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RECYCLING OF BITUMINOUS SHOULDERS: LABORATORY TESTING AND PERFORMANCE PREDICTIONS

by
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A Report of the Investigation of
Recycling of Bituminous Shoulders
Project IHR-410
Illinois Cooperative Highway Research Program

conducted by the
TRANSPORTATION RESEARCH LABORATORY
DEPARTMENT OF CIVIL ENGINEERING
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
in cooperation with the
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DEPARTMENT OF TRANSPORTATION
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Conducted by

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16. Abstract

This is the second report detailing the laboratory characterization of the recycled bituminous mixes that were described in the first report. Two reclaimed pavements and two recycling agents were examined. Their behavior in fatigue, permanent deformation, and thermal cracking were determined and used to predict performance in typical pavement sections designed for three traffic levels. The behavior and performance of the recycled mixes were compared to the same properties developed for the mixture composed of all new materials. The laboratory testing indicates the difficulties noted in the mixture design phase where the recycling agents do have a definite influence on the properties in the compacted mixes. These differences are particularly noticeable in the laboratory testing where they did not show up in the mix design testing. The results indicate that suitable mixes can be produced but the properties will be highly variable and require testing before they can be used in place of an all new surface mixture. Current recycling practices should produce mixes of suitable quality to be used as binder material and as surface material in limited situations.

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CHAPTER 1

INTRODUCTION

In the first report of this project, the results of the Marshall mixture design procedure were presented for the mixes analyzed for performance comparisons in this report. The Marshall design procedure clearly indicated that differences in mix properties could be produced by using different materials and recycling agents. The design properties of the mixes generally met the Marshall design criteria and could be called equivalent to the new mixture being evaluated. The items of importance included the percentage of reclaimed pavement being recycled, the type and amount of the recycling agent being used, and the preparation and testing procedure used as relate to timing before the tests were run. The general interpretation of the results in the first report show that the mixes require further evaluation in addition to a simple mix design to ensure adequate performance in the field.

This report presents the results of extensive testing conducted on material prepared according to the mix design parameters developed in the initial report. The laboratory tests are designed to illustrate any long term differences between an all new mix and a recycled mixture. The differences between the mixtures indicated by the tests results should be indicative of the differences which may be expected in maintenance expenditures for the mixes when placed in the field.

Several procedures are available to make these perfomance comparisons. They vary from empirical relationships to sophisticated structural tests. The properties can be directly compared and perfomance infered or they can be used in state-of-the-art computer programs to indicate the field performance characteristics of the mixes when used in a pavement.

The primary result of this work is to demonstrate the equivalencies, if any, that exist between recycled mixes and the new mix selected for this analysis. The same aggregates , asphalt cement and gradations were utilized in all samples. The only differences between the samples tested in this study were the mix design parameters. These mixture properties, selected from the Marshall design values, are different densities, air voids, etc. in the different materials. These properties have been identified by many researchers as having the principal influence on the performance of an asphalt mix. The differences between the individual recycled mixes are primarily the amount of new asphalt added, the amount of recycling agent, and the amount of new aggregate used in the mix.

CHAPTER 2

TESTING PROGRAM

The new aggregate used in sample preparation was the Fairmont aggregate described in the first report. This aggregate was used in all recycled samples and in the all new mixture. The asphalt cement selected was an AC-10. By using the same materials in all samples, any differences in performance should be a result of the differences produced by the recycling process and not by the materials themselves.

The density values obtained in the mix design analysis were evaluated for the material combinations to ensure that a good repeatable density could be obtained for all samples. The materials used and the samples prepared include the following:

- 100% Reclaimed pavement
  - Decatur Millings (D)
  - Peoria Shoulder (P)
  - Paxole Recycling Agent (Pa)
  - Cyclogen Recycling Agent (C)
  - Material Combinations: DPa, DC, PPa, PC
- 100% All New Mix
  - Fairmont Aggregate (F)
- 30% Reclaimed Pavement 70% All New Mix
  - Decatur/Fairmont/Paxole (DFPa 30/70)
  - Decatur/Fairmont/Cyclogen (DFC 30/70)
  - Peoria/Fairmont/Paxole (PFPa 30/70)
  - Peoria/Fairmont/Cyclogen (PFC 30/70)

While it was initially planned to prepare samples of 50 percent reclaimed pavement for analysis, material availability and handling difficulties, and equipment limitations in the laboratory did not allow for adequate samples to be prepared for analysis.

Sample Preparation

Two types of samples were prepared for the structural evaluation of the mixes. Beam samples were prepared for the fatigue analysis and cylindrical samples were prepared for the creep compliance, static-incremental permanent deformation study, and the indirect tension study. The samples are shown in Figure 2-1.

The samples were proportioned and mixed in the same manner as was done for the mix design study reported previously. These samples were compacted differently than the procedure that is normally done in the Marshall mix design procedure. The different procedure was needed to ensure that density was maintained near the laboratory value established by the mix design testing in the various geometries of sample used.

The compaction procedure was the double-ended static-plunger method. This method requires the exact amount of material be placed in the mold prior to compaction. Compaction is accomplished using a large testing machine capable of placing a high compressive force on the sample end plates. The end plates are placed on the sample and the plates are forced down, compacting the samples. The deformation of the end plates is monitored, and when a predetermined sample height is reached the desired density is attained. The testing machine used for the beam and cylindrical samples and the molds are shown in Figure 2-2. This method of compaction proved to be very repeatable and produced densities very close to the desired values. The densities obtained for the samples tested in this study are given in Table 2-1.

Tests Performed

The samples were prepared in the manner described in the previous section and were then allowed to cure for a three to four week period to ensure that diffusion of the recycling agent had taken place. This was necessary to ensure that adequate material properties were allowed time to develop to their full potential during the time period the recycling agent is diffusing into the aged asphalt cement.

Flexural Fatigue Beam Tests

The beam samples were tested in a repeated third point loading device similar to that shown in Figure 2-3. An LVDT (Linear Variable Differential Transducer) was positioned directly under the center of the beam to record the deformation produced by the load. The fatigue testing method used was the constant stress mode. In this method, the load remains constant throughout the entire duration of the test as contrasted to the constant strain test where the initial flexural strain remains constant during the test. The constant strain test would require continual monitoring and adjustment to the load which is impractical given the capabilities of most laboratory equipment and the time available to conduct the tests. The number of load repetitions to produce failure in the beam is recorded and the initial flexural strain (at 200 loadings) is also recorded. For the results presented here, failure is defined as a total crack through the sample.

The data required to analyze a fatigue test is obtained by testing a number of samples and plotting the number of loadings to failure against the initial strain on logarithmic scales which produce straight line relationships. Typical fatigue curves are shown in Figure 2-4. All tests were conducted at 72°F in a temperature controlled cabinet.

Creep Compliance Testing

The cylindrical samples were utilized to obtain several material properties related to performance potential, primarily stiffness, temperature susceptibility, and permanent deformation data. Creep compliance data was obtained using the procedures outlined in the VESYS manual (4). This procedure includes the sample conditioning loads, the incremental-static loading sequence to determine the permanent deformation characteristics, and the 1000 second creep curve.

The Creep test Machine used in this research is shown in Figure 2-5.

Static-Incremental Loadings. The static-incremental loading sequence was developed to simulate the results that would be obtained if a sample was loaded repeatedly, recording the permanent deformation as a function of the number of load repetitions. A loading of a specified duration is applied to the sample, and then it is released. The permanent deformation remaining in the sample after a specified amount of recovery time is recorded along with the duration time of the load. Following a specified rest time, the next load pulse is applied and the procedure is repeated. The loading times are 0.1, 1, 10, 100, and 1000 seconds. The 1000 second loading pulse is used for the creep compliance data also. The duration of the load pulse, the resilient modulus of the sample and the permanent deformations are then used to plot a permanent deformation curve similar to that shown in Figure 2-6. The properties of interest are the ALPHA and GNU parameters. Permanent deformation tests were conducted at three temperature levels, 40, 70, and 100°F to provide variation with climatic influences.

<u>Creep Testing</u>. The Creep test is a viscoelastic test that determines the stiffness of the mixture and its relationship with temperature and rate of loading. This compliance test data is also used in the analyses of the potential for thermal cracking damage to occur. In the creep test, a constant load is applied to the sample for a specified duration, and the deformation of the sample is recorded at predetermined time intervals. The creep compliance of the sample is the strain at any time divided by the constant magnitude of the load. The creep compliance is often expressed as the relaxation modulus (stiffness) which is approximately the inverse of the creep compliance. The creep test is repeated at several temperature levels to obtain an indication of the influence of temperature on softening the material in the summer or hardening during the winter. The three temperature levels used in this testing program include 40°F, 72°F, and 100°F.

The compliance determined at each temperature level is plotted on the same graph, as shown in Figure 2-7. These individual curves can be converted to a single master curve that represents the stiffness of the material over an extended rate of loading at the particular temperature chosen. This is accomplished by horizontally translating the curves until they overlay varying portions of the master curve T_{master} or T_m. The horizontal distance each curve must be shifted to obtain the master curve relationship is recorded as a_t. The temperature difference, T minus T_m is recorded, and the two values are plotted to give the Log a_t curve. The steps are indicated in Figure 2-8. This process is called time-temperature superposition and takes advantage of the principle that time of loading and temperature of the sample are interrelated, i.e. a long time of loading on a cold sample may be equivalent to a short loading on a hot sample. Using this relationship, the stiffness of a mixture can be calculated for any temperature and rate of loading once the tests have been conducted. The data can be represented analytically and stored very easily for use in computer programs such as VESYS using the a_t relationship. This same viscoelastic data can be analyzed to predict the potential for thermal cracking to occur in the mixture using the actual temperature history of the asphalt concrete in the appropriate viscoelastic analysis program.

Indirect Tensile Test

The cylindrical creep samples were sawn into two Marshall sized specimens after the creep testing was completed. The tensile strength was determined using the indirect tensile test. This test splits the sample by applying a load at the edge of the cylinder along the diameter as depicted in Figure 2-9. The tensile strength is determined from the equation:

$$\sigma_t = 2P/\pi Dt$$

where:

σ_t is the indirect tensile strength, psi

P is the vertical load in pounds

D is the diameter of the cylinder in inches, typically 4 inches for a Marshall cylinder

t is the thickness of the specimen

The tensile strength indicates the structural adequacy of the material to resist failure under a high load, and also may relate to the fatigue of the mixture according to a relationship prepared by Maupin (5) which will be discussed later. Studies have been performed which indicate that the indirect tensile test may be an appropriate test for mixture design considerations.

Lottman Procedure, Moisture Susceptibility

The Lottman Procedure (6) is a test to evaluate the potential for moisture damage to occur in the mixture, primarily stripping of the asphalt from the aggregate which may result in a mixture with low strength and a high potential to develop permanent deformation or fatigue cracking.

Half of the samples for indirect tension testing from the creep cylinders were saved to be run through the Lottman procedure to show the potential for moisture damage. The procedure consists of running the samples through vacuum saturation with water, and a series of 18 freeze-thaw cycles which accelerate the development of stripping. The indirect tensile test and resilient modulus test are used as a comparison tool to indicate the structural adequacy of the samples before and after the cycling procedure. There are definite limits set for the allowable change in these properties following the saturation and freeze-thaw cycling process, (generally a 50 percent decrease) and a visual examination of the cores must be performed to determine the extent of any stripping problem.

Mixture and Asphalt Cement Properties

Properties in a compacted asphalt concrete mixture and the properties of the asphalt cement in the mixture have been the basis for a number of empirical procedures for predicting structural properties of a mixture. The most recognized procedure is the nomographic relationship between mixture properties, asphalt cement properties and the stiffness of the sample developed by Van der Poel and extended by Heukelom and Klomp (7). This procedure has been computerized and is the version used in this study to accurately predict the stiffness of the samples under varying conditions of loading and temperatures.

The Shell design procedure (8) has adapted the nomographic procedure to predict the stiffness of the mixtures and to compare tendencies for permanent deformation to develop. The permanent deformation procedure utilizes the same mixture and asphalt properties required for stiffnes predictions, and calculates the permanent deformation in a standard pavement section. The stiffness and asphalt properties can also be used to predict the fatigue of the asphalt concrete mixture under either constant strain or stress conditions.

Finn et. al. (9) in an NCHRP study examining premature cracking of asphaltic concrete pavement developed a regression equation from extensive laboratory data that predicts the fatigue life of an asphalt concrete mixture. This procedure uses the standard asphalt cement properties, mixture properties, and the stiffness of the mixture. All of these properties are being collected during the testing portion of the study and will be used to make comparisons.

These tests and procedures will be used to evaluate the properties of new mixes and recycled mixes of varying composition in the next section of this report.

Table 2-1

Densities of the Samples Tested

Sample Number	% of Recycled Materials	% of All New Mix	Material Combination	Fluids Content (% by W_s)	Cylinder Sample Density (PCF)
F01	0	100	F	5.00	140.9
F02	0	100	F	5.00	140.3
F52	0	100	F	5.05	147.6
F53	0	100	F	5.00	148.4
1B1	30	70	PFPa	5.00	145.0
2B1	100	0	DPa	5.77	144.4
3B1	100	0	DC	6.45	145.4
4B1	30	70	DFC	4.50	141.5
5B1	100	0	PC	6.45	145.8
6B1	100	0	DPa	5.77	145.4
7B1	30	70	DFC	4.50	142.2
8B1	30	70	DFPa	5.00	138.7
9B2	30	70	PFC	4.50	140.2
10B2	100	0	DC	7.20	140.8
11B2	100	0	PPa	4.93	145.6
12B2	100	0	DC	7.20	139.4
13B2	100	0	PPa	5.93	147.0
14B2	30	70	PFC	4.50	142.9
15B2	30	70	PFPa	5.00	137.9
16B2	30	70	DFPa	5.00	139.2
17B1	30	70	PFC	4.50	142.5
18B1	30	70	DFPa	5.00	139.5
19B1	100	0	DC	7.20	142.8
20B1	30	70	DFPa	5.00	139.0
21B1	30	70	PFC	4.50	141.3
22B1	100	0	PPa	5.93	145.0
23B1	100	0	PPa	5.93	146.3
24B1	100	0	DC	7.20	142.9
25B2	30	70	DFC	4.50	141.5
26B2	30	70	PFPa	5.00	138.0
27B2	100	0	PC	6.45	146.1
28B2	100	0	PC	6.45	145.3
29B2	100	0	DPa	5.77	143.8
30B2	30	70	DFC	4.50	141.7
31B2	30	70	DFPa	5.00	139.0
32B2	100	0	DPa	5.77	143.7

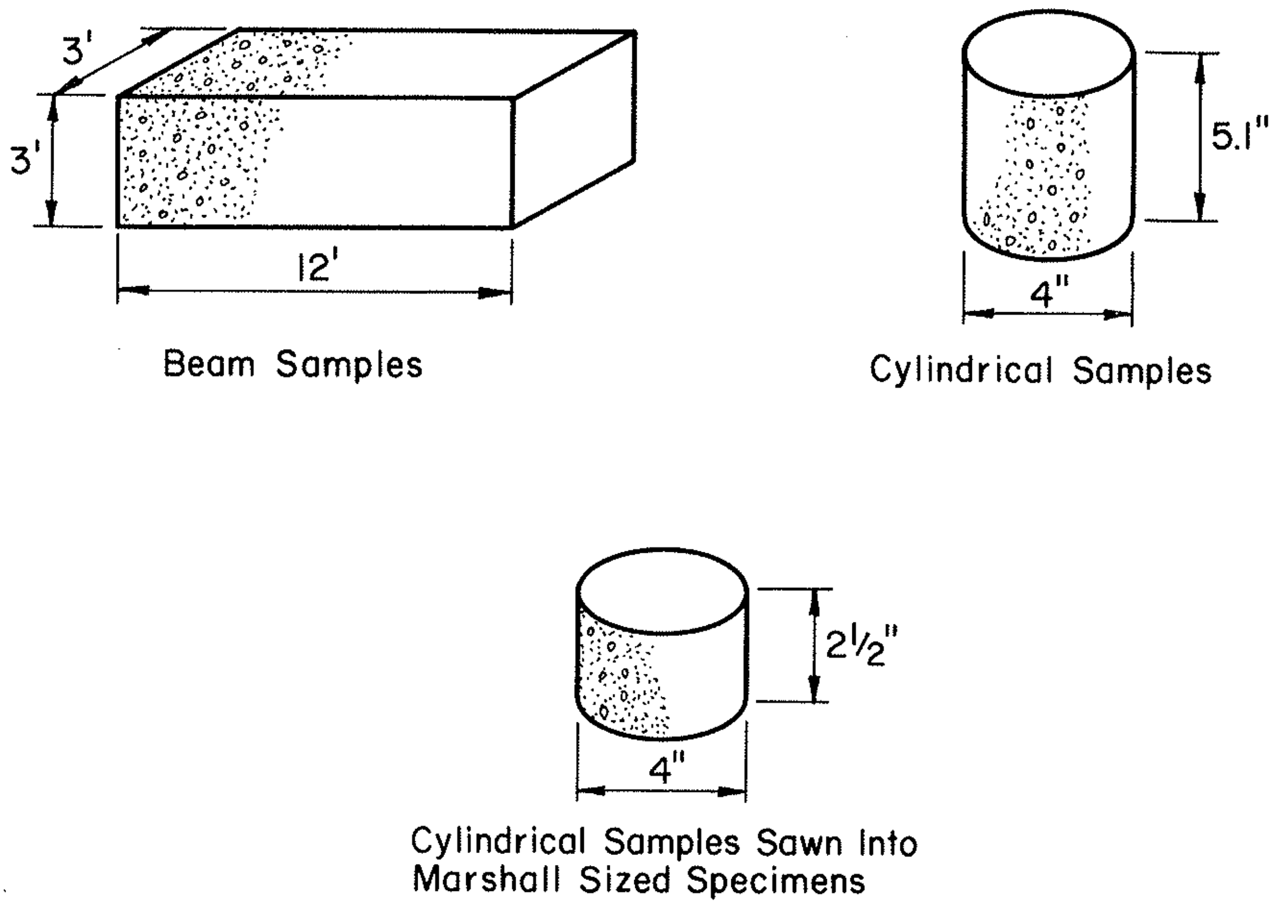


Figure 2-1 Samples Configuration.

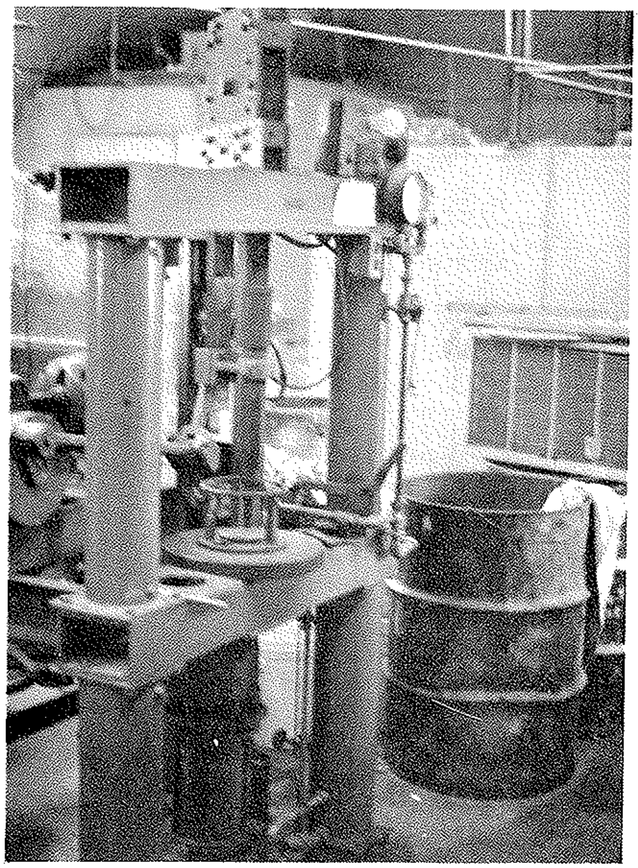
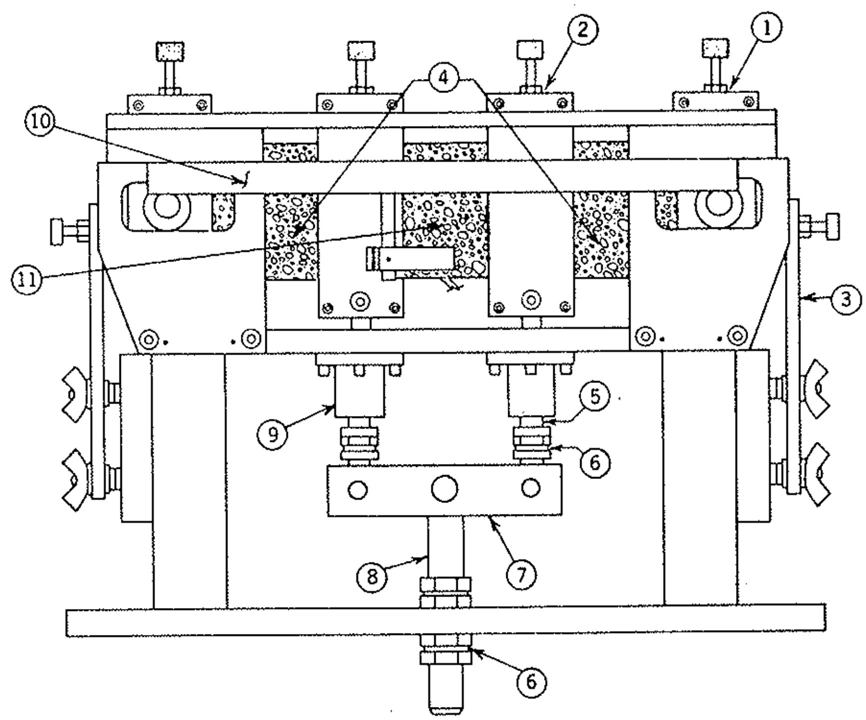


Figure 2-2 Photograph of Kneading Compactor Used to Prepare Specimens.



Key:

1. Reaction clamp
2. Load clamp
3. Restrainer
4. Specimen
5. Loading rod
6. Stop nuts
7. Load bar
8. Piston rod
9. Thompson ball bushing
10. LVDT holder
11. LVDT

Figure 2-3 Flexural Fatigue Test Apparatus (1).

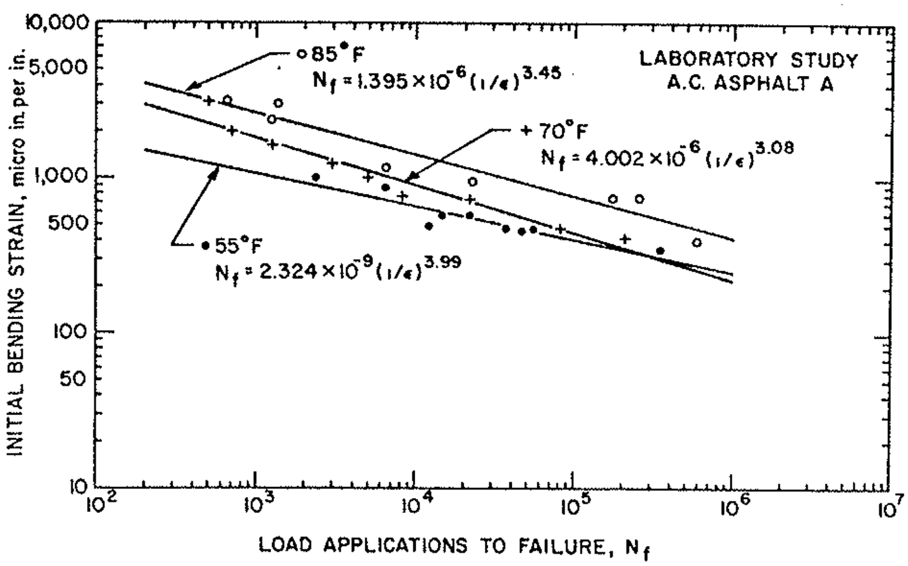


Figure 2-4 Typical Fatigue Curves (2).

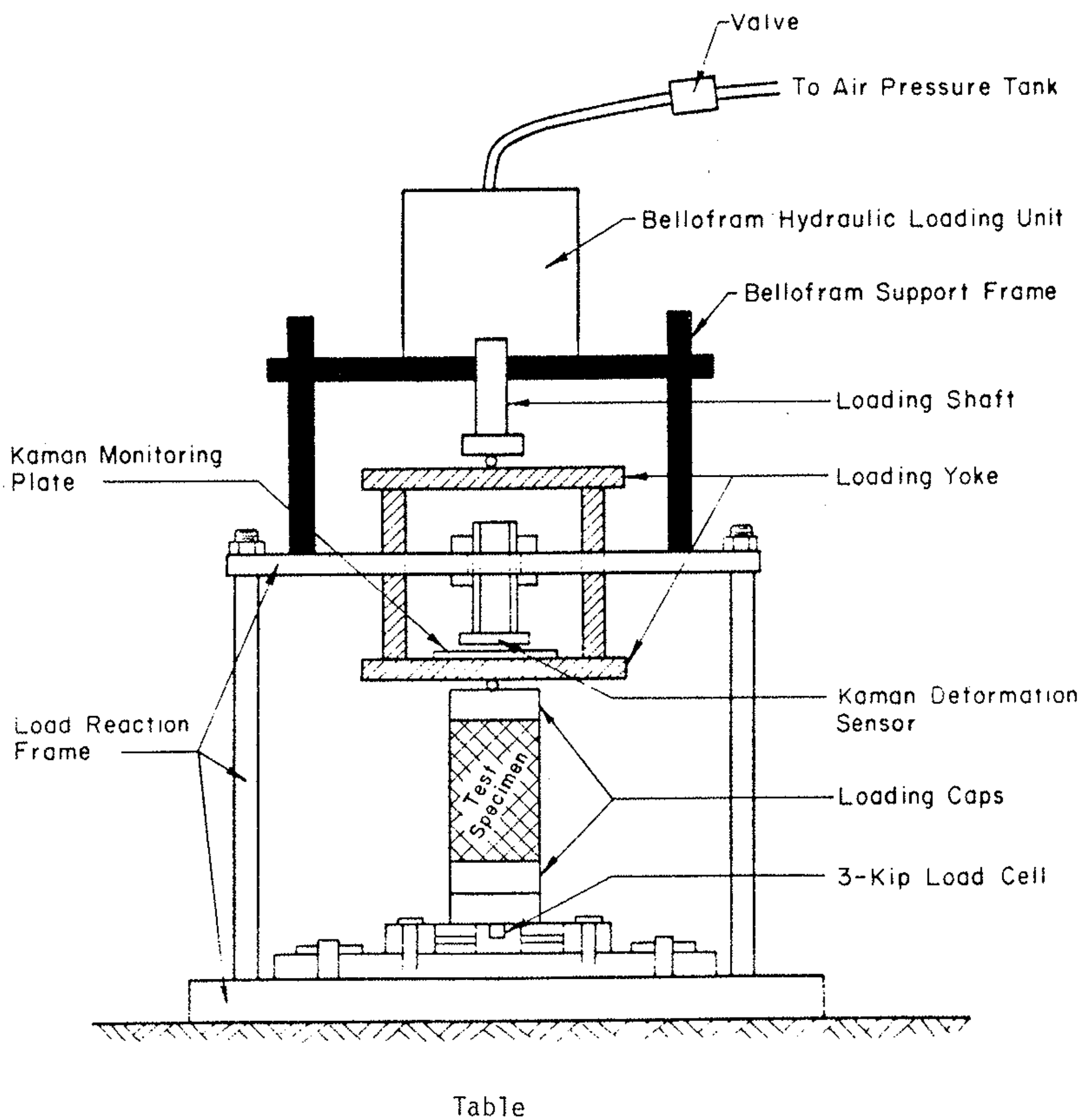


Figure 2-5 Creep Test Machine (3).

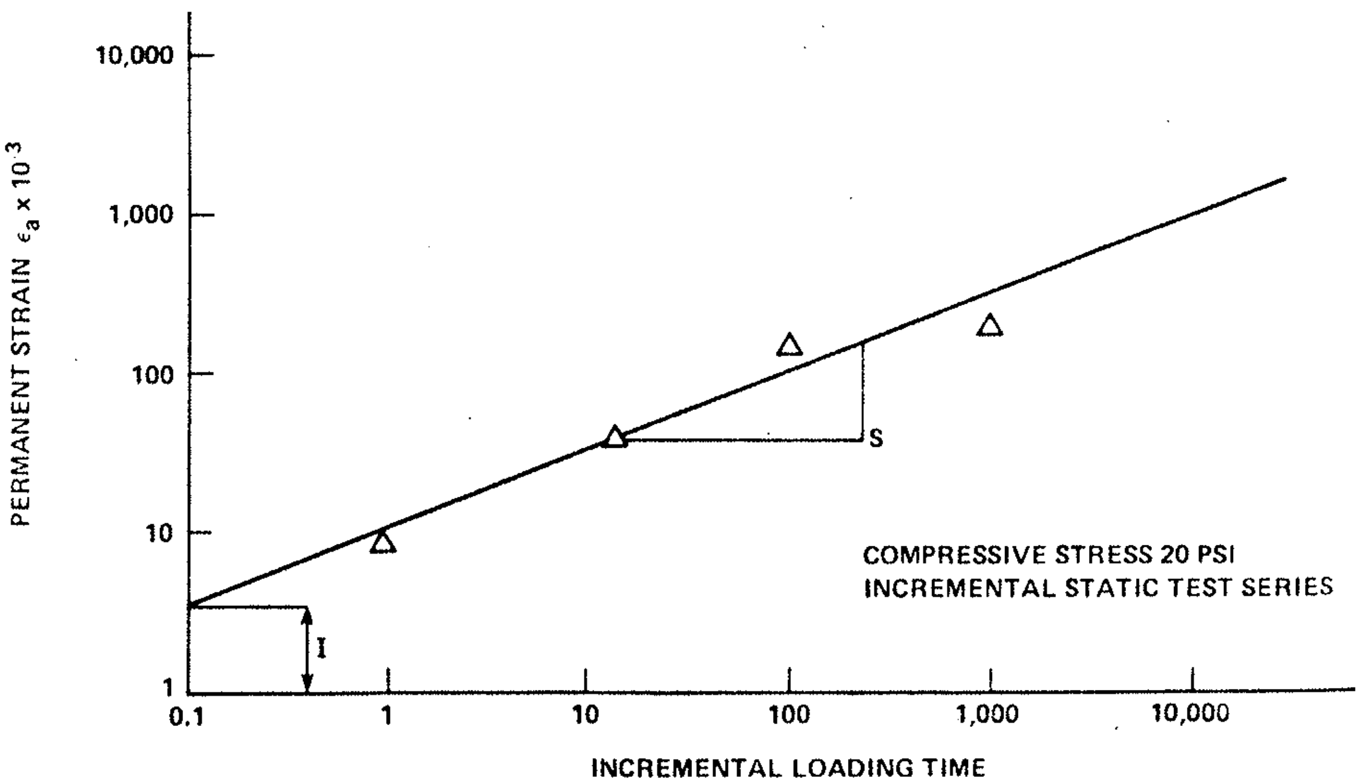


Figure 2-6 Typical Incremental Static Permanent Deformation Curve (4).

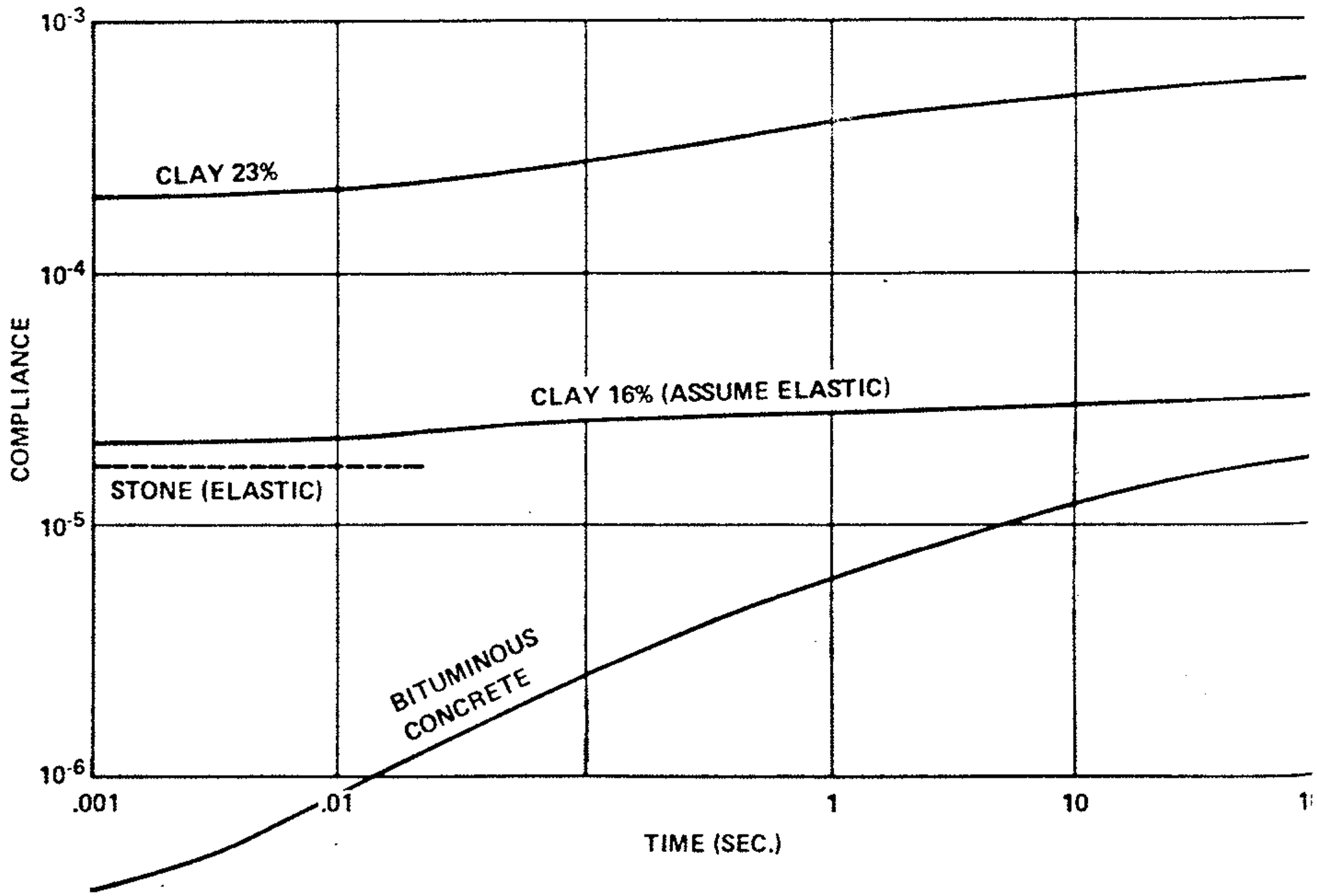


Figure 2-7 Typical Compliance Curves (4).

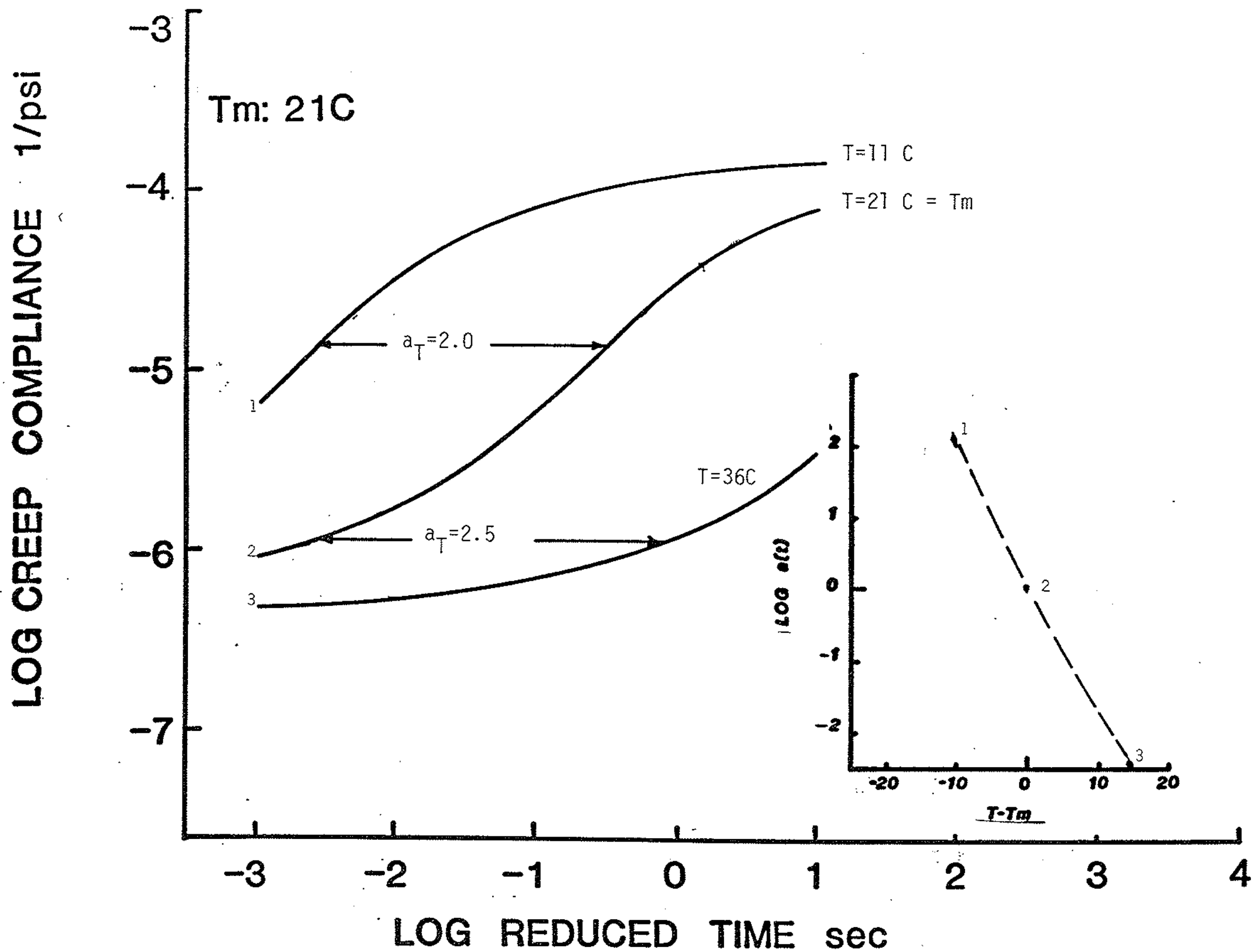


Figure 2-8 Creep Compliance Curves Illustrating Reduction to Develop a_T Shift Factor Curve.

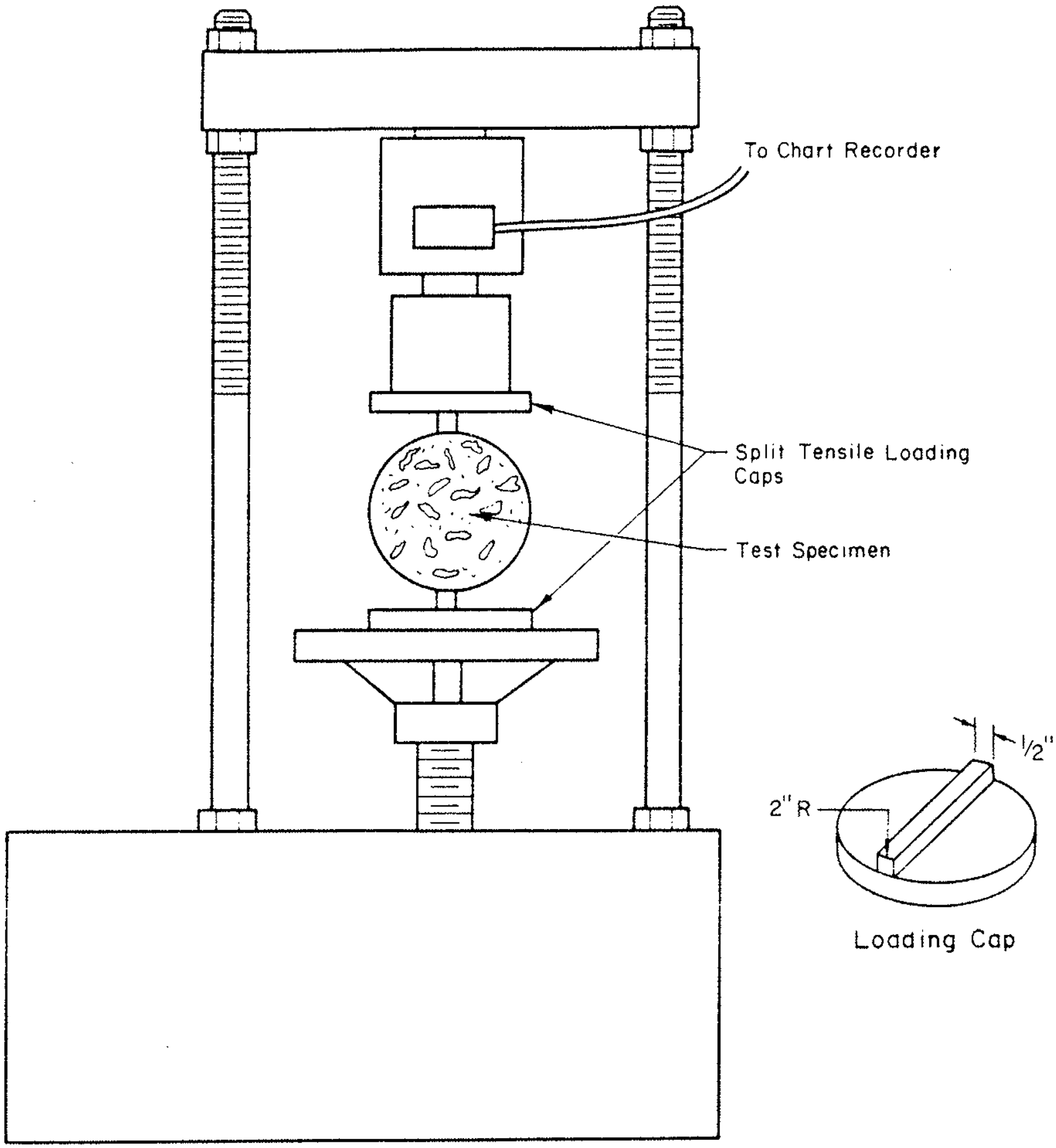


Figure 2-9 Split Tensile Strength Test Device (3).

CHAPTER 3
PRESENTATION OF TEST RESULTS

The results of the testing program will be described and the data collected will be presented in this section of the report. In the following section the results will be interpreted and compared for performance predictions. The test results to be presented here include:

- Fatigue
  - Flexural Fatigue Tests
  - Shell procedures
  - NCHRP Equation
  - Maupin Indirect Tensile Strength Relationship
- Creep Compliance
  - Laboratory Creep test
  - Computer nomograph with asphalt properties
- Indirect Tensile Strength
- Lottman Procedure For Moisture Susceptibility
- Permanent deformation
  - Shell permanent deformation
  - VESYS permanent deformation

Fatigue

Flexural Fatigue Beam Tests

The results for the beam fatigue tests consist of a logarithm plot of loadings to failure against the initial strain in the outer fiber of the beam. The results of the laboratory testing are shown in Figure 3-1 through Figure 3-7. The limited tests on the inadequately prepared 50/50 mixes tested initially did not differ from the 30/70 mixes but they were of insufficient quality to continue testing with due to laboratory problems.

Each set of samples had the appropriate fatigue equation calculated for the best fit line to the data. The following equations were obtained:

All New Fairmont Mix

$N_f=7.4x10^{-7}(1/\varepsilon)^{3.111}$

100 Percent Recycled Mixes

$N_f=1.2x10^{-5}(1/\varepsilon)^{2.089}$ - PPa

$N_f=4.6x10^{-10}(1/\varepsilon)^{3.117}$ - PC

$N_f=1.2x10^{-10}(1/\varepsilon)^{4.080}$ - DPa

$N_f=2.7x10^{-8}(1/\varepsilon)^{3.494}$ - DC

Recycled Blends

$N_f=3.6096x10^{-7}(1/\varepsilon)^{3.1698}$ - 30/70 PFPa

$N_f=4.1766x10^{-39}(1/\varepsilon)^{11.0836}$ - 30/70 DFC

$N_f=6.2470x10^{-23}(1/\varepsilon)^{7.0398}$ - 30/70 PFC

$N_f=1.1219x10^{-12}(1/\varepsilon)^{4.1887}$ - 30/70 DFPa

The initial examination of these equations indicates that the exponents for the 30/70 reclaimed mixes appear to be very different from normally expected values that were obtained for the all new mix and the 100 percent recycled mixes.

Shell Procedures

The Shell fatigue equations (8) utilize the nomographic stiffness as calculated using the mixture properties and the asphalt cement properties to obtain an equation showing the relationship between the bending strain in a flexural fatigue test and the number of loadings until failure. Two equations have been developed, one for constant strain and one for constant stress. The equation for constant strain has been used for comparison with the fatigue testing reported here.

The equation is as follows:

$$\varepsilon_i = 0.3PI - 0.015PI \times V_b + 0.08V_b - 0.198 \times S_m^{-0.28} \times N^{-0.2}$$

where:

PI is the penetration index of the asphalt cement

V_b is the volumetric asphalt content of the mixture

S_m is the stiffness modulus of the mixture, N/m^2

N is the number of cycles in failure

ε_i is the initial bending or radial strain

Using the mixture and asphalt properties of the mixes tested, the following equations were developed. They have been converted into the standard format for presenting fatigue data. They are similar to the equations obtained from actual testing.

All New Mix

$N_f = 1.479 \times 10^{-14} \, (1/\varepsilon)^5$

100 Percent Recycled

PC: $N_f = 1.351 \times 10^{-12} \, (1/\varepsilon)^5$

PPa: $N_f = 3.765 \times 10^{-13} \, (1/\varepsilon)^5$

DC: $N_f = 2.152 \times 10^{-12} \, (1/\varepsilon)^5$

DPa: $N_f = 2.437 \times 10^{-12} \, (1/\varepsilon)^5$

30/70 Recycled Mixture

DFPa: $N_f = 1.997 \times 10^{-14} (1/\varepsilon)^5$

DFC: $N_f = 7.046 \times 10^{-16} (1/\varepsilon)^5$

PFPa: $N_f = 4.847 \times 10^{-12} (1/\varepsilon)^5$

PFC: $N_f = 4.892 \times 10^{-16} (1/\varepsilon)^5$

NCHRP EQUATION

The relationship developed by Finn et. al. was derived from a large literature data base of laboratory testing (9). The equation makes use of many of the same variables found in the Shell equation, although in a slightly different format. The equation is as follows:

$$N = (1.213 \times 10^6)(0.10PEN)^{0.22}(V_A)^{-1.79}(P_B)^{-1.81}$$
$$(0.00015S_m)^{-0.71}(0.01 \times 10^{-6}\ \varepsilon)^{-3.07}$$

where:

PEN is the penetration of the asphalt cement in the mixture

P_b is the asphalt content of the mixture

S_m is the stiffness modulus of the mixture, psi

N is the number of loadings to failure

ε is the initial bending or radial strain

These relationships also have been converted into the standard fatigue equations for the individual mixes and are as follows:

All New Mix

$N_f = 3.230 \times 10^{-7} (1/\varepsilon)^{3.07}$

100 Percent Recycled Mix

PC: $N_f = 1.39 \times 10^{-6} (1/\varepsilon)^{3.07}$

PPa: $N_f = 8.283 \times 10^{-7} (1/\varepsilon)^{3.07}$

DC: $N_f = 1.277 \times 10^{-6} (1/\varepsilon)^{3.07}$

DPa: $N_f = 8.02 \times 10^{-7} (1/\varepsilon)^{3.07}$

30/70 Recycled Mix

DFPa: $N_f = 3.340 \times 10^{-7} (1/\varepsilon)^{3.07}$

DFC: $N_f = 4.172 \times 10^{-7} (1/\varepsilon)^{3.07}$

PFPa: $N_f = 1.604 \times 10^{-7} (1/\varepsilon)^{3.07}$

PFC: $N_f = 4.261 \times 10^{-7} (1/\varepsilon)^{3.07}$

The three sets of fatigue data as represented by the equations described in this section have been plotted in Figure 3-1 through Figure 3-7 over the actual laboratory data curves.

The Peoria material produced the poorest curves for the 100% recycled mixture. The addition of aggregate in the 30/70 blends improved the curves somewhat. In all instances the Paxole recycling agent produced the poorest material from the fatigue standpoint. This is likely not due to any deficiency or chemical makeup of the recycling agent, but rather to the total amount of asphalt in the mixture, which varies from material to material due to the viscosity level of the recycling agent used. This was demonstrated in the mix design phase also when very different mix properties were obtained with the different recycling agents.

The trend shown by the Peoria material was reversed in the Decatur material in that new aggregate decreased the fatigue performance of the mix. This illustrates the interaction between asphalt content and aggregate in fatigue and shows why testing is required to estimate fatigue behavior of mixes when their similarity to a normal high quality mixture is not known.

Maupin Fatigue Relationship

There is one final relationship for predicting fatigue behavior. It was developed by Maupin (5) from indirect tensile strength data. This equation takes the following form:

$$N_f = K_1(1/\varepsilon_i)^{K2}$$

where:

N_f is the number of loads to failure

ε_i is the initial or radial strain

$K_2 = 0.0374\ \sigma_{IT} - 0.744$

$\text{LOG } K_1 = 7.92 - 0.122\ \sigma_{IT}$

$_{IT}$ is the indirect tensile strength of the mix in psi.

The data for the indirect fatigue relationship was not used in the fatigue analysis presented in the next section because it lacked the accuracy to predict recycled mixture behavior. These equations were developed on standard high quality mixes, and the properties of the recycled mixes were evidently far too different to allow the use of this equation. This will be explained in more detail in the section detailing the indirect tensile strength data results.

Creep Compliance

Laboratory Creep Test

The creep compliance data have been reduced to a master curve at the 70 F temperature. The a_t curves have also been prepared and included with the compliance curves. These are shown in Figure 3-8 through Figure 3-20. The test data indicate much the same results seen in other research (3) in that the compressive creep compliance test does not show much variation between mixes even though the mixes themselves may show very different behavior. The major variable influencing the creep curve is the asphalt cement in the mix, gradation differences do not show up well in the test. The results obtained for the recycled mixes are similar to standard values of compliance and are acceptable for the initial investigation.

Computer Nomograph and Asphalt Properties

The asphalt cement properties and the mixture properties were used to calculate the stiffness curves with the Poel-Ponos computer program (10). This is the computerized Van der Poel nomograph. It can be used to calculate stiffness-rate of load-temperature curves similar to those obtained during the testing program. These compliance curves with the corresponding a_t curves are illustrated in Figure 3-8 to 3-20, superimposed over the laboratory creep compliance cuves.

The computer curves generally relate to the laboratory data as well as can be expected. A factor of two difference between the compliance or stiffness values is acceptable. The match between the two curves is generally better at one certain point along the curve, generally at a normal temperature and rate of load that is commonly used in the laboratory. These data indicate that the computer curves can function as a general indication of the stiffness-temperature relationship of the actual mixture, but for detailed theoretical analyses as will be done later in this report, they lack the appropriate sensitivity. This point will be discussed later.

Indirect Tensile Strength

The indirect tensile test was run on all the samples that were tested in the laboratory in creep and permanent deformation. One of the first interesting facts that was noticed about the recycled samples was that the indirect tension values changed quite a bit depending on when the test was run in relation to when the sample was prepared. This was mentioned in the first report in relation to the resilient modulus or stiffness of the samples. Tests conducted on a limited number of samples indicated that the indirect tensile strength immediately following compaction were as low as 30 psi. After the diffusion process was allowed to take place, the tensile strengths increased to the range of 120 psi. This diffusion required from 2 to 60 days depending on the asphalt cement and recycling agent used. The indirect tensile strengths determined at 72°F are given in Table 3-1.

It is because of this diffusion process that the fatigue relationships developed by Maupin can be considered questionable for recycled materials. The equation for fatigue, presented earlier, is plotted in Figure 3-21 and 3-22 for different tensile strengths. It can be seen that the fatigue curve merely rotates about a fixed point. This is not the normal variation seen in fatigue data for different mixes. The empirical equations shown earlier all indicate the curves have a constant slope. These constant slopes were derived from laboratory fatigue curves, and perhaps are more realistic than the indirect tensile relationship for indicating mixture variation. This drawback may be minimized when comparisons are done only for a conventional mix prepared to standard density using a conventional asphalt cement. Because of the results shown here, however, the indirect tensile strength relationship was not used, and is not recommended for recycled mixes which do not have a history of fatigue data to indicate their behavior and allow the inference that they behave as a normal mix in fatigue.

Lottman Procedure

The Lottman procedure (6) was developed to provide an accelerated indication of the potential for moisture damage to occur in an asphalt concrete mixture. The indirect tensile strength or resilient modulus is measured before vacuum saturation and 18 freeze-thaw cycles are then imposed on the samples. Following the freeze-thaw cycling, the indirect tensile strength or resilient modulus is measured again and compared with the initial value. If the value decreases by more than 50 percent of the original value the mixture is susceptible in moisture damage.

An important part of this analysis must include a visual examination of the samples following the testing program as was illustrated for a material evaluation of asphalt concrete pavements which were not recycled. A series of tests were conducted on cores taken from the overlay on Interstate 70 in Southern Illinois near Marshall, Illinois in 1980. The mix developed rutting up to 0.6 inches at a very early age (less than one year) and developed extensive stripping within a very short period of two months during the summer of 1981.

Ten slabs were sawed from the overlay early in July. None of these slabs showed any indication of stripping. The slabs were cored to provide Marshall sized samples for testing. The conditions of the cores is indicated in the photograph in Figure 3-23. Indirect tensile tests and resilient modulus values were determined for these cores and the results are given in Table 3-2. These tests indicate a lack of structural adequacy in the mix as the values are very low. A set of samples was run through the Lottman procedure, and the resulting change in the structural properties is indicated in Figure 3-24 and 3-25. None of the samples showed a decrease of 50 percent after testing as compared to the original value. This is due primarily to the low values in the materials to begin with. According to the criteria for the Lottman test, these samples passed the test for moisture susceptibility. A visual test, however, clearly indicated that these samples were very susceptible to moisture damage.

The sample condition following the vacuum saturation and freeze-thaw cycling clearly indicate stripping of the asphalt away from the aggregate. In all cases, the stripping was on the bottom of the overlay, and was over the bottom one-third to half of the overlay thickness. The appearance of these laboratory samples is extraordinarily similar to the appearance of the overlay in the field when it was lifted off the concrete pavement with a backhoe in late August of 1981. At this time, it was noted that the entire overlay project was exhibiting stripping of the bottom half of the overlay.

Because of this, a visual examination was done on all the recycled samples tested in the Lottman procedure to verify the presence of any stripping. This visual examination did not show any evidence of visual stripping in the recycled mixes.

Results of the indirect tension testing for the recycled mixtures is given in Figure 3-26 . There was a significant decrease in the strength of some samples which may indicate moisture influence even though none of the recycled mixes exceeded the 50 percent change criteria.

Permanent Deformation

The Shell Method

By means of this method (8) the amount of permanent deformation or rutting in the asphaltic layers expected during the design life of a pavement can be estimated. Eight stages must be computed to determine permanent deformation. The estimation is made from the product of the thickness of the asphalt concrete layer, the average stress, a correction factor for dynamic effects and the mixture stiffness. Total rut depth is finally obtained by adding the estimated permanent deformation in the unbound base and subbase layers to the reduction in the thickness of the asphaltic layers.

VESYS Permanent Deformation Parameters

In the VESYS rut depth model (4), the materials are characterized as viscoelastic, exhibiting a non-linear behavior dependent on previous load history, plastic effects, applied stress and time of loading. In this model, a flexible pavement with a previous loading history is subjected to a haversine load pulse of a given amplitude and duration. As the number of load repetitions increases the permanent deformation at each individual load pulse becomes smaller. For each incremental temperature, the model is represented mathematically as:

$$Rp(n) = \Delta v \; F(n)$$

where:

$Rp(n)$ = permanent deformation at load repetition n.

Δv = general deflection response of pavement surface

F(n) = a monotonically decreasing function of the number of previously applied loads. Where F(n) is represented as:

$$F(n) = \mu_{sys} n^{-\alpha_{sys}}$$

where

n = load repetition

μ_{sys} = the fractional part of the general response that becomes permanent

α_{sys} = the rate of change of permanent deformation.

The rut depth model in the VESYS subsystem combines viscoelastic layer theory with a laboratory based permanent deformation accumulative damage law.

Briefly, the Incremental Static test is performed by applying loads for a duration of 0.1, 1, 10, 100 and 1000 seconds; the total permanent deformation remaining when the load is removed, after certain unloading time is measured. During the 1000 seconds load the relaxation test is performed by recording the magnitude of creep deformation at predetermined time intervals. Finally, repeated haversine loading is applied to the specimen at the same stress level used during the test, and the peak to peak strain (e) at the 200th cycle is recorded for use in calculating a resilient modulus of the mixture. The detailed laboratory test procedure and the necessary equipment can be found in other references (4).

The Incremental Static test was performed here on 4 inch diameter by 5 inch tall specimens, under a direct compression stress of 20 PSI for the 70°F tests to estimate the permanent deformation properties of the recycled mixes. The test was repeated on samples at 40°F and 100°F temperature levels to account for changes in the materials properties due to seasonal effects.

The Permanent deformation coefficients GNU (μ) and ALPHA (α), represent matematical parameters for fitting the relation of permanent strain to cycles of load on a Log-Log plot, where :

$\mu = Is/e$

$\alpha = 1 - s$

where:

s is the slope of the Log Permanent Strain Curve as a function of the Log Incremental Loading Time.

I is denoted by the value of the Permanent Strain at the intersection with LogN = 1.

e is the strain amplitude at the 200 cycle of the repeated haversine loading.

Permanent Deformation characteristics in terms of VESYS material parameters ALPHA and GNU for recycled bituminous mixtures as influenced by the temperature, amount of reclaimed materials , modifier type and reclaimed material source are studied here. A summary of the permanent deformation laboratory derived data is provided in Table 3-3.

The general trends noted in the data for these recycled materials are:

1. When ALPHA was plotted versus GNU as shown in Figure 3-27, it was found that as ALPHA increases GNU also increases. This shows the inter-dependency of these two parameters which affect the comparisons of the different trends. This relationship was studied in the past (11,12), and similar results were obtained.

2. The ALPHA results are similar to standard values found in other research (4,11), but the GNU values are drastically lower for all mixes. This means that is a more complex parameter and more sensitive to material properties and test factors.

3. Figure 3-28 presents a plot of ALPHA and GNU as function of Temperature. GNU and ALPHA both decreased with increasing temperature for the all new material mix. The decreasing trend in ALPHA is usually associated with higher permanent deformation predictions, which agrees with the well established effect of increasing temperatures in higher rut depth.

   In general the recycled mixes did not show any distinct relationship for and as each combination had its own trend for both parameters. The relationship for the blends containing Cyclogen was less well behaved and indicated an opposite trend compared to the standard mix primarily in combination with the Decatur material, (ie., μ and α decrease as the temperature increases), and the numerical values for ALPHA are similar.

4. As has been the case in previous research (11), the percent asphalt content does not relate well to the values of GNU and ALPHA for a given mix although this is typically an important performance parameter for other distresses.

5. When ALPHA and GNU are plotted as a function of the stiffness (T=70°F, t=0.1 Sec) for the different mixes tested, even though there is considerable scatter, ALPHA decreases as the stiffness increases as shown in Figure 3-29), while GNU does not show any significant relationship.

This is consistent with previous research (11), which shows that as the stiffness of the mix increases, decreases at a slow rate. Although this implies that rutting increases as stiffness increases, this is not the case. This can be explained by examining F(n). As ALPHA decreases, it is F(n), the percentage of the total deformation that becomes permanent, that will increase. The overall deformation under the constant wheel load will actually decrease because the stiffness increases, which will produce an overall decrease in the rate of rutting.

Table 3-1

Indirect Tensile Strengths Determined at 72^{o}F

Sample Number	Load to Failure (lbs)	Indirect Tensile Strengths (PSI)
F01	1600	99.9
F02	1600	99.9
F52	2900	171.5
F54	2900	171.5
131	1150	71.8
2B1	1550	96.7
3B1	1330	80.9
4B1	1725	105.6
5B1	1150	78.8
6B1	1475	92.1
7B1	1425	85.4
8B1	1400	87.4
9B2	1100	67.3
10B2	625	39.1
11B2	1325	84.4
12B2	700	43.7
13B2	1650	103.0
14B2	1625	98.2
15B2	1700	105.1
16B2	1675	104.5
17B1	1475	88.3
18B1	1750	109.2
19B1	850	54.1
20B1	1350	84.3
21B1	1450	88.0
22B1	1300	81.1
23B1	1300	81.1
24B1	800	49.3
25B2	1700	80.7
26B2	1275	80.2
27B2	1300	81.1
28B2	1025	64.0
29B2	1350	73.2
30B2	1400	86.5
31B2	1075	67.1
32B2	1150	70.4

Table 3-2

Indirect Tensile Strength and Resilient Modulus Values for the All New Cores from I-70

Strength Test	Sample Number	DRY	Vacuum Saturation at 70°F	Testing Condition 1 Freeze Soak Cycle	18 Freez-Thaw Cycles
Indirect Tensile Strength (PSI)	178	66.4	61.3	63.5	50.3
	242	73.1	73.5	60.4	55.5
	248	66.1	60.0	56.0	57.2
	309	73.2	77.3	63.5	55.7
	575			48.4	
Resilient Modulus (10^3 PSI)	178	260	167	213	
	242	330	335	249	
	248	470	403		
	309	351	364		

Table 3-3

Permanent Deformation, Laboratory Derived Data

Sample Number	Vertical Pressure (PSI)	Test Temp. °F	ALPHA	GNU
F01	37.9	69	0.526	0.007
F02	38.1	70	0.503	0.005
F52	36.0	41	0.484	0.037
F53	36.2	41	0.688	0.059
1B1	20.9	69	.599	0.250
2B1	20.2	70	0.762	0.095
3B1	19.4	71	0.489	0.131
4B1	19.9	70	0.556	0.026
5B1	20.2	69	.555	0.123
6B1	20.5	70	0.571	0.082
7B1	79.6	70	0.498	0.033
8B1	19.5	70	0.647	0.063
9B2	18.9	68	0.622	0.025
10B2	19.1	68	0.714	0.056
11B2	19.6	72	0.574	0.144
12B2	20.5	68	0.529	0.047
13B2	20.2	69	0.540	1.686
14B2	19.3	70	0.562	0.030
15B2	20.3	70	0.627	0.047
16B2	20.1	69	0.408	0.011
17B1	26.4	41	---	---
18B1	35.3	42	0.625	0.212
19B1	33.4	41	0.339	0.009
20B1	37.7	44	0.592	0.037
21B1	37.7	41	0.507	0.017
22B1	37.7	43	0.320	0.136
23B1	37.7	41	0.093	0.002
24B1	34.4	41	0.372	0.046
25B1	24.4	42	0.526	0.040
26B2	25.5	41	0.292	0.004
27B2	27.9	41	0.739	0.118
28B2	27.7	41	0.455	0.041
29B2	35.3	41	0.486	0.009
30B2	36.1	41	0.013	0.0004
31B2	37.2	40	0.353	0.005
32B2	47.7	41	0.355	0.025

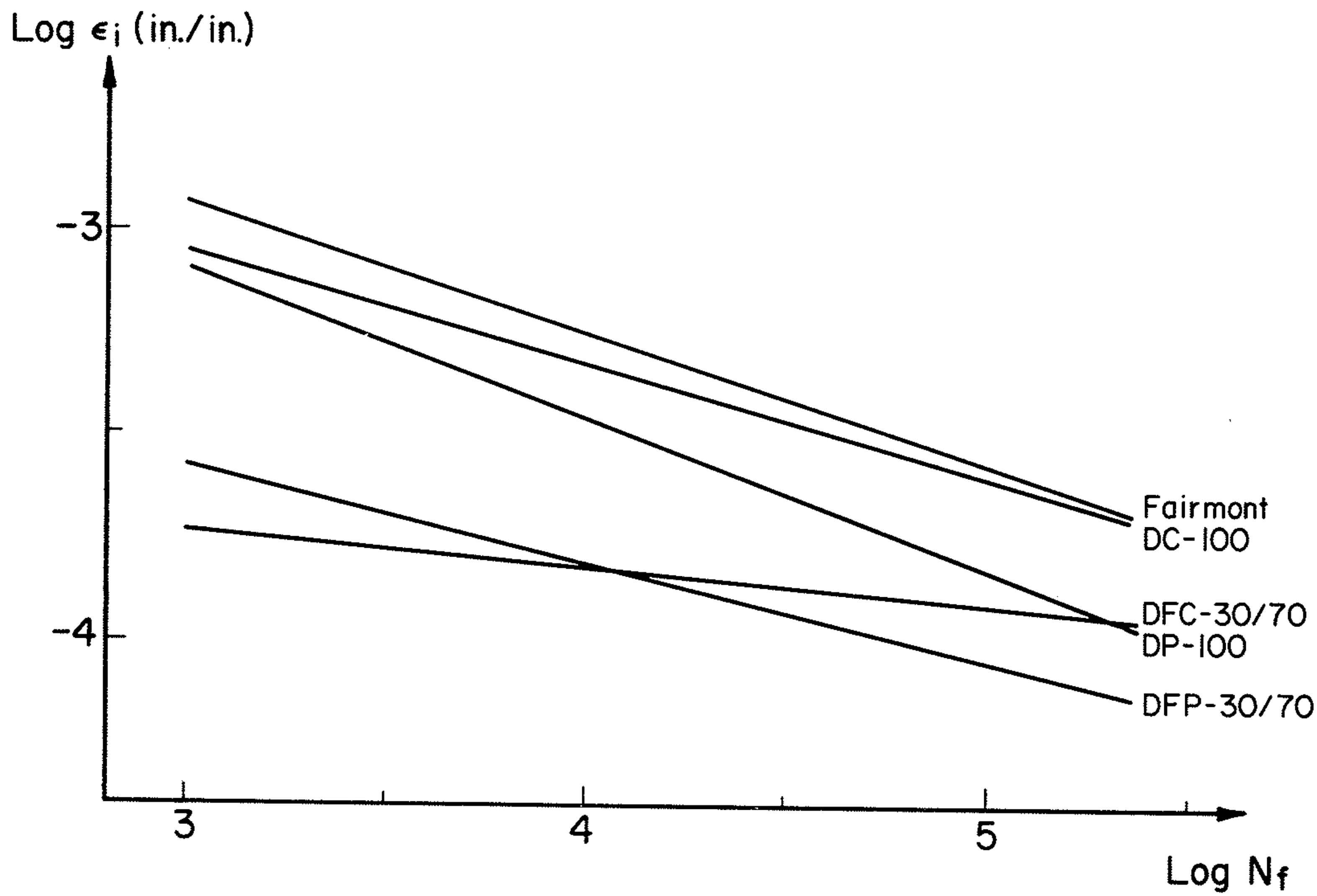


Figure 3-1 Fatigue Curves for All New Mix and Decatur Recycled Blends.

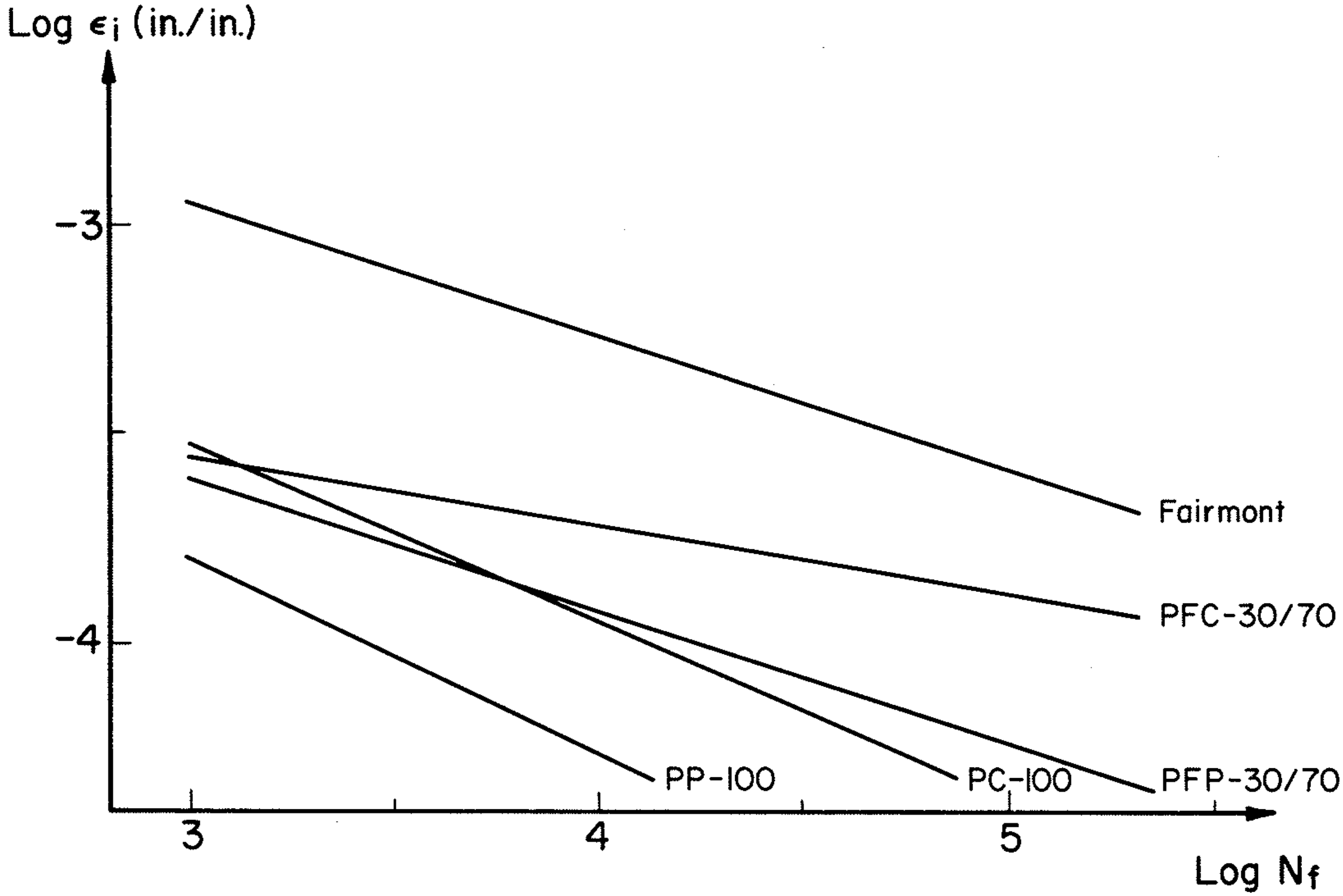


Figure 3-2 Fatigue Curves for All New Mix and Peoria Recycled Blends.

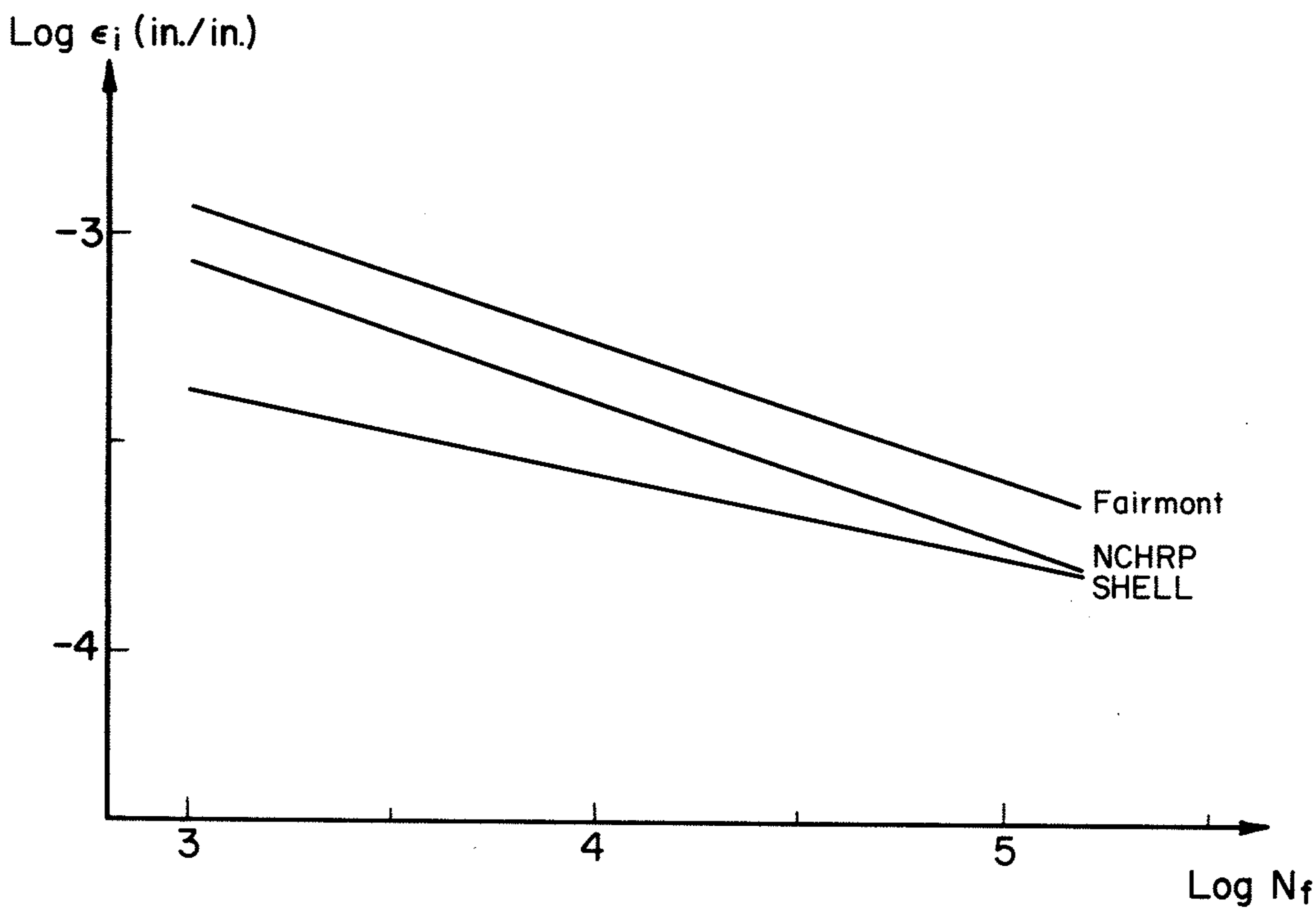


Figure 3-3 Fatigue Curves for All New Mix.

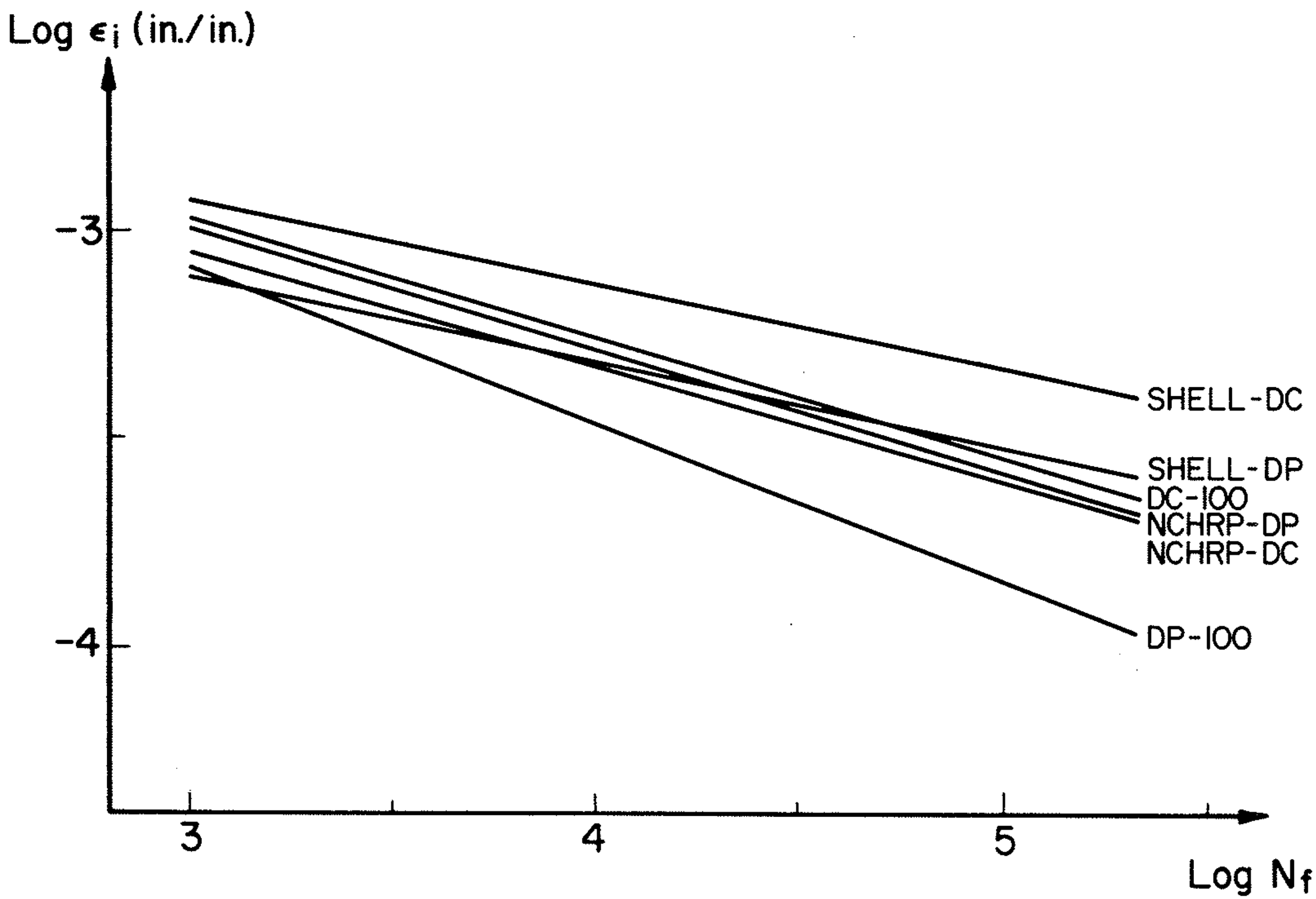


Figure 3-4 Fatigue Curves for 100% Decatur Recycled Mixes.

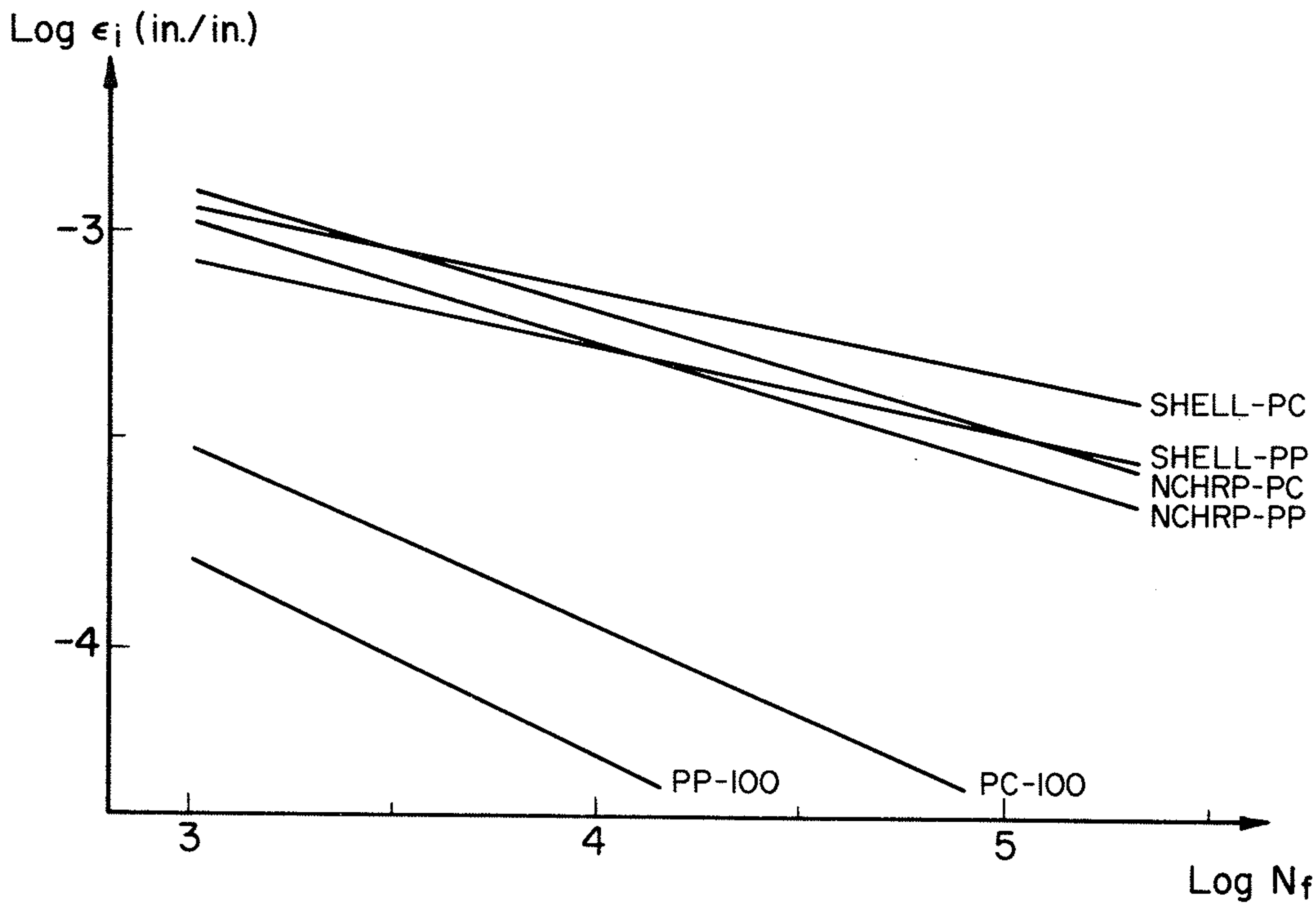


Figure 3-5 Fatigue Curves for 100% Peoria Recycled Mixes.

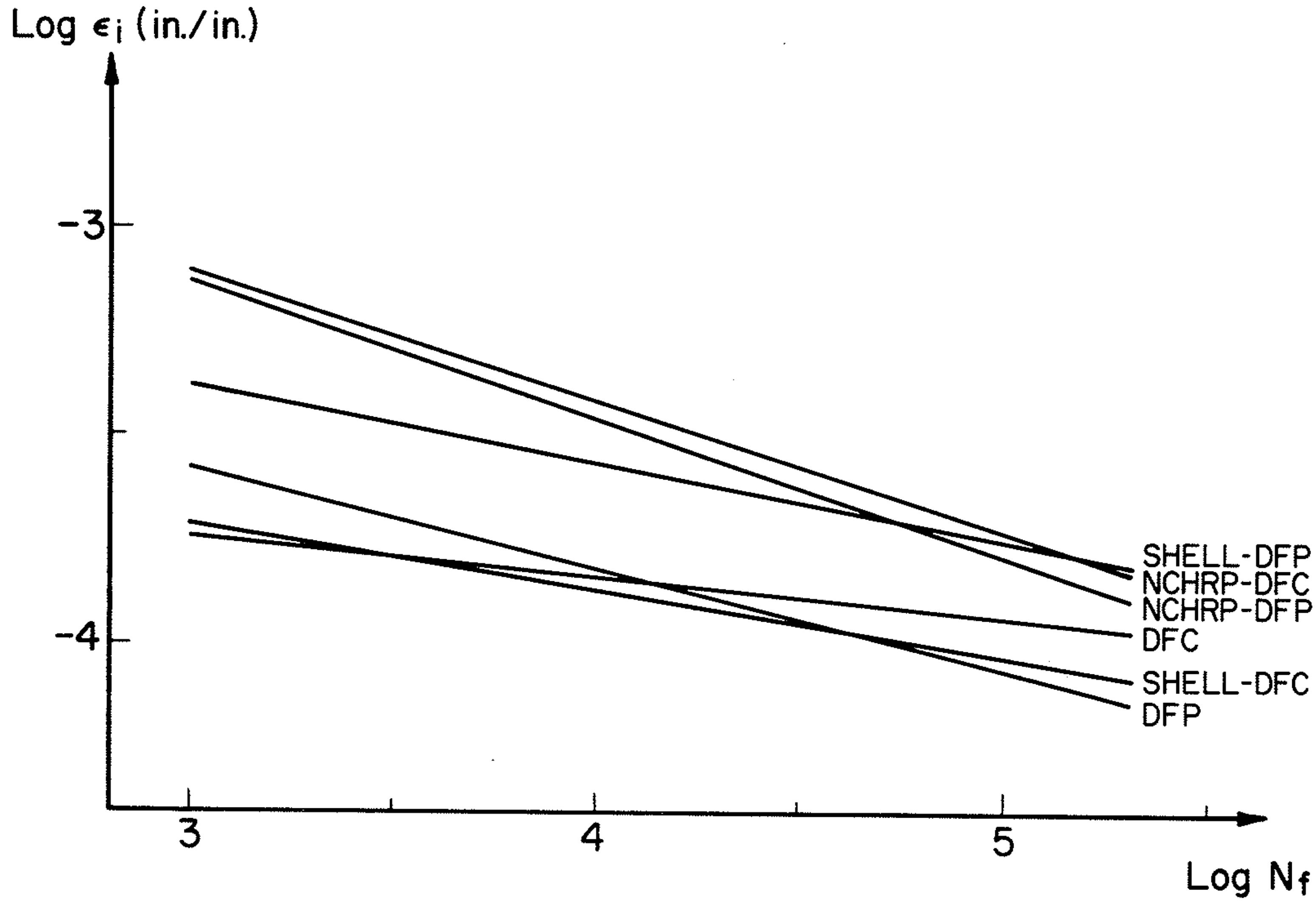


Figure 3-6 Fatigue Curves for 30/70 Decatur-Fairmont Recycled Blends.

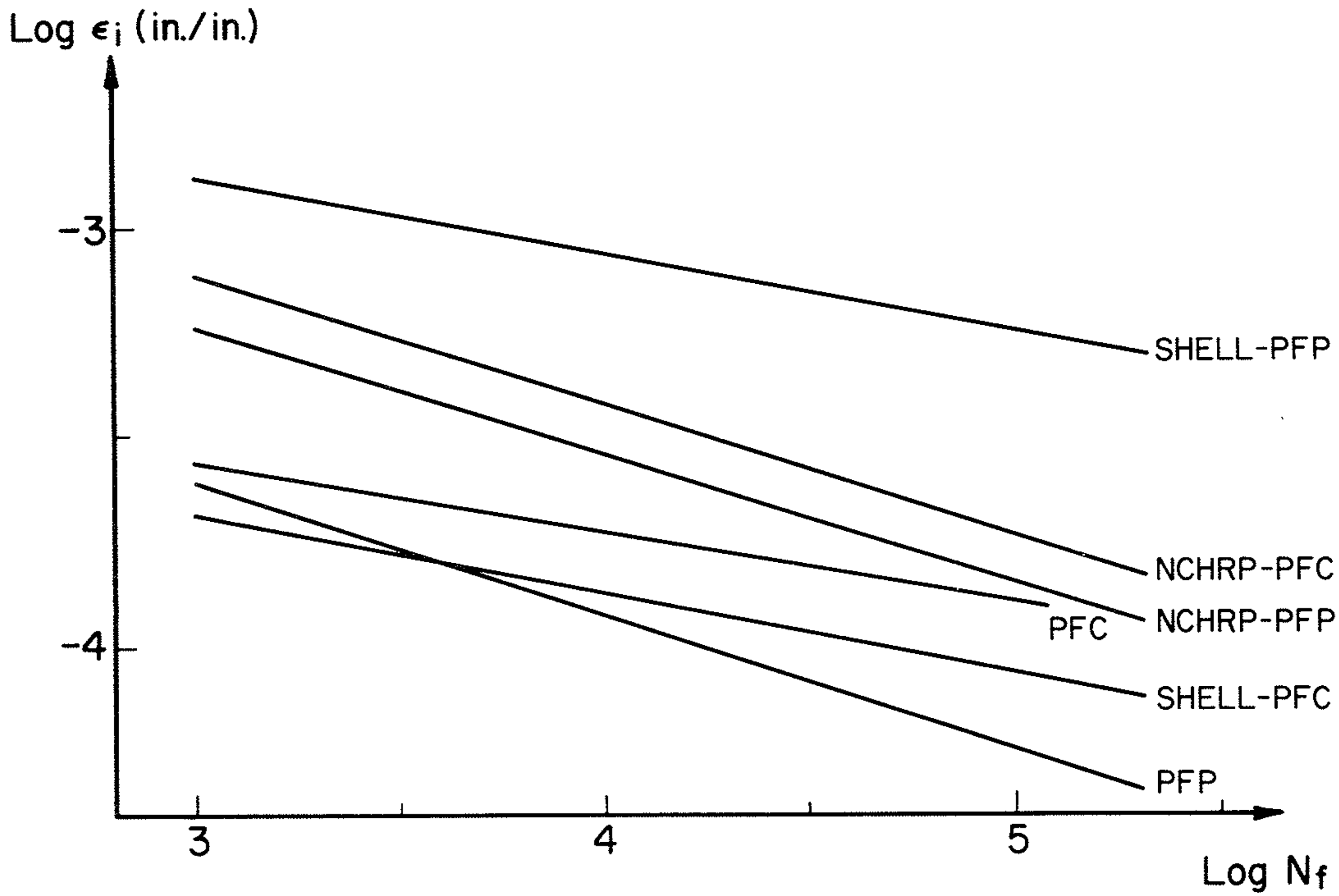


Figure 3-7 Fatigue Curves for 30/70 Peoria-Fairmont Recycled Blends.

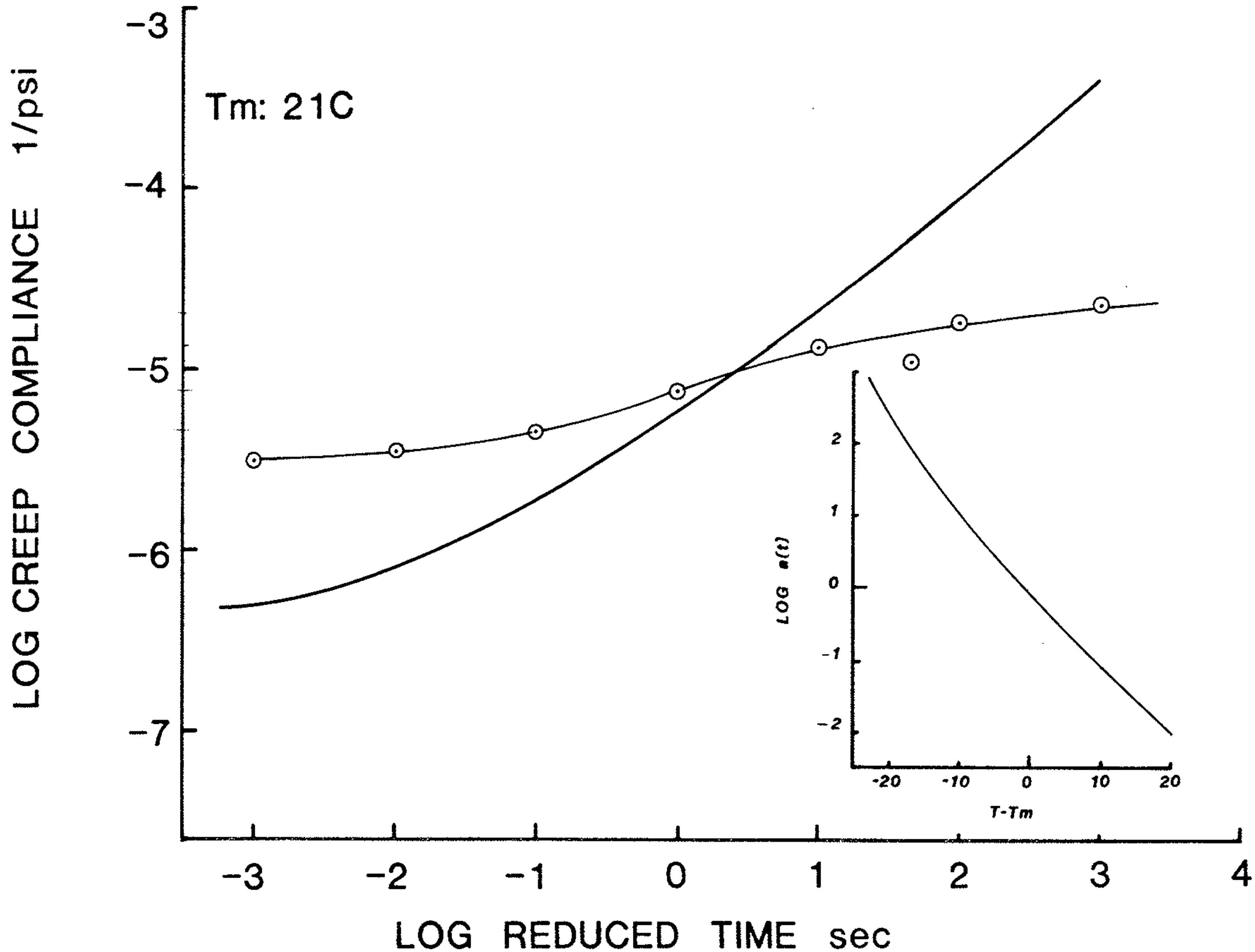


Figure 3-8 Compliance Curve for 100-F With a_T Curve Indicated.

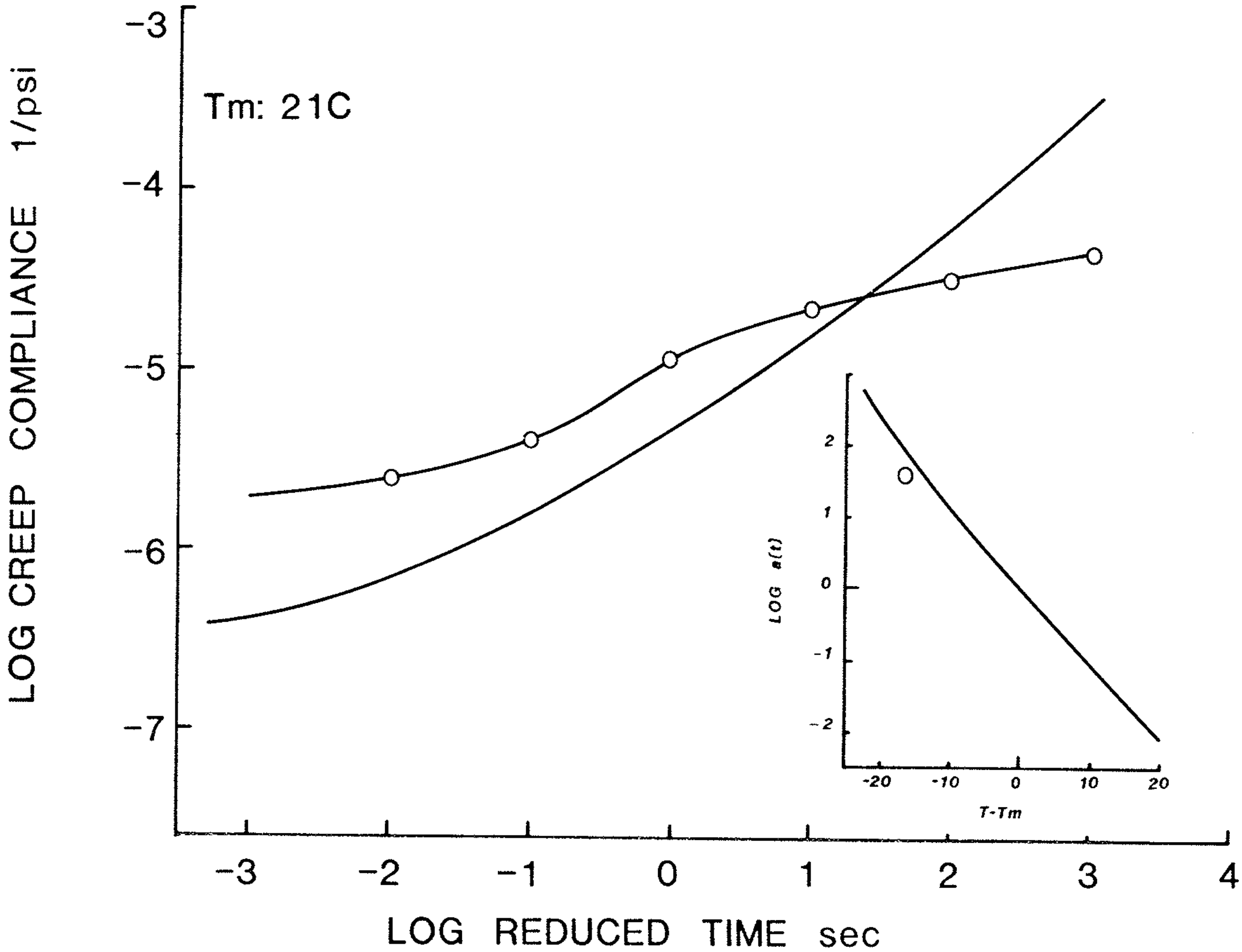


Figure 3-9 Compliance Curve for 30/70 DFC With a_T Curve Indicated.

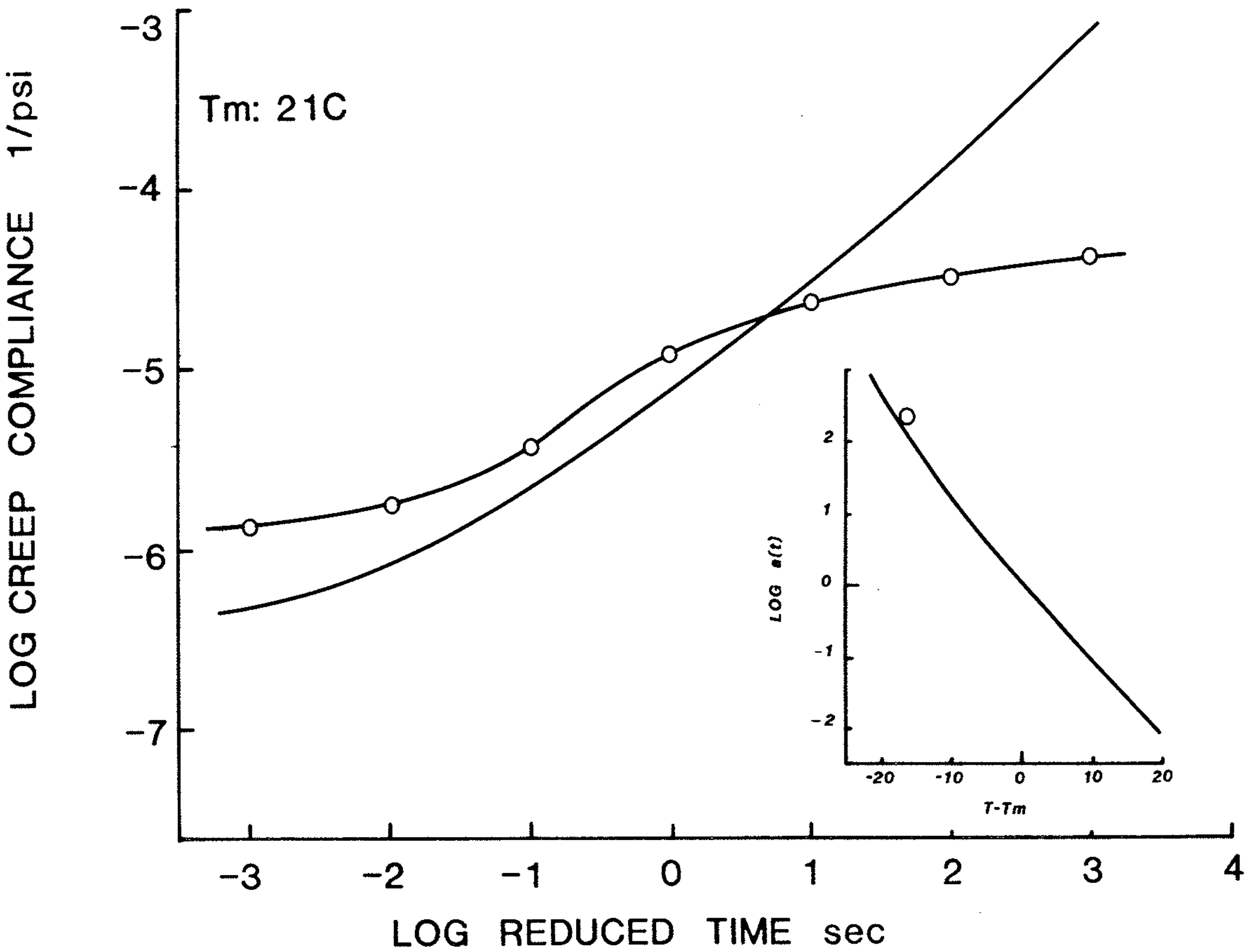


Figure 3-10 Compliance Curve for 30/70 DFPa With a_T Curve Indicated.

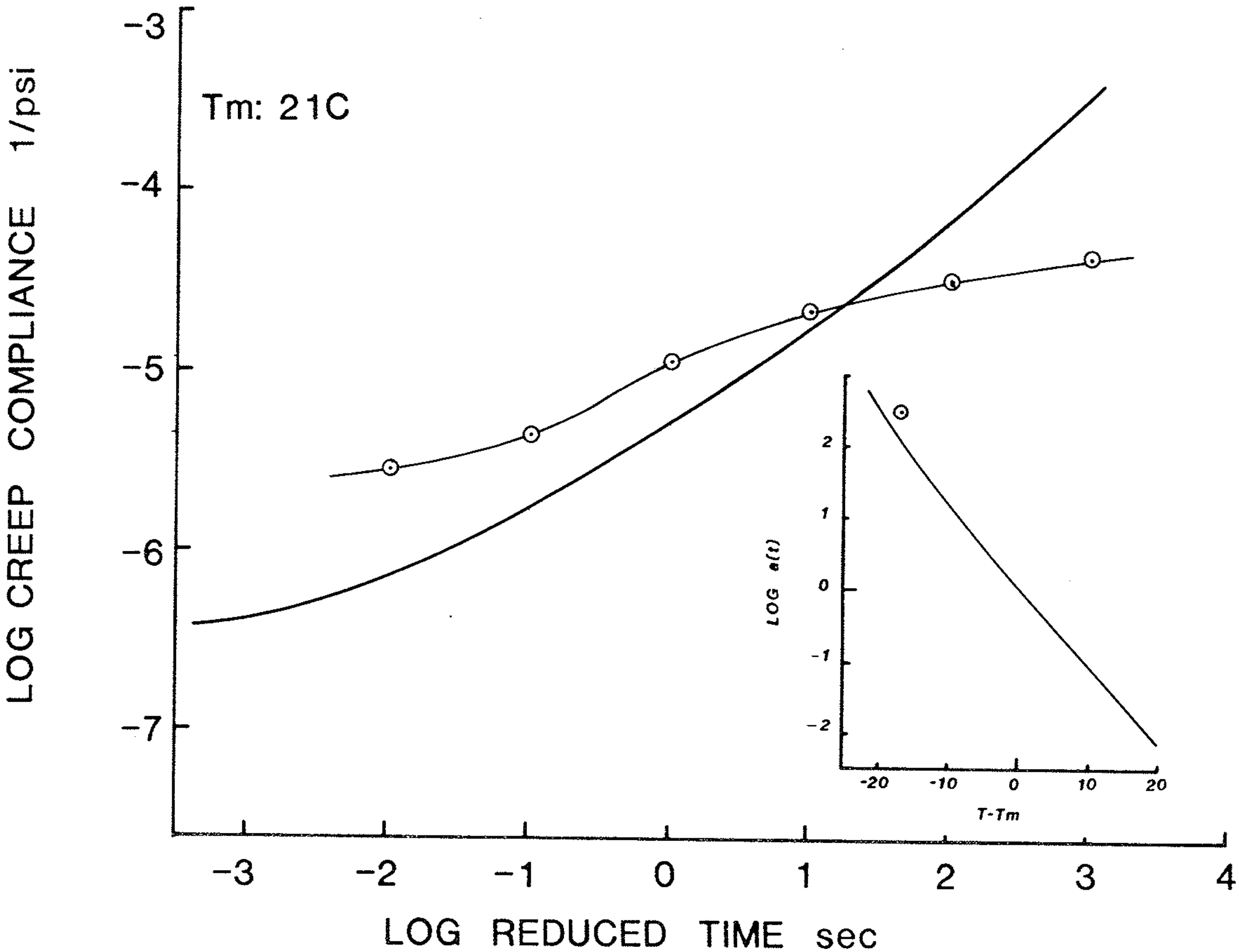


Figure 3-11 Compliance Curve for 30/70 PFC With a_T Curve Indicated.

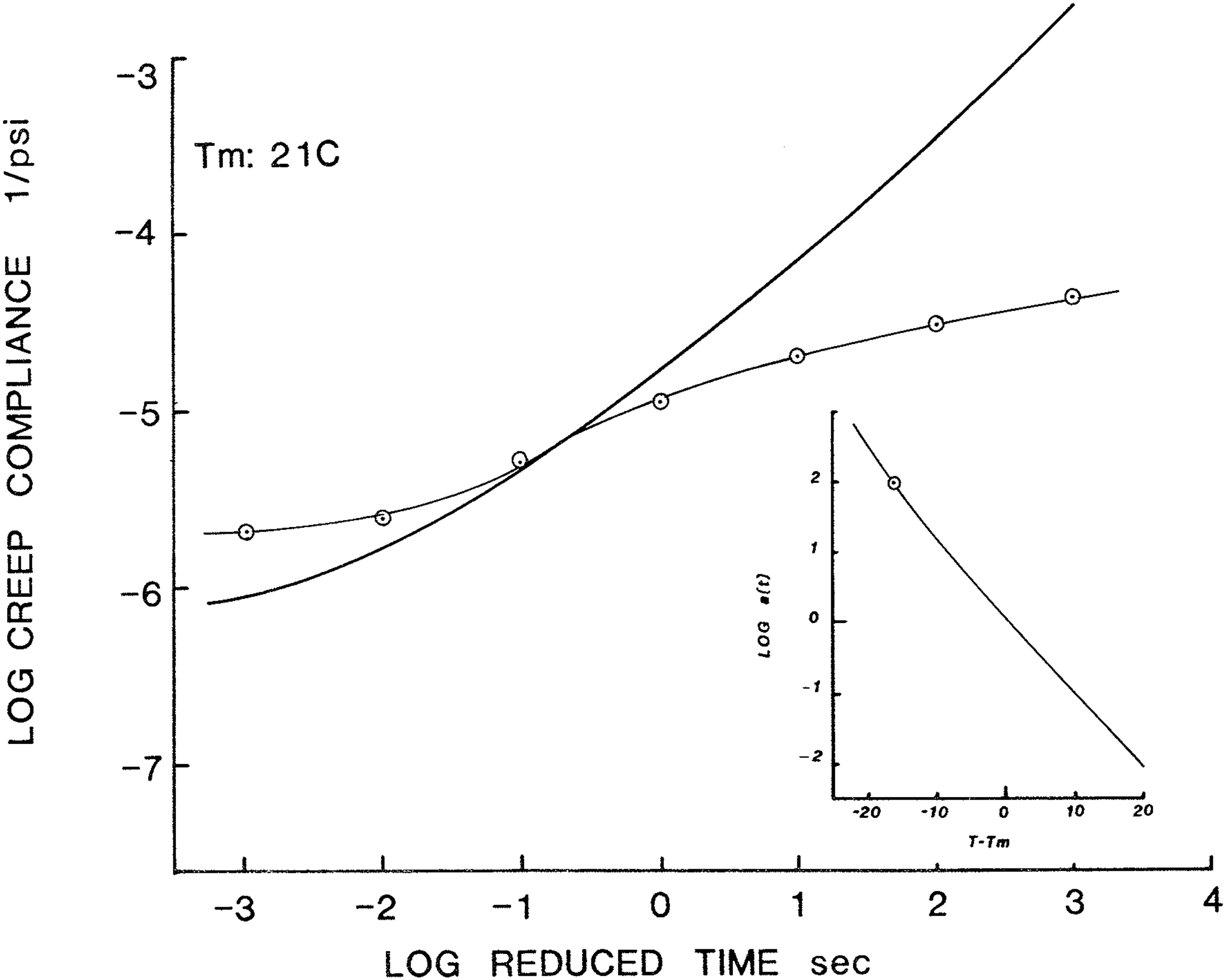


Figure 3-12 Compliance Curve for 30/70 PFPa With a_T Curve Indicated.

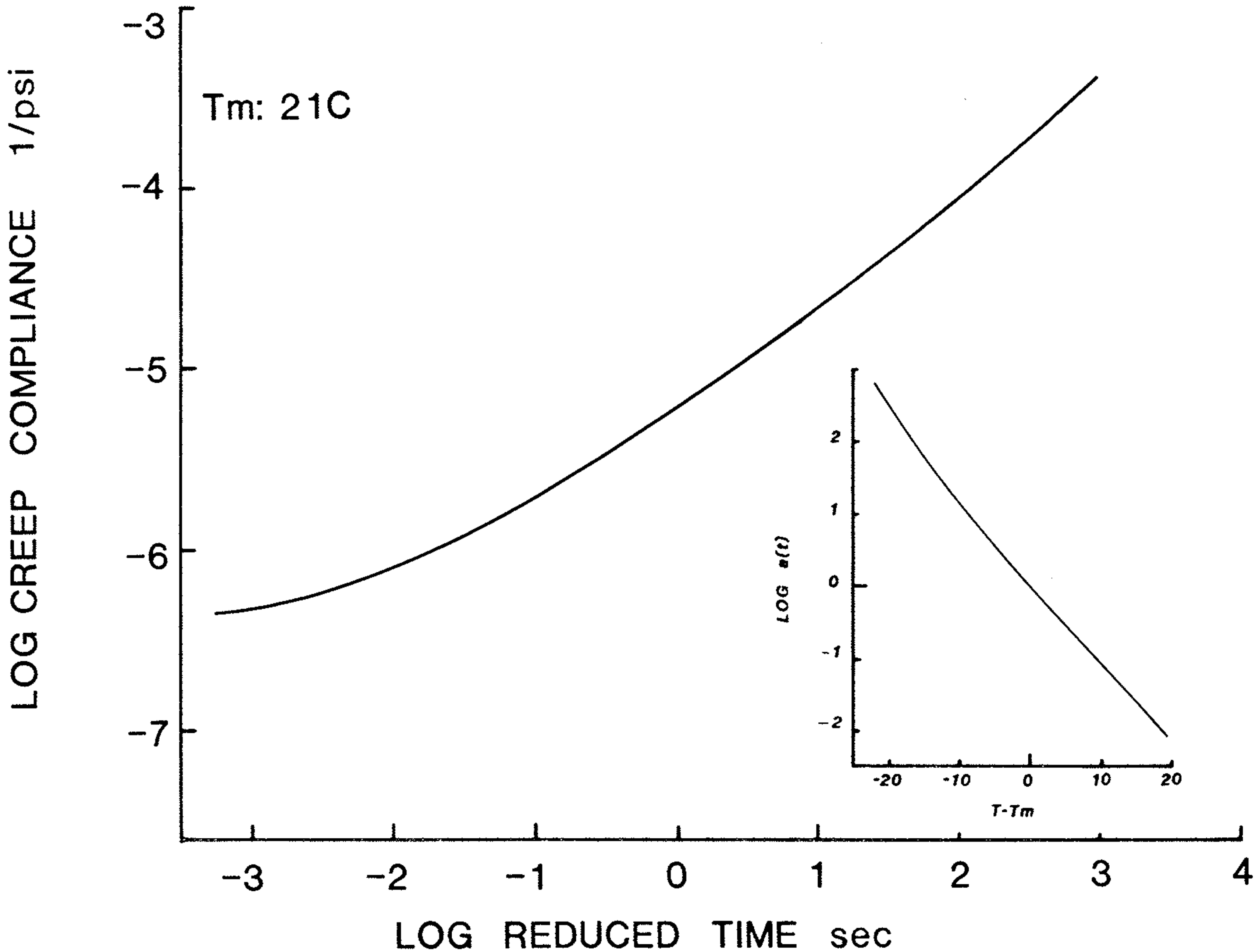


Figure 3-13 Compliance Curve for 50/50 DFC With a_T Curve Indicated.

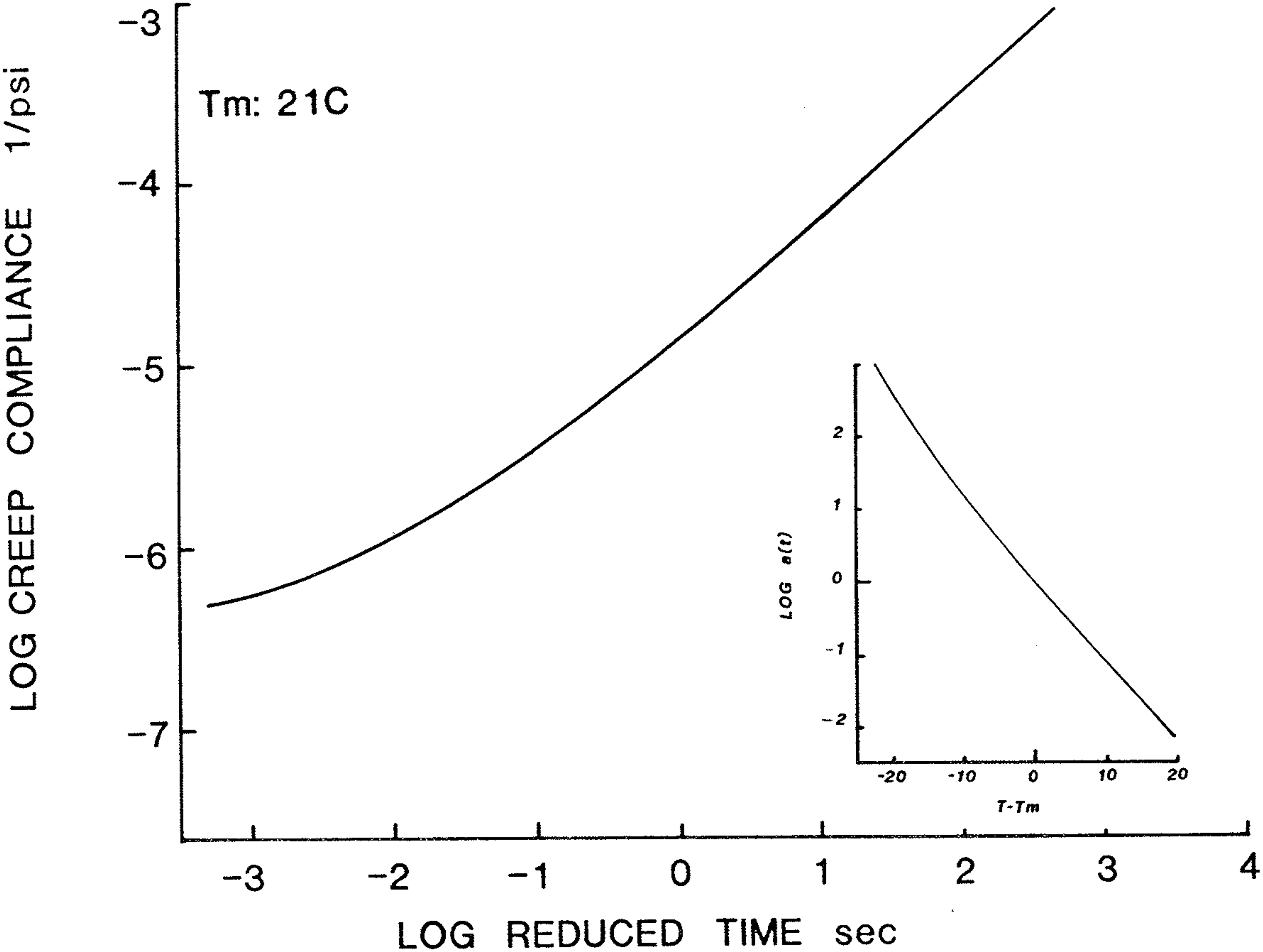


Figure 3-14 Compliance Curve for 50/50 DFPa With a_T Curve Indicated.

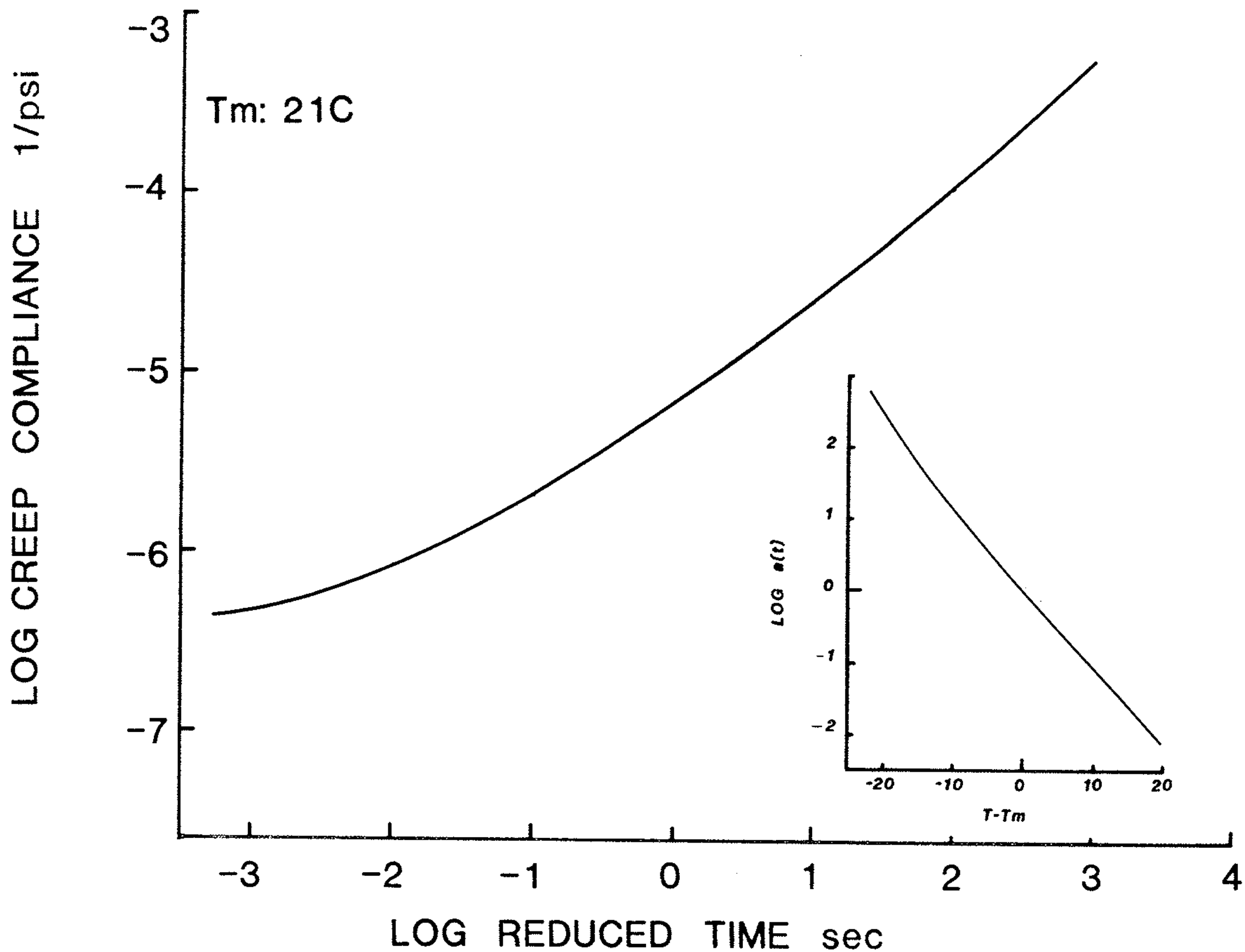


Figure 3-15 Compliance Curve for 50/50 PFC With a_T Curve Indicated.

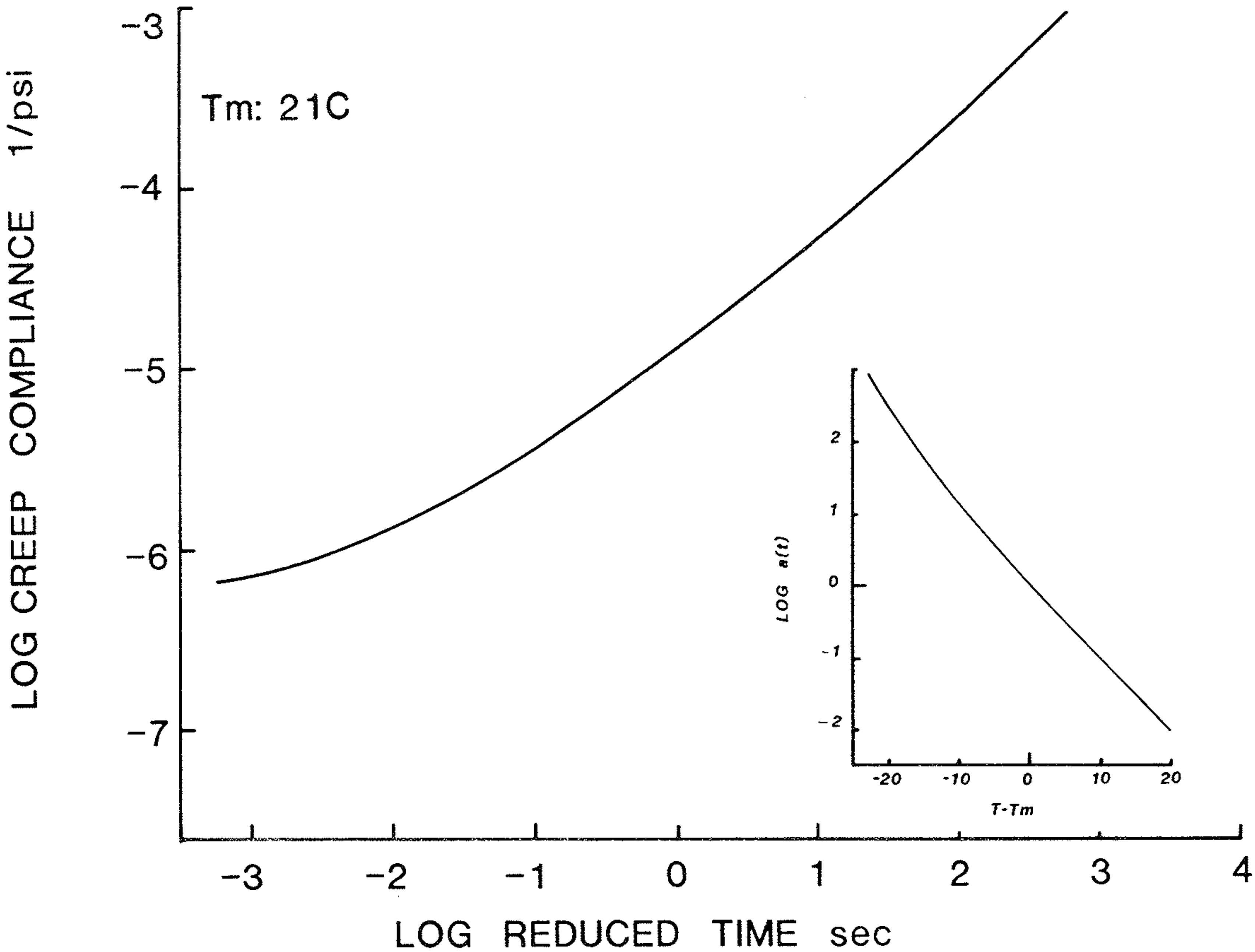


Figure 3-16 Compliance Curve for 50/50 PFPa With a_T Curve Indicated.

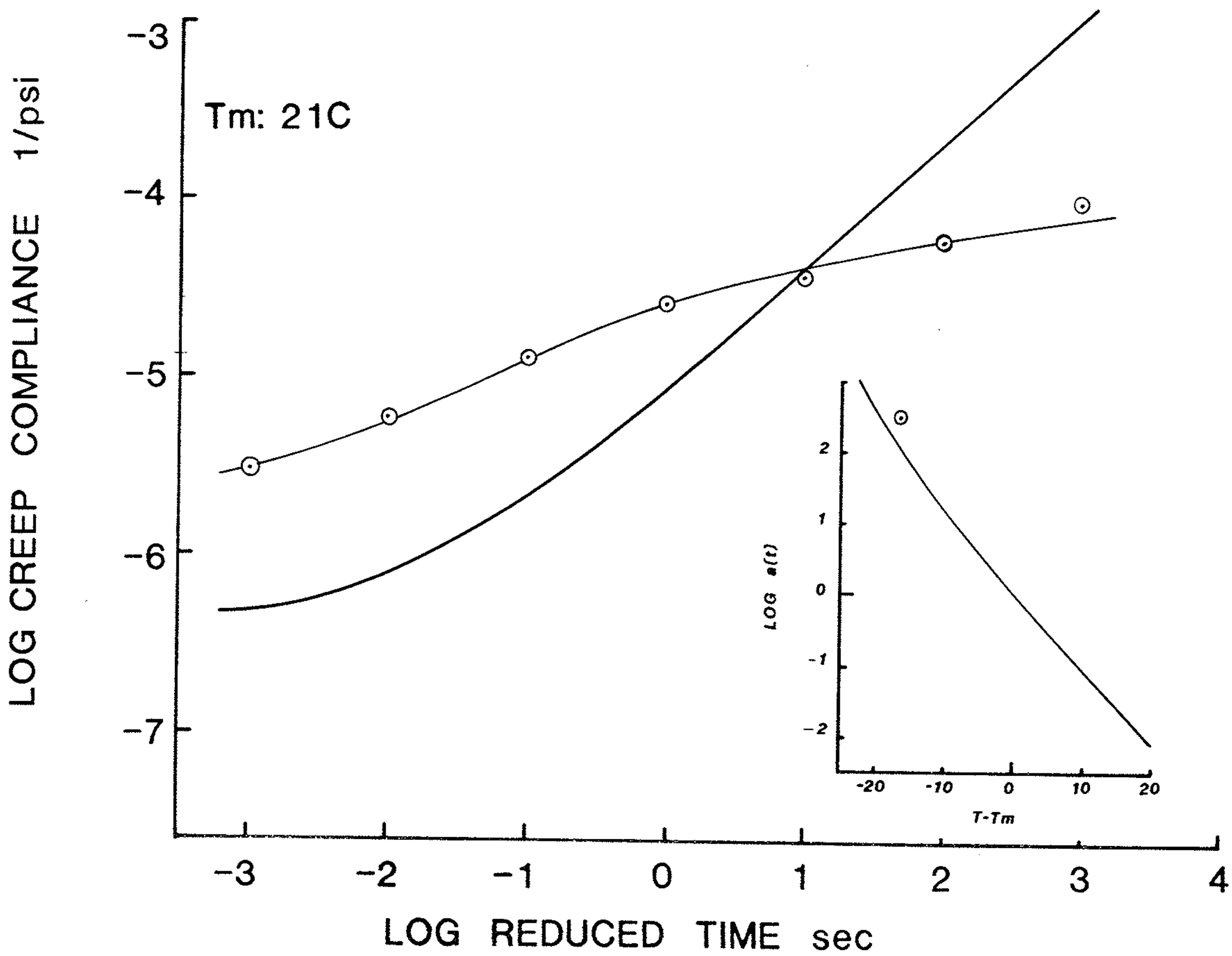


Figure 3-17 Compliance Curve for 100-DC With a_T Curve Indicated.

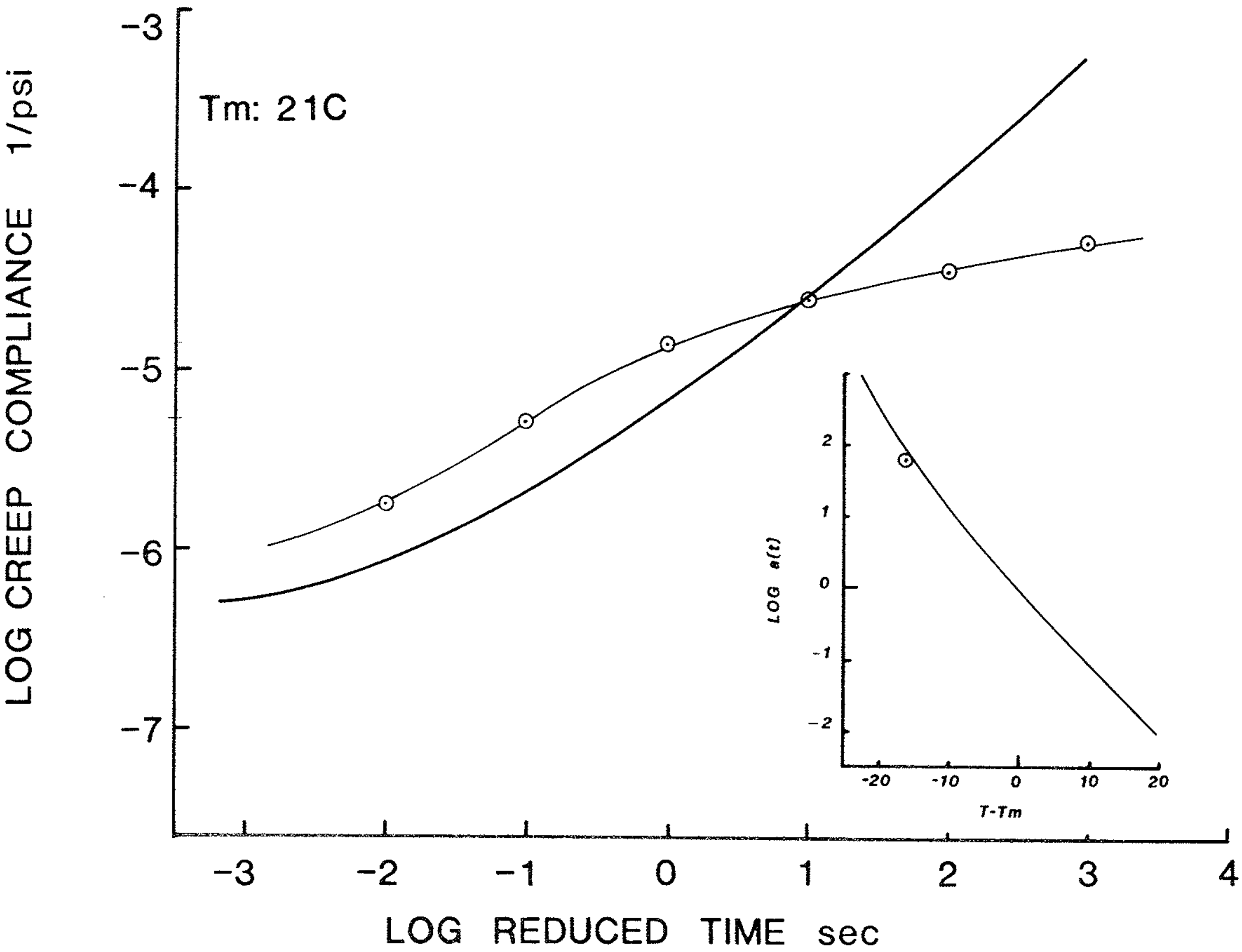


Figure 3-18 Compliance Curve for 100-DPa With a_T Curve Indicated.

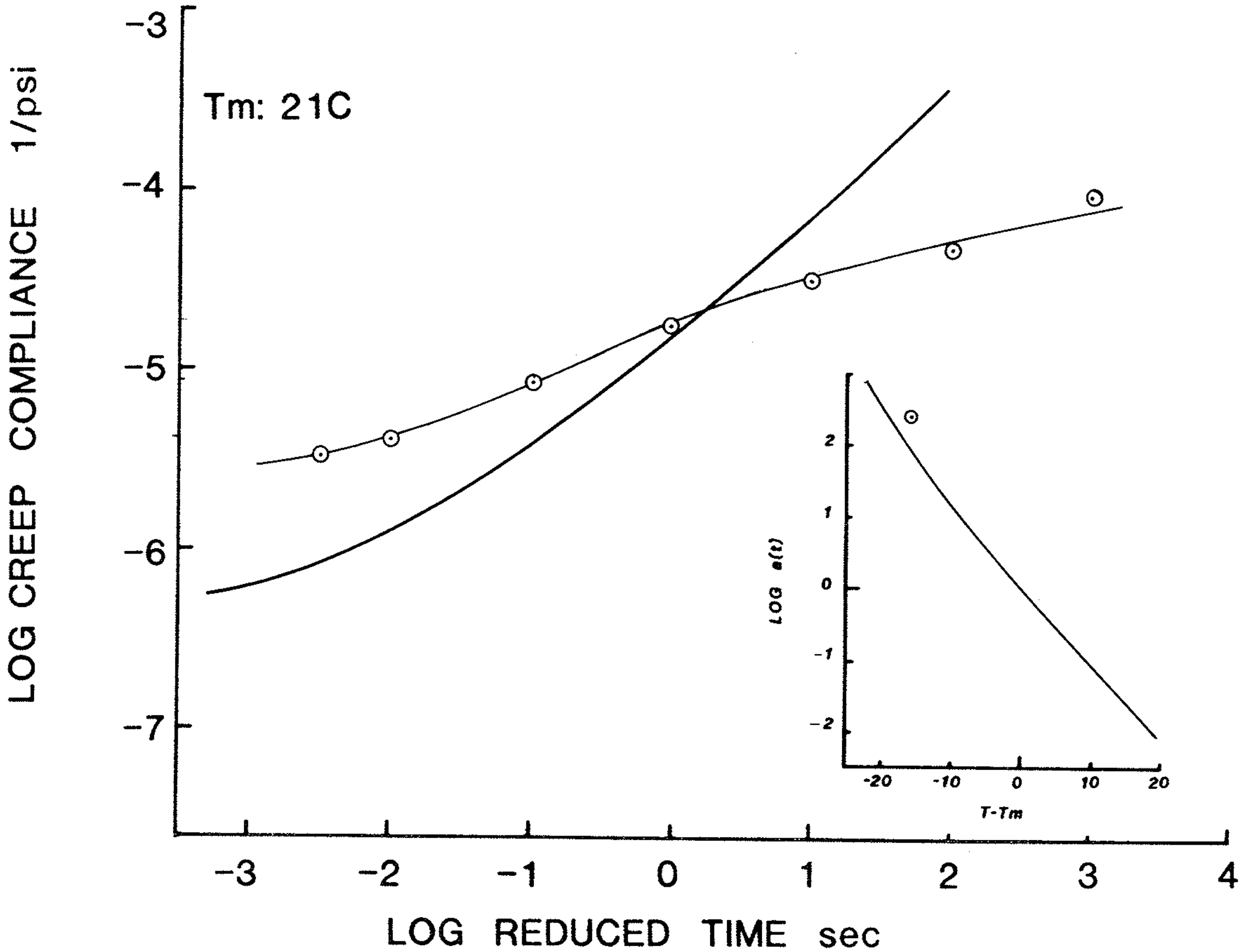


Figure 3-19 Compliance Curve for 100-PC With a_T Curve Indicated.

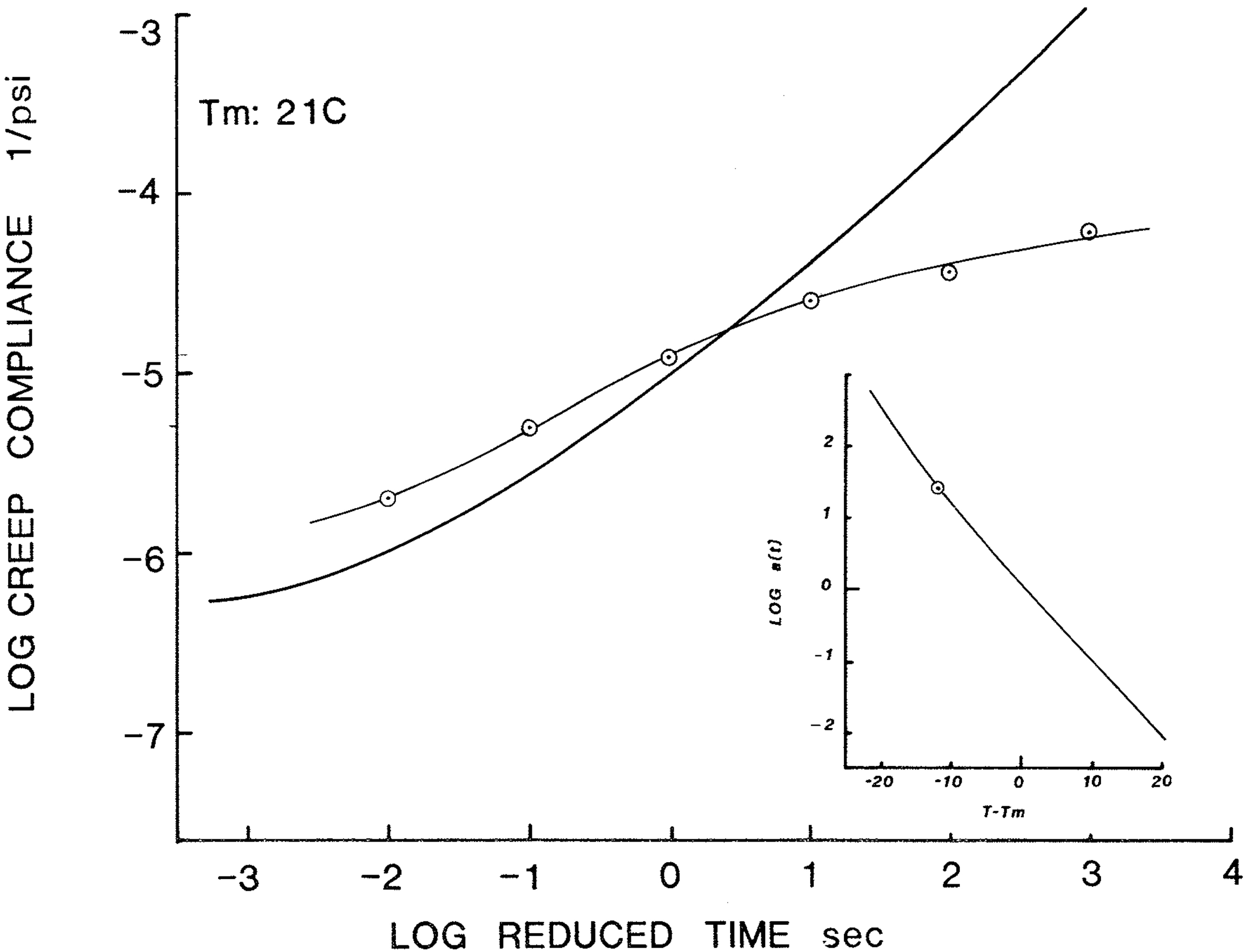


Figure 3-20 Compliance Curve for 100-PPa With a_T Curve Indicated.

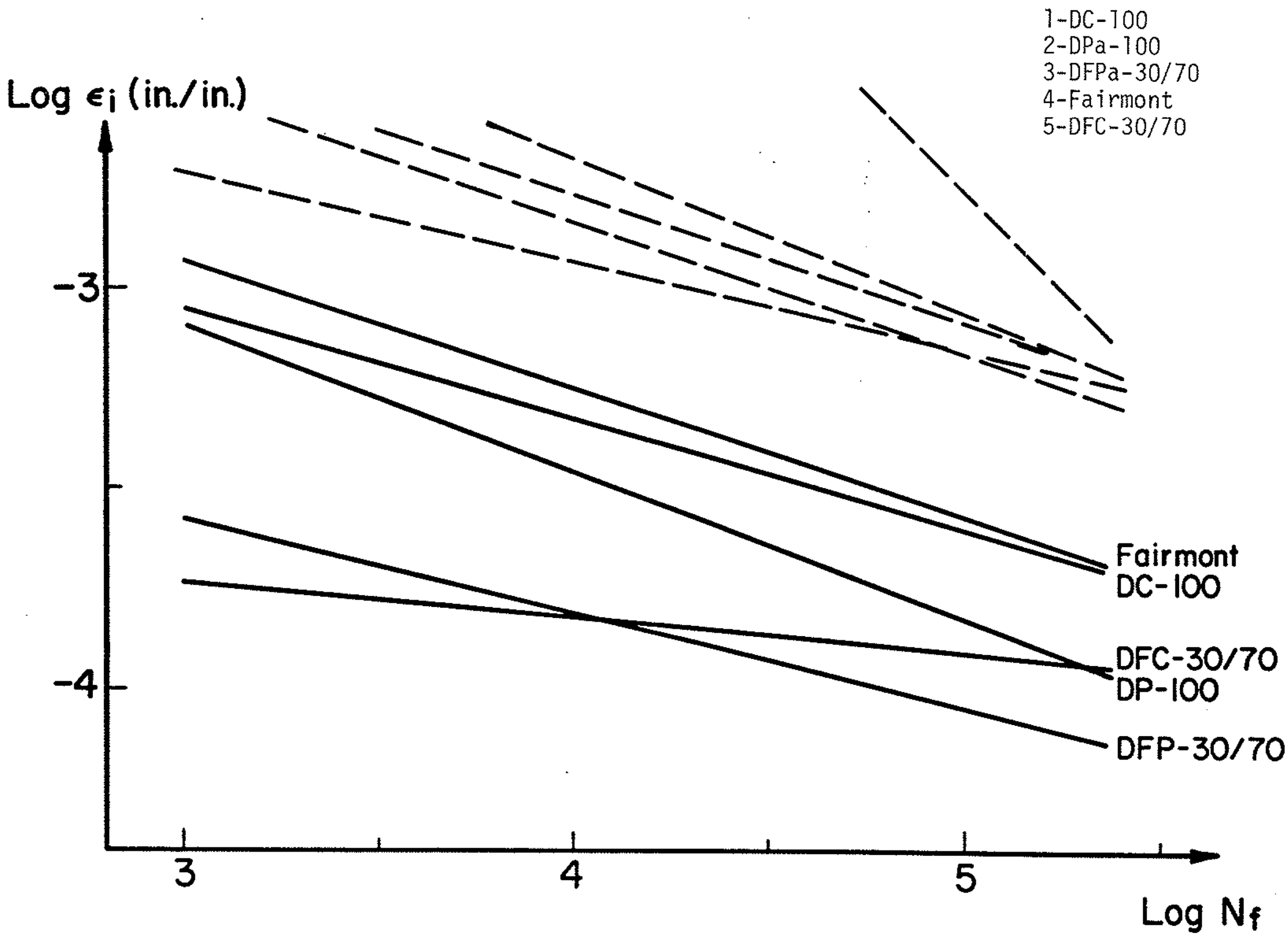


Figure 3-21 Fatigue Curves for All New Mix and Decatur Recycled Blends, With Maupin's Equation Curve Superimposed.

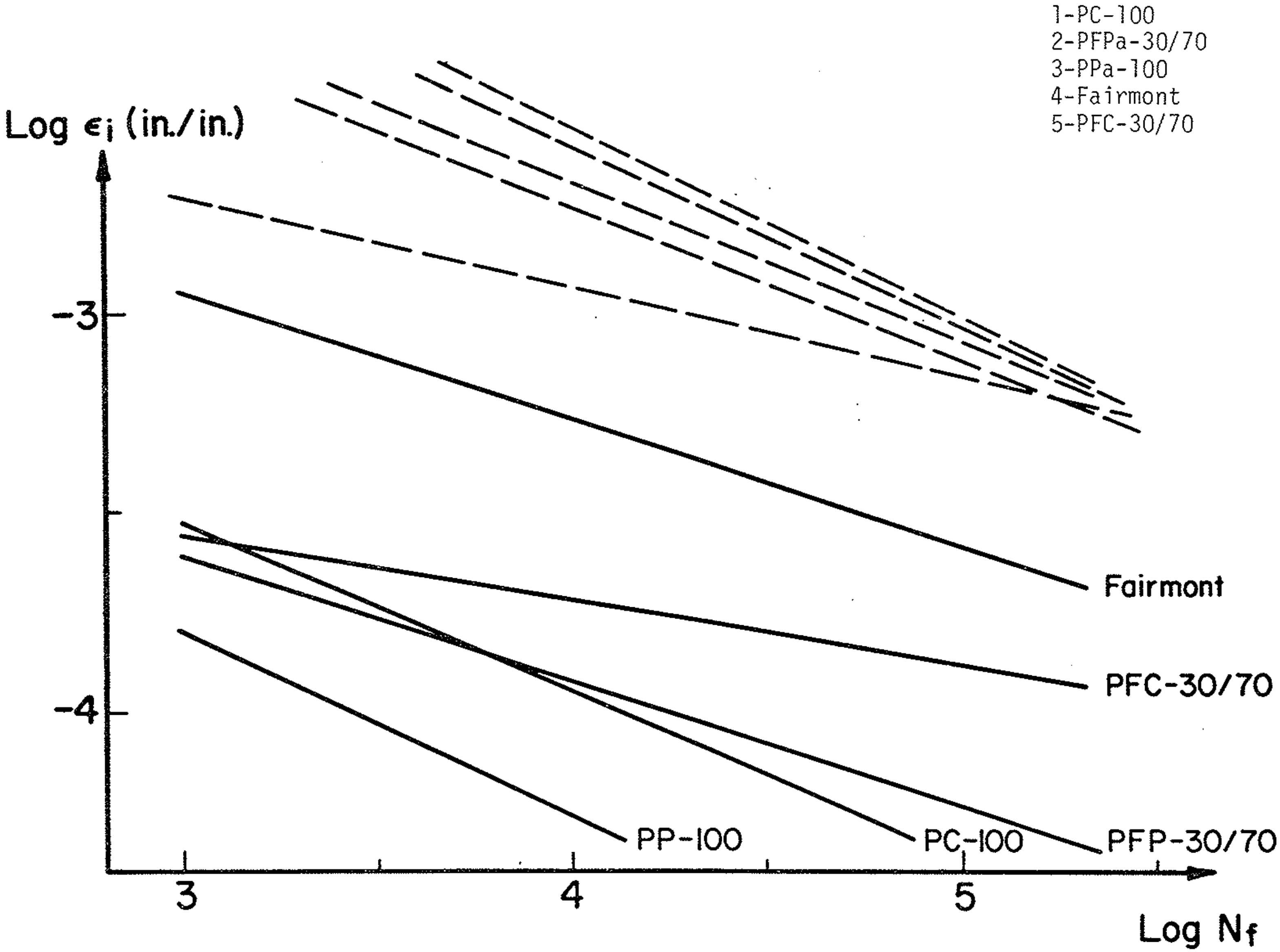
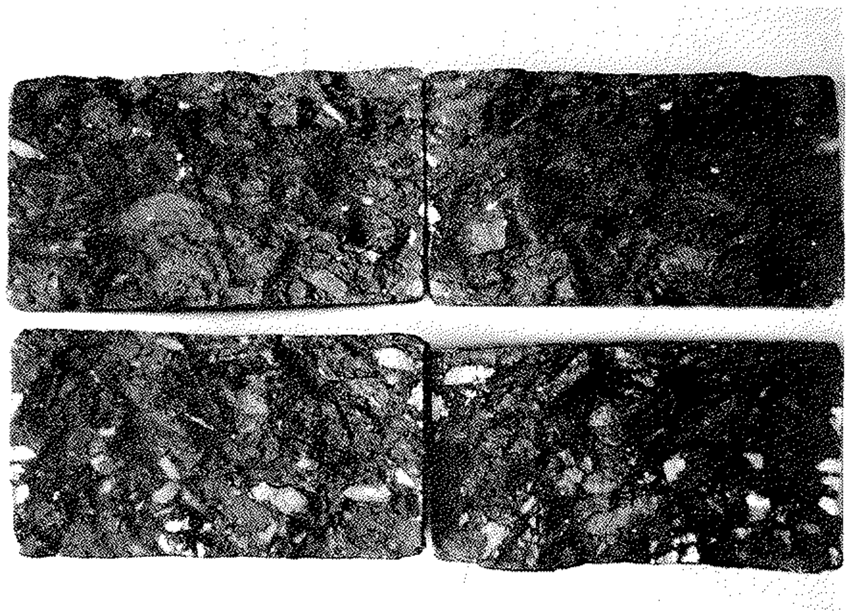


Figure 3-22 Fatigue Curves for All New Mix and Peoria Recycled Blends, With Maupin's Equation Curve Superimposed.



Top

Normal Core Before
Stripping Evaluation

Bottom

Top

Core After Stripping
Evaluation by Lottman Procedure

Bottom

Figure 3-23 Stripped Condition of I-70 Cores.

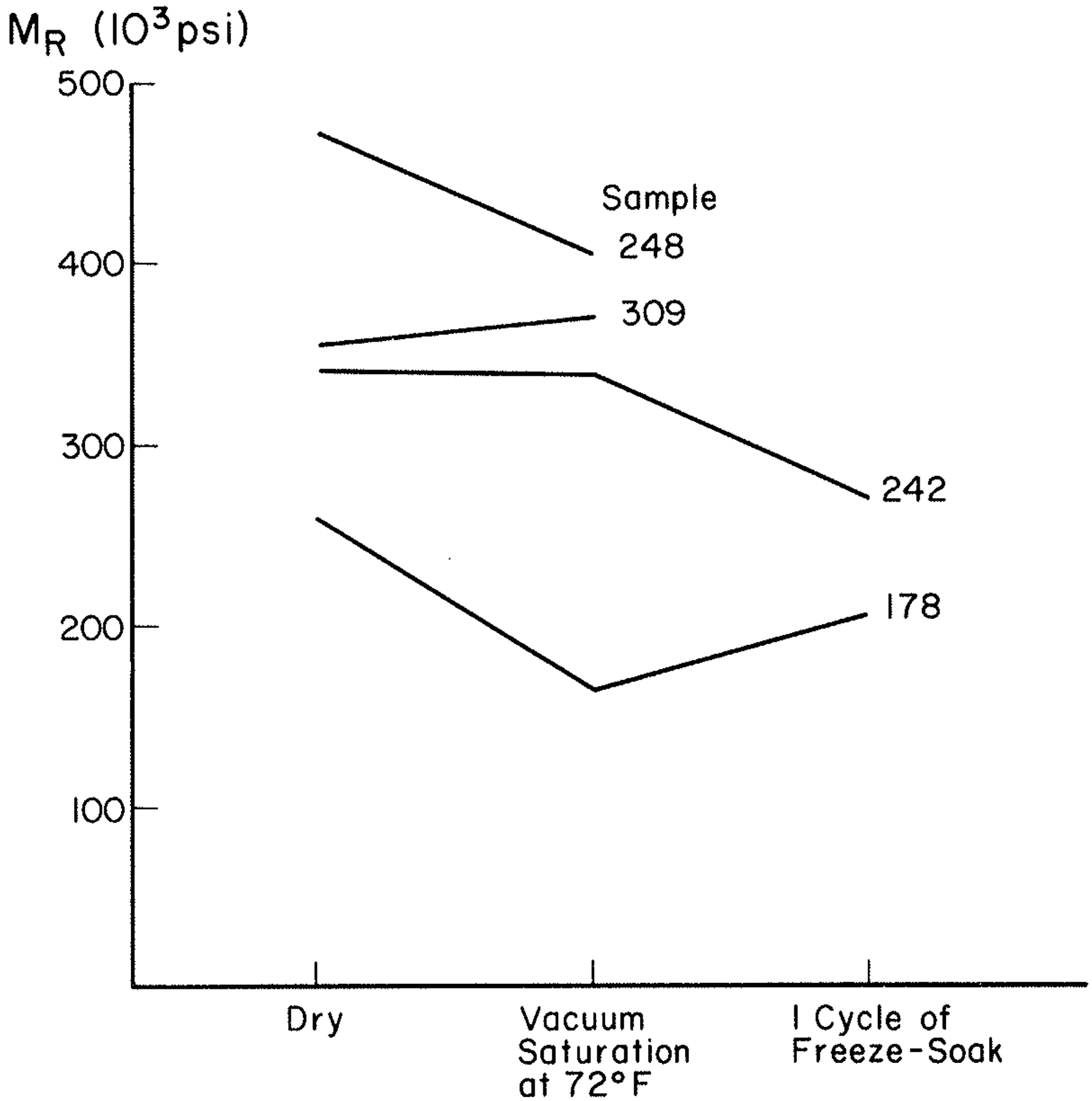


Figure 3-24 Resilient Modulus Change After Lottman Procedure for the I-70 Overlay Cores.

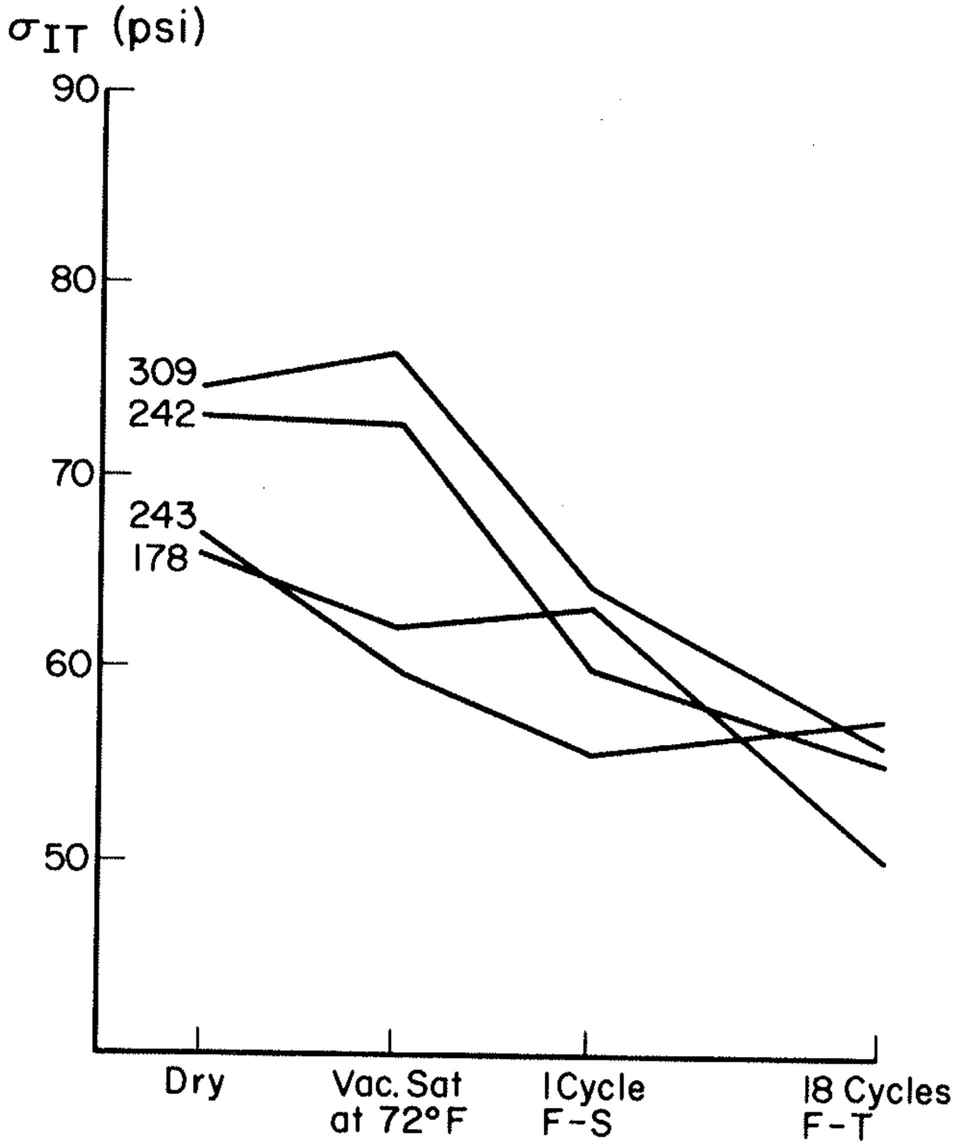


Figure 3-25 Indirect Tensile Strength After Lottman Procedure for I-70 Overlay Cores.

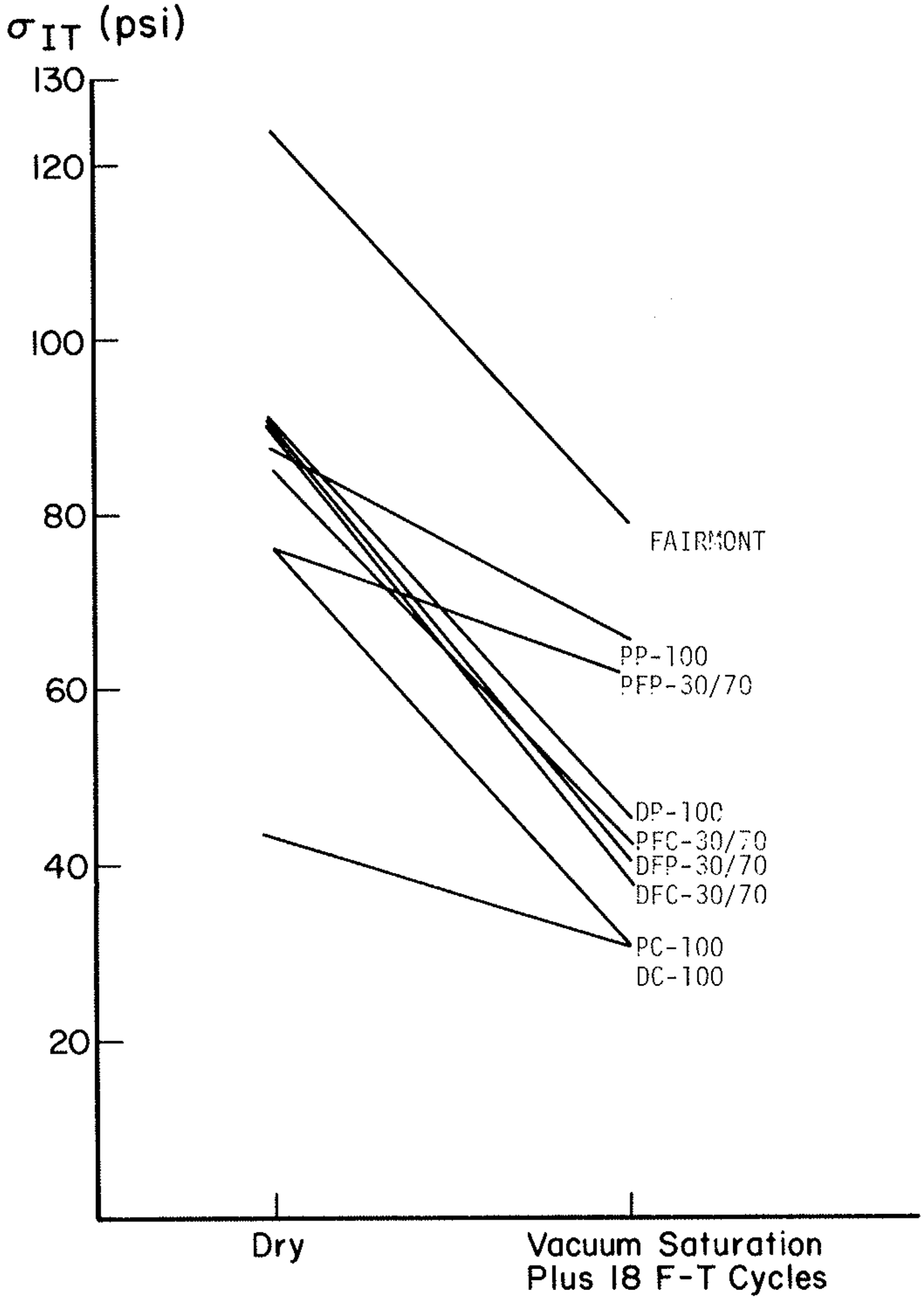


Figure 3-26 Indirect Tensile Strength After Lottman Procedure for Recycled Mixes.

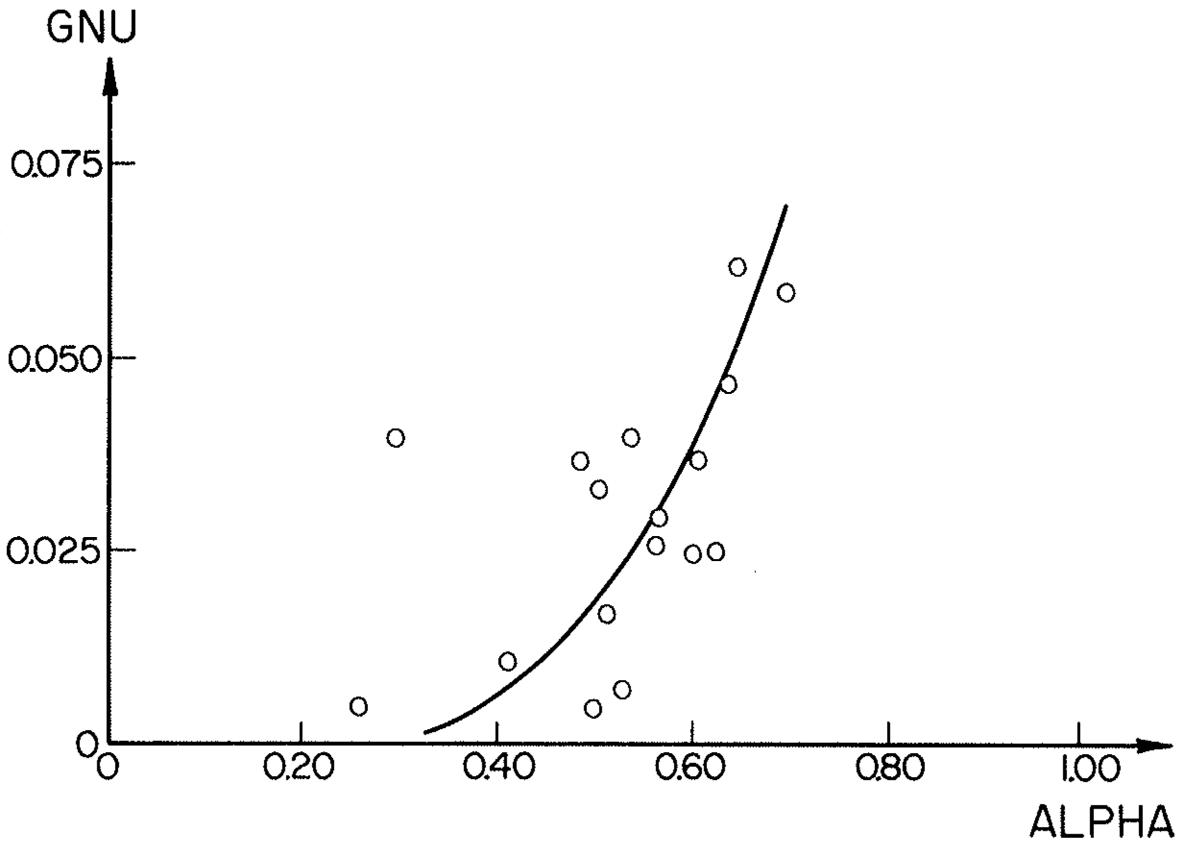


Figure 3-27 Relation between ALPHA and GNU for all Mixes.

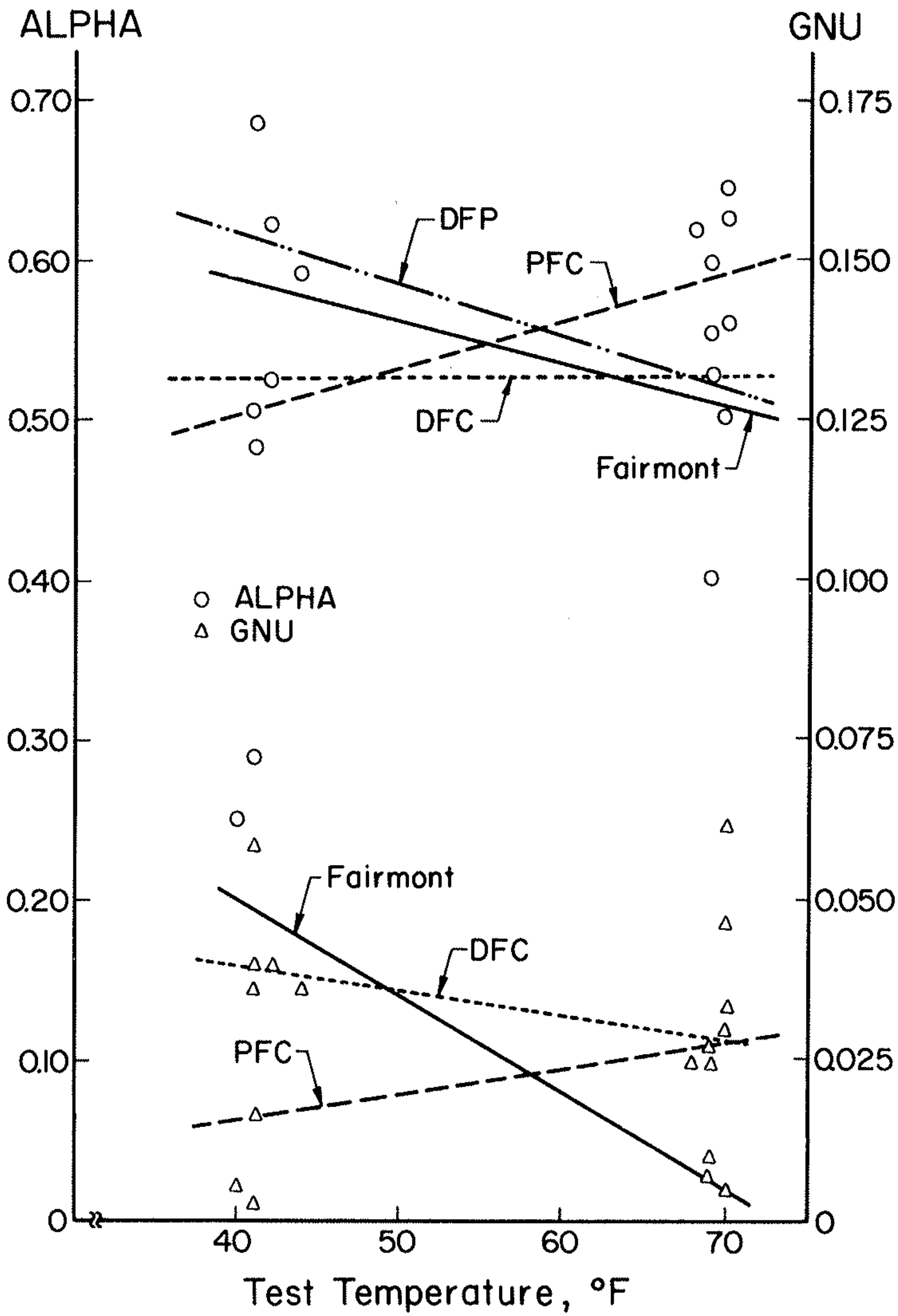


Figure 3-28 ALPHA and GNU as a Function of Temperature.

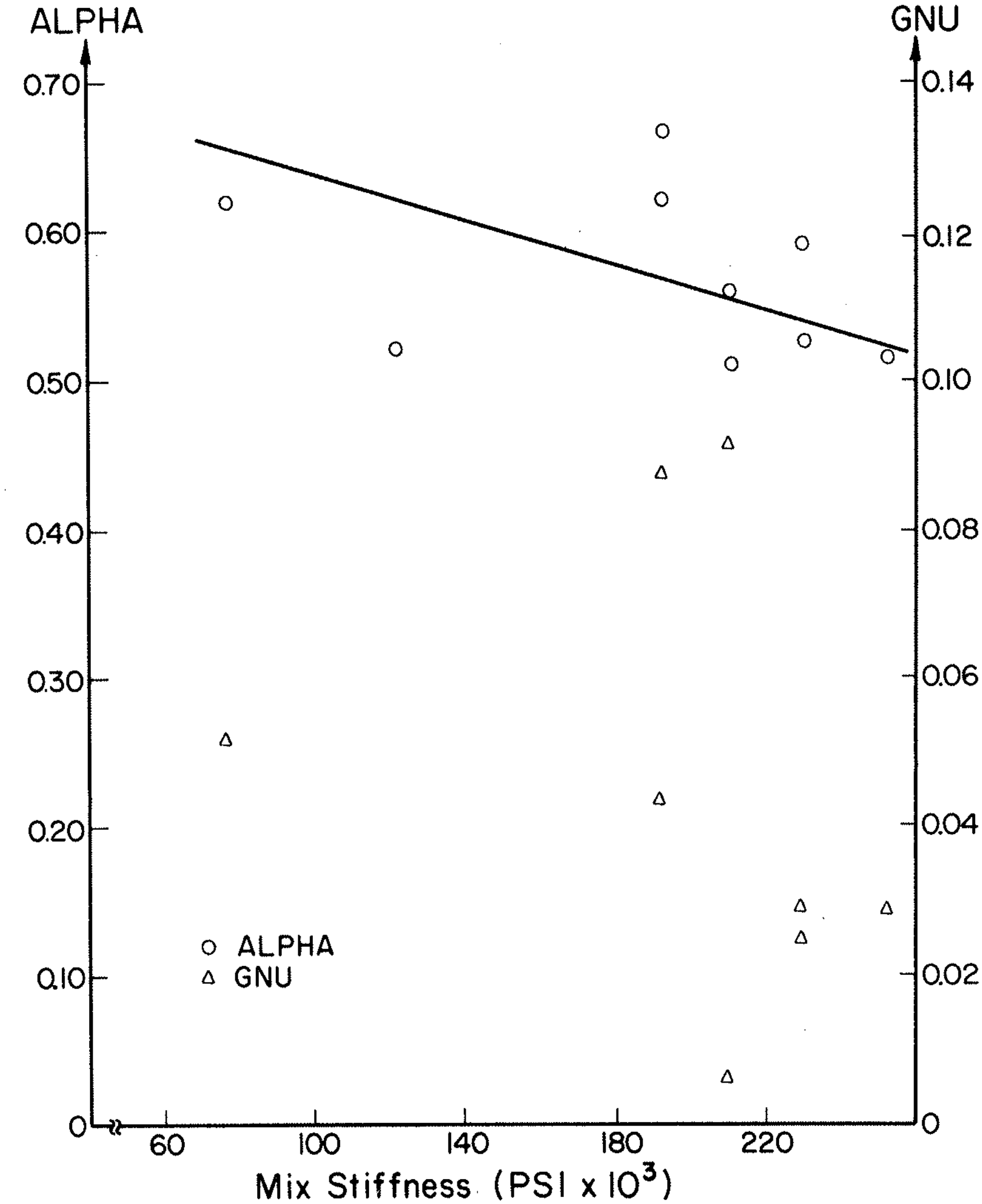


Figure 3-29 ALPHA and GNU versus Mix Stiffness.

CHAPTER 4
DISCUSSION OF LABORATORY RESULTS

The extensive laboratory testing conducted on the recycled materials described in the previous section provide data illustrating the differences between an all new material mixture and a recycled mixture. The differences seen between the test data show how these mixes could perform in the field. The actual field performance comparisons will be made in the next section of the report, but the lab differences will be discussed here.

The Marshall mixture design procedure (13) indicated that differences in mixture properties could be produced by using different materials and recycling agents. These properties were similar to those of a mixture prepared using all new materials, but they did show a large degree of variability that would indicate that a mixture with acceptable mix parameters could have very different performance characteristics.

Fatigue

The flexural fatigue tests on the incomplete 50/50 blend and the 30/70 blends did not show any appreciable differences given the scatter of the data. The actual curves indicate that the fatigue life for these mixes is not up to the standard values associated with a quality mixture as commonly reported in the literature (3,8). The prediction schemes utilizing asphalt cement properties and mix properties produced fatigue curves that were similar to the curves obtained from the laboratory testing program which indicates that the curves may be representative of the actual fatigue behavior of the mixes.

The prediction of fatigue life using Maupin's indirect tensile relationship showed no relationship with the laboratory data due to the low tensile strength of the recycled mixes, and resulting from the problems with the gradual change of strength with the diffusion of the recycling agent.

Stiffness

Stiffness values determined in the relaxation testing produced a range of stiffness as a function of temperature and rate of loading. These data correspond very well with the empirical procedures of commonly accepted nomographs at a standard rate of loading. Differences at extreme temperatures or rates of loading indicate the problems associated with using empirical procedures rather than actual test data. The differences shown in these curves indicates the ability of the mix to perform at high or low temperatures, both of which are important in Illinois, given the prevailing climatic conditions.

The stiffness curves indicate that these recycled mixes are less susceptible to low-temperature cracking than the standard mixture, but will have a lower stiffness at the high temperatures which may lead to higher permanent deformation.

Tensile Strength

The tensile strength data as taken from the indirect tension test showed a great amount of variability. The magnitude of the strengths indicated slightly lower tensile strengths in the recycled mixes. This was especially true in the mixes immediately after preparation due to the diffusion of the recycling agent. The tensile strength started low and gradually increased to its final value.

The low values for tensile strength indicate a slightly higher potential for permanent deformation in the recycled mixes. Attention is called to the all new I-70 mixture that was examined previously which had a very low tensile strength which can be indirectly related to the excessive permanent deformation which resulted on this mixture.

Moisture Susceptibility

The Lottman procedure to accelerate the appearance of moisture problems in the mixture did not produce strength drops of more than the allowable fifty percent, although several mixes did approach this value. The visual examination of the specimens following the freeze-thaw testing did not show any evidence of the onset of stripping. The recycling procedure did not produce a mixture with a higher susceptibility for stripping than a normal mixture.

Permanent Deformation

The analysis of the permanent deformation parameters shows no discernible relationship between mixture variables and potential for permanent deformation. The VESYS analysis for ALPHA and GNU produced results that show the potential for permanent deformation to increase and decrease for the same mixture depending on temperature and stiffness. The overall analysis is that these parameters are not sensitive enough to differentiate between the recycled mixes on a consistent basis for a qualitative comparison. The Decatur mixes demonstrated the closest relationship with the standard mixture representing new construction. The new mixture itself, however, did not produce parameters that could be used in the VESYS program to calculate permanent deformations due th the mathematical limitations inherent in ths program when these two parameters differ widely from the normal values required in the program.

Thermal Cracking

The creep compliance curves and the asphalt cement properties indicate that these recycled mixtures can resist thermal cracking better than an all new mixture, given the properties evaluated in this study. This was clearly demonstrated in the Study presented by Carpenter (17) which evaluated the potential for thermal cracking in surface recycled mixes composed of mixes with properties taken from those presented in this study.

This brief comparison of the laboratory data indicates that on the whole, the recycling process produces mixes with similar properties to those of an all new mixture in most respects. The structural properties indicate that slightly more permanent deformation may be expected with these materials, and a slightly lower fatigue resistance may develop, but the differences appear to be within the expected scatter of data from the testing program. The next section of the report will analyze the individual properties when taken as a whole in a pavement section.

CHAPTER 5

PERFORMANCE PREDICTIONS

This research project was developed to evaluate the long term performance differences between an all new mix and a recycled mixture. The procedures used in this section to compare the behavior of recycled mixes as compared to all new mixes was to design a typical pavement section and obtain the primary responses to load by means of the Elastic Layered System Computer Program (14). The use of the FHWA VESYS computer program was not feasible due to the inability to obtain accurate permanent deformation data. The response parameters (stresses and strains in critical locations) were directly compared and later used for predictions of the fatigue life and permanent deformation.

Pavement Structure

The initial pavement design was done with the AASHTO Interim Guide Method (15). The pavement was designed for Central Illinois conditions and for three traffic levels. The Equivalent 18 kip single axle load (ESAL) for the design lane are typical of the Illinois Interstate System and are shown in Table 5-1.

The pavement design is a standard flexible pavement with an asphalt concrete surface (all new or recycled materials), crushed stone base and a typical Illinois subgrade. All sections were designed for a life of twenty years under the assigned traffic levels. A summary table of the pavement structures for low, medium and high traffic are presented in Table 5-2.

The designs were verified using The Asphalt Institute Method (16). The results by both methods were similar, with the Asphalt Institute method giving a thinner total section. For medium and high traffic, a design composed of a smaller cross-section was not recommended because its relatively thin structure would require extensive maintenance during its design life.

Response Parameters

The pavement response (strain, stresses and deflections) under a standard 9000 pound single wheel load were computed using the Elastic Layered System program (14) with the design cross sections.

The program parameters used to characterize the pavement model are:

Total load, 9000 pounds,

tire pressure, approximately 70 psi,

moduli of elasticity of each layer,

Poisson's ratio of each layer,

thickness of the surface and base layers.

The properties of the surface layer of each section were changed to correspond to the different mixes under study. This would show any similarities or differences in performance characteristics of the different mixes when placed as surface layers. Also, the recycled mixes were investigated for use as a binder layer with a surface layer composed of all new mix. A summary of the response parameters for the pavements composed of the various recycled materials used as surface and binder layer are given in Tables 5-3 to 5-7.

Mixture stiffness (E_{AC}) as calculated from the laboratory creep compliance data for a temperature of 70°F and a rate of loading of 0.1

seconds is also shown in these tables. A comparison of the modulus of elasticity shows that three out of four of the 30/70 recycled mixtures have slightly higher modulus of elasticity than the 100 Fairmont (Standard Mix). The 100 PPa has the same stiffness as the all new material mix, and the rest show lower values of stiffness. Because the response parameters change in correspondence with the stiffness of the asphalt concrete layer, the variation of the tensile strain will be described here.

The permanent deformation of the total pavement system is primarily a function of the vertical strain or stress on the subgrade. The variation in mixture properties does not appreciably influence this response parameter. The reduction of vertical stress with changing stiffness is marginal. The permanent deformation characteristics of the mixtures as defined by their creep curves and limited data from the interpretation of the VESYS data indicate that these mixes have a slightly higher likelihood for rutting than an all new mix. This would preclude their use as a surface for high trafficked pavement at present.

Table 5-8 shows the tensile strain at the bottom of the bituminous layer for the mixes analyzed. The tensile strain is smaller for the 30/70 DFC, DFPa, and PFC mixes as compared to the standard mixture (they show a higher E_{AC}) and greater for the 100 DC, DPa, and PC mixes. Thus, for a given loading condition the first four mixes listed above will have a longer fatigue life than the standard mixture.

When comparing the responses of recycled materials in a binder layer, the mixes with higher stiffness than the 100% Fairmont showed an increase in the tensile strain. For binder layers with a lower stiffness than the surface layer, the strain was somewhat lower. This performance is expected in relation to the fatigue life, but the inclusion of a softer layer under the stiff layer decreases the performance of the asphalt concrete layer in rutting. Similar results were obtained for the medium and low traffic pavement designs. The responses became much closer to the critical level as the pavement structure became thinner. This would increase the problems with quality control and construction control and their influence on performance if the responses were close to a failure value.

Predicted Life

The Flexural Fatigue Tests were performed as described in previous sections,and the results were shown previously. The appropriate fatigue equation for each mixture was used to calculate the allowable number of passes (N_f) before failure occurred. Fatigue life predictions using these equations for the recycled materials as surface and binder layer are given in Table 4-9 and 4-10 respectively.

When comparing the predicted behavior of the mixes the results are much the same as obtained when comparing the Fatigue Curves alone. The 100 percent reclaimed Peoria material produced the shortest fatigue life. The addition of new aggregate in the 30/70 mix significantly improved its performance to the level that the 30/70 PFPa is one of the materials with the best fatigue behavior. This can be contrasted to the trend shown by the Decatur material where the new aggregate decreased the fatigue life of the mix.

The recycling agent did not show a discernible effect on fatigue life. Rather, the blending of aggregate old pavement and recycling agent seemed to show the biggest differences. This can be related to the influence shown in the mixture design process where the combinations of different asphalt type in the old pavement and the recycling agent produced mixes with very different properties, although they were all acceptable.

The best performance for the structures proposed for low, medium and high traffic was obtained for the standard mix followed closely by the 30/70 PFPa, 100 DC and 100 DPa. This indicates the ability of a completely recycled material developing acceptable properties for use in a pavement. This also clearly shows that recycling can produce mixes with properties that are below standard which possess acceptable mixture parameters. Adequate laboratory testing must be conducted before they are used indiscriminantly.

Fatigue Life predictions for the high traffic level designs show a longer life than the thinner sections. This is a result of the load carrying capacity added by the relatively thicker base course material in this section.

When comparing the performance of the recycled materials as a surface or binder layer, the differences in strain are translated into load repetition levels that are not significantly different. This is explained by the differences in the fatigue equations for each individual material which may translate different tensile strains into similar fatigue lifes.

General Results

Pavement sections were designed for low, medium and high traffic, for central Illinois environmental and subgrade conditions. The proposed pavement sections were then analyzed in a structural model to show differences in recycled bituminous mixtures used in various layers of the surface.

The response parameters of the pavements constructed of recycled mixes are within the expected range shown by similar pavement structures composed of all new materials as characterized by the mixture evaluated in this study. This mixture may or may not be typical, but it is representative, being composed of the same aggregate as was used in the recycled mixes. The 30/70 recycled blends demonstrated similar performance to the all new material mix. In general the 100 percent reclaimed blends presented the poorest response with one exception.

The 100 percent Fairmont mix, representing the standard mixture presented the best performance, followed closely by the 30/70 PFPa material. The 30/70 PFC and 100DC and 100DPa showed a large number of allowable passes to failure. The materials with the poorest fatigue behavior were 100 PC, 100 PPa, 30/70 DFC, 30/70 DFPa.

The trends developed by the materials indicate the different origin and different recycling agent and their influence on each blend. This illustrates the interaction between material properties (% asphalt, Aggregate type, Recycling Agent etc.) and performance predictions. This interaction clearly demonstrates why testing is required to estimate the performance of each mix. Recycled materials in bituminous mixes can be equivalent to standard mixes for certain combinations of recycling agents and new material.

Recycled materials in general can be recommended for use as binder material in pavements with a wide amount of traffic, from low to high as a result of the testing and analysis performed in this study. The use of recycling agents complicates the use of the material, and for Illinois pavements, the use of a softer grade of asphalt will generally produce mixes with properties which exceed those of a mixture with a recycling agent unless the old pavement is so oxidized that it is useless. The use of 30 percent reclaimed pavement is in the range where adequate performance is indicated from this study.

Table 5-1

Design Traffic Levels

Level of Traffic	ADT 1979	ADT 1999	ESAL 1999
Low	4500	7200	$3x10^6$
Medium	24000	83499	$16x19^6$
High	36000	57600	$24x10^6$

Table 5-2

Proposed Pavement Structures

Traffic Level	Material	Thickness (in.)
Low	Asphalt Concrete	8
	Crushed Stone	10
Medium	Asphalt Concrete	10
	Crushed Stone	13
High	Asphalt Concrete	11
	Crushed Stone	15

Table 5-3

Primary Response Low Traffic

Material Type	E $(10^6$ PSI)	Δ_v $(10^{-2}$ in) SURFACE	ε_t $(10^{-4}$ in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v $(10^{-4}$ in/in)
100 Fairmont	.209	3.259	2.537	68.85	-16.08	-2.795	-.186	-7.407
30/70 DFC	229	3.192	2.438	78.19	-15.30	-2.708	-.185	-7.186
30/70 DFPa	.251	3.127	2.338	77.59	-14.53	-2.623	-.185	-6.974
30/70 PFC	.229	3.192	2.438	73.19	-15.30	-2.708	-.186	-7.186
30/70 PFPa	.191	3.326	2.634	64.63	-16.88	-2.88	-.188	-7.26
100 DC	.076	4.152	3.408	25.97	-25.74	-3.842	-.277	-10.229
100 DPa	.191	3.326	2.634	64.63	-16.88	-2.881	-.188	-7.626
100 PC	.120	3.704	3.092	43.91	-21.23	-3.347	-.215	-8.851
100 PPa	.209	3.259	2.537	68.85	-16.08	-2.795	-.186	-7.407

Table 5-4

Primary Response Medium Traffic

Material Type	E (10^6 PSI)	Δ_v (10^{-2} in) SURFACE	ε_t (10^{-4} in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v (10^{-4} in/in)
100 Fairmont	.209	2.706	1.864	50.54	-11.94	-1.755	-.120	-4.658
30/70 DFC	229	2.648	1.784	53.51	-11.33	-1.701	-.121	-4.524
30/70 DFPa	.251	-2.592	1.704	56.51	-10.74	-1.648	-.122	-4.395
30/70 PFC	.229	2.648	1.784	53.51	-11.33	-1.701	-.121	-4.524
30/70 PFPa	.191	2.766	1.943	47.64	-12.56	-1.808	-.120	-4.787
100 DC	.076	3.533	2.641	20.28	-19.59	-2.412	-.158	-6.385
100 DPa	.191	2.766	1.943	47.64	-12.56	-1.808	-.120	-4.789
100 PC	.120	3.109	2.334	33.16	-15.98	-2.100	-.128	-5.538
100 PPa	.209	2.706	1.864	50.54	-11.94	-1.755	-.120	-4.658

Table 5-5

Primary Response High Traffic

Material Type	E (10^6 PSI)	Δ_v (10^{-2} in) SURFACE	ε_t (10^{-4} in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v (10^{-4} in/in)
100 Fairmont	.209	2.498	1.606	43.46	-10.48	-1.407	-.108	-3.760
30/70 DFC	229	2.443	1.535	45.96	- 9.939	-1.366	-.109	-3.660
30/70 DFPa	.251	2.391	1.465	48.48	- 9.415	-1.324	-.110	-3.558
30/70 PFC	.229	2.443	1.535	45.96	- 9.939	-1.377	-.109	-3.660
30/70 PFPa	.191	2.553	1.676	41.01	-11.03	-1.449	-.107	-3.863
100 DC	.076	3.298	2.319	17.77	-17.29	-1.914	-.132	-5.081
100 DPa	.191	2.553	1.676	41.01	-11.03	-1.449	-.107	-3.863
100 PC	.120	2.881	2.029	28.75	-14.07	-1.674	-.111	-4.436
100 PPa	.209	2.498	1.606	43.46	-10.48	-1.407	-.108	-3.760

Table 5-6

Primary Response Low Traffic Recycled materials as Binder Layer

Material Type	E (10^6 PSI)	Δ_v (10^{-2} in) SURFACE	ε_t (10^{-4} in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v (10^{-4} in/in)
100 Fairmont	.209	3.26	2.539	68.85	-16.08	-2.795	-0.1863	-7.407
30/70 DFC	229	3.236	2.961	73.77	-15.70	-2.768	-0.1937	-7.356
30/70 DFPa	.251	3.212	2.384	78.92	-15.33	-2.741	-0.2313	-7.305
30/70 PFC	.229	3.236	2.461	73.77	-15.70	-2.768	-0.1937	-7.356
30/70 PFPa	.191	3.285	2.611	64.20	-16.46	-2.822	-0.1792	-7.458
100 DC	.076	3.586	3.195	26.05	-20.18	-3.140	-0.1336	-8.1519
100 DPa	.191	3.285	2.611	64.20	-16.46	-2.822	-0.1792	-7.458
100 PC	.120	3.426	2.964	42.92	-18.40	-2.971	-0.148	-7.761
100 PPa	.209	3.26	2.537	68.85	-16.08	-2.795	-0.1863	-7.407

Table 5-7

Primary Response Medium Traffic Recycled Materials as Binder Layer

Material Type	E (10^6 PSI)	Δ_v (10^{-2} in) SURFACE	ε_t (10^{-4} in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v (10^{-4} in/in)
100 Fairmont	.209	2.709	1.864	50.54	-11.94	-1.755	-0.120	-4.658
30/70 DFC	229	2.688	1.807	54.11	-11.65	-1.737	-0.1247	-4.623
30/70 DFPa	.251	2.667	1.749	57.83	-11.36	-1.720	-0.1296	-4.592
30/70 PFC	.229	2.688	1.807	54.11	-11.65	-1.737	-0.1247	-4.623
30/70 PFPa	.191	2.730	1.920	47.16	-12.23	-1.772	-0.1155	-4.690
100 DC	.076	2.992	2.358	19.16	-15.01	-1.974	-0.08556	-5.128
100 DPa	.191	2.730	1.920	47.16	-12.23	-1.771	-0.1155	-4.690
100 PC	.120	2.852	2.185	31.59	-13.71	-1.866	-0.09539	-4.880
100 PPa	.209	2.709	1.864	50.54	-11.94	-1.755	-0.120	-4.658

Table 5-8

Primary Response High Traffic Recycled Materials as Binder Layer

Material Type	E (10^6 PSI)	Δ_v (10^{-2} in) SURFACE	ε_t (10^{-4} in/in)	σ_t PSI	σ_v PSI BASE	σ_v PSI	σ_t PSI SUBGRADE	ε_v (10^{-4} in/in)
100 Fairmont	.209	2.497	1.606	43.46	-10.48	-1.407	-0.1078	-3.760
30/70 DFC	229	2.477	1.556	46.52	-10.22	-1.394	-0.1114	-3.736
30/70 DFPa	.251	2.457	1.505	49.71	- 9.961	-1.381	-0.1151	-3.712
30/70 PFC	.229	2.477	1.556	46.52	-10.22	-1.394	-0.1114	-3.736
30/70 PFPa	.191	2.517	1.655	40.55	-10.73	-1.420	-0.1042	-3.785
100 DC	.076	2.757	2.033	16.93	-13.16	-1.577	-0.08062	-4.124
100 DPa	.191	2.517	1.655	40.55	-10.73	-1.420	-0.1042	-3.785
100 PC	.120	2.628	1.884	27.15	-12.03	-1.493	-0.08863	-3.932
100 PPa	.209	2.497	1.606	43.46	-10.48	-1.407	-0.1078	-3.760

Tables 5-9

Tensile Strain at the Bottom of the Bituminous Layer

Material Type	ε_t (10^{-4} in/in)		
	Structural Level		
	Low	Medium	High
100 Fairmont	2.537	1.864	1.606
30/70 DFC	2.438	1.784	1.353
30/70 DFPa	2.338	1.704	1.465
30/70 PFC	2.438	1.784	1.535
30/70 PFPa	2.634	1.943	1.676
100 DC	3.408	2.641	2.319
100 DPa	2.634	2.943	1.676
100 PC	3.092	2.334	2.029
100 PPa	2.537	1.864	1.606

Table 5-10

Fatigue Life Predictions

Material Type	Allowable Number of Repetitions Traffic Level Low	Medium	High
100 Fairmont	113,600	296,400	471,200
30/70 DFC	50	1,480	7,810
30/70 DFPa	1,820	6,840	12,890
30/70 PFC	1,700	15,310	44,130
30/70 PFPa	112,790	290,570	335,550
100 DC	35,220	85,840	135,210
100 DPa	48,202	166,810	304,890
100 PC	40	96	150
100 PPa	390	740	1,012

Table 5-11

Fatigue Life Predictions
Recycled Material as Binder Layer

Material Type	Allowable Number of Repetitions Traffic Level Low	Medium	High
100 Fairmont	113,600	296,400	471,150
30/70 DFC	40	1,280	6,715
30/70 DFPa	1,680	6,130	11,510
30/70 PFC	1,590	13,990	40,100
30/70 PFPa	82,310	218,100	349,230
100 DC	44,130	127,550	135,210
100 DPa	49,960	175,110	320,990
100 PC	50	120	190
100 PPa	390	740	1,010

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Recycling of bituminous materials as done in this study produces mixtures with very different properties in the mix depending on the relative percentages of materials used, and the particular recycling agents used. Extensive laboratory testing conducted on recycled and standard materials demonstrated that:

1. Mixture design procedures indicated that acceptable mix design properties for recycled mixes could be obtained with very little effort.
2. Flexural fatigue testing on the recycled mixes examined in this study indicate that the fatigue lifes are shorter than those of an all new mix as characterized in this study.
3. Lower stiffness values obtained in the recycled mixes as compared to standard mixes indicates a slightly higher potential for permanent deformation.
4. Compressive creep relaxation testing did not show significant differences between mixes. Asphalt content produced the most significant variability in the compressive stiffness.
5. The stiffness of the recycled mixes obtained from the creep relaxation testing showed the expected ranges as a function of temperature and rate of loading. The differences at extreme environmental and loading conditions indicate that the recycled mixes are less susceptible to low-temperature cracking, but they have the potential for more permanent deformation at elevated temperatures.

6. There was no conclusive relationship between mixture properties and the potential for permanent deformation. The VESYS permanent deformation parameters ALPHA and GNU are not sensitive enough to evaluate the recycled and standard mixtures differences.
7. Fatigue performance predictions were highly dependent on the characteristics of each blend. This is an effect of the blending of different materials in each mixture.
8. Recycled materials in bituminous mixtures can be equivalent to standard mixes if certain blending percentages of new material, recycling agent, and new asphalt are maintained.
9. It is recommended that recycled mixtures be thoroughly tested when using high percentages of reclaimed pavement and significant percentages of recycling agents to rejuvenate the aged asphalt cement in the old pavement. Their use as a surface mixture for moderate to high volume pavements is questionable at present. Their use as a base or binder material would appear to be satisfactory from the results in this study. Binder materials are insulated from high temperature extremes, and the fatigue parameters are comparable to a new mixture.
10. Fundamental laboratory testing should be performed whenever possible to characterize the reclaimed materials and to obtain an indication of the performance potential of the mix.
11. The current recycling technology which uses relatively low percentages of reclaimed pavement (30 percent) and a soft asphalt cement rather than a recycling agent will produce a mixture with properties which in some respects avoid the problems associated

with recycling agents and high amounts of reclaimed pavement. This recycling technology should produce materials that are as good as an all new mixture. When higher percentages are contemplated, the results of this research will be more crucial to producing a mixture with satisfactory long-term performance characteristics.

Recommendations

It is not feasible to perform all the tests conducted here on every recycled mixture to show whether the mix design parameters are sufficient or not. A better means of characterizing long term performance in a mix design concept needs to be developed. This is true not only for recycled mixes, but it is also a critical need for new mixes.

This characterization must also furnish data that can be used to determine structural adequacy of the mixture for a thickness selection because the variety of mixes and their resulting properties may make it uncertain to design a uniform thickness for materials with very different properties.

Finally, the data presented in this study indicate that adequate recycled mixes can be obtained, but there are a variety of problems which must be considered to ensure adequate performance. The data do not present any reasons for changing the current material considerations for recycled material useage in Illinois pavements.

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