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JOINT HIGHWAY RESEARCH PROGRAM
PROJECT 77-02-3
SEALING CRACKS IN FLEXIBLE PAVEMENTS
INTERIM REPORT III

SCHOOL OF CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY

RESEARCH REPORT

LABORATORY TESTS OF ASPHALT SEALANTS

by

Ismail M. Basha
Phillip G. Manke

Publication No. R(S)-20

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by the

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER I

INTRODUCTION

A survey of literature pertaining to materials and methods of sealing highway pavement cracks indicated a scarcity of information and a lack of standard testing procedures for asphalt pavement crack sealants. Therefore, the proposal for research on "Sealing Cracks in Flexible Pavements" called for evaluating and/or developing a series of laboratory test procedures that could be used to predict a sealant material's ultimate field performance.

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 grades 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 temperatures and compatibility with the pavement binder, and certain physical and rheological 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 indicators 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. The experimental design for this proposed program has been included.

CHAPTER II

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) (2) (3) (4) (5). Although the testing procedures and equipment may differ, the essential features of this test, as described in Interim Report I (6), 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 low-temperature cabinets or freezers and temperature and displacement rate monitoring devices. Figure 1 shows some of the basic design features of the machine and its position in the freezer. Figure 2 illustrates the details of one of the clamping frame assemblies. The respective components and their basic specifications are also listed in Table III, Appendix A.

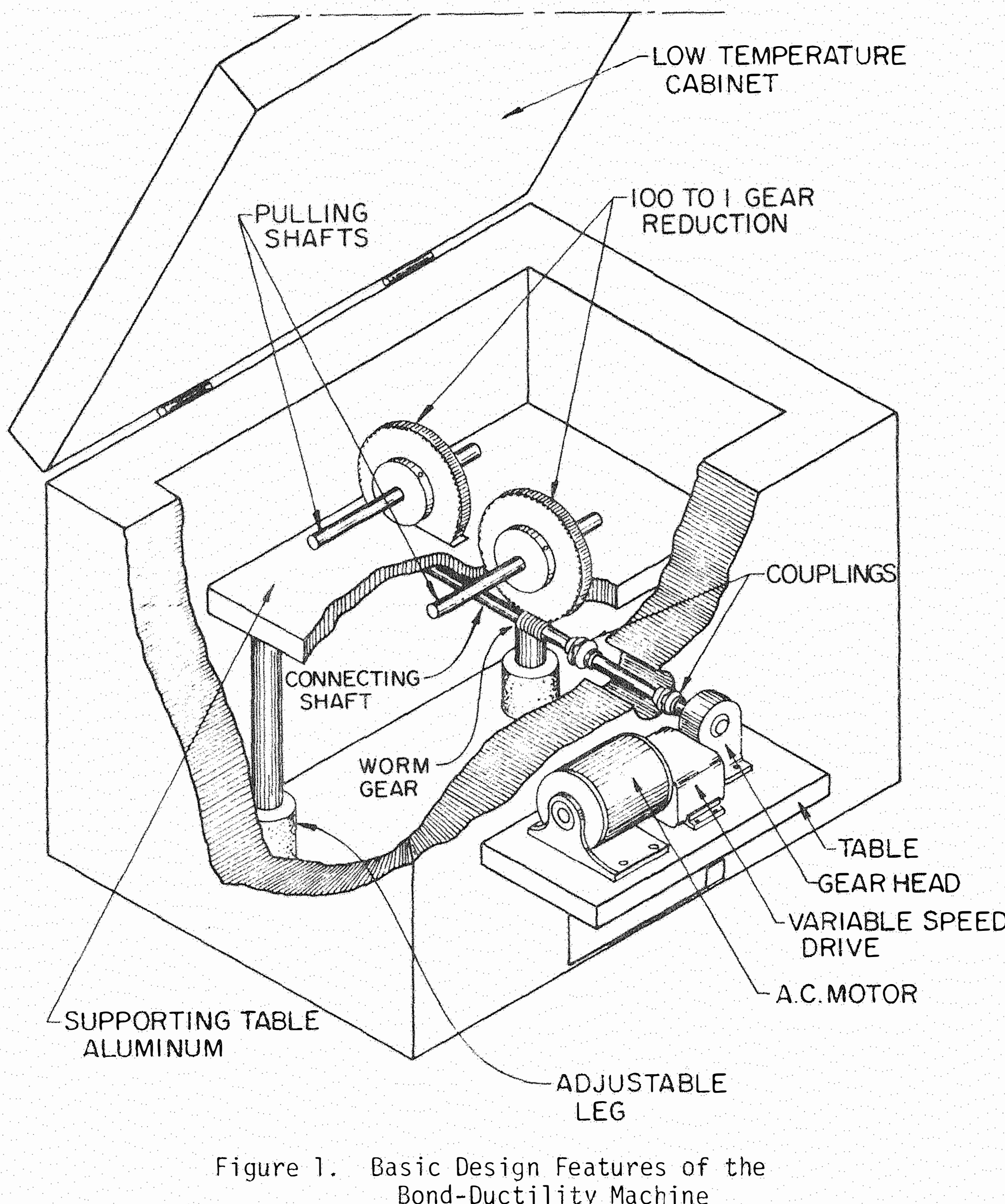


Figure 1. Basic Design Features of the Bond-Ductility Machine

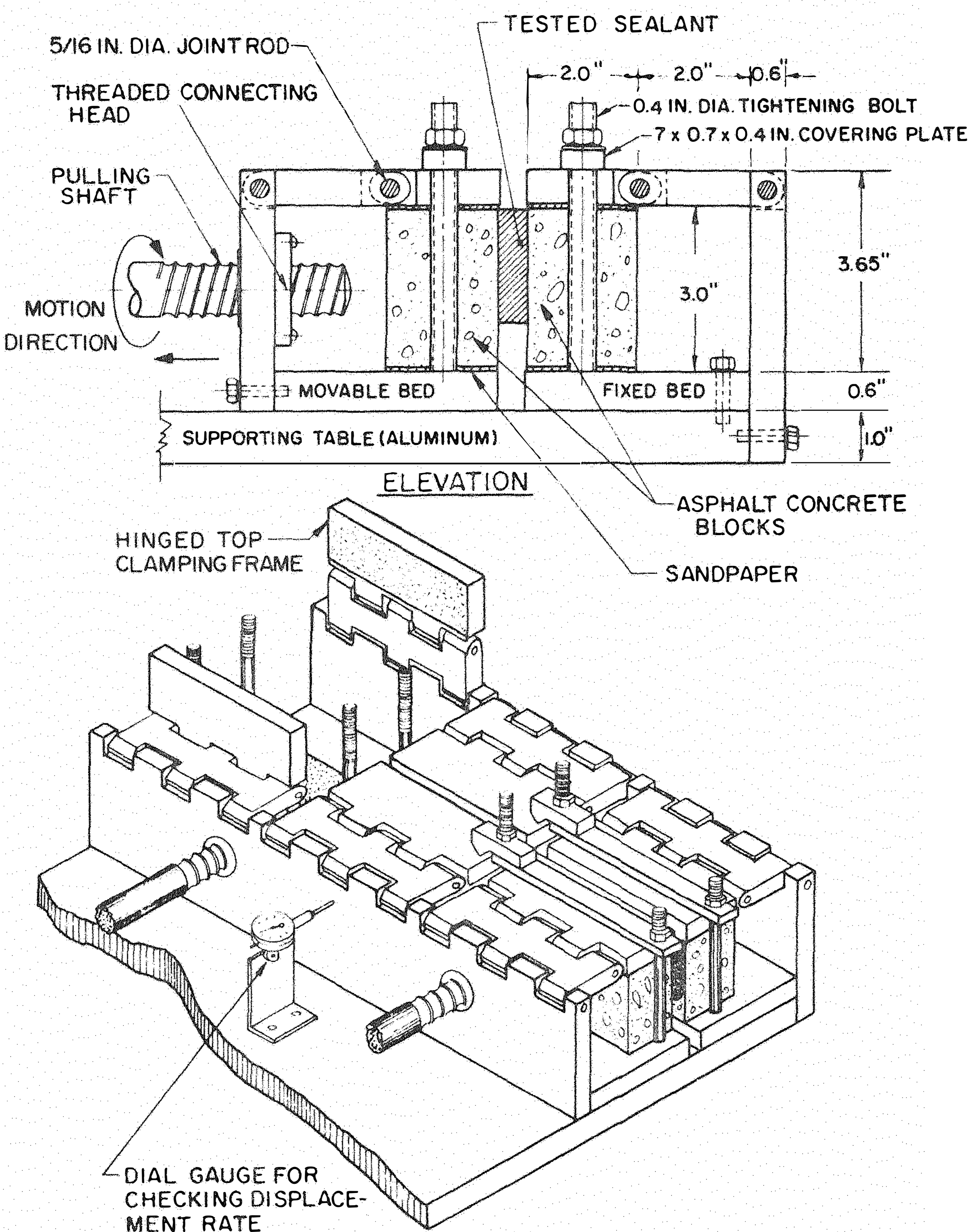


Figure 2. Details of Clamping Frame Assembly for the Bond-Ductility Machine

Motor

Based on an assumed stiffness modulus of 441 psi (31 kg/cm^2) for an asphalt material (7) 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 (8) (9) 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 1). 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 1. The schematic arrangement and data for these parts is presented in Table IV, Appendix A. 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 2). 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 2. 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 III

LABORATORY TEST PROCEDURES

Six sealing materials were initially selected for evaluation by the proposed laboratory tests (6). 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 (6). Two more sealants were added to the study in its latter stages. One of these was a special type emulsion which was 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 I in Appendix B 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 cutback 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 3). 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 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 (10) for cold-poured type concrete joint sealers and the preliminary curing and setting studies indicated that

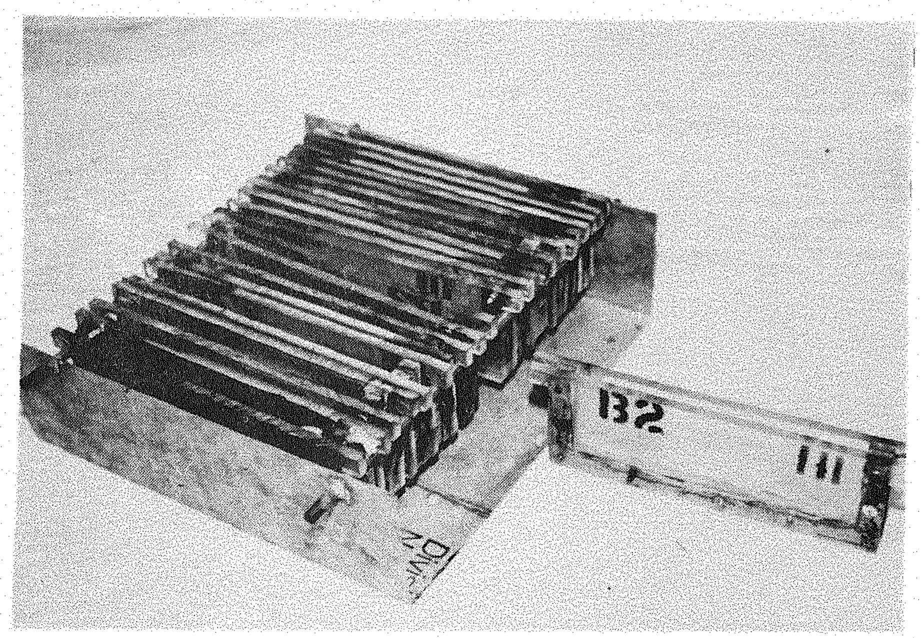


Figure 3. Lucite Plates Simulated Cracks Used for Liquid Sealants Curing and Setting Study

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 4 and Figure 5 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 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 325 F (163 C), the temperature specified for heating concrete joint sealers (10). 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.

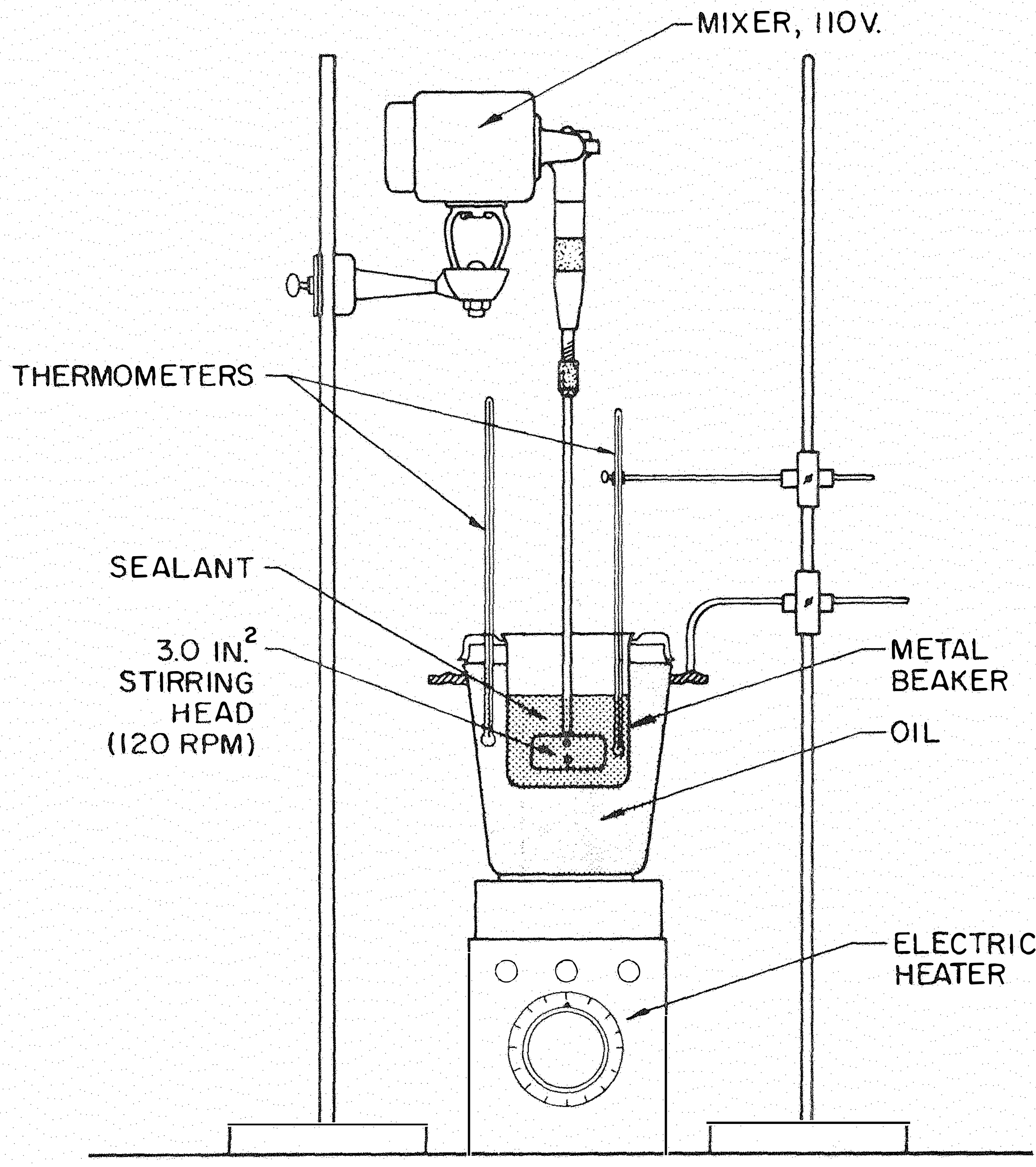


Figure 4. Sealant Evaporation and Heating Equipment

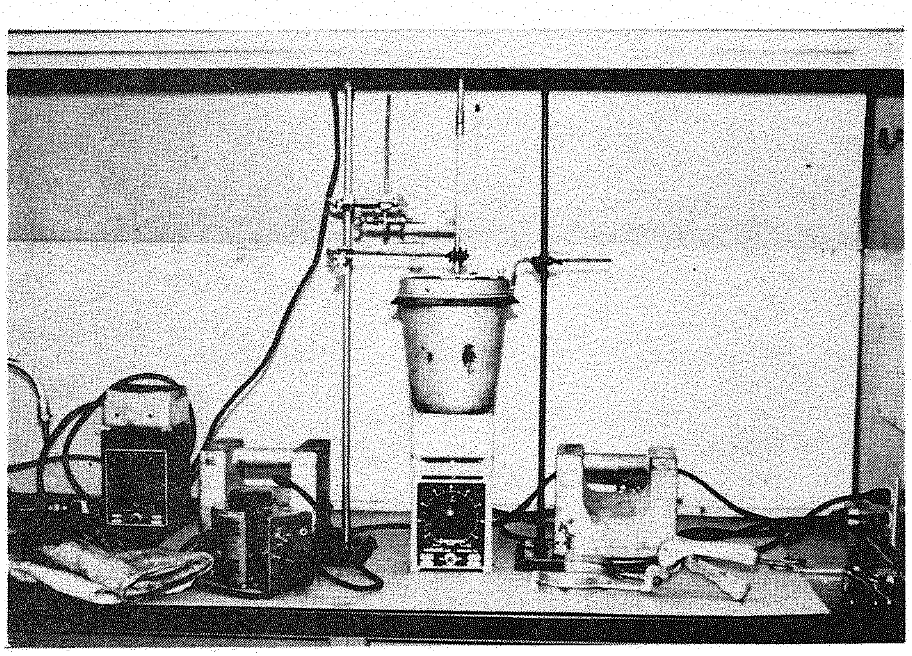


Figure 5. Sealant Evaporation and Heating Equipment

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 6). 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 II). This test temperature was based on a study of Oklahoma climatological data (11). An extension rate of 0.125 in./hr (3 mm/hr) which had been used by many previous investigators (2) (3) (4) was applied to the sealants by the extensometer.

The 6 in.(152 mm) length of the test blocks was based on Cook's recommendation (1). Several widths and depths of sealant were tested to study the effect of shape factor on sealant performance (12). 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)

1) 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 18, Appendix B. 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

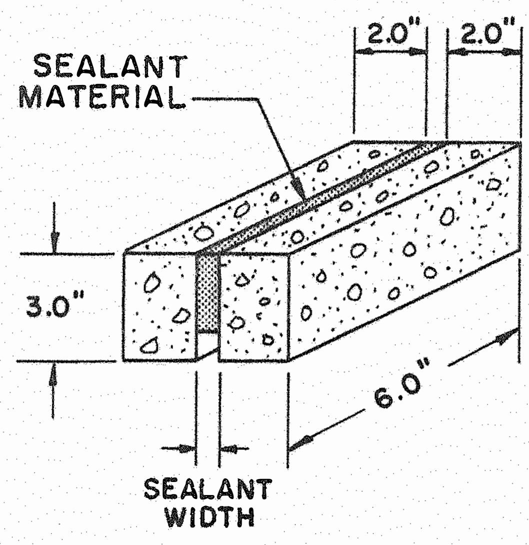


Figure 6. Bond-Ductility Test Blocks

x 76 mm). The compacted density of these bars was about 94 percent. A kneading compactor conforming with ASTM D-1561 (10) was used. The compactor was modified to mold the rectangular bars. A 2 by 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 19, 20, 21, 22 and 23, Appendix B. 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 24, Appendix B). These blocks were than washed, dried and stored prior to assembly and pouring of the sealants.

2) 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 7). 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

Figure 7. Specimen Preparation for Bond-
Ductility Test

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.

3) 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 8). 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 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.

4) 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 9 shows a specimen being compressed in the jacking frame.

5) 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

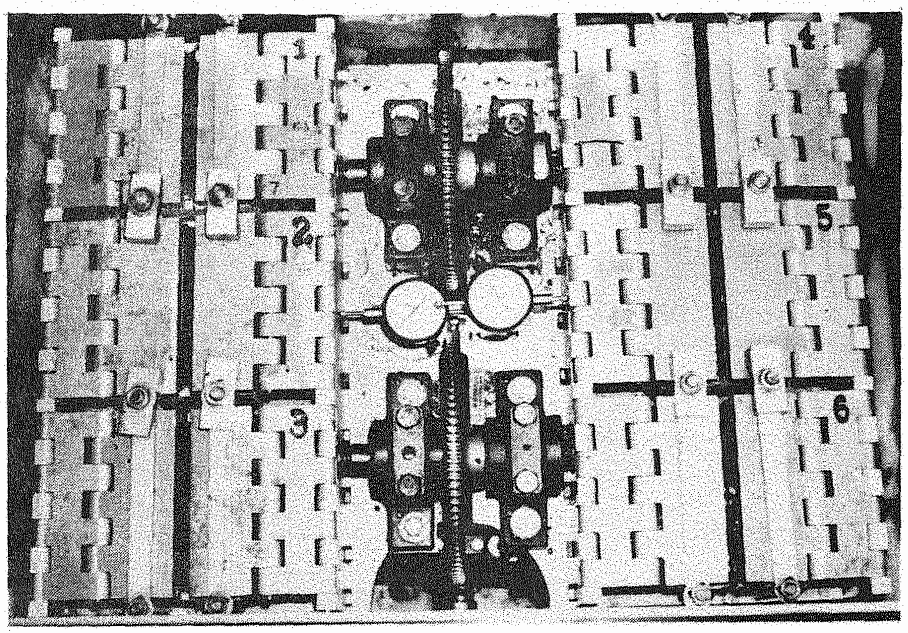


Figure 8. Bond-Ductility Machine Stretching
Six Sealant Specimens

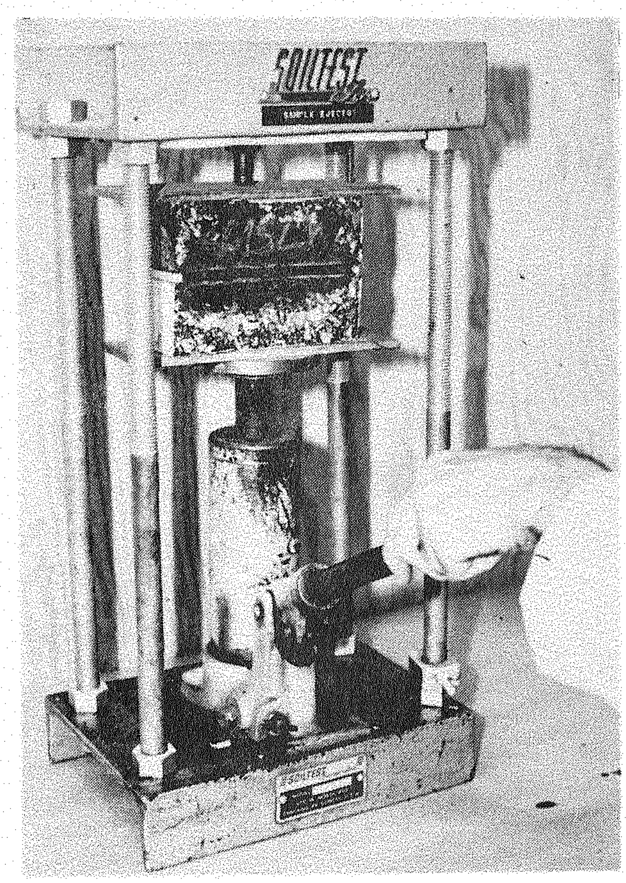


Figure 9. Jacking Frame for Specimen Compression

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 10(a) shows a typical cohesive failure in a specimen and Figure 10(b) shows a brittle type of cohesive failure that was frequently encountered.

Penetration Test: (ASTM D 3407-75T)

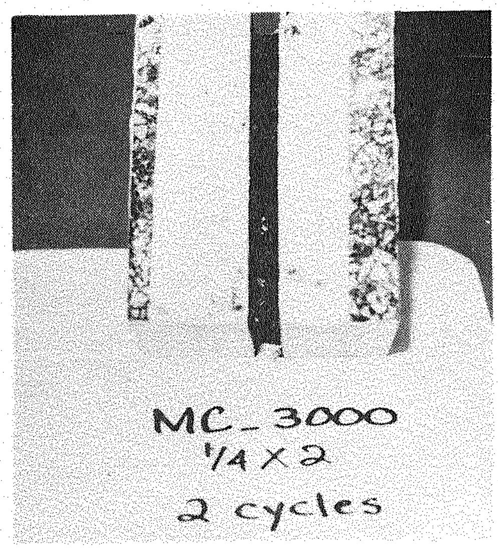
This is a tentative test (10) used to provide a measure of sealant consistency. It is similar to the standard penetration test except that a specially dimensioned cone is used instead of the penetration needle (Figure 11). Other consistency tests were also conducted on the selected sealants. The kinamatic and absolute viscosity values of these materials were reported along with the cone penetration values.

Resilience Test: (ASTM D 3407-75T)

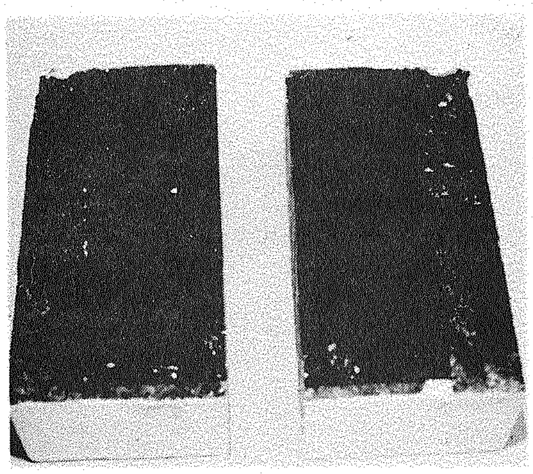
This test was performed as described in the ASTM Standards (10). The test is performed using a ball penetration tool and the results are reported as the recovery percentage or percent of recovered depth of penetration. Resilience values provide an indication of the elasticity of the sealant materials.

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 (10). Results could not be reported due to rapid and extensive flow of the selected sealants on the 75 degree inclined panel (Figure 12). Some modifications had to be



(a) Cohesion Failure



(b) Brittle Failure (Glossy Conchoidal Fracture Surface)

Figure 10. Sealant Failures in Bond-Ductility Test Specimens

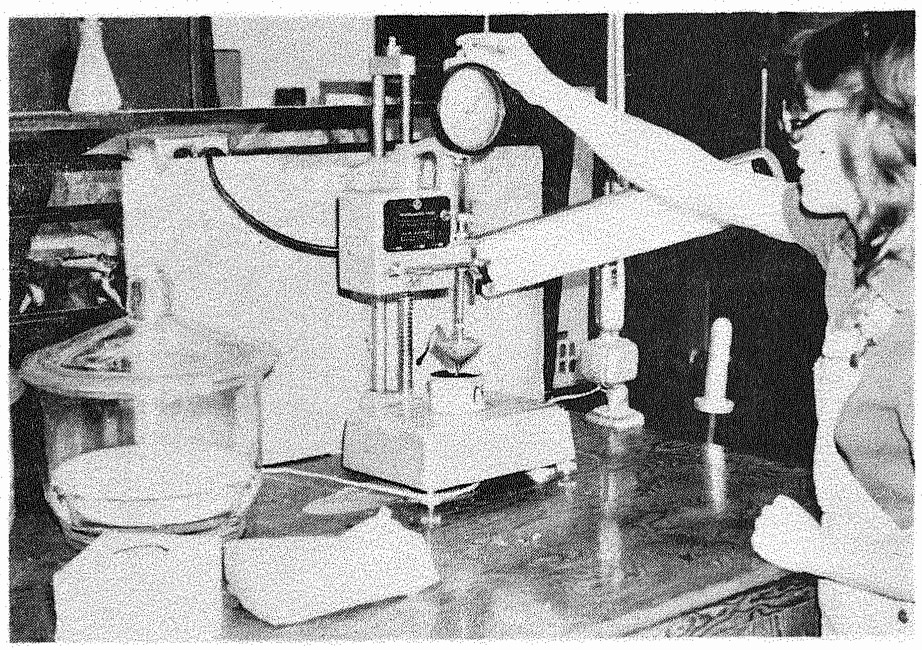


Figure 11. Penetration Test for Sealants using a Penetration Cone

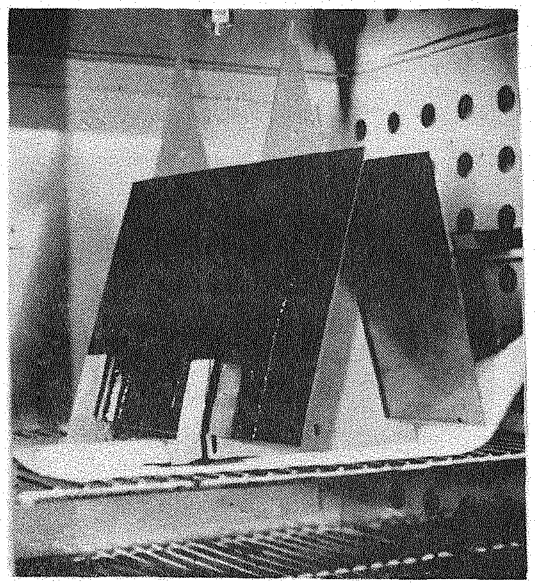


Figure 12. Flow Test at 75 Degree after 10 Min.

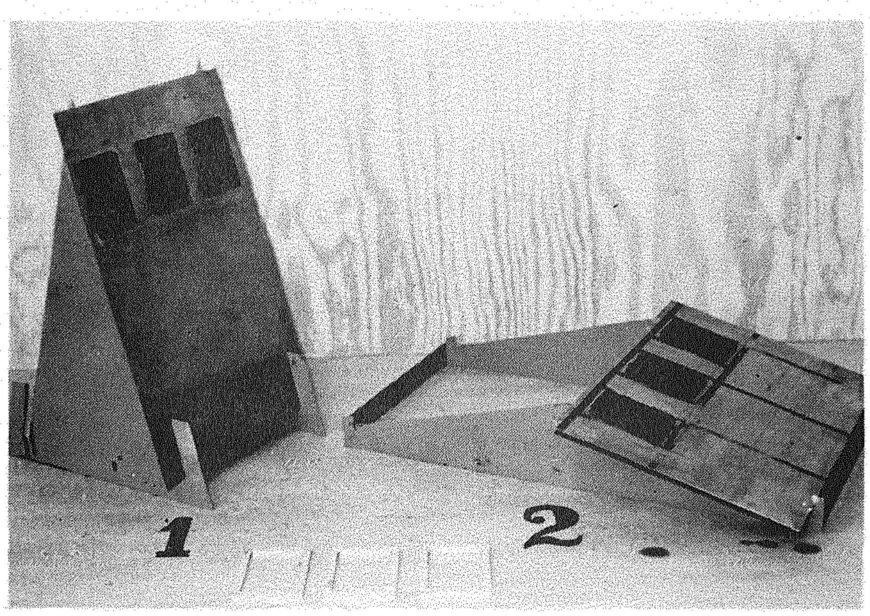


Figure 13. Standard and Modified Flow Test Panels

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 13). 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.

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.

1) 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 (13). A 1.5 ounce ($44 \times 10^{-6} m^3$) 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 (1.9×10^{-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.

2) 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 IV

RESULTS AND DISCUSSION

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 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 14 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.

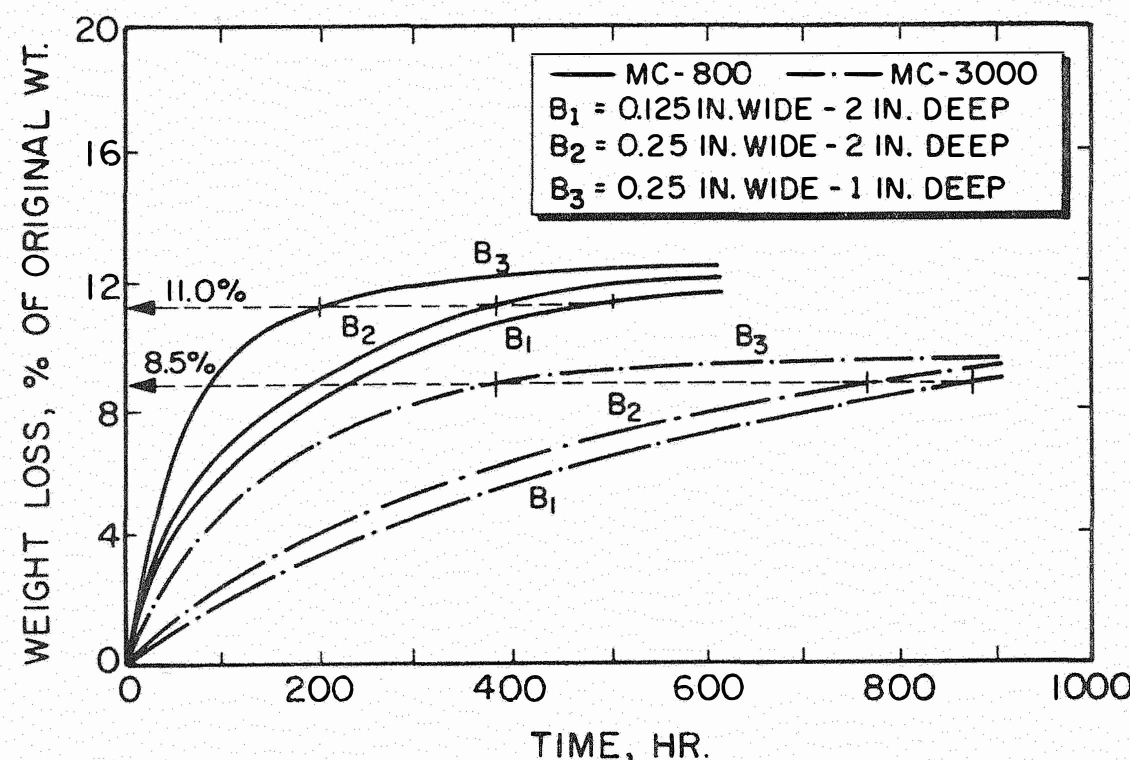


Figure 14. Curing Curves for Cutbacks in Lucite Cracks Molds -at 150°F.

The wider and more shallow samples 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 15. 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 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 14 and 15). 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

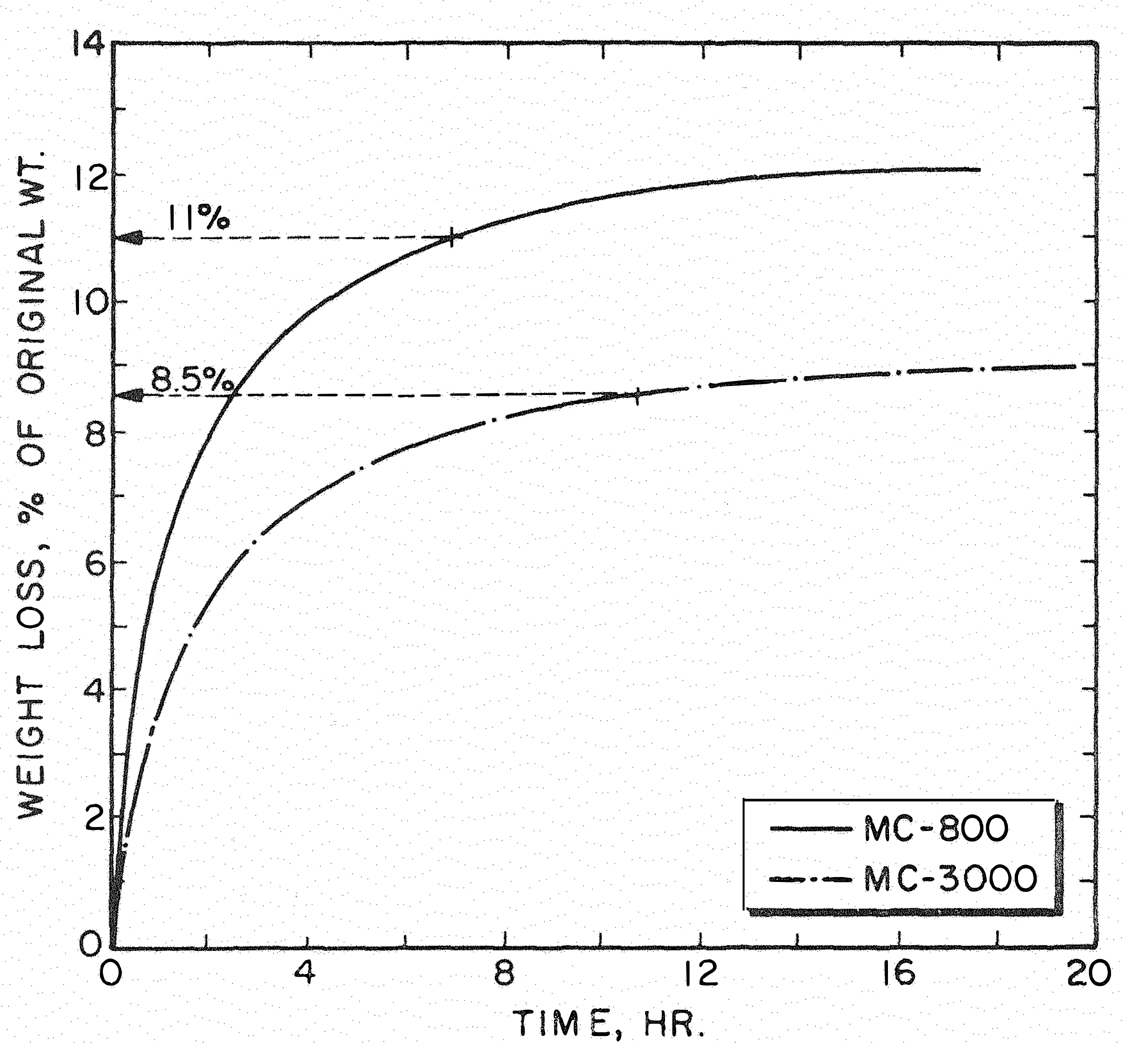


Figure 15. Curing Curves for Cutbacks in Shallow Pans-at 150° F

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 16. 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 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 C), a

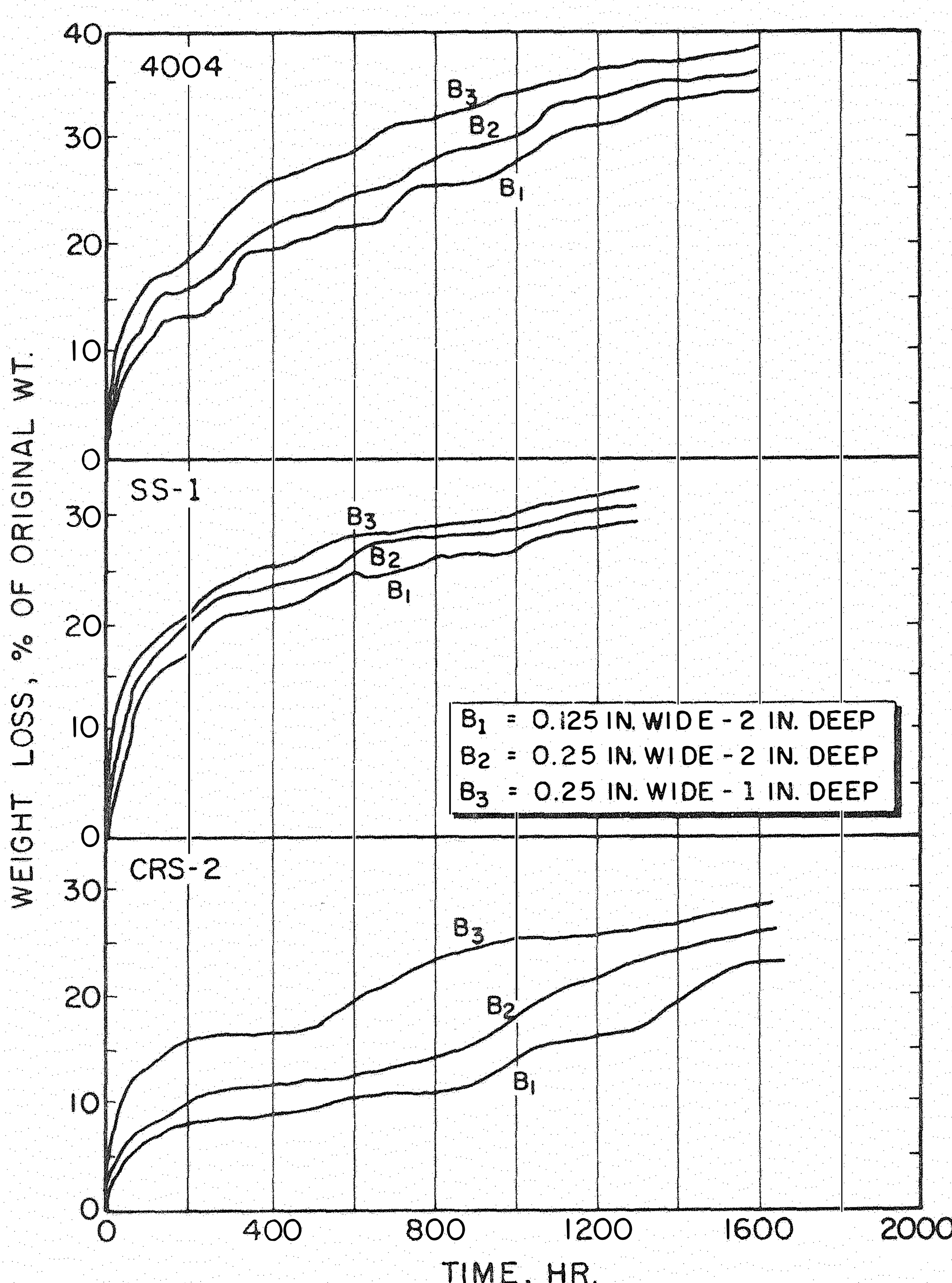


Figure 16. Setting Curves for Emulsions in Asphalt Concrete Crack Molds-at Room Temperature

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 I). 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 (6).

Sealants: Table II 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.

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 I). 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 (3) and Schutz (12) in that, with other conditions being the

TABLE I

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 II

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

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 II). 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 V Appendix B) 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 (14) 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 (10) 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 17 were plotted using the Hewlett-Packard Calculator Plotter (Model 9862A).

In previous research work (2) and in standard tests for sealants (10)(13) limits of flow are established and the test results reported as passing or failing based on whether these limits are exceeded. Based on results of the modified test, the slope of the lime 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 (10). However, there was no apparent

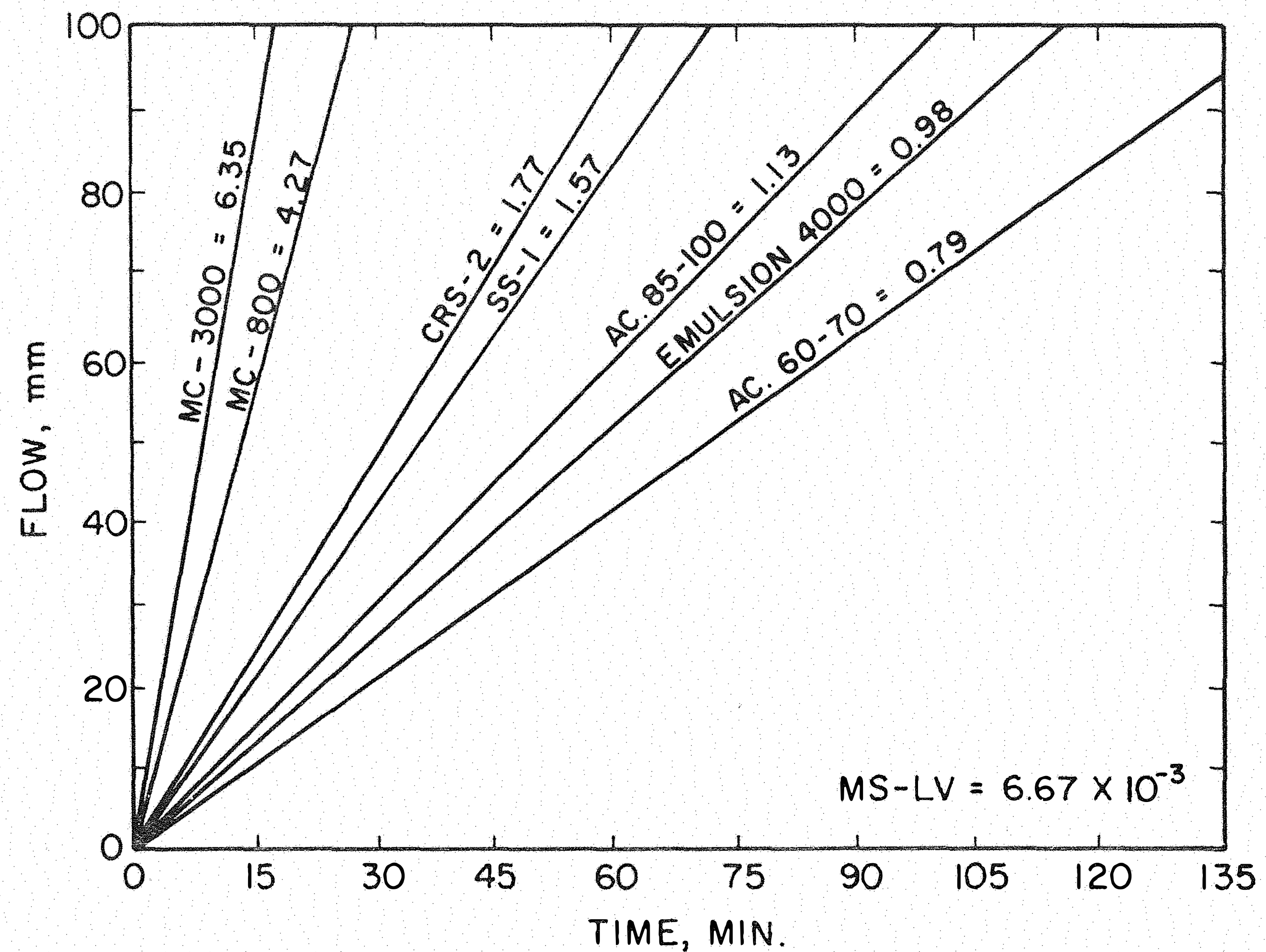


Figure 17. Relationship Between Flow and Time at 15° Angle

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 II. 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

Tests 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 (15), 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 (17) (18) (19). 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 (20) 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 drop 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 (20) and Traxler (21).

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This 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 <u>and</u> 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

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

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 D.

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APPENDIX A

BOND-DUCTILITY MACHINE

TABLE III

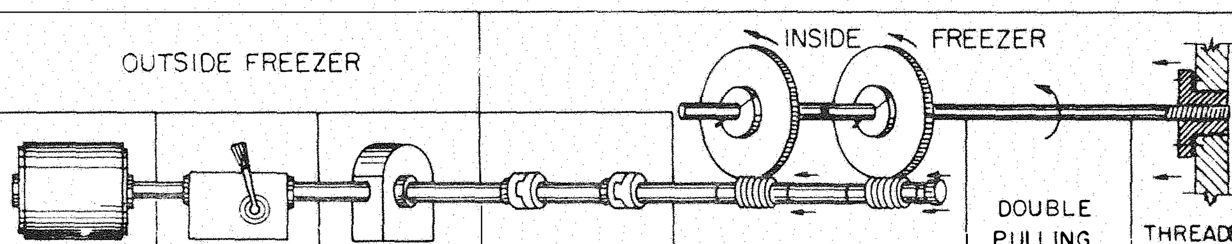
BOND-DUCTILITY TESTING MACHINE COMPONENTS

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 IV

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 B

LABORATORY MATERIALS AND MIXTURES INFORMATION

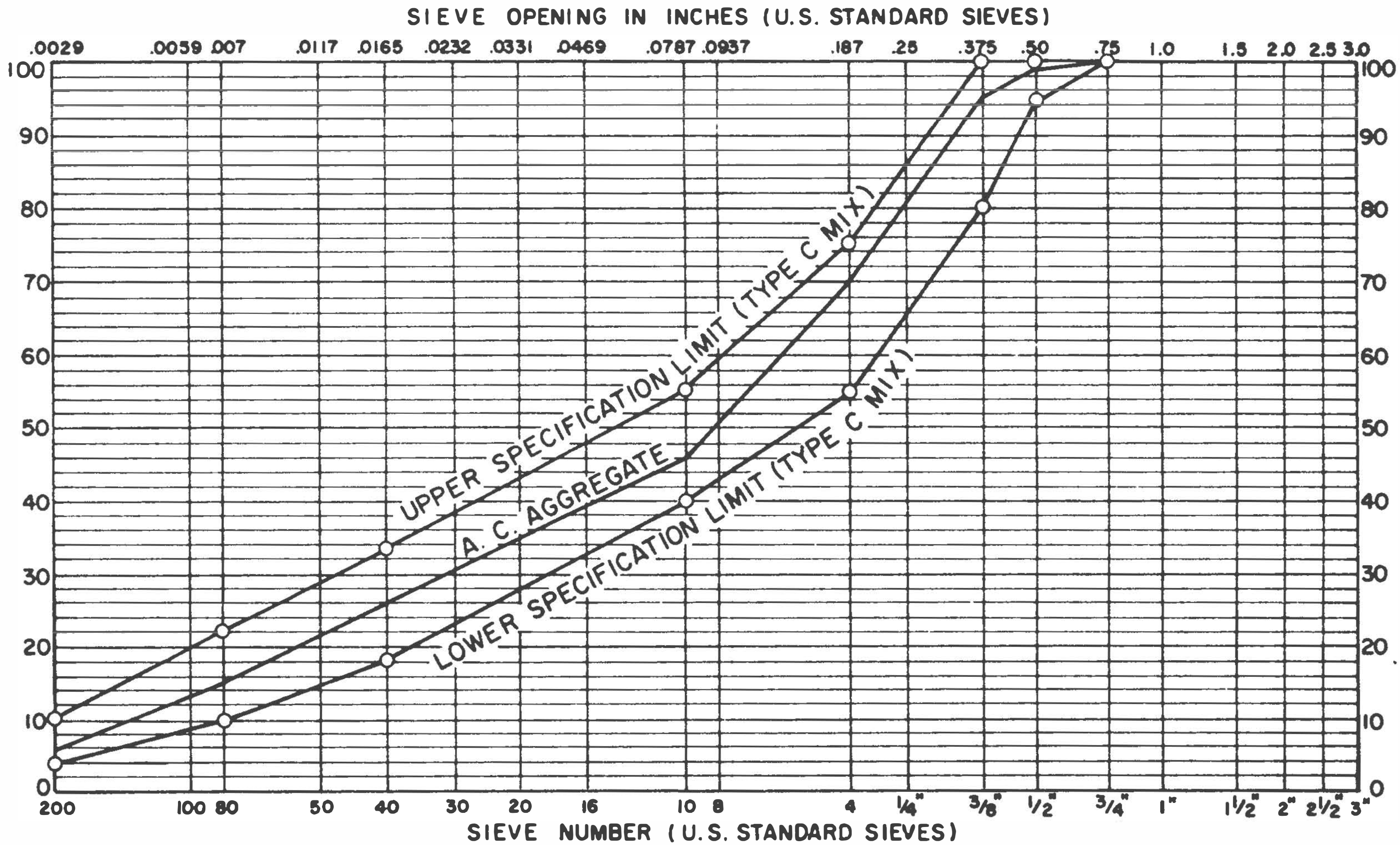


Figure 18. Sieve Analysis of Extracted Hot-Mix Aggregate

<u>Procedure for fabricating 12 by 4 by 3 in. asphalt concrete bars.</u>

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).

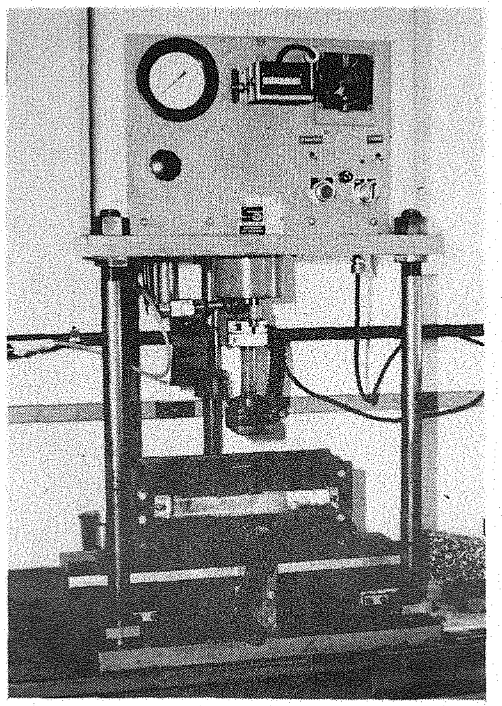


Figure 19. Kneading Compactor with Bar Mold and Carriage

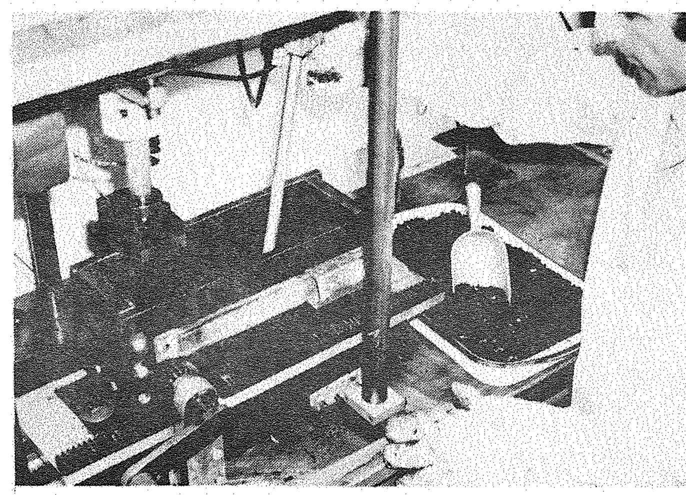


Figure 20. AC Mixture Being Roded with 3/8-in. Bullet-Nosed Rod

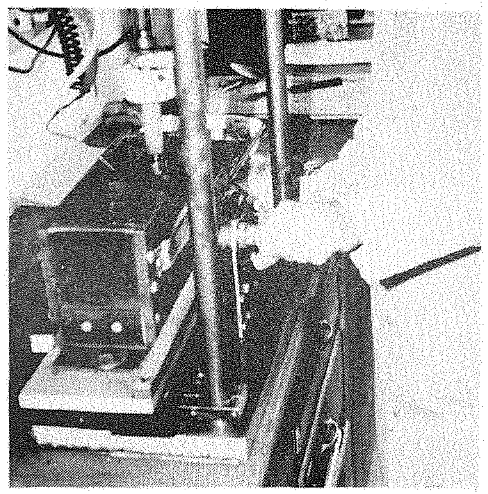


Figure 21. AC Bar Being Fabricated. Crank Turned 1/4 Revolution for Each Stroke of Compactor Foot

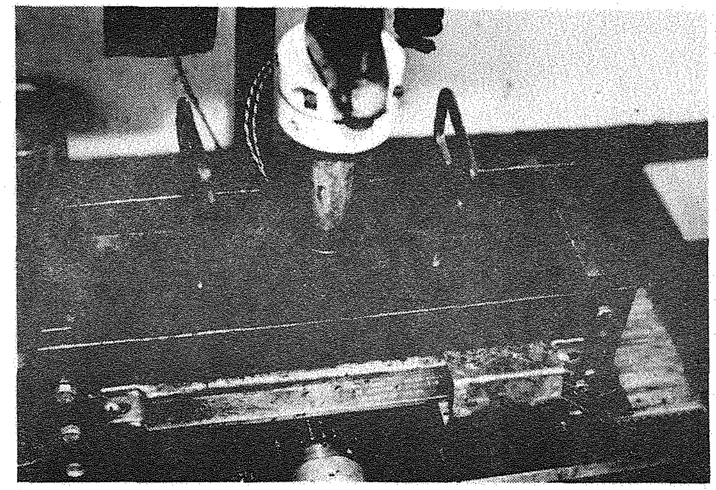


Figure 22. AC Bar Receiving Leveling Load

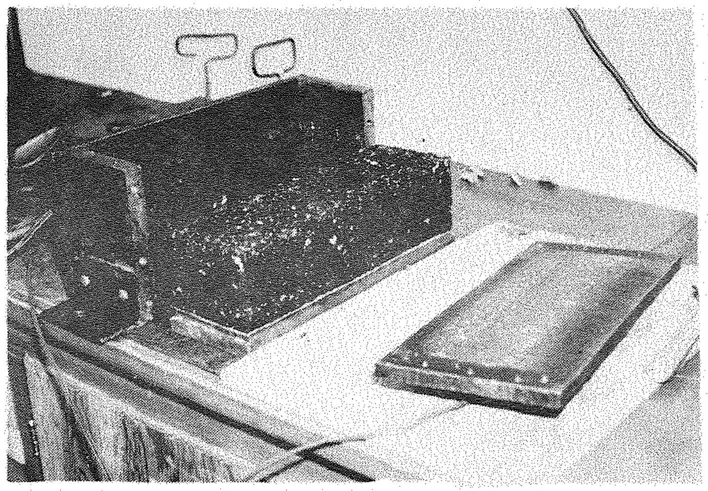


Figure 23. Metal Mold Being Removed From AC Bar

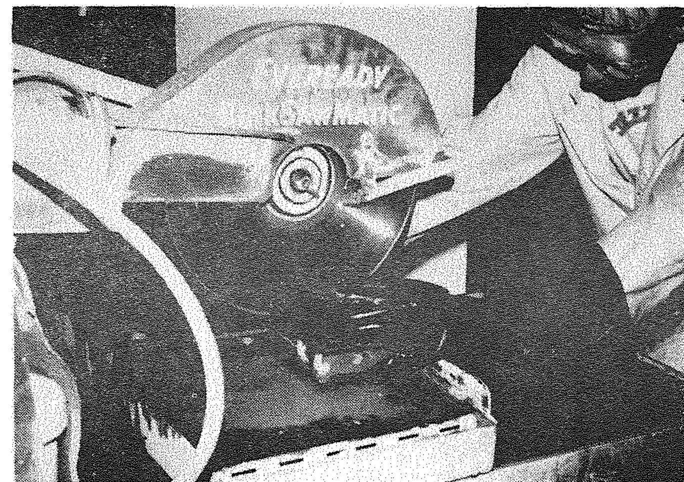


Figure 24. AC Bar Being Cut With Masonry Saw

TABLE V

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

TABLE VI

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
<u>Tests on Residue:</u>							
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 C

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 D

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.