TENSILE TESTING OF ASPHALTIC CONCRETE

by

Sulaiman Abdullah Al-Juraiban

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This thesis has been approved on the date shown below:

R. A. Jimenez (signature) — March 15, 1976

R. A. JIMENEZ
Professor of Civil Engineering

Date

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ABSTRACT

The data presented here are concerned with the analysis and comparison of tensile strength and modulus of elasticity of asphaltic concrete obtained by axial loading and by a double punch method.

Four variables introduced were the rate of deformation, temperature, mixture type, and height of specimen. All specimens were of four inches (101.6 mm) in diameter and compacted by the Jimenez Vibratory Kneading Compactor.

The range of the maximum tensile stresses obtained by the axial and double punch was 66 to 494 psi (454,700 to 3,403,700 N/m^2) and 54 to 247 psi (372,200 to 1,701,800 N/m^2), respectively. The modulus of elasticity ranged between 5,620 and 28,240 psi (38,770,000 and 194,573,600 N/m^2) for the axial method of loading and between 26,200 and 166,860 psi (180,483,600 and 1,149,644,700 N/m^2) for the double punch method of loading.

CHAPTER 1

INTRODUCTION AND REVIEW

Tensile strength of asphaltic concrete is the most important property in relation to pavement durability. Asphaltic roads can crack under the tensile stresses produced by traffic, by changes in the subgrade, and by thermally induced expansions and contractions [1].

Pore water pressure causes debonding of binders from the aggregate surfaces, hence reducing the tensile strength of the aggregate-binder combination and finally the overall strength of the pavement.

Tensile cracks are a result of high active forces that are greater than the capacity of the pavement. Cracks usually start small in the pavement and propagate progressively under the continuation of active forces (traffic) until the full depth of the pavement is damaged.

In pavement design, the engineer must know the tensile strength and modulus of elasticity for the asphaltic concrete. These characteristics are important these days where tensile failure is the primary mode of failure in an asphaltic concrete pavement because of the increase in auto and truck transportation.

Tensile strength of asphaltic concrete mixture is a direct function of the binder aggregate bond [2].

Temperature rise causes air pore pressure in the nonsaturated asphaltic concrete mixture. Jones and Darter [3] found that asphaltic concrete exhibits larger thermal coefficients of expansion than the coefficients of contraction. In expansion, the air voids are exerting pressure and causing visco-elastic creep of the asphaltic binder.

Although today the conventional test to determine the strength of asphaltic concrete is the compressive, we need to know the tensile strength of the asphaltic concrete probably more than the compressive. Different tests have been developed to determine the tensile characteristics of asphaltic concrete. The latest method is the double punch and it is thought to be the best method among all other methods. Methods of tension testing can be classified as: (a) direct tensile tests, (b) bending tests, or (c) indirect tension tests.

In the direct tensile test an axial tensile force is applied directly to the specimen and the stress-strain characteristics of the material are measured. Some direct tensile tests have been performed [4-8] and the test results indicate that this method is simple in theory and principle, but the preparation of end grips is hard and time consuming. It requires either a special mold to thicken the ends or attachment of steel plates to both top and bottom of the specimen. Additionally, bending stress may arise due to misalignment of the load or eccentricity and the addition of stress concentration at the grips. In the evaluation of test results it is assumed that the stress is distributed uniformly across the cross-section; $\sigma_T = P/A$, where P is the applied load, A is the cross-sectional area, and σ_T is the tensile stress.

The bending test involves applying a bending load to a beam specimen. This test basically involves two types of loading conditions, which are (a) the common flexure test where a load is applied to a simply supported beam, and (b) the cohesiometer test which involves the application of a bending moment to a specimen through a cantilever arm [9]. The bending test is simpler than the previous one (direct) and requires less time in the preparation of the specimens. Many engineers favor it because of the fact that the loading conditions are similar to the field loading conditions of pavement materials [9].

If the common flexure test is used, the results are usually expressed as the modulus of rupture which is calculated by the standard flexure formula which assumes a linear stress-strain relationship which is in some error even for elastic materials at failure. If the cohesiometer test is conducted, the load required to cause failure (a one-half inch downward movement of the free end of the cantilever arm) is used to calculate the cohesiometer value which is empirical.

In both bending tests there is the problem of non-uniformity and undefined stress distribution existing across the specimen [9].

The indirect tensile test was first developed in both Brazil by Garneiro and in Japan by Akazawa at the same time and independently [2]. Here, a cylindrical specimen is loaded with compressive loads distributed along two opposite elements of the specimen. Livneh and Shklarsky [10] used this test to evaluate the anisotropic cohesion of asphaltic concrete. Usually the specimen fails by splitting vertically along the loaded plane as shown in Figure 1. The first use of this method was to determine the tensile strength of Portland cement concrete, then it was extended to determining the tensile strength of asphaltic concrete [2]. The vertical stress along the horizontal diameter A-A' is a compressive stress and varies from a maximum value of $\frac{6P}{\pi HD}$ at the center to zero at the circumference. The horizontal stress along the vertical diameter B-B' is a tensile stress of constant value of $\frac{2P}{\pi HD}$ [2, 9]. We are interested in the tensile strength determination, so the tensile strength by the split cylinder method is equal to

$$\sigma_T = \frac{2P}{\pi DH}$$

where P is the failure load in pounds, H and D are the height and diameter of specimen in inches, respectively. This method of testing is simple to perform but it has the

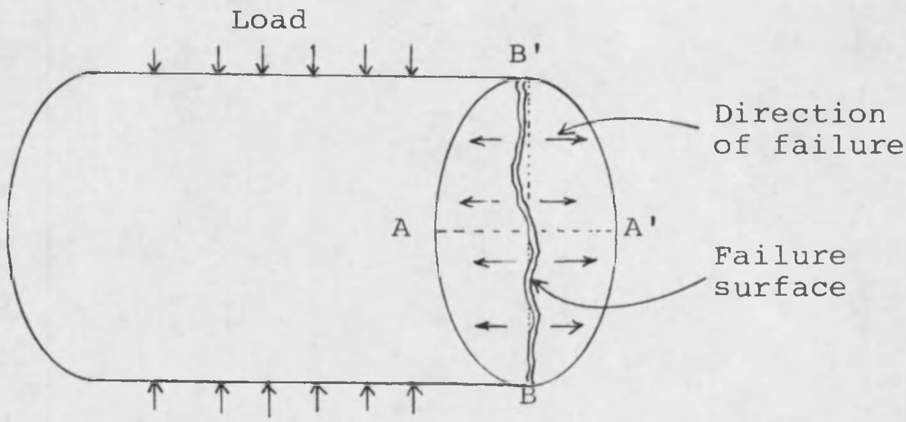

Figure 1. Illustration of Split Cylinder Loading

disadvantages that the loading conditions do not resemble those in the field. The previous (tensile strength by split cylinder) analysis was done by Frocht as reported by Lottman [2]. He assumed that the specimen was circular and in a plane stress condition and the material obeyed Hooke's Law so that the tensile stress obtained would be uniform. However, Lottman [2] found that the specimen does not remain circular at the end of the test and he noticed an amount of flattening of about 1 inch wide occurring at the loading zones of the specimen. This problem of flattening changes the point load applied at the beginning of the test into a distributed load over the width of the flattened specimen after the application of load. This problem introduces an error in the ultimate tensile strength calculated by

Frocht's equation and some modification is required to account for flattening.

Wright (after Lottman [2]) extended Frocht's theory to find the tensile stress distribution in a cylinder subjected to a compressive load which is distributed over a width of one-tenth of the diameter of the cylinder. Lottman indicated that some asphaltic concrete specimens flatten more than one-tenth of their diameters which means that Wright's theory is not useful to determine the tensile strength of these specimens, and he developed an analytical method to determine the actual tensile stress distribution in a cylinder subjected to a compressive load which is distributed over widths more than one-tenth of the diameter of the cylinder using finite element method. He came up with large and empirical formulas for tensile strength [2].

Investigators continued searching for more adequate and suitable methods and Chen [11] proposed the double punch method in 1970 as an alternative method of testing to determine the tensile strength of Portland cement mortar specimens.

Simply, the double punch method consists of loading a specimen with two steel rods (punches) centered on both flat surfaces of the cylindrical specimen. The test will be described in detail later.

Chen [11] developed a new formula for computing the tensile stress based on perfect-plasticity theory. The tensile stress is equal to

$$\sigma_T = \frac{P}{\pi(cbH - a^2)}$$

where P is the applied load in pounds, H is height of specimen in inches, a is the radius of punch in inches, b is the radius of specimen in inches, and c is a dimensionless coefficient. Fang and Chen [12] chose a coefficient of 1.0 because this coefficient is not too sensitive to the internal friction angle. R. A. Jimenez [13] suggested the use of 1.2 as a coefficient for asphaltic concrete tensile strength computation.

Fang and Chen [12] found that the effect of specimen height to its diameter ratio and the effect of punch diameter to specimen diameter ratio on the tensile strength is approximately a linear relation. They found that a height-to-diameter ratio of the specimen varying from 0.8 to 1.2 and a ratio of diameter of the punch to the diameter of specimen varying from 0.2 to 0.3 are suitable for tensile testing of Portland cement mortar by double punch.

In this study, the double punch and the axial methods of testing were chosen to determine the tensile strength of asphaltic concrete. The results were compared to see if the double punch method can replace the other methods with a certain reliability and relationship. Choosing the double punch method among the previous methods of testing for tensile strength was based on the fact that it is simple, adequate, and not time consuming. Also, as reported in [13], the repeatability of the double punch test is better than that of the split tensile test.

Scope of Study

Twenty-seven specimens were tested, usually at replicates of three. The variables introduced to see their effects on the tensile strength of asphaltic concrete include the following:

1. Three types of mixture,
   a. 3/4 inch hot mixture, 6% asphalt content,
   b. 3/8 inch hot mixture, 6% asphalt content,
   c. 3/8 inch cold mixture, 5% asphalt content.
2. Three deformation rates (R), particularly 0.5 in/min, 1.0 in/min, and 1.5 in/min.[1]
3. Three test temperatures (T), in particular 12°C (53.6°F), 25°C (77°F), and 35°C (95°F).
4. Three specimen heights (H) of 2 inches (50.8 mm), 3 inches (76.2 mm), and 4 inches (101.6 mm).

The choice of 3/4 and 3/8 inch mixtures was based on the fact that they are available in large quantities so that we minimize composition variability.

The average E and σ_T were reported and the density of each specimen was determined according to AASHO Method of Test T166.

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1. 1 inch/min = 41.5×10^{-6} m/s.

CHAPTER 2

ASPHALTIC CONCRETE MIXTURES

The three mixtures were obtained from Tanner Construction Company in Tucson, Arizona. Tests were mainly done on the 3/4 inch and 3/8 inch hot mixtures.[1] The gradation limits of these two mixtures appear in Table A.1 (Appendix A). The gradation curves appear in Figure 2.

A 3/8 inch cold mixture was tested for the purpose of evaluating its strength and modulus by the double punch method only.

The 3/4 inch hot mixture had an asphalt content of 6% AR-4000, so had the 3/8 inch hot mixture. The 3/8 inch cold mix had 5% asphalt content.

Preparation of Specimens

The mixtures were stored sealed in buckets of about 70 pounds capacity. The bucket was heated to about 140°F (60°C) in the oven for three hours so that it became loose. Different weights of mixture were cut out and put into pans according to the desired height of specimen and type of mix as follows:

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1. The 3/4 inch and 3/8 inch mixtures mean that the largest particle size is either 3/4 inch or 3/8 inch.

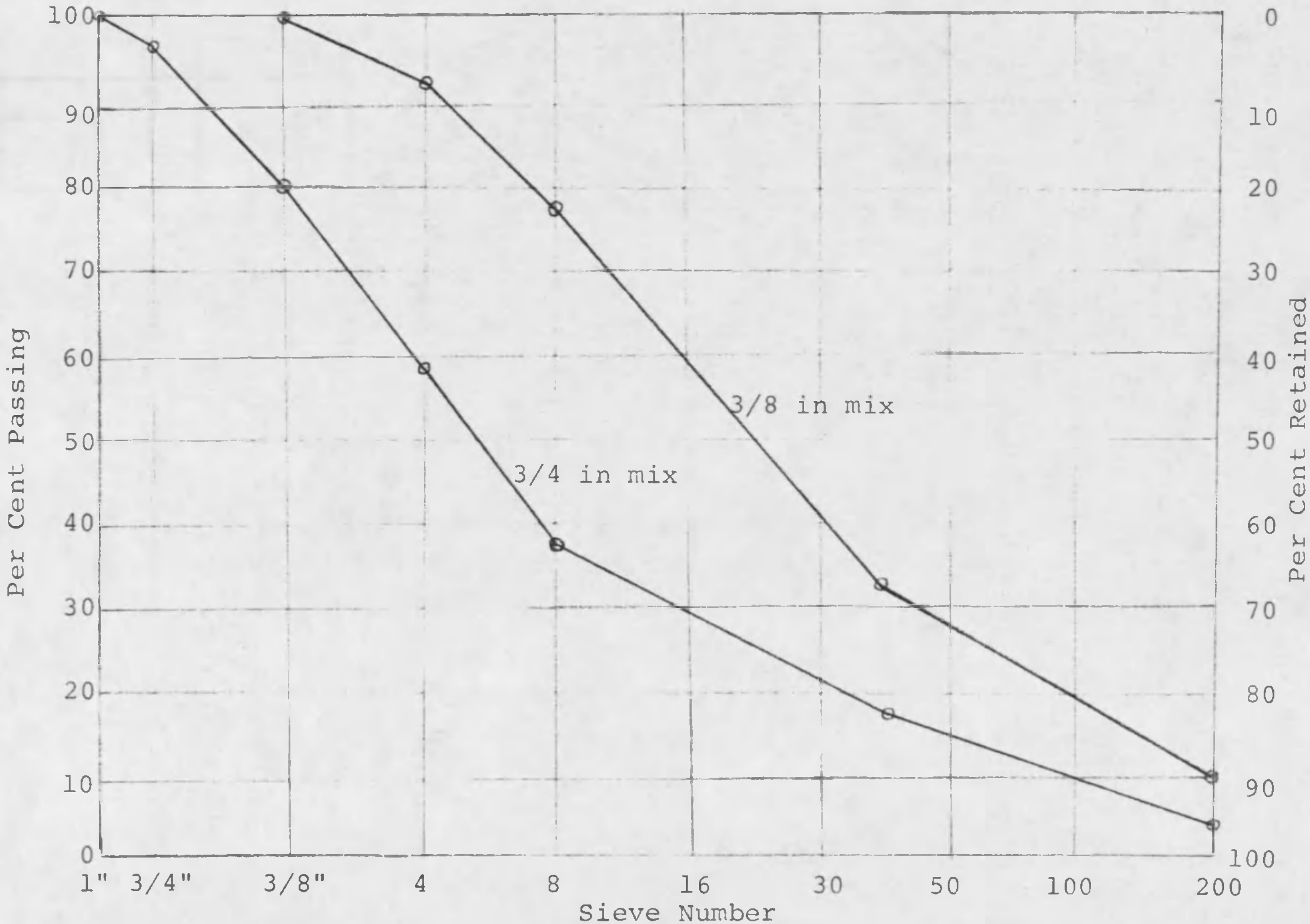


Figure 2. Aggregate Gradation Curves

1. 3/8" mixture:

Height, inches	Weight, grams
2	880
3	1320
4	1760

These were obtained by compacting a sample specimen and measuring its height, H_1, and weight, W_1, then using the ratio $(\frac{W_1}{H_1})$ to determine the weight, W_2, for the desired height, H_2, where $W_2 = H_2 \frac{W_1}{H_1}$.

2. 3/4" mixture:

Height, inches	Weight, grams
2	941
3	1415
4	1882

The samples were put in the oven for vibratory kneading compaction at 250°F (121.1°C) for three to four hours and then compacted. Specimens were numbered and left for one day at lab temperature. The specimens to be tested by the axial method were capped by gluing two steel plates at the two ends of the specimen. They they were kept in an oven at 85°F (29.4°C) for three days to cure. They were taken out after that and set into the desired test temperature for one day and then tested. Specimens to be tested by double punch were set into the desired test temperature for one day and then tested.

Compaction

Kneading compaction was chosen because it is thought that it simulates the densification received by heavy traffic during the road life-time [4]. The compactor used is illustrated by Figure 3. This is the Jimenez vibratory kneading compactor and it provides the vibratory kneading compaction to the loose mix with a dead load of 283 lb and a dynamic load of about 400 lb caused by the counter rotation of eccentric masses at a frequency of about 1200 rpm. The turntable of the compactor can be tilted to impose horizontal forces on the mixture. For more details on the development of this compactor, the reader is advised to refer to a report submitted to the Texas Highway Department by R. A. Jimenez in 1962 under the title "An Apparatus for Laboratory Investigations of Asphaltic Concrete Under Repeated Flextural Deflections" as reported by Hassan [14].

Compaction was performed at 250°F (121.1°C). The 4-inch (101.6 mm) diameter mold was heated to the same temperature prior to compaction so that the temperature of the specimen remained at 250°F. Each specimen was compacted at a tilt of 1 degree for a certain time depending on its height and finally the compacted specimen was leveled at 0 degree and compacted for 30 seconds. Each 2-inch (50.8 mm) high specimen was compacted as one layer for two minutes at 1 degree tilt then compacted for 30 seconds to level off. Each 3-inch (76.2 mm) specimen was compacted in two layers

Figure 3. The Jimenez Vibratory Kneading Compactor -- The upper section is the loading system and the lower part is the turntable.

of approximately 1-1/2 inch (38.1 mm) height. The first layer was compacted at 1 degree tilt for 1-1/2 minutes then the other layer was added and compacted for 1-1/2 minutes at the same tilt, and finally leveled off at 0 degrees and compacted for 30 seconds. Each 4-inch (101.6 mm) high specimen was compacted the same way as the 3-inch thick, but each layer was 2 inches (50.8 mm) and compacted for 2 minutes at one degree tilt then leveled off for 30 seconds at 0 degree. For the 3 and 4 inch (76.2 and 101.6 mm) high specimens where they were compacted in two layers it is recommended to make grooves or scratches between the first and second layer to improve bonding between the two layers.

CHAPTER 3

AXIAL TESTING (DIRECT METHOD)

Capping Procedure

To perform the direct axial tensile test it was necessary to glue two rounded steel plates to the flat ends of each specimen and then pull through the center of the steel plates, as illustrated in Figure 4. Also, a photograph of a fabricated specimen is shown in Figure 5. The formula for preparing the epoxy mixture was provided by Mr. James Douglas Kriegh, a Professor of Civil Engineering and Engineering Mechanics, The University of Arizona. It is as follows: 100 grams of epoxy resin EPI-R12-510 (46 5% by weight), 35 grams of curing agent EPI-Cure 872 (16.3% by weight), 40 grams of asbestos filler (18.6% by weight, Johns-Manville Co. designation 7-PF-1), and 40 grams of silica filler, -325 mesh (18.6% by weight).

Before mixing the above elements, the specimen was weighed in air and in water for density determination. The steel plates were cleaned with the aid of a sanding machine to get rid of the previous epoxy. They were also wiped with a clean rag saturated with ethyl alcohol. Also, the two flat ends of the specimen were brushed before capping. The fillers were weighed on a 0.1 gram balance and they were

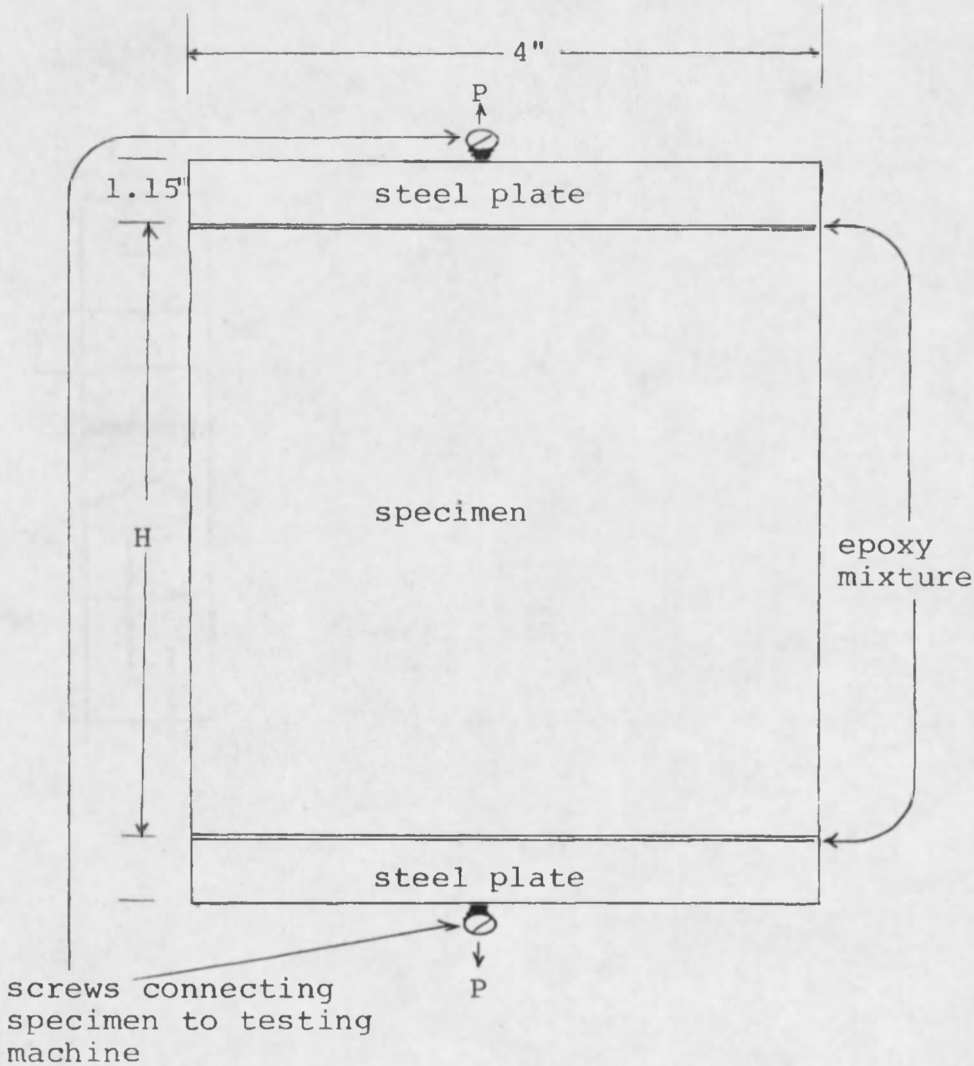


Figure 4. Sketch Showing How the Specimens Were Prepared (Fabricated) for Direct Tensile Test

Figure 5. Specimen as Capped for Axial Testing

thoroughly mixed. The 35 grams of curing agent were weighed first and then 100 grams of epoxy resin were added to it. They were thoroughly mixed. The two mixtures were added together and a thorough and complete mixing of the two was done in a cardboard cup. This amount of mixture was found to be enough to cap seven specimens of 4 inch (101.6 mm) in diameter. The epoxy was now ready to be used and the specimen was ready to be capped. The bottom steel plate was leveled first and a thin layer of the epoxy mixture was spread on it, then the specimen was placed on the top of the steel plate, then another layer of epoxy mixture was spread on the upper specimen surface, and finally the second steel plate was placed on the top of the specimen. The capped specimen was left where it was for one day so that the steel plates did not slide, in order to obtain central loading. On the next day, the specimen was placed in an oven for two days at a temperature of 85°F (29.4°C) to ensure complete curing. The specimen was then taken out from the oven and stored into the desired test temperature for one day, and then tested.

Rubber gloves should be used when preparing the epoxy mixture and when capping the specimen because the epoxy mixture is poisonous and in case of getting the epoxy mixture on any part of the body it should immediately be cleaned with soap and water.

After the tensile test was performed, the epoxy mixture was removed from the steel plates by putting them in the oven for six hours at 300°F (149°C), then the epoxy mixture could be easily scraped. The steel plates were sanded and prepared for another specimen.

It can be seen how tedious and time-consuming the capping of specimens for axial or direct method of tensile test was.

Testing Procedure

In order to perform the axial tensile testing on the prepared specimens, the testing machine (60 K Riehle Testing Machine) and the recorder were turned on. The deflection device which appears on the bottom left side of Figure 6 was fixed on the machine and attached to the recorder to record deflection (for more details on the setup of the deflection device, the reader can look at [15]). The magnification used here was always 100. The load scale used ranged between 3000 pounds and 6000 pounds. The specimen was attached to the testing machine as shown in Figure 6. The rate of deformation (R) was set and the loading button was pushed. When failure occurred, the maximum load was noted and all required information such as rate of deformation (R), temperature (T), load scale, and date were recorded on the load-deflection chart. The deflection was read from the

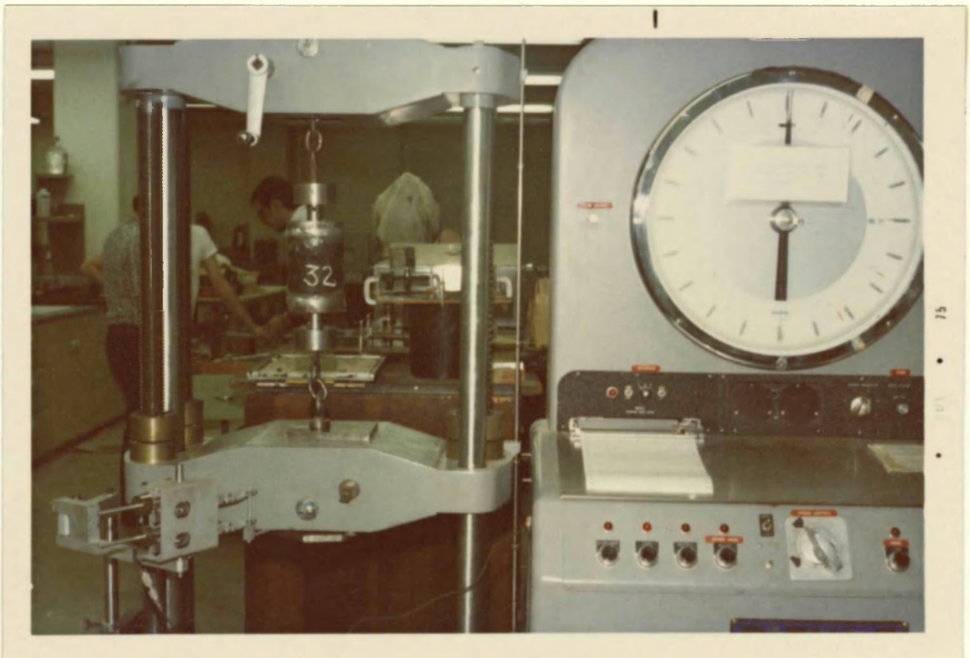


Figure 6. Specimen is Ready to be Loaded Axially

chart as inches then multiplied by 1/100 because of the magnification.

CHAPTER 4

DOUBLE PUNCH METHOD
(INDIRECT METHOD)

This method of tensile testing was first proposed by Chen [11] in 1970. He used this method to evaluate the tensile strength of concrete. In 1971 [12] it was extended to evaluate tensile strength of soils. It was thought that this method was applicable to the determination of asphaltic concrete tensile strength and modulus of elasticity.

Test Procedure

The test procedure is described in detail in Appendix B. Generally it consists of applying a vertical load through two steel rods on both flat ends of the specimen. When the specimen cracks, the failure load is noted and the tensile strength and modulus of elasticity can be calculated from the maximum load and the deflection. The radial deflection was measured through deflection bars contacting the specimen at mid-height. These two bars were vertical and moved horizontally when pushed by the dilated specimen. They contained strain gauges which were connected to a Sanborn Dual Channel Carrier-Amplifier Recorder, Model 321, which plotted load and displacement on a chart from which the deflection corresponding to the failure (maximum load) was taken as recorder deflection in millimeters. The recorder deflection is then changed to diametral dilation in inches by the use of the calibration chart of the Civil Engineering Laboratory at The University of Arizona. This is to enable determination of the modulus of elasticity E for asphaltic concrete.

Figure 7 shows the specimen ready to be tested. On the left bottom of the picture appears the Sanborn Dual Channel Carrier-Amplifier Recorder.

Tensile Stress and Modulus of Elasticity Determination

When the test had been completed, the tensile strength was calculated as follows:

$$\sigma_T = KP \tag{1}$$

where: $K = \dfrac{1}{\pi(cbH-a^2)}$

where c is a coefficient depending on material type and is assumed to be 1.2 for asphaltic concrete. For simplicity of calculations of tensile strength, σ_T conversion constants were calculated for 4 inch diameter specimen and 1 inch punch diameter as show in Table 1, which was obtained from a work done in the Civil Engineering Laboratory at The University of Arizona.

According to Jimenez [16], D. A. Dadeppo derived an equation for modulus of elasticity of asphaltic concrete

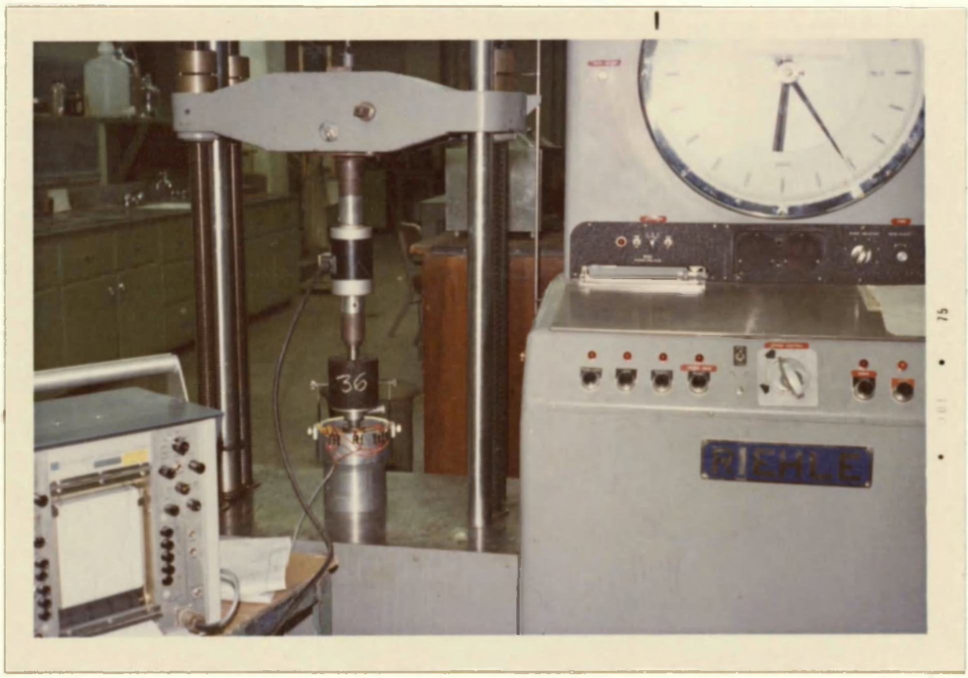


Figure 7. Specimen is Ready to be Tested by the Double Punch Method

Table 1. Tensile strength coefficients for double punch method where D = 4 inches and a = 1/2 inch.

Specimen Height H, inches	K
2.0	0.0700
2.2	0.0633
2.4	0.0578
2.6	0.0531
2.8	0.0492
3.0	0.0458
3.2	0.0428
3.4	0.0402
3.6	0.0379
3.8	0.0359
4.0	0.0340

when tested by double punch method. The equation is as follows:

$$E[\frac{d}{b}][\frac{\pi b^2}{P}][\frac{1}{1+\mu}] = f[\frac{a}{b}, \frac{H}{b}, \mu]$$

and can be reduced to

$$E = \frac{K'P}{d} \tag{2}$$

where P is the applied load; d is half the diametral dilation or radial displacement at mid-height; and K' is a coefficient depending on Poisson's ratio, specimen height and diameter ratio, and the punch diameter to specimen diameter ratio (see [16]).

The chart deflection plotted by the Carrier-Amplifier Recorder is divided by two because it is a measure of deflection on two sides of the specimen, then multiplied by the deflection attenuation of the Carrier-Amplifier Recorder which is equal to two here. So, we go directly to chart on Figure 8 and pick d in inches. The coefficient K' is obtained from Table 2 and the modulus of elasticity is obtained in pounds per square inch.

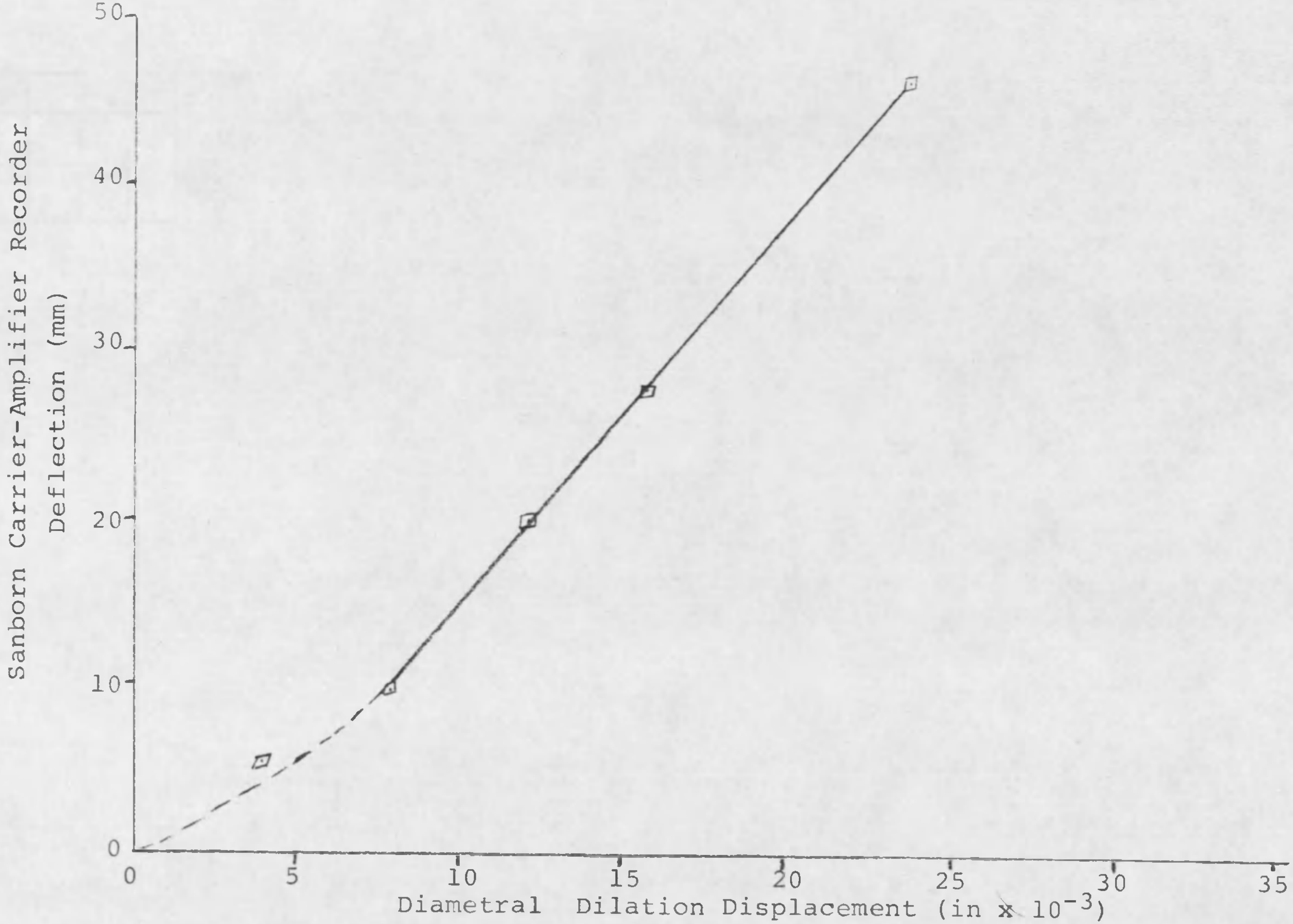


Figure 8. Chart Deflection vs. Diametral Dilation for the Double Punch Method of Testing

Table 2. Coefficient for modulus of elasticity, K'-- Specimen diameter = 4 inches, punch diameter = 1 inch, and Poisson's ratio = 0.35.

Specimen Height (Inches)	Coefficient for Modulus of Elasticity by U of A Double Punch Test (K')
1.6	0.203
1.8	0.224
2.0	0.244
2.2	0.258
2.4	0.268
2.6	0.273
2.8	0.272
3.0	0.267
3.2	0.258
3.4	0.246
3.5	0.239
4.0	0.119

Note: Poisson's Ratio is assumed to be 0.35 from a review of the literature indicated in [17] E = K'P/d.

CHAPTER 5

TEST RESULTS AND DISCUSSION

The axial and double punch methods of tensile testing were performed smoothly and results were thought to be very satisfactory. One can see the good location of failure by the axial method in Figure 9 where the specimen failed in the middle. Also one can see the irregularity or non-uniformity of the failure surface which indicates that there was no plane of weakness at the interface of the two compacted layers when height of specimen was more than two inches. Another typical failure is shown in Figure 10, where one can see the broken aggregates as white spots.

Some of the specimens (about 50 per cent) broke at the top or bottom half of the specimen and these were accepted only if the failure plane location was at a distance greater than twice the maximum particle size. If the location of break was less than that (which rarely happened), the specimen was discarded and replaced by a new one, and the occurrence of failure here was referred to weakness of the epoxy bond.

Plots of load-deflection curves were obtained with the recorder for both methods of testing for the determination of modulus of elasticity. Xeroxed and traced sample

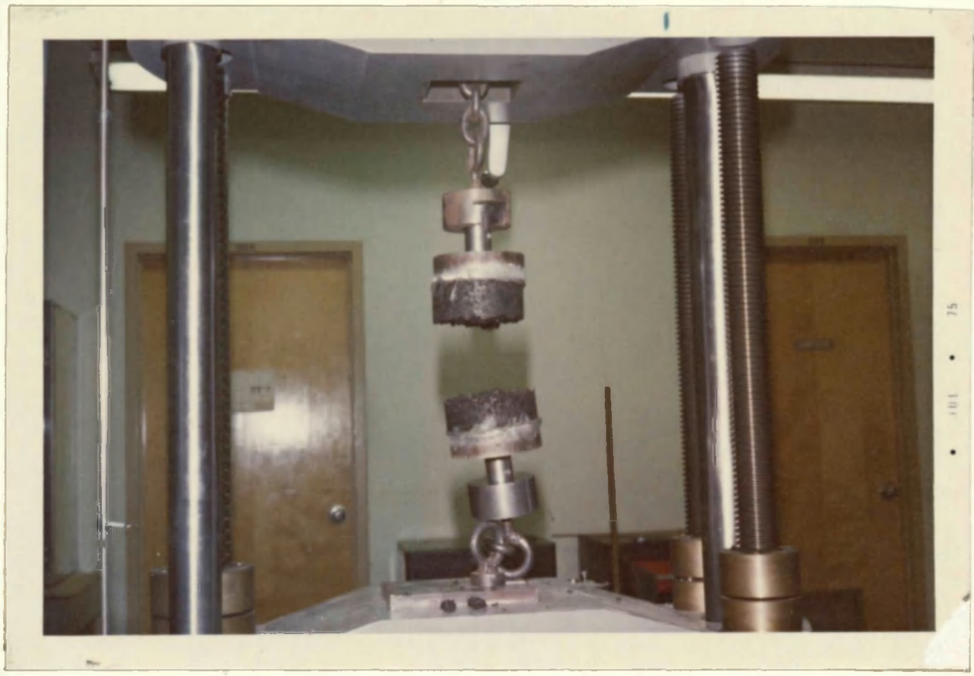


Figure 9. A Typical Failure by Tension (Axial Method)

Figure 10. Surface of Failure where Aggregates were Broken Apart (Axial Method)

curves from the original ones appear in Appendix C. This has been done just for the purpose of improving appearance. Curves for the axial method are on the lower left part of the pages in the appendix while the double punch method curves appear on the upper right corner of the page.

The double punch method was found to be very easy in obtaining the maximum tensile stress, but some difficulties were encountered when the radial deflection was to be obtained for determining E and this is explained in the next paragraph.

Figure 11 shows a good break where the specimen cracked in a direction perpendicular to the plane of the two deflection bars. In this case, the bars will record the maximum movement of the failed specimen. A bad failure is shown in Figure 12, where the break occurred in a line with the deflection bars. Here, the movement of the failing specimen was parallel to the plane of the bars and they did not record the maximum deflection, since they were not being pushed as much by the specimen. The addition of two more deflection bars in the other two directions would have solved this problem.

Results of the two methods of testing are tabulated in Tables 3 and 4. In Table 3, the temperature was held constant at 77°F (25°C) and the rate of deformation (R) was also constant and equal to 1 inch/minute. The variables here are the mixtures, height of specimen (H), and method

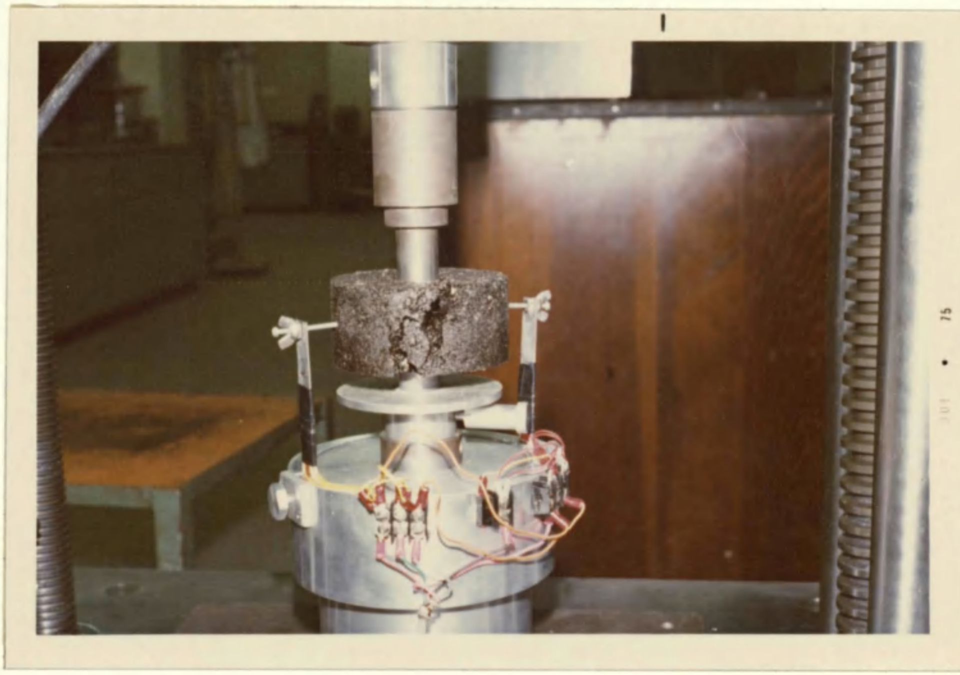


Figure 11. Specimen Failed by Double Punch Loading in a Way where an Accurate Deflection Measurement was Recorded

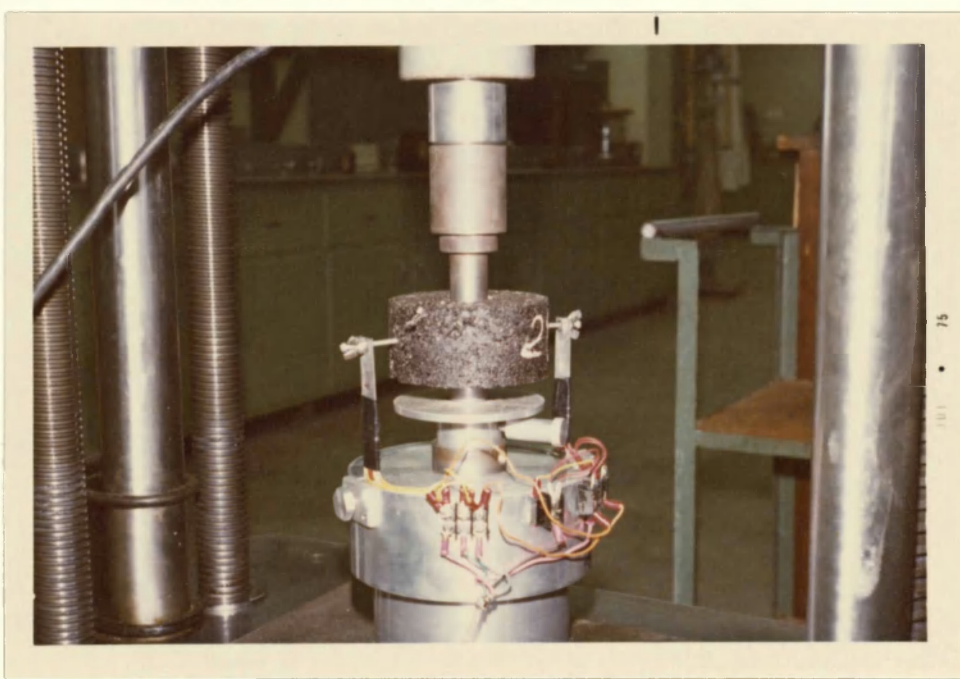


Figure 12. Specimen Failed by Double Punch Loading in a Way That Deflection was not Measured Accurately

Table 3. Tensile strength and modulus of elasticity with test temperature, T = 25°C, rate of deformation, R = 1 inch/minute.

	Test method										
	Axial					Double punch					
	Mixture										
	3/8"	3/8"	3/8"	3/4"	3/4"	3/8"	3/8"	3/8"	3/4"	3/4"	3/4" cold mix
Specimen height, inches	2	3	4	2	4	2	3	4	2	4	2
Replicates	3	2	3	3	3	2	3	4	2	4	2
Density, gm/cc (average)	2.21	2.24	2.23	2.30	2.31	2.24	2.24	2.22	2.23	2.31	2.28
Failure load, pounds (average)	2,910	2,300	2,300	2,740	2,550	2,280	2,510	2,400	2,530	3,070	1,820
Failure stress σ_T psi (average)	230	183	183	218	203	160	114	82	177	104	127
Failure deflection, inches (average)	3.2×10^{-2}	2.9×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.3×10^{-2}	8.03×10^{-3}	9.0×10^{-3}	10.9×10^{-3}	8.2×10^{-3}	12.83×10^{-3}	7.68×10^{-3}
Modulus of elasticity, E, psi (average)	14,470	18,950	24,440	14,550	24,380	69,250	74,560	26,200	75,130	28,420	57,770
Coefficient of variation in σ_T, %	6.0	3.5	0.78	6.0	9.3	4.9	5.0	5.9	4.2	4.6	7.2
Coefficient of variation in E, %	5.5	1.3	3.0	2.0	3.2	11.3	9.4	4.0	12.9	4.5	2.7

Table 4. Tensile strength and modulus of elasticity for 3/8" mixture and height of specimen of 3 inches.

	Test method															
	Axial								Double punch							
Temperature, Centigrade	12	25	35	12	25	12	25	35	12	25	35	12	25	12	25	35
Deformation rate, inch/minute	0.5	0.5	0.5	1.0	1.0	1.5	1.5	1.5	0.5	0.5	0.5	1.0	1.0	1.5	1.5	1.5
Replicates	3	3	3	3	2	2	3	2	2	3	3	3	3	3	3	3
Density, gm/cc (average)	2.24	2.22	2.24	2.25	2.24	2.25	2.25	2.24	2.24	2.24	2.25	2.27	2.24	2.24	2.24	2.24
Failure load, pounds (average)	5,110	1,900	825	5,870	2,300	6,210	2,970	1,230	4,690	2,250	1,180	5,230	2,510	5,420	2,730	1,630
Failure stress, σ_T, psi (average)	406	152	66	462	183	494	236	98	213	102	54	238	114	247	124	74
Failure deflection, inches (average)	10.39×10^{-2}	5.40×10^{-2}	3.50×10^{-2}	7.20×10^{-2}	2.90×10^{-2}	5.25×10^{-2}	2.90×10^{-2}	1.63×10^{-2}	7.50×10^{-3}	8.03×10^{-3}	10.73×10^{-3}	8.15×10^{-3}	9.00×10^{-3}	7.80×10^{-3}	9.00×10^{-3}	12.60×10^{-3}
Modulus of elasticity, E, psi (average)	11,730	8,420	5,630	19,250	18,950	28,240	24,420	17,940	166,860	74,700	29,360	171,240	74,550	185,600	80,070	34,610
Coefficient of variation in σ_T, %	2	3.2	8.5	3.7	3.5	4	5.1	11.3	4.6	2.6	1.5	1.3	5.0	2.0	4.2	1.9
Coefficient of variation in E, %	6	2.2	10	7.6	1.3	3	3.1	10	2.6	7.8	13	9.7	9.4	4.0	6.3	12

of testing. In Table 4, the main variables are temperature (T), rate of deformation (R), and method of testing where the mixture was the 3/8" hot mix and H equal to 3 inches (76.2 mm) for all specimens.

Effect of Variables on σ_T

In order to visualize the behavior and results obtained for the asphaltic concrete mixture in this study, curves were plotted from Tables 3 and 4. Figure 13 represents the tensile strength vs. height of specimen obtained from Table 3 where T = 25°C and R = 1 in/min for both axial and double punch methods. We notice that the tensile strength is independent of height when obtained by the axial method.

For the 3/8" mixture in Figure 13, the point where H equals 2 inches and σ_A = 230 psi (1,584,700 N/m^2) was neglected for the following reasons:

1. If we look at Table 3 or Figure 13 we see that the 3/4 inch mixture always gives higher values of strength than the 3/8 inch mixture for the same test conditions except that point where H = 2 inches, which may put this point in error.
2. The two other heights, i.e., H = 3 and H = 4 inches, gave identical values of strength which suggests that there is no reason to have an increase of about 30 per cent in strength at H = 2 inches.

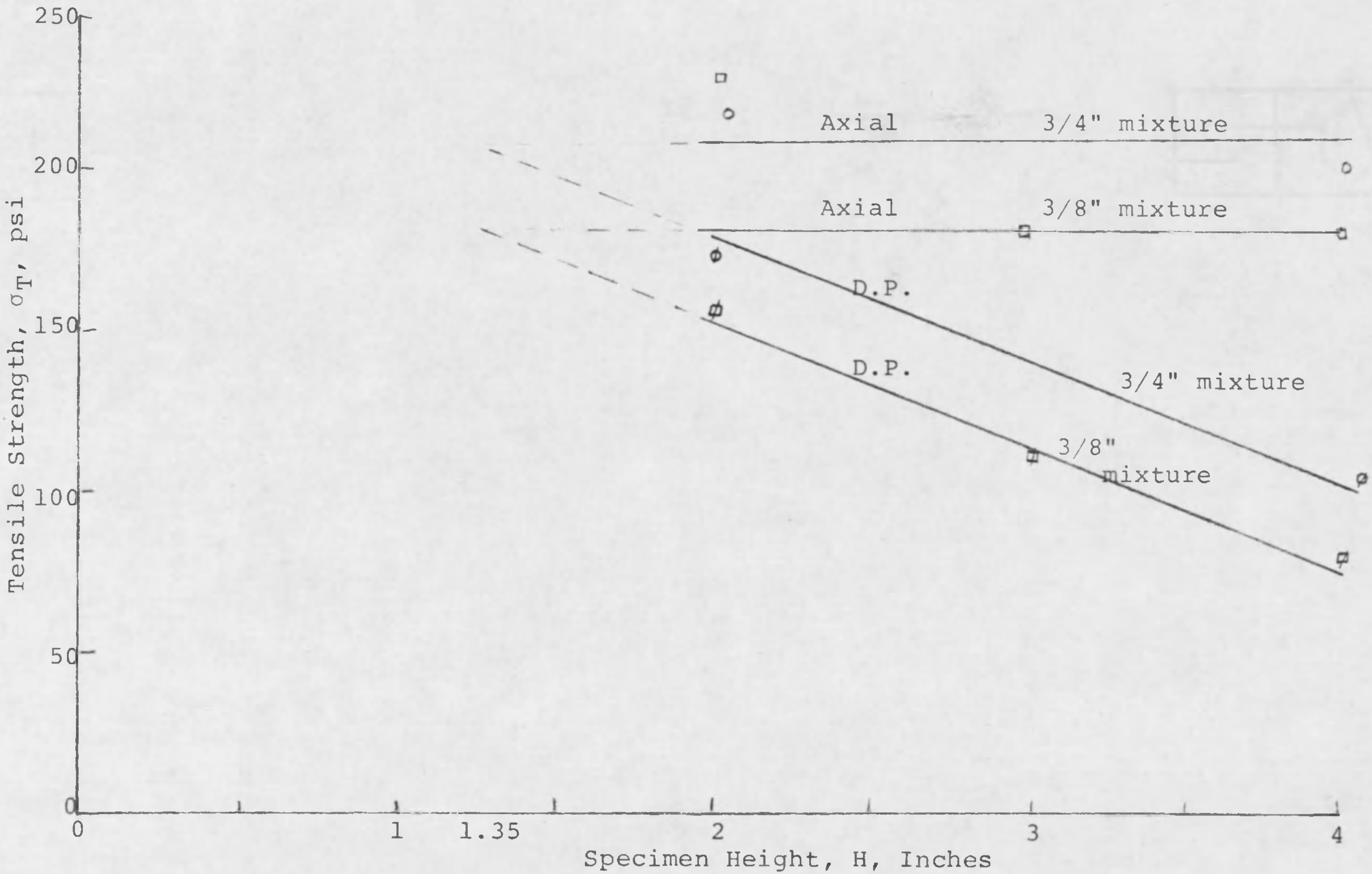


Figure 13. Relationship Between Specimen Height and Tensile Strength for the Two Testing Procedures at T = 25°C and R = 1 in/min

3. For that point, i.e., where H = 2 inches, the test samples were the starting point of the study and they were the first ones to be tested and an error in the setting of the testing machine or so might have happened due to less familiarity with the testing machine and deflection device.

The double punch testing curves show that as the height of specimen increases, the tensile strength decreases. σ_D is inversely proportional to H.

The tensile strength obtained by the axial and double punch method, σ_A and σ_D respectively, can be related by the use of Figure 13. The 3/8 inch and 3/4 inch curves obtained by the double punch and axial method meet at a height of about H = 1.35 inch although σ_T is different for each at that height. We can calculate a factor f' to relate the 3/8 inch curves for the two methods of testing:

$$f' = \frac{\sigma_A - \sigma_D}{\Delta H} = \frac{\sigma_A - \sigma_D}{H - 1.35} .$$

Take the point where H = 3" at which σ_A = 183 psi and σ_D = 116 psi:

$$f' = \frac{183 - 116}{3 - 1.35} = 40$$

where f' is in pounds per cubic inch. So, for any height

$$\sigma_A = 40(H - 1.35) + \sigma_D \qquad (4)$$

where T = 25°C (77°F) and R = 1 in/min. This relation is also true for the 3/4 inch mixture, since the 3/4 inch and the 3/8 inch mixture curves are parallel for the axial and double punch and the distances between them are equal.

In Figure 14, the tensile strength, σ_T, for double punch and axial method was plotted against the rate of deformation, R, for different temperatures, i.e., T = 12°C, 25°C, and 35°C. The specimen height is 3 inches and the mixture is 3/8 inch mixture. These curves show that as the rate of deformation increases, the tensile strength increases too. The double punch method gave lower values of tensile strength than the direct method for the same temperature. The lower the temperature, the higher the tensile strength. The axial method gave a relatively higher strength at T = 12°C. The relation between σ_T and R is linear for any temperature but with different slopes for different temperatures.

A relationship may be constructed between the tensile strength obtained by the double punch method and that obtained by the axial method at different temperatures.

1. For T = 25°C (77°F): The two curves meet at R = -0.15 (this does not mean that the rate of deformation is less than zero, but we are taking this point as a reference point to simplify the calculations). We can obtain a factor, f_1, for the two curves where f_1 is in pound-min per cubic inch. Generally,

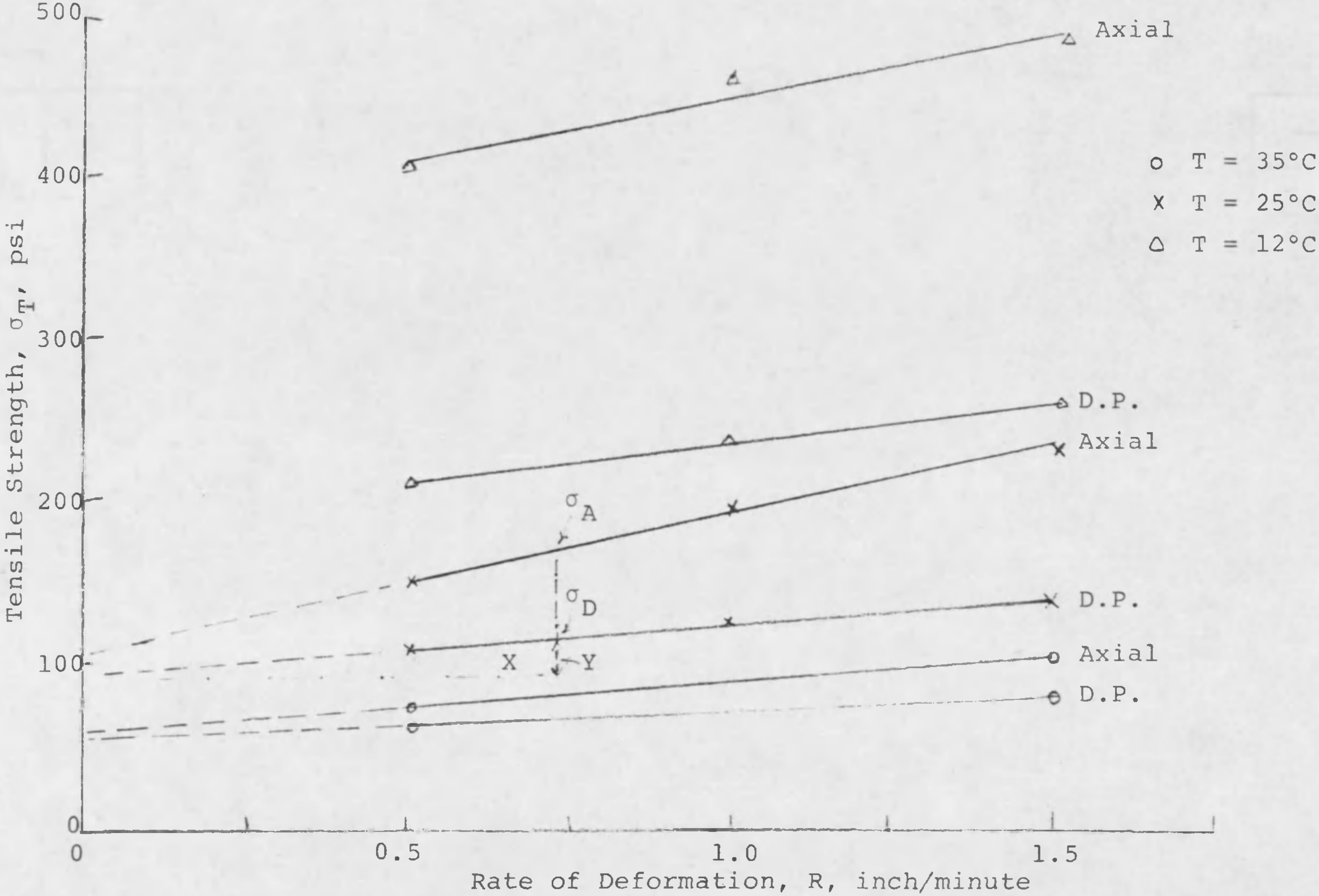


Figure 14. Effect of Rate of Deformation and Test Temperature on Tensile Strength of Asphaltic Concrete for 3/8" Mixture and H = 3 Inches

$$f_1 = \frac{\sigma_A - \sigma_D + Y}{R + 0.15}$$

where Y is the distance between the double punch curve and the horizontal axis, X, and

$$\frac{Y}{R + .15} = \frac{15}{.65} = 23.$$

Take the point where R = 0.5 in/min: $f_1 = \frac{60}{.65} = 92.$

So, we substitute this value in f_1 equation and we get

$$\frac{\sigma_A - \sigma_D}{R + .15} = 69$$

$$\therefore \quad \sigma_A = 69R + \sigma_D + 10.3.$$

2. T = 35°C. Similarly,

$$\sigma_A = 13R + \sigma_D + 2,$$

and so for each temperature a relationship could be obtained.

Figure 15 shows the tensile strength σ_T vs. temperature T for a 3/8 inch mixture of specimen height H = 3 inches. The rate of deformation R is variable running between 0.5 and 1.5 inch/minute. The axial method and double punch method curves show the same trend. They are nonlinear curves and they show the fact that as temperature goes down, the strength of asphaltic concrete goes up. The higher the rate of deformation, the higher the force

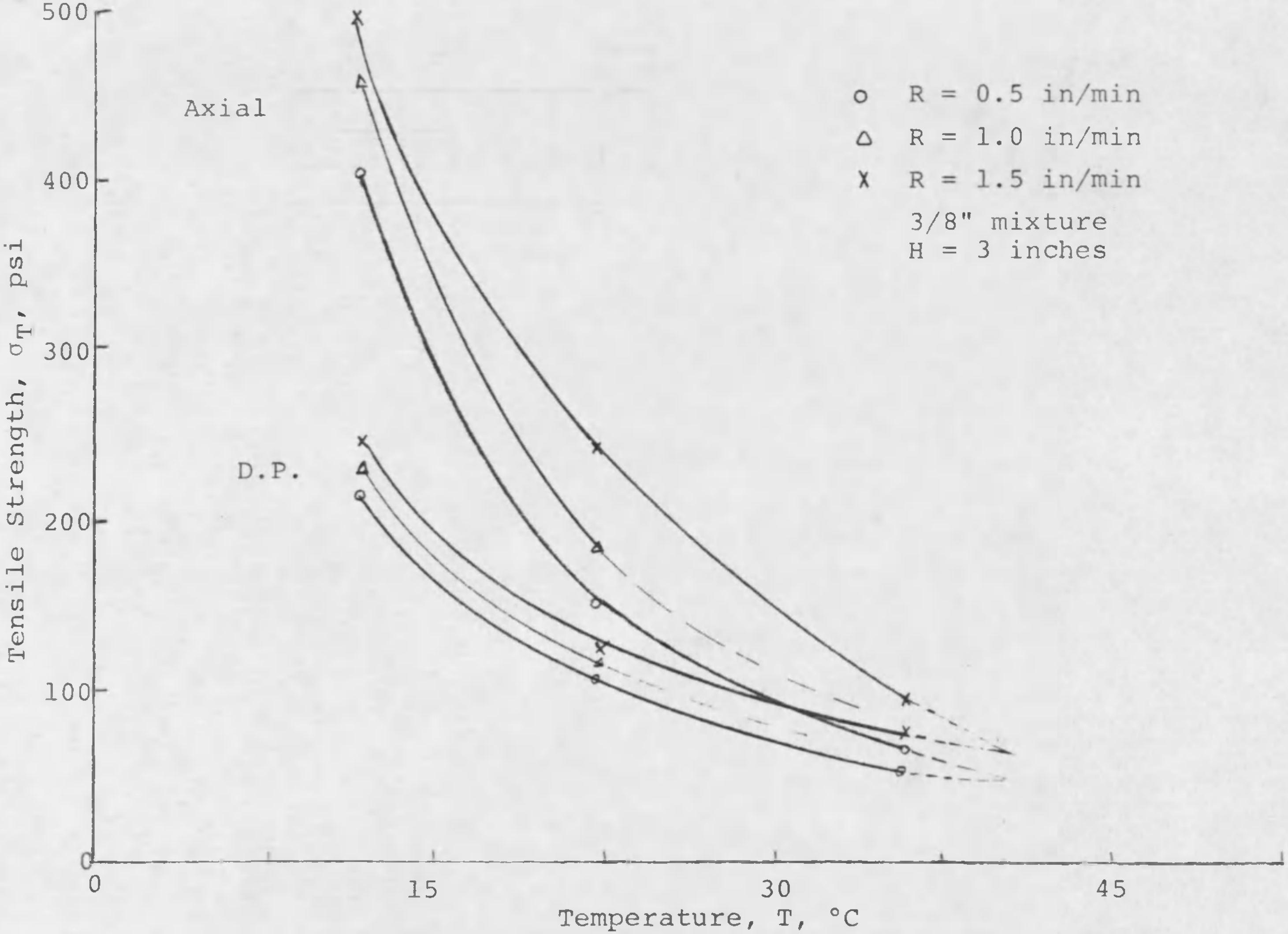


Figure 15. Effect of Temperature on Tensile Strength at Different Rates of Deformation for the Two Testing Procedures

necessary to cause failure, i.e., the higher the strength. The axial method shows higher values for stress than double punch, and the magnitude of the stress becomes almost two times higher at low temperatures such as 12°C.

The axial and double punch curves for the same rate of deformation, R, meet at a point of about 40°C (Figure 15).

Figure 16 shows a relationship between σ_A and σ_D where the tensile strength obtained by the axial method was plotted against that obtained by the double punch method. The main variables were temperature (T = 12°C, 25°C, and 35°C) and rate of deformation (R = 0.5 in/min, 1.0 in/min, and 1.5 in/min). The specimen height was 3 inches and the mixture was a 3/8 inch mixture. The relation obtained was a straight relationship between axial and double punch. A regression analysis program was run to find the best fitting curve (Figure 16) and the following equation was obtained:

$$\sigma_A = -61 + 2.22\ \sigma_D$$

with $R^2 = .995$ and $n = 8$.

The above equation gives a very useful relationship between the two testing procedures regardless of rate of deformation and temperature (within the ranges used).

Effect of Variables on E

Now let us look at the effect of test variables on the asphaltic concrete modulus of elasticity, E. In Figure 17 where the height of specimen was plotted against modulus

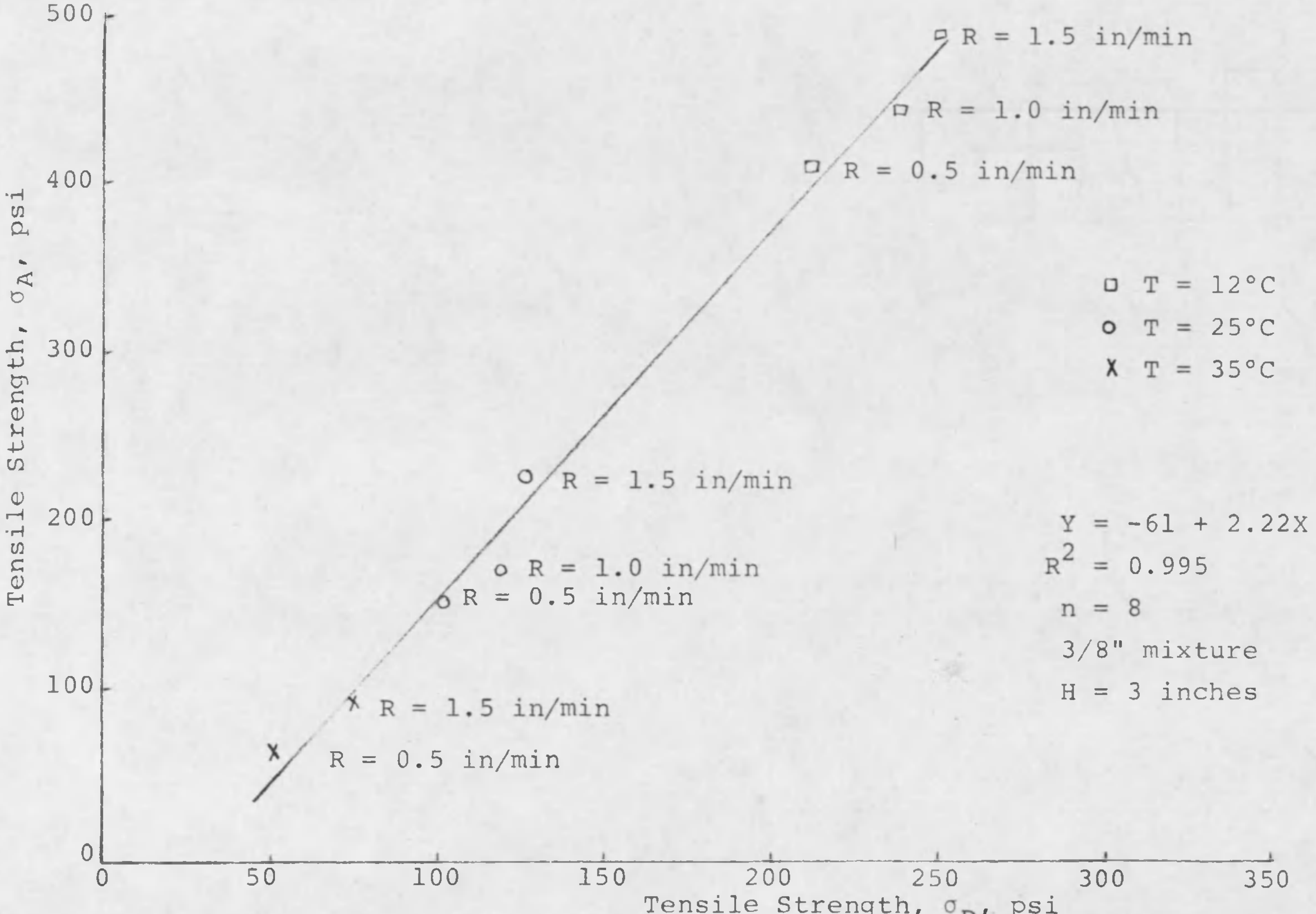


Figure 16. Relationship Between Tensile Strength Obtained by Axial Method and by Double Punch Method for Different Rates of Deformation and Temperature

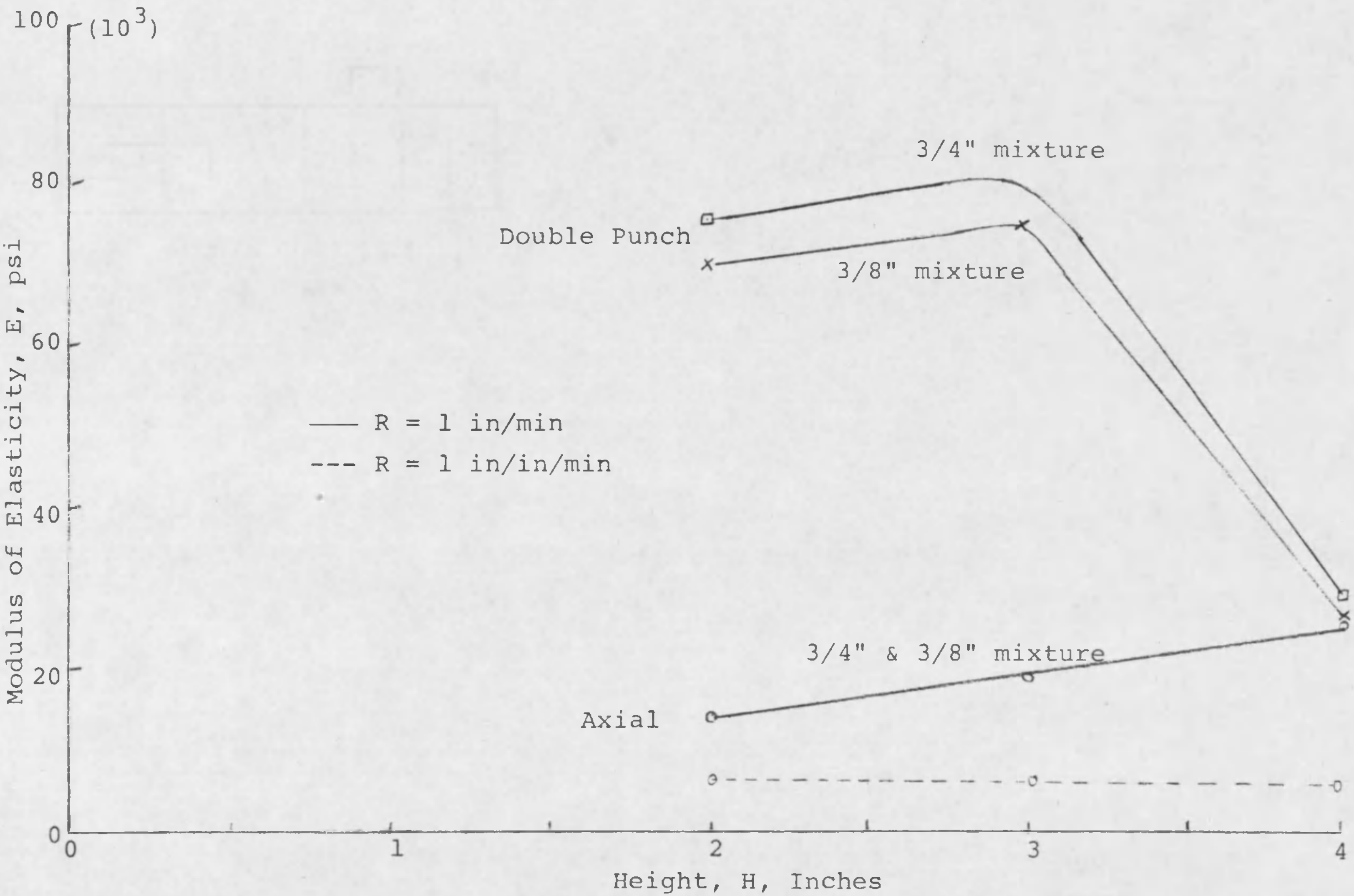


Figure 17. Relationship Between Height of Specimen and Modulus of Elasticity for Both Methods of Testing at T = 25°C and Constant Rate of Deformation

of elasticity, we can see that E increases with height by the axial method when we consider rate of deformation as inches per minutes (shown as a solid line). However, if we consider the rate of strain, i.e., R = inch/inch/minute (shown as a dotted line) E stays constant. For the double punch E increases with height then goes down as the height exceeds 3 inches. This is because of the decrease in K' factor as H increases according to Table 2. As the height of specimen increases, the two methods give an equal value for E at a height of about 4 inches when considering rate of deformation.

In Figure 17, temperature was constant: T = 25°C (77°F); and rate of deformation: R = 1 inch/minute.

Figure 18 shows the modulus of elasticity, E, plotted against rate of deformation, R, for the 3/8 inch mixture. Specimens were of 3 inches in height and temperatures were fixed at 12°C, 25°C, and 35°C. The relation is linear and E increases as the rate of deformation increases. Both axial and double punch method show a similar trend in the increase in E. E and R has a straight relationship. One can see that the higher the temperature, the lower the modulus of elasticity in both cases because of the higher load at low temperatures. The values for E obtained by the double punch method are tremendously higher than those obtained by the axial method.

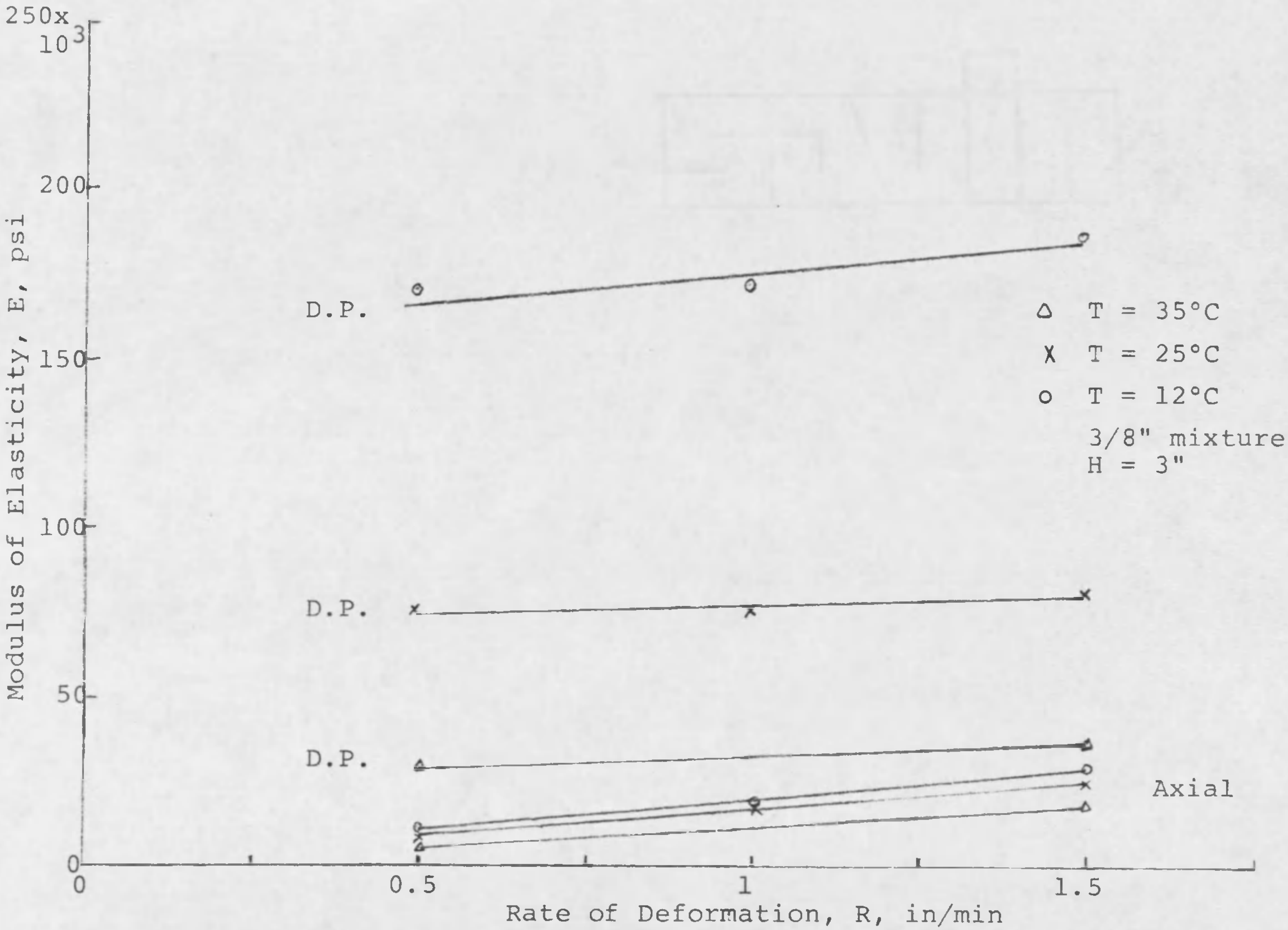


Figure 18. Effect of Rate of Deformation and Temperature on Modulus of Elasticity for the Two Testing Procedures

In fact, the reliability of comparison for the values of E is weak because sometimes the deflection bars failed to catch the maximum deflection when the specimen failed in a direction in line with the deflection bars.

The change in E values obtained by the axial method is low for different temperatures relative to that obtained by the double punch; i.e., the effect of T on E is less for axial than for double punch. For example, the value of E obtained axially at T = 35°C is almost doubled when T = 12°C at any rate of deformation, while the change in E values obtained by the double punch method at T = 35°C is almost five times less than the value when T = 12°C. This is probably due to the fact that when the asphalt is too cold, the bonding is high and it is hard for the rod (punch) to go through it. Consequently the force needed to break or crack the specimen becomes high even though deflection is low.

Figure 19 shows the relationship between modulus of elasticity values obtained by the axial method and the double punch method for different temperatures and rates of deformation. These curves are for 3/8 inch mixture and specimen height of 3 inches. The relation could be approximated by a straight-line relationship. Increasing rate of deformation shifts the curve up. The figure indicates that there is a vast difference between E obtained by double punch and axial method at low temperatures.

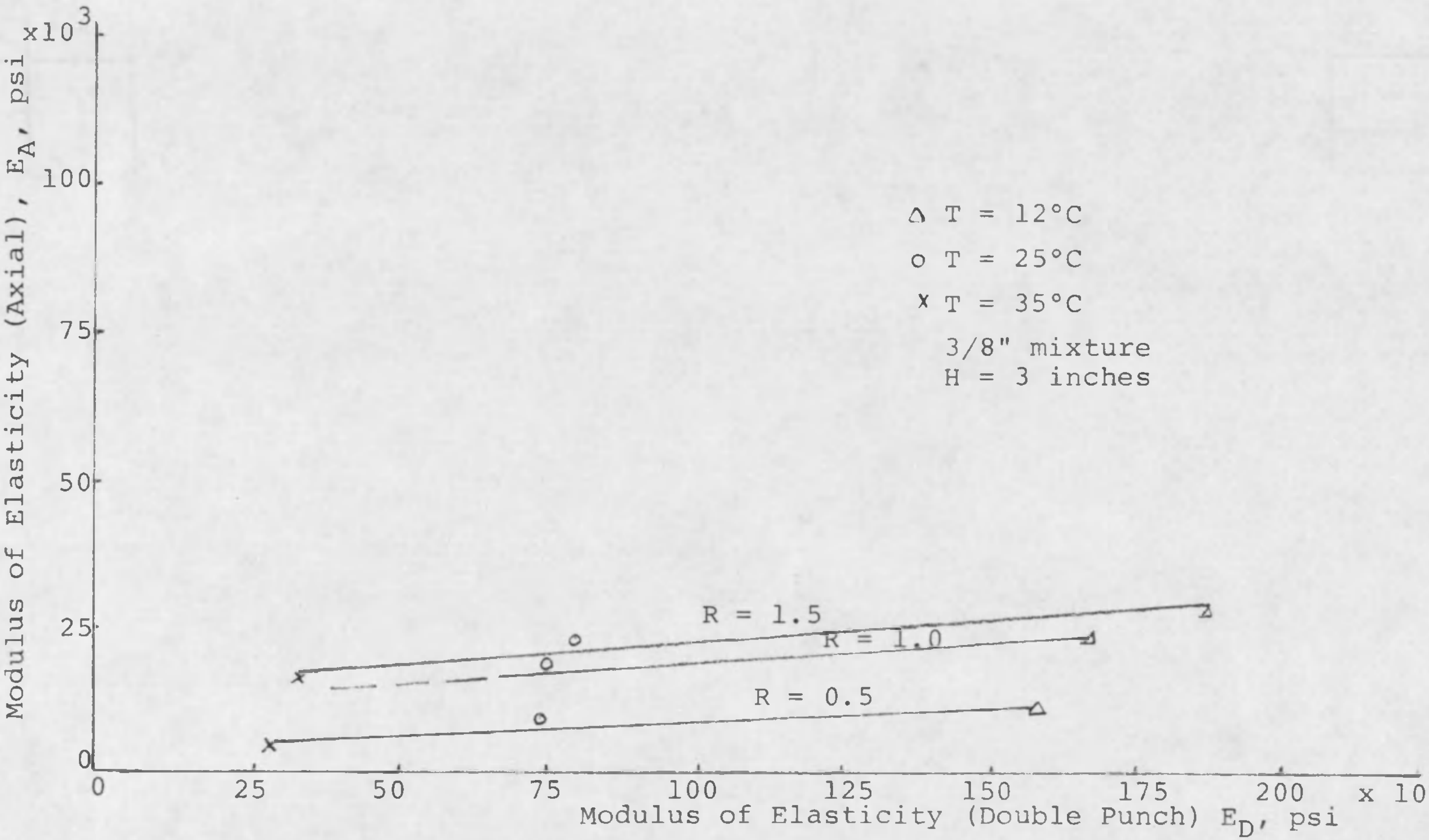


Figure 19. Relationship Between Modulus of Elasticity Obtained by Double Punch and by Axial Method for Different Temperatures and Rates of Deformation

From Figure 19 we can establish a relationship between E_A and E_D depending on rate of deformation using the same method of relating σ_A to σ_D on page 40 as follows:

1. $R = 0.5$ in/min;

$$E_A = 0.0515\ E_D + 2.38 \times 10^3$$

2. $R = 1.0$ in/min;

$$E_A = 0.0794\ E_D + 10.71 \times 10^3$$

3. $R = 1.5$ in/min;

$$E_A = 0.0873\ E_D + 12.5 \times 10^3.$$

We have to keep in mind that the above relations are valid only for specimen height less than or equal to 3 inches. The plot of E against H, Figure 17, shows that the DaDeppo equation yielded E's not linearly dependent on H and therefore can not be presently corrected to an E equivalent to that found by the axial when H is greater than 3 inches.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Modulus of elasticity and strength of asphaltic concrete at fracture have been shown to be related [5, 18] such that $\sigma_T = E\varepsilon$ under any conditions where ε is the asphaltic strain at fracture. The reader is to note that conclusions and discussion were based on the ranges of variables mentioned on page 7; other than those variables the case might be different.

For the fixed specimen and punch diameters used in this study we can point out the following:

1. The double punch method is an easy and adequate method for determining the tensile strength of asphaltic concrete and also its modulus.
2. Values for tensile strength obtained by the double punch method are related to those obtained by the axial method (Figure 16, $\sigma_A = 2.22\sigma_D - 61$ for $H = 3"$).
3. The double punch method gave higher values for modulus of elasticity than the axial (Figure 19) for the same variables. H is less than or equal to 3 inches. The relationship between E_A and E_D is a straight relationship depending on rate of

deformation. For specimen height greater than 3 inches there is not a good relationship between E_A and E_D because E_D is highly dependent on H (Figure 17).

4. Modulus of elasticity increases with specimen height when tested by the axial method and rate of deformation (R = inch/min) is considered. It is constant when we consider the rate of strain (R = inch/inch/min).
5. Tensile strength is not affected by specimen height when axial is considered. When considering the double punch method, the tensile strength decreases when specimen height is increased as shown in Figure 13.
6. Tensile strength and modulus of elasticity increase with rate of deformation (Figures 14 and 18). Both increase when temperature is decreased (Figures 15 and 19).
7. The double punch method has a better repeatability than the axial method when determining the tensile strength (Tables 3 and 4).
8. Although the variables introduced here are different from the ones in the literature cited, one can see the agreement in the trend obtained by the axial method (Table A.2).

9. From the above it is seen that the objective of finding a relationship between σ_A and σ_D was found, but no good relationship between E_A and E_D was obtained (especially when $H > 3"$).

Recommendations

1. More research is needed before the double punch method of evaluating asphaltic concrete tensile strength can be used to replace other methods. It is preferable to the axial method because of its simplicity and its better repeatability.
2. More additional deflection bars are required to obtain a good and true measurement of deflection when double punch method is used to evaluate modulus of elasticity.
3. Comparison between the double punch and the flextural test (which simulates the field conditions) is recommended.
4. More investigations are needed to evaluate the effect of different rates of deformations and temperatures on the strength and modulus of elasticity of asphaltic concrete when double punch method is used.

APPENDIX A

TABLES

Table A.1 Aggregate gradation limits for the asphaltic concrete mixture.

Sieve size	Per cent passing	
	3/4" mix	3/8" mix
1"	100	100
3/4"	95-100	100
3/8"	70-90	100
#4	45-70	85-100
#8	25-50	65-90
#40	10-25	25-40
#200	3-8	5-15

Table A.2. Comparison of tensile strength results by axial method with previous work -- Rate of strain = 0.4 inch/inch/minute.

	Reference	
Temperature	Figure 14	[7]
12°C	450 psi	300
25°C	200 psi	150
35°C	95 psi	80

APPENDIX B

DOUBLE PUNCH TEST PROCEDURE FOR OBTAINING σ_T AND E

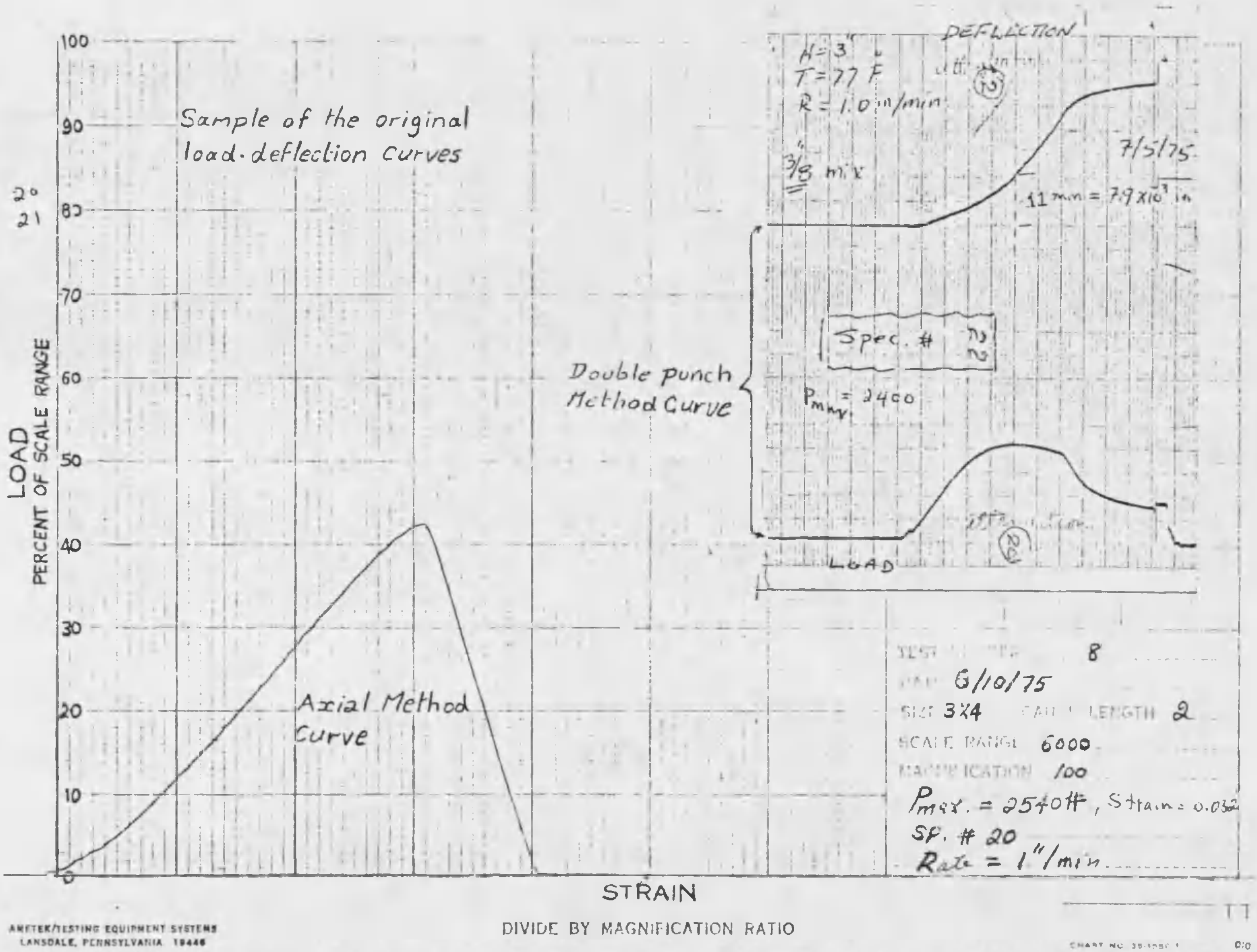
1. Turn the testing machine on.
2. Turn the dual channel carrier-amplifier recorder on.
3. Wait for about 20 minutes.
4. For instructions on the calibration and adjustment of the Sanborn dual channel carrier-amplifier recorder see [19].
5. Attach the upper punch rod to the compression testing machine and attach the dual channel carrier-amplifier to the strain gages.
6. Place the bottom punch rod and strain gauge device on the lower part of the compression testing machine.
7. Lower the crosshead of the testing machine slowly to center the two punch rods.
8. Raise the crosshead and put the specimen between the two punches.
9. Center the specimen on the lower punch by means of the 4 inch (101.6 mm) diameter aluminum plate.
10. Adjust the height of the screws in the deflection bars so that they touch the mid-height of the specimen.

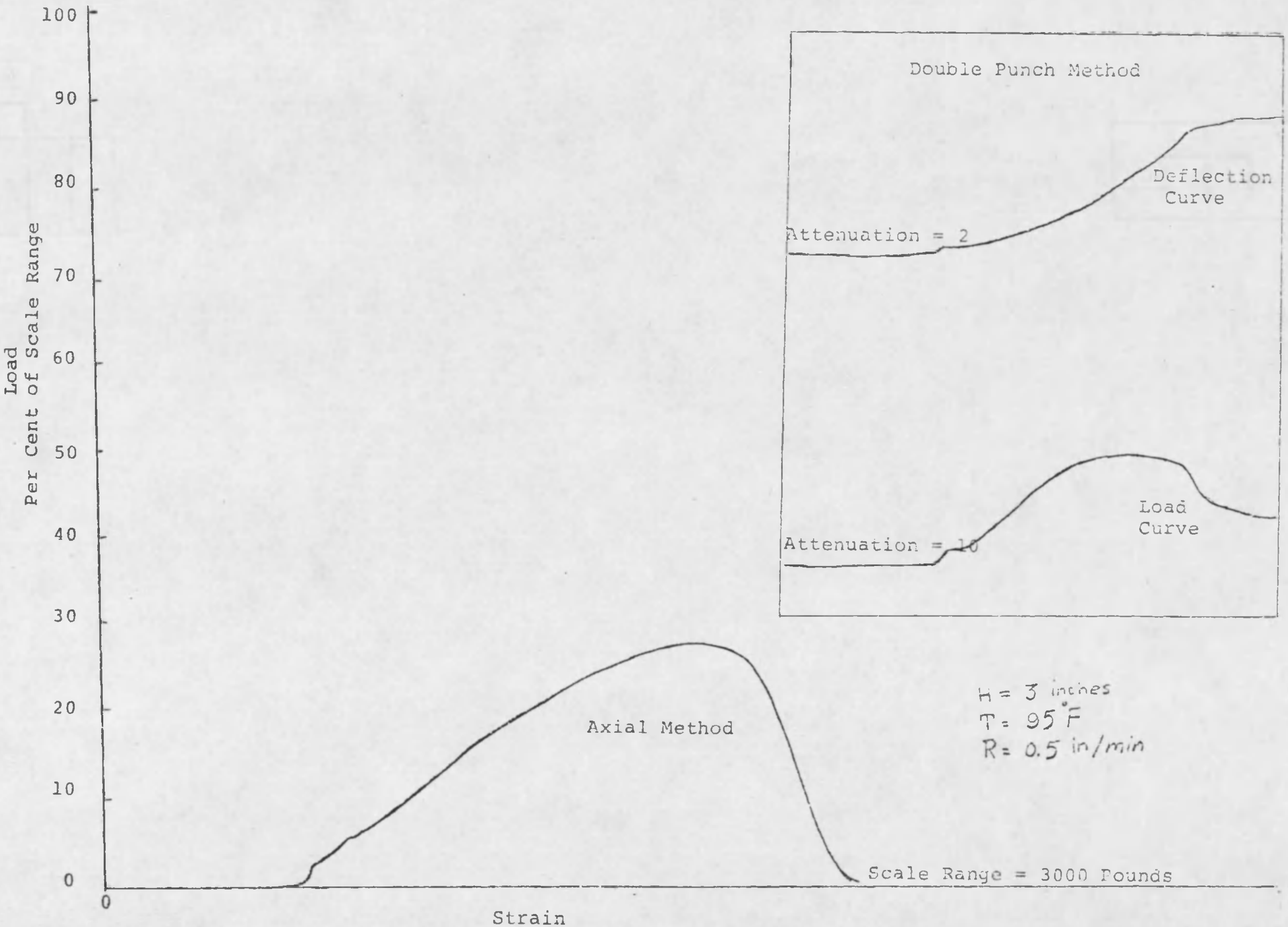
11. Lower crosshead slowly until the upper punch rod barely touches the specimen without loading the specimen.
12. Release the aluminum plate of item 10.
13. Set the desired rate of deformation, R.
14. Choose an attenuation scale on the Sanborn carrier-amplifier recorder for both load and deflection making sure that it is not off scale.
15. Make sure that the writing arms are operating.
16. Set the paper drive on 5 mm/sec to record the baseline position of the writing arms.
17. Apply a compressive load until the specimen cracks and record the maximum load.
18. When specimen fails, unload the testing machine and turn off paper drive of the Sanborn carrier-amplifier recorder.
19. Record all necessary information on the graph paper, which are: specimen number, failure load, load and deflection attenuation, rate of deformation, temperature, height of specimen, mixture type, and date.
20. Take the tested specimen away and note the plane of failure.
21. Calibrate the recorder again and so the same steps to test the other specimens.

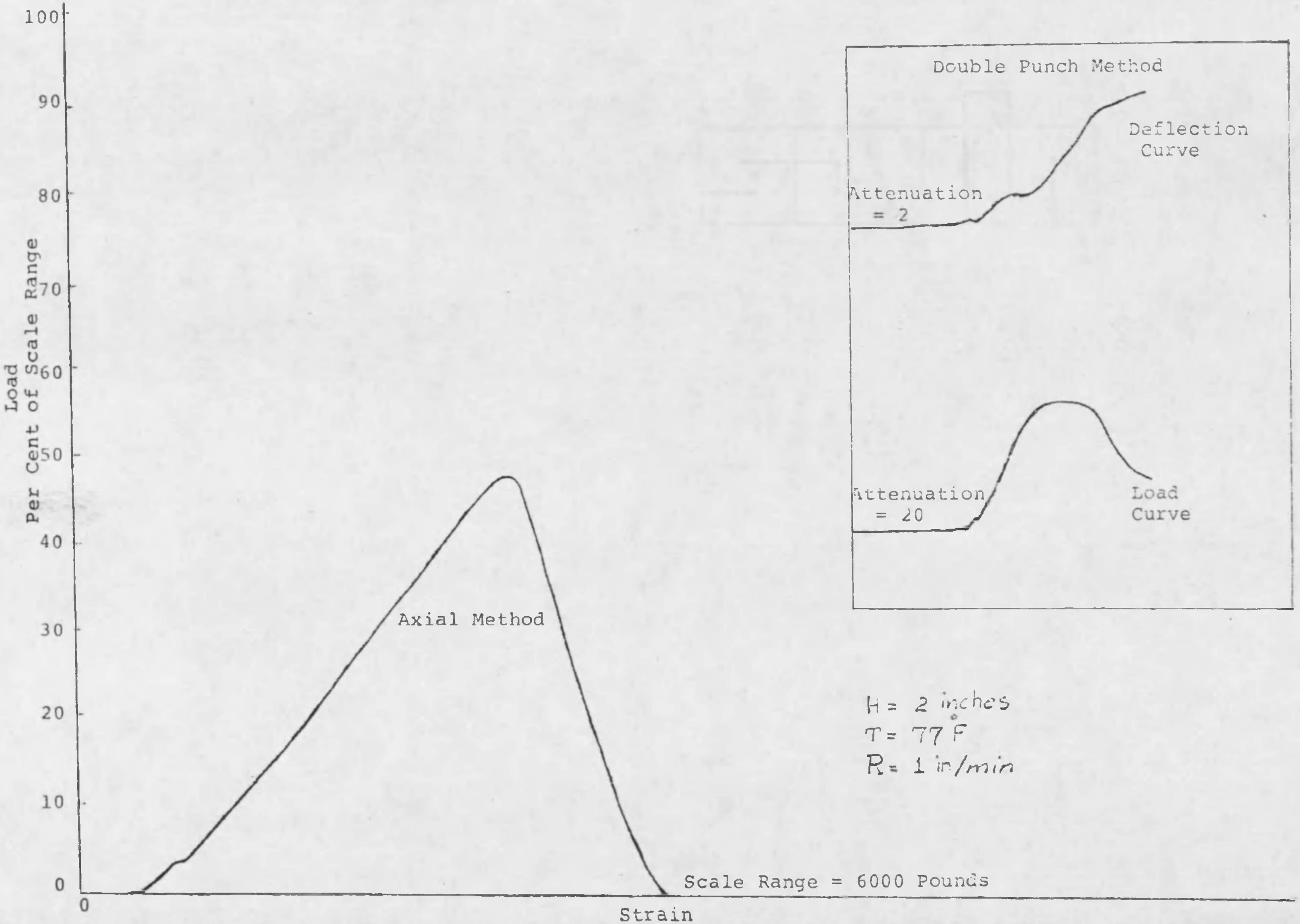
APPENDIX C

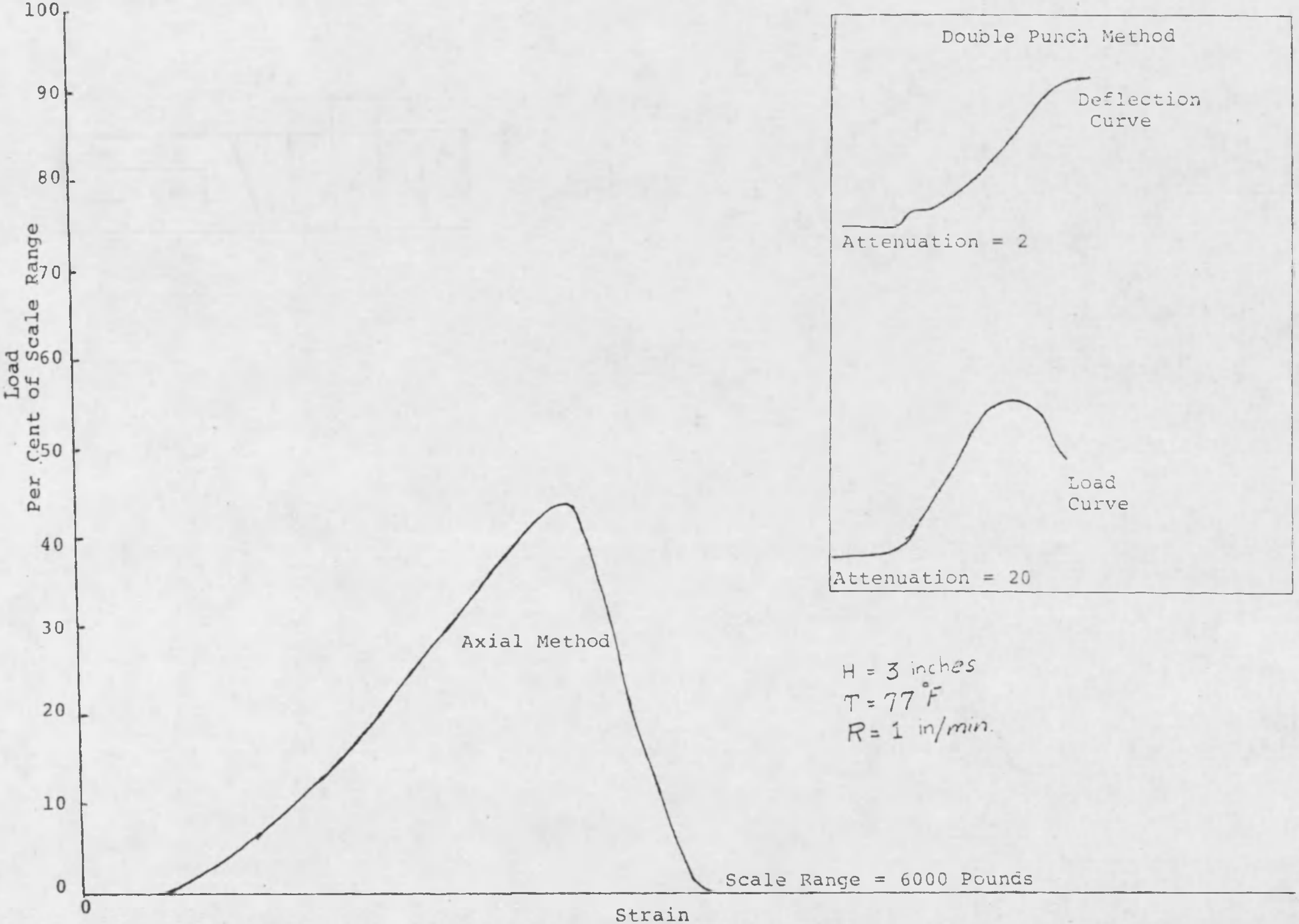
TYPICAL LOAD-DEFLECTION CURVES

Axial on lower right corner. Double punch on upper left corner. Note: Strain means deflection in inches in the axial load-deflection curves.

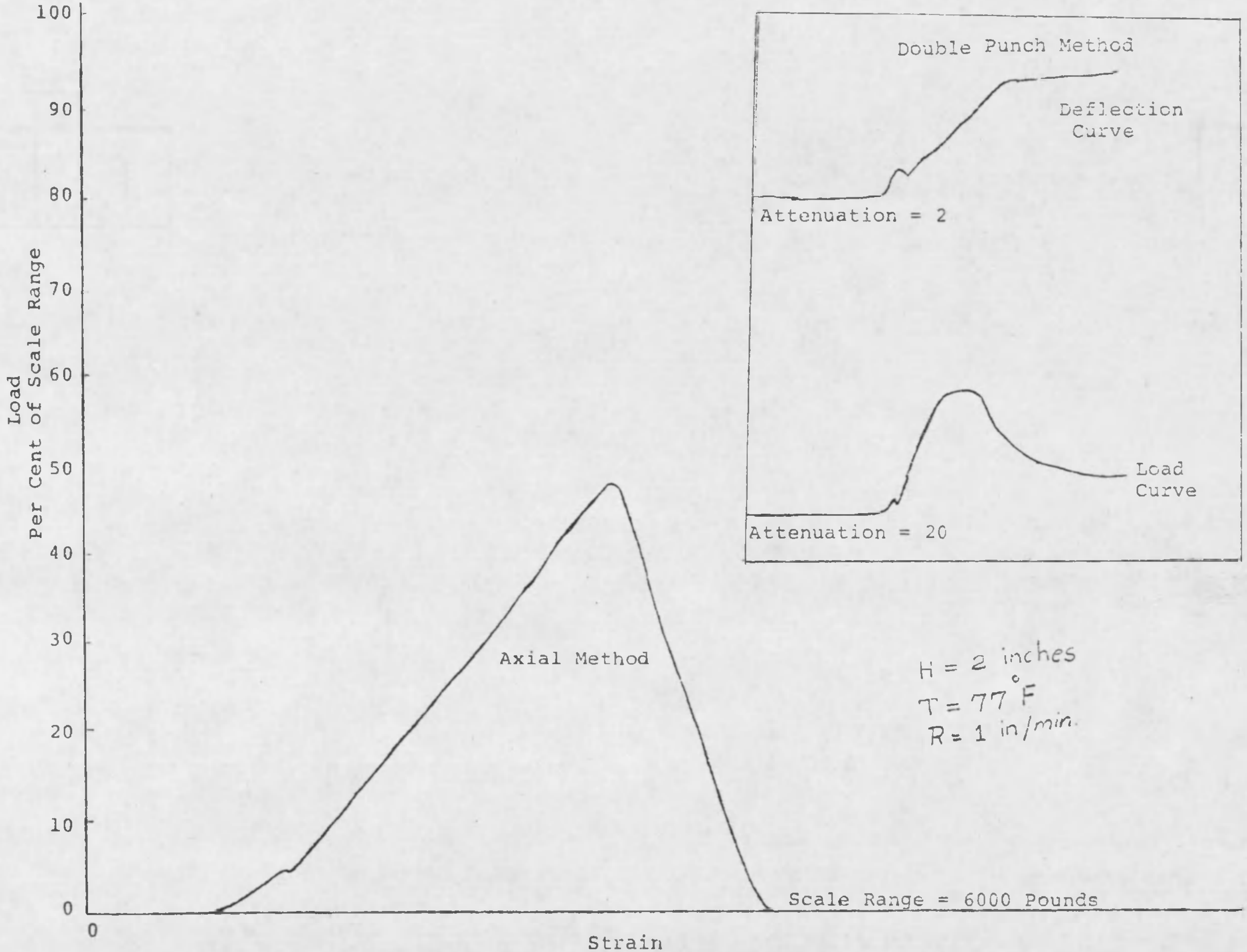

Sample of the original load-deflection curves
LOAD
PERCENT OF SCALE RANGE
STRAIN
DIVIDE BY MAGNIFICATION RATIO
Axial Method Curve
Double punch Method Curve
DEFLECTION
H = 3"
T = 77 F
R = 1.0 in/min
3/8" mix
7/5/75
11 mm = 7.9 x 10⁻³ in
Spec. #
P max = 2400
LOAD
TEST 8
6/10/75
SIZE 3X4
GAUGE LENGTH 2
SCALE RANGE 6000
MAGNIFICATION 100
P max = 2540#, Strain = 0.032
SP. # 20
Rate = 1"/min
AMETEK/TESTING EQUIPMENT SYSTEMS
LANSDALE, PENNSYLVANIA 19446

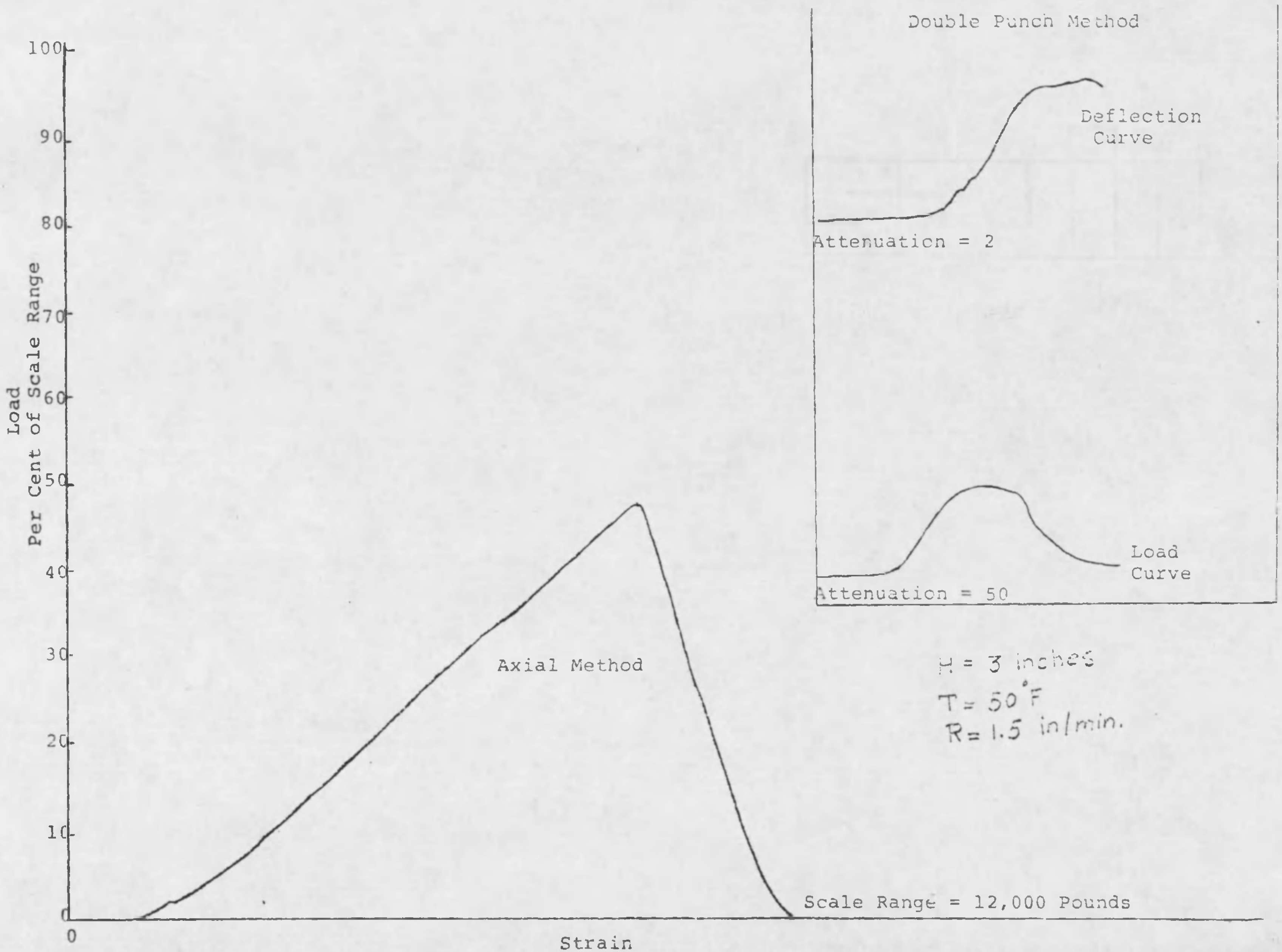

Double Punch Method
Deflection Curve
Attenuation = 2
Load Curve
Attenuation = 10
Load
Per Cent of Scale Range
100
90
80
70
60
50
40
30
20
10
0
0
Strain
Axial Method
H = 3 inches
T = 95°F
R = 0.5 in/min
Scale Range = 3000 Pounds


100
90
80
70
60
50
40
30
20
10
0
Load
Per Cent of Scale Range
0
Strain
Axial Method
Scale Range = 6000 Pounds
Double Punch Method
Deflection Curve
Attenuation = 2
Attenuation = 20
Load Curve
H = 2 inches
T = 77° F
R = 1 in/min

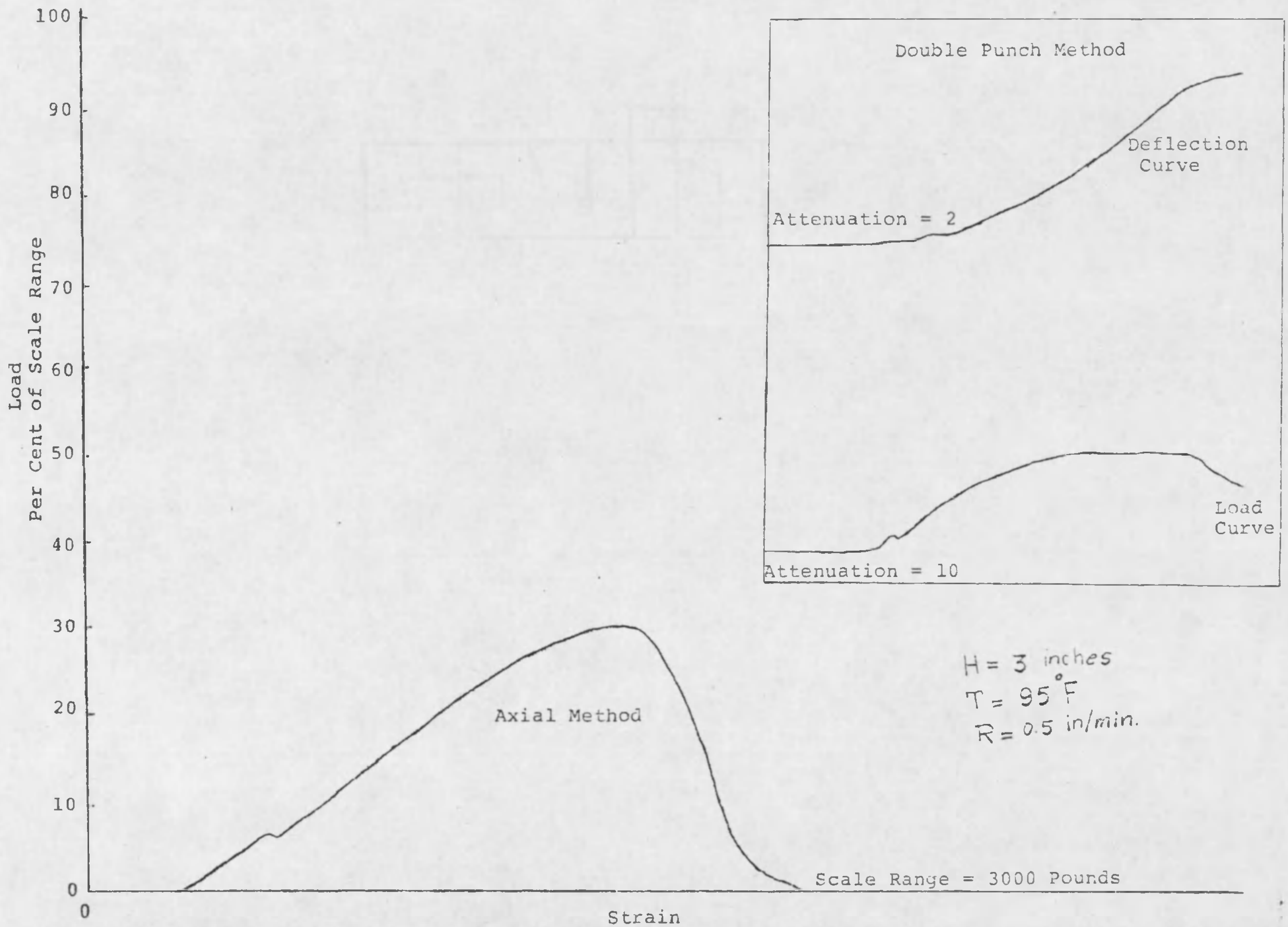


Load
Per Cent of Scale Range
100
90
80
70
60
50
40
30
20
10
0
0
Strain
Axial Method
Scale Range = 6000 Pounds
Double Punch Method
Deflection Curve
Attenuation = 2
Load Curve
Attenuation = 20
H = 3 inches
T = 77 °F
R = 1 in/min.


Double Punch Method
Deflection Curve
Attenuation = 2
Load Curve
Attenuation = 20
Load
Per Cent of Scale Range
100
90
80
70
60
50
40
30
20
10
0
Axial Method
H = 2 inches
T = 77 °F
R = 1 in/min.
Scale Range = 6000 Pounds
0
Strain



Double Punch Method
Deflection Curve
Attenuation = 2
Load Curve
Attenuation = 50
H = 3 inches
T = 50°F
R = 1.5 in/min.
Axial Method
Scale Range = 12,000 Pounds
Load
Per Cent of Scale Range
Strain
0
10
20
30
40
50
60
70
80
90
100


100
90
80
70
60
50
40
30
20
10
0
Load
Per Cent of Scale Range
0
Strain
Double Punch Method
Deflection Curve
Attenuation = 2
Load Curve
Attenuation = 10
Axial Method
H = 3 inches
T = 95°F
R = 0.5 in/min.
Scale Range = 3000 Pounds

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