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# Sulfur Extended Asphalt Pavement Evaluation Design and Construction

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This report summarizes the placement of sulfur extended asphalt (SEA) paving mixtures at two test sites near Pullman, Washington. One site was on an existing state highway and the other made use of the Washington State University Test Track. The report includes the preliminary mix designs, pavement thickness determination, construction details and initial performance data for the test pavements. A major experimental feature of the study was the use of 0/100 (conventional asphalt concrete), 30/70 and 40/60 SEA binder ratios in the experimental paving mixtures.

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# SULFUR EXTENDED ASPHALT PAVEMENT EVALUATION IN THE STATE OF WASHINGTON: DESIGN AND CONSTRUCTION REPORT

By

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# CHAPTER I

## INTRODUCTION

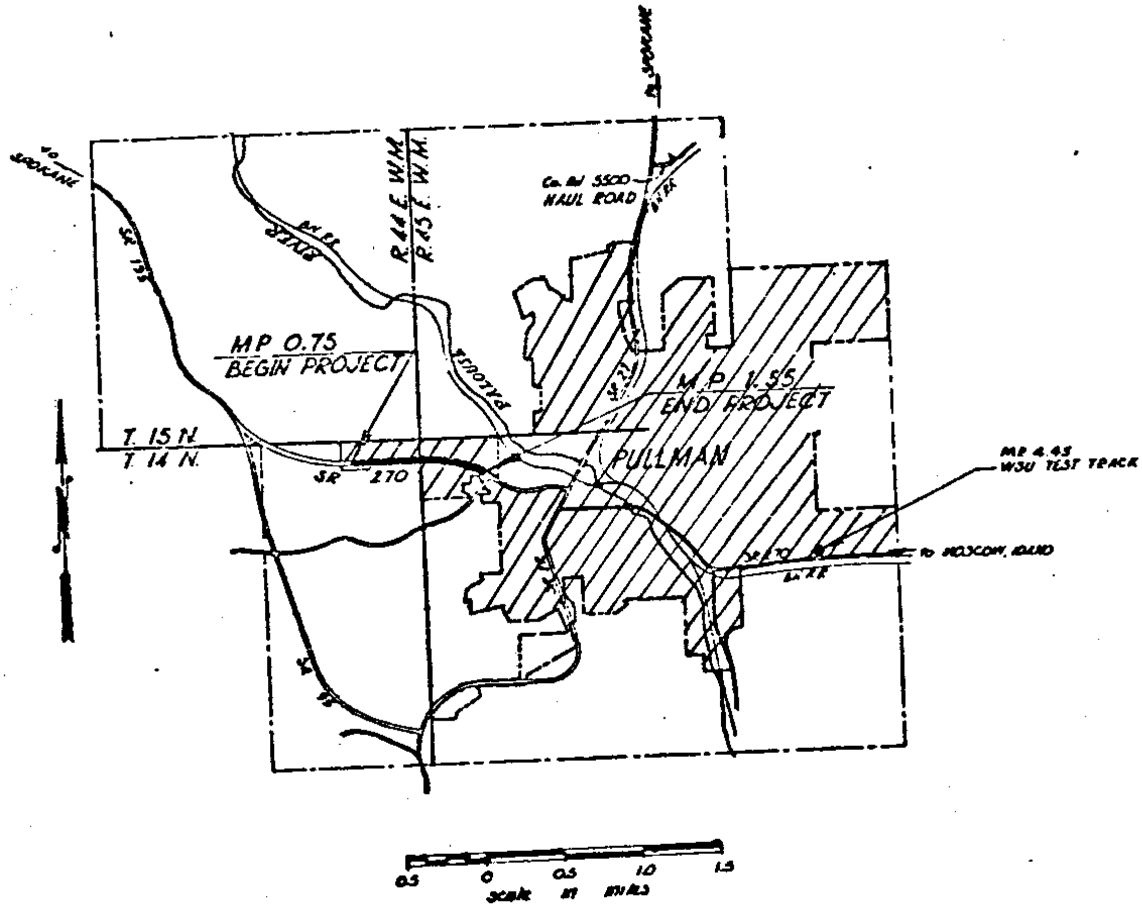
A number of laboratory-analytical studies have been conducted by various research organizations to investigate the effect of combining sulfur, asphalt and various aggregates in paving mixtures. Additionally, several full-scale experimental highway projects have been built in the United States, Canada and elsewhere using various combinations of these materials.

Much of this work has been reported and some research efforts, particularly the field trials, are still in progress. It has been observed that, in general, the laboratory-analytical studies have shown the use of sulfur extended asphalt (SEA) binders to be promising, and possibly superior to conventional asphalt concrete paving materials. The results of the full-scale experimental highway projects are, at this time, somewhat inconclusive. This is not to say that compared to conventional paving mixtures sulfur-asphalt bound pavement materials are performing poorly under normal highway traffic and realistic environmental conditions.

The study being reported is intended to help bridge the gap between the laboratory-analytical studies and the full-scale experimental highway projects. This work comprised building full-depth pavement structures for repetitive wheel load testing at the Washington State University G.A. Riedesel Pavement Test Facility (hereafter identified as the "Test Track") as well as construction and evaluation of a companion highway project. Both types of test pavements were located in the immediate vicinity of Pullman, Washington (Southeastern Washington as shown in Figure 1), and were constructed in August, 1979. This experimental configuration allowed for the concurrent construction of both the test track and highway project. Thus, the same materials and central batch plant were used for both jobs.

There were a number of unique advantages involved in using the WSU test track. One is that a limited number of variables were monitored under controlled conditions. The use of a test track thus eliminated some of the uncertainties and variabilities encountered in constructing and evaluating experimental highway projects. It also provided a more realistic assessment of the performance of the composite pavement structure than obtained through laboratory studies. Additionally, a conventional asphalt batching plant and associated laydown equipment were used to produce and place the various mixtures and thicknesses investigated. It was considered important to simulate actual highway construction procedures to the maximum extent possible.

The sponsors for the study included the Washington State Department of Transportation (WSDOT), Federal Highway Administration (FHWA), Sulfur Development Institute of Canada (SUDIC), and the Asphalt Paving Association of Washington. The prime contractor for the conduct of the study was the University of Washington (UW) with Washington State University (WSU) as subcontractor. The Washington State Department of Transportation provided substantial funding for the study as well as participation in the construction and evaluation of the test pavements.




1 km = 0.6 miles

Figure 1. Vicinity Map of Experimental Pavements

This report is the first of three detailing the conduct and findings of the study and deals primarily with the construction of the experimental pavements and initial findings.

## BACKGROUND

Recent investigations of emerging technologies such as the recycling of asphalt concrete, asphalt rejuvenation, and asphalt extension through the use of wood lignins or sulfur have produced generally encouraging results in saving or recovering asphalt cement. The reported study involves the construction and initial evaluation of SEA concrete mixtures in the State of Washington. The specific system used to produce the SEA binders at Pullman was the Pronk mixing process which was developed for SUDIC. To expand the understanding of this mixing system and others that are available, brief descriptions of the Pronk system as well as the Gulf Oil Canada, Societe Nationale des Petroles d'Aquitaine and the U.S. Bureau of Mines systems follow.

## SEA TECHNOLOGIES

SEA binders are generally placed into paving mixtures by two methods. The first method utilizes a preblended sulfur-asphalt emulsion which is a dispersion of molten, liquid sulfur in asphalt cement. The sulfur-asphalt emulsion is then added to preheated aggregates using one wet-mix cycle to produce the hot mix used in construction of the pavement. The second method is similar to the first with the exception that the asphalt cement and sulfur are not preblended prior to mixing with the aggregate.

Table 1 shows the primary SEA technologies that have been developed to date. It should be noted that with the exception of the U.S. Bureau of Mines process, all processes are patented.

### Pronk

This process was developed by Frank E. Pronk with the support of SUDIC starting in 1973 (Figure 2)[1]. An element of this system is the addition of a small amount (approximately .001 percent based on weight of asphalt) of organosiloxane polymer as a stabilizer. The sulfur percentage of a typical mixture is 30-40 percent by weight, with a mixing temperature of 266-293°F (130-145°C). SUDIC recommends that the asphalt cement, stabilizing agent and sulfur be emulsified by use of an in-line mixer prior to their coming in contact with the aggregate; although, mixing of the asphalt (with additive), sulfur and aggregate can be accomplished in a pugmill. Pronk illustrated the stabilizing effect of this paricular polymeric organosiloxane with two identical emulsions of sulfur and asphalt cement prepared at 279°F (137°C), the only difference between the two emulsions being the addition of the stabilizing agent to one [2]. The samples were stored at 266°F (130°C) and gently agitated with a propellor-type stirrer. The emulsions were sampled periodically over a 72 hour period and the specific gravity at the top was compared to the specific gravity at the bottom of each sample. These results are shown

Table 1. Summary of Available SEA Technologies

| Process | Patent | Year of Development | Optimum SEA Ratio by Weight | Additive |
|---|---|---|---|---|
| Pronk | Yes | 1973 | 40:60 | Yes |
| Gulf Oil Canada Limited | Yes | 1973 | 30:70 | No |
| SNPA | Yes | 1973 | 30:70 | No |
| U.S. Bureau of Mines | No | 1976 | 35:65 | No |

in Table 2. To provide a comparison, Table 3 contains specific gravities for various SEA ratios with uniform disperison of sulfur and asphalt.

The particular class of polymeric organosiloxanes favored by Pronk had been used previously in conventional asphalt concrete mixes to eliminate foaming in the presence of moisture and to alleviate tearing problems encountered when placing certain types of hot mixes [3, 4]. The tearing problem was attributed to the presence of moisture and/or air bubbles at the mix surface.

Gulf Oil Canada

Gulf Oil Canada has developed and field tested a procedure for the introduction of sulfur into conventional asphalt concrete mixes (Figure 2). In this system the total amount of binder is approximately the same as it would be in a conventional mix.

Liquid sulfur is dispersed into the asphalt cement to produce a SEA binder. This system utilizers a Sulfur Asphalt Module (SAM) mixing unit which is manufactured by the Barber Greene Company. The molten sulfur and asphalt cement are blended by high-shear mixing [10]. This process (as with Pronk) provides for the mixes to be handled with conventional mixing and paving equipment while eliminating the hazards of dangerous buildups of high concentrations of hydrogen sulfide in storage and transfer tanks. Up to 50 percent replacement (by weight) of asphalt by liquid sulfur is dispersed in the SEA binder.

Laboratory tests have indicated that coagulation and settlement of sulfur particles occurs after approximately three hours [5], though some plasticizers have improved the stability of the binder system [6].

Conclusions by Gulf Oil Canada based on Marshall stability tests indicated that SEA concrete mixes relative to conventional asphalt concrete mixes are [5]:

1. SEA stabilities are higher than those for conventional asphalt mixes.
2. Stability increased with an increase of sulfur content.
3. No significant change in flow or properties at 140°F (60°C) was noted.
4. Stability of SEA mixes was not affected after water soaking.
5. Various types of asphalt can be utilized with sulfur to produce adequate SEA binders.

Societe Nationale des Petroles d'Aquitaine (SNPA)

In the SNPA process molten sulfur is dispersed in asphalt cement by first passing both components through an in-line blender and then a homogenizer turbine (Figure 2) [6, 10]. The resulting SEA binder is then stored in a surge tank. By this process a 50/50 SEA binder can be produced. The mixing units can produce 6 to 15 tons of binder per hour. All necessary equipment is mounted on a trailer.

Table 2. Stability of Sulfur-Asphalt Emulsions [2]

| Sample* | 1/2h | | 5h | | 24h | | 48h | | 72h | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom |
| X | 1.19 | 1.18 | 1.05 | 1.80 | 1.04 | 1.75 | 1.05 | 1.62 | 1.05 | 1.23 |
| Y | 1.19 | 1.19 | 1.10 | 1.21 | 1.05 | 1.23 | 1.14 | 1.21 | 1.15 | 1.20 |

*X = 37.5/62.5 SEA Ratio - No Additive
Y = 37.5/62.5 SEA Ratio - with Additive

Table 3. Specific Gravity of SEA Binders [After 5]

| Sample Description | Composition, % wt. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Blend of 85/100 pen Asphalt / Elemental Sulfur | 100 | 90 / 10 | 80 / 20 | 70 / 30 | 60 / 40 | 55 / 45 | 50 / 50 | 40 / 60 | 100 |
| Specific Gravity 60°F (16°C) | 1.027 | 1.055 | 1.120 | 1.183 | 1.232 | 1.285 | 1.344 | 1.434 | 1.956 |

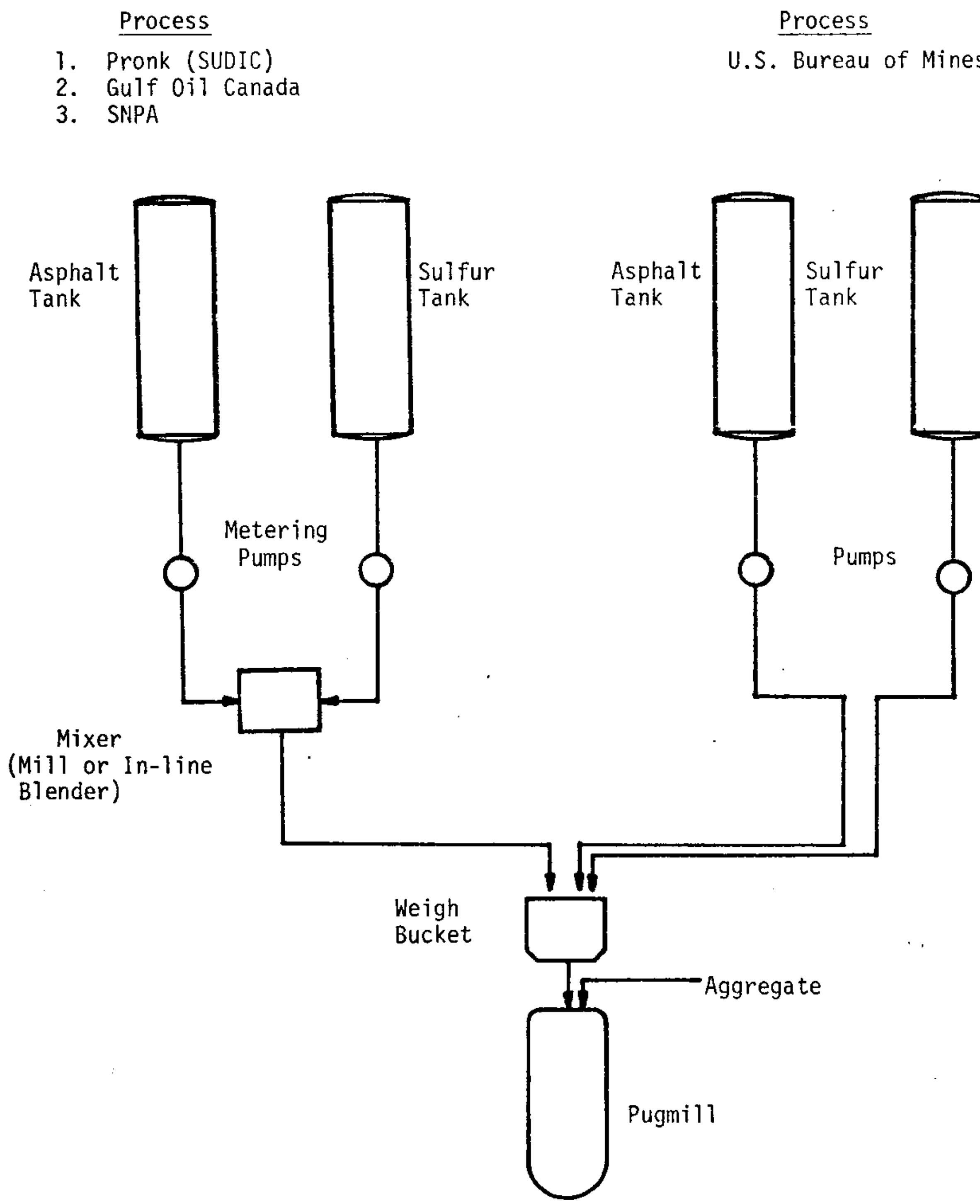



Figure 2. Generalized Sulfur Blending Methods for a Batch Plant

This process was used to construct the first SEA field project in the United States at Lufkin, Texas during September, 1975 [11]. The conduct of this field trial demonstrated that SEA mixtures could be produced and paved using conventional equipment.

U.S. Bureau of Mines

The U.S. Bureau of Mines study of utilization of elemental sulfur in asphalt concrete mixtures was oriented toward development of a simplified procedure for preparing and utilizing the SEA binder. In an effort to utilize sulfur as an extender for asphalt, McBee and Sullivan [7, 8] directed their studies toward the direct combination of sulfur and asphalt cement within the mixer without premixing them as required in the Pronk, Gulf, and SNPA process (Figure 2).

McBee and Sullivan were unable to discern any appreciable differences between the emulsified and the non-emulsified SEA binders. Based upon their laboratory data, the fact that sulfur is highly soluble (about 20 percent by weight) in most grades of asphalt cement in the common mixing temperature range of 248°F (120°C) to 302°F (150°C), and the high shear energy developed in mixing the binder and aggregates, they concluded that hot-mix plant pugmills could be used as the principal mixing mechanism for sulfur and asphalt cement.

A test program to determine the effectiveness of substituting sulfur for asphalt cement in pavement mixes and the results of these tests were compared to those of conventional paving mixtures. Field testing was done first with small patch tests and then by constructing a full-scale road test on a section of U.S. Highway 93 near Boulder City, Nevada during January 1977. The results of the laboratory and post-construction data of the field tests show that SEA mixes prepared by the direct addition procedure were equivalent to conventional asphalt concrete in all respects of performance and superior with respect to ease and amount of required compaction [9].

## CHAPTER II

## PAVEMENT MIXTURES AND STRUCTURAL DESIGNS

Laboratory mix designs were performed for the test pavements at the Construction Materials Laboratory at the University of Washington [12], R.M. Hardy and Associates (for SUDIC) [13], and the WSDOT Materials Laboratory [14]. The results which follow represent a compendium of the data from these three laboratories.

### INDIVIDUAL MATERIAL CHARACTERISTICS

The aggregate, a crushed columnar basalt, was obtained from a quarry operated by United Paving, Inc. (WSDOT Designation QS-P-95) and adjacent to the WSU Test Track in Pullman, Washington. The bulk specific gravity and moisture absorption values are shown in Table 4. The percent asphalt absorption as measured by WSDOT was 1.3 percent and by Hardy and Associates 1.1 percent. The aggregate gradation used was in accordance with the WSDOT Class B specification (Table 5).

The asphalt cement, an AR-4000W, was produced by Husky Oil Company and was tested in accordance with ASTM D 70 for its specific gravity, which was found to be 1.024.

Characterization tests on the original asphalt cement as reported by Hardy and Associates [13] follows:

| | |
|---|---|
| 1. Absolute viscosity @ 140°F (60°C): (300 mm vacuum)(ASTM D2171) | 1879 poises (187.9 Pa.s) |
| 2. Kinematic viscosity @ 275°F (135°C): (ASTM D2170) | 380 cSt (380 $mm^2/s$) |
| 3. Penetration @ 77°F (25°C): (100 g., 5 sec)(ASTM D5) | 78 |

Additional testing by Hardy and Associates for SUDIC evaluated the resulting binder properties after the asphalt cement and sulfur were mixed. The mixing sequence was accomplished as follows [13]:

1. Hot liquid sulfur and asphalt cements at a temperature of 284°F (140°C) were blended together in a heated container for 10 minutes. Approximately 1000 g. of binder are prepared at a time using a turbine impeller rotating at a speed of approximately 750-1000 rpm. The high shear mixing which results produces a finely dispersed sulfur-in-asphalt emulsion.

2. The Dow Corning 200, 1000 cSt (1000 $mm^2/s$) @ 77°F (25°C) additive is normally added to the asphalt cement, diluted with a solvent such as varsol or diesel fuel. In this way an accruate and reproducible quantity of additive can be introduced with an eye dropper or syringe. The additive concentration is based on the weight of asphalt cement.

Table 4. Specific Gravity and Absorption of the Crushed Basalt Aggregate [12,13]

| Aggregate Gradation | Bulk Specific Gravity | | Percent Absorption (Moisture) | |
|---|---|---|---|---|
| | Mean | Range | Mean | Range |
| 1. Coarse (ASTM C 127) | 2.75 | 2.74-2.75 | 2.14 | 1.98-2.29 |
| 2. Fine (ASTM C 128) | 2.75 | - | 2.09 | - |
| 3. Laboratory Blend (40% Coarse, 40% Fine, 20% Blend Sand) | | | | |
| (a) Coarse (ASTM C 127) | 2.80 | - | 1.56 | - |
| (b) Fine (ASTM C 128) | 2.72 | - | 1.61 | - |

Table 5. Aggregate Gradation WSDOT Class B [15]

| Sieve Size | Cumulative Percent Passing (UW Lab) | Cumulative Percent Passing (WSDOT Lab) | Cumulative Percent Passing (SUDIC) | WSDOT Specification Limits |
|---|---|---|---|---|
| 5/8" | 100 | 100 | 100 | 100 |
| 1/2" | 93 | 96 | 88 | 90-100 |
| 3/8" | 77 | 82 | 79 | 75-90 |
| 1/4" | 58 | 61 | 62 | 55-75 |
| No. 10 | 34 | 35 | 35 | 32-48 |
| No. 40 | 16 | 17 | 16 | 11-24 |
| No. 80 | 10 | 11 | 10 | 6-15 |
| No. 200 | 5 | 6.6 | 6.5 | 3-7 |
| -200 | 0 | | | 0 |

1 cm = 0.394 in

Physical tests were then performed on the SEA binders with the following modifications:

1. SEA binder densities were determined after 24 hours curing.
2. SEA binder viscosities were determined shortly after initial preparation.

The following test results were reported [13]:

1. Absolute viscosity @ 140°F (60°C):
   (300 mm vacuum)(ASTM D2171)

   (a) 30/70 SEA  666 poises (66.6 Pa.s)
   (b) 40/60 SEA  683 poises (68.3 Pa.s)
   (c) 50/50 SEA  723 poises (72.3 Pa.s)

2. Kinematic viscosity @ 275°F (135°C):
   (ASTM D2170)

   (a) 30/70 SEA  151 cSt (151 $mm^2/s$)
   (b) 40/60 SEA  164 cSt (164 $mm^2/s$)
   (c) 50/50 SEA  176 cSt (176 $mm^2/s$)

3. Specific gravity @ 77°F (25°C):
   (ASTM D70)

   (a) 30/70 SEA  1.161
   (b) 40/60 SEA  1.228
   (c) 50/50 SEA  1.314

The sulfur, used in the UW laboratory work, was an 80-mesh ground sulfur from the Montana Sulfur and Chemical Company, Billings, Montana. The sulfur was not tested for purity due to attested purity claimed by the producer and available literature statements that small variances of impurity have little impact on SEA mixtures.

SAMPLE PREPARATION

A total of 90 samples were prepared in the UW mixture design testing program (45 samples for the Marshall mix design and 45 samples for the Hveem mix design). These 90 samples were further subdivided into 6 sets of 15 samples each, sets A through F. Sets A, B and C were prepared by the Marshall compaction method (ASTM D1559) and D, E and F were prepared by kneading compaction (Washington State Test Method 701). Sets A and D had a SEA ratio of 0/100, B and E a SEA ratio of 50/50, and C and F a SEA ratio of 30/70. All SEA ratios reported are based on weight, i.e., a 30/70 SEA ratio indicates that 30 percent of the binder by weight is added sulfur and 70 percent is asphalt cement.

For each mix design method three samples were made at the following binder contents: 4.5, 5.0, 5.5, 6.0 and 6.5 percent by weight of total mix.

However, since sulfur and asphalt cement do not have the same specific gravity (asphalt cement is approximately half that of sulfur), appropriate adjustments were made to the SEA binder contents to equate them at equal volumes for comparison to conventional asphalt binders. These adjustments are shown in Table 6.

Table 5 contains the gradation used in the laboratory work compared to the gradation specification limits for Class B. It should be noted that the gradation utilized tends to be on the coarse side of the Class B specification.

For the Marshall mix design method, the samples were prepared in accordance with ASTM D1559 with modifications recommended by Pronk [1]. These guidelines are as follows:

1. The blending of sulfur and asphalt cement was accomplished with a laboratory mixer (Scovall Model No. 936-1), at medium speed.

2. Siloxane polymer (0.001 percent by weight of binder) in the form of Dow Corning 200 was added to the sulfur-asphalt mixture to facilitate the dispersion of the sulfur and improve the stability of the resulting emulsion.

For the Hveem mix design method, the samples were prepared identically to those of the Marshall method except that compaction was accomplished with a pneumatic kneading device rather than the drop hammer employed with the Marshall method. Figure 3 shows the preparation sequence of the 90 samples for both the Hveem and Marshall prepared samples.

The WSDOT Materials Laboratory accomplished mix designs with the Pullman aggregate for three SEA ratios: 0/100, 10/90 and 30/70. The gradation used is shown in Table 5. The WSDOT mixing procedure was to prepare the mixture (aggregate plus binder) then condition overnight (12 to 16 hours) in a 140°F (60°C) oven in a uncompacted state. The mix was then reheated to 275°F (135°C) and compacted. Stability tests were then determined within two to four hours after compaction [14].

Hardy Associates performed a mix design for SUDIC utilizing a 40/60 SEA ratio. The laboratory gradation used is shown in Table 5. The mixing was accomplished at a temperature of 280°F (138°C) per ASTM D1559 with a Holbart mixer for a total of 100 sec [13]. Following this, the mixture was placed into Marshall molds then into a 250°F (121°C) oven for one hour. Compaction was accomplished with a automatic Marshall hammer with 40 blows per face. The resulting samples were then cured seven days prior to Marshall testing.

## SAMPLE TESTING

For the UW laboratory testing, sets A, B and C (45 samples) were tested for resilient modulus, bulk specific gravity, Marshall stability and flow, and maximum specific gravity (Figure 4). Sets D, E and F were tested for

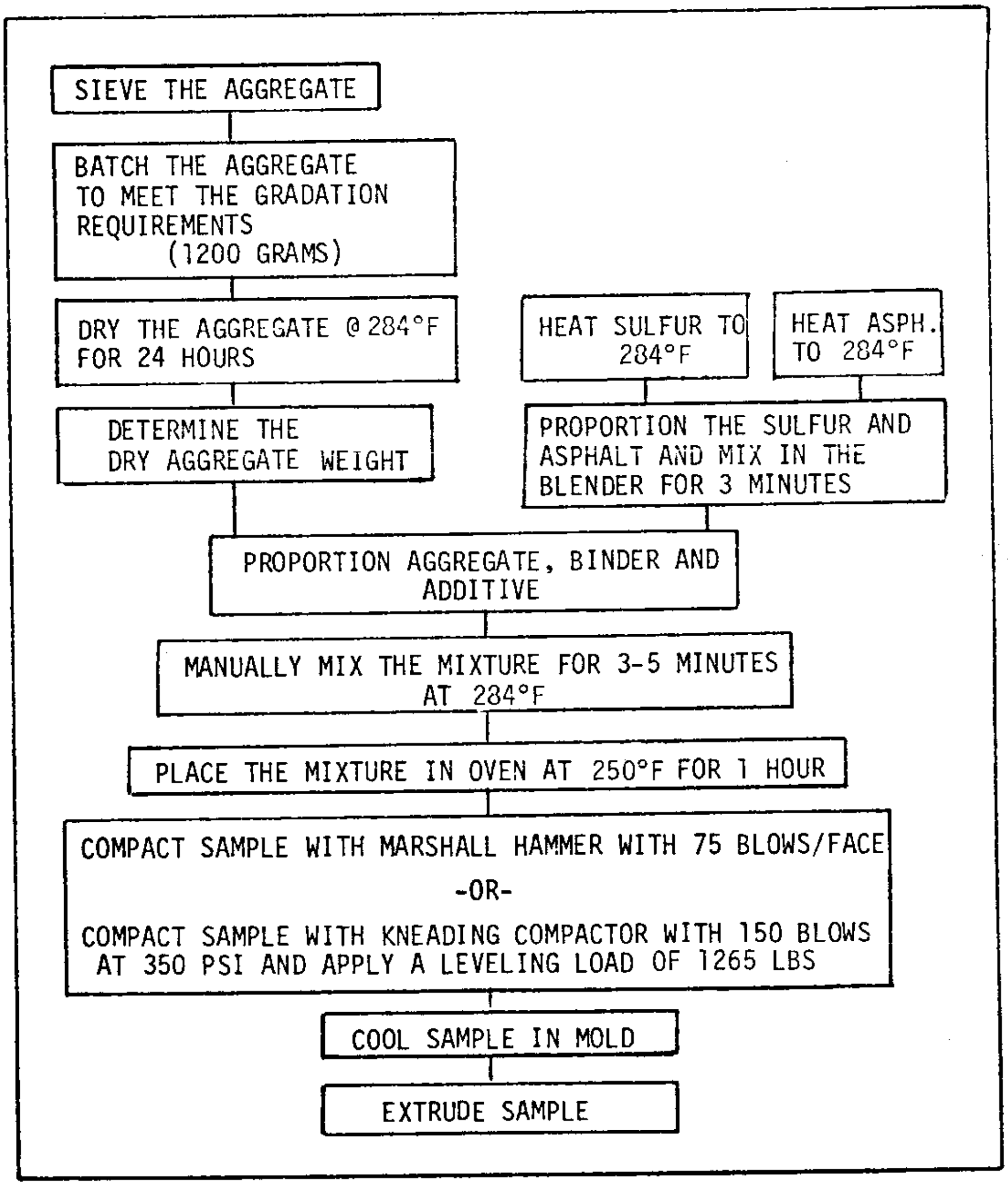
Table 6. Volume Equivalent Binder Contents for 30/70 and 50/50 SEA Binders Compared to Asphalt Cement (0/100).

| SEA Ratio | Percent by Weight | | | | |
|---|---|---|---|---|---|
| 0/100 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
| 30/70 | 5.3 | 5.9 | 6.5 | 7.1 | 7.7 |
| 50/50 | 6.1 | 6.7 | 7.4 | 8.1 | 8.8 |

Table 7. Summary of the UW Marshall and Hveem Mixture Design Data at Optimum Binder Content

| Data Type | Test Value at Optimum Binder Content | | |
|---|---|---|---|
| | 0/100 SEA | 30/70 SEA | 50/50 SEA |
| 1. Marshall | | | |
| (a) Stability (lb) | 3650 | 4800 | 9660 |
| (b) Unit Weight (pcf) | 154 | 155 | 156 |
| (c) Air Voids (%) | 3.5 | 5.0 | 3.8 |
| 2. Hveem | | | |
| (a) Stabilometer Value | 46 | 52 | 64 |
| (b) Unit Weight (pcf) | 161 | 161 | 159 |
| (c) Air Voids (%) | 1.5 | 1.2 | 1.3 |
| 3. Optimum Binder Content (% by Weight of Total Mix) | 5.5 | 6.5 | 7.4 |

1 N = 2.248 lbf
1 $Mg/m^3$ = 62.4 $lb/ft^3$




°C = (F-32)(5/9)
1 kPa = 0.1451 psi
1 kg = 2.205 lbs

Figure 3. Marshall and Hveem Sample Preparation Sequence

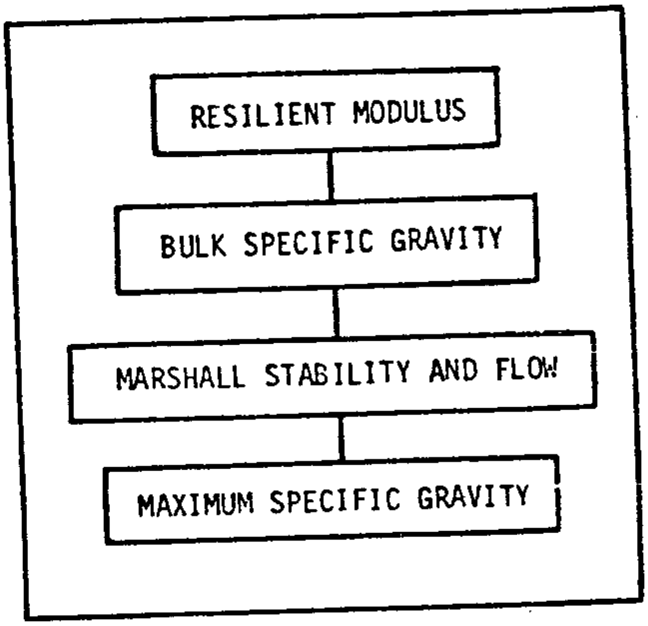



Figure 4. Marshall Sample Testing Sequence

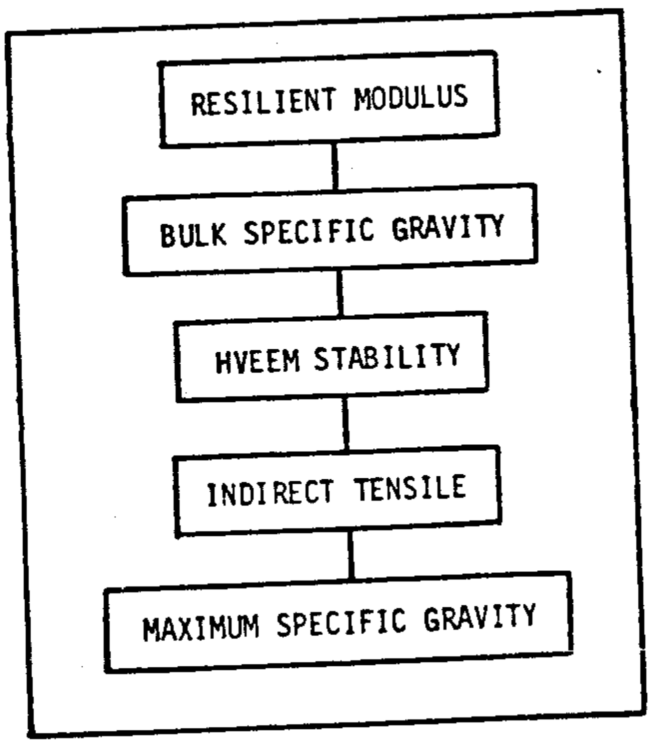



Figure 5. Hveem Sample Testing Sequence

resilient modulus, bulk specific gravity, Hveem stability, indirect tensile strength, and maximum specific gravity (Figure 5). The testing was done in accordance with established testing procedures as indicated.

MARSHALL SAMPLES (Sets A, B, C)

| Test | Reference |
|---|---|
| Resilient Modulus - | Proposed ASTM "Indirect Tensile Test Method for Resilient Modulus of Bituminous Mixtures" |
| Bulk Specific Gravity - | WSDOT Test Method 704 |
| Marshall Stability and Flow - | ASTM Test Designation D1559 |
| Maximum Specific Gravity - | WSDOT Test Method 705 |

HVEEM SAMPLES (Set D, E, F)

| Test | Reference |
|---|---|
| Resilient Modulus - | Same as for Samples A, B, C |
| Bulk Specific Gravity - | Same as for Samples A, B, C |
| Hveem Stability - | WSDOT Test Method 703 |
| Indirect Tensile Strength - | ASTM Designation C496 |
| Maximum Specific Gravity - | Same as for Samples A, B, C |

The WSDOT testing program included the determination of bulk density, maximum density, Hveem stability and percent air voids. The Hardy Associates testing program for SUDIC reported bulk density, percent air voids, percent voids in the mineral aggregate and Marshall stability and flow.

Results of the Marshall and Hveem Mix Design

A summary of the UW optimum mix designs for both the Marshall and Hveem procedures is shown in Table 7. These results are reported for 0/100, 30/70 and 50/50 SEA ratios. Originally, a 50/50 SEA ratio was planned for the field study in lieu of the 40/60 SEA ratio ultimately used. The laboratory mixture data indicated a binder content of 5.5 percent by weight of total mix was optimum for the 0/100 SEA mixture (conventional asphalt concrete). Similarly, the 30/70 and 50/50 mixtures indicated similar optimums (on an approximate equivalent volume basis) at 6.5 and 7.4 percent, respectively. It is of interest that the kneading compaction technique (Hveem) resulted in lower air void contents and slightly higher densities at the "optimum" binder contents as compared to those obtained from the Marshall compaction method.

The optimum asphalt binder content recommended by the UW to WSDOT was 5.5 percent equivalent binder content. This was based upon examination of all laboratory work and the knowledge that the optimum binder content for field conditions may be higher than obtained in the laboratory. Subsequent to the recommendation, it was learned that historically, the optimum binder content for this aggregate blend is between 5.5 and 6.0 percent

The optimum binder content reported by the WSDOT Materials Laboratory was 5.7 percent for the conventional asphalt concrete mix. Hardy Associates recommended an optimum of 7.25 percent for the 40/60 SEA mixture examined for SUDIC. The associated mixture properties for these two binder contents are shown in Table 8.

Figures 6 and 7 summarize the resulting data from all three laboratories for the various SEA ratios investigated for both the Marshall and Hveem compaction procedures. Appendix A contains tabular data summaries for these mixes.

Resilient Modulus

The resilient modulus ($M_R$) is a nondestructive dynamic test defined as the ratio of the repeated axial deviator stress to the recoverable axial strain. The test may be conducted on all types of material ranging from cohesive to stabilized materials [16].

In the study, the $M_R$ was obtained in the UW laboratory for each sample for seven consecutive days. Each sample was loaded on two diametral axes and the average deformation was used to calculate $M_R$ with the following formula:

$$M_R = \frac{P(\mu + 0.2734)}{t\Delta h}$$

where

$M_R$ = resilient modulus

$P$ = vertical load

$\mu$ = Poisson's ratio

$t$ = thickness

$\Delta h$ = recoverable deformation

The temperature of the samples during testing was 77°F (25°C). Upon completion of the seven days testing, the samples were tested at 41°F (5°C) and 104°F (40°C) to determine $M_R$ as a function of temperature.

A plot of $M_R$ vs. time after compaction for the Hveem prepared samples is shown in Figure 8. All samples are at the same volume equivalent binder content (5.5 percent by weight). It is significant that the $M_R$ continues to in-

Table 8. Summary of WSDOT and SUDIC Mixture Design Data at Optimum Binder Content [After Refs 13,14]

| Data Type | Test Value at Optimum Binder Content | |
|---|---|---|
| | 0/100 SEA | 40/60 SEA |
| 1. Marshall (SUDIC) | | |
| (a) Stability (lb) | - | 3700 |
| (b) Flow | - | 11 |
| (c) Unit Weight (pcf) | - | 156 |
| (d) Air Voids (%) | - | 2.5 |
| 2. Hveem (WSDOT) | | |
| (a) Stabilometer Value | 20 | - |
| (b) Unit Weight (pcf) | 160 | - |
| (c) Air Voids (%) | 2.3 | - |
| | | - |
| 3. Optimum Binder Content (% by Weight of Total Mix) | 5.7 | 7.25 |

1 N = 2.248 lbf
1 $Mg/m^3$ = 62.4 $lb/ft^3$

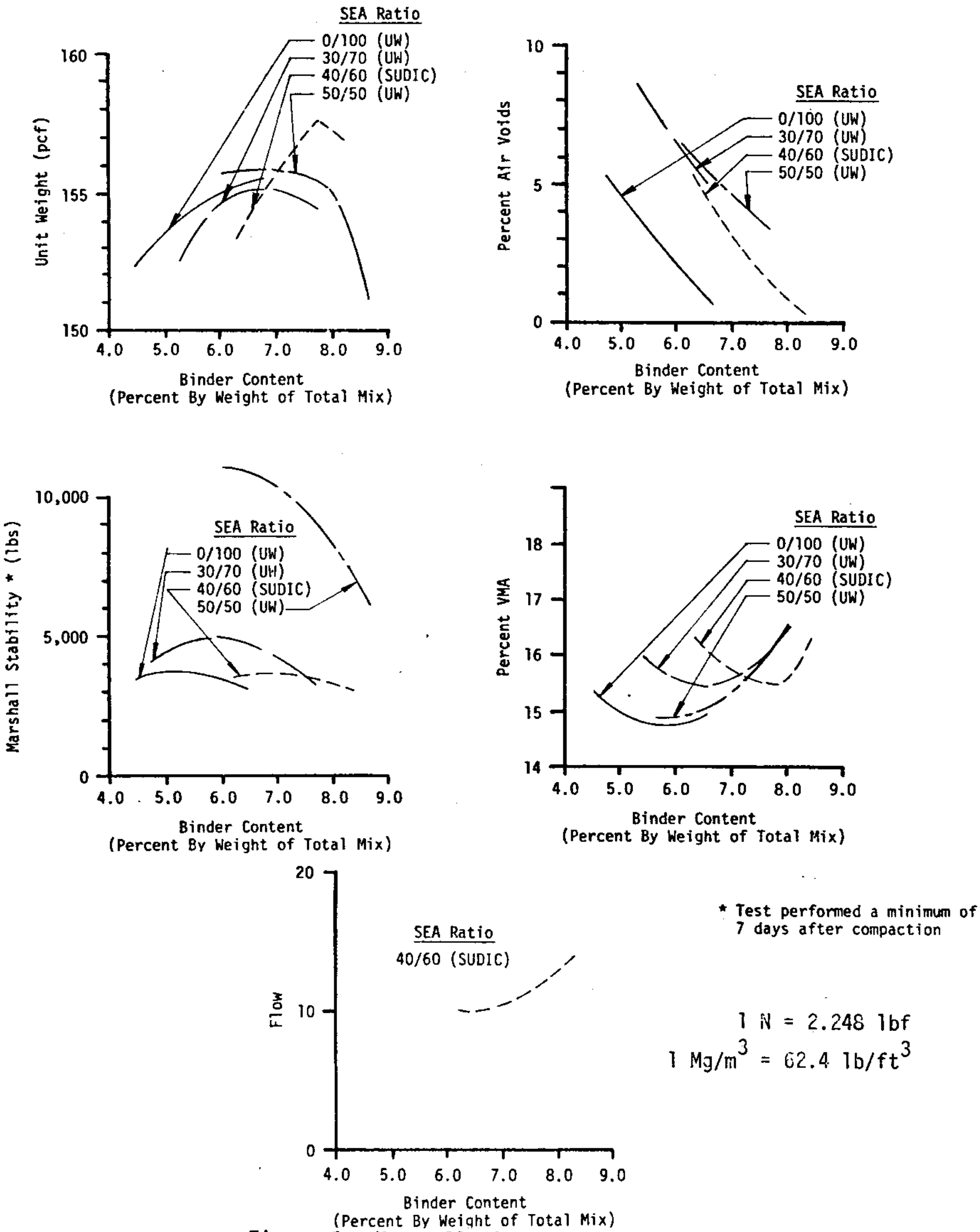
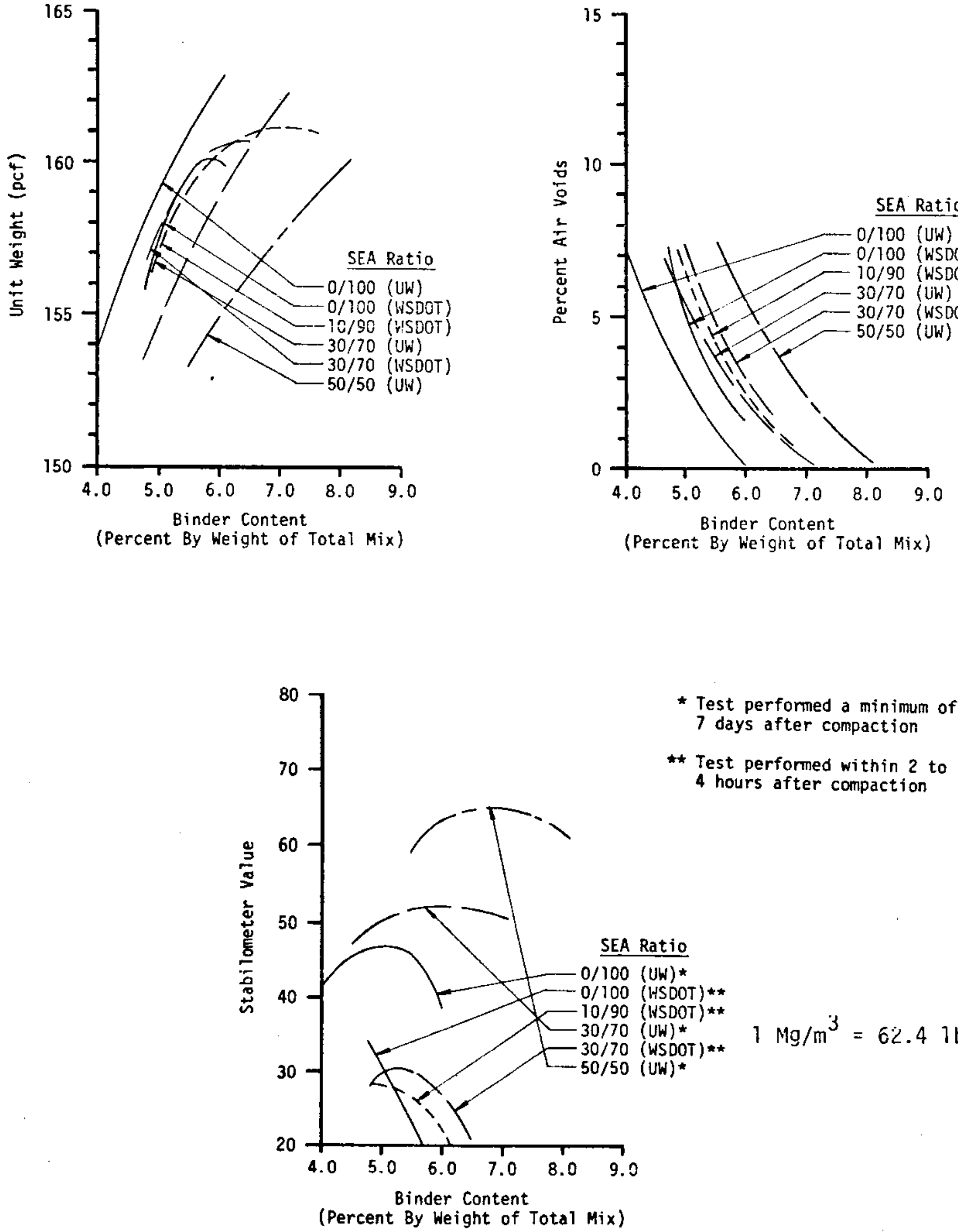



Figure 6. Marshall Mix Design Summary




$1\ Mg/m^3 = 62.4\ lb/ft^3$

Figure 7. Hveem Mix Design Summary

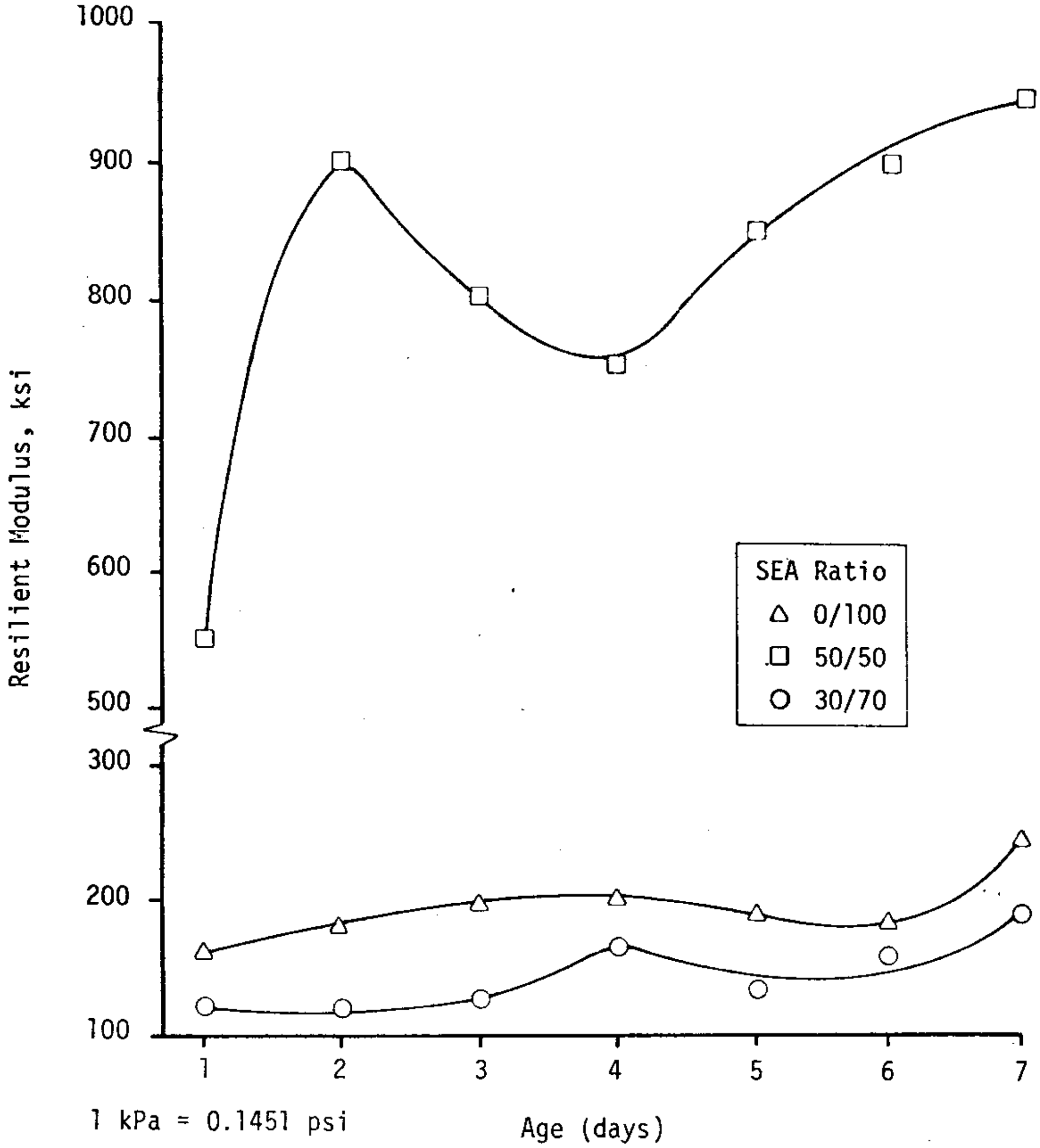



Figure 8. Resilient Modulus for Hveem Samples at 5.5 Percent Equivalent Asphalt Content.

crease up to seven days for all mixes. Also notable are the high modulus values for the 50/50 SEA mixture (700-900,000 psi (4,800,000-6,200,000 kPa)). The $M_R$ response of the samples at the recommended design binder content as a function of temperature is illustrated for the Marshall samples in Figure 9 and for the Hveem samples in Figure 10.

## PAVEMENT THICKNESS DESIGN

To design the appropriate thicknesses for the test track sections, a key factor considered was that previous pavement studies at the WSU Test Track had indicated that there was a tendency for the spring thaw to dramatically promote the failure of test track pavements. It was, therefore, considered advantageous to have failure in all sections prior to freezing of the subgrade. The expected date that this would occur was estimated to be December 1, 1979.

It was estimated that 1.5 million load repetitions could be applied to the track by December 1, 1979. This was based on an average expected loading rate of 500,000 repetitions per month and expected full months of operation from August 1 through December 1, 1979.

A computer analysis utilizing the BISAR computer program (Bitumen Structures Analysis in Roads - developed by Shell Oil Co.) was accomplished whereby various thicknesses of each of the mixes were analyzed. The essential items developed from the BISAR analysis were the predicted initial maximum horizontal and vertical strains in the pavement for thicknesses varying from a two inch (5.1 cm) to a six inch (15.2 cm) base course at 41°F (5°C), 77°F (25°C) and 104°F (40°C) for each thickness and SEA ratio. The results of this analysis are illustrated in Figures 11 and 12.

The essential items of input for the BISAR program are as follows:

| Element Required | Used in Analysis |
|---|---|
| 1. Number of layers. | 3 (surface course, base course and subgrade). |
| 2. Young's modulus of each layer (estimated by $M_R$). | Appropriate $M_R$ for each temperature as developed in laboratory for Hveem samples and a $M_R$ of 18,000 psi (124,000 kPa) for the subgrade. |
| 3. Poisson's ratio for each layer. | Assumed to be 0.30. |
| 4. Thickness of all but base layer. | 1.8 in (4.6 cm) for surface course and from 2 to 6 in (5.1 to 15.2 cm)-1 in (2.5 cm) increments. |
| 5. Loads | 2 each 5,300 lb (2,360 N) normal loads. |

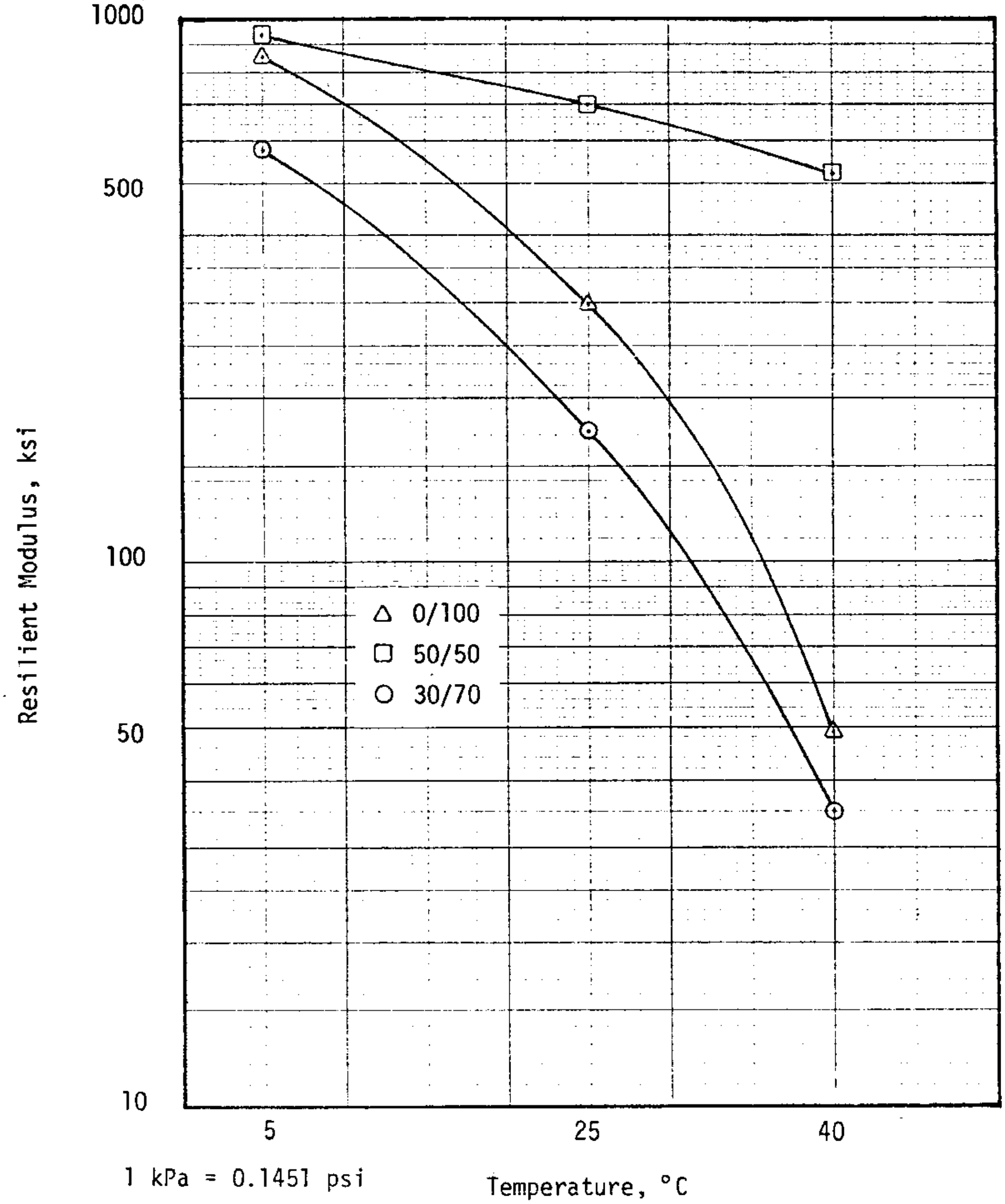



Figure 9. Resilient Modulus vs. Temperature for Marshall Prepared Samples at 5.5 Percent Equivalent Asphalt Content.

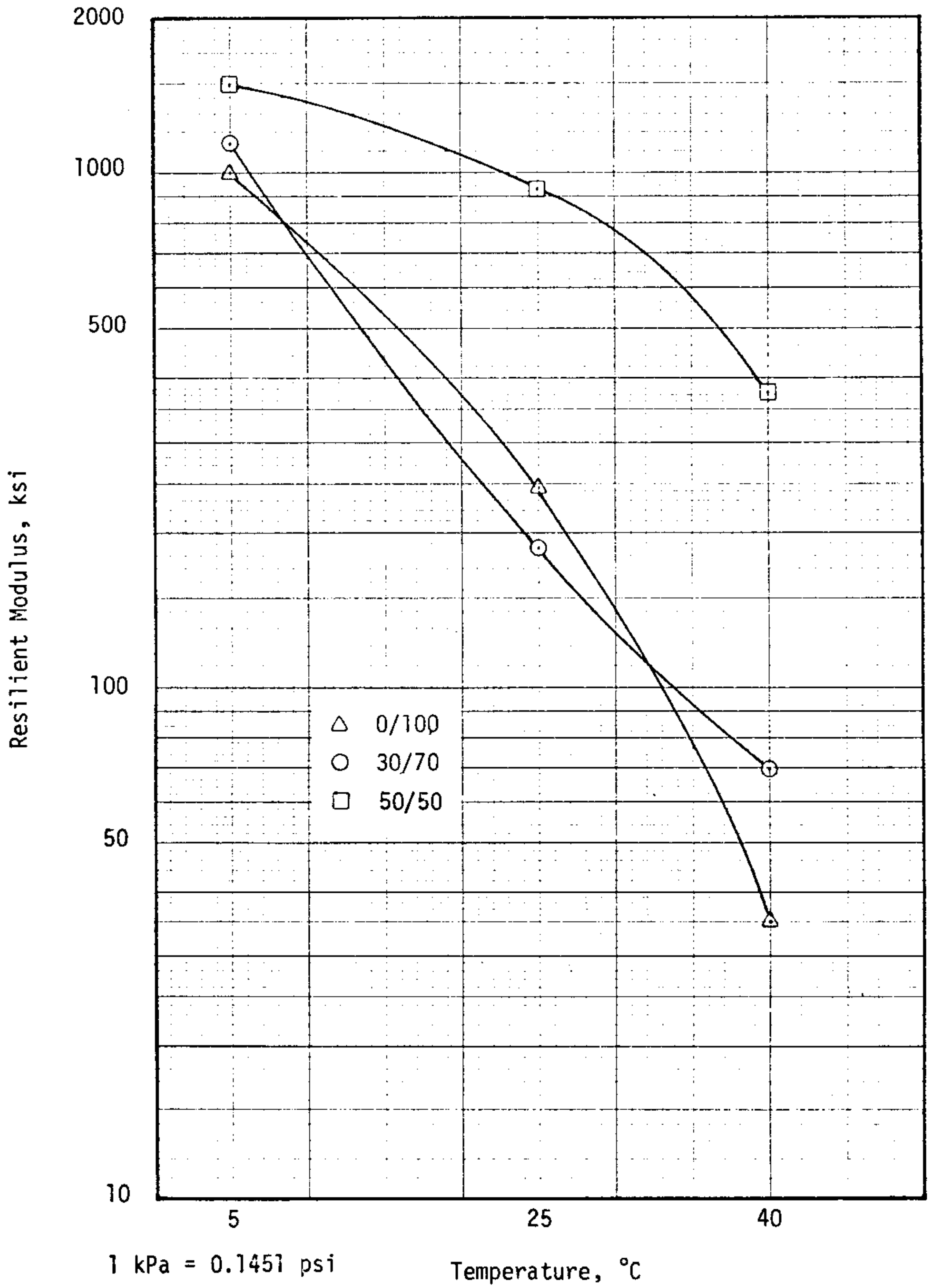



Figure 10. Resilient Modulus vs. Temperature for Hveem Prepared Samples at 5.5 Percent Equivalent Asphalt Content.

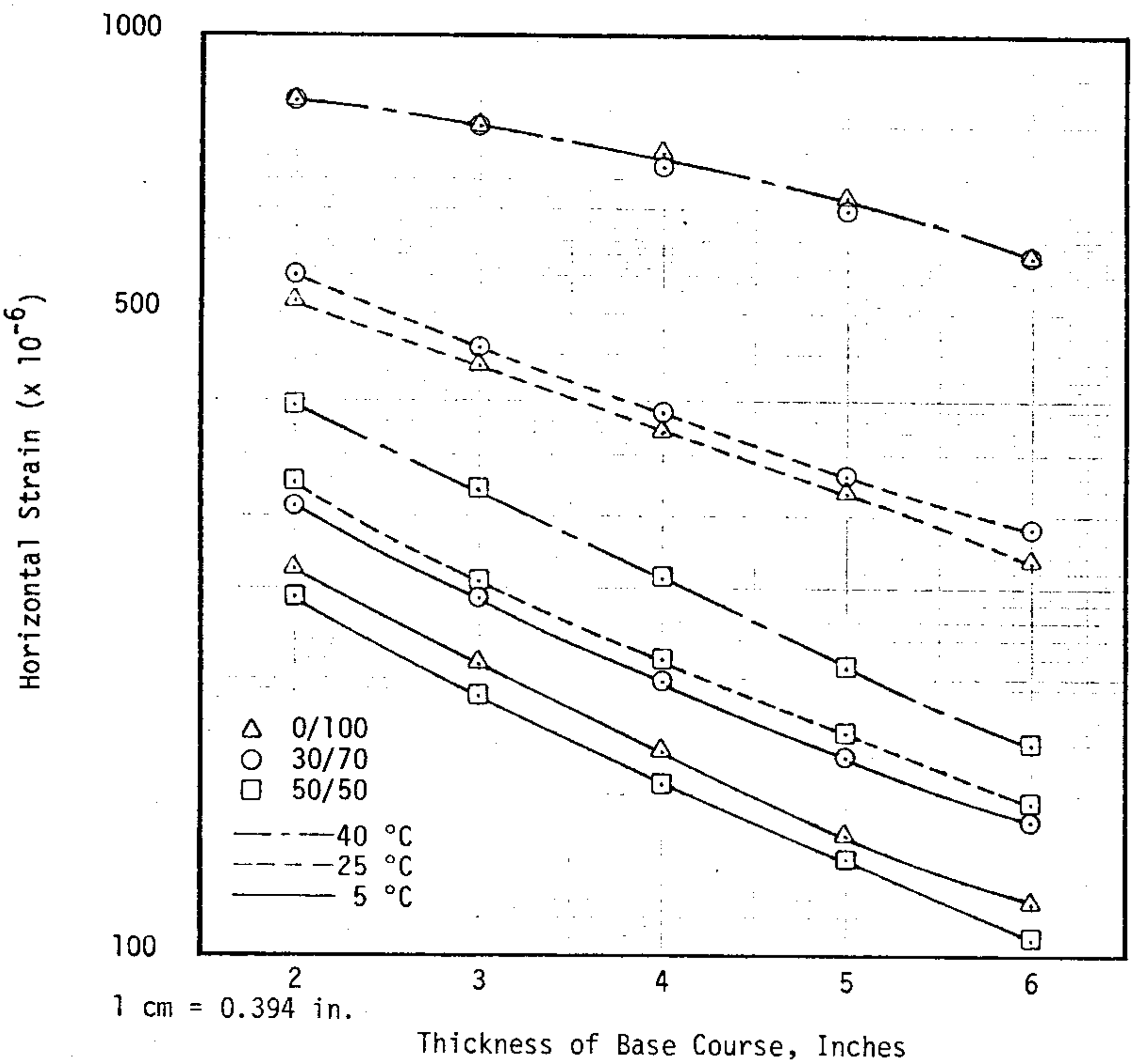
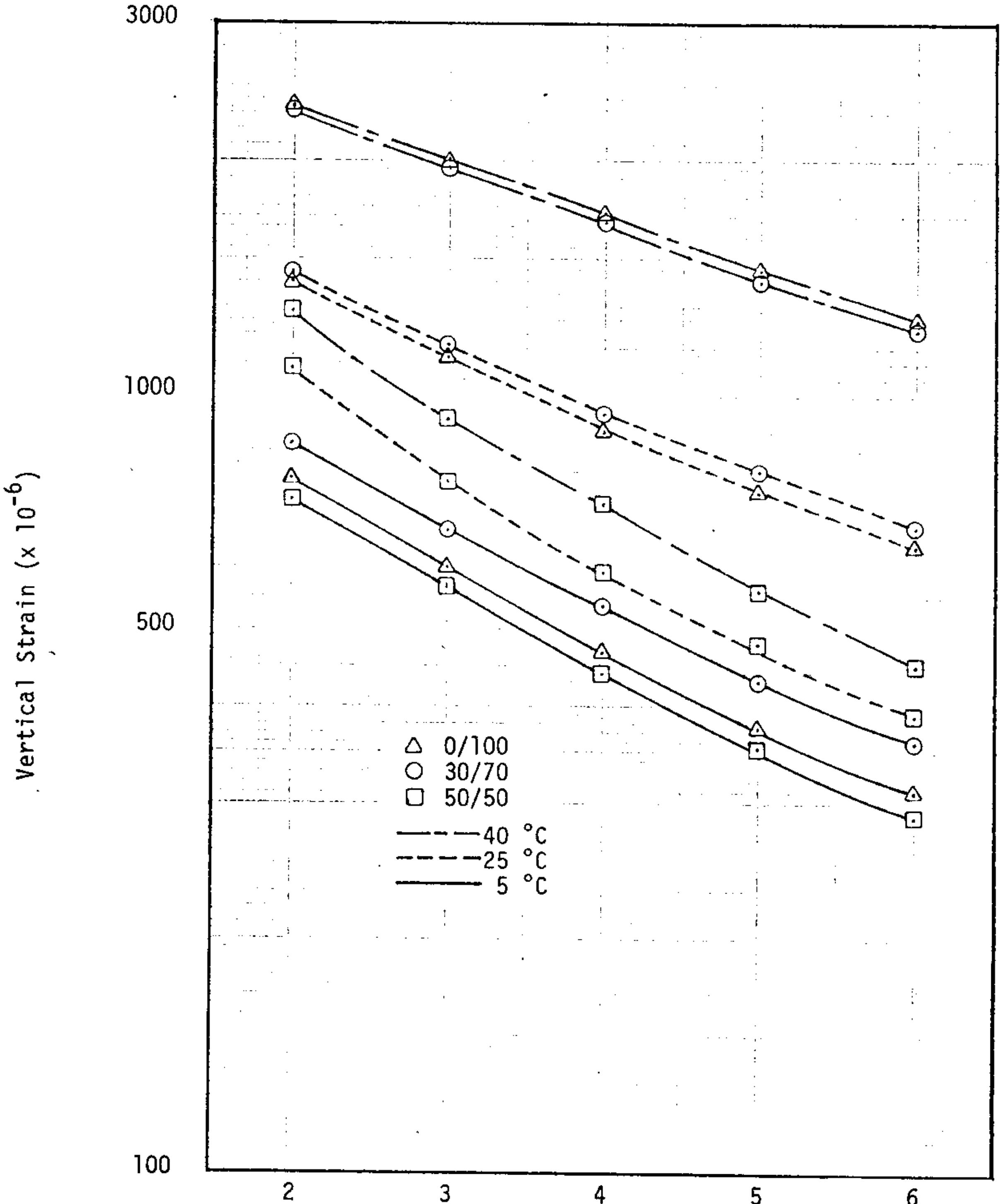



Figure 11. Bisar Predicted Maximum Initial Horizontal Strain vs. Various Base Course Thicknesses




1 cm = 0.394 in.

Thickness of Base Course, Inches

Figure 12. Bisar Predicted Maximum Initial Vertical Strain vs. Various Base Course Thicknesses

| Element Required | Used in Analysis |
|---|---|
| 6. Load position | Above loads separated by 13 in (33 cm) |

A subgrade $M_R$ of 18,000 psi (124,000 kPa) was based upon an expected moisture content of approximately 16-17 percent. Following construction and during track operations this modulus was found to be too high. The $M_R$ of the subgrade should have been closer to 4,000 psi (27,600 kPa) which corresponds to a water content of approximately 21 percent.

Utilizing the maximum horizontal strains developed by BISAR and Kingham and Kallas's equation [17] for estimating the number of load repetitions to failure, Figure 13 was developed. Utilizing this figure with a specific number of load applications, an expected operating temperature and a SEA ratio of 0/100, 30/70 or 50/50, the thickness of the required base course can be found. By entering Figure 13 with $1.5 \times 10^6$ load repetitions at 77°F (25°C), a 5.5 in (14 cm) SEA 30/70 or 0/100 pavement would fail by December 1, 1979.

The thicknesses finally selected were 5 and 2.5 in (12.7 and 2.5 cm) respectively, for the thick and thin base courses. This decision was based on two points. First, it had been decided for simplicity that the thick sections would be twice the thickness of the thin sections. Secondly, it was felt that application of 1.5 million repetitions was overly optimistic. By reducing the thickness 1/2 in (1.3 cm), failure was assured before the subgrade was expected to freeze.

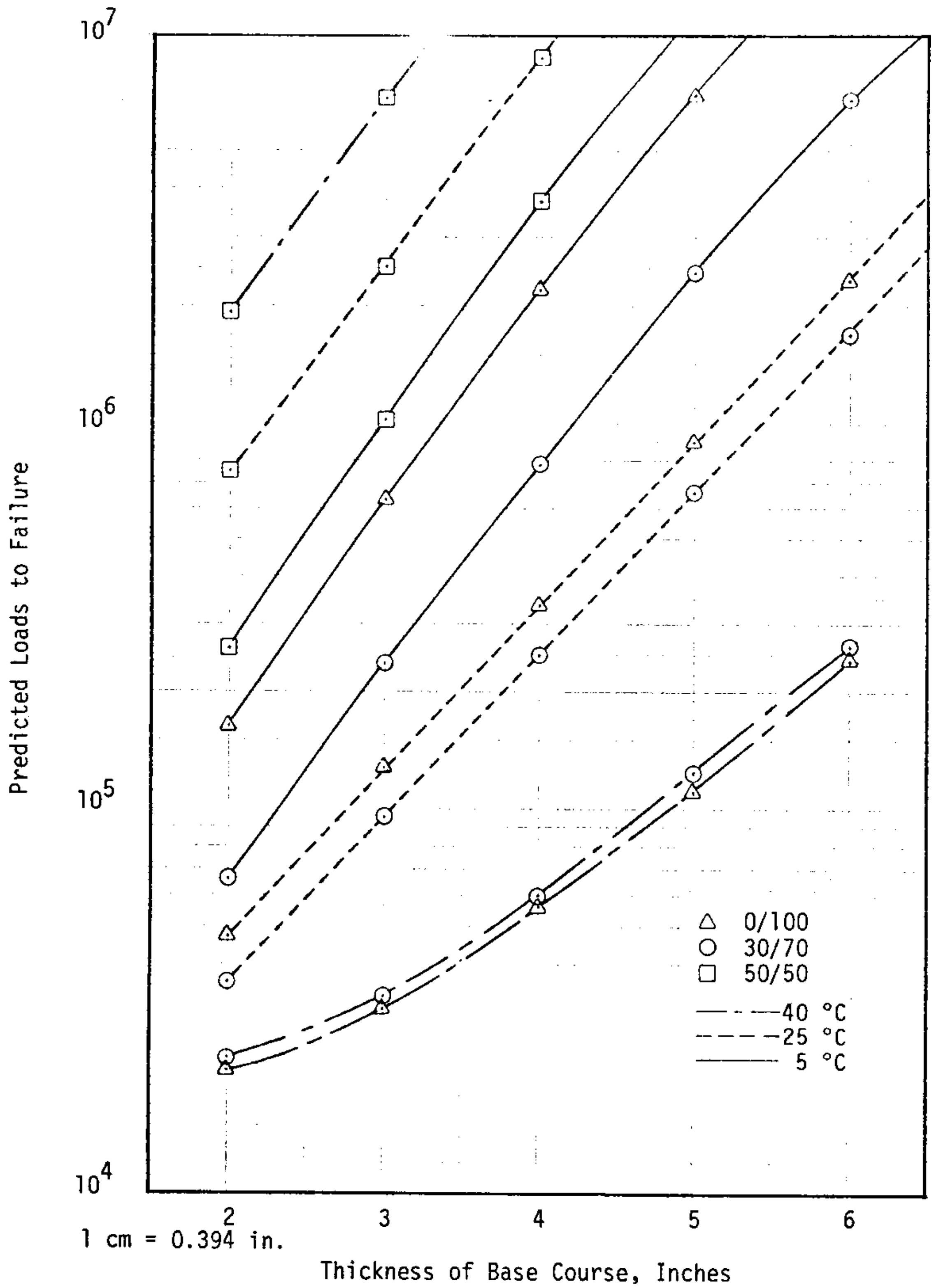



Figure 13. Predicted Loads to Failure vs. Thickness of Base Course

## CHAPTER III

## CONSTRUCTION AND INSTRUMENTATION OF THE TEST PAVEMENTS

### WSU TEST TRACK LOAD APPARATUS

The loading apparatus at the test track consists of a 15-ton structural steel frame (Figures 14-16) and a water tank revolving over a 85 ft (25.9 m) diameter ring. This applies approximately 11,100 lbs (5034 kg) to each of three sets of dual wheels. Actual weights taken by WSDOT with portable load scales indicated the following loads are actually being applied:

| | | |
|---|---|---|
| Arm and Tire Assembly | No. 1: | 11,400 lbs (5170 kg) |
| | No. 2: | 11,650 lbs (5283 kg) |
| | No. 3: | 10,350 lbs (4694 kg) |

All instrumentation was constructed to be activated by Assembly No. 1. This was done because Assembly No. 1 is closest to the average weight (actually about 2 percent above the average weight).

A feature of the test track that was not utilized during this test is capability of adding water to the water tank. By doing so the load on each set of duals can be brought to over 20,000 lbs (9070 kg).

To keep the wheels from continuously moving in the same wheel path, the center of rotation of the structure is designed so that various wheel path widths can be applied to the pavement structure. In this study, the wheel path was set at 4 ft (1.2 m) from outside to inside of wheel path. This yielded a loading distribution as illustrated in Figure 17.

The loading frame is guided by a 6.5 in (16.5 cm) diameter vertical steel shaft. This shaft rotates in a self-aligning bearing mounted in a power-driven revolving frame. The frame is designed to operate in either a clockwise or counterclockwise direction at speeds of 1 to 45 mph (1.6 to 72 kph). The frame is powered by a 440 volt three-phase alternating current 200 horsepower General Electric Kinamatic Speed Variator which supplies 220 volt direct current to each of three 60 horsepower motors geared directly to the wheels. Power is supplied only to the inside wheel of each dual.

During the testing the frame rotated in a clockwise direction at a normal operating speed of less than 30 mph ( 48 kph). Speed was reduced even further when the track began to deteriorate in order to reduce excessive dynamic loading due to bouncing of the load assemblies.

### TEST PAVEMENT CONFIGURATIONS

The test pavement configurations are shown in Figures 18, 19 and 20. Figures 18 and 19 show the final design cross sections ( and SEA ratios) as well as a plan view of the twelve test sections at the WSU Test Track. The test track pavements were constructed 16 ft (4.9 m) wide (Figure 19). This width not only accommodated the wheel tracking but also provided

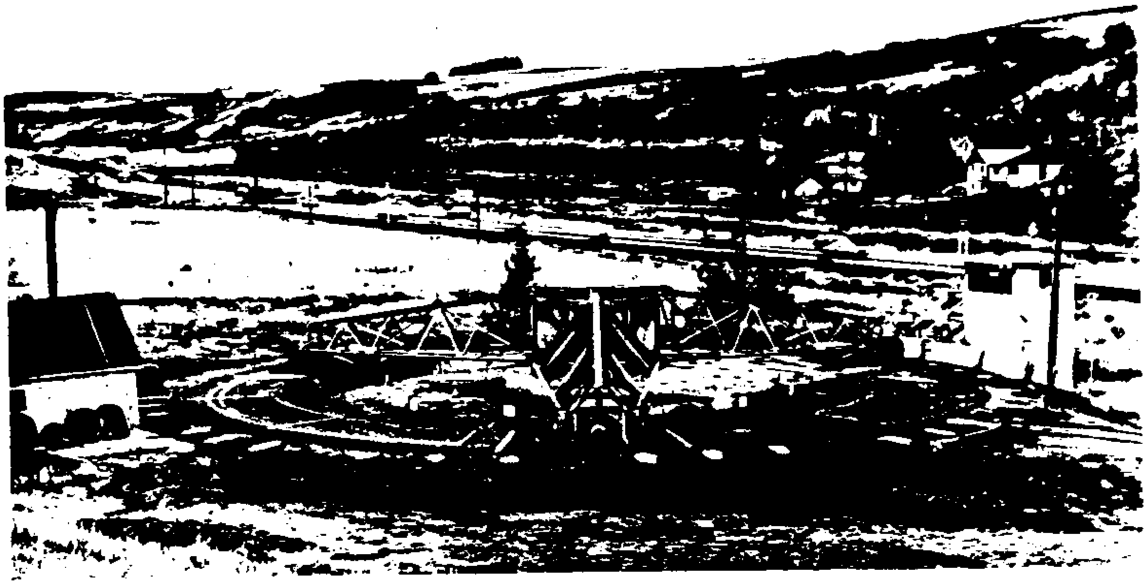


Figure 14. G.A. Riedesel Pavement Test Facility Following Construction of Test Pavements

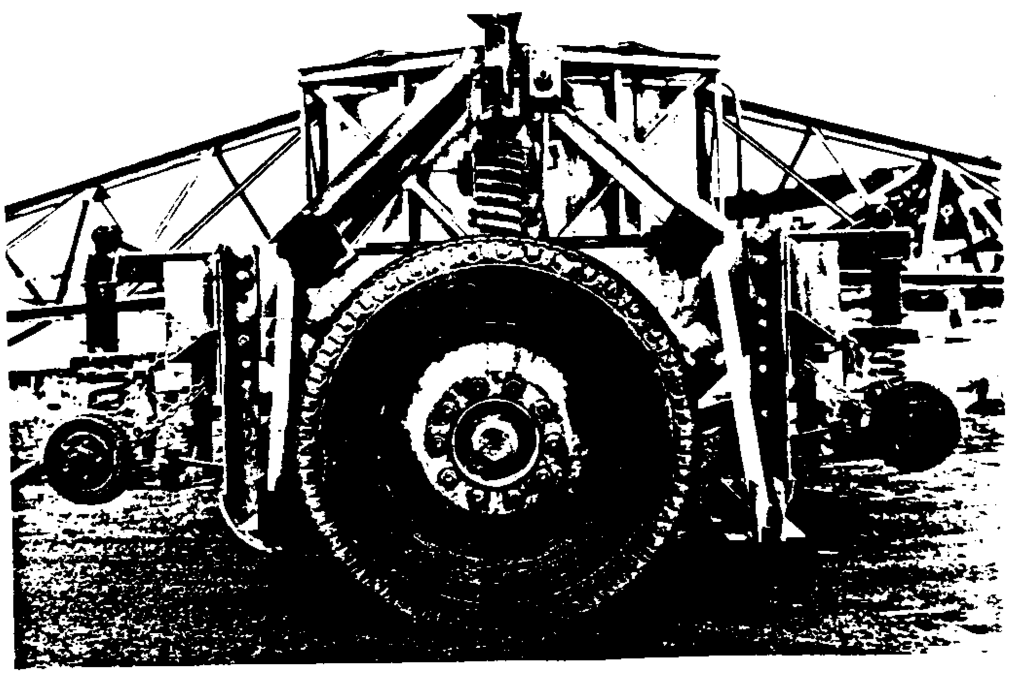


Figure 15. One of Three Sets of Dual Tires Used to Apply Loads to Test Pavements

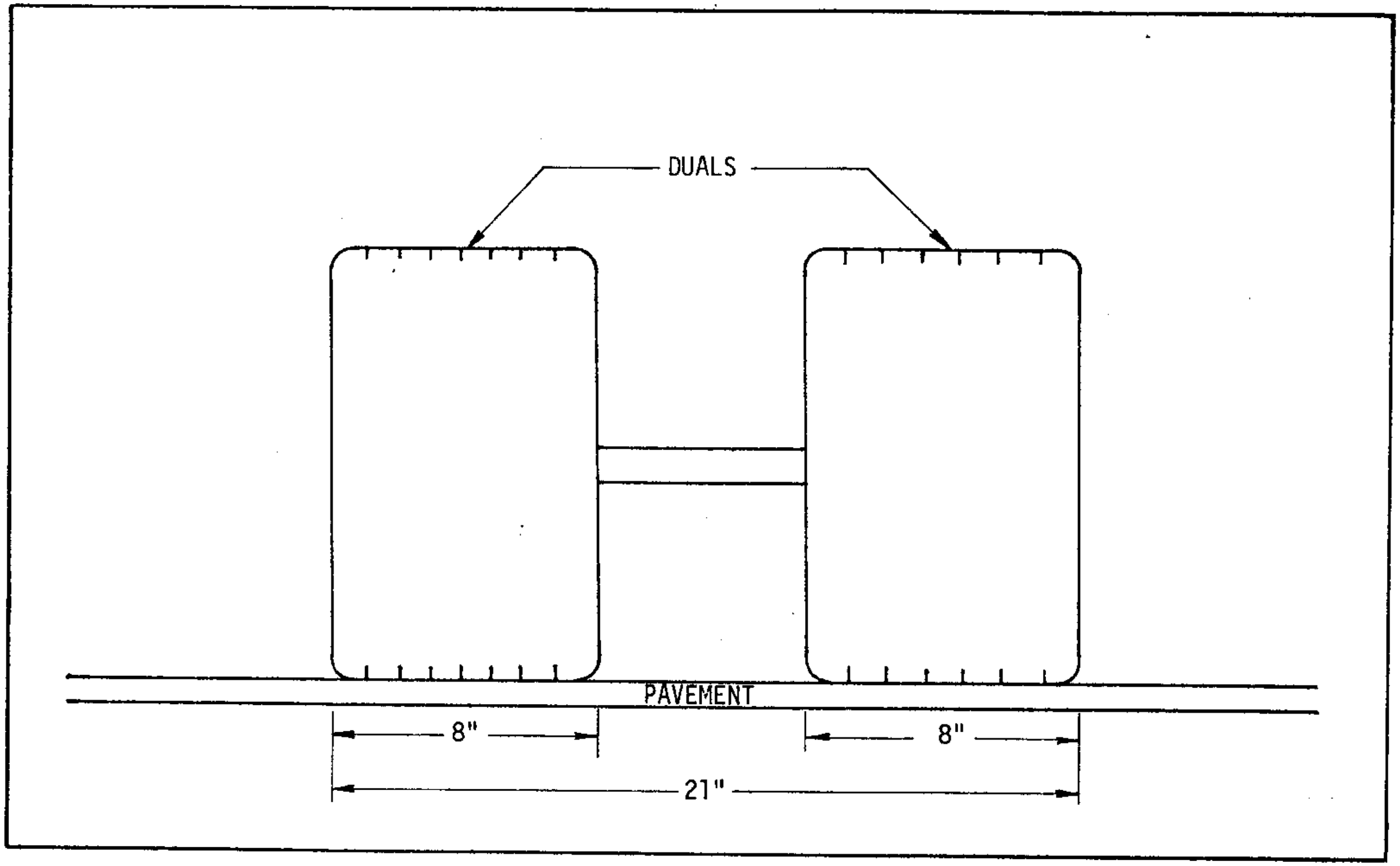



Figure 16. Schematic of Dual Tire Size and Spacing

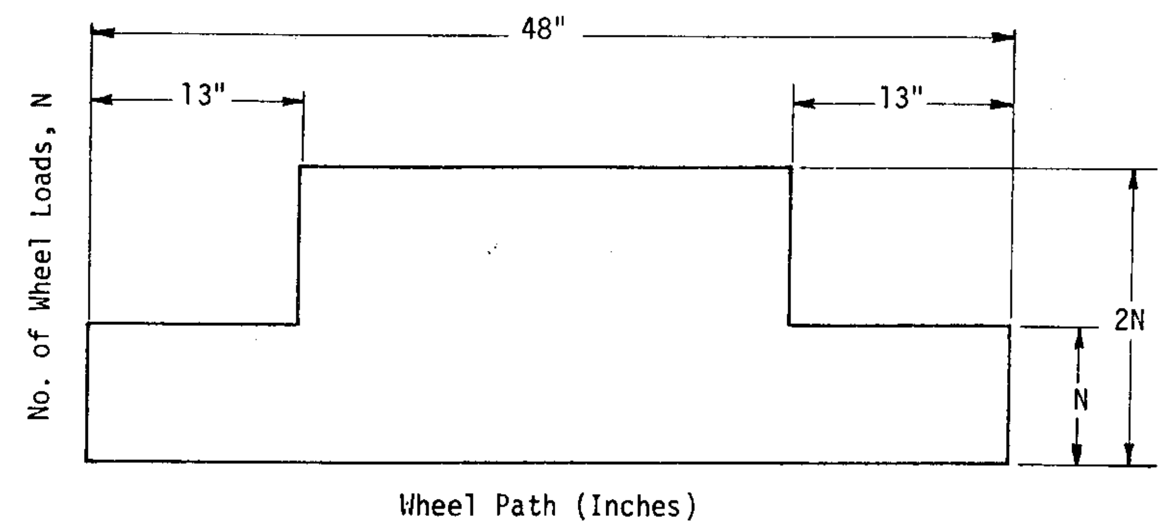



Figure 17. Load Distribution in Wheel Path

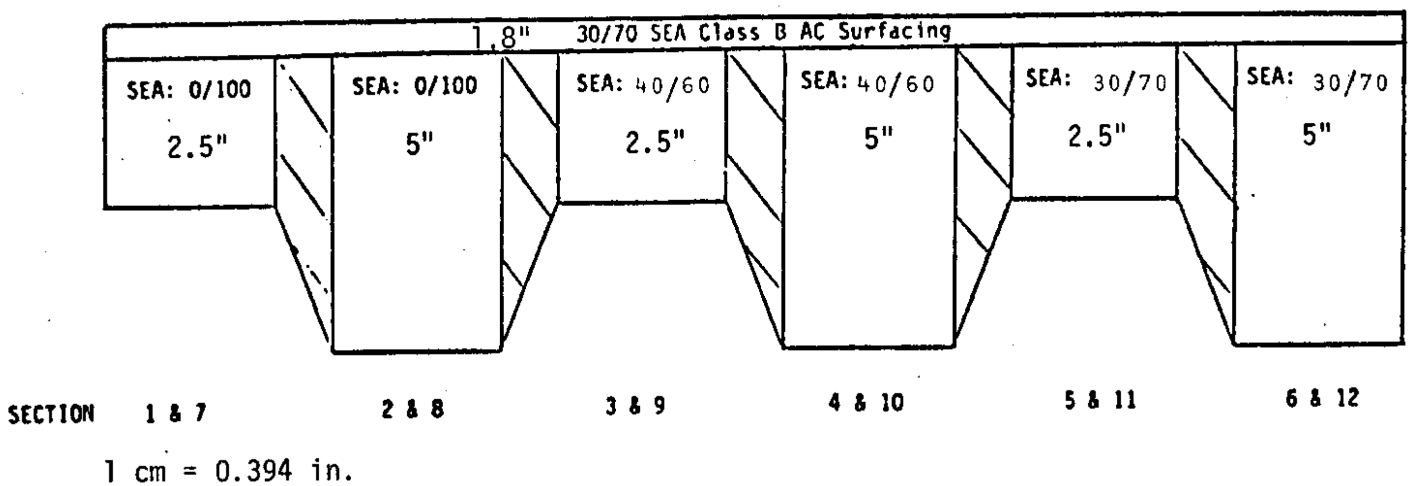
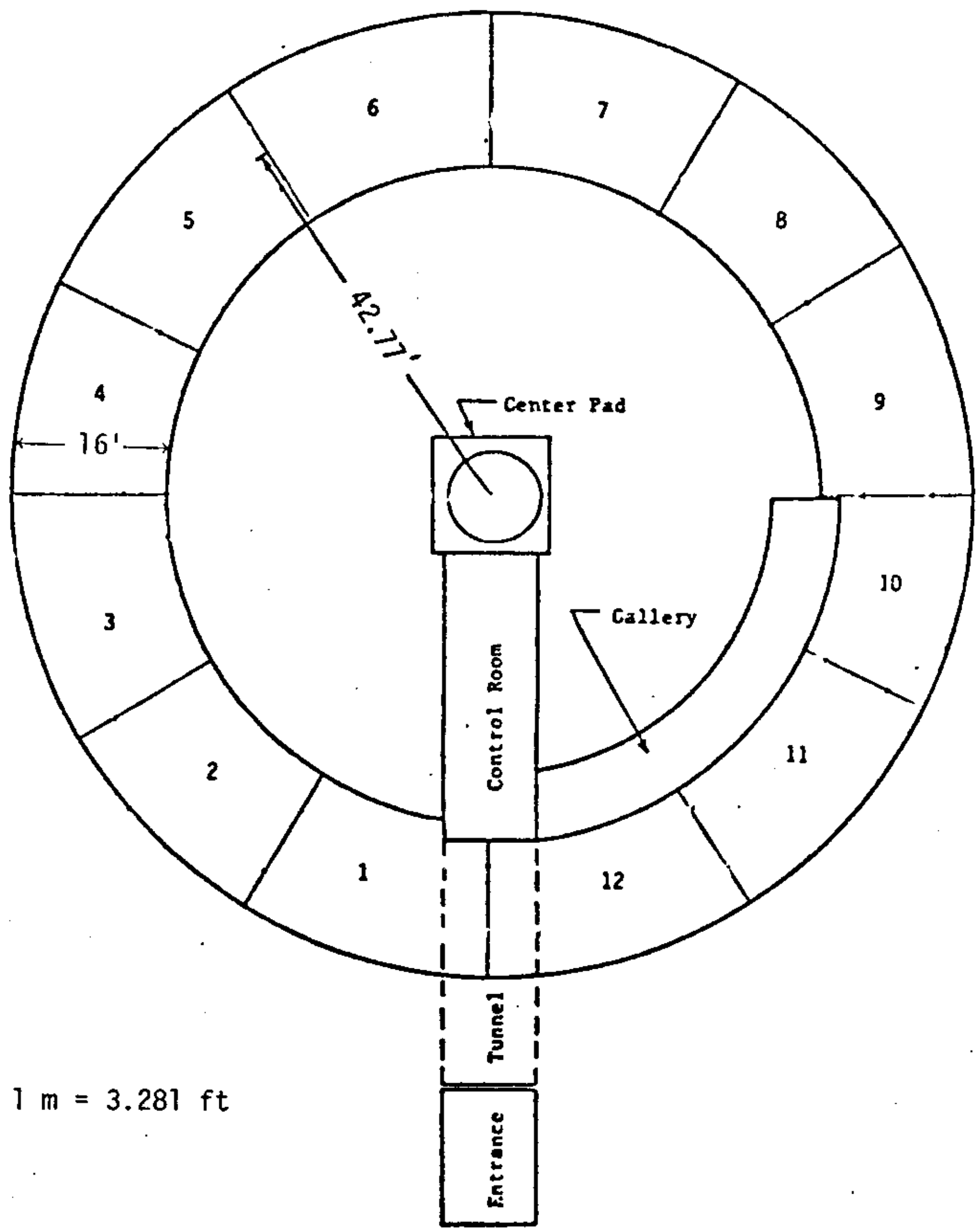



Figure 18. Schematic Profile of Test Track




1 m = 3.281 ft

Figure 19. Plan View of Test Track

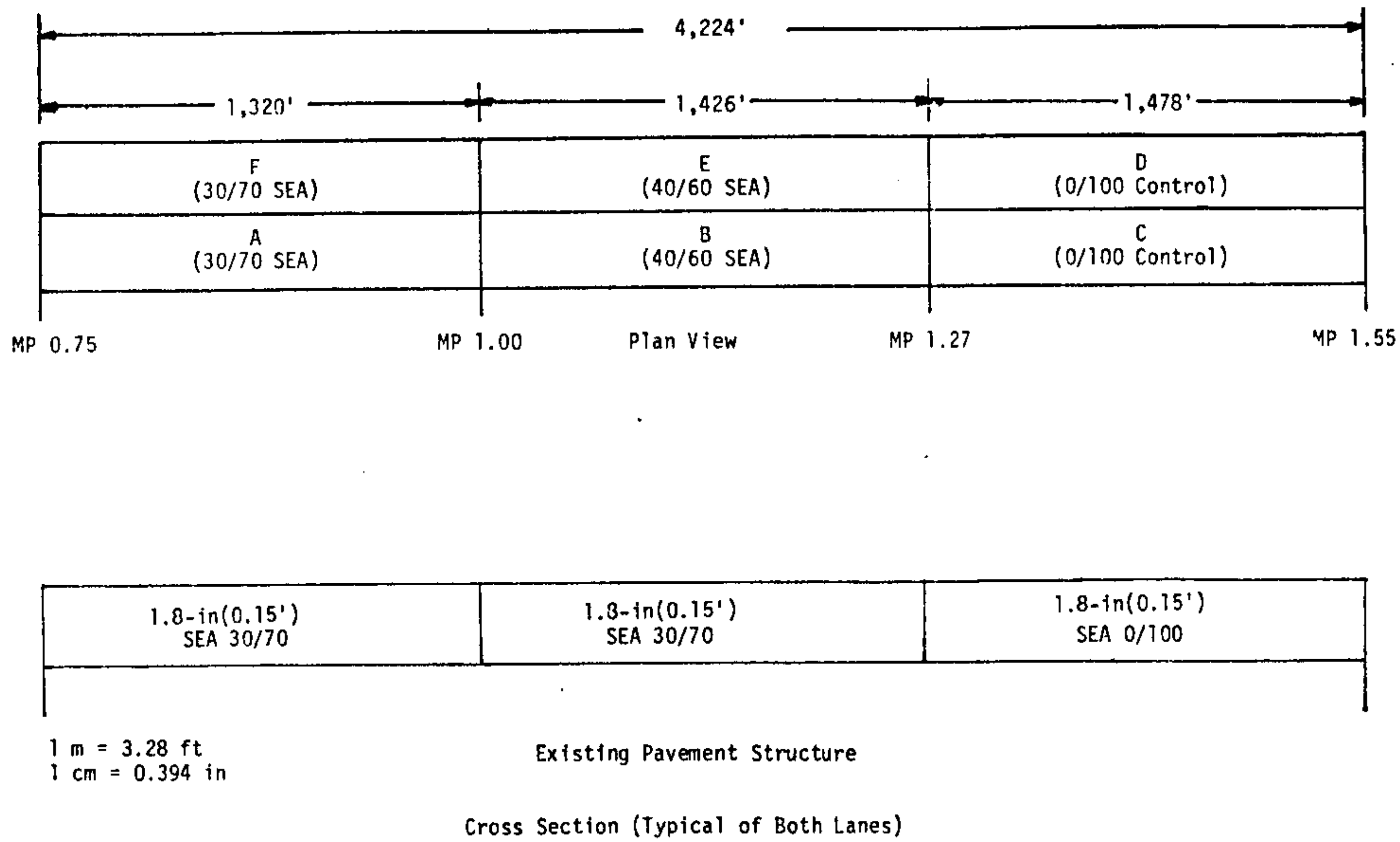



Figure 20. Layout of Experimental Highway Project (SR 270)

adequate paving material for subsequent sampling (cores and saw cut beams).

The test pavements placed on SR 270 were constructed as an overlay 1.8 in (4.6 cm) thick (Figure 20). There are a total of six sections so that each SEA mixture would experience traffic in either direction. The primary value of the SR 270 sections is to provide a long-term durability and surface wear evaluation of the three SEA mixtures. The total length of the SR 270 project is 0.8 mi (1.3 kilometre). Paving was accomplished between the outer edges of each shoulder (two main lanes and shoulders were paved). This provides for observing possible differences between traffic associated surface wear in the main lanes and environmental deterioration on the non-trafficked shoulders.

## TEST TRACK INSTRUMENTATION

Various types of measurements were obtained in order to characterize the performance of the test pavements. These measurements included the following:

1. Strain (vertical and horizontal)
2. Benkelman Beam deflections
3. Temperature (air, pavement and subgrade)
4. Visual condition surveys
5. Load repetition counts
6. Load acceleration

Primarily, the instrumentation system was designed to automatically measure three variables: strain, temperature and vertical wheel accelerations. It was also designed to perform preliminary data reduction, data storage and control operations. The strain sensor system measured both the long-term (static) and dynamic strains. The transducers used to make these measurements were developed around a system of wire-wound inductance coil strain sensor pairs. The main advantages of these sensors are that they are independent of mechanical linkages and their relative location and initial separation can be determined after placement (Figure 21). Also, they are rugged, unaffected by changes in their environment and minimize the distrubance of the material to be measured. A single strain sensor consists of a minimum of two wire-wound disk shaped coils which can be used in either a coplanar or coaxial configuration. The coil sizes used were one, two and four inch (2.5, 5.1 and 10.2 cm) diameters with corresponding thicknesses of 0.1, 0.25 and 0.4 in (0.25, 0.63 and 1.0 cm), respectively.

The initial coil separation can vary from less than one to four coil diameters, with the nonlinear scale factor favoring the closer spacing range to obtain maximum sensitivity. The sensors are connected to an off-the-shelf instrument package (Bison 4101A), which was modified for this study and consisted of the necessary excitation voltage, calibration system, balancing adjustments, readout and analog outputs. The sensors are capable of measuring dynamic strains of 0.005 percent and long-term static strains of 0.05 percent with a resolution of one percent.

Figure 21. In Situ Location of Buried Bison Coil (4 Inch Diameter)

## Strain and Displacement Measurements

The actual arrangement of the strain sensors was identical for all of the first 12 transducer sets (hence test sections). This arrangement consisted of five free-floating coils and an extensometer arranged in such a manner as to allow the measurement of two vertical strains, three vertical displacements, and the transverse and longitudinal strains at the pavement-subgrade interface. The configuration used is shown in Figure 22. It consisted of three coplanar coils: one at the pavement surface, one between the pavement and subgrade, and one attached to the top of the extensometer approximately two coil diameters below the bottom of the pavement. Two other coils were placed at the pavement-subgrade interface to allow the measurement of the longitudinal and transverse strains at this location (Figure 23). In this arrangement only the central coil is excited thus inducing a voltage into the other four coils.

The displacement of the lower coil is obtained from the extensometer to which it is attached. The extensometer uses a pair of one inch (2.5 cm) coils as a sensing device and is constructed of two inch (5.1 cm) PVC pipe and stainless steel rod with an overall length of approximately 16 feet (4.9 m) (sketch-Figure 24 and installation photograph - Figure 25). From the coil on top of the extensometer, the initial coil separation reading and relative displacement of the two coils above it, the displacement of each of these three coils can be obtained. This allows the measurement of seven variables from seven coils and five Bison instruments.

## Temperature Measurements

The temperature measurements were made at various locations throughout the test track and are given in Table 9. These measurement were made using J type thermocouples capable of measuring temperatures from below freezing to 392°F (200°C) with a resolution of approximately 0.2°F (0.1°C) and an accuracy of ±0.5 percent or ±1.8°F (+1°C) (whichever is larger). This information was tabulated, printed and stored on a disc with each strain measurement summary.

## Acceleration Measurements

Acceleration measurements were made of the vertical motion of the dual steel axles approximately two feet inside of the centerline of the dual wheels (Model 303B Sanstrand accelerometers). The accelerometers have an infinite resolution and are limited only by the inherent electrical noise within the signal conditioning electronics and by the analog to digital conversion resolution which was 12 bits over a calibrated range of ±2 g's. These signals (along with the power to the accelerometers) were transmitted back to the data acquisition system via an existing set of slip rings. These slip rings were adjacent to others carrying high voltage DC power and other signals for operation and control of the large DC motors used for powering the test track. Problems were experienced with the transmission of these signals, which resulted in intermittent operation.

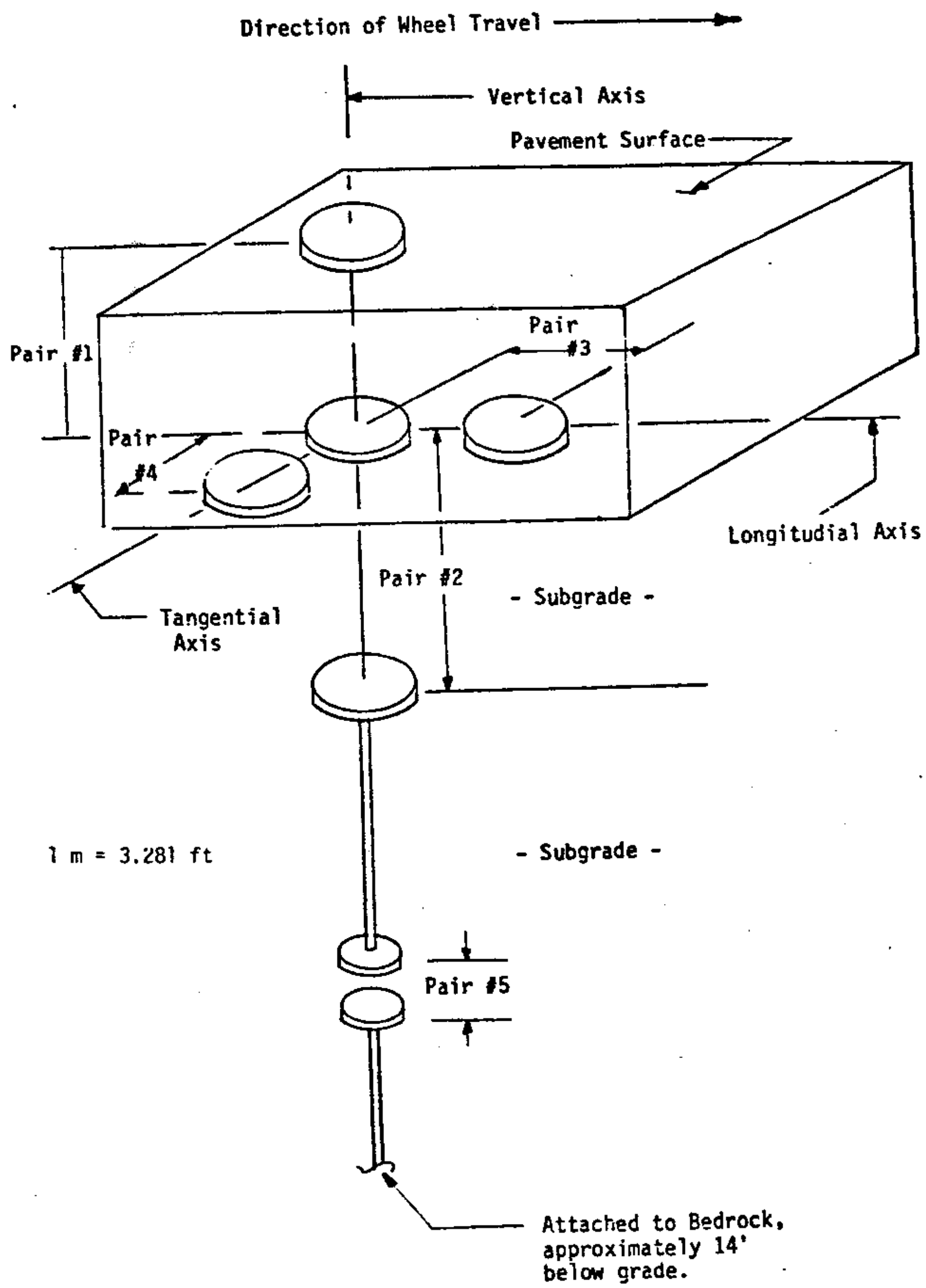



Figure 22. Bison Strain Coil Layout for Each Test Section

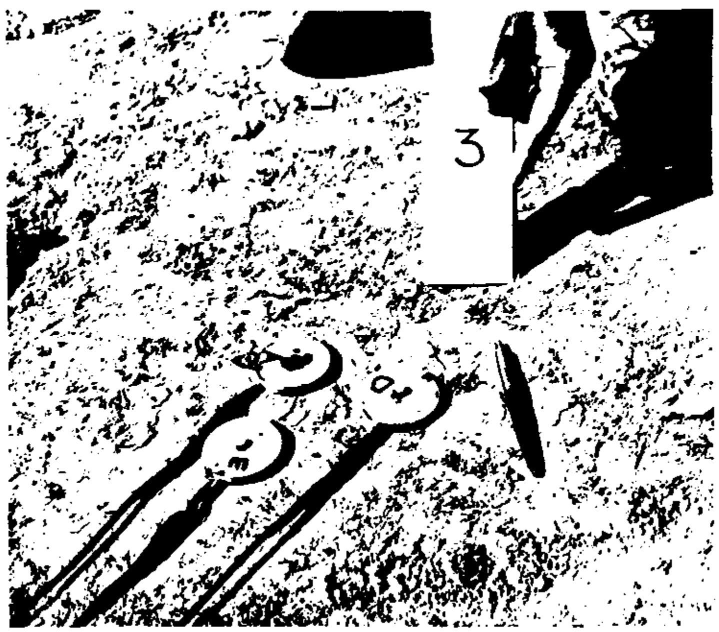
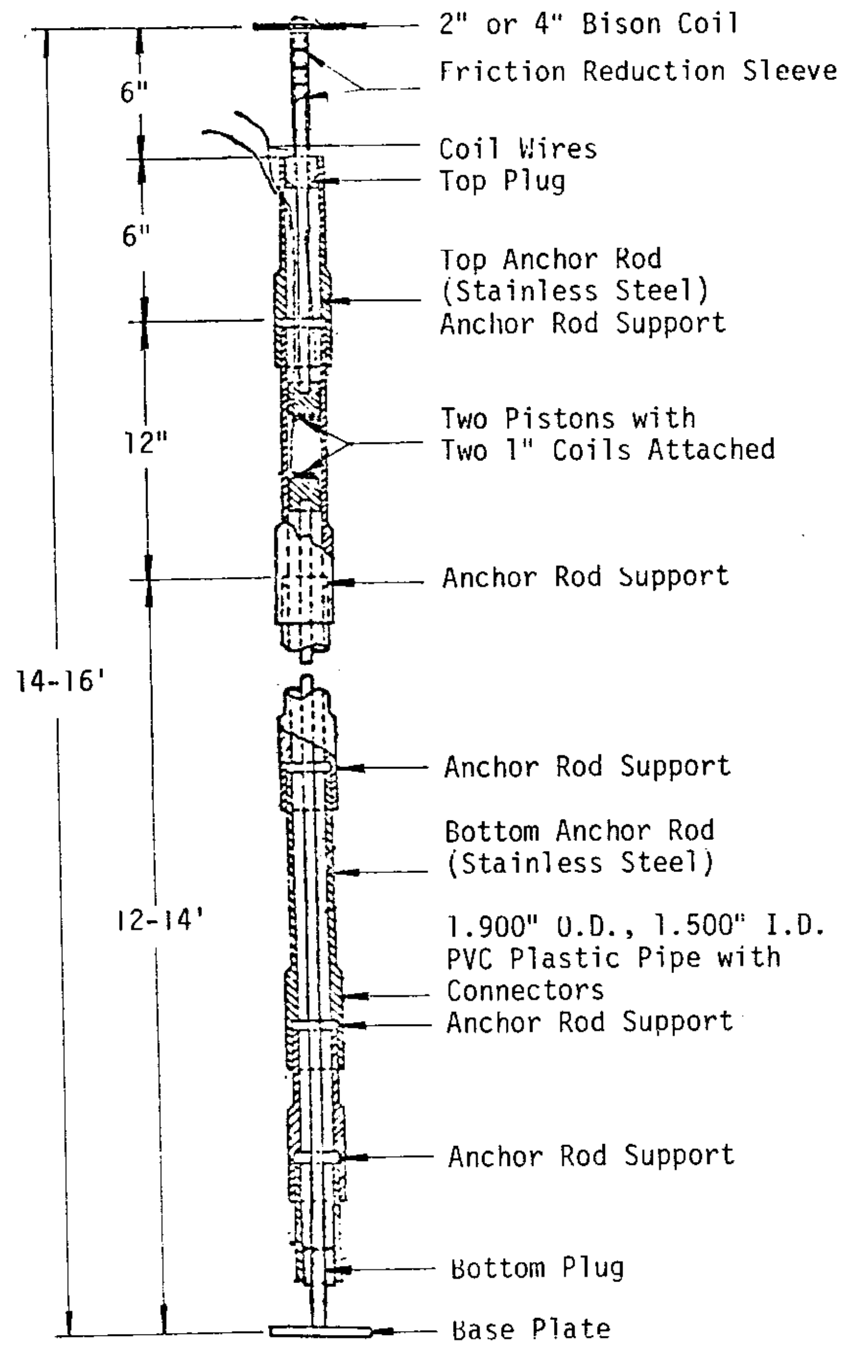



Figure 23. Bison Coils Installed on Top of Prepared Subgrade (Section 3)




1 m = 3.281 ft
1 cm = 0.394 in

Figure 24. Extensometer

Table 9. Location of Thermocouples at WSU Test Track

| Thermocouple No. | Test Section | Description of Location |
|---|---|---|
| 1 | 5 | 15 inches into the subgrade |
| 2 | 6 | Exposed to the air |
| 3 | 6 | 0.5 inch below pavement surface |
| 4 | 6 | Between asphalt and subgrade |
| 5 | 9 | Exposed to the air |
| 6 | 9 | 2 inches into the subgrade |
| 7 | 9 | 15 inches into the subgrade |
| 8 | 10 | 4.5 inches into the subgrade |

1 cm = 0.394 in

Table 10. Classification of Subgrade Material (After 19)

| Test or Classification Systems |
|---|
| 1. Atterberg Limits |
| (a) Liquid Limit: 35 |
| (b) Plasticity Limit: 20 |
| (c) Plasticity Index: 15 |
| 2. AASHTO Classification: A-6(10) |
| 3. Unified Classification: CL |

Figure 25. Installation of Extensometer (Extensometer Protected by PVC Casing Until Backfilling Operation Completed)

Figure 26. Data Control System and Bison Instruments Installed in Test Track Tunnel

These transducers were used to provide a measure of the true load on each individual wheel as it passed over a transducer set. These signals were averaged over a special interval of approximately ±1 ft (0.3 m) either side of the strain measurements. Where available, the readings were given in g's about a zero mean. Thus, a measure of +1/2 g would indicate that on the average over the interval measured the wheel was being accelerated upwards, resulting in approximately 1/2 of its mass being applied to the pavement structure.

Measurement and Control System

The heart of the instrumentation system was a small microcomputer (64K byte, 16-bit word) by Analog Devices (MACSYM II). This system was set up to handle 32 differential analog inputs, eight thermocouple inputs, eight priority interpret digital inputs and sixteen digital outputs (see Figure 26). The analog inputs were used for the strain sensors and accelerometers while the digital inputs and outputs were used for controlling the data acquisition and control functions of the overall instrumentation system.

A key component in this system was a switching network, which allowed one set of five Bison soil strain instruments to be switched between 12 sets of strain coils placed in the roadbed. Also independent controls for the amplitude and phase adjustments and for the coil separation settings were switched for each individual strain measurement.

The primary mode of operation was to follow a single set of wheels as they rotated around the track and to accumulate the primary statistics (maximum, minimum, mean and standard deviation) for the peak values of each strain measurement caused by the wheel passing, for each set of 200 wheel rotations, and the 12 transducer sets. This corresponded to approximately a 30° rotation of the eccentricity angle or eight inches of radial tire movement across the four-foot wheel path. This data was then printed and stored on a floppy disc before starting a new data set. This was done continuously throughout the major part of the testing period. A second mode of operation, which switched the Bison instruments from one transducer set to the next was used for static calibration, initial no-load coil separation readings, dynamic calibrations and observation of readings for multiple wheel passes over a single transducer set.

The five major elements (computer system, signal conditioning, switching network, control system, and computer software) are covered in detail in Appendix C.

PREPARATION OF WSU TEST TRACK PRIOR TO PAVING

A previous study at the test track had used reinforced concrete sections on six inches of crushed basalt base (removal of previous test pavements shown in Figure 27). In order to insure uniform support for the SEA test sections and to simplify the data collection and analysis, the test sections were constructed directly on the local subgrade soil (Palouse silt).

Figure 27. Demolition of Previous Test Pavements at Test Track

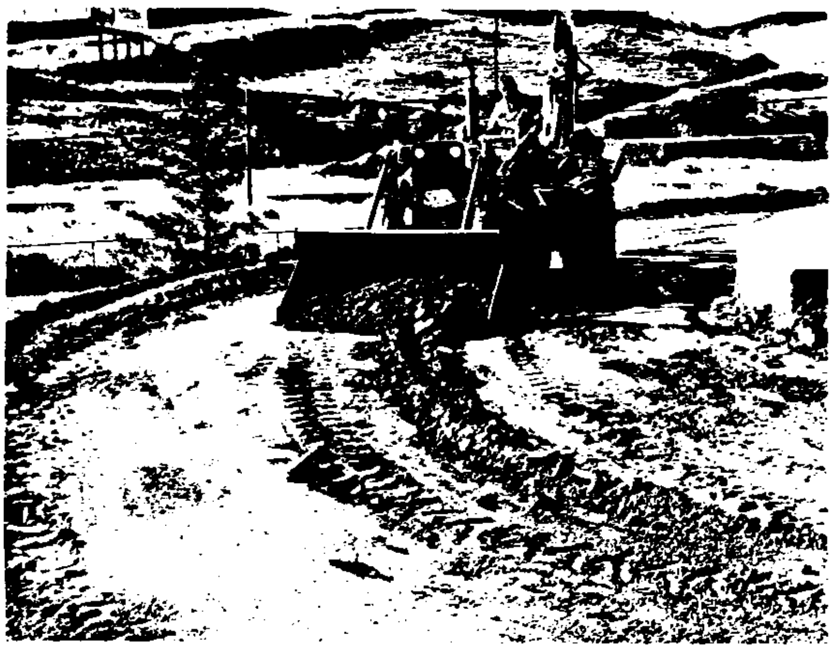


Figure 28. Excavation of Previous Base and Non-uniform Subgrade Material

The characteristics of the subgrade soil are shown in Tables 10 and 11. These results show that the subgrade is a CL material (Unified System). In Table 11, various laboratory and field data are presented. The CBR is relatively low (2.8%) for the field compaction moisture contents. Additionally, the amount of field compaction achieved was slightly less than 95 percent of the maximum. Frequent rain showers occurred during the subgrade preparation resulting in somewhat less than desirable uniformity.

To insure complete removal of non-uniform subgrade material, all material to a depth of 12 in (30 cm) below the previous pavement structure was removed (Figure 28). For grade purposes, Palouse silt borrow was placed on the track in two lifts of 6 in (15 cm) each. As described in Table 10, the average moisture content was one percent higher than optimum. This provided a benefit in that the Palouse silt has a relatively uniform resilient modulus in this condition (although low) thus aiding the subsequent analysis of the test pavement performance. This same material at moisture contents of four to seven percent less (total of 16 to 13 percent by weight) exhibit resilient moduli five to eight times larger. Thus, the supporting ability of the subgrade soil is very sensitive to moisture content. Individual moisture contents measured in each test section are shown in Figure 29.

## PAVING OF TEST SECTIONS

The paving sequence associated with the construction of the WSU Test Track and SR 270 sections was as shown in Table 12. All paving was accomplished during a total of six working days. The paving mixtures were essentially the same for both paving locations. The total size of the project was small, about 2,300 tons (2090 metric tons). The size of the project is important in that little time (or tonnage) was available to achieve an efficient, smooth running mix production - paving sequence.

The major equipment items used in constructing the test pavements include the following:

1. Mixing plant: Standard (3,000 lb (1360 kg) pugmill capacity) with 30 second wet mix time for all mixes (Figures 30 and 31).

2. Pavers: Blaw Knox 8 and 12 ft (2.4 and 3.7 m) widths (Figure 32).

3. Rollers: Gallion 8 and 10 ton steel wheel (static) supplemented with a pneumatic roller as required.

The original project goal was to produce SEA mixtures with ratios of 0/100, 30/70 and 50/50. Due to plant start-up and initial calibration problems and the relatively small amount of hot-mix produced, the final paving mixes consisted of 0/100, 30/70 and 40/60 SEA mixtures. The actual binder contents used were 5.7 percent (by weight of total mix) for the 0/100 mixture, and 6.6 percent for the 30/70 and 40/60 mixtures. By equivalent volume of asphalt cement, the 40/60 SEA binder would have been placed at a content of 7.1 percent (by weight). Thus, the 40/60 SEA sections were placed at approximately 0.5 percent binder content below optimum. This was not planned

Table 11. Summary of Subgrade Material Properties

| TEST | DATA |
|---|---|
| 1. Compaction | |
| (a) Laboratory (ASTM D698) | |
| (i) Maximum Density: | 107.8% pcf |
| (ii) Optimum Moisture Content: | 18.8% |
| (b) Laboratory CBR @ $\gamma_d$ = 105.8 pcf and wc = 19.3%: | 2.8% |
| (c) Field Results | |
| (i) Density (top 18"): | |
| Mean: | 101.3 pcf |
| Standard Deviation: | 3.4 pcf |
| (ii) Moisture Content (top 12"): | |
| Mean: | 19.8% |
| Standard Deviation: | 2.3% |
| 2. Resilient Modulus ($M_R$) | |
| (a) Range of $M_R$ at $\gamma_d$ = 105.0 pcf and wc = 19.2% for Various Deviator Stresses. | 3500-4500 (psi) |
| 3. Unified Soil Classification | CL |

1 $Mg/m^3$ = 62.4 $lb/ft^3$
1 cm = 0.394 in
1 kPa = 0.1451 psi

Note: Average moisture content is indicated inside the test track diameter. Sample locations are indicated by (.)'s.

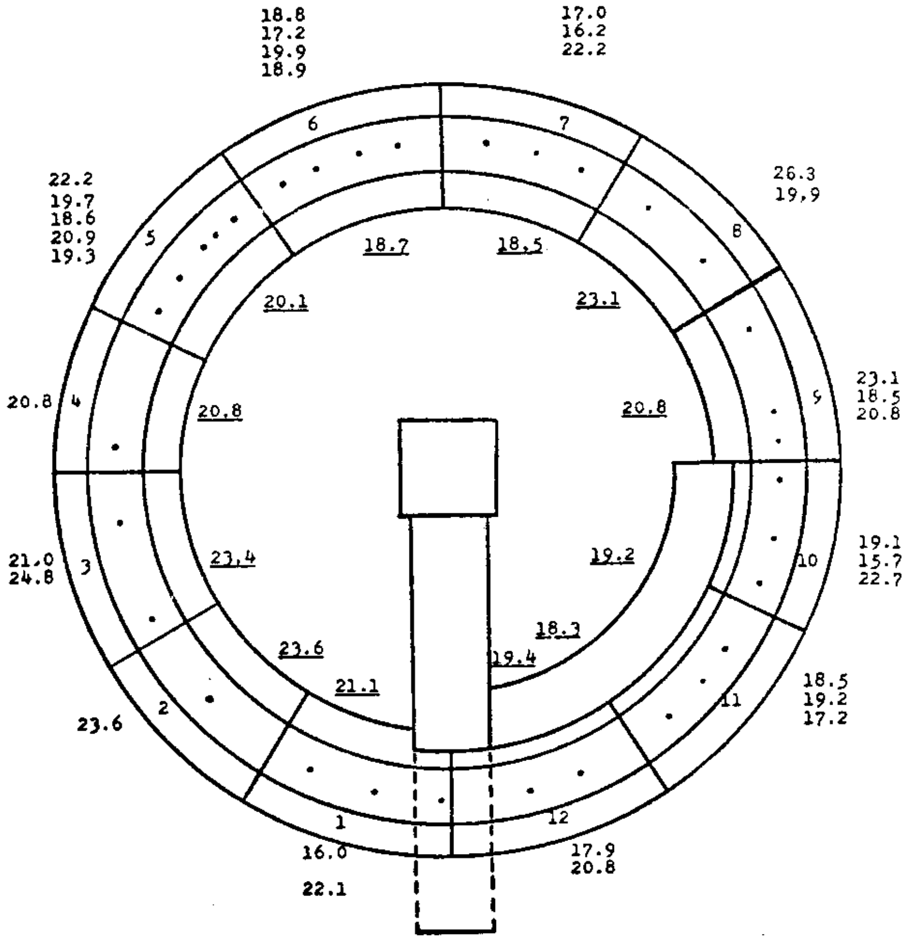



Figure 29. Moisture Content (%) of the Subgrade as Placed and Average Moisture Content Per Section

Table 12. Paving Sequence

| Date | Type of Mix (SEA Ratio ) | Mix Produced (tons) | Paving Location |
|---|---|---|---|
| 8/20/79 | 0/100 | 772 | SR 270 |
| 8/21/79 | 0/100 | 105 | SR 270 |
| | | | WSU Test Track (Sections 1,2,8) |
| 8/22/79 | 0/100 | 15 | WSU Test Track (Sections 7,8) |
| 8/24/79 | 40/60 | 596 | SR 270 WSU Test Track (Sections 3,4,9,10) |
| 8/27/79 | 30/70 | 424 | SR 270 WSU Test Track (Sections 5,6,11,12) |
| 8/28/79 | 30/70 | 435 | SR 270 WSU Test Track (Wearing Course - all sections) |
| | | Total 2,347 | |

1 ton (metric) = 1.102 ton (short, 2000 lbm)

Figure 30. United Paving Mixing Plant

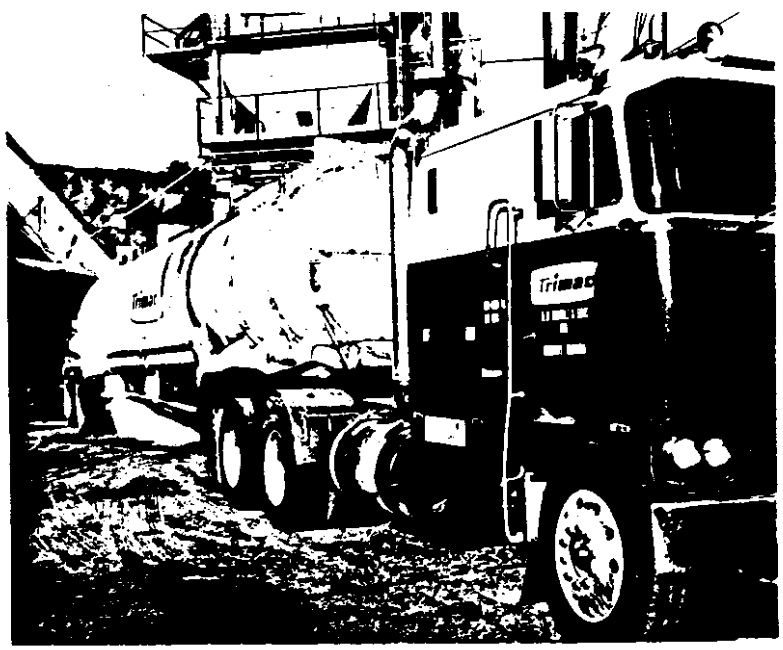



Figure 31. Tanker Used for Transport and On-site Storage of Molten Sulfur

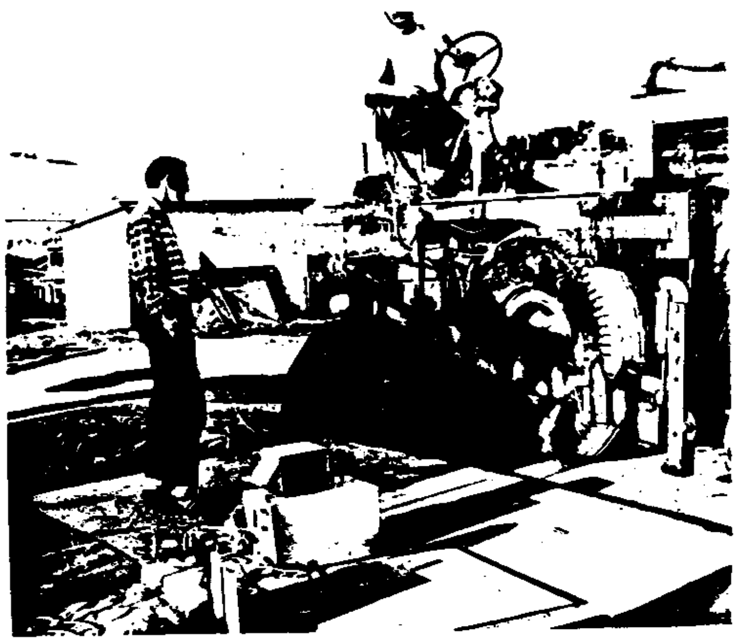


Figure 32. Blaw Knox Paver Used at Test Track and Environmental Monitoring Equipment

in the initial experimental design but provided the opportunity to evaluate a SEA mixture below the volume equivalent of the 0/100 SEA mixture. Additionally, a short section of Section A (30/70 SEA) on SR 270 was paved at 7.1 percent (by weight) instead of 6.6 percent. This is providing the opportunity to investigate the surface wear differences of the 30/70 SEA mixture at optimum binder content (6.6 percent) and at 0.5 percent higher (7.1 percent).

Prior to the actual construction, it was decided that the addition of the siloxane polymer to achieve improved mixing of the asphalt cement and sulfur was not required.

Test Track and SR 270 Thicknesses

The initially planned test track thicknesses were 2.5 and 5.0 in (6.3 and 12.7 cm) for the thin and thick sections all of which were to receive a wearing course of 1.8 in (4.6 cm) of the 30/70 SEA mixture. Thus, the planned total thicknesses were 4.3 and 6.8 in (10.9 and 17.3 cm), respectively, for the thin and thick sections. The constructed pavement thicknesses varied from those originally planned. The wearing course was varied to achieve a more uniform total pavement cross section. The average total depths for the thin sections (measured by pavement cores) ranged from 3.3 to 4.9 in (8.4 to 12.4 cm) and the thick sections from 6.0 to 7.0 in (15.2 to 17.8 cm). This variation in pavement thickness was higher than desired but paving in the confined area of the test track was difficult. This was further complicated by the instrumentation located in each of the test sections. The individual test section thickness measurements are shown in Figure 33. These measurements are based on the initial set of pavement cores obtained from the test track. Also based on pavement cores, the average thickness for the SR 270 overlay was 1.9 in (4.8 cm) versus the planned 1.8 in (4.7 cm).

Paving Temperatures

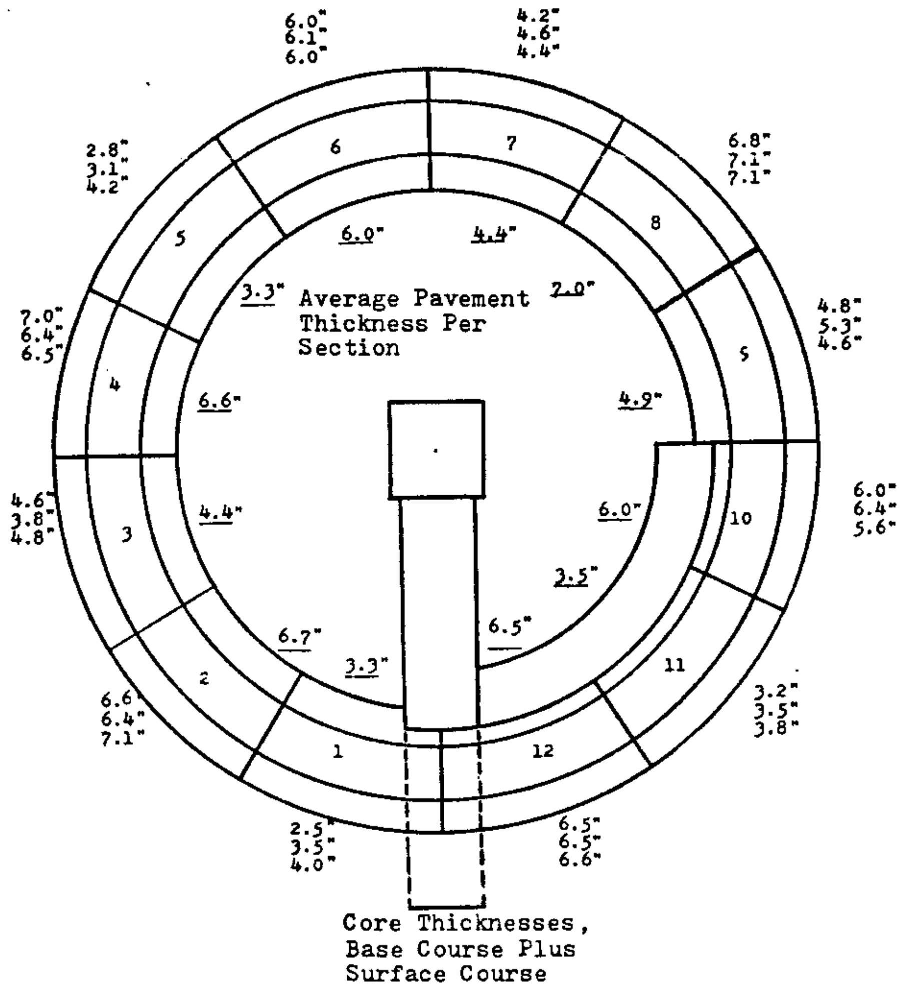
Numerous paving mixture temperature measurements were obtained throughout the construction sequence primarily with contact thermometers but also infrared (Figure 34). Tables 13 and 14 provide statistical summaries; both temperatures taken both at the plant and behind the paver, respectively. In general, the mixing and compaction temperatures are within acceptable ranges; although, a few low temperature batches were placed in the various test sections (test track and SR 270). Table 15 provides more detailed temperature data specifically for the WSU Test Track sections. The relatively low laydown temperatures were due to the delays which occurred during the paving of the test track sections. Each test section contained instrumentation which could not be disturbed hence causing extra equipment maneuvering. It is difficult to move construction equipment quickly on the small area of the test track at anytime.

Paving Densities

The target density for all mixes was set at 92 percent of maximum theoretical (which was 160 pcf (2.564 Mg)). Thus, during rolling, a lower limit of 147.2 pcf (2.359 Mg) was targeted. All field densities were measured by

THICKNESS OF LEVELING COURSE (IN)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| THICKNESS | 1.1 | 1.4 | 1.4 | 1.2 | 1.1 | 1.9 | 1.6 | 1.6 | 1.1 | 1.7 | 1.5 | 1.5 |
| SECTION | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |




1 cm = 0.394 in

Figure 33. Actual Pavement Thicknesses at Test Track

Figure 34. Temperature Measurement of First Lift of Base on Section 10 (40/60 SEA Mix) at the Test Track

Figure 35. Density Measurement on Section F (30/70 SEA Mix) on SR 270 (Westbound Lane)

Table 13. Mixture Temperature at Plant

| Date | Type of Mix (SEA Ratio) | Mixing Temperature (°F) | | | |
|---|---|---|---|---|---|
| | | Mean | Standard Deviation | Range (Min-Max) | No. of Measurements |
| 8/20/79 | 0/100 | 284 | 12 | 250-310 | 27 |
| 8/21/79 | 0/100 | 270 | 31 | 215-290 | 5 |
| 8/22/79 | - | - | - | - | - |
| 8/24/79 | 40/60 | 272 | 15 | 235-300 | 40 |
| 8/27/79 | 30/70 | 263 | 18 | 240-305 | 25 |
| 8/28/79 | 30/70 | 270 | 10 | 255-300 | 29 |

°C = (F -32)(5/9)

Table 14. Mixture Temperatures Taken Behind the Paver

| Date | Type of Mix (SEA Ratio) | Mix Temperature (°F) | | | |
|---|---|---|---|---|---|
| | | Mean | Standard Deviation | Range (Min-Max) | No. of Measurements |
| 8/20/79 | 0/100 | 262 | 27 | 230-300 | 8 |
| 8/21/79 | 0/100 | - | - | - | - |
| 8/22/79 | 0/100 | - | - | - | - |
| 8/24/79 | 40/60 | 266 | 17 | 245-295 | 24 |
| 8/27/79 | 30/70 | 256 | 26 | 215-300 | 17 |
| 8/28/79 | 30/70 | 246 | 13 | 230-260 | 5 |

°C = (F -32)(5/9)

Table 15. Placement Temperature of SEA Mixes at the WSU Test Track

| Type of Mix (SEA Ratio) | Test Section | Lift | Date | Temperature (°F) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Air | Truck | Lay Down | Finished Rolling |
| 0/100 | 2 | 1 | 8/21/79 | 70 | | 235 | 180 |
| | 8 | 1 | | 70 | 250 | 225 | 160 |
| | 1 | 1 | | 70 | 250 | 230 | 185-200 |
| | 2 | 2 | | 60 | 250 | 230 | 185-200 |
| | 8 | 2 | 8/22/79 | 80 | NA | 250 | 200 |
| | 7 | 1 | | 80 | NA | 250 | 200 |
| 40/60 | 10 | 1 | 8/24/79 | 80 | 265 | 240 | NA |
| | 4 | 1 | | 80 | 300 | 240 | NA |
| | 9 | 1 | | 80 | 260 | 235 | NA |
| | 10 | 2 | | 80 | 295 | 235 | NA |
| | 3 | 1 | | 80 | | 235 | NA |
| | 4 | 2 | | 80 | | 235 | NA |
| 30/70 | 12 | 1 | 8/27/79 | 75 | 280 | 260 | 160 |
| | 6 | 1 | | 75 | 280 | 250 | NA |
| | 12 | 2 | | 75 | 285 | 265 | NA |
| | 11 | 1 | | 75 | 285 | 265 | NA |
| | 6 | 2 | | 75 | 285 | 260 | NA |
| | 5 | 1 | | 75 | 285 | 260 | NA |
| 30/70 | Wearing Course | | 8/28/79 | 70 | 270 | 210-250 | 170 |

°C = (F -32)(5/9)

WSDOT personnel using a Troxler Nuclear gage (No. 4661) (Figure 35). Tables 16 through 19 are used to present a summary of the field densities obtained during construction.

Table 16 is a summary of the field densities for the sections paved on SR 270. Recall that these sections are overlays over the preexisting pavement structure. Overall, for all three paving mixes, the measured densities generally meet or exceed the target value. The mean values are generally slightly above the target and the associated standard deviations are relatively low. One comment made by the WSDOT Project Inspector was that the 30/70 and 40/60 SEA mixes compacted more readily than the 0/100.

Tables 17, 18 and 19 are density summaries for the paving at the WSU Test Track. Table 17 is a summary for the "thin" (odd numbered) test sections. It is significant that this was the first lift placed directly on the compacted subgrade. This fact is the primary reason the target density (147.2 pcf (2.359 Mg)) was often not obtained (as measured by the nuclear gage); although, the densities were considered generally acceptable under the prevailing conditions. The data in this table also provides some insight into the number of roller passes required to achieve a given density. Overall, the 30/70 and 40/60 SEA mixtures achieved higher densities with fewer roller passes.

Tables 18 (0/100 mix) and 19 (30/70 and 40/60 SEA mixes) contain field density summaries for the "thick" sections (even numbered) at the test track. In general, the target density was difficult to achieve for the first lift. This was primarily due to the placement of the paving mix directly on the compacted subgrade. This condition was further complicated for Section 8 (0/100 mix) by low mix temperatures at the time of compaction. Target density for the second lift was achieved for all sections except Section 2. The low densities in this section appear to be associated with a lower than desirable mix temperature prior to compaction.

In general, the test track sections were paved late in the afternoon. This resulted in final compaction being accomplished during a time when the air temperature dropped rapidly. This, combined with the delays associated with placing the paving mixtures and the "full-depth" design concept, resulted in slightly less than target densities. These minor construction problems are not known to have significantly affected the resulting performance of any of the pavement sections (test track or SR 270).

Typical pavement surface appearances following compaction of the test track bases are shown in Figures 36-38; Figure 36 (Section 2 - 0/100), Figure 37 (Section 6 - 30/70), and Figure 38 (Section 4 - 40/60). Figure 39 is used to show the compaction of the 30/70 SEA surface course which was applied over all test sections and Figure 40 the rolling of the same mixture on SR 270.

### Mixture Gradations

Table 20 contains a summary of the mixture gradations obtained at the WSDOT field laboratory (Figure 41). The tests were performed by District 6 personnel as part of the WSDOT Quick Wash test method. In general, the percent passing

Table 16. Nuclear Gage Densities Obtained During Construction of SR 270 Sections

| Date | Type of Mix (SEA Ratio) | Milepost | Travel Direction* | Densities (pcf) | | | | No. of Roller Passes |
|---|---|---|---|---|---|---|---|---|
| | | | | Mean | Standard Deviation | Range | No. of Tests | |
| 8/20/79 | 0/100 | 1.30-1.53 | WB | 149.7 | 2.2 | 147.1-152.9 | 10 | - |
| | | 1.30-1.40 | EB | 144.2 | 2.1 | 142.1-147.4 | 10 | - |
| | | 1.45-1.54 | EB | 147.5 | 1.5 | 145.6-150.8 | 10 | - |
| 8/24/79 | 40/60 | 1.10-1.25 | WB | 150.8 | 1.9 | 148.3-153.3 | 10 | - |
| | | 1.05-1.22 | EB | 144.8 | 3.0 | 138.9-147.1 | 10 | Initial |
| | | 1.05-1.22 | EB | 147.1 | 2.6 | 143.5-150.4 | 10 | Final |
| 3/27/79 | 30/70 | 0.80-0.96 | WB | 147.9 | 1.1 | 146.5-149.5 | 10 | 8 |
| | | 0.80-0.90 | EB | 148.9 | 2.4 | 144.3-151.7 | 10 | - |

1 $Mg/m^3$ = 62.4 $lb/ft^3$

*WB = Westbound
EB = Eastbound

Table 17. Nuclear Gage Densities Obtained During Construction of the WSU Test Track (Thin Sections)

| Date | Type of Mix (SEA Ratio) | Test Section | Densities (pcf) | | | | No. of Roller Passes |
|---|---|---|---|---|---|---|---|
| | | | Mean | Standard Deviation | Range | No. of Tests | |
| 8/21/79 | 0/100 | 1 | 141.4 | - | 140.6-142.1 | 2 | 8 |
| | | | 143.0 | - | 142.4-143.5 | 2 | 16 |
| | | 7 | 141.4 | - | 141.0-141.7 | 2 | 4 |
| | | | 144.0 | 4.7 | 143.4-144.6 | 6 | 8 |
| | | | 144.6 | 6.4 | 143.9-145.7 | 6 | 13 |
| 8/24/79 | 40/60 | 3 | 147.0 | - | 146.7-147.3 | 2 | 7 |
| | | 9 | 146.5 | - | 146.0-146.9 | 2 | 6 |
| 8/27/79 | 30/70 | 5 | 146.2 | - | 146.1-146.3 | 2 | 4 |

$1\ Mg/m^3 = 62.4\ lb/ft^3$

Table 18. Nuclear Gage Densities Obtained During Construction of the WSU Test Track for Thick Sections - 0/100 SEA Mixture (Conventional ACP)

| Date | Type of Mix (SEA RAtio) | Test Section | Densities (pcf) | | | | No. of Roller Passes |
|---|---|---|---|---|---|---|---|
| | | | Mean | Standard Deviation | Range | No. of Tests | |
| 8/21/79 | 0/100 | 2(Bottom Lift) | 147.1 | 1.7 | 144.1-149.6 | 8 | 10 |
| | | 2(Top Lift) | 142.6 | 7.6 | 140.6-143.2 | 4 | 8 |
| | | | 145.6 | 2.1 | 142.6-147.5 | 6 | 12 |
| | | | 144.6 | - | 143.5-145.6 | 2 | 16 |
| | | 8(Bottom Lift) | 128.4 | - | - | 2 | 4 |
| | | | 136.4 | - | - | 2 | 6 |
| | | | 139.0 | 2.5 | 137.0-143.5 | 6 | 13 |
| 8/22/79 | | 8(Top Lift) | 143.1 | - | 142.8-143.3 | 2 | 4 |
| | | | 148.3 | - | 147.3-149.2 | 2 | 8 |
| | | | 147.9 | 1.3 | 146.4-149.8 | 6 | 13 |

$1\ Mg/m^3 = 62.4\ lb/ft^3$

Table 19. Nuclear Gage Densities Obtained During Construction of the WSU Test Track for Thick Sections - 40/60 and 30/70 SEA Mixtures

| Date | Type of Mix (SEA Ratio) | Test Section | Densities (pcf) | | | | No. of Roller Passes |
|---|---|---|---|---|---|---|---|
| | | | Mean | Standard Deviation | Range | No. of Tests | |
| 8/24/79 | 40/60 | 4(Bottom Lift) | 141.2 | 3.1 | 135.5-143.4 | 6 | 3 |
| | | | 143.6 | 3.3 | 138.9-145.9 | 6 | 6 |
| | | 4(Top Lift) | 147.4 | 1.4 | 145.5-149.4 | 6 | 7 |
| | | 10(Bottom Lift) | 137.0 | 2.5 | 134.6-140.1 | 6 | 3 |
| | | | 143.8 | 1.8 | 141.8-146.1 | 6 | 6 |
| | | 10(Top Lift) | 143.0 | - | 142.9-143.1 | 2 | 4 |
| | | | 148.5 | 1.5 | 146.9-150.7 | 6 | 6 |
| 8/27/79 | 30/70 | 6(Bottom Lift) | 142.0 | 3.9 | 137.1-146.6 | 6 | 5 |
| | | | 145.3 | 1.6 | 144.0-147.2 | 4 | 8 |
| | | 6(Top Lift) | 148.5 | 2.8 | 146.1-152.1 | 6 | 4 |
| | | 12(Bottom Lift) | 142.7 | 2.9 | 139.0-146.8 | 6 | 3 |
| | | | 145.4 | 3.7 | 139.9-149.2 | 6 | 5 |
| | | | 145.4 | 1.5 | 143.4-146.8 | 4 | 7 |
| | | 12(Top Lift) | 148.7 | 1.0 | 147.1-149.8 | 6 | 4 |

1 $Mg/m^3$ = 62.4 $lb/ft^3$

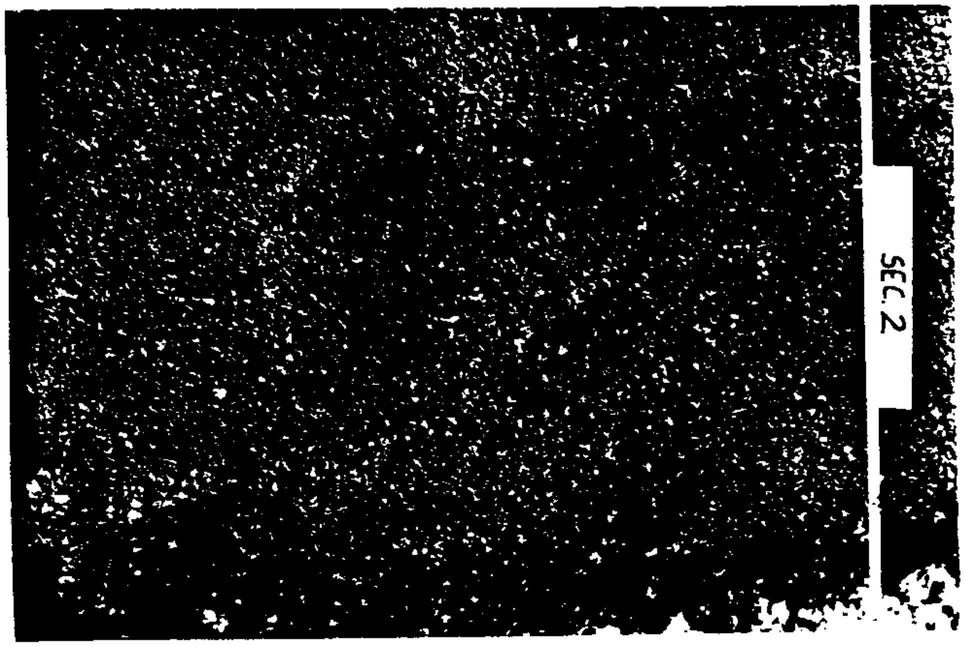



Figure 36. Surface of 0/100 SEA Mix (Section 2 Base Course) Following Final Compaction

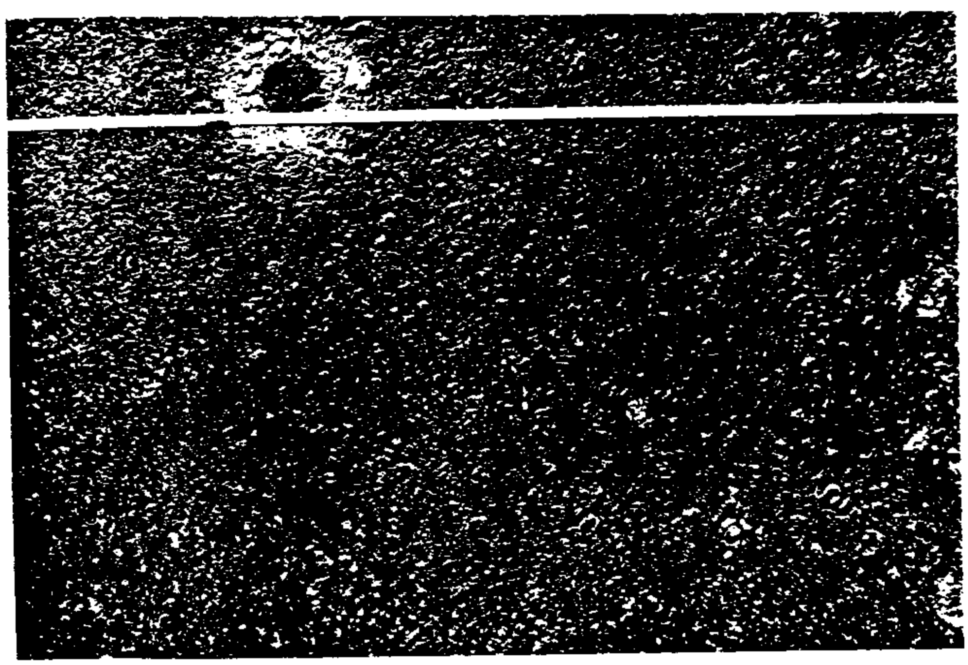


Figure 37. Surface of 30/70 SEA Mix (Section 6 Base Course) Following Final Compaction

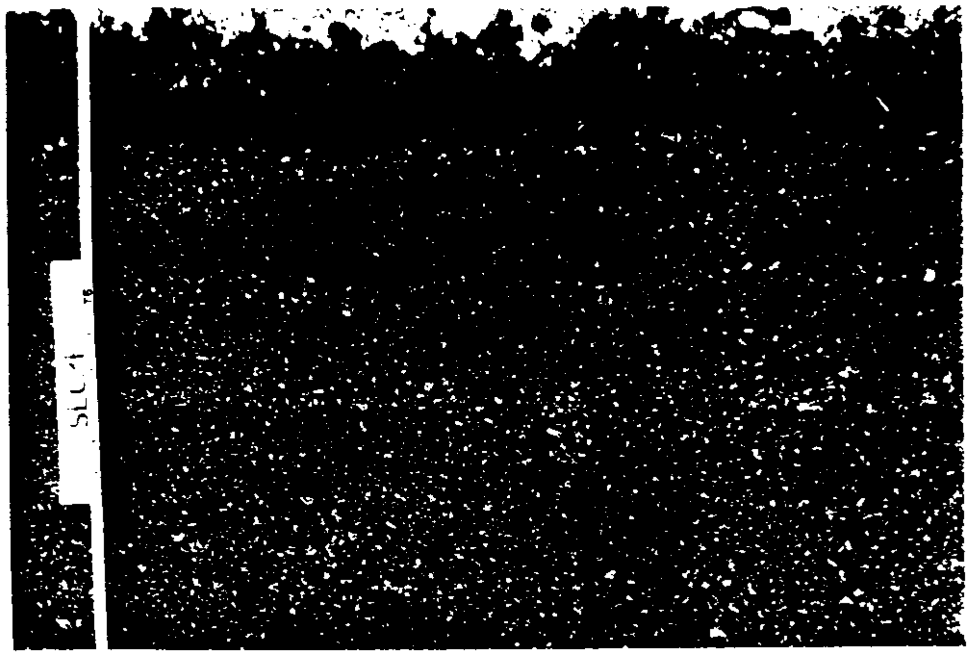


Figure 38. Surface of 40/60 SEA Mix (Section 4 Base Course) Following Final Compaction

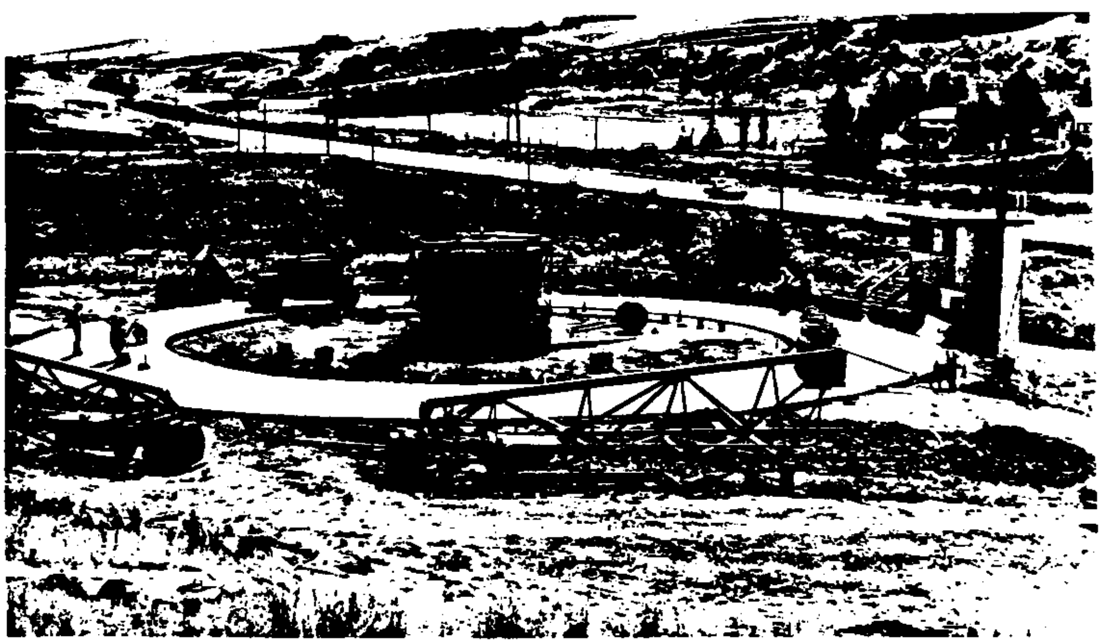


Figure 39. Final Rolling of Surface Course (30/70 SEA Mix) at the Test Track

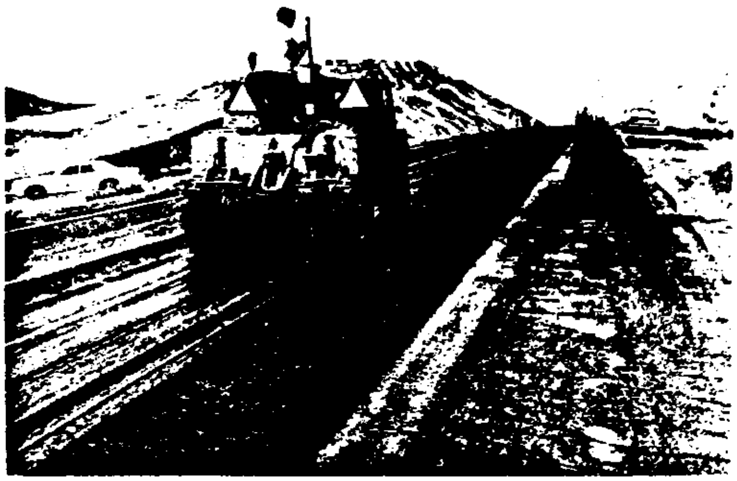


Figure 40. Rolling of Overlay on SR 270
(Section F - 30/70 SEA Mix)

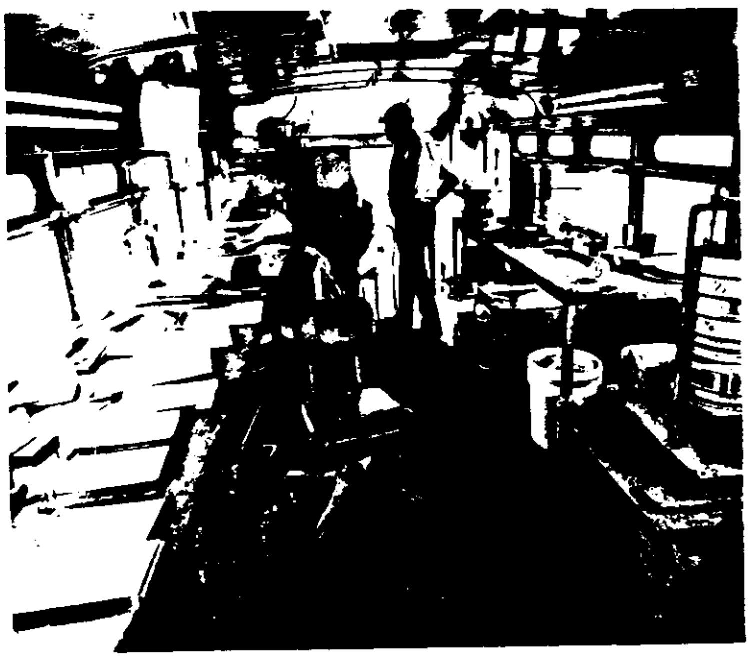


Figure 41. WSDOT Mobile Laboratory Adjacent
to Mixing Plant

Table 20. Summary of Mixture Gradations

| Date | Type of Mix (SEA Ratio) | No. of Tests | Percent Passing | Sieve Size | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 5/8" | 1/2" | 3/8" | 1/4" | No.10 | No.40 | No.80 | No.200 |
| 8/20/79 | 0/100 | 7 | Mean | 100 | 98 | 86 | 65 | 36 | 16 | 11 | 7 |
| | | | Range | - | 95-99 | 83-90 | 59-71 | 30-41 | 12-19 | 7-13 | 4-9 |
| 8/21/79 | 0/100 | 2 | Mean | 100 | 97 | 85 | 66 | 39 | 14 | 8 | 5 |
| | | | Range | - | 95-99 | 82-88 | 64-69 | 38-41 | 14-15 | 8-9 | 4-5 |
| 8/22/79 | 0/100 | 1 | Mean | 100 | 98 | 89 | 66 | 37 | 11 | 6 | 3 |
| | | | Range | - | - | - | - | - | - | - | - |
| 8/24/79 | 40/60 | 4 | Mean | 100 | 98 | 88 | 68 | 39 | 16 | 12 | 7 |
| | | | Range | - | 97-99 | 86-90 | 64-72 | 35-41 | 15-18 | 11-13 | 6-8 |
| 8/27/79 | 30/70 | 3 | Mean | 100 | 97 | 85 | 64 | 38 | 17 | 12 | 6 |
| | | | Range | - | 96-98 | 84-86 | 61-67 | 35-40 | 16-18 | 11-12 | 6-7 |
| 8/28/79 | 30/70 | 2 | Mean | 100 | 98 | 88 | 66 | 38 | 16 | 12 | 7 |
| | | | Range | - | - | 87-89 | 65-67 | 37-39 | 16-17 | 11-12 | - |
| Class B Specification Range | | | | 100 | 90-100 | 75-90 | 55-75 | 32-48 | 11-24 | 6-15 | 3-7 |

1 cm = 0.394 in

all sieves (both mean and range) are within specification limits. The 30/70 and 40/60 SEA mixes as well as the initial 0/100 mix are on the high side of the No. 200 sieve specification limit (seven percent).

Toxicity Monitoring

A summary of the toxicity monitoring performed during the construction phase is contained in Appendix F. In general, no significant $SO_2$ or $H_2S$ emissions were detected. Monitoring was performed both at the plant and paving sites (Figures 42 and 43).

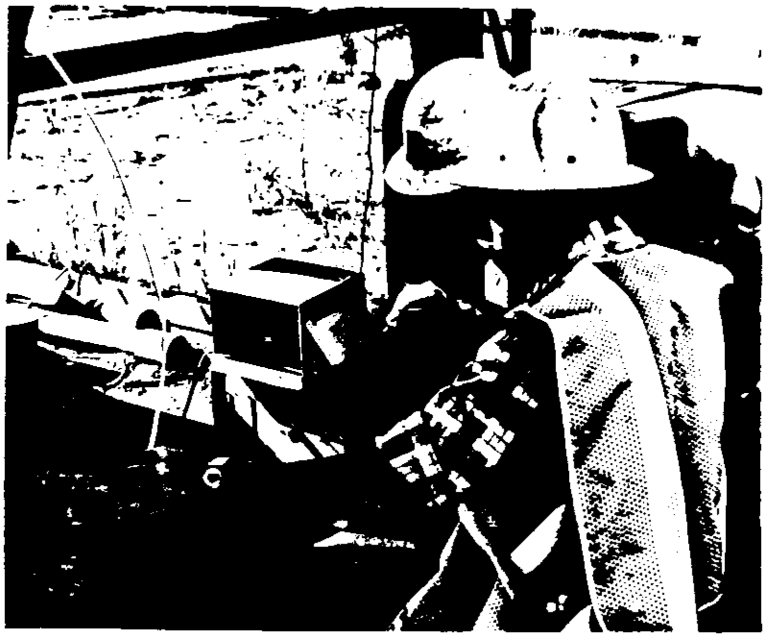


Figure 42. Environmental Monitoring at the Plant

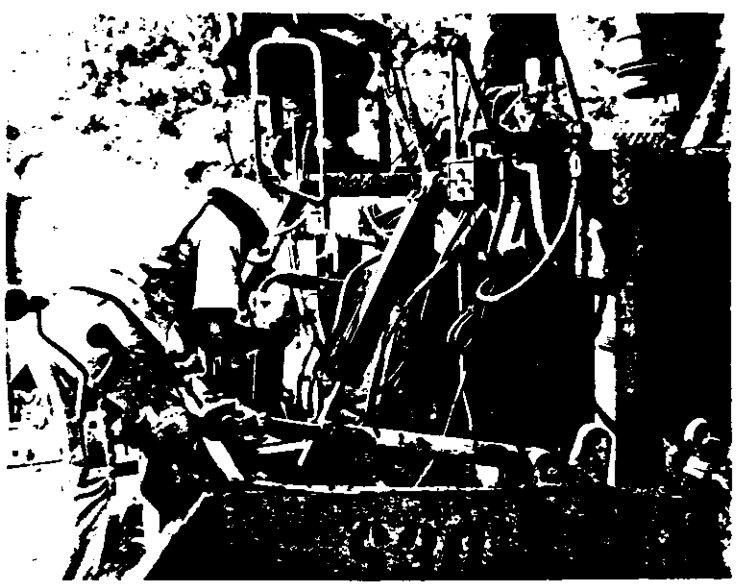


Figure 43. Environmental Monitoring at the Paver (SR 270 Paving Location)

# CHAPTER IV

# POST-CONSTRUCTION EVALUATION

## INTRODUCTION

Immediately following the construction of the SR 270 test pavements, the highway was reopened to traffic. Approximately one month later, wheel load repetitions were started at the WSU Test Track. The information which follows is an introduction to some of the resulting performance and material property data which have been collected following the initiation of traffic loadings to these test pavements. A final project report will summarize all collected data and analyses.

The following post-construction data is being collected:

1. Traffic counts
2. Weather data
3. Benkelman Beam deflections
4. Pavement cores

   (a) Density
   (b) Air voids
   (c) Hveem stability
   (d) Resilient modulus

5. Strain measurements
6. Pavement moisture and temperature
7. Visual condition surveys (photographs)
8. Friction Numbers (SR 270 pavement surface)

Many of the above data items will be presented in the final project report; although, some information can be presented now. These include:

1. WSU Test Track wheel repetitions
2. Friction Numbers (SR 270)
3. Initial evaluations of pavement cores (test track and SR 270)
4. Traffic counts (SR 270)

## WSU TEST TRACK REPETITIONS

The test track was constructed during late August 1979, and operation began slowly in early October. Operations increased during the late part of October with approximately 80,000 loadings complete on November 1. By November 15, when the air temperature began dropping below freezing, 216,000 loadings had been completed and by November 17 all thin sections had failed. Operation of the track continued through January and into February 1980, when operations ceased with approximately 500,000 loadings completed. A summary log of the critical events and general comments is contained in Appendix D.

The wheel loads (recall that an average load of 11,100 lb (5030 kg) was applied by each of three sets of duals) were applied to each of the twelve test sections until failure occurred. The basis used to determine repetitions to failure ($N_f$) for any test section was when the section exhibited 25 percent or more of fatigue (alligator) cracking on the pavement surface. The estimated number of load repetitions to failure for each of the twelve sections is shown in Table 21.

Table 22 contains a further summarization of the wheel loading data. For the "thin" sections, the relative performance of the three SEA mixtures based on repetitions to failure and ranked from best to worst appears to be: 40/60, 0/100 and 30/70. The 30/70 SEA sections are ranked lowest due to the large variability observed for the two 30/70 sections. For the "thick" sections, the same ranking method results in the following: 0/100, 30/70 and 40/60. Thus, a consistent trend is not apparent. Analyses currently being conducted will use this information and more to show which of the three materials exhibit superior performance. Such items as subgrade strength, layer thicknesses, etc. influenced the performance of each test section and must be taken into account. The results of these analyses will be presented in the final project report.

## SURFACE FRICTION TESTING

The friction tests which have been obtained by WSDOT for the SR 270 sections are summarized in Table 23. The skid tester used to obtain this data is the locked-wheel type (manufactured by K.J. Law, Inc.). The initial tests (October, 1979) were obtained shortly after construction completion. Six months later (April, 1980), the Friction Numbers are essentially the same for all three types of SEA mixes and appear to be adequate.

## EVALUATION OF PAVEMENT CORES

Core samples were obtained by WSDOT personnel for use in determining the post-construction material properties. These properties include resilient modulus, density and air void contents. The initial set of cores (sampled December, 1979) were obtained by use of a core barrel measuring 3.75 in (9.5 cm) in diameter. Three full-depth cores were obtained from each of the test track and highway sections. Of the total cores obtained approximately one-half were sent to the UW and the remainder retained by the WSDOT Materials Laboratory.

The UW laboratory investigation included a determination of resilient modulus (at 41°F (5°C), 77°F (25°C) and 104°F (40°C)), density and air void determinations. Originally, Marshall stability and flow were to be obtained as well but the small diameter of the initial cores prevented testing in the Marshall apparatus.

The twelve initial test track cores sent to the UW were saw cut at the horizontal interfaces between the various layers, resulting in 30 samples identified by section and layer. Likewise, the overlay cores from SR 270 were also saw cut in order to remove the overlay form the underlying existing asphalt concrete pavement. The initial core samples were tested approximately

Table 21. Load Repetitions to Failure for the WSU Test Track Sections

| Section | Type of Mix (SEA Ratio) | Repetitions to Failure ($N_f$) |
|---|---|---|
| 1 | 0/100 | 130,000 |
| 2 | 0/100 | 500,000 |
| 3 | 40/60 | 173,000 |
| 4 | 40/60 | 474,000 |
| 5 | 30/70 | 246,000 |
| 6 | 30/70 | 500,000 |
| 7 | 0/100 | 173,000 |
| 8 | 0/100 | 500,000 |
| 9 | 40/60 | 216,000 |
| 10 | 40/60 | 244,000 |
| 11 | 30/70 | 84,500 |
| 12 | 30/70 | 438,000 |

Table 22. Comparison of Repetitions to Failure for the SEA Mixtures (WSU Test Track)

| Type of Section | Type of Mix (SEA Ratio) | Repetitions to Failure ($N_f$) | |
|---|---|---|---|
| | | Mean | Range (Max-Min) |
| Thin | 0/100 | 151,500 | 43,000 |
| | 30/70 | 165,000 | 161,500 |
| | 40/60 | 194,000 | 43,000 |
| Thick | 0/100 | 500,000 | - |
| | 30/70 | 469,000 | 62,000 |
| | 40/60 | 359,000 | 230,000 |

Table 23. Surface Friction Tests for SR 270 Sections

| Type of Mix (SEA Ratio) | Travel Direction* | Friction Numbers | | | | | |
|---|---|---|---|---|---|---|---|
| | | Date: 10/79 | | | Date: 4/80 | | |
| | | Mean | Range | No. of Tests | Mean | Range | No. of Tests |
| 0/100 | WB | 39 | - | 1 | 45 | 0 | 2 |
| | EB | 32 | 0 | 2 | 48 | 3 | 2 |
| 30/70 | WB | 41 | 6 | 3 | 49 | 2 | 2 |
| | EB | 42 | 9 | 3 | 48 | 1 | 2 |
| 40/60 | WB | 38 | 2 | 2 | 49 | - | 1 |
| | EB | 38 | 15 | 2 | 48 | 0 | 2 |

*WB Westbound
EB Eastbound

nine months after the sections were constructed.

Also reported are the results from the second set of pavement cores (SR 270 only) obtained in December, 1980 (approximately 16 months after construction). These cores were tested in a similar manner to that described above but also included Marshall stability and flow.

## Test Procedures

A pneumatic repeated loading device, two linear variable displacement transducers (LVDT) and strip recorder (previously described) were used to determine the resilient modulus of each of the test samples, using a repeated load of 100 lb (44.5 N). This was done first at 77°F (25°C). The samples were then placed in a refrigerated environment, cooled to 41°F (5°C) for a minimum of 24 hours, and then tested again. Following this series of tests, the samples were placed in a 104°F (40°C) enclosure for 24 hours and then once again tested. The resulting deformation values together with the measured thickness of each sample were used to determine the resilient modulus.

Following the determination of all resilient modulus values, the same samples were used in obtaining bulk and theoretical maximum specific gravities in accordance with ASTM standards.

## Resilient Modulus

Figures 44 through 48 provide summaries of resilient modulus data obtained for the first set of pavement cores (sampled December, 1979). Tabular values are provided in Appendix E.

Figure 44 shows the relative stiffness of the three types of mixes placed on SR 270. Two features are readily apparent. One, the 30/70 and 40/60 SEA mixes have essentially the same stiffness and, two, these mixes are consistently stiffer than the 0/100 mix (conventional) over a wide range of temperatures. The slope or rate of change of mixture stiffness with increases in temperature is slightly less for the 30/70 and 40/60 mixes as compared to 0/100.

Figure 45 was developed from all resilient modulus data available for the three mixes. The trends are similar to those described for the samples from the SR 270 overlay with the exception that the 30/70 SEA mix appears to have a lower resilient modulus at low temperatures (as compared to 40/60)—a desirable mixture characteristic. This feature is more apparent for the samples obtained from the bottom lifts (base course) for the thin test track sections (Figure 46). The resilient moduli for the top lift ($L_2$) and bottom lift ($L_1$) for the thick section bases are shown in Figures 47 and 48, respectively.

In general, the individual resilient modulus measurements for the various layers in the test pavements are fairly consistent. The 40/60 SEA mix for all cases is stiffer than the other two mixtures. When compared to the 0/100 mix, the 30/70 SEA mix has an interesting feature in that it exhibits about the same modulus at low temperatures and is stiffer at high temperatures. Thus,

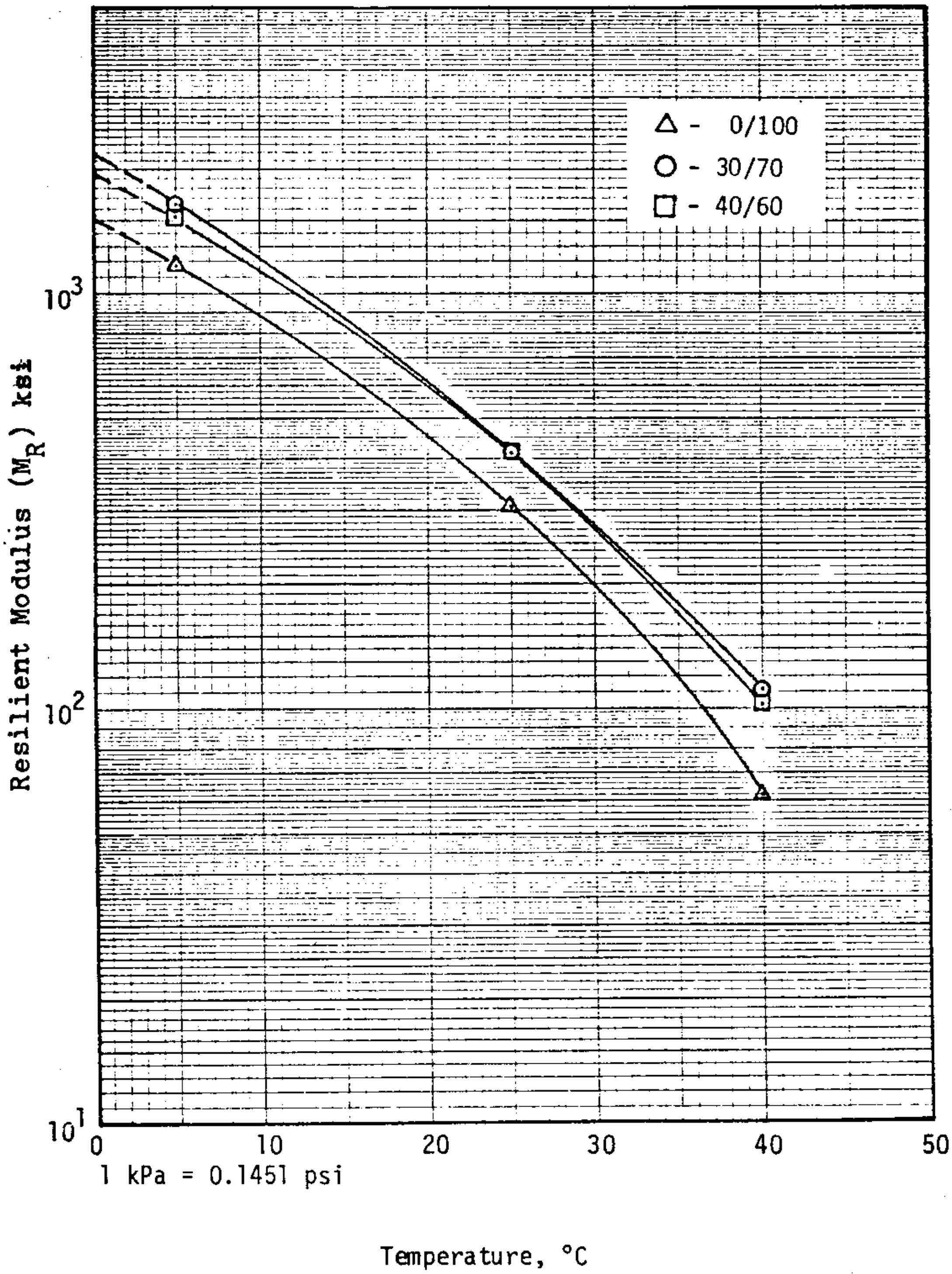



Figure 44. Resilient Modulus vs. Temperature, SR 270 Overlay.

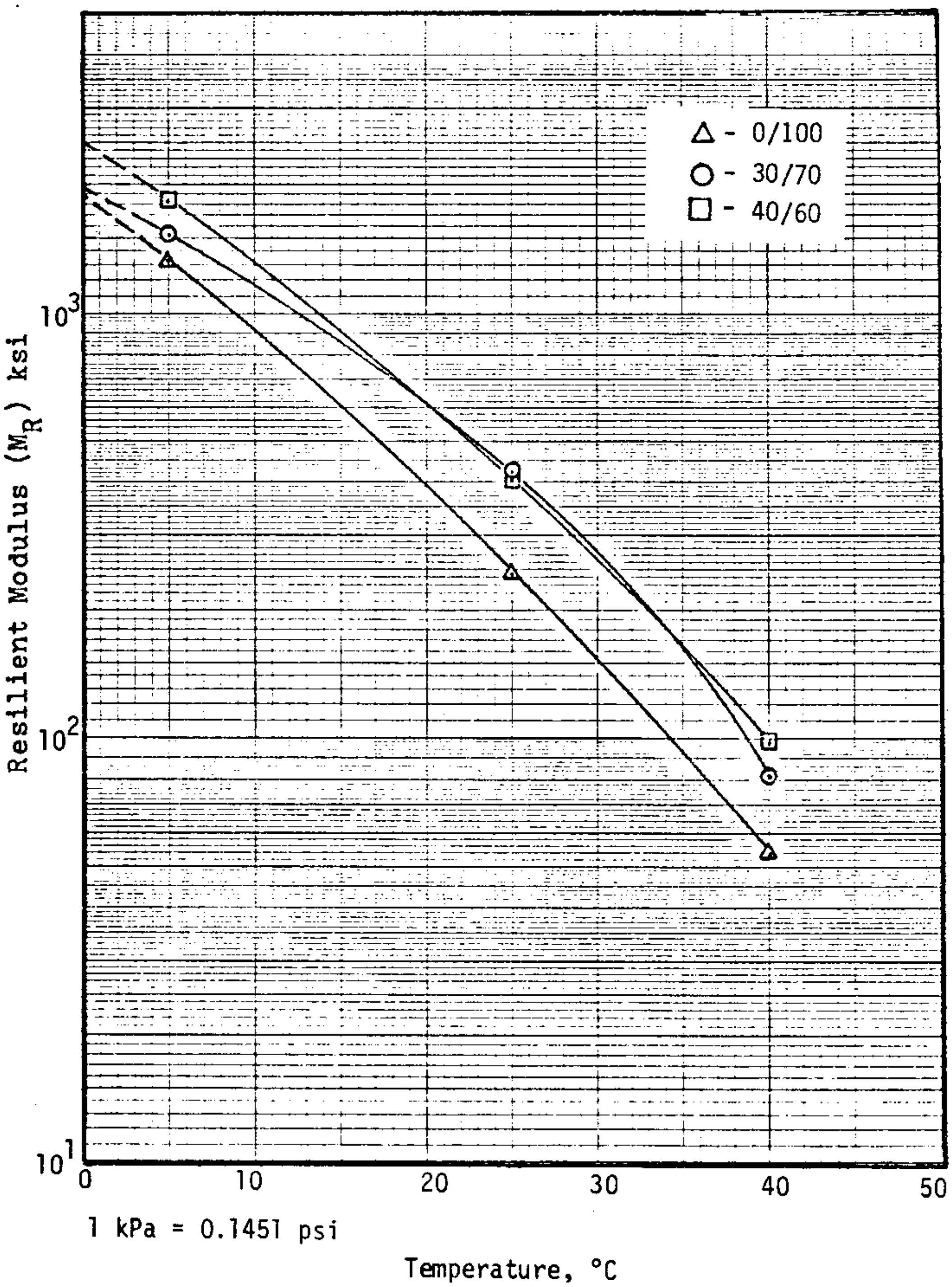



Figure 45. Resilient Modulus vs. Temperature, Average of All Layers and Test Sections.

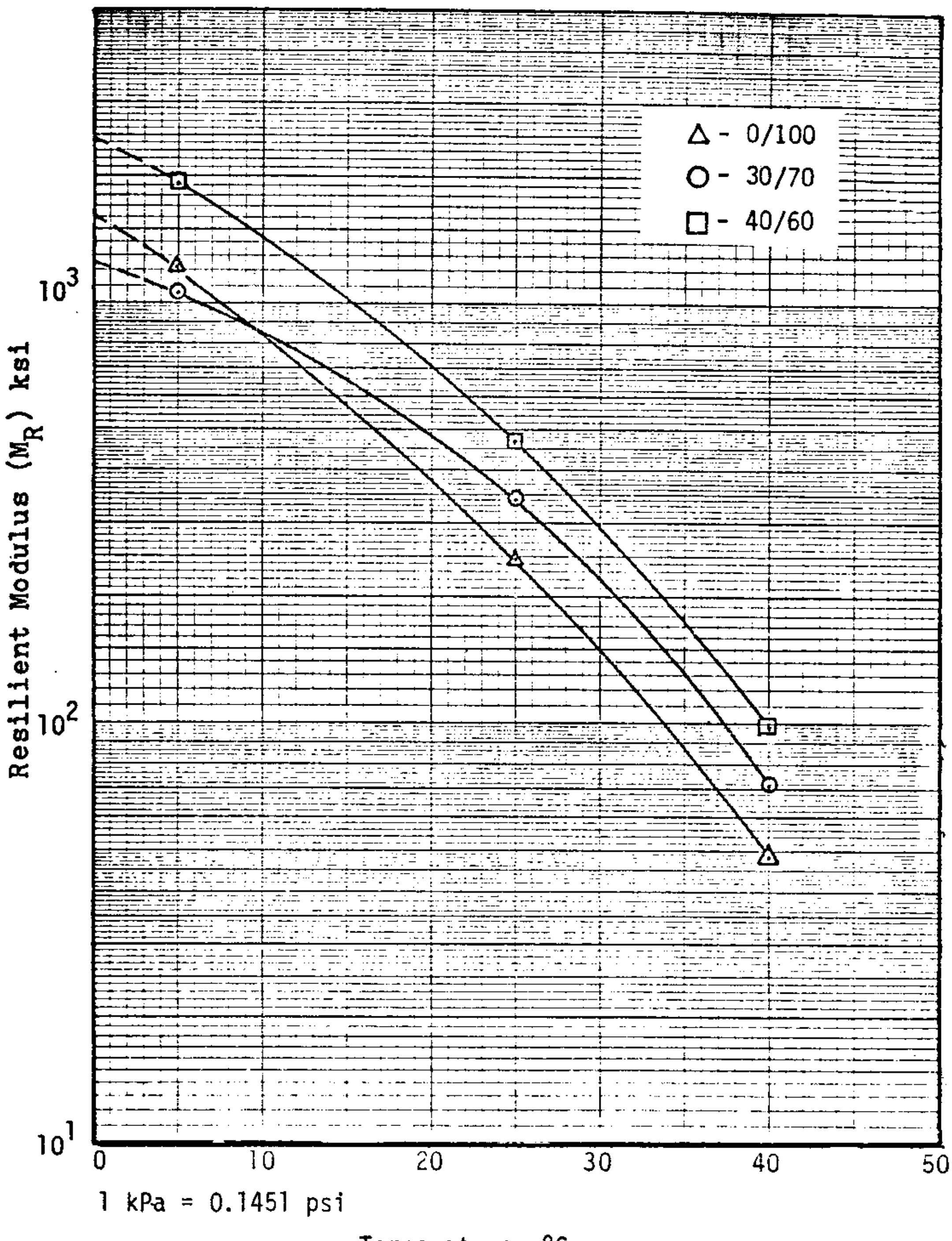



Figure 46. Resilient Modulus vs. Temperature, Base Course Layers of Thin Sections.

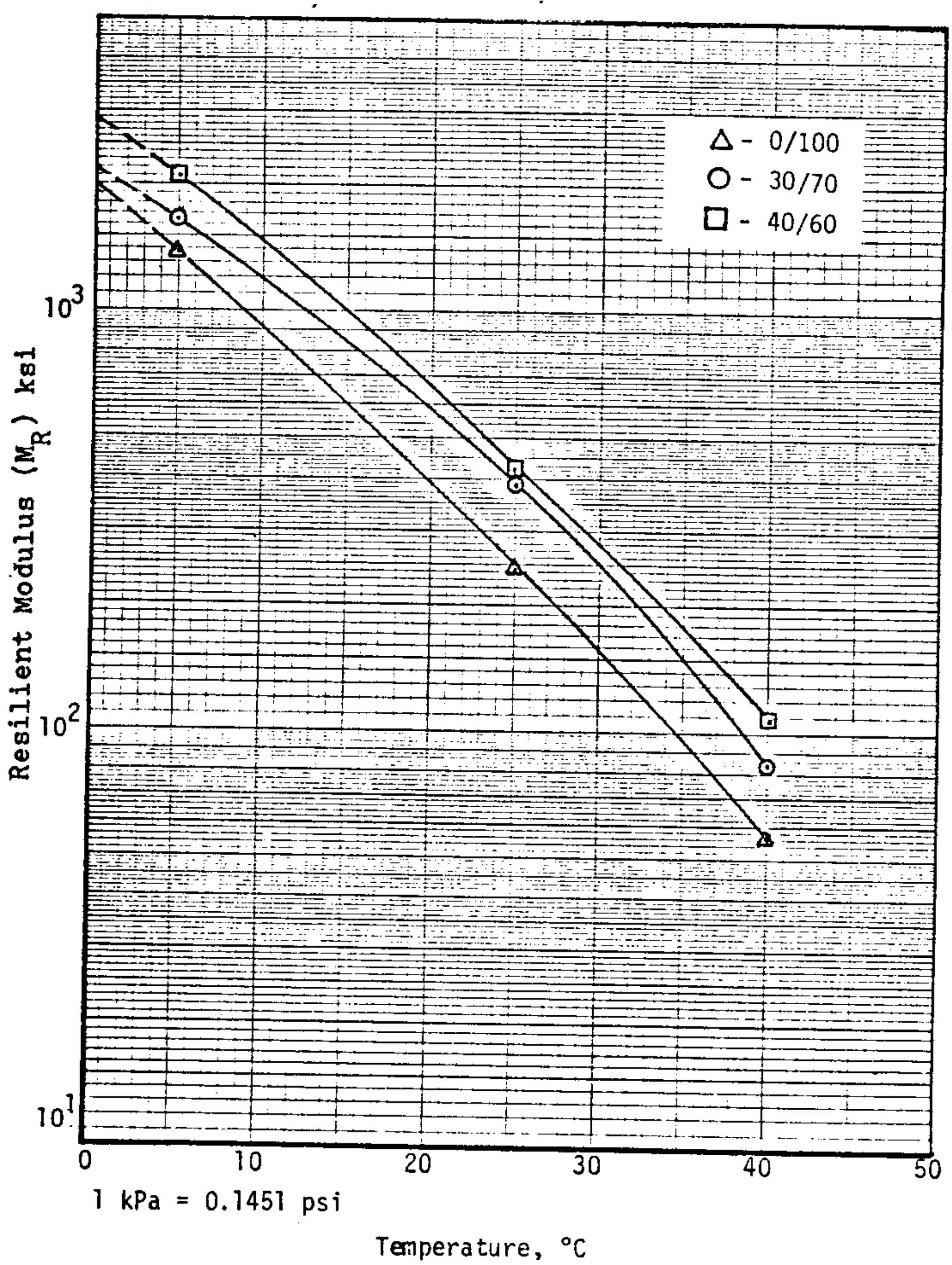
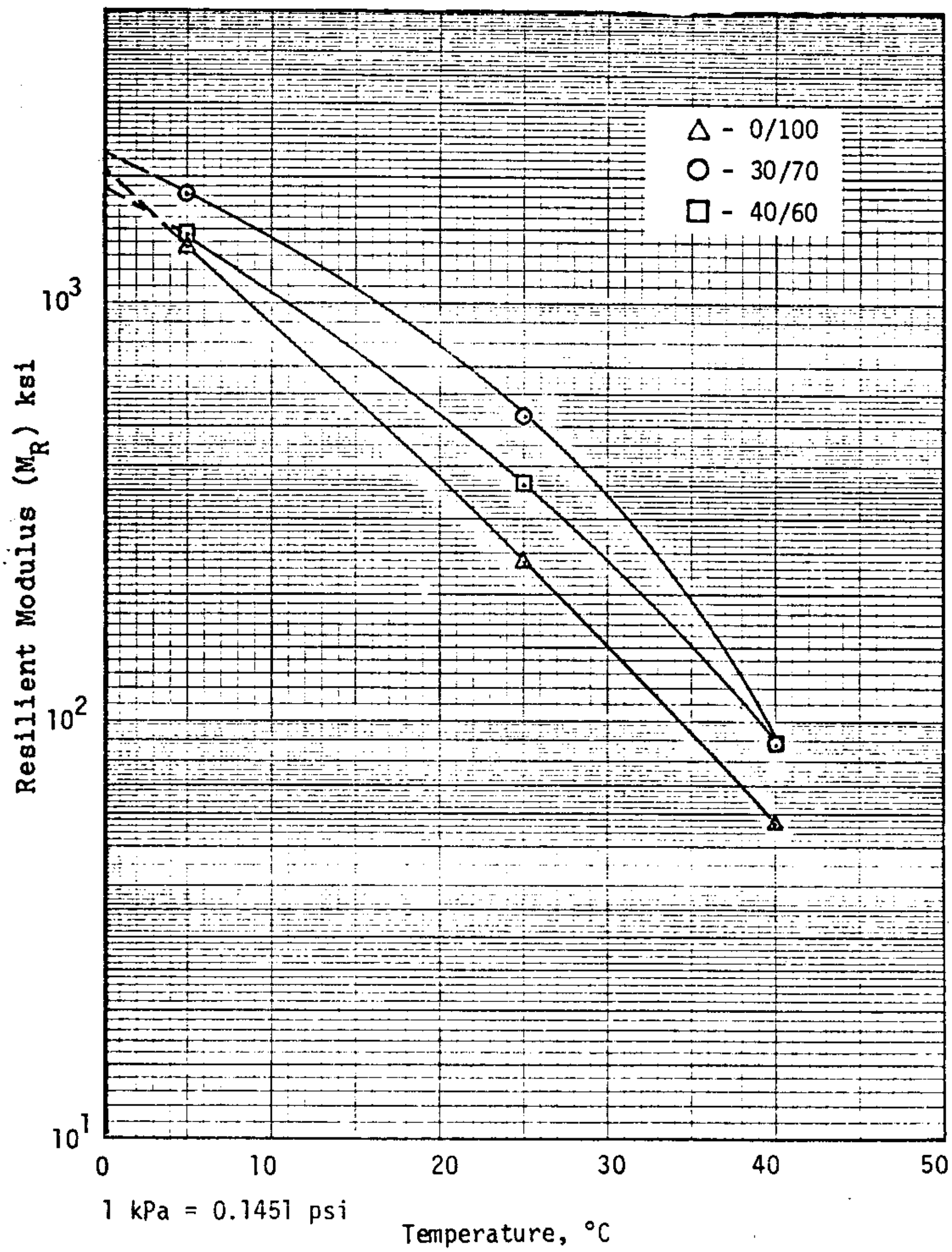



Figure 47. Resilient Modulus vs. Temperature, Top Base Course Layer ($L_2$), Thick Sections.




1 kPa = 0.1451 psi

Figure 48. Resilient Modulus vs. Temperature, Bottom Base Course Layer ($L_1$), Thick Sections.

it may be no more susceptible to low temperature cracking and should be more resistant to rutting at high temperatures when compared to conventional Class B asphalt concrete. Although, the stiffness differences between the 0/100 and 30/70 mixes are relatively small and the potential differences in durability and surface wear are still being investigated.

The second set of pavement cores (obtained 16 months after construction) from SR 270 have been tested for resilient modulus. A comparison of core moduli from the same test sections on SR 270 for this set and the first set (obtained 4 months after construction) is shown in Table 24. For the three temperatures examined, the moduli have increased significiantly at 41°F (5°C) for all three mixes with the 40/60 SEA mix showing the largest increase. In general, all three mixes are gaining stiffness with time.

Marshall Stability and Flow

For the second set of pavement cores from SR 270, Marshall stability and flow, air voids and unit weights were obtained. These results are reported in Table 25. There does not exist significant differences in Marshall stability for the three mixes; although, the low air voids associated with the 30/70 and 40/60 SEA mixes (westbound lane) can be associated with the higher stabilities. The higher air voids appear to have a casual relationship with the lower flow values; although, all flow values are above the minimum value normally recommended for mix design [18].

Density and Air Voids

Tables 26 through 28 are used to summarize the density and air void levels for the initial and second set of pavement cores. Table 26 provides a comparison of the core densities for each of the three mixes and two travel directions at the SR 270 test site. The pavement core densities are shown along with the mean densities obtained with the nuclear gage during construction. In general, good agreement is observed for the two measurement systems even though the difference in sample size is large. No significant increase in density following construction is apparent. The pavement core data reveals that the original construction target density was met or exceeded in all but one case.

Table 27 provides a comparison of core densities for the three mixtures placed at the WSU Test Track (cores sampled December, 1979). The densities from the cores are compared to those obtained following final rolling during construction. Overall, most of the core densities met or exceeded the target construction value. A notable exception is the bottom lift of Section 8 (0/100). The low density reported was at least in part due to low mix temperature during placing and rolling. A comparison of core densities to the nuclear gage data shows that either additional densification has taken place since construction (unlikely due to the core sampling location) or the nuclear gage readings were influenced by the lower density subgrade.

Air voids for the compacted paving mixtures are shown in Table 28. The air void contents tend to be slightly higher at the SR 270 test site when compared to the test track. All air voids are higher than the initial

Table 24. Summary of Resilient Moduli (SR 270)

| Type of Mix (SEA Ratio) | Travel Direction | Resilient Modulus ($x10^3$ psi) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 41°F (5°C) | | | 77°F (25°C) | | | 104°F (40°C) | | |
| | | 4 mo* | 16 mo* | %Δ | 4 mo* | 16 mo* | %Δ | 4 mo* | 16 mo* | %Δ |
| 0/100 | WB | 1170 | 1762 | +51 | 312 | 314 | +6 | 82 | 77 | +6 |
| | EB | 1214 | 1377 | +13 | 303 | 274 | -10 | 65 | 85 | +31 |
| 30/70 | WB | 1872 | 2328 | +24 | 468 | 438 | -6 | 110 | 97 | -12 |
| | EB | 1440 | 2027 | +41 | 360 | 552 | +53 | 112 | 109 | -3 |
| 40/60 | WB | 1618 | 2547 | +57 | 405 | 444 | +10 | 97 | 93 | -4 |
| | EB | 1409 | 2042 | +31 | 423 | 559 | +32 | 106 | 140 | +32 |

1 kPa = 0.1451 psi

*Time between construction and sampling

Table 25. Core Sample Properties (SR 270)

| Type of Mix (SEA Ratio) | Travel Direction | Unit Weight (pcf) | Air Voids (%) | Marshall | |
|---|---|---|---|---|---|
| | | | | Stability (lb) | Flow |
| 0/100 | WB | 149.1 | 8.1 | 1670 | 12.9 |
| | EB | 147.3 | 9.2 | 1700 | 11.7 |
| 30/70 | WB | 154.1 | 5.7 | 2060 | 16.0 |
| | EB | 147.9 | 10.6 | 1700 | 11.2 |
| 40/60 | WB | 157.2 | 4.9 | 2450 | 17.1 |
| | EB | 147.9 | 10.6 | 1790 | 8.4 |

1 $Mg/m^3$ = 62.4 $lb/ft^3$
1 N = 2.248 lbf

Table 26. Comparison of Mixture Density Measurements SR 270

| Type of Mix (SEA Ratio) | Travel Direction | Density (pcf) | | |
|---|---|---|---|---|
| | | Pavement Cores | | Nuclear Gage** (Mean) |
| | | 12/79* | 12/80* | |
| 0/100 | WB | 145.9 | 149.1 | 149.7 |
| | EB | 149.6 | 147.3 | 144.2 |
| 30/70 | WB | 150.3 | 154.1 | 147.9 |
| | EB | 148.4 | 147.9 | 148.9 |
| 40/60 | WB | 153.4 | 157.2 | 150.8 |
| | EB | 148.4 | 147.9 | 147.1 |

1 $Mg/m^3/m^3 = 62.4\ lb/ft^3$
* Date sampled
** Obtained during construction

Table 27. Comparison of Mixture Density Measurements-WSU Test Track

| Type of Mix (SEA Ratio) | Test Section | Density (pcf) Pavement Core* | Density (pcf) Nuclear Gage (Mean)** |
|---|---|---|---|
| 0/100 | 1 (Base) | 146.2 | 143.0 |
| | 7 (Base) | 145.8 | 144.6 |
| | 2 (Top lift) | 147.4 | 144.6 |
| | 2 (Bottom lift) | 149.8 | 147.1 |
| | 8 (Top lift) | 150.4 | 147.9 |
| | 8 (Bottom lift) | 144.2 | 139.0 |
| 30/70 | Wearing Course (all sections) | 148.6 | - |
| | 5 | 149.8 | 146.2 |
| | 11 | 148.0 | - |
| | 6 (Top lift) | 147.6 | 148.5 |
| | 6 (Bottom lift) | 156.1 | 145.3 |
| | 12 (Top lift) | 153.4 | 148.7 |
| | 12 (Bottom lift) | 153.2 | 145.4 |
| 40/60 | 3 | 152.6 | 147.0 |
| | 9 | 151.6 | 146.5 |
| | 4 (Top lift) | 149.2 | 147.4 |
| | 4 (Bottom lift) | 151.1 | 143.6 |
| | 10 (Top lift) | 152.9 | 148.5 |
| | 10 (Bottom lift) | 150.4 | 143.0 |

1 $Mg/m^3$ = 62.4 $lb/ft^3$
* Sampled December, 1979
** Obtained during construction

Table 28. Mixture Air Void Contents*

| Test Pavement Location | Type Mix (SEA Ratio) | Layer Type | Percent Air Voids | |
|---|---|---|---|---|
| | | | 12/79** | 12/80** |
| SR 270 | 0/100 | Overlay | 8.3 | 8.7*** |
| | 30/70 | Overlay | 8.9 | 8.1*** |
| | 40/60 | Overlay | 10.0 | 7.7*** |
| Test Track (Thick Sections) | 0/100 | Top Lift | 9.7 | - |
| | | Bottom Lift | 8.2 | - |
| | 30/70 | Top Lift | 6.4 | - |
| | | Bottom Lift | 6.9 | - |
| | 40/60 | Top Lift | 8.0 | - |
| | | Bottom Lift | 8.6 | - |

* Based on single core specimens except where noted
** Date sampled
*** Average based on cores from EB and WB lanes

laboratory mixture design (approximately 2 to 4 percent higher than Marshall) but then the field densities are slightly lower than the laboratory mix designs.

## TRAFFIC COUNTS

A permanent mechanical traffic count station was installed at milepost 1.32 on SR 270 following completion of the paving. A brief summary of some of the resulting data is shown in Table 29. Based on this information the average daily traffic (both directions) for this highway is about 3,000. Since construction of the test pavements, a total of approximately 2,000,000 vehicles have trafficked the test pavements (or 1,000,000 vehicles in each direction).

Table 29. Summary of SR 270 Traffic Count Data

| Month | ADT (Both Directions) | Accumulated for Month (Both Directions) |
|---|---|---|
| 1979 Oct. | 1820 | 54,560 |
| Nov. | 3690 | 110,820 |
| Dec. | 2880 | 89,220 |
| 1980 Jan. | 2540 | 78,650 |
| Feb. | 3260 | 94,520 |
| Mar. | 3280 | 101,710 |
| Apr. | 3430 | 103,010 |
| May | - | - |
| Jun. | - | - |
| Jul. | 3080 | 95,440 |
| Aug. | 3130 | 96,920 |
| Sep. | - | - |
| Oct. | - | - |
| Nov. | 3090 | 92,760 |
| Dec. | 2810 | 87,220 |
| 1981 Jan. | - | - |
| Feb. | - | - |
| Mar. | - | - |
| Apr. | 3540 | 106,270 |

# CHAPTER V

## SUMMARY AND CONCLUSIONS

### SUMMARY

Based on the information contained in this report the following summary is presented:

1. Sulfur extended asphalt (SEA) paving mixtures were prepared and placed at two test sites near Pullman, Washington. One test site is located on an existing highway (SR 270). At this site, the paving mixes were placed as a 1.8 in (4.6 cm) thick overlay. The second test site is the WSU Test Track where sections of varying thickness were placed for subsequent controlled wheel tracking. The test mixtures were 0/100 (conventional WSDOT Class B asphalt concrete), 30/70 and 40/60 SEA mixtures. The construction was started and completed during August, 1979.

2. The laboratory mix designs (UW, WSDOT and SUDIC) indicated that binder contents (by weight of total mix) of 5.5 to 5.7 percent (0/100), 6.5 percent (30/70), and 7.1 to 7.2 percent (40/60) were appropriate (result was dependent on mixture design criteria and compaction technique). Actual binder contents of 5.7 percent (0/100) and 6.6 percent (30/70 and 40/60) were used for construction.

3. The modification of the contractor's plant to accommodate molten sulfur was directed by representatives from SUDIC. This activity went smoothly except for an initial inadequate steam source for heating the sulfur tanker and supply lines. Once a larger steam plant was acquired, the construction was able to proceed.

4. All controlled wheel tracking at the WSU Test Track has been completed. A subsequent report will describe this phase of the study in detail.

5. Initial field performance data is summarized and presented in the report.

### CONCLUSIONS

The following conclusions are warranted:

1. The laboratory mix designs (Marshall and Hveem) indicated that equal volume binder contents over the range of sulfur-asphalt ratios used were appropriate.

2. SEA pavements were successfully constructed using conventional mixing, paving and compaction equipment.

3. The SUDIC in-line blending system produced SEA binders which resulted in uniform paving mixes.

4. The construction of the test pavements confirmed that the 30/70 and 40/60 SEA mixtures achieved compaction with fewer roller passes when compared to conventional mix (0/100). Although, the need for a pneumatic roller was greater for the 30/70 and 40/60 SEA mixes in order to achieve a tight, crack-free mat.

5. The initial data from the wheel tracking at the WSU Test Track does not indicate major differences in fatigue performance for the three mixes used in the study.

6. A continuing evaluation of the SR 270 highway sections is being performed. Information to date reveals that the 30/70 and 40/60 SEA mixes were initially more susceptible to studded tire wear than the 0/100 sections. The non-trafficked areas of the SR 270 sections indicate no differences in performance between the three mixes.

## REFERENCES


1. Rennie, W.J., "Sulphur Asphalts," New Uses for Sulphur Technology Series No. 2, Sulfur Development Institute of Canada, 1979.

2. Pronk, F.E., A.F. Soderberg, R.T. Frizzele, "Sulphur Modified Asphaltic Concrete," Proceedings, Canadian Tech. Asphalt Association, p. 135, 1975.

3. Waddill, P.M., D.W. Cagle, J.A. Price and D.M. Little, "Silicones Combat Foaming in Residium Storage Tanks," Oil and Gas Journal, p. 85-87, February 27, 1961.

4. ______________, "Effect of Silicones on Hot Mix Asphalt Pavements," Information Series 16, National Asphalt Paving Association, December, 1966.

5. Kennephol, G.J.A., A. Logan and D.C. Beam, "Conventional Paving Mixes with Sulfur-Asphalt Binders," Proceedings , Association of Asphalt Paving Technologists, p. 485-508, 1975.

6. Societe Nationale des Petroles d'Aquitaine, "Properties of Sulphur-Bitumin Binders," VII International Road Federation World Meeting, Munich, 1973.

7. McBee, W.C. and T.A. Sullivan, "Sulfur Utilization in Asphalt Paving Materials," New Uses of Sulfur-II, Advances in Chemistry Series, No. 165, American Chemistry Society, p. 135, 1978.

8. McBee, W.C. and T.A. Sullivan, "Direct Substitution of Sulfur for Asphalt in Paving Materials," Report of Investigations 8303, Bureau of Mines, U.S. Department of the Interior, 1978.

9. Izatt, J.O., "Sulfur-Extended Asphalt Paving Project, Boulder City, Nevada," Construction Report, The Sulphur Institute, Washington DC, December, 1977.

10. McBee, W.C., T.A. Sullivan and J.O. Izatt, "State-of-the-Art Guideline Manual for Design, Quality Control, and Construction of Sulfur-Extended-Asphalt Pavements," Report FHWA-IP-80-14, Federal Highway Administration, U.S. Department of Transportation, August, 1980.

11. Gallaway, B.M. and D. Saylak, "Sulphur/Asphalt Mixture Design and Construction Details Lufkin Field Trials," FHWA-TS-78-203 (Reprint of original Texas Transportation Institute Report), Federal Highway Administration, U.S. Department of Transportation, 1977.

12. Sharkey, P.D., "Mix Design and Resilient Modulus Evaluation of Sulphur-Extended Asphalt Pavements," Thesis, University of Washington, 1979.

13. Soderberg, A.F. and F.E. Pronk, "Washington Test Track S/A Mix Design," Report Submitted to the Sulphur Development Institute of Canada by Hardy Associates Ltd., August 1, 1979.

14. Gietz, R.H., "SEA Binder Evaluation," Letter received by J.P. Mahoney (UW), August 3, 1981.

15. ___________, State of Washington Standard Specification for Road and Bridge Construction, Washington State Department of Transportation, 1974.

16. Yoder, E.J. and M.W. Witzak, Principles of Pavement Design, Second Edition, John Wiley and Sons, Inc., New York, 1975.

17. Kingham, R.I. and B.F. Kallas, "Laboratory Fatigue and Its Relationship to Pavement Performance," Research Report 72-3, The Asphalt Institute, April, 1972.

18. Mix Design Methods for Asphalt Concrete, Manual Series No. 2, The Asphalt Institute, March, 1974.

19. Krukar, M. and J. Cook, "Experimental Ring No. 2: A Study of Untreated, emulsion-treated, and Asphaltic Cement Treated Bases - Volume 2," Report on Research Project Y-651, Washington State Department of Highways, July, 1968.

## APPENDIX A

## LABORATORY MIX DESIGN DATA

Table A-1. Marshall Mix Design Data (UW)*

| SEA Ratio | Binder Content (% by Weight of Total Mix) | Unit Weight (pcf) | Maximum Density (pcf) | VMA (%) | Air Voids (%) | Marshall Stability (lbs) |
|---|---|---|---|---|---|---|
| 0/100 | 4.5 | 152.3 | 160.7 | 15.3 | 5.2 | 3340 |
| | 5.0 | 155.1 | 161.9 | 14.3 | 4.4 | 4060 |
| | 5.5 | 153.7 | 159.4 | 15.4 | 3.6 | 3650 |
| | 6.0 | 154.6 | 157.8 | 15.4 | 2.1 | 3280 |
| | 6.5 | 156.2 | 157.1 | 14.9 | 0.6 | 3270 |
| 30/70 | 5.3 | 152.5 | 166.9 | 16.0 | 8.6 | 5060 |
| | 5.9 | 153.9 | 165.5 | 15.5 | 7.0 | 5410 |
| | 6.5 | 155.4 | 163.7 | 15.3 | 5.1 | 4060 |
| | 7.1 | 155.0 | 162.9 | 16.1 | - | 3760 |
| | 7.7 | 154.6 | 162.1 | 16.8 | - | 3450 |
| 50/50 | 6.1 | 155.6 | 166.2 | 14.8 | 6.4 | 11,240 |
| | 6.7 | 156.0 | 164.0 | 15.3 | 5.0 | 11,160 |
| | 7.4 | 155.2 | 162.4 | 16.2 | 4.4 | 9,660 |
| | 8.1 | 155.7 | 162.5 | 16.6 | - | 7,980 |
| | 8.7 | 150.9 | - | - | - | 6,350 |

1 $Mg/m^3$ = 62.4 $lb/ft^3$

1 N = 2.248 lbf

*Values shown are the average of three specimens.

Table A-2. Marshall Mix Design Data
40/60 SEA Ratio [After Ref. 13]

| Binder Content (% by Weight of Total Mix | Unit Weight (pcf) | VMA (%) | Air Voids (%) | Marshall Stability (lbs) | Marshall Flow |
|---|---|---|---|---|---|
| 6.25 | 153.3 | 16.3 | 5.4 | 3503 | 10.0 |
| 6.75 | 154.8 | 15.9 | 3.9 | 3684 | 10.0 |
| 7.25 | 156.0 | 15.8 | 2.5 | 3705 | 11.0 |
| 7.75 | 157.5 | 15.4 | 1.1 | 3573 | 12.5 |
| 8.25 | 157.0 | 16.2 | 0.8 | 3224 | 14.0 |

$1\ Mg/m^3 = 62.4\ lb/ft^3$

1 N = 2.248 lbf

Table A-3. Hveem Mix Design Data (UW)*

| SEA Ratio | Binder Content (% by Weight of Total Mix) | Unit Weight (pcf) | Maximum Density (pcf) | Air Voids (%) | Stabilometer Value |
|---|---|---|---|---|---|
| 0/100 | 4.0 | 153.9 | 166.3 | 7.4 | 42 |
| | 4.5 | 156.4 | 163.4 | 4.3 | 47 |
| | 5.0 | 158.6 | 163.3 | 2.9 | 46 |
| | 5.5 | 160.4 | 163.3 | 1.7 | 48 |
| | 6.0 | 162.9 | 163.1 | 0.1 | 38 |
| 30/70 | 4.7 | 153.5 | 164.7 | 6.8 | 47 |
| | 5.3 | 157.1 | 164.1 | 4.3 | 50 |
| | 5.9 | 159.1 | 163.5 | 2.7 | 53 |
| | 6.5 | 160.1 | 162.9 | 1.7 | 52 |
| | 7.1 | 161.9 | 162.2 | 0.4 | 51 |
| 50/50 | 5.4 | 153.3 | 165.4 | 7.6 | 59 |
| | 6.1 | 155.4 | 164.1 | 5.3 | 64 |
| | 6.7 | 155.1 | 162.9 | 5.0 | 61 |
| | 7.4 | 158.9 | 161.6 | 1.7 | 67 |
| | 8.1 | 160.2 | 160.4 | 0.2 | 61 |

1 Mg - 62.4 $lb/ft^3$

*Values shown are the average of three specimens.

Table A-4. Hveem Mix Design Data (WSDOT Materials Laboratory)

| SEA Ratio | Binder Content (% by Weight of Total Mix) | Unit Weight (pcf) | Maximum Density (pcf) | Air Voids (%) | Stabilometer Value |
|---|---|---|---|---|---|
| 0/100 | 4.8 | 155.8 | 164.4 | 6.4 | 34 |
| | 5.2 | 158.6 | | 4.0 | 26 |
| | 5.7 | 160.2 | | 2.3 | 20 |
| | 6.1 | 159.8 | | 1.7 | 14 |
| 10/90 | 4.8 | 156.3 | 165.9 | 7.1 | 28 |
| | 5.2 | 158.3 | | 5.0 | 28 |
| | 5.7 | 158.9 | | 4.0 | 26 |
| | 6.1 | 161.0 | | 2.0 | 19 |
| | 6.5 | 160.7 | | 1.4 | 15 |
| | 7.0 | 161.1 | | 0.5 | 8 |
| | 7.4 | 160.4 | | 0.1 | 3 |
| 30/70 | 4.8 | 156.8 | 164.4 | 7.3 | 28 |
| | 5.2 | 157.3 | | 6.3 | 31 |
| | 5.7 | 159.9 | | 4.9 | 29 |
| | 6.1 | 160.9 | | 2.6 | 26 |
| | 6.5 | 160.4 | | 2.2 | 21 |
| | 7.0 | 157.6 | | 3.2 | 42 |

1 Mg = 62.4 16/ft$^3$

## APPENDIX B
## CALIBRATION OF BISON STRAIN GAGES

The Bison strain gages (manufactured by Bison Instruments, Inc.) were used extensively in the research described in this report. To enable a better understanding of how these instruments were used, a review of the calibration process is appropriate.

The calibration process involves three distinct steps. These are:

1. Development of coil spacing versus amplitude plots for Ranges 1, 2 and 4 in (2.5, 5.1 and 10.2 cm) diameter strain gages.

2. Development of coil spacing versus inches per volt relationships for the 1, 2 and 4 in (2.5, 5.1 and 10.2 cm) diameter strain gages.

3. Development of strain multiplication factors (k') versus calibration signal.

Item 1 described above resulted in the initial relationships which enable measurement of the distance between any two strain coils. Thus, deflections between two strain coils can be measured over time or between a load or no load condition. These relationships can be directly used for static loading conditions. Dynamic measurements require additional relationships which will subsequently be described.

The results of these initial calibration efforts are shown as Figures B-1 through B-5 and indicate the relationship between coil spacing and amplitude. The amplitude is used to achieve a signal balance or null condition, i.e., the difference between two amplitude readings correlates with change in coil spacing. Also shown in these figures are three coil separation ranges. These ranges correspond to a rough measure of coil separation distance (in terms of coil diameter) as follows:

Range 1: 1 to 2 diameters
Range 2: 1.5 to 3 diameters
Range 3: 2.5 to 4.5 diameters

The same generalized curvilinear relationships for coil separation versus amplitude hold for 1 in (2.5 cm) diameter (Figure B-1), 2 in (5.1 cm) diameter (Figures B-2 and B-3) and 4 in (10.2 cm) diameter (Figures B-4 and B-5) strain coils. For the 2 in (5.1 cm) and 4 in (10.2 cm) diameter coils, calibrations for both parallel and coplanar configurations were necessary. Only one calibration was necessary for the 1 in (2.5 cm) diameter coil because these were used only in a parallel configuration; although, regression models were developed for the 1 in (2.5 cm) coil in the coplanar configuration.

The procedure used to obtain the relationships shown in Figures B-1 through B-5 was to place two coils in a wooden jig designed and constructed for this purpose. The two coils were then connected to the Bison instrument.

One coil was slowly moved via use of a micrometer and corresponding amplitude readings were obtained. In this way a full series of coil spacing versus amplitude readings were obtained. The initial coil spacing was measured with a scale at three separate locations around the circumference of the coils. This distance was taken as a center-to-center coil measurement. The sensitivity of the Bison instrument during this calibration process was at the maximum possible value.

Although the previously described calibration process was adequate for measurements made in a static loading mode, additional calibrations were required to allow measurement of dynamic deflections (hence strains). Dynamic deflection measurements required the use of voltages to determine changes in coil spacings. Thus, amplitude readings were not sufficient and coil spacing versus inches of deflection per volt were made. This calibration process was similar to that previously described except that a volt meter was used to measure changes in coil spacings. These calibrations were made for all three coil sizes and both configurations (parallel and coplanar). This information is shown in Figures B-6 through B-11.

The calibrations shown in Figures B-6 through B-11 allow the use of a known coil spacing to determine a value of inches of deflection per volt. By measuring the voltage change between two coils during loading, the change in distance between coils can be computed. This relationship does not need to be modified if the Bison instrument is at full sensitivity. During the test track operation, lower sensitivities were necessary thus requiring additional calibrations.

The final series of calibrations were used to find relationships between change in deflection for constant voltage changes taken over a range of Bison instrument sensitivities. The sensitivity of the Bison instrument was quantified by use of the "Calibration Signal" which ranges from 1000 (maximum sensitivity) to 0 (no sensitivity). The ratio of the change in deflection at any calibration signal level and the change in deflection at a calibration signal level of 1000 was calculated and denoted as k'. This value is used as a multiplier to increase the deflection value determined from the calibrations shown in Figure B-1 through B-11. Thus, appropriate deflections can be determined for any Bison instrument sensitivity. The results of these calibrations are shown as Figures B-12 through B-14 for the three coil sizes. The k' values were determined for both the parallel and coplanar coil configurations but resulted in essentially the same relationship. Thus, the overall calibration procedure was simplified slightly.

All calibration relationships were quantified by use of regression techniques. This enabled more accurate determinations of deflections (strains) to be made from the raw data.

The regression equations (polynomials) are as follows (including coefficient of determination and root mean square error):

1. Coil spacing vs Amplitude

(a) One inch diameter Bison coils

(i) Parallel

Range 1: $CS = 0.79787 + 1.471(10^{-4})(A) + 1.306(10^{-6})(A^2)$
$-2.1778(10^{-9})(A^3) + 1.5251(10^{-12})(A^4)$

$R^2 = 1.000$, RMSE = 0.00354

Range 2: $CS = 1.5145 - 5.2(10^{-5})(A) + 2.623(10^{-6})(A^2)$
$-3.9865(10^{-9})(A^3) + 2.5646(10^{-12})(A^4)$

$R^2 = 1.000$, RMSE = 0.00602

Range 3: $CS = 2.17169 + 7.983(10^{-4})(A) - 4.40(10^{-7})(A^2)$
$+1.074(10^{-9})(A^3)$

$R_2 = 1.000$, RMSE = 0.00306

(ii) Coplanar

Range 1: Not available

Range 2: $CS = 1.54262914 - 6.267(10^{-4})(A)$
$+ 1.24(10^{-6})(A^2)$

$R^2 = 1.000$, RMSE = 0.0

Range 3: $CS = 1.82771935 + 2.645(10^{-4})(A)$
$+6.6(10^{-7})(A^2)$

$R^2 = 1.000$, RMSE = 0.00037

(b) Two inch diameter Bison coils

(i) Parallel

Range 1: $CS = 1.184 + 4.801(10^{-3})(A) - 7.083(10^{-6})(A^2)$
$+4.8172(10^{-9})(A^3)$

$R^2 = 1.000$, RMSE = 0.00857

Range 2: $CS = 3.4901 + 4.92(10^{-4})(A) + 3.588(10^{-6})(A^2)$
$-5.6325(10^{-9})(A^3) + 4.1549(10^{-12})(A^4)$

$R^2 = 1.000$, RMSE = 0.00747

Range 3: $CS = 5.0548 + 2.51(10^{-4})(A) + 6.34(10^{-6})(A^2)$

$-1.02(10^{-8})(A^3) + 6.8685(10^{-12})(A^4)$

$R^2 = 1.000$, RMSE = 0.0163

(ii) Coplanar

Range 1: $CS = 3.14153394 - 2.83295(10^{-3})(A)$

$+2.87(10^{-6})(A^2)$

$R^2 = 1.000$, RMSE = 0.0

Range 2: $CS = 2.97441623 + 1.74196(10^{-3})(A)$

$+2.37(10^{-6})(A^2)$

$R^2 = 1.000$, RMSE = 0.00284

Range 3: $CS = 4.19000098 + 1.39654(10^{-3})(A)$

$-7.8(10^{-7})(A^2)$

$R^2 = 1.000$, RMSE = 0.00760

(c) Four inch diameter Bison coils

(i) Parallel

Range 1: $CS = 3.5276 + 4.129(10^{-3})(A) - 6.16(10^{-6})(A^2)$

$+5.9608(10^{-9})(A^3)$

$R^2 = 0.999$, RMSE = 0.0345

Range 2: $CS = 7.1017 - 4.06(10^{-4})(A) + 1.297(10^{-5})(A^2)$

$-1.973(10^{-8})(A^3) + 1.2690(10^{-11})(A^4)$

$R^2 = 1.000$, RMSE = 0.0210

Range 3: $CS = 9.878 + 8.54(10^{-3})(A) - 1.421(10^{-5})(A^2)$

$+1.4302(10^{-8})(A^3)$

$R^2 = 0.999$, RMSE = 0.114

(ii) Coplanar

Range 1: $CS = 5.130 - 2.375(10^{-3})(A)$

$+3.75(10^{-6})(A^2)$

Range 2: $CS = 6.63532513 - 1.74969(10^{-3})(A)$

$+1.150(10^{-5})(A^2) - 1.0(10^{-8})(A^3)$

$R^2 = 1.000$, RMSE = 0.00447

Range 3: $CS = 8.22638138 + 5.08093(10^{-3})(A)$

$-5.86(10^{-6})(A^2) + 1.0(10\text{-}^{8})(A^3)$

$R^2 = 1.000$, RMSE = 0.0

2. Inches per Volt vs Coil Spacing

(a) One inch diameter Bison coils

(i) Parallel

$$IV = -3.3927(10^{-4}) + 3.2517(10^{-4})(CS) - 3.6854(10^{-4})(CS^2) +5.4961(10^{-4})(CS^3)$$

$R^2 = 0.997$, RMSE = 0.00024

(ii) Coplanar

$$IV = -1.70526657 + 3.67436707(CS) -2.93789420(CS^2) +1.03293895(CS^3) -1.3442790(10^{-1})(CS^4)$$

$R^2 = 0.990$, RMSE = 0.00050

(b) Two inch diameter Bison coils

(i) Parallel

$$IV = -6.2544(10^{-4}) + 1.63682(10^{-3})(CS) -7.7564(10^{-4})(CS^2) +1.5644(10^{-4})(CS^3)$$

$R^2 = 0.998$, RMSE = 0.00034

(ii) Coplanar

$$IV = -1.395128(10^{-2}) + 1.314043(10^{-2})(CS) -4.13193(10^{-3})(CS^2) +5.1743(10^{-4})(CS^3)$$

$R^2 = 0.998$, RMSE 0.00040

Range 2: $CS = 6.63532513 - 1.74969(10^{-3})(A)$

$+1.150(10^{-5})(A^2) - 1.0(10^{-8})(A^3)$

$R^2 = 1.000$, RMSE = 0.00447

Range 3: $CS = 8.22638138 + 5.08093(10^{-3})(A)$

$-5.86(10^{-6})(A^2) + 1.0(10\text{-}^{8})(A^3)$

$R^2 = 1.000$, RMSE = 0.0

2. Inches per Volt vs Coil Spacing

(a) One inch diameter Bison coils

(i) Parallel

$IV = -3.3927(10^{-4}) + 3.2517(10^{-4})(CS) - 3.6854(10^{-4})(CS^2)$

$+5.4961(10^{-4})(CS^3)$

$R^2 = 0.997$, RMSE = 0.00024

(ii) Coplanar

$IV = -1.70526657 + 3.67436707(CS) -2.93789420(CS^2)$

$+1.03293895(CS^3) -1.3442790(10^{-1})(CS^4)$

$R^2 = 0.990$, RMSE = 0.00050

(b) Two inch diameter Bison coils

(i) Parallel

$IV = -6.2544(10^{-4}) + 1.63682(10^{-3})(CS) -7.7564(10^{-4})(CS^2)$

$+1.5644(10^{-4})(CS^3)$

$R^2 = 0.998$, RMSE = 0.00034

(ii) Coplanar

$IV = -1.395128(10^{-2}) + 1.314043(10^{-2})(CS) -4.13193(10^{-3})(CS^2)$

$+5.1743(10^{-4})(CS^3)$

$R^2 = 0.998$, RMSE 0.00040

(c) Four inch diameter Bison coils

(i) Parallel

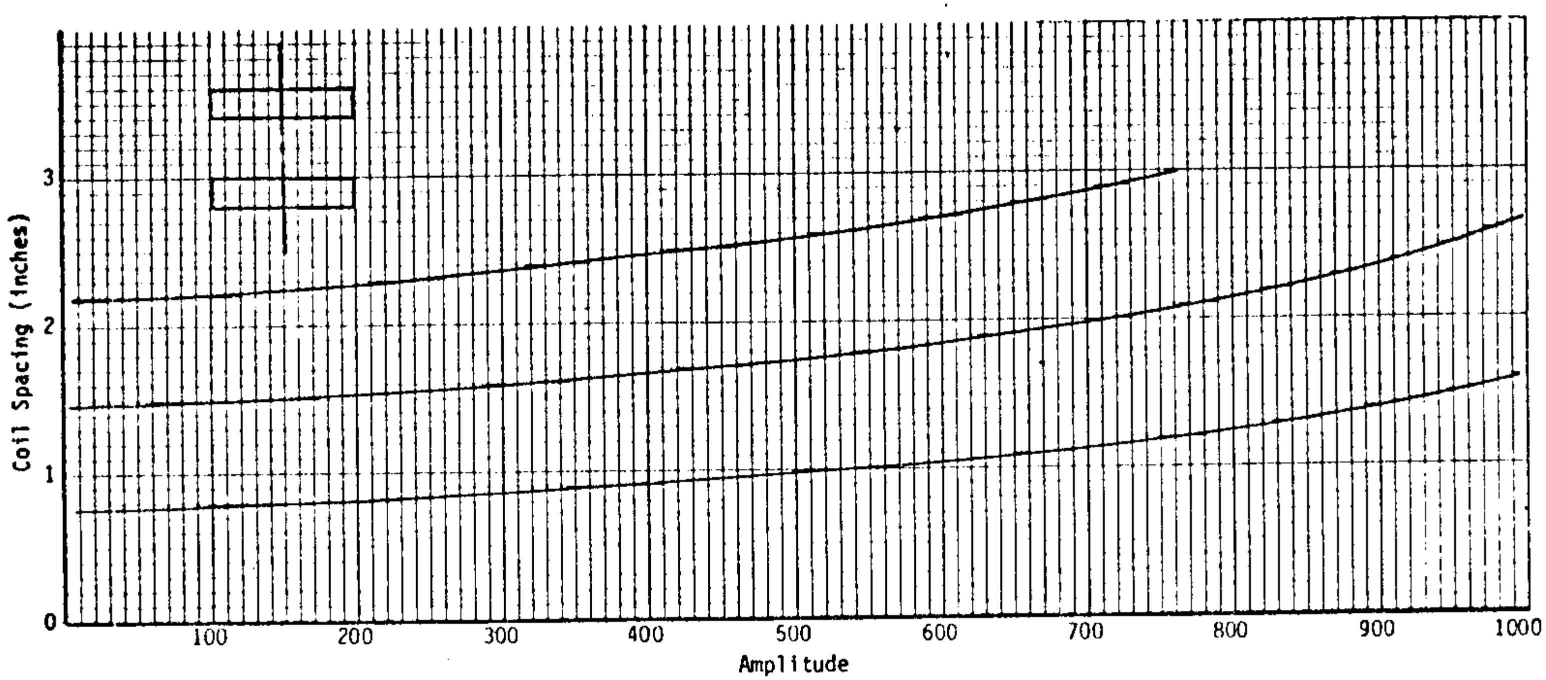
$$IV = -5.31776(10^{-3}) + 3.97848(10^{-3})(CS) - 8.5165(10^{-4})(CS^2) + 7.715(10^{-5})(CS^3) - 9.9(10^{-7})(CS^4)$$

$R^2$ = 1.000, RMSE = 0.00030

(ii) Coplanar

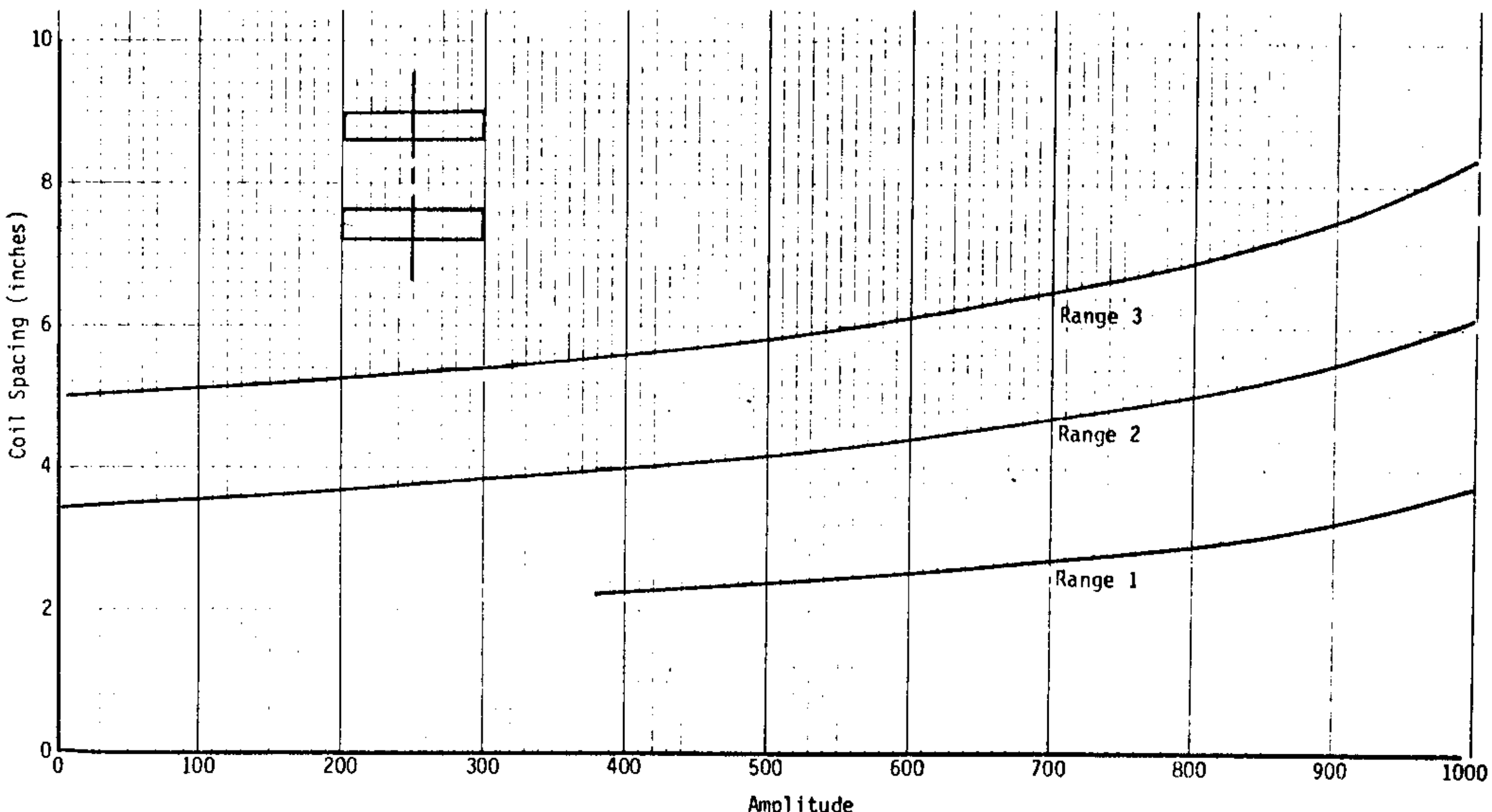
$$IV = -2.88144(10^{-2}) + 1.294754(10^{-2})(CS) - 2.04106(10^{-3})(CS^2) + 1.2767(10^{-4})(CS^3)$$

$R^2$ = 0.997, RMSE = 0.00011



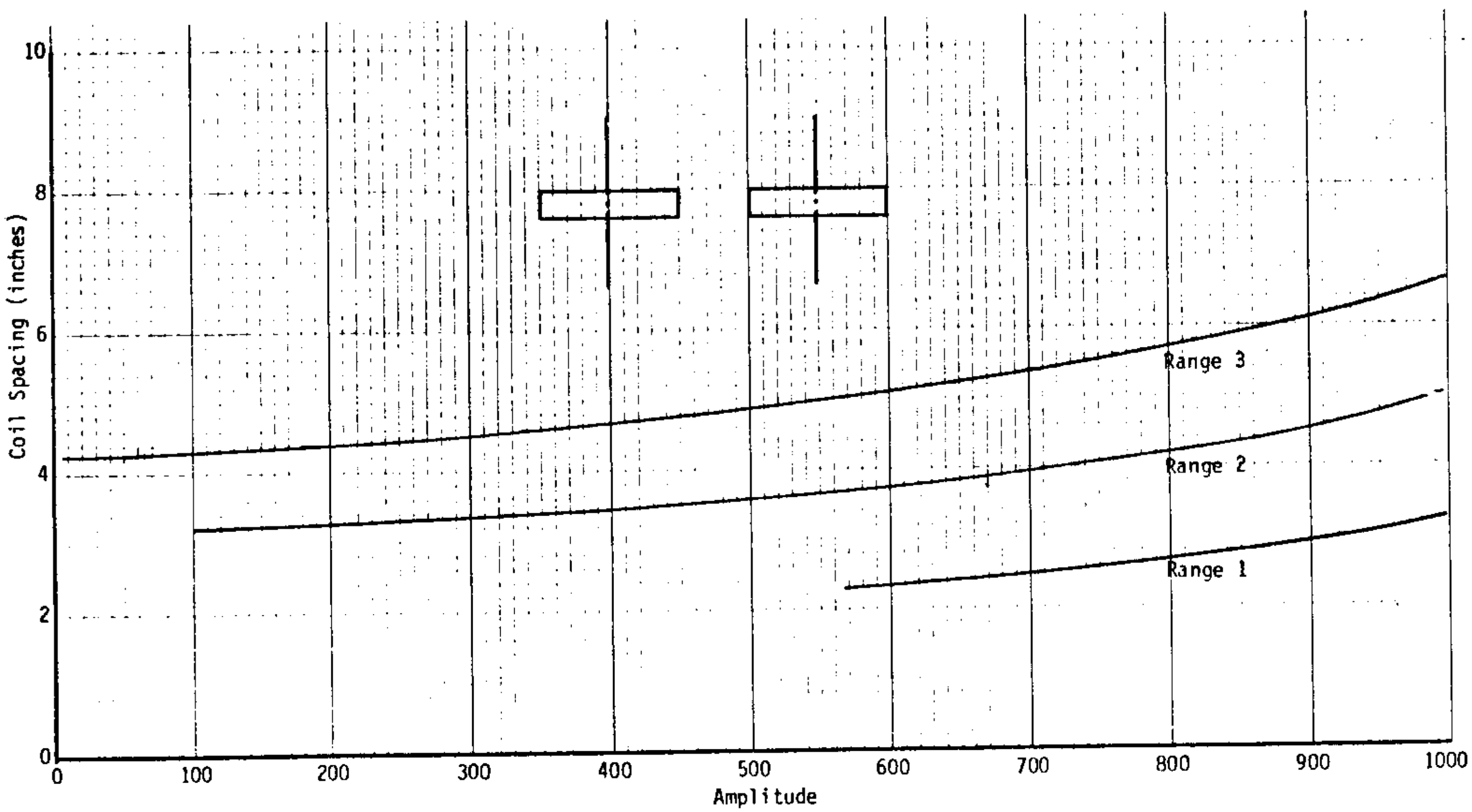

1 cm = 0.394 in

Figure B-1. Coil Spacing vs. Amplitude for One Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)



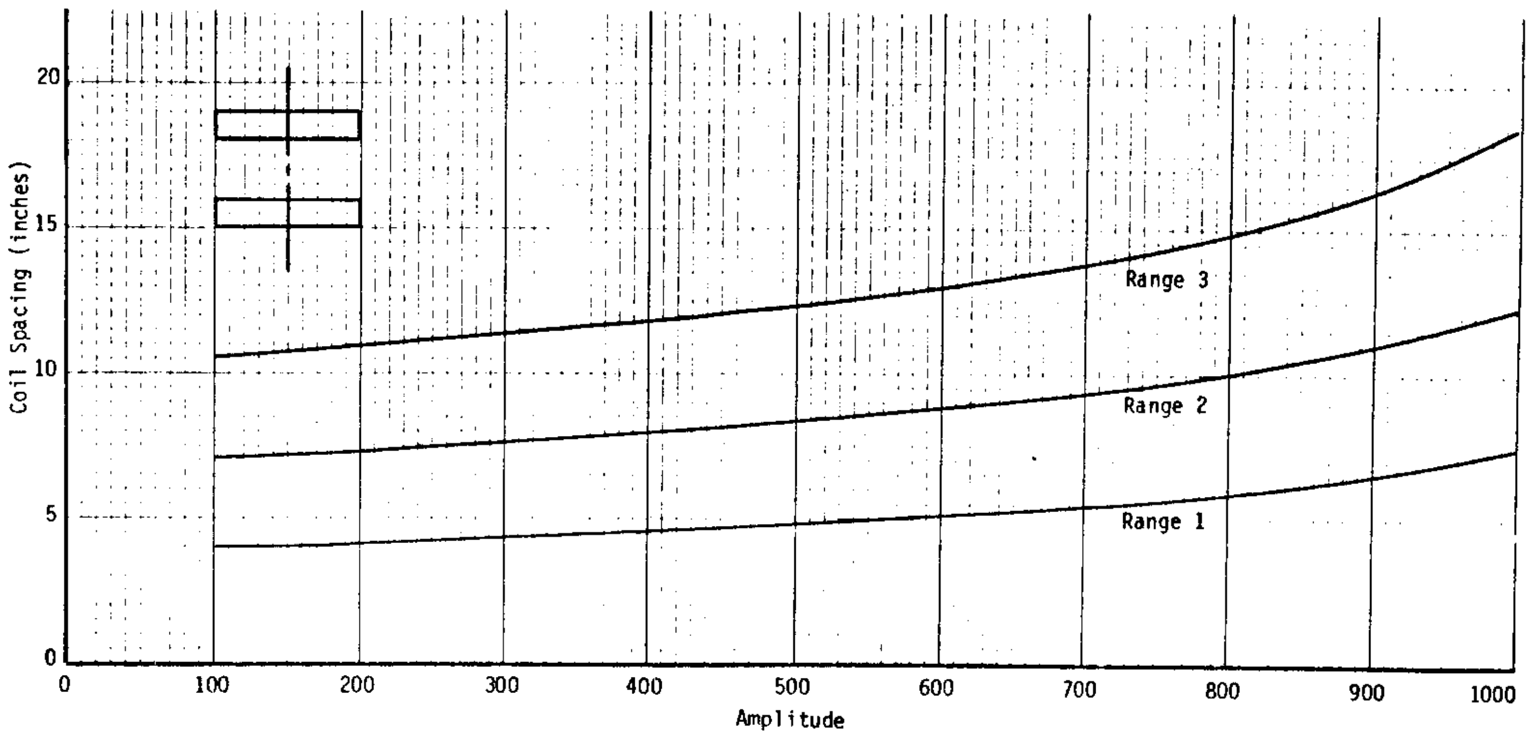

1 cm = 0.394 in

Figure B-2. Coil Spacing vs. Amplitude for Two Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)



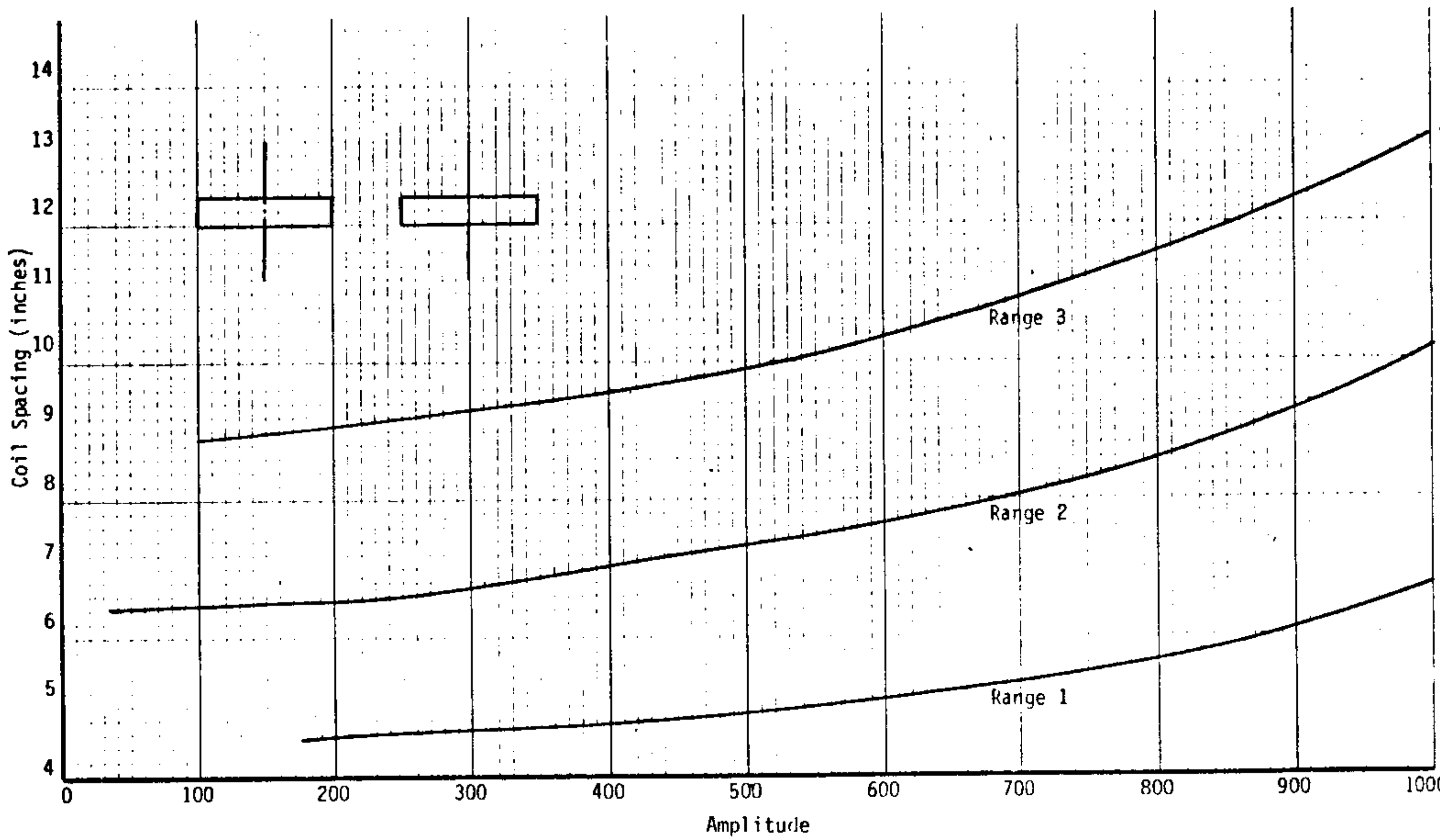

1 cm = 0.394 in

Figure B-3. Coil Spacing vs. Amplitude for Two Inch Diameter Bison Strain Coils (Coplanar Configuration and Maximum Sensitivity)



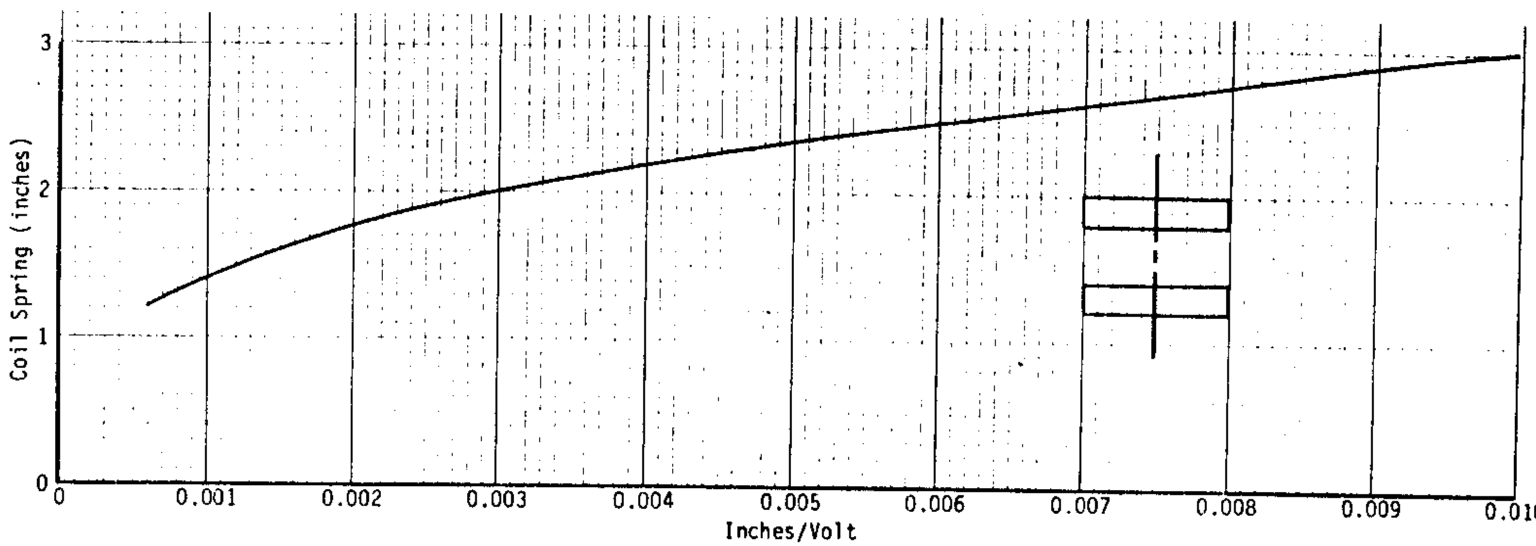

1 cm = 0.394 in

Figure B-4. Coil Spacing vs. Amplitude for Four Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)




1 cm = 0.394 in

Figure B-5. Coil Spacing vs. Amplitude for Four Inch Diameter Bison Strain Coils (Coplanar Configuration and Maximum Sensitivity)




1 cm = 0.394 in

Figure B-6. Coil Spacing vs. Inches Per Volt for One Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)

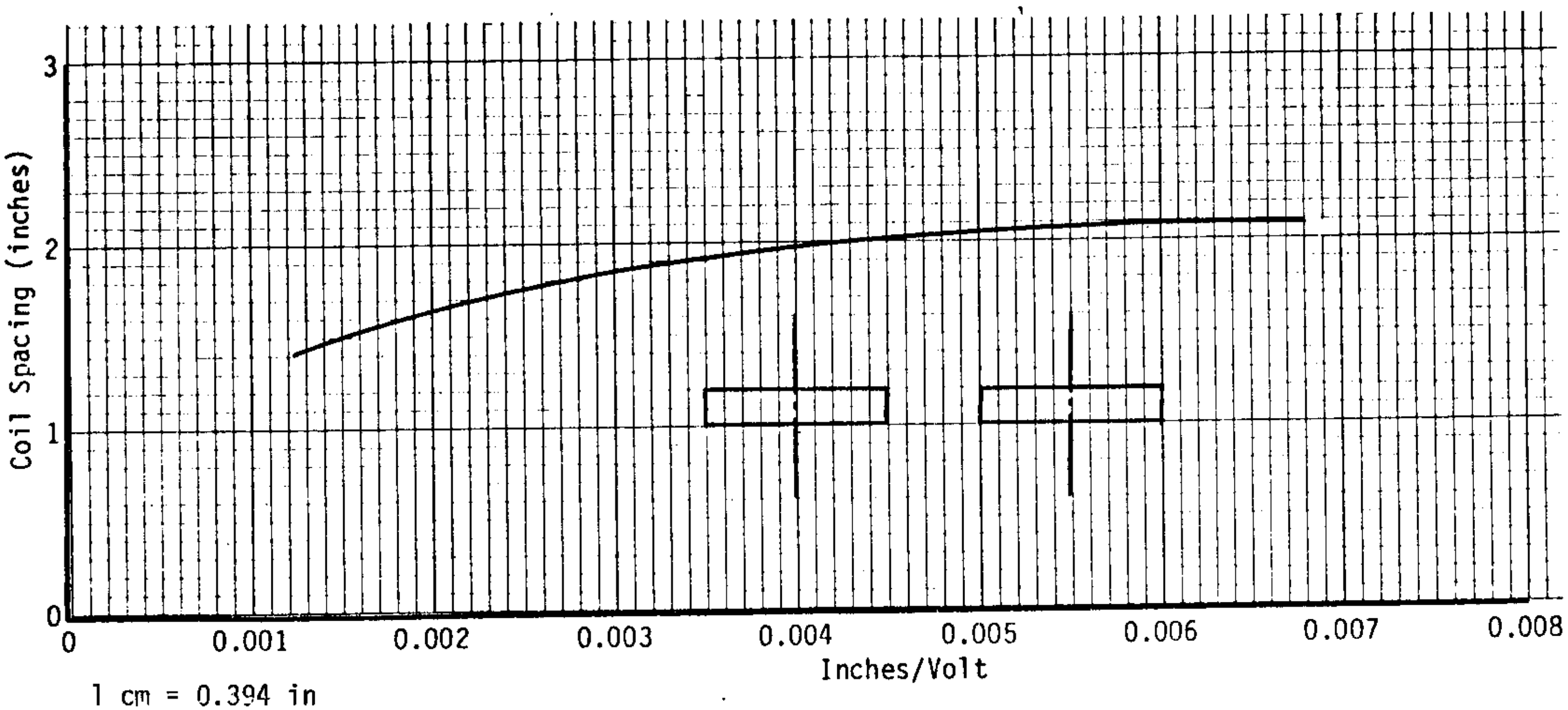
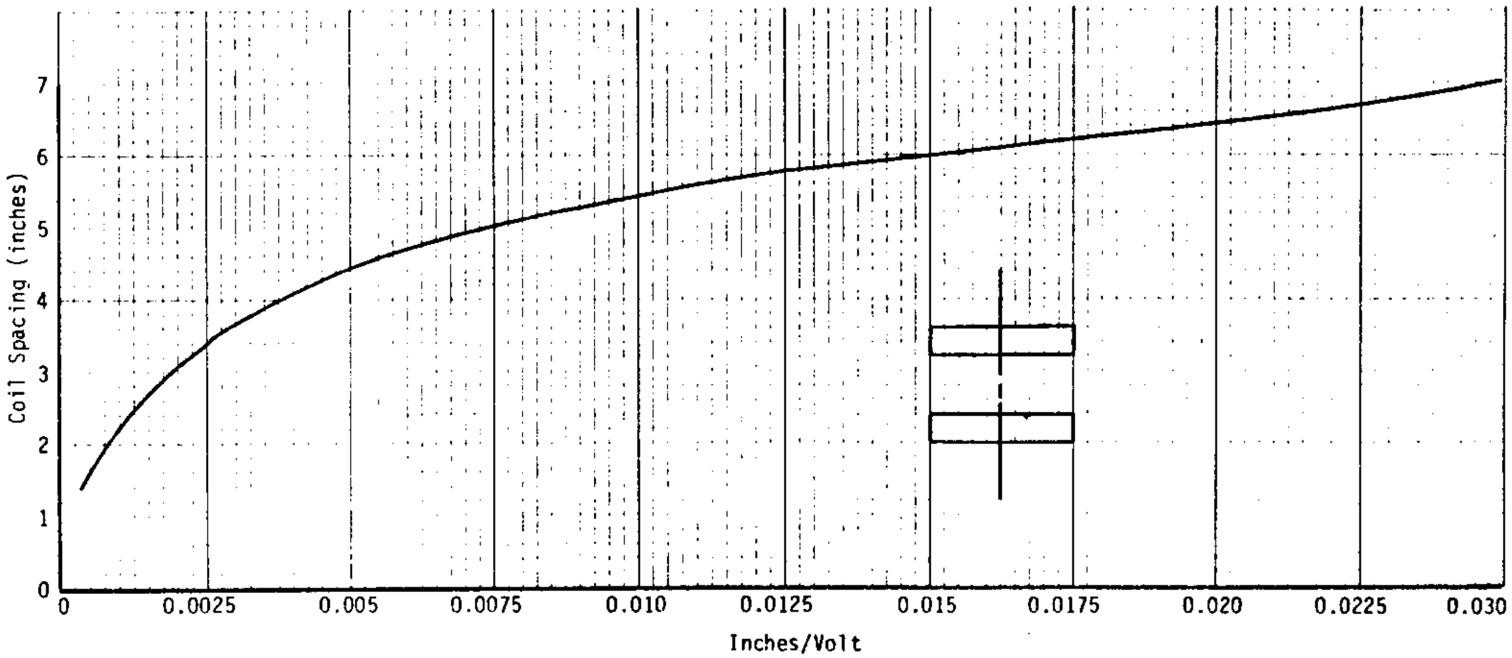
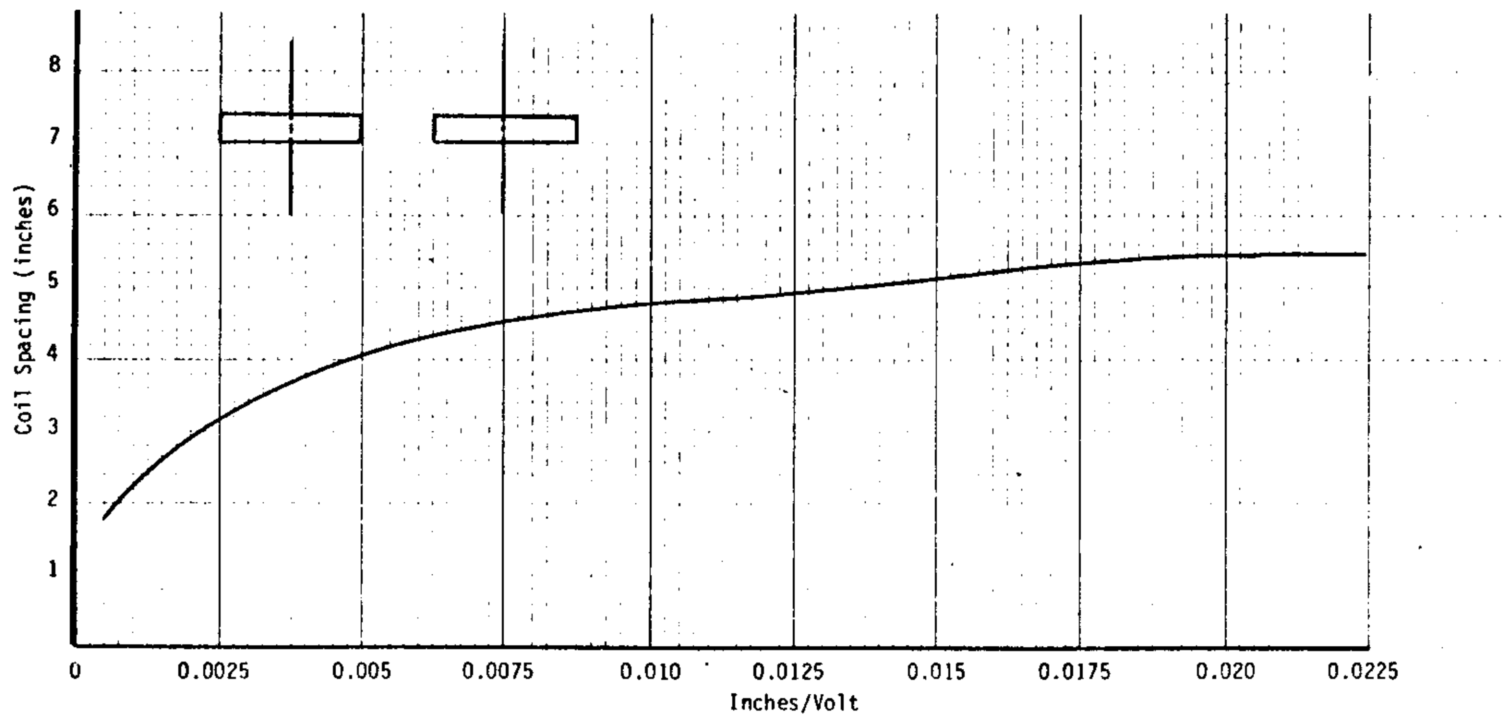



Figure B-7. Coil Spacing vs. Inches Per Volt for One Inch Diameter Bison Strain Coils (Coplanar Configuration and Maximum Sensitivity)



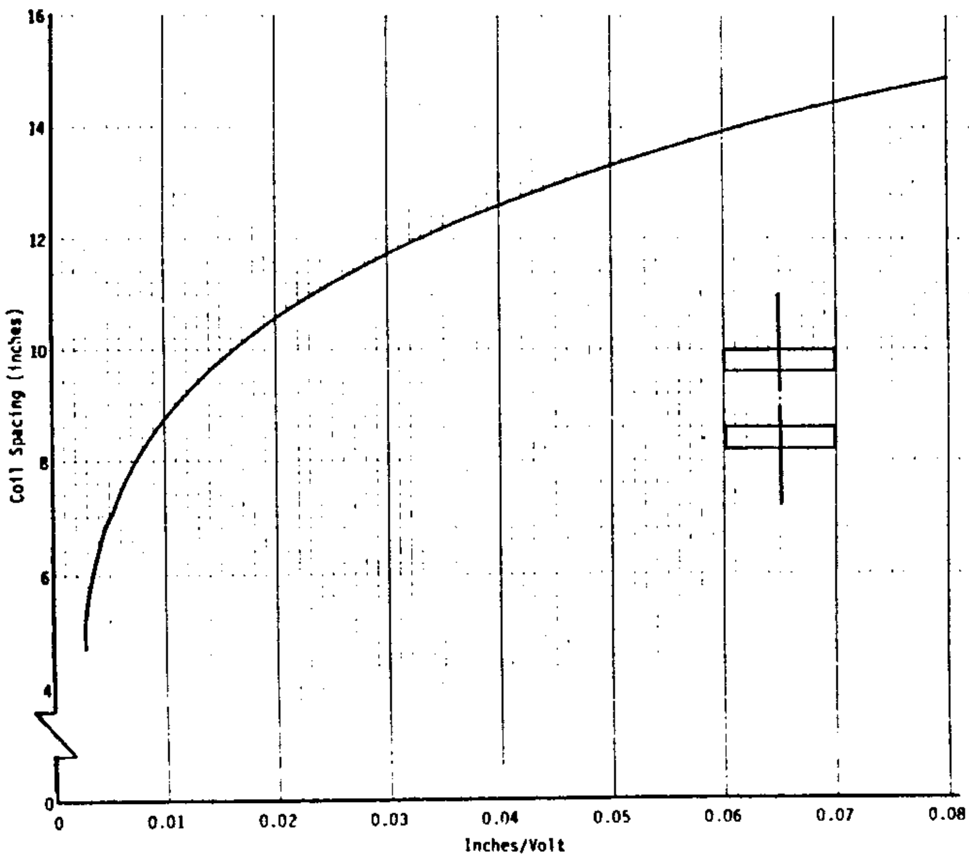

1 cm = 0.394 in

Figure B-8. Coil Spacing vs. Inches Per Volt for Two Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)



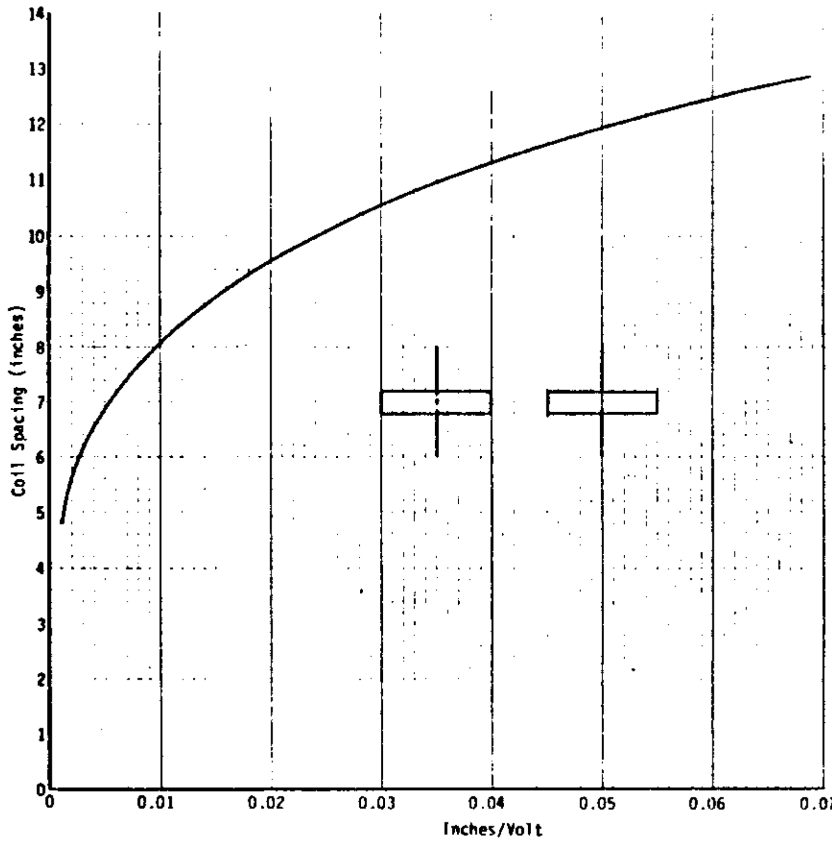

1 cm = 0.394 in

Figure B-9. Coil Spacing vs. Inches Per Volt for Two Inch Diameter Bison Strain Coils (Coplanar Configuration and Maximum Sensitivity)




1 cm = 0.394 in

Figure B-10. Coil Spacing vs. Inches Per Volt for Four Inch Diameter Bison Strain Coils (Parallel Configuration and Maximum Sensitivity)




1 cm = 0.394 in

Figure B-11. Coil Spacing vs. Inches Per Volt for Four Inch Diameter Bison Strain Coils (Coplanar Configuration and Maximum Sensitivity)

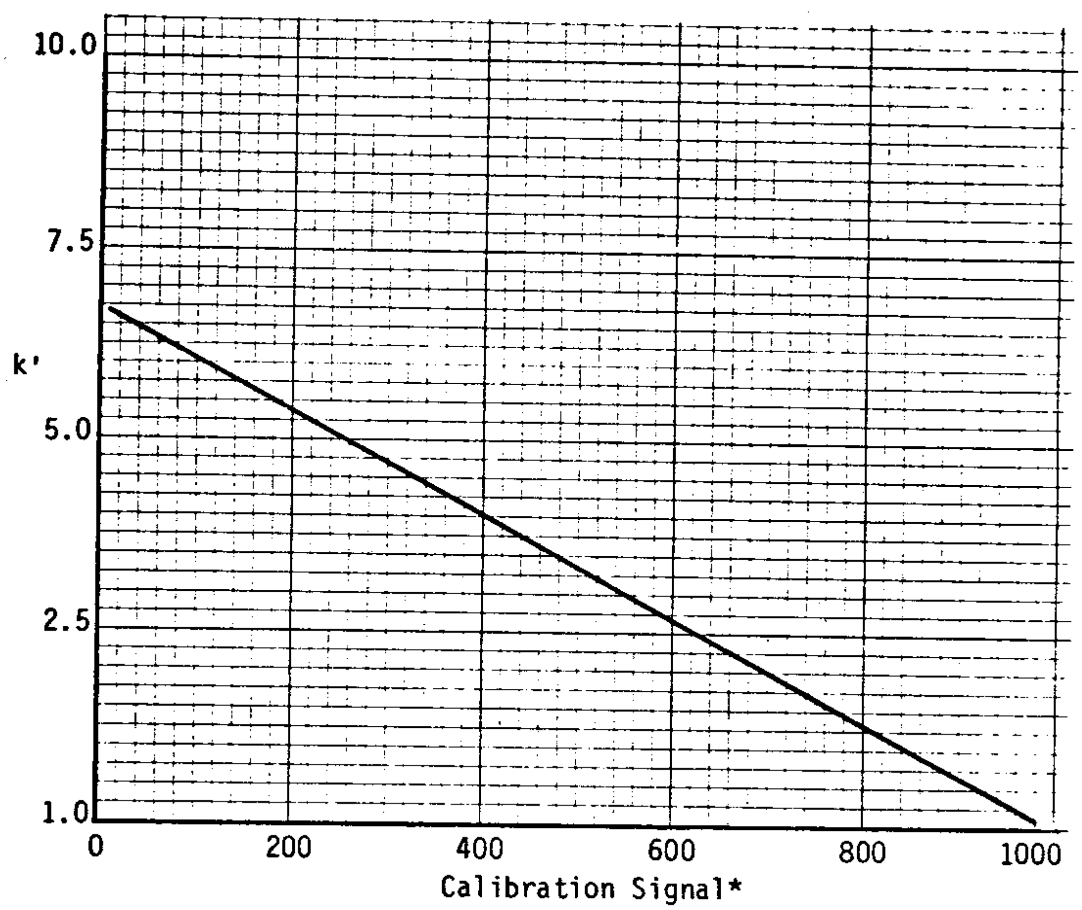



Figure B-12. k' vs. Calibration Signal for One Inch Diameter Bison Strain Coils (Parallel and Coplanar Configuration)

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*Note: Calibration signal = 1000 maximum sensitivity.

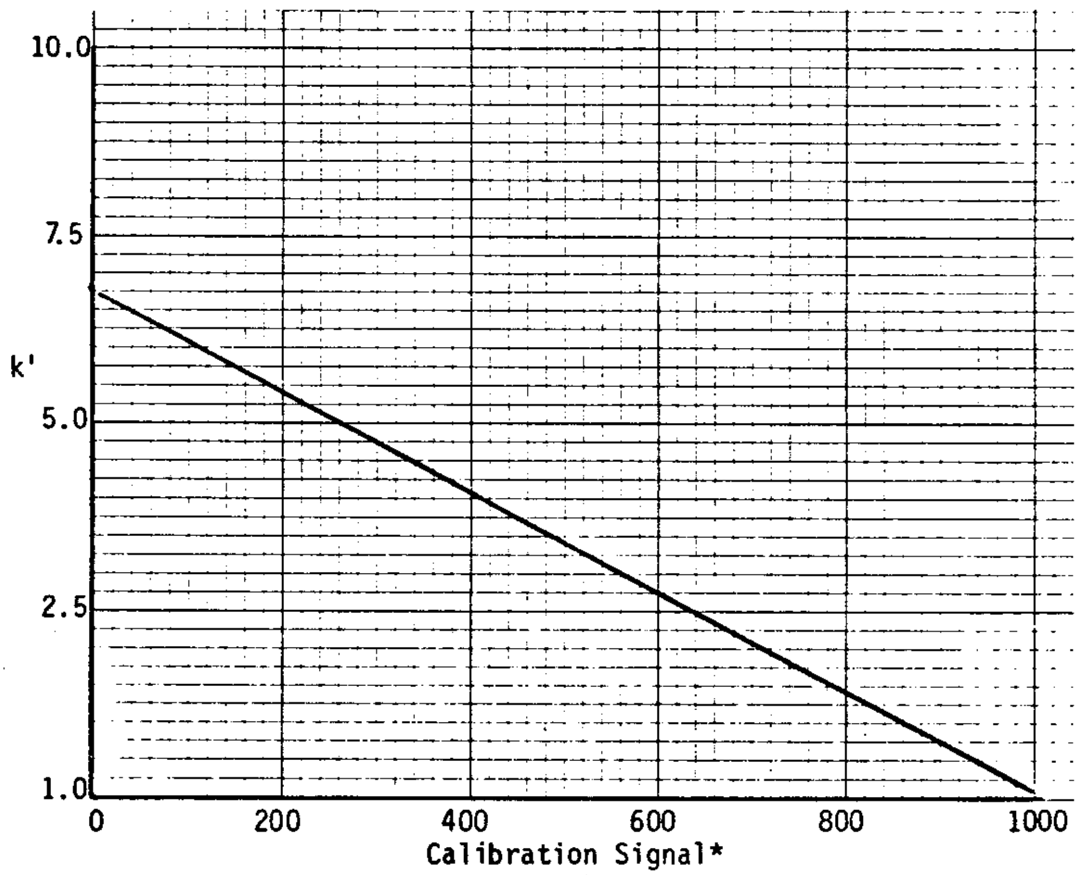


Figure B-13. k' vs. Calibration Signal for Two Inch Diameter Bison Strain Coils (Parallel and Coplanar Configuration)

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*Note: Calibration signal = 1000 maximum sensitivity.

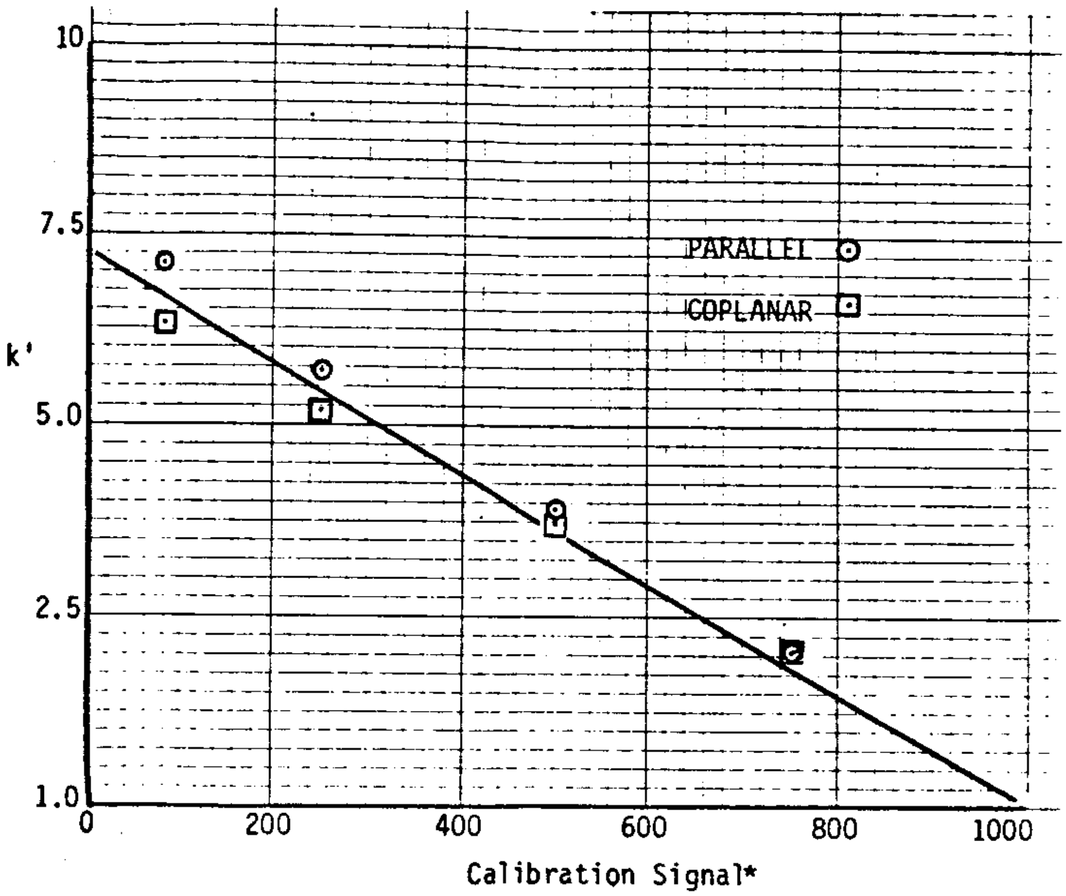


Figure B-14. k' vs. Calibration Signal for Four Inch Diameter Bison Strain Coils (Parallel and Coplanar Configuration)

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*Note: Calibration signal = 1000 maximum sensitivity.

APPENDIX C

DESCRIPTION OF DATA

ACQUISITION SYSTEM

## DATA ACQUISITION SYSTEM

The data acquisition system developed for the WSU Test Track was primarily composed of five major elements:

1. Computer system
2. Signal conditioning
3. Switching network
4. Control system
5. Computer software

Each of these elements will be discussed.

### COMPUTER SYSTEM

The computer was a small 16 bit digital microcomputer with 32K words of core, a dual 256K byte floppy disc drive, keyboard, CRT and a Teletype Model 43 printing terminal. The computer was designed for data acquisition and control operations and uses an extended form of the BASIC computer language to control all I/O operations in a simple and efficient format. The computer was used to control a switching network that switched a single set of five Bison instruments, along with the amplitude, phase and coil separation adjustments for each strain measurement, from one set of strain transducers to the next. This switching network could be operated in several ways but was used basically in two separate modes. The first was to move from one transducer set to the next at the operators request for observing the dynamic output of a single set of strain coils during multiple wheel passes of all three wheels and as a mode for taking periodic static readings and calibrations, with the wheels not in motion and either located on or off the desired transducer set depending on the measurements being made.

The second mode was to follow a single wheel around the test track (through all twelve sections)and to compile the peak value statistics for each of the individual strain and displacement measurements for multiple wheel passes. This could be done for "linear" wheel speeds of up to 20 mph (32 kph) and was the primary mode of data collection.

The computer was also used to collect, store and display the data. In the primary mode of operation this was done by compiling the statistics in core while the system was following the wheel rotations and periodically (every 209 rotations) listing those statistics out to the printer and also storing them on a disk. This corresponded to 30° rotation of the eccentricity which is approximately eight inches (20 cm) of radial movement of the dual wheels across the four foot (1.2 m) tire path. The computer was also used for the final data reduction and presentation.

Many other possibilities and applications also existed but limited time and impinging winter weather conditions limited the level of effort that could be expended on the initial development stage of the above instrumentation system.

SIGNAL CONDITIONING

During the initial phases of this project many assumptions had to be made with regard to the signal conditioning electronics. Some of these were: expected strain and displacement levels, frequency content of expected dynamic signals, and the type of noise and signal calibration problems to expect from passing the large steel arms and DC motors over and near the inductance coils. Also a large 440 volt AC motor-generator set was located within a few feet of the measuring instruments and concern about electrical interference and power surges and spikes influenced the design plans. Also, over one hundred coaxial leads from the different sets of coils had to be switched between one set of five Bison soil strain gage instruments.

The Bison inductance measuring system was relatively new at this time and had never been used, to our knowledge, under as severe and adverse conditions. This was the first attempt at switching coils between a common set of instruments. To add to this the University of Washington had limited access to the test track (350 miles away) and had no access to or experience with the Bison equipment during the initial planning and design phase. The projects initial conception, design, construction and installation had to be completed within approximately a six month time schedule. This left little or no room for any second thoughts or redesign once the process was started.

A key element was to design a signal conditioning package that was as versatile and fool-proof as possible. Figure C-1 outlines the system as conceived and used. Fortunately most of the signal conditioning problems were not as severe as anticipated, with the exception of the AC power line surge and related problems. These problems occurred due to the inability to completely isolate the power for the instrumentation system. This resulted in the data acquisition system having to be restarted everytime the track was shut down and resulted in several component failures in the system over the duration of the project.

A flow chart of the signal conditioning electronics for the Bison measurements, along with the input channel configuration to the computer is given in Figure C-2. Both filtered and unfiltered analog signals, along with the absolute value from the peak and hold outputs were available to the computer at all times. The band pass filters were designed to reduce the DC offset along with any undersirable higher frequency noise. The band pass limits were 1 and 20 Hertz. The signals were fed either directly into the computer or through the absolute value peak and hold circuitry via solid state software controlled switches. The absolute value was acquired by detecting the peak values of each signal along with its inverse. These two signals algebraically summed together to give the true signal or strain variation for that wheel loading. The sign associated with the signal was lost and had to be determined from the straight analog input or from known physical constraints.

The reason for doing this type of absolute excursion measurement, along with the band pass filtering, was to minimize the overall signal offset caused by both the steel mass of the support arms moving over the transducer sets and signal drift caused by permanent deformations and electronic drift. It turned out, however, that the arms were high enough above the pavement that in almost all instances no signal distortion could be detected by their presence. Also, no measureable effect could be detected from the DC motors mounted on each arm.

## SWITCHING NETWORK

The switching network consisted of two basic components. The first being a rack of mercury wetted relay switches which were used to switch a single set of five Bison instruments between the different transducer sets in each section of the test track. The mechanical type relay switches were required to switch the co-axial cables leading from each set of inductance coils because of the extreme effect on inductance type devices caused by varying amounts of low resistances which were associated with other types of switches, including solid state and non-wetted relay switches.

The second component was the switching of the individual controls of amplitude, phase and coil separation adjustments, for each of the strain measurements. This was done using solid state FET switches mounted on each Bison instrument and consisted of bypassing the original adjustments and supplying a separate adjustment pot for each of the three adjustments; for each of the five measurements with the individual sections or a total of 90 separate adjustments. Both of these switching functions were controlled by the computer and once initial adjustments were made, the system could run continuously with little or no maintenance until the measurements began to go off scale due to permanent deformation of the pavement.

## CONTROL SYSTEM

The primary function of this system was to let the computer know at all times exactly where the wheels were located, so the switching of the different functions could be coordinated with the wheel locations. This was done by attaching a series of rings to the end of the shaft that the wheel mechanism rotated around. Notches were cut in the rings which corresponded to key locations on the test track. These notches were sensed with photo cells which generated signals that communicated this information to the computer. Micro switches were also located at key locations on the outer eccentric ring.

## COMPUTER SOFTWARE

The key element to any computer controlled instrumentation package is the integration of the hardware and software systems, since the true test of the computer itself is the relative power of its software. The software developed for this project was successful because of the flexibility and power that has been built into the MACSYM II data acquisition system. It was possible to develop the complete software system without resorting to machine language programming. Also, it was possible to simulate the switching signal, thus allowing the complete development of the software prior to installing the system. This greatly enhanced the system development and installation.

All programming was done in BASIC and consisted of several separate programs, three of which are included in this appendix.

Three of the major programs are:

1. CLOCK - A clocking program used for manually selecting a desired section for calibration, initial readings and observation purposes.

2. SCALE - This program was used for computing all the calibration factors and initial (static) coil separation values, given the initial polynomials for the different calibration curves and the initial Bison readings for the coil separation values. This program was also used for the input of the coil separation switch settings for each measurement. The information generated by this program was stored in arrays on disk and was read in by the main control and clock programs.

3. MAIN - This program did the data acquisition and control functions along with storing and displaying the data.

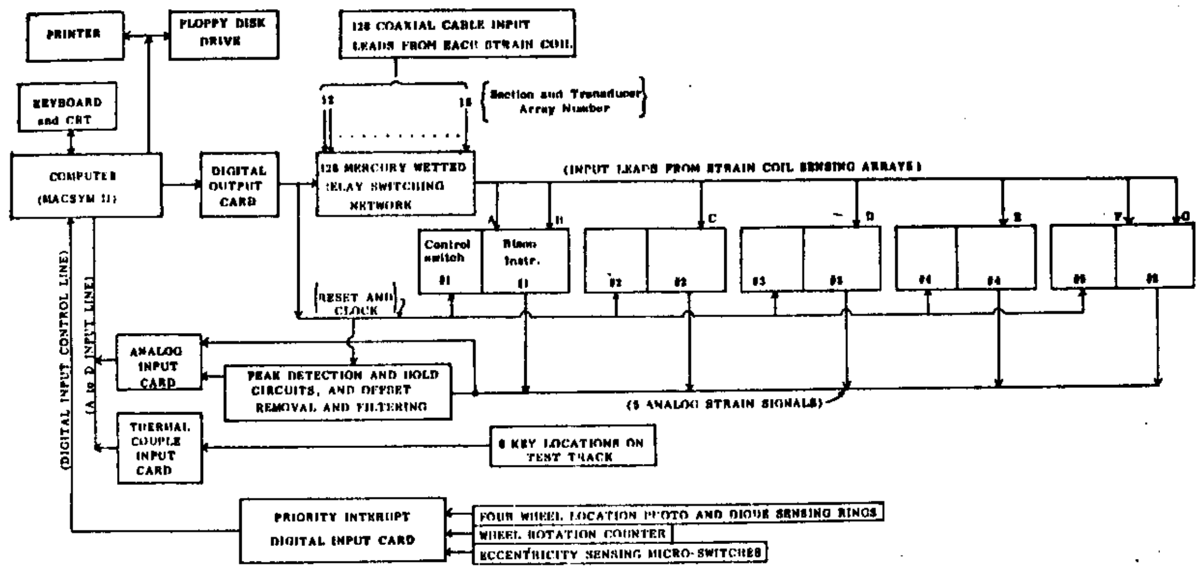


Figure C-1. Instrumentation Control and Recording System

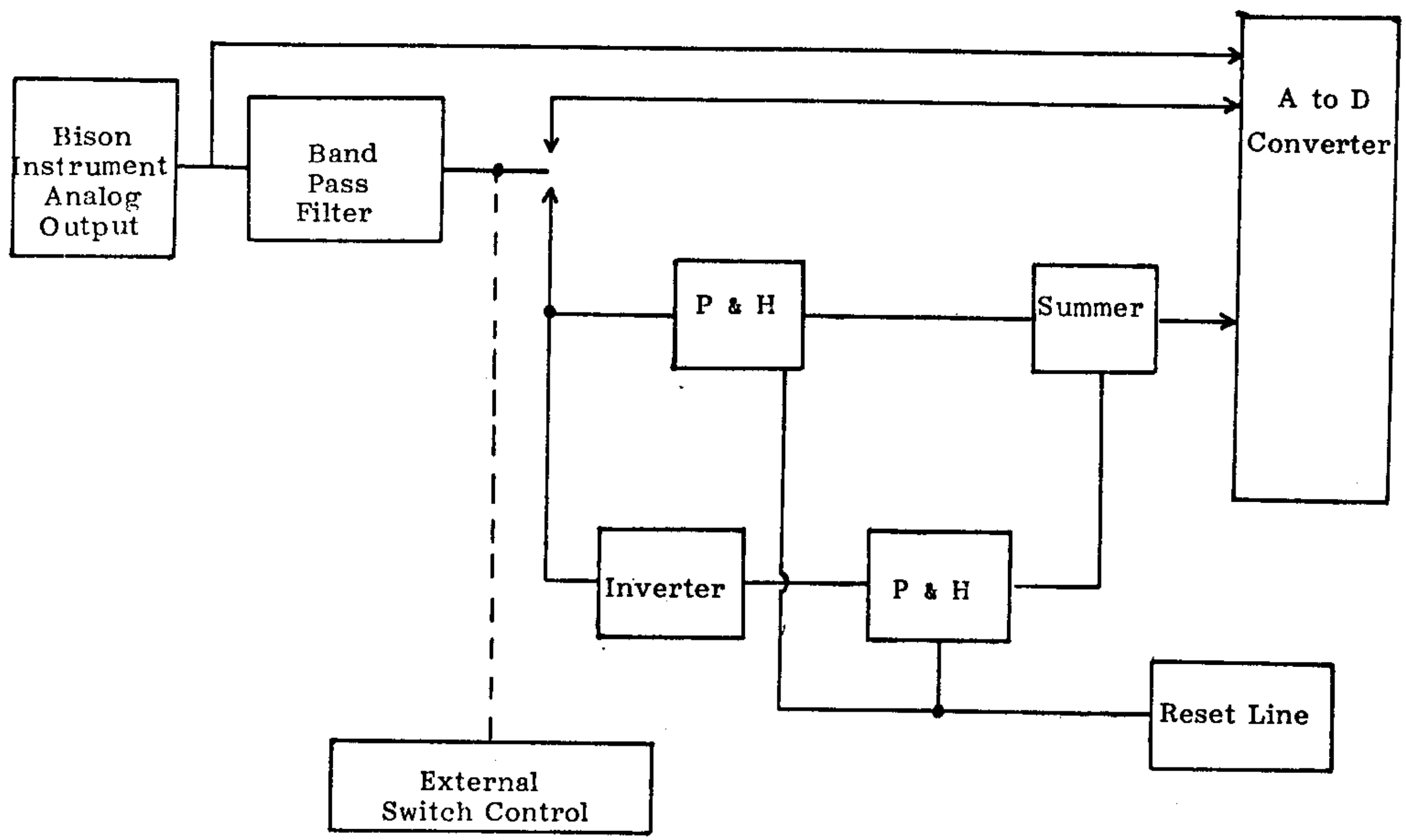


Figure C-2. Signal Conditioning Circuit Diagram for Dynamic Bison Signals

"CLOCK" PROGRAM

```
 20 DIM C1'(5,18)
 30 DIM A(20)
 40 A(1)=1 A(2)=3 A(3)=4 A(4)=6 A(5)=7 A(6)=9 A(7)=11 A(8)=12 A(9)=14 A(10)=16 A(11)=17
 50 A(12)=19 A(13)=10 A(14)=13 A(15)=15 A(16)=8 A(17)=18 A(18)=20
 60 LOAD ARRAY C1'(1) "2:CSS"
 80 INPUT D
100 DOT(10,14)=1
120 DOT(10,14)=0
130 INPUT "SECTION # "M
135 IF M<1 PRINT "INPUT ERROR TRY AGAIN " GOTO 130
136 IF M>18 PRINT "INPUT ERROR TRY AGAIN " GOTO 130
140 J=5
150 IF M=0 GOTO 80
160 FOR I = 3 TO 11 STEP 2
170   DOT(10,I,I+1,1)=C1'(J,M)
180   J=J-1
190 NEXT I
200 IF M = 0 GOTO 80
205 FOR I = 1 TO M DOT(10,0)=1 DOT(10,0)=0 NEXT I
207 IF M=1 GOTO 80
208 M=A(M)
210 FOR I = 1 TO M-1 DOT(10,1)=1 DOT(10,1)=0 NEXT I
270 GOTO 80
280 STOP
```

"SCALE" PROGRAM

```
 10 REM S3(5,18) = AMPL. VALUES FROM BISON INSTR.
 20 REM S4(5,18) = CALCULATED COIL SPACINGS
 30 REM S5(5,18) = SENSITIVITY SCALE FACTORS.
 40 REM C7(30) = POLY. COEF. FOR VOLTS TO MICRO-INCH CONV.
 50 REM C8(90) = POLY. COEF. FOR AMPL. READINGS TO COIL SPACING
 60 REM C1´(91) = INITIAL COIL SEP.SET. FOR CMOS SWITCHES"
 70 REM C2´(90) = INITIAL COIL SEP. SET. FOR BISON GAGES"
 80 DIM C2´(5,18)
 90 DIM C1´(91),G´(110),S3(91),S(110)
100 DIM S2(3),G2´(3),C9(75)
110 DIM C7(30),C8(90),S4(5,18),S5(5,18)
120 DIM C1´(5,18),G´(6,18),S3(5,18),S(6,18)
130 PRINT "TYP 1 IF ARRAYS ARE NOT TO BE READ IN";
140 INPUT S1
150 IF S1=1 GOTO 210
160 LOAD ARRAY C1´(1) "2:CSS" LOAD ARRAY S3(1) "2:ICS" LOAD ARRAY G´(1) "2:GAIN"
170 LOAD ARRAY S(1) "2:SCFA" LOAD ARRAY S2(1) "2:ASF" LOAD ARRAY G2´(1) "2:AGN"
180 LOAD ARRAY C8(1) "2:COEFCS" LOAD ARRAY C7(1) " 2:COEFMV"
190 LOAD ARRAY S4(1) "2:FSS" LOAD ARRAY S5(1) "2:SSF"
200 LOAD ARRAY C2´(1) "2:CSST"
210 INPUT "GAIN VAL  "S1 IF S1=0 GOTO 320
220 FOR J´ = 1 TO 18 FOR I´ = 1 TO 5
230     PRINT "GAIN TRANS # ";I´;" SEC # ";J´;
240     INPUT S1
250     IF S1 =0 GOTO 270
260     G´(I´,J´)=S1
270   NEXT I´ NEXT J´
280 FOR I´ = 1 TO 3 PRINT "GAIN ACC, # ";I´
290   INPUT S1 IF S1=0 GOTO 310
300   G2´(I´)=S1
310 NEXT I´
320 INPUT "POLYNOMIAL COEF´S. FOR COIL SEP. CALC."S1
330 IF S1=0 GOTO 410
340 FOR I = 1 TO 90
350   PRINT "COEF # ";I;
360   INPUT S1
370   IF S1=99999 S1=0 GOTO 390
380   IF S1=0 GOTO 400
```

```
390   C8(I)=S1
400 NEXT I
410 INPUT "POLYNOMIAL COEF'S. FOR MICRO INCH CALC. "S1
420 IF S1=0 GOTO 490
430 FOR I = 1 TO 30 PRINT "COEF # ";I;
440   INPUT S1
450   IF S1=99999 S1=0 GOTO 470
460   IF S1=0 GOTO 480
470   C7(I)=S1
480 NEXT I
490 INPUT "SENSITIVITY DATA "S1 IF S1 =0 GOTO 550
500 FOR J' = 1 TO 18 FOR I' = 1 TO 5
510     PRINT "SENS. # ";I';" SEC # ";J';
520     INPUT S1 IF S1=0 GOTO 540
530     S5(I',J')=S1
540   NEXT I' NEXT J'
550 INPUT "SCALE FACTORS FOR ACC.  "S1
560 IF S1=0 GOTO 640
570 FOR I' = 1 TO 3
580   PRINT "SCALE FAC. ACC # ";I';
590   INPUT S1 IF S1=0 GOTO 610
600   S2(I')=S1
610 NEXT I'
620 PRINT
630 PRINT "SCALE FOR ACC.  "S2(1),S2(2),S2(3)
640 INPUT "COIL SEP. SETTING "S1 IF S1=0 GOTO 710
650 FOR J' = 1 TO 18 FOR I' = 1 TO 5 PRINT "COIL SEP. # ";I';" SEC # ";J';
660     INPUT S1 IF S1=0 GOTO 700
670     IF S1=1 S1=0
680     IF S1=3 S1=1
690     C1'(I',J')=S1
700   NEXT I' NEXT J'
710 PRINT "COIL SEP. SET. FOR SEP. CALC.(TRUE VALUES)"
720 INPUT S1
730 IF S1=0 GOTO 790
740 FOR J' = 1 TO 18 FOR I' = 1 TO 5
750     PRINT "COIL # ";I';" SEC ";J';
760     INPUT S1 IF S1=0 GOTO 780
770     C2'(I',J')=S1
780   NEXT I' NEXT J'
```

```
790 INPUT "INITIAL COIL SPACING "S1 IF S1=0 GOTO 1140
800 IF S1<0 GOTO 940
810 FOR J' = 1 TO 12 STEP 2 FOR I' = 1 TO 5
820     E3=C2'(I',J')-1
830     IF E3<0 E3=0
840     IF I'<3 K'=16 L'=21
850     IF I'>2 K'=61 L'=16
860     IF I'=5 K'=1 L'=1
870     K'=K'+E3*5
880     PRINT "K' L' ";K';L'
890     PRINT "COIL SPACING ";I';" SEC # ";J';
900     INPUT S1 IF S1=0 GOTO 980
910     IF S1<0 S1=S3(I',J')
920     S3(I',J')=S1
930     S4(I',J')=POLY(S1,C8(K'),5)
940     S(I',J')=POLY(S4(I',J'),C7(L'),5)*S5(I',J'+1)
950     S(I',J')=S(I',J')*1E+6
960     IF I'=5 GOTO 980
970     S(I',J')=S(I',J')/S4(I',J')
980     E3=C2'(I',J'+1)-1
990     IF I'<3 K'=31 L'=21
1000    IF I'>2 K'=76 L'=26
1010    IF I'=5 K'=1 L'=1
1020    K'=K'+E3*5
1030    PRINT "K' L' ";K';L'
1040    PRINT "COIL SPACING # ";I';" SEC # ";J'+1;
1050    INPUT S1 IF S1=0 GOTO 1130
1060    IF S1<0 S1=S3(I',J'+1)
1070    S3(I',J'+1)=S1
1080    S4(I',J'+1)=POLY(S1,C8(K'),5)
1090    S(I',J'+1)=POLY(S4(I',J'+1),C7(L'),5)*S5(I',J'+1)
1100    S(I',J'+1)=S(I',J'+1)*1E+6
1110    IF I'=5 GOTO 1130
1120    S(I',J'+1)=S(I',J'+1)/S4(I',J'+1)
1130  NEXT I' NEXT J'
1140 INPUT "TYP 0 IF NO LISTING OR STORING OF INPUT "S1
1150 IF S1=0 GOTO 1800
1160 IF S1=2 GOTO 1750
1170 PRINT
```

```
1180 PRINT "GAIN FOR ACC.  ";G2'(1),G2'(2),G2'(3)
1190 PRINT
1200 PRINT "GAIN FACTORS"
1210 FOR I' = 1 TO 5 PRINT FOR J' = 1 TO 18 PRINT G'(I',J'); NEXT J' NEXT I'
1220 PRINT
1230 PRINT
1240 FOR I3' = 1 TO 18 G'(6,I3')=G2'(1) NEXT I3'
1250 PRINT " INITIAL COIL SPACING  AMPLITUDE #'S FROM BISON GAGES "
1260 FOR I' = 1 TO 5 PRINT FOR J' = 1 TO 18 PRINT USING"-#.###^^^^"S3(I',J');
1270     IF J'=12 PRINT
1280   NEXT J' NEXT I' PRINT
1290 PRINT
1300 PRINT "COIL SEPARATION SWITCH SETTINGS"
1310 FOR I' = 1 TO 5 PRINT FOR J' = 1 TO 18 PRINT C1'(I',J');
1320   NEXT J' NEXT I' PRINT
1330 PRINT
1340 PRINT
1350 PRINT "COIL SEPARATION SETTINGS USED IN SPACING CALC."
1360 FOR I' = 1 TO 5 PRINT FOR J' = 1 TO 18 PRINT C2'(I',J');
1370   NEXT J' NEXT I' PRINT
1380 PRINT
1390 PRINT " POLYNOMIAL COEF'S. FOR INITIAL COIL SPACING CALC'S."
1400 PRINT
1410 M=0 FOR I = 1 TO 90
1420   PRINT USING"-#.####^^^^"C8(I);
1430   M=M+1 IF M=5 M=0 PRINT
1440 NEXT I
1450 PRINT
1460 PRINT "POLYNOMIAL COEF'S. FOR VOLTS TO MICRO-INCH CALC'S."
1470 PRINT
1480 M=0 FOR I = 1 TO 30
1490   PRINT USING"-#.####^^^^"C7(I);
1500   M=M+1 IF M=5 M=0 PRINT
1510 NEXT I
1520 PRINT
1530 PRINT "CALCULATED COIL SPACING IN INCHES"
1540 FOR I' = 1 TO 5 PRINT FOR J' = 1 TO 18
1550     PRINT USING"-#.####^^^^"S4(I',J');
1560     IF J'=12 PRINT
```

```
1570   NEXT J′ NEXT I′ PRINT
1580 PRINT
1590 PRINT "CALCULATED SCALE FACTORS (MICRO-INCHES/VOLT)"
1600 FOR I′ = 1 TO 5 PRINT FOR J′ = 1 TO 18
1610     PRINT USING"-#.####^^^^"S(I′,J′);
1620     IF J′=12 PRINT
1630   NEXT J′ NEXT I′
1640 PRINT
1650 PRINT
1660 PRINT "SENSITIVITY SCALE FACTORS"
1670 FOR I′ = 1 TO 5 PRINT FOR J′ = 1 TO 18
1680     PRINT USING"-#.####^^^^"S5(I′,J′);
1690     IF J′=12 PRINT
1700   NEXT J′ NEXT I′ PRINT
1710 PRINT
1720 PRINT
1730 PRINT
1740 IF S1=1 GOTO 1800
1750 SAVE ARRAY C1′(1) "2:CSS" SAVE ARRAY S3(1) "2:ICS" SAVE ARRAY G′(1) "2:GAIN"
1760 SAVE ARRAY S(1) "2:SCFA" SAVE ARRAY S2(1) "2:ASF" SAVE ARRAY G2′(1) "2:AGN"
1770 SAVE ARRAY C8(1) "2:COEFCS" SAVE ARRAY C7(1) "2:COEFMV"
1780 SAVE ARRAY S4(1) "2:FSS" SAVE ARRAY S5(1) "2:SSF"
1790 SAVE ARRAY C2′(1) "2:CSST"
1800 INPUT "CORRECTIONS NEEDED TYPE 1 "S1 IF S1=1 GOTO 130
```

MAIN PROGRAM

```
  5 DIM L$(130),C1'(91),W'(2,13),C(18)
 10 FOR I' = 1 TO 130 STEP 2 L$(I',I'+1)=" " NEXT I'
 15 L$(20,28)="VERT.PAV."
 20 L$(32,41)="VERT.SUB.G"
 25 L$(50,54)="LONG."
 30 L$(62,67)="TRANS."
 35 L$(71,80)="LOW.DISPL."
 40 L$(84,93)="MID.DISPL."
 45 L$(97,106)="SURF.DISPL."
 50 L$(110,119)="VERT.ACC."
 55 DIM G'(110),S(110),S9'(19),Z$(8),Z1$(10),Z2$(12)
 60 DIM T'(3),D'(3),S2(3),G2'(3)
 65 DIM K9'(6),T1(5),T7(8)
 66 FOR I' = 1 TO 2 FOR J' = 1 TO 12 W'(I',J')=2 NEXT J' NEXT I'
 67 W'(1,3)=1 W'(1,5)=1 W'(1,8)=1 W'(1,11)=1 W'(2,1)=9 W'(2,2)=3 W'(2,4)=3
 68 W'(1,13)=0 W'(2,6)=0
 70 K9'(1)=0 K9'(2)=1 K9'(3)=2 K9'(4)=3 K9'(5)=4 K9'(6)=10
 76 C(1)=16.13 C(2)=46 C(3)=75.3 C(4)=105.74 C(5)=133.57 C(6)=163.44
 77 C(7)=196.38 C(8)=223.86 C(9)=254.53 C(10)=286.56 C(11)=316.09 C(12)=346.3
 78 C(13)=128.06 C(14)=215.35 C(15)=236.69 C(16)=249.27 C(17)=333.63 C(18)=253.63
 79 B1=2 B2=42
 80 N2'=0 N3'=0 N4'=0 N5'=0 N6'=0 N7'=0 N9'=0
 85 M1'=12 M2'=8 M3'=0 M4'=1 M5'=0
 86 A3=0 A4=0 A5'=0 F1'=0 J2'=0 J1'=0 J3'=0 R6'=12
 87 J4'=2 R4'=250
 90 R2'=0 R3'=0 I'=0 J'=0 K'=0
 91 N1'=0
110 J5'=288*J4'+8 J6'=J5'/2
115 INPUT "ROT'S PER SEGMENT "S1
120 N7'=S1 R1'=N7'*J4' R'=R1'*2
121 G3'=R1'
125 P=20 T9=.0005
130 R5=0
135 DIM A'(J5'),A1(J6')
140 INPUT "ROTATION INDEX "S1
```

```
145 IF S1<0 N=0
150 IF S1>0 N=S1
155 PRINT "WHEEL ROTATION COUNT IS";
156 PRINT USING"-#######."N
160 DIM A′(6,4,12,J4′),A1(6,2,12,J4′)
165 FOR I1′ = 1 TO 6 FOR I2′ = 1 TO 4 FOR I3′ = 1 TO 12 FOR I4′ = 1 TO J4′
170         A′(I1′,I2′,I3′,I4′)=0
171         IF I2′=2 A′(I1′,I2′,I3′,I4′)=32767
175         IF I2′>2 GOTO 185
180         A1(I1′,I2′,I3′,I4′)=0
185       NEXT I4′ NEXT I3′ NEXT I2′ NEXT I1′
205 FOR I′ = 1 TO 3 G2′(I′)=0 S2(I′)=1 NEXT I′
210 DIM C1′(5,18),G′(6,18),S4(5,18),S(6,18)
215 LOAD ARRAY C1′(1) "2:CSS" LOAD ARRAY G′(1) "2:GAIN"
218 LOAD ARRAY S(1) "2:SCFA" LOAD ARRAY S2(1) "2:ASF" LOAD ARRAY G2′(1) "2:AGN"
220 LOAD ARRAY S4(1) "2:FSS"
405 N2′=0
415 J′=1 FOR I′ = 1 TO 5 S9′(J′)=1 S9′(J′+1)=I′+4 S9′(J′+2)=0 J′=J′+3 NEXT I′
420 S9′(16)=1 S9′(17)=10 S9′(18)=0
425 DIM Z3$(64)
430 I′=1 FOR J′ = 0 TO 9
435   Z3$(I′,I′+1)="0" STR$(J′)
440   I′=I′+2 NEXT J′
445 I′=21 FOR J′ = 10 TO 31
450   Z3$(I′,I′+1)=STR$(J′)
455   I′=I′+2 NEXT J′
460 T1(1)=0 T1(2)=1.97510E-2 T1(3)=-1.85426E-7 T1(4)=8.36840E-12 T1(5)=-1.32806E-16
465 FOR I′ = 0 TO 14 DOT(10,I′)=1 NEXT I′
466 WAIT 1 DOT(10,0,1)=0 DOT(10,14)=0
487 INPUT "APPROX.LOC.OF ECC.IN DEG. "C2
490 V=30 D7=4/(V*R1′) D8=1.5/V D9=3/V
491 D3=360./2625.
495 N8=-1
500 TASK 1,1000
515 TASK 2,4000
520 TASK 3,5000
525 TASK 4,6000,2
530 TASK 5,7000
535 TASK 6,8000,100
```

```
545 ACTIVATE 1
565 ACTIVATE 2 ON EVENT  (11,0,1)
570 ACTIVATE 3 ON EVENT  (11,1,0)
575 ACTIVATE 4 ON EVENT  (11,2,0)
580 ACTIVATE 5 ON EVENT  (11,3,1)
585 END
590 DECLARE (I')
600 PRINT "            UW/WSU SULFUR ASPHALT PROJECT"
605 GDATE D'(1),D'(2),D'(3) GTIME T'(1),T'(2),T'(3)
610 PRINT "            ECCENTRICITY ANGLE IN DEGREES ";C2
620 PRINT "            ";
625 PRINT "DATE   ";D'(1);D'(2);D'(3)
630 PRINT "            ";
635 PRINT "TIME   ";T'(1);T'(2);T'(3)
640 RETURN
1000
1050 DOT(10,13)=0 R3'=0 R6'=12 M5'=0
1060 IF N2'>0 IF M4'*N2'-N1'=0 R3'=1 R6'=5 M4'=M4'+1 M5'=12 DOT(10,13)=1
1070 N1'=N1'+1 N4'=0 N5'=1 N9'=1 R2'=1
1900 N8=-1
1990 DISMISS GOTO 1000
4000 N3'=0 M3'=0 N=N+1 IF N8=0 GOTO 4069
4040 N4'=N4'+1 DOT(10,14)=1 DOT(10,14)=0
4050 C2=C2+D3 IF C2>360 C2=0
4060 N8=1
4069 ACTIVATE 2 ON EVENT  (11,0,1) DISMISS GOTO 4000
5000 IF N8<=0 GOTO 5140
5010 N3'=N3'+1 DOT(10,0)=1 DOT(10,0)=0
5030 IF R3'=0 IF N3'=1 J'=1 GOTO 5090
5040 IF R3'=1 IF N3'=1 M3'=12 M5'=12 J'=2 FOR I' = 1 TO 12 DOT(10,0)=1 DOT(10,0)=0 NEXT I' GOTO 5090
5060 FOR I' = 1 TO W'(J',N3') DOT(10,1)=1 DOT(10,1)=0 NEXT I'
5090 M3'=M3'+1 K'=5 FOR I' = 3 TO 11 STEP 2 DOT(10,I',I'+1,1)=C1'(K',M3') K'=K'-1 NEXT I'
5140 ACTIVATE 3 ON EVENT  (11,1,0) DISMISS GOTO 5000
6000 IF N8<=0 GOTO 6040
6030 A4=AVG(1,10,0,P,T9)
6040 ACTIVATE 4 ON EVENT  (11,2,0) DISMISS GOTO 6000
7000 IF N8<=0 GOTO 7160
7030 N6'=N5'*N7'-N4'+1
7035 IF N6'<=0 GOTO 7040
```

```
7037 GOTO 7050
7040 IF N9′>=J4′ R2′=-1
7041 IF N9′>=J4′ IF N4′=R1′+1 R2′=0
7042 IF N9′<=1 IF R2′<=0 R2′=1
7045 N9′=N9′+R2′ N5′=N5′+1
7050 FOR K1′ = 1 TO 6
7060   A3=-AIN(1,K9′(K1′),G′(K1′,N3′+M5′),1)
7070   IF K1′=6 THEN  A3=A4
7080   A5′=(((A3+10.)/20.)*32767.)
7090   IF A5′>A′(K1′,1,N3′,N9′) THEN  A′(K1′,1,N3′,N9′)=A5′
7100   IF A5′<A′(K1′,2,N3′,N9′) THEN  A′(K1′,2,N3′,N9′)=A5′
7110   A1(K1′,1,N3′,N9′)=A1(K1′,1,N3′,N9′)+A3
7120   A1(K1′,2,N3′,N9′)=A1(K1′,2,N3′,N9′)+A3*A3
7130 NEXT K1′
7140 IF N4′=G3′ IF N3′=R6′ ACTIVATE 6
7160 ACTIVATE 5 ON EVENT  (11,3,1) DISMISS GOTO 7000
8000 IF N8<=0 GOTO 8610
8005 N8=0 D4=N PRINT
8015 DIM A1(6,2,12,J4′),A′(J5′)
8020 M1′=12 M2′=8 IF R3′=1 M1′=5 M2′=5
8025 J′=-1 K′=5 FOR I′ = -7 TO 0 J′=J′+1
8030   T7(I′+8)=POLY(AIN(K′,J′)*1E6,T1(1),5) A′(J5′+I′)=T7(I′+8)*100.
8040   IF J′=3 J′=-1 K′=6
8045 NEXT I′
8050 DIM A′(6,4,12,J4′)
8055 S1=100
8060 FOR I1′ = 1 TO 6 FOR I3′ = 1 TO M1′ FOR I4′ = 1 TO J4′
8065        A8=A1(I1′,2,I3′,I4′)/(N7′-1) A9=(A1(I1′,1,I3′,I4′)^2)/(N7′*(N7′-1)) A7=A8-A9
8070        IF A7<=0 THEN  A7=1E-20
8075        A′(I1′,4,I3′,I4′)=SQR(A7)*S1 A′(I1′,3,I3′,I4′)=A1(I1′,1,I3′,I4′)/N7′*S1
8080     NEXT I4′ NEXT I3′ NEXT I1′
8085 DIM A1(8,4)
8087 GOSUB 590(I′)
8090 PRINT "            TOTAL ROTATIONS ";
8092 PRINT USING"-#######."N
8095 PRINT "            NO. OF PTS. USED IN CALC.  ";N7′
8100 N4′=0 I′=2*(D′(2)+1) J′=2*(T′(1)+1)
8120 Z2$(1,4)="2:UW"
8125 Z1$(1,2)="UW"
8130 IF R3′=1 THEN  Z2$(1,4)="2:UX"
```

```
8135 IF R3'=1 THEN  Z1$(1,2)="UX"
8140 Z$(1,2)=Z3$(I'-1,I')
8145 Z$(3,4)=Z3$(J'-1,J')
8150 Z$(5,8)=STR$(N1')
8155 Z1$ =Z1$(1,2) Z$
8160 Z2$ = Z2$(1,4) Z$
8165 IF N1'>R4' SAVE ARRAY A'(1) Z1$ PRINT "           DISK FILE NAME  "Z1$
8170 IF N1'<R4' SAVE ARRAY A'(1) Z2$ PRINT "           DISK FILE NAME  "Z2$
8175 PRINT "           TEMP. DATA (DEG. CENT.)"
8180 PRINT "          ";
8185 FOR I' = 1 TO 8 PRINT USING"       -#"I'; NEXT I' PRINT
8205 PRINT "          ";
8210 FOR I' = 1 TO 8 PRINT USING"-#####.##"T7(I'); NEXT I' PRINT
8235 IF R5=-1 THEN  GOTO 8535
8240 FOR I4' = 1 TO J4' I6'=0
8250   IF R5 = 1 THEN  GOTO 8265
8255   IF R3'=1 I6'=12
8260   IF I4'<>(J4'/2+1) THEN  GOTO 8530
8265   FOR I3' = 1 TO N1' I6'=I6'+1 FOR I2' = 1 TO 4 FOR I1' = 1 TO 7 I' =11
8270         I'=I1'
8290         IF I1'=7 THEN  GOTO 8320
8295         S6=S(I1',I6')
8300         IF I1'=6 THEN  S6=S2(1) I'=8
8305         IF I2'<=2 THEN  A1(I',I2')=(((A'(I1',I2',I3',I4')/32767.)*20.)-10.)*S6
8310         IF I2'>=3 A1(I',I2')=(A'(I1',I2',I3',I4')/S1)*S6
8315         GOTO 8330
8320         A1(6,I2')=A1(5,I2')+A1(2,I2')*S4(2,I3')
8325         A1(7,I2')=A1(6,I2')+A1(1,I2')*S4(1,I3')
8330       NEXT I1' NEXT I2' PRINT
8345     PRINT "                ";
8350     PRINT "STATISTICAL DISPLACEMENT AND STRAIN DATA (IN MICRO INCHES & MICRO STRAINS) FOR STATION  ";I6'
8355     IF R3'=0 THEN  GOTO 8385
8360     FOR I' = 1 TO 6 PRINT USING"              -#"I'; NEXT I' PRINT
8380     GOTO 8390
8385     PRINT L$
8390     PRINT "            MAX.";
8395     FOR I1' = 1 TO M2'
8400       PRINT USING"   -#.###^^^^"A1(I1',1);
```

```
8405     NEXT I1'
8410     PRINT
8415     PRINT "             MIN.";
8420     FOR I1' = 1 TO M2'
8425       PRINT USING"   -#.###^^^^"A1(I1',2);
8430     NEXT I1'
8435     PRINT
8440     PRINT "             MEAN";
8445     FOR I1' = 1 TO M2'
8450       PRINT USING"   -#.###^^^^"A1(I1',3);
8455     NEXT I1'
8460     PRINT
8465     PRINT "             STDV";
8470     FOR I1' = 1 TO M2'
8475       PRINT USING"   -#.###^^^^"A1(I1',4);
8480     NEXT I1'
8485     I'=1
8490     IF I3'=6 IF R3'=1 THEN  I'=33
8495     IF I3'=4 THEN  I'=18
8500     IF I3'=8 THEN  I'=24
8505     IF I3'=12 THEN  I'=19
8510     FOR J' = 1 TO I' PRINT NEXT J'
8520   NEXT I3'
8530 NEXT I4'
8535 DIM A'(6,4,12,J4'),A1(6,2,12,J4')
8540 FOR I1' = 1 TO 6 FOR I2' = 1 TO 4 FOR I3' = 1 TO 12 FOR I4' = 1 TO J4'
8560         A'(I1',I2',I3',I4')=0
8565         IF I2'=2 THEN  A'(I1',I2',I3',I4')=32767
8570         IF I2'>2 THEN  GOTO 8580
8575         A1(I1',I2',I3',I4')=0
8580       NEXT I4' NEXT I3' NEXT I2' NEXT I1'
8600 C2=C2+(N-D4)*D3
8605 ACTIVATE 1
8610 DISMISS GOTO 8000
```

## APPENDIX D
## WSU SUMMARY OF DAILY TRACK OPERATIORS JOURNAL

### Section 1

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | Pavement okay, no visible cracking |
| 11-06-79 | 43,225 | Half of section developing alligator cracks; logitudinal crack (3 ft) along outside edge of wheel path |
| 11-09-79 | 50,639 | 3 ft long, ½" longitudinal shear failure on outside edge of wheel path; continued development of alligator cracking within wheel path of beginning half of the section |
| 11-11-79 | 57,698 | Continued expansion of longitudinal crack; noticeable shear separation outside edge of wheel path; permanent deformation beginning |
| 11-12-79 | 62,052 | Cold patched deepest deflections |
| 11-14-79 | 72,140 | Pavement outside wheel path heaving, 2½" vertical separation |
| 11-17-79 | 81,475 | Water ponding in deflected areas; subgrade pumping; entire length of section failed |
| 11-18-79 | 83,068 | Section dug out; hot asphalt placed |

### Section 2

| | | |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No visible cracking |
| 11-06-79 | 43,225 | No visible cracking |
| 11-29-79 | 108,090 | No apparent cracking |
| 12-02-79 | 120,567 | No apparent cracking |
| 12-14-79 | 129,323 | Transition 2-3 forming transverse cracks (18" length) |
| 12-18-79 | 133,698 | No change |
| 01-02-80 | 138,659 | No evidence of cracking |
| 01-23-80 | 152,000 | No evidence of cracking |

## Section 3

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | 8 transverse cracks within wheel path; 2 ft lengths |
| 11-06-79 | 43,225 | 10 transverse cracks across complete wheel path; permanent deformation noticeable |
| 11-09-79 | 50,639 | No noticeable change |
| 11-11-79 | 57,698 | Noticeable deflection; longitudinal crack development at middle of section and on outside edge of wheel path; alligator cracking beginning to develop |
| 11-14-79 | 68,517 | Transverse crack the width of the wheel path covering entire first half of section |
| 11-15-79 | 77,713 | Water ponding in permanent deformation; mud visible in cracks; considerable increase in alligator cracking |
| 11-18-79 | 83,068 | Section dug up; hot asphalt placed |

## Section 4

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No visible cracks |
| 11-06-79 | 43,225 | No visible cracks |
| 11-12-79 | 60,968 | Longitudinal cracks beginning to form |
| 11-23-79 | 87,447 | 3 ft longitudinal crack on inner half of wheel path; only crack evident |
| 11-24-79 | 91,324 | Gauge lost cover |
| 11-29-79 | 108,090 | No change; transition 4-5 forming transverse cracks at patch joint; some settlement occurring |
| 11-30-79 | 111,481 | Longitudinal crack expanded to 5 ft length |
| 12-14-79 | 129,323 | No change |
| 12-18-79 | 133,698 | No change |
| 01-02-80 | 138,659 | Transverse cracks beginning to form from longitudinal crack |

Section 4 (continued)

| Date | Revolutions | Description of Events |
|---|---|---|
| 01-21-80 | 145,311 | At outside of track middle of section, 4 transverse cracks 2 ft in length; no change in longitudinal crack |
| 1-23-80 | 152,000 | 7 ft longitudinal crack; 6 transverse cracks, about 2 ft wide, center of section |

Section 5

| | | |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No visible cracks |
| 11-06-79 | 43,225 | No visible cracks |
| 11-12-79 | 60,968 | A few small transverse cracks beginning to form (5" to 8" in length) |
| 11-15-79 | 77,713 | A few small transverse cracks beginning to form (5" to 8" in length) |
| 11-18-79 | 83,068 | Alligator cracking and permanent deformation at beginning end of section; transverse cracks the width of the wheel path across remaining center of the section; water ponding in depressions<br>Section dug up, replaced with asphalt |
| 12-07-79 | 121,732 | Section dug up again and portland cement concrete placed |

Section 6

| | | |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No cracks |
| 11-06-79 | 43,225 | No cracks |
| 11-29-79 | 108,090 | No visible evidence of cracking |
| 12-02-79 | 120,567 | No visible evidence of cracking |
| 12-06-79 | 129,323 | Cracking progressing from 6-7 line into section 6 (transverse and longitudinal cracking) approximately 3 ft into section 6 |
| 12-18-79 | 133,698 | No change; 5-6 transition patched with portland cement concrete |

## Section 6 (continued)

| Date | Revolutions | Description of Events |
|---|---|---|
| 01-02-80 | 138,543 | Section 6 showing no evidence of cracking |
| 01-14-80 | 143,302 | No change |
| 01-16-80 | 144,096 | No change |
| 01-22-80 | 148,785 | No change |
| 01-23-80 | 152,000 | No evidence of cracking in section 6, except around transition zones |

## Section 7

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | 7 transverse cracks within wheel path, 2½ ft lengths |
| 11-06-79 | 43,225 | Subgrade squeezed out at center of section, 3 ft X width of wheel path; covered with alligator cracking; longitudinal cracks along inside and outside edge of wheelpath; noticeable permanent deformation |
| 11-09-79 | 50,639 | Shear failure developing along outside edge of wheel path |
| 11-11-79 | 55,215 | 7 and 8 transition zone 2" depression |
| 11-11-79 | 57,698 | Alligator cracking expanding throughout section; increasing permanent deflection; noticeable heaving of outside edge of wheel path |
| 11-12-79 | 60,968 | Entire section covered by alligator cracking; permanent deflection full length of section |
| 11-12-79 | 62,052 | Cold patched |
| 11-17-79 | 81,475 | Entire section failed; outside of wheel path heaving |
| 11-18-79 | 83.068 | Section dug up; hot asphalt patch placed |
| 12-07-79 | 121,732 | Portland cement concrete placed because of patch break-up |

## Section 8

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No crack development |
| 11-06-79 | 43,225 | Transition 7 and 8, transverse cracking developing |
| 11-12-79 | 62,052 | No change |
| 11-29-79 | 108,090 | Longitudinal crack ( 2 ft length) formed center section |
| 12-01-79 | 119,043 | No change |
| 12-14-79 | 129,323 | Longitudinal crack expanding at center of section; no evidence of any transverse cracks; longitudinal crack progressing inward from both transition zones |
| 12-18-79 | 133,698 | Center longitudinal crack 5 ft long, longitudinal from section 7, 6 ft long |
| 12-22-79 | 137,565 | Section 9 collapse progressing 3 ft into section 8 |
| 01-02-80 | 138,659 | Longitudinal crack from Section 7 expanded 8 ft into section 8 |
| 01-14-80 | 143,302 | No change |
| 01-23-80 | 152,000 | No change |

## Section 9

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No cracks |
| 11-06-79 | 43,225 | Fatigue cracking at 9 and 10 transition zone |
| 11-10-79 | 51,953 | 8" transverse crack; slight deflection with wheel pass |
| 11-10-79 | 52,438 | Transverse cracks spreading from 9 and 10 transition zone |
| 11-11-79 | 58,324 | No development of longitudinal cracks as of yet |
| 11-12-79 | 60,968 | Alligator cracks beginning to form at 9 and 10 transition zone |
| 11-14-79 | 69,920 | Same |

## Section 9 (continued)

| Date | Revolutions | Description of Events |
|---|---|---|
| 11-18-79 | 83,068 | Transverse cracks throughout entire section; noticeable permanent deformation at center of section; subgrade pumping. Section dug up; hot asphalt placed |

## Section 10

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No cracks |
| 11-06-79 | 43,225 | Fatigue cracking at 9 and 10 transition zone |
| 11-12-79 | 60,968 | Evidence of small transverse crack |
| 11-14-79 | 72,140 | Transverse cracking continuing to form within the section |
| 11-18-79 | 83,068 | Transverse cracking throughout entire section; noticeable permanent deflection; hot asphalt placed at 9 and 10 transition zone; zealous paving crew replaced almost half of the section with asphalt |
| 11-22-79 | 85,806 | Extreme alligator cracking, plus longitudinal cracking inside and outside edges of wheel path; mud working up from subgrade; permanent deflection on remaining unpaved part of section |
| 11-26-79 | 95,750 | Deep depression, continued break-up |
| 12-07-79 | 121,732 | Portland cement concrete placed over entire section |

## Section 11

| Date | Revolutions | Description of Events |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | 2 ft x 4 ft fatigue failure; alligator cracking developing |
| 11-05-79 | 38,562 | Alligator cracking developed throughout entire section; pumping of subgrade; longitudinal cracking (14 ft) along outside edge of wheel path; noticeable deformation |
| 11-06-79 | 43,225 | Outside edge heaving; 3 ft x ½" deep shear failure outside edge, continued development of alligator cracking |
| 11-09-79 | 50,639 | 1" to ½" vertical pavement sepa ation along entire outside edge of the wheelpath; extreme alligator cracking developing over entire section area |

Section 11 (continued)

| Date | Revolutions | Description of Events |
|---|---|---|
| 11-12-79 | 62,052 | Continued pavement separation on edge of outside wheel path, extreme permanent deformation for entire length of section<br>Cold patch applied to reduce wheel bounce |
| 11-14-79 | 72,140 | 3½" separation heave on outside of wheel path; cold pateh applied |
| 11-18-79 | 83,068 | Section dug up; asphalt hot mix placed |

Section 12

| | | |
|---|---|---|
| 10-25-79 | 5,875 | Round the clock track operation begun |
| 11-02-79 | 28,152 | No cracking |
| 11-06-79 | 43,225 | No cracking |
| 11-09-79 | 50,639 | 11 and 12 transition zone break-up |
| 11-14-79 | 72,140 | Longitudinal crack from section 11 expanding through transition zone of 11 and 12; center of section 12 still intact |
| 11-18-79 | 83,068 | Center section still okay |
| 11-29-79 | 108,090 | 14" longitudinal crack at center of section |
| 11-30-79 | 111,481 | 3 transverse cracks ( 1 ft length), center of section; longitudinal crack 2 ft long |
| 12-01-79 | 110,043 | 5 (1 ft) transverse cracks; longitudinal crack 30" in length |
| 12-14-79 | 129,323 | 8 transverse cracks now extend across wheel path; longitudinal crack 33" long |
| 12-15-79 | 131,620 | Alligator cracking developing; noticeable subgrade expulsion |
| 12-22-79 | 137,565 | 2 ft x 3 ft alligator cracking around area by sensor |
| 01-02-80 | 138,543 | Transverse cracks developing throughout entire section within wheel path |
| 01-14-80 | 143,302 | No increase or change |
| 01-16-80 | 144,096 | No increase or change |

Section 12 (continued)

| Date | Revolutions | Description of Events |
|---|---|---|
| 01-23-80 | 152,000 | 3 ft by width of wheel path around center of section covered with alligator cracks; rest of section okay, only slightly visible evidence of transverse cracking |

Testing terminated February, 1980. All sections failed or cracking.

# APPENDIX E

## POST-CONSTRUCTION PAVEMENT CORES MATERIAL PROPERTIES

Table E-1. Summary of Resilient Moduli (Initial Set of Pavement Cores)*

| Section | Sample No.** | Thickness (in.) | 5°C | | 25°C | | 40°C | |
|---|---|---|---|---|---|---|---|---|
| | | | $\Delta h (x10^{-6}$ in | $M_R (x10^3$ psi | $\Delta h (x10^{-6}$ in | $M_R (x10^3$ psi | $\Delta h (x10^{-6}$ in | $M_R (x10^3$ psi |
| 1 | 2S | | | | | | | |
| | 2B | 2-1/2 | 18 | 1311 | 84 | 273 | 454 | 51 |
| 2 | 5S | | | | | | | |
| | $5L_1$ | 2-1/2 | 14 | 1638 | 77 | 298 | 420 | 55 |
| | $5L_2$ | 2-9/16 | 18 | 1279 | 84 | 266 | 420 | 53 |
| 3 | 7S | 1-3/8 | | | 126 | 331 | | |
| | 7B | 2-1/2 | 14 | 1638 | 49 | 468 | 245 | 94 |
| 4 | 11S | | | | | | | |
| | $11L_1$ | 2-7/16 | 14 | 1680 | 63 | 373 | 245 | 96 |
| | $11L_2$ | 2-3/4 | 10 | 1986 | 56 | 372 | 245 | 85 |
| 5 | 14S | | | | | | | |
| | 14B | 2-5/16 | 21 | 1181 | 63 | 394 | 280 | 89 |
| 6 | 17S | 1-3/4 | | | 92 | 356 | | |
| | $17L_1$ | 2-5/16 | 18 | 1417 | 49 | 506 | 315 | 79 |
| | $17L_2$ | 1-7/8 | 21 | 1456 | 95 | 322 | 468 | 65 |
| 7 | 21S | 1-9/16 | | | 112 | 328 | | |
| | 21B | 2-7/16 | 21 | 1120 | 105 | 224 | 525 | 45 |
| 8 | 24S | 1-1/2 | | | 126 | 303 | | |
| | $24L_1$ | 2-7/16 | 21 | 1120 | 138 | 177 | 420 | 56 |
| | $24L_2$ | 2-3/4 | 14 | 1489 | 92 | 227 | 350 | 60 |
| 9 | 27S | | | | | | | |
| | 27B | 2-1/2 | 10 | 2184 | 49 | 468 | 224 | 102 |
| 10 | 28S | 1-5/8 | | | 92 | 384 | | |
| | $28L_1$ | 1-11/16 | 28 | 1214 | 98 | 347 | 420 | 81 |
| | $28L_2$ | 2-1/2 | 10 | 2184 | 49 | 468 | 175 | 131 |
| 11 | 32S | 1-1/2 | | | 133 | 287 | | |
| | 32B | 1-5/8 | 35 | 1008 | 126 | 280 | 700 | 50 |
| 12 | 36S | 1-5/16 | | | 133 | 328 | | |
| | $36L_1$ | 2-1/2 | 10 | 2184 | 42 | 546 | 245 | 94 |
| SR 270 Overlay | 2 | 1-5/8 | 24 | 1440 | 98 | 360 | 315 | 112 |
| | 18 | 2-3/16 | 14 | 1872 | 56 | 463 | 238 | 110 |
| | 6 | 1-15/16 | 21 | 1409 | 70 | 423 | 280 | 106 |
| | 14 | 1-11/16 | 21 | 1618 | 84 | 405 | 350 | 97 |
| | 7 | 1-11/16 | 28 | 1214 | 112 | 303 | 525 | 65 |
| | 12 | 1-3/4 | 28 | 1170 | 105 | 312 | 399 | 82 |

*Sampled December, 1979

**Note: S = Surface Course (30/70 SEA Mix) $L_1$ = Bottom Lift Thick Section $L_2$ = Top Thick Section
B = Base Course (First) Lift for a Thin Section
1 cm = 0.394 in
1 kPa = 0.1451 psi

Table E-2. Average Resilient Moduli (X $10^3$ psi)*

| Test Track | | 5°C | 25°C | 40°C |
|---|---|---|---|---|
| $B_{avg}$ | 0/100 | 1216 | 249 | 48 |
| | 40/60 | 1911 | 468 | 98 |
| | 30/70 | 1094 | 337 | 70 |
| $L_{1avg}$ | 0/100 | 1379 | 238 | 56 |
| | 40/60 | 1447 | 360 | 88 |
| | 30/70 | 1801 | 526 | 86 |
| $L_{2avg}$ | 0/100 | 1384 | 246 | 56 |
| | 40/60 | 2085 | 420 | 108 |
| | 30/70 | 1638 | 388 | 84 |
| Avg | 0/100 | 1326 | 243 | 53 |
| | 40/60 | 1814 | 415 | 98 |
| | 30/70 | 1511 | 416 | 80 |

| Overlay | 5°C | 25°C | 40°C |
|---|---|---|---|
| 7, 12 0/100 | 1192 | 308 | 73 |
| 6, 14 40/60 | 1514 | 414 | 101 |
| 2, 18 30/70 | 1656 | 414 | 111 |

Note 1: Each $B_{avg}$, $L_{1avg}$, $L_{2avg}$, and Overlay value above is the average of 2 values for the corresponding layer, SEA ratio, and temperature shown in Table E-1.

Note 2: Each "Avg" value above is the average of 3 values for $B_{avg}$, $L_{1avg}$, $L_{2avg}$ in Table E-2. (e.g. 1326 is the average of 1216, 1379, and 1384)

*Sampled December, 1979

1 kPa = 0.1451 psi

Table E-3. Summary of Densities-Initial Pavement Cores.*

| Section Number** | | SEA Ratio | Bulk Secific Gravity | Density (pcf) |
|---|---|---|---|---|
| 1 | 2S | 30/70 | 2.313 | 144.3 |
| 2 | 5S | 30/70 | 2.333 | 145.6 |
| 3 | 7S | 30/70 | 2.390 | 149.1 |
| 4 | 11S | 30/70 | 2.388 | 149.0 |
| 5 | 14S | 30/70 | 2.416 | 150.8 |
| 6 | 17S | 30/70 | 2.375 | 148.2 |
| 7 | 21S | 30/70 | 2.396 | 149.5 |
| 8 | 24S | 30/70 | 2.402 | 149.9 |
| 9 | 27S | 30/70 | 2.382 | 148.6 |
| 10 | 28S | 30/70 | 2.416 | 150.8 |
| 11 | 32S | 30/70 | 2.376 | 148.3 |
| 12 | 36S | 30/70 | 2.396 | 149.5 |
| 1 | 2B | 0/100 | 2.343 | 146.2 |
| 3 | 7B | 40/60 | 2.445 | 152.6 |
| 5 | 14B | 30/70 | 2.400 | 149.8 |
| 7 | 21B | 0/100 | 2.337 | 145.8 |
| 9 | 27B | 40/60 | 2.430 | 151.6 |
| 11 | 32B | 30/70 | 2.373 | 148.0 |
| 2 | 5$L_1$ | 0/100 | 2.400 | 149.8 |
| 4 | 11$L_1$ | 40/60 | 2.422 | 151.1 |
| 6 | 17$L_1$ | 30/70 | 2.502 | 156.1 |
| 8 | 24$L_1$ | 0/100 | 2.311 | 144.2 |
| 10 | 28$L_1$ | 40/60 | 2.410 | 150.4 |
| 12 | 36$L_1$ | 30/70 | 2.455 | 153.2 |
| 2 | 5$L_2$ | 0/100 | 2.362 | 147.4 |
| 4 | 11$L_2$ | 40/60 | 2.391 | 149.2 |
| 6 | 17$L_2$ | 30/70 | 2.366 | 147.6 |
| 8 | 24$L_2$ | 0/100 | 2.410 | 150.4 |
| 10 | 28$L_2$ | 40/60 | 2.450 | 152.9 |
| 12 | 36$L_2$ | 30/70 | 2.459 | 153.4 |
| SR 270 Overlay | 2 | 30/70 | 2.387 | 148.4 |
| | 18 | 30/70 | 2.408 | 150.3 |
| | 6 | 40/60 | 2.378 | 148.4 |
| | 14 | 40/60 | 2.459 | 153.4 |
| | 7 | 0/100 | 2.397 | 149.6 |
| | 12 | 0/100 | 2.383 | 145.9 |

1 Mg = 62.4 lb/ft$^3$

*Sampled December, 1979

** S = Surface course

B = Base course (1st lift - thin sections)

$L_1$ = Bottom lift thick sections

$L_2$ = Top lift thick sections

APPENDIX F

TOXICITY MONITORING

OF CONSTRUCTION

Environmental monitoring was accomplished during the construction. A full report on this activity was submitted to the Washington Department of Transportation on February 6, 1980. The operations and the report were accomplished by the Air Pollution Research Section, Chemical Engineering Department, College of Engineering, Washington State University.

Edited portions of the report are as follows:

"<u>RESULTS AND DISCUSSION</u>

1. One complete source test (on plant dryer stack) was performed between 10:21 and 11:21 AM on August 20, 1979, at the United Paving Batch Mix Plant, while producing Class B asphalt. It was a successful valid test and indicated particulate emissions of 0.056 grains per dry standard cubic foot and 7.54 pounds per hour.

2. The $SO_2$ emissions from the plant stack ranged from 0.1 to about 5 parts per million and apparently were caused by fuel combustion in the kiln (dryer). Incremental contributions of $SO_2$ emissions caused by addition of sulfur in the hot mix could not be determined in this variable regime, as they were small compared to the normal variable level of emissions. Spot sampling for fugitive $SO_2$ emissions was performed periodically at the hot mix plant and at the laying site. No hazardous levels were found. At the hot mix plant maximum levels were 0.47 and 0.30 ppm, while at the laying site (SR 270) maximum levels were 0.53 and 0.44 ppm. These levels apparently developed when extensive stirring and/or mixing of the hot mix occurs in combination with low ventilation. Other variables which may be a factor are temperature of the hot mix, length of time it sets in the truck during transportation, and the engine exhaust emissions of the laying machine.

3. Monitoring efforts at the test track were directed towards measuring outgassing of freshly-laid asphalt and determining whether significant levels of sulfur gases other than $SO_2$ were emitted. Exhaust emissions from the engines on the laying machine and the roller/packer substantially exceeded the asphalt outgassing and were a major interference in making the measurements; however, it was obvious that the first pass of the roller/packer effectively seals the surface and regardless of temperature or mix the emission levels dropped to 0.06 ppm $SO_2$ equivalent or less (only slightly above background air).

## CONCLUSIONS

1. At no time during the project did the $SO_2$ concentration exceed the Washington State ambient air standard of 0.4 ppm by volume one-hour average, either at the asphalt plant or at the laying site. The few times the concentration exceeded this near the asphalt laying machine were of brief duration and one-hour average concentrations, even during continuous laying operations, would be much lower since laying is interrupted periodically to change trucks. It should be noted that worker exposure standards are higher than ambient air standards, and so were obviously not exceeded.

2. The concentration of sulfur-gas emissions other than $SO_2$ from the asphalt mixes used was less than 0.1 ppm $SO_2$ equivalent by volume near the asphalt surface. These concentrations are much lower than either ambient air standards or worker exposure standards."

Of additional interest is that the presence of sulfur aroma has been noted in 1980 and 1981 on the highway test sections. The level of awareness seems to be a function of the sensitivity of the olfactory nerves of the individual, with some individuals admitting that the signs identifying sulfur research might have triggered if not intensified the sensation.

Monitoring of the runoff from the highway pavement is being accomplished under a separate contract with the University of Washington/Washington State University. A separate report will be made on this aspect of SEA."