelopment, thus permitting concomitant solution of several problems and introducing additional design variables. This solution could be particularly fortunate, especially when considering the problem of oxidation or corrosion of metal elements used in the proposed manner, since the saving in material could make economic the use of stainless steel or other corrosion-resistant alloy, requiring no surface treatment which would tend to be ineffective at the pivoting corner where the material is subject to abrasion.

SPRING INSERT (GROUP II)

Figure 15a follows the form suggested by Figure 2 and Figure 15b shows the same insert fully compressed in a closed joint. The spring insert comprises an elastomeric superstructure bonded to a spring base and collapsible voids which serve similar purposes as in the levered insert. Some of the changes in configuration are illustrative of design latitude, but the full-depth center notch, although not essential, suggests

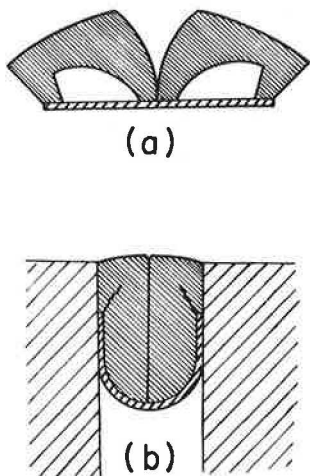


Figure 15. Spring insert: (a) uncompressed, and (b) fully compressed.

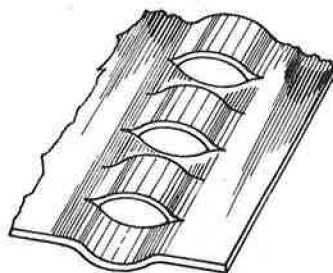


Figure 16. Preparation of metal spring element for extrusion keying of elastomer.

a basic difference; here the support element provides the spring force which in the levered insert is carried by the lower central portion of the elastomer. In other respects the two are quite similar, including manner of installation, wedge-like resistance to withdrawal and definitive pivoting against the sidewalls of the concrete.

Extrusion keying of the elastomer presents a slightly different problem since it is unwise to weaken localized portions of a spring element, e.g., by a line of perforations. However, it is permissible to stiffen relatively narrow sections without serious effect on spring action. This may be accomplished by cross-shearing and drawing the connecting segments inward and outward alternately in the manner illustrated in Figure 16.

SURFACE DEFLECTION

Despite differences in styling and construction of the various inserts, deflection of their top surfaces tends to follow the same basic pattern, depressing in the median range and rising again as the joint closes further (as indicated in Figs. 8 and 13). Although this deviation may be so slight as to make its investigation seem academic, an examination into what makes it occur is helpful both in better understanding its mechanical behavior and in developing more advanced forms.

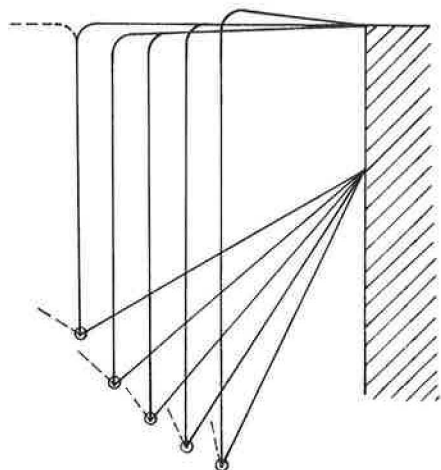


Figure 17. Deflection of hinged lever.

A linear appraisal is adequate for our immediate purpose. We may consider the top horizontal and vertical center planes and the supporting lever or spring elements as simple nondistensible elements. This technique is applied to the hinged lever arrangement (Fig. 1) in Figure 17, showing a half section with its external contour multi-positioned relative to its outboard edge and supporting pivot. The illustration is constructed by maintaining constant the combined length of the exposed top surface and the vertical center plane, and positioning the range midpoint of the inclined lever slightly below 45° , the point of equality between sine and cosine at which vertical and horizontal motion are equal. The top surface falls and rises in the prescribed manner as the half-width diminishes.

Figure 18 shows the effect of a compound or knee-jointed lever substituted for the

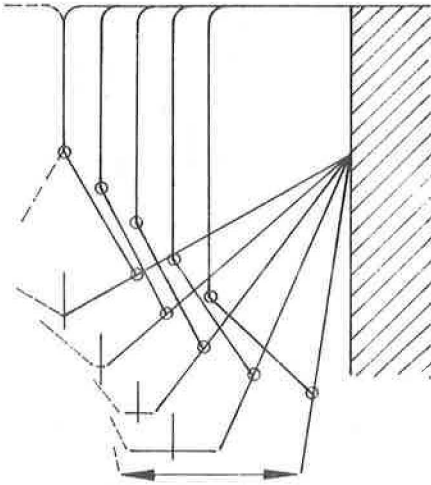


Figure 18. Deflection of knee-jointed lever.

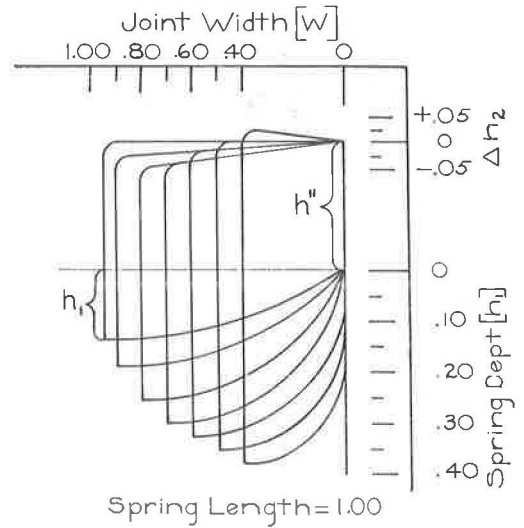


Figure 19. Deflection of spring insert.

direct-hinged arrangement of Figures 1 and 17. This illustrates the type of motion developed by the construction shown in Figure 13, wherein the levers are hinged elastomerically and flexibly somewhat in the manner of the diagram. If its actual performance were to match the stepped showing of the illustration, the top surface would not deviate from its established plane. This characteristic develops as an interesting and perhaps valuable byproduct of permitting the levers to spread to increase occupiable space for the elastomer.

Figure 19 shows the action of a spring-supported insert. This has been calculated precisely and provides specific data on its behavior. Like the last two diagrams, it shows progressive positioning of a half-section contour, but its units of width are in terms of spring length which remains constant as the chord of the arc segment diminishes with the narrowing of the joint. The indicated width range is from 0.95 (maximum span) to 0.40 (minimum), slightly broader than the specified 2:1 ratio. Vertical positioning is given in the same unit. Within the range specified, the height of the arc segment (h_1 , centerline depth below the chord connecting the pivotal ends of the spring) increases from 0.134 at maximum width to 0.386 when deeply deflected. When the joint is positioned at 0.637, the full arc segment reaches 180° and thus its height equals its half chord. Beyond this point the depth combines the diminishing radius of the reducing half circle and the lengthening sidewall tangent, together providing the total depth figure given.

Initial deflection of the top surface (h_2) from its starting level position is rapid, bottoming when spanned 0.80 (spring length), then rising very gradually but at an increasing rate to 0.637. Beyond this point, the rate is constant, returning to level at 0.504, and thereafter deflecting upward above its original position. The indicated maximums of h_2 are -0.045 and $+0.024$. In the case of a $\frac{1}{2}$ - to $\frac{1}{4}$ -in. joint, there would be a depression of $\frac{1}{45}$ in. when the joint was a little less than $\frac{7}{16}$ in. wide and a rise of $\frac{1}{90}$ in. if it were over-squeezed to $\frac{7}{32}$ in.

VOLUME CONSIDERATIONS

When a solid block is deformed from a horizontal shape (e.g., a rectangle or a triangle) to an inversely dimensioned vertical form, its cross-sectional area is unchanged. Each half section of the elastomeric prototype essentially is such a block of material. Thus, its mean depth or thickness when maximally spread is limited to half the minimum width of the joint; it will be confined into this space when fully com-

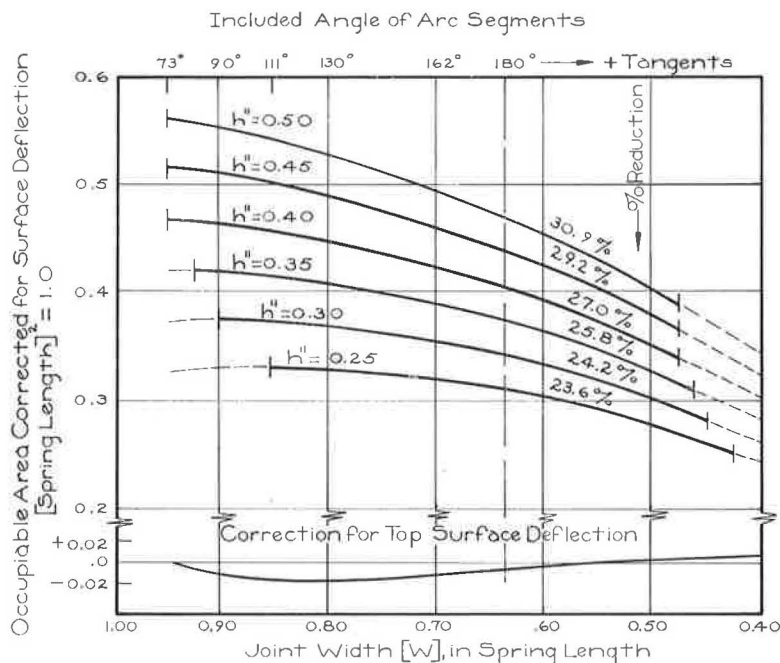


Figure 20. Cross-section areas of spring inserts with different pivoting depths.

pressed. Assuming that the insert's design width range is 2:1 and that its mean depth doubles under compression, its starting mean thickness must not exceed a fourth of its maximum span. By providing internal voids, such as was done in both the levered and the spring inserts, this limitation on initial gross mean depth may be relieved considerably. As far as gross or occupied volume is concerned, this is equivalent to using a variable volume composition, except that the voids are unified into definitive shapes instead of being dispersed. Figure 13 illustrates the progressive collapse of such voids, which permits reduction in gross volume as the joint narrows.

Figure 20 shows cross-sectional area data based on the half-section showing of the spring-supported insert in Figure 19. The units (flat spring length) are identical except that the ordinates are squared. The lower curve indicates the area lost or gained by deflection of the top surface. This set of calculations is based on linear data, whose validity in establishing the actual contour and positioning of the top surface lessens as the modulus of elasticity of the elastomer decreases. Its validity is improved, as is all linear behavior, under the opposite condition. Since one of my objectives is the use of tougher compositions, there need be less concern at this point with its application to softer materials.

The principal curves in the graph indicate the cross-sectional areas within the various contours, developed in the manner illustrated in Figure 19. The several curves differ with respect to initial depth or thickness of the superstructure (h''), or the depth below the pavement surface at which each end of the supporting spring segment pivots against the concrete sidewall. These cover pivoting depths of 0.25 to 0.5 spring length. The greater the pivoting depth, the greater is the excess volume of material for which occupiable space must be available as the joint narrows.

The optimum 2:1 range in design width is indicated for each curve; the shallow superstructures require greater initial deflection to avoid an increase in occupiable area which occurs in all cases when deflection begins.

The reduction in area, or that portion which must be voided, is indicated for each of the curves. Doubling the depth of the superstructure in the range indicated increases the void requirement by less than a third, or from 23.6 to 30.9 percent. Since voiding

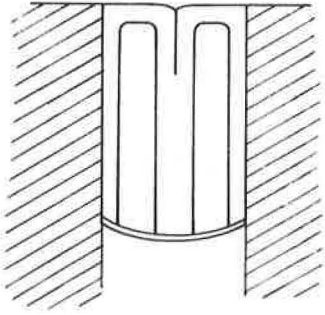


Figure 21. Deep contoured insert.

only about 30 percent of such a cross-section is a relatively modest requirement, it is apparent that greater depthing can be tolerated.

DIVISION OF FUNCTIONS

As often occurs in the evolution of a design, the obvious is not immediately apparent. Enlightenment in this case stems from the last stated observation concerning tolerance for additional depthing of the superstructure. Its basis lies in functional division of the upper rolling gland section and the lower spring support element (this division actually was made

in both the levered and the spring inserts) and in the formation of collapsible voids which sculpture the opposing vertical half sections of the elastomer easily into inverted U shapes. Once narrowed sufficiently to permit containment within the closed joint, the vertical connecting legs may be extended indefinitely without change in their newly conceived function, allowing the spring support or motor element to be positioned at any desired depth in the joint. Thus, the deep contoured insert evolves as illustrated in Figure 21, which is classified as Group IV.

MOTOR ELEMENT

Of these separated elements, the motor segment should be first investigated more critically. Although the basic pattern of defective behavior tends to complement the closure of the joint, the pattern is not without fault. The data previously presented were ideal calculations based on the use of a metal spring element having no thickness. Because in most applications the motor element is likely to be elastomeric and thick, the data must be corrected for the lessened span between pivots. In addition, the rate of descent must be variable to allow for differences in demands of the surface section and in the linear behavior of elastomers of various moduli. Although the defective behavior of arced sections is incontrovertible, we are not without means for its modification.

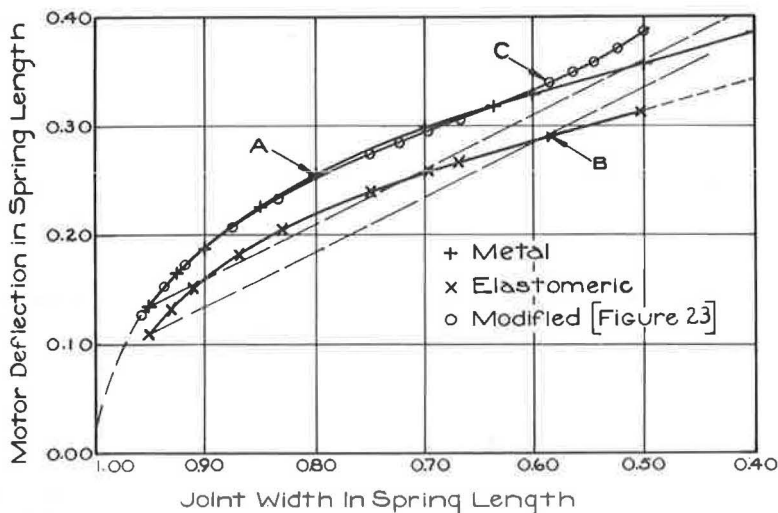


Figure 22. Comparative vertical motion of three motor elements.

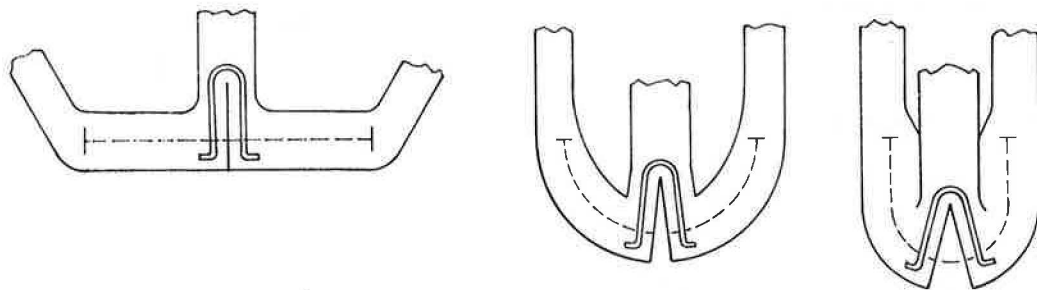


Figure 23. Modified motor element (Curve C in Fig. 22).

The curves in Figure 22 compare the deflection of three motor elements as the joint varies in width. The diagonals indicate perfect depthing relative to the starting points of each of the curves, the two upper curves bearing to a common diagonal. Curves A and B cross their respective diagonals and thus their top surfaces protrude above the pavement when the joint is closed. Curve C does not cross, but tends rather to parallel under the same condition.

Curve A is based on the ideal calculations of a metal spring element having no thickness. Thus, its pivots span the exact width of the joint. Curve B shows the motor action of a simple elastomeric element of uniform thickness (0.22 of net spring length) pivoted inward from each supporting abutment a distance equal to half its thickness. This also is an ideal curve since it presumes perfect mean circular arcs and radii, unchanging spring lengths, and constancy of pivotal positions. In addition, it fails to allow for lateral vertical displacement of the inner arced segment occasioned by increasing compression as the radius shortens. Thus, the effective depth of deflection would be less than the curve indicates and this deviation would increase as the joint narrows.

Curve C charts the behavior of a modified elastomeric element of uniform thickness (0.20) pivoted as that shown in Curve B. This also is a theoretical curve because it is based on the same assumptions. Two added factors account for its difference: (a) the spring length increases as a function of flexure (calculated in terms of opposed stresses, each levered proportionately to mean radius), and (b) it includes an equivalent of the compound levering action previously suggested in the discussion of Group I (levered) inserts and illustrated in the knee-jointed arrangement of Figure 18. In addition, it eliminates the principal source of the last-named error of Curve B by anchoring the central vertical leg to the body of the arced section rather than to its inner top surface.

Both of these contributive factors have been accomplished by the modification illustrated in Figure 23. An inverted U-shaped metal spring segment has been molded into the motor element at its center. The elastomer shrouds the metal but is disconnected at the center plane, thus permitting the metal spring segment to open to the degree that it is stressed without tensiled interference by the connecting elastomer. Being well anchored, especially along its lower edges, the metal insert becomes an integral portion of the deflected arc segment, which behaves in a normal manner except that its mean circumference (spring length) increases as the metal insert opens under greater stress and leverage as the radius of the deflected arc shortens. The second factor derives from the lowering of the pivot of the metal spring insert as it opens under stress. Both the spring lengthening and the levering factors accelerate their contributions to vertical motion as the deflexive radius shortens, together accounting for the favorable behavior of Curve C in its lesser spanned range, thus bringing the closed joint portion of the curve under control.

We now attack the initial end of the curve, where the deflection is too severe. Curves A and B show an inadequate but constant rate of deflection when their net half widths equal their heights, this being the point at which the full 180° arc is developed and the deflected element becomes a rolling gland with an ever-shortening radius and its excess

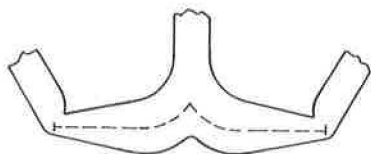


Figure 24. Constant rate motor element.

tempt the amount of compensation necessary if the full 180° circular arc were initiated at the maximum span. Instead let us make partial use of this full-arc'd phenomenon by tapering the thickness of the motor element, deepening its center and shallowing its ends. Initial deflection of such an element becomes shallow elliptical rather than circular or vertically elliptic. Thus the depth of the arc segment is lessened and the more flexible outboard ends are merged tangentially with the supporting abutments in the manner of the full circular arc, thereby introducing a controllable amount of full arc'd behavior early in the deflective cycle. By combining this treatment of the initial curve with the spring-lengthening technique, it is indeed possible to develop vertical motion approaching perfection.

Figure 24 combines these principles in an elastomeric motor element. By reversing the central portion of the arc so that under strain it resembles an inverted V, the design incorporates the lengthening and levering phenomena of the spring-modified element shown in Figure 23.

DESIGN OF TOP STRUCTURE

Development of the deep contoured insert (Group IV) also permits specialization of the top structure, which becomes an ideal application of the rolling gland (Fig. 5). Although the motor element is highly demanding, especially when great range is required, the surface structure is freed from the manifold problems of drastic deformation, and its elastic requirement is that of simple but relatively sharp flexure. Figure 25 illustrates the type of action to which it is subject; the sketch shows progressive positioning of one of the opposed half sections.

It will be noted that the rolling section is tapered. Since horizontal compression increases as the joint narrows, tapering helps to maintain relative constancy of the external radii of the intermating arcs. These, of course, will flatten abruptly as they merge at the vertical centerplane in the same manner as the surface of an automobile tire is sharply radiused and its surface stretched as it meets the pavement. This tapering also reduces the amount of upward force (K) required to square the rolling section when the joint is open and thus lessens the work required of the motor element

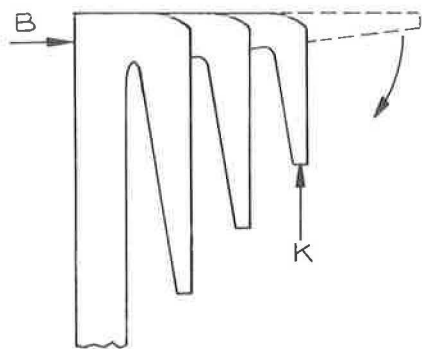


Figure 25. Progressive positioning of tapered rolling section.

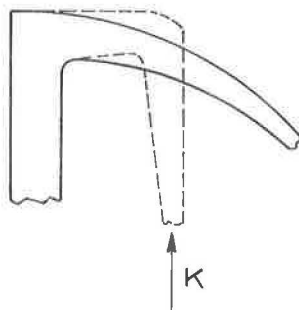


Figure 26. Curvilinear section, strain relieved in flexure by reverse prestressing.

circumference laid out in tangents against the supporting abutments. The root factor of vertical to horizontal motion here is $0.57 \left(\text{or } \frac{\pi}{2} - 1 \right)$ and, thus, the vertical motion is inadequate. Even though we have learned how to compensate for this inadequacy in the closed portion of the range, it would seem inadvisable to at-

when it is only partially deflected. This can be significant since the motor element's positive force is downward rather than supporting.

Figure 26 shows the rolling section formed as a tapered arc, which best adapts itself to the design of the total insert. As the gland is squared into closed position, the flattened sections are oppositely prestressed, thus relieving to some degree the strains which occur in sharp flexure. Although this design may require a slight increase in vertical motor force (K), the leverage against horizontal compression approaches infinity. By tapering the rolling section, the mean horizontal force inclines slightly upward, forming an inside angle of less than 90° from vertical when the top surface is leveled, thus overcentering the opposed horizontal forces. When so positioned, the compressive resistance of the horizontal sections partially relieves the motor element of the indicated need for vertical support, conceivably with the possibility (however improbable) of stress reversal of such support. This further indicates the importance of the role played by the motor element wherein perfection in its design can reduce its work load, permit reduction in thickness and severity of deformation, and thereby improve its performance and service life.

BUTTERFLY INSERTS (GROUP IV)

Now let us put these elements together in a deep contoured insert nominally deepening twice the maximum joint width. Figure 27 shows a series of such inserts in which the center leg is split to varying depths, each performing identically when squared in the joint. The outboard sections are arced and thus can be stressed into pressured contact with the supporting concrete.

Most tubular inserts may be installed by forcible depression into place, but they will differ in how reliably they may be deepened. Although lubricity at the pressured interfaces affects placement, force applied directly to the mechanics of deformation is more positive. For example, in the tubular insert shown in Figures 9 and 10, downward force applied to the top center of the superstructure brings the bottom surface of the motor element immediately into contact with the lower membrane and draws the sidewalls of the insert into place. However, if the sidewalls were pressed downward, relatively minor changes in frictional resistance would result in different placement. Similarly downward force applied at the base of the center notch of the butterfly insert will deflect the motor element and draw the sidewalls into the joint space behind it. The most certain application of such force would occur in the insert having the deepest notch, thereby minimizing reliance on elastomeric transmission to the motor element. Thus, insofar as reliability of installation is concerned, the lesser modulus elastomers would require the deeper separation of the center support.

Alternatively, it may be necessary to improve the dimensional stability of the center support so that deflection of the motor element is reproduced more faithfully at the top surface. Figure 28 introduces such a stiffening element molded within the center support section. It will be apparent that the stiffening element could comprise the total center support, especially if surface protection were not needed, and that the complete insert might be coextruded of dissimilar compositions.

Since the stress-strain requirements of the various elements differ so markedly from each other, further compositional specialization could be dictated, especially for critical applications demanding maximal performance. Furthermore, in all cases

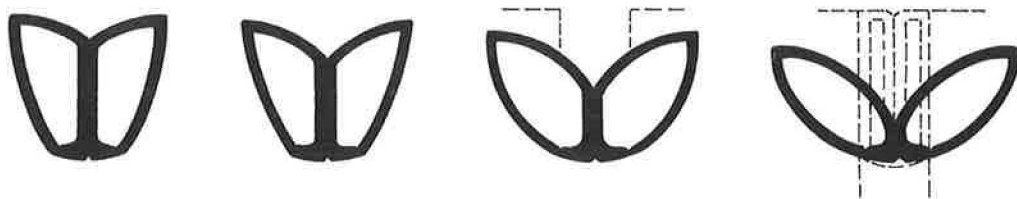


Figure 27. Deep contoured butterfly inserts.

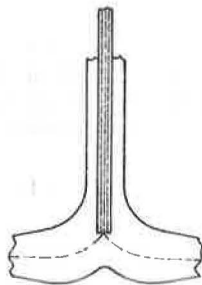


Figure 28. Stiffened center support section.

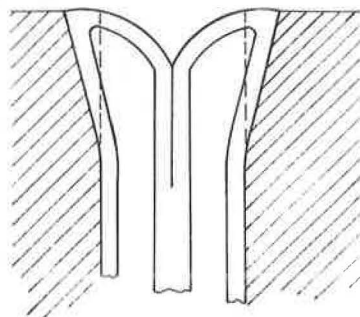


Figure 29. Sealing flared slot.

the surface sections are exposed to hazards such as abrasion and exposure to sunlight from which the motor element may be shielded. This is mainly shown by jet aircraft ramps and runways, especially in engine starting and warm-up areas where the seals are subjected to localized heat, fuel and flame.

Although Group IV inserts may be formed effectively in low-modulus elastomers, the design is adaptable to much higher polymers than were heretofore deemed feasible for variable gapped sealing. Thus, it is not inconceivable that hitherto impossible specifications may be met satisfactorily. Due to the increased stiffness and durability of such materials and their potentially reliable use in lesser cross-section, combined with suitably compositioned motor elements designed for longer stroke, the range of operable width may be extendible beyond the 2:1 ratio originally specified. In addition, as progressively harder compositions are used in the outer vertical and top surface sections, the butterfly insert more closely resembles externally the cantilevered retaining assembly illustrated in Figure 12.

The inserts earlier presented in this paper and classified within Groups I to III require horizontal containment within reasonably close limits relative to the designed width. Indeed, one of the purposes of the retaining elements (Figs. 11 and 12) was to permit their effective use in malformed slots. In contrast, the deep contoured butterfly inserts have considerable tolerance for slot irregularities above the level of the motor pivots. Figure 29 shows the insert positioned in a fully opened joint with its exposed surface 100 percent wider than the specified minimum. The rolling sections still join compressively but at a lower level; in this particular case the centerline surface is depressed about three-quarters the amount of the overwidth.

REJECTION OF FOREIGN MATTER

When installed in reasonably width-toleranced joints—this applies to all inserts discussed—the radii of the intermating arcs is so exceedingly short adjacent to the actual point of center plane contact, due to the opposing sections being forcibly impacted together, that none but the tiniest of particles could be carried inward as the joint closes. Such inconsequential matter as may be seized will be rolled out and freed in the reopening phase of each cycle. But in the extreme example shown in Figure 29, the converging sections are less impacted and thus larger radiused in this critical area. When subjected to greater proportional slot overwidths, the centerline mating is more deeply depressed and longer arc segments become wedge-inclined and capable of seizing ever-larger particles. When this occurs, a most interesting phenomenon develops: the seizing of such a particle separates the opposing surfaces and thus shortens the distance which the top sections must span. Each inclusion tends to correct the operative width of the insert. It is not improbable that the center fill of foreign matter may indeed tend to duplicate the overwidth contour of the slot adjacent to the surface of the pavement; under this condition the top sections of the insert would be restored to perfect top level and thereafter perform in strict accordance with designed behavior.

ICING CONDITIONS

In operation at subfreezing temperatures, the ever-changing relationship of the top surfaces should contribute favorably to breaking the interfacial bond with surface ice. In addition, the insert's susceptibility to vertical load flexure when broadly spanned similarly could cause it to function like the de-icing element on the leading edge of an airplane wing. Continuous fill of the surface portion of the joint is most significant, especially in contrast to sealants which withdraw measurably, since no formation of ice can wedge between the spallable abutments.

MATERIALS

The omission of definitive identification of elastomeric compositions stems neither from neglect nor from lack of acquaintance with such materials. Following the original thesis, this paper covers the development of mechanical concepts applicable to the subject purpose and shows how compositions of widely differing specification may be utilized effectively in the sealing of joints in concrete. These concepts must be executed in materials suited to the demands of a particular design and to the service requirements to which they will be subjected. Their success, therefore, is dependent on intelligent choice and engineering design, and their limitations are inherent in the selected materials.

CONCLUSION

The evolution of compressible insert design as herein developed from the beginning prototype to the butterfly has been a challenging experience. Although I consider the deep contoured insert a significant accomplishment—the validity of which may be attested by the fact that this design could be operable if fabricated totally in spring metal—I do not propose that further development of these concepts should be unanticipated; nor do I wish to imply that the task is hereby completed, when in fact it is little more than begun.

REFERENCE

1. Tons, Egons. Factors in Joint Seal Design. Highway Research Record No. 80, 1965.