A Theoretical Approach to Design of a Road Joint Seal

EGONS TONS, Research Engineer,
Joint Highway Research Project,
Massachusetts Institute of Technology

● THE SEALING of pavement joints is a common practice. It is done both in new concrete road construction and during subsequent maintenance in the form of joint resealing and crack filling. Even after an old portland cement concrete roadway is covered by a bituminous resurfacing, sealing usually has to continue because of reflection cracks.

A pavement joint undergoes continued changes in width due to such influences as temperature and moisture fluctuations within the concrete slabs. When a joint (or crack) is filled with a sealing compound, strains and stresses caused by every opening or closing movement must develop both within the sealer and along the bond interfaces between sealer and pavement. The mass of sealer in the joint can be pictured as a sort of bridge spanning the gap between two slabs. Just as we try to design a bridge before it is built by using known quantities and methods, we should attempt to design a seal before it is placed in the joint.

The need for a more exact approach to joint sealing has been expressed by various individuals and organizations associated with road construction and research. The 1953 Committee on Joint Materials in Concrete Pavements, in HRB Bulletin 78, states the case as follows:

> "There should, in fact, be a proper relationship between: (1) the amount of change in joint width, (2) the capabilities of the sealing material, and (3) the width of the joint space."

Work on this problem started with a simple joint model test. It was soon discovered that the depth of seal in the joint is another equally important variable.

PURPOSE OF THE STUDY

The purpose of this study was to correlate mathematically and by experiment (a) the joint width, (b) sealed depth, (c) joint expansion, and (d) the extensibility of the sealer, and then hopefully to outline a joint seal design procedure for future practical use in the field.

This paper describes the theoretical analysis and computations of strains in a sealed joint and presents experimental laboratory data to verify the basic theory and to point out its limitations. An approach to a practical joint seal design procedure is given in Appendix B.

THEORY OF JOINT SEAL BEHAVIOR

Basic Assumptions

The theory presented in this paper is based on maximum strain calculations in the sealer due to joint width variations. The following assumptions were made to facilitate the analysis:

The joint cross-section is rectangular (see Fig. 1).

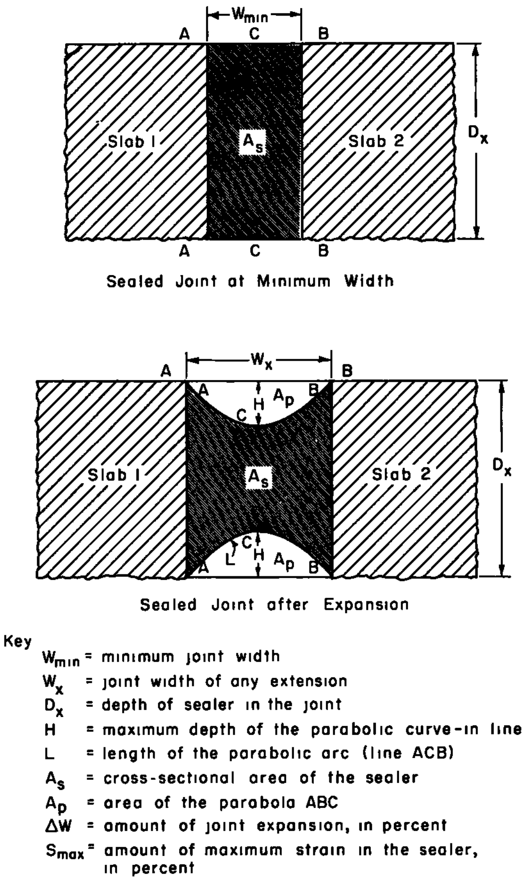


Figure 1. A sealed joint before and after expansion.

The sealer is a liquid-type homogeneous compound which cannot change in volume but instead changes its shape when the joint varies in width (see Fig. 1).

The majority of sealing compounds currently used fall closely within this group. They show little if any change in volume when extended or compressed.

The curve-in top and bottom surfaces of the sealer resulting from joint expansion are parabolic in shape (see Fig. 1).

This assumption is based both on observations of pavement joints and measurements in laboratory bond-ductility tests. These show that the curve-in line seems to correspond quite closely to a parabola for a wide range of sealed widths and expansions (this is discussed in "Laboratory Tests to Verify Theory and Calculations").

The sealer curves in equally from the top and the bottom of the joint (see Fig. 1).

In many cases the bottom of the joint contains foreign matter which prevents adhesion. As will be seen in later calculations, there is a definite advantage in having the sealer curve in from top and bottom (see "Procedure of Strain Computations"). In order to prevent adhesion and to control the depth of seal, appropriate filler materials will have to be used in the bottom of the joint.

The minimum and maximum joint widths are the indicators of the total strains in the sealer, no matter what the width of the joint when it is first sealed.

The minimum joint width has a significant effect on future strain in the sealer. If joints are sealed in fall during moderate temperatures, the compound will not be stretched much the first winter. The following summer the joint will narrow down to its minimum width expelling some of the compound. From then on this smaller volume of sealing material will have to keep the joint sealed at all its various widths.

The strain in the sealer along the parabolic curve-in line is uniformly distributed.

According to observations in laboratory tests, this assumption holds reasonably true for a wide range of joints at various stages of expansion (see "Laboratory Tests to Verify Theory and Calculations").

Notation

Most of the symbols used in this paper are shown in Figure 1. In order to provide a complete list, all of them are summarized below;

- W_{min} - minimum joint width
- W_x - joint width at any extension
- W_{max} - maximum joint width
- W_f - joint width at the time of failure in a bond-ductility test
- ΔW - linear expansion or change in joint width, in percent

$$\frac{W_x - W_{min}}{W_{min}} \times 100$$

- D_{min} - minimum depth of seal
- D_x - any sealed depth
- D_{max} - maximum depth of seal
- H - maximum depth of the parabolic curve-in
- L - length of the parabolic arc
- S_{max} - maximum total strain in the sealer along the parabolic curve-in line, in percent

$$\frac{L - W_{min}}{W_{min}} \times 100$$

- A_s - cross-sectional area of the sealer
- A_p - cross-sectional area of the parabola ABC (see Fig. 1)

Minimum Joint Width and Strains in Sealer

For like conditions, the wider the joint at its minimum width, the less the sealer filling will be strained.

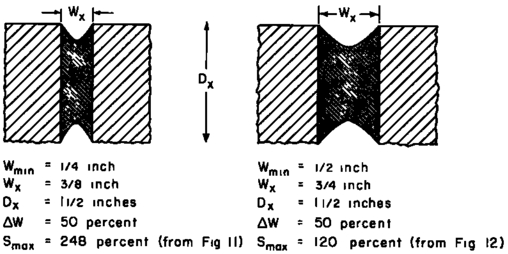


Figure 2. Comparison of maximum strains (S_{max}) in the sealer for two joint widths (W_{min}) with 50 percent expansion (ΔW = 50).

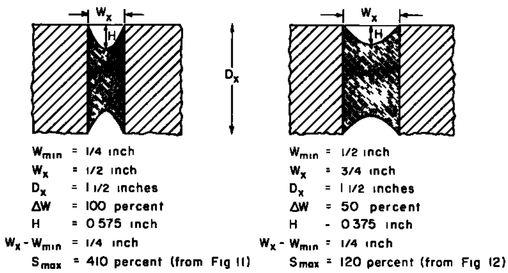
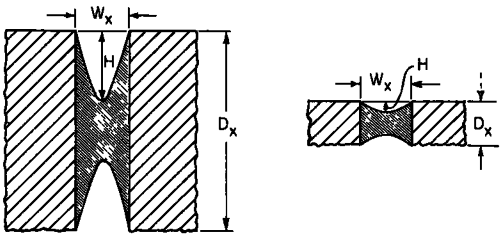


Figure 3. Comparison of maximum strains (S_{max}) in the sealer for two joint width (W_{min}) with $\frac{1}{4}$ in. expansion.

The amount of strain in a common liquid-type sealer is not directly proportional to joint expansion because the surface of the sealer curves down in the joint and does not stretch in a straight line (see Fig. 1). Furthermore, the narrower the joint, the more severe the strain forces for any given percent of joint expansion (see Fig. 2; calculation procedure will be given later). If a narrow joint expands as much as a wider joint, remarkable strain differences will result (see Fig. 3).

Influence of Sealed Depth

While the effect of joint width upon the performance of a seal has been recognized for a long time, the equally important depth of seal has on the whole been left unnoticed. In fact, it is commonly assumed that the deeper a joint is sealed the better. Theoretical calculations indicate the opposite is true; i.e., the shallower the seal, the less "curve-in" and the smaller the strains in the sealer (see Fig. 4). This appears to be confirmed by laboratory tests (see "Laboratory Tests to Verify Theory and Calculations").



W_{min} = 1/4 inch	W_{min} = 1/4 inch
W_x = 1/2 inch	W_x = 1/2 inch
ΔW = 100 percent	ΔW = 100 percent
H = 0.75 inch	H = 0.19 inch
D_x = 2 inches	D_x = 1/2 inch
S_{max} = 550 percent (calculated)	S_{max} = 160 percent (from Fig 11)

Figure 4. Comparison of maximum strains (S_{max}) for 2-in. deep and $\frac{1}{2}$-in. deep seals (D_x = 2 in. and D_x = $\frac{1}{2}$ in.).

<u>Procedure of Strain Computations</u>

Figure 1 shows the shape of the sealer cross-section before and after extension. If the joint width before expansion is W_{min} (minimum width) and after expansion becomes W_x and the joint has been sealed to a depth D_x, the increase in the joint cross-sectional area is $(W_x - W_{min}) \times D_x$. Since the sealing material acts like a liquid and is not able to change its cross-sectional area A_s, the two parabolic areas A_p will be equal to this increase (see Fig. 1) and the maximum curve-in value H can be calculated as follows:

$$2A_p = (W_x - W_{min})D_x$$

$$A_p = \tfrac{1}{2}(W_x - W_{min})D_x$$

but A_p-2/3 HW_x (equation for a parabolic area)

from which $H = 3/2 \dfrac{A_p}{W_x} = \dfrac{3/4\ D_x\ (W_x - W_{min})}{W_x}$

where H = the maximum curve-in distance
A_p = area of one of the parabolas (area ACB)
W_x = the width of the sealed joint after expansion
W_{min} = minimum joint width

Any cross-section of a sealed joint can be divided into numerous layers. If the width of the joint is increased, the outer layers which follow the parabolic curve will be stretched most (see Fig. 5). The length of this outer skin can be computed by using the formula for the arc length of a parabola:

$$I = \tfrac{1}{2}\sqrt{W_x^2 + 16H^2} + \frac{W_x^2}{8H}$$

$$\log_e \frac{4H + \sqrt{W_x^2 + 16H^2}}{W_x}$$

where L = length of arc ACB (see Fig. 1)
H = the maximum curve-in distance
W_x = the width of the sealed joint after extension

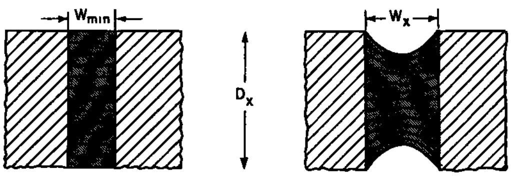


Figure 5. Visual strain comparison in the sealer at different levels for W_{min} = $\frac{1}{2}$ in. and W_x = 3/4 in.

Once the length of the curve-in line is known, the actual maximum strains in the surface of the sealer under various conditions can be calculated:

$$S_{max} = \frac{L - W_{min}}{W_{min}} \times 100$$

where S_{max} = maximum strain in the sealer, in percent
L = length of arc ACB (see Fig. 1)
W_{min} = minimum joint width, also equal to minimum L

The calculated maximum strain S_{max} in the sealer under ideal conditions depends, (a) upon the minimum joint width, (b) the amount of Joint expansion, and (c) the depth of seal. The numerous and repetitious calculations to correlate these factors were done by an electronic computer and the results were compiled in curve form1/.

Discussion of Theoretical Curves

By this procedure, the maximum strains in the sealer can be computed for any combination of depth of seal, joint width and joint expansion up to 200 percent2/; nine sets of curves are included for illustration (Figs. 6-14). They show that strains in the sealer can be decreased by either increasing the minimum joint width or by decreasing the depth of seal.

Figures 6 to 9 show the variation of maximum strain (S_{max}) occurring along the parabolic curve-in line at various joint openings for eight minimum joint widths (W_{min}) and four different seal depths (D_x). Thus Figure 8 gives comparisons for joints which have all been sealed to a depth of 2 in. (quite a common practice). The curves indicate considerable differences in strain developments. For example, a joint with a minimum width of 1 in. ($W_{min} = 1$) expanding 50 percent, or an additional $\frac{1}{2}$ in., will induce an 87 percent strain in the outside layer of the sealer ($S_{max} = 87$). If, similarly, a $\frac{1}{4}$-in. joint ($W_{min} = \frac{1}{4}$) opens 50 percent, or 1/8 in., the maximum strain in the sealing compound would be about 342 percent (S_{max} = 342) which is nearly four times as much. The differences in strain could be more surprising if the $\frac{1}{4}$-in. joint would have to take the same expansion ($\frac{1}{2}$ in.) as the 1 in. wide. In this case the strain induced in the outside skin of the sealer would be 780 percent or about nine times as much as in the wider joint.

Figures 10 to 13 show the variation of maximum strains (S_{max}) in the sealer with change in joint width for eight sealed depths (D_x) and four minimum joint widths (W_{min}). For example, if in Figure 11 the maximum strains (S_{max}) in the sealer are compared for sealed depths of $\frac{1}{2}$ and 2 in. at 50 percent expansion the same 87 percent versus 342 percent strains are found, just as in the previous example.

Figure 14 presents the calculated curves in a compounded form correlating ΔW, W_{min}, D_x, and S_{max}. To get it, Figure 13 ($W_{min} = 1$) was expanded and a ratio D_x/W_{min} was introduced which makes this figure valid for various joint widths and depths of seal. Thus, if the stretchability

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1/ A fully derived equation for the maximum strain in the sealer (S_{max}) along the surface is given in Appendix E.

2/ Theoretically, the two parabolas (see Fig. 1) intersect at 200 percent of joint expansion no matter what joint width or depth is taken. A mathematical proof is given in Appendix E.

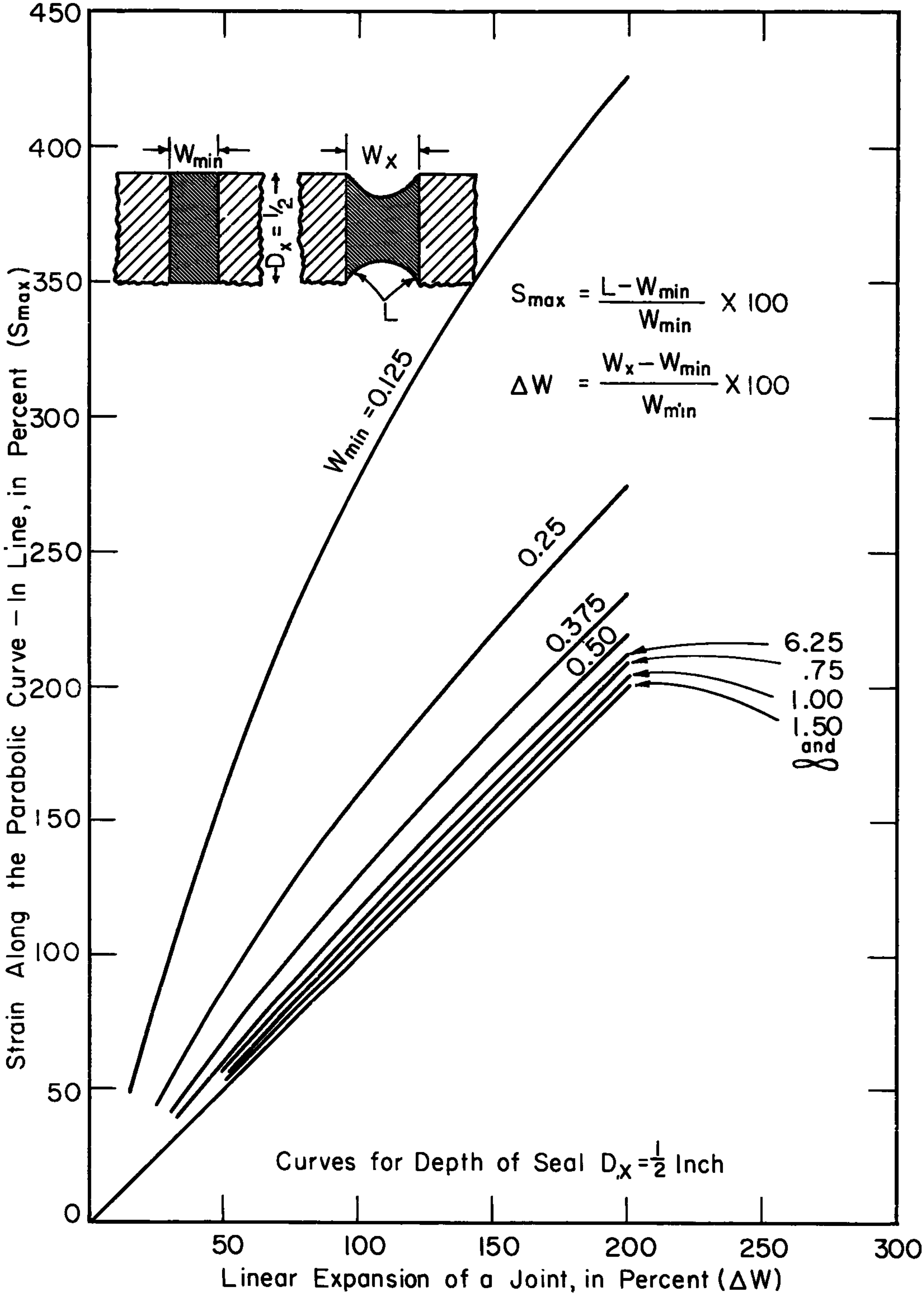

Figure 6. Comparison of strains in the sealer for various joint widths and $\frac{1}{2}$-in. depth.

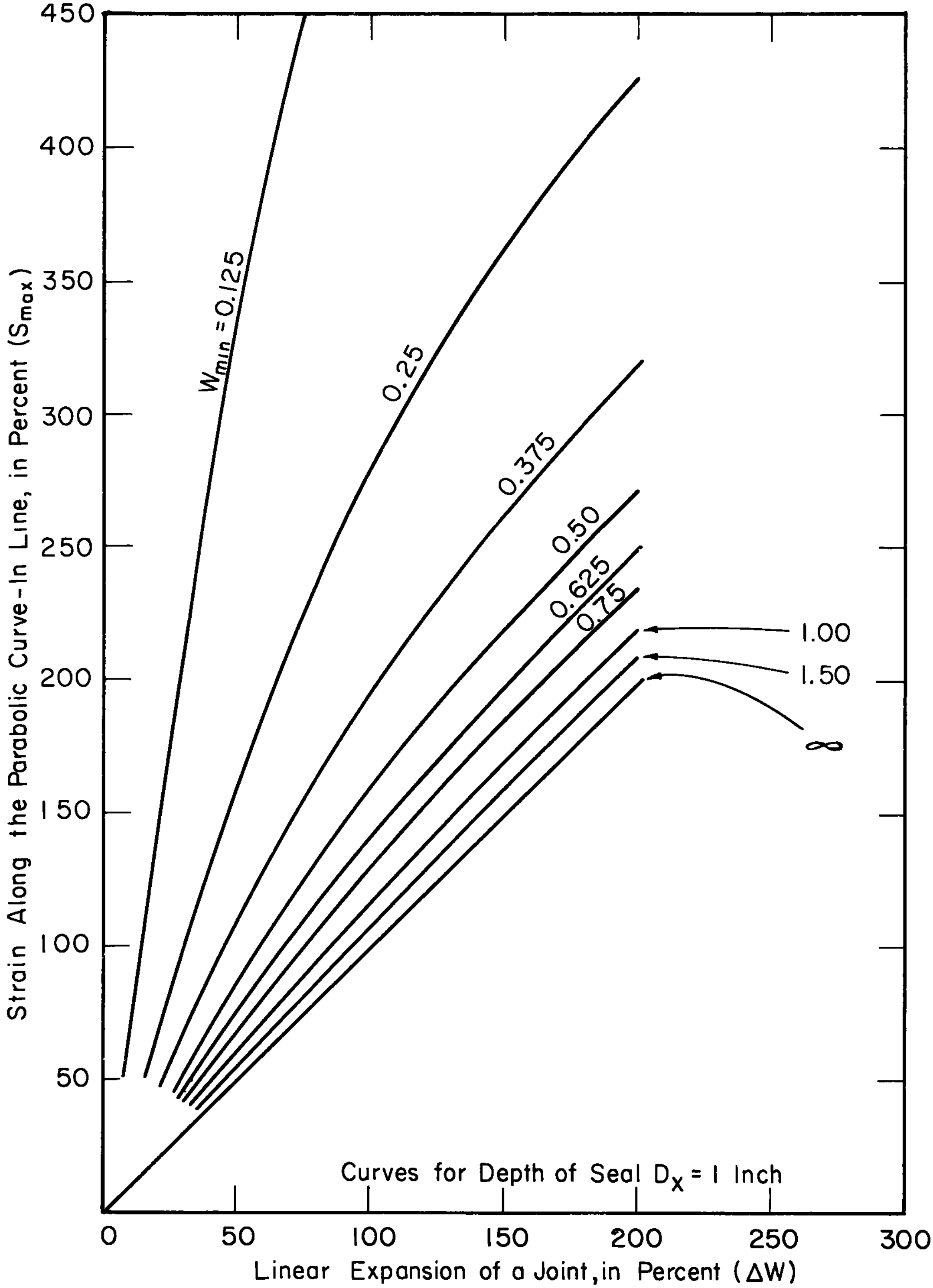

Figure 7. Comparison of strains in the sealer for various joint widths and 1-in. depths.

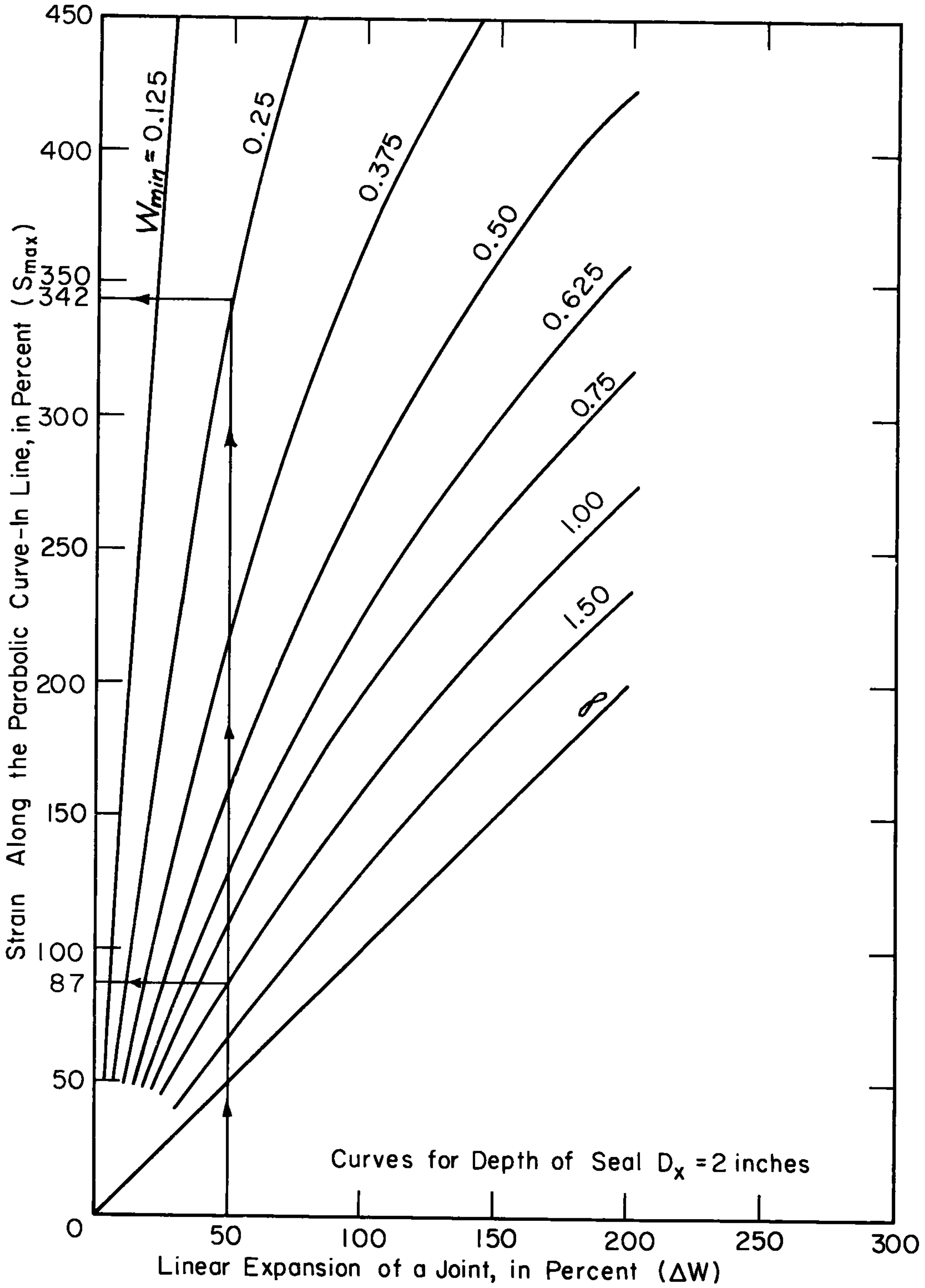

Figure 8. Comparison of strains in the sealer for various joint widths and 2-in. depth.

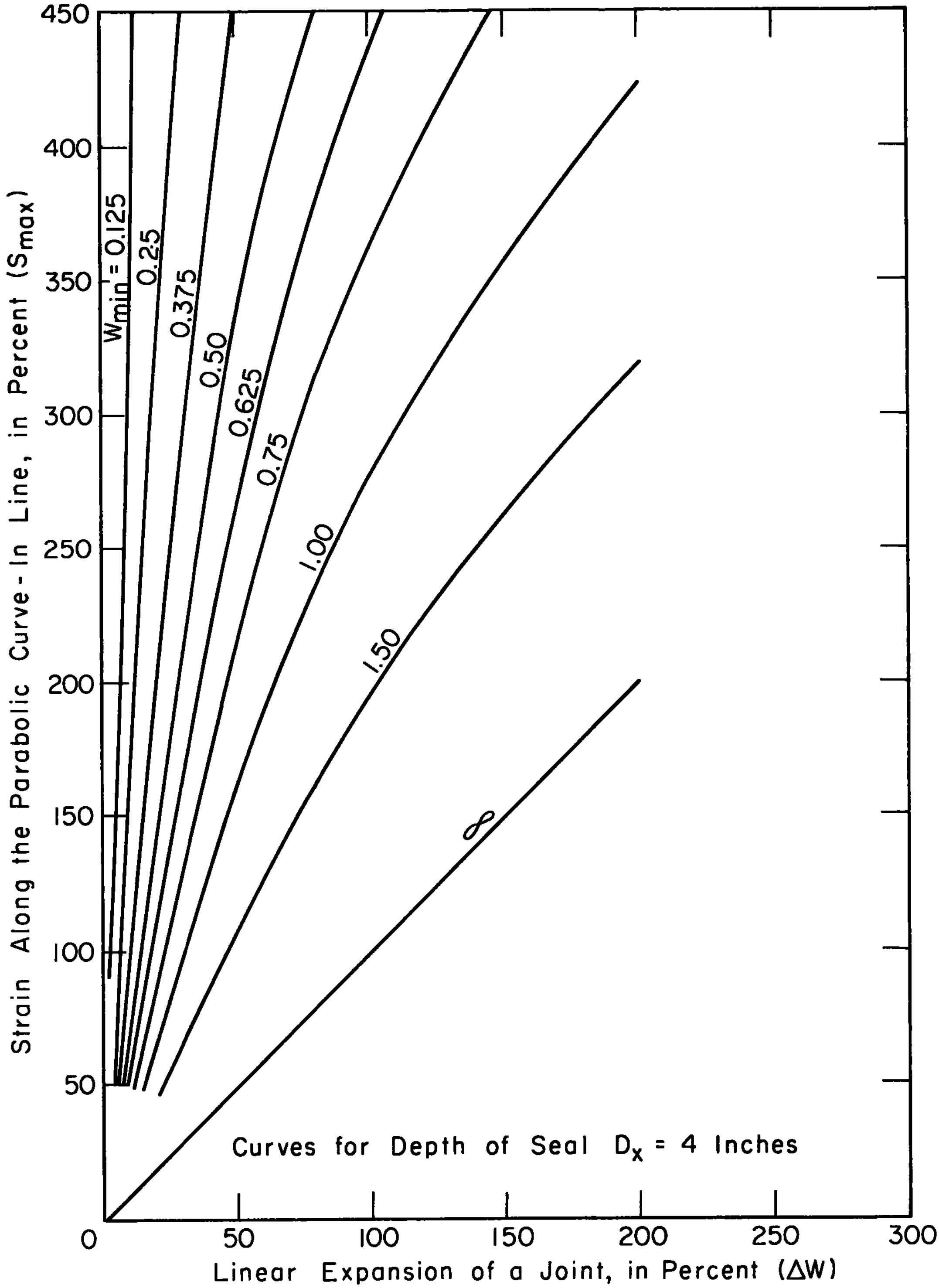

Figure 9. Comparison of strains in the sealer for various joint widths and 4-in. depth.

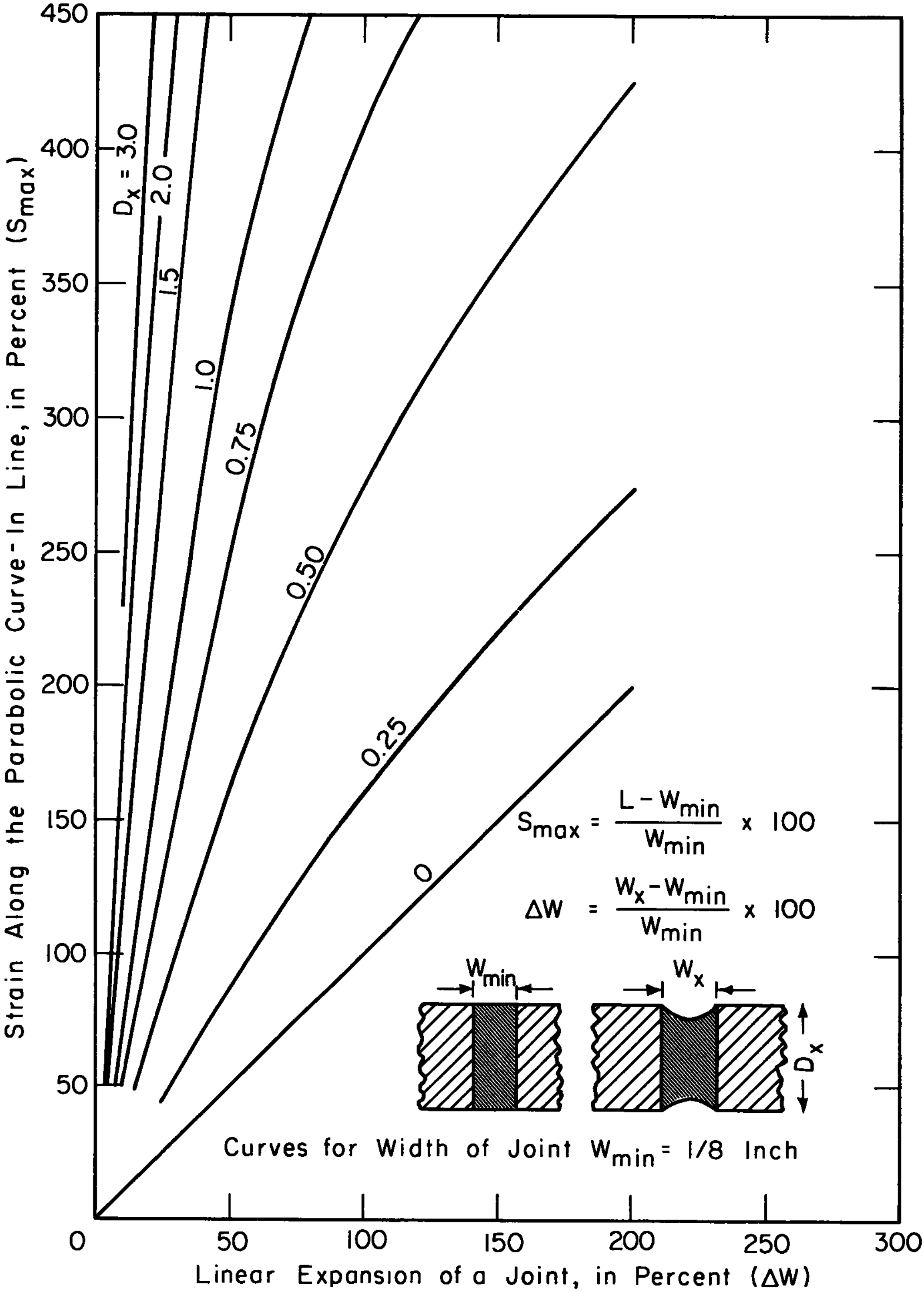

Figure 10. Comparison of strains in the sealer for various depths of seal and 1/8-in. width.

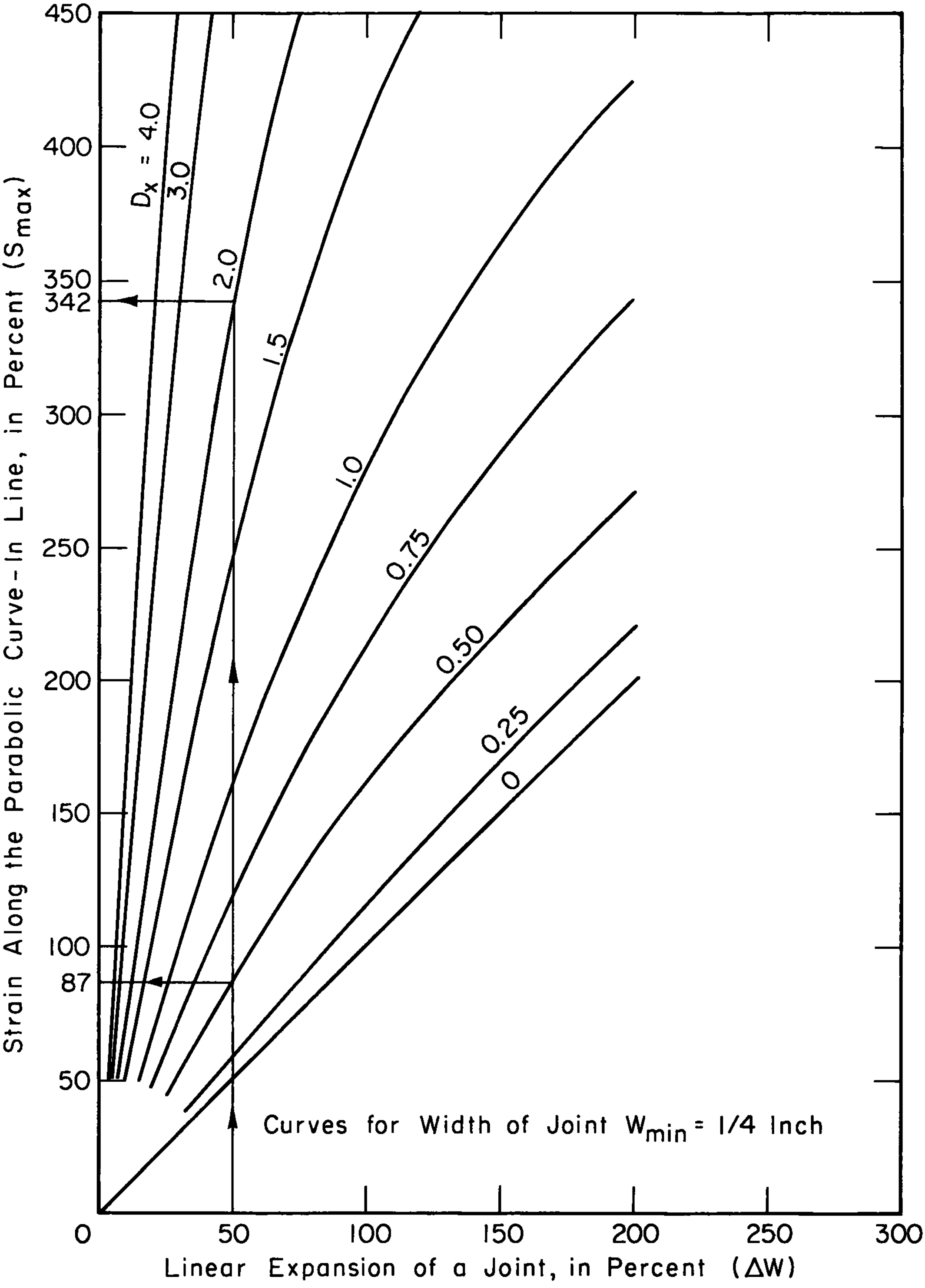

Figure 11. Comparison of strains in the sealer for various depths of seal and $\frac{1}{4}$-in. width.

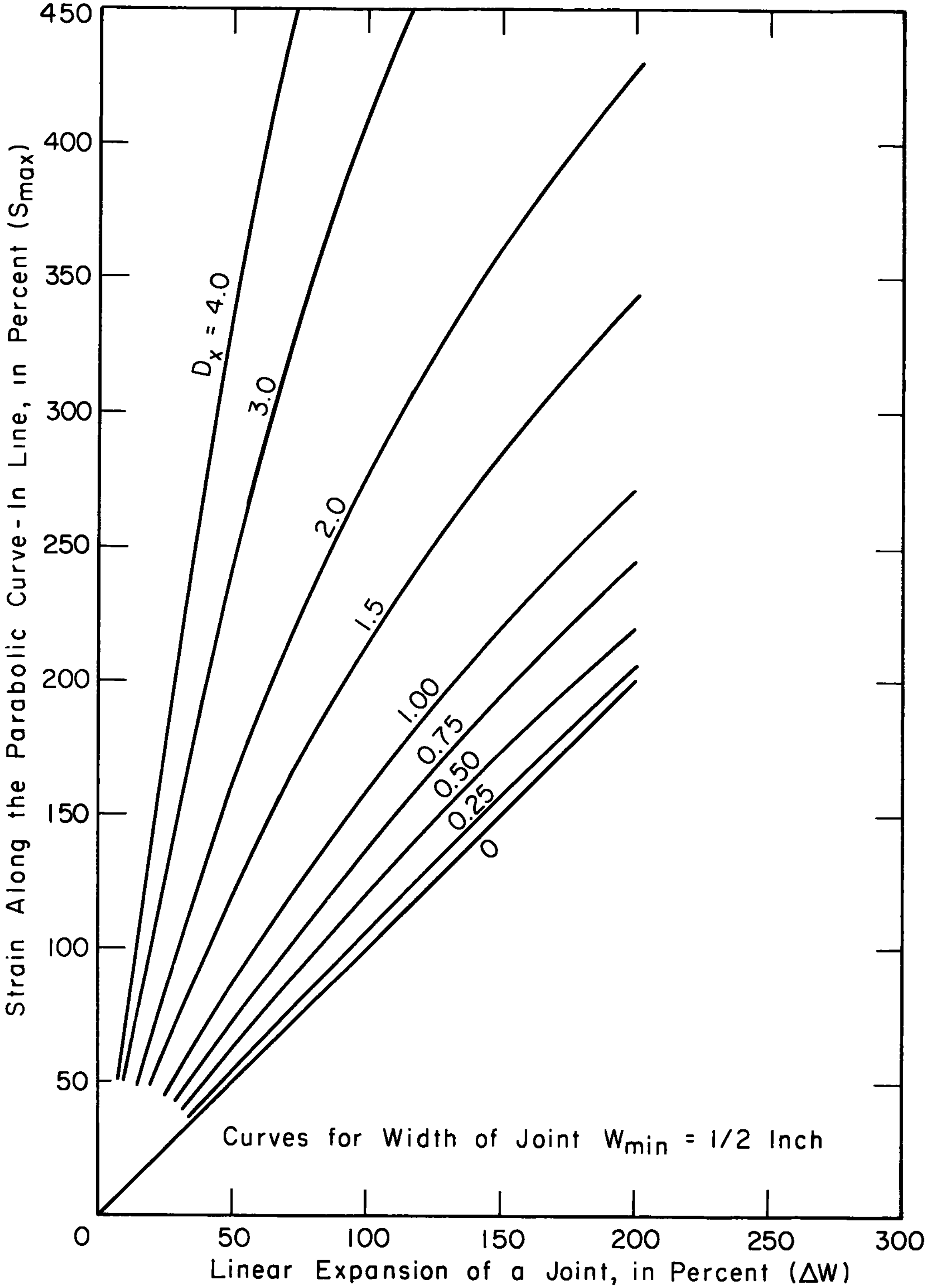

Figure 12. Comparison of strains in the sealer for various depths of seal and $\frac{1}{2}$-in. width.

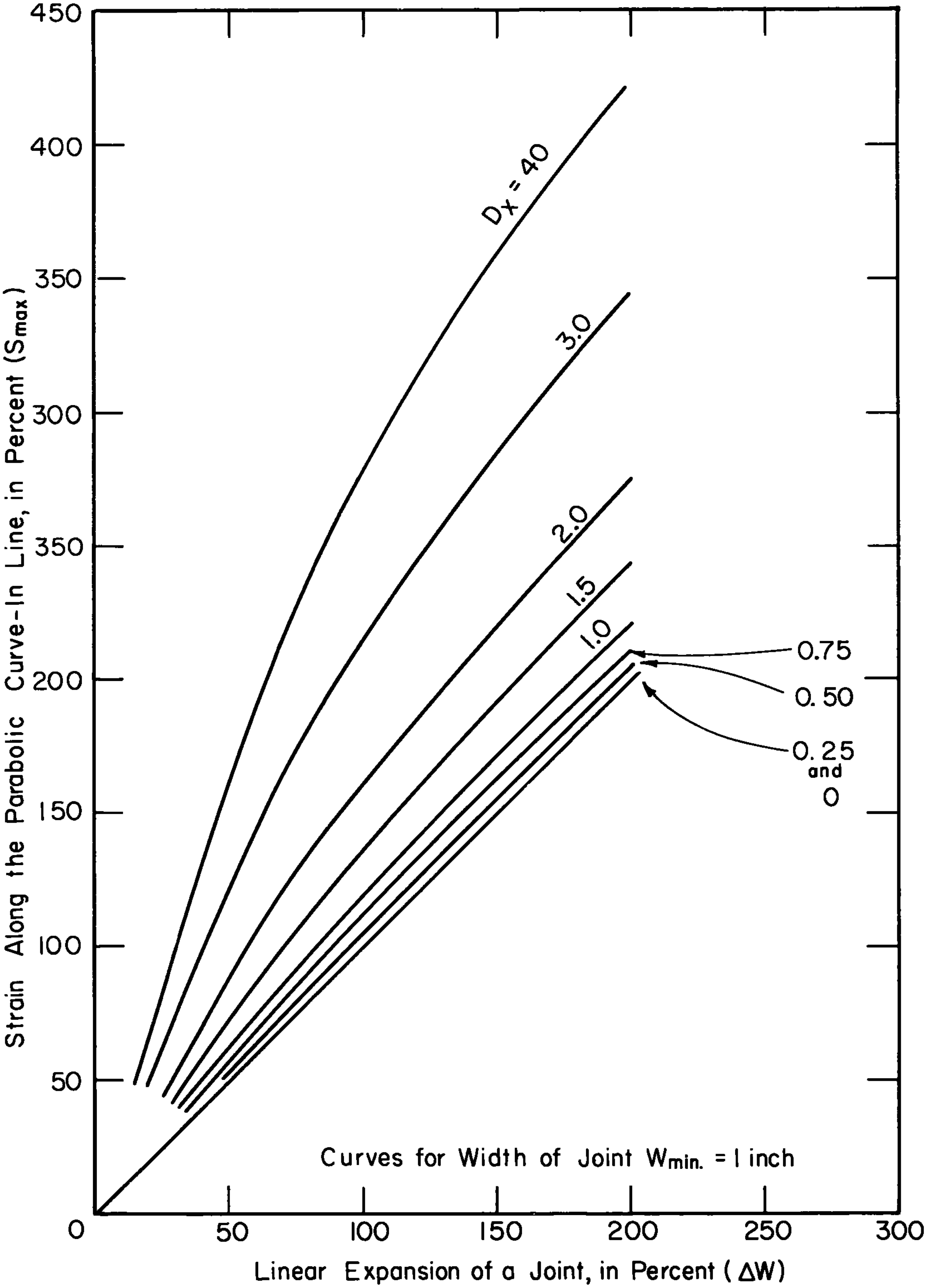

Figure 13. Comparison of strains in the sealer for various depths of seal and 1-in. width.

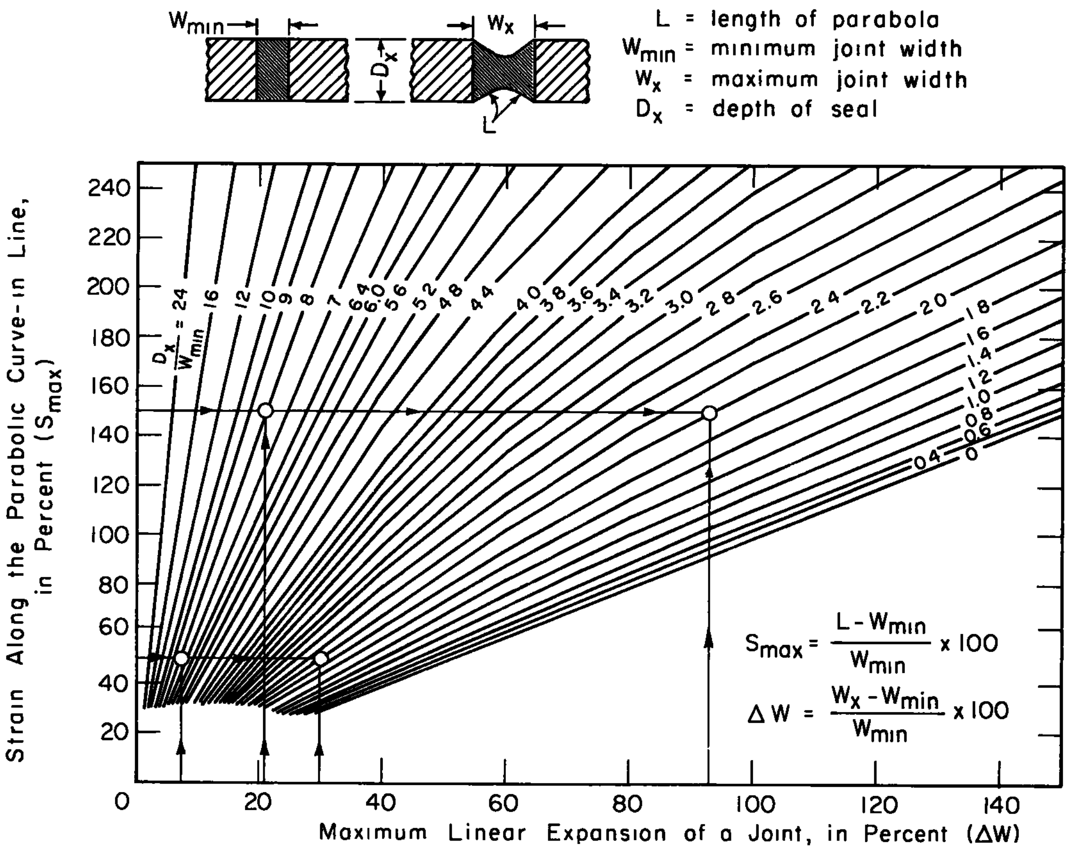

Figure 14. Relationship between ΔW, W_{min}, D_x and S_{max} in a sealed joint.

of the sealer (S_{max}) and the amount of joint expansion (ΔW) are known, D_x can be found for any desired joint width (W_{min}).

Figure 14 clearly indicates the importance of the depth of seal and joint width ratio (D_x/W_{min}). The lower this ratio the more stretchable the seal will be, other factors being the same. For instance, a sealer with maximum allowable strain S_{max} = 150 percent placed in a 3/8-in. joint can take only 21 percent of joint expansion (ΔW) if D_x/W_{min} = 8 and 93 percent if D_x/W_{min} = 2. In other words, the shallower a certain joint is sealed, the more strain a given sealer will take before it fails.

A similar comparison can be made with a low extensibility sealer (S_{max} = 50) as illustrated in Figure 14. The comparative benefits obtained are much smaller in this case. For D_x/W_{min} = 8, ΔW is 13.5 percent and for D_x/W_{min} = 2, ΔW is 30 percent.

Present data is insufficient to recommend a definite D_x/W_{min} ratio for joint seals. This will depend upon type of sealer used, the service it is put to and other requirements yet to be defined. As an estimate, this ratio (D_x/W_{min}) might be around one and may go as high as four for most practical applications. From a sealing standpoint a 3/8-to-$\frac{1}{2}$-in. depth of seal is probably the minimum that should be attempted as it would be difficult to place anything shallower.

LABORATORY TESTS TO VERIFY THEORY AND CALCULATIONS[3/]

Test Outline

The parabolic curve-in surface was observed in numerous bond-ductility tests in this laboratory during the past four years using various sealing compounds; additional tests were recently performed to obtain more accurate measurements to justify the assumptions in "Theory of Joint Seal Behavior."

In the new series a modified bond-ductility test was adopted. The length of the specimens was increased to 6 in. in order to minimize the effect of curve-in from the two ends of the test blocks. The opening between the blocks (W_{min}) as well as the depth of seal (D_x) were varied to check the different ranges of the theoretical curves in Figures 6 to 14. The maximum sealed depth in these tests was limited to 3 in., as this is usually the maximum for pavement joints.

The test procedure, preparation and testing were similar to that outlined in Appendix A, except that the temperature was 80 F during this test. Previous laboratory observations have indicated that the basic curve-in pattern (parabola) is similar at 80 F and 0 F if the same liquid-type, homogeneous sealer is strained between two blocks (joint). However, the total strain that can be applied before the seal fails is usually less in the cold test.

In these test series two sealing compounds were used: (a) a hot-poured rubber-asphalt and (b) a cold-applied, two-component synthetic polymer. They were chosen because they are well-known materials, appeared to represent a fairly large group of sealers currently used and this laboratory has already had extensive experience with them.

The following measurements and observations were made:

1. The maximum curve-in distance H was measured at different percentages of extension (joint expansion) on each specimen and compared with the calculated values (curve). This was taken as an indication of how closely the actual curve-in line approaches a parabola (see "Laboratory Test Data").
2. The uniformity of strains along the curve-in surfaces was checked by marking them and observing the strains between various points visually.
3. The amount of curve-in from the top and the bottom of the specimen was compared.
4. Cohesion and other failures were closely watched and recorded.

The test data on the H measurements are compiled in a graphical form in Figures 15 to 22. A discussion of the test results follows:

Laboratory Test Data

Figures 15 to 18 summarize the H readings obtained on specimens of hot-poured rubber-asphalt sealer of varying depth (D_x). The horizontal axis gives the simulated joint expansion while the vertical one denotes the calculated maximum curve-in values (H). The solid line represents the computed H curve for a certain depth of seal (D_x) on each figure,

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3/ A test road using various joint widths and depths of seal was installed near Syracuse, New York, in September 1958. It is briefly described in Appendix D.

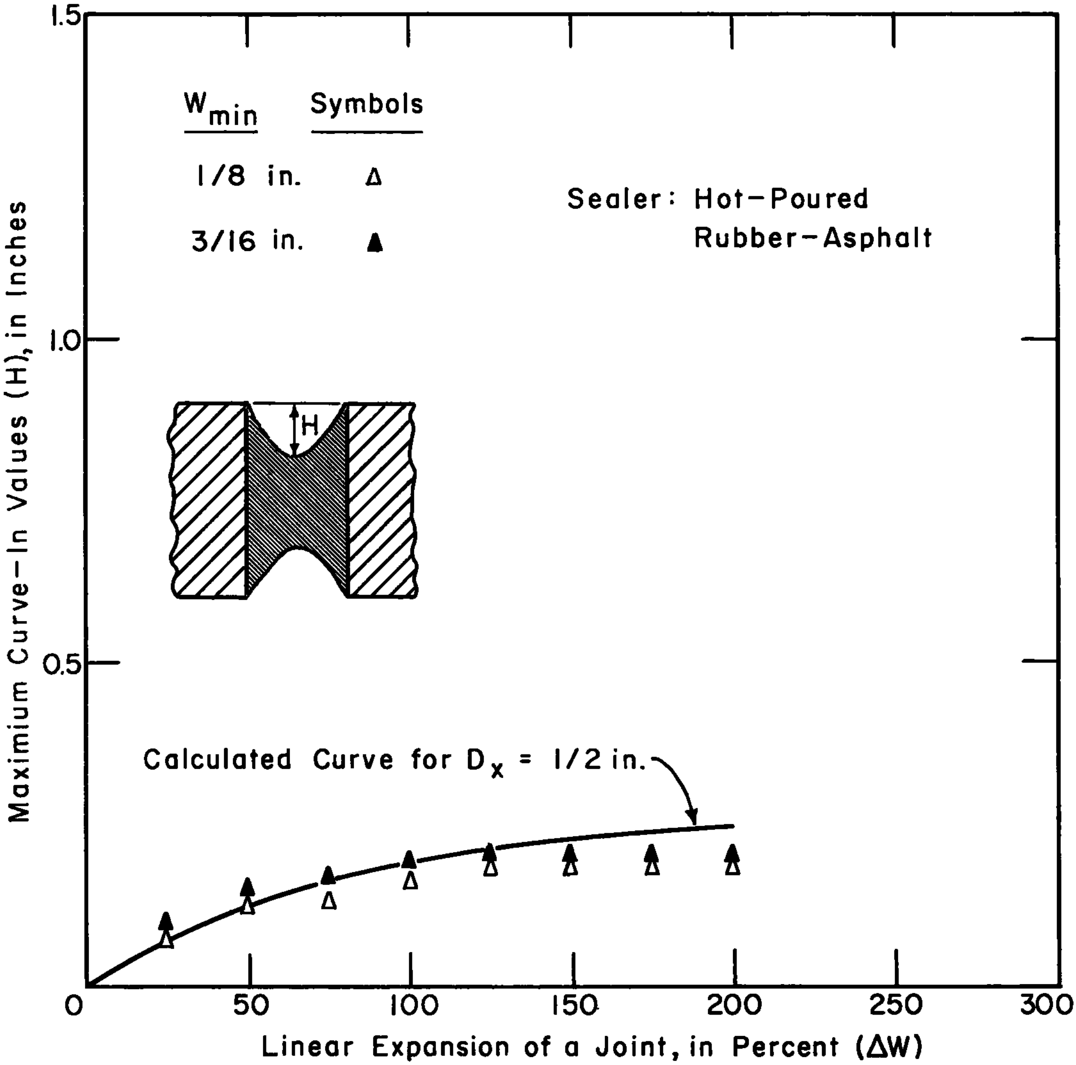

Figure 15. Comparison of calculated curve-in values (H) with those measured in the laboratory for $D_x = \frac{1}{2}$ in. and varied joint width (W_{min}).

with which the measurements obtained in the laboratory strain test are compared[4/] The mathematical equation for the curves is:

$$H = 3/4\ D_x \left(1 - \frac{100}{100{+}\Delta W}\right)$$

It must be pointed out that H is independent of W_{min} and will be identical for any minimum joint width (W_{min}) and one depth (D_x) at points of equal ΔW.

4/ The mathematical equation for the parabolic H curves in Figures 15 to 22 is: $H = 3/4\ D_x \left(1 - \frac{100}{W{+}100}\right)$ (derived in Appendix E). If the measured H values at different depths of seal (D_x) and various expansions (ΔW) satisfy this equation, the curve-in line has to approximate a parabola.

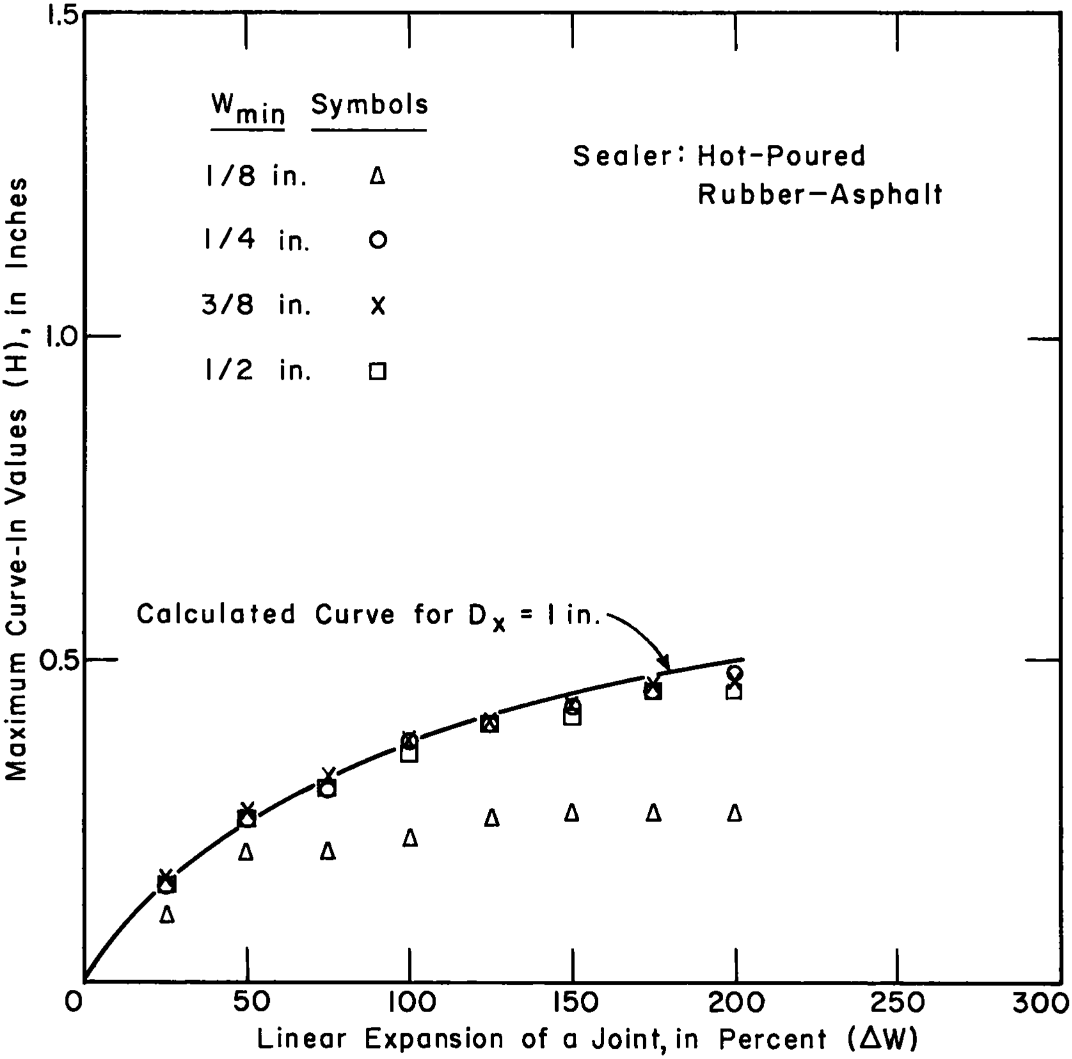

Figure 16. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 1 in. and varied joint width (W_{min}).

The hot-poured rubber-asphalt specimens were strained to the maximum theoretical limit which is 200 percent. The sealer in the $\frac{1}{2}$-in. deep specimens followed the calculated H value curve very well (see Fig. 15). It did not break at 200 percent extension but continued to stretch in a thin band without showing any signs of failure. When the depth of seal was increased to 1 in. (see Fig. 16) the narrow 1/8-in. specimens showed a marked deviation at about 75 percent of expansion with some visible indications of separations within the sealer. When the sealed depth of 2 in. was tested a similar departure from the basic curve was noted for the $\frac{1}{4}$-in. specimens while 3/8-in, and $\frac{1}{2}$-in. wide seals fell below the curve after about 100 percent expansion (see Fig. 17). Finally, when the compound was tested in 3-in. deep specimens, only the 1-in. wide seal (W_{min} = 1) followed the curve closely (see Fig. 18). Again inside separations

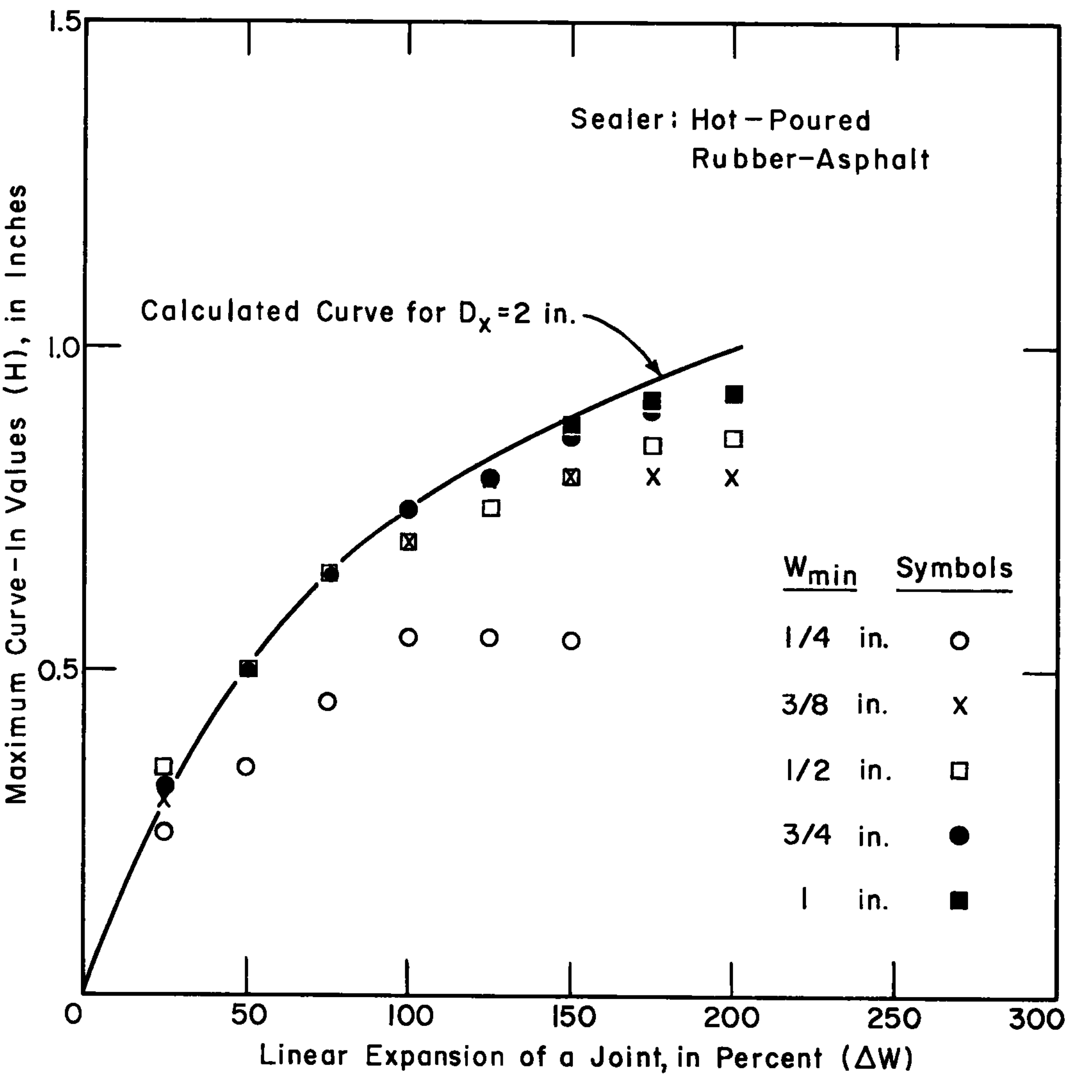

Figure 17. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 2 in. and varied joint width (W_{min}).

and even openings in the outside surfaces of the sealer were registered as soon as the H measurements dropped about 10 percent below those calculated.

The maximum curve-in value measurements for the cold-applied rubber polymer are summarized in Figures 19 to 22. The force required to pull this type of seal apart was considerably higher than that for the rubber-asphalt compound. Due to some limitations in the strain apparatus the specimens in these series were extended only by 100 percent. The trend of the actual measurements was very similar to the previously discussed rubber-asphalt results. Even the separations and openings in the sealer when the H values started to drop below the theoretical curve were of the same nature.

The results obtained on the two sealers indicate that the H measure-

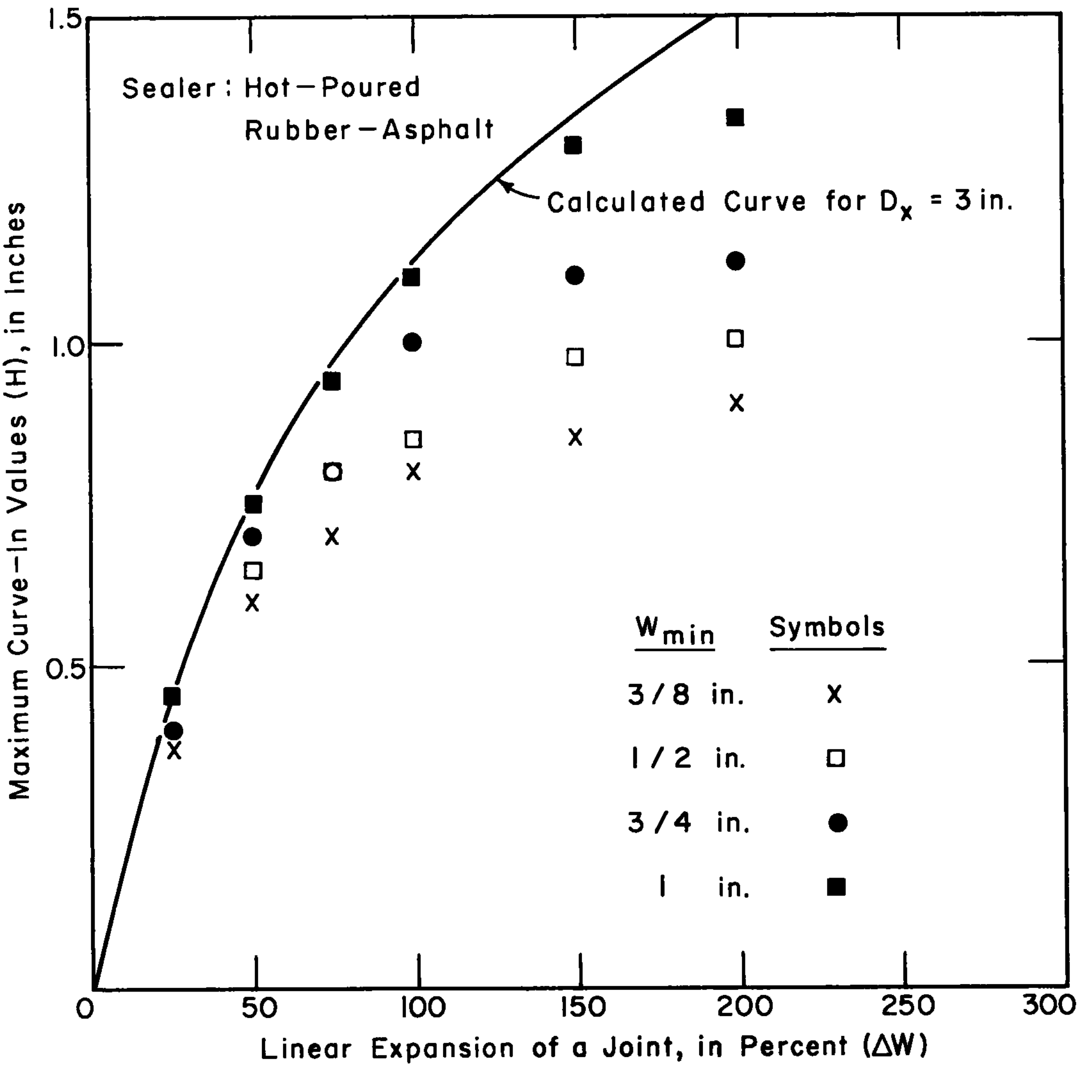

Figure 18. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 3 in. and varied joint width (W_{min}).

ments taken in the laboratory were comparable to the calculated ones, which in turn means that the curve-in line of the surface of the sealer closely approached a parabola[4]. The apparent deviations from the parabolic curvature occurred:

1. When the sealer was placed to a shallow depth and unreasonably large strains were applied (around 200 percent extension) (see Fig. 23).

2. When the seal lost homogeneity and started to form air spaces inside (see Fig. 24). This is much more likely to happen when a narrow and deeply sealed joint expands. Observations so far indicate that in case of homogeneous materials, as those used in the tests and under the conditions described, such air spaces form when the tangent to the parabola has an angle of 15 to 25 degrees to the vertical (see Figs. 24 and 25). Ap-

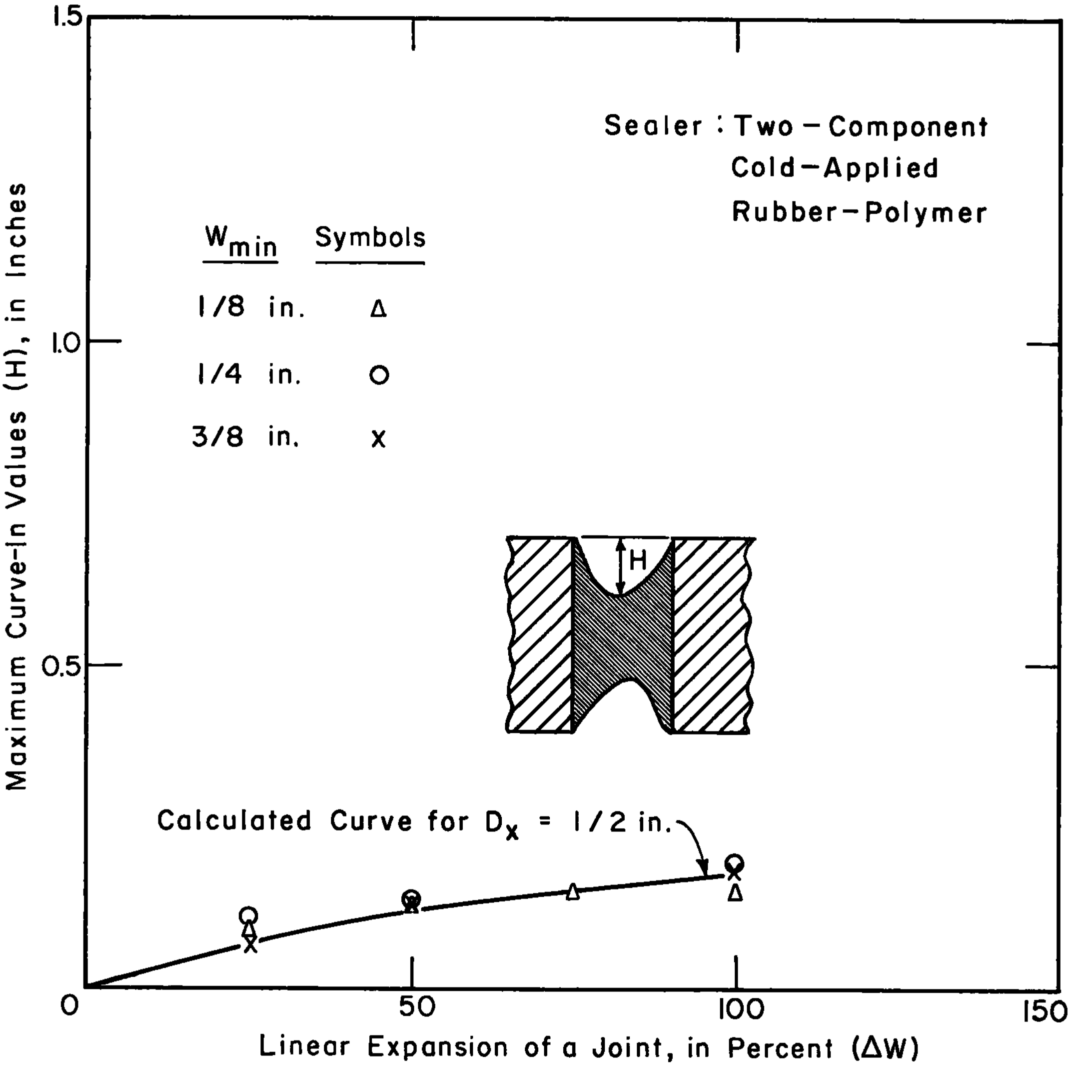

Figure 19. Comparison of calculated curve-in values (H) with those measured in the laboratory for $D_x = \frac{1}{2}$ in. and varied joint width (W_{min}).

parently this phenomenon is related to the magnitude of the shear and tension forces in the sealer along the joint walls.

Visual observations of the distribution of the strain along the curve-in surface of the sealer indicated that it is uniform at low percentages of extension but tends to vary slightly when the strains get high and the sealer has sagged deep into the opening (joint). For all practical purposes the assumption of a uniform strain along the surfaces of the sealer seems reasonable.

The amount of curve-in at the bottom of the specimen was also measured and was found to average out identical to the one on the top.

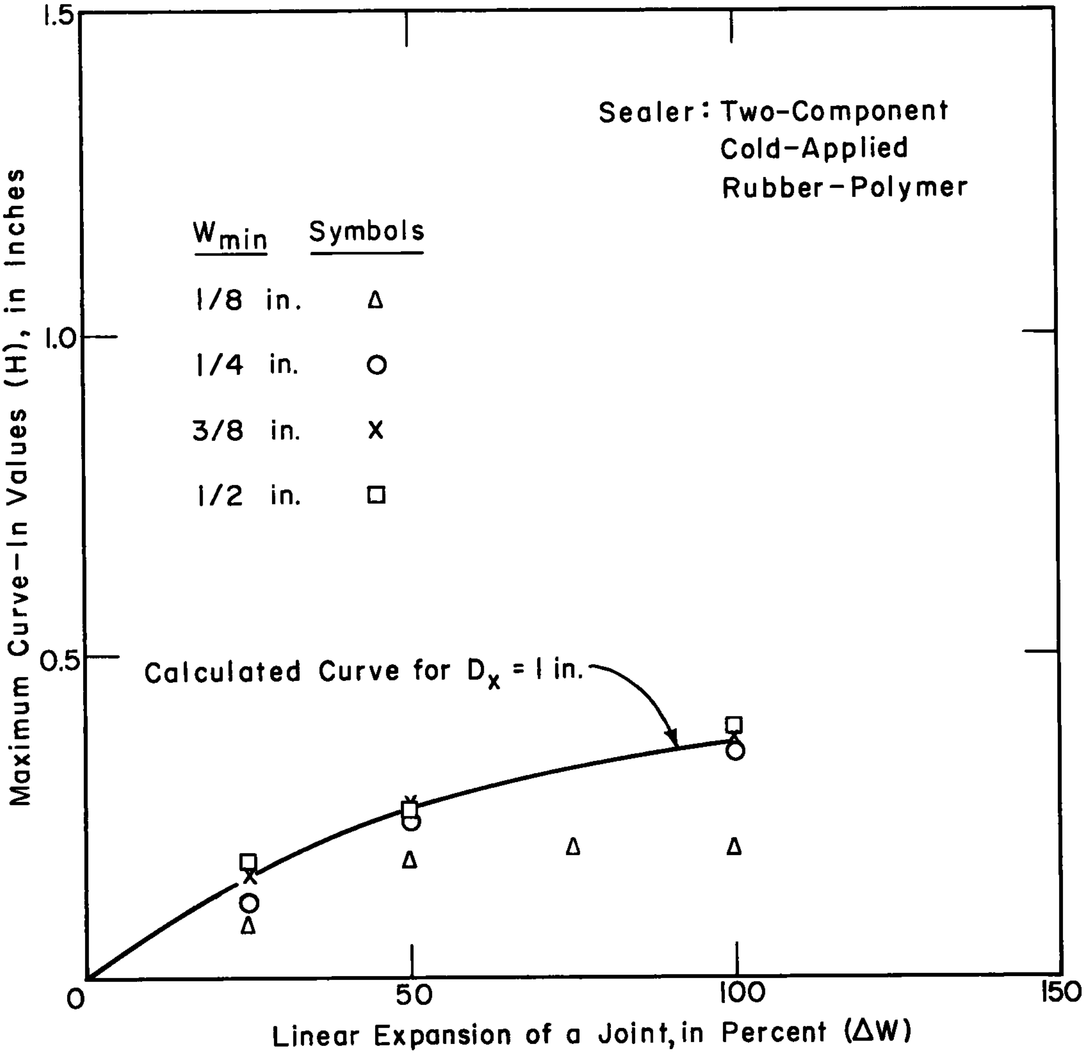

Figure 20. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 1 in. and varied joint width (W_{min}).

CONTEMPLATED PRACTICAL APPLICATION

Evaluation of Bond and Ductility

In order to design a seal, the properties of the sealing material have to be known, particularly the maximum strain (S_{max}) the sealer can endure. The present bond-ductility test does not test the sealer to failure5/. The strain pattern in the sealer during the four-hour extension period appears to be complex and different from what would be encountered in a road joint; due mainly to the small size of the specimens and the chance for the material to curve in from all four sides. Measurements and computations of the maximum strain in the sealer after the specified

5/ See Federal Specification SS-R-406C, Method 223.11.

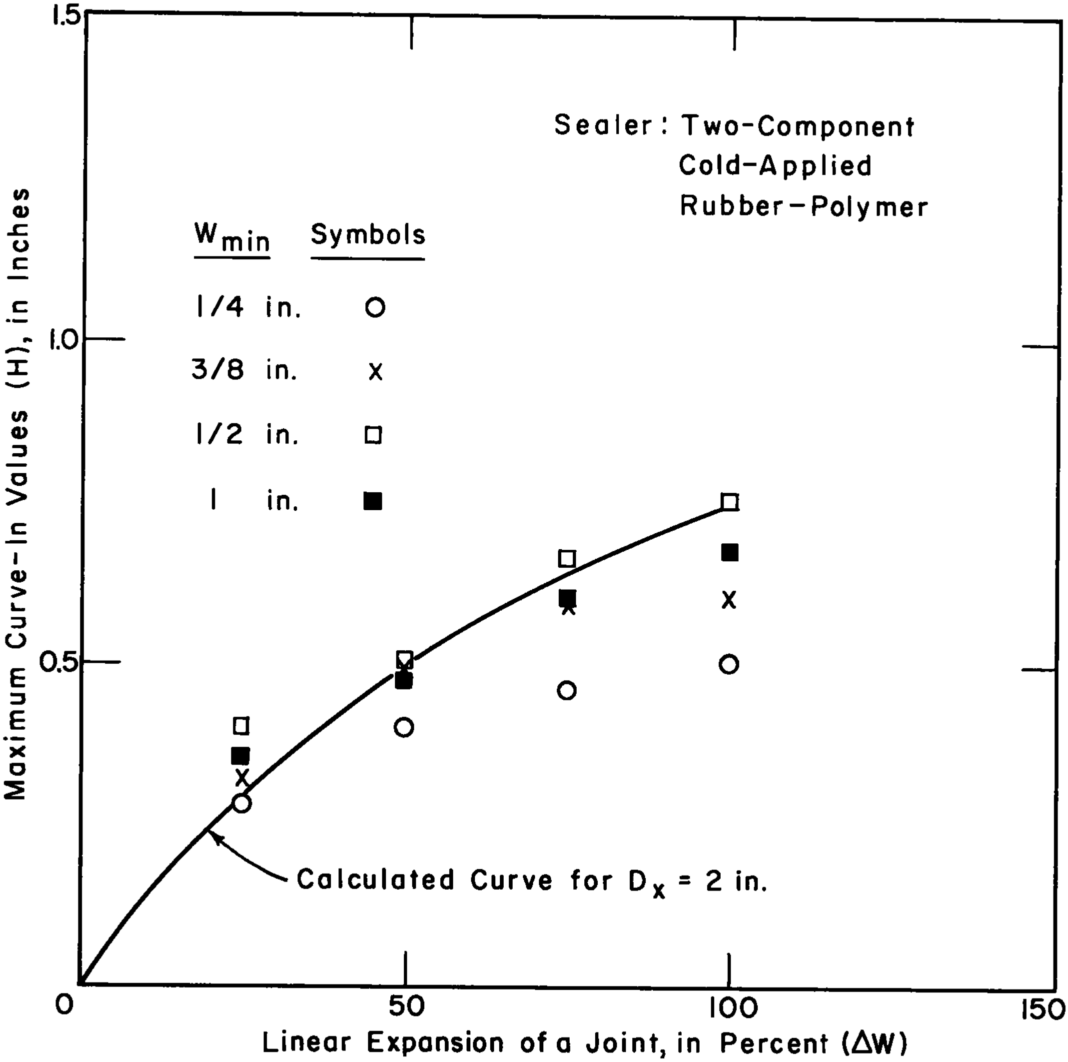

Figure 21. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 2 in. and varied joint width (W_{min}).

50 percent extension indicate that the strain is about 62 percent. Under present practice if the sealer meets this specification it is then used to seal any size joint which might induce much greater strains. If such a compound is placed in a $\frac{1}{4}$-in. joint, sealed to 2-in. depth and expanded 50 percent (1/8 in.), the maximum strain in the sealer will be 342 percent, or more than five times as much as it was tested for.

The best way to predict the performance of a sealer would be to test it in a joint similar to that in which it is going to serve. This is often impractical and would involve difficulties in the standardization of the test. If the maximum strains in the sealer can be correlated mathematically for different joint widths and depths, the test can still be standardized. In Appendix A of this paper it was attempted to outline

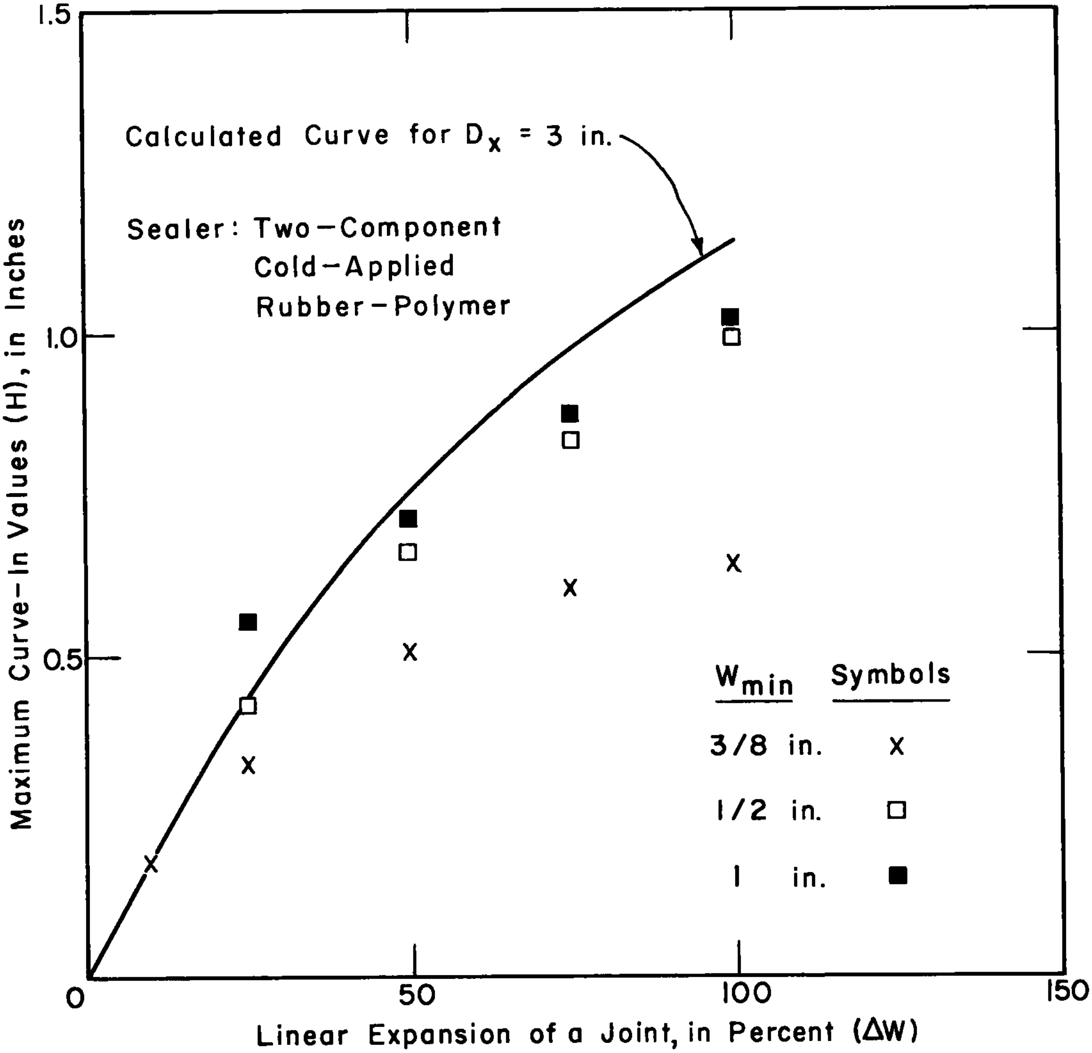

Figure 22. Comparison of calculated curve-in values (H) with those measured in the laboratory for D_x = 3 in. and varied joint width (W_{min}).

what might be a more realistic approach to the evaluation of the capabilities of different sealing materials. The new test would use longer (6 in.) test blocks, 1 in. deep and spaced ½ in. apart. The sealing material would be placed in the opening, cooled to 0 F and extended to failure in cohesion or bond. For the design of joint seals a safety factor of 2 would be applied; i.e. only one-half of the obtained failure strain value would be used in the actual design.

Actual Design

Once the strain capabilities are known, the necessary joint width and depth of seal can be determined for any known joint expansion. An outline of how this can be done is given in Appendix B.

Other Important Variables

It should be pointed out once more that this method of designing a seal for road joints is concerned primarily with the proper geometric relationships. Careless sealing techniques, insufficient adhesion, excessive shear at the joints and other influences might render a seal ineffective no matter how well it is proportioned.

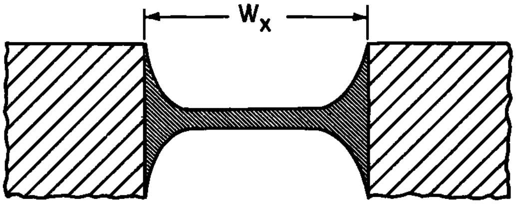

Figure 23. At joint expansion approaching 200 percent a sealer in a shallow joint might not follow a parabolic curve-in line.

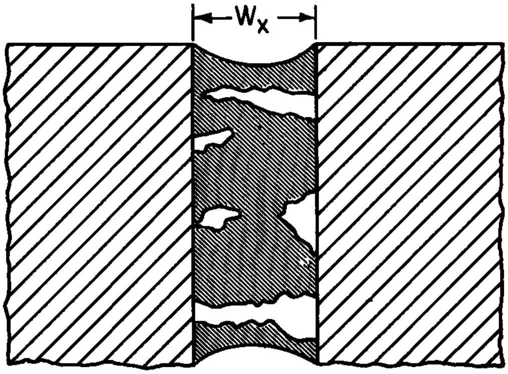

Figure 24. In most cases if a sealer does not follow the parabolic curve-in line an internal (cohesion) rupture is imminent.

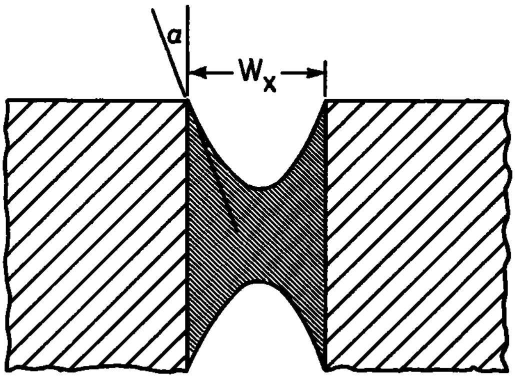

Figure 25. The tangent angle **a** was found to be 15 to 25 degrees at the time of most failures of deep seals.

CONCLUSIONS

This paper outlines a procedure for esti ating tension strains in a homogeneous liquid-type sealer used for sealing joints and cracks in pavements. The assumptions and theoretical calculations have been verified by laboratory test. The major conclusions from this study are:

1. Laboratory tests indicate that if a homogeneous liquid type sealer is placed in a rectangular joint and subjected to strain (expansion) the curve-in surface closely follows a parabolic curve (except under certain conditions discussed in "Laboratory Test Data").
2. Maximum strains in the sealer can be calculated by using parabolic equations and relationships.
3. The calculations show that for like conditions, the greater the minimum width of the joint, the less the sealer will be strained for the same percentage of joint opening.
4. The shallower the joint is sealed, the less the sealer will be strained when the joint opens, other conditions being the same.
5. Observations in the laboratory show that if a sealer does not follow the parabolic curve-in line closely and appears sound from the outside, inner cohesion separations and formation of air spaces are taking place.

6. The present bond-ductility test does not indicate the actual strain capabilities of a sealer.

7. A bond-ductility test in which the sealer is strained to failure should be a better way to evaluate the material.

RECOMMENDATIONS

Additional research is needed to broaden the scope of this basic theory and to further check its limitations.

1. A bond-ductility test for testing the sealer to failure needs to be standardized and perfected.
2. Performance of various types of joint sealer compounds should be studied in laboratory and field tests to determine agreement with the theory and to observe what is happening when the sealer does not follow the predicted strain pattern.
3. The influence of temperature on the maximum allowable strains for various sealers should be studied.
4. The strain and stress distribution at various stages of extension as well as the tangent angle (see Fig. 25) at the time of failure or departure from the parabolic curve-in line should be further investigated in a laboratory.
5. The optimum ratio of D_x/W_{min} should be studied for various compounds.
6. In addition, it is felt that research and data gathering are needed on the following subjects:

    a. Adhesion of sealer to joint walls.
    b. Influence of shear movements at the joints on the performance of the seal.
    c. Accumulation of joint movement data in various parts of the country.
    d. Development of a durability test for joint seals.

7. The final goal should be to define types and shapes of sealers the pavement engineer needs, so that the manufacturers can make them.

ACKNOWLEDGMENTS

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APPENDIX A

Outline of a Bond-Ductility Test for Evaluation of Sealers

Background

In January 1958, Kuenning[6] presented some experimental test data from a bond-ductility test on one hot-poured rubber-asphalt sealer. The basic outline for the current paper was ready at that time and it was encouraging to note that Kuenning's test values agreed with the author's theoretical calculations. Kuenning used what may be a more meaningful bond-ductility test for sealers. He tested his specimens to failure rather than using the usual 5-cycle, 50 percent extension method. He also used specially prepared longer test specimens to come closer to actual road joint conditions.

Outline of the Test Procedure

More direct research work is needed for giving a definite test procedure. This is only a projected example of thinking what such a test might look like as compared to the present test[7].

1. The test blocks could be longer, shallower, and the spacing between them should be decreased. For instance, some observations indicate that 6-in. long, 1-in. deep specimens spaced $\frac{1}{2}$ in. apart to receive the sealer are a promising combination.

2. The molded specimen could be extended in a suitable machine at a low temperature until the seal fails. Failures at the very ends of the specimens should be neglected. This could be used as an indication of seal performance.

3. The preparation of the bond surfaces of the blocks should be brought closer to actual pavement conditions than it is in the present test. It might well be wise to introduce moisture into the blocks before the sealer is poured.

4. Otherwise, the specimen preparation and testing features could be similar to the present test[7].

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[6] Kuenning, W. H., "Laboratory Tests of Sealers for Sawed Joints." HRB Bull. 211 (1959).

[7] Federal Specification SS-R-406C, Method 223.11.

APPENDIX B

Probable Joint Seal Design Procedure

Step 1

Extend the sealer in a bond-ductility test until it fails[8]. The test blocks should be made and arranged so that a $\frac{1}{2}$-in. wide ($W_{min} = \frac{1}{2}$), 1-in. deep and 6-in. long gap can be filled with the sealer. Note the block distance (W_f) at the time of failure.

Step 2

Compute the percent of expansion at the time of failure

$$\Delta W = \frac{W_f - \frac{1}{2}}{\frac{1}{2}} \times 100$$

and enter the value at the bottom of Figure 26. From this point intersect the curve and note on the left side the maximum allowable strain (S_{max}) for the sealer. Factor of safety (SF = 2) is already included in the left side figures.

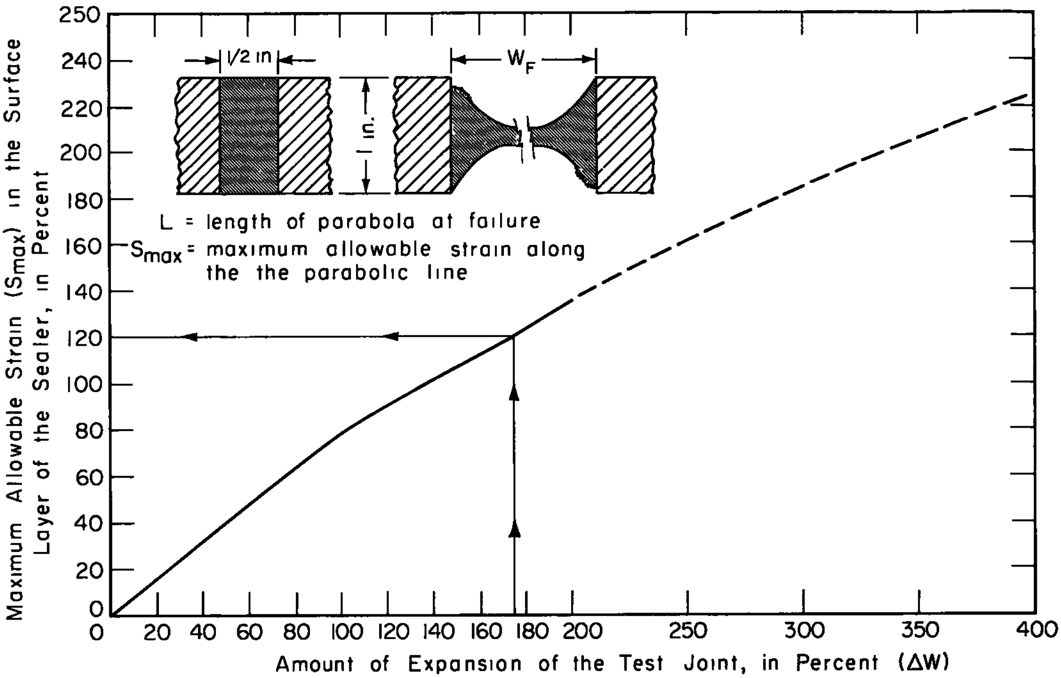

Figure 26. Allowable strains in the sealer, as determined by a bond-ductility test in a laboratory.

Step 3

Assume desirable slab length and estimate from field measurements on other pavements the maximum joint width variation ($W_{max} - W_{min}$). If such

8/ An outline of the procedure is given in Appendix A.

data are not available, assume a reasonable coefficient of expansion for the concrete[9] and, taking the maximum temperature differential for a year, calculate the maximum change in joint opening ($W_{max} - W_{min}$).

Step 4

Assume desirable joint width (W_{min}) and calculate the maximum joint expansion (ΔW) in percent, using the value obtained in Step 3.

$$\Delta W = \frac{W_{max} - W_{min}}{W_{min}} \times 100$$

Step 5

Take the maximum joint expansion value (ΔW) from Step 4 and enter from the bottom of Figure 27. Then using the maximum allowable strain (S_{max}) found in Step 2 enter Figure 27 from the left side. Where the two lines intersect the D_{max}/W_{min} ratio will be indicated. Using the in Step 4 assumed W_{min} value, D_{max} can be calculated.

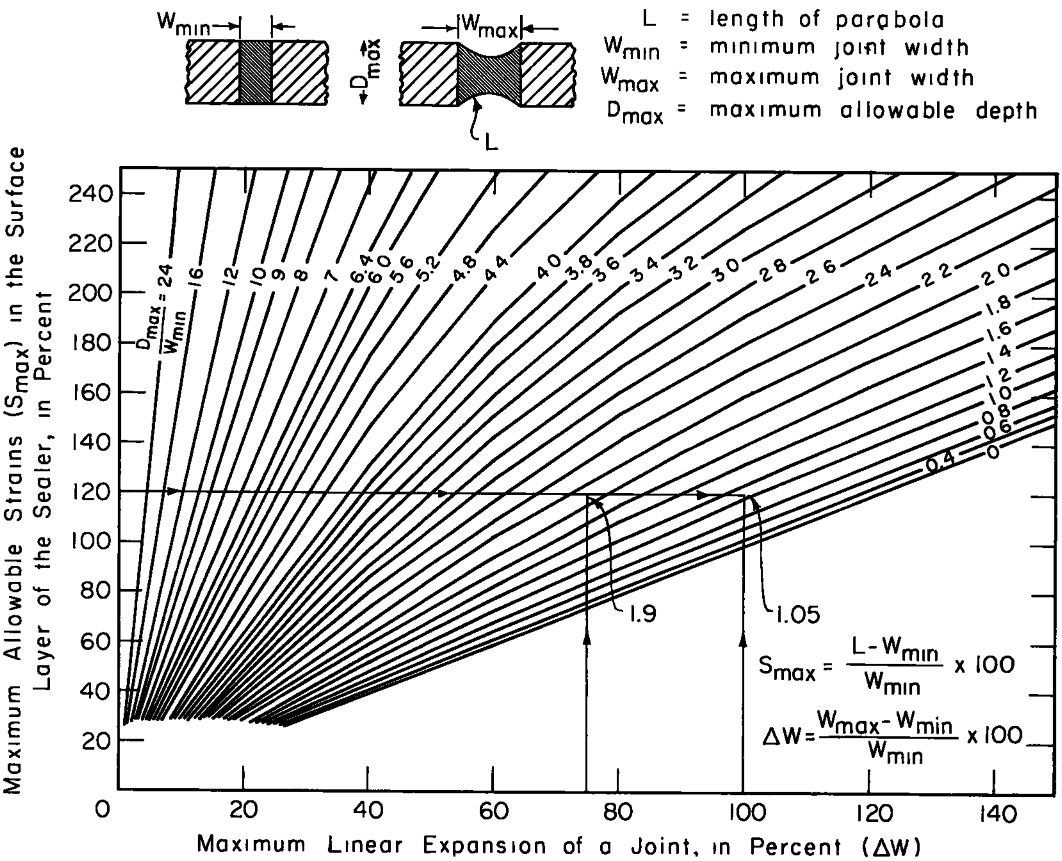

Figure 27. Maximum allowable filling depth for a known sealer for a given joint width and expansion.

[9] Values of 4.0, 5.0 and 6.0 x 10^{-6} have been suggested in the literature.

Step 6

The found depth value (D_{max}) should be equal to greater than the minimum joint width (W_{min}) but never less than ½ in.10/. If this is not so, take smaller slab length or wider minimum joint width and repeat Steps 3, 4 and 5.

Step 7

Finally, check by Figure 28 whether the sealer does not curve in too deep for the seal as determined in Step 5. If H exceeds ½ in.10/, foreign matter might accumulate on the top of the sealer.

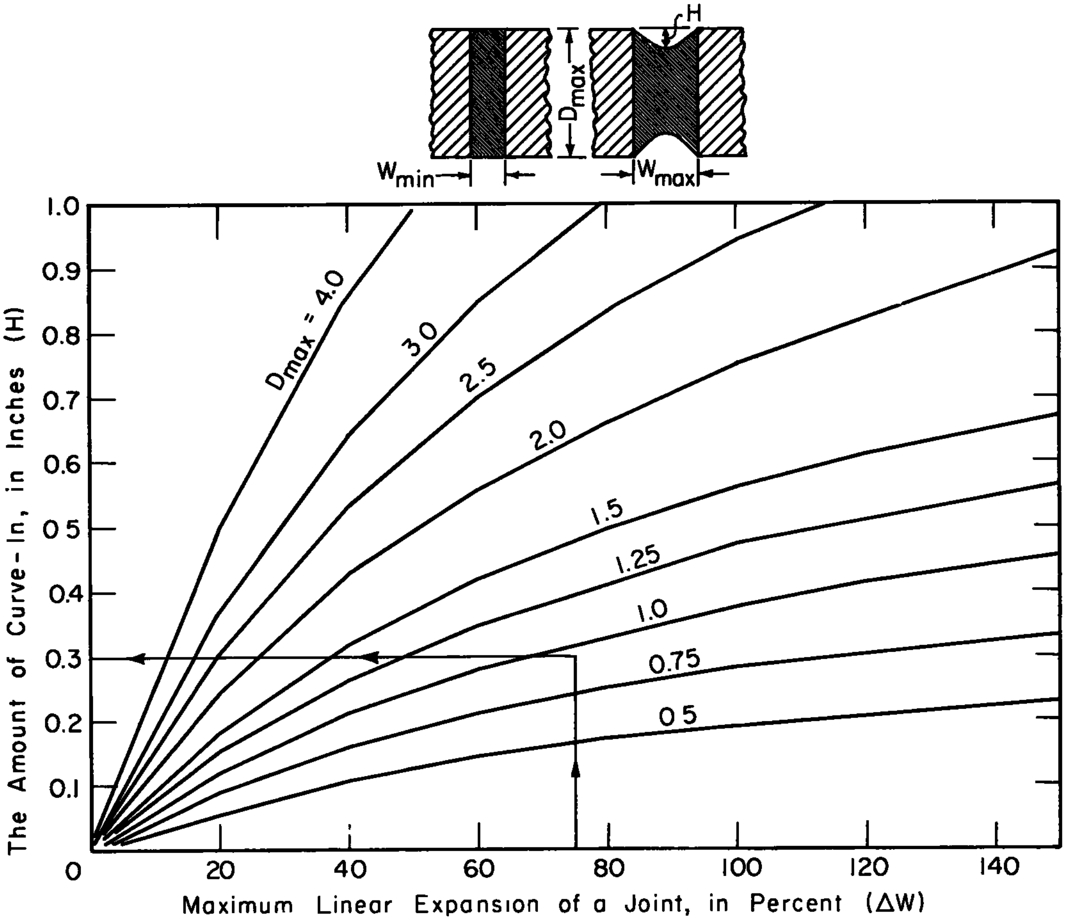

Figure 28. Maximum curve-in (H) values.

EXAMPLE

Step 1

A hot-poured rubber-asphalt sealer was tested in the laboratory in a ½-in. opening. It failed at 1.37 in. (W_f = 1.37) or after 0.87-in. extension.

10/ See discussion in Appendix C.

Step 2

The percent of test joint expansion at failure was 0.87:0.5 - 174 percent. Entering this value at the bottom of Figure 26 and intersecting the line, 120 percent for maximum allowable strain in the sealer is obtained.

Step 3

State "X" specifies contraction joints only, spaced 75 ft apart. Measured joint movements at numerous places of similar pavements indicate that the maximum joint expansion is about 0.375 in.

The same State "X" does not have field measurements to rely upon. They know that the difference between maximum and minimum yearly temperatures is about 105 F. They estimate the coefficient of expansion for the concrete to be 4.0×10^{-6}. Thus the maximum joint expansion can be calculated: $75 \times 12 \times 105 \times 4.0 \times 10^{-6} = 0.378$ in.

Step 4

They would like to have as narrow joints as possible, but they realize that for 75-ft spacing 1/8- and $\frac{1}{4}$-in. joints might not be sufficient. They assume 3/8 in. ($W_{min} = 3/8$) for the first trial. This means that the maximum joint expansion is 3/8:3/8 or 100 percent ($\Delta W = 100$).

Step 5

The sealed depth design curves are found in Figure 27. Entering 100 percent at the bottom and 120 percent from the left side, a point of intersection is obtained. It happens to be at a point where $D_{max}/W_{min} = 1.05$ or $D_{max} = 1.05/0.375 = 0.4$ in. This is slightly below the minimum specified 0.5 in. and maybe a $\frac{1}{2}$-in. joint would be more desirable in this case[11].

Step 6

A $\frac{1}{2}$-in. joint (after going through Steps 4 and 5 again) can have maximum depth of 0.95 in. which is all right ($\Delta W = 75$; $D_{max} = 0.95$).

Step 7

The $\frac{1}{2}$-in. wide and 0.95-in. deep seal will curve in about 0.3 in. at $\Delta W = 75$ according to Figure 28, and is acceptable.

11/ Reduction of slab length would permit keeping the 3/8-in. joint.

APPENDIX C

Discussion of Proposed Design Procedure

Step 1 describes the physical dimensions of the bond-ductility specimen. The $\frac{1}{2}$-in. width and 1-in. depth were suggested because this combination so far gave the most uniform and reliable strain values in laboratory investigations. The 6-in. length appeared to be the minimum needed to eliminate the influence of the specimen ends on the strain pattern in the center of the seal.

Step 2 tells how to use Figure 26. The curve for this figure is taken from Figure 12 ($W_{min} = \frac{1}{2}$, and $D_x = 1$ in.) using only one-half of the calculated strain values (safety factor of two). It was extended for possible failures beyond the 200 percent limit (ΔW) where the validity of the parabolic curve ends. This part of the curve, therefore, is only an approximation and should have significance only in the laboratory test, to the results of which a safety factor of two is applied. Kuenning has shown that the maximum allowable strain (S_{max}) for a certain hot-poured rubber-asphalt sealer was around 110 percent (SF = 2 is included).

Step 3 and Step 4 are self-explanatory.

Step 5 describes how to use Figure 27 which is basically identical to Figure 14. It shows the correlation between joint width, depth of seal, joint expansion, and the maximum strain in the sealer. Even though the chart permits strain estimates for extensions up to 150 percent, it is questionable whether in actual practice this can ever be reached. Extreme expansions might affect the ability of the sealer to recover when the joint closes.

Step 6 calls for $\frac{1}{2}$-in. minimum sealed depth. This value was assumed to be the shallowest seal that can be placed under field conditions.

Step 7 calls for a maximum allowable curve-in of $\frac{1}{2}$ in. This was considered the maximum depth at which the surface of the sealer could be kept clean through the suction action of passing traffic.

Finally, it should be emphasized that more thought and data are needed to check this seal design procedure and the assumptions.

APPENDIX D

Test Road to Check Joint Seal Design Theory

The basic outline of the joint seal design theory was presented at the last meeting of Committee D-3 of the Highway Research Board. It was considered useful to test on the road various combinations of joint width and depth of seal. Through cooperation of the State of New York and Committee D-3 some 140 transverse joints were sealed in September 1958. The joint widths were $\frac{1}{4}$, 3/8 and $\frac{1}{2}$ in. The depth of the sealer in the joints was $\frac{1}{2}$, 1 and 2 in. A hot-poured rubber-asphalt sealer was used to fill the joints. The joint expansion and the curve-in depths will be measured periodically and compared with the predicted theoretical values.

APPENDIX E

Miscellaneous Equations

A. <u>Equation for Curves in Figure 14</u> (also Figures 6 to 13 and Figure 27 in Appendix B)

$A_p = \frac{2}{3} H W_x$ (parabolic area) and

$H = \frac{3}{2} \frac{A_p}{W_x}$ but $A_p = \frac{1}{2} (W_x - W_{min}) D_x$, therefore

$$H = \frac{3}{2} \frac{\frac{1}{2} (W_x - W_{min}) D_x}{W_x} = \frac{3}{4} \frac{D_x}{W_x} (W_x - W_{min})$$

$$L = \frac{1}{2} \sqrt{W_x^2 + 16 H^2} + \frac{W_x^2}{8H} \ln \frac{4H + \sqrt{W_x^2 + 16 H^2}}{W_x}$$

Substituting H

$$L = \frac{1}{2} \sqrt{W_x^2 + 9 \frac{D_x^2}{W_x^2} (W_x - W_{min})^2} + \frac{W_x^2}{6 \frac{D_x}{W_x} (W_x - W_{min})} \ln \frac{3 \frac{D_x}{W_x} (W_x - W_{min}) + \sqrt{W_x^2 + 9 \frac{D_x^2}{W_x^2} (W_x - W_{min})^2}}{W_x}$$

$$= \frac{1}{2W_x} \sqrt{W_x^4 + 9 D_x^2 (W_x - W_{min})^2} + \frac{1}{6} \frac{W_x^3}{D_x (W_x - W_{min})} \ln \frac{1}{W_x} \left(3 \frac{D_x}{W_x} (W_x - W_{min}) + \frac{1}{W_x} \sqrt{W_x^4 + 9 D_x^2 (W_x - W_{min})^2} \right)$$

$$S_{max} = \frac{L - W_{min}}{W_{min}} \times 100;$$

$$S_{max} = \left[\left[\frac{\frac{1}{2W_x} \sqrt{W_x^4 + 9 D_x^2 (W_x - W_{min})^2} + \frac{1}{6} \frac{W_x^3}{D_x} \frac{1}{W_x - W_{min}} \ln \frac{1}{W_x^2} \left(3 D_x (W_x - W_{min}) + \sqrt{W_x^4 + 9 D_x^2 (W_x - W_{min})^2} \right)}{W_{min}} \right] - W_{min} \right] \times 100$$

B. Theoretical Joint Expansion Limit for a Sealer in any joint is 200 Percent.

If $A_s = (W_{min} \times D_x)$ at 0 percent expansion (ΔW) the cross-sectional area of the joint at 200 percent expansion will be:

$$A_s + 2A_p = 3\,(W_{min} \times D_x) \text{ or}$$

$$2A_p = 2\,(W_{min} \times D_x) \text{ and } A_p = (W_{min} \times D_x)$$

$$\text{but } A_p = \frac{2}{3} H W_x = (W_{min} \times D_x) \text{ from which}$$

$$H = \frac{3}{2}\,\frac{W_{min}\,D_x}{W_x} \text{ at 200 percent expansion } W_x = 3W_{min}$$

$$\text{or } H = \frac{3}{2}\,\frac{W_{min}\,D_x}{3W_{min}} = \frac{1}{2}\,D_x$$

or the sealer has to break (theoretically) in the middle at $\Delta W = 200$

C. Equation for Curves in Figures 15 to 22.

$$A_p = \frac{1}{2}\,(W_x - W_{min})\,D_x$$

$$H = \frac{3}{2}\,\frac{A_p}{W_x} = \frac{3}{2}\cdot\frac{1}{2}\,\frac{(W_x - W_{min})\,D_x}{W_x} = \frac{3}{4}\,D_x\left(1 - \frac{W_{min}}{W_x}\right) \qquad (1)$$

$$\text{as } \Delta W = \left(\frac{W_x - W_{min}}{W_{min}}\right) \times 100 = 100\,\frac{W_x}{W_{min}} - 100$$

$$\text{or } \Delta W + 100 = 100\,\frac{W_x}{W_{min}}$$

$$\text{or } \frac{1}{\Delta W + 100} = \frac{1}{100}\,\frac{W_{min}}{W_x}$$

$$\text{or } \frac{W_{min}}{W_x} = \frac{100}{\Delta W + 100}$$

which substituted in (1) gives $H = \frac{3}{4} D_x \left(1 - \frac{100}{\Delta W + 100}\right)$