PAINT MARKING DURABILITY

Project Number ST-2019-5

Final Report

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ABSTRACT

Two laboratory tests were developed to evaluate properties of pavement marking paints that could be used to predict durability of the stripes in the field. Tensile tests of free film specimens of paint yielded several properties derived from the stress-strain curves. Abrasion tests provided results for paint specimens tested both dry and submerged in distilled water. The tests produced consistent results and repeatability.

Ten paint samples representing five different vehicles were evaluated using the laboratory tests developed. The paints were quite different as reflected in the tensile properties. The water base paints were considerably more ductile than the solvent base and alkyd resin paints. The load rate used for the test had significant effect on the results due to increased viscous creep introduced at slower load rates. The effect of temperature and humidity during the curing of the paints is also reported.

The ten paint samples tested in the laboratory were applied to two asphalt surfaces of different ages in the form of transverse stripes. None of the stripes showed significant abrasion wear during the 42 weeks that they were monitored. There was a definite correlation between the tensile properties recorded in the laboratory and observed cracking in the stripes. The paints that were the most brittle and stiff all developed transverse cracks at approximately 8 weeks and continued to worsen over the observation period. These same paints also caused the asphalt surface to crack around the periphery of the stripes. Two of the water base paints that were the most ductile underwent a premature chipping failure due to a lack of adhesion to the asphalt surface. The paints that exhibited average ductility in the laboratory have performed the best to date.

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I Introduction

1.1 Statement of Problem

Highway pavement markings are subjected to traffic and environmental forces that combine to wear them away and therefore require a continuous remarking effort. Pavement markings that become unacceptable due to deterioration are safety and operational hazards. Any improvements in durability, or evaluating durability, to increase the life of pavement markings will reduce maintenance costs.

Possible modes of failure for pavement markings include poor adhesion, chipping, abrasion, loss of reflectivity (poor bead retention), and discoloration. Factors affecting the performance of traffic paint include:

- paint formulation
- substrate
- surface preparation
- humidity and temperature
- traffic volume
- striping equipment

The increased demands of pavement markings have led to the consideration of thermoplastic marking materials, raised markers, and rapid-drying traffic paint in areas of high traffic volume to reduce interruption to traffic. Field tests have been utilized in the past to evaluate durability, reflectivity, and other characteristics of pavement marking materials. However, the rapid introduction of new materials are not conducive to lengthy and less controllable field evaluations.

A laboratory testing procedure that predicts durability in the field will be useful to highway officials in selecting pavement marking materials. The tests can also be used in quality control procedures to ensure that the delivered and applied product will provide expected performance.

1.2 Objectives

The overall objective of this research effort was to improve the durability and cost-effectiveness of highway pavement markings. Specific objectives of the research presented herein were:

- Review current and past efforts to develop laboratory tests to predict field service of pavement markings.
- Develop a laboratory test to be used to evaluate relative durability of highway pavement marking materials.
- Demonstrate and evaluate the procedure identified above by testing a spectrum of materials including currently used materials by the Alabama Highway Department.
- Provide guidelines to help in acceptance testing of new products and for quality control testing.

1.3 Scope

A laboratory test program was developed and carried out on ten different traffic paint samples. Paint from the same sample batches was applied to a road surface in the form of transverse stripes and observed over a 42 week period.

This project was concerned only with durability and did not consider reflectivity or bead retention of the paint stripes. In fact, only two of the paints contained beads which were premixed into the paint. Tests were conducted that relate to chipping and abrasion failures, but not to general loss of adhesion.

The following considerations were given to the five factors that affect paint performance:

- paint formulation - five different paint vehicles were represented in the samples (water base, modified alkyd-chlorinated rubber, alkyd resin, solvent base, and modified alkyd resin).
- substrate - no laboratory tests were conducted to evaluate the effect of substrate, but for the field tests, two different asphalt surfaces were used (1 year old surface and 3 year old surface).
- surface preparation - the paints in the field were applied to the surfaces with no preparation.
- humidity and temperature - for the tensile tests, the samples were cured for 48 hours at four different humidity and temperature conditions (room conditions, 50% humidity and 50° F, 50% humidity and 90° F, 90% humidity and 90° F) and for the abrasion tests, the samples were tested dry and submerged in distilled water.
- traffic volume - the site selected for the field tests was on U.S. Highway 29 (South College St.) in Auburn, Alabama. This site was selected because there were contiguous asphalt surfaces of different ages. The traffic volume over all four lanes is approximately 12,500 ADT at the test site.
- striping equipment - unfortunately, a walk-behind striping unit had to be used due to the difficulty in using a truck-mounted heated paint striper for the small quantities of paint obtained for the test stripes.

II Background and Literature Review

2.1 Background

Confronted with a serious problem of rehabilitation and maintenance of the state's highway system, the Alabama Highway Department is faced with many resource allocation decisions. Any increase in durability of pavement markings or in assurance of quality control with respect to durability will have a tremendous economic impact on the overall maintenance budget. The highway engineers need independent and reliable testing procedures to provide durability information for new or modified marking materials. The only way a sound economic judgement can be made on a choice of pavement marking material is if reliable data is available concerning the expected life of the marking for its intended use.

Currently, the Alabama Highway Department utilizes both a composition and performance specification for traffic marking materials as provided in Sections 856 and 857 of reference [2.1]. These materials are divided into two classes - Class 1 for paints, and Class 2 for plastics. These classes are further categorized as Type A or Type B, designating reflectorized or non-reflectorized, respectively. The AHD specifies two types of fast-dry traffic paints - solvent based and acrylic water based.

With regard to paint usage, a breakdown of the number of gallons (total batch gallons) tested by the AHD during fiscal year 1985 as well as total gallons applied by state forces is given in Table 2.1 [2.2].

Table 2.1 AHD Paint Usage (in gallons)

	Solvent base		Water Base	
	White	Yellow	White	Yellow
Tested	92,200	88,895	113,359	104,775
Applied	4,015	0	103,785	76,505

This indicates that overall, the highways of Alabama are striped with an even balance of solvent and water base paints, however, state forces overwhelmingly prefer water base paints.

For solvent based paints, the following composition specifications are included:

- <u>percent pigment</u> - between 50 and 54% by weight.
- <u>volumetric weight of pigmented binder</u> - not less than 13.5 pound/gal.
- <u>vehicle solids percent of total vehicle</u> - not less than 40% by weight.
- <u>total non-volatiles percent of pigmented binder</u> - not less than 70% by weight.
- <u>extenders</u> - no amorphous or crystalline silica permitted.

The following performance specifications are also required for solvent based paints:

- no-tracking time - both laboratory and field tests demonstrating 20 second to 60 second no-tracking condition on dry pavement.
- viscosity - good spraying characteristics for heated application.
- flexibility - no cracking or flaking when a prepared painted panel is bent through an arc of 180° around a 1/2" steel rod.
- dry opacity of pigmented binder - minimum contrast ratio of 0.96.
- color and daylight reflectance - without beads, at least 82% for white and 52% for yellow relative to magnesium oxide.
- fineness of grind - pigmented binders ground to clean 4 on a Hegman Grind Gauge.
- film shrinkage - cured film thickness greater than 60% of thickness of freshly applied paint.
- glass bead adhesion - abrasion test using the falling sand method.
- bleeding - minimum ratio of 0.97 on asphalt saturated felt.
- accelerated weathering - 160 hours in an Atlas Twin Arc Weathering machine.

In addition, although not mentioned in [2.1], personnel at the AHD Testing Laboratory perform a Taber Abraser abrasion test on solvent based paints.

For water based paints, the following composition specifications are required:

- percent pigment - between 45% and 55% by weight.
- total non-volatiles - at least 73% by weight.
- non-volatile vehicle - at least 48% by weight.
- organic matter - volatiles shall contain less than 150 grams of volatile organic matter per liter of paint material.
- solids - volume of solids at least 58%.

- volumetric weight - paint shall weigh at least 12 pounds/gallon.

The following performance specifications are required for water based paints:

- no-tracking time - less than 60 seconds applied heated.
- viscosity - between 70 and 90 Krebs at 77° F.
- flexibility - see solvent based criteria.
- dry opacity - minimum contrast ration of 0.97.
- daylight reflectance - at least 85% for white and 54% for yellow relative to magnesium oxide.
- abrasion resistance - falling sand test.
- glass bead adhesion - falling sand test.
- bleeding - see solvent based criteria.
- scrub resistance - 300 cycles minimum using ASTM D-2486.
- freeze-thaw stability - no coagulation or significant decrease in scrub resistance.
- dilution test - water clean up.
- storage stability - at least 30 days storage in 3/4 filled, closed container.

With all of the above listed specifications, one would think that acceptance and quality control testing of paints is adequately accomplished. However, the correlation of these tests with the actual service life of the paints has not been thoroughly evaluated and many of the tests are not routinely performed. Also, these tests are minimum standards for which literally hundreds of paint formulations would pass. The answer to the question of which of these paints, acceptable according to current standards, would prove to be the most durable in service is not presently known.

2.2 Literature Review

A thorough reporting of the Alabama Paint Specification, ASTM tests that might be used, and previous research work with regard to laboratory tests to predict service life of pavement marking materials was given in [2.3]. The most relevant past research work that influenced the direction and development of the laboratory tests presented in this report are summarized below.

System Research & Development Service of the U.S. Department of Transportation [2.4] conducted a survey of the state-of-the-art of airfield marking paints. A review of abrasion study results using simulated traffic wheels, Taber Abrasers, falling sand tests, and other methods were found to correlate poorly with field results. Poor correlation was due to the fact that such lab tests determine resistance to abrasion where traffic markings fail mainly due to chipping. A qualitative measure of flexibility of traffic paints can be determined by bending a thin painted panel over a cylinder and checking for cracking. Quantitatively, tensile strength and paint elongation, determined by the free film method, have been shown to correlate well with field testing.

A three year study on the development of an accelerated laboratory test program correlated with field tests at three different climatic sections of the United States to predict traffic marking material durability, was done by Harris Research Laboratories and Gillette Research Institute sponsored by the U.S. Department of Transportation [2.5]. The field test consisted of applying stripes of different kinds of paints to the surface of Portland cement concrete (PCC) and bituminous asphaltic concrete. The stripes were tested for chipping, abrasion, reflectance, night visibility, candlepin test, and sweepings. The laboratory tests on films of different paints consisted of dry and wet tensile tests, weather-ometer exposures, dry field stripe thickness, Taber Abraser, falling sand, shear test, peel test, hardness, mandrel test, reflectance, blister test, and elcometer test.

Conclusions from this research indicated that:

- Field tests on the paints can give an overall durability ranking.
- Data from six accelerated laboratory tests can predict the field result with a high degree of reliability. If field tests are performed in parallel with the laboratory tests, statistical methods can be used to select the least number of tests required, and to provide coefficients for predictive equations. These tests were:

    1) tensile breaking strength of dry free film.
    2) initial tensile modulus of dry free film.
    3) tensile elongation at break of dry free film.
    4) tensile work-to-break of dry free film.
    5) Taber Abraser weight loss of dry specimens.
    6) falling sand test of dry specimens.

The Department of Transportation of New York State conducted a study on durability of several different pavement marking materials [2.6]. Their goal was to select paints for in-field evaluation that would be capable of providing year-round delineation on at least part of the state's highway system. The results of this study, relative to the paints found to be most durable, have little relevance to the State of Alabama considering the difference in climatic conditions. However, some observations regarding failure modes is worthy of note. Of the 125 sets of paint stripes from seven major paint families, over half of the sets failed in abrasion, about one quarter in chipping, and the remaining sets failed in both modes simultaneously. The study pointed out that the alkyd paints failed predominantly in abrasion and that the water base paints failed predominantly in chipping. The chlorinated rubber paints were split between abrasion and chipping failures.

A team of AHD and FHWA personnel reviewed the performance of striping materials at 42 sites across the state [2.7]. The results of this study may provide some additional data regarding the correlation of service life different paints with the results of the laboratory testing program described herein. Visual ratings at daytime and nighttime were given for approximately 2600 miles of striping during January 1986. Daytime reflectivity readings were also taken with the Ecolux RetroreFlectometer and compared to the visual nighttime ratings. The review team agreed on the following conclusions:

- Average daily traffic had little effect on performance of longitudinal stripes with minimal contact with tires.
- Thermoplastic materials have a useful life of 6 years while solvent and water base paints have a useful life of approximately 3 years.
- Quality control of water base paints was questioned. Inexperienced crews and equipment problems were noted as reasons.
- Solvent and water base paints were concluded as providing equal performance with the exception of the quality control problem stated above.
- A good correlation between visual nighttime ratings and daytime reflectance readings was reported.

2.3 References

2.1 State of Alabama Standard Specifications for Highway Construction, 1985 edition.

2.2 Information provided by William J. Hartzog, Construction Engineer, AHD, Letter dated April 15, 1986.

2.3 Shoemaker, W., Parker, F., Alifarhani, F. and Corte, T., Pavement Marking Durability, Interim Report: Literature Review and Current Practices, Alabama Highway Department Project #ST.-2019-5, September 1986.

2.4 U.S. Department of Transportation, Federal Aviation Administration, "Airfield Marking Paints," Final Report FAA-RD-78-104, September 1978.

2.5 Buras, E., and Patrick, R., "Accelerated Test of Traffic Marking Material Durability," Harris Research Laboratories, Gillette Research Institute, FHWA-RD-78-93, June 1978.

2.6 Bryden, J., and Lorini, R., "Traffic Paint Performance in Accelerated Wear Tests," Second Interim Report - Project 167-1, Engineering Research and Development Bureau, New York State Department of Transportation, Albany, N.Y., March 1986.

2.7 Anderson, G., et. al., "Striping Review," Alabama Highway Department, in cooperation with FHWA, unpublished report, 1986.

III Laboratory Tests

Two testing methods were selected based on (1) the findings and recommendations cited in the literature review, (2) types of failure modes expected of paint, and (3) tests most likely to predict susceptibility to these different failures. Tensile tests of free film samples were used to quantify susceptibility to chipping and abrasion tests were used to quantify susceptibility to normal wear. It was also felt that these tests would be relatively simple and fast.

3.1 Tensile Tests

3.1.1 Scope

Free film tensile tests, used successfully in other cited research efforts, involves applying the paint to a backing material from which the paint can be separated after drying. Cut into the shape of a normal tensile coupon (bone shape), the sample can then be tested while load-deformation data is recorded for later evaluation of several tensile properties.

3.1.2 Sample Preparation

The following procedure was used to produce the tensile test coupons:

1) A 2" wide teflon tape was applied to a metal plate. A minimum of three specimens were prepared for each paint sample.
2) The paint was puddled at one end of the taped plate (Figure 3.1), and a Bird film applicator was used to draw a 15 mil wet film thickness across the surface. The 6" long Bird applicator that was used can be seen in Figure 3.1, just above the plates. It should be noted that originally, a dip-coater, which is an

electric motor device used to evenly draw a sample from a container of paint was tried in an effort to obtain a uniformly coated surface. However, this method did not work well for all of the paints because the tape "shed" some of the paints when placed in a vertical position to dry.

3) The samples were allowed to dry for 24 hours at room conditions, then they were die cut to the desired shape. The die cutter was manufactured to the specifications shown in Figure 3.3. The samples were cut using a hydraulic press that cut through the paint, but not through the teflon tape.

4) After being cut, the paint coupon could be "peeled" from the teflon tape, using an exacto knife. This procedure was very successful except for the chlorinated rubber paints, which were very brittle. One of these paints could not be peeled off of the tape without cracking. After being removed from the tape, the paint coupons were hung vertically in a humidity/temperature controlled chamber for 48 hours at the specified curing condition.

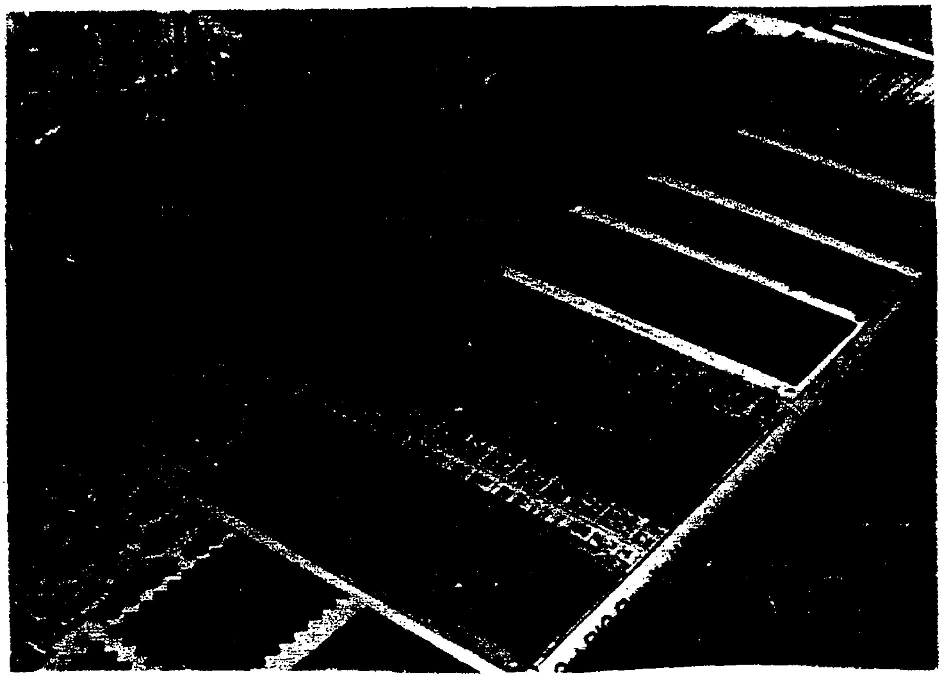


Figure 3.1 Applying Paint to Teflon Taped Specimen Plate

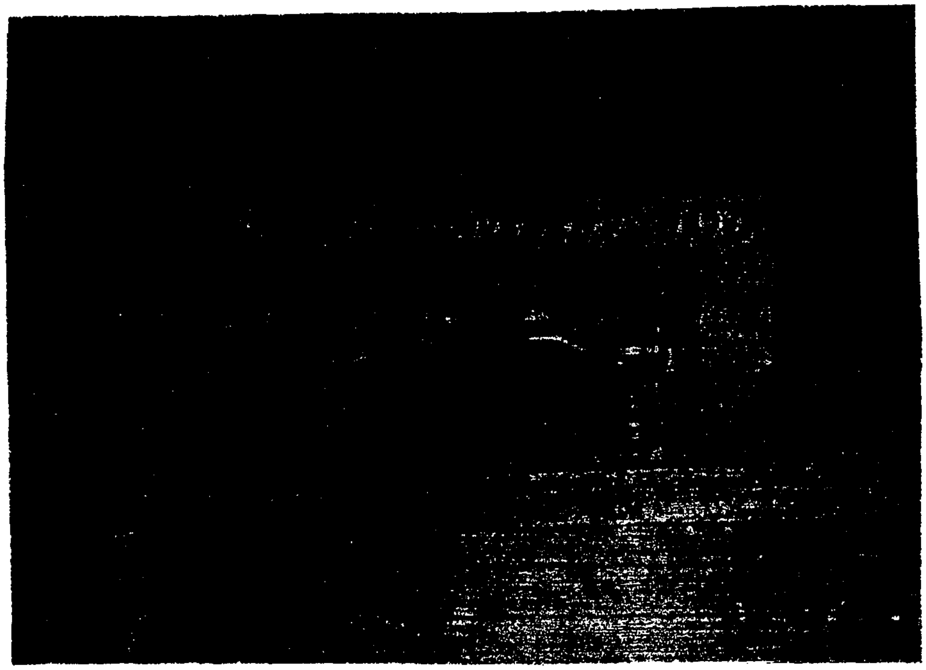
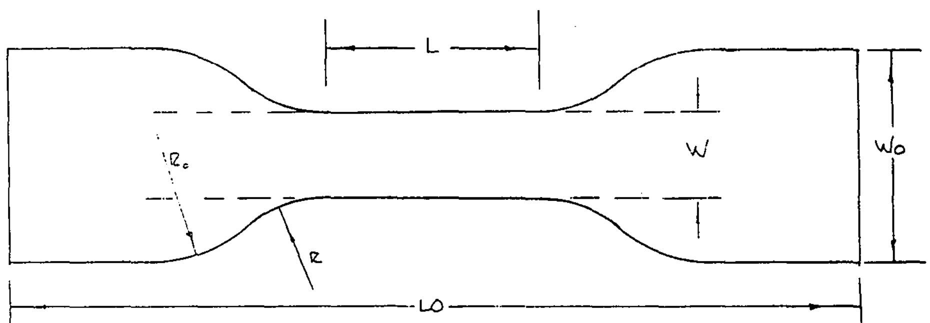


Figure 3.2 Paint Coupon Die Cutter



NOTE: DRAWING NOT TO SCALE

DIMENSIONS	VALUES (INCHES)
L - LENGTH OF NARROW SECTION	1.30
LO - LENGTH OVERALL	4.50
R - RADIUS OF FILLET	0.56
Ro - OUTER RADIUS	1.00
W - WIDTH OF NARROW SECTION	0.25
Wo - WIDTH OVERALL	0.75

Figure 3.3 Specification for Die Cutter

3.1.3 Tensile Test Procedure

A Tinius Olsen universal testing machine was used for the tensile testing of the paint samples. Some special modifications were needed to accommodate the requirements of the test. Rubber-lined, low capacity grips were purchased and are shown in Figure 3.4. Also, the tensile loads required to break the paint samples were too low to use the load indicator on the high capacity machine. A more sensitive load cell with a capacity of 10 lbs. was installed between the crosshead and the upper grip and can be seen in the top of Figure 3.4. The tensile test was conducted under a deformation rate mode in a specified inches per minute.

Data recorded during the test consisted of monitoring the voltage from the linear voltage displacement transducer (LVDT) attached to the hydraulic ram and the voltage from the load cell indicator. These voltages were proportional to the displacement and load, respectively. A microcomputer-based data acquisition system was used to monitor and store data from these two channels.

A series of paint samples was tested after a calibration procedure was performed on the load cell and the LVDT. The load cell was calibrated using hanging masses of known weight, and the LVDT voltage was zeroed when the specimen was in place in the grips. Voltages from the load cell were calibrated in grams and voltages from the LVDT were calibrated in inches. The paint coupons were placed in the grips so that the gage length was 1.5 inches.

The paint samples that were stored in the environmental chamber were removed for testing just prior to the test. The thickness of each paint sample was measured with a micrometer to the nearest 1/2 mil and recorded for use in the conversion from force to stress.

$$\sigma = \frac{P}{(t_w)(t)} \times 1000$$

where,

σ = stress in psi

P = force in lbs

t_w = throat width (0.25 in)

t = thickness of paint in mils

and

$$\epsilon = \frac{\delta}{G}$$

where,

ϵ = strain in in./in.

δ = LVDT deflection in in.

G = gage length (1.5 in.)

The load-deformation data from each test was stored on magnetic media and converted to stress-strain diagrams using plotting software and data reduction programs.

Figure 3.4 Paint Sample After Tensile Test

3.2 Abrasion Tests

3.2.1 Scope

Abrasion tests performed on paints are typically either a test using an abrading rotating wheel, or a falling sand test where sand free falls onto a painted surface. A Taber Abraser (available from Teledyne Taber, North Tonawanda, New York), of the former variety, was selected due to its wide use in other highway departments and studies. ASTM Standard D-4060-81 and Federal Test Method Standard No. 141a provide testing procedures for using the Taber Abraser.

3.2.2 Specimen Preparation

The following procedure was used to produce the specimens used for the abrasion tests:

1) Paint thinner was used to clean 4- by 4-inch steel specimen plates.
2) A Bird applicator was used to apply a 15 mil wet film thickness of paint. Five specimens were prepared for each paint sample.
3) The prepared specimens were allowed to dry for 24 hours at room conditions.

3.2.3 Abrasion Test Procedure

The three testing parameters for the Taber Abraser are the choice of abrasive wheels, the weight placed on the wheels, and the number of cycles to which the specimen is subjected. The wheels selected were CS-17 resilient wheels composed of rubber and abrasive grain which produce a harsh abrasive action. The arms were weighted each with 1000 grams. The specimens that were tested dry were subjected to 2000 cycles and the specimens that were tested submerged in distilled water were subjected to 500 cycles. The following test procedures were followed:

1) The specimen plates were weighed using a Metler balance.
2) The CS-17 wheels were refaced by running them for 50 cycles over an S-11 abrasive disk with 1000 grams on each arm.
3) The pre-weighed specimen plate was mounted on the Taber Abraser and the CS-17 wheels lowered into position as shown in Figure 3.5.
4) The automatic counter was set to the appropriate number of cycles and started. The vacuum pick-up was used to remove loose particles from the specimen.
5) At the end of the cycles, the specimen plate is weighed and the wear index computed as:

$$\text{Wear Index} = \frac{(A-B) \times 1000}{C}$$

where,

A = weight before abrasion

B = weight after abrasion

C = number of cycles

6) For the specimens tested submerged under distilled water, a special rimmed specimen holder was used.
7) The CS-17 abrasive wheels were used for a maximum of 10 tests before being discarded.

Figure 3.6 shows two specimens after the abrasion test. The specimen on the left shows slight wear, while the specimen on the right wore completely through to the steel plate. The later condition was undesirable since the actual wear index would be higher than that indicated. However, some samples did wear completely through and this is noted in the results.

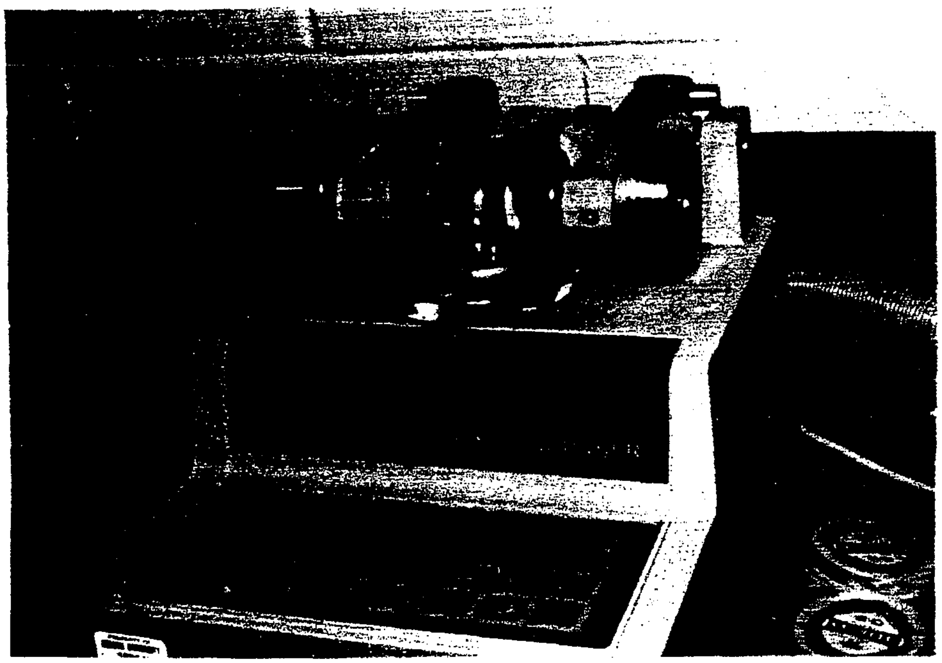


Figure 3.5 Specimen Mounted on Taber Abraser

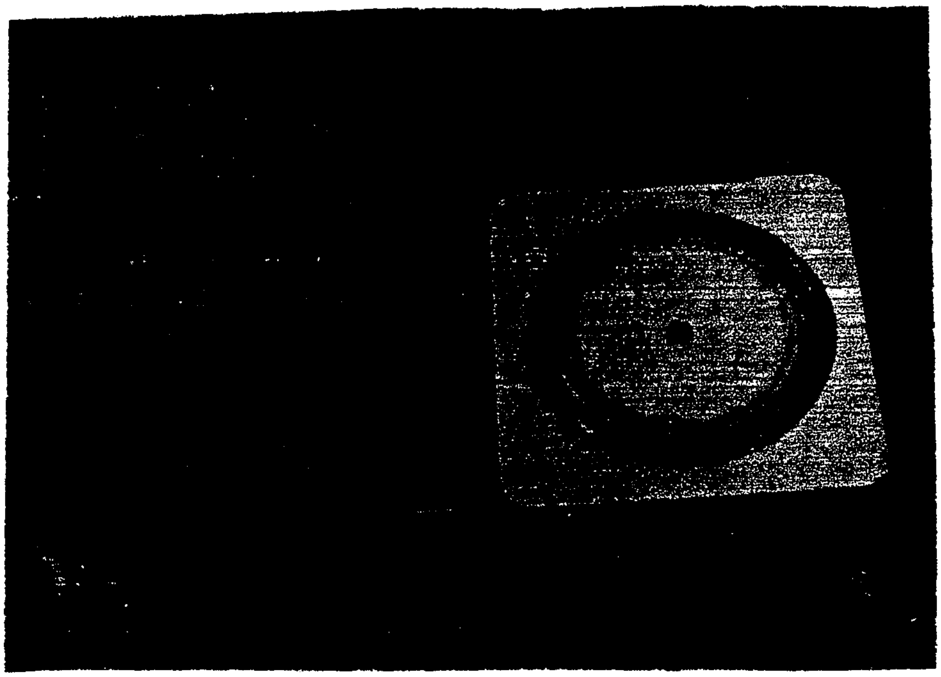


Figure 3.6 Two Abrasion Specimens After Test

IV Paint Samples

4.1 Alabama Highway Department

Division 4 personnel provided samples of currently used paints. These samples, to be tested in the laboratory, were obtained at the time the field stripes were placed. Four different paints were obtained from AHD as follows (identification code is in brackets):

- water base (white) [WB-2-W]
- water base (yellow) [WB-3-Y]
- solvent base (white) with premixed beads [SB-1-W]
- solvent base (yellow) with premixed beads [SB-2-Y]

4.2 Paint Vendors

A list of various paint manufacturers that respond to solicitations for bids for maintenance striping paint was furnished by the AHD. The list contained 16 paint companies, 8 of which were contacted with regard to furnishing samples for this study. Three companies consented to sending a total of 5 different paints for the study. The paints received were as follows:

- water base (white) [WB-1-W]
- modified alkyd-chlorinated rubber (white) [CR-1-W]
- modified alkyd-chlorinated rubber (yellow) [CR-2-Y]
- alkyd resin (yellow) [AR-1-Y]
- modified alkyd resin (white) [MAR-1-W]

In addition, for an extreme data point, a sample of white latex (water base) house paint [HP-1-W] was purchased and tested. This provided a total of ten different paints utilizing five different vehicles.

V Field Stripes

5.1 Application

The test stripes were placed with a walk-behind unit by experienced Division 4 personnel. Figure 5.1 shows the application of the transverse stripes which were in the outer, northbound lane of U.S. 29 in Auburn, Alabama. The paints were placed on March 26, 1987. The temperature was in the 70's. All of the paints were applied at ambient temperature except for the AHD supplied water base white [WB-2-W] which was heated because it was siphoned off of a truck-mounted striper at the test site.

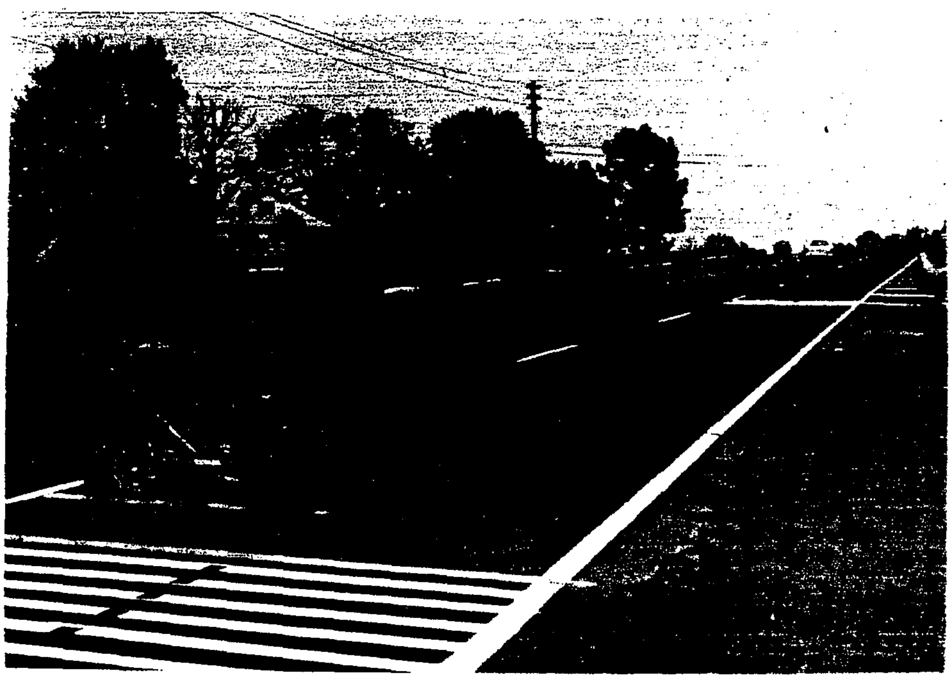


Figure 5.1 Application of Field Stripes

Two test stripes were placed of each paint on both a three year old and one year old asphalt surface as detailed in the next section. For the second stripe placed on each surface, a steel plate (like those used in the Taber Abraser test), was placed in the center of the lane as shown in Figure 5.1 in the way of the striper. The average thickness of the dried stripes was measured using a magnetic thickness gauge by taking the thickness reading at each corner of the plate. No attempt was made to measure the wet film thickness as the stripes were applied. The control of the thickness of the test stripes was difficult with the manually operated walk-behind unit and closer field monitoring might have been warranted to obtain more uniformity in the thickness of the test stripes. Table 5.1 contains the average thicknesses of the paint on the plates taken from the field.

Table 5.1 Field Stripe Thicknesses			
Test Stripe Code	Paint Code	Thick. (mils) Old Surface	Thick. (mils) New Surface
X-1-2	HP-1-W	12.75	12.00
X-2-2	WB-1-W	14.00	15.25
X-3-2	WB-2-W	12.25	10.50
X-4-2	CR-1-W	7.75	6.75
X-5-2	MAR-1-W	8.75	8.25
X-6-2	SB-1-W	11.25	13.50
X-7-2	CR-2-Y	6.88	5.88
X-8-2	WB-3-Y	11.50	11.50
X-9-2	AR-1-Y	5.50	9.00
X-10-2	SB-2-Y	12.00	8.38

5.2 Placement

The test stripes were placed transversely at one foot spacings. The distance between the test stripe pattern on the old asphalt surface and the test stripe pattern on the new asphalt surface was approximately 50 feet. The test stripe pattern used on both surfaces is shown in Figure 5.2.

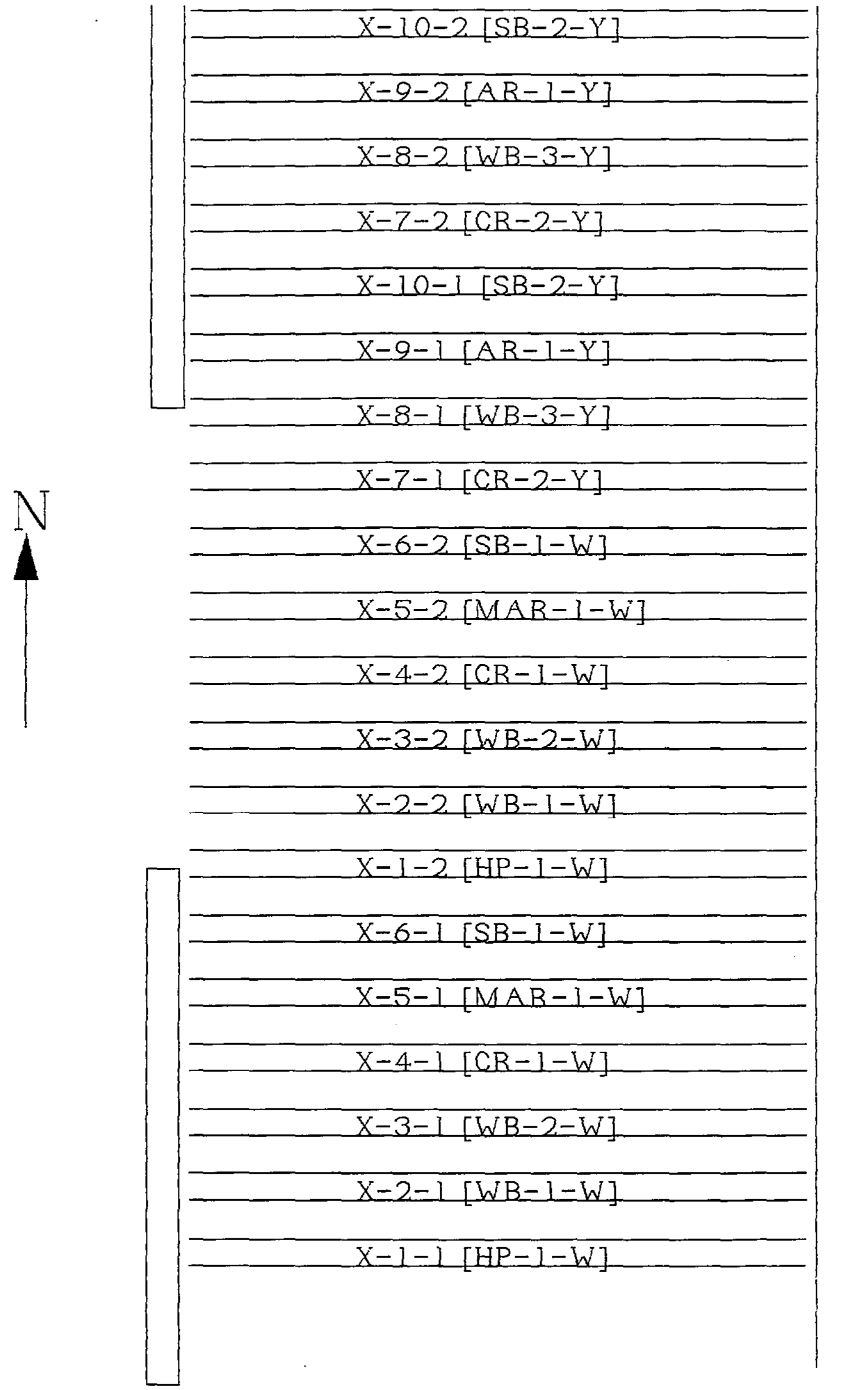


Figure 5.2 Test Stripe Pattern

VI Results

6.1 Tensile Tests

6.1.1 Load Rate Tests

The first series of tensile tests were conducted to evaluate the effect of the load rate on the tensile properties. It should be noted that throughout this report, "load rate" will be used to refer to the displacement rate of the hydraulic cylinder on the testing machine. This series of tests was done to determine the best rate to use in subsequent tests and to determine the sensitivity of a typical paint to a wide range of load rates. For this series of tests, a sample of water base paint from the AHD was used. This paint was similar to [WB-2-W], but was from a completely different batch. The samples were prepared as described in Section 3.1.2 and cured at room conditions. The tests were conducted as described in Section 3.1.3 at six different load rates. Three samples were tested at each load rate.

Figure 6.1 illustrates the tensile properties refered to in this report as they relate to the stress-strain curve of a typical paint sample.

The average tensile properties from this set of tests are listed in Table 6.1 for each load rate. The coefficient of variation given is the ratio of the standard deviation to the average of the three samples at each load rate. The toughness property is the area under the stress-strain curve up to the breaking point as shown on Figure 6.1 and characterizes a material's ability to absorb energy before fracturing.

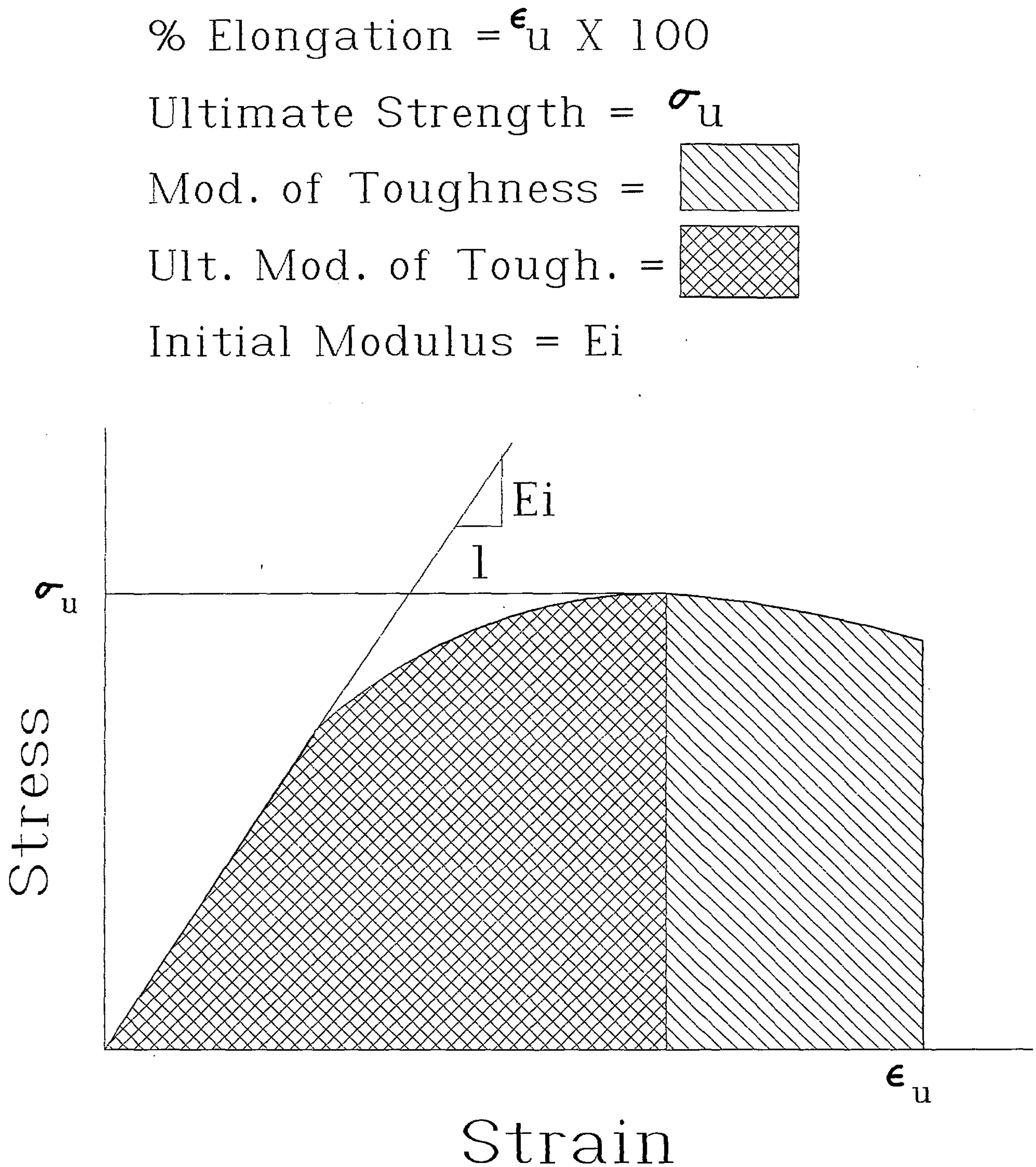


Figure 6.1 Illustration of Tensile Properties From Stress-Strain

The average values at each load rate for the ultimate tensile strength and the toughness are plotted on Figures 6.2 and 6.3, respectively. The load rate did not have any relational effect on the percent elongation for this series of tests.

A load rate of 0.5 in/min was selected for the tensile tests because the lowest coefficients of variation were recorded at this rate.

Table 6.1 Load Rate Effect on Tensile Properties of Water Base Paint

Load Rate (in/min)	Ultimate Strength (psi)		Mod. of Toughness (psi)		Percent Elongation	
	Ave.	Var.	Ave.	Var.	Ave.	Var.
2.00	392	0.02	310	0.02	57	0.05
1.00	340	0.02	208	0.01	64	0.08
0.50	287	0.00	173	0.01	60	0.02
0.20	224	0.03	133	0.03	65	0.05
0.10	203	0.02	129	0.01	71	0.08
0.05	181	0.01	110	0.02	64	0.05

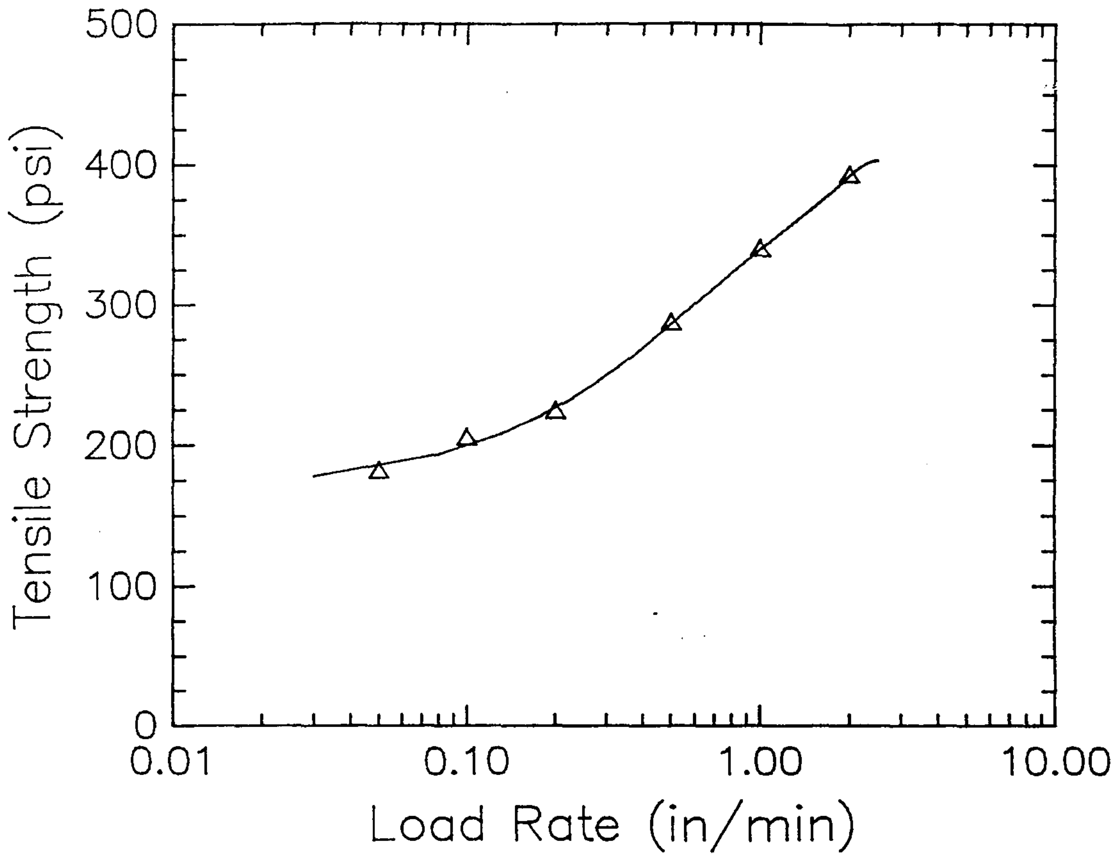


Figure 6.2 Effect of Load Rate on Ultimate Tensile Strength (Water Base)

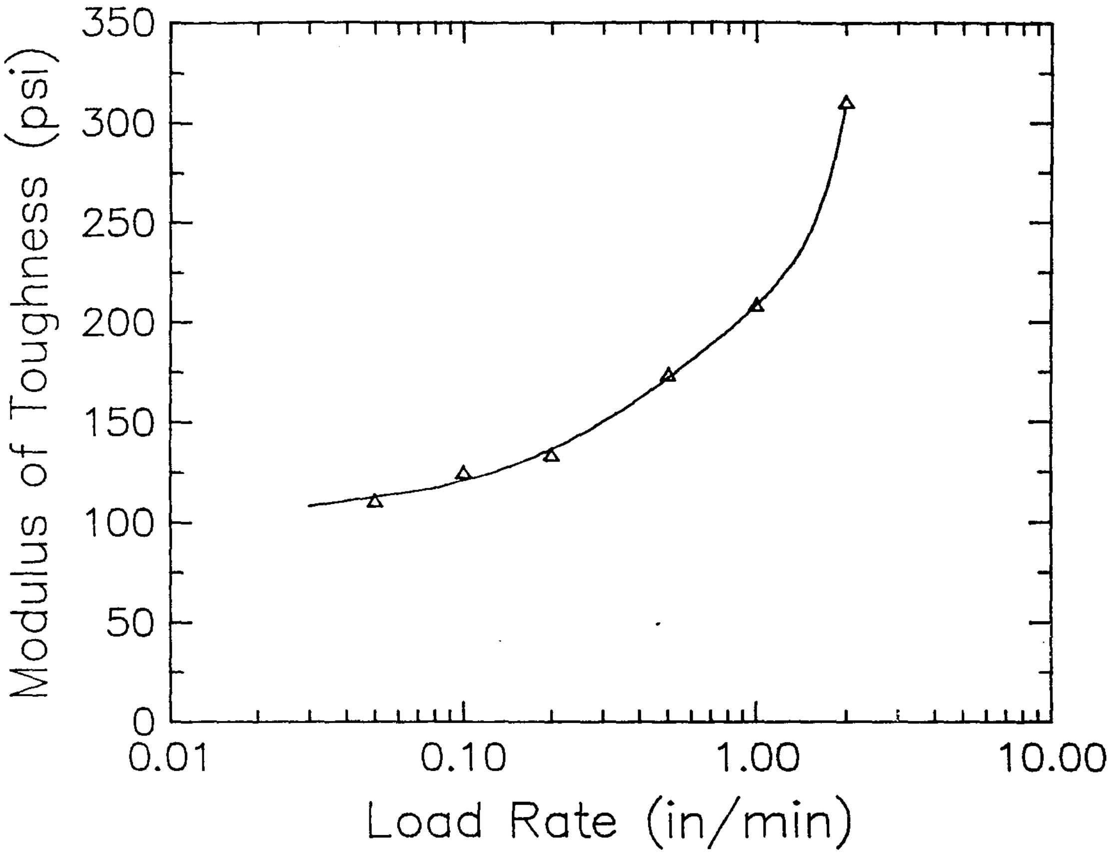


Figure 6.3 Effect of Load Rate on Toughness (Water Base)

6.1.2 Paint Batch Tests

Tensile tests were performed on nine different paint batches (samples of [CR-2-Y] could not be prepared due to brittleness). For the samples cured at room conditions, two load rates were used (0.2 in/min and 0.5 in/min). These tests were done to determine if all of the paints exhibited similar characteristics as the water base paint described in the previous section, without such an extensive set of load rates. The properties for these tests are given in Table 6.2 and Table 6.3. The ultimate modulus refers to the modulus of toughness as explained in the previous section, but the area under the stress-strain curve is taken up to the ultimate stress as opposed to the breaking strength. This was done because of an inconsistency in the total elongation in many of the paint samples. The initial modulus refers to the initial elastic modulus of the paint samples. This was a difficult property to determine from many of the stress-strain curves as the high coefficient of variation indicates. Figures A1-A9 in the appendix show the stress-strain curves for all samples cured at room conditions and at load rates of 0.2 and 0.5 in/min.

Tensile tests were also performed at three different curing conditions as outlined in Sections 1.3 and 3.1.2. Tensile properties obtained from these tests are shown in Tables 6.4-6.6, and stress-strain curves are given in Figures A10-A18.

Table 6.2 Tensile Properties (Cure: Room Cond., Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	8.5	0.45	397	0.13	105	0.31	352	0.19	30	0.29	10750	0.24
WB-1-W	14.9	0.18	592	0.05	195	0.06	418	0.06	39	0.11	12000	0.10
WB-2-W	14.0	0.25	252	0.09	298	0.25	198	0.08	133	0.19	4000	0.35
WB-3-Y	12.4	0.32	253	0.06	209	0.25	171	0.07	100	0.27	3775	0.17
CR-1-W	12.6	0.21	1248	0.26	20	0.32	1248	0.26	2	0.30	60000	0.37
MAR-1-W	19.6	0.09	175	0.03	61	0.07	128	0.06	40	0.10	2875	0.14
SB-1-W	15.9	0.15	425	0.04	7	0.13	425	0.04	2	0.23	41750	0.56
SB-2-Y	9.3	0.05	678	0.09	18	0.12	678	0.09	4	0.15	20000	0.14
AR-1-Y	15.1	0.09	683	0.06	15	0.12	683	0.06	3	0.15	27750	0.21

Table 6.3 Tensile Properties (Cure: Room Cond., Rate: 0.2 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	10.2	0.06	306	0.04	179	0.20	216	0.10	67	0.19	3750	0.01
WB-1-W	16.0	0.20	451	0.08	213	0.14	255	0.11	60	0.18	4375	0.01
WB-2-W	17.7	0.06	173	0.02	226	0.12	116	0.02	152	0.14	1500	0.01
WB-3-Y	15.5	0.07	181	0.03	189	0.08	116	0.01	139	0.12	1350	0.02
CR-1-W	11.0	0.07	1496	0.08	32	0.26	1495	0.08	3	0.21	69000	0.32
MAR-1-W	12.0	0.07	125	0.03	46	0.13	58	0.09	45	0.10	1875	0.01
SB-1-W	15.9	0.01	462	0.06	10	0.16	456	0.07	4	0.07	16450	0.33
SB-2-Y	16.0	0.06	523	0.01	14	0.05	523	0.01	6	0.16	14175	0.41
AR-1-Y	9.8	0.18	605	0.17	18	0.15	605	0.17	4	0.15	27250	0.28

Table 6.4 Tensile Properties (Cure: 50% H, 50° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	10.2	0.06	340	0.05	96	0.03	305	0.04	30	0.04	13750	0.33
WB-1-W	11.3	0.08	574	0.03	172	0.19	431	0.09	35	0.20	12250	0.17
WB-2-W	13.0	0.15	245	0.04	250	0.10	183	0.06	118	0.08	2075	0.18
WB-3-Y	15.0	0.10	222	0.05	169	0.20	164	0.07	87	0.17	2350	0.16
CR-1-W	10.8	0.21	1144	0.21	20	0.17	1144	0.21	3	0.26	105000	0.98
MAR-1-W	12.8	0.25	149	0.08	47	0.24	108	0.08	36	0.20	10000	0.29
SB-1-W	17.7	0.05	361	0.07	7	0.27	361	0.07	3	0.19	20800	0.15
SB-2-Y	16.9	0.12	487	0.05	17	0.19	487	0.05	5	0.16	19250	0.13
AR-1-Y	10.2	0.16	411	0.58	10	1.13	411	0.58	2	0.88	101500	1.10

Table 6.5 Tensile Properties (Cure: 50% H, 90° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	9.7	0.06	568	0.01	150	0.44	512	0.05	31	0.36	26500	0.04
WB-1-W	15.3	0.13	837	0.04	193	0.08	692	0.04	28	0.08	14250	0.20
WB-2-W	15.2	0.19	332	0.02	455	0.11	243	0.01	162	0.13	2500	0.16
WB-3-Y	12.0	0.07	336	0.03	262	0.34	245	0.08	92	0.32	3000	0.47
CR-1-W	14.2	0.23	1270	0.25	58	0.34	1268	0.25	6	0.33	50000	0.16
MAR-1-W	16.0	0.07	259	0.01	85	0.10	170	0.11	45	0.17	7150	0.12
SB-1-W	19.7	0.10	553	0.08	9	0.09	553	0.08	2	0.18	32250	0.23
SB-2-Y	16.3	0.13	810	0.07	20	0.14	811	0.07	4	0.12	30000	0.31
AR-1-Y	10.8	0.08	797	0.05	15	0.07	797	0.05	3	0.04	31500	0.07

Table 6.6 Tensile Properties (Cure: 90% H, 90° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	9.7	0.09	265	0.09	138	0.26	215	0.21	61	0.32	3000	0.27
WB-1-W	16.0	0.06	576	0.03	157	0.13	440	0.06	33	0.13	9000	0.22
WB-2-W	19.7	0.17	204	0.15	276	0.16	137	0.39	196	0.10	2000	0.20
WB-3-Y	19.5	0.06	245	0.06	279	0.03	187	0.06	131	0.03	3250	0.10
CR-1-W	13.8	0.05	924	0.08	12	0.29	924	0.08	2	0.33	120000	0.78
MAR-1-W	12.5	0.03	75	0.03	32	0.08	39	0.10	50	0.09	750	0.09
SB-1-W	18.6	0.07	429	0.08	8	0.20	429	0.08	3	0.06	20500	0.51
SB-2-Y	16.8	0.13	557	0.21	13	0.10	557	0.21	4	0.09	21250	0.11
AR-1-Y	10.1	0.06	501	0.30	9	0.47	501	0.30	2	0.25	22000	0.25

6.1.3 Discussion of Tensile Test Results

6.1.3.1 Load Rate Tests

The load rate tests performed on a typical water base paint demonstrated the visco-elastic nature of the material. Figures 6.2 and 6.3 clearly show the dramatic effect that the load rate has on this type of material. The slower the load rate, the more time the material has to undergo viscous creep. The two major implications of these results are:

1) Any comparative study done in the laboratory must be closely monitored and prescribed as to the load rate used.
2) What load rate is more indicative of the actual load rate experienced by the inplace paint stripe?

The answer to the second implication can be addressed in general terms. For loading induced by thermal movements in the surface, the rate is toward the lower end of the scale, and for loads induced by traffic, the rate is toward the higher end of the scale. Therefore the tensile properties within the entire range may be significant with regard to different failure mechanisms at work.

As far as selecting a load rate to use in subsequent testing, it would be desirable to use a load rate that was less sensitive to deviations with respect to tensile properties of the specimen. Figures 6.2 and 6.3 show the properties leveling off as the load rate decreases. However, given that some paints to be tested elongate as much as 2 inches, this translates into a test that would run for over 3 hours at a rate of 0.01 in/min. This is far too long for practical purposes and would also be undesirable due to probable changes in the temperature/humidity over this long of a test period. A rate of 0.5 in/min was selected because for the water base paint tested in this load rate study, a lower coefficient of variation was noted for all of the properties measured as shown in Table 6.1. This greater consistency in the data did not manifest itself in all subsequent tests, but based on the data available and the reasons stated, it seemed like a logical selection.

6.1.3.2 Paint Batch Tests

For discussion purposes, the 10 paints evaluated in this study were categorized according to their ductility, or percent elongation, recorded at room condition curing and a load rate of 0.5 in/min. This classification was given as ductile (% elongation > 50%), brittle (% elongation < 10%), or average ductility.

Load Rate

The effect of the two different load rates used on the 10 paints evaluated is summarized in Table 6.7, which lists the percent change in the tensile properties from a load rate of 0.5 in/min to 0.2 in/min. It can be seen that the ductile and average ductility paints exhibited similar changes in ultimate strengths and breaking strengths whereas this relationship was very inconsistent for the brittle paints. A major reason for this is that the brittle paints are more sensitive to slight misalignments in the applied tensile load as was evident in the greater variation in the data for these paints. The effect of the load rate on the ultimate modulus of toughness was quite variable and no correlation to the paint types was evident.

Table 6.7 Effect of Decreased Load Rate on Tensile Properties

(% change from 0.5 in/min to 0.2 in/min)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	-22.9	+70.5	-38.6	+123.3	-65.1
Ductile	WB-1-W	-23.8	+9.2	-39.0	+53.8	-63.5
Ductile	MAR-1-W	-28.6	-24.6	-54.7	+12.5	-34.8
Average	WB-2-W	-31.3	-24.2	-41.4	+14.3	-62.5
Average	WB-3-Y	-28.5	-9.6	-32.2	+39.0	-64.2
Brittle	CR-1-W	+19.9	+60.0	+19.8	+50.0	+15.0
Brittle	SB-1-W	+8.7	+42.9	+7.3	+100.0	-60.6
Brittle	SB-2-Y	-22.9	-22.2	-22.9	+50.0	-29.1
Brittle	AR-1-Y	-11.4	+20.0	-11.4	+33.3	-1.8

The percent elongation was the only property that was affected in the same direction for all of the paints tested. The slower load rate produced higher elongations in all of the paints due to increased viscous creep. All of the paints, except one very brittle sample [CR-1-W], yielded lower initial elastic moduli at the slower load rate. These lower moduli were due to the increase in viscous creep which caused increased strain at the same stress.

These load rate tests showed that the ductile and average ductility paints were more consistent with regard to the effect of the load rate on the various properties. They also pointed out the need to monitor the load rate very carefully because of the effect of viscous creep on the tensile properties.

Curing Condition

The effect of the temperature/humidity curing condition on the tensile properties was very substantial and of interest due to the extreme environmental conditions to which the paints will be exposed in service.

The effect of increased temperature on the change in tensile properties is shown in Table 6.8. It can be seen that the ultimate strength, ultimate modulus of toughness, and breaking strength all increase to varying degrees. The percent elongation and initial elastic modulus are erratic and show no pattern with regard to paint type or vehicle.

The effect of increased humidity on the change in tensile properties is shown in Table 6.9. The ultimate strength, ultimate modulus of toughness (with one exception), and breaking strength of all of the paints decreased. All of the water base paints had an increase in percent elongation with the increased humidity. This is readily explained since the water base paints cured at the higher humidity would not dry properly and remain more ductile.

The significance of these results in predicting whether a paint will be more durable in the field depends on which properties are determined to be the key indicators in this respect. If the ultimate strength or breaking strength are key predictors, then stripes placed during warmer or less humid conditions should attain a higher strength based on the results of this study. On the other hand, if percent elongation is determined to be a key indicator, then the effect of environmental factors is less clear.

Table 6.8 Effect of Increased Curing Temperature on Tensile Properties

(% change from 50%H, 50°F to 50%H, 90°F)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	+67.1	+56.3	+67.9	+3.3	+92.7
Ductile	WB-1-W	+45.8	+12.2	+60.6	-20.0	+16.3
Ductile	MAR-1-W	+73.8	+80.9	+57.4	+25.0	-28.5
Average	WB-2-W	+35.5	+82.0	+32.8	+37.3	+20.5
Average	WB-3-Y	+51.4	+55.0	+49.4	+5.7	+27.7
Brittle	CR-1-W	+11.0	+190.0	+10.8	+100.0	-52.4
Brittle	SB-1-W	+53.2	+28.6	+53.2	-33.3	+55.0
Brittle	SB-2-Y	+66.3	+17.6	+66.5	-20.0	+55.8
Brittle	AR-1-Y	+93.9	+50.0	+93.9	+50.0	-69.0

Table 6.9 Effect of Increased Curing Humidity on Tensile Properties

(% change from 50% H, 90°F to 90%H, 90°F)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	-53.3	-8.0	-58.0	+96.8	-88.7
Ductile	WB-1-W	-31.2	-18.7	-36.4	+17.9	-36.8
Ductile	MAR-1-W	-71.0	-62.4	-77.1	+11.1	-89.5
Average	WB-2-W	-38.6	-39.3	-43.6	+21.0	-20.0
Average	WB-3-Y	-27.1	+6.5	-23.7	+42.4	+8.3
Brittle	CR-1-W	-27.2	-79.3	-27.1	-66.7	+140.0
Brittle	SB-1-W	-22.4	-11.1	-22.4	+50.0	-36.4
Brittle	SB-2-Y	-31.2	-35.0	-31.3	0.00	-29.2
Brittle	AR-1-Y	-37.1	-40.0	-37.1	-33.3	-30.2

6.2 Abrasion Tests

6.2.1 Specimens Tested Dry

Abrasion tests were run on five specimens for all ten paint batches as described in Section 3.2. The specimens were tested dry for 2000 cycles. Table 6.10 contains all of the results from this test series.

6.2.2 Specimens Tested Submerged

Abrasion tests were run on five specimens submerged in distilled water for all ten paint batches as described in Section 3.2 for a total of 500 cycles. Results for the house paint [HP-1-W] were not useful because the paint lost adhesion to the specimen plate. Table 6.11 contains all of the results from this test series.

Table 6.10 Taber Abraser Results for Specimens Tested Dry

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
HP-1-W-1	77.011	76.129	0.441		
HP-1-W-2	76.024	75.216	0.404		
HP-1-W-3	76.408	75.523	0.443	0.419	0.048
HP-1-W-4	76.611	75.828	0.392		
HP-1-W-5	79.619	78.784	0.417		
WB-1-W-1	83.565	83.212	0.176		
WB-1-W-2	78.753	78.438	0.157		
WB-1-W-3	79.234	78.917	0.158	0.167	0.045
WB-1-W-4	79.158	78.820	0.169		
WB-1-W-5	80.494	80.150	0.172		
WB-2-W-1	77.730	77.327	0.202		
WB-2-W-2	80.825	80.465	0.180		
WB-2-W-3	79.161	78.765	0.198	0.198	0.053
WB-2-W-4	81.141	80.741	0.200		
WB-2-W-5	82.035	81.610	0.212		
WB-3-Y-1	79.410	78.980	0.215		
WB-3-Y-2	79.873	79.432	0.221		
WB-3-Y-3	81.015	80.557	0.229	0.222	0.022
WB-3-Y-4	80.816	80.363	0.227		
WB-3-Y-5	79.901	79.459	0.221		
MAR-1-W-1	80.328	79.202	0.563		
MAR-1-W-2	81.398	80.293	0.552		
MAR-1-W-3	79.008	77.862	0.573	0.574	0.026
MAR-1-W-4	77.918	76.740	0.589		
MAR-1-W-5	77.974	76.792	0.591		

Table 6.10 (Cont.) Taber Abraser Results for Specimens Tested Dry

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
CR-1-W-1	79.028	78.458	0.285		
CR-1-W-2	75.525	75.125	0.200		
CR-1-W-3	79.771	79.336	0.218	0.221	0.201
CR-1-W-4	78.703	78.396	0.154		
CR-1-W-5	79.363	78.865	0.249		
CR-2-Y-1	77.389	76.735	0.327		
CR-2-Y-2	78.248	77.560	0.344		
CR-2-Y-3	------	No Data	------	0.350	0.045
CR-2-Y-4	79.607	78.870	0.368		
CR-2-Y-5	78.604	77.884	0.360		
SB-1-W-1	82.181	80.352	0.914		
SB-1-W-2	80.604	79.058	0.773		
SB-1-W-3	79.409	78.391	0.509	0.691	0.234
SB-1-W-4	80.430	79.863	0.284	<-Bad	
SB-1-W-5	78.716	77.580	0.568		
SB-2-Y-1	81.530	79.929	0.800		
SB-2-Y-2	79.226	77.805	0.710	0.761	0.052
SB-2-Y-3	77.704	76.800	0.452	<-Bad	
SB-2-Y-4	79.904	78.437	0.733		
SB-2-Y-5	80.831	79.234	0.799		
AR-1-Y-1	78.310	77.837	0.236		
AR-1-Y-2	78.637	78.211	0.213		
AR-1-Y-3	79.321	78.896	0.212	0.220	0.041
AR-1-Y-4	76.964	76.516	0.224		
AR-1-Y-5	77.502	77.071	0.215		

Table 6.11 Taber Abraser Results for Specimens Tested Submerged

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index Data	Ave.	Var.
HP-1-W-1	77.360	------			
HP-1-W-2	77.685	------			
HP-1-W-3	77.177	------	Unable	to test	
HP-1-W-4	76.574	------			
HP-1-W-5	77.685	------			
WB-1-W-1	78.884	------	No	Data	-----
WB-1-W-2	79.196	78.825	0.742		
WB-1-W-3	79.862	79.520	0.684	0.586	0.220
WB-1-W-4	80.488	80.255	0.466		
WB-1-W-5	81.426	81.200	0.452		
WB-2-W-1	79.614	79.376	0.476		
WB-2-W-2	77.330	77.091	0.478		
WB-2-W-3	77.415	77.179	0.472	0.458	0.045
WB-2-W-4	79.598	79.381	0.434		
WB-2-W-5	78.107	77.891	0.432		
WB-3-Y-1	79.354	78.950	0.808		
WB-3-Y-2	78.860	78.481	0.758		
WB-3-Y-3	77.727	77.370	0.714	0.758	0.058
WB-3-Y-4	77.561	77.209	0.704		
WB-3-Y-5	79.133	78.730	0.806		
MAR-1-W-1	78.647	78.119	1.056		
MAR-1-W-2	77.753	77.425	0.656		
MAR-1-W-3	76.571	76.250	0.642	0.762	0.198
MAR-1-W-4	78.330	77.967	0.726		
MAR-1-W-5	78.228	77.863	0.730		

Table 6.11 (Cont.) Taber Abraser Results for Specimens Tested Submerged

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index Data	Ave.	Var.
CR-1-W-1	79.998	79.837	0.322		
CR-1-W-2	78.015	77.832	0.366		
CR-1-W-3	76.207	76.021	0.372	0.366	0.063
CR-1-W-4	79.928	79.736	0.384		
CR-1-W-5	78.162	77.970	0.384		
CR-2-Y-1	76.503	76.155	0.696		
CR-2-Y-2	77.971	77.646	0.650		
CR-2-Y-3	78.116	77.847	0.538	0.611	0.260
CR-2-Y-4	78.542	78.131	0.822		
CR-2-Y-5	79.040	78.865	0.350		
SB-1-W-1	79.788	79.542	0.492		
SB-1-W-2	79.173	78.875	0.596		
SB-1-W-3	79.194	78.999	0.390	0.455	0.178
SB-1-W-4	77.268	77.059	0.418		
SB-1-W-5	77.720	77.531	0.378		
SB-2-Y-1	82.801	82.582	0.438		
SB-2-Y-2	77.839	77.675	0.328		
SB-2-Y-3	78.706	78.519	0.374	0.383	0.112
SB-2-Y-4	80.336	80.123	0.426		
SB-2-Y-5	80.277	80.103	0.348		
AR-1-Y-1	77.981	77.839	0.284		
AR-1-Y-2	76.707	76.574	0.266		
AR-1-Y-3	78.584	78.451	0.266	0.284	0.057
AR-1-Y-4	78.751	78.597	0.308		
AR-1-Y-5	79.831	79.684	0.294		

6.2.3 Discussion of Abrasion Test Results

Table 6.12 contains a summary of the relative ratings of the paints tested. The paints are listed best to worst for both dry and wet tests.

Table 6.12 Abrasion Rating Summary

Rating	Dry Test	Wet Test
1	[WB-1-W]	[AR-1-Y]
2	[WB-2-W]	[CR-1-W]
3	[AR-1-Y]	[SB-2-Y]
4	[CR-1-W]	[SB-1-W]
5	[WB-3-Y]	[WB-2-W]
6	[CR-2-Y]	[WB-1-W]
7	[HP-1-W]	[CR-2-Y]
8	[MAR-1-W]	[WB-3-Y]
9	[SB-1-W]	[MAR-1-W]
10	[SB-2-Y]	[HP-1-W]

The most significant results of these tests were the relatively poor performance of the water base paints when submerged in water. This would indicate that a water base paint would be a poor choice in an area susceptible to ponding. If the abrasion tests are eventually deemed significant with respect to predicting durability, the alkyd resin paint was the best performer overall considering both conditions. The solvent base paints performed poorly in the dry test while doing better in the submerged test. The modified alkyd resin paint tested performed poorly in both abrasion test conditions.

6.3 Field Tests

The 42 week period that the test stripes were observed has not been long enough, considering the volume of traffic at the test site, to see significant failure due to abrasion. There have been some interesting observations, relating to the laboratory test results, that will be presented here and discussed. Based on the tensile tests, it was seen that the paints exhibit very different ductility characteristics (percent elongation). The same classification used in Section 6.1.3 will be used for discussion as shown in Table 6.13. In addition to a lower percent elongation, the brittle paints had a much higher initial elastic modulus. The breakdown of the paints into these categories is as follows:

Table 6.13 Ductility Classifications

Brittle	Average	Ductile
[CR-1-W]	[HP-1-W]	[WB-2-W]
[CR-1-Y]	[WB-1-W]	[WB-3-Y]
[AR-1-Y]	[MAR-1-W]	
[SB-1-W]		
[SB-2-Y]		

6.3.1 General Observations

1) The house paint [HP-1-W] did not adhere to either asphalt surface and the stripes were obliterated after only 2 to 3 days, as shown in Figure 6.4.
2) Water base paint [WB-1-W] experienced excessive premature chipping.
3) No abrasion failure distinctions could be made on any of the paints after 42 weeks.
4) The test stripes on the old and new asphalt surfaces have performed similarly after 42 weeks.
5) Replicate samples for all paints performed similarly.

6.3.2 Brittle Paints

The five brittle paints exhibited very similar characteristics in the field. Figure 6.5 shows a progression of the same segment of stripe

[SB-1-W] from 8 weeks, 16 weeks, and 42 weeks. At 16 weeks, a few small transverse cracks appeared and at 42 weeks, the cracks had grown in size and number. These cracks penetrated the asphalt surface. In addition, cracks formed in the asphalt around the periphery of the stripes.

Figures 6.6-6.9 show the same characteristics of the rest of the brittle paints - transverse cracking in the paint and asphalt and asphalt cracking outlining the stripe. Aside from this cracking, the stripes showed no signs of failure due to abrasion or chipping.

6.3.3 Average Paints

Not counting the house paint, whose formulation was not compatible with the asphalt surface, the average ductility paints exhibited the best wear characteristics to date. No cracking has appeared and no other wear has been observed. Paints [WB-3-Y] and [MAR-1-W] at 42 weeks are shown in Figures 6.10 and 6.11, respectively.

6.3.4 Ductile Paints

The two water base paints, that were much more ductile than the other paints tested, have not performed well in the field. Both of these paints started chipping at two weeks as shown in Figures 6.12 and 6.13. It can also be seen that the chipping had not worsened at 42 weeks as indicated in the same figures. The ductility and toughness of these paints probably held the chipping down to the levels shown at two weeks. The inherent problem of getting water base paints to adhere to asphalt is the likely reason that the chipping initiated very soon after placement of the stripes. The chipping of paint [WB-1-W] was much more severe than [WB-2-W] as can be seen in

Figure 6.4. Paint [WB-1-W] is second and eighth from the bottom and paint [WB-2-W] is third and ninth from the bottom in this figure. It should also be noted that paint [WB-2-W] was applied heated as in normal practice, and paint [WB-1-W] was not.

6.3.5 Discussion of Field Results

Two properties of the brittle paints caused the cracking noted; low elongation at failure (brittleness) and high initial modulus (stiffness). The differences in these properties for the various paints are apparent in Tables 6.2-6.6. Paints [CR-1-W], [AR-1-Y], [SB-1-W], and [SB-2-Y] have much lower failure elongation and higher initial modulus. Tensile test specimens for [CR-1-Y] could not be prepared due to brittleness. Brittleness is primarily responsible for the transverse cracking. As the paint dries and shrinks and as the pavement/paint expands and contracts with temperature, shear stresses at the paint-pavement interface induce tensile stresses in the paint film that cause cracking. The more ductile paints are able to tolerate the tensile stresses.

The large stiffness of the brittle paints is primarily responsible for the periphery cracking. As the pavement expands and contracts in response to average temperature changes and flexes in response to temperature gradients through the asphalt, the stiff paint stripe confines the asphalt preventing conformity. This results in stress concentrations around the periphery of the stripe leading to cracking. The more flexible and ductile paints are better able to conform to pavement movements.

6.1.2 Paint Batch Tests

Tensile tests were performed on nine different paint batches (samples of [CR-2-Y] could not be prepared due to brittleness). For the samples cured at room conditions, two load rates were used (0.2 in/min and 0.5 in/min). These tests were done to determine if all of the paints exhibited similar characteristics as the water base paint described in the previous section, without such an extensive set of load rates. The properties for these tests are given in Table 6.2 and Table 6.3. The ultimate modulus refers to the modulus of toughness as explained in the previous section, but the area under the stress-strain curve is taken up to the ultimate stress as opposed to the breaking strength. This was done because of an inconsistency in the total elongation in many of the paint samples. The initial modulus refers to the initial elastic modulus of the paint samples. This was a difficult property to determine from many of the stress-strain curves as the high coefficient of variation indicates. Figures A1-A9 in the appendix show the stress-strain curves for all samples cured at room conditions and at load rates of 0.2 and 0.5 in/min.

Tensile tests were also performed at three different curing conditions as outlined in Sections 1.3 and 3.1.2. Tensile properties obtained from these tests are shown in Tables 6.4-6.6, and stress-strain curves are given in Figures A10-A18.

Table 6.2 Tensile Properties (Cure: Room Cond., Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	8.5	0.45	397	0.13	105	0.31	352	0.19	30	0.29	10750	0.24
WB-1-W	14.9	0.18	592	0.05	195	0.06	418	0.06	39	0.11	12000	0.10
WB-2-W	14.0	0.25	252	0.09	298	0.25	198	0.08	133	0.19	4000	0.35
WB-3-Y	12.4	0.32	253	0.06	209	0.25	171	0.07	100	0.27	3775	0.17
CR-1-W	12.6	0.21	1248	0.26	20	0.32	1248	0.26	2	0.30	60000	0.37
MAR-1-W	19.6	0.09	175	0.03	61	0.07	128	0.06	40	0.10	2875	0.14
SB-1-W	15.9	0.15	425	0.04	7	0.13	425	0.04	2	0.23	41750	0.56
SB-2-Y	9.3	0.05	678	0.09	18	0.12	678	0.09	4	0.15	20000	0.14
AR-1-Y	15.1	0.09	683	0.06	15	0.12	683	0.06	3	0.15	27750	0.21

Table 6.3 Tensile Properties (Cure: Room Cond., Rate: 0.2 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	10.2	0.06	306	0.04	179	0.20	216	0.10	67	0.19	3750	0.01
WB-1-W	16.0	0.20	451	0.08	213	0.14	255	0.11	60	0.18	4375	0.01
WB-2-W	17.7	0.06	173	0.02	226	0.12	116	0.02	152	0.14	1500	0.01
WB-3-Y	15.5	0.07	181	0.03	189	0.08	116	0.01	139	0.12	1350	0.02
CR-1-W	11.0	0.07	1496	0.08	32	0.26	1495	0.08	3	0.21	69000	0.32
MAR-1-W	12.0	0.07	125	0.03	46	0.13	58	0.09	45	0.10	1875	0.01
SB-1-W	15.9	0.01	462	0.06	10	0.16	456	0.07	4	0.07	16450	0.33
SB-2-Y	16.0	0.06	523	0.01	14	0.05	523	0.01	6	0.16	14175	0.41
AR-1-Y	9.8	0.18	605	0.17	18	0.15	605	0.17	4	0.15	27250	0.28

Table 6.4 Tensile Properties (Cure: 50% H, 50° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	10.2	0.06	340	0.05	96	0.03	305	0.04	30	0.04	13750	0.33
WB-1-W	11.3	0.08	574	0.03	172	0.19	431	0.09	35	0.20	12250	0.17
WB-2-W	13.0	0.15	245	0.04	250	0.10	183	0.06	118	0.08	2075	0.18
WB-3-Y	15.0	0.10	222	0.05	169	0.20	164	0.07	87	0.17	2350	0.16
CR-1-W	10.8	0.21	1144	0.21	20	0.17	1144	0.21	3	0.26	105000	0.98
MAR-1-W	12.8	0.25	149	0.08	47	0.24	108	0.08	36	0.20	10000	0.29
SB-1-W	17.7	0.05	361	0.07	7	0.27	361	0.07	3	0.19	20800	0.15
SB-2-Y	16.9	0.12	487	0.05	17	0.19	487	0.05	5	0.16	19250	0.13
AR-1-Y	10.2	0.16	411	0.58	10	1.13	411	0.58	2	0.88	101500	1.10

Table 6.5 Tensile Properties (Cure: 50% H, 90° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	9.7	0.06	568	0.01	150	0.44	512	0.05	31	0.36	26500	0.04
WB-1-W	15.3	0.13	837	0.04	193	0.08	692	0.04	28	0.08	14250	0.20
WB-2-W	15.2	0.19	332	0.02	455	0.11	243	0.01	162	0.13	2500	0.16
WB-3-Y	12.0	0.07	336	0.03	262	0.34	245	0.08	92	0.32	3000	0.47
CR-1-W	14.2	0.23	1270	0.25	58	0.34	1268	0.25	6	0.33	50000	0.16
MAR-1-W	16.0	0.07	259	0.01	85	0.10	170	0.11	45	0.17	7150	0.12
SB-1-W	19.7	0.10	553	0.08	9	0.09	553	0.08	2	0.18	32250	0.23
SB-2-Y	16.3	0.13	810	0.07	20	0.14	811	0.07	4	0.12	30000	0.31
AR-1-Y	10.8	0.08	797	0.05	15	0.07	797	0.05	3	0.04	31500	0.07

Table 6.6 Tensile Properties (Cure: 90% H, 90° F; Rate: 0.5 in/min)

Paint Code	Thickness (mils)		Ultimate Strength (psi)		Ultimate Modulus (psi)		Breaking Strength (psi)		Percent Elong.		Initial Modulus (psi)	
	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.	Ave.	Var.
HP-1-W	9.7	0.09	265	0.09	138	0.26	215	0.21	61	0.32	3000	0.27
WB-1-W	16.0	0.06	576	0.03	157	0.13	440	0.06	33	0.13	9000	0.22
WB-2-W	19.7	0.17	204	0.15	276	0.16	137	0.39	196	0.10	2000	0.20
WB-3-Y	19.5	0.06	245	0.06	279	0.03	187	0.06	131	0.03	3250	0.10
CR-1-W	13.8	0.05	924	0.08	12	0.29	924	0.08	2	0.33	120000	0.78
MAR-1-W	12.5	0.03	75	0.03	32	0.08	39	0.10	50	0.09	750	0.09
SB-1-W	18.6	0.07	429	0.08	8	0.20	429	0.08	3	0.06	20500	0.51
SB-2-Y	16.8	0.13	557	0.21	13	0.10	557	0.21	4	0.09	21250	0.11
AR-1-Y	10.1	0.06	501	0.30	9	0.47	501	0.30	2	0.25	22000	0.25

6.1.3 Discussion of Tensile Test Results

6.1.3.1 Load Rate Tests

The load rate tests performed on a typical water base paint demonstrated the visco-elastic nature of the material. Figures 6.2 and 6.3 clearly show the dramatic effect that the load rate has on this type of material. The slower the load rate, the more time the material has to undergo viscous creep. The two major implications of these results are:

1) Any comparative study done in the laboratory must be closely monitored and prescribed as to the load rate used.
2) What load rate is more indicative of the actual load rate experienced by the inplace paint stripe?

The answer to the second implication can be addressed in general terms. For loading induced by thermal movements in the surface, the rate is toward the lower end of the scale, and for loads induced by traffic, the rate is toward the higher end of the scale. Therefore the tensile properties within the entire range may be significant with regard to different failure mechanisms at work.

As far as selecting a load rate to use in subsequent testing, it would be desirable to use a load rate that was less sensitive to deviations with respect to tensile properties of the specimen. Figures 6.2 and 6.3 show the properties leveling off as the load rate decreases. However, given that some paints to be tested elongate as much as 2 inches, this translates into a test that would run for over 3 hours at a rate of 0.01 in/min. This is far too long for practical purposes and would also be undesirable due to probable changes in the temperature/humidity over this long of a test period. A rate of 0.5 in/min was selected because for the water base paint tested in this load rate study, a lower coefficient of variation was noted for all of the properties measured as shown in Table 6.1. This greater consistency in the data did not manifest itself in all subsequent tests, but based on the data available and the reasons stated, it seemed like a logical selection.

6.1.3.2 Paint Batch Tests

For discussion purposes, the 10 paints evaluated in this study were categorized according to their ductility, or percent elongation, recorded at room condition curing and a load rate of 0.5 in/min. This classification was given as ductile (% elongation > 50%), brittle (% elongation < 10%), or average ductility.

Load Rate

The effect of the two different load rates used on the 10 paints evaluated is summarized in Table 6.7, which lists the percent change in the tensile properties from a load rate of 0.5 in/min to 0.2 in/min. It can be seen that the ductile and average ductility paints exhibited similar changes in ultimate strengths and breaking strengths whereas this relationship was very inconsistent for the brittle paints. A major reason for this is that the brittle paints are more sensitive to slight misalignments in the applied tensile load as was evident in the greater variation in the data for these paints. The effect of the load rate on the ultimate modulus of toughness was quite variable and no correlation to the paint types was evident.

Table 6.7 Effect of Decreased Load Rate on Tensile Properties

(% change from 0.5 in/min to 0.2 in/min)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	-22.9	+70.5	-38.6	+123.3	-65.1
Ductile	WB-1-W	-23.8	+9.2	-39.0	+53.8	-63.5
Ductile	MAR-1-W	-28.6	-24.6	-54.7	+12.5	-34.8
Average	WB-2-W	-31.3	-24.2	-41.4	+14.3	-62.5
Average	WB-3-Y	-28.5	-9.6	-32.2	+39.0	-64.2
Brittle	CR-1-W	+19.9	+60.0	+19.8	+50.0	+15.0
Brittle	SB-1-W	+8.7	+42.9	+7.3	+100.0	-60.6
Brittle	SB-2-Y	-22.9	-22.2	-22.9	+50.0	-29.1
Brittle	AR-1-Y	-11.4	+20.0	-11.4	+33.3	-1.8

The percent elongation was the only property that was affected in the same direction for all of the paints tested. The slower load rate produced higher elongations in all of the paints due to increased viscous creep. All of the paints, except one very brittle sample [CR-1-W], yielded lower initial elastic moduli at the slower load rate. These lower moduli were due to the increase in viscous creep which caused increased strain at the same stress.

These load rate tests showed that the ductile and average ductility paints were more consistent with regard to the effect of the load rate on the various properties. They also pointed out the need to monitor the load rate very carefully because of the effect of viscous creep on the tensile properties.

<u>Curing Condition</u>

The effect of the temperature/humidity curing condition on the tensile properties was very substantial and of interest due to the extreme environmental conditions to which the paints will be exposed in service.

The effect of increased temperature on the change in tensile properties is shown in Table 6.8. It can be seen that the ultimate strength, ultimate modulus of toughness, and breaking strength all increase to varying degrees. The percent elongation and initial elastic modulus are erratic and show no pattern with regard to paint type or vehicle.

The effect of increased humidity on the change in tensile properties is shown in Table 6.9. The ultimate strength, ultimate modulus of toughness (with one exception), and breaking strength of all of the paints decreased. All of the water base paints had an increase in percent elongation with the increased humidity. This is readily explained since the water base paints cured at the higher humidity would not dry properly and remain more ductile.

The significance of these results in predicting whether a paint will be more durable in the field depends on which properties are determined to be the key indicators in this respect. If the ultimate strength or breaking strength are key predictors, then stripes placed during warmer or less humid conditions should attain a higher strength based on the results of this study. On the other hand, if percent elongation is determined to be a key indicator, then the effect of environmental factors is less clear.

Table 6.8 Effect of Increased Curing Temperature on Tensile Properties

(% change from 50%H, 50°F to 50%H, 90°F)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	+67.1	+56.3	+67.9	+3.3	+92.7
Ductile	WB-1-W	+45.8	+12.2	+60.6	-20.0	+16.3
Ductile	MAR-1-W	+73.8	+80.9	+57.4	+25.0	-28.5
Average	WB-2-W	+35.5	+82.0	+32.8	+37.3	+20.5
Average	WB-3-Y	+51.4	+55.0	+49.4	+5.7	+27.7
Brittle	CR-1-W	+11.0	+190.0	+10.8	+100.0	-52.4
Brittle	SB-1-W	+53.2	+28.6	+53.2	-33.3	+55.0
Brittle	SB-2-Y	+66.3	+17.6	+66.5	-20.0	+55.8
Brittle	AR-1-Y	+93.9	+50.0	+93.9	+50.0	-69.0

Table 6.9 Effect of Increased Curing Humidity on Tensile Properties

(% change from 50% H, 90°F to 90%H, 90°F)

Paint Type	Paint Code	Ultimate Strength	Ult. Mod. of Tough.	Breaking Strength	% Elong.	Init. Modulus
Ductile	HP-1-W	-53.3	-8.0	-58.0	+96.8	-88.7
Ductile	WB-1-W	-31.2	-18.7	-36.4	+17.9	-36.8
Ductile	MAR-1-W	-71.0	-62.4	-77.1	+11.1	-89.5
Average	WB-2-W	-38.6	-39.3	-43.6	+21.0	-20.0
Average	WB-3-Y	-27.1	+6.5	-23.7	+42.4	+8.3
Brittle	CR-1-W	-27.2	-79.3	-27.1	-66.7	+140.0
Brittle	SB-1-W	-22.4	-11.1	-22.4	+50.0	-36.4
Brittle	SB-2-Y	-31.2	-35.0	-31.3	0.00	-29.2
Brittle	AR-1-Y	-37.1	-40.0	-37.1	-33.3	-30.2

6.2 Abrasion Tests

6.2.1 Specimens Tested Dry

Abrasion tests were run on five specimens for all ten paint batches as described in Section 3.2. The specimens were tested dry for 2000 cycles. Table 6.10 contains all of the results from this test series.

6.2.2 Specimens Tested Submerged

Abrasion tests were run on five specimens submerged in distilled water for all ten paint batches as described in Section 3.2 for a total of 500 cycles. Results for the house paint [HP-1-W] were not useful because the paint lost adhesion to the specimen plate. Table 6.11 contains all of the results from this test series.

Table 6.10 Taber Abraser Results for Specimens Tested Dry

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
HP-1-W-1	77.011	76.129	0.441		
HP-1-W-2	76.024	75.216	0.404		
HP-1-W-3	76.408	75.523	0.443	0.419	0.048
HP-1-W-4	76.611	75.828	0.392		
HP-1-W-5	79.619	78.784	0.417		
WB-1-W-1	83.565	83.212	0.176		
WB-1-W-2	78.753	78.438	0.157		
WB-1-W-3	79.234	78.917	0.158	0.167	0.045
WB-1-W-4	79.158	78.820	0.169		
WB-1-W-5	80.494	80.150	0.172		
WB-2-W-1	77.730	77.327	0.202		
WB-2-W-2	80.825	80.465	0.180		
WB-2-W-3	79.161	78.765	0.198	0.198	0.053
WB-2-W-4	81.141	80.741	0.200		
WB-2-W-5	82.035	81.610	0.212		
WB-3-Y-1	79.410	78.980	0.215		
WB-3-Y-2	79.873	79.432	0.221		
WB-3-Y-3	81.015	80.557	0.229	0.222	0.022
WB-3-Y-4	80.816	80.363	0.227		
WB-3-Y-5	79.901	79.459	0.221		
MAR-1-W-1	80.328	79.202	0.563		
MAR-1-W-2	81.398	80.293	0.552		
MAR-1-W-3	79.008	77.862	0.573	0.574	0.026
MAR-1-W-4	77.918	76.740	0.589		
MAR-1-W-5	77.974	76.792	0.591		

Table 6.10 (Cont.) Taber Abraser Results for Specimens Tested Dry

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
CR-1-W-1	79.028	78.458	0.285		
CR-1-W-2	75.525	75.125	0.200		
CR-1-W-3	79.771	79.336	0.218	0.221	0.201
CR-1-W-4	78.703	78.396	0.154		
CR-1-W-5	79.363	78.865	0.249		
CR-2-Y-1	77.389	76.735	0.327		
CR-2-Y-2	78.248	77.560	0.344		
CR-2-Y-3	------	No Data	------	0.350	0.045
CR-2-Y-4	79.607	78.870	0.368		
CR-2-Y-5	78.604	77.884	0.360		
SB-1-W-1	82.181	80.352	0.914		
SB-1-W-2	80.604	79.058	0.773		
SB-1-W-3	79.409	78.391	0.509	0.691	0.234
SB-1-W-4	80.430	79.863	0.284	<-Bad	
SB-1-W-5	78.716	77.580	0.568		
SB-2-Y-1	81.530	79.929	0.800		
SB-2-Y-2	79.226	77.805	0.710	0.761	0.052
SB-2-Y-3	77.704	76.800	0.452	<-Bad	
SB-2-Y-4	79.904	78.437	0.733		
SB-2-Y-5	80.831	79.234	0.799		
AR-1-Y-1	78.310	77.837	0.236		
AR-1-Y-2	78.637	78.211	0.213		
AR-1-Y-3	79.321	78.896	0.212	0.220	0.041
AR-1-Y-4	76.964	76.516	0.224		
AR-1-Y-5	77.502	77.071	0.215		

Table 6.11 Taber Abraser Results for Specimens Tested Submerged

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
HP-1-W-1	77.360	------			
HP-1-W-2	77.685	------			
HP-1-W-3	77.177	------	Unable	to test	
HP-1-W-4	76.574	------			
HP-1-W-5	77.685	------			
WB-1-W-1	78.884	------	No	Data	-----
WB-1-W-2	79.196	78.825	0.742		
WB-1-W-3	79.862	79.520	0.684	0.586	0.220
WB-1-W-4	80.488	80.255	0.466		
WB-1-W-5	81.426	81.200	0.452		
WB-2-W-1	79.614	79.376	0.476		
WB-2-W-2	77.330	77.091	0.478		
WB-2-W-3	77.415	77.179	0.472	0.458	0.045
WB-2-W-4	79.598	79.381	0.434		
WB-2-W-5	78.107	77.891	0.432		
WB-3-Y-1	79.354	78.950	0.808		
WB-3-Y-2	78.860	78.481	0.758		
WB-3-Y-3	77.727	77.370	0.714	0.758	0.058
WB-3-Y-4	77.561	77.209	0.704		
WB-3-Y-5	79.133	78.730	0.806		
MAR-1-W-1	78.647	78.119	1.056		
MAR-1-W-2	77.753	77.425	0.656		
MAR-1-W-3	76.571	76.250	0.642	0.762	0.198
MAR-1-W-4	78.330	77.967	0.726		
MAR-1-W-5	78.228	77.863	0.730		

Table 6.11 (Cont.) Taber Abraser Results for Specimens Tested Submerged

Paint Code	Initial Weight (gm)	Final Weight (gm)	Wear Index		
			Data	Ave.	Var.
CR-1-W-1	79.998	79.837	0.322		
CR-1-W-2	78.015	77.832	0.366		
CR-1-W-3	76.207	76.021	0.372	0.366	0.063
CR-1-W-4	79.928	79.736	0.384		
CR-1-W-5	78.162	77.970	0.384		
CR-2-Y-1	76.503	76.155	0.696		
CR-2-Y-2	77.971	77.646	0.650		
CR-2-Y-3	78.116	77.847	0.538	0.611	0.260
CR-2-Y-4	78.542	78.131	0.822		
CR-2-Y-5	79.040	78.865	0.350		
SB-1-W-1	79.788	79.542	0.492		
SB-1-W-2	79.173	78.875	0.596		
SB-1-W-3	79.194	78.999	0.390	0.455	0.178
SB-1-W-4	77.268	77.059	0.418		
SB-1-W-5	77.720	77.531	0.378		
SB-2-Y-1	82.801	82.582	0.438		
SB-2-Y-2	77.839	77.675	0.328		
SB-2-Y-3	78.706	78.519	0.374	0.383	0.112
SB-2-Y-4	80.336	80.123	0.426		
SB-2-Y-5	80.277	80.103	0.348		
AR-1-Y-1	77.981	77.839	0.284		
AR-1-Y-2	76.707	76.574	0.266		
AR-1-Y-3	78.584	78.451	0.266	0.284	0.057
AR-1-Y-4	78.751	78.597	0.308		
AR-1-Y-5	79.831	79.684	0.294		

6.2.3 Discussion of Abrasion Test Results

Table 6.12 contains a summary of the relative ratings of the paints tested. The paints are listed best to worst for both dry and wet tests.

Table 6.12 Abrasion Rating Summary

Rating	Dry Test	Wet Test
1	[WB-1-W]	[AR-1-Y]
2	[WB-2-W]	[CR-1-W]
3	[AR-1-Y]	[SB-2-Y]
4	[CR-1-W]	[SB-1-W]
5	[WB-3-Y]	[WB-2-W]
6	[CR-2-Y]	[WB-1-W]
7	[HP-1-W]	[CR-2-Y]
8	[MAR-1-W]	[WB-3-Y]
9	[SB-1-W]	[MAR-1-W]
10	[SB-2-Y]	[HP-1-W]

The most significant results of these tests were the relatively poor performance of the water base paints when submerged in water. This would indicate that a water base paint would be a poor choice in an area susceptible to ponding. If the abrasion tests are eventually deemed significant with respect to predicting durability, the alkyd resin paint was the best performer overall considering both conditions. The solvent base paints performed poorly in the dry test while doing better in the submerged test. The modified alkyd resin paint tested performed poorly in both abrasion test conditions.

6.3 Field Tests

The 42 week period that the test stripes were observed has not been long enough, considering the volume of traffic at the test site, to see significant failure due to abrasion. There have been some interesting observations, relating to the laboratory test results, that will be presented here and discussed. Based on the tensile tests, it was seen that the paints exhibit very different ductility characteristics (percent elongation). The same classification used in Section 6.1.3 will be used for discussion as shown in Table 6.13. In addition to a lower percent elongation, the brittle paints had a much higher initial elastic modulus. The breakdown of the paints into these categories is as follows:

Table 6.13 Ductility Classifications

Brittle	Average	Ductile
[CR-1-W]	[HP-1-W]	[WB-2-W]
[CR-1-Y]	[WB-1-W]	[WB-3-Y]
[AR-1-Y]	[MAR-1-W]	
[SB-1-W]		
[SB-2-Y]		

6.3.1 General Observations

1) The house paint [HP-1-W] did not adhere to either asphalt surface and the stripes were obliterated after only 2 to 3 days, as shown in Figure 6.4.
2) Water base paint [WB-1-W] experienced excessive premature chipping.
3) No abrasion failure distinctions could be made on any of the paints after 42 weeks.
4) The test stripes on the old and new asphalt surfaces have performed similarly after 42 weeks.
5) Replicate samples for all paints performed similarly.

6.3.2 Brittle Paints

The five brittle paints exhibited very similar characteristics in the field. Figure 6.5 shows a progression of the same segment of stripe

[SB-1-W] from 8 weeks, 16 weeks, and 42 weeks. At 16 weeks, a few small transverse cracks appeared and at 42 weeks, the cracks had grown in size and number. These cracks penetrated the asphalt surface. In addition, cracks formed in the asphalt around the periphery of the stripes.

Figures 6.6-6.9 show the same characteristics of the rest of the brittle paints - transverse cracking in the paint and asphalt and asphalt cracking outlining the stripe. Aside from this cracking, the stripes showed no signs of failure due to abrasion or chipping.

6.3.3 Average Paints

Not counting the house paint, whose formulation was not compatible with the asphalt surface, the average ductility paints exhibited the best wear characteristics to date. No cracking has appeared and no other wear has been observed. Paints [WB-3-Y] and [MAR-1-W] at 42 weeks are shown in Figures 6.10 and 6.11, respectively.

6.3.4 Ductile Paints

The two water base paints, that were much more ductile than the other paints tested, have not performed well in the field. Both of these paints started chipping at two weeks as shown in Figures 6.12 and 6.13. It can also be seen that the chipping had not worsened at 42 weeks as indicated in the same figures. The ductility and toughness of these paints probably held the chipping down to the levels shown at two weeks. The inherent problem of getting water base paints to adhere to asphalt is the likely reason that the chipping initiated very soon after placement of the stripes. The chipping of paint [WB-1-W] was much more severe than [WB-2-W] as can be seen in

Figure 6.4. Paint [WB-1-W] is second and eighth from the bottom and paint [WB-2-W] is third and ninth from the bottom in this figure. It should also be noted that paint [WB-2-W] was applied heated as in normal practice, and paint [WB-1-W] was not.

6.3.5 Discussion of Field Results

Two properties of the brittle paints caused the cracking noted; low elongation at failure (brittleness) and high initial modulus (stiffness). The differences in these properties for the various paints are apparent in Tables 6.2-6.6. Paints [CR-1-W], [AR-1-Y], [SB-1-W], and [SB-2-Y] have much lower failure elongation and higher initial modulus. Tensile test specimens for [CR-1-Y] could not be prepared due to brittleness. Brittleness is primarily responsible for the transverse cracking. As the paint dries and shrinks and as the pavement/paint expands and contracts with temperature, shear stresses at the paint-pavement interface induce tensile stresses in the paint film that cause cracking. The more ductile paints are able to tolerate the tensile stresses.

The large stiffness of the brittle paints is primarily responsible for the periphery cracking. As the pavement expands and contracts in response to average temperature changes and flexes in response to temperature gradients through the asphalt, the stiff paint stripe confines the asphalt preventing conformity. This results in stress concentrations around the periphery of the stripe leading to cracking. The more flexible and ductile paints are better able to conform to pavement movements.

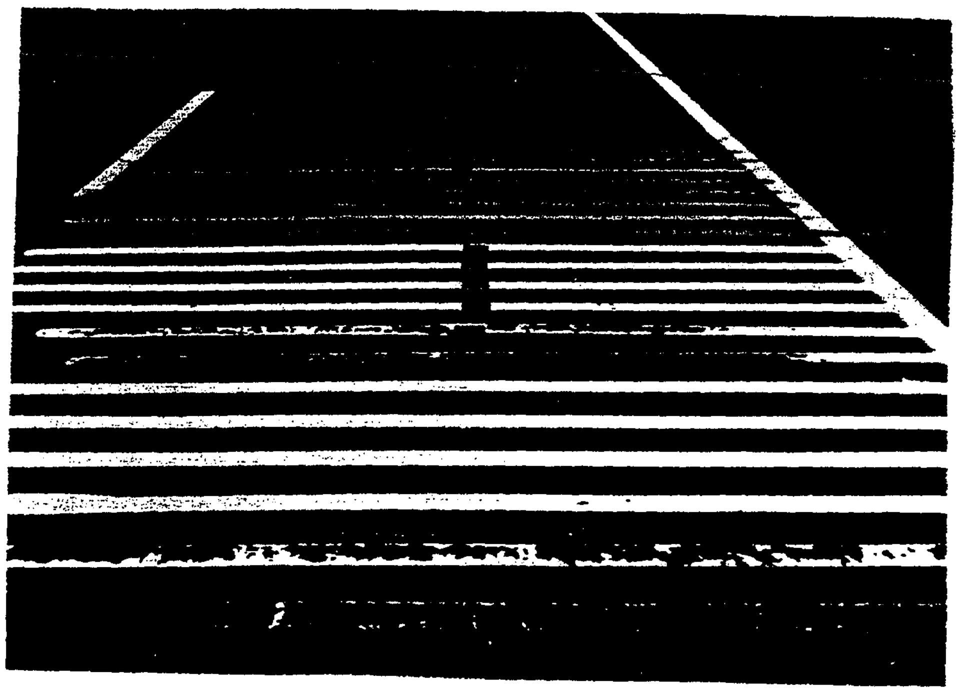
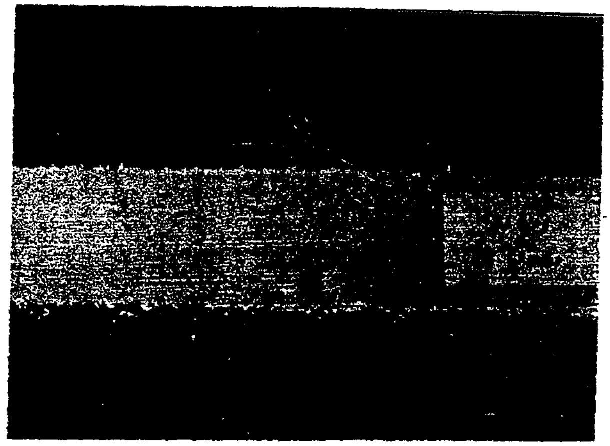
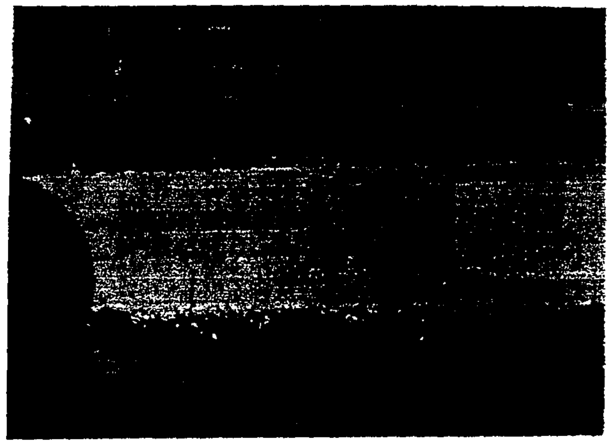


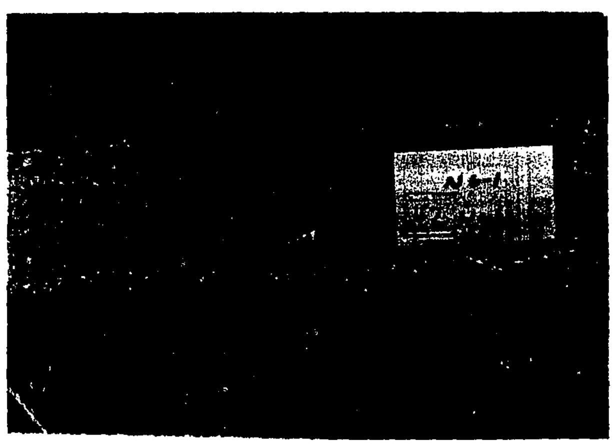
Figure 6.4 Test Stripes on Old Asphalt at Two Weeks



(a) 8 weeks



(b) 16 weeks



(c) 42 weeks

Figure 6.5 Typical Failure Progression in Brittle Paint [SB-1-W]

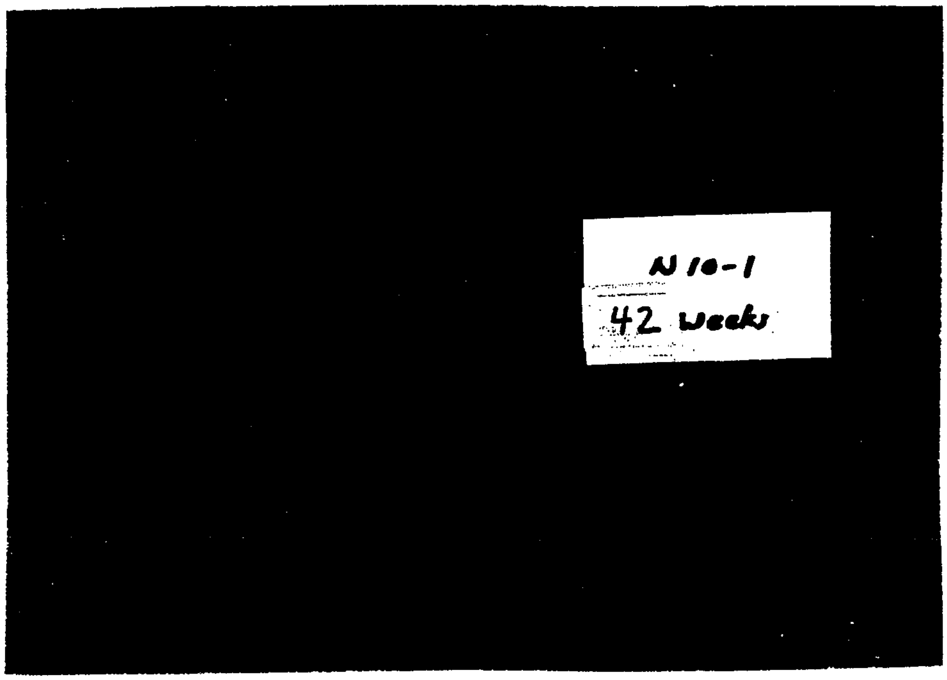


Figure 6.6 Paint [SB-2-Y] After 42 Weeks

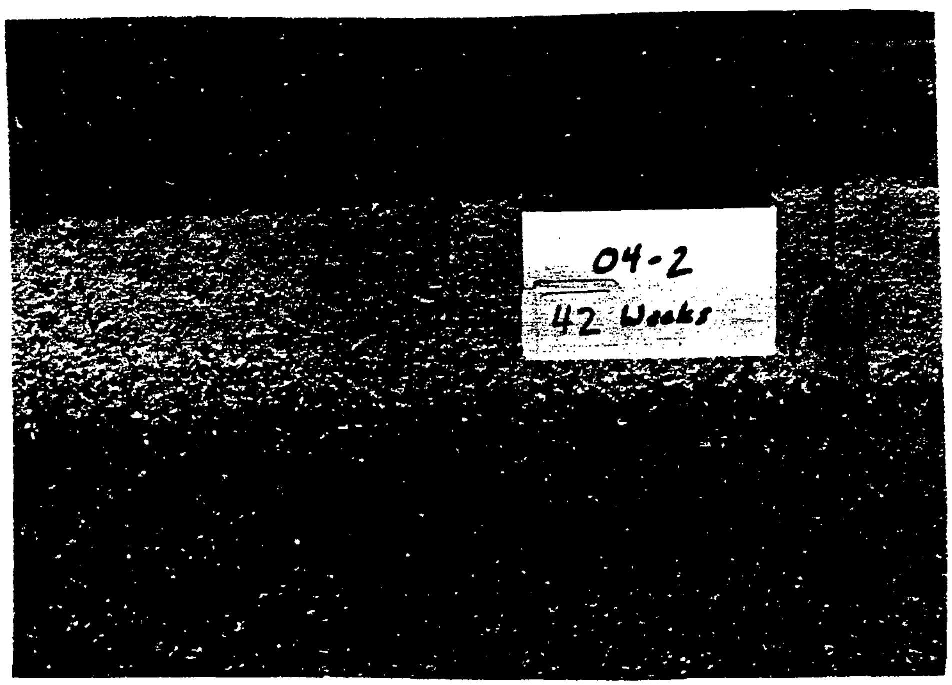


Figure 6.7 Paint [CR-1-W] After 42 Weeks

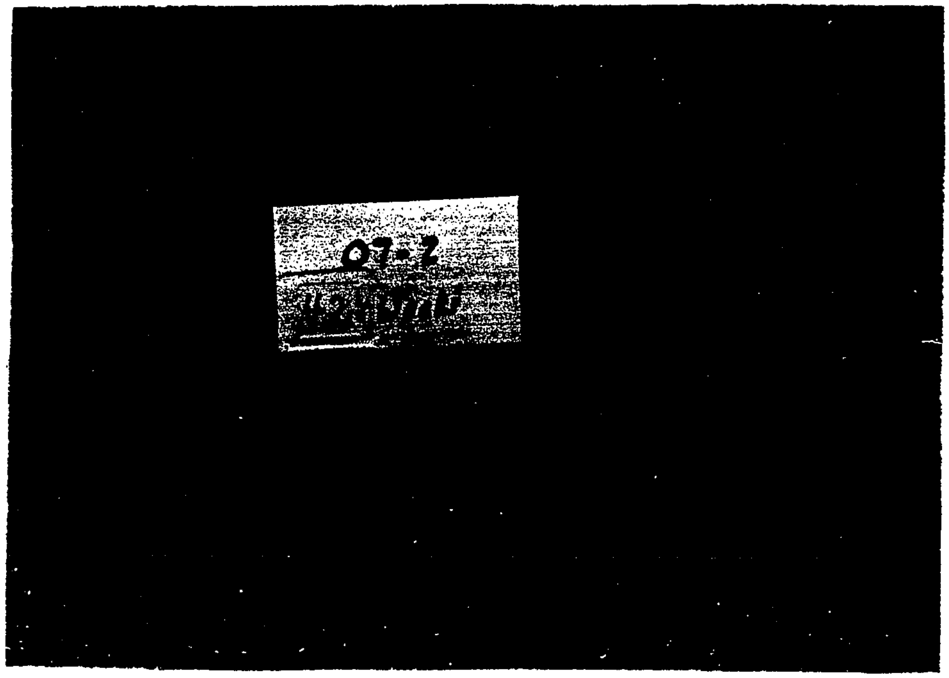


Figure 6.8 Paint [CR-2-Y] After 42 Weeks

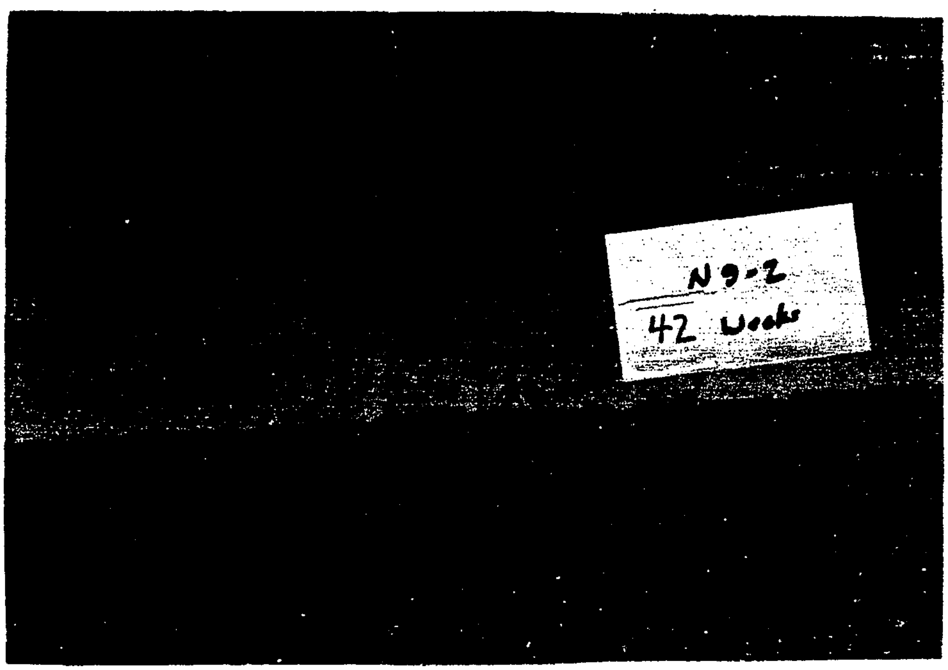


Figure 6.9 Paint [AR-1-Y] After 42 Weeks

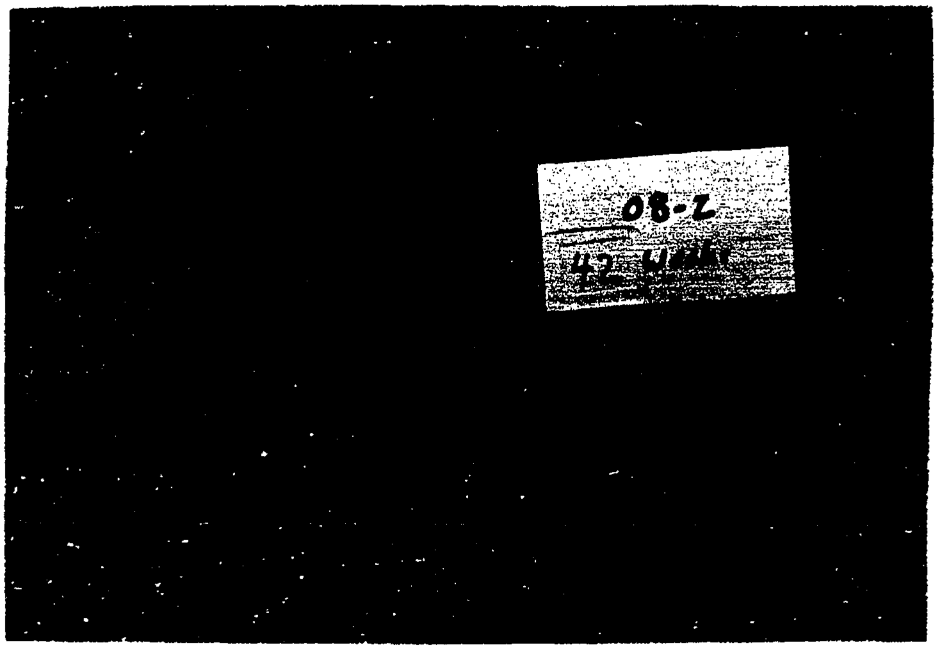


Figure 6.10 Paint [WB-3-Y] After 42 Weeks

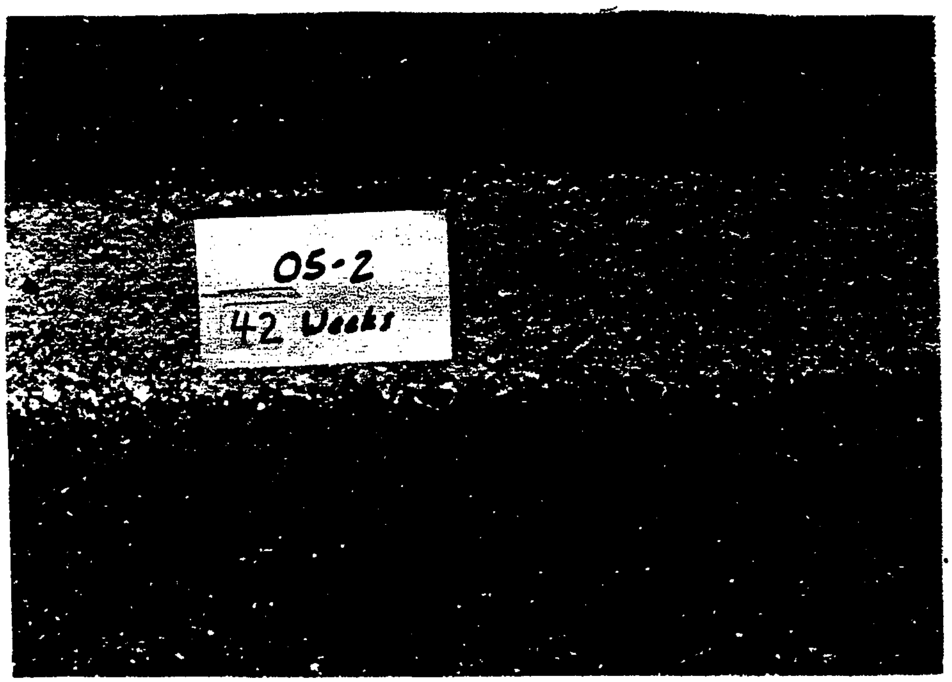
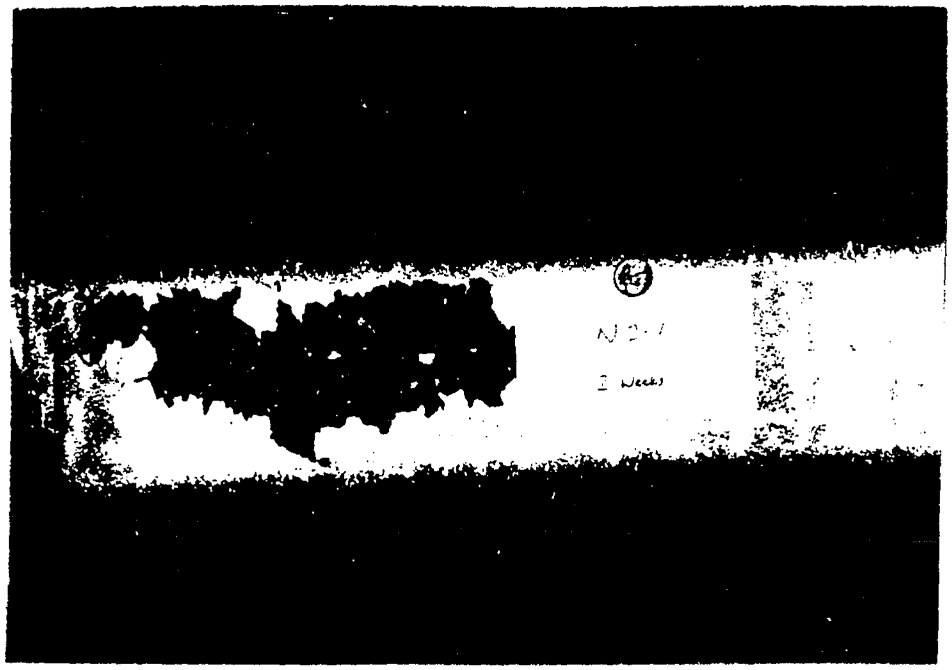
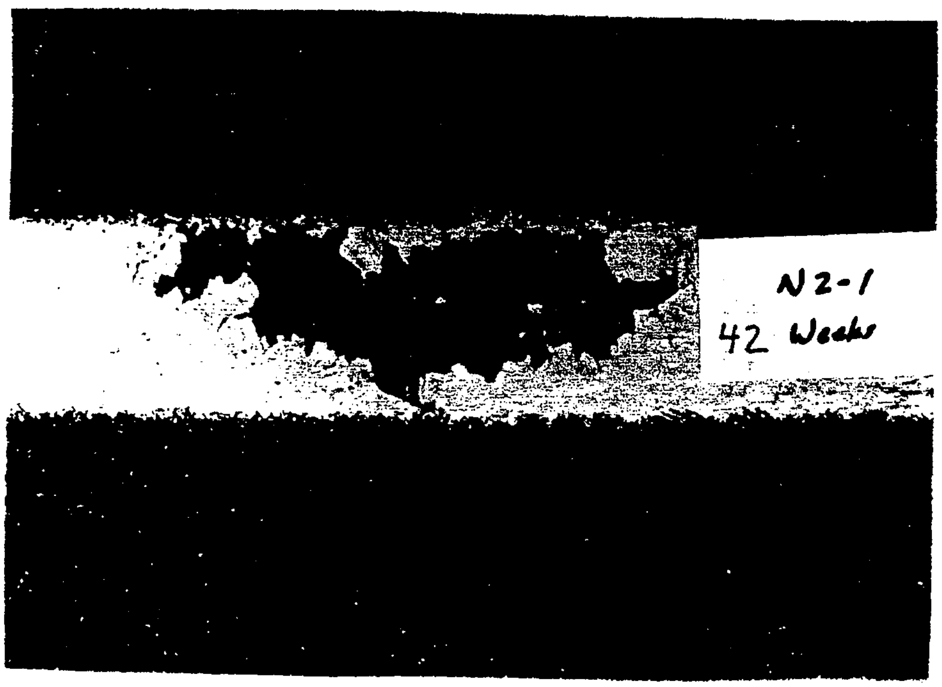


Figure 6.11 Paint [MAR-1-W] After 42 Weeks

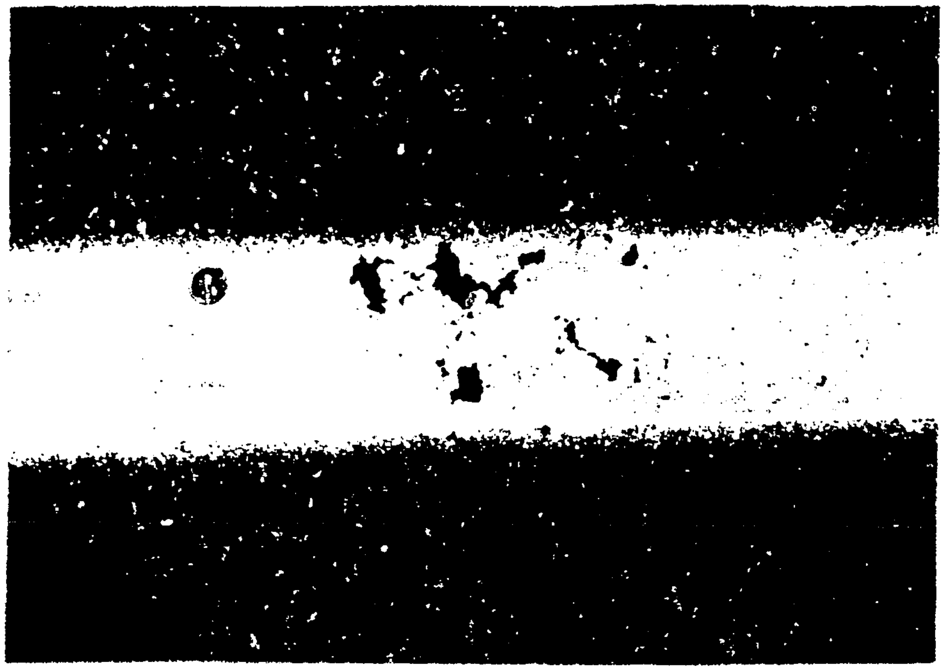


(a) 2 weeks

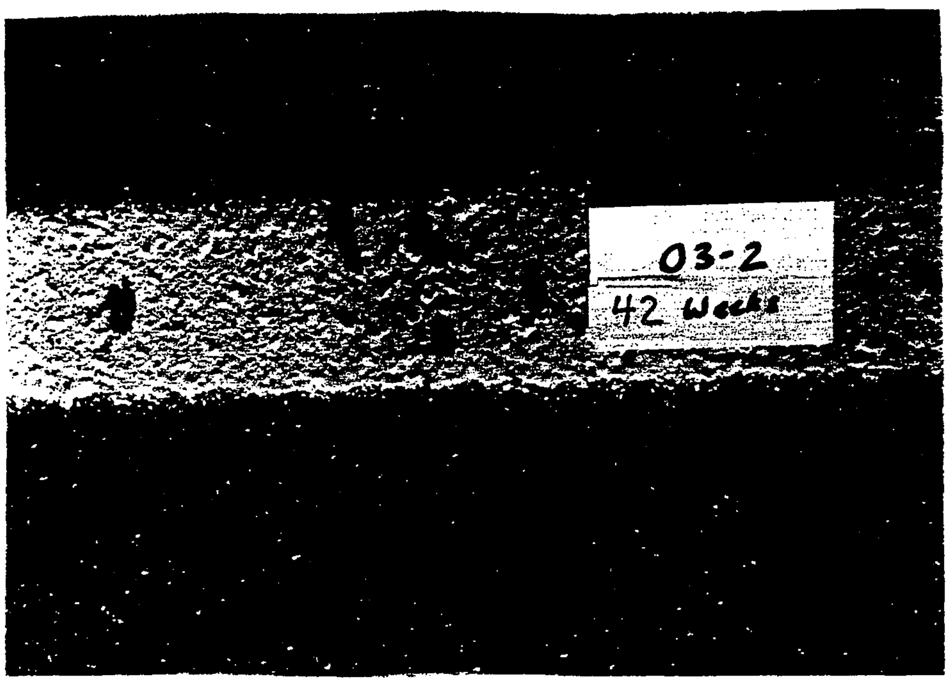


(b) 42 weeks

Figure 6.12 Paint [WB-1-W] Chipping Evolution



(a) 2 weeks



(b) 42 weeks

Figure 6.13 Paint [WB-2-W] Chipping Evolution

VII Conclusions and Recommendations

7.1 Conclusions

Two laboratory tests were developed to evaluate properties of pavement marking paints that could be used to predict durability of the stripes in the field. Tensile tests of free film specimens of paint yielded several properties derived from the stress-strain curves. Abrasion tests provided results for both wet and dry paint specimens. The tests produced consistent and repeatable results that varied widely for the different types of paints tested. These are positive indications that the tests will prove valuable for controlling paint quality.

Ten paint samples representing five different vehicles were evaluated using the laboratory tests developed. The paints were quite different as reflected in the tensile properties. The water base paints were considerably more ductile than the solvent base and alkyd resin paints. The load rate used for the test had significant effect on the results due to increased viscous creep introduced at slower load rates. On the average, paints cured at a higher humidity exhibited a 38% lower ultimate strength. Water base traffic paints cured at a higher humidity were more ductile and averaged a 23% higher percent of elongation. Paints cured at a higher temperature averaged a 55% higher ultimate strength. The effect of these different curing conditions on the tensile properties indicates the influence environmental factors have on the performance of traffic paints and one of the reasons why different geographic regions report different service from the various paints.

The abrasion tests also produced a wide variation of results among the ten paints tested. Water base paints performed poorly when tested wet, indicating that they would not be a good choice in a location where there is a ponding potential. The relevance of abrasion tests in predicting durability in the field is questionable for longitudinal stripes where traffic volume has little effect on the service life of the paint. The alkyd resin paint tested had the highest abrasion resistance considering both wet and dry test results.

The ten paint samples tested in the laboratory were applied to two asphalt surfaces of different ages in the form of transverse stripes. The stripes were monitored for 42 weeks as to their performance. None of the stripes showed significant abrasion wear. There was a definite correlation between the tensile properties recorded in the laboratory and observed cracking in the stripes. The paints that were the most brittle and stiff all developed transverse cracks at approximately 8 weeks and continued to worsen over the observation period. These same paints also caused the asphalt surface to crack around the periphery of the stripes. Two of the water base paints that were the most ductile underwent a premature chipping failure due to a lack of adhesion to the asphalt surface. The paints that exhibited average ductility in the laboratory have performed the best to date.

The problem of bead retention was not addressed in this study. The loss of reflectivity is also considered a failure of the marking material, but was not within the scope of this project. The glass beads are thought to have an effect on the chipping propensity of different paints and could influence the durability results noted here.

7.2 Recommendations

This study has provided significant insight into measuring properties of paint in the laboratory that can be used to predict the service life of the results to the prediction of durability.

It is recommended that an ongoing project be implemented in which paint samples from AHD striping projects be tested in the manner described in this report and the laboratory results correlated with the observed performance of the marking materials. With sufficient data, obtained from stripes that are placed using normal techniques and application machinery, it is felt that a correlation can be made to determine which properties are the key predictors in evaluating durability.

VIII Appendix

Stress-Strain Curves

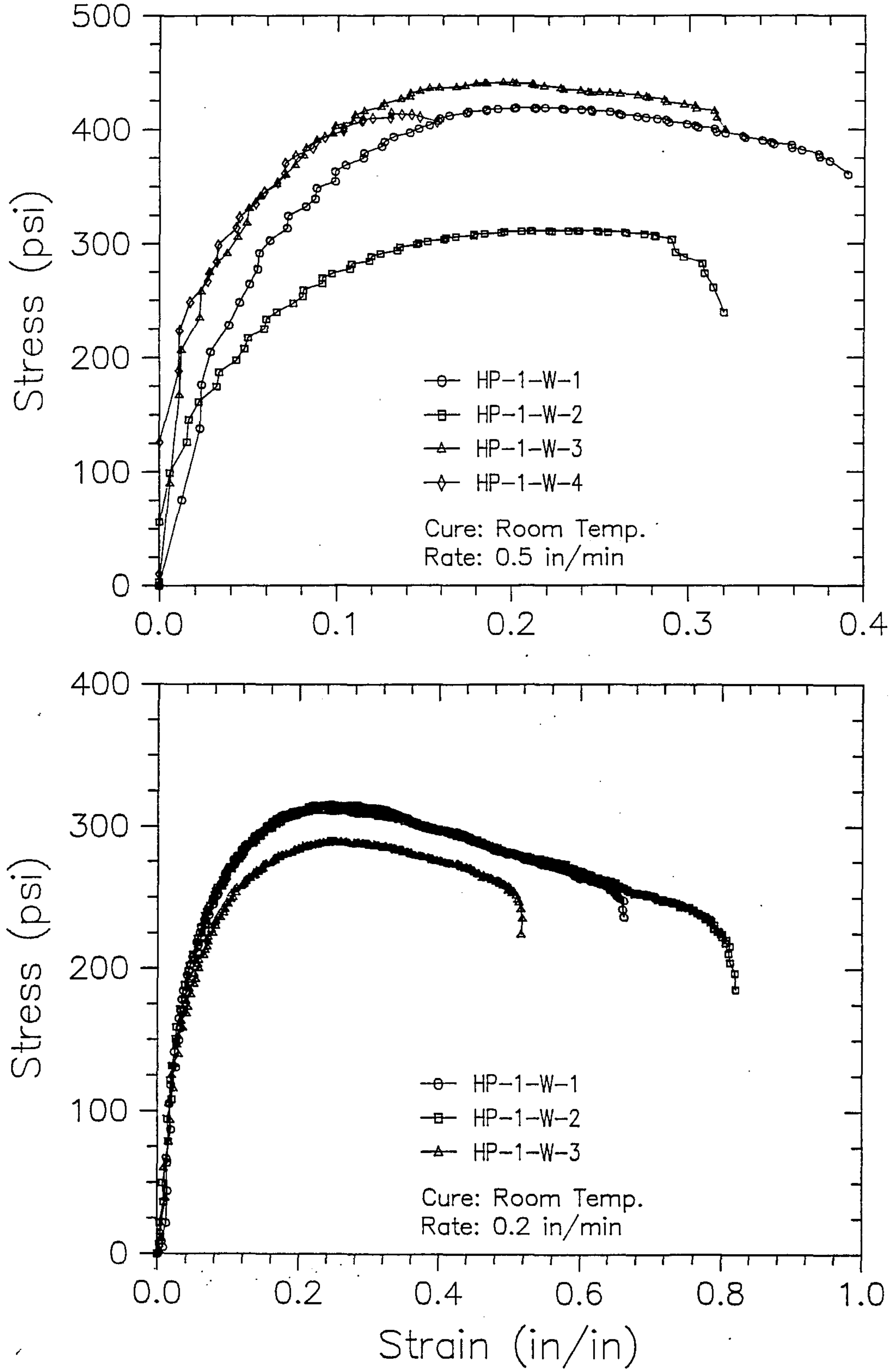


Figure A1 Load Rate Comparison at Room Cure for [HP-1-W]

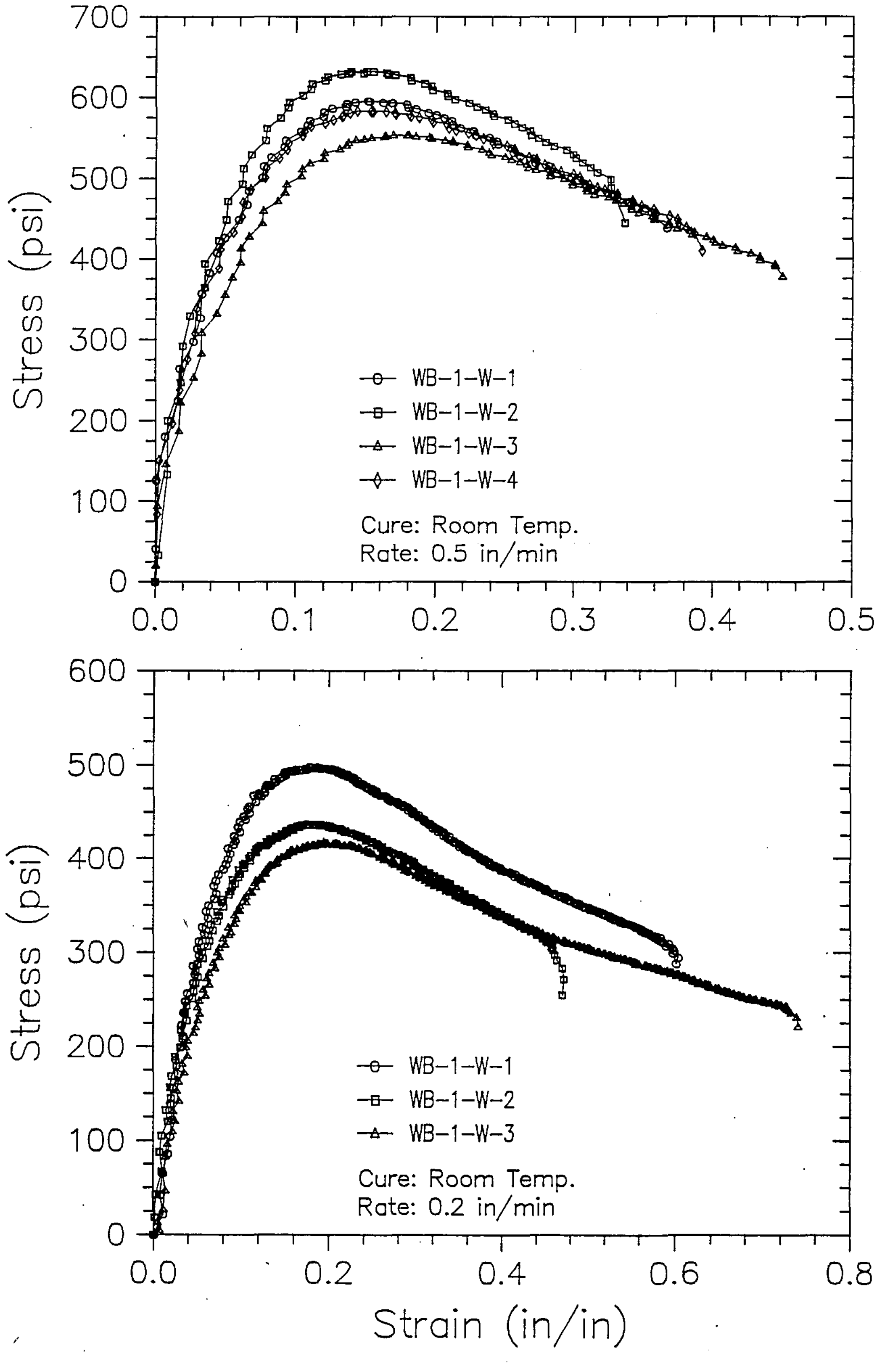


Figure A2 Load Rate Comparison at Room Cure for [WB-1-W]

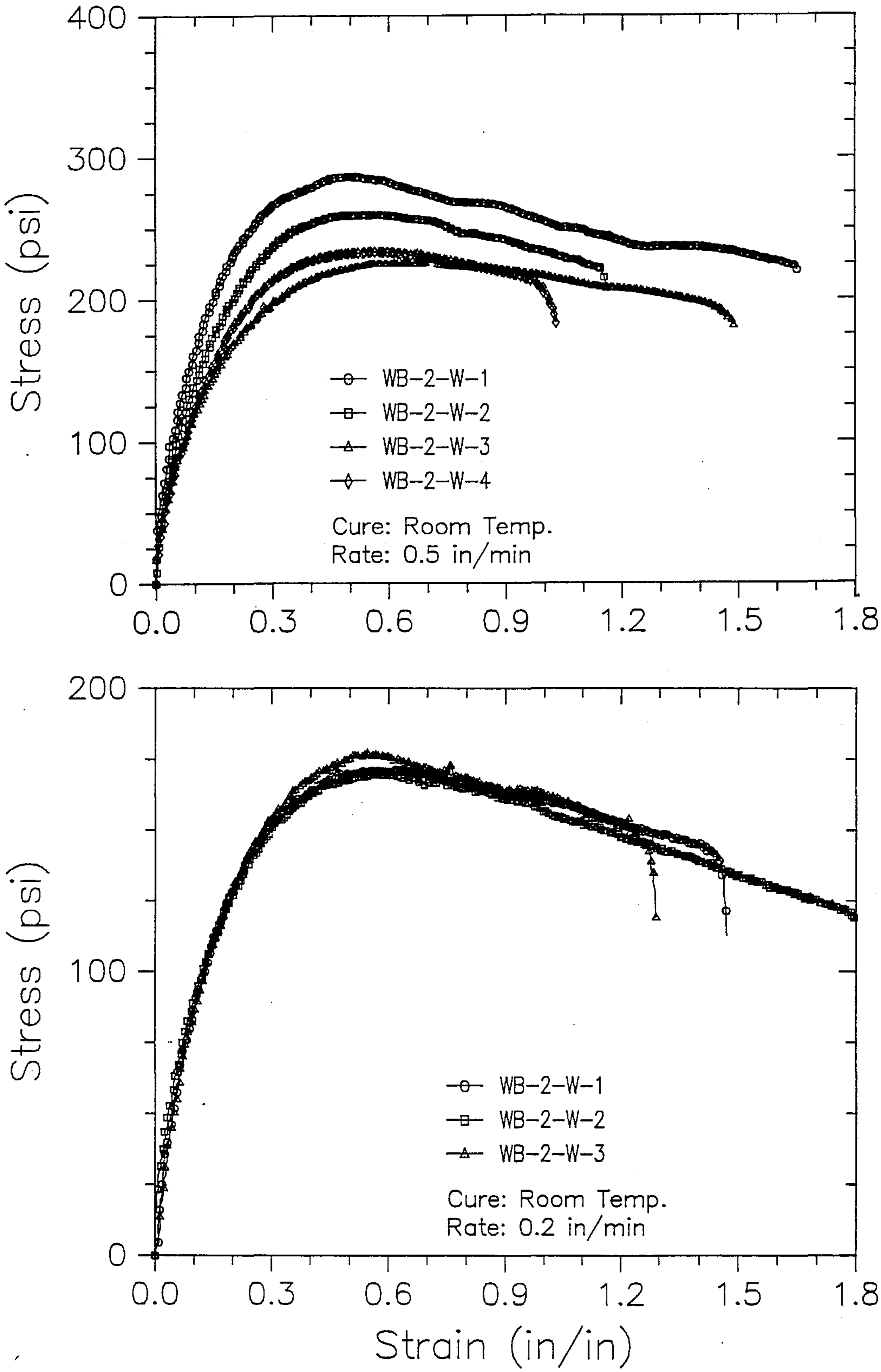


Figure A3 Load Rate Comparison at Room Cure for [WB-2-W]

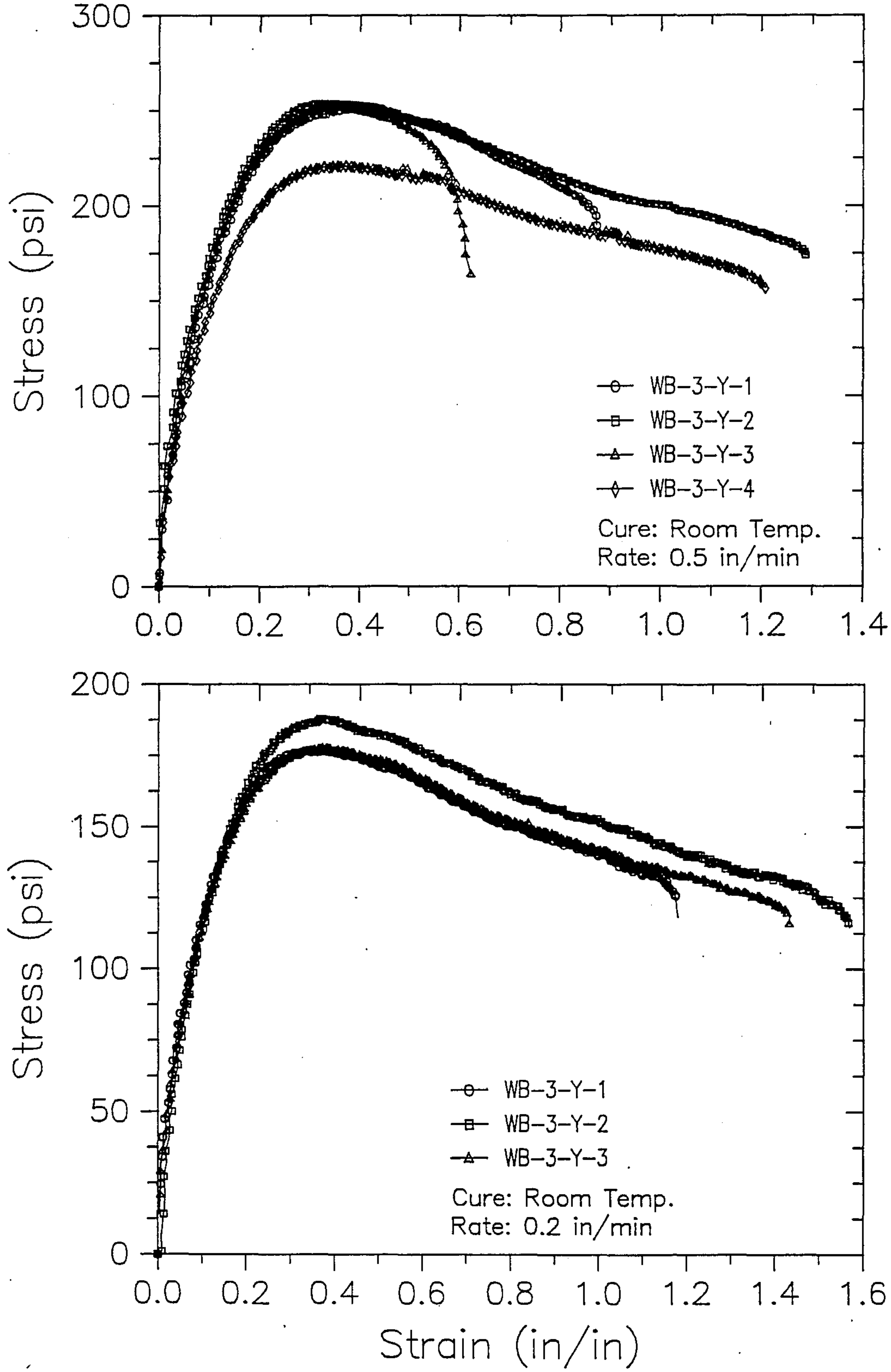


Figure A4 Load Rate Comparison at Room Cure for [WB-3-Y]

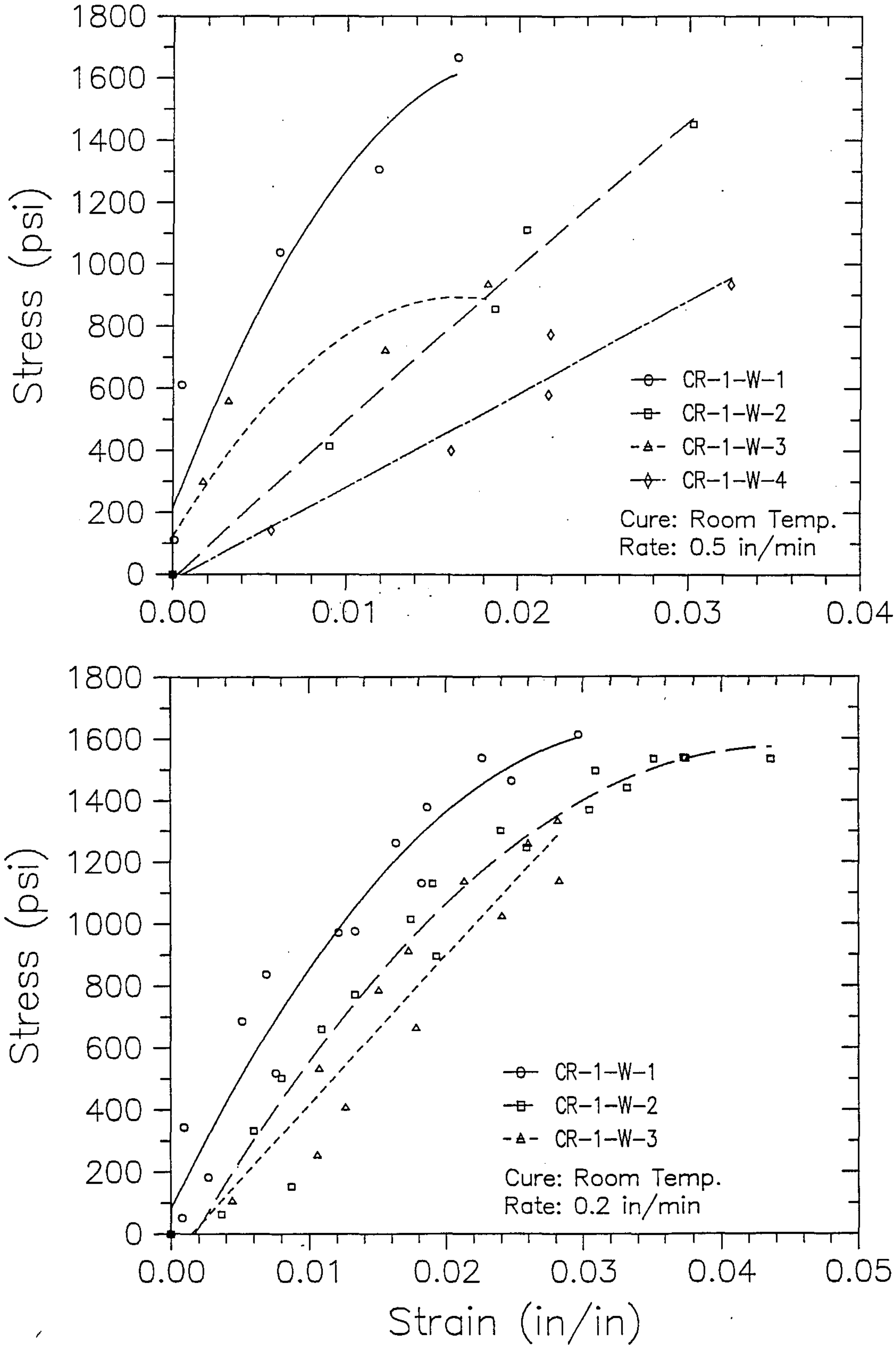


Figure A5 Load Rate Comparison at Room Cure for [CR-1-W]

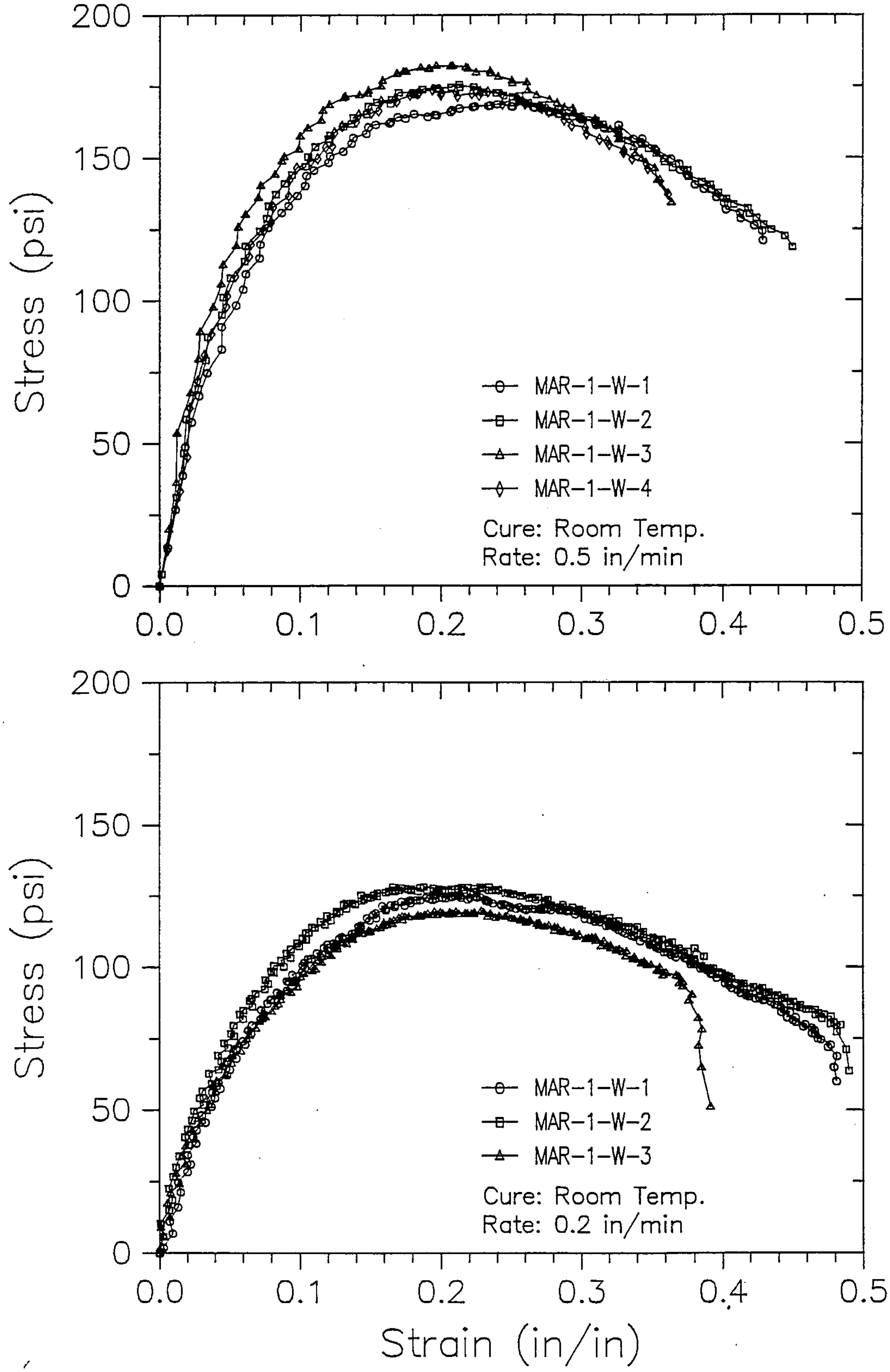


Figure A6 Load Rate Comparison at Room Cure for [MAR-1-W]

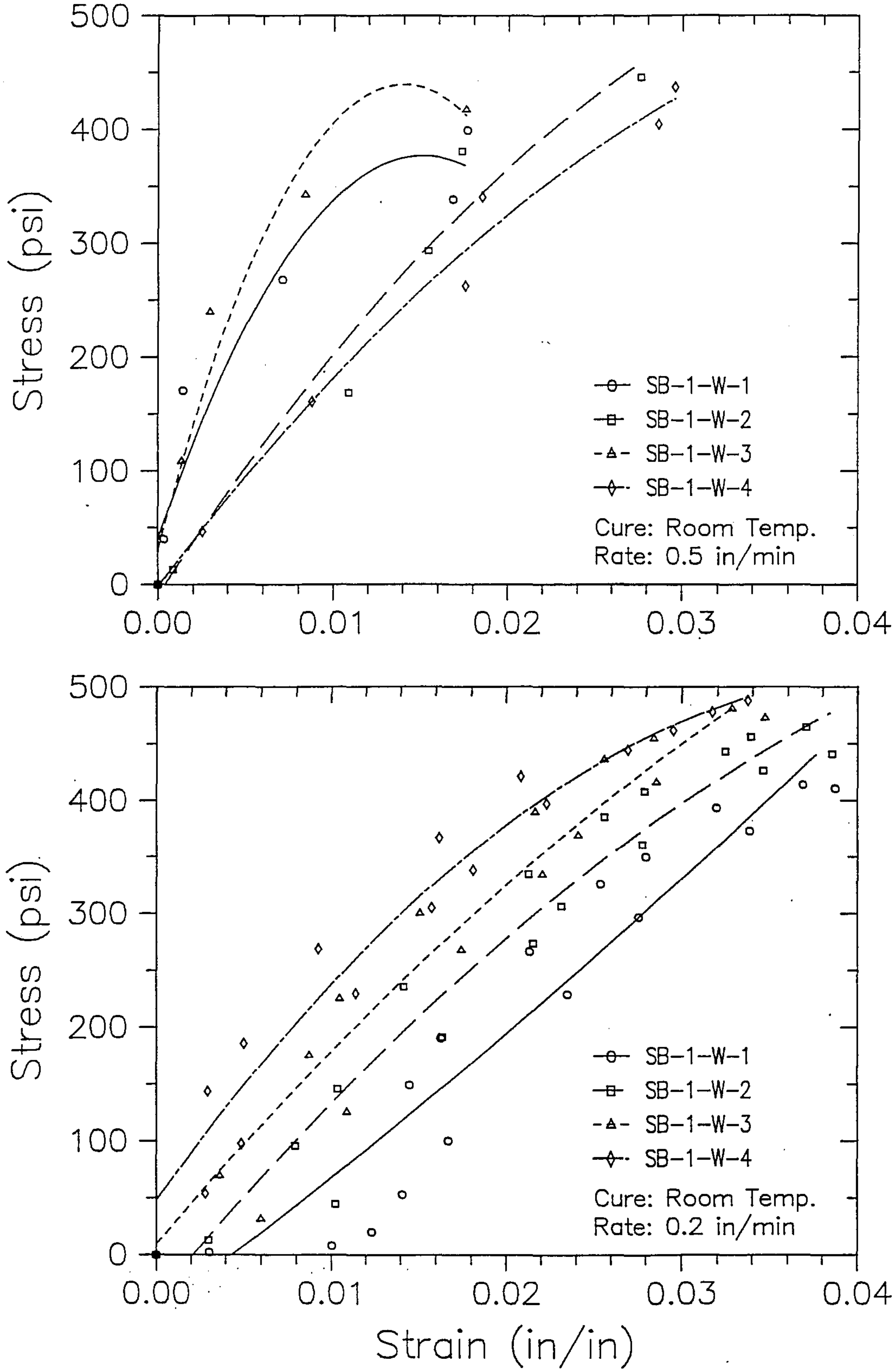


Figure A7 Load Rate Comparison at Room Cure for [SB-1-W]

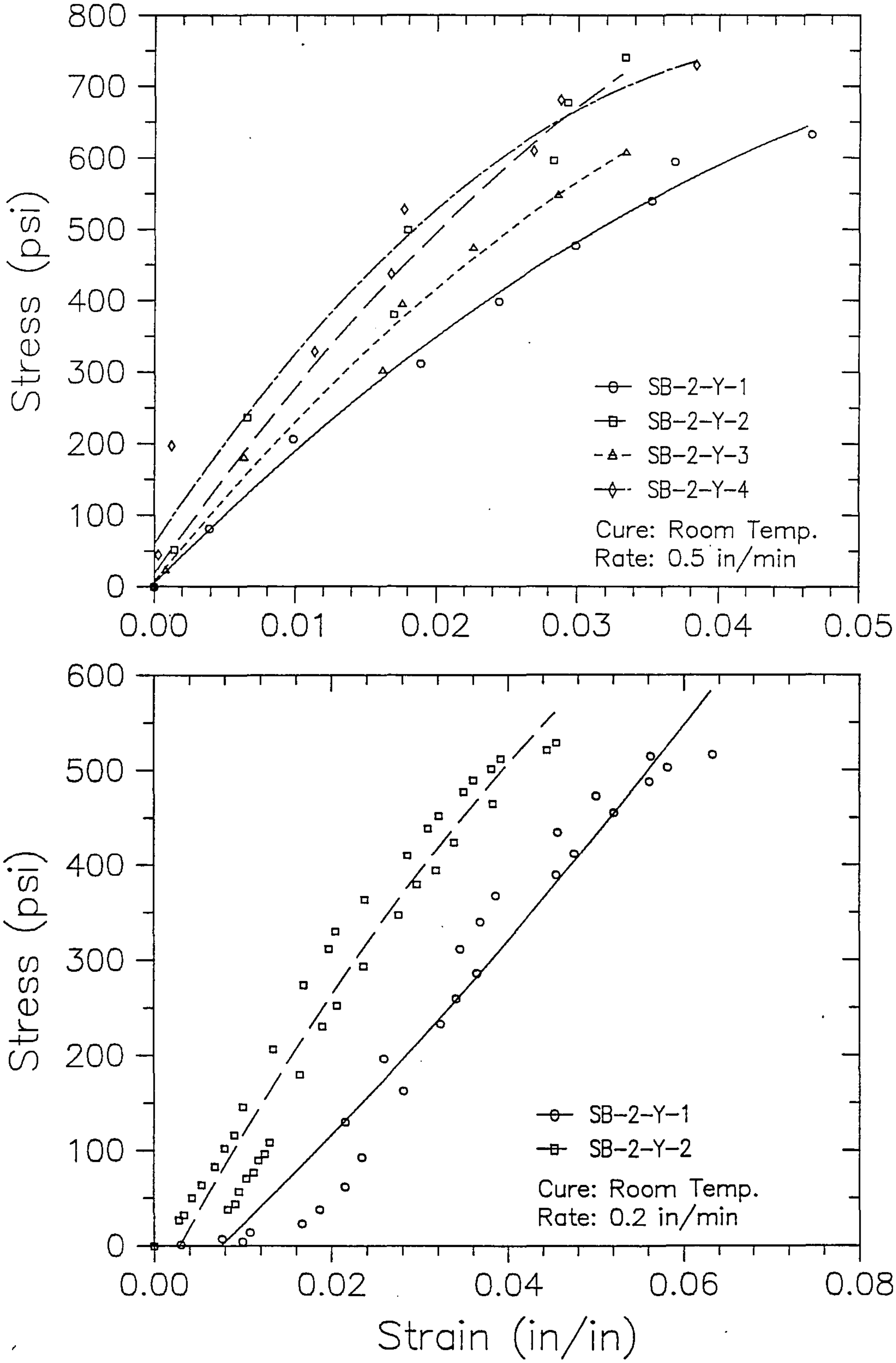


Figure A8 Load Rate Comparison at Room Cure for [SB-2-Y]

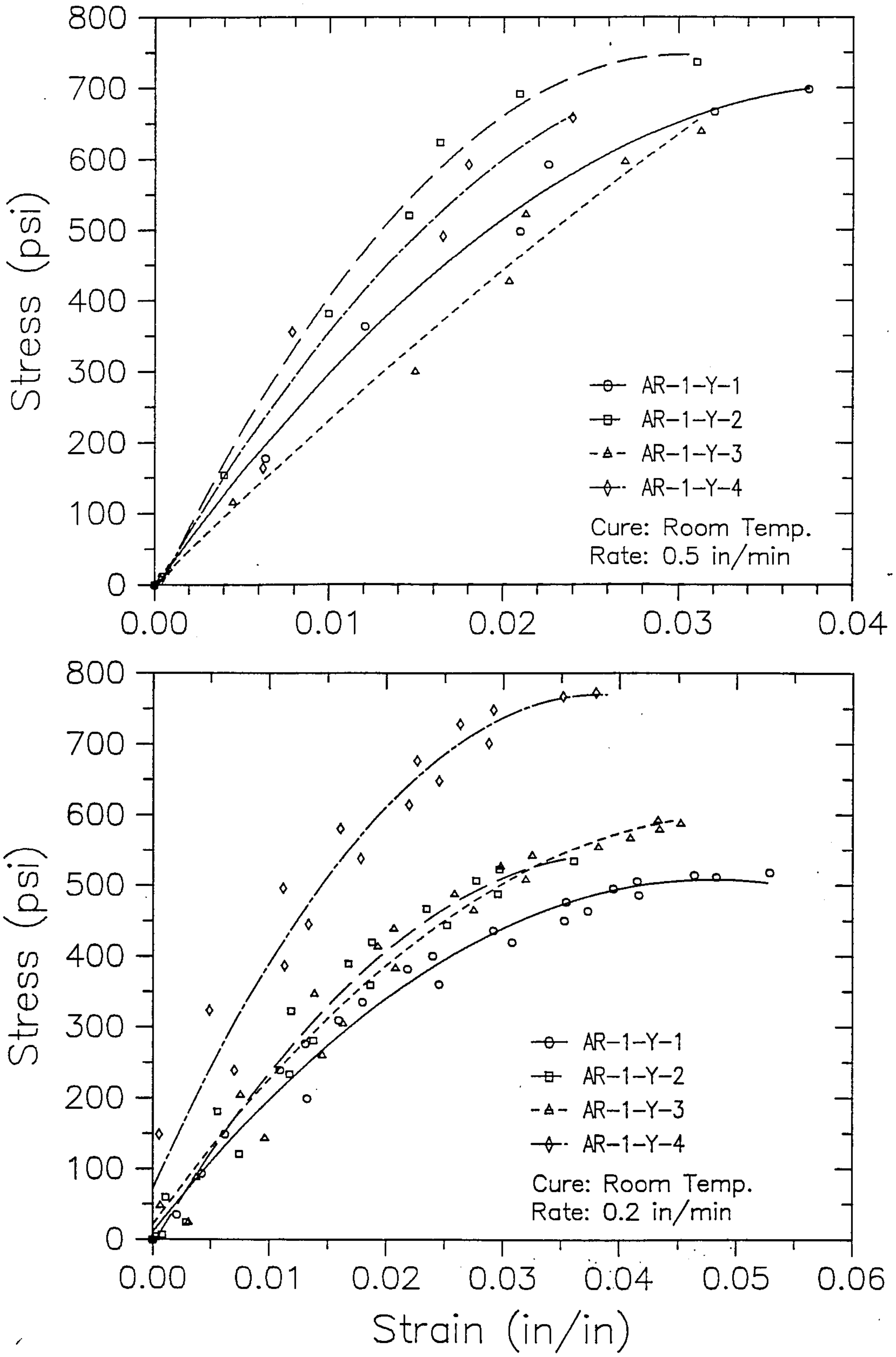


Figure A9 Load Rate Comparison at Room Cure for [AR-1-Y]

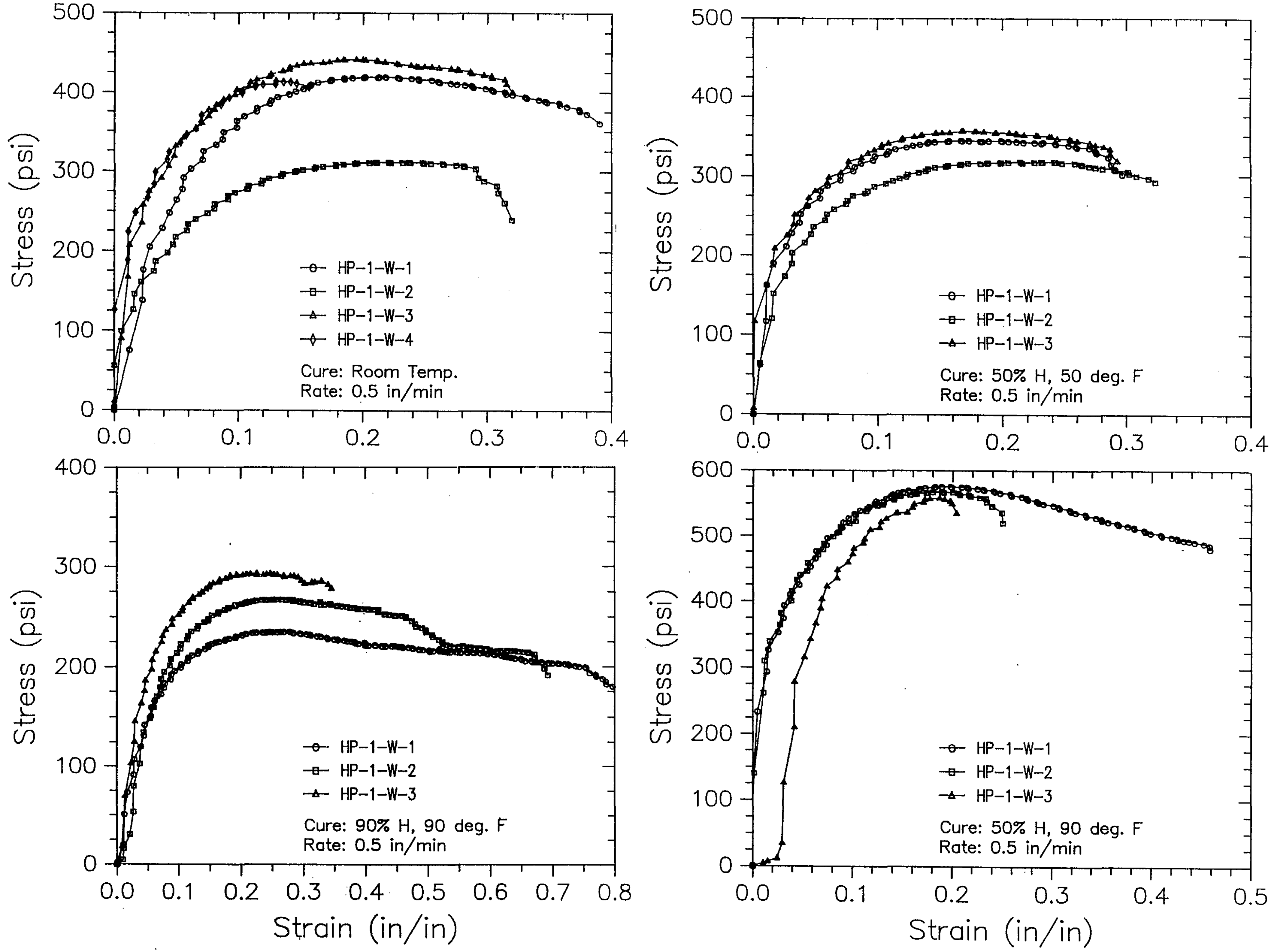


Figure A10 Stress-Strain Curves For [HP-1-W]

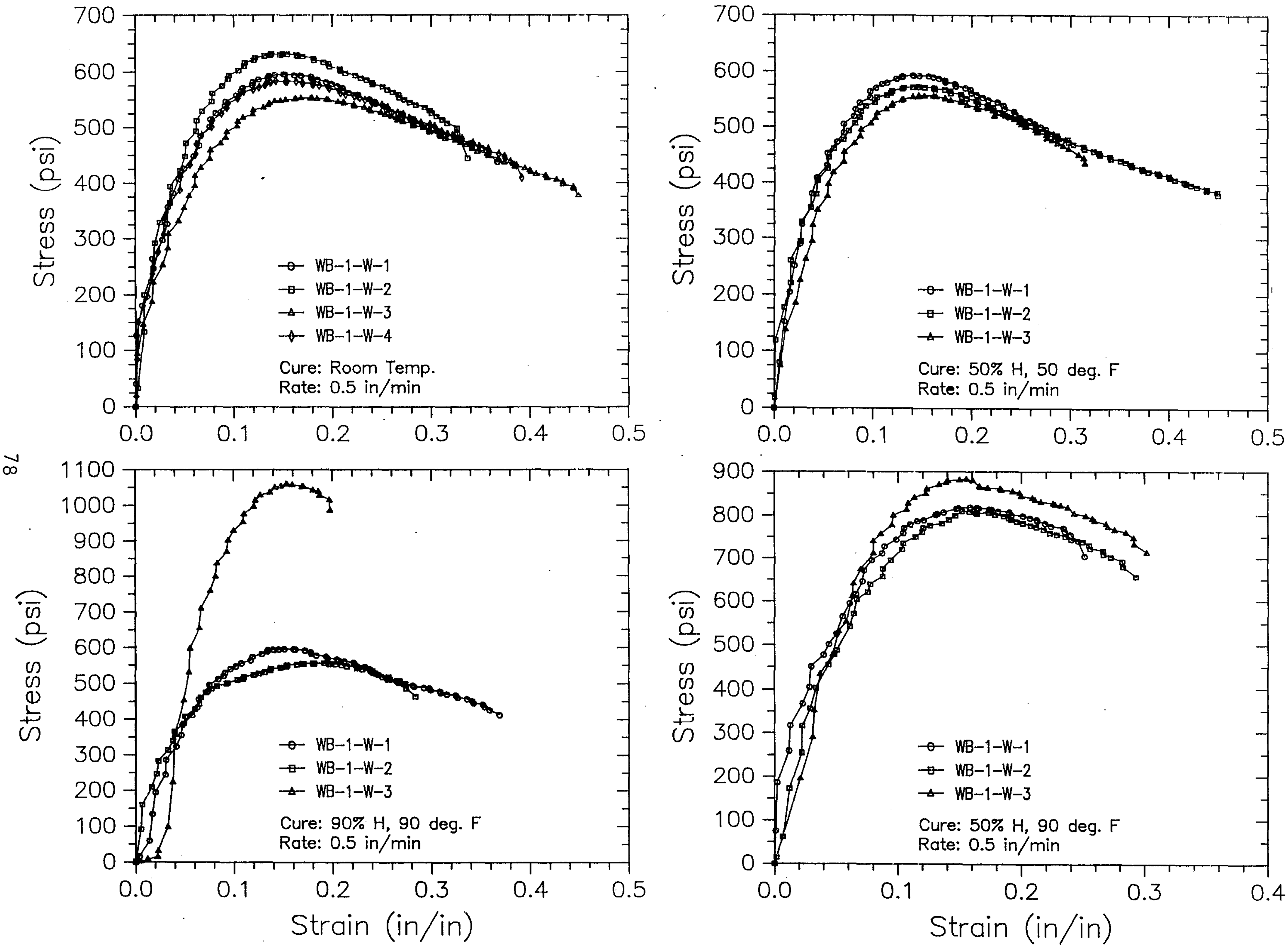


Figure A11 Stress-Strain Curves For [WB-1-W]

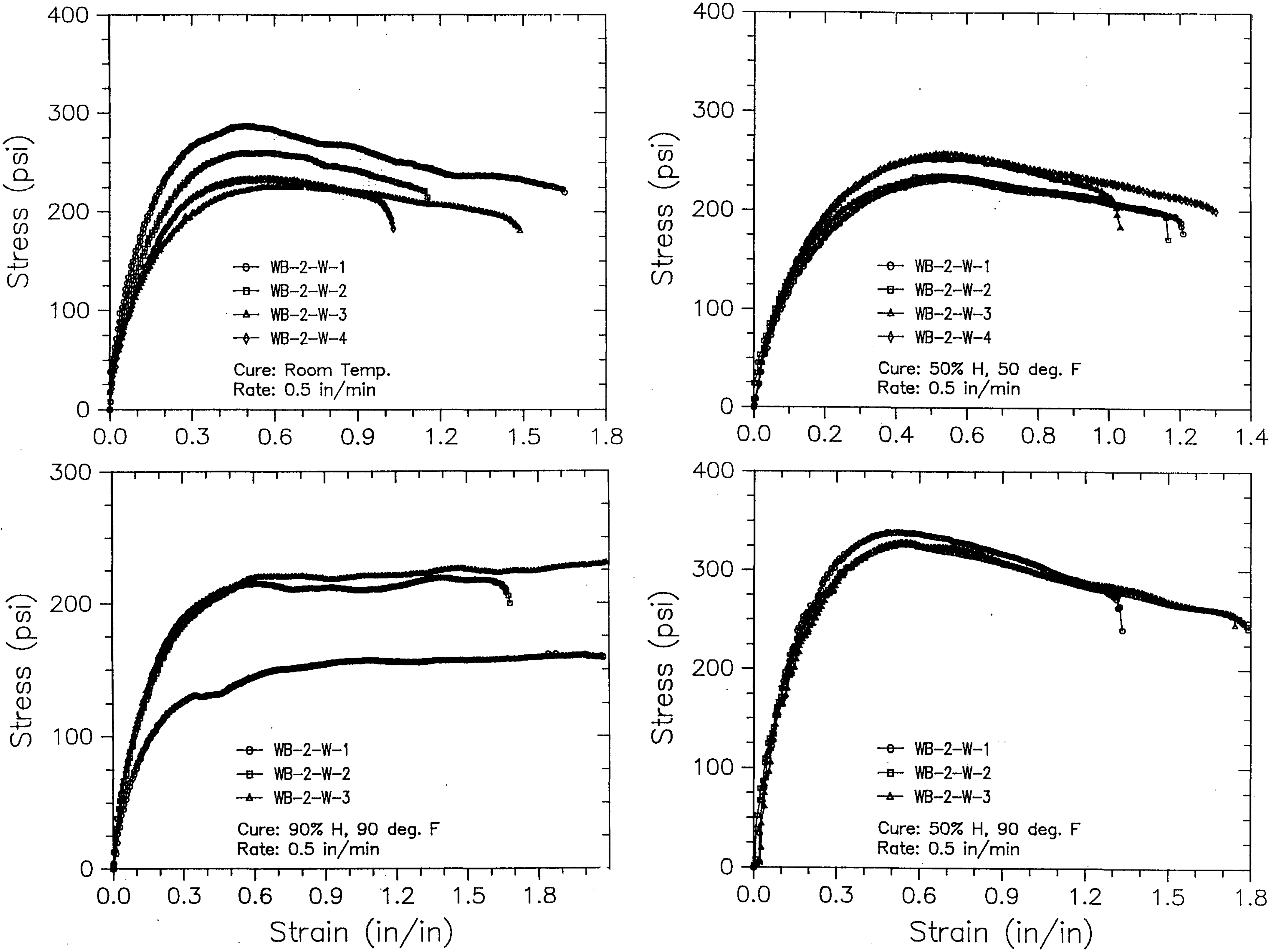


Figure A12 Stress-Strain Curves For [WB-2-W]

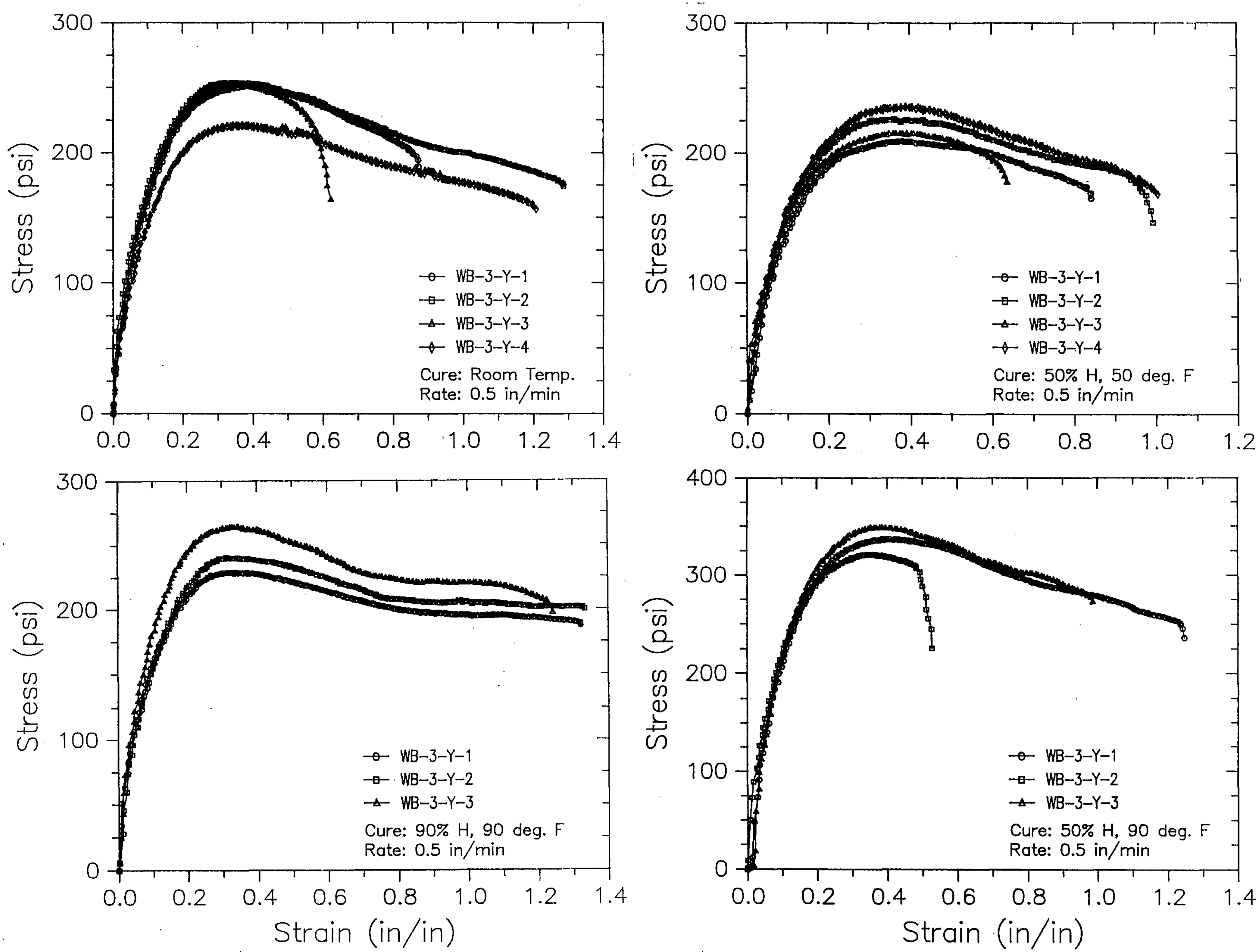


Figure A13 Stress-Strain Curves For [WB-3-Y]

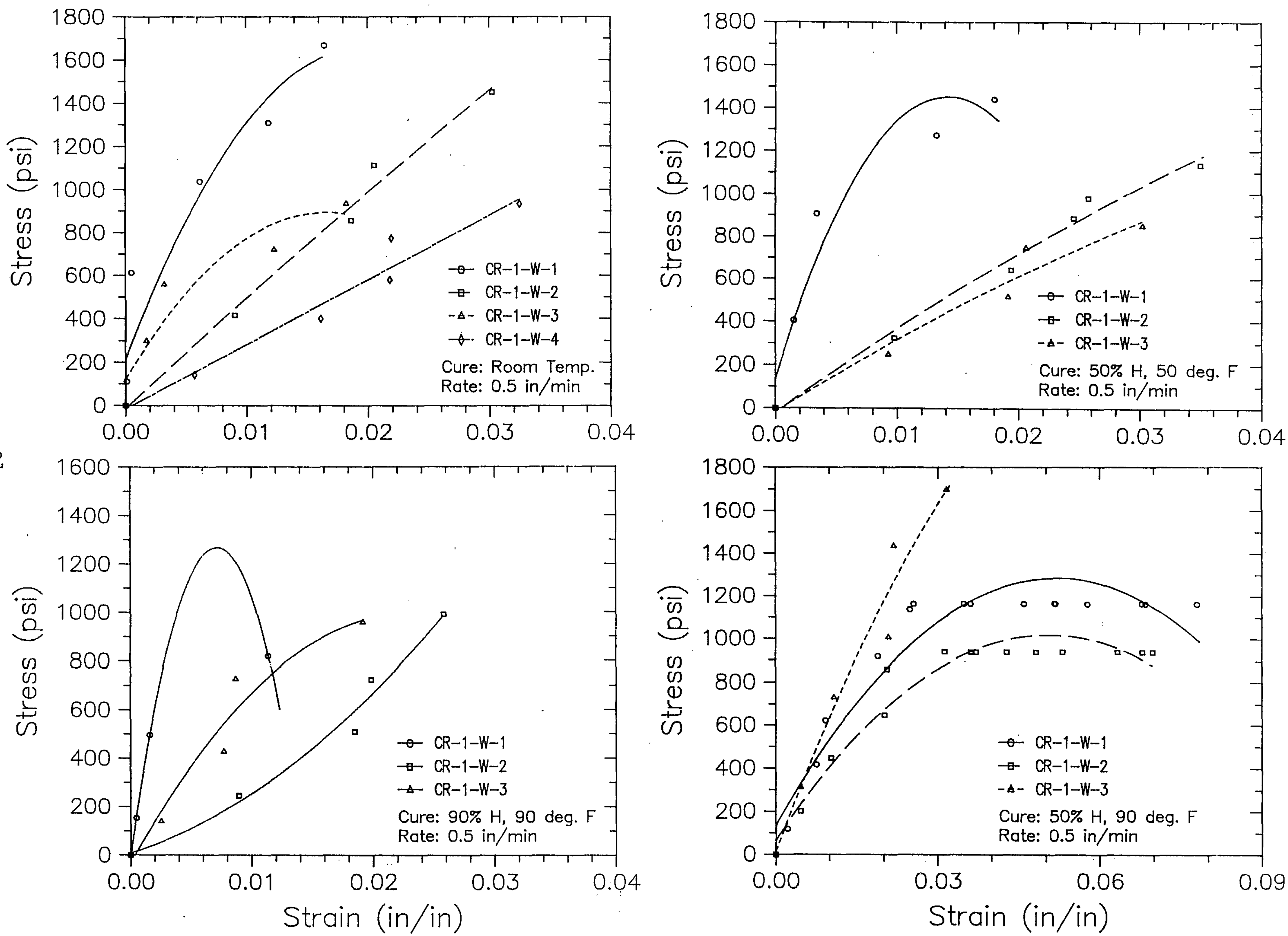


Figure A14. Stress-Strain Curves For [CR-1-W]

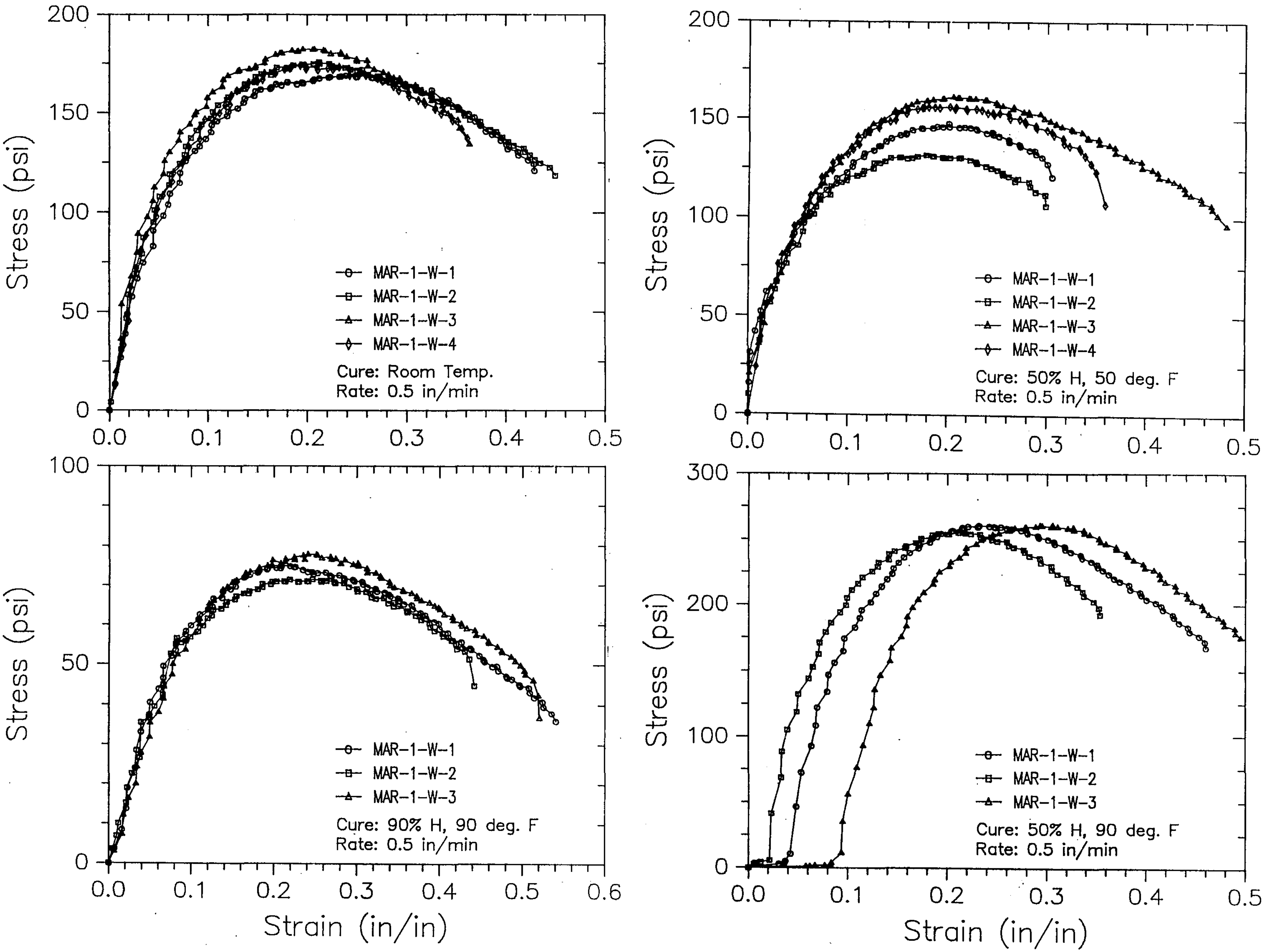


Figure A15 Stress-Strain Curves For [MAR-1-W]

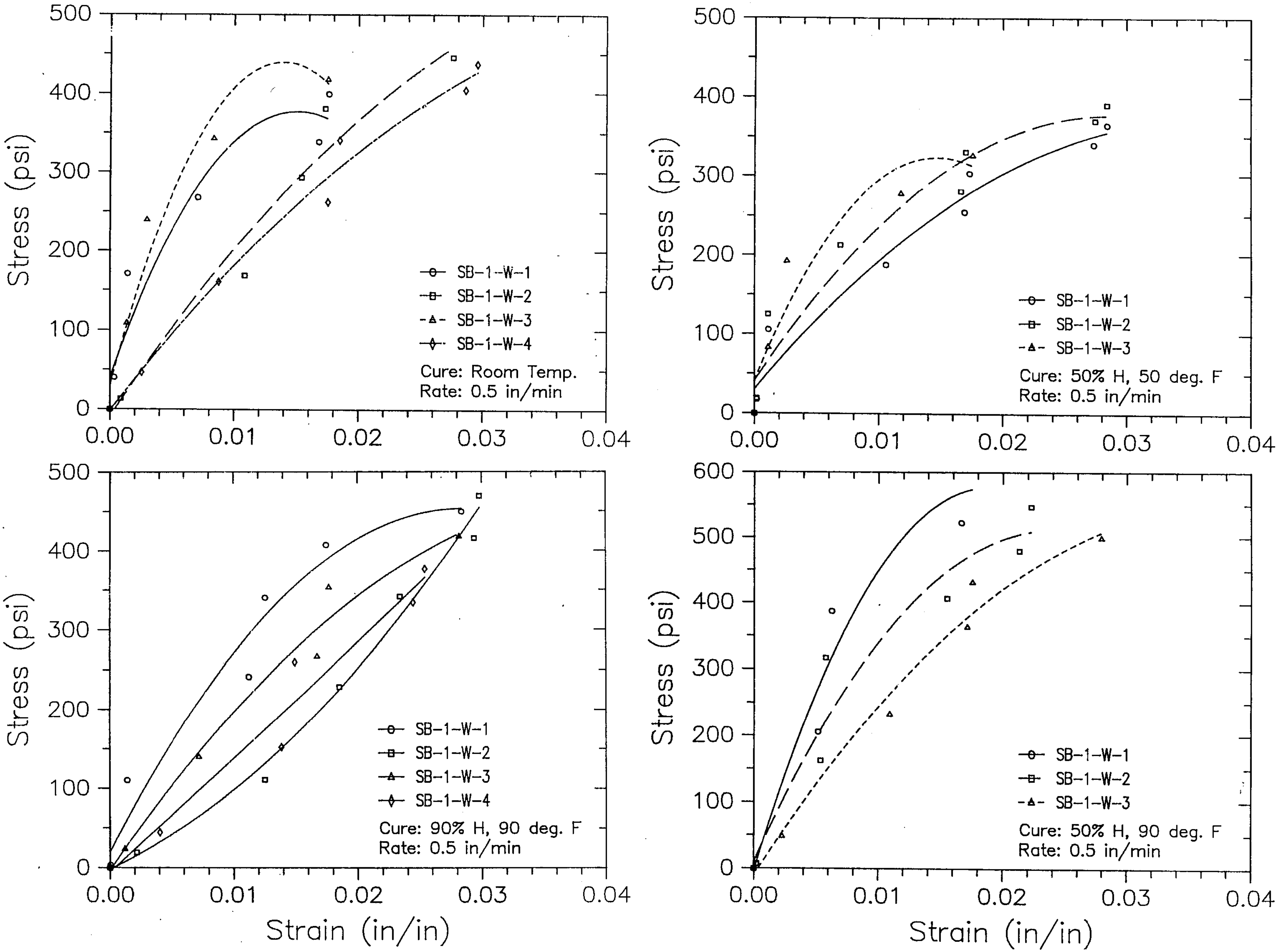


Figure A16 Stress-Strain Curves For [SB-1-W]

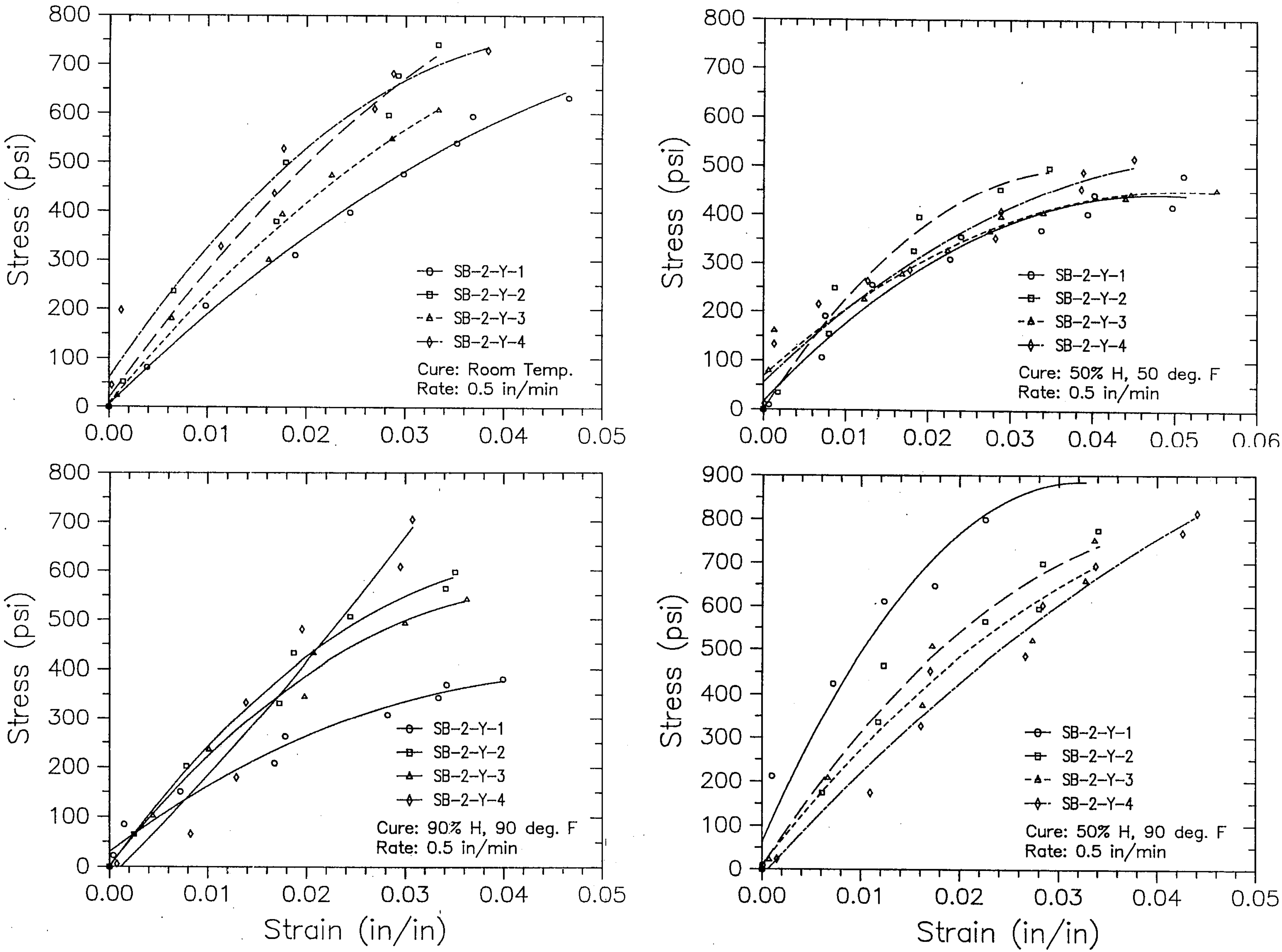


Figure A17 Stress-Strain Curves For [SB-2-Y]

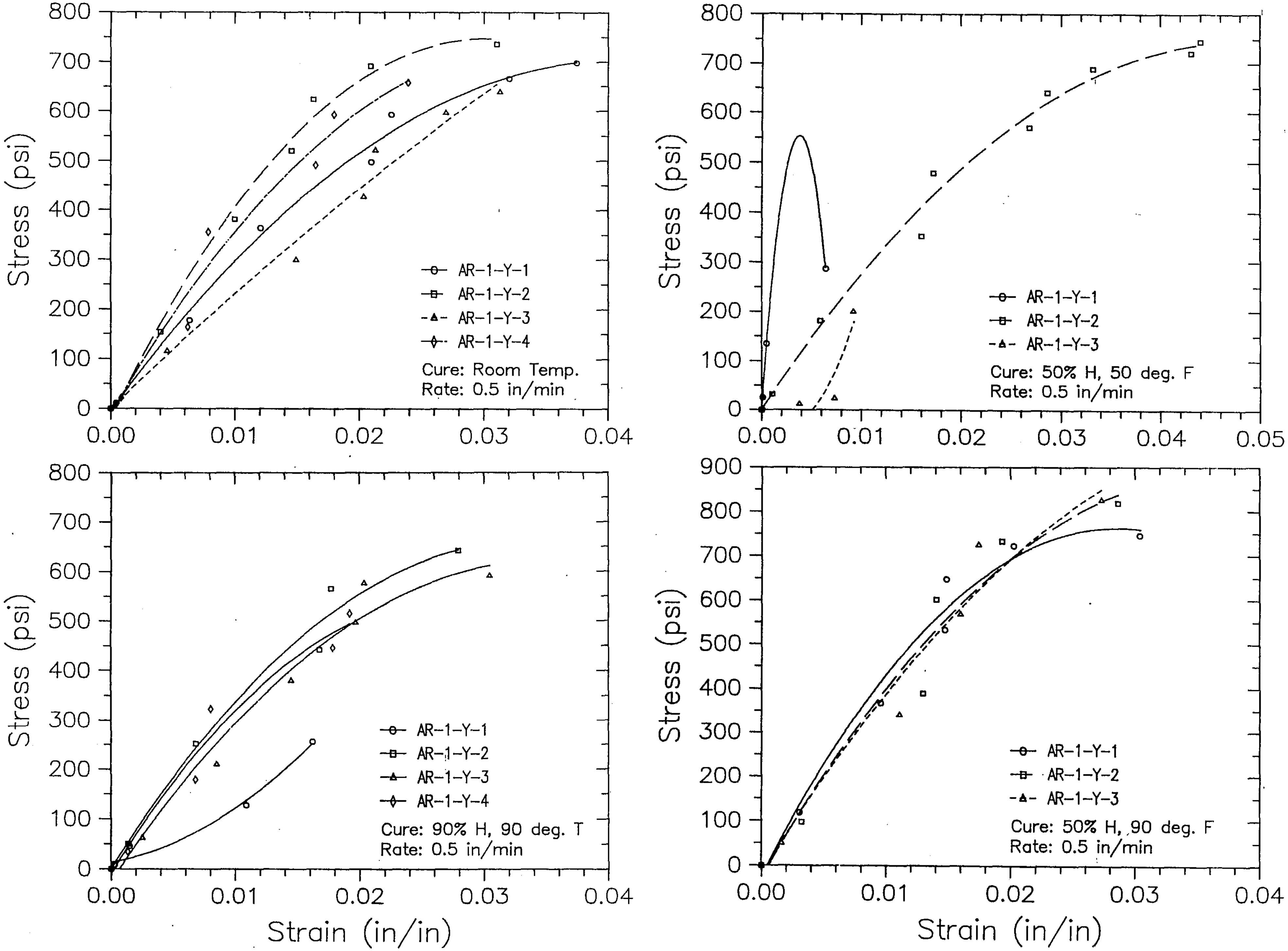


Figure A18 Stress-Strain Curves For [AR-1-Y]