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Robert N. Doty and Gary W. Mann

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Due to the questionable validity of the in-situ measurements, the accuracy of the layered elastic theory approach studied could not be conclusively determined. It was concluded that the apparent instrumentation difficulties encountered will have to be overcome before a conclusive evaluation of the layered elastic theory approach can be completed.

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Asphalt pavements, asphalt concrete, instrumentation, pavement design, pavement deflection, fatigue life, strain measurement, layered viscoelastic system, elastic theory

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DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

ANALYSIS OF FULL DEPTH AC PAVEMENTS USING LAYERED ELASTIC THEORY

FINAL REPORT

FHWA-CA-TL-3489-77-13

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Caltrans

CALIFORNIA DEPARTMENT OF TRANSPORTATION

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

FHWA No. D-4-80
TL No. 633489

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

ANALYSIS OF FULL DEPTH AC PAVEMENTS
USING LAYERED ELASTIC THEORY

Study made by . . . . Roadbed & Concrete Branch

Under the Supervision of . . . . Donald L. Spellman, P. E.

Principal Investigator . . . . Robert N. Doty, P. E.

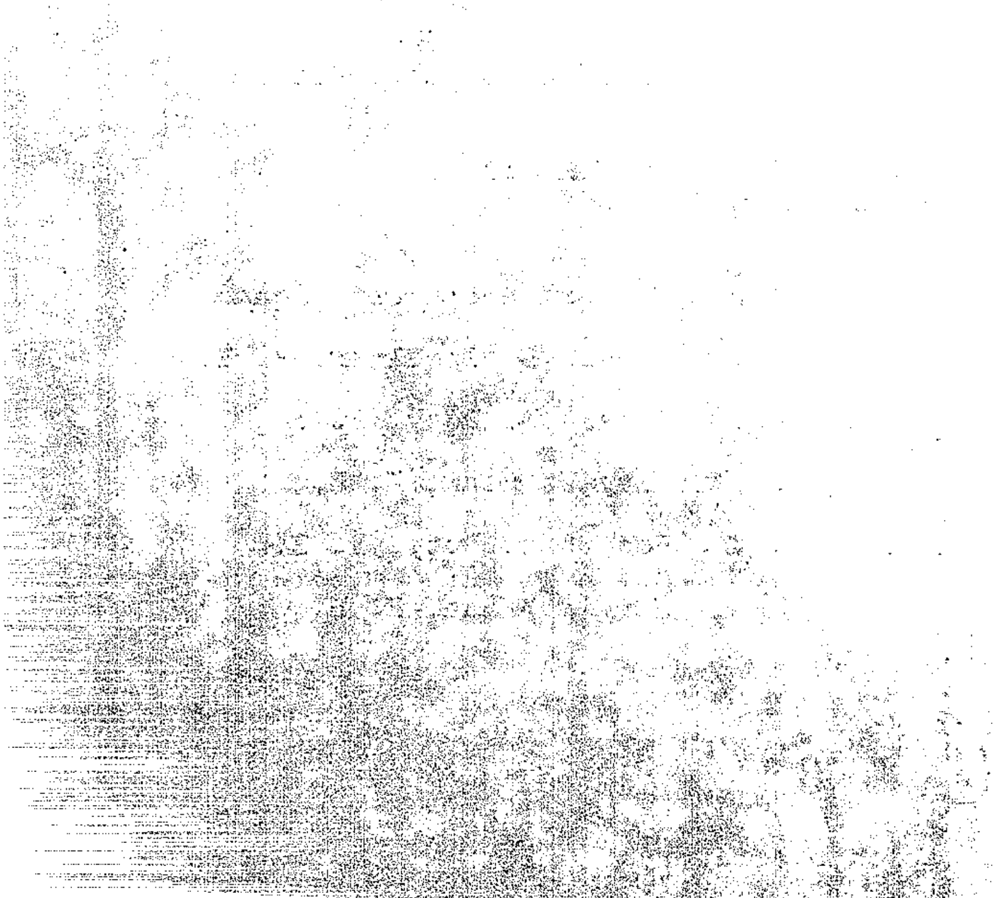
Co-Investigator . . . . Gary W. Mann, P. E.

Report Prepared by . . . . Robert N. Doty, P. E.
and
Gary W. Mann, P. E.

Very truly yours,

GEORGE A. HILL
Chief, Office of Transportation Laboratory

RND/GWM:bjs
Attachment



ACKNOWLEDGEMENTS

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The work reported herein was accomplished under Highway Planning and Research Authorization D-4-80 in cooperation with the U. S. Department of Transportation, Federal Highway Administration. The opinions, findings, and conclusions expressed are the views of the Transportation Laboratory which is responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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I. INTRODUCTION

The procedure used by the California Department of Transportation (Caltrans) when designing full depth asphalt concrete pavements is a modification of the conventional R-value design procedure(1). This R-value procedure is an empirical approach to pavement design that is based upon extensive experience. The modification used for full depth AC pavement design, however, is not based upon extensive previous experience as Caltrans' use of full depth AC has been somewhat limited. Because of the absence of this extensive previous experience, the need existed for a system that could be used to evaluate the load carrying capacity of full depth AC pavements, and thus provide a more rational approach to full depth AC design. The results of previous research reported by Carl L. Monismith of the University of California, Berkeley, indicated that layered elastic theory might provide this approach. Monismith(2) had stated that "layered system elastic theory is the most readily available theoretical representation of the response of pavements to moving wheel loads and is one which appears to produce, at least to an engineering approximation, a reasonable indication of pavement response". Monismith further stated that even though the materials comprising the structural section were not elastic within the strict definition of elasticity, the use of the assumption of elasticity within the framework of elastic theory "permits the prediction of pavement response under moving wheels to a satisfactory degree". It was reasoned that this response could be used to determine the theoretical fatigue life of the structural section for comparison with the design traffic index to complete the analysis of a structural section design. In support of this approach, Kasianchuk(3) concluded that, in general, "a sufficient body of knowledge based on laboratory investigations exists to justify the application of such data to the design of asphalt concrete pavements". However, the use of this approach involved the measurement or estimation of the subgrade resilient modulus and, because of the thermoplastic nature of AC, the calculation of theoretical temperature gradients within the AC so the stiffness of the AC pavement could be determined. In addition, a substantial portion of the AC fatigue research had been conducted using laboratory fabricated and aged test specimens in lieu of measurements of in-service pavement response. It was therefore considered worthwhile to attempt to further verify the elastic layered theory approach.

Three full depth AC pavements were subsequently instrumented during construction and the responses of these pavements under known loads measured so that comparisons with the theoretical responses could be accomplished. All three structural sections were designed using the modified R-value procedure. The pavement response was characterized by theoretical and measured stresses, strains, and deflections. Theoretical and measured temperature gradients were also obtained as well as subgrade resilient moduli. The elastic layered approach used was that developed per research conducted at the University of California, Berkeley, under the direction of Monismith.

Considerable difficulty was encountered when attempting to instrument and test the pavements. The instrumentation used and the difficulties encountered were described in the project interim report titled "Full Depth Asphalt Concrete Test Section Instrumentation", November, 1973(4). This final report contains the calculated and measured data and a discussion of the apparent "accuracy" of the layered elastic theory.

II. CONCLUSIONS AND RECOMMENDATIONS

The results of this study were generally inconclusive regarding the validity of the theoretical pavement analysis procedure used. The procedure developed by Barber to calculate pavement temperature proved to be reasonably accurate. However, the computer programs used for AC stiffness calculations, which are dependent on both pavement temperature and assumed time of loading, provided some values considerably less than those generally reported for AC. Because the AC strains and deflections are calculated using these theoretical stiffnesses, they did not generally correlate well with those measured. Also, there was considerable scatter in the data, thus indicating that the in-situ measurements were of questionable accuracy.

The fatigue life calculations, which also require these AC stiffness and strain calculations, appear to be somewhat conservative for one of the two Blythe test sections (13.4 years), quite reasonable for the Willits test section (10.7 years), and very short (1.3 years) for the other Blythe test section. Unfortunately, the accuracy of the first two calculations cannot, as yet, be determined as the test sections were constructed in the early 1970's (1971-1973). The 1.3-year period has been exceeded with no signs of fatigue distress.

Thus, the data acquired per this research project must be considered somewhat inconclusive regarding the accuracy and, therefore, the usefulness of the theoretical pavement analysis procedures studied. The difficulties encountered when attempting to measure in-situ AC pavement stress, strain, and deflection must be overcome before a conclusive in-situ evaluation of the layered elastic theory approach can be accomplished.

III. IMPLEMENTATION

Some of the instrumentation techniques developed as part of this study and described in the interim report can and will be used for future AC pavement research requiring in-situ measurement of asphalt concrete stress, strain, deflection, and/or temperature. Implementation of the remaining findings developed per this study should consist of additional study of the analytical approach by making measurements at the time of pavement construction that will be required to calculate the theoretical fatigue life, and subsequently compare this with actual in-service performance of the roadway. This approach, if done on several jobs, would be of considerable value to the Caltrans' maintenance and rehabilitation program now underway.

A simplified approach developed by Santucci(5) can be used to avoid the extensive testing and data acquisition required for the detailed computer approach used for this study. If the theoretical determination of fatigue life proves to be reasonably accurate, it can and should then be incorporated into the Caltrans' flexible pavement design procedure.

IV. DISCUSSION

A. General

The four types of pavement "failure" most frequently associated with asphalt concrete are generally described as (1) rupture, or cracking caused by load associated fatigue type failure and/or moisture and/or thermal induced stresses, (2) distortion, or rutting, which is most often caused by excessive binder and subsequent loss of stability in the AC and/or inadequate bearing strength in the supporting materials, (3) disintegration, or raveling, as often occurs when the AC asphalt content is deficient or a problem exists regarding the aggregate, and (4) bleeding, which is caused by excessive asphalt. The predominant type of AC failure on Caltrans' highways is that designated as (1) above, i.e., fatigue failure. This distress mechanism has been described as the cumulative effect of repeated load application. Monismith(2) has outlined a framework for use when determining the suitability of a proposed or existing AC structural section from the standpoint of fatigue. In essence, it consists of three major elements. These are (1) the characterization of the various materials used for the structural section, (2) the determination of the theoretical fatigue life, and (3) the comparison of this fatigue life with the projected, or design, service life. He suggests that the materials characterization procedure take the anticipated traffic and climatic conditions into account. These features would be used when selecting test conditions such as the magnitude, duration, and frequency of load application, test temperatures (for thermoplastic materials such as AC), and moisture contents for moisture sensitive subgrade materials. Although he recognized that the structural section components were not "elastic" within the classical sense, Monismith(2) concluded that, from an engineering standpoint, the use of elastic layered theory provided a means to predict pavement response (i.e., stress, strain, and deflection) under moving wheel loads to a satisfactory degree.

Due to the lack of field data supporting the contention that layered elastic theory could be used to accurately evaluate in-situ conditions, three full depth AC pavements were instrumented and subsequently tested to substantiate this contention regarding layered elastic theory. Initially, the work envisioned for this study consisted of instrumenting a full depth AC pavement under construction near Indio, California, to measure temperatures and subgrade moisture contents, then using this data and layered elastic theory to analyze the full depth AC pavement design for the Blythe and Willits (California) contracts. This was to be followed by in-situ pavement measurements to evaluate the layered elastic theory analysis procedure. Difficulties encountered with a resilient modulus testing machine constructed to test the Blythe and Willits subgrade materials and with the adaptation of the layered elastic theory computer program and associated programs to the Caltrans' computer precluded the completion of the structural section design analysis prior to the award of the construction contracts. The full depth AC structural sections were, therefore, all designed using the modified R-value procedure and constructed prior to the completion of a layered elastic theory analysis.

When developing the instrumentation plans for the Indio test section, a literature search revealed no proven techniques for measuring AC pavement stress, strain, and deflection in-situ. The plans for Indio were therefore revised to also include an evaluation of various methods of making these in-situ measurements so that "proven" procedures could be used for the instrumentation of the Blythe and Willits test sections.

The method used by the Transportation Laboratory to determine the fatigue life of an asphalt concrete pavement was essentially the method described by D. A. Kasianchuk and C. L. Monismith of the University of California's Institute of Transportation and Traffic Engineering(2) and subsequently modified by D. B. McLean(6). Basically, the method consists of three separate computer programs which are as follows:

1. The determination of the traffic weighted mean stiffness of the AC (program developed by D. A. Kasianchuk);

2. The calculation of theoretical stress, strain and deflection using the modified Chevron 5-Layer (PSAD-2) Program; and

3. The determination of the fatigue life of the asphalt concrete pavement using the procedure designated as "FATIG".

B. Test Section Description, Instrumentation, Materials Properties and Testing

Indio

The widening of Interstate 10 west of Indio afforded an opportunity to instrument the pavement at the time of construction and then test this pavement to verify the extent to which the modifed Chev 5L approach could be used to accurately calculate pavement response. The widening consisted of adding an additional lane in the median by placing 0.85 foot (259 mm) thick AC on a 0.25 foot (76 mm) thick aggregate base working table. The instrumentation included gypsum moisture blocks for use with a Buoyoucos Moisture Meter to measure subgrade moisture content, Nuclear-Chicago equipment to measure subgrade moisture content, Gentran Model GT-621 soil pressure cells to measure stress at the AC/aggregate base interface, strain gages oriented longitudinally and transversely within the AC to measure AC strain in each direction at several distances below the pavement surface, Type J Iron-constatan thermocouples to measure AC temperature at several distances below the pavement surface, and linear variable differential transformers (LVDT's) to measure AC deflection at several distances below the surface. In addition, pavement surface deflections were measured with the California Deflectometer (TM No. Calif. 356) as this equipment was used to apply the moving load to the pavement during testing. Details regarding this instrumentation are included in the 1973 interim report by Svetich(4). The temperature and moisture data were required for the computer programs used to calculate pavement stress, strain, deflections and theoretical fatigue life. The in-situ measurements of stress, strain, and deflection were obtained for comparison with the calculated values.

Considerable instrumentation difficulties with strain gages and pressure cells were encountered at the Indio test site. Strain-gage casualty rates (failures) were excessive, and it was not realized that some of the gages had failed until after the tests were completed. The limited moisture and strain data made it difficult to analyze the Indio data. Because of the climatic similarity of the Indio and Blythe test sections, and the similarity between the Indio structural section and one of the structural sections tested at Blythe, the decision was made to fully analyze only the Blythe and Willits test section results.

Blythe

The Blythe project is a four lane divided freeway (Interstate 10) which by-passes the City of Blythe, California. Blythe is located in the "low" California desert adjacent to the Colorado River. The climate in Blythe is hot and dry, with the average maximum daily temperature being greater than 100°F (38°C) between June and September. The average minimum temperature during the cool months (December and January) is above 40°F (4°C). The average yearly rainfall is about two inches (51 mm). Two 1000 foot (305 m) sections were set aside as test sections. Originally, the structural section designs were to be analyzed using elastic layered theory and modified as required prior to construction; however, due to mechanical difficulties with the equipment required to measure the resilient modulus of the subgrade and difficulties with the modified Chev 5L computer program adaptation to Caltrans' computer facilities, it was not possible to use this procedure prior to construction. Therefore, these sections were designed using the California modified R-value method then in use for full depth AC pavements.

The test section locations and their design structural thicknesses were as follows:

Test Section	Location	AC Design Thickness
A	Sta 265+00 to Sta 275+00 #2 Eastbound Lane (Travel lane)	0.85' (259 mm)
B	Sta 366+00 to Sta 376+00 #2 Eastbound Lane (Travel lane)	1.50' (457 mm)

The AC was placed directly on the subgrade material. The subgrade material of test section A was a silty sand with an R-value(7) in excess of 70. This is equivalent to a CBR in excess of 37. Test section B was originally designed assuming that an inorganic clay subgrade material with an R-value of less than 15 (CBR of less than 2.5) would be imported for the test section. However, the "low R-value" material subsequently used was of considerably higher quality than originally thought. Thus, a clayey-silt material with an R-value of 62 was used as test section B subgrade material.

A material characteristic required to calculate the theoretical otress, strain, and deflection at various locations within the AC is the subgrade resilient modulus i.e., the ratio of stress to recoverable (elastic) strain. For California Class 2 aggregate base material(8), McLean has concluded that the resilient modulus can be characterized using the equation

$$M_R = 3470\ (\theta)^{0.65}$$

where θ is the sum of the principal stresses(9). The measurement of the resilient modulus of more cohesive materials has revealed a relationship of the form

$$M_R = K_1 (\sigma_3)^{K_2} \tag{9}$$

where K_1 and K_2 are constants and σ_3 is the confining pressure.

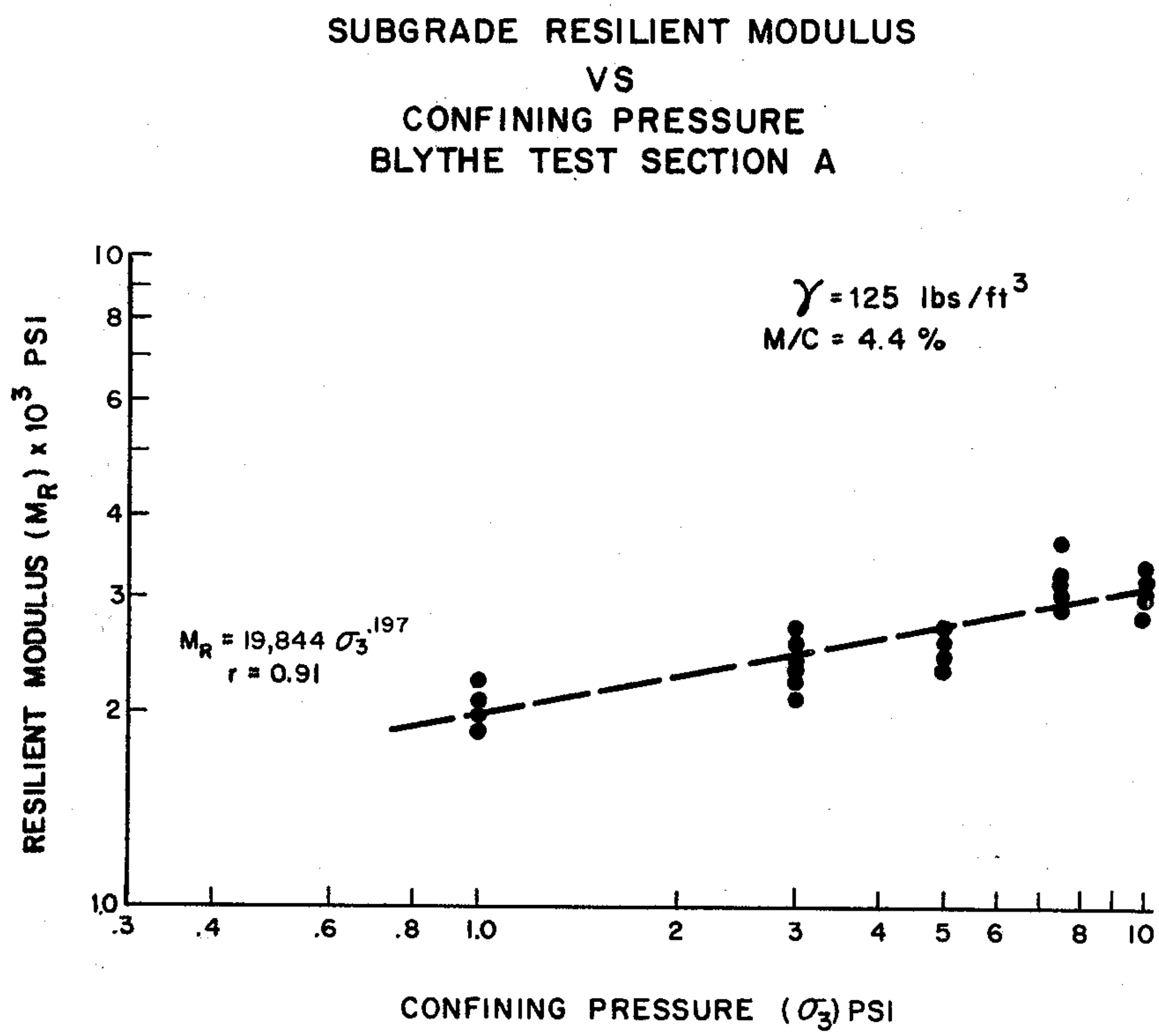
To determine the resilient modulus of the Blythe subgrade materials, samples of each material were tested at moisture contents approximating the in-situ conditions (4-5%).

The tests were conducted in conformance with the test method contained in Appendix A of Reference 9. Linear regression analyses were completed for the log-log relationship of resilient modulus versus the sum of principal stress, and resilient modulus versus confining pressure (Figures 1 thru 4). The results for both test sites indicated that the resilient modulus was essentially independent of the confining pressure as the range of measured M_R values was from 20,000 psi to 30,000 psi (138 to 207 MPa) for confining pressures of from 1 to 10 psi (6.9 to 68.9 KPa). It was therefore concluded that for the confining pressures anticipated at the base surface (3 to 5 psi (20.7 to 34.5 kPa)), a somewhat conservative resilient modulus of 25,000 psi (172 MPa) would be used for the calculations of AC stress, strain, and deflection at all the Blythe test sites.

Tables 1 and 2 show the physical properties of the asphalt concrete and subbase materials used for the Blythe projects. This data was discussed in detail in the interim report(4).

The test section instrumentation installed at Blythe was similar to that used for the Indio test section. Because of problems encountered at Indio with the Gentran pressure cells, stress gages of the type used by the University of California(10) were constructed and installed beneath the AC at the Blythe test

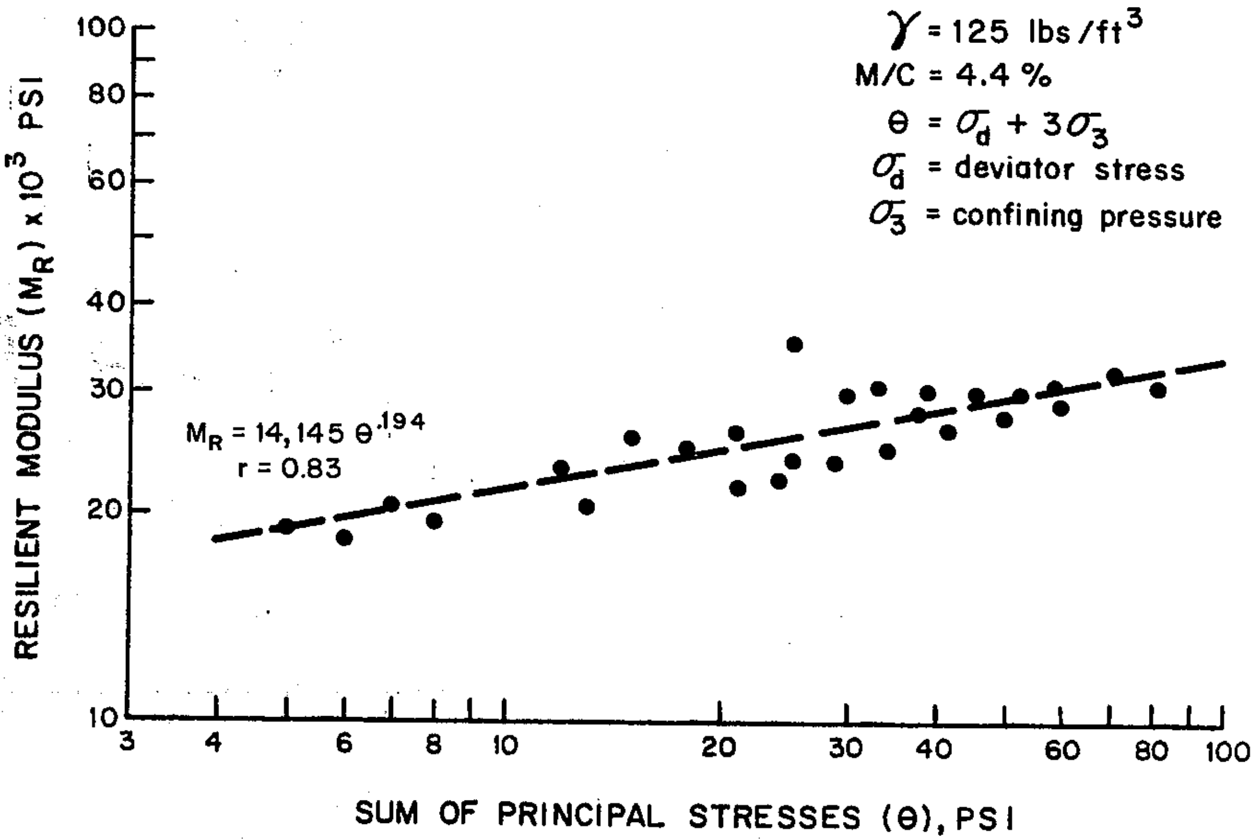
Figure 1



NOTE: 1000 psi = 6.89 MPa
1 psi = 6.89 kPa
1 pcf = 16.02 kg/m³

Figure 2

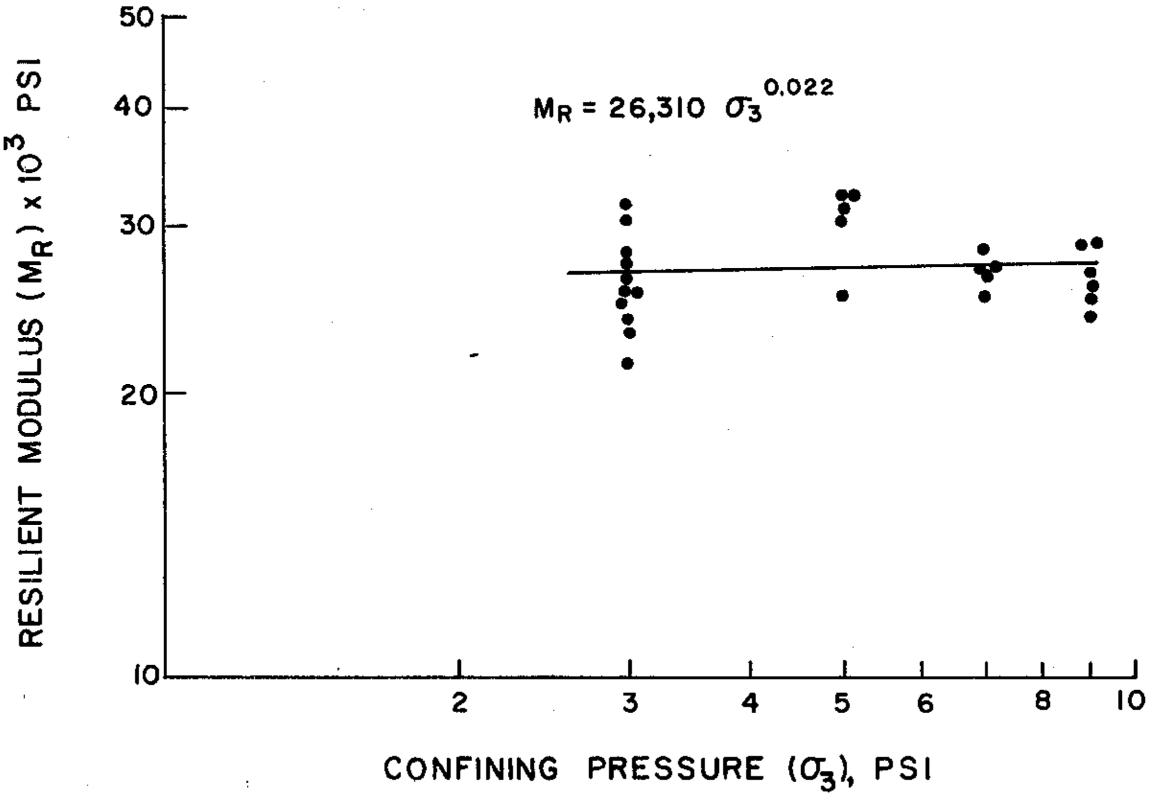
SUBGRADE RESILIENT MODULUS
VS
SUM OF PRINCIPAL STRESSES
BLYTHE TEST SECTION A



NOTE: 1000 psi = 6.89 MPa
1 psi = 6.89 kPa
1 pcf = 16.02 kg/m^3

Figure 3

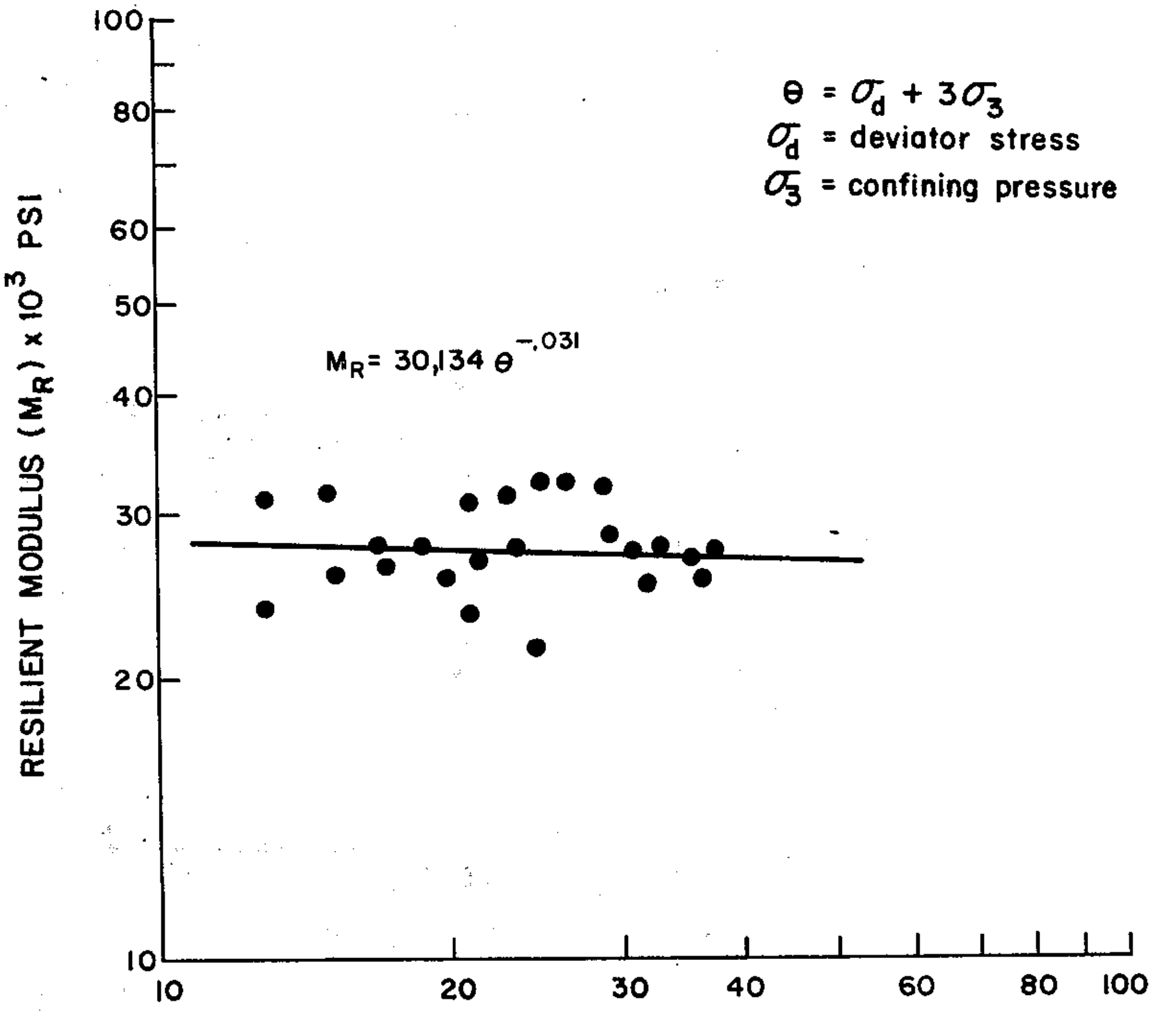
SUBGRADE RESILIENT MODULUS VS CONFINING PRESSURE BLYTHE TEST SECTION B



NOTE: 1000 psi 6.89 MPa
1 psi 6.89 kPa

Figure 4

SUBGRADE RESILIENT MODULUS VS SUM OF PRINCIPAL STRESSES BLYTHE TEST SECTION B



NOTE: 1000 psi = 6.89 MPa
1 psi = 6.89 kPa

Table 1

BLYTHE TEST SECTION
ASPHALT CONCRETE PROPERTIES

AC Type	Test Section A Design Thickness (Ft.)	Test Section A "As Built" (July, 1972) 273+00 (Ft.)	Test Section A "As Built" (July, 1972) 274+00 (Ft.)	Test Section B Design Thickness (Ft.)	Test Section B "As Built" (July, 1972) 374+00 (Ft.)	Test Section B "As Built" (July, 1972) 375+00 (Ft.)
OGAC	0.05	0.03	0.04	0.05	0.04	0.05
AC Surf.	0.20	0.32	0.31	0.30	0.17	0.16
					0.15	0.20
AC Base	0.60	0.18	0.26	1.20	0.27	0.27
		0.40	0.33		0.29	0.27
					0.25	0.29
					0.28	0.29
Total	0.85	0.93	0.94	1.55	1.45	1.53

Asphalt Grade:
ACS 120-150
ACB 85-100

Asphalt Content:
ACS 4.4%
ACB 3.9%

Properties of Material Recovered From Cores Taken January, 1973
(Material from Sections A & B combined, then tested)

	Percent Asphalt	Percent Voids	Pen. @ 77°F	R&B Soft Pt.	Ductility @ 77°F	Gradation - Percent Passing 1	3/4	1/2	3/8	#4	#8	#30	#200
Surface AC	3.9	8.8	45	118°F	150+	100	97	83	72	49	37	22	6
Base AC	3.6	6.3	31	129°F	150+	100	96	76	61	46	38	24	6

Note: 1 Ft = 30.5 mm
77°F = 25°C

Table 2

BLYTHE TEST SECTION SUBGRADE PROPERTIES

Grading (% Passing)	Test Section A	Test Section B
1-1/2 (38 mm)	100	
1 (25 mm)	99	
3/4 (19 mm)	99	
1/2 (13 mm)	98	
3/8 (10 mm)	98	
No. 4	96	
8	95	
16	92	
30	86	
50	65	100
100	33	98
200	20	83
5µ	11	17
1µ	7	10
R-value (TM No. Calif. 301)	73	62
% Moist. @ 300 psi (20.7 MPa) exud. pressure	11.6	15.3
Dry density (TM No. Calif. 216)	121 pcf (1937 kg/m^3)	110 pcf (1762 kg/m^3)
Resilient Modulus (M_R) (Per procedure in Ref. 9, Appendix A)	25000 psi (172 MPa)	25000 psi (172 MPa)

sections. Some additional methods of measuring AC strain were tried in addition to most of those used at Indio. To measure pavement temperature, Type J Iron-constatan thermocouples were again used and an attempt again made to measure subgrade moisture content using a nuclear gage. In-situ deflection was also again measured using LVDT's and, for comparison, a Benkleman beam (surface deflection only). The instrumentation used is shown schematically on Figures 5 and 6. The lift thicknesses were determined by coring the pavement at the conclusion of the testing.

During the period from January 12 through January 17, 1973, the Blythe test sites were tested. A dual-wheel dump truck loaded with sand (18,600 pound (8,165 kg) axle load) was used for this testing. The tire pressure was 80 psi (552 kPa). Several runs were made at speeds of less than 3 mph (1.3 m/s) and the location of the dual wheel path noted with respect to the location of the strain gauges and LVDT's. The location of the truck relative to the instrumentation was required to identify those runs for which either the dual tires or one of the duals was centered (visually) over the strain gauges and LVDT's as these are the conditions assumed for the modified Chev 5L Program. Tables 3-6 show the results of the runs that were considered "good" by this process for the four test sites (two locations each within Test Sections A and B). Not all the gauges for each run gave what appeared to be reliable data. This is noted on the tables.

During the construction of the Blythe B Test Sections, gauges placed on or in the first two lifts were located in the outer wheel path of the travel lane and were subsequently damaged by construction traffic. Consequently, on subsequent lifts the gauges were placed 2 feet (0.61 m) inside the wheel path to

Figure 5

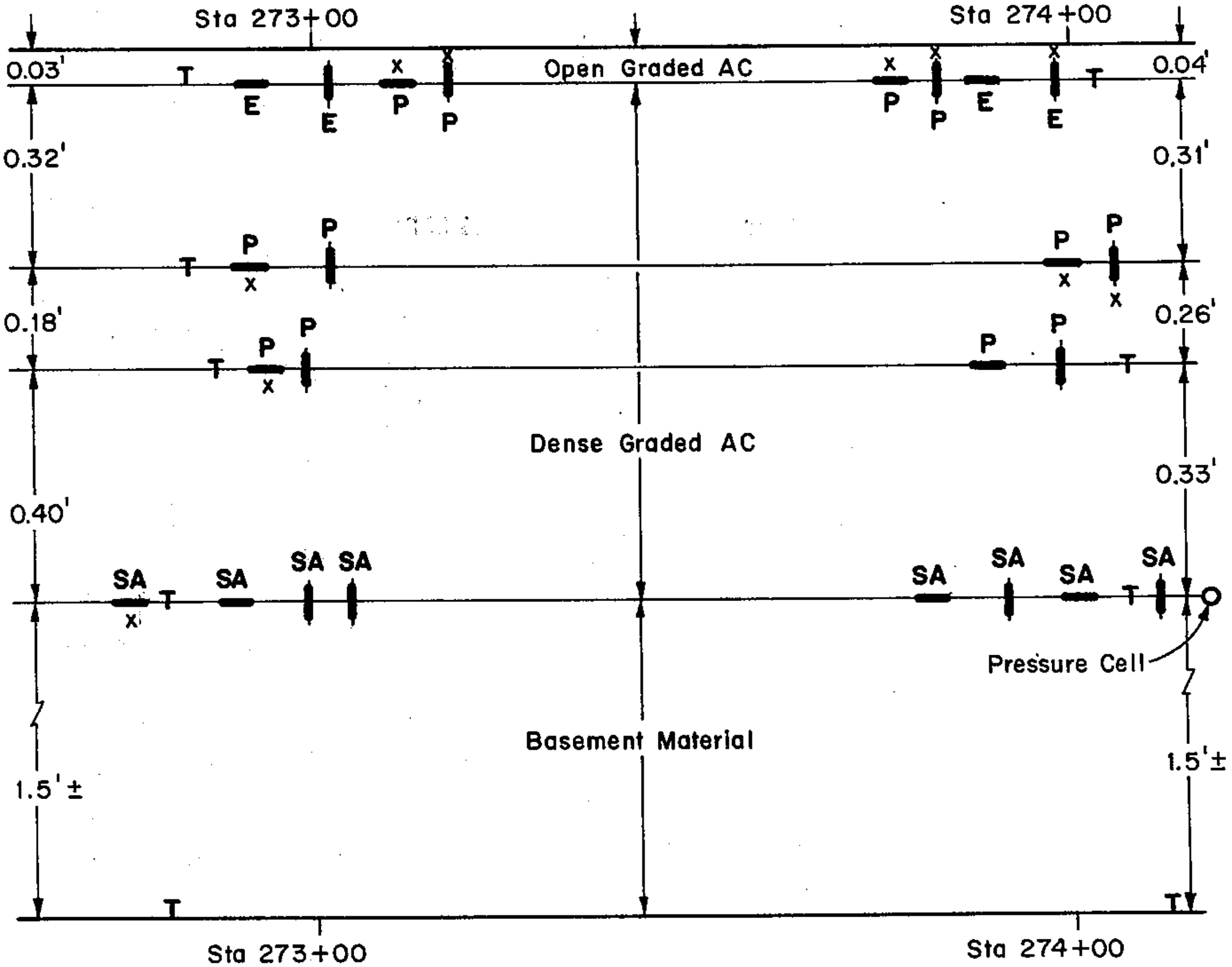
INSTRUMENTATION

BLYTHE

TEST SECTION A

Axle Load = 18600 lbs. (8437 kg)
Wheel Load = 4650 lbs. (2109 kg)
Tire Pressure = 80 psi (552 KPa)

Working Strain Gauges:
Longitudinal 6 of 12 = 50%
Transverse 8 of 12 = 67%



Lift thicknesses shown were determined from cores. 1 Ft. = 305 mm

(vertical bar symbol) = Strain gauges placed transversely.
(horizontal bar symbol) = Strain gauges placed longitudinally.
T = Thermocouple.
SA = Strain gauge adhered to sand asphalt carriers.
P = Strain gauge adhered to polymide sheets.
E = Strain gauge epoxied to pavement.
x = Inoperative strain gauge

Figure 6

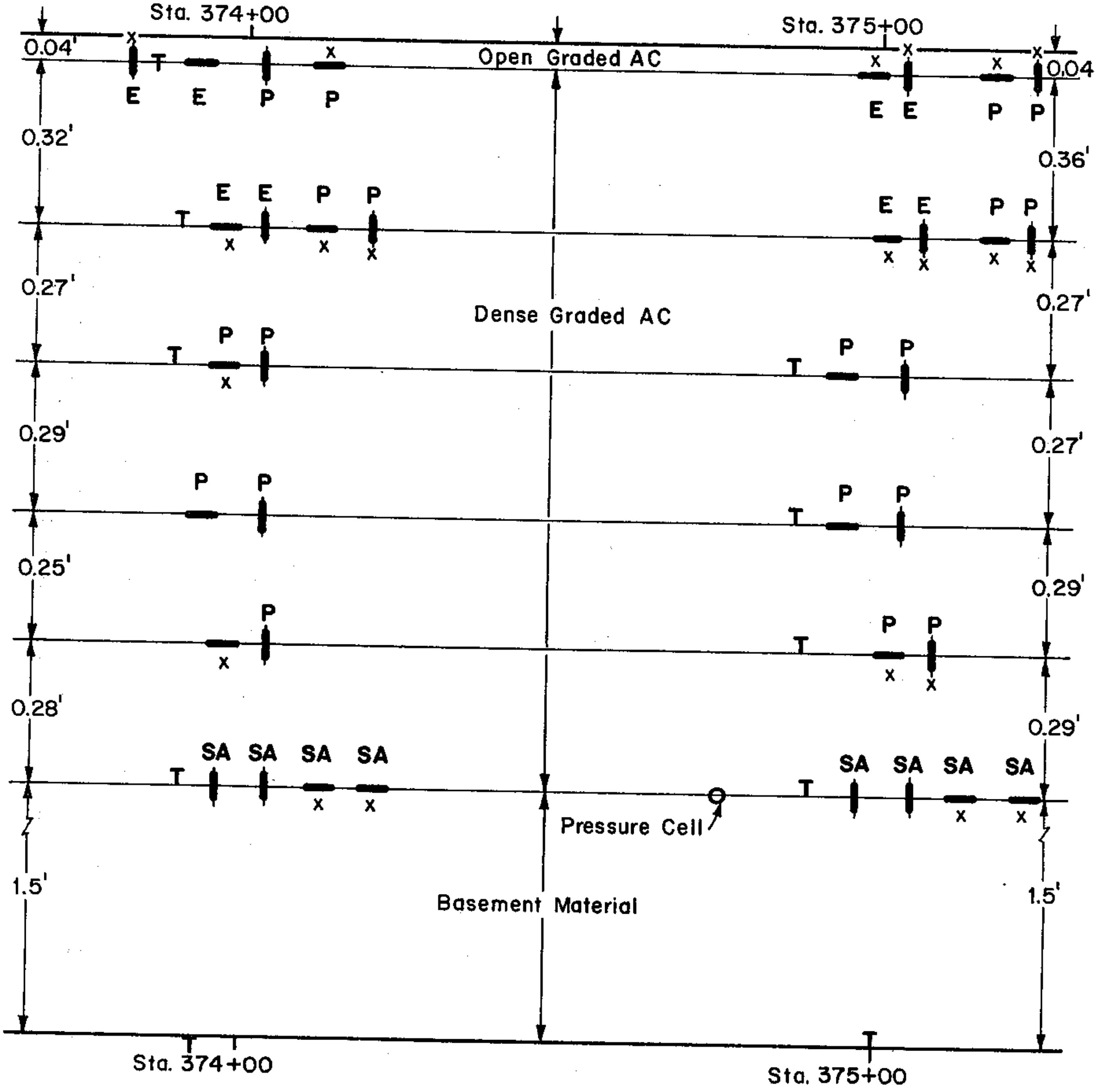
INSTRUMENTATION

BLYTHE

TEST SECTION B

Axle Load = 18600 lbs.(8437 kg)
Wheel Load = 4650 lbs. (2109 kg)
Tire Pressure = 80 psi (552 KPa)

Working Strain Gauges:
Longitudinal 4 of 18 = 22%
Transverse 11 of 18 = 61%



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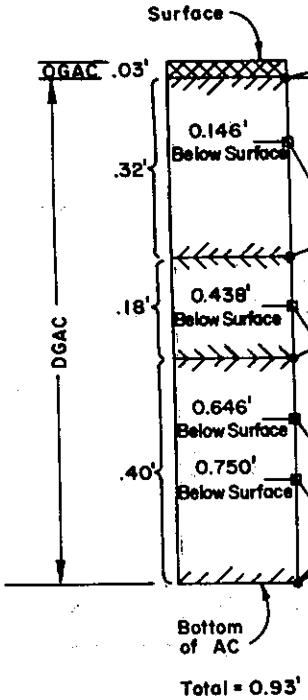
x = Inoperative strain gauge

Table 3

STRAIN DATA
BLYTHE TEST SECTION A
STATION 273+00

Weight on dual tires = 4650 lbs (2109 kg) per tire
Tire pressure = 80 psi (552 kPa)



MAXIMUM STRAIN, MICRO-INCHES PER INCH

LONGIT. OR TRANS.	STRAIN GAUGE NO.	EPOXIED, POLYMIDE OR SAND-ASPHALT CARRIER	RUN #11 1-12-73 11:40 0.90 MPH	RUN #12 1-12-73 11:45 0.68 MPH	RUN #14 1-12-73 11:50 0.98 MPH	RUN #13 1-12-73 11:47 0.62 MPH	RUN #15 1-12-73 11:55 0.75 MPH
L	71	E	E_o	115T	E	72 C	104 C
T	72	E	E_o	83 T	E_o	151C	123C
T	28	P	41 C	48 C	46 C	E_o	49 C
T	42	P	11 C	17 C	16 C	20C	13C
T	14	S	40T	54 T	43 T	84T	44 T
T	10	S	46 T	60 T	45 T	108 T	51 T
L	9	S	105 T	140T	110T	128 T	130T
			MAXIMUM DEFLECTION – INCHES				
LVDT	1		.0082	.0082	.0080	.0080	I
LVDT	2		.0082	.0085	E	I	.0090
LVDT	3		.0095	.0100	.0100	.0105	.0100
LVDT	4		.0080	.0080	.0082	I	I

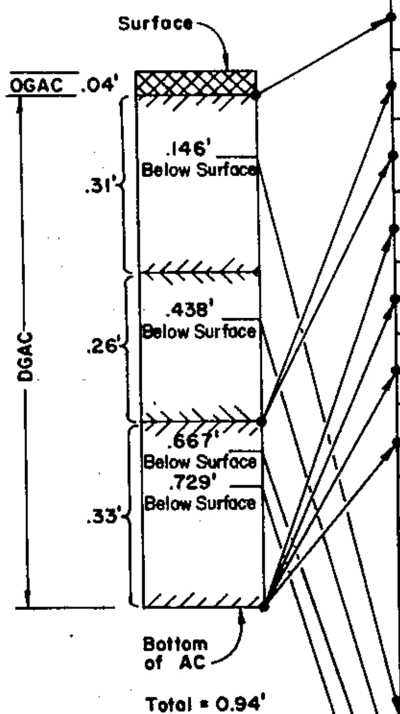
NOTE:
1 MPH = 0.447 m/s
1 Ft = 305 mm

Legend:

I = Incorrect wheel placement over the gauges.
E = Erratic load trace on the chart.
E_o = Erratic zero load trace – Impossible to get a confident reading.
T = Tension
C = Compression

Table 4
STRAIN DATA
BLYTHE TEST SECTION A
STATION 274+00

Weight on dual tires = 4650 lbs (2109 kg) per tire
Tire pressure = 80 psi (552 kPa)



MAXIMUM STRAIN, MICRO-INCHES PER INCH

LONGIT. OR TRANS.	STRAIN GAUGE NO.	EPOXIED, POLYMIDE OR SAND-ASPHALT CARRIER	RUN #20 1-12-73 15:03 0.40 MPH	RUN #23 1-12-73 15:18 0.90 MPH	RUN #24 1-12-73 15:21 0.70 MPH	RUN #26 1-12-73 15:25 0.55 MPH	RUN # 18 1-12-73 14:53 0.68 MPH	RUN # 19 1-12-73 14:58 0.25 MPH	RUN #22 1-12-73 15:13 0.40 MPH
L	73	E	158c	58c	113c	137c	E	160c	E
T	46	P	E	E	E	E	E	E	E
L	45	P	E	E	E	E	E	E	E
T	12	S	82T	56T	80T	80T	86T	91T	91T
L	11	S	94T	78T	84T	85T	97T	100T	93T
T	16	S	96T	41T	86T	82T	92T	94T	94T
L	15	S	60T	40T	52T	52T	54T	61T	53T
LOAD CELL			7.11 psi	8.37 psi	4.71 psi	5.23 psi	5.75 psi	7.53 psi	6.69 psi
MAXIMUM DEFLECTION – INCHES									
LVDT	1		I	.0105	.0100	.0108	.0115	I	.0110
LVDT	2		E	.0120	.0112	.0125	.0125	I	.0125
LVDT	3		.0130	.0125	.0120	.0125	.0125	E	.0113
LVDT	4		I	.0085	.0090	.0090	.0095	E	.0095

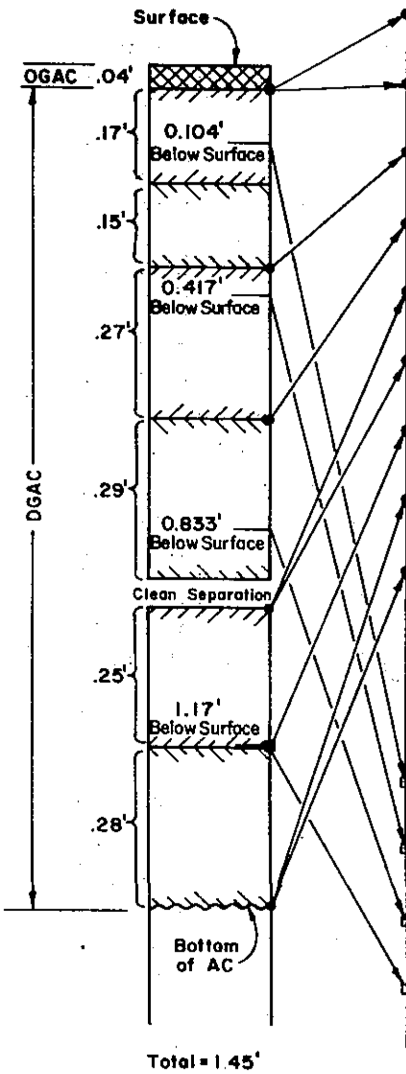
NOTE:
1 MPH = 0.447 m/s
1 Ft = 305 mm
1 PSI = 6.89 kPa

Legend:

I = Incorrect wheel placement over the gauges.
E = Erratic load trace on the chart.
T = Tension
C = Compression

Table 5

STRAIN DATA
BLYTHE TEST SECTION B
STATION 374 + 00



MAXIMUM STRAIN, MICRO-INCHES PER INCH

LONGIT. OR TRANS.	STRAIN GAUGE NO.	EPOXIED, POLYMIDE OR SAND-ASPHALT CARRIER	RUN #101 1-16-73 14:25 0.70 MPH	RUN #102 1-16-73 14:29 0.90 MPH	RUN #113 1-16-73 15:50 1.18 MPH	RUN #115 1-16-73 15:56 1.00 MPH	RUN #106 1-16-73 14:58 0.78 MPH	RUN #107 1-16-73 15:10 0.98 MPH	RUN #112 1-16-73 15:48 1.15 MPH	RUN #114 1-16-73 15:53 1.15 MPH	RUN #103 1-16-73 14:32 0.90 MPH	RUN #105 1-16-73 14:47 0.90 MPH	RUN #109 1-16-74 15:20 0.85 MPH	RUN #111 1-16-74 0.90 MPH	RUN #117* 1-16-74 16:00 1.00 MPH
L	67	E	39	44C	I	I	28c	37c	I	I	36C	39C	33c	36c	I
T	30	P	E	71C	I	I	E	E	I	I	39C	38C	37c	47c	I
T	7	E	20C	20C	I	I	14c	15c	I	I	18C	19C	19c	20c	I
T	48	P	16C	19c	I	I	14c	14c	I	I	17c	16C	20C	17c	I
T	52	P	6c	7C	I	I	8c	5C	I	I	7c	4C	6C	4C	I
L	51	P	8T	9T	I	I	9T	10T	I	I	4T	8T	9T	9T	I
T	54	P	I	I	11T	13T	I	I	4T	2T	I	I	I	I	12T
T	4	S	I	I	17T	13T	I	I	16T	17T	I	I	I	I	17T
T	8	S	I	I	33T	32T	I	I	30T	26T	I	I	I	I	42T
MAXIMUM DEFLECTION — INCHES															
LVDT	1		.0040	N	I	I	.0036	.0042	I	I	.0038	.0035	E	.0034	I
LVDT	2		.0041	N	I	I	.0039	.0042	I	I	.0038	.0040	.0040	.0039	I
LVDT	3		.0038	N	I	I	.0040	.0036	I	I	.0037	.0038	.0040	.0040	I
LVDT	4		.0042	N	I	I	.0040	.0038	I	I	.0040	.0040	.0039	.0040	I

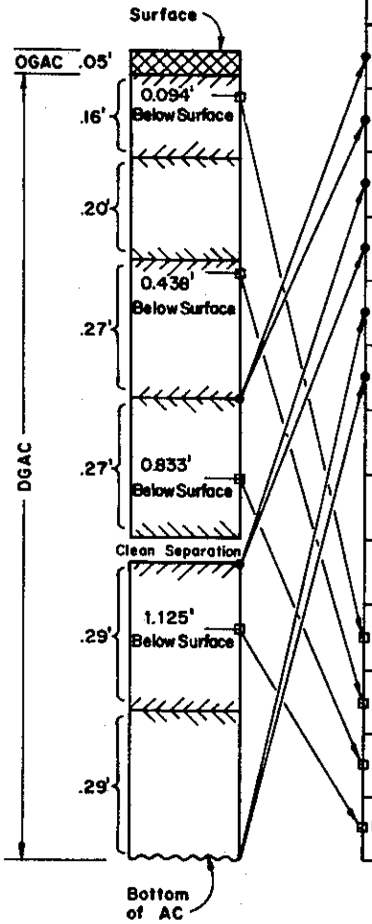
NOTE: There are two separate runs marked #117-One at sta. 374 & one at 375 (Runs #116, 117, & 118 exist for both sta. 374 & 375)

1 MPH = 0.447 m/s
1 Ft = 305 mm

Legend:

I = Incorrect wheel placement over the gages shown; (This was due to the fact that gauges TS4P, T4S, & T8S were placed 2' laterally from the remaining gauges, and separate runs had to be made over them.)
E = Erratic load trace on chart.
N = No recording was made of the force traces this run.
T = Tension
C = Compression

Table 6
STRAIN DATA
BLYTHE TEST SECTION B
STATION 375+00



MAXIMUM STRAIN, MICRO-INCHES PER INCH

LONGIT. OR TRANS.	STRAIN GAUGE NO.	EPOXIED, POLYMIDE OR SAND-ASPHALT CARRIER	RUN #117*, 1-17-73, 10:20, 1.18 MPH	RUN #118, 1-17-73, 10:37, 0.65 MPH	RUN #119, 1-17-73, 10:40, 0.75 MPH	RUN #127, 1-17-73, 11:04, 0.68 MPH	RUN #130, 1-17-73, 11:13, 0.95 MPH	RUN #134, 1-17-73, 11:20, 0.90 MPH	RUN #122, 1-17-73, 10:50, 0.85 MPH	RUN #124, 1-17-73, 10:56, 0.65 MPH	RUN #116, 1-17-73, 10:17, 1.00 MPH	RUN #121, 1-17-73, 10:45, 1.12 MPH	RUN #128, 1-17-73, 11:07, 0.58 MPH	RUN #135, 1-17-73, 11:19, 0.92 MPH
T	44	P	E_o	7c	10c	E	I	I	18c	12c	15c	15c	15c	I
L	43	P	E_o	E	18T	17T	I	I	15c	8T	18T	15c	11T	I
T	50	P	22T	30T	F	25T	I	I	12T	10T	20T	20T	21T	I
L	49	P	5T	11T	F	9T	I	I	5T	9T	12T	11T	11T	I
T	6	S	I	I	I	I	19T	36T	I	I	I	I	I	32T
T	2	S	I	I	I	I	25T	21T	I	I	I	I	0.0	18T
LOAD CELL			3.24 psi	3.66 psi	F	3.97 psi	I	I	3.03 psi	3.14 psi	3.35 psi	3.97 psi	3.66 psi	I
MAXIMUM DEFLECTION - INCHES														
LVDT	1		.0042	.0045	F	.0035	I	I	.0040	.0042	.0032	.0032	.0035	I
LVDT	2		.0032	.0038	F	.0039	I	I	.0032	.0035	.0033	.0035	.0038	I
LVDT	3		.0038	.0040	F	.0042	I	I	.0038	.0038	.0037	.0040	.0045	I
LVDT	4		E	.0030	F	.0038	I	I	.0030	.0032	E	.0028	.0035	I

NOTE: There are two separate runs marked #117-One at sta. 374 & one at 375 (Runs #116, 117, & 118 exist for both sta. 374 & 375)

1 MPH = 0.447 m/s
1 Ft = 305 mm
1 PSI = kPa

Legend:

I = Incorrect wheel placement over the gages shown; (This was due to the fact that gauges TS4P, T4S, & T8S were placed 2' laterally from the remaining gauges, and separate runs had to be made over them.)

E = Erratic load trace on chart.

F = Traces too faint to be read on the chart. Paper or exposure problem.

E_o = Erratic zero load trace - impossible to get a confident reading.

T = Tension

C = Compression

avoid further damage of this type. This is the reason for the notation (I), incorrect wheel placement, shown on the data summary sheets.

The percentage of working gauges for each direction (transverse and longitudinal) is shown on Figures 5 and 6. Roughly one half of the gauges (52%) were lost during the construction phase, with the highest percentage of those lost being the gauges placed in the longitudinal direction. As discussed in the interim report (Ref (4) page 36), the majority of the longitudinal gauges failed during the breakdown rolling of the AC lift containing the gauges. It was considered particularly unfortunate that due to gauge failure no direct comparison was possible between gauges epoxied directly to the top surface of the lower lift and gauges epoxied to polymide sheets which were in turn attached to the top surface of the lower lift.

Willits

The Willits project (01-Men-101, 01-111804) consisted of widening and resurfacing U.S. Route 101 in the central portion of the City of Willits. Willits is located about 120 miles (193 km) north of San Francisco and 30 miles (48 km) inland from the Pacific coast. Its annual rainfall is about 44 inches (1,118 mm) per year, with the largest portion of that coming during November through March. The climate in the winter is cool and wet, with the average minimum temperature around 30°F (-1°C) for January. In the summer it is warm and dry, with the average maximum temperature around 87°F (31°C) in July and August. The project involved the addition of a left-turn lane in the middle of the two lane roadway. This required the construction of a full-depth asphalt concrete section 1.0 foot (305 mm) thick along the outside of the existing traveled way. This full-depth section was designed using the California modified R-value method. The instrumentation was placed in the AC at Stations 139+00 and 140+00 in the new southbound travel lane.

The design AC thickness of 1.0 foot (305 mm) consisted of 0.92 feet (280 mm) of dense graded asphalt concrete and .08 feet (25 mm) of open-graded asphalt concrete surfacing. The subbase material at the test location was fill material from the previous construction project. For this project, the old asphalt concrete shoulder and some of the subgrade soil were removed. The exposed surface of the remaining subgrade material was then compacted to comply with the following specification:

"The subgrade shall be thoroughly compacted to form a firm, stable base before placing the asphalt concrete."

Table 7 (see page 26) contains the results of several soil characterization tests of the Willits subgrade soil. A 10 percent moisture content (dry density = 130 pcf (2083 kg/m^3)) was selected as the appropriate moisture content for the 95 percent relative compaction that normally is required of subgrade material by Caltrans. The 10 percent moisture content was then used for resilient modulus tests of this soil. The test results are shown on Figure 7 and the values selected for the modified Chev 5L calculations are shown in Table 8, below:

Table 8

DEVIATOR STRESS VS. RESILIENT MODULUS
WILLITS TEST SECTION

Deviator Stress (σ_d) psi	Resilient Modulus (M_R) psi
3	48,000
6	41,000
9	37,000

Note: 1,000 psi = 6.89 MPa
1 psi = 6.89 kPa

Table 7

WILLITS TEST SECTION
SUBGRADE PROPERTIES

R-value	- 60
Liquid Limit	- 24
Plastic Limit	- 21
Plasticity Index	- 3
Unified Soil Classification System - Corps of Engrs Gravelly, Silty Sand	- SM
Specific Gravity	- 2.69

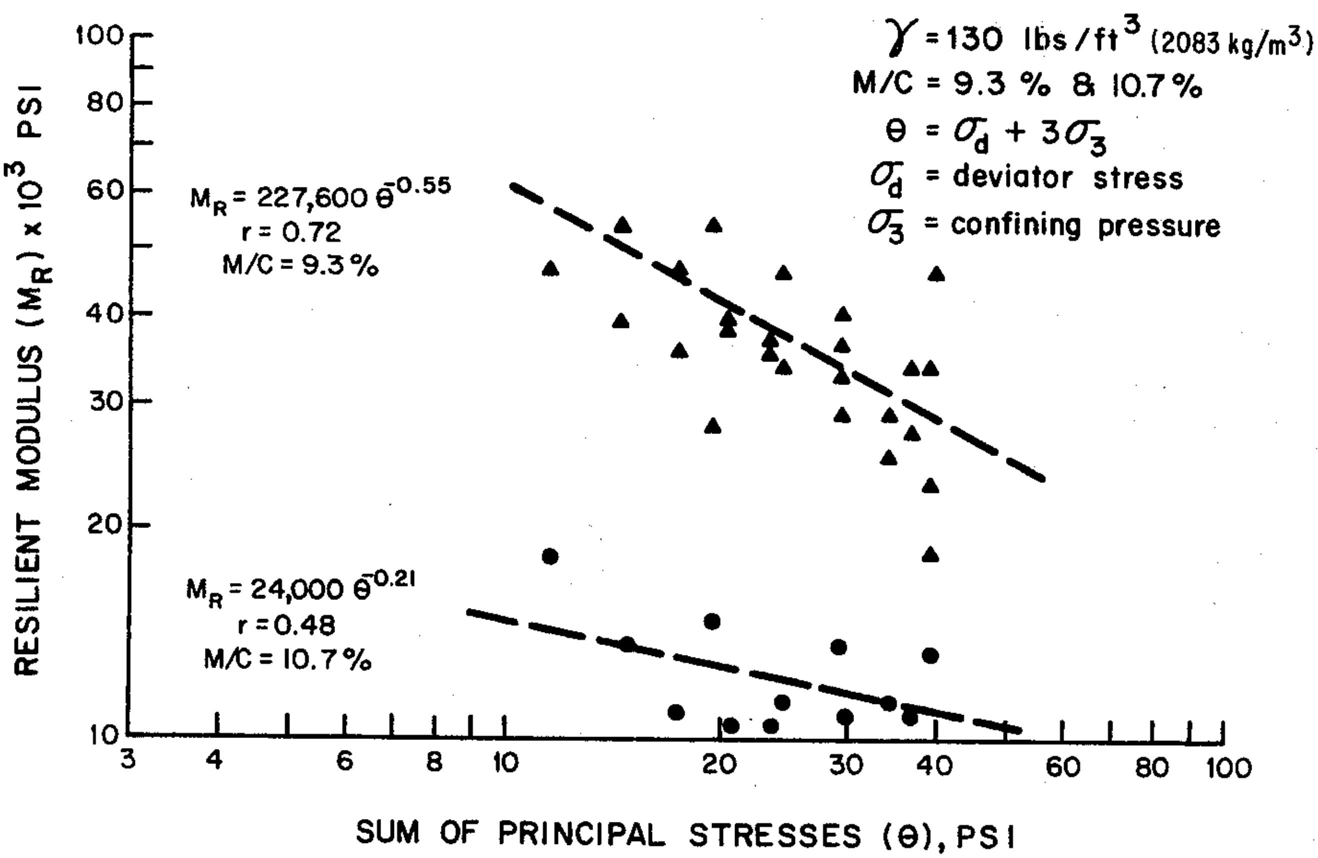
Grading Analysis

Sieve Size	In Place	As Used For Resilient Modulus Tests
2 (51 mm)	100	
1-1/2 (38 mm)	99	
1 (25 mm)	97	
3/4 (19 mm)	94	100
1/2 (13 mm)	89	95
3/8 (10 mm)	86	92
#4	74	79
8	67	71
16	61	65
30	56	60
50	49	52
100	38	40
200	31	33
5 Micron	12	13
1 Micron	5	5

Moisture Content (%)	Dry Density (pcf - TM No. Calif. 216)
6.0	130.0 (2083 kg/m3)
8.0	135.0 (2163 kg/m3)
10.0	130.3 (2087 kg/m3)

Figure 7

SUBGRADE RESILIENT MODULUS VS SUM OF PRINCIPAL STRESSES WILLITS TEST SECTION



NOTE: 1000 psi = 6.89 MPa
1 psi = 6.89 kPa

FROM REFERENCE (11)

The properties of the asphalt concrete from the Willits test section are summarized in Table 9.

Table 9

ASPHALT CONCRETE PROPERTIES
WILLITS TEST SECTION

Item	Distance Below Surface (Ft.)	Aspahlt Grade	Percent Asphalt
AC Surface	0.08 to 0.20	85-100	5.7
AC Base	0.20 to 1.08	85-100	5.4
Unit Weight			140 pcf
Void Content			10.0%
Volume Concentration of Aggregate			0.886
Properties of Recovered Asphalt			
Penetration @ 77°F (25°C)			57
Ring and Ball Softening Point. . . .			128°F (53°C)

Notes: 1 ft = 305 mm
1 pcf = 16.02 kg/m^3

The test section instrumentation used at Willits was very similar to that used at Blythe. There were, however, some changes in the strain gauge instrumentation and procedures tried. Also, an Austron Inc. Model DL-1200 Digilogger was used to record the temperature measurements obtained with the thermocouples placed within the pavement. Stress at the AC/subgrade interface was again measured using stress gauges identical to those used at Blythe. Deflections were also again measured using LVDT's affixed to brackets placed at various distances below the AC surface. This procedure was identical to that used at Blythe. In addition to the LVDT's, the California Deflectometer and a Benkleman beam were both used to measure the AC surface deflections during the test runs. The location of the instrumentation used is shown schematically on Figure 8. Fortunately, a higher percentage of the gauges was operational during the field tests than was true at Blythe. As at Blythe, the casualty rate for the longitudinal gauges at Station 140+00 was higher than that for the transverse gauges of Station 140+00.

The testing was completed during the week of June 13-17, 1973. The California Deflectometer was used as the test vehicle. This dual-wheeled truck had an axle load of 18,800 pounds (8527 kg) and a tire pressure of 70 psi (483 kPa).

To determine the actual AC lift thicknesses and total depth of asphalt concrete, cores were taken at each test site. Tables 10 and 11 show the measured lift thicknesses and the location of the working strain gauges and the linear variable differential transformers (LVDT's).

C. AC Temperature

Indio

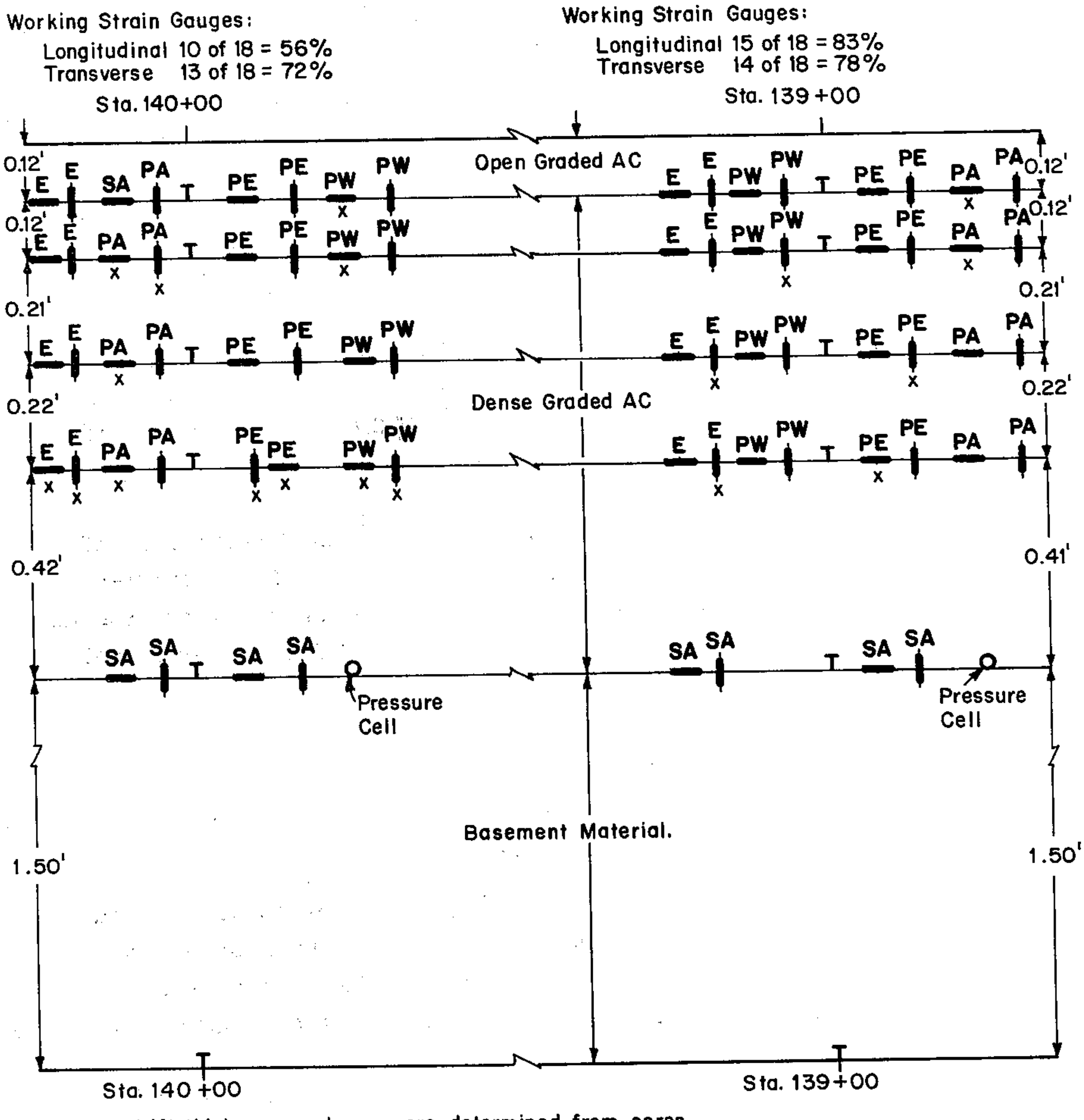
Indio weather data for June 22 and 23, 1971 were obtained from the U. S. Department of Commerce National Climatic Center in Asheville, North Carolina, and used to calculate theoretical pavement temperatures using Kasianchuk's computer program(6).

The AC pavement temperatures measured compared quite favorably with those calculated temperatures near the surface. Figure 9 is an example of this comparison and shows that the calculated values generally exceeded the measured values during the morning and at lower depths were lower than the measured temperatures during the afternoon. As predicted by Barber's theory, the maximum temperature decreased with depth. However, the measured maximum temperature

Figure 8

INSTRUMENTATION

WILLITS

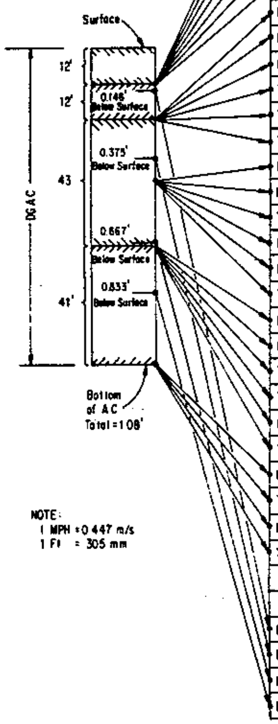


Lift thicknesses shown were determined from cores.

1 Ft. = 305 mm

- ▮ = Strain gauges placed transversely.
- ▬ = Strain gauges placed longitudinally.
- T = Thermocouple.
- SA = Strain gauge adhered to sand asphalt carriers.
- E = Strain gauge epoxied to pavement.
- PA = Polymide strain gauge adhered w/asphalt.
- PW = Polymide strain gauge adhered w/waterproofing agent.
- PE = Polyester strain gauges adhered w/waterproofing agent.
- x = Inoperative strain gauge.

Table 10
STRAIN DATA
WILLITS TEST SECTION
STATION 139+00



NOTE:
1 MPH = 0.447 m/s
1 Ft = 305 mm

Longit. or Trans	Strain Gauge No	Epoxied Polyimide or Sand-Asphalt Carrier	Run 5-2 6-19-73 9:44 0.58 MPH	Run 5-5 10:18 0.58 MPH	Run 7-3 12:34 0.62 MPH	Run 7-6 13:15 1.70 MPH	Run 7-10 13:21 2.21 MPH	Run 8-5 14:02 0.63 MPH	Run 9-6 6-19-73 15:03 1.85 MPH
L	83	E	268 C	308 C					Off Chart
T	84	E	E_0	86 T					
L	59	PW							
T	60	PW							
L	71	PE			273 C	158 C	176 T		
T	74	PE			92 T	132 T	58 C		
T	40	PA						775±T	
L	79	E	104 C	124 C					
L	63	PW							
L	69	PE			134 C	100 C	102 C		
T	70	PE			93 T	71 C	90 C		
T	80	E							543 T
T	66	PA							824 T
L	21	E	85 C	79 C					
L	27	PW							
T	28	PW							
L	19	PE			117 T	X	X		
L	45	PA						714±T	
T	46	PA						431 T	
L	13	E	136 T	123 T					
L	37	PW							
T	38	PW							
T	10	PE			125 T	53 T	45 T		
L	35	PA						306 T	
T	36	PA							99 T
L	19	SA	273 T	287 T					304 T
T	20	SA	68 T	68 T					
L	17	SA						522 T	
T	18	SA						120 C	
MAXIMUM DEFLECTION – INCHES									
LVDT	1		041	.038	.046	044	.042	.057	.051
LVDT	2		.030	.030	.034	.033	.032	.039	.035
LVDT	3		.030	.031	.036	.035	.035	.040	.033
LVDT	4		.022	.025	.027	.026	.025	.025	.024

Longit. or Trans	Strain Gauge No	Carrier	Run 5-8 6-19-73 10:27 2.24 MPH	Run 5-10 10:30 2.56 MPH	Run 5-11 10:32 2.44 MPH	Run 6-1 10:45 2.80 MPH	Run 6-3 10:52 0.57 MPH	Run 6-4 10:55 0.60 MPH	Run 6-9 11:21 1.77 MPH	Run 6-10 11:22 2.47 MPH	Run 7-1 12:28 2.22 MPH	Run 7-5 13:12 0.56 MPH	Run 7-8 13:18 2.06 MPH	Run 7-9 13:20 1.85 MPH	Run 8-1 13:40 1.91 MPH	Run 8-3 13:48 0.58 MPH	Run 8-6 14:03 1.61 MPH	Run 8-8 14:26 1.80 MPH	Run 8-11 14:32 1.88 MPH	Run 8-12 14:34 1.56 MPH	Run 9-1 14:49 1.61 MPH	Run 9-2 14:53 1.50 MPH	Run 9-4 14:59 1.75 MPH	Run 9-8 6-19-73 15:06 1.61 MPH
L	83	E	149 C	159 C	155 C																193 C	406 T	204 T/C	241 T
T	84	E	347 C	347 C	316 C																			
L	59	PW				264 C	I	I	374 C	E_0														
T	60	PW				363 C	I	I	436 C	E_0														
L	71	PE									37 C	76 T	27 C	39 T/C										
T	74	PE									171 C	257 C	141 C	197 C										
T	40	PA													E_0	333 C	580±C	407 C	891±C	581 C				
L	79	E	120 C	135 C	116 C																			
L	63	PW				220 C	I	I	286 C	271 C														
L	69	PE									73 C	E_0	67 C	92 C										
T	70	PE									108 C	200 C	86 C	75 C										
T	80	E																			Off Chart	275 C	469 C	457 C
T	66	PA																			Off Chart	708 C	507 C	626 C
L	21	E	44 C	44 C	53 C																			
L	27	PW				73 C	I	I	106 C	86 C														
T	28	PW				95 C	I	I	114 C	166 C														
L	19	PE									37 C	X	X	X										
L	45	PA													108 C	145 C	112 C	155 C	131 C	127 C				
T	46	PA													323 C	250 C	383 C	347 C	377 C	384 C				
L	13	E	72 T	59 T	62 T																			
L	37	PW				127 T	I	I	143 T	122 T														
T	38	PW				44 C	I	I	96 C	77 C														
T	10	PE									24 C	67 T	41 T/C	61 T										
L	35	PA													158 T	147 T	155 T	166 C	151 T	140 T				
T	36	PA																			149 C	E_0	110 C	144 C
L	19	SA	246 T	242 T	236 T																352 T	352 T	361 T	361 T
T	20	SA	76 T	74 T	70 T																			
L	17	SA													418 T	458 T	469 T	463 T	465 T	497 T				
T	18	SA													57 C	136 C	82 C	92 C	76 C	92 C				
MAXIMUM DEFLECTION – INCHES																								
LVDT	1		.032	.032	.032	.032	.038	.040	.036	.034	Trace Too Faint	.050	.045	.046	.044	.048	.046	.044	.046	.046	.048	.046	.046	.045
LVDT	2		.026	025	025	025	.031	.032	.029	.028	.030	.036	.033	.034	.034	.037	.036	.035	.036	Trace Too Faint	.037	.036	.036	.036
LVDT	3		.027	026	026	.026	I	I	.031	Trace Too Faint	.033	.037	.036	.035	.036	.040	.038	.037	Trace Too Faint	.038	.038	.039	.037	.040
LVDT	4		.020	021	.020	.024	I	I	.024	.023	.025	.028	Trace Too Faint	.026	.026	.039	.027	.026	.026	.037	.026	.027	.037	.028

Longit. or Trans	Strain Gauge No	Carrier	Run 5-1 6-19-73 9:38 0.57 MPH	Run 5-3 9:48 0.55 MPH	Run 5-6 10:23 2.60 MPH	Run 6-2 10:47 2.64 MPH	Run 7-11 13:23 2.01 MPH	Run 8-10 6-19-73 14:30 1.95 MPH
L	83	E	219 C	298 C	201 C			
T	84	E	90 C	106 C	57 T			
L	59	PW				275 C		
T	60	PW				E		
L	71	PE					237 C	
T	74	PE					82 T	
T	40	PA						721 T
L	79	E	79 C	104 C	60 C			
L	63	PW				216 C		
L	69	PE						
T	70	PE						
T	80	E						
T	66	PA						
L	21	E	81 C	92 C	44 C			
L	27	PW				108 C		
T	28	PW				E_0		
L	19	PE						
L	45	PA						
T	46	PA						
L	13	E	130 T	151 T	66 T			
L	37	PW				137 T		
T	38	PW				68 T		
T	10	PE					84 T	
L	35	PA						233 T
T	36	PA						
L	19	SA	248 T	287 T	244 T			
T	20	SA	58 T	68 T	58 T			
L	17	SA						459 T
T	18	SA						38 C
MAXIMUM DEFLECTION – INCHES								
LVDT	1		.043	.039	.033	.034	.047	.049
LVDT	2		.032	.030	.026	.025	.034	.037
LVDT	3		.030	.030	.025	.026	.032	.034
LVDT	4		.020	.022	.020	.020	.024	.034

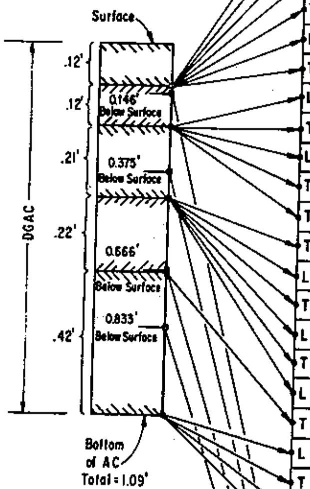
DIRECTION
L = Longitudinal
T = Transverse

GAUGES
E = Epoxied
SA = Sand-Asphalt Carrier
PE = Polyester with Waterproofing
PA = Polyimide with Asphalt
PW = Polyimide with Waterproofing

LEGEND
I = Incorrect wheel placement over the gauges.
X = Gauge Inoperative.
± = Trace went a bit off chart paper (Interpolated value)
Off Chart = Trace went off chart paper
Trace Too Faint = Unreadable
E_0 = Erratic zero load trace–impossible to get a confident reading.

T = Tension
C = Compression

Table 11
STRAIN DATA
WILLITS TEST SECTION
STATION 140+00



Longit. or Trans.	Strain Gauge No.	Epoxied Polyamide or Sand-Asphalt Carrier	Run 1-1 6-13-73 14:27 2.76 MPH	Run 1-5 6-13-73 15:21 0.56 MPH	Run 2-4 6-14-73 10:40 2.08 MPH	Run 2-12 6-14-73 10:59 1.87 MPH	Run 1-2 6-13-73 14:45 0.56 MPH	Run 1-6 6-13-73 15:28 0.63 MPH
L	81	E						
T	82	E						
L	49	PA						
T	50	PA						
T	72	PE						
L	73	PE						
T	48	PW						
L	77	E						
T	78	E						
L	67	PE						
T	68	PE						
T	58	PW						
T	42	E			23 C	58 C		
L	43	PW			61 C	98 C		
T	44	PW			85 C	144 C		
L	15	PE			146 T	74 C		
T	14	PE			60 T	58 T		
L	41	E	199 T	413 T	86 C	133 C	268 T	308 T
T	34	PA	50 T	165 C			110 T	165 T
L	21	SA	366 C	572 C			620 C	620 C
T	22	SA	79 C	100 C			79 C	98 C
L	23	SA	382 C	592 C			592 C	611 C
T	24	SA	43 C	58 C			62 C	74 C
MAXIMUM DEFLECTION – INCHES								
LVDT	1			.036	Incomplete Trace			.034
LVDT	2			.032	Incomplete Trace			.032
LVDT	3			.028	.023			.030
LVDT	4			.023	.020			.028

Longit. or Trans.	Strain Gauge No.	Carrier	Run 2-2 6-14-73 10:26 2.30 MPH	Run 2-3 10:30 2.19 MPH	Run 2-5 10:45 1.90 MPH	Run 2-6 10:46 2.03 MPH	Run 2-7 10:49 1.63 MPH	Run 2-10 10:55 1.82 MPH	Run 3-1 11:39 1.94 MPH	Run 3-3 11:52 2.03 MPH	Run 3-4 11:57 2.13 MPH	Run 3-5 12:01 2.16 MPH	Run 3-10 12:13 2.03 MPH
L	81	E											
T	82	E											
L	49	PA											
T	50	PA											
T	72	PE											
L	73	PE											
T	48	PW							2842 C	378 C	I	596 C	378 C
L	77	E							250 C	257 C	I	265 C	288 C
T	78	E							231 C	221 C	I	237 C	262 C
L	67	PE							78 C	78 C	I	95 C	78 C
T	68	PE							108 C	130 C	I	90 C	101 C
T	58	PW							400 C	400 C	I	550 C	563 C
T	42	E	62 C	81 C	91 C	77 C	87 C	96 C					
L	43	PW	45 C	59 C	59 C	61 C	59 C	83 C					
T	44	PW	79 C	108 C	110 C	E_0	102 C	140 C					
L	15	PE	41 T	39 T	89 T	70 T	55 T	37 T					
T	14	PE	78 C	80 C	84 C	78 C	86 C	96 C					
L	41	E	63 C	72 C	82 C	91 C	87 C	95 C					
T	34	PA											
L	21	SA											
T	22	SA											
L	23	SA											
T	24	SA											
MAXIMUM DEFLECTION – INCHES													
LVDT	1		.028	.029	.030	I	.031	.031	.032	.032	I	.033	.034
LVDT	2		.019	.019	.021	I	.022	.023	.023	.022	I	.023	.025
LVDT	3		.022	.023	.023	I	.024	.024	.024	.025	.024	.025	.026
LVDT	4		.020	.020	.022	I	Invisible Trace	.022	.023	.023	.022	.024	.025

Longit. or Trans.	Strain Gauge No.	Carrier	Run 4-4 14:29 2.33 MPH	Run 4-5 14:31 2.48 MPH	Run 4-8 14:53 2.29 MPH	Run 4-9 14:56 2.30 MPH	Run 4-10 6-14-73 14:58 2.26 MPH	Run 1-7 6-13-73 15:34 0.56 MPH	Run 2-1 6-14-73 10:22 2.30 MPH	Run 2-8 6-14-73 10:51 1.94 MPH	Run 2-9 6-14-73 10:53 2.09 MPH	Run 2-11 6-14-73 10:57 2.00 MPH	Run 3-7 6-14-73 12:06 2.35 MPH	Run 3-8 6-14-73 12:09 2.10 MPH	Run 4-11 6-14-73 15:01 2.00 MPH
L	81	E	168 C	E_0	153 C	169 C	154 C								403 C
T	82	E	277 C	396 C	380 C	301 C	324 C								127 T
L	49	PA	245 C	253 C	326 C	282 C	298 C								939 T
T	50	PA	293 C	969 C	862 C	349 C	388 C								646 T
T	72	PE	37 C	29 C	X	X	X								X
L	73	PE	132 C	140 C	160 C	100 C	144 C								120 T
T	48	PW	568 C	672 C	691 C	541 C	676 C						E	E_0	345 T
L	77	E											221 C	175 C	
T	78	E											178 C	82 C	
L	67	PE											119 C	117 C	
T	68	PE											119 T	22 C	
T	58	PW											E	E_0	
T	42	E							35 C	60 C	42 C	96 C			
L	43	PW							59 T	83 C	61 C	75 C			
T	44	PW							E_0	157 C	106 C	98 C			
L	15	PE							92 T	E_0	85 T	35 C			
T	14	PE							42 T	16 C	66 T	94 C			
L	41	E						388 T	59 C	106 C	118 C	95 C			
T	34	PA						184 C							
L	21	SA						566 C							
T	22	SA						85 C							
L	23	SA						539 C							
T	24	SA						87 C							
MAXIMUM DEFLECTION – INCHES															
LVDT	1		.034	.038	.040	.036	.038	.032	.031	.028	.029	I	.033	.031	E_0
LVDT	2		E_0	.029	.027	Trace Too Faint	.028	.030	.019	.022	.020	I	.023	.021	.028
LVDT	3		.029	Trace Too Faint	.029	.029	.029	.029	.021	.023	.021	I	.025	.023	.029
LVDT	4		.027	.028	.029	.028	.029	.029	.018	.021	.021	I	.024	.023	.028

DIRECTION
L = Longitudinal
T = Transverse

GAUGES
E = Epoxied
SA = Sand-Asphalt Carrier
PE = Polyester with Waterproofing
PA = Polyamide with Asphalt
PW = Polyamide with Waterproofing

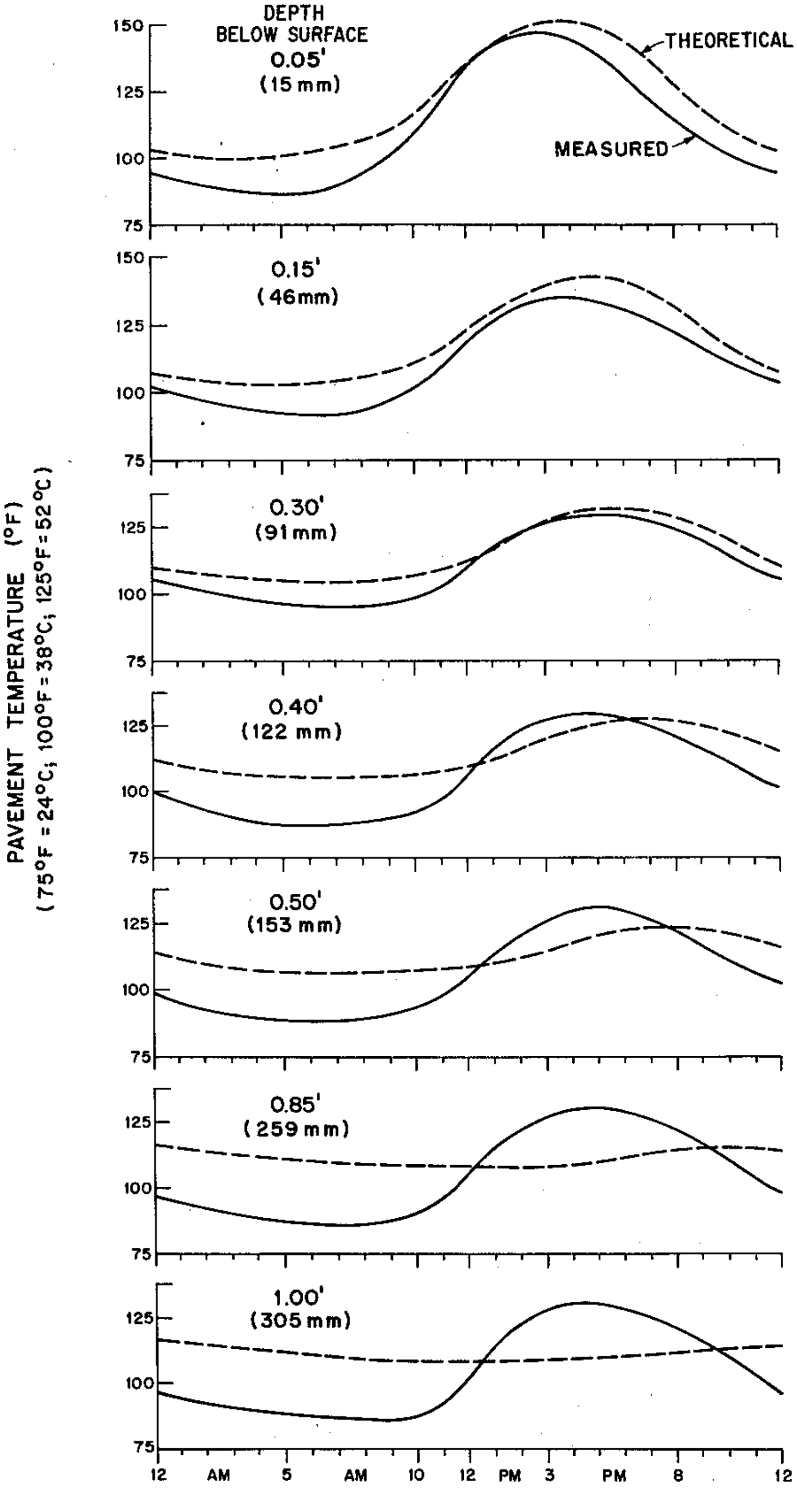
LEGEND
I = Incorrect wheel placement over the gauges.
X = Gauge inoperative.
± = Trace went a bit off chart paper (Interpolated value).
Trace Too Faint = Unreadable.
E = Erratic load trace on chart.
E_0 = Erratic zero load trace - impossible to get a confident reading.

T = Tension
C = Compression

NOTE:
1 MPH = 0.447 m/s
1 Ft = 3

FIGURE 9

TIME VS TEMPERATURE
INDIO
JUNE 22-23, 1971



HOUR OF THE DAY

did not decrease nearly as much as the theoretical values nor did the theoretical dampening effect (with depth) occur. It should also be noted that peak pavement temperatures approaching 150°F (66°C) were measured at this desert (Indio) location in June. Even 1.0 foot (305 mm) below the surface, a peak temperature of approximately 130°F (54°C) was measured with a minimum temperature of more than 85°F (29°C) also noted. These measurements tend to support the often used AC test temperature of 140°F (60°C).

Blythe

The temperature simulation program developed by Kasianchuk(6) was again used to calculate theoretical pavement temperatures at various depths below the pavement surface. Weather data for January 20, 1973 and July 7, 1973 were obtained for the weather station at the Blythe airport which is within a mile of the test sections. As at Indio, this information, which is presented in Table 12, was obtained from the U. S. Department of Commerce National Climatic Center in Asheville, North Carolina. The date in January was chosen as the one with recorded thermocouple values closest to the field test date. The July data were requested to provide a comparison of the theoretical and actual temperature gradients during very hot weather.

The comparative results are shown on Figures 10 and 11. There was a more significant decrease in temperature with depth than that measured at Indio. As was true for the Indio test site, the comparisons between the theoretical and measured temperatures indicate that the theoretical method provides a method of calculating pavement temperature at various depths with a reasonable degree of accuracy. Kasianchuk noted in his work that the calculated temperatures generally were higher than those measured during the

FIGURE 10

TIME VS TEMPERATURE
BLYTHE
JAN. 20, 1973

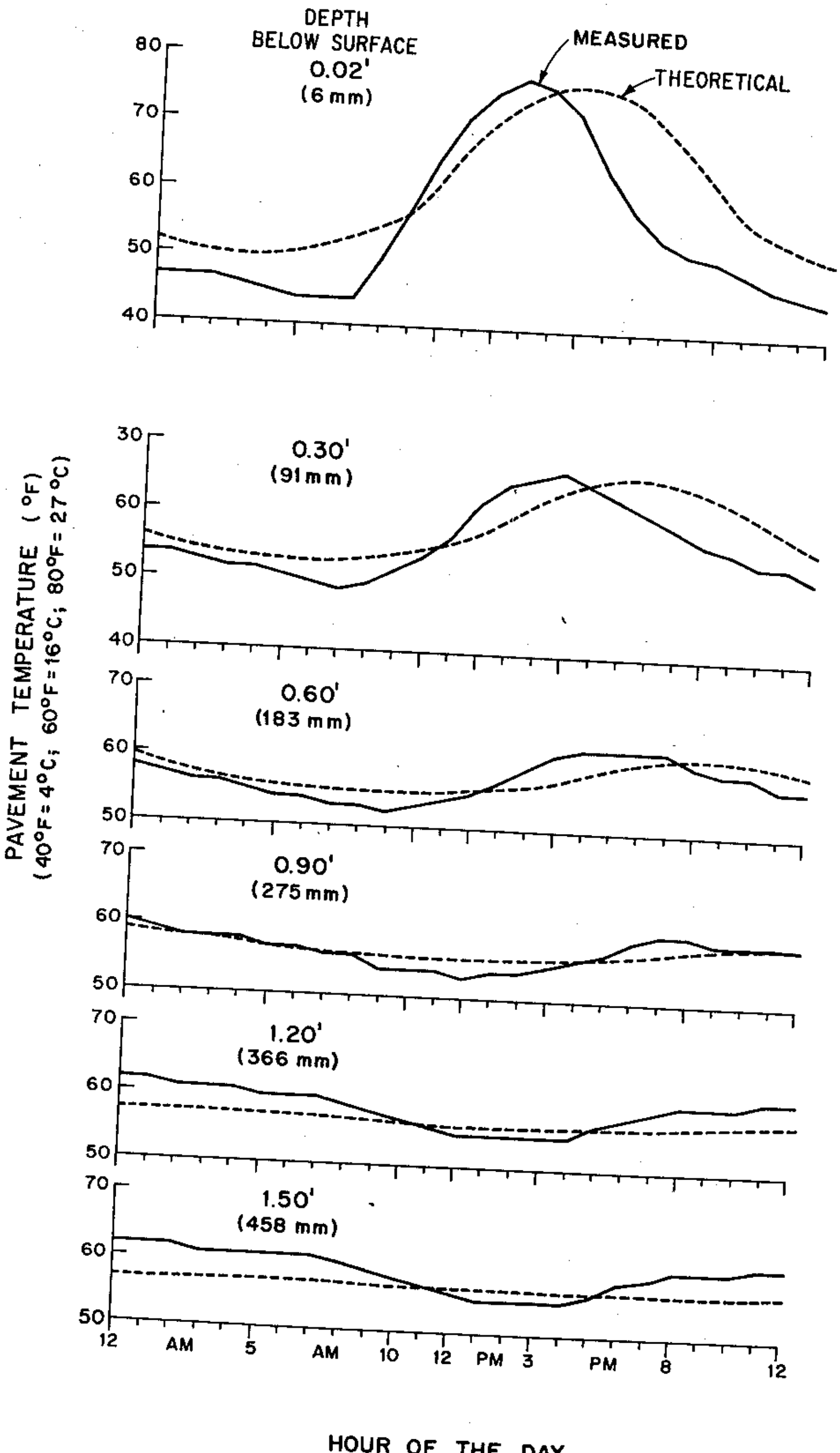


FIGURE 11

TIME VS TEMPERATURE
BLYTHE
JULY 7, 1973

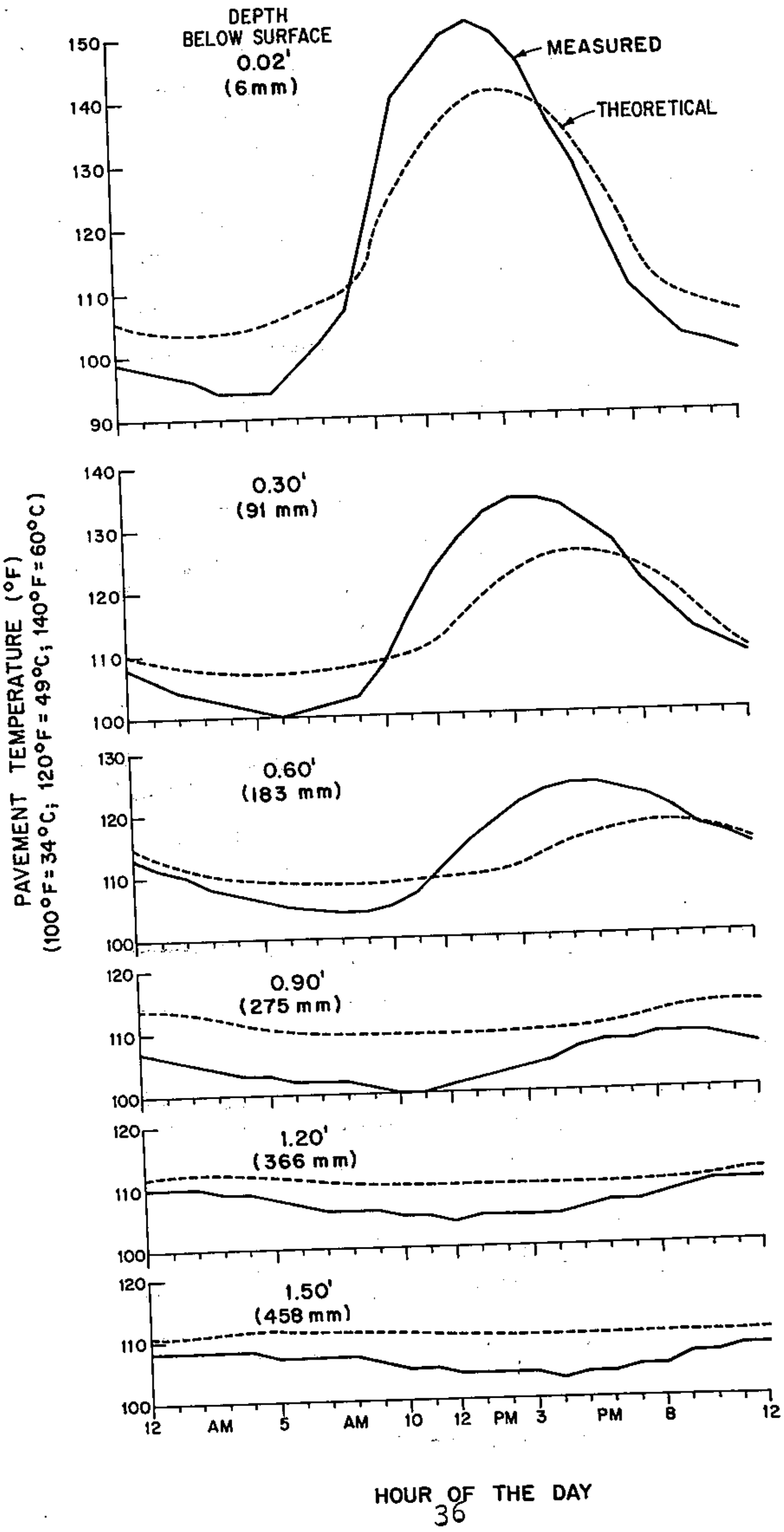


Table 12

WEATHER DATA, BLYTHE F.A.A.

(a) January 20, 1973

Mean Air Temperature	50.5°F (10.3°C)
Diurnal Range	19.0F° (12C°)
Mean Wind Velocity	13.5 mph (6.0 m/s)
Solar Insolation	360 Langleys per day
Sky Cover	0.1

(b) July 7, 1973

Mean Air Temperature	99.0°F (37°C)
Diurnal Range	20.0F° (12.5C°)
Mean Wind Velocity	12.5 mph (5.6 m/s)
Solar Insolation	640 Langleys per day
Sky Cover	0.3

night hours at all depths and that the time of the maximum temperature also deviated somewhat from that measured(6). These two observations are also applicable to much of the Indio and the Blythe data.

Willits

Attempts were made to obtain June 13-17, 1974 weather data from the U. S. Department of Commerce for use in the calculation of the theoretical temperatures within the Willits AC pavement to be compared with the temperatures measured with the thermocouples. However, no response was received from the DOC so these comparisons could not be made. Estimates of appropriate climatic conditions for Willits were subsequently made based upon data obtained from Reference 12. These estimates are listed below and were used for the theoretical calculations of pavement stress, strain, deflection, and fatigue life.

Mean Air Temperature	62.4°F (17°C)
Diurnal Range	33.9F° (21C°)
Mean Wind Velocity	8 mph (3.6 m/s)
Solar Insolation	650 Langleys per day
Mean Sky Cover	5.8

D. AC Strain

Blythe

Strain gauges were attached to sand asphalt carriers or polymide sheets and oriented in both the longitudinal (tangential) and transverse (radial) directions at Blythe. Where time between construction of the AC lifts permitted, duplicate gauges were epoxied to the surface of the lower AC lift. The field load testing was accomplished with the duals of the truck centered over the gauge location, and with one of the duals located directly over the center of the gauges. Four strains that could, therefore, be compared with the theoretical computer print-outs were as follows:

1. Transverse (radial) strain beneath center of dual wheel load.

2. Longitudinal (tangential) strain beneath center of dual wheel load.

3. Transverse (radial) strain directly beneath the center of one of the dual wheels.

4. Longitudinal (tangential) strain directly beneath the center of one of the dual wheels.

The selection of the appropriate time of loading to be used in the computer solution for each test location presented a problem. The actual conditions that existed in the field during the time of testing were the primary concern for the comparative study. Because time of loading influences the magnitude of AC stiffness and because stiffness values are required as input for the elastic layered program, it was thought that for best accuracy measured values should be used regardless of the time of day. The initial attempt was to measure this directly from the strain gauge traces. However, the strain gauge traces were sometimes extremely difficult to interpret due to the strain reversals (shifts from tension to compression or compression to tension) measured by the transverse gauges during the passage of the load and what appeared to be an inordinate delay in returning to the "zero" load condition (rebound) after the application of loads by the slow moving truck. This resulted in some interaction between the influence of the front and rear wheels of the truck. As the majority of the working strain gauges were oriented in the transverse direction, it seemed that a better solution would be to avoid the uncertainties of using the strain gauge traces to establish the time of loading. Because the traces for the LVDT's used to measure deflection were much "cleaner" (see Figure 12), these traces were used to estimate the time of loading at four depths within the pavement. The times used were the averaged results for the various runs.

In some instances, a time of loading of as much as 9 seconds was indicated. These extremely long times of loading did not appear to be realistic when compared with other sources such as the charts by Barkdale and Hicks (Figure 13) which have been used by several researchers for establishing laboratory test time. For example, the time of loading for a 0.70 mph (0.31 m/s) truck speed and a pavement depth of 1.5 feet (458 mm), from interpolation, would only be approximately 3.7 seconds per Figure 13 whereas times of loading as great as 9.5 seconds were indicated by the LVDT traces. This apparent anomaly was not resolved.

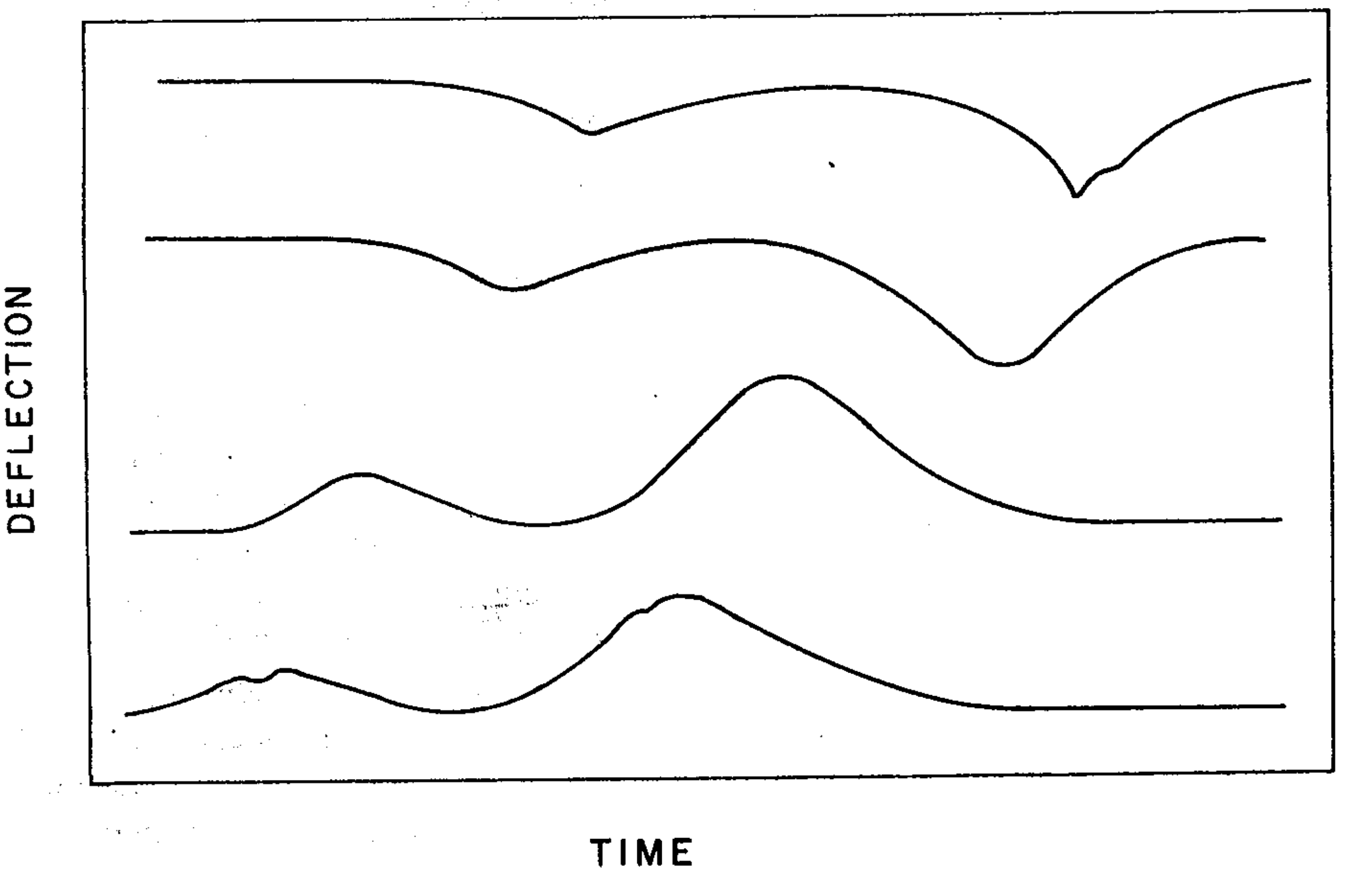


Figure 12

TYPICAL LVDT DATA
USED FOR
MEASUREMENT OF TIME OF LOADING

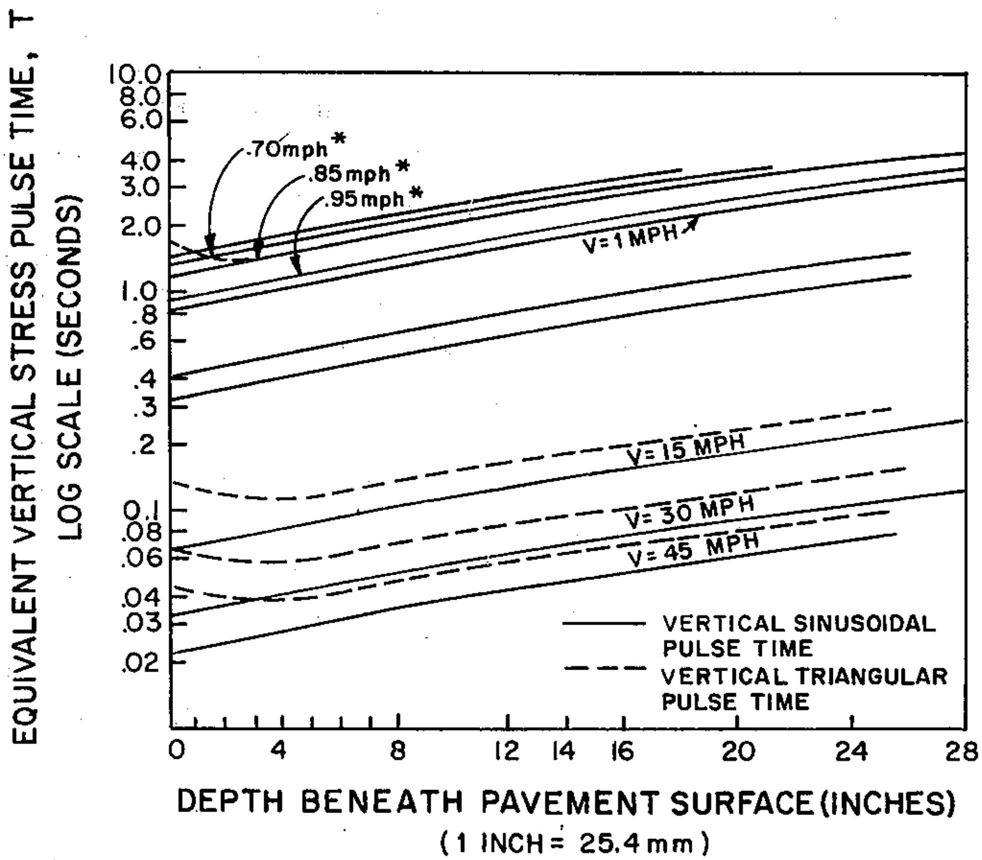
Another unusual aspect of the LVDT data was the decrease in time of loading that was measured as the distance beneath the AC surface increased for both Test Section A stations. The indicated load times for both Test Section B stations showed the expected increase with depth. The trend in deflections measured also was contrary to that expected in that they generally increased with depth. Thus, although no definite conclusions could be reached, it appeared as though the Blythe A LVDT data may have been reversed - i.e., an error in record keeping and identification during the testing phase may have occurred, or the leads to the recorder not properly identified or attached. Also, the requirement of the computer program that the same stiffness be assigned to all the AC, regardless of depth below the surface, for a given computer "run" was contrary to that measured and to Barksdale and Hicks' data, thus suggesting that multiple "runs" and superposition would be required.

Because of the problems encountered regarding determination of the time of loading, three different approaches were used for input to the computer. The first consisted of using the data obtained from the LVDT traces. The second and third consisted of using the times of loading obtained from the Barksdale and Hicks data (Figure 13) by interpolation. In one case, the times were selected according to the distance below the AC surface - i.e., an increase with depth. In the other case, the time of load indicated for the AC surface per Barksdale and Hicks was used for every level within the AC in accordance with the work reported by Monismith.

The velocity of the truck used to apply the test load was determined for each run using the known distance between the front and rear wheels of the truck and the time interval on the LVDT traces between the maximum deflection due to each of these loads. The truck was operated at creep speed so that the pavement surface deflection could be measured with the Benkelman beam in the conventional manner. Because the sensitivity of the time of loading per Barksdale and Hicks was relatively small within the range of test load velocities used, the velocity used for the selection of time of loading from Figure 13 was the average of all the test runs for each station. The pavement stiffness values were determined using the method developed by Kasianchuk to calculate the stiffness/temperature relationship and then selecting the calculated stiffness associated with the measured (thermocouple or estimated) temperature for each layer.

Figure 13

TIME OF LOADING
VS
SPEED AND DEPTH



NOTE: 1 MPH = 0.447 m/s

*INTERPOLATED VALUES

From Reference 13

The input values and the calculated AC stiffnesses are summarized on the following Tables 13 and 14. These data reveal the substantial dependency of calculated AC stiffness upon time of loading and temperature - i.e., the thermoplastic properties of AC. Substantial AC stiffness differences were obtained when the different times of loading were assumed. However, the use of superposition wherein all the AC was assigned each of the times-of-loading, the AC stiffnesses calculated for all levels, and the stiffness only for the level associated with the selected time of loading then assembled and reported, may or may not be valid. This is discussed in more detail later. In several instances, the change in calculated stiffness for a given temperature was as great when the assumed time of loading changed 6± seconds (Col. 1 versus Col. 2) as it was when the time of loading changed as little as 0.2 seconds (Col. 3 versus Col. 2). This result appears to be somewhat questionable and indicates that (1) the use of this theoretical approach may not be valid for times of loading on the order of 7-10 seconds (Col. 1) or (2) there may be a limiting value between 2± and 7± seconds beyond which the effect of time of loading upon AC stiffness decreases significantly. The calculations also indicate that the range in stiffnesses to be expected between the top and bottom of 12 to 18 inch (305 to 458 mm) thick AC is substantial. These values may differ by as much as a factor of 6 (Station 273+00, Col. 1). However, in some instances, the difference between the calculated AC stiffness at the surface and that in the bottom lift was essentially zero. Also, the range in stiffnesses that would be encountered during a one year period due to temperature and other changes will also probably be significant. Thus, any mix design optimization (by lift) to obtain a particular AC stiffness, either initially and/or over the expected service life of the pavement, does not appear to be appropriate based upon these data.

Table 13

AC STIFFNESS
BLYTHE TEST SECTION A

Depth Below Surf.-In.	Temp.* °F (°C)	Time of Loading (sec.) From LVDT Data	Time of Loading (sec.) From Barksdale & Hicks**	Time of Loading (sec.) From Barksdale & Hicks**	Calculated AC Stiffness (Ksi) For Each Time of Loading (Col. 1)	(Col. 2)	(Col. 3)
Station 273+00							
0-1.75	74 (23)	9.5	1.4	1.4	53.0	148.0	148.0
1.75-4.20	62 (17)	8.9	1.6	1.4	139.5	247.5	390.5
4.20-6.36	58 (14)	8.2	1.8	1.4	207.5	497.5	521.5
6.36-11.16	54 (12)	7.4	2.1	1.4	339.5	459.0	683.0
Station 274+00							
0-1.75	70 (21)	8.7	1.6	1.6	64.0	180.0	180.0
1.75-4.20	66 (19)	8.6	1.8	1.6	92.5	265.0	207.5
4.20-7.32	63 (17)	8.5	2.0	1.6	126.5	284.5	237.0
7.32-11.28	58 (14)	8.0	2.5	1.6	225.5	343.0	351.5

*Temperatures measured with thermocouples at the time of testing
**Avg. veh. velocity 0.79 mph for testing at Station 273+00, 0.63 mph for testing at Station 274+00

Note: 1-inch = 25.4 mm
1-ksi = 6.89 MPa
1-mph = 0.45 m/s

Table 14

AC STIFFNESS
BLYTHE TEST SECTION B

Depth Below Surf.-In.	Temp.* °F.(°C)	Time of Loading (sec.) From LVDT Data	From Barksdale & Hicks**	From Barksdale & Hicks**	Calculated AC Stiffness (Ksi) For Each Time of Loading (Col. 1)	(Col. 2)	(Col. 3)
Station 374+00							
0-4.32	70 (21)	6.8	1.1	1.1	79.5	212.5	212.5
4.32-7.56	62 (17)	7.4	1.3	1.1	173.0	390.5	440.5
7.56-11.04	57 (14)	7.7	1.6	1.1	264.5	400.0	648.5
11.04-17.40	55 (13)	8.2	2.1	1.1	275.0	443.0	752.0
Station 375+00							
0-4.92	62 (17)	7.8	1.3	1.3	173.0	390.5	390.5
4.92-8.16	54 (12)	8.4	1.8	1.3	301.5	649.0	683.0
8.16-11.40	54 (12)	9.3	2.2	1.3	296.5	459.0	683.0
11.40-18.36	56 (13)	10.6	2.7	1.3	193.5	409.5	597.5

*Temperatures measured with thermocouples at the time of testing
**Avg. veh. velocity 0.95 mph for testing at Station 374+00 and 0.85 mph at Station 375+00

Note: 1-inch = 25.4 mm
1-ksi = 6.89 MPa
1-mph = 0.45 m/s

Both transverse and longitudinal strains were calculated for locations beneath the center of the dual wheels and beneath one of the dual wheels. The strains were calculated at the surface of the DGAC pavement and at four distances beneath this surface. The strain gauge data was then assembled, examined, and the theoretical and measured values compared. These data for Test Section A are presented in Table 15.

Examination of these data revealed several instances in which excellent agreement between individual calculated and measured strains was obtained. However, there also were several instances in which these values differed by factors of two or more. There was generally good agreement of the measured strains from run to run, thus lending some credibility to the repeatability of the equipment and indicating that the difference in load application speed and location did not significantly influence the magnitude of the measured strain. Because the AC stiffnesses used for the calculation of theoretical strains differed substantially in many instances depending upon the time of loading assumed, there also were substantial differences in the magnitude of theoretical strains. For the two or three cases in which all three calculated strains were approximately equal (see No. 13, Table 15), agreement between the calculated and measured strains was poor. Unfortunately, comparisons of the measured strains and the theoretical strains using the three different time-of-loading values for calculating AC stiffness did not indicate that any of the three was obviously superior in all instances. These comparisons did reveal that the strain calculated using AC stiffness based upon measured time of loading agreed with the average measured strain best in nine of the eighteen cases studied. In some instances, this agreement was very good (Nos. 1 and 9, Table 15). However, for some of the other cases, the use of measured times of loading per LVDT data for subsequent strain calculations resulted in very poor agreement between measured and calculated strains (Nos. 4, 5, 8, 10 and 14, Table 15). In some of these cases, none of the calculated strains

Table 15

COMPARISON OF CALCULATED AND MEASURED AC PAVEMENT STRAIN

BLYTHE TEST SECTION A

No.	Gauge Conditions	Calculated (10^{-6} in./in.) LVDT[1]	B&H[2]	B&H[3]	Measured (10^{-6} in./in.) Various Runs				Avg.	Gauge Location - Distance Below Surface Ft.	(mm)
1	Longit. direction under ℄ duals	-92.4	-79.6	-67.2	-72	-104			-88	0.03	(9)
2		110.3	85.5	67.8	128	130			129	0.93	(284)
3	Longit. direction under ℄ duals	-122.8	-93.5	-96.3	-160				-160	0.04	(12)
4		138	98.7	100.8	97 54	100 61	93 53		76	0.94	(287)
5	Longit. direction under ℄ one wheel	-48.3	-70.2	-50.9	115				115	0.03	(9)
6		106.9	82.4	65.2	105	140	110		118	0.93	(284)
7	Longit. direction under ℄ one wheel	-126.9	-96.8	-108.0	-158	-58	-113	-137	-116	0.04	(12)
8		134.2	95.2	97.4	94 60	78 40	84 52	85 52	68	0.94	(287)
9	Transv. direction under ℄ duals	-142.4	-66.5	-71.1	-151	-123			-137	0.03	(9)
10		-103.4	-49.5	-46.3	-49				-49	0.35	(107)
11		-32.9	-17.7	-14.2	-20	-13			-16	0.53	(162)
12		41.9	38.5	32.6	84 108	44 51			72	0.93	(284)
13	Trans. ℄ duals	43.9	41.9	40.6	86 92	91 94	91 94		91	0.94	(287)
14	Trans. direction under ℄ one wheel	-16.4	-46.1	-31.2	-83				-83	0.03	(9)
15		48.9	12.5	13.1	-41	-48	-46		-45	0.35	(107)
16		24.2	21.6	12.6	-11	-17	-16		-15	0.53	(162)
17		68.4	54.4	43.7	40 60	54 60	43 45		48	0.93	(284)
18	Transv. ℄ one wheel	84.5	62.0	63.1	82 96	56 41	80 86	80 82	75	0.93	(284)

1. AC stiffness per time of loading from LVDT data.
2. AC stiffness per Barksdale & Hicks for each layer.
3. AC stiffness for all layers per Barksdale & Hicks for surface.

agreed well with the average measured strain. Also, in three of these five cases, only one strain measurement was obtained and in the other two cases, the range in measured values was substantial. When comparing the two calculation procedures incorporating Barksdale and Hicks times of loading, the application of different times of loading appropriate for each of the layers and subsequent superposition appeared to be the better of the two approaches. The strain calculated using this procedure agreed best with the average measured strain in six of the eighteeen cases. In some instances this agreement was very good (Nos. 10 and 11, Table 15). Thus, for 15 of the 18 comparisons made, the assignment of times of loading appropriate for each layer of AC to the entire thickness of AC, calculation of strains, and assembly of these calculations using only the values for the appropriate layer from each calculation resulted in the best agreement with the measured values for Blythe Test Section A.

The calculated and measured strains for Blythe Test Section B were assembled and evaluated in the same manner (see Table 16). In this case, 26 different combinations were compared. Again, the majority of the strain gauges providing data were oriented transversely. There again was good repeatability of the measured values from run to run, thus indicating that the differences in test vehicle speed and wheel location relative to the instrumentation from run to run generally did not significantly influence the strain gauge readings. Also, there again was very good agreement between the measured values and one or more of the calculated values in some cases (Nos. 5, 6, 11, 13, 14, 20, 23, and 26, Table 16) and rather poor agreement in other cases (Nos. 8, 9, 16, and 18, Table 16). The overall agreement, however, was considerably better than that for Test Section A. There were very few instances in which all of the calculated values differed from the measured values substantially. Contrary to the results for Test Section A, the theoretical approach that provided the best agreement

Table 16

COMPARISON OF CALCULATED AND MEASURED AC PAVEMENT STRAIN

BLYTHE TEST SECTION B

No.	Gauge Conditions	Calculated (10^{-6} in./in.) LVDT(1)	B&H(2)	B&H(3)	Measured (10^{-6} in./in.) Various Runs				Avg.	Gauge Location - Distance Below Surface Ft.	(mm)
1	Longit direction under ℄ duals	-42.1	-40.9	-27.7	-36	-39	-33	-36	-36	0.04	(12)
2		28.3	18.8	10.2	4	8	9	9	8	0.92	(281)
3	Longit direction under ℄ duals	28.4	17.5	9.7	18	-15	11		15	0.68	(207)
4		40.3	20.3	14.2	12	11	11		11	0.95	(290)
5	Longit. direction under ℄ one wheel	-70.0	-52.0	-37.6	-39	-44	-28	-37	-37	0.04	(12)
6		29.2	19.0	10.6	8	9	9	10	9	0.92	(281)
7	Longit. direction under ℄ one wheel	34.3	20.7	12.7	18	17	-15	-8		0.68	(207)
8		39.6	19.8	14.0	5	11	9	5	8	0.95	(290)
9	Transv. direction under ℄ of duals	-5.1	-11.0	-10.9	-39	-38	-37	-47	-40	0.04	(12)
10		-11.3	-5.2	-49.9	-18	-19	-19	-20	-19	0.36	(110)
11		-35.5	-18.8	-17.3	-17	-16	-20	-17	-18	0.63	(192)
12		0.8	3.2	0.3	-7	-4	-6	-4	-5	0.92	(281)
13		22.3	17.1	11.9	12				12	1.17	(357)
14		42.1	30.9	23.4	17	42			30	1.45	(442)
15	Transv. direction under ℄ of duals	-13.5	-7.2	-8.2	-15	-15	-15		-15	0.68	(207)
16		10.8	6.6	3.8	20	20	21		20	0.95	(290)
17		43.1	28.0	22.9	32	18			25	1.53	(467)
18	Transverse direction under ℄ of one wheel	-66.5	-45.0	-34.9	-71				-71	0.04	(12)
19		76.1	27.5	24.9	-20	-20	-14	-15	-17	0.36	(110)
20		26.5	17.0	8.3	-16	-19	-14	-14	-16	0.63	(192)
21		19.3	12.8	7.1	-6	-7	-8	-5	-6	0.92	(281)
22		24.6	17.5	12.1	11	13	4	2	8	1.17	(357)
23		40.1	28.6	21.5	17	13	16	17	23	1.45	(442)
					33	32	30	26			
24	Transverse direction under ℄ of one wheel	24.5	14.6	9.0	-7	-10	-18	-12	-12	0.68	(207)
25		25.9	13.4	9.4	22	30	25	10 12	20	0.95	(290)
26		39.1	25.1	20.6	19	25	36	21	25	1.53	(467)

1. AC stiffness per time of loading from LVDT data.
2. AC stiffness per Barksdale and Hicks for each layer.
3. [illegible]

between measured and calculated strains was that incorporating AC stiffnesses determined by assigning the time of loading per Barksdale and Hicks (Figure 13) for the AC surface to the entire AC thickness.

Willits

Strain gauges were placed in both the longitudinal (tangential) and transverse (radial) directions at each lift for the two test stations at Willits. The testing was accomplished with the duals straddling the gauges and with one of the duals centered over the gauges. Only 8 gauges could be recorded at any one time. At Station 139, the gauges were monitored such that the data from at least one strain gauge from each lift would be recorded for each run. At Station 140, all the gauges at each lift were recorded at the same time. Again, as at Blythe, the strain measurements that could be compared with the calculated strains were the following:

1. Transverse (radial) strain beneath center of dual load.

2. Longitudinal (tangential) strain beneath center of dual load.

3. Transverse (radial) strain beneath the center of one wheel of the duals.

4. Longitudinal (tangential) strain beneath the center of one wheel of the duals.

The times of loading used for the calculation of AC stiffness were based on the same criterion as that used for the Blythe test section data, i.e., (1) use the time of loading measured on the LVDT traces for each layer, determine the stiffness of the AC in each layer using each time of loading for the entire thickness of AC, then combine the data by assembling the stiffness value from each set of calculations only for the layer for which the time of loading had been determined, (2) use the time of loading appropriate

Table 18

AC STIFFNESS

WILLITS TEST SECTION

Station 140+00

Depth Below Surface-In.	Avg. Veh. Vel MPH (m/s)	Temp* °F (°C)	Time of Loading (Sec.) From LVDT Data	Time of Loading (Sec.) From Barksdale and Hicks	Time of Loading (Sec.) From Barksdale and Hicks	Estimated AC Stiffness For Each Time of Loading (KSI) (Col. 1)	(Col. 2)	(Col. 3)
0 - 1.44	2.35	117(47)	2.3	0.4	0.4	<2.0	<8.0	<8.0
1.44 - 2.88	(1.05)	110(43)	2.1	0.4	0.4	<2.0	<8.0	<8.0
2.88 - 8.04		95(35)	2.2	0.5	0.4	2.0	8.0	8.0
8.04 - 13.08		84(29)	2.2	0.6	0.4	6.0	18.0	18.0
0 - 1.44	2.11	105(41)	2.5	0.4	0.4	<2.0	<8.0	<8.0
1.44 - 2.88	(0.94)	94(34)	2.4	0.5	0.4	<2.0	<8.0	<8.0
2.88 - 8.04		82(28)	2.5	0.5	0.4	8.0	21.5	21.5
8.04 - 13.08		78(26)	2.4	0.6	0.4	11.0	30.5	30.5
0 - 1.44	2.03	92(33)	2.7	0.4	0.4	3.0	9.5	9.5
1.44 - 2.88	(0.91)	82(28)	2.6	0.5	0.4	8.0	21.5	21.5
2.88 - 8.04		75(24)	2.8	0.6	0.4	15.0	41.0	41.0
8.04 - 13.08		77(25)	2.8	0.7	0.4	12.0	34.0	34.0
0 - 1.44	0.59	121(49)	6.8	2.1	2.1	<2.0	<3.0	<3.0
1.44 - 2.88	(0.26)	101(38)	6.2	2.3	2.1	<2.0	<3.0	<3.0
2.88 - 8.04		84(29)	7.4	2.8	2.1	4.0	6.5	6.5
8.04 - 13.08		76(24)	6.9	3.0	2.1	9.0	14.0	14.0

*Temperature measured with thermocouples at the time of testing.

1 Ft. = 305 mm
1 KSI = 6.89 MPa

for Station 139 using the measured times of loading (Col. 1) were significantly less than 25 ksi (172 MPa). Even the stiffnesses calculated for Station 139 using the significantly shorter Barksdale and Hicks times of loading were, in all but one case, also less than 25 ksi (172 MPa). The same was true for the AC located at Station 140 in that only six combinations of the 48 tried resulted in theoretical AC stiffnesses of 25 ksi (172 MPa) or more. This was true even though the times of loading were generally of the same order of magnitude as those encountered at Blythe when using the Barksdale and Hicks data (Figure 13). Thus, it appears as though the only major contributors to the tremendous difference in AC stiffness between Blythe and Willits were the pavement temperature and the penetration of the recovered asphalt. These differences of from 55 to 80°F (13 to 27°C) in pavement temperature and from 31 and 45 to 57 in penetration of the recovered asphalt resulted in calculated AC stiffness varying from 450 ksi (3100 MPa) to less than 2 ksi (13.8 MPa). The shear magnitude of this difference raises questions regarding the validity of the apparent sensitivity of the computer program used when considering the difficulties that will often be encountered when attempting to get climatic data, and the fairly rapid change in asphalt penetration that sometimes occurs as pavements age. Also, there is the possibility that the frequently assumed 25 ksi (172 MPa) AC stiffness is not appropriate. However, the extremely low values estimated for a number of combinations (less than 2 ksi (13.7 MPa)) also seem to be somewhat questionable.

In an attempt to determine the accuracy and apparent sensitivity of the modified Chev 5L program for use in calculating pavement stress, strain, and deflection, two sets of AC stiffnesses were assumed for the calculation of pavement strain. The first series of theoretical strains was calculated using those theoretical stiffness values closest to 25 ksi (172 MPa) for each AC layer at Station 139. The second series of strain calculations was made assuming an AC stiffness of 25 ksi (172 MPa) throughout. These theoretical strains were then compared with those strains measured at Station 139 in an attempt to verify the results of the modified Chev 5L procedure. These data are presented in Table 19. Each measured strain reported is the average of up to six measured strains from one or two gauges. Examination of these data revealed the apparent lack of correlation between the values calculated using both sets of AC stiffness and the measured strains. Generally, the average measured strains were less than the calculated strains using either of the AC stiffnesses. Thus, the very low calculated stiffnesses on the order of 2000 psi (13.8 MPa) and less appear to be questionable in that AC stiffnesses consistent with the measured strains would generally be greater than the stiffness values used. A few of the sets of measured strains look fairly reasonable regarding change in magnitude with depth, such as the second and third sets under one of the duals in the longitudinal direction (Table 19). There were isolated instances when one or more of the measured strains was approximately the same magnitude as one or both of the calculated values but this was the exception. There was no obvious superiority noted for either of the sets of calculated values. Examination of the data indicated that the agreement between the measured and calculated strains became progressively poorer as the depth below the surface increased. The greatest theoretical strain occurred in the second or third layer in all cases. The maximum measured strain varied throughout the AC depth from run to run.

The data accumulated at Station 140 provided an opportunity to determine the uniformity of the various methods of in-situ strain measurement used with regard to "repeatability" and with regard to comparative measured values at the same distance below the AC surface for the same "run". These data are presented in Table 20 and indicates that gauges located at the same depth within the AC measured strains differing by as much as a factor of 30 for a single application of the load (Run No. 2, transverse

Table 19

COMPARISON OF CALCULATED AND MEASURED AC PAVEMENT STRAIN
WILLITS TEST SECTION

Station 139-00

No.	Gauge Conditions	Calculated (10^{-6} in./in.) Meas(1)	Calculated (10^{-6} in./in.) Assume(2)	Measured (10^{-6} in./in.) Various Runs				Avg.	Gage Location – Distance Below Surface Ft.	(mm)
1	Longit direction under ƀ duals	52	41	76	-220	-34 39		-	0.12	(37)
2		145	185	---	-191	-77		-134	0.24	(73)
3		267	294	-145	-68	-112		-108	0.45	(137)
4		287	285	147	98	51		99	0.67	(204)
5		145	145	458	241	415		371	1.08	(329)
6	Transv. direction under ƀ duals	-338	-217	-295	-362	-424		-360	0.12	(37)
7		-366	-425	-200	---	-368		-284	0.24	(73)
8		-335	-359	-250	-125	-363 -166		-246	0.45	(137)
9		-196	-186	67	-72	151		---	0.67	(204)
10		-1	-0-	136	73	-80		---	1.08	(329)
11	Longit direction under ƀ one wheel	-429	276	-273	-278	-238	-198	-247	0.12	(37)
12		501	584	-134	-103	-138	-101	-119	0.24	(73)
13		523	559	416	-84	-76	359	---	0.45	(137)
14		407	396	306	135	102	233	194	0.67	(204)
15		149	149	522	274	244	382	356	1.08	(329)
16	Transv. direction	432	274	92	86 -98	57	-58 107 -81	---	0.12	(37)
17	under ƀ one wheel	477	553	93	---	---	684	---	0.24	(73)
18		458	488	431	---	---	75	253	0.45	(137)
19		322	310	125	---	68	70	88	0.67	(204)
20		10	9	-120	66	58	38	---	1.08	(329)

1. The AC stiffnesses used were the maximum values calculated for each layer. They were as follows:

Layer		
1	M_R =	11,000 psi (76 MPa)
2		16,000 psi (110 MPa)
3		28,000 psi (193 MPa)
4		24,500 psi (169 MPa)

2. The AC stiffness assumed for all the layers was 25,000 psi (172 MPa)

Table 20

COMPARISON OF CALCULATED AND MEASURED AC PAVEMENT STRAIN

WILLITS TEST SECTION

Station 140+00

Run No.	Location	Measured Strain (10^{-6} in./in.) Longitudinal by Gauge			Transverse by Gauge				Calculated Strain[1] Long	Trans.
1	Bottom Layer 1	-188	-245	-132	-277	-37	-568	-293		
2	(-0.12')	----	-253	-140	-396	-29	-672	-969		
3		-153	-326	-160	-380	---	-691	-862	+40.6	-217
4		-169	-282	-100	-301	---	-541	-349		
5		-154	-298	-144	-324	---	-676	-388		
6	Bottom Layer 2	-250	-78	----	-231	-108	-400			
7	(-0.24')	-257	-78	----	-221	-130	-400		+185	-425
8		-265	-95	----	-237	-90	-550			
9		-288	-78	----	-262	-101	-563			
10	Middle Layer 3	-45	+41[2]	-63	-62	-79	-78			
11	(-0.45')	-59	+39[2]	-72	-81	-108	-80			
12		-59	+89[2]	-82	-91	-110	-84		+294	-359
13		-61	+70[2]	-91	-77	----	-78			
14		-59	+55[2]	-87	-87	-102	-86			
15		-83	+37[2]	-95	-96	-140	-96			
16	Bottom Layer 4	-620	-592		-79	-62			+145	+1
17	(-1.09')	-620	-611		-98	-74				

1. Using assumed AC stiffness of 25 ksi for each layer.
2. Probably should be compression based on other measured values.
3. 1 Ft. = 305 mm.

gauges). The extreme values for a single run usually differed by a factor approaching two or more. The agreement between the measured strains and those calculated using an AC stiffness of 25 ksi (172 MPa) was very poor. The measured values were considerably greater than the calculated values near the surface whereas they were considerably less than the calculated strains for layer 3. Comparison of the strains measured by individual gauges from run to run revealed reasonably good "repeatability". Thus, the strain data from the extensively instrumented Willits Test Section definitely indicated that none of the instrumentation methods was obviously superior. Also, the data included in Tables 19 and 20, although somewhat inconclusive, indicates that the theoretical procedure used may not be appropriate for the pavements studied.

E. Pavement Deflection

Indio

Pavement deflections were measured with LVDT's, the Deflectometer, and the Dynaflect at Indio. A representative set of surface deflection data is presented in Table 21, below. Although the measured surface deflection was minimal, very good agreement was achieved between the California Deflectometer, Dynaflect (when adjusted per correlation curves), and the in-situ deflection measured with the LVDT located closest to the pavement surface.

Table 21

PAVEMENT DEFLECTION
INDIO

Device	Deflection
LVDT	0.007 in. (0.177 mm)
Deflectometer	0.008 in. (0.203 mm)
Dynaflect	0.007 in. (0.177 mm)

Because of the difficulties encountered when attempting to interpret and analyze the other in-situ measurements at Indio, the effort required for comparisons of only the theoretical and measured pavement deflections was not considered warranted.

Blythe

Deflections were measured using a Benkleman beam and using LVDT's attached to brackets imbedded in the AC at various distances below the surface as shown on Figure 14. The tests were conducted using a truck that applied an 18,600 pound (8,437 kg) axle load to the pavement. The tire pressure was 80 psi (552 kPa). Comparison of the measured surface deflections (see Table 22) shows the values obtained with the Benkelman beam to be greater than those obtained with the LVDT's for all four test locations. At first glance, there appears to be no pattern for the different deflection methods. However, when the LVDT readings were subtracted from the Benkelman beam readings the differences were .0040, .0028, .0034, .0027. In terms of the precision of the Benkleman beam data reported, these differences are 4, 3, 3, and 3 thousandths of an inch (0.10 and 0.08 mm). One contributing factor to this nearly constant difference probably was the location of the upper LVDT's. In order to function, they were placed 1-3/4 inch (44 mm) and 1-1/4 inch (32 mm) below the surface of the AC at Test Sections A and B, respectively. It is quite possible that the approximately 0.003 inch (0.08 mm) difference in the deflection measured with the Benkelman beam occurred within this uppermost 1-1/4 to 1-3/4 inches (32 to 44 mm) of pavement.

Pavement deflections were measured at various depths within the AC using the LVDT's for comparison with those deflections calculated using the modified Chev 5L program. The deflections were calculated three times for each location so that the stiffnesses previously calculated using the different measured or assumed times of loading could be used for the pavement deflection calculations in a manner similar to that used for the strain calculations.

Figure 14

AC DEFLECTION MEASURING DEVICE

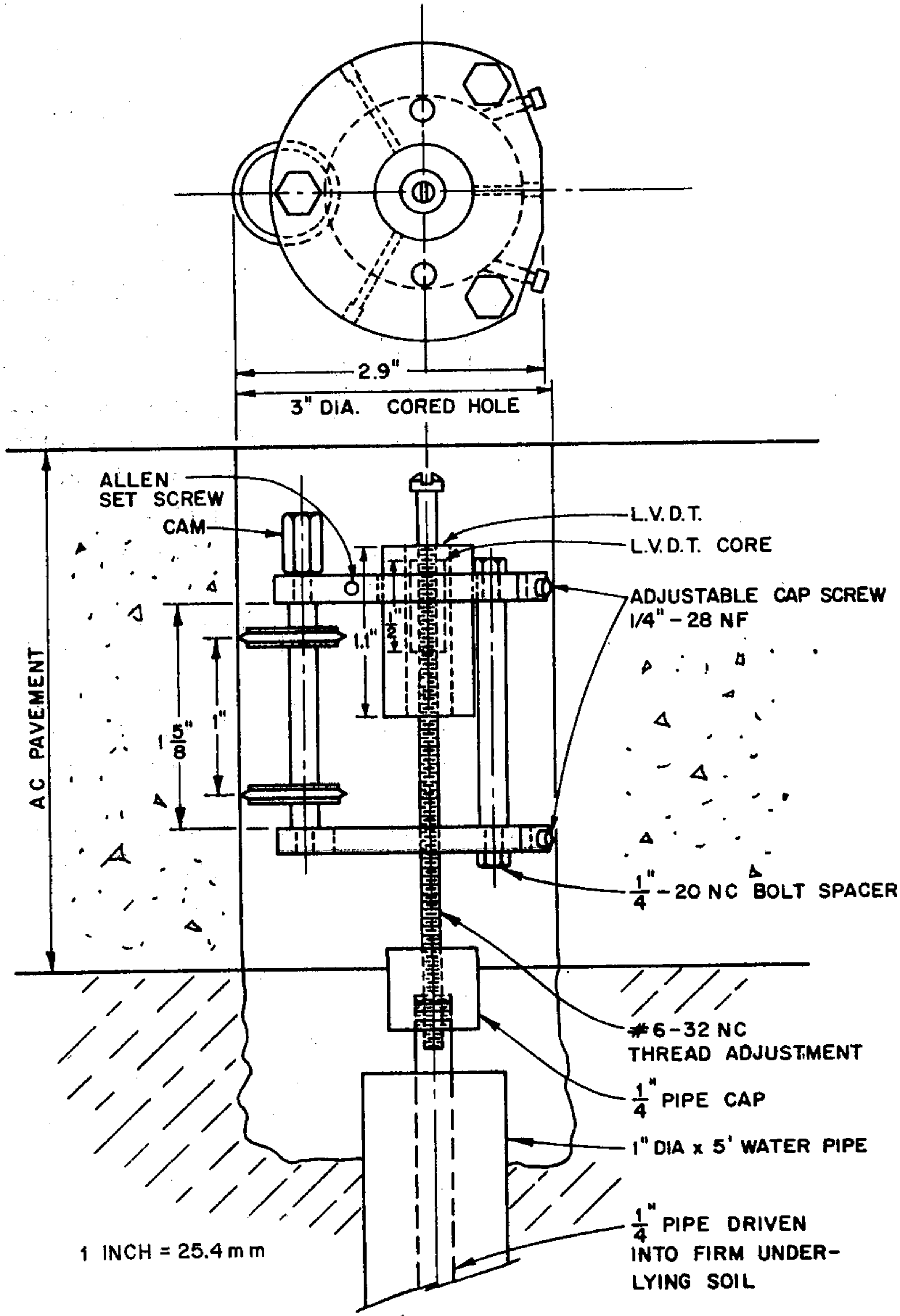


Table 22

AC PAVEMENT SURFACE DEFLECTION
BLYTHE TEST SECTION

Test Section A

Station		Benkelman Beam (In.)	"Surface" LVDT (In.)
273+00		0.013	0.0080
"		0.012	(0.20 mm)
"		0.012	
	Avg.	0.012 (0.30 mm)	
273+75		0.014	
274+00		0.015	0.0112
274+25		0.014	(0.28 mm)
	Avg.	0.014 (0.36 mm)	

Test Section B

Station		Benkelman Beam (In.)	"Surface" LVDT (In.)
373+75		0.007	
374+00		0.007	0.0036
374+25		0.006	(0.09 mm)
	Avg.	0.007 (0.18 mm)	
374+75		0.008 and 0.006	
375+00		0.008 and 0.006	0.0033
375+25		0.006 and 0.005	(0.08 mm)
	Avg.	0.006 (0.15 mm)	

These deflection data are presented in Tables 23 and 24. Examination of the data in Table 23 indicates that none of the sets of calculated deflections correlated well with the measured deflections. Individual calculated and measured values agreed quite well in some cases, however. The measured deflections did not even show the expected trend toward decreasing deflection with depth beneath one of the dual tires. The only trend apparent in the measured values was toward maximum deflections at or near mid-depth within the AC. This is consistent with the calculated values for deflection beneath the center of the dual wheels. As expected, the longer times of loading, which resulted in lower AC stiffness, also resulted in higher calculated deflections for the Barksdale and Hicks supperposition procedure and the LVDT-determined time of loading. The prediction and measurement of maximum deflection at mid-depth apparently is a measure of the heaving action that often takes place in unstable AC between dual tires.

The deflection data does not show a definite pattern for any one time of loading procedure for all four test locations. For Blythe A, the longest time of loading (designated LVDT) gave the best comparative results for both test sections, while for Blythe B, the constant (Barksdale and Hicks) time of loading with depth gave the best results. The LVDT readings for the Blythe A (12-inch (305 mm) thick) test sections were almost always greater than the theoretical results while the reverse was true for the Blythe B test sections (which contained 18-inch (458 mm) thick AC).

The overall deflection results for Blythe indicate no one time of loading would be best for all the conditions tested. The results did indicate the deflections near the bottom of each layer had a tendency to converge toward the calculated values. However, the correlation between measured and calculated deflections was, with rare exception, uniformly poor and the trend of the measured values questionable. With this in mind, the refinement of determining the time of loading for each layer does not appear to be necessary.

Table 23

PAVEMENT DEFLECTION
COMPARISON OF MEASURED AND CALCULATED VALUES

BLYTHE TEST SECTION A

Station 273+00

Depth Below Surface (Ft.)	Beneath Center of One Wheel: LVDT Time (1)	B&H (2)	B&H (3)	Meas. (LVDT)	Beneath Center of Dual Wheels: LVDT (1)	B&H (2)	B&H (3)	Meas.
		(In. x 10^{-4})				(In. x 10^{-4})		
0	107	82	74		80	72	66	123(BB) (4)
0.15	94	78	71	81	82	72	68	80
0.35	87	74	68		84	74	68	
0.44				84				90
0.53	83	73	67		86	74	68	
0.65				98				103
0.73	82	72	66		84	74	68	
0.75				81				
0.93	79	69	65		82	72	68	

Station 274+00

Depth Below Surface (Ft.)	Beneath Center of One Wheel: LVDT Time (1)	B&H (2)	B&H (3)	Meas. (LVDT)	Beneath Center of Dual Wheels: LVDT (1)	B&H (2)	B&H (3)	Meas.
0	120	85	88		88	74	76	143(BB) (4)
0.15	110	82	86	107	90	76	78	112
0.35	98	78	80		92	78	78	
0.44				120				123
0.61	90	75	76		92	78	78	
0.67				125				123
0.73				90				95
0.78	88	74	75		90	76	78	
0.94	85	72	73		88	74	76	

(1) Time of loading determined from LVDT charts.
(2) Time of loading determined from Barksdale and Hicks' chart.
(3) Time of loading determined from Barksdale and Hicks' chart for surface - this time used for all layers.
(4) Benkelman beam measurement.
(5) 1-inch = 25.4 mm.

Table 24

PAVEMENT DEFLECTION
COMPARISON OF MEASURED AND CALCULATED VALUES

BLYTHE TEST SECTION B

Station 374+00

Depth Below Surface (Ft.)	One Wheel: LVDT Time(1)	One Wheel: B&H(2)	One Wheel: B&H(3)	One Wheel: Meas. (LVDT)	Dual Wheels: LVDT(1)	Dual Wheels: B&H(2)	Dual Wheels: B&H(3)	Dual Wheels: Meas.
	(In. x 10^{-4})				(In. x 10^{-4})			
0	94	63	58		60	50	44	
0.10				40				36
0.36	69	54	49		63	52	46	
0.42				41				39
0.63	63	52	47		63	52	46	
0.83				38				39
0.92	60	50	46		62	51	46	
1.17				42				40
1.45	56	48	44		58	49	45	

Station 375+00

Depth Below Surface (Ft.)	One Wheel: LVDT Time(1)	One Wheel: B&H(2)	One Wheel: B&H(3)	One Wheel: Meas. (LVDT)	Dual Wheels: LVDT(1)	Dual Wheels: B&H(2)	Dual Wheels: B&H(3)	Dual Wheels: Meas.
0	73	53	50		57	45	41	143(BB)(4)
0.09				41				33
0.41	61	48	45		59	46	43	
0.44				36				35
0.68	58	47	43		59	46	43	
0.83				40				41
0.95	56	45	43		58	45	42	
1.12				34				32
1.53	52	43	41		53	43	40	

(1) Time of loading determined from LVDT charts.
(2) Time of loading determined from Barksdale and Hicks' chart.
(3) Time of loading determined from Barksdale and Hicks' chart for surface - this time used for all layers.
(4) Benkelman beam measurement.
(5) 1-inch = 25.4 mm.

Willits

Several methods were used to measure pavement deflection at Willits for subsequent comparison with the pavement deflections calculated using the modified Chev 5L computer program. LVDT's were used to measure deflection at four depths in the pavement. These locations were noted on Tables 10 and 11. For additional information, deflections were also measured with the Benkelman beam and with the Deflectometer, which was used as the test vehicle for all the Willits testing. The comparative results for the surface deflections are shown on Tables 25 and 26. The LVDT data is from only the device nearest the top of the pavement surface. For each Station, the results have been separated for the morning and afternoon tests. Slightly higher deflections were recorded for the afternoon tests, presumably due to the higher pavement temperatures.

At the Blythe test sections, the deflections measured with the Benkelman beam were consistantly more than those measured with the "surface" LVDT's. Just the opposite was true for the Willits test section. The results at each Willits test location were consistant in that the greatest deflection was measured with the LVDT's and the least deflection with the Deflectometer. The range in test results obtained with each of the three methods at each location was not excessive. Also, the values for the various test methods agreed reasonably well with the exception of the LVDT's in the afternoon at Station 139.

The LVDT's were used to measure the in-situ deflections for comparison with the calculated values at different depths within the pavement. These measurements are presented in Table 27. Again, three sets of AC stiffnesses were used for the calculation of the theoretical deflections. Comparison of the measured and calculated deflections indicates that the measured deflections beneath the center of the duals exceeded the calculated values by factors of two or

Table 25

AC PAVEMENT SURFACE DEFLECTION
(INCHES)
WILLITS TEST SECTION
(STATION 139)

AM Tests

Deflectometer	Benkelman Beam	L.V.D.T.[1]
0.024	0.028	0.038
0.025	0.032	0.040
0.024	0.025	0.039 (0.99 mm)
0.025	0.033	
0.025	0.032	
0.027	0.028	
0.025	0.038	
0.029	0.033	
0.026 (0.66 mm)	0.029	
	0.031 (0.79 mm)	

Avg. of all Devices = 0.032 (0.81 mm)
Range = 0.013 (0.33 mm)

PM Tests

Deflectometer	Benkelman Beam	L.V.D.T.[1]
0.028	0.037	0.050
0.028	0.031	0.048
0.030	0.027	0.049 (1.24 mm)
0.029	0.044	
0.030	0.033	
0.030	0.026	
0.035	0.042	
0.032	0.034	
0.035	0.030	
0.031 (0.79 mm)	0.034 (0.86 mm)	

Avg. of all Devices = 0.038 (0.96 mm)
Range = 0.018 (0.46 mm)

(1) Individual readings for the L.V.D.T. nearest the top of the AC pavement - June 19, 1973

Table 26

AC PAVEMENT SURFACE DEFLECTION
(INCHES)
WILLITS TEST SECTION
(STATION 140)

AM Tests

Deflectometer	Benkelman Beam	L.V.D.T.[1]
0.024	0.022	No "AM" Readings
0.025	0.034	
0.024	0.032	
0.025	0.032	
0.025	0.030 (0.76 mm)	
0.027		
0.025		
0.029		
0.026 (0.66 mm)		

Avg. of all Devices = 0.028 (0.71 mm)
Range = 0.004 (0.10 mm)

PM Tests

Deflectometer	Benkelman Beam	L.V.D.T.[1]
0.028	0.030	0.034 (0.86 mm)
0.028	0.029	
0.030	0.040	
0.029	0.035	
0.030	0.032	
0.030	0.041	
0.035	0.030	
0.032	0.034 (0.86 mm)	
0.035		
0.031 (0.79 mm)		

Avg. of all Devices = 0.033 (0.84 mm)
Range = 0.003 (0.08 mm)

(1) Individual readings for the L.V.D.T. nearest the top of the AC pavement

Table 27

PAVEMENT DEFLECTION
COMPARISON OF MEASURED AND CALCULATED VALUES
WILLITS TEST SECTION

Depth Below Surface (Ft.)	Beneath Center of One Wheel ($In. \times 10^{-4}$) Calculated* #1	#2	#3	Meas. AM	Meas. PM	Beneath Center of Dual Wheels ($In. \times 10^{-4}$) Calculated #1	#2	#3	Meas. AM	Meas. PM
Station 139										
0.12	455	263	200			114	78	86		
0.15				335	466				330	456
0.24	343	189	174			118	82	88		
0.38				255	342				263	348
0.45	231	135	130			116	84	88		
0.67	143	97	100	255	338	104	80	83	272	370
0.83				200	266				220	283
1.08	71	68	67			72	68	68		
Station 140										
0.12	455	263	200			114	78	86		
0.15				250	320				300	360
0.24	343	189	174			118	82	88		
0.38				200	220				210	260
0.45	231	135	130			116	84	88		
0.67	143	97	100	220	240	104	80	83	210	280
0.83				200	240				220	270
1.09	71	68	67			72	68	68		

*

	M_R-#1	M_R-#2	M_R-#3
Layer 1	3500 psi	8000 psi	25000 psi
2	5500 "	8000 "	" "
3	10400 "	21500 "	" "
4	10400 "	30500 "	" "
5	37688 "	37688 "	37688 "

1 Ft = 305 mm; 1 ksi = 6.89 MPa

more, even when using the lower AC stiffnesses to calculate deflection. Somewhat better agreement between the measured and calculated deflections was obtained near the surface of the AC beneath a single wheel when using the lower AC stiffnesses. The decrease in measured deflection with depth was considerably lower than that calculated using the modified Chev 5L Program. Also, the sets of measured deflection data did not show the expected trend toward progressively less deflection with depth.

Additional tests were conducted at slower vehicle speeds which, as expected, resulted in even higher measured deflections. These results indicate that the AC stiffness required to force the calculated deflections to agree with the measured deflections would be unreasonably low in most cases. Because of the unexpected trend and magnitude of the measured deflections, it must again be concluded that the measured data is of questionable validity and, as such, should not be used as a basis for conclusions regarding the validity of the modified Chev 5L method of calculating anticipated AC deflection.

F. Stress at Subgrade Surface

Two University of California type pressure cells were installed at the AC/subgrade interface at Blythe, with one at Test Section A and one at Test Section B. The gauges were made in the Caltrans Laboratory and calibrated prior to installation. The interim report (4) contains a description of the gauges. They proved to be easy to install and provided data that seemed reasonable.

The comparative stress data are shown on Table 28. The stress at the bottom of the asphalt concrete pavement was calculated using the three groups of AC stiffnesses used for the calculations of AC strain and deflection.

The average measured stress agreed very well with one or more of the theoretically determined values at each of the locations. The best results for the 12 inch (305 mm) section (Blythe A) were obtained using the times of loading per Barksdale and Hicks (Figure 13). For the thicker Blythe B section (18 inch 458 mm), the best results were obtained when AC stiffnesses calculated using the time of loading from the LVDT data was used. In all four cases, the agreement between the average measured stress and one of the calculated stresses was very good. In three of the four cases, the use of different times of loading in accordance with the different levels within the AC provided the best correlation. Thus, contrary to many of the findings for strain and deflection, the stress data indicate that the assignment of AC stiffness layer by layer is the superior approach.

G. Theoretical Fatigue Life (Blythe and Willits)

The theoretical fatigue lives were determined for the Blythe and Willits Test Sections using the computer programs described previously in addition to a final computer program developed by Monismith (6). The AC stiffness values and frequency of occurrence

Table 28

STRESS DATA
(PSI)
COMPARISON OF MEASURED AND CALCULATED VALUES
BLYTHE TEST SECTION

Test Section A
Station 274+00
0.94' Below Surf.

Beneath Center of Load		Beneath Center of One Wheel	
Calculated	Meas.	Calculated	Meas.
8.75 per LVDT(1)	5.75	9.19 per LVDT(1)	7.11
6.45 per B&H(2)	7.53	6.54 per B&H(2)	8.37
6.69 per B&H(3)	6.69	6.82 per B&H(3)	4.71
			5.23
Avg.	6.69 psi (46.1 kPa)	Avg.	6.36 psi (43.8 kPa)

Test Section B
Station 375+00
1.53' Below Surf.

Beneath Center of Load		Beneath Center of One Wheel	
Calculated	Meas.	Calculated	Meas.
3.71 per LVDT(1)	3.35	3.43 per LVDT(1)	3.14
2.48 per B&H(2)	3.97	2.33 per B&H(2)	3.03
2.16 per B&H(3)	3.66	1.85 per B&H(3)	3.97
			3.66
			3.24
Avg.	3.66 psi (25.2 kPa)	Avg.	3.41 psi (23.5 kPa)

(1) Time of loading determined from LVDT charts
(2) Time of loading determined from Barksdale & Hicks' chart
(3) Time of loading determined from Barksdale & Hicks' chart for surface - this time used for all layers
(4) 1 foot = 305 mm

were determined using the program that incorporates the nomograph developed by Shell (AC stiffness at different temperatures) and Barber's equation for AC temperature variation with depth based upon climatological conditions. The strain at the bottom of the asphalt concrete pavement was determined using the modified Chevron 5L program. The data from these programs were then input into the program "FATIG" to determine the fatigue life of the structural section. One particular feature of the present system that limits its practicality for design is that it must be used with an actual or assumed structural section design.

The procedure then becomes one of trial and error until a structural section is found that has a theoretical fatigue life equivalent to the anticipated traffic. For the structural sections studied, the problem was only one of determining the predicted life for the existing materials, physical conditions, and structural sections.

The weather data for Blythe were obtained from the Climatological Data published by the U. S. Department of Commerce and are shown on Table 29. Table 30 contains the asphalt concrete properties and stiffness values determined from the Shell nomograph. These data were used to determine the stiffness moduli, using the computer solution described earlier, and to develop the frequency matrix (Tables 31 and 32). The frequencies shown are the number of months that each one hour interval had a mean stiffness in the group shown.

These data plus the estimated annual average daily truck traffic (Table 33) were used for an analysis of a five-layer system consisting of 4 layers of asphalt concrete on a semi-infinite subgrade. The modified Chev 5L program was used with 12 different load-stiffness combinations to cover the range of stiffnesses and traffic loads anticipated. These were:

Table 29

WEATHER DATA USED IN THE SIMULATION OF PAVEMENT TEMPERATURES

BLYTHE

Month	Avg. Monthly Air Temp. (°F)	Avg. Daily Air Temp. Range (°F)	Avg. Monthly Wind Velocity (mph)	Avg. Monthly Solar Insol. (Langleys per Day)	Avg. Monthly Sky Cover (0-10)
Jan.	53.5	25.7	7	305	4.9
Feb.	59.0	26.4	8	405	3.4
March	63.0	28.0	8	515	3.5
April	70.5	29.6	9	610	2.8
May	79.5	31.0	9	700	2.3
June	87.0	31.2	9	720	1.5
July	95.3	26.4	10	670	2.8
Aug.	94.7	25.1	9	650	2.5
Sept.	86.8	27.3	7	560	1.5
Oct.	75.8	29.2	7	430	1.5
Nov.	62.9	25.7	7	325	2.8
Dec.	53.1	24.6	6	270	3.8

Note: 1 mph = 0.447 m/s
°C = (°F -32)/1.8
C° = 0.556F°

Table 30

STIFFNESS CALCULATIONS

BLYTHE

Ring and Ball Softening Pt = 129°F (53.8°C)

Penetration at 77°F (25°C) = 31

Unit Weight of AC = 147.3 pcf (2360 kg/m^3)

Air Voids Content = 6.3%

Vol. Conc. of Aggreg. (Cv) = 0.913

Sp Gr. of Agg. = 2.65

Asphalt Content = 3.6%

P.I. = -1.0

Time of Loading = 0.10 sec.

R&B Temp. (1) °C	Pvt. Temps. (2) °F	Pvt. Temps. (3) °C	Temperature Difference (4)=(1)-(3) °C	Stiffness* (5) N/m^2	Stiffness(6) (6)= (5)x1.02x10^{-5} Kg/cm^2
53.8					
	40	4.4	49.4	2.2x10^8	2300
	50	10.0	43.8	1 x10^8	1020
	60	15.6	38.2	4.8x10^7	490
	70	21.1	32.7	1.9x10^7	195
	80	26.7	27.1	5.0x10^6	51
	90	32.2	21.6	1.5x10^6	16
	100	37.8	16.0	5.5x10^5	6
	110	43.3	10.5	2.0x10^5	2
	120	48.9	4.9	9.0x10^4	0.9
	130	54.4	-0.6	3.0x10^4	0.3
	140	60.0	-6.2	1.2x10^4	0.12
	150	65.6	-11.8	5.0x10^3	0.05

*Obtained from Nomograph for Determining the Stiffness Modulus of Bitumens, 3rd Edition 1972.

Table 31

THEORETICAL ASPHALT CONCRETE STIFFNESSES - KSI

BLYTHE TEST SECTION A

Month	Depth		
	0 - 2.5"	2.5 - 6.5"	6.5 - 10.25"
January	1,352,780	1,444,790	1,497,200
February	874,950	967,560	1,030,800
March	624,680	685,700	743,270
April	329,820	340,760	358,570
May	141,750	148,600	158,650
June	74,970	79,790	86,290
July	54,270	57,750	61,270
August	52,960	56,830	60,600
September	82,780	89,950	97,580
October	228,720	239,000	252,520
November	725,040	795,660	853,050
December	1,325,550	1,424,180	1,480,740

Determined for a time of loading of 0.1 sec.

1-inch = 25.4 mm

1 KSI = 6.89 MPa

Table 32

FREQUENCY OF OCCURRENCE OF STIFFNESS

BLYTHE TEST SECTION A

Time Interval	Stiffness Group - PSI x 10^3 25-50	50-75	75-100	100-200	200-300	300-400	400-600	600-800	800-1000	1000-1500	1500-2000
12-1 am	0	2	1	2	1	1	0	1	1	1	2
1-2	0	2	0	3	1	0	1	0	2	1	2
2-3	0	0	2	2	1	1	1	0	2	1	2
3-4	0	0	2	2	1	1	1	0	1	2	2
4-5	0	0	2	2	1	1	1	0	1	2	2
5-6	0	0	2	2	1	1	1	0	1	2	2
6-7	0	0	2	2	1	1	1	0	1	2	2
7-8	0	0	2	2	1	1	1	0	1	2	2
8-9	0	0	2	2	1	1	1	0	2	1	2
9-10	0	2	0	3	1	0	1	0	2	1	2
10-11	0	2	1	2	1	1	0	1	1	1	2
11-12 noon	0	2	2	1	1	1	0	1	2	2	0
12-1 pm	0	3	1	1	1	1	0	2	1	2	0
1-2	2	1	1	1	2	0	1	1	1	2	0
2-3	2	2	0	2	1	0	1	2	0	2	0
3-4	2	2	1	1	1	0	1	2	0	2	0
4-5	3	1	1	1	1	0	2	1	0	2	0
5-6	3	1	1	2	0	0	2	1	0	2	0
6-7	3	1	1	2	0	0	2	1	0	2	0
7-8	3	1	1	1	1	0	2	1	0	2	0
8-9	3	1	1	1	1	0	1	2	0	2	0
9-10	2	2	0	2	1	0	1	1	1	2	0
10-11	0	3	1	1	1	1	0	2	1	2	0
11-12	0	2	2	1	1	1	0	1	1	3	0

1 PSI - 6.89 kPa

1 KSI = 6.89 MPa

Table 33

ANNUAL AVERAGE DAILY TRUCK TRAFFIC
STATEWIDE SURVEY*

AM

Hour	12-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
% Traffic	2.8	2.7	2.9	3.1	3.5	4.1	4.2	4.3	4.8	5.0	5.2	5.2

PM

Hour	12-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
% Traffic	5.2	5.6	5.7	5.7	5.4	4.5	3.8	3.5	3.3	3.2	3.3	3.0

*Based on 1967 Classified Vehicle Study in California
Data Received from D.O.T. Traffic Department.

1. Three stiffness moduli for the asphalt concrete: 75,000; 350,000; and 1,250,000 psi (517, 2412, and 8613 MPa) (Blythe A) or 1,500,000 psi (10,335 MPa) (Blythe B). Poisson's ratio for each layer was assumed to be 0.40,

2. Four axle load groups: 4, 10, 18, and 24 kips (1.8, 4.5, 8.2, and 10.9 kg) (dual wheels with 75 psi (517 kPa) tire pressure), and

3. Subgrade modulus of a constant 25,000 psi (172 MPa) with a Poisson's ratio of 0.35.

The maximum strain (usually the tangential strain) on the underside of the asphalt concrete was then plotted on a graph of stiffness versus strain, as shown on Figure 16, and then as computed strains versus axle loads for a range of layer stiffnesses (Figure 17 - at least one for each stiffness group as determined in Table 32). Using these data and the results of fatigue tests conducted by Monismith of "strain versus repetitions to failure", (see Figures 18 and 19) Table 34 was developed. This shows the relationship between stiffness, axle group, strain, and fatigue life.

The final phase in the fatigue life determination is the input of these data into the program "FATIG". The program combines the data obtained from the multi-layered elastic system and the temperature simulation system with traffic and fatigue data to obtain the expected fatigue life of an asphalt concrete pavement. A linear summation is then used to determine the annual fatigue life damage. The volume of truck traffic was increased at an assumed annual growth rate and the computations repeated until the accumulated fatigue damage reached a value of 1.0. The results for the Blythe sections were as follows:

Based on initial ADTT = 1464

Annual rate of traffic expansion = 2.13%

Figure 16

STRAIN VS STIFFNESS MODULUS (FOR LOADS SHOWN)

BLYTHE TEST SECTION A

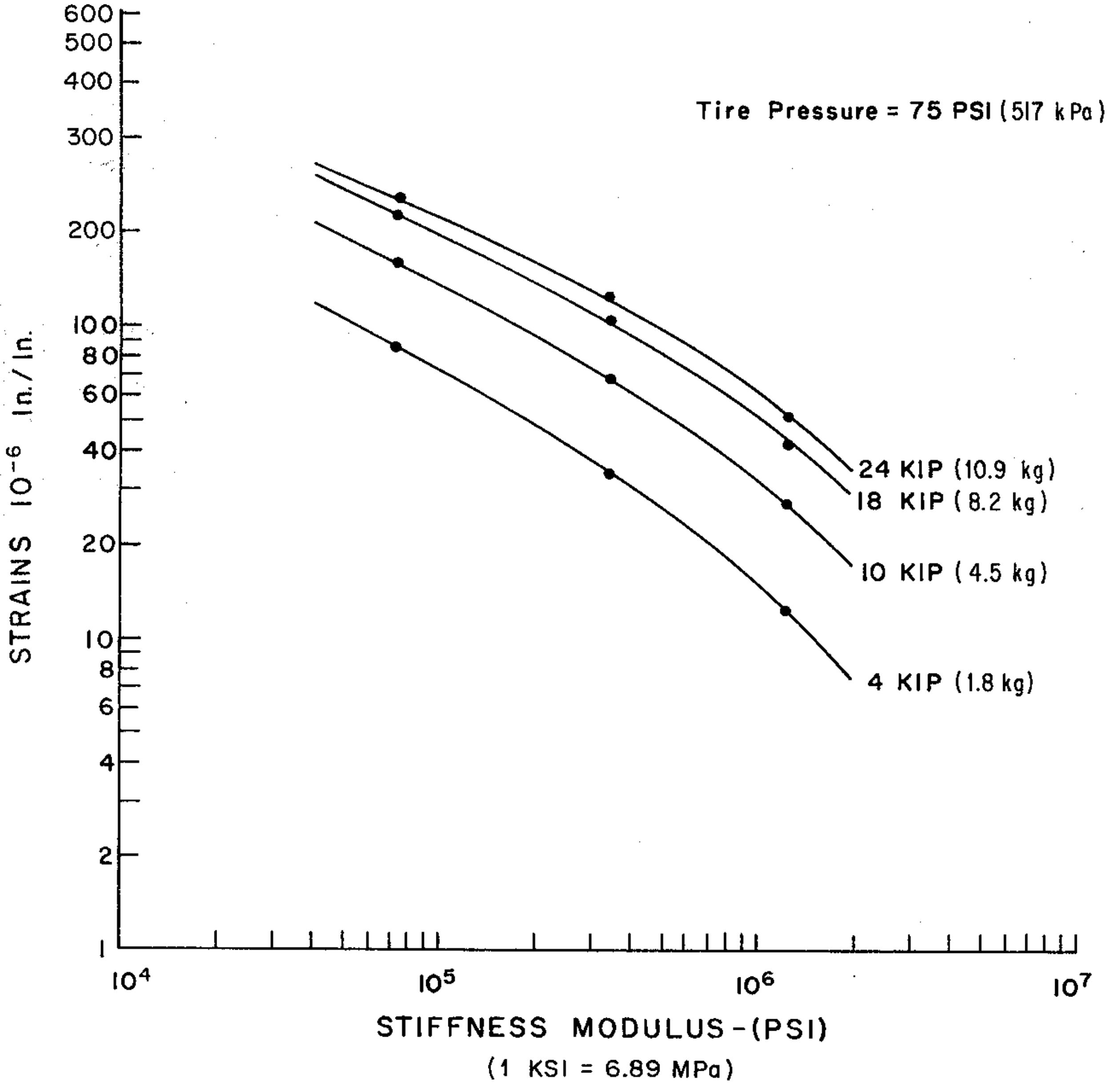


Figure 17

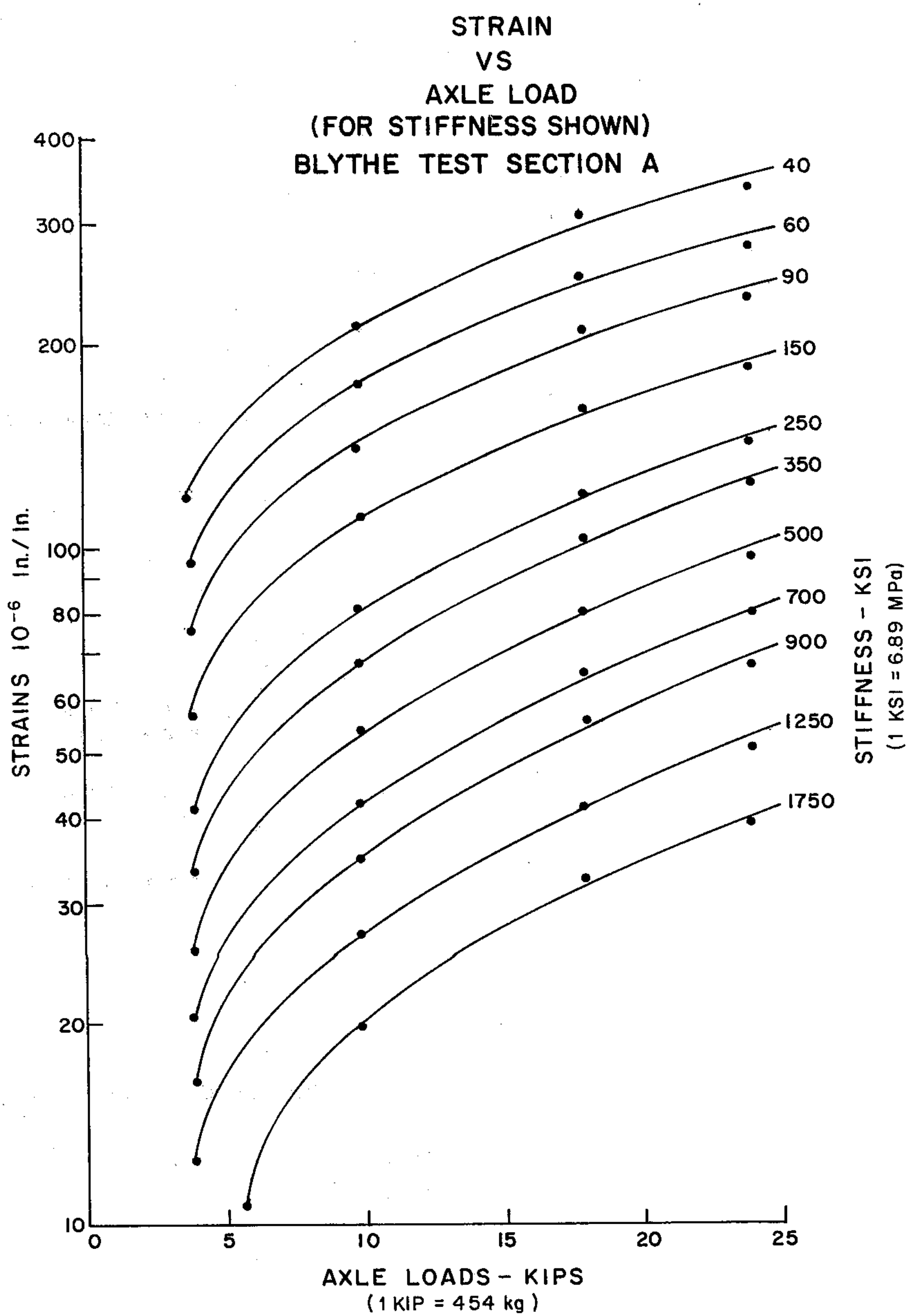
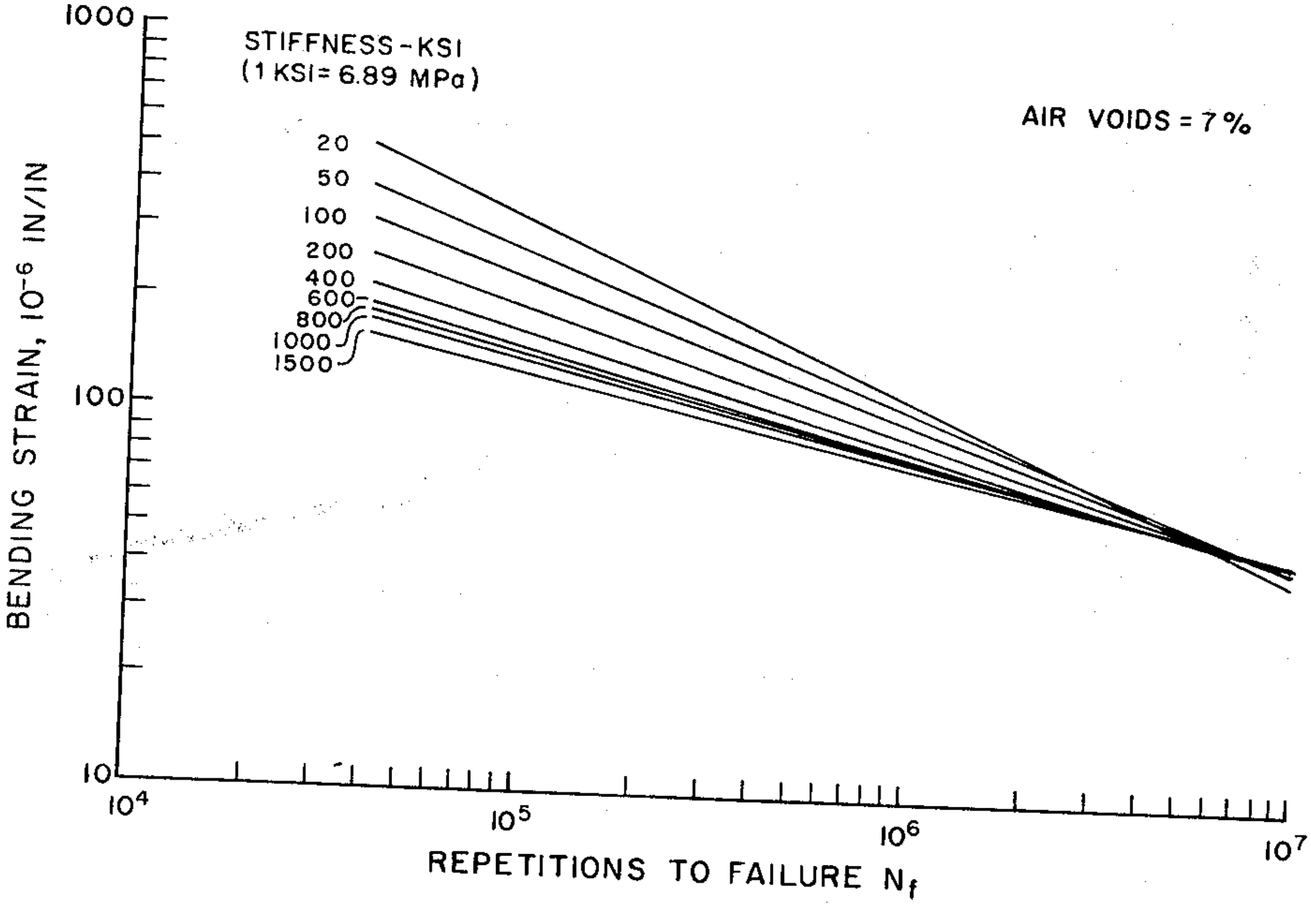

STRAIN
VS
AXLE LOAD
(FOR STIFFNESS SHOWN)
BLYTHE TEST SECTION A
400
300
200
100
80
60
50
40
30
20
10
STRAINS 10⁻⁶ In./In.
0
5
10
15
20
25
AXLE LOADS - KIPS
(1 KIP = 454 kg)
40
60
90
150
250
350
500
700
900
1250
1750
STIFFNESS - KSI
(1 KSI = 6.89 MPa)

Figure 18

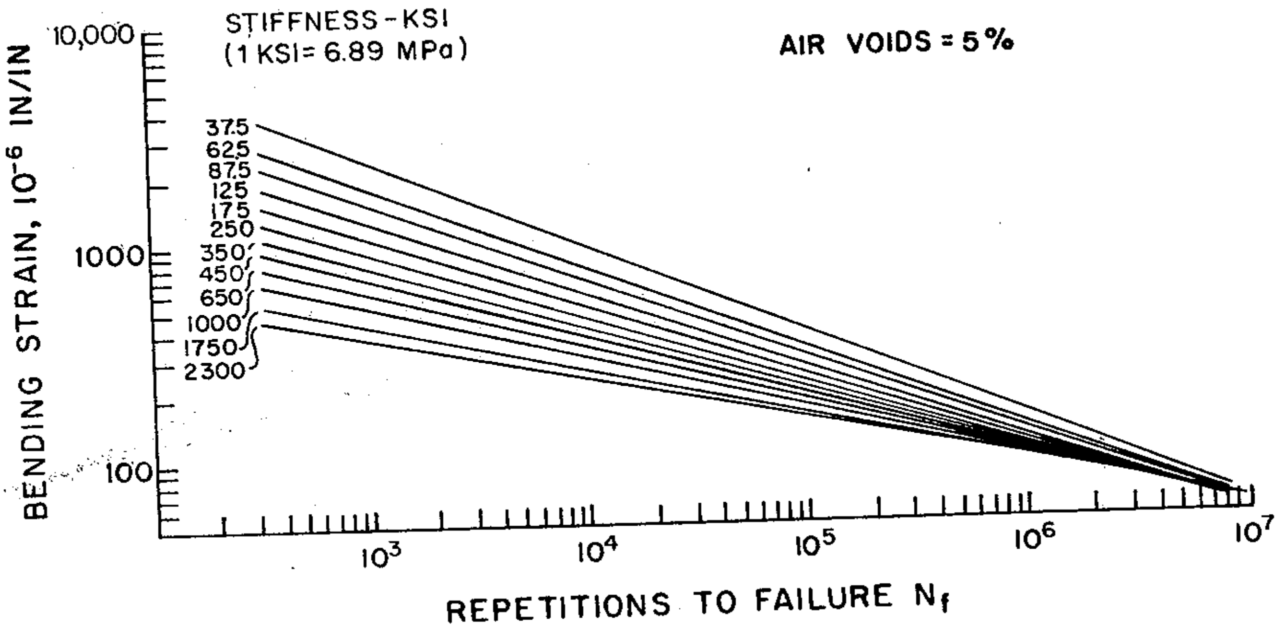
STRAIN
VS
REPETITIONS TO FAILURE
FOR THE GENERAL FATIGUE RELATIONSHIP



From Reference 6

Figure 19

STRAIN
VS
REPETITIONS TO FAILURE
FOR THE GENERAL FATIGUE RELATIONSHIP



From Reference 6

Table 34

RELATIONSHIP OF STIFFNESS, AXLE LOAD, STRAIN, AND FATIGUE LIFE

BLYTHE TEST SECTION A

Axle Load Group (kips)	Strain in./in.x10^{-6} / Cycles to Failure	Stiffness Groups - PSI x 10^3 25-50	50-75	75-100	100-200	200-300	300-400	400-600	600-800	800-1000	1000-1500	1500-2000
<3	ε	95	74	<70	<70	<70	<70	<70	<70	<70	<70	<70
	N_f	1.35E6	2.3E6	∞	∞	∞	∞	∞	∞	∞	∞	∞
3-7	ε	145	118	96	73	<70	<70	<70	<70	<70	<70	<70
	N_f	5E5	7.2E5	1.1E6	1.9E6	∞	∞	∞	∞	∞	∞	∞
7-8	ε	182	150	123	94	<70	<70	<70	<70	<70	<70	<70
	N_f	2.9E5	4E5	5.7E5	1E6	∞	∞	∞	∞	∞	∞	∞
8-12	ε	212	176	145	110	81	<70	<70	<70	<70	<70	<70
	N_f	2.05E5	2.65E5	3.8E5	6.3E5	1.3E6	∞	∞	∞	∞	∞	∞
12-16	ε	255	211	175	135	100	85	<70	<70	<70	<70	<70
	N_f	1.35E5	1.7E5	2.3E5	3.5E5	6.8E5	1.1E6	∞	∞	∞	∞	∞
16-16.25	ε	277	230	190	147	110	94	74	<70	<70	<70	<70
	N_f	1.1E5	1.35E5	1.8E5	2.7E5	5.1E5	8.5E5	1.7E6	∞	∞	∞	∞
16.25-18	ε	286	237	197	152	114	97	77	<70	<70	<70	<70
	N_f	1.04E5	1.28E5	1.65E5	2.4E5	4.6E5	7.2E5	1.35E6	∞	∞	∞	∞
18-18.5	ε	300	245	205	158	120	102	81	<70	<70	<70	<70
	N_f	9.2E4	1.15E5	1.5E5	2.2E5	3.8E5	6.5E5	1.1E6	∞	∞	∞	∞
18.5-20	ε	310	255	213	165	125	108	85	<70	<70	<70	<70
	N_f	8.5E4	1.06E5	1.35E5	1.9E5	3.4E5	5.4E5	9.5E5	∞	∞	∞	∞
20-22	ε	326	269	222	174	132	115	90	72	<70	<70	<70
	N_f	7.6E4	9.4E4	1.2E5	1.6E5	2.8E5	4.3E5	8E5	∞	∞	∞	∞
22-24	ε	345	282	236	185	142	123	97	78	<70	<70	<70
	N_f	6.6E4	8.2E4	1.05E5	1.35E5	2.2E5	3.2E5	6E5	1.1E6	∞	∞	∞
24-26	ε	362	295	250	195	151	132	104	84	72	<70	<70
	N_f	5.8E4	7.3E4	9E4	1.15E5	1.8E5	2.5E5	4.6E5	8.8E5	1.4E6	∞	∞
26-30	ε	384	311	262	206	162	142	113	92	79	<70	<70
	N_f	5.1E4	6.4E4	7.8E4	1E5	1.45E5	2E5	3.2E5	6E5	1E6	∞	∞
>30	ε	396	320	271	214	170	150	121	99	85	<70	<70
	N_f	4.8E4	6E4	7E4	9E4	1.3E5	1.65E5	2.7E5	4.5E5	7.5E5	∞	∞

Notes: 1 KIP = 454 kg
1 psi = 6.89 kPa
1 KSI = 6.89 MPa

Blythe A

Year	Annual Damage	Accumulated Damage
1	.758139	.758139
2	.774287	1.53243

Blythe B

Year	Annual Damage	Accumulated Damage
1	.065146	.065146
2	.066533	.131679
3	.067950	.199629
4	.069398	.269027
5	.070876	.339903
6	.072386	.412288
7	.073927	.486216
8	.075502	.561718
9	.077110	.638828
10	.078753	.717581
11	.080430	.798011
12	.082143	.880154
13	.083893	.964047
14	.085680	1.049729

Interpolating gives the following predicted time of incipient cracking at the bottom of the AC:

Predicted Life

Blythe A = 1.3 years

Blythe B = 13.4 years

This same procedure was then used again to determine the fatigue life of the Willits test section pavement. All the data were assembled in the same manner as discussed for the Blythe sections. As at Blythe, the modified Chev 5L program was used for 12 load-stiffness combinations. These were:

1. Three stiffness moduli for the asphalt concrete: 60,000; 200,000; and 550,000 psi (413, 1378, and 3790 MPa); Poisson's ratio for each layer was assumed to be 0.40.

2. Four axle load groups: 4, 10, 18, and 24 kips (1.8, 4.5, 8.2, and 10.9 kg) (dual wheels with 75 psi (517 kPa) tire pressure).

3. Subgrade modulus data used as shown above with a subgrade Poisson's ratio of 0.35.

The results of the program "FATIG" were as follows:

Based on initial ADTT = 789 per day
Annual rate of traffic expansion = 3% per year

<u>Willits</u>

Year	Annual Damage	Accumulated Damage
1	.080388	.080388
2	.082800	.163188
3	.085284	.248472
4	.087842	.336314
5	.090478	.426792
6	.093192	.519984
7	.095988	.615972
8	.098867	.714839
9	.101833	.816672
10	.104888	.921561
11	.108035	1.029596

Interpolation gives the final results as:

Predicted Life = 10.7 years

Thus, this approach to fatigue life prediction resulted in a reasonable value for Willits, but a somewhat low value for Blythe B considering it was designed for a subgrade R-value of 15 and placed on a subgrade material having an R-value of 62 and an unreasonable short fatigue life prediction for Blythe A.

H. Summary

The theoretical procedure employed to calculate pavement temperature provided values that correlated reasonably well with those measured at Indio and Blythe. The procedure is, however, predicated on the availability of climatic input applicable to the location of the pavement. These data may not be available. Difficulties were encountered at Willits that resulted in a substantial difference between measured and calculated pavement temperatures. Thus, if the procedure developed by Barber and modified by Kasianchuk is to be used, reasonably accurate values for the climatic characteristics shown in Table 12 must be available, either from tables or actual on-site measurements.

Considerable difficulties were encountered when calculating AC stiffness for subsequent calculation of AC stress, strain, and deflection due to the dependency of AC stiffness on time of loading and temperature. The computer program used to calculate stiffness will accept only one time-of-loading value for all the AC per run. Because this is contrary to Barksdale and Hicks and to the measured times of loading, both of which indicate that a change with depth occurs, a procedure consisting of multiple computer runs and superposition was tried in addition to the conventional assignment of only the surface time of loading to all the AC regardless of depth. The intent was to then examine the computed and measured stresses, strains, and deflections to evaluate the suitability of using this superposition procedure, and to determine whether the relatively long measured times of loading were realistic. Unfortunately, so many other difficulties and anomalies were encountered regarding theoretical and measured AC temperatures (Willits), strain, and deflection that very little could be inferred from the data. The use of superposition resulted in the best agreement between measured and calculated AC strain for Blythe Test Section A. However, the opposite was true for Blythe Test Section B. In addition, very low AC stiffnesses were calculated for Willits (less than 2000 psi (13.8 MPa) in several instances). This necessitated a change in procedure regarding assumed stiffness that resulted in poor agreement between the measured and calculated strains. Also, the Willits data indicated that none of the instrumentation methods tried was obviously superior and that all the measured strains were of questionable accuracy due to the scatter in the measured values. The deflection data also were inconclusive in that the agreement between calculated and measured values was generally poor, the trend in measured values was questionable, and no single AC time-of-loading procedure resulted in the best agreement of measured and calculated values in every case. Thus, the deflection analysis also could not be used as a basis for conclusions regarding the validity of the modified Chev 5L method of calculating pavement strain and deflection. The comparision of measured and calculated stress at the bottom of the AC indicated that the assignment of different AC stiffnesses to each AC layer in accordance with the anticipated differences in time of loading was appropriate and would provide a good estimate of in-situ stress. The fatigue data indicated that the theoretical procedures used may provide very conservative estimates of fatigue life.

Because of the numerous unexplained differences between calculated and measured values revealed by this study, the theoretical procedure used could not be effectively substantiated or refuted. However, the intent of the entire study was to determine whether the theoretical pavement fatigue approach should be incorporated into the Caltrans' design procedure. The fatigue life estimates calculated for Blythe appear to be conservative but sufficient time has not yet passed to fully verify these estimates. Thus, it appears desirable to attempt to further verify the theoretical approach examined herein by making the necessary preliminary measurements and calculating the theoretical fatigue lives for several additional pavements. No additional extensive instrumentation of in-service pavements appears to be warranted, however, until the instrumentation difficulties encountered are resolved.

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