A STUDY OF FLEXIBLE PAVEMENT CRACK DYNAMICS AND SEALANTS

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A STUDY OF FLEXIBLE PAVEMENT CRACK

DYNAMICS AND SEALANTS

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CHAPTER I

INTRODUCTION

Statement of Problem

Flexible pavements comprise a major portion of Oklahoma's highway system and cracking of these pavements is widespread throughout the state. Many factors, such as excessive and repeated load deflections, thermal expansion and contraction, moisture changes, consolidation, freeze-thaw action, and brittleness of the pavement may contribute to or be directly responsible for the occurrence of cracks.

At the time of occurrence, cracking has relatively little effect on pavement performance and riding quality. However, further deterioration of the pavement surface usually follows in the form of additional cracking, spalling, permanent deformation and faulting. Consequently, the desired pavement performance and serviceability are adversely affected and then reduces the useful life of the pavement structure.

Modification of current asphalt mix design procedures and pavement construction practices will be necessary to help prevent flexible pavement cracking. Cracks in existing pavements should be satisfactorily sealed to prevent or at least postpone the development of secondary deterioration and the need for more elaborate and costly repair.

A wide variety of sealing materials has been used in many states with different degrees of success. These include asphalt cements, emulsions, cutbacks and asphalt cements plus additives such as rubber, synthetic polymers, epoxys, and sulphur in various proportions. There is an apparent need to develop practical laboratory testing procedures that can be utilized to evaluate the expected performance of different crack sealing materials under actual field conditions.

Method and Scope of Study

The primary objective of this research was to evaluate and/or develop laboratory test procedures for flexible pavement crack sealant materials that would reasonably predict their field performance. After establishing the desirable characteristics and properties of an effective long lasting crack sealing material, these tests can be used to ascertain whether a prospective sealant conforms to the selected criteria.

A secondary objective was to conduct a field study of crack movements and behavior under varying load and temperature conditions. This study was considered necessary to help establish reasonable criteria for sealant performance based on average conditions in Oklahoma pavements.

The first phase of the study was devoted to concern about conducting a complete review of literature on the materials and methods of installation used in sealing flexible pavement cracks. Conducting an in-state and surrounding state survey to determine the effectiveness of currently used sealing materials and practices was a part of this phase.

The second phase of the proposed research involved a crack dynamics study. The purpose of this study was to obtain measurements of the relative horizontal and vertical movements of adjacent pavement sections at transverse cracks in the roadway surface.

This study was limited to transverse type cracks, since the relative movements of the adjacent pavement sections were expected to be greater than for other types of cracks. Measurements of the width of crack opening and the ambient temperatures at several cracked sections of Oklahoma highway were made at monthly intervals over a period of one year. Vertical deflections at the selected cracks under a loaded dump truck were measured at three month intervals during the same period. The influence of certain environmental factors (pavement temperature, geological type of subgrade material, and spacing of adjacent cracks) on the relative horizontal and vertical movements at these test sites cracks was determined.

Standard or tentative standard ASTM tests have been developed for rigid pavement crack and joint sealing materials. Due to differences in the type of sealants and performance requirements, many of these tests are not directly applicable to flexible pavement sealers. However, a group of tests based on these standard procedures were selected and applied with minor modifications to the type and grade of materials used for sealing asphalt pavement cracks in Oklahoma. These tests were selected to evaluate both performance characteristics, i.e., adhesion and ductility at low temperature and compatibility with the pavement binder, and certain physical and rhealogical properties, i.e., consistency, flow, resilience and shrinkage, of the asphalt sealing materials.

Two aspects were considered in evaluating the results of this series of laboratory tests. First, an attempt was made to assign significance to the respective tests with regard to their value as an indicator of either material quality or expected field performance of a sealant. Secondly, the asphalt materials used in the tests were appraised as to their effectiveness as crack sealers. However, the true criterion, in this case, is how well a sealant performs under actual field conditions.

This will be true until a correlation between laboratory test results and field performance has been established.

In order to establish this correlation and to determine the most effective application procedures for flexible pavement crack sealants, a field test program was planned. An experimental design for this proposed program has been included.

CHAPTER II

LITERATURE SURVEY

Sealants

The problem of sealing cracks in flexible pavements is, perhaps, more formidable than that of sealing joints in rigid pavements. Flexible pavement cracks have no regular or uniform interfacial space in which preformed gasket material can be placed, the irregular and often times contaminated (dust and moisture) interfacial surfaces prevent good adherence of cold-poured elastomeric type sealants, and there is the possibility of lack of compatibility between the sealant material and the asphalt binder in the pavement.

The materials currently being used for sealing cracks in flexible pavements can be separated into two broad categories, hot-poured sealants and cold-poured materials. An investigation conducted by Cook (1) showed that the hot-poured materials were used for this purpose more frequently.

Hot-Poured Materials

Hot-poured sealants are either straight-run asphalt cements or asphalt cements that have been modified by the addition of mineral fillers and/or rubber (1) (2) (3) (4) (5). The use of paving-grade asphalt cements seems to be limited to certain types and widths of cracks (4), e.g., in the case of very narrow crack openings, these asphalts tend to bridge over the crack and do not penetrate deep enough to provide an effective seal.

It has been reported that the addition of rubber improves the flexibility, ductility, adhesion and cohesion properties of asphalt cement (6) (7). The beneficial aspects of using rubberized-asphalt, containing 20 to 35 percent rubber by weight, as a crack sealing material have been demonstrated by many investigators (1) (3) (5) (8) (9) (10). In some reports, the rubber additive used was ground recycled tire rubber and this material may also have both economical and ecological advantages in view of the rising cost of asphalt cement.

Sulphur has also been used as an additive to improve the resilience of asphalt cement used as a joint filler. Also, many kinds of pulverized mineral fillers, e.g., talc, limestone and silica, have been used to harden or inverse the viscosity of asphalt cements (5).

Cold-Poured Materials

Cold-poured sealants include liquid asphalt materials such as cutbacks, standard emulsions, and rubber-asphalt emulsions (1) (2) (4) (6). Apparently, little or no use of cold-poured elastomeric materials for sealing flexible pavement cracks has been reported (1). Most of the liquid asphalt products that have been used for sealing cracks are included in the following list recommended by the Asphalt Institute (4):

Cutbacks......................		RC-70
Emulsions.........	(Anionic)...	RS-1
	(Anionic)...	SS-1, in slurry mix
	(Anionic)...	SS-1h, in slurry mix

Emulsions.........(Cationic)... CRS-2
(Cationic)... CSS-1, in slurry mix
(Cationic)... CSS-ih, in slurry mix

Laboratory Investigations of Sealants

Tons (11) summarized the major factors influencing the performance of a sealant as (1) the characteristics of the crack to be sealed, (2) properties of the sealant to be used, (3) properties and conditions of the sealant-crack interface, (4) quality of workmanship (related to application of the sealant), and (5) types of service to which the sealed crack is subjected. Under various field conditions the sealants may fail in adhesion, cohesion, extrusion, or a combination of these three types of failures (see Figure 1).

Adhesion failure is simply a loss of bond between the sealant and the crack wall under a tensile load. This happens during contraction of the pavement when the sealant builds up tensile stresses at the bond interfaces and it has no inherent ability for stress relaxation (11). Such sealants may also cause tensile failure (parallel cracking) of the surfacing if the bond strength exceeds the tensile strength of the bituminous concrete adjacent to the sealed crack. Adhesion failure was reported as the type most frequently observed under field conditions despite the fact that the sealants showed no signs of adhesion weakness in laboratory tests (2) (11).

Cohensive failure is a tearing or pulling apart of the sealant material and is a manifestation of a weakness of the forces binding together the molecules of the material. This failure also occurs during contraction of the pavement and is caused by stresses that exceed the

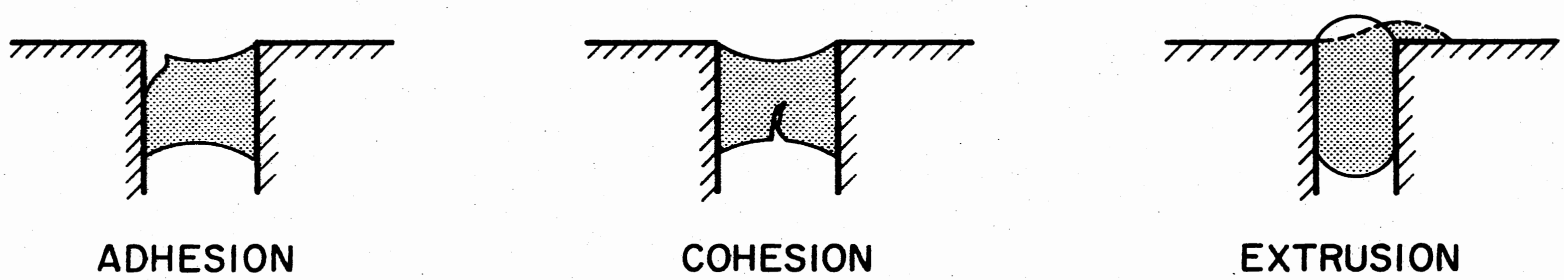


Figure 1. Types of Crack Sealant Failure

inherent tensile strength of the sealant. Observation of sealed crack test sections indicated that most materials that successfully passed laboratory tests designed to check this characteristic showed little or no cohesion type failure in the field (2).

Extrusion failure occurs during hot weather as the pavement expands and the sealant is compressed. A portion of the sealant material is extruded above the pavement surface and, under the action of vehicle wheels, is flooded or flattened onto the adjacent pavement surface. The flattened portion of the material cannot recover and no longer serves its intended function.

Based on the aforementioned factors affecting sealant performance and the respective types of sealant failure, some idea as to the properties and characteristics of a good sealant can be obtained. Tons (12, p. 20) outlined what he called "the established criteria for a satisfactory crack sealer" as follows:

1. The sealer should possess a good adhesion property that will enable it to adhere firmly to the cracked surfaces to seal it effectively under any conditions.

2. The sealer should withstand repeated stretching and compression over long periods, i.e., it should have good cohesion characteristics.

3. The sealer should neither flow out of the crack nor change its properties when exposed to hot weather.

4. The sealer should not shrink excessively due to cooling or evaporation of solvents so as to eliminate the need for repeated pouring.

5. The sealer should not extrude or become tacky on its exposed surface during high summer temperatures.

6. The sealant should not react with asphalt, salt, oil, etc.

7. The sealant material should be durable and should neither harden nor soften with age.

The ASTM tentative specification, D 3405-75T (13), for hot-poured crack sealant materials stipulates almost the same requirements and lists an additional one pertaining to compatibility of the sealant with the asphalt binder in the pavement. That is, there should be no formation of an oily exudate at the interface between the sealant and the asphalt concrete nor any softening or other deleterious effects from the sealant.

Selected Laboratory Tests

Bond-Ductility Test

This appears to be a basic test used by many investigators (1) (12) (13) (14) (15) (16) (17) to evaluate a sealant material as to its bond or adherence to the cracked surfaces and to its stretchability or ductility at low temperatures. Essentially, the test consists of pouring sealants between spaced specimen blocks and then pulling the blocks apart at a specified rate on an extension machine. The temperature and amount of extension of the sealant are controlled. After a certain amount of extension is reached, the test samples are recompressed to their initial width at lab temperature and this constitutes a cycle. Table I lists the major features of bond-ductility tests used by several investigators and the ASTM tentative test procedure. Cook (1) has described a number of extension machines developed for this type of test by various agencies.

In this type of test, the sealing material, because of its limited

TABLE I

MAJOR FEATURES OF BOND-DUCTILITY TESTS USED BY INVESTIGATORS AND ASTM

Test Features	Agency or Investigators		
	ASTM. D3407-75. (13)	Egon Tons. (12)	William Kuenning. (16)
Block Material Used	Mortar Blocks	Bituminous concrete cut from an old resurfacing	Concrete Blocks
Block Dimensions (in.)	1 x 2 x 3	2½ x 2½ x 2½	2½ x 4 x 8
Initial Block Spacing (in.)	1/2	1/8 and 1/2	1/8, 1/4, 3/8 and 1/2
Final Block Spacing (in.)	a. 3/4 b. 1	3/8	--
Rate of Extension (in./hr.)	1/8	1/8	1/32
Extension Percentage (%)	a. 50 b. 100	300	Vary from 60 to 160
Extension Temperature (°F)	a. -20 b. 0	5	Vary from 0 to 73
Recompression	Specimens warmed to room temperature & compressed to initial width by placing one block over the other.	Specimens warmed to 80°F for two hours & compressed to initial width by hand at rate of 0.1 in./minute.	--
Number of Cycles	3	5	Until failure
Failure Criteria	Development of crack, separation, or other opening in the sealer or between the sealer and the block during the test.	1. Separation at any place of more than 1/4 in. deep. 2. Opening of more than 1/2 in. at any direction in the sealing material. 3. Opening of more than 1/8 in. in the exposed surface connected with voids inside specimen.	Cohesion or adhesion failure.
General Description of Extension Machine	An extension machine that can expand 1/2 in., at a uniform rate of 1/8 in./hr., suitable for testing three specimens simultaneously. Requires environmental chamber	Consisted essentially of two screws, rotated by an electric motor. Uniform stretching rate of 1/8 in./hr. Capable of testing two specimens at the same time. Requires environmental chamber.	Built in PCA laboratories. Rate of stretching = 1/32 in./hr. Mounted on casters for ease of transfer. Requires environmental chamber.

dimensions, accommodates to the stretching action by becoming concave on all four of its exposed surfaces (14) (15). In an actual crack, the sealer becomes concave only on its top and cottom surfaces due to its greater length. Thus, any given amount of crack opening will impose a greater strain on the sealing material than the same amount of extension of a laboratory specimen. This problem was realized by a number of investigators (1) (12) (14) (15) (17) (18) and they recommended the use of fairly long test specimens. Cook (18) determined that a six inch specimen length was probably the optimum based on reducing the amount of error between field and laboratory results and the practicality of the test specimen dimensions.

Penetration Test

This test is performed on hot-poured materials to obtain a measure of the consistency of the sealant. The test procedure is outlined in ASTM D 3407-75T (13) and employs a penetration cone instead of the standard needle. Tons (12) tested the penetration of the sealers that he employed according to the procedure of Federal Specification 55-5-164 (19).

Flow Test

The flow test is designed to show the mobility or amount of flow exhibited by the sealant (hot and cold-poured mastic type materials) at elevated temperatures. A specified size of sample is poured onto a tin panel, allowed to cool, and then placed at a 75 degree angle of inclination in a 140°F oven for five hours. The change in length of the sample in millimeters is reported as the flow. The test procedure is outlined in ASTM D 3407-75T (13) and in the Federal Specification 55-5-164 (19).

Resilience Test

This test procedure is detailed in ASTM D 3407-75T (13) and measures the capability of a sealant specimen to recover its size and shape after being deformed. A minimum recovery of 60 percent for a sealant is specified in ASTM D 3405-75T (13).

Compatibility Test

The compatibility test is used to determine if a sealant is compatible with the asphalt in the pavement, i.e., does the sealant have any kind of deleterious effects on the asphalt concrete. The test method and failure criteria are outlined in ASTM D 3407-75T (13).

Pour-Point and Safe Heating Temperature Tests

These tests apply primarily to hot-poured type sealants. The pour-point test determines the range of temperatures in which the sealers can be poured in both narrow and wide cracks. The safe heating temperature is the highest temperature to which the sealant can be heated without the danger of catching fire or damage to the sealant. These tests are outlined in Federal specification 55-5-164 (19).

Other Tests

Some additional tests on sealants have been devised and reported by Tons and Roggeveen (12). The "volume change test" was used to check the shrinkage of the sealants (primarily cold-poured materials) during a specified curing time after pouring in order to determine whether repouring would be necessary in the field. The "tackiness test" was used as an indication of the amount of adhesion or pick-up of the sealant on rubber tires that could be expected. The "age hardening test" provided a relative measure of the hardening and skin forming tendencies of a sealant after a 28 day exposure to the elements.

Field Application Experience

Many different crack sealing procedures have been reported in the literature. The essential repair techniques for sealing and/or correction of various forms of cracking are discussed in the Asphalt Institute's Manual Series No. 16 (4). According to the Asphalt Institute, these sealing procedures have proven to yield neat long-lasting results.

Field studies by many agencies have been conducted to evaluate various crack sealing techniques. The investigators concluded that the amount of failure noticed depended largely on the crack preparation procedures that were used, and that the extra care exercised in cleaning and preparing the cracks prior to sealing was justified by the results obtained (2) (8) (20).

Adhesion failure was reported to be the major and most frequently observed type of failure that occurred in the sealed cracks (2) (8) (11) (20). Several approaches were tried to improve the bond between the sealer and the pavement. Cleaning the crack by some mechanical means, i.e., brooming or brushing, removed dust from the crack walls and loose paving materials. This provided cleaner and more stable crack surfaces and promoted better adhesion of the sealant. Excellent results were reported in a Minnesota field study (8) where a wire twist brush was used for this purpose.

Air-blowing and priming of the crack surfaces have also been used with conflicting results reported by various investigators. Apparently, air-blowing of the crack alone did not noticeably improve adhesion but it did allow the sealer to penetrate deeper into the crack. The reported results vary as to the effectiveness of priming cracks with a thin cutback or emulsion prior to sealing. Tons (2) believed that the prime penetrated and coated the dust on the crack walls, softened the pavement binder, and promoted better adhesion of the sealer. However, Wolter's (8) field tests of three different prime materials indicated that they should not be used. Also, slight overfilling of the sealed cracks, i.e., an overlap of sealant along the crack edges, seemed to prevent adhesion failures and provide longer service life.

Routing of cracks to relatively uniform grooves (approximately 0.5 in. wide by 1.0 in. deep) that hold more sealer than do narrow, ragged edged cracks was recommended to enhance the service life of the sealed crack (2) (8). Also, sealers in 0.25 in. or wider cracks showed considerably less failure than sealers in cracks under 0.25 in. in width. Apparently, the larger the volume of sealer in the crack, the smaller the stresses in the sealer as the adjacent pavement sections move horizontally and vertically. This conclusion corresponds with theoretical calculations (14) concerning the effect of width to depth ratio on the amount of strain in the sealer.

The sealant in a crack is similar to a short single-span bridge fixed to two abutments that move back and forth in opposite directions with temperature changes. The advantages of having the sealer become concave or "curve-in" on the top and bottom surfaces during extension was discussed by Tons (14). He indicated that, contrary to common assumptions, a relatively shallow sealed crack is better than a deeply sealed one. The shallow seal permits concavity to occur in both top and bottom surfaces and this reduces the total strain. In deeply sealed cracks, the sealant bond at the bottom of the crack pervents this. Consequently, a paper rope "bond breaker" was used to limit the penetration of the sealant in deep cracks in a field test program (8). The results of these tests were very poor, however. Nothing was found in the literature concerning the use of sand or crusher screenings for this purpose.

Crack Dynamics

Pavements are subjected to various environmental and service effects which can cause horizontal and vertical movements of adjacent sections at cracks or joints. Many studies have been made of gross pavement movements (1) (8) (11) (20) (21) (22) but most of these have been concerned with localized conditions and the results may not be applicable over a wider range of climatic conditions, subbase types, load-transfer systems and crack spacings. Determination of the magnitude of the relative horizontal and vertical movements at cracks that occur seasonally and under traffic loads in a particular geographic locality would be extremely beneficial to a crack sealing study.

Vertical Movement

Little data on vertical movements at both cracks and joints was found. An approach to determine the average vertical shear strain in joint sealants has been used in Massachusetts (11). In this study of rigid pavement joint movements, vertical displacements at 1.0 in. wide non-doweled joints under a 20,000 lb axle load were measured. The average shear strain of 0.01 in. was about five percent of the tensile strain experienced by the sealant and it was concluded that the effect of vertical movements on joint sealers was negligible. They did, however, indicate that further study was needed.

A method of measuring vertical movements at cracks in flexible pavements has been reported in a Virginia study (22), which was concerned with reducing reflective cracking of overlays on rigid pavements. A Benkelman beam was placed on the shoulder of the road with its point near the edge of a crack. A dump truck with an 18,000 lb rear axle load was positioned on the opposite side of the crack as shown in Figure 2. With the loaded rear axle at point 1, an initial beam reading was taken. The truck was then driven slowly across the joint and beam readings taken as points 2 and 3 were traversed. The beam reading with the axle at point 2 indicated the deflection caused by the load on that side of the crack and comparison of the readings made with the axle at points 1 and 2 indicated the differential deflection or load transfer capability of the crack. The reading made with the axle at point 3 was used to ensure that the beam was no longer within the area of influence of the axle load.

Horizontal Movement

The horizontal displacements of roadway sections adjacent to cracks or joints in flexible pavements is much more complex, i.e., is more variable and depends on more factors, than in rigid pavements. This probably accounts for the scarcity of information on this phenomenon relative to bituminous surfaced roads. Many references were found concerning field measurements of the horizontal movement at Portland cement concrete

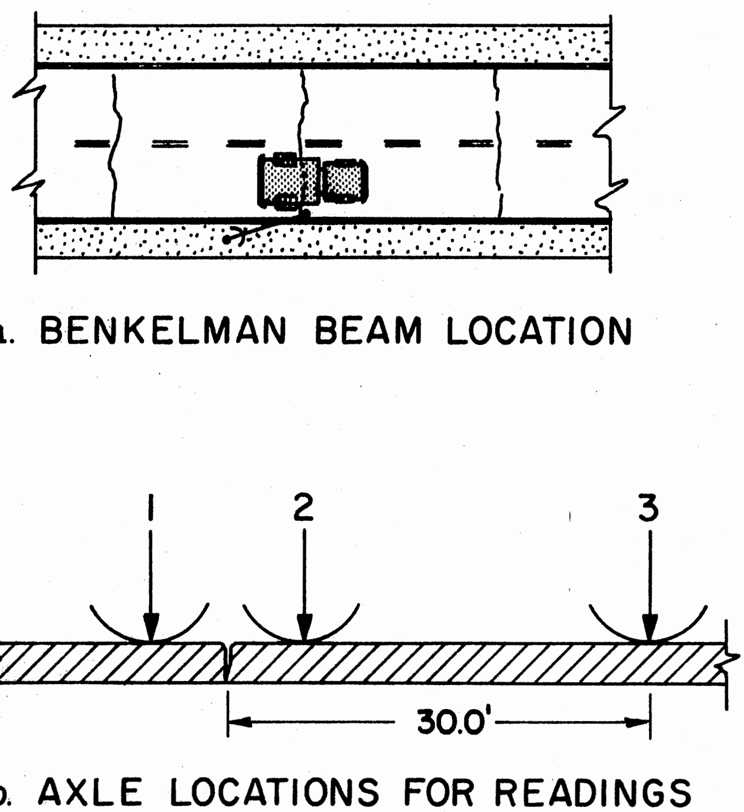


Figure 2. Measuring Vertical Movement
With Benkelman Beam

joints (1) (8) (11) (20) (21) (23). These studies showed the prominence of temperature effects. By plotting the amount of joint opening per degree change in temperature against the slab length, a straight line relationship was obtained and this relationship was used for practical estimation of the amount of joint opening to be expected. Unfortunately, this relationship does not apply to bituminous concrete pavements because of the difference in behavior of the respective materials. For example, the average thermal coefficient of expansion of asphalt concrete between 0 F and 80 F is about four times higher than that of Portland cement concrete. Also, the variation in thicknesses and the lack of material uniformity in the respective layers of flexible pavements make it difficult to reliably predict crack widths for any given temperature change.

However, an approach that indicated the relative amount of horizontal movement at transverse cracks in flexible pavements was developed in a Minnesota study (8). This was accomplished through the use of an "effective crack spacing" concept which was defined as "the distance to the first transverse crack on both sides of the crack in question." Transverse cracks with different "effective crack spacing" were selected, steel nails were driven into the asphalt surfacing on each side of the crack 10 in. apart, and the amount of opening and closing of the crack was determined on subsequent dates as the temperature fluctuated. The results indicated that the relative horizontal movements at cracks in Minnesota flexible pavements was approximately equal to 0.01 in. per 10 ft of effective crack spacing.

CHAPTER III

QUESTIONNAIRE RESULTS

In order to obtain additional information on flexible pavement crack sealing practices, a mail survey was conducted. This survey consisted of a questionnaire (see Appendix A) which requested information on currently used sealants and methods of application, as well as the experience and opinions of field personnel relative to the magnitude of cracking as a maintenance problem and the general effectiveness of sealing cracks. These questionnaires were sent to the Maintenance Engineers of all eight Oklahoma Department of Transportation divisions and similar ones to the State Maintenance Engineers of Arkansas, Colorado, Kansas, Missouri, New Mexico, Tennessee and Texas.

Replies were received from all Oklahoma divisions and the selected states that were asked to complete the questionnaire. Abbreviated information contained in these replies has been tabulated and is presented in Tables II and III. The results of the survey are also discussed briefly under the following subject headings.

Sealing Materials

The sealing materials currently used in Oklahoma and surrounding states are predominantly standard types and grades of asphalt products, i.e., asphalt cements, cutbacks and both anionic and cationic emulsions. Some use is made of latex additives in emulsions and special products

TABLE II

SUMMARY OF QUESTIONNAIRE RESPONSES FROM OKLAHOMA DIVISION MAINTENANCE ENGINEERS

Division Number	What kind of sealant material is used in: A. Longitudinal B. Transverse C. Alligator		Are materials used now doing an effective job?	Is flexible pavement cracking a major maintenance problem?	Criteria used to determine necessity for sealing cracks?	Type of crack preparation prior to sealing operations.	Suggestions and Comments.	Method of periodic crack surveying.
	Material	Application Method						
1.	ABC. MC-3000 AB. CRS-2, wide cracks C. SS-1	pouring pouring spraying	Yes	No	Attempt to maintain a water-proof surface.	None, unless cracks are full of foreign materials.	None	Visual inspection, bi-weekly, quarterly and annually.
2.	AB. MC-250 SS-1 C. SS-1	pouring pouring spraying	No	Yes	Number of cracks per mile and crack must be open 1/16 in. or more.	Blowing, brooming, routing and priming when needed.	Sealant must be economical and easy to apply.	Visual inspection, day-to-day basis, during driving.
3.	AB. AC 60-70 Emulsions C. Emulsions	pouring pouring spraying	No	Yes, time consuming and costly.	Number of cracks per mile and crack must be open 1/16 in. or more.	Cleaning--blowing and brooming are required.	Need inexpensive sealant with more plasticity.	Visual inspection, periodic, to check for development and water infiltration.
4.	AB. AC 60-70 MC-800 SS-1 C. SS-1	pouring pouring pouring spraying	No	No	Crack must be open 3/16 in. for pouring. Extent of surface cracking for fog seals.	Blowing and/or brooming are required.	None	Visual inspection, daily observation for surface and base failures.
5.	ABC. MC-800 SS-1 SS-1 with Pliopave	injection pouring spraying	Yes, time needed for evaluation.	Yes	When cracks become apparent.	Blowing and brooming if needed.	Good results obtained with SS-1 blotted with limestone screenings which work their way into cracks and formod a slurry-type seal.	Visual inspection, regular basis, 3 to 4 times monthly.
6.	AB. MC-800 CRS-2 C. MC-800 CRS-2	pouring pouring spraying spraying	Yes	Yes, because most road bases are soil asphalt.	Number of cracks per mile and width of crack (not specificed).	None	Sealing cracks is a never ending job, but is effective in this Division.	Visual inspection
7.	ABC. AC 60-70 AC 85-100 MC-800, 3000 CRS2h, SS-1	pouring pouring pouring pouring	Yes	No	Number of cracks per mile.	Blowing is required.	None	None
8.	A. AC 60-70 AC 85-100 AC 120-150 B. MC-800 SS-1	spraying spraying spraying spraying spraying	No	Yes	Number of cracks per mile (500) and crack must be open 1/32 in. or more.	None	Sealants with good resiliance are needed.	Visual inspection, every 60 days by driving.

TABLE III

SUMMARY OF QUESTIONNAIRE RESPONSES FROM SELECTED STATE MAINTENANCE ENGINEERS

State	What kind of sealant material is used in: A. Longitudinal B. Transverse C. Alligator		Are materials used now doing an effective job?	Is flexible pavement cracking a major maintenance problem?	Criteria used to determine necessity for sealing cracks.	Type of crack preparations prior to sealing operations.	Suggestions and Comments.	Method of periodic crack surveying.
	Material	Application Method						
Arkansas	ABC. RC-250, CRS-2 D-80, Lion Oil Co. (no distinction made as to type and grade of material used for sealing cracks.)	pouring pouring	Yes	Yes, sealing should be done on a regular basis.	Crack must be open 1/8 in. or more. Spalling and deterioration of surface adjacent to crack.	Brooming if crack is wide enough, and blowing are required.	Hopefully, a material of the nature of an unheated elastomeric polymer material can be found which will do a better job and last for 20 years.	Visual inspection, weekly by area foremen.
Colorado	ABC. MC-800 RC-800	pouring pouring	No	No	Deterioration of surface adjacent to crack.	Routing, blowing and brooming are required.	We question the benefits of crack sealing operations compared to the cost. In areas like Colorado with < 15" of rainfall, the moisture can't be causing much of a problem.	None
Kansas	ABC. CRS-1h (?)	pouring	Yes	No	Crack must be open 3/16 in. or more.	Blowing with air is required.	Prior to letting a resurfacing contract, a formal inspection of roadway is conducted and the number of cracks and crack pouring are factors considered in this inspection.	No formalized inspection for cracks. Crack surveillance is a routine function of field personnel.
Missouri	AB. RC-800 CRS-2 C.	pouring pouring seal or resurface	Yes	No	Crack must be open 1/8 in. or more. Spalling and deterioration of surface adjacent to crack.	None, Work is done in latter part of the year when temperature is below 40°F and cracks are open.	By far, the majority of crack sealing is done with RC-800. The RC is not used when pavement is wet and CRS-2 is not used below freezing.	None
New Mexico	ABC. MC-250 MC-3000 plus Gilsonite	pouring and pressure injection	Yes	Yes	Crack must be open 1/8 to 1/2 in. or more.	None. If crack is deep, it is partially filled with small rock (1/4 to 3/8 in.)	Have experimented with many commercial crack sealants, but found that an MC/Gilsonite mixture works best. Use 50-75% Gilsonite by weight.	Visual inspection, continuously by maintenance forces.
Tennessee	ABC. RC-250	pouring	Yes	No, scheduled resurfacing tends to keep this from becoming a major problem.	Crack must be open 3/16 in. or more.	Blowing and temperature range 30° to 70°F for applying sealant is required.	None	Visual inspection, daily.
Texas	ABC. RC-250, HMRS with and without latex, cat-blown asphalt, 75 and 42 penetration.	pouring and/or spraying	Yes	Yes	Crack must be open 1/8 in. or more. Deterioration and excessive alligator cracking.	Blowing, routing, brooming are sometimes used, but not required.	Sealants currently being used are effective but can be improved. Current methods are very expensive. Have also used hot-poured rubber, but due to cost and heating problems, it has been discontinued.	Visual inspection, periodically by foremen and annually by trained rating teams.

(exact type unknown) were reported used in Arkansas and Texas. New Mexico reported using Gilsonite as an additive in medium curing cutbacks with the percentage by volume of the Gilsonite varying from 25 percent in the summer to 50 percent in mixtures used during colder weather.

Apparently, there is no standard sealant for treating longitudinal and transverse cracks in Oklahoma. Four divisions use 60-70 and/or 85-100 penetration asphalt cements as well as medium curing cutbacks and emulsions for this purpose. The other divisions use medium curing cutbacks (250 to 3000 grades) or anionic and cationic emulsions for these types of cracks. The majority of the surrounding states favor the use of rapid curing cutbacks (250 and 800 grades) or cationic rapid setting emulsions for sealing all categories of cracks. Texas reported using asphalt cements that had been catalytically blown to penetrations of 42 and 75.

In Oklahoma, slow setting anionic emulsion (SS-1) is used predominatly for sealing alligator type cracking and in some divisions it is also employed on longitudinal and transverse cracks. Division 5 reported excellent results obtained by filling the wider cracks with SS-1 and then blotting the surface with limestone screenings to form a slurry-type seal. The surrounding states that use emulsions prefer the cationic type for sealing alligator cracks, and Divisions 1, 6, and 7 also employ CRS-2 and CRS-2h emulsions for this purpose.

Criteria Used to Determine Necessity for Sealing

The majority of the Oklahoma divisions use some number of cracks per mile of roadway and crack widths, varying from 1/32 in. to 3/16 in. or more, as a basis for deciding the need for sealing operations.

Other divisions simply try to maintain a waterproof surface on the roads or begin sealing when the cracks become apparent. Most adjacent states utilize crack width (1/8 in. or more) and/or deterioration of the surface adjacent to the crack as the determining criteria for applying sealants.

Crack Preparation

The replies from the respondents to the question concerning the types of crack preparation made prior to sealing operations can be grouped into three catagories:

1. Crack preparations are required. These preparations include brooming, blowing, routing, priming and partial filling of large deep cracks with fine aggregate, in various combinations.

2. No crack preparation required. Various combination of the above treatments are used when needed. The decision is apparently left to the experience and judgement of the maintenance personnel. Time and availability of equipment probably influence the ultimate decision.

3. No crack preparation at all prior to sealing operations.

Application Methods

Application methods used by the respondents seemed to be rather uniform. That is, hand pouring of the sealant is used on the more open or wider types of cracks and spraying on the more narrow and closely spaced cracks. Distributor truck spraying with hand wands or from the spray bar depends on the extent of the crack system. Pressure injection of sealants into the cracks was listed by one division and one of the selected states.

Specialized Mechanical Equipment Used

The questionnaire requested information on special mechanical equipment used for crack preparation and sealing work. None of the respondents indicated any experience with or use of apparatus beyond that which would be considered normal equipment for maintenance crews engaged in sealing cracks.

Pavement Inspection and Crack Surveying

All replies indicated that visual inspection was the only method used to survey flexible pavements in order to determine crack development and extent of surface deterioration at the cracks. This type of inspection is probably carried out largely from slow moving vehicles and in some cases by walking observers. Seven of the Oklahoma division and five of the states reported that they made periodic crack surveys with this technique. Generally, these surveys or inspections on a given section of road are carried out by the maintenance personnel responsible for that section. Texas indicated that specially trained rating teams performed such surveys annually in some of their districts.

Is Cracking a Major Maintenance Problem?

In the opinion of the Oklahoma respondents, 62 percent considered flexible pavement cracking a major maintenance problem, while 38 percent did not. In contrast, only 43 percent of the respondents from the surrounding states thought it a major problem and 57 percent did not. It is difficult to interpret these replies and the answers, apparently, are related to a number of factors such as:

1. geographic location, i.e., temperature ranges and annual rainfall amounts;

2. type of base materials employed;

3. type of subgrade soils;

4. traffic volumes and weights;

5. efficiency of sealants being used;

6. philosophy of the agency as related to the cost-benefit ratio of sealing operations, i.e., it may be more economical in some cases to ignore cracking and schedule complete resurfacing as surface conditions deteriorate beyong a tolerable level.

Are Sealants Effective?

Replies from 50 percent of the Oklahoma divisions states that the presently used sealant materials were not doing an effective job of sealing the cracks, while 86 percent of the surrounding states considered their sealants to be effective. Again, these replies are considered to depend on some of the above mentioned factors, as well as the type of crack preparations and sealants employed and the timing of the sealing operations. Intuitively, sealing cracks as soon as possible after they occur will help to preserve the integrity of the total pavement system and extend considerably the useful life of the surface.

Suggestions and Comments

The comments and suggestions received on all of the questionnaires are briefly summarized as follows:

1. A sealant should be economical and easy to apply.

2. Crack sealing is time consuming—need some type of inexpensive

sealant that has more plasticity.

3. Good results achieved this season with SS-1 emulsion blotted with good limestone screenings. Screenings work their way into cracks and appear to form a slurry-type seal. Time needed for further evaluation.

4. Crack sealing is a never ending job, but is effective.

5. In second year after application the sealants have no resilience and the crack re-opens.

6. A material of the nature of an unheated elastomeric polymer is needed that will last 15-20 years.

7. We question the benefits compared to cost of crack filling operations in areas with less than 15 in. of annual precipitation.

8. The majority of our crack sealing is done with RC-800 when temperature is below 40 F and cracks are open.

9. Scheduled resurfacing tends to keep cracking from becoming a major problem.

10. Sealants currently being used are effective but could be improved. Current methods of application are expensive. We have also used hot-poured rubber (asphalt cement with rubber additive) but discontinued this due to cost and problems with heating equipment.

11. We have experimented with a great many commercial crack sealants but have found that an MC/Gilsonite mixture works best.

CHAPTER IV

CRACK DYNAMICS FIELD STUDY

EXPERIMENTAL DESIGN

An experiment is a planned inquiry to obtain new facts or to confirm or deny the results of previous experiments (24). The design of an experiment is the complete sequence of steps taken ahead of time to insure that the appropriate data will be obtained in a way which permits an objective analysis leading to valid inferences. The crack dynamics field study was set up as a statistically designed experiment to obtain and analyze data on the relative horizontal and vertical displacements of the pavement surface adjacent to full width transverse cracks.

As previously discussed, test sites were established on transversely cracked state highway sections in the central, north-central and northeast areas of the state. Selected transverse cracks at each test site were monitored for their horizontal movements with varying temperature and for their vertical displacements under a specified loading condition.

The Research and Development Division of the Oklahoma Department of Transportation (ODOT) asked specifically that the study include cracks located on certain geological formations of interest. This along with some limitation on travel distance aided in the search for suitable test site locations on the state highway system.

Various highway sections exhibiting different degrees of transverse cracking in a number of maintenance division areas were visited. Some of these sections were suggested by the maintenance engineers and others were located by research personnel during field trips to different locations in Oklahoma for another research program. Preliminary site visits for these locations were made to: (1) locate the cracks and determine their suitability for the intended study, and (2) check the geometric alignment and adequacy of shoulder parking at the prospective sections. This latter aspect was given great consideration to assure that the safety of research personnel could be maintained during future field operations. The final selection of suitable test sites was based on the results of this initial survey and the planned time schedule. The selected sites were situated so that data could be collected at several sections during a single trip. Each of these sites was identified for the respective Maintenance Division so that sealing or overlaying operations would not be carried out at these locations during the study period.

Identification of the test sites was made by attaching a 10.0 in. x 11.0 in. (25.4 cm x 27.9 cm) red painted metal plate to the right-of-way fence at each test site. These markers were located at a measured odometer distance from the nearest intersection, bridge or the boundary line of the county in which the test sites were located. At each test site, a 0.25 mile (0.40 km) length of pavement was chosen for detailed crack surveying and measurement of the crack spacing. To keep the amount of experimental work within practical research capabilities, a total of nine test sites was finally selected. The selected sites included five sections located on the Wellington-Admire geological unit, two on the Boone unit, and one on both the Senora and the Garber units (25). Table XIII in Appendix B shows the exact locations and the corresponding geological formation unit for these sites.

Horizontal Movement Study

The primary objective of this study was to determine the amount of horizontal movement at transverse cracks during a specified period of time (one year) and relate this movement to seasonal temperature fluctuations and Effective Crack Spacing (ECS). ECS (8) is the average of the distances between adjacent transverse cracks on either side of a crack being studied. It was considered that the pattern of crack movement for various ECS's with respect to temperature variation might lead to a suitable method for predicting horizontal crack movements.

The study started with counting and measuring distances between the cracks within the chosen length of pavement (a Rolatape, Model 200, was used for these measurements). Five cracks were selected at random from among cracks that extended across the full width of pavement. Two steel concrete nails were driven into the bituminous pavement, one on each side of a selected crack. These nails were driven flush with the surface of the pavement to assure no damage from traffic and/or snow removal equipment. A small indentation was placed in the head of each nail to provide reference points for the subsequent measurement of the crack movements.

At the time of their installation, initial measurement of the distance between the two nails was made. This distance was recorded along with the air temperature, the pavement surface temperature and the pavement temperature at a depth of 2.0 in. (51 mm).

At monthly intervals as the temperature fluctuated, the sites were visited and the spacing of the five pairs of nails in each site were measured. Air, surface, and subsurface temperatures were determined at the time of the spacing measurement. The amount of movement, i.e., opening or closing of the crack, was calculated by comparing the initial or original spacing measurement with subsequent ones.

Elements of the statistical design for this study are: (1) Experimental units, includes the geological formation, pavement surface and subsurface types, the average width and degree of cracking and the ECS of a given crack; (2) Treatment, the factor applied to the experimental units or, in this case, the environmental temperature [Note: It is known that the air temperature and the surface and subsurface pavement temperatures are closely related (26) (27), but in this study it was necessary to monitor each to determine which had the greatest influence on crack width]; (3) Response, the amount of movement that takes place at each crack.

A regression analysis method was adopted for analyzing the data of this multivariate experiment, and to develop a mathematical functional relationship between the variables. Some precautions or reservations had to be made in the inference part of the analysis to account for the fact that the ECS element was not chosen at random every time the readings were taken. For practical reasons the ECS was randomly selected initially and then fixed during the remainder of the experiment.

Vertical Movement Study

Based on findings of a Massachusetts study (11), in which shear strain in expansion joints on Portland cement concrete (PC) pavements was found to be relatively small compared with the tensile strain, it was speculated that this might also hold for asphalt pavement cracks. This study was directed toward finding the range of relative vertical displacement of the opposing pavement edges at a transverse crack and comparing this with the maximum expected horizontal movement. It was hoped that the results would substantiate that the shear strain has a limited effect on the failure of sealants. The seasonal effect on both the total and relative deflection was also investigated.

The method used for measuring vertical crack movements was adopted from the previously cited Virginia study (22). Vertical deflections caused by a truck with an 18,000 lb (8,165 kg) rear axle load were determined using a Benkelman beam. The Research Division of ODOT trained the project personnel in the use of the Benkelman beam and provided the loaded truck for these measurements. They also furnished an experienced man to assist with the beam operation when these measurements were made in the field.

The measurements were made at the same five cracks at each site used in the horizontal movement study. The Benkelman beam was placed on the left side of the loaded truck, which moved in the traffic direction, to make it easier for the driver to locate the rear tire exactly on a painted mark (Figure 3). Hand signals from the measuring crew assisted the driver in positioning the truck. This procedure insured that the load would be applied to the same area each time. Dial readings were taken at three tire positions (Figure 3) with the truck moving forward and, as a check, three more readings with the truck moving backward.

Statistically the experiment can be defined as a "split-plot in time" (24) where crack deflections represented the experimental units. The units secured from each crack (crack No. 1 to crack No. 5) were divided according to their location into eight "main plots", sections 1 through 8. Each main plot was subdivided into four subplots for the winter, spring, summer and fall measurements.

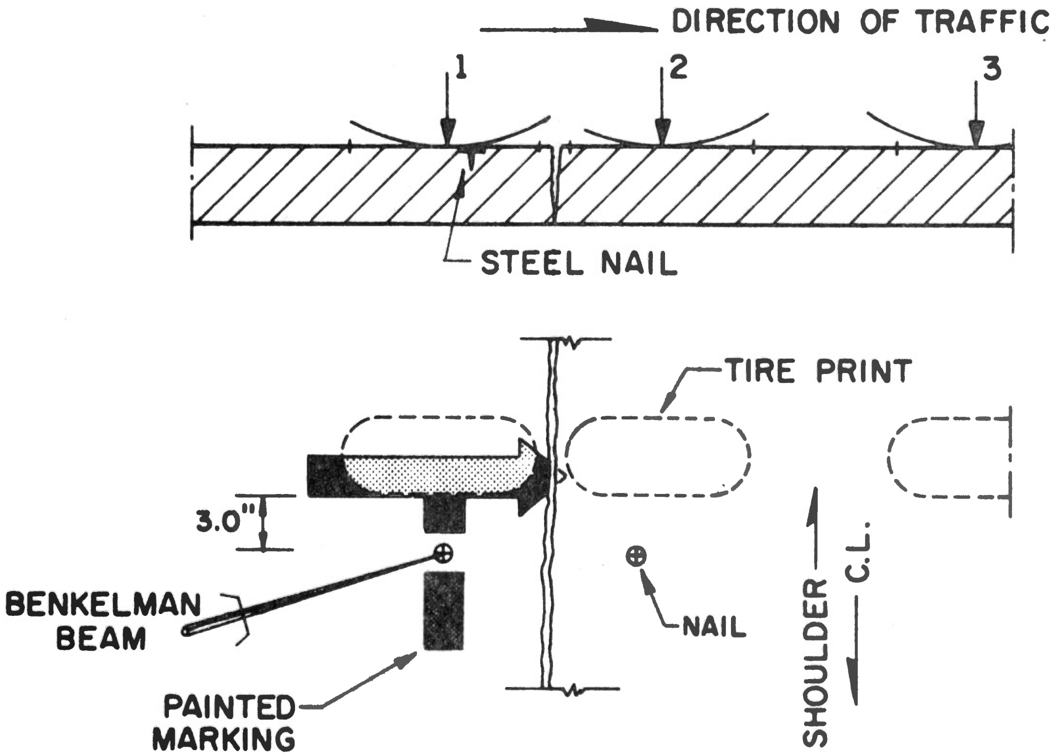


Figure 3. Respective Location of Truck Tires and Benkelman Beam at a Transverse Crack

CHAPTER V

BOND-DUCTILITY TEST EQUIPMENT

The bond-ductility test is an attempt to duplicate field conditions at pavement cracks with regard to the tensile strains imposed on sealants as the temperature of adjacent pavement sections decreases. It is a basic test used by many previous investigators (1) (12) (14) (16) (17). Although the testing procedures and equipment may differ, the essential features of this test, as described in Chapter II, are the same.

The extension machines used by the respective agencies or investigators cited were not commercially available, not reasonably priced, or not considered suitable for the intended investigation. Therefore, it was decided to design and construct such a device to fit the needs and constraints of the subject research project.

Many factors were considered during the design of this machine. The primary ones were those dealing with the size, capacity, and cost of the device. Other design considerations included the capability of handling multiple test samples of specific length and the need for precision controls to regulate the operational speed. The size constraint was imposed by the need to house the machine in an available low-temperature cabinet, which was to provide the controlled temperature environment for the tests. The machine had to fit into the cabinet with some leeway for operational manipulation and adjustment.

Design Features

The bond-ductility machine developed for this project was designed to test multiple samples of sealant materials poured between spaced specimen blocks of asphalt concrete. These blocks are clamped in the machine and pulled apart at a controlled rate of tensile strain under low temperature conditions. The machine has several other noteworthy features: (1) it is portable and compact in size; (2) its rate of extension of the sealant samples can be varied and controlled precisely; (3) the machine controls can be reversed to provide compressive stress on the test samples; and (4) it can accommodate test specimen blocks up to 6.0 in (152 mm) in length. These features provide the machine a considerable amount of versatility relative to testing other types of sealants, e.g., PC concrete crack sealing and joint filler materials, and to use in more comprehensive research investigations involving extension and compression tests in an environmental chamber.

Testing Equipment

The bond-ductility machine consists of the following components: (1) electric motor, (2) speed reduction and drive assembly, (3) supporting table, and (4) two clamping frames. Auxiliary equipment includes two two-temperature cabinets or freezers and temperature and displacement rate monitoring devices. Figure 4 shows some of the basic design features of the machine and its position in the freezer. Figure 5 illustrates the details of one of the clamping frame assemblies. The respective components and their basic specifications are also listed in Table XVI, Appendix C.

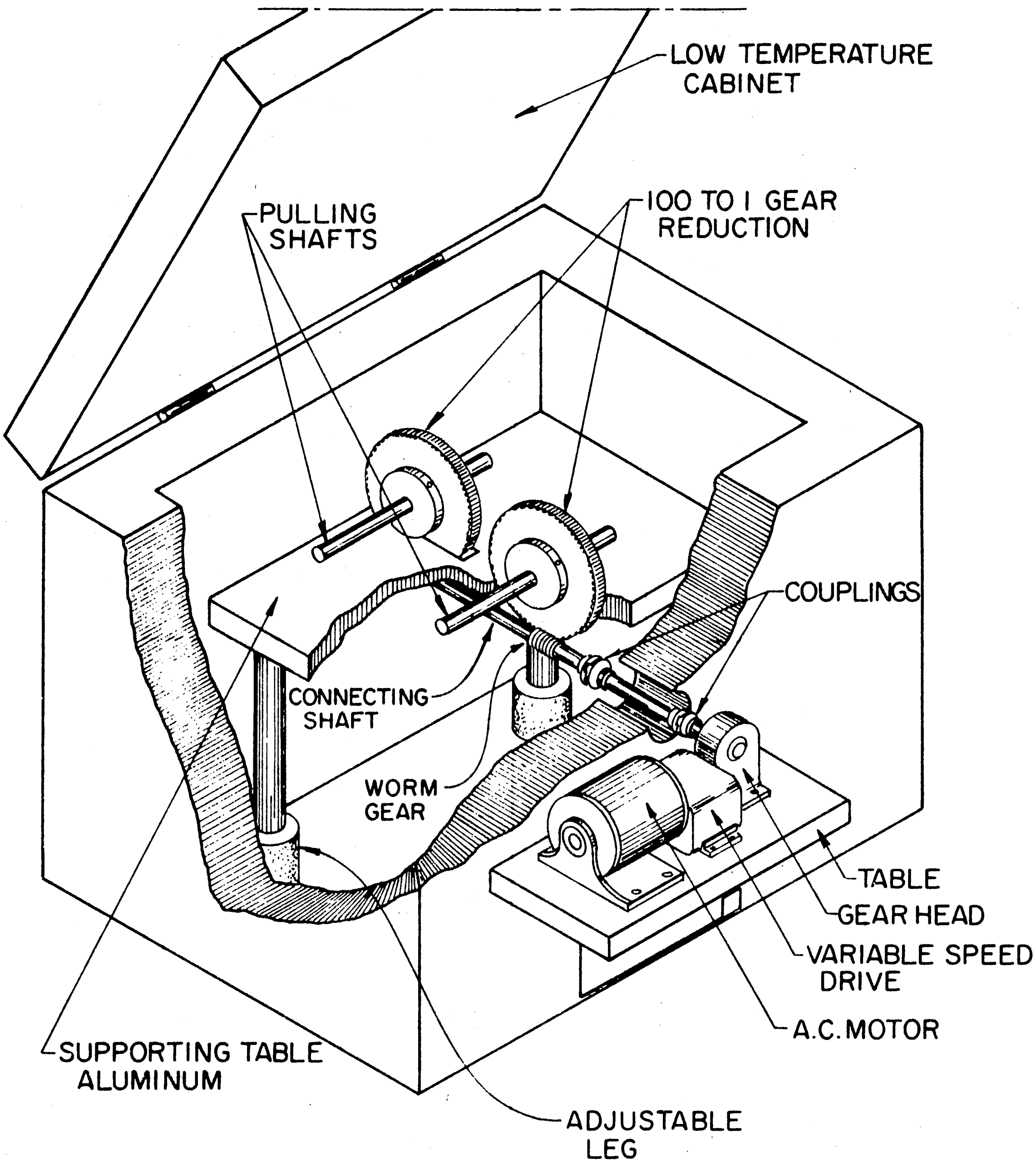


Figure 4. Basic Design Features of the Bond-Ductility Machine

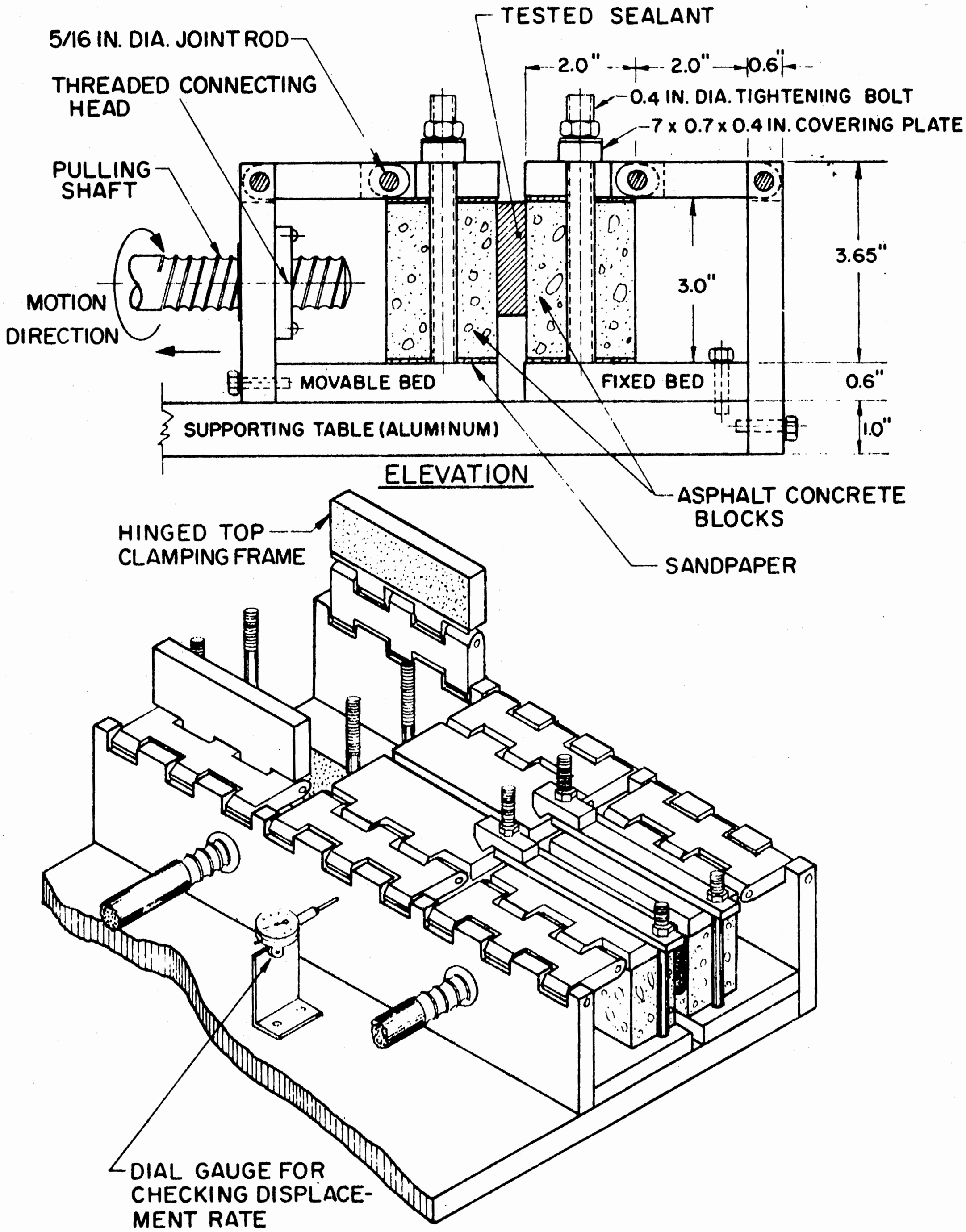


Figure 5. Details of Clamping Frame Assembly for the Bond-Ductility Machine

Motor

Based on an assumed stiffness modulus of 441 psi (3040 kPa) for an asphalt material (28) and a unit strain, the force required to laterally stretch six sealant samples, 6.0 in. (152 mm) long and 2.0 in. (51 mm) deep, was determined to be 31,745 lb (14,399 kg). The design of the machine called for this force to be transmitted through two 1.0 in. (25 mm) diameter pulling shafts rotating at 1/60 rpm. Design calculations (29) (30) using this information, indicated that at least a 1/168 Hp motor was required.

A 1/3 Hp Zero-Max electric motor with a speed of 1725 rpm was selected as the power source. The motor and speed reduction components of the equipment were ultimately located outside the freezer compartment with a connecting shaft through the freezer wall to the machine's gears (see Figure 4). Operational convenience, space limitations, and heat from the motor made this a practical arrangement.

Speed Reduction and Drive Assembly

The speed reduction and drive components of the machine are illustrated in Figure 4. The schematic arrangement and data for these parts is presented in Table XVII, Appendix C. The basic parts of the assembly are: a variable and a fixed gear head connected to the motor outside the freezer; a 0.5 in. (13 mm) diameter connecting shaft with couplings; and two 8.3 in. (211 mm) pitch diameter cast iron and brass worm gears with two 1.0 in. (25 mm) pitch diameter steel worms. Two 1.0 in. (25 mm) diameter steel shafts through the center of the brass worm gears provided the drive or pulling force on the moveable bed of the clamping frames. Both ends of each of these shafts were threaded (four threads per inch) and turned in similarly threaded 1.38 in.(35 mm) diameter brass connecting heads on the clamping frames.

Functionally, the gear heads and worm gears reduce the operating speed of the motor and rotate the pulling shafts. The threaded connecting heads transform the rotation or turning motion of the pulling shafts to the desired rate of horizontal displacement for testing purposes.

Several alternatives for the "gear train" or drive assembly to transmit force to the moveable clamping beds were considered in the design. One of these was a chain drive arrangement. However, the worm gears with a 100 to 1 reduction ratio eliminated the need for an additional gear head, reduced the amount of "play" in the system, and cost less than the other alternatives. After the machine was constructed and operational, only one design modification was necessary. This involved placing a steel pin through the brass worm gear hubs to prevent slippage of the pulling shafts with unbalanced loading of the clamping frames.

Supporting Table

The supporting table or platform of the machine consists of a rectangular 1.0 in.(25 mm) thick aluminum plate mounted on four adjustable pipe legs. The dimensions and height of this table were controlled by the necessity to use an available low-temperature cabinet or freezer to provide the desired temperature for sealant testing. The supporting table had to fit into this freezer.

The center of the table was slotted to receive and support the worm gear assembly. Clamping frames for securing the test specimen blocks were positioned on the table on each side of the brass worm gear drives.

The adjustable pipe legs for the table were necessary to level the machine and to support the clamping frame assemblies at a convenient working height when the machine was in the freezer.

Clamping Frames

The clamping frames have two parts, a fixed bed and a moveable bed. The fixed bed is bolted to the aluminum supporting table and the moveable bed is actuated by the pulling shafts rotating in the threaded connecting heads (see Figure 5). The threading directions of the ends of the pulling shafts and the connecting heads on one side of the machine were opposite to those on the other side so that the turning motion of the shafts was transformed into opposing directions of travel for the two moveable clamping beds. Two pulling shafts were used to insure even pulling on the test specimens and parallel alignment of the clamping frame beds.

The design speed of travel of the moveable beds is 0.125 in./hr (3 mm/hr) horizontally. This desired speed can be regulated precisely with the Zero-Max variable speed drive which is equipped with a screw control. Other speeds ranging from slightly over zero to 0.75 in./hr (19 mm/hr) can also be achieved. These same controls have the capability of reversing the direction of travel of the machine so that compressive forces rather than tensile force can be applied to test specimens in the clamping frames.

Each clamping frame holds three test samples of sealant. The sealant sample is poured between two asphalt concrete blocks. The approximate block dimensions are: 6.0 in.(152 mm) long by 2.0 in. (51 mm) wide by 3.0 in.(76 mm) high. The test sample blocks are secured to the beds of the clamping frame as illustrated in Figure 5. The double joint configuration of the frame's top permitted some variation in the height of the blocks used.

Low-Temperature Cabinets

A Lab-Line freezer was used to house the bond-ductility machine and provide the low-temperature environment for testing the sealant samples. The inside dimensions of this freezer are: length, 31.0 in. (79 mm); width, 21.0 in. (53 mm); depth, 27.0 in. (69 mm). As previously mentioned, these dimensions largely controlled the size and configuration of the testing machine.

Previous investigators used a test temperature of 0 F (-17.8 C) and this temperature was adopted based on a study of climatological data. This temperature could be achieved and maintained within ± 0.5 F (± 0.3 C) in the freezer.

It was projected that approximately ninety samples of various sealants would have to be tested and that in most cases, several cycles of extension would be required to obtain failure. To reduce the time required for testing, an additional low-temperature cabinet was provided to store the ready-for-testing samples and cool them to the testing temperature. After pre-cooling the samples could be placed in the machine housed in the other freezer and the test started immediately. This process eliminated a waiting period for the samples to cool to the test temperature after placing them in the machine.

Monitoring Devices

The horizontal displacement rate or travel speed of the moveable clamping beds was periodically checked using two dial gages and an electric stop watch. The dial gages were mounted on aluminum angles attached to the supporting table.

Both the cabinet temperature and the test sample temperatures were monitored during the testing process using special temperature probes (thermistors). The wires from these thermistors were connected to a YSI scanning tele-thermometer unit located outside the freezing compartment.

CHAPTER VI

STUDY PROCEDURES

Crack Dynamics

The field study portion of this investigation was divided into two parts. The first part consisted of measuring the horizontal movement or displacement at transverse cracks due to expansion and contraction of the adjacent pavement sections. The second part of the study involved determination of the relative vertical displacements of the transverse crack sides under application of a heavy wheel load. Knowledge of the magnitude of these respective movements was considered essential to the study and evaluation of crack sealant materials.

Horizontal Movements

Safety. The planning and conduct of all field work on the highways was controlled to a considerable extent by the necessary precautions to insure the safety of the research personnel. Selection of the test sites was based primarily on the availability of adequate sight distance and good shoulder parking conditions for the research vehicle. Field work was not conducted if there was any form of precipitation on the roadway.

No traffic control was provided for the horizontal measurements. The research vehicle, a quarter-ton pickup truck equipped with flashing caution lights, was parked on the shoulder in advance of a test site location to warn oncoming traffic. Research personnel wore high visibility safety vests and hats and one man served as a "lookout", observing traffic, while the other man made the necessary measurements.

Initial Installation and Measurements. After selecting a transversely cracked section of pavement for study, measurements of the spacing between full width cracks was made and the ECS (8) was calculated for each crack. Five cracks were randomly selected and their location marked with spray paint on the pavement.

At the selected cracks, steel concrete nails with indentations in the heads were driven into the pavement on each side of the crack approximately 10.0 in. (254 mm) apart. A 24 in. (610 mm) vernier caliper equipped with points to fit the indentations in the nail heads was used to measure the distance between nails (Figure 6). The initial as well as the subsequent monthly measurements were made to the nearest 0.001 in. (0.025 mm).

A 0.25 in. (6.4 mm) diameter hole, 2.0 in. (50.8 mm) deep, was drilled near the edge of the pavement at a location central to the five cracks in a test site. A temperature probe or thermistor was inserted in this hole to obtain the subsurface pavement temperature. A steel bolt and caulking compound were used to seal this hole between the monthly temperature readings. These readings were made using a remote sensing tele-thermometer (YSI Model 47) with separate thermistor probes for gaging the subsurface and surface pavement temperature and the air temperature. Power for the tele-thermometer unit was obtained from a 12 volt battery through a 200 watt inverter.

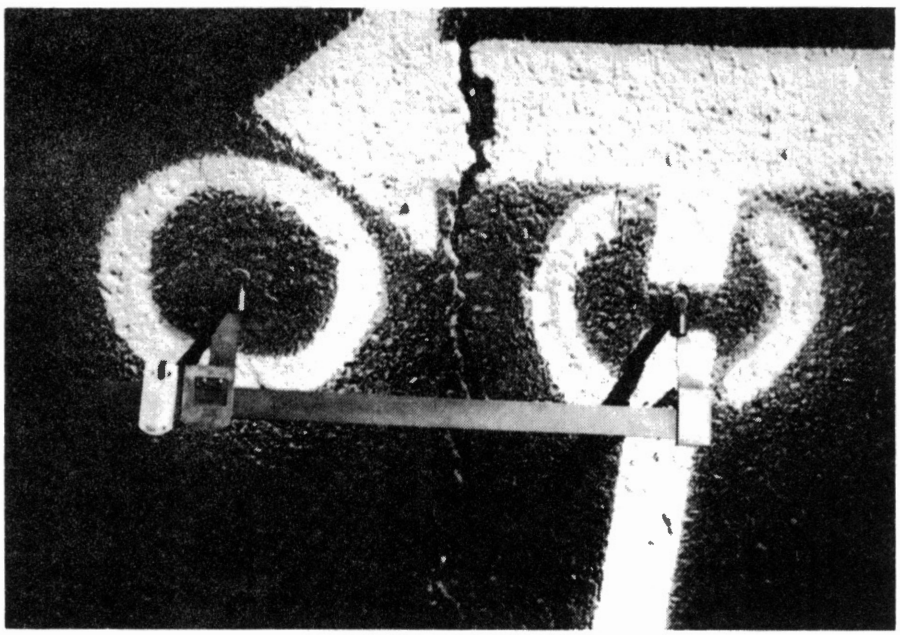


Figure 6. Placement of Reference Nails

Monthly Measurements. Each test site was visited once a month over a one year period. The test sites were grouped according to their location into three areas. All of the sites in a particular area could be visited, the respective measurements taken and the return trip made within one day. Thus, only three trips per month were required to collect the necessary data from all the test sites.

The nails at the transverse cracks and the temperature probe hole were marked with white painted rings for ease in relocation. After reaching a test site, the truck was parked on the shoulder with lights flashing and the temperature monitoring equipment was set up at the pavement edge (Figure 7). Traffic cones were used to delineate the working area. The subsurface probe was inserted in the prepared hole and the surface probe taped to the pavement surface. The air temperature probe was placed on top of the tele-thermometer unit, approximately 10.0 in. (254 mm) above the pavement surface. The probe temperatures were allowed to stabilize and the readings were recorded.

The distance between the nails at each of the five cracks were then measured with the calipers. Two separate measurements were made at each crack to reduce the chance of error in reading and recording the values. Following these measurements, the various temperatures were again read and recorded to check for variations.

The data collected from each site visit was punched on computer cards using the Statistical Analysis System (SAS) code (31). A card similar to that shown in Figure 8 was made for each transverse crack with the spacing and temperature measurements and other pertinent information punched in the card.

Initial examination of the data obtained after the first few months

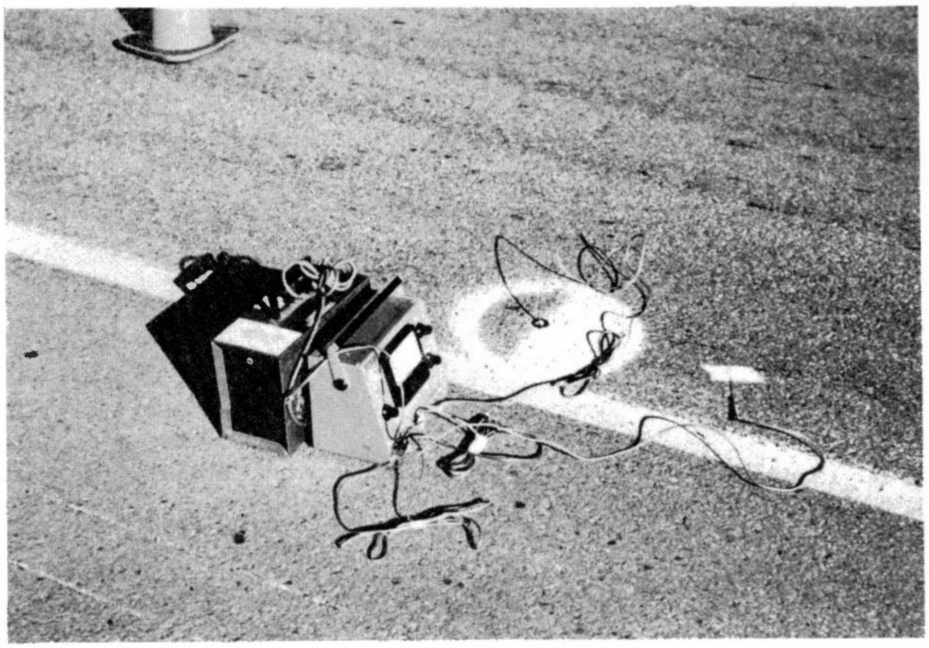


Figure 7. Temperature Monitoring Equipment

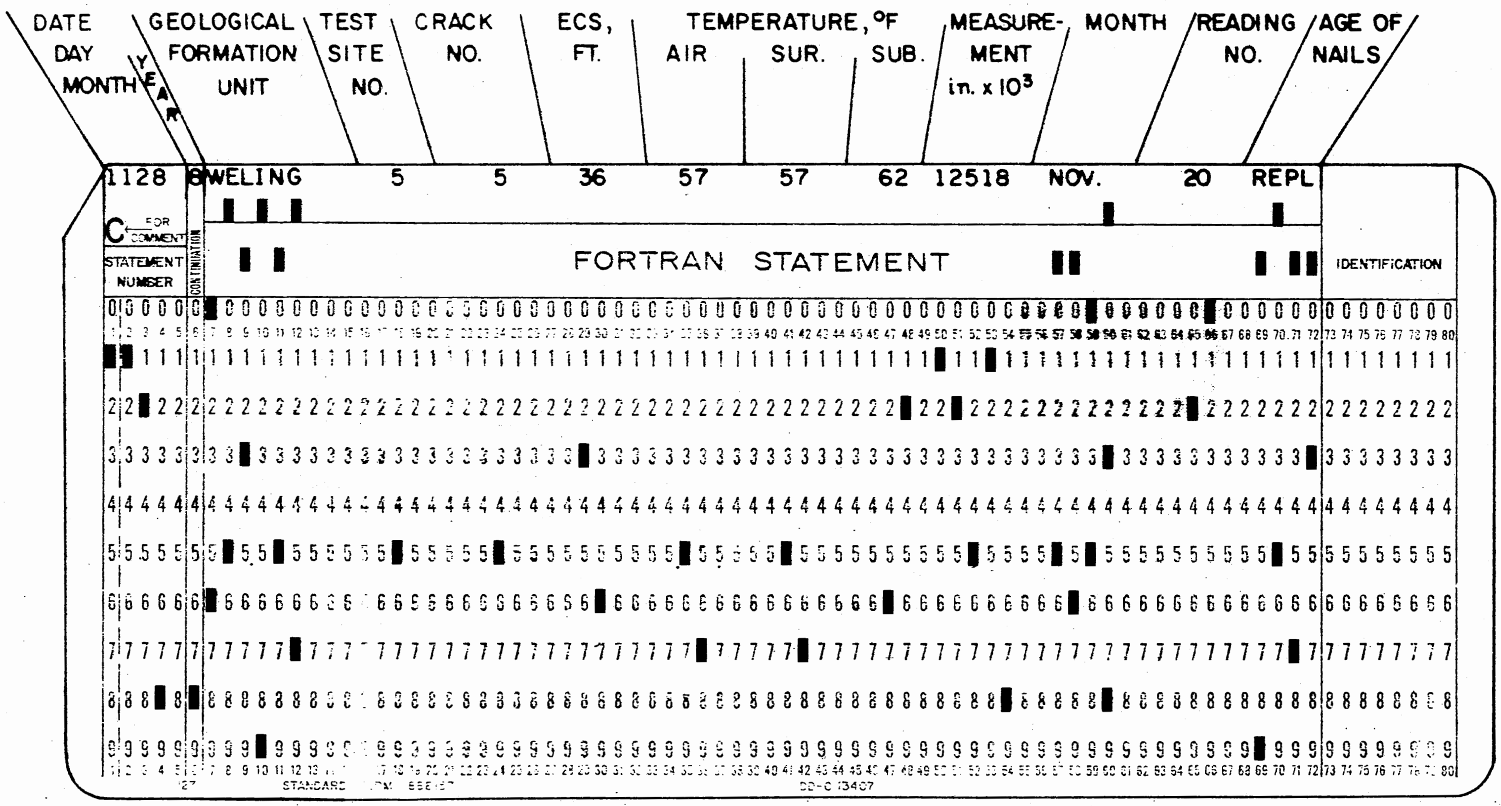


Figure 8. Computer Card with Transverse Crack Data

indicated a need for more information on the affect of crack spacing. Thus, test site No. 9 with a total of 46 cracks was added to the study.

Lost Nails. A major problem during the one year observation period was the loss of some of the nails or gage points at the cracks. Although the nails were driven flush with the pavement surface, snow removal equipment also removed a few of these nails. The nails at one test site location were covered with an asphalt overlay. As soon as the losses were discovered, the nails were replaced and new initial measurements made but all previous data at these locations were invalidated.

Vertical Deflections

Safety. The vertical deflection measurement procedure required more elaborate safety precautions. One lane of the highway was kept open to traffic while the other was blocked for the measuring operations. At sites with high traffic volumes, appropriate warning signs were placed at least 880 yd (805 m) in advance of the work area. The warning signs were followed by directional markers (traffic cones) and flagmen. The advanced warning signs were not required at test sites with low traffic volumes. After completing the deflection measurements in one lane, the directional markers were switched to permit work in the other lane. All traffic control was handled by ODOT personnel from the Research and Development Division and/or the respective Maintenance Division in which a test site was located.

Site Visit Schedule. Due to the difficulty in arranging cooperative field work as required for the vertical deflection measurements, a different schedule was adopted for these tests. Instead of the monthly schedule used for the horizontal displacement measurements, the vertical deflections at the respective test sites were measured only four times—during the winter, spring, summer and fall seasons of the year. These measuring operations were scheduled in advance with the Research and Development Division. Table XIV in Appendix B shows a copy of the tentative schedule that was sent to the ODOT. Measurements at the eight sites during a particular season were made within a one week period. This was an attempt to obtain the data under approximately the same environmental conditions at all the test sites.

Deflection Measurements. Having blocked the test lane to all vehicular traffic, the Benkelman beam was placed near the center line of the road with the beam point on top of one of the nails used for the horizontal displacement study (Figure 9). A dump truck loaded to 18,000 lb (8,165 kg) on its rear axle was positioned with its left rear dual tire about 3.0 in. (76 mm) from the beam point (Figure 10). The dial indicator on the beam was set to zero, as the initial beam reading (point 1 in Figure 11a). The first set of measurements was taken with the truck moving in the traffic direction. As the truck was driven slowly across the crack, readings were taken as it reached points 2 and 3. After the reading with the truck tire at point 3 was recorded, the dial indicator was again set to zero and a second set of readings were taken with the truck moving backward to check the initial set of readings (Figure 11b).

The "B" and "D" readings indicate the total amount of deflection of the pavement on one side of the crack under the loaded truck. The dial reading with the truck tire at point 2 is a measure of the amount of relative deflection between the crack sides as the load moves from one

Figure 9. Starting Position For Deflection Measurements

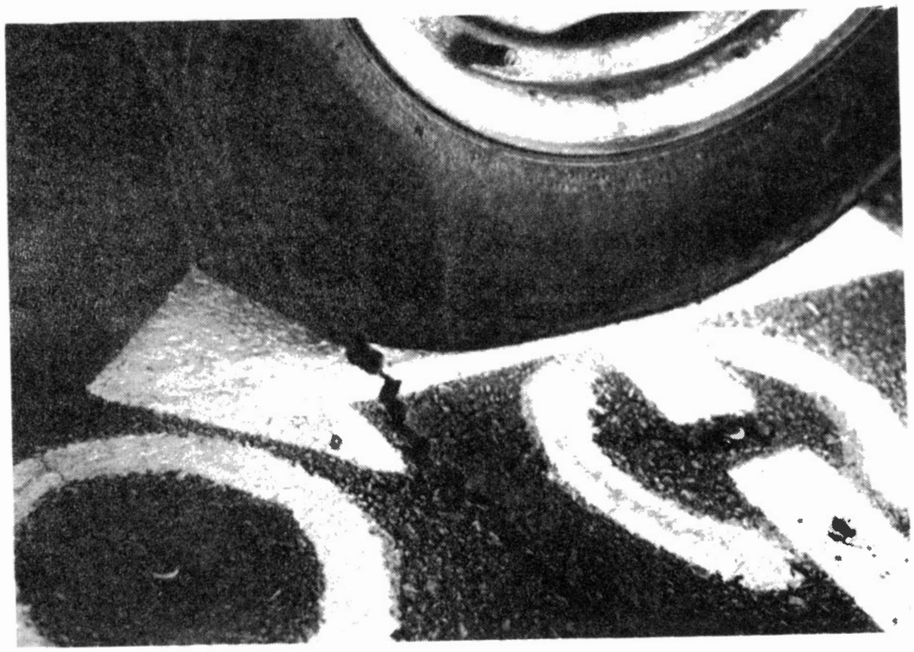


Figure 10. Tire Position for Vertical Movement Measurement

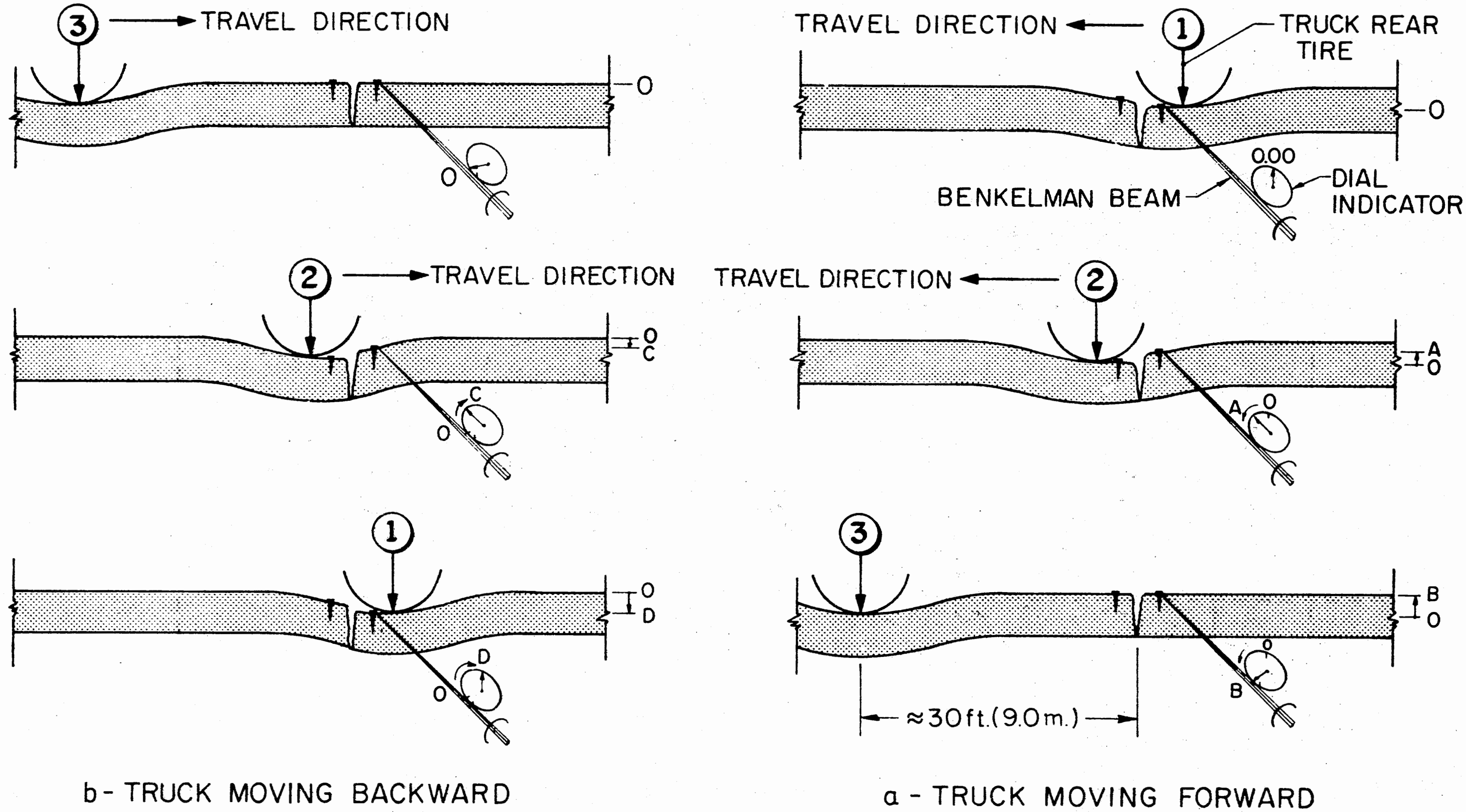


Figure 11. Schematic Showing Deflection Testing Procedure

side of the crack to the other. The relative deflection was obtained using an expression that averages three different measurements. From Figure 11, the total and relative deflections can be expressed as:

$$\text{Total Deflection, (T)} = \frac{B+D}{2}$$

$$\text{Relative Deflection, (R)} = 1/4[(\frac{B+D}{2} - C)+(D-C)+2A]$$

Deflection measurements were made at each of the five cracks at a test site. Temperature readings were also observed at the time of the deflection measurements in order to compare them with average temperatures from climatic records for a particular season of the year.

Deflection measurements with a Benkelman beam are normally made with the beam positioned between the dual tires of a loaded truck (Figure 12). To facilitate measurements during backward motion of the truck, the beam was placed to the side of the dual tires rather than in the usual position. A preliminary study at test site No. 3 indicated a negligible difference in readings with the beam placed between the dual tires and those with the beam placed to the side of the tires. This latter technique simplified the measurement procedure and required considerably less time to obtain the data.

Laboratory Test Procedures

Six sealing materials were initially selected for evaluation of the proposed laboratory tests. These materials included two asphalt cements, two cutback asphalt products and two asphalt emulsions. The selection was based on the more effective or more widely used sealants reported in the in-state survey. Two more sealants were added to the study in its latter stages. One of these was a special type emulsion which was

Figure 12. Deflection Measurements with the Benkelman Beam Positioned Normally

included at the request of the ODOT, and the other added sealant was a rubberized asphalt product. Sufficient quantities of these sealants were obtained from sources recommended by the Research and Development Division of ODOT. Table XVIII in Appendix D lists the types of sealants tested and their source.

Curing and Setting Studies

A basic problem involved in testing the liquid asphalt products was that of removing a major portion of the liquifying agent, i.e., the cut-back solvent and/or the emulsifying water. While the fluid consistency of these materials facilitates their application in cracks, the material cannot function as a sealant until "curing" or "setting" has occurred. Also, results of tests on the liquid cold-poured products could not be directly compared with the results for the hot-poured materials. Thus, it was necessary to test these materials in a condition approximating that of the base asphalt cement from which they were formulated.

Several ancillary investigations were made to study the curing and setting process of these liquid sealants. One of these studies involved placing the cutbacks in simulated cracks and oven drying the specimens at an expected maximum environmental temperature to ascertain the time required for field curing. The 6 in. (152 mm) long simulated cracks were made from lucite plates (Figure 13). Spacers of different thicknesses between the plates were used to form sealant specimens with a variety of widths and depths. After filling these "crack" molds with sealant, the molds were weighed and then placed in an oven at 150 F (65.56 C) for extended periods. The weight loss of the specimen was checked periodically. The same approach was employed but two asphalt

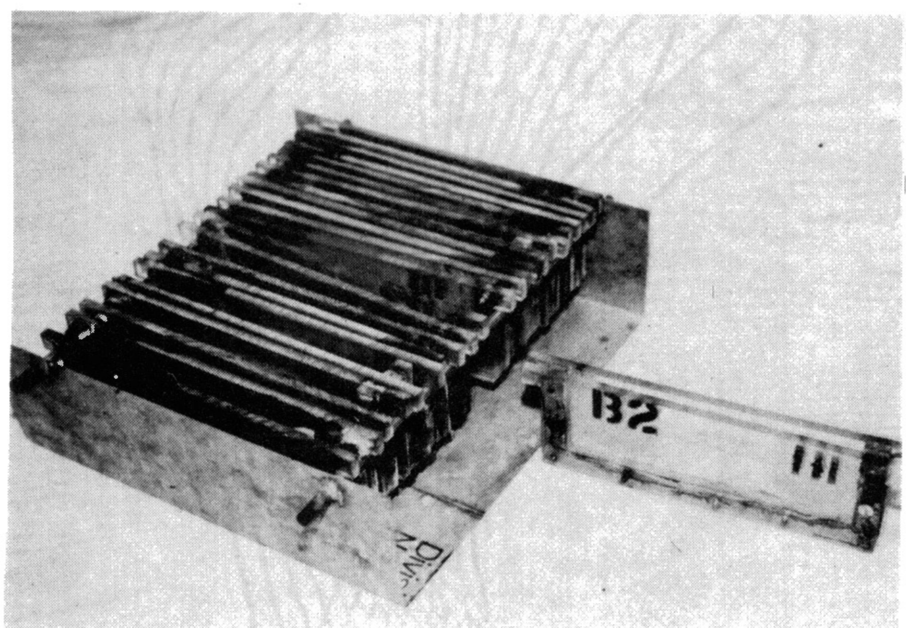


Figure 13. Lucite Plates Simulated Cracks Used for Liquid Sealants Curing and Setting Study

concrete blocks were used to form the simulated crack molds. Because leaking of the sealant from the blocks during oven exposure was a major problem, new test samples were cured at laboratory temperature and subjected to a draft from an oscillating fan.

Additionally, samples of the two cutback products (MC-800 and MC-3000) were placed in shallow, 5.55 in. (141 mm) diameter pans. These samples with a large surface area to depth ratio were oven cured at 150 F (65.56 C). The weight loss with time of curing for these samples was monitored and the results used to establish a relationship between this rapid curing procedure and the curing behavior of the cutback products in the simulated cracks.

Sample Preparation

Standard test procedures (13) for cold-poured type concrete joint sealers and the preliminary curing and setting studies indicated that test specimens of the liquid sealants be prepared from materials from which a major portion of the solvents had been evaporated. This necessitated the development of equipment and procedures for accelerating this evaporation process. This equipment is shown schematically in Figure 14 and Figure 15 is a photograph of the equipment.

Approximately 600 g of the liquid sealing materials were placed in a metal beaker 4.5 in. (114 mm) in diameter and 5.5 in. (140 mm) in height. The beaker was inserted in the oil bath maintained at a high temperature by an electric heater. During the heating period, the sealant was stirred continuously at the rate of 120 rpm with a small metal paddle attached to a 110V mixer. The cutback products were heated to a temperature of 225 F (107 C) for a period of 12 hr. To avoid foaming of

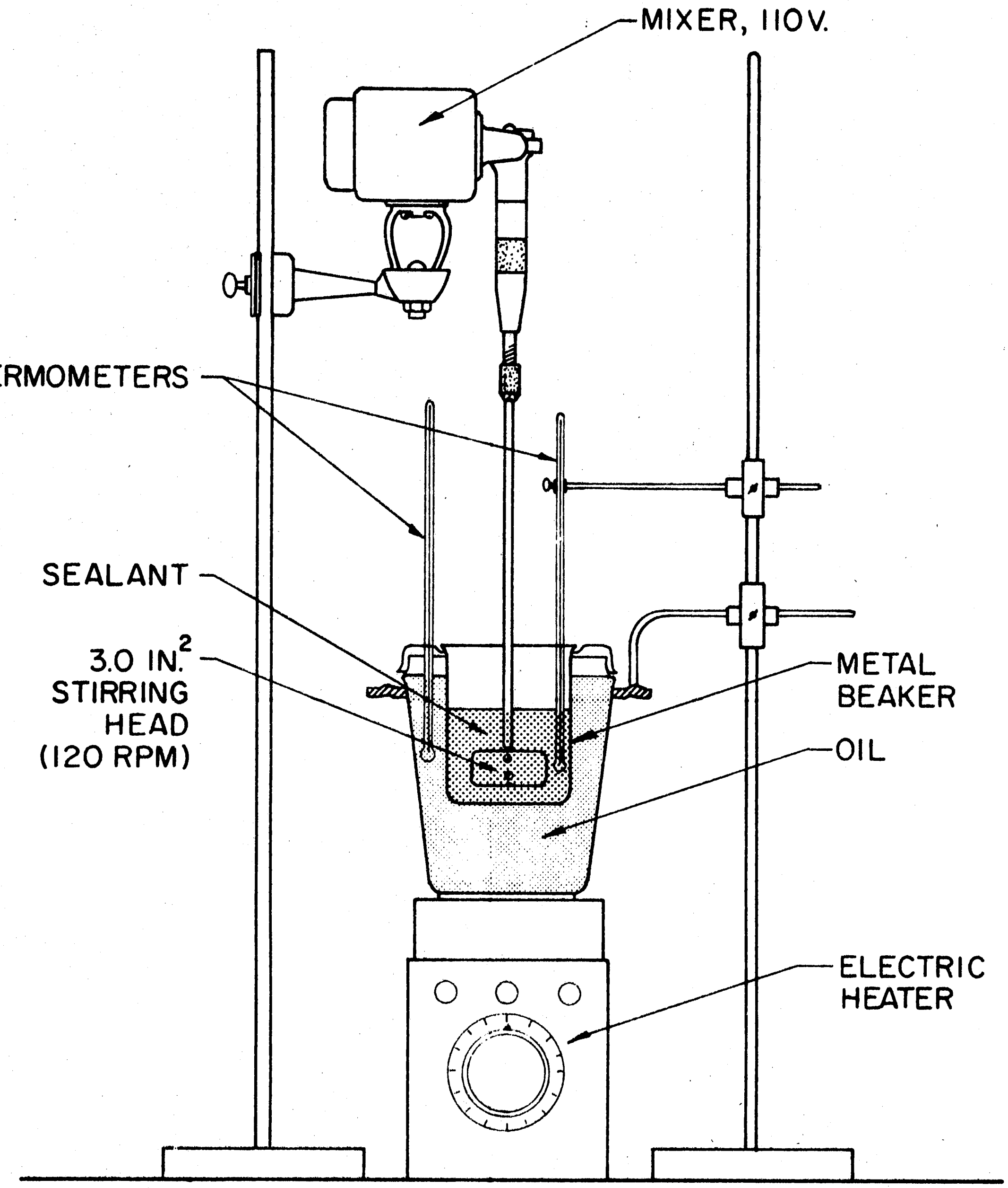


Figure 14. Sealant Evaporation and Heating Equipment

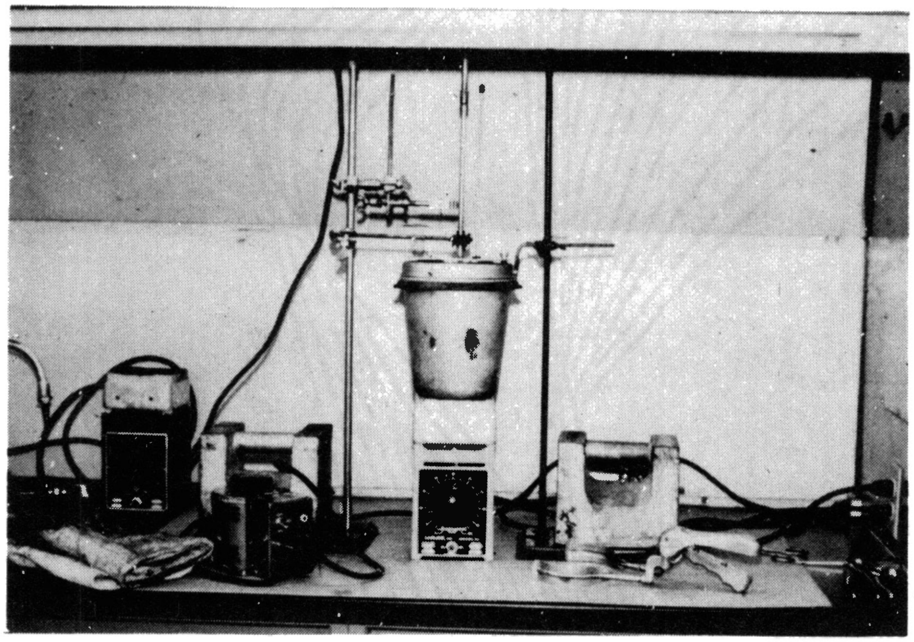


Figure 15. Sealant Evaporation and Heating Equipment (photo)

the emulsions, these products were heated to 190 F (88 C) for a period of 15 hr. This procedure was carried out with the heating equipment housed in a fume hood. A major portion of the cutback's solvents (8.5 percent for MC-3000 and 11 percent for MC-800 by weight) and all the emulsifying water was removed from the liquid sealants by this process.

The same heating unit was used for heating the cured sealants and the semi-solid sealing materials to the required pouring consistency. All sealants, except the rubber asphalt product, were heated to 326 F (163 C), the temperature specified for heating concrete joint sealers (13). Upon reaching this temperature the container was immediately removed from the bath and portions of the material were poured into molds and cans for testing. The supplier of the rubberized asphalt sealant recommended that the material be slowly heated to approximately 175 F (79 C) but a higher temperature, 250 F (121 C) was necessary to obtain suitable pouring consistency.

Bond-Ductility Test

The Bond-Ductility test was considered the most important of the laboratory tests performed. Specimens of the sealers were placed between two bituminous concrete blocks (Figure 16). These test specimens were cooled to a temperature of 0 F (-17.8 C) and the blocks were slowly moved apart, using an extensometer device designed and developed for this study (Chapter V). This test temperature was based on a study of Oklahoma climatological data (32). An extension rate of 0.125 in./hr (3 mm/hr) which had been used by many previous investigators (12) (14) (16) was applied to the sealants by the extensometer.

The 6 in. (152 mm) length of the test blocks was based on Cook's

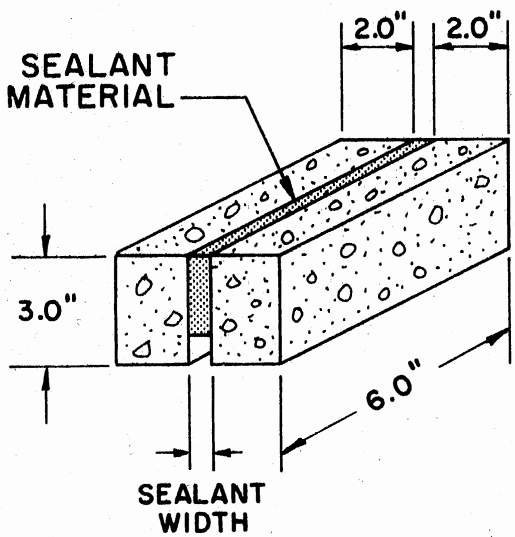


Figure 6. Bond-Ductility Test Blocks

recommendation (18). Several widths and depths of sealant were tested to study the effect of shape factor on sealant performance (15). Dimensions of the test samples of sealant between the asphalt concrete blocks were:

1 - 0.125 in. width x 2.0 in. depth (3 mm x 51 mm)

2 - 0.25 in. width x 2.0 in. depth (6 mm x 51 mm)

3 - 0.25 in. width x 1.0 in. depth (6 mm x 25 mm)

Asphalt-Block Preparation. The blocks used in this study were prepared from reheated type 'C' asphalt concrete surface course mixture obtained from a hot-mix plant in Oklahoma City. The mixture contained 5 percent by weight asphalt cement and the gradation analysis of the extracted aggregate is shown in Figure 39, Appendix D. The hot mixture was hauled from the plant to the laboratory in insulated drums and then divided into 6,000 g batches which were placed in paper bags. After cooling, the sacked batches were stored to await compaction.

A 6000 g batch of mix was heated to 250 F (121 C) and then compacted into rectangular bars 12 in. long, 4 in. wide and 3 in. thick (305 x 102 x 76 mm). The compacted density of these bars was about 94 percent. A kneading compactor conforming with ASTM D-1561 (13) was used. The compactor was modified to mold the rectangular bars. A 2 x 4 in. (51 x 102 mm) steel tamping foot was mounted on the booster ram and a specially designed cranking carriage with a rectangular mold replaced the turntable on the machine. The procedure used for fabricating the asphalt concrete bars and details of the compacting machine are shown in Figures 40, 41, 42, 43 and 44, Appendix D. Compacted specimens were removed from the mold and transferred to a smooth flat sheet of plywood where they were allowed to stand for one day at room temperature. The bars were then cut into four equal size blocks using a masonry saw (Figure 45, Appendix D). These blocks were then washed, dried and stored prior to assembly and pouring of the sealants.

Test Specimens. Two blocks were assembled with rough (uncut) sides facing each other to form a test specimen. An aluminum spacer was placed between the two blocks to create an open space approximately 6 in. (152 mm) long. Spacers of different thickness and height were used to obtain the required sealant dimension between the blocks. Masking tape was used to hold the blocks in position and to prevent any leakage (Figure 17). The hot sealant was poured into the space between the blocks in sufficient quantities to fill the simulated crack flush with the surface of the blocks. A 50 cc ($5 \times 10^{-5} m^3$) glass syringe was employed in placing the sealant into the 0.125 in. (3 mm) wide crack specimens. The rubberized asphalt sealant had to be placed in the specimens with a heated spatula. Three test specimens for each of the three sample dimensions were prepared from the respective sealant materials. The specimens were allowed to stand at room temperature for 48 hr, then any excess material was trimmed and the spacers were removed. The specimens were then stored in a low-temperature cabinet at 0 F (-17.8 C) for testing.

Extension at Low Temperature. Six specimens having the same width and depth of sealant were removed from the low-temperature storing cabinet and immediately mounted in the clamping frames of the extension machine (Figure 18). These sealant specimens were then extended to 100 percent of their original width at a uniform rate of 0.125 in. (3 mm) per hour. During extension the temperature surrounding the test

Figure 17. Specimen Preparation for Bond-Ductility Test

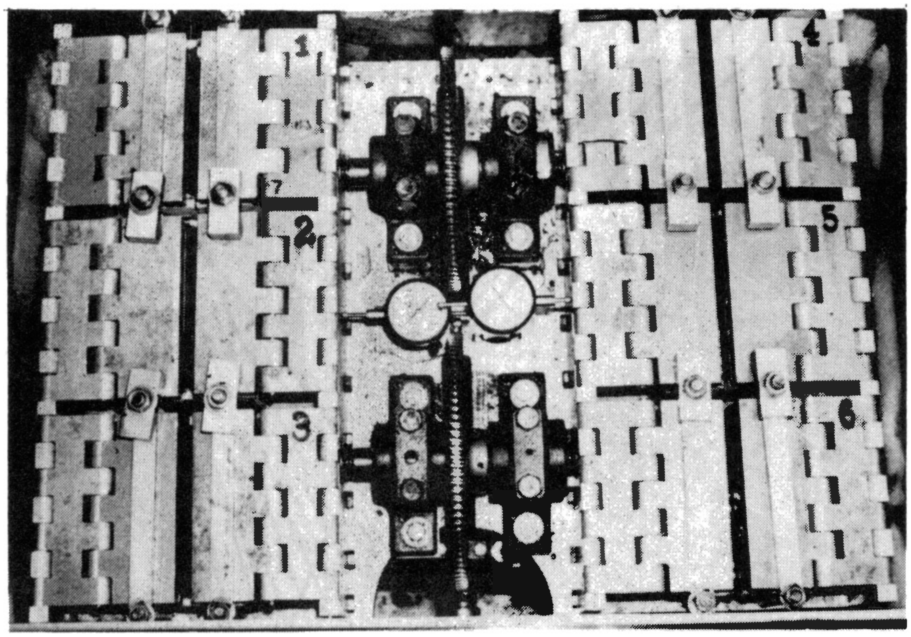


Figure 18. Bond-Ductility Machine Stretching Six Sealant Specimens

specimens was maintained at 0 ± 1 F (-17.8 ± 0.5 C). The condition of the specimens was checked and recorded periodically during extension and closely examined at the end of each test cycle for any signs of failure.

Compression. After extension, the specimens were removed from the clamping frames of the machine and the original width spacers were placed between the blocks. The specimens were turned on their sides and allowed to warm for two hours at room temperature. The warmed specimens were then inserted in a jacking frame and slowly compressed to their original width. Figure 19 shows a specimen being compressed in the jacking frame.

Failure Criteria. An extension followed by compression constituted one complete cycle for the specimens used in the Bond-Ductility test. Testing cycles were repeated until failure occurred in the specimens and the results were recorded as the number of cycles to failure. After removing the specimens from the extension machine, they were thoroughly examined for separation within the sealant (cohesion failure) and between the sealant and the blocks (adhesion failure). Development of surface crazing or cracking, opening in the sealant or any separation between the sealant and the asphalt blocks extending for 15 percent (approximately 25 mm) or more of the specimen length constituted failure. Although difficult to distinguish, Figure 20(a) shows a typical cohesive failure in a specimen and Figure 20 (b) shows a brittle type of cohesive failure that was frequently encountered.

Penetration Test: (ASTM D 3407-75T)

This is a tentative test (13) used to provide a measure of sealant consistency. It is similar to the standard penetration test except that

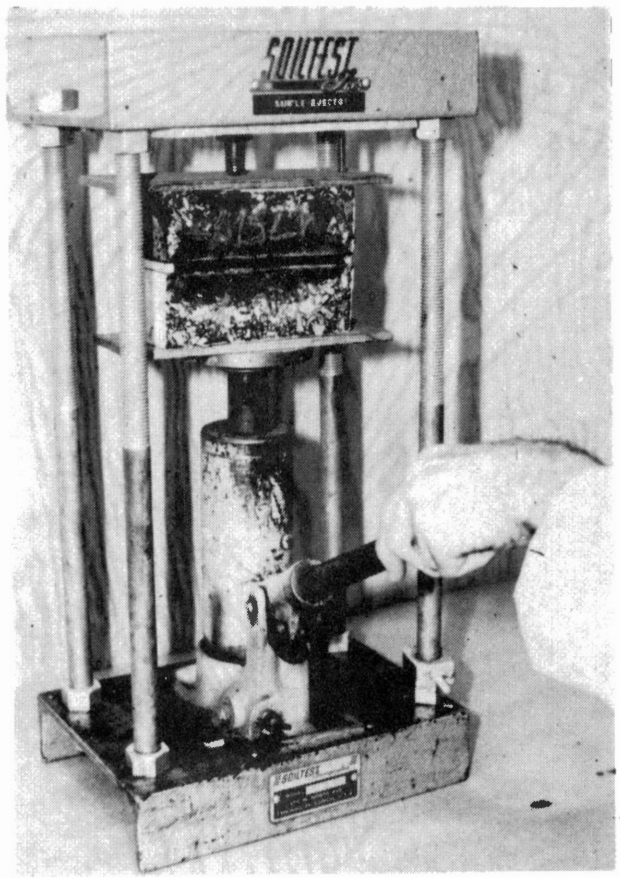
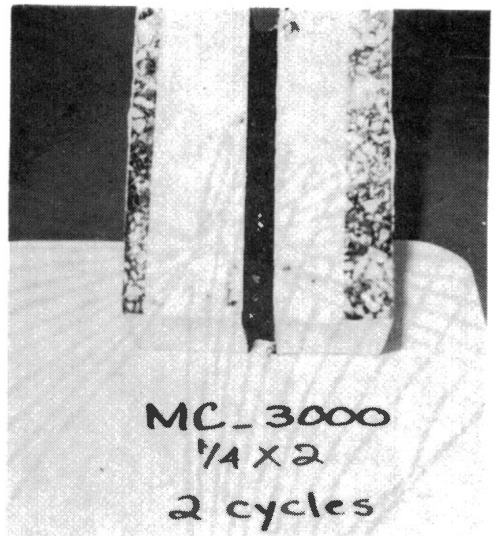
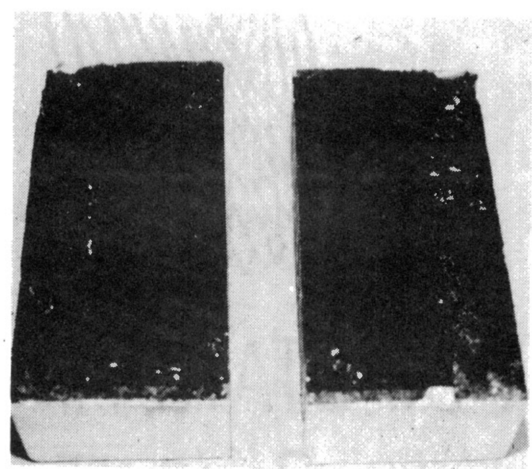


Figure 19. Jacking Frame for Specimen Recompression



(a) Cohesion Failure



(b) Brittle Failure (Glossy Conchoidal Fracture Surface)

Figure 20. Sealant Failures in Bond-Ductility Test Specimens

a specially dimensioned cone is used instead of the penetration needle (Figure 21). Other consistency tests were also conducted on the selected sealants. The kinematic and absolute viscosity values of these materials were reported along with the cone penetration values.

Resilience Test: (ASTM D 3407-75T)

This test was performed as described in the ASTM Standards (13). The test is performed using a ball penetration tool and the results are reported as the recovery percentage or percent of recovered depth of penetration. Resilience values provided an indication of the elasticity of the sealant materials.

Flow Test: (ASTM D 3407-75T modified)

This test is designed to show the mobility or flow characteristics of a sealer at a temperature of 140 F (60 C). The test was initially performed as outlined in ASTM standards (13). Results could not be reported due to rapid and extensive flow of the selected sealants on the 75 degree inclined panel (Figure 22). Some modifications had to be made to make the test more suitable for the variety of sealant types used in the study.

A new supporting frame with a 15 degree angle of inclination was used (Figure 23). The panels on the supporting frame were placed in a 140 F (60 C) oven and the change in length of the sample with time was monitored. A plot of the change in length of sample versus time was made and the flow value for a sample was taken as the slope of this curve.

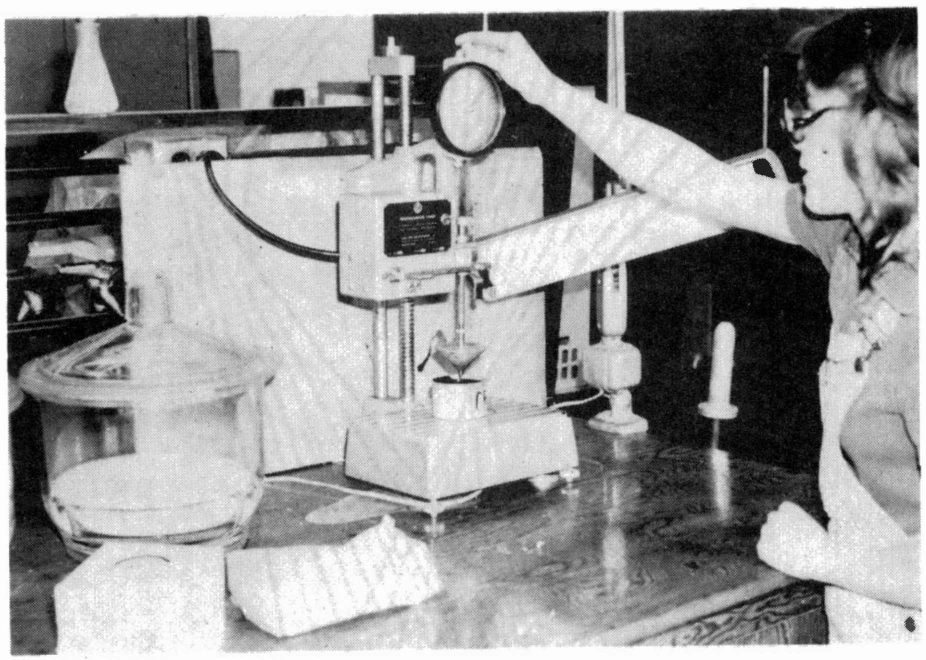


Figure 21. Penetration Test for Sealants using a Penetration Cone

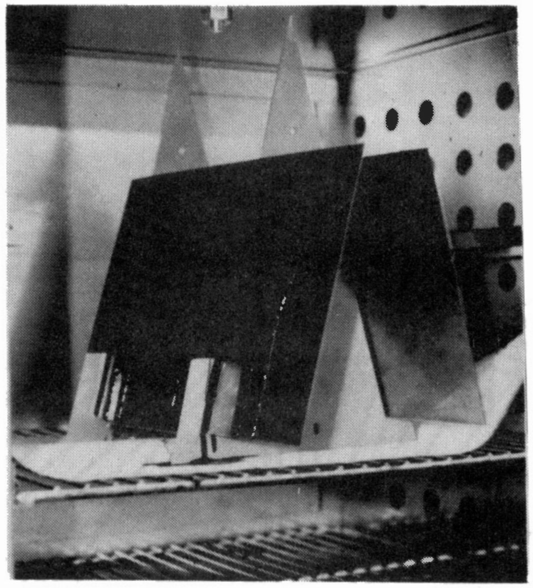


Figure 22. Flow Test at 75 Degree after 10 Min.

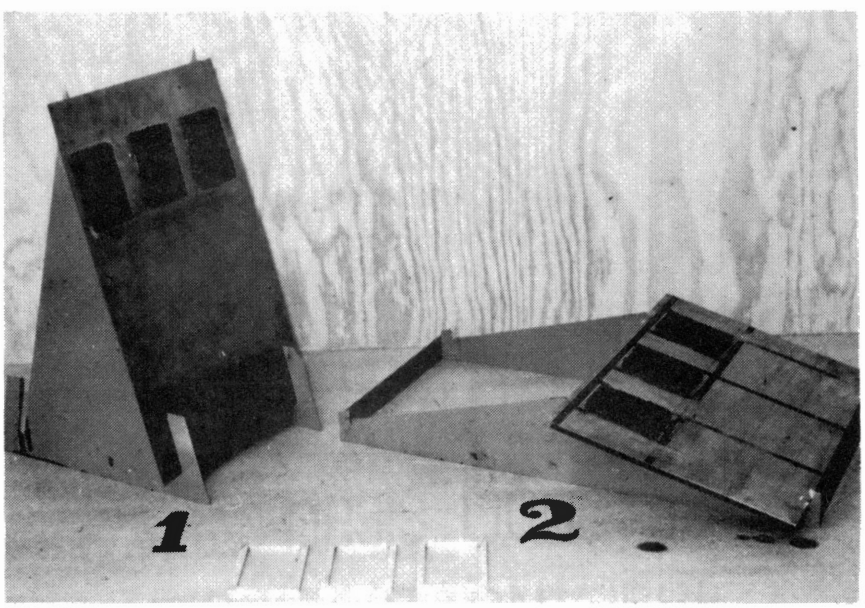


Figure 23. Standard and Modified Flow Test Panels

Volume Change Test

The purpose of this test was to determine the approximate amount of shrinkage or reduction in volume of the cold-poured sealants that occurred during the curing or setting process. Two different methods were used for this test. The procedure used with the cutbacks was not suitable for the emulsions due to the difficulty in determining the volume change in the emulsions.

Cutbacks (Federal Specification SS-S-195B - modified. The change in volume for the cutback sealants was determined using a procedure similar to that stipulated in Federal Specifications for cold applied concrete joint materials (19). A 1.5 ounce ($44x10^{-6}m^3$) calibrated glass jar is filled flush to the top with the sealer. After determining the material's original volume, the jar is placed in a 158 F (70 C) forced draft oven for 170 hours. The sealant is then cooled in air for 1 hour. The change in volume is compared with the original volume and the result is reported in percentage as the shrinkage value of the sealant.

The specified test procedure was slightly modified so available equipment in the O.S.U. Civil Engineering Asphalt Laboratory could be used. A 0.5 gallon ($1.9x10^{-3}m^3$) jar with rubber gasket, conical cap, and a hose connection was used instead of the suggested weight-per-gallon metal cup. To evacuate entrapped air which might influence accuracy of the results a vacuum pump was used. For comparative purposes, volume changes in both the asphalt cements and the rubberized sealant were determined using this testing procedure.

Emulsions. The loss of water in the setting process is the prime reason for shrinkage in asphalt emulsions. Weight was monitored during the preparation process in the heating unit. When all the water was driven out, the weight loss was compared to the original weight of the material. This was reported in percentage as the material-volume change, assuming the specific gravity for the tested emulsions to be 1.0. This was considered a very reasonable assumption on the basis that the major components of these materials (asphalt cement and water) both have a specific gravity near 1.0.

Compatibility Test: (ASTM D 3407-75T)

Asphalt products from different sources may not be compatible with each other. That is, their different chemical compositions are such that they cannot be placed together without the occurrence of harmful reactions, primarily exudation or fluxing. Thus, crack sealants can react with the asphalt binder in the pavement to reduce the effectiveness of the seal. The test consists of pouring the sealants in a groove cut into the top surface of asphalt concrete test specimens. The specimens and applied sealants are placed in a 140 F (60 C) oven for 72 hours, removed and allowed to cool and then examined for any deleterious effects. Results were reported on a pass or fail basis.

CHAPTER VII

RESULTS AND DISCUSSION

Horizontal Movement

The measurements of horizontal movement at transverse cracks were used as input data for a statistical regression analysis. The Statistical Analysis Systems (SAS) computer program (31) was used to develop several mathematical functional relationships between the horizontal movement and the influencing variables. The following model form was used to study the general effect of the temperature and ECS factors on crack movement:

$$Y = f(T,\ ECS,\ ECS^2).$$

where Y = crack movement, in.$\times 10^{-3}$.

T = temperature, F.

ECS = Effective Crack Spacing, ft.

Also, several models of the form:

$$Y = f(T, ECS,\ ECS^2,\ GFU)$$

where GFU = geological formation unit.

were developed to analyze the effect of the geological formation underlying a cracked section of the pavement.

The SAS program was also used to conduct tests for evidence of real differences in the observed values. The results of these tests indicated the observed significance level and acceptance or rejection of the null-hypothesis (no-difference) was based on a reasonable significance level value of 0.05. Because measurements were taken from the same cracks during the study and not from randomly selected cracks each time, it was suspected that the magnitude of the experimental error would be reduced. Smaller experimental errors give smaller observed significance levels and a tendency to reject the null-hypothesis. This usually becomes critical when the observed significance level is close to the rejection level. Fortunately, the observed significance levels in this study were either very high or very low, and this problem was not encountered. The results of this analysis and the correlation studies with the three affecting factors (temperature, effective crack spacing and geological formation unit) are discussed below.

Temperature

Based on a preliminary study of the relationship between the crack movement and the recorded temperatures, the analysis of the temperature affect was made using only the subsurface pavement temperature. This study indicated that correlation with subsurface temperature was higher than with either air temperature or the pavement surface temperature. This had been expected because temperature measurements for both air and pavement surface were influenced by ambient conditions not considered, i.e., wind velocity and solar radiation. Also, there is an inherent lack of reliability in measured surface temperatures due to factors discussed by Straub (27).

Point of Curvature: Inspection of the scatter diagrams for subsurface temperature versus movement suggested the possibility of a skewed relationship for the data obtained during the warming cycle of a given pavement section (Figure 27). The heating line appears to have an inflection point at some particular temperature. This phenomenon was reported by Littlefield (33) in his investigation of the thermal expansion behavior of asphalt concrete materials. He also found that differences in grade and source of asphalt cement yielded different temperatures for the beginning of the curved portion of the plot which he called the point of curvature (PC).

It is thought that the following factors, either separately or jointly, are responsible for this phenomenon. (1) Because asphalt is a viscoelastic material, it has the characteristics of a solid at low temperatures. At high temperature it responds as a viscous liquid and, since asphalt concrete is a mixture of asphalt cement and graded aggregate, the transition point between these two states in the mixture is not sharp. At low temperatures, the length of a sample varies linearly with temperature. At high temperature, the asphalt acts as a liquid and does not transmit the expansion forces but rather tends to flow from points of high pressure towards lower pressure areas. In doing so, it extrudes laterally and the longitudinal expansion of a sample is greatly reduced. Thus, the expansion in the longitudinal direction would be primarily due to expansion of the aggregate in the sample. Even though the absolute volume does increase with temperature, at high temperature it is accompanied by a different rate of change in length. (2) Particulate materials (sand, spawl from crack sides, etc.) partially fill the opened crack and then provide compressional resistance when the adjacent pavement sections expand and the crack begins to close. This reduces the rate of change of crack width during a warming cycle.

The PC points were determined for each site using a computer

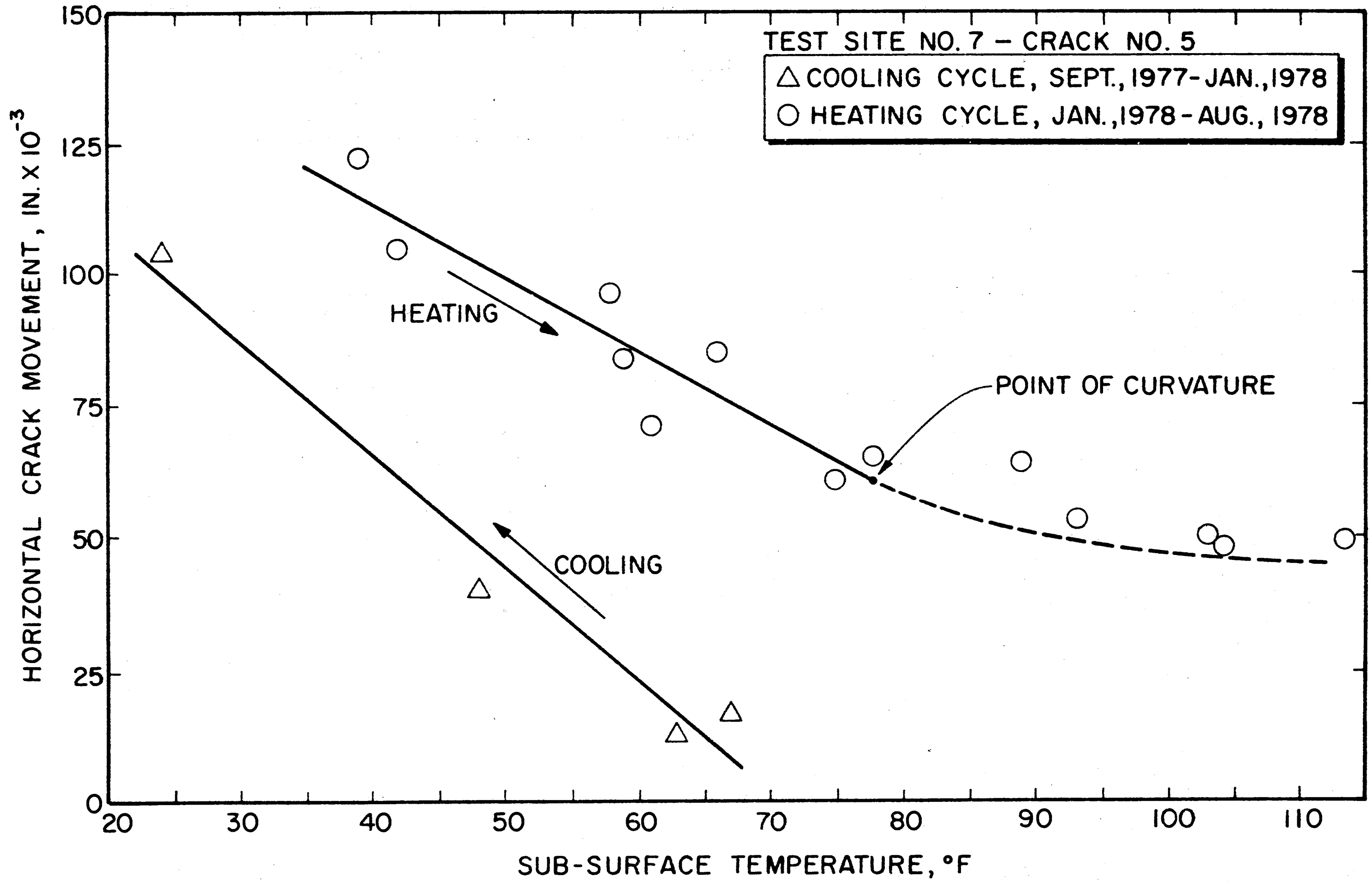


Figure 24. A Scatter Diagram for Relationship Between Horizontal Movement and Pavement Sub-Surface Temperature

program to solve equations derived by Holbert and Broemeling (34). Results were obtained in the form of a probability associated with each of the measured temperatures corresponding to the PC in a given test site. The average PC temperatures are given in Table IV, which lists the points with the highest probability. Table III in Appendix B shows a summary of the computer results.

The average amount of crack movement that takes place between 0 F (-17.8 C) and the PC temperatures are shown in Table II. Approximately 80 percent of the total movement at a crack occurs between these two temperatures. This percentage of movement is very close to what Littlefield found in his study (33). This strongly implies that the temperature of the PC is closely related to the properties of the asphalt concrete material.

Only measurements associated with subsurface temperatures colder than at the PC of each site were used to fit the regression models for the study. Measurements at temperatures higher than at the PC were not included, because the movement behavior of the cracks were completely different in these two regions.

Temperature Effect: Temperature had a very significant affect on crack movement. The regression lines, coefficient of determination (R^2) and observed significance level ($\hat{\alpha}$) for the temperature affect are illustrated in Figure 25. Extrapolating the regression lines to 0 F (-17.8 C), based on Oklahoma climatic data, the average amount of opening is about 0.25 in. (6 mm).

It is interesting to note that measurements taken during the cooling period (September through January) were smaller than the ones taken at

TABLE IV

TEMPERATURES AT THE POINT OF CURVATURE FOR TEST SITES

Site No.	Temperature at Point of Curvature, °F
1	63
3	88
4	88
5	74
6	75
7	78
8	67
9	79
Average	77

TABLE V

AVERAGE AMOUNT OF HORIZONTAL CRACK MOVEMENT BELOW PC TEMPERATURE

Site No.	Crack* Movement at 0°F in.X10^{-3}	Crack Movement at PC in.X10^{-3}	% Of Movement Below PC Temp.	Average %
1	143	28	80	
3	105	16	85	
4	367	0	100	
5	235	49	79	83
6	221	8	96	
7	266	23	91	
8	142	0	100	
9	198	129	35	

*Estimates based on Mathematical Model

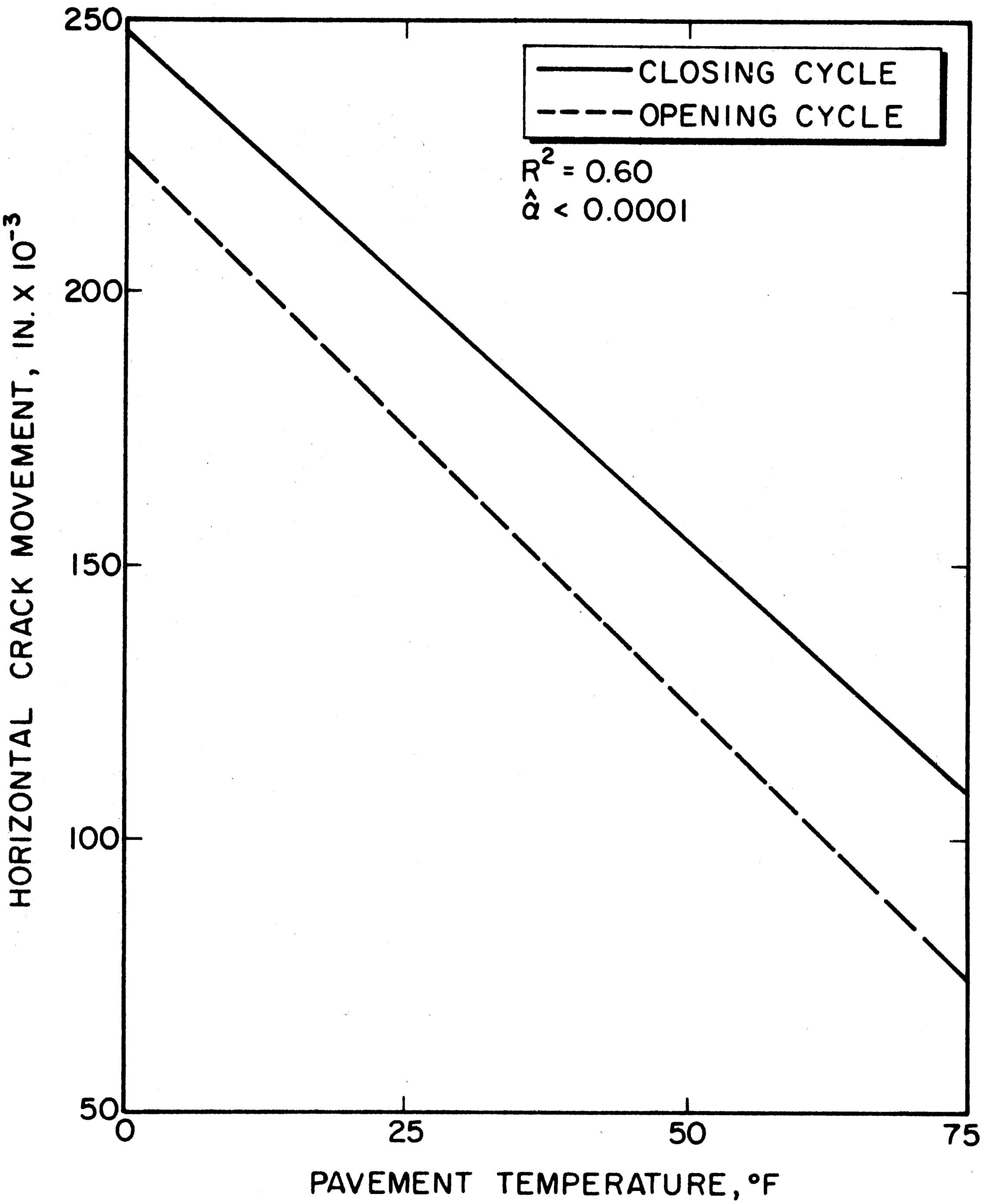


Figure 25. Relationship Between Pavement Temperature and Horizontal Crack Movement (Max. ECS=123 ft)

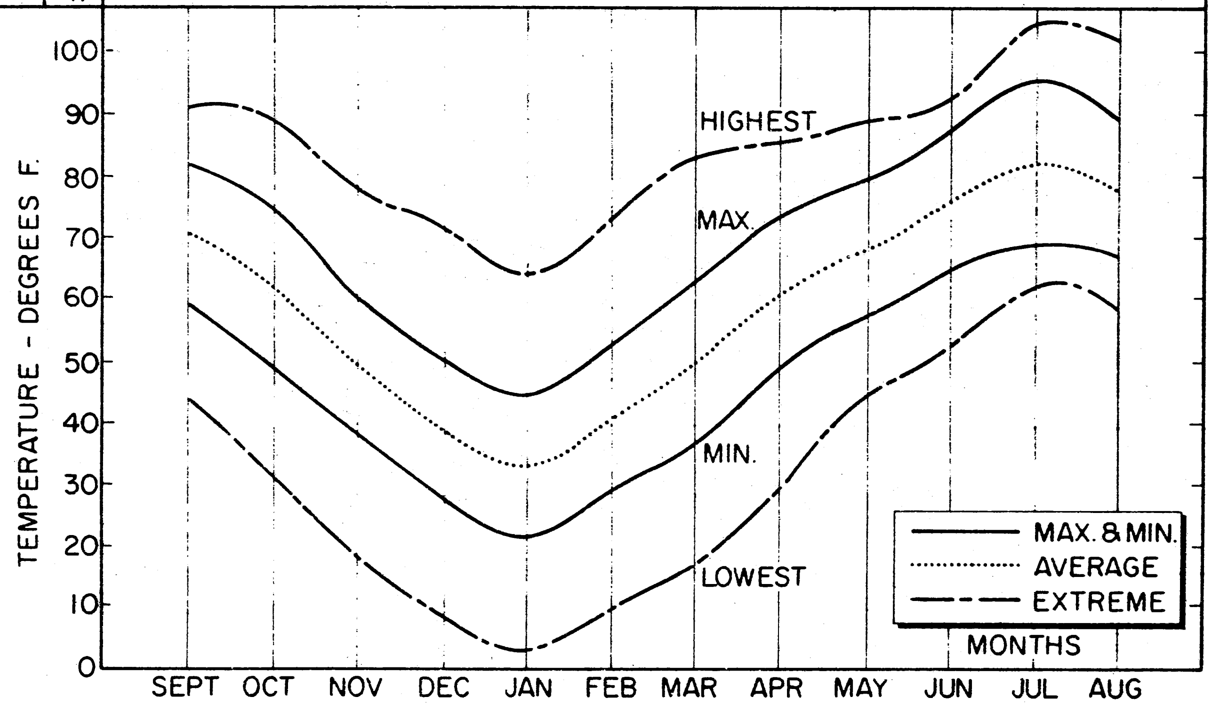
comparable temperatures during the heating period (January through August). This is illustrated in Figure 24. The existence of two lines was highly significant ($\hat{\alpha}$=0.0001). Also the lines were significantly not parallel to each other ($\hat{\alpha}$=0.03). These results indicate that the opening "potential" is greater than the closing "potential". That is, a crack will not close to its original width of opening. A permanent increment in crack width will remain after each yearly cooling and heating cycle. The average amount of the permanent opening during a one year cycle was found to be about 0.03 in. (0.8 mm).

This concept of a permanent increment of crack width helps to explain why cracks that usually start as unseen hairline cracks develop with the years into relatively wide ones. Littlefield (33) reasoned that this was the result of densification in the asphalt concrete material due to the cooling and heating cycles.

Climatic Data: Recorded temperature information (32) from stations located close to the test sites were averaged for a five year period to correlate the model temperatures with respective months of the year. Figure 26 shows that temperature changes uniformly from its highest in July to its lowest in January. This figure also indicates that minimum air temperatures experienced during January and February may be maintained long enough for the pavement to cool to 0 F (-17.8 C).

Figure 27 shows the results of applying the average monthly temperature data to the general movement model. Since the usual time for applying crack sealants is in the fall, this plot indicates that the applied sealants are subjected to almost equal amounts of extension and compression. This important fact was not taken into consideration in any of the cited laboratory bond ductility testing procedures.

NO. OF DAYS MAX. TEMP. °F	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
≥90	5.6	0.98	0	0	0	0	0.1	0.1	2.2	11.1	26.7	22.9
≤32	0	0	0.6	1.3	7.1	3.1	0.2	0.1	0	0	0	0



NO. OF DAYS MIN. TEMP. °F	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
≤32	0	1.4	9.7	22.2	25.6	18.6	10.3	1.5	0	0	0	0
≤0	0	0	0	0	0.7	0.2	0	0	0	0	0	0

Figure 26. Relationship Between Average Climatic Temperatures for Test Locations and Months of the Year (Average for 5 Years, 1974-1979)

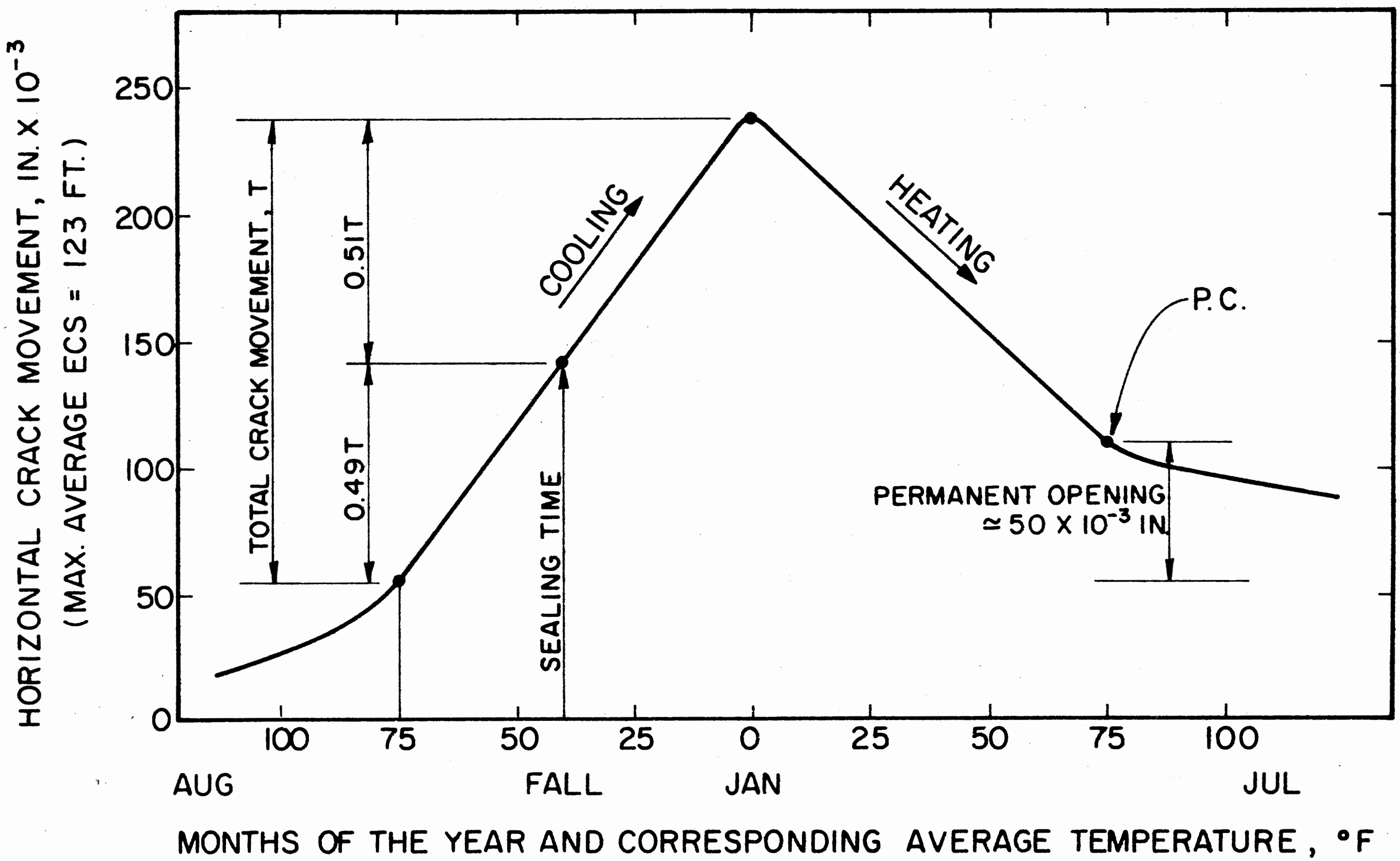


Figure 27. Relationship Between Horizontal Crack Movement and Average Seasonal Temperature

Effective Crack Spacing (ECS)

As can be seen in Figure 28, the amount of crack movement increases with increasing values of ECS ($\hat{\alpha}$=0.0001), till it reaches a peak between 100 and 125 ft (31 and 38 m) and then the movement decreases. The ECS^2 term in the model was highly significant with an observed significance level equal to 0.0001.

Since the road surface is more or less bonded to the underlying base course, these results indicate that the freedom of movement of the asphalt concrete surface is reduced by frictional forces. These frictional forces will increase as the length of paved surface increases until horizontal movement is stopped. The average amount of movement per inch of surface length per degree F was calculated for each test site and these values are presented in Table VI. Comparable figures of the coefficient of thermal expansion for bond free asphalt concrete surfacing (33), were about three times higher than the tabular values. The difference is due to the developed frictional forces, which depend on the bond between surface and base as well as the stability of the base course.

The resistance to expansion movement will produce compression stresses and the resistance to shrinkage movement will produce tensile stresses in the surfacing material. In cold weather if the effective crack spacing is large, these stresses will be great enough to cause another crack at approximately the midpoint between adjacent cracks. This new crack will reduce the ECS and the tensile stresses. However, if the reduced stresses are still greater than the tensile strength of the asphalt concrete surfacing, additional midpoint cracks will develop.

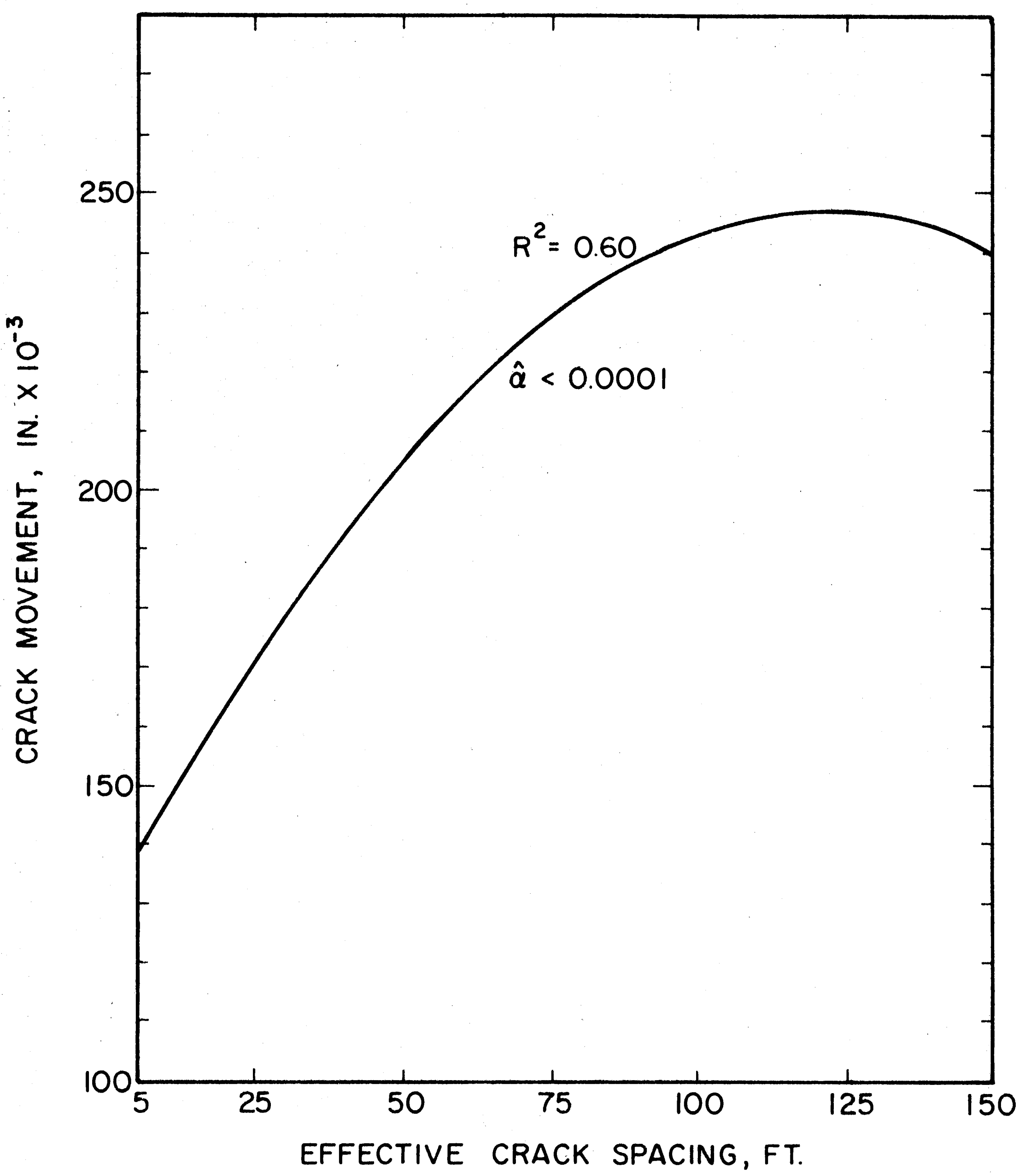


Figure 28. Relationship Between Effective Crack Spacing and Horizontal Crack Movement

TABLE VI

AVERAGE HORIZONTAL CRACK MOVEMENT PER INCH OF PAVEMENT LENGTH PER DEGREE FARENHEIT

Site No.	Average ECS, ft.	Movement at 0°F, in.X10^{-3}	Average Movement/°F=in., in.X10^{-6}
1	35	143	5.206
3	40	105	2.270
4	105	367	2.496
5	63	235	3.020
6	55	221	3.889
7	81	266	2.295
8	25	142	12.470
9	40	198	2.204

Results of a correlation study to investigate the general trend of the crack movement with test site average ECS values from Table VI indicated a coefficient of determination (R^2) equal to 0.89 (Figure 29). This is a very strong relationship. The amount of crack movement at 0 F was found to increase as the pavement section average ECS increased. This result emphasizes the previous discussion about the additional crack development mechanism to reduce movement stresses.

Geological Formation Unit (GFU)

The variation between the study sections or test sites was highly significant ($\hat{\alpha}$<0.0001). This variation is thought to be due to differences in one or more of the following: 1) location or climatic affect, 2) initial crack widths, 3) surface and base type and thickness, 4) construction and maintenance history, and 5) geological formations underlying the cracked sections. The influence of only the latter of these factors was investigated in this study.

Site No. 3 and four other test sites were located on the Wellington geological formation. The asphalt surface at this site was an overlay on an old section of Portland cement concrete pavement. The analysis of variance showed that this section differed significantly from other sites on the Wellington formation and also from all other sites on flexible bases ($\hat{\alpha}$<0.0001). The results of this analysis indicate that site No. 3 should not be grouped with the other Wellington sites but given a classification of its own with no regard to geological formation.

Geological formation unit terms were introduced in the model to study their effect on the behavior of the cracks. Each GFU was given a separate designation term. Test site No. 3 on the Wellington formation

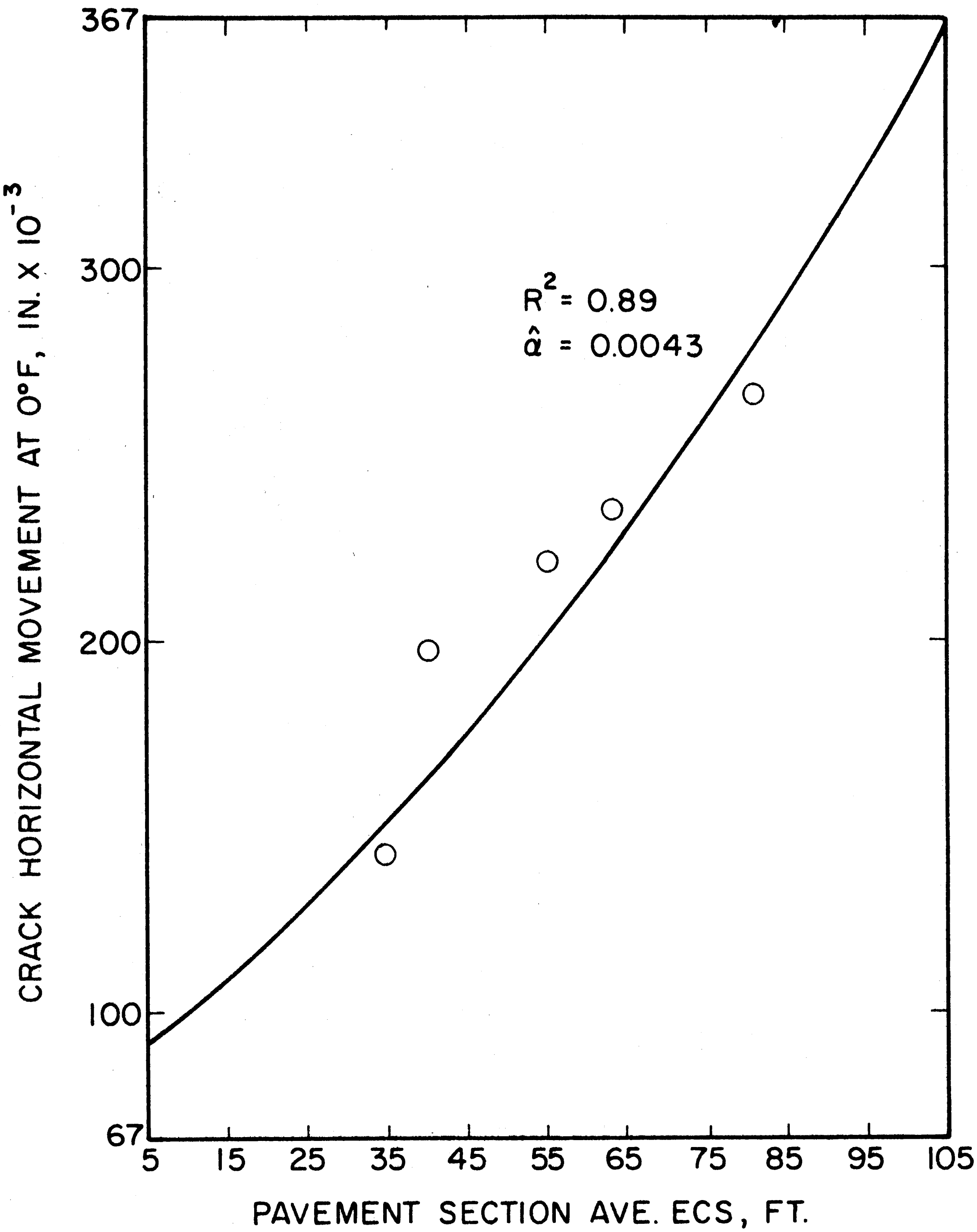


Figure 29. Relationship Between Horizontal Crack Movement at 0°F and Average ECS

was assigned a designation term of its own. The observed significance level for this grouping was <0.0001.

The differences between the model describing variations among study sections and the one for geological formation units were significant ($\hat{\alpha}<0.005$). This result indicates that a great portion of the variation among the sections was unexplained by the GFU's effect. Determination of the exact amount of variation explained by the GFU is not possible from the study data. However, such a determination could be made through a comparison of the analysis of variance of several models. The results showed that adding the test site terms to the model had increased its capability to describe the data by about 34 percent above the general model. Adding the geological formation group terms increased it only 28 percent above the general model capability.

The interaction between temperature and GFU was highly significant ($\hat{\alpha} = 0.0001$), indicating that temperature has a different effect on the behavior of cracks located on different geological formation units. The regression lines, coefficients of determination and corresponding observed significance levels ($\hat{\alpha}$) are illustrated in Figures 30 and 31 for opening and closing cycles respectively.

Average values for the slopes of these regression lines are shown in Table VII. These values are a measure of the temperature effect on crack movement, i.e., the greater the slope, the greater the amount of crack movement and, thus, greater stresses applied to a sealant material. Study site No. 4, located on the Garber formation, had the greatest slope value and was followed by the sites on the Wellington, Senora and Boone formations respectively. The regression line slope for the concrete overlay study site was on the average about three times smaller

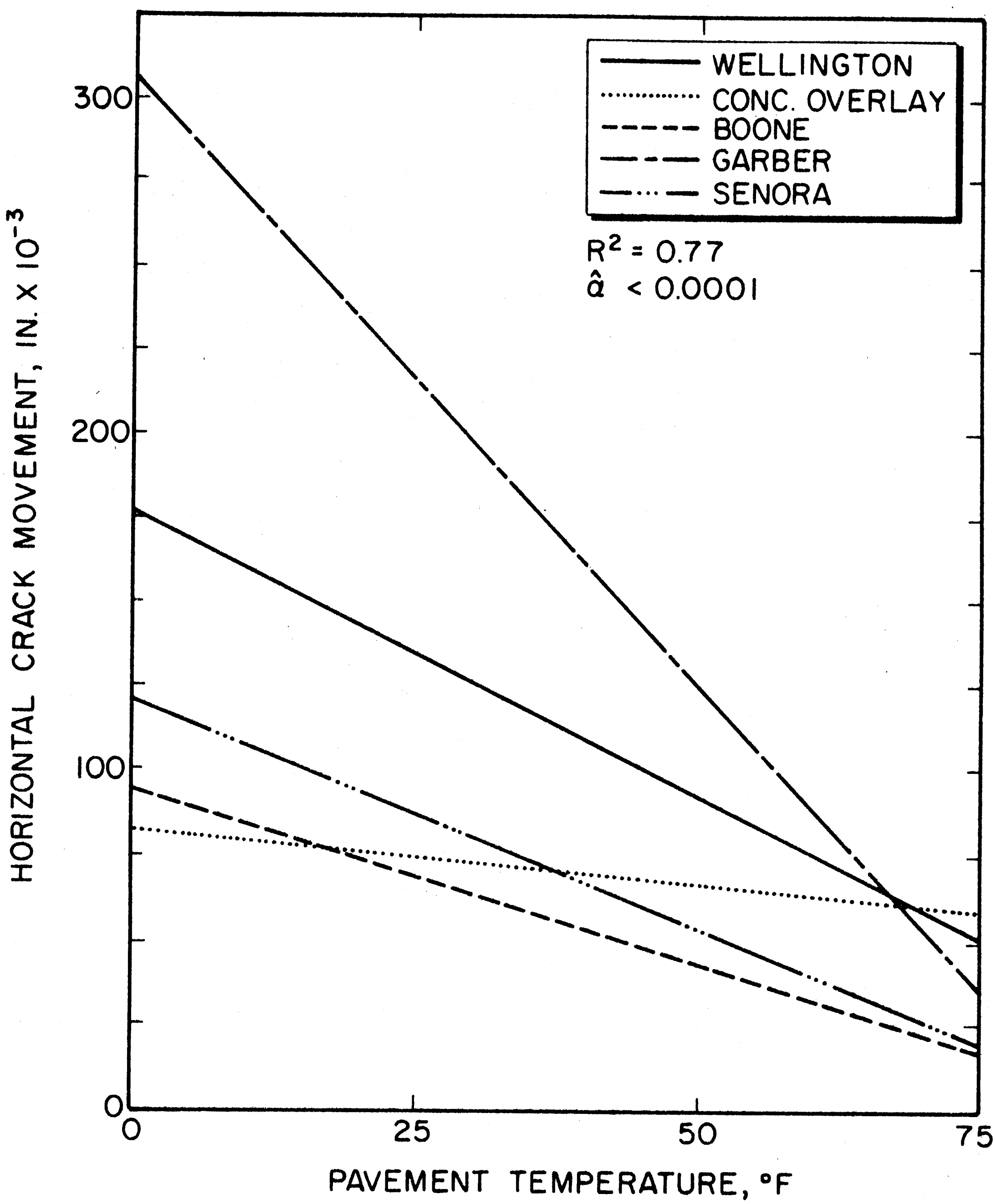


Figure 30. Relationship Between Opening Movement and Pavement Temperature (Optimum ECS Used for Each Unit)

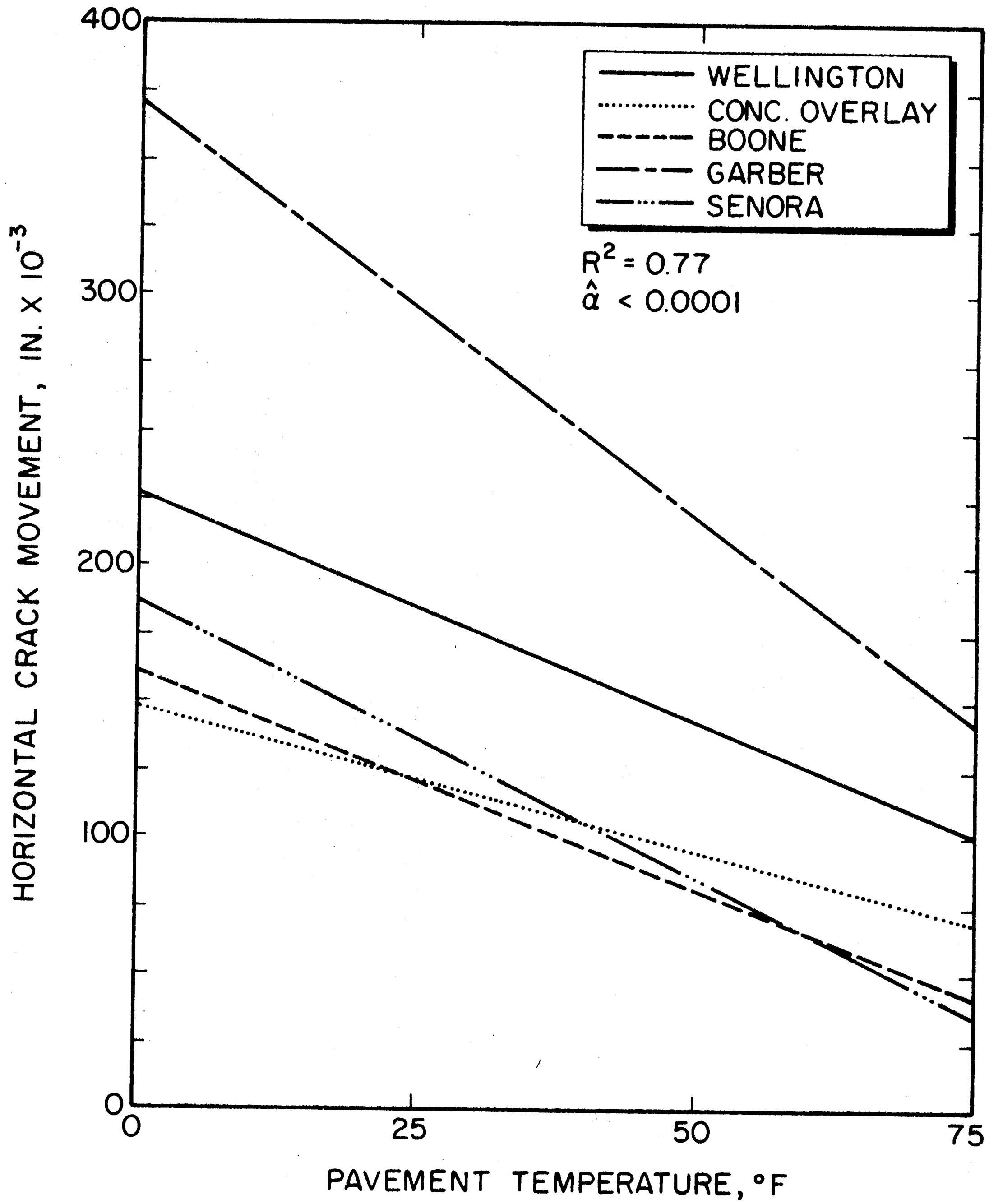


Figure 31. Relationship Between Closing Movement and Pavement Temperature (Optimum ECS Used for Each Unit)

TABLE VII

AVERAGE REGRESSION LINE SLOPE (TEMPERATURE VS MOVEMENT) FOR GEOLOGICAL FORMATION UNITS

Regression Line Slope, in.X10^{-3}/°F	Corresponding GFU
3.32	Garber
1.87	Wellington
1.67	Senora
1.22	Boone
0.7	Con. Overlay

than the rest. Since the average thermal coefficient of expansion between 0 F and 80 F (-17.8 C and 26.7 C) for bituminous concrete is about four times than that of portland cement concrete (11), this result substantiates that an underlying concrete pavement has a different and predominant effect on crack movement.

The analysis of variance indicated a high significance level for the interaction between ECS and geological formation unit ($\hat{\alpha}$ = 0.005). Figure 32 shows the ECS effect for sites located on different geological formations. The ODOT Research Division reported cracking problems with pavements located on the Boone Chert formation. Figure 32 shows that on this formation, reducing the ECS by the development of additional transverse cracks greatly reduces the amount of pavement expansion and contraction. Subgrade conditions appear to intensify the horizontal movements of the pavement and when transverse cracks develop they multiply more rapidly than on the other geological formations.

Vertical Movement

Effect of Beam Position on Measurements

In this study a Benkelman beam was used to measure the vertical movement of the crack sides. The beam probe was placed to the side of the truck's dual tires rather than in the usual between the tires position. A factorial experiment was designed to determine what difference this placement of the beam probe had on both the relative displacement and the total deflection of the cracks.

Comparable measurements were made at site No. 3 during the four season period of the study. The average vertical movement values are

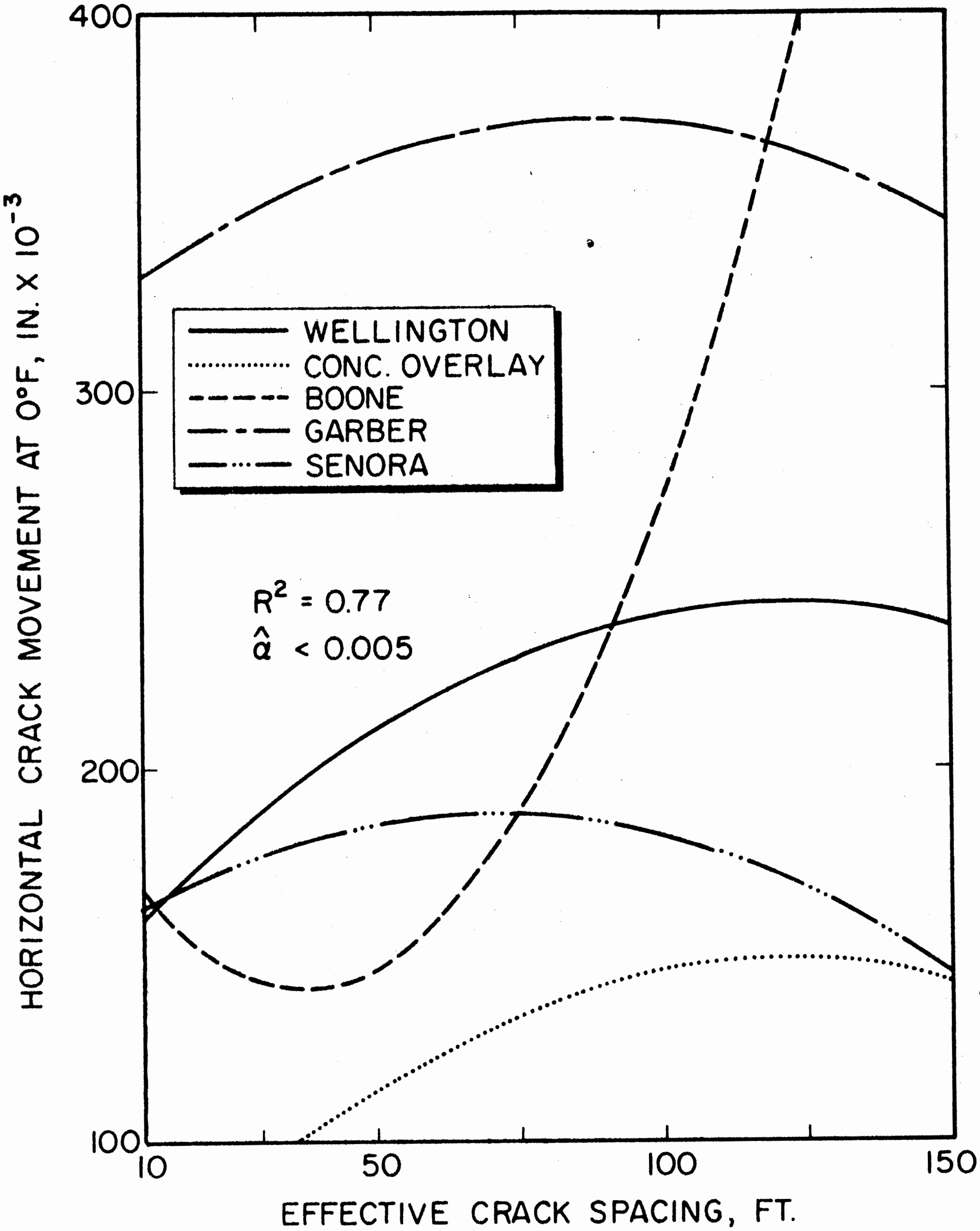


Figure 32. Relationship Between ECS and Horizontal Movement at 0°F for Cracks on Different Geological Formations for Closing Cycle

given in Table VIII. The analysis of variance did not show evidence of significant difference between the two measuring methods in the case of relative displacement ($\hat{\alpha}$<0.103). However, a strong evidence of difference was found in the case of total crack deflection ($\hat{\alpha}$ = 0.0001). Results of the correlation analysis are shown in Figure 33. These results indicate that the method of beam placement had little or no effect on measurements taken to determine the relative displacement of the crack sides.

Relative Displacement and Total Deflection

Deflection measurement data were analyzed by the Analysis of Variance Procedure (ANOV.PROC.) SAS computer program. Analyses were made for both relative and total deflections. The analysis of variance showed that the seasons has a significant effect on both deflection values ($\hat{\alpha}$=0.0001). Although the interaction between seasons of the year and study sites were significant ($\hat{\alpha}$=0.0001), in general, the highest deflection values were observed during the winter-spring period. Average values for relative and total deflections are given in Table IX.

A correlation study was made to investigate the relationship between the relative displacement and the total deflection. Data was fed into a Hewlett-Packard Calculator Plotter (Model 9862A) to determine the appropriate fitted curve and the coefficient of determination (R^2) was then computed by the SAS computer program. As can be seen in Figure 34, a strong relationship exists between the relative displacement and total deflection with an observed significance level $\hat{\alpha}$<0.0001.

Relative vertical displacement of opposing crack edges is a measure of the shearing strain to which a sealant would be subjected. A previous investigation (11) indicated that the effect of vertical movements on

TABLE VIII

AVERAGE VERTICAL DEFLECTIONS
FOR SITE NO. 3

Vertical Movement, in. $X10^{-3}$	Wheel Position	SEASONS			
		Winter	Spring	Summer	Fall
Relative Displacement, D, in. $X10^{-3}$	Outside Wheels	17.364	2.076	0.526	10.036
	Between Duals	18.852	1.008	0.302	13.890
Total Deflection, T, in. $X10^{-3}$	Outside Wheels	25.250	14.000	11.600	20.650
	Between Duals	31.100	18.450	15.900	26.250

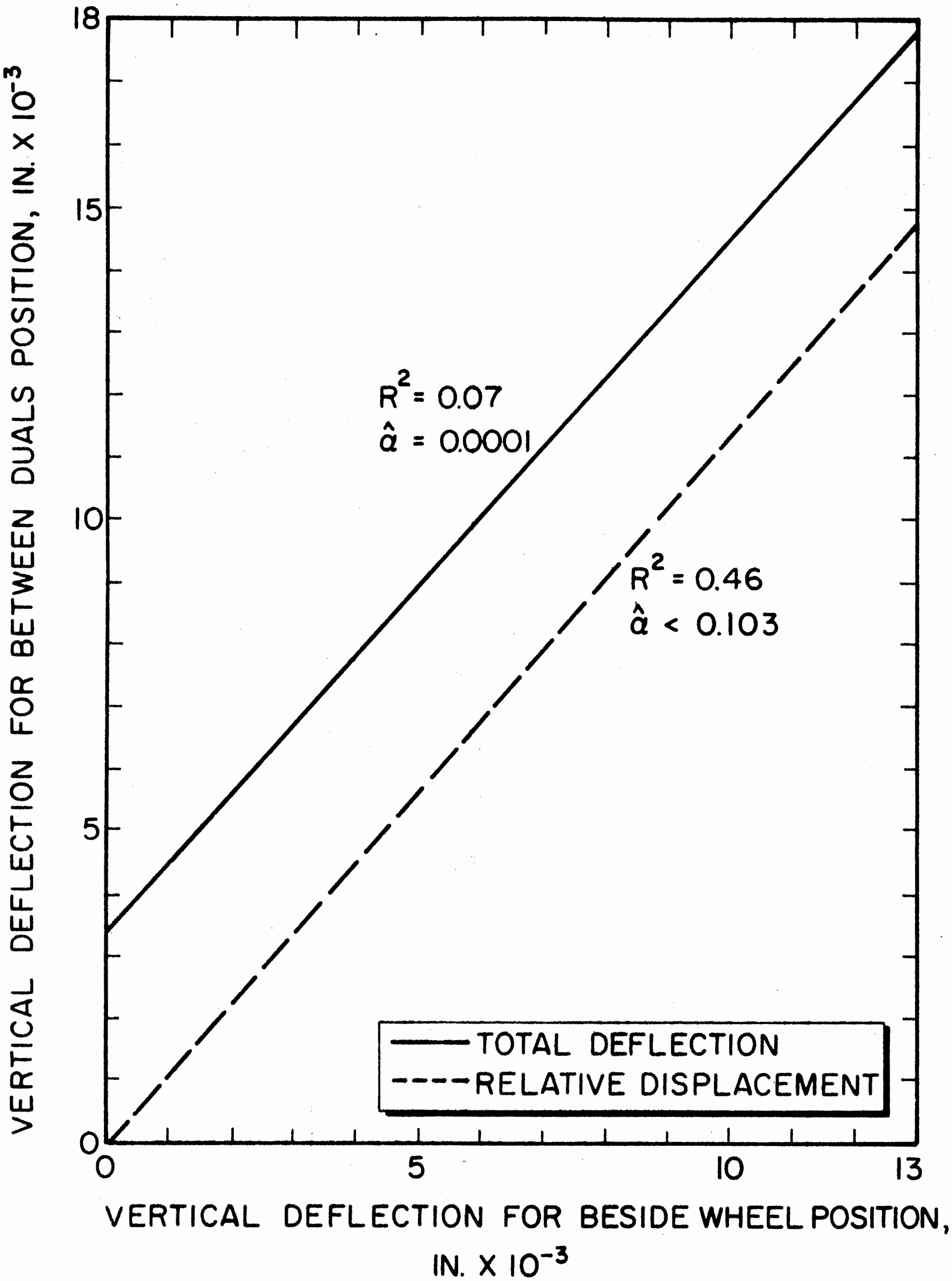


Figure 33. Relationship Between Benkelman Beam Position Measurements for Site No. 3

TABLE IX

AVERAGE RELATIVE DISPLACEMENTS AND TOTAL DEFLECTIONS AT THE STUDY SITES

Season	Site No.	Relative Displacement, in.X10^{-3}		Total Deflection, in.X10^{-3}	
		Site Avg.	Season Avg.	Site Avg.	Season Avg.
Winter	1	15.588	15.353	24.040	22.184
	3	17.364		25.250	
	4	20.750		28.500	
	5	14.728		18.600	
	6	15.900		20.900	
	7	9.902		16.800	
	8	13.424		21.200	
Spring	1	11.464	13.837	18.550	23.999
	3	2.076		14.000	
	4	17.288		27.550	
	5	10.750		18.100	
	6	15.938		28.050	
	7	14.600		28.800	
	8	24.740		32.942	
Summer	1	7.350	11.419	11.700	20.736
	3	0.526		11.600	
	4	15.426		21.550	
	5	8.276		15.400	
	6	13.100		24.400	
	7	14.638		28.550	
	8	20.614		31.950	
Fall	1	9.400	10.533	15.000	20.000
	3	10.036		20.650	
	4	11.514		21.650	
	5	10.202		17.700	
	6	10.962		20.050	
	7	8.690		20.850	
	8	12.926		24.100	

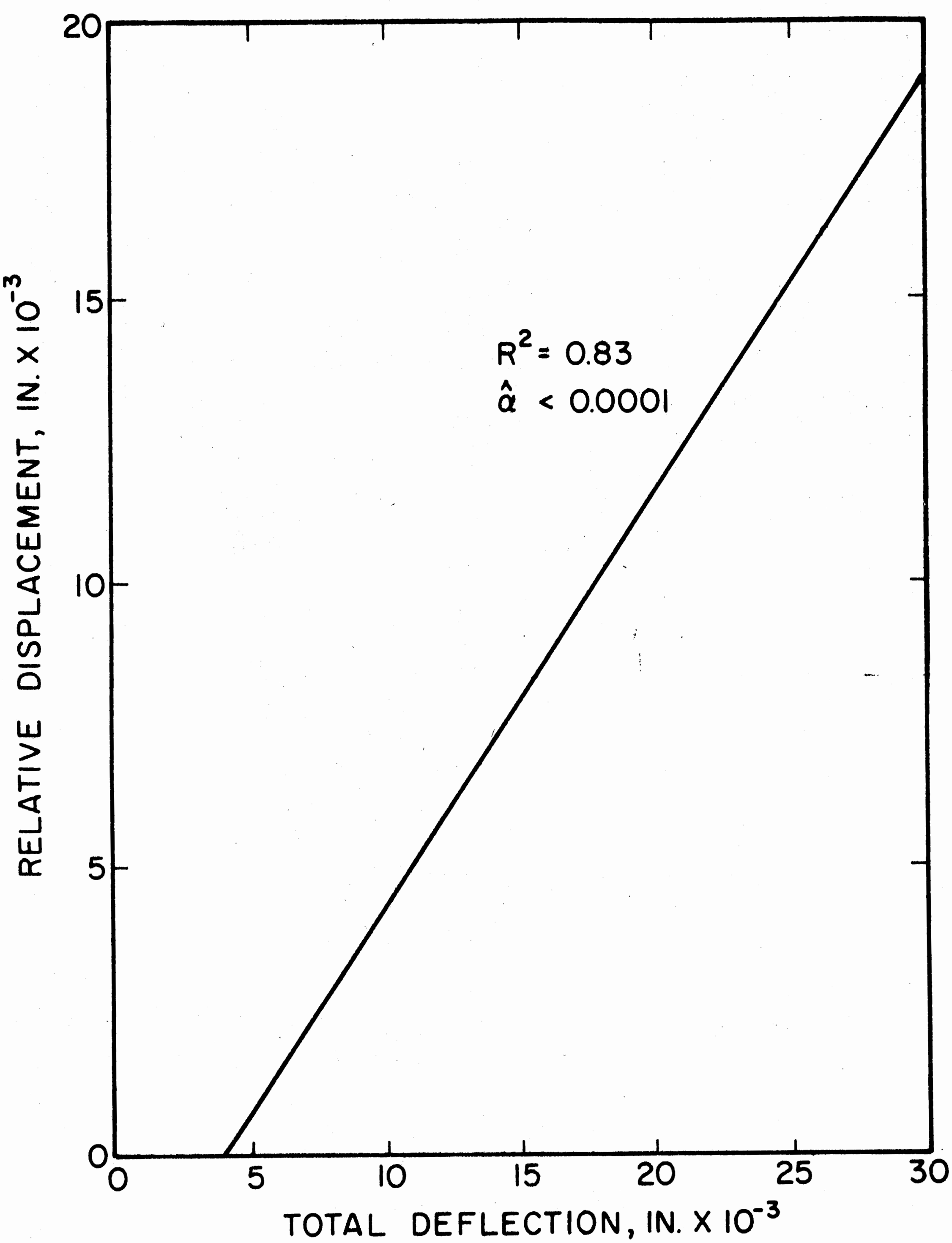


Figure 34. Relationship Between Total Deflection and Relative Displacement

joint sealers was negligible in comparison to the effect of horizontal movements.

In order to check this finding, an estimate of the horizontal crack movement that might be expected during the four seasons of a year was calculated using the regression model and a five year average temperature (32) for the respective seasons. The computed horizontal crack opening values were compared with the measured relative vertical displacements at each test site for the corresponding season (Table X). On the average, the vertical or shear strain was 10.4 percent of the horizontal or tensile strain. As expected, this percentage value was about double that obtained in the study of portland cement concrete expansion joints (11). However, the shear strain is still small enough to not be considered a major factor in sealant failure.

Laboratory Tests

Curing and Setting Study

Duplication in the laboratory of the actual environmental conditions that exist at cracks in a roadway pavement would be virtually impossible. However, it was desired to know more about the curing behavior of quantities of liquid sealants in dimensions (volume and shape) similar to those they might assume when poured in pavement cracks. The curing studies of sealants installed in simulated cracks made it possible to determine a reasonable end point weight loss to use in preparing samples of these materials for the other tests used in this investigation.

As previously discussed, some of these simulated cracks were formed from lucite plates and others from blocks of asphalt concrete. Some of the "crack" samples were cured at room temperature under an oscillating

TABLE X

AVERAGE RATIO OF RELATIVE VERTICAL DISPLACEMENT TO HORIZONTAL CRACK OPENING

Site No.	Ratio of Relative Vertical Displacement to Horizontal Crack Opening*			
	Season	Site-Season Average Ratio	Study Site Average, %	Average, %
1	Winter	.104	9.60	10.4
	Spring	.116		
	Summer	.097		
	Fall	.067		
2	Winter	.180	8.6	
	Spring	.037		
	Summer	.013		
	Fall	.115		
4	Winter	.059	6.2	
	Spring	.073		
	Summer	.079		
	Fall	.035		
5	Winter	.068	6.7	
	Spring	.075		
	Summer	.075		
	Fall	.051		
6	Winter	.078	10.3	
	Spring	.126		
	Summer	.147		
	Fall	.059		
7	Winter	.036	5.9	
	Spring	.075		
	Summer	.089		
	Fall	.035		
8	Winter	.088	25.3	
	Spring	.323		
	Summer	.504		
	Fall	.096		

*Estimates for horizontal crack opening calculated using regression model and average 5 yrs. seasonal temperature.

fan and others in an oven at 150 F (65.6 C). The major problems encountered in the study were the extremely slow weight loss of the samples and leakage of the sealant from some of the simulated cracks and subsequent loss of data from the leaking samples.

Cutbacks. Figure 35 shows the relationship between weight loss and time of curing at 150 F (65.6 C) for the cutback sealants in lucite cracks. The width to depth ratio of the sealant samples in these simulated cracks had a marked effect on the rate of curing of the materials. The wider and more shallow samples were initially cured at a greater rate.

Predictably, the MC-800 samples exhibited the higher initial rates of curing and the greater total weight loss. After about 600 hours of exposure at the curing temperature, the slope of each of the curves approached zero. Some weight loss in the samples was still occurring after 900 hours of curing.

The curing curves for samples of the cutbacks sealants in shallow pans are shown in Figure 36. These plots are similar to those in the previous figure but show that evaporation of the diluent from these samples occurred much more rapidly than from the samples in the simulated cracks. This illustrates the influence of amount of exposed sealant surface area on the time of curing.

These results indicated that curing of the cutback products under prevailing field conditions would require extended periods of time. It is quite likely that it could take as long as several years for complete evaporation of the volatile constituents from cutback sealants in pavement cracks.

It appeared however, that for all samples of a particular cutback

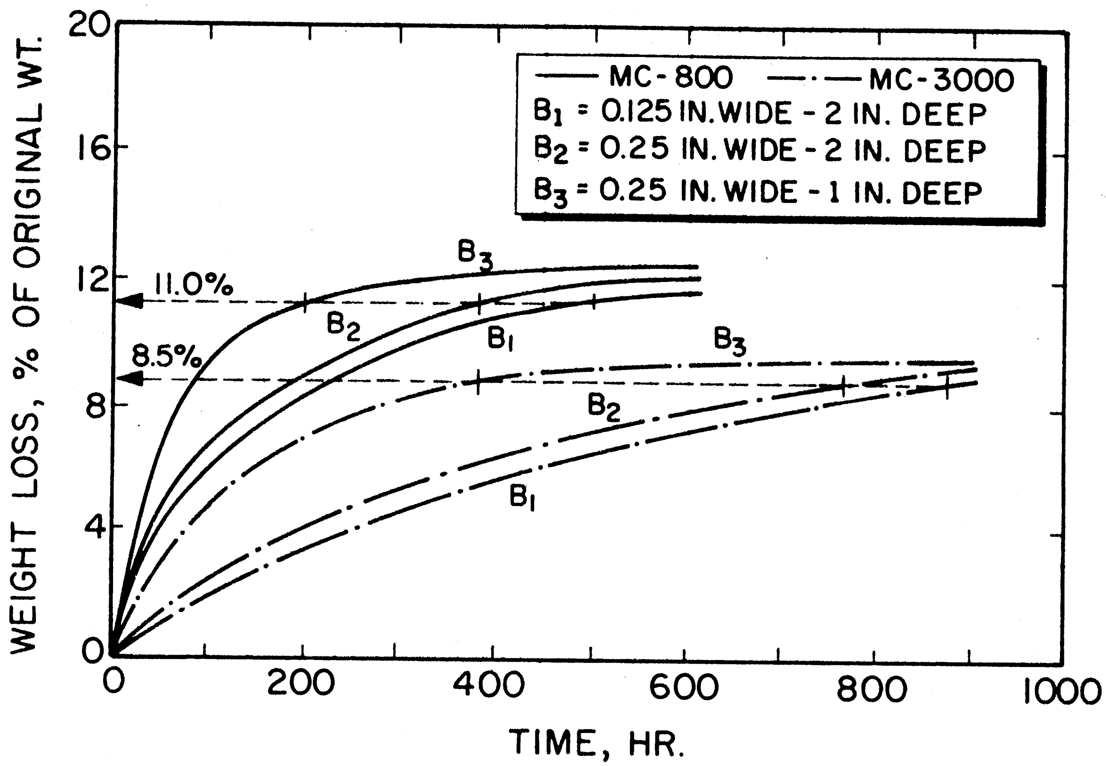


Figure 35. Curing Curves for Cutbacks in Lucite Cracks Molds-at 150°F

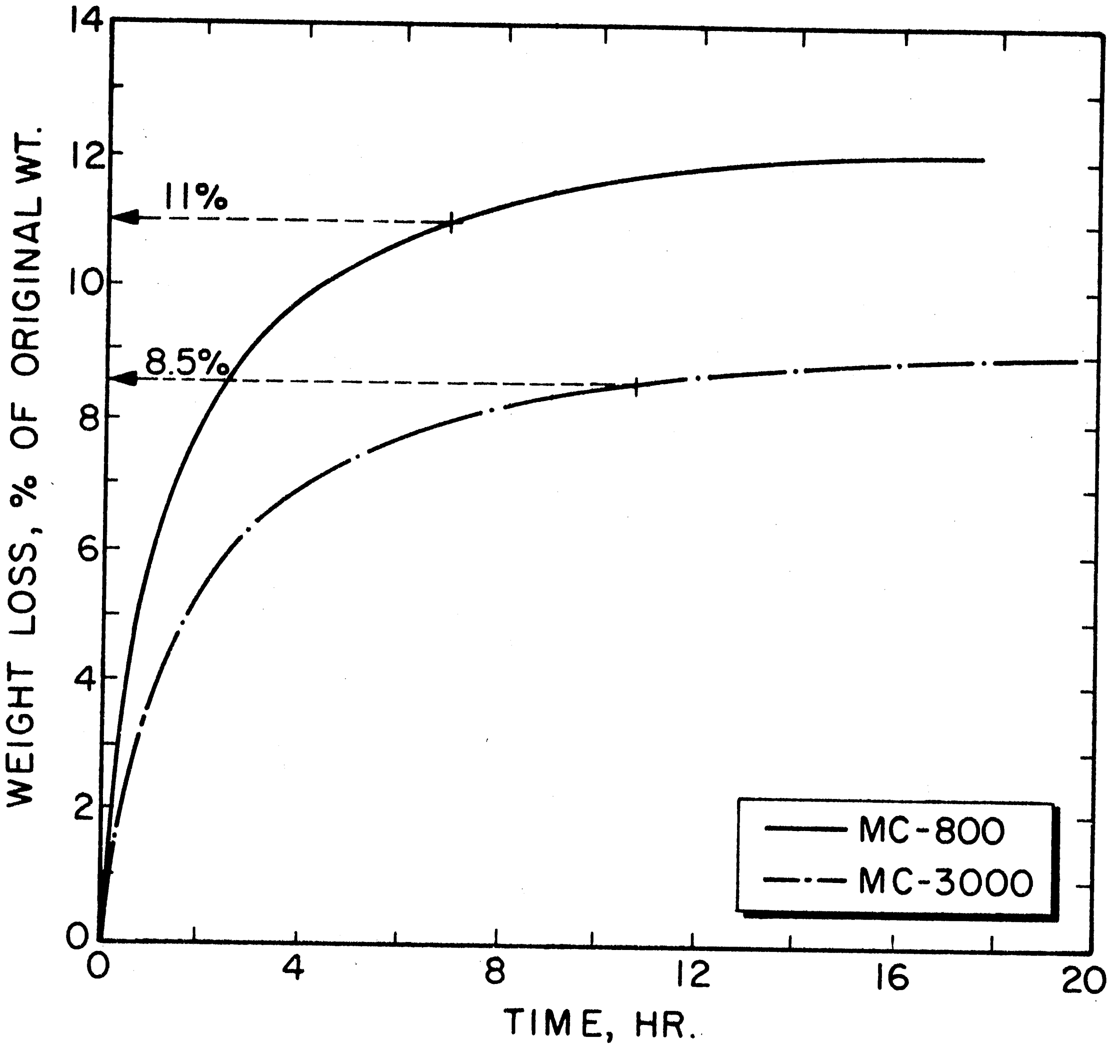


Figure 36. Curing Curves for Cutbacks in Shallow Pans-at 150°F

the rate of curing (slope of the weight loss versus curing time curve) was drastically reduced at about the same percentage of weight loss. This loss was about 11 percent for the MC-800 material and about 8.5 percent for the MC-3000 material (see Figures 35 and 36). These arbitrary weight loss values were taken as the end points for the respective cutbacks in the evaporation process used to prepare samples of the sealants for the Bond-Ductility and other tests.

Emulsions. Several problems developed in the study of the setting or breaking behavior of emulsions in the simulated cracks. One of these was leakage of the sealants from the crack molds that were oven dried. Then, the liquid tight crack molds seemed to inhibit the breaking process since the only way for the emulsifying water to escape was through evaporation at the surface of the crack.

Data was obtained on samples placed in asphalt concrete crack molds and air dried at room temperature. The setting curves for these samples are shown in Figure 37. These curves were plotted using the "Curve Through Points" program in a Hewlett-Packard Calculator Plotter (Model 9862A). Again, the effect of width to depth ratio of the sealant sample is evident in the three types of emulsions.

The weight loss versus curing time curves exhibit a plateau effect with periods of rapid weight loss followed by periods of slow weight loss during a two month drying time. Coalescence of the dispersed asphalt droplets in both the anionic and cationic types of emulsion created a film at the surface of the crack specimens. These films prevented evaporation of the emulsifying water from the samples and prolonged the setting process. However, during periodic examination and weighing of the crack molds these films were disturbed enough to permit

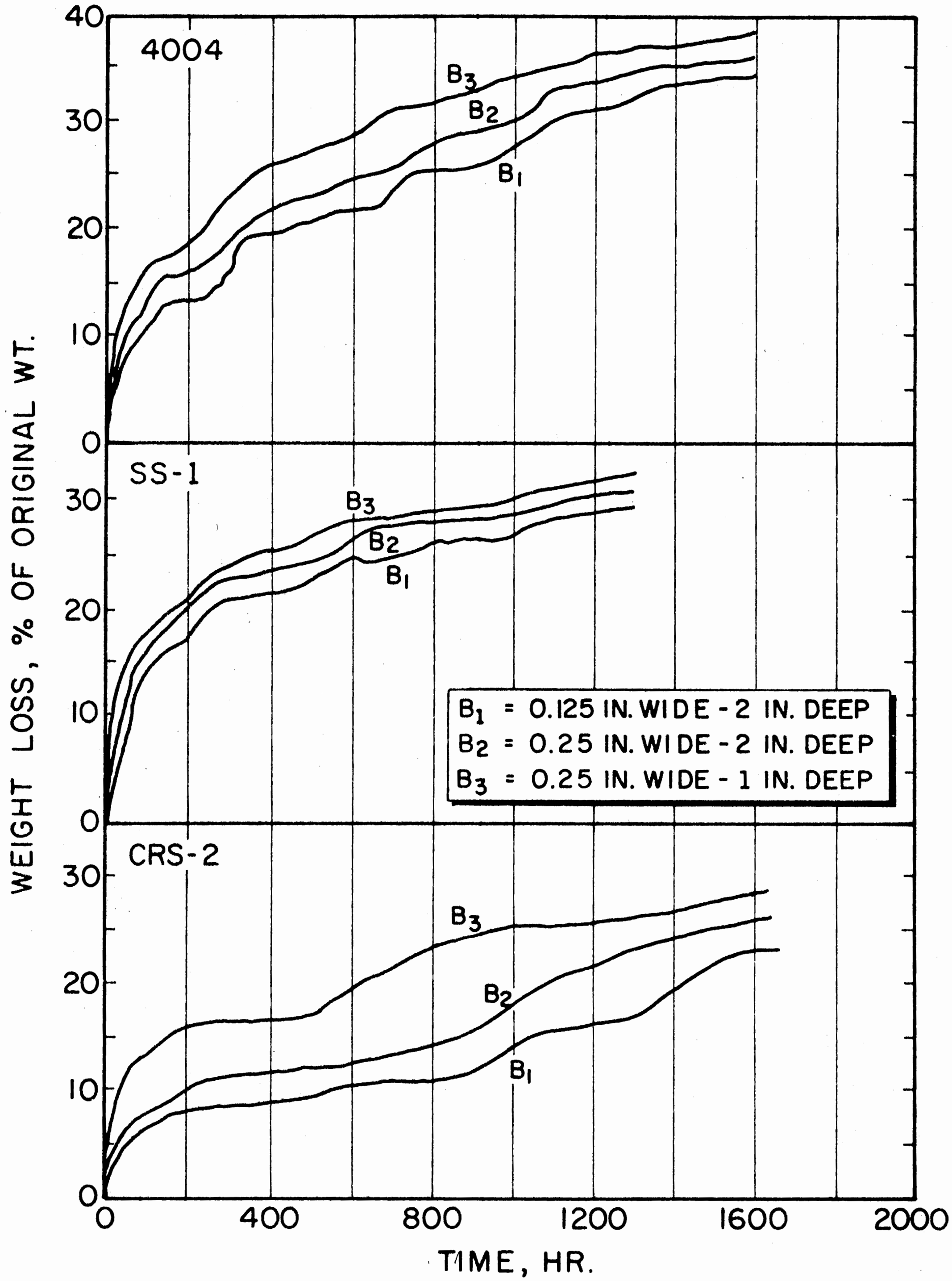


Figure 37. Setting Curves for Emulsions in Asphalt Concrete Crack Molds - at Room Temperature

additional evaporation to take place and this resulted in the rather erratic setting curves. Complete setting of the emulsions in the simulated cracks required several months, but under actual field conditions where drainage can take place thorough breaking and elimination of the water should occur much faster.

Bond-Ductility Test

Although this test was performed in accordance with a planned statistical design (detail of the design is outlined in Appendix E), a statistical approach could not be used to analyze the data. Several of the selected sealants failed during the first cycle of elongation and, thus, there was no measurable response for statistical analysis (see Table XI). The lack of data also precluded a planned statistical correlation study between the Bond-Ductility test and the other tests that were conducted. This development was not anticipated since each of the materials was selected on the basis of reported effectiveness as a crack sealant.

Sealants. Table XII presents a summary of the laboratory test results. Tabular values are averages of the results obtained from three tested samples. Brittle type failure occurred in the asphalt cement and emulsion test samples during extension in their first cycle. The nature of these failures indicated a high stiffness modulus of these asphalt products at 0 F. The cutback sealants better performance can be related to a higher penetration base asphalt cement having a lower stiffness modulus.

The rubberized asphalt sealant was definitely superior to the other sealants in the B.D. (Bond-Ductility) test. An average of over eight cycles was required to fail the test samples of this material.

TABLE XI

BOND-DUCTILITY TEST RESULTS
ON SEALANTS

Sealant	No. of Cycles to Failure*		
	Crack Dimensions, in.		
	2 X 0.125	2 X 0.25	1 X 0.25
AC. 60-70	—	—	—
AC. 85-100	—	—	—
CRS-2	—	—	—
SS-1	—	—	—
4004	—	—	—
MC-800	3.33	2	2
MC-3000	1	2	3.67
MS-LV	7	8	10

*Average of three samples

TABLE XII

SUMMARY OF LABORATORY TEST RESULTS

Sealant Material	B.D. Test Avg. No. of Cycles	Penetration, mm.		Resilience %	Flow Slope mm/min	Shrinkage %	Compatibility
		Cone	Std. Needle				
AC.60-70	—	40	57	11	0.79	1.26	Pass
AC.85-100	—	66	80	1.7	1.13	1.13	Pass
CRS-2	—	80	82	1.0	1.77	29.54	Pass
SS-1	—	81	88	-1.5	1.57	29.25	Pass
4004	—	68	72	7.75	0.98	42.8	Pass
MC-800	2.44	144	>250	-13.5	4.27	12.76	Pass
MC-3000	2.22	182	>250	-36.5	6.35	8.22	Pass
MC-LV	8.33	45	55	39	6.67×10^{-3}	0/45	Pass

Shape Factor. The shape factor of the crack, i.e., width to depth dimensions, has an effect on the capacity of a sealant to withstand extension and compression. In spite of the limited data obtained in this test, the results indicate that a higher number of cycles was obtained when the sealant width was increased from 0.125 in. to 0.25 in. (Table XI). A similar improvement was found when the depth was reduced from 2 in. to only 1 in. This result coincides with the findings of both Tons (14) and Schutz (15) in that, with other conditions being the same, the greater the minimum width of the crack and the shallower the crack is sealed the less the sealer will be strained when the crack opens.

Penetration Test

As expected, the cone penetration values for asphalt materials run considerably less than the standard penetration test values (Table XII). Cone penetration values ranged from a low of 40 for the 60-70 penetration asphalt cement to a high of 182 for the partially cured MC-3000. SS-1 and CRS-2 products are usually made from asphalt cements having a standard penetration of (100-200). Test results on residue from distillation of these materials (Table XIX, Appendix D) indicate that they were made from asphalt cements having standard penetration on the low end of the above range.

From the limited data, it appears that penetration values below about 100 would indicate a sealant with undesirable stiffness properties. This coincides with Manke and Noureldin's (35) finding based on the limiting stiffness concept that the 85-100 penetration asphalt is considered too hard a grade at 0 F (-17.8 C). Such an asphalt cement would exhibit very low ultimate tensile strains. Thus, failure at the first

B.D. extension cycle for the asphalt cement and the emulsion sealants is not surprising. However, this does not apply to the rubberized sealant and strongly suggests the need for direct evaluation of a sealant's stiffness modulus.

Resilience Test

The resilience test provides a measure of the elasticity of the sealant materials. The negative resilience values in Table II were obtained because the 0.675 in. (17 mm) diameter ball penetration head used to conduct the test (13) continued to penetrate the sample when the clutch was released.

Rubberized asphalt had the highest recovery percentage followed by the 60-70 penetration asphalt cement. For the rubberized asphalt, there seems to be a good correlation of the test results with performance in the B.D. test. This may suggest that the test is an important indicator of the sealant performance but a more definitive series of tests are needed to establish this.

Flow Test

A linear relationship between time (in terms of minutes) and flow distance (in terms of millimeters) was found for all sealants at a 15 degree angle of inclination of the flow plane. These relationships shown in Figure 38 were plotted using the Hewlett-Packard Calculator Plotter (Model 9862A).

In previous research work (12) and in standard tests for sealants (14) (19) limits of flow are established and the test results reported as passing or failing based on whether these limits are exceeded. Based

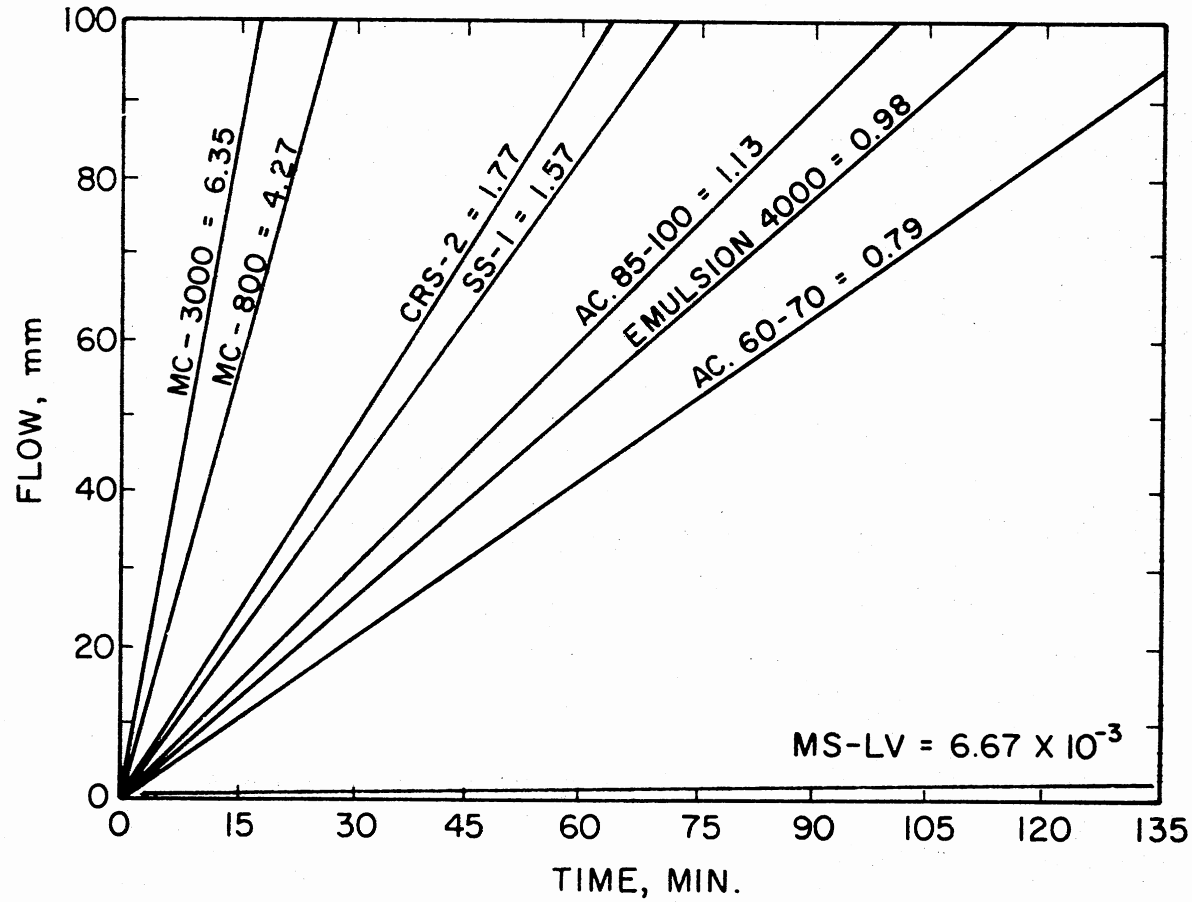


Figure 38. Relationship Between Flow and Time at 15° Angle

on results of the modified test, the slope of the line for a particular sealing material was considered more descriptive of its mobility or flow characteristics. Thus, the slope of the plotted lines in Figure 17 were reported as the flow values for the sealants. These values ranged from 6.35 for the partially cured MC-3000 to 6.67×10^{-3} for the rubberized sealant. The latter result is close to the 3.0 mm (after 4 hours) tentative specification flow limit (14). However, there was no apparent relationship between results of this test and those of other tests performed.

Volume Change Test

Average shrinkage or reduction in volume (in terms of percentage) of the respective cold-poured sealants is shown in Table XII. Emulsions exhibited the higher shrinkage values with maximum of 42.8 percent for the 4004 special emulsion. The MC-3000 had the minimum shrinkage value of 8.22 percent for the cold-poured materials. Values for the hot-poured sealants are also reported for comparative purposes. These materials showed very little volume change using the standard test procedure.

The test results indicate the approximate amount of shrinkage to be expected in the field. It is thought that a volume reduction of more than 30 percent in the field would require a second application of the sealant in order to assure good performance. The extra costs involved in additional applications would naturally limit the use of such sealants. Thus, a reasonable shrinkage limit of 30 percent could be used as an acceptable value.

Compatibility Test

All sealants passed this test with no visible sign of incompatibility (formation of an oily exudate at the interface between the sealant and the asphalt concrete). Although standard test procedures use laboratory specimens of asphalt concrete, the test should be performed using core samples from the cracked pavement to be sealed.

Evaluation of the Test Program

Test such as resilience, flow, compatibility, and the various hardness and penetration tests can serve to indicate sealant materials with inferior physical properties. These tests do not, however, have the capability of simulating actual crack conditions as does the B.D. test. This was demonstrated in the Louisiana study (36), where correlation between the sealants test properties and the observed field performance was found only with the results of a similar B.D. test.

Although the use of longer specimens made the conducted B.D. test conditions in this study more severe, the results of this test should permit reliable prediction of sealant field performance. In view of the findings of the crack dynamic study (16), it might be well to modify this test to include both extension and compression cycles under closely controlled conditions.

No direct relation was found between the penetration results and the number of B.D. cycles for the tested sealants. Several studies on the stiffness modulus of asphalt materials at low temperature have agreed that high stiffness modulus values are associated with low ultimate strains for the materials (37) (38) (39). Thus, it seems that a better indication of the sealant's required strain capacity might be obtained by determining its stiffness modulus.

No definite relationship could be established between the results of the resiliance test and those of the other tests that were conducted. Additional testing and evaluation is needed to determine the value of this test as an indicator of sealant performance.

Although a better measure of the flow property of standard asphalt sealing materials was developed in this research, the sealant mobility is thought to have no direct bearing on performance and this test could be eliminated as an evaluative procedure. Also, the volume change test is considered to have no critical value as a measure of performance, but it does have some practical value.

The compatibility test as conducted is a subjective test. It depends on a visual evaluation of the samples and the accuracy of the results depends on the skill and training of the personnel examining the test specimens. This requires the development of good examples (test specimens) showing incompatibility-oil exudations, etc., at the interface between the sealant and asphalt concrete samples to establish criteria for the pass-fail classification of results. The importance of this test is often overlooked by paving asphalt technologists. This test, with possible modifications, should be retained to evaluate prospective sealants.

Adverse reactions between dissimilar asphalt materials might best be determined using Oliensis' procedure (40) instead of the standard compatibility test. Using this procedure, a recovered sample of asphalt cement (ASTM D-1856) from the cracked pavement to be sealed is placed in a shallow pan and dusted with fine talc. Several drops of the sealant are placed on the talc-covered surface and the assembly is heated at

110 F (43.3 C) for 72 hours. The results are reported as the width to the nearest 0.1 millimeter of the dark ring in the talc-covered surface surrounding the crop of sealant. A very narrow ring (less than 0.5 mm) would be classed compatible. Illustrations for contact compatibility and incompatibility for such a test are shown in books by Oliensis (40) and Traxler (41).

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Crack Dynamics Study

Based on the information compiled during the one year (September 1977 to September 1978) study of transversely cracked flexible pavement sections on Oklahoma highways, the following conclusions are made:

1. Under typical Oklahoma climatic conditions, the average maximum amount of horizontal crack movement observed at the test sites was estimated to be 0.25 in. (6.125 mm).

2. About 80 percent of the total horizontal crack movement occurred between subsurface pavement temperatures of 0 F and 77 F (-17.8 C and 25.0 C).

3. The relationship between horizontal crack movement and subsurface pavement temperature for the monitored cracks differed considerably during the annual heating and cooling periods experienced by the pavement during the one year study period.

4. A permanent incremental increase in crack width remains after each yearly cooling and heating cycle. This tends to support an earlier study of asphalt concrete expansion behavior. For the cracks studied, the average increase in crack opening was 0.03 in. (0.762 mm) per year.

5. The information shows that sealants applied during the fall

season are subjected to about equal amounts of extension and compression following their installation.

6. It appears that the amount of horizontal crack movement increases with increasing values of ECS up to approximately 120 ft (36.6 m). Frictional resistance to this movement during cooling of the pavement produces tensile stresses that can cause additional cracks at the midpoint between adjacent transverse cracks.

7. The geological formation on which the study sites is constructed appears to have some effect on subsequent cracking of the pavement and crack behavior but this relationship could not be exactly determined. The greatest amount of crack movement was observed at test sites located on the Barber formation and there was indication of a high cracking potential in pavement site located on the Boone chert formation.

8. The largest vertical deflections at transverse cracks were observed during the winter and spring seasons.

9. The relative vertical displacement of the crack sides, under an 18,000 lb (8,165 kg) axle load, was approximately 10 percent of the estimated horizontal crack movement.

Laboratory Tests

The laboratory investigation was directed towards evaluating and/or developing test procedures for sealant materials that would reasonably predict their field performance. Based on this work, the following conclusions are made:

1. The bond-ductility machine developed for this project provides a reliable means of testing asphalt sealing materials for their bonding characteristics and ductility behavior under conditions similar to

those experienced in the field.

2. The machine and its ancillary equipment can test multiple samples of sealant at precisely controlled rates of tensile strain under a wide range of temperature conditions.

3. The machine is versatile and can be employed to closely simulate seasonal crack movements through cyclic application of tensile and compressive strains to sealant specimens.

4. The rubberized asphalt was superior to the other sealants in the bond-ductility test. The results indicate that the asphalt cements and the emulsions are too stiff, i.e., they fail in adhesion and/or cohesion under tensile strain at low temperature, and will not function adequately as a "sealing" material. The performance of the cutback asphalts was only slightly better in this regard.

5. As conducted, the bond-ductility test may be too rigorous from the standpoint of extending the sealant specimens to 100 percent of their original width.

6. There was little or no correlation between the results of the respective tests performed on the sealants.

7. The penetration, resilience, flow, shrinkage and compatibility tests have some value as indicators of quality and other desirable sealant properties but denote little concerning expected field performance of a sealant.

Recommendations

Dynamics Study

In view of the observations and conclusions made in this investigation, the following recommendations are presented:

1. Additional crack dynamics research should be conducted to determine the influences of (a) initial crack width, (b) type and thickness of surfacing material, (c) type and thickness of base material and (d) underlying geological formation on horizontal crack movements. Special considerations should be given to the inexplained behavior of cracks located on the Boone formation.

2. Relative to the above recommendation, detailed field measurements of crack movements at temperatures below 20 F (-6.7 C) should be made to study the hysteresis in crack width.

3. Modifications in the "Bond-Ductility" laboratory test procedure (see Interim Report II) to include both extension and compression cycles should be considered.

Laboratory Tests

1. The bond-ductility test should be adopted as the basic evaluative procedure for crack sealing materials. It is suggested that the test be modified to include both extension (at 0 F) and compression (at 77 F) of the sealant specimens. The applied tensile and compressive strains should be limited to about 50 percent of the original specimen width.

2. Before testing liquid asphalt products for desirable sealant characteristics, all water from the emulsions and at least 95 percent of the diluent or solvent in the cutbacks should be removed.

3. A determination of the stiffness modulus of standard asphalt products should be included in evaluative test procedures for sealant materials. In previous work, this parameter has been shown to satisfactorily characterize the low-temperature response of asphalts.

4. A limited field test program to evaluate the effectiveness of various sealant materials and application techniques should be conducted. The results of such a study will assist in determining the value of laboratory test procedures and in establishing reasonable criteria for sealants based on actual service conditions and performance. A proposed statistical design for such an investigation is outlined in Appendix E.

BIBLIOGRAPHY

1. Cook, J. P. and R. M. Lewis, "Evaluation of Pavement Joint and Crack Sealing Materials and Practices," NCHRP Report No. 38, Highway Research Board, 1967.

2. Tons, E. and V. J. Roggeveen, "Field Testing of Materials for Sealing Cracks and Joints in Bituminous Concrete Resurfacings," Highway Research Board Bulletin No. 166, Highway Research Board, 1953.

3. Nelson, R. O., "Use of Rubber-Asphalt Blend to Seal Cracks in Asphaltic Pavements," Special Report on "Use of Equipment and Methods of Maintenance," Federal Highway Administration, May 1974.

4. The Asphalt Institute, "Asphalt in Pavement Maintenance," Manual Series No. 16, 1967.

5. Dzimian, R. J., "Hot-Poured Sealants," Highway Research Record No. 320, 1970.

6. Anderson, A. A., "Current Practice Questionnaire-Jointing, Fillers, Sealers, and Equipment," Highway Research Board Bulletin No. 138, 1956.

7. Itakura, C. and T. Sugawara, "Some Characteristics of Rubber-Blended Asphalt and Its Mixtures at Low Temperatures," Proceedings of the Association of Asphalt Paving Technologists, 1959.

8. Walters, R. O., "Sealing Cracks in Bituminous Pavements," Investigation No. 185, Final Report, Minnesota Department of Highways, 1973

9. Morris, G. R., "Asphalt-Rubber Stress-Absorbing Membranes: Field Performance and State of the Art," Transportation Research Record No. 595, 1976.

10. McDonald, C. H., "A New Patching Material for Pavement Failures," 45th Annual Meeting, Highway Research Board, January 1966.

11. Tons, E., "Factors in Joint Seal Design," Highway Research Record No. 80, Highway Research Board, 1965.

12. Tons, E. and V. J. Roggeveen, "Laboratory Testing of Materials for Sealing Cracks in Bituminous Concrete Pavements," Highway Research Abstracts, Vol. 25, No. 8, Highway Research Board, 1955.

13. "Annual Book of ASTM Standards, American Society for Testing and Materials," Part 15, 1976.

14. Tons, E., "A Theoretical Approach to Design of a Road Joint Seal," Highway Research Board Bulletin No. 229, Highway Research Board, 1959.

15. Schutz, Raymond J., "Shape Factor in Joint Design," Civil Engr., Vol. 32, No. 10, pp. 32-36, Oct. 1962.

16. Tons, E., "Comparative Testing of Joint Sealers in Sixteen Laboratories," Highway Research Board Bulletin No. 211, Highway Research Board, 1959.

17. Kuenning, W. H., "Laboratory Tests of Sealers for Sawed Joints," Highway Research Board Bulletin No. 211, Highway Research Board, 1959.

18. Cook, J. P., "Effects of Specimen Length on Laboratory Behavior of Sealants," Highway Research Record No. 80, Highway Research Board, 1965.

19. Federal Specification SS-S-164.

20. Fickles, L. A. and C. C. Rhodes, "A Field Study of Joint and Crack Resealing Methods and Materials," Highway Research Board Bulletin No. 166, Highway Research Board, 1957.

21. "The AASHTO Road Test-Report 5, Pavement Research," Report No. 61E, Highway Research Board Specification, 1962.

22. McGhee, K. H., "Efforts to Reduce Reflective Cracking of Bituminous Concrete Overlays of Portland Cement Concrete Pavements," R-20, Virginia Highway and Transportation Research Council, 1976.

23. Olson, R. C. and J. C. Hale, "Criteria for Seal Coating Bituminous Surfaces," Investigation No. 626, Final Report, Minnesota Department of Highways, 1974.

24. Steel, R.G.D. and J. H. Torrie, "Principles and Procedures of Statistics," McGraw-Hill Book Company, 1960.

25. "Engineering Classification of Geologic Materials," Prepared by Research and Development Division of Oklahoma Highway Department, 1970.

26. Kallas, B. F., "Asphalt Pavement Temperatures," A paper prepared presentation at the 1966 Annual Meeting of the Highway Research Board, Washington, D.C.

27. Straub, A. L., "Bituminous Pavement Temperature Related to Climatic," Highway Research Record No. 256, 1968.

28. Barth, E. J., "Asphalt Science and Technology," Garden and Breach Science Publisher, New York, 1962.

29. Hicks, T. G., "Standard Handbook of Engineering Calculations," McGraw-Hill Book Company, 1972.

30. "Zero-Max Variable Speed Drives," ZM Catalog 673-2, Zero-Max Industries, Inc., Minneapolis, Minnesota, 1973.

31. "A User's Guide to the Statistical Analysis System," Department of Statistics, North Carolina State University, August, 1972.

32. "Climatological Data, Oklahoma," U. S. Department of Commerce, 1979.

33. Littlefield, G., "Thermal Expansion and Contraction Characteristics Utah Asphaltic Concretes," Proceedings of the Association of Asphalt Paving Technologists, Vol. 36, 1967, p. 673.

34. Holbert, D. and L. Broemeling, "Bayesian Inferences Related to Shifting Sequences and Two-Phase Regression," Communications in Statistics Theory and Methods, Vol. A6. No. 1, A(3), 265-275, 1977.

35. Manke, P. G. and M. S. Noureldin, "A Study of Transverse Cracking in Oklahoma Flexible Highway Pavements," Oklahoma State University, Research Project 72-03-3, Unpublished Interim Report V, January 1977.

36. Kinchen, R. W., "Evaluation of Joining Sealant Materials," Louisiana Department of Transportation and Development, Research Project No. 69-2G, Final Report No. 105, May 1977.

37. McLeod, N. W. Prepared discussion on Ste. Anne Test Road. Proceedings of the Canadian Technical Asphalt Association, 1969.

38. Burgess, R. A., O. Kopvillem, and F. D. Young, "Ste. Anne Test Road ..... Relationships Between Predicated Fracture Temperatures on Low-Temperature Field Performance." Proceedings of the Association of Asphalt Paving Technologists, Vol. 40 (1971), pp. 148-226.

39. Fromm, H. J. and W. A. Phang. "Temperature Succeptibility Control in Asphalt Cement Specifications," Department of Highways of Ontario, Report IR 35, November, 1970.

40. Oliensis, G. L., "Exudation and Allied Reactions Between Bitumens," Forest Park, Ill., Chicago Bureau of Bituminous Technology, 1949.

41. Traxler, Ralph N., "Asphalt-Its Composition Properties and Uses," Reinhold Publishing Corporation, 1961.

APPENDIX A

QUESTIONNAIRE FORM

QUESTIONNAIRE

Flexible Pavement Crack Sealing Study

1. What type of sealant materials have been used successfully in your Division of sealing the following types of cracks in flexible pavements?

Longitudinal Cracks: (Please check one or more and supply additional information)

_____ Asphalt cements; penetration grade used ______________________.

_____ Rubberized A.C.'s penetration grade and % rubber ______________.

_____ Cutback asphalts; type and grade ______________________________.

_____ Asphalt emulsions; type and grade _____________________________.

_____ Other sealants; please specify ________________________________.

Transverse Cracks: (Please check one or more and supply additional information)

_____ Asphalt cements; penetration grade used ______________________.

_____ Rubberized A.C.'s penetration grade and % rubber ______________.

_____ Cutback asphalts; type and grade ______________________________.

_____ Asphalt emulsions; type and grade _____________________________.

_____ Other sealants; please specify ________________________________.

Alligator or Map Cracks: (Please check one or more and supply additional information

_____ Asphalt cements; penetration grade used ______________________.

_____ Rubberized A.C.'s penetration grade and % rubber ______________.

_____ Cutback asphalts; type and grade ______________________________.

_____ Asphalt emulsions; type and grade _____________________________.

_____ Other sealants; please specify ________________________________.

2. In your Division, what criteria are used to determine the necessity for sealing flexible pavement cracks?

_____ Number of cracks per mile of roadway.

_____ Width of Crack; please specify width __________________________.

_____ Spalling or deterioration of surface adjacent to crack.

_____ Other; please specify ____

____.

3. Does your Division require any type of crack preparation, i.e., blowing, brooming, routing, priming, etc., prior to application of the sealant? ______. If so, please specify treatment ____

____.

4. In your Division, what is the predominant method of applying sealants to the respective types of cracks (e.g., pouring, spraying, pressure injection, etc.)?

____.

Longitudinal cracks _______________________________.

Transverse cracks _________________________________.

Alligator or map cracks ___________________________.

5. Does your Division utilize any specialized mechanical equipment for crack preparation and sealing ? __________. If so, please list the names of this equipment and their purposes. ______________________

____

____

____

6. Does your Division conduct periodic inspections or surveys of its flexible pavements to ascertain crack development and/or extent of surface deterioration at the cracks? __________. If so, please describe briefly the method of survey used and the frequency of the surveys.______________________

____

____

____

7. In your opinion, is flexible pavement cracking a major maintenance problem in your Division? ______________________________

____

____

8. In your opinion, are the presently used sealants doing an effective job ? _____

9. Additional comments and suggestions : ______________________

____

____

____

10. Name ____________________. Division No. ____________________.

THANK YOU for your time and efforts in completing this questionnaire !!!!

APPENDIX B

TEST SITE INFORMATION

TABLE XIII

TEST SITE INFORMATION

Test Site Number	Highway Number	Location	Geological Formation Unit	Maintenance Division Number
1	S.H. 20	1.0 mile West of Spavinaw Dam	Boone Chert	8
2	S.H. 20	12.6 miles East of I 44 Jct.	Boone Chert	8
3	S.H. 15	2.0 miles West of I 35 Jct.	Wellington-Admire	4
4	U.S. 64	1.5 miles West of S.H. 74 Jct.	Garber	4
5	U.S. 177	0.7 miles South of U.S. 66 Jct.	Wellington-Admire	4
6	U.S. 177	4.5 miles South of U.S. 66 Jct.	Wellington-Admire	4
7	S.H. 51	0.4 miles West of S.H. 18 Jct.	Wellington-Admire	4
8	U.S. 75	4.0 miles North of Hughes County South Line	Senora	3
9	U.S. 177	1.0 mile North of U.S. 62 Jct.	Wellington-Admire	4

TABLE XIV

TENTATIVE SCHEDULE FOR VERTICAL CRACK MOVEMENT FIELD STUDY

Test Site No.	Maintenance Divis. No.	Site Description	SUGGESTED DATE Winter Feb.	Spring May	Summer Aug.	Fall Nov.
1 2	8	S.H. 20, 1.0 mi W. of Spavinaw Dam S.H. 20, 12.6 mi E. of I 44 Jct.	Feb. 6, 1978 1:00 P.M. at Site No. 1	May 10, 1978 1:00 P.M. at Site No. 1	Aug. 14, 1978 1:00 P.M. at Site No. 1	Nov 14, 1978 1:00 P.M. at Site No. 1
3 4	4	S.H. 15, 2.0 mi W. of I 35 Jct. U.S. 64, 1.5 mi W. of S.H. 74 Jct.	Feb. 13, 1978 2:00 P.M. at Site No. 3	June 9, 1978 9:00 A.M. at Site No. 3	Aug. 15, 1978 9:00 A.M. at Site No. 3	Nov. 15, 1978 9:00 A.M. at Site No. 3
5 6 7	4	U.S. 177, 0.7 mi S. of U.S. 66 Jct. U.S. 177, 4.5 mi S. of U.S. 66 Jct. S.H. 51, 0.4 mi W. of S.H. 18 Jct	Feb. 15, 1978 1:30 P.M. at Site No. 7	June 9, 1978 After Sites 3 & 4 1:30 P.M. at Site No. 7	Aug. 15, 1978 After Sites 3 & 4	Nov. 15, 1978 After Sites 3 & 4
8	3	U.S. 75, 4.0 mi N. of Hughes County south line.	Feb. 14, 1978 1:00 P.M.	May 12, 1978 1:00 P.M.	Aug. 16, 1978 1:00 P.M.	Nov. 16, 1978 1:00 P.M.

TABLE XV

COMPUTER RESULTS FOR POINT OF CURVATURE
TEMPERATURE PROBABILITIES

Test Site No.														
1	Temp., °F	39	43	59	63	68	75	76	100	118	122		
	Prob., %		31	23	34	9.8	.33	.36	0	0	0		
3	Temp., °F	25	38	40	50	50	76	80	81	88	94	100	121
	Prob., %	—	0	.01	.06	3.6	3.6	3.8	32.6	38.7	17.1	0	0
4	Temp., °F	28	29	58	82	88	92	98	110	123			
	Prob., %	—	.56	.58	2.2	69.1	17.9	9.6	0	0			
5	Temp., °F	24	39	58	62	74	87	94	98	103	108	110	115
	Prob., %	—	14.9	7.9	33.1	37.7	4.4	.58	.30	.48	.56	0	0
6	Temp., °F	26	39	60	65	75	87	89	95	98	105	107	109
	Prob., %	—	23.2	10.1	5.9	10.5	3.9	5.6	20.1	6.4	14.3	0	0
7	Temp., °F	39	42	58	59	61	66	75	78	89	103	104	129
	Prob., %	—	4.6	2.2	5.3	3.6	26.4	18.1	35.8	2.1	1.87	0	0
8	Temp., °F	51	67	77	85	86	98	104	107	115	124		
	Prob., %	—	67.1	31.6	.84	.41	0	0	0	0	0		
9	Temp., °F	35	40	45	46	71	79	86	98	100	100	113	114
	Prob., %	—	5.9	3.5	8.6	8.9	22.4	20.1	12.7	3.5	14.4	0	0

APPENDIX C

BOND-DUCTILITY MACHINE

TABLE XVI

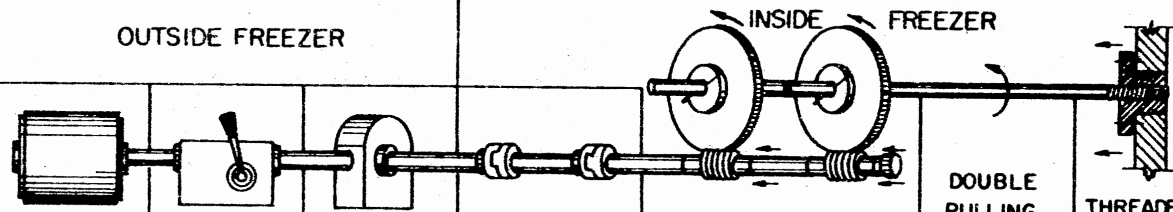
BOND-DUCTILITY TESTING MACHINE COMPONENTS

No.	Components	Quantity	Specifications
1	Motor*	1	Zero-Max. M3, $\frac{1}{3}$ Hp. power 115/1/60
2	Variable Speed Drive*	1	Zero-Max. JK3, speed range 400-0-400-Torque Rating 25 in.-lbs.
3	Gearhead*	1	Zero-Max. W4, Right angle, Gear Ratio 40:1-Torque Rating 300 in.-lbs.
4	Extended Screw Control	1	Zero-Max.
5	Couplings †	1	Boston Couplings, FC 12, Max Torque 200 in.-lbs. Boxton Couplings, FC 15, Max Torque 500 in.-lbs.
6	Bearings †	2 3	Boston Pillow Blocks, Split Cast Iron, Catalog #34450SRP16 Boston Pillow Blocks, Split Cast Iron, Catalog #34438SRP8
7	Steel worms	2	Boston Worms, Lead Angle = 4°46', Cat. #L1056
8	Worm Gears	2	Boston Worms, Bronze, pressure angle = 14 1/2°, Cat. #GB1055
9	Clamping Frame	2	0.6 in. thick aluminum, Figure 5.
10	Supporting Table	1	1.0 in. thick aluminum with 4 adjustable legs. Figure 3.
11.	Low-Temperature Cabinet	1 1	For Extensometer, Lab-Line Cat. #3922, power 120/1/60 For Samples Storing, So-Low Inc. Cat. #PR50-G, power 230/1/60
12.	Dial Gages	2	
13	Stop-Watch	1	Electric - Lab-Line Timer, 120/60
14	Temperature Probe (thermistors)	1 1	General purpose, imbeded in A.C. block, YSI Series 401. Air-Temperature, YSI Series 405
15	Tele-Thermometer	1	Scanning Tele-Thermometer, YSI Model 47

* Obtained as one unit, JK3-W4-M3 † Boston Gear Catalog

TABLE XVII

SPEED REDUCTION ARRANGEMENT



LOCATION	OUTSIDE FREEZER				INSIDE FREEZER		
EQUIPMENT* USED	MOTOR	VARIABLE GEAR HEAD	GEAR HEAD	CONNECTING SHAFT	WORM GEARS	DOUBLE PULLING SHAFTS	THREADED CONNECTING HEAD
• HP	1/3	—	—	—	—	—	$\frac{1}{168}$
• RPM, IN	—	1725	66.8	1.67	1.67	$\frac{1}{60}$	$\frac{1}{60}$
• REDUCTION RATIO	—	26 : 1	40:1	—	100:1	—	—
• TORQUE, lb.in.	—	2.9	116.0	116.0	—	7936	7936
• RPM, OUT	1725	66.8	1.67	1.67	$\frac{1}{60}$	$\frac{1}{60}$	—
• SHAFT DIA., in.	—	—	0.75	0.50	—	1.00	1.00
• NO. OF THREADS PER in.	—	—	—	—	—	—	4
• TRAVELLING SPEED, in./hr	—	—	—	—	—	—	$\frac{1}{8}$
• FORCE, 10^3 lb.	—	—	—	—	—	2 X 11.0	—

*TABLE 1. APPENDIX A SPECIFIES IN DETAIL THE EQUIPMENT USED.

APPENDIX D

LABORATORY MATERIALS AND MIXTURES INFORMATION

TABLE XVIII

TESTED SEALANT INFORMATION

Sealant No.	Type	Grade	Source
1	Asphalt Cement	AC 60-70	Kerr-McGee Corporation Refinery, Wynnewood, OK.
2	Asphalt Cement	AC 60-70	Kerr-McGee Corporation Refinery, Wynnewood, OK.
3	Cutback	MC-800	Champlin Refinery, Enid, OK.
4	Cutback	MC-3000	Champlin Refinery, Enid, OK.
5	Emulsion	SS-1	Nu Way Emulsions, Oklahoma City, OK.
6	Emulsion	CRS-2	Nu Way Emulsions, Oklahoma City, OK.
7	Emulsion	Spical Product 4004	Allied Materials Corporation Refinery, Stroud, OK.
8	Rubberized Asphalt	Overflex MS-LV*	Sahuaro Petroleum & Asphalt Co., Phoenix, Arizona

*LV stands for Low-Viscosity

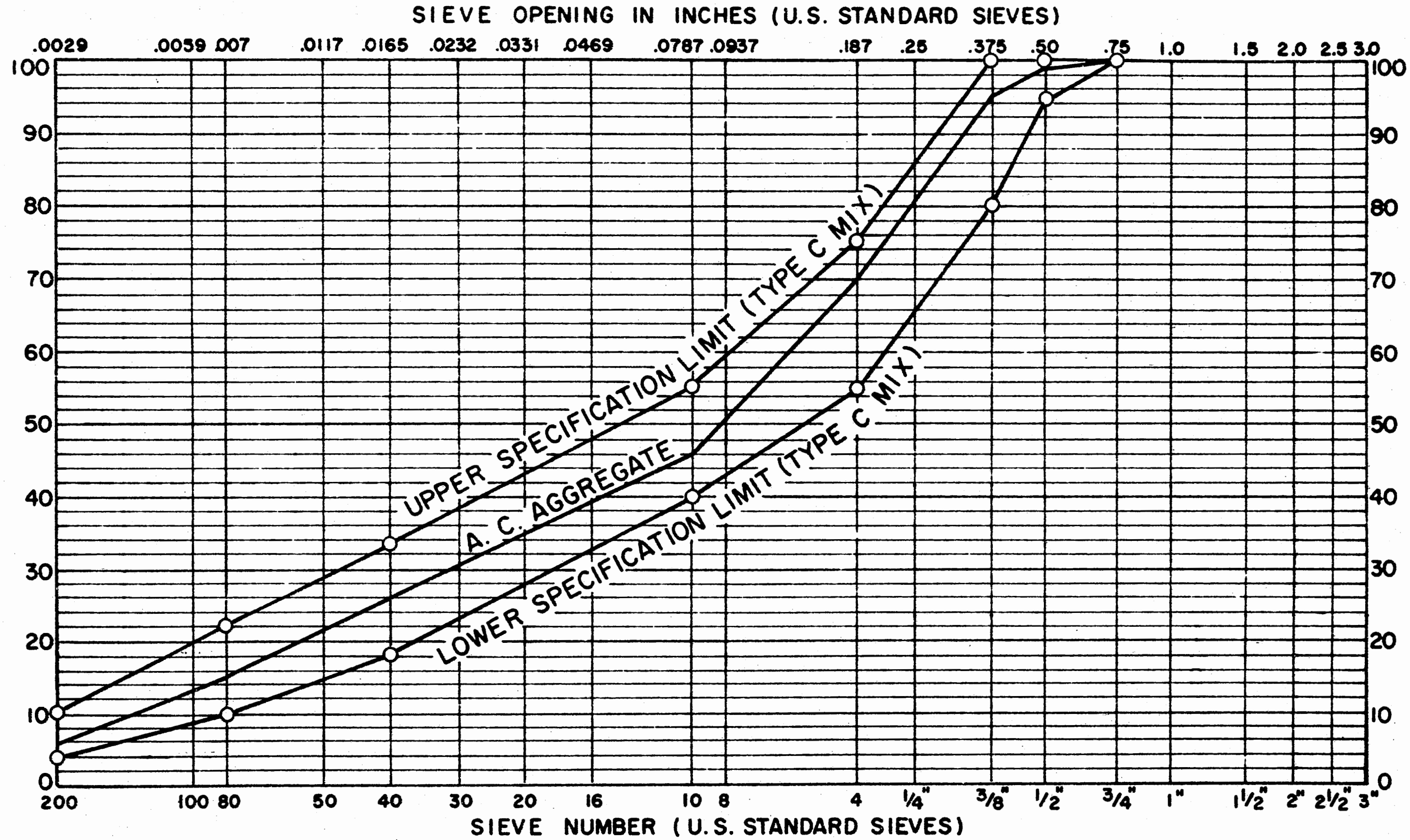


Figure 39. Sieve Analysis of Extracted Hot-Mix Aggregate

Procedure for Fabricating 12 by 4 by 3 in. Asphalt Concrete Bars.

1. Place approximately 6,000 g of asphalt concrete mixture in a 250 F (121 C) oven for at least 2 hr.

2. Into a 12 by 5 by 4 in. steel mold (Figure 19) preheated to 200°F, place sufficient asphalt concrete mix to fill the mold one-half full.

3. Rod the mix 20 blows with a 3/8 in. diameter bullet-nosed rod (Figure 20).

4. Compact specimen for 5 min at 250 psi pressure on the dial of the kneading compactor (Figure 21). The carriage crank is rotated one-quarter turn, back and forth, for each stroke of the tamping foot.

5. Add sufficient material to fill the mold.

6. Rod second lift 20 blows. (Be sure mix is well rodded around the periphery of the mold).

7. Compact specimen for 5 min at 250 psi pressure as before.

8. Continue compaction for an additional 5 min at a pressure of 500 psi on the dial of the compactor (Figure 21).

9. Place a steel leveling plate (11.85 by 3.86 by 0.98 in.) on the specimen and compact for 2 min at 500 psi pressure to level the compacted specimen (Figure 22).

10. Remove mold and place compacted specimen on smooth sheet of plywood (Figure 23).

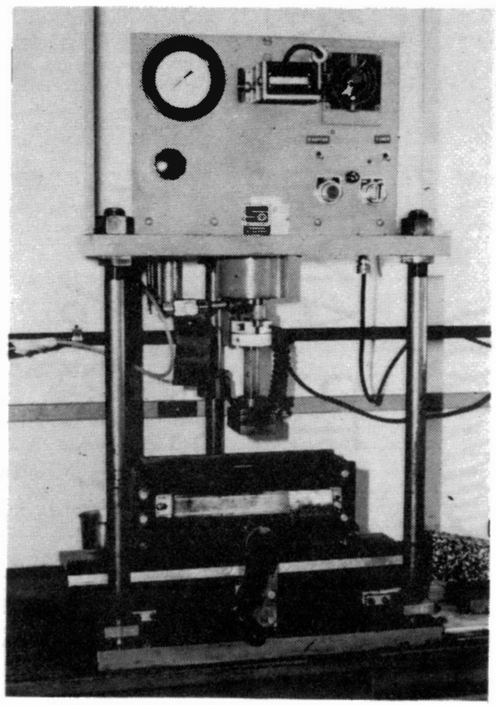


Figure 40. Kneading Compactor with Bar Mold and Carriage

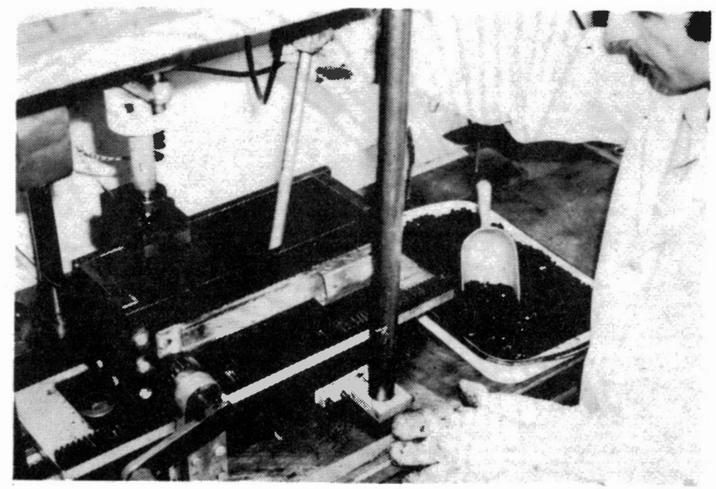


Figure 41. AC Mixture Being Roded with 3/8-in. Bullet-Nosed Rod

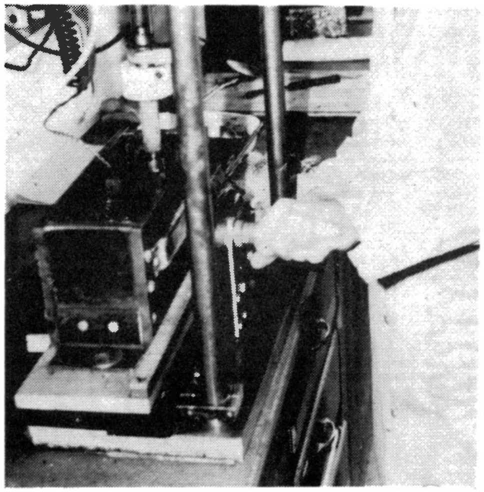


Figure 42. AC Bar Being Fabricated. Crank Turned 1/4 Revolution for Each Stroke of Compactor Foot

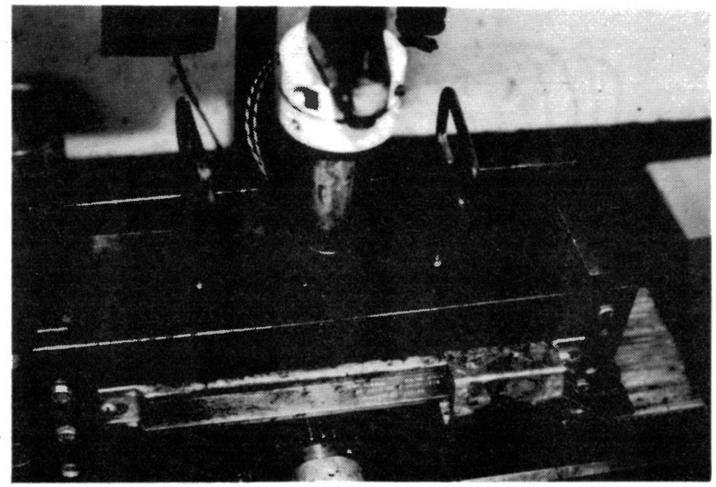


Figure 43. AC Bar Receiving Leveling Load

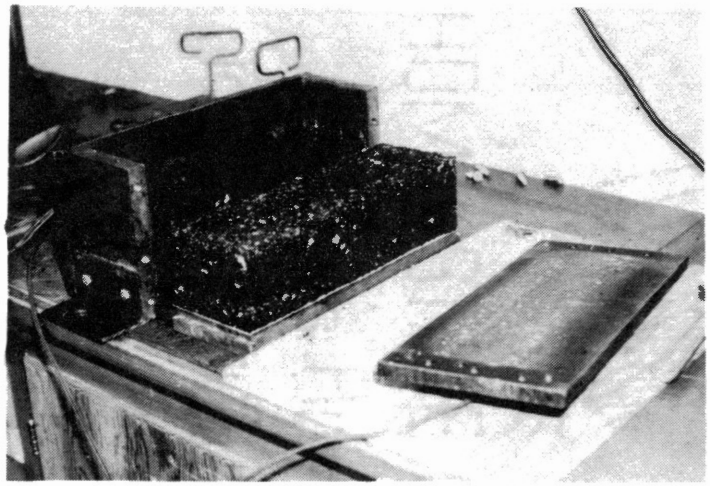


Figure 44. Metal Mold Being Removed From AC Bar

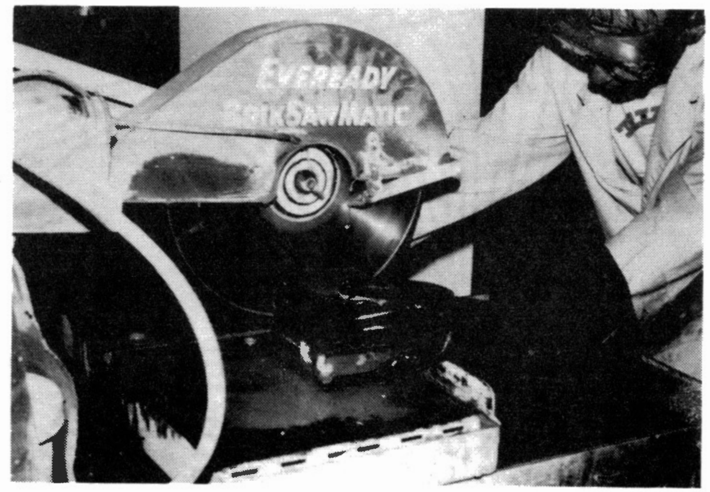


Figure 45. AC Bar Being Cut With Masonry Saw

TABLE XIX

INFORMATION ON SEALANT MATERIALS

Tests	Asphalt Cement		Liquid Asphalt				
			Cutback		Emulsion		
	60-70	85-100	MC-800	MC-3000	CRS-2	SS-1	4004
Specific Gravity	1.0058	.9956	.9509	.9567	—	—	—
Pentration 25°C 100 g, 5 sec	52	86	—	—	—	—	—
Viscosity 60°C	3012	1128	—	—	—	—	—
Viscosity 135°C	519	347	—	—	—	—	—
Kinematic Visc. @ 140°F	—	—	1525	3495	—	—	—
Furol Visc. at 77°F	—	—	—	—	374	38	28
Distillation, (% to 680°F)							
To 437°F	—	—	0	0	—	—	—
To 500°F	—	—	30.3	21.7	—	—	—
To 600°F	—	—	75.8	73.9	—	—	—
Residue 680°F	—	—	83.5	88.5	—	—	—
Residue from Distillation	—	—	—	—	62.0	62.5	62.0
Tests on Residue:							
Absolute Visc. @ 140°F	—	—	529	501	—	—	—
Pen., 77°F 100 g., 5 sec.	35	55	180	185	99	105	79
Ductility at 77°F	150+	150+	105	112	150+	150+	65
Visc. 60°C	7410	2473	—	—	—	—	—
Visc. 135°C	758	471	—	—	—	—	—

APPENDIX E

STATISTICAL EXPERIMENTAL DESIGN
FOR BOND-DUCTILITY TEST

Experimental Design for Bond-Ductility Test

The test was statistically designed as a classical split-plot experiment (22) where tested samples represented experimental units. The two factors, sealant types and sealant dimensions, were considered as treatments. The levels of the dimension factor were applied randomly to the experimental units to end up with three "main plots". Each main plot was then subdivided into six subplots to which the aforementioned sealant levels were randomly applied. To increase the precision of the experiment, each sealant level (subplot treatment) was applied to three samples (replicates). The number of test cycles the sealant experienced before failure was taken as the test response.

APPENDIX F

FIELD TEST PROGRAM EXPERIMENTAL DESIGN

Experimental Design for Proposed Field Test Program

The proposed test program is designed to study and develop information on the field behavior of selected flexible pavement crack sealing materials over a period of several years. The field performance of crack sealing materials in expected to be influenced primarily by: 1) the type and quality of the sealant, 2) the method of preparing cracks for sealant installation, 3) the amount of horizontal crack movement (related to the pavement temperature and effective crack spacing) and, 4) temperature extremes, particularly the minimum low temperature experienced by a pavement section. All of these factors have been considered in the experimental design.

In order to correlate the results of this investigation with those from the crack dynamics study (Interim Report II), the field test program will be limited to transverse type flexible pavement cracks. Three transversely cracked pavement sections have been located during previous work and appear suitable as study sites for the proposed field test program. These pavement sections are located as follows:

U. S. 177, 4.5 miles south of U. S. 66 junction

I. 35, 4.0 miles north of Perry

U. S. 64, 1.5 miles west of U. S. 74 junction

These recommended sites have enough full width transverse cracks to satisfy the experimental requirements and are located near Stillwater so that they can be conveniently monitored during the study period. At least two of these sites will be included in the field test program.

A detailed crack survey will be conducted at each of the selected study sites. This will include counting, mapping and measuring the distance between adjacent cracks to determine the effective crack spacing (ECS). Subsequently, the cracks at a site will be categorized as to small, medium or large ECS's. A small ECS will range between 10 and 25 feet, a medium ECS, between 25 and 55 feet, and a large ECS will be over 55 feet in length. Based on the established relationship between horizontal crack movement and ECS, the expected sealant strains will be approximately equal for each of these spacing categories.

Selection of the sealants used in the field test program will be based primarily on the laboratory test results presented in Interim Report III. It is suggested that the selected sealants include the rubberized asphalt, one of the cutback asphalts and one of the asphalt emulsions used in the laboratory study. One or two additional sealing materials could be added but this would necessitate additional laboratory testing.

Cleaning and preparation of cracks prior to sealing have been reported to promote good adhesion between the sealant and the crack sides. Methods of crack preparation include air blowing, brushing the surface and/or crack sides, priming the crack sides, routing of the crack to a set width and depth, and placement of a "bond breaker" or filler material in the crack to limit the depth of penetration of the sealant. Based on reported results in the literature, it is suggested that only the first three of these crack preparation methods, i.e., air-blowing, brooming or brushing, and priming, be used in the proposed field test program.

An equal number of cracks will be selected for sealing at each study site. The total number of cracks selected will depend on the number of sealants, crack preparation methods, and replications desired in the study. The length of each crack to be treated will be determined and coded numbers painted on the pavement will identify the treatment to be applied to each crack.

The preparation and sealing of the transverse cracks at the respective study sites will be performed by experienced ODOT maintenance crews under the direction of research project personnel. Sealing of the cracks will be completed by October 31, 1979, or as soon as possible, thereafter. Pavement temperatures at the time of the sealing operations will be recorded. It is also suggested that the pavement temperature be recorded at the time of subsequent surveys of sealant performance.

These surveys or inspections of the sealed cracks will be done on a periodic basis. During the first year after sealing the cracks will be inspected for evidence of failure approximately six times. Failures will be classified as to type, i.e., adhesive or cohesive, and the extent of failure determined by linear measurement. Evaluation will be based on the percentage of total length that failed for any combination of sealant type, crack preparation method and ECS. Final statistical evaluation of the respective treatment will be made after exposure to field conditions for a full year.

Statistically the design of this field test program can be classified as a "factorial experiment" with the treatments arranged in three factors having various levels. The sealant type factor will have up to five levels and both the crack preparation method factor and the ECS factor will have three levels. This design results in approximately 45 treatment combinations that will be applied randomly to the selected cracks in each study site or "block". To increase the precision, each treatment will be applied to at least two (preferably three) cracks in the same blocks.

VITA

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Thesis: A STUDY OF FLEXIBLE PAVEMENT CRACK DYNAMICS AND SEALANTS

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