VISCOELASTIC CHARACTERIZATION
OF RUBBER ADDITIVE ASPHALT

BY

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ABSTRACT

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Submitted to the Department of Civil Engineering on 23 May
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This study investigated the effects of rubber modi-
fication on the creep, relaxation, and fracture response
of sand asphalt mixtures. Results of tests indicate that
rubber modification improves the resistance of sand asphalt
mixtures to creep under constant load. Relaxation moduli
of modified mixes were found to be higher than unmodified
mixes at all temperatures tested. Rubber modification was
found to reduce the temperature susceptibility of sand as-
phalt mixtures. The time-temperature superposition princi-
ple was applied to creep and relaxation data taken at dif-
ferent temperatures and master creep and relaxation curves
were constructed. Results of impact and notched beam tests
indicate that rubber modification improves the resistance
of sand asphalt mixtures to brittle fracture at low temper-
atures.

Thesis Supervisor: Fred Moavenzadeh, Ph.D.
Title: Associate Professor of Civil Engineering

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I INTRODUCTION

One of the means toward improving highway pavements lies in better understanding of their response under different conditions of loading and environment. Presently pavement design methods for asphalt pavements do not explicitly consider the time and temperature dependency of the properties of asphalt. These methods generally treat the paving materials as elastic. Attempts are presently being made to develop design methods which consider the effects of loading time and temperature. However, before these methods can be applied designers must be furnished with data which characterizes the paving materials' response to different loading times and temperatures. In part this study is aimed at evaluating the effects of time and temperature on the properties of sand asphalt mixtures. This evaluation is done using creep, relaxation, and fracture tests.

One desirable feature of sand asphalt mixtures is their temperature susceptibility, i.e. the sensitivity of their properties to changes in temperatures. Typically a high viscosity asphalt will produce a sand-asphalt mixture which possesses good consistency at the higher range service temperatures. However, this mixture will not exhibit a high resistance to brittle fracture at low service temperatures. Conversely a low viscosity asphalt will usually not possess good consistency at high service temperatures while possessing adequate resistance to brittle fracture at low

temperatures. This feature of asphalt behavior makes difficult the choice of an asphalt for use in situations calling for performance at both ends of the range of service temperatures. A second means toward improved pavement performance is the partial or complete elimination of such an undesirable feature. Rubber modification has shown potential in this respect. Previous studies done on binders without aggregate indicated that rubber modification can significantly improve the resistance of asphalt binders to brittle fracture at low temperatures (2). In this study fracture tests are used to evaluate the effect of rubber modification on brittle fracture of sand asphalt mixtures at low temperatures. Creep and relaxation tests are used to investigate the effects of this modification on the properties of sand asphalt mixtures in the middle to high service temperature range.

Scope and Objectives

The following tests were conducted in this study to evaluate the effect of rubber modification on the response of a sand-asphalt mix.

1. Creep and relaxation tests: These tests were conducted at different temperatures to characterize the viscoelastic response of rubber modified and unmodified sand asphalt mixes. The time-temperature superposition principle was used to construct master curves for creep compliance and relaxation modulus at different temperatures. The temperature susceptibility of the mixes was

compared.

2. The concepts of fracture mechanics were applied to the study of the materials at low temperatures. Bending tests were conducted on notched beams in order to investigate the resistance of the materials to brittle fracture at low temperatures. The critical strain energy release rates of the two mixes are computed and compared. Izod type impact tests were used to investigate the response of the materials to impact fracture at low temperatures.

II REVIEW OF LITERATURE

The review of literature presented in this study is divided
into three sections. The first section discusses laboratory and
field experience with rubber modified asphalts and asphalt mixes, the
second section discusses the nature of a visco-elastic material and
the techniques applicable to the characterization of such a
material. The final section treats the development of fracture
mechanics and its application to the study of asphalt and asphalt
mixes.

Properties of Rubber Modified Asphalts

Asphalt is a petroleum product widely used as a binder in paving
mixtures. In this role it is subjected to a wide range of environ-
mental changes. Such changes affect the various properties of
asphalt and in turn its performance as a paving material.

Long exposures to the weather cycle of temperature and moisture
change cause hardening of the asphalt binder. Some of the mechanisms
responsible for this hardening are (1)

     1. Evaporation of more volatile components.

     2. Chemical action of atmospheric oxygen.

     3. Age-hardening in which the internal structure of the

        binder changes with time.

     4. Polymerization involving chemical changes in the

        material.

One of the observed effects of the above-mentioned mechanisms is
an increase in the viscosity of the binder usually accompanied by a
loss of resistance to brittle fracture. Binders modified by the
addition of rubber additives have been shown to be resistant to this
aging process. Alexander (2) found the resistance to brittle
fracture of aged specimens increased by the addition of latex. The
addition of neoprene was found to reduce the change in penetration
and the increase in softening point of binders in thin film aging
tests. This effect was attributed to the retention of volatiles
by the neoprene (3).

When exposed to low temperatures asphalt binders lose ductility
and become brittle. The temperature range to which asphalt binders
are exposed in service is often such that the asphalt will undergo
this transition from ductile to brittle behavior. Binders modified
by the addition of rubber have been shown to be more resistant to
brittle fracture at low temperatures (2,4,5,6,7).

Softening point and viscosity are especially important con-
siderations when high service temperatures are to be expected.
Asphalts of low softening point and viscosity are less desirable
for this application. In this respect the addition of rubber
additives is beneficial in that they increase both the viscosity
(1,5) and the softening point (1,3,5,6,8) of asphalt. This would
suggest that rubber modified asphalts are more resistant to creep
at elevated temperatures. Rubber modification also results in a

decrease of penetration (1,3,5,6) and increases toughness (3,5,8) and tenacity (8).

The literature is less definitive about the field performance of rubber modified asphalt mixtures. However, it does reveal that the addition of rubber reduces bleeding (1,5,8) and improves aggregate retention (1,5,8,9). This retention of aggregate is especially evident on newly opened roads. Some reports claim improved skid resistance (4). This is probably due to improved aggregate retention by the rubber modified binder.

The literature contains evidence of greater toughness (8), reduced brittleness at low temperatures (4) and improved high temperature stability (5). In general, the available literature indicates that the performance of rubber modified asphalt is not inferior to that of conventional asphalt mixtures and that in some applications its performance is superior.

Viscoelastic Considerations

An elastic material is one that obeys Hooke's law, i.e. the stress and strain are related by a constant which is independent of time. In a viscous material stress is independent of strain but is proportional to the rate of strain. A viscoelastic material combines these two forms of response such that stress and strain are related by some function of time. In a linear viscoelastic material a change in stress will produce a proportional change in strain for a given time of loading at constant temperature. Sand

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asphalt mixtures have been found to be linear viscoelastic for small strains (12).

As a viscoelastic material asphalt exhibits a dependency on both time and temperature, characterization of asphalt mixes for design purposes therefore requires that consideration be given to this time – temperature dependency.

Creep, relaxation, constant strain rate and dynamic tests are used for the characterization of such a material.

In a creep test a constant stress σ_0 is applied and the resulting time dependent strain $\varepsilon(t)$ is recorded. The creep compliance $D_c(t)$ is defined as $\dfrac{\varepsilon(t)}{\sigma_0}$. From creep tests plots of creep compliance versus time can be constructed.

Stress relaxation tests are conducted by imposing a step strain ε_0 and recording the stress $\sigma(t)$ necessary to maintain that strain. The relaxation modulus $E_r(t)$ is defined as $\dfrac{\sigma(t)}{\varepsilon_0}$. From relaxation tests plots can be made of relaxation modulus versus time.

Constant strain rate tests are conducted by subjecting a material to a constant rate of strain and recording the stress as a function of time or strain. By conducting several tests at constant temperature but different strain rates one can construct a plot of relaxation modulus versus time.

This is accomplished by recording the slope $\dfrac{d\sigma}{d\varepsilon}$ or $E(t)$ at some strain ε_0 obtained from several constant strain tests

ran at different strain rates. If a material is simple viscoelastic

in response then the plot of E(t) versus time for some conveniently

chosen ϵ will be the same as the plot of ϵ(t) versus time result-

ing from a stress relaxation test (15).

A thermorheologically simple material is one that exhibits

the following behavior. When plots of creep compliance or stress

relaxation versus time at different temperatures are plotted

together the curves should submit to superposition by shifting

along the log time axis. This is the application of the well known

time-temperature superposition principle which says that a change

of temperature at constant loading time is equivalent to a log

rithmic change of loading time at constant temperature for a given

material (10). The application of this principle to sand asphalt

mixes has been done successfully in the past (10, 11, 12).

Application of this principle enables one to separate and evaluate

the effects of the two independent parameters time and temperature.

The superposition of data taken at different temperatures can

be used to form a single master curve of creep compliance or

relaxation modulus versus time for a time range much larger than

that feasible in normal laboratory practice.

In this study creep, stress relaxation and constant strain

rate tests are conducted in order to characterize and compare the

properties of rubber modified and unmodified sand asphalt mixes.

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Fracture Mechanics

Current theories in the fracture of brittle materials have stemmed from attempts to explain the disparity between observed fracture strengths and strengths as predicted from theoretical atomic bond strengths. Typically, theoretical strengths are 10 to 100 times as large as observed strengths.

Presently it is thought that this reduction in strength arises from the presence of flaws or inclusions not accounted for, or considered when strengths are predicted from theoretical atomic bond strengths. The presence of such flaws give rise to local stress fields of high intensity that may exceed the atomic bond strength of a material in the vicinity of such flaws.

Griffith treated the problem of an infinite plate of unit thickness with a tensile stress imposed perpendicular to a line crack. He introduced the concept of surface energy which is the work that must be done to create a new surface in a material.

As a crack propagates through a material, the excess strain energy due to the presence of the crack is dissipated in the form of surface energy to create new surfaces. Griffith proposed that if the strain energy released in propagating the crack some incremental distance was equal to the surface energy required for that propagation, then brittle fracture would occur. This is Griffith's criterion for the onset of brittle fracture. This criterion is satisfied when

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$$\sigma = \sqrt{\frac{2\gamma E}{\pi c}}$$

where γ is the surface energy term, E the modulus of elasticity, c is one half the length of the line crack and σ is the nominal tensile stress imposed on the plate.

Experimental results have shown that this expression yields a value of maximum tensile strength which is in many instances several orders of magnitude below that observed in tests. This disparity is due in part to the assumption that materials fail by separation of atomic planes. While this assumption is sometimes true, it is not the rule. Many materials when fractured exhibit a cleavage surface which has a zone of plastic work due to the locally high strains associated with the tip of the propagating crack. With this phenomenon in mind, the Griffith criterion has been modified to

$$\sigma = \sqrt{\frac{2 E \gamma_P}{\pi c}}$$

where γ_P includes all work done in creating the new surfaces. This expression remains valid as long as the region of plastic work is restricted to the vicinity of the crack tip.

A somewhat different approach to these ideas was taken by Irwin.

Instead of taking the derivative of the difference between excess strain energy and surface energy, Irwin differentiated the expression for excess strain energy to get

$$G = \frac{d\,\Delta U}{dc} = \frac{2\pi c \sigma^2}{E}$$

This expression yields the strain energy release rate which is the true driving force behind the propagation of the crack.

The value of G at the onset of rapid and unstable propagation of the crack is termed the critical strain energy release rate and is a material property.

In this study G_c is measured using the analytical method employed by Alexander, Kakel, and Marsh (2,13,14). Because the geometrics of specimens and loading create a condition of plain strain, equation 2 must be modified by replacement of E by $E/(1-\nu^2)$ where E is the modulus of elasticity and ν is Poisson's ratio. Also, because the notch used in this is only one half the crack considered by Griffith equation (2) must be divided by 2. These modifications yield the below expression for the strain energy release rate.

$$G = \frac{(1-\nu^2)\,c\,\sigma^2}{E}$$

For the rectangular beams used in this study, this expression becomes

$$G = \frac{(1 - \nu^2) \, \sigma_n^2 \, h}{E} \, f(c/d)$$

where σ_n is the nominal bending stress at the tip of the notch, $f(c/d)$ is a function of notch depth ratio, and h is the net depth of the beam at the notch.

The above technique was applied to the study of B2960 asphalt binder modified by the addition of latex rubber (2). Results of this study showed that the addition of the rubber significantly improved the resistance of the binder to brittle fracture at very low temperatures. In this study this technique will be applied to examine the influence of the rubber on sand asphalt mixes in the same temperature range.

III MATERIALS AND PROCEDURES

Aggregate

Because of the large volume of aggregate used in sand asphalt mixes, the choice of a suitable aggregate is important. The aggregate chosen for use in this study was Ottawa sand. Flint powder was chosen for use as mineral filler. The gradation chosen conforms with ASTM 1663-59T. Table (1) contains the aggregate gradation by sieve analysis.

Binders

In this study two types of binders were employed. One consisted of unmodified asphalt coded B-2960 by the Bureau of Public Roads and manufactured by the Shell Oil Co. Properties of the B2960 asphalt are presented in Table (2). The mixes employing unmodified B2960 asphalt contained 9% binder by weight of aggregate or 180 grams of binder for a 2000 gram batch of aggregate. The other binder used consisted of a mix of B2960 asphalt and a latex rubber. The latex used was Pliopave L-170 manufactured by the Goodyear Tire and Rubber Company. This material is an anionic copolymer consisting of 70% butadiene and 30% styrene with 72% solids. L-170 has a ph of 10 and a Mooney Viscosity (ML-4 AT 22°F) of 100. It possesses excellent storage and mechanical stability. The binder produced contained 4.5% L-170 (solids) by weight of asphalt in the binder. The mixes employing this binder contained 9% binder by weight of aggregate.

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TABLE 1

Typical Gradation of 2000 Gram
Batch of Aggregate

SIEVE SIZE	% TOTAL	WT. GRAMS
7 - 16	0	0
16 - 30	25	500
30 - 50	30	600
50 - 100	19	380
100 - 200	11	220
200*	15	300
TOTAL	100	2000

*Flint Power

TABLE 2

The Results of Typical Tests on
Asphalt Used in This Study

Specific Gravity	1.03
Melting Point	125°F
Flash Point, Cleveland Open Cup	515°F
*Glass Transition Temperature	-20.2°F

*Schmidt, R. J. and Santucci, L. E., "A Practical Method for Determining the Glass Transition Temperature of Asphalts and Calculation of their Low Temperature Viscosities," Proceedings, Association of Asphalt Paving Technologists, Vol. 35, 1966, p. 61.

Mix Preparations

Mixes used for preparation of both cylinder and slab specimens were prepared in the same manner except for the quantities of materials involved.

Sand was taken in the proportions shown in Table (1) and placed in a mixing bowl. It was then mixed for one minute at low speed to avoid loss of fines and to insure uniform gradation of the aggregate. Next the bowl of sand along with spatulas, dashers, spoons, and molds were placed in a thermostatically controlled oven, preheated to 164°C.

Asphalt was then chipped from a five gallon container stored in a freezer and weighed out in a mixing bowl placed on scales. For cylindrical specimens, 200 grams were used and for slabs 300 grams. The mixing bowl containing the asphalt was then placed in an oven preheated to 164°C. After one hour, the bowl containing the sand was placed on scales where the correct amount of asphalt was added from the asphalt bowl by pouring into a cone formed in the sand. The correct amount was 180 grams and 225 grams for cylinders and slabs respectively, since the mix for cylinders contained 2000 grams of aggregate and that for slabs, 2,500 grams. The bowl containing the sand and asphalt was then placed on the mixer and allowed to mix at low speed for one minute. The mixing bowl was then scraped with a heated spatula to free the mixture from the bottom and sides of the bowl. Mixing was then resumed for one minute, after which

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the bowl containing the mix was replaced in the oven pending specimen preparation.

The preparation of mixes containing latex was somewhat different. The oven was preheated to 140°C instead of 164°C. After one hour in the oven, asphalt was combined with unheated latex while mixing at low speed. The latex was poured in a fine stream to avoid globbing and to encourage uniform distribution of the latex in the binder mix. After three minutes of mixing the latex-asphalt binder was returned to the oven for 20 minutes after which it was removed and mixed for three minutes and returned to the oven. At this point the oven temperature was set for 164°C. After 30 minutes of heating the latex-asphalt binder was combined with the sand in the same fashion as for sand-asphalt mixes previously described. This procedure being finished, the bowl containing the mix was returned to the oven pending specimen preparation.

Specimen Preparation

Specimen preparation began immediately following mix preparation and was as follows:

Cylinders

A heated steel mold measuring 3 in. by 1.4 inches in diameter was taken from the oven and placed on the scales. The mold was then filled with approximately 170 grams of mix material taken from the mix bowl using a heated spoon. The mold was then removed from the scales and compacted. Compaction was done using a compactive

effort corresponding to medium traffic density category (ASTM).

The hammer employed weighed 5.33 pounds and had a free fall of

10 inches. The foot-pound to volume of specimen relationship was

maintained as in the full size Marshall test. This required 48

blows of the hammer per specimen. Each end of the specimens was

compacted using 24 blows of the hammer which delivered 4.45 ft. lb.

per blow.

After approximately 15 minutes of cooling the specimens were

removed from the molds by extrusion. This was accomplished using a

specially constructed apparatus employing a hydraulic jack. After

demolding the specimens were placed on trays constructed by steel

tubing cut in half along the longitudinal axis. After about 15

minutes of air cooling the trays containing the specimens were

placed in a freezer to await testing.

This process produced specimens of uniform density as

evidenced in Table (3) which presents bulk densities of samples of

both asphalt and modified asphalt binder. Bulk density is defined as

$$\rho = \frac{\text{weight in air}}{\text{weight in air} - \text{weight in water}}$$

Slab Specimens

Mixes used for slab specimens were prepared in 2,500 gram

batches. Immediately after preparation, the mix was placed in a

TABLE 3

Sample Densities of Cylinder Specimens

SAMPLE NUMBER UNMODIFIED	DENSITY	SAMPLE NUMBER MODIFIED	DENSITY
1	2.13	200	2.11
2	2.13	201	2.12
3	2.04	202	2.09
4	2.15	203	2.11
5	2.18	204	2.12
6	2.14	205	2.12
7	2.13	206	2.11
8	2.13	207	2.13
9	2.16	208	2.11
10	2.17	209	2.13
11	2.18	210	2.21
12	2.18	300	2.13
13	2.18	301	2.14
14	2.14	302	2.14
15	2.18	303	2.12
16	2.18	304	2.14
17	2.10	305	2.16
18	2.16	306	2.15
19	2.10	307	2.16
20	2.17	308	2.17
AVERAGE VALUE	2.15	AVERAGE VALUE	2.13

preheated brass mold. The mold consisted of a box of inside
dimensions 12" by 5 1/2" by 1" with a moveable top plate so con-
structed as to permit compaction of the mix. The mix was placed in
two lifts. The first lift was placed in the mold to form a layer
approximately 3/4 inch thick after leveling and mild compaction by
an air powered vibrator rigged with a small plate. The mold was
then placed in a preheated hydraulic press where a load of 9,600 lbs.
was applied to develop a vertical stress of 145 PSI on the mix. The
load was then released and the mold removed from the press. A
second lift of 3/4 inches was then placed and levelled using the
vibrating plate. This lift extended 1/4 inch above the edge of the
mold. The mold was then returned to the press and subjected to a
load of 19,200 lbs. or 290 psi. This load was left in place for
15 minutes which permitted some relaxation in the material and
resulted in some reduction of the load. After the 15 minutes
relaxation period the load was raised again to 19,200 lbs. and then
released. The mold was removed from the press and permitted to
cool for approximately 20 minutes. Next, the slabs were demolded
and placed on flat surfaces and stored in a freezer. After the
slabs were frozen, they were sawed up into beams of dimensions
1 in. by 1 in.by 5 in. while exercising care that the beams were
true. After sawing, the beams were stored in a freezer until
needed for tests. This method produced specimens of bulk densities
2.16 and 2.20 for rubber and conventional mixes respectively.

Impact Specimens

Impact test specimens were cut from asphalt slabs fabricated in the same manner as those used for beam specimens. The prepared specimen measured 11/16 by 15/16 by 2 1/2 inches instead of the standard 1/2 by 1/2 by 2 1/2 inches specimen suggested by ASTM D256-56. The larger specimen was necessary because specimens of standard dimension did not possess impact strengths high enough for accurate measurement in the tester available for this study. Notches were then cut to a depth of 3/16 in. using a diamond saw which resulted in very sharp notches of uniform radius. Prior to sawing, specimens were kept in dry ice to insure that the asphalt did not soften during the sawing process. After sawing, the specimens were placed in a freezer pending testing.

Test Procedure

- Creep Test

A static creep test is conducted by loading a material with constant stress and observing the deformation as a function of time. The setup used in this study is illustrated in Figure (1). The stress was applied utilizing various combinations of weights. Deformation was measured by a Daytronics LVDT and recorded by a GR-14 Strip Recorder.

The temperature of the specimen was maintained by circulating water of constant temperature around the specimen. This technique proved to be effective in maintaining temperature within .1 degree

Centigrade. For temperatures below 0°C ethelyne glycol was added
to the circulating water to prevent freezing.

Each specimen tested was placed in the water at least one hour
prior to testing to insure that the specimen was in thermal equili-
brium with its surroundings. Prior to testing, specimens were
preconditioned by loading for ten minutes, after which the load was
removed for 10 minutes. This cycle was repeated three times before
the actual test began. Such preconditioning was necessary to reduce
end effects and to insure reproductability of the data. Strains
during the test were limited 1% to prevent specimen failure.

At each temperature, two specimens were tested at each of two
stress levels, i.e., four specimens at each temperature.

- Relaxation Tests

A relaxation test is conducted by subjecting a material
to a step strain and observing how the stress necessary to maintain
that strain, behaves as a function of time. The relaxation test
apparatus is illustrated in Figure (2). Specimens were given at
least one hour to come to thermal equilibrium with the circulating
water whose temperature was controlled in the same manner as in
the creep tests. The Instron machine was used to impose the
desired strain as well as to record the stress as a function of
time. A cross-head speed of .2 IN/MIN was used since this rate was
close to a step strain and still permitted adequate control of the
amount of strain imposed. Specimens were preconditioned by
straining to .3%, allowing the specimen to relax for five minutes,

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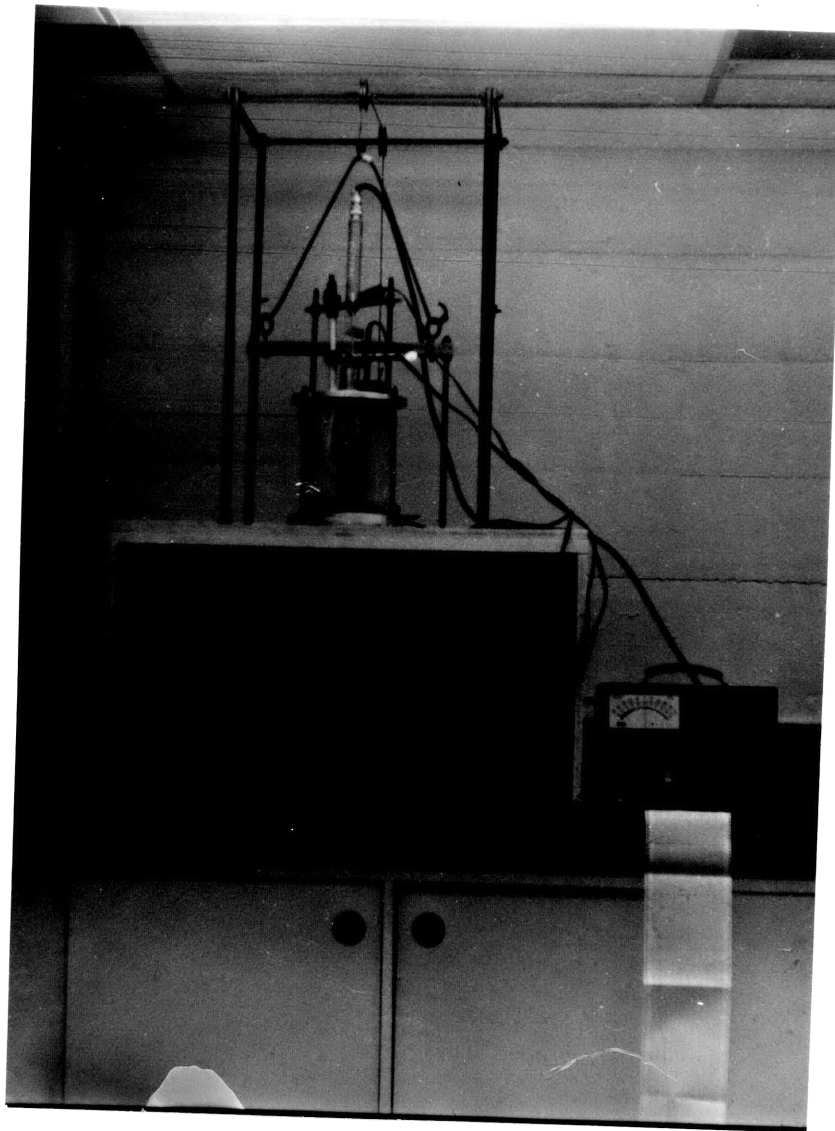
Figure (1) Creep Test Apparatus
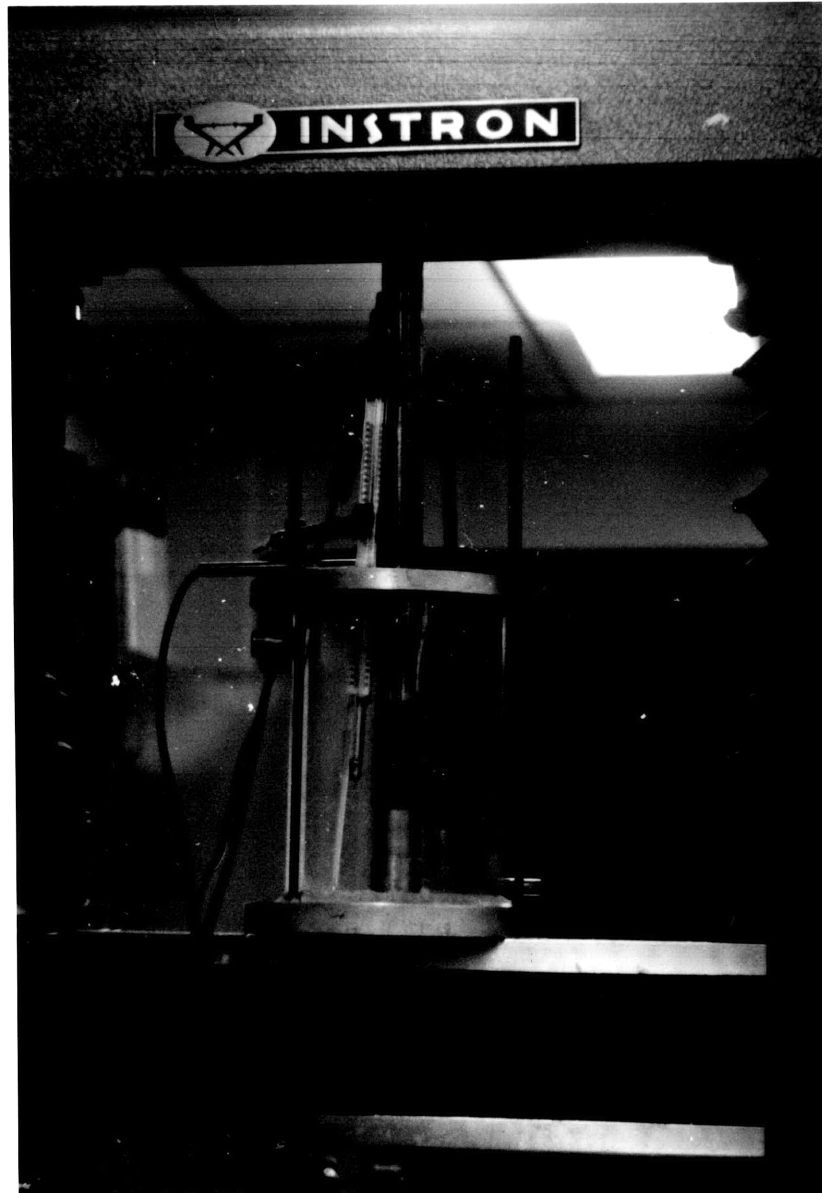
Figure (2)   Relaxation Test Apparatus

and then releasing the load until the specimen reached equilibrium under zero stress. This cycle was repeated three times prior to testing.

- Impact Tests

The impact test employed in this study was the Izod test described in ASTM D256. A Baldwin Type Impact Testing machine with a one ft. lb. pendulum arm was the tester used. Tests were conducted at 0, -20, and -37°F in refrigerated rooms where the temperature was controlled within ± 1°F. Specimens were conditioned by being placed in the respective rooms at least one hour prior to testing. Five specimens of each mix were tested at each temperature as recommended by ASTM D256.

- Notched Beam Tests

Beams containing a sharp 3/16 in. midspan notch were tested in three point bending. The beam span was 4 in. and the load was applied at midspan opposite the side containing the notch. A strain rate of .1 in/min. was used. Beams were placed in the testing chamber and allowed a minimum of 30 minutes to come to thermal equilibrium with their surroundings. Tests were conducted at -10, -20 and -30°C in a chamber where the temperature was controlled to within 1°C. The temperature was controlled by controlling the rate at which liquid nitrogen entered the chamber. Five specimens of each mix were tested at each temperature; two

for modulus and three for G_c . The critical strain energy release rate was calculated as discussed previously in the section on fracture mechanics. The notched beam testing apparatus is illustrated in Figure (3).
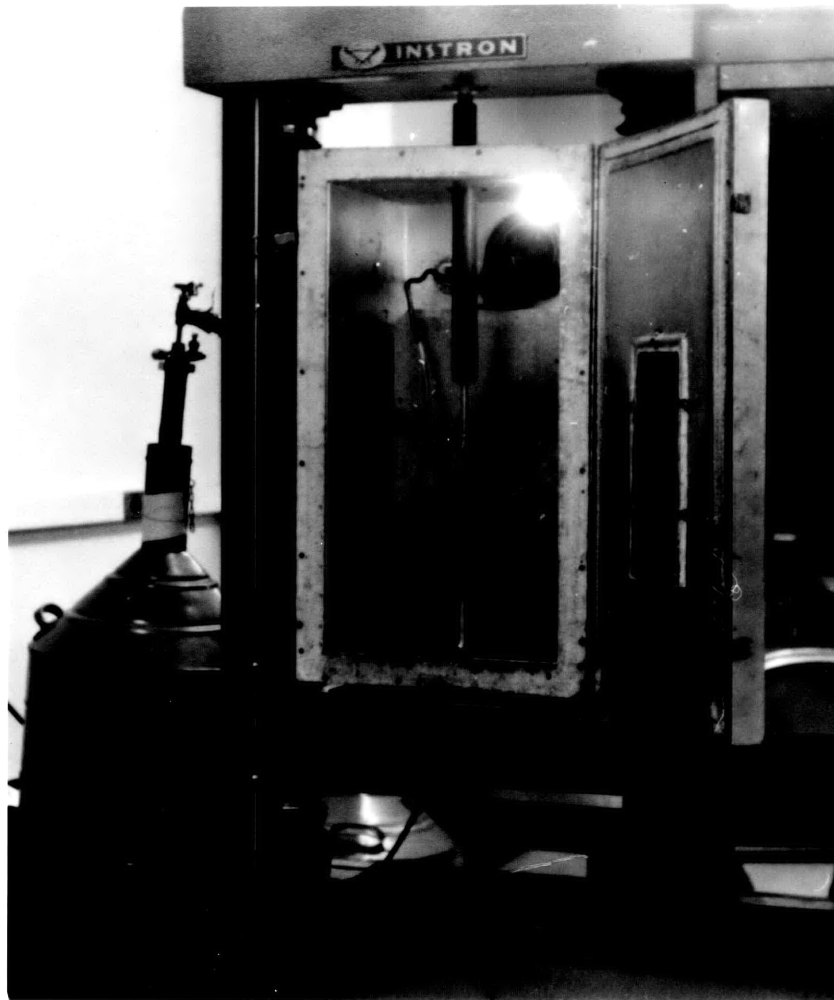
Figure (3)   Notched Beam Testing Apparatus

IV RESULTS AND DISCUSSION

Creep Tests

The response of both unmodified and rubber modified sand

asphalt mixes was found to be different for successive loadings.

However, by conditioning the specimen with three cycles of loading

and unloading at ten minute intervals, the response of the

material became reproducible.

Ideally the load in a creep test should be applied instan-

taneously; however, this is not usually practical due to considera-

tions of inertia effects and equipment limitations. Results are

not generally affected by the duration of loading after ten times

the loading time. In this study loading times were of the order of

.2 seconds and data is not reported for less than 3 seconds.

Reduced Creep Compliance

Creep compliance is defined as the ratio $\dfrac{\varepsilon(t)}{\sigma_o}$ where

$\varepsilon(t)$ is the strain recorded as a function of time when a

material is subjected to a constant stress level σ_o . In this study

creep compliance data was plotted as reduced creep compliance

i.e. $D_c \dfrac{T}{T_o}$ to facilitate further use of the data in generation

of master creep curves. Figure (4) is an example of such a plot

for rubber modified and unmodified mixes at $273°K$ or $0°C$. Plots of

reduced creep compliance at various temperatures can be found in

the Appendix.

Examination of the reduced creep compliance versus time plots
will reveal that the reduced creep compliance of rubber modified
mixes is smaller than that for unmodified mixes. Closer examination
of these plots reveals that the difference in creep response of the
two materials below 20°C is quite small as compared to the differ-
ences in response observed above 20°C. Apparently the relative
increase in viscosity as a result of rubber modification is much
greater above 20°C than below. This could be explained by assum-
ing that the distribution of the rubber and the nature of the
rubber network is constant in this temperature range while the
viscosity of the unmodified asphalt drops off sharply above 20°C.
At temperatures below 20°C the unmodified asphalt's flow rate
through the rubber network is so slow that the presence of the
rubber network doesn't present much interference while at temperatures
above 20°C the flow rate of the unmodified asphalt is such that
the rubber network represents a much more significant resistant to
flow. This model is proposed because the rubber forms an inter-
connected network when used in percentages exceeding 1.5% by
weight binder. (23)

Time-Temperature Superposition

The time temperature superposition principle was applied to
creep compliance data obtained in this study. The creep compliances

were corrected for entropy changes by multiplying them by the factor $\frac{T}{T_o}$ where T is the temperature at which data was taken and T_o is the temperature at which the master creep compliance curve was to be constructed. No correction was made for density changes since these were of the order of .5%. Log $D_c \frac{T}{T_o}$ plots versus log time were constructed for the various temperatures used in this study. These plots are reproduced in figures (5) and (6). These curves were shifted graphically to superimpose and create the master creep curves at 293°K which are reproduced in figures (7) and (8). These curves superimposed very well if portions above 10^3 seconds were ignored at the three highest temperatures. This was to be expected since it was previously found that the limits of linearity at these higher temperatures were in the range of 10^3 seconds for similar specimens and loading conditions (12).

Temperature Susceptibility

A plot of log t versus $\frac{1}{T}$ for constant creep compliance can be constructed utilizing the plots of reduced creep compliance versus log t figures (5) and (6). By choosing a reduced creep compliance and extending a horizontal line across several isothermal lines on the reduced creep compliance versus log t plot, a new plot of log t versus $\frac{1}{T}$ for constant reduced creep compliance can be constructed. Such a plot can be valuable in determining the temperature susceptibility of different materials.

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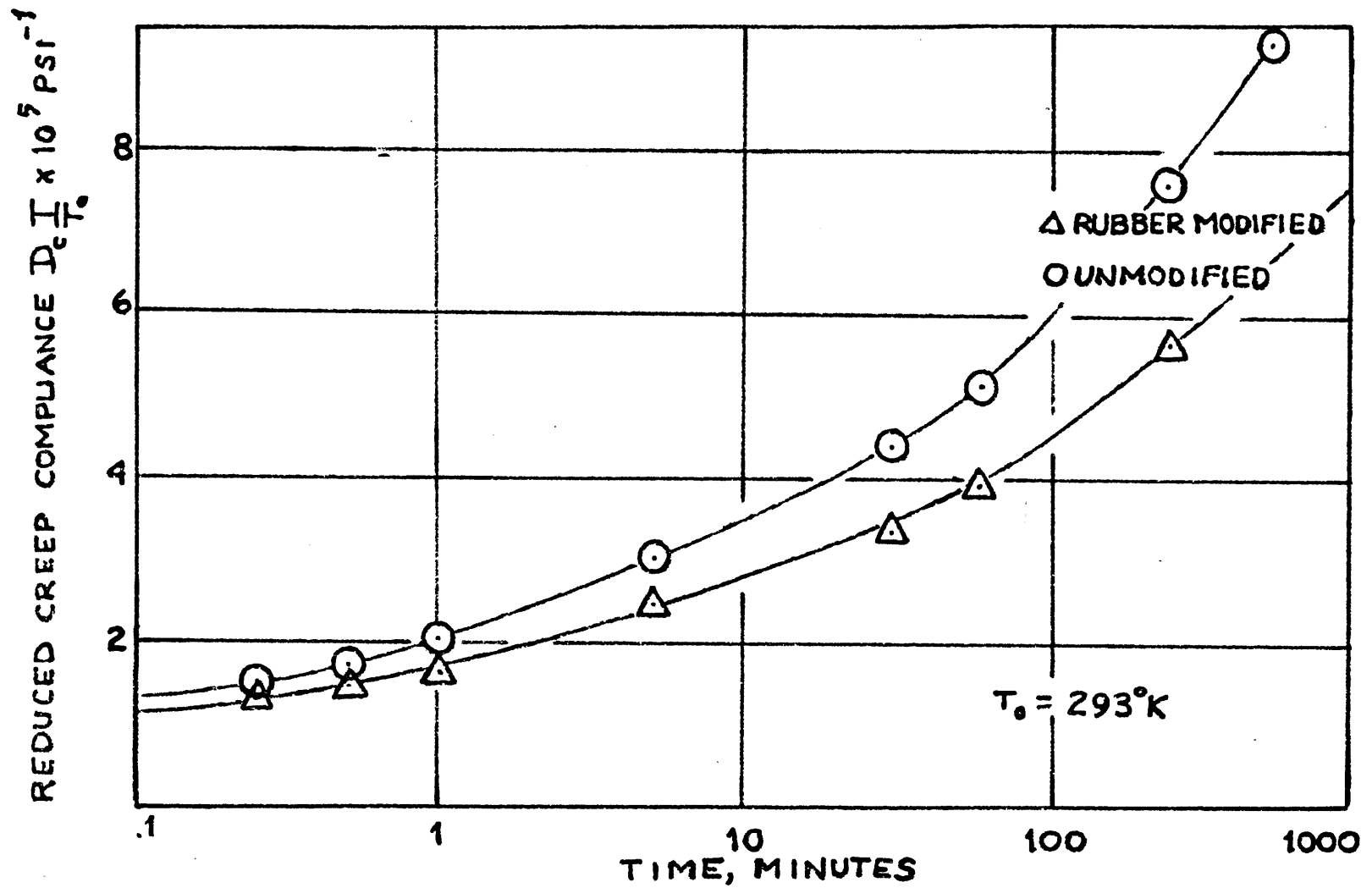
FIGURE (4) REDUCED CREEP COMPLIANCE AT 273°K
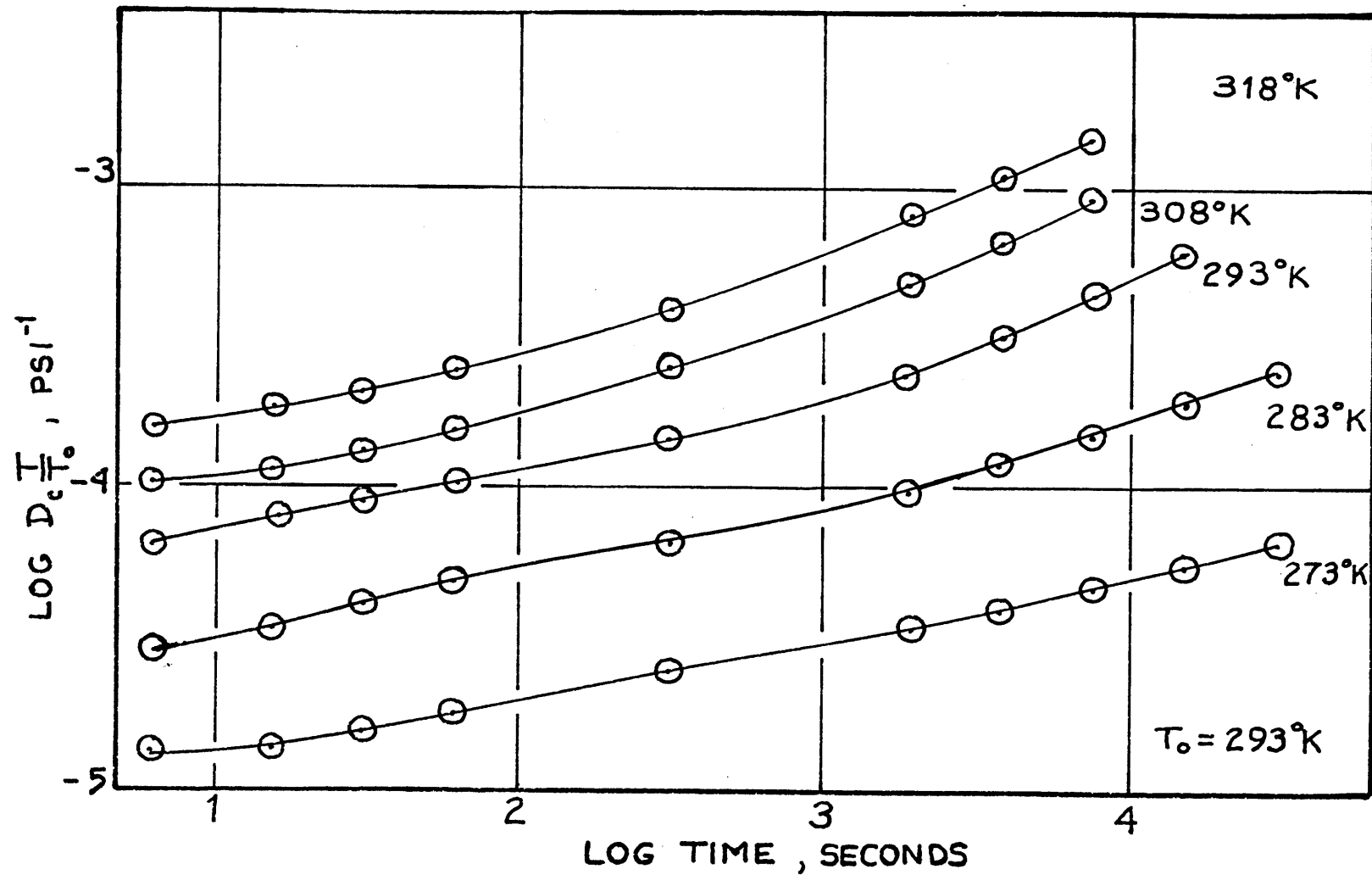
FIGURE (5)   REDUCED CREEP COMPLIANCES AT DIFFERENT
TEMPERATURES FOR RUBBER MODIFIED MIXTURE
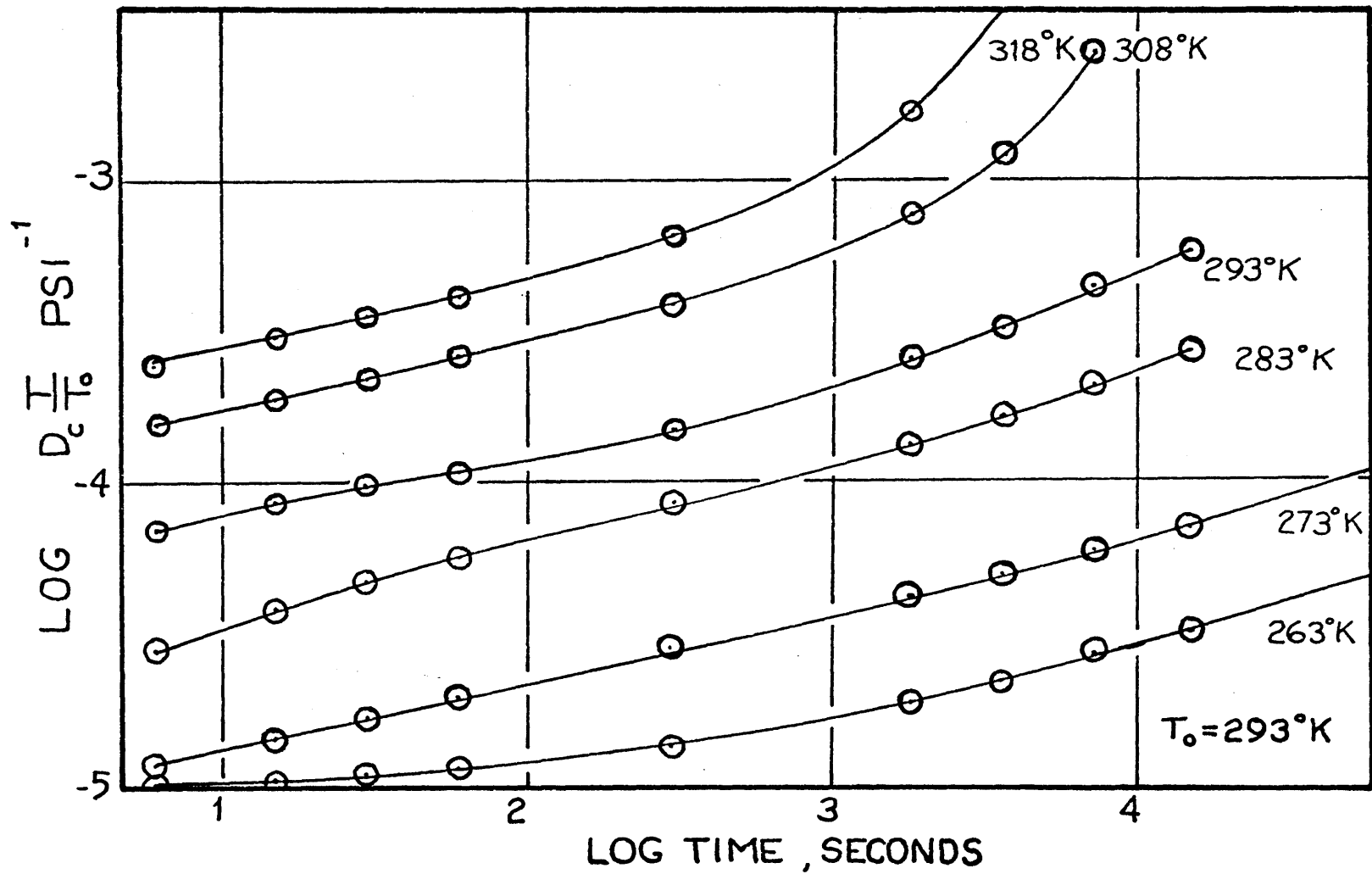
FIGURE (6)   REDUCED CREEP COMPLIANCES AT DIFFERENT
TEMPERATURES FOR UNMODIFIED MIXTURE

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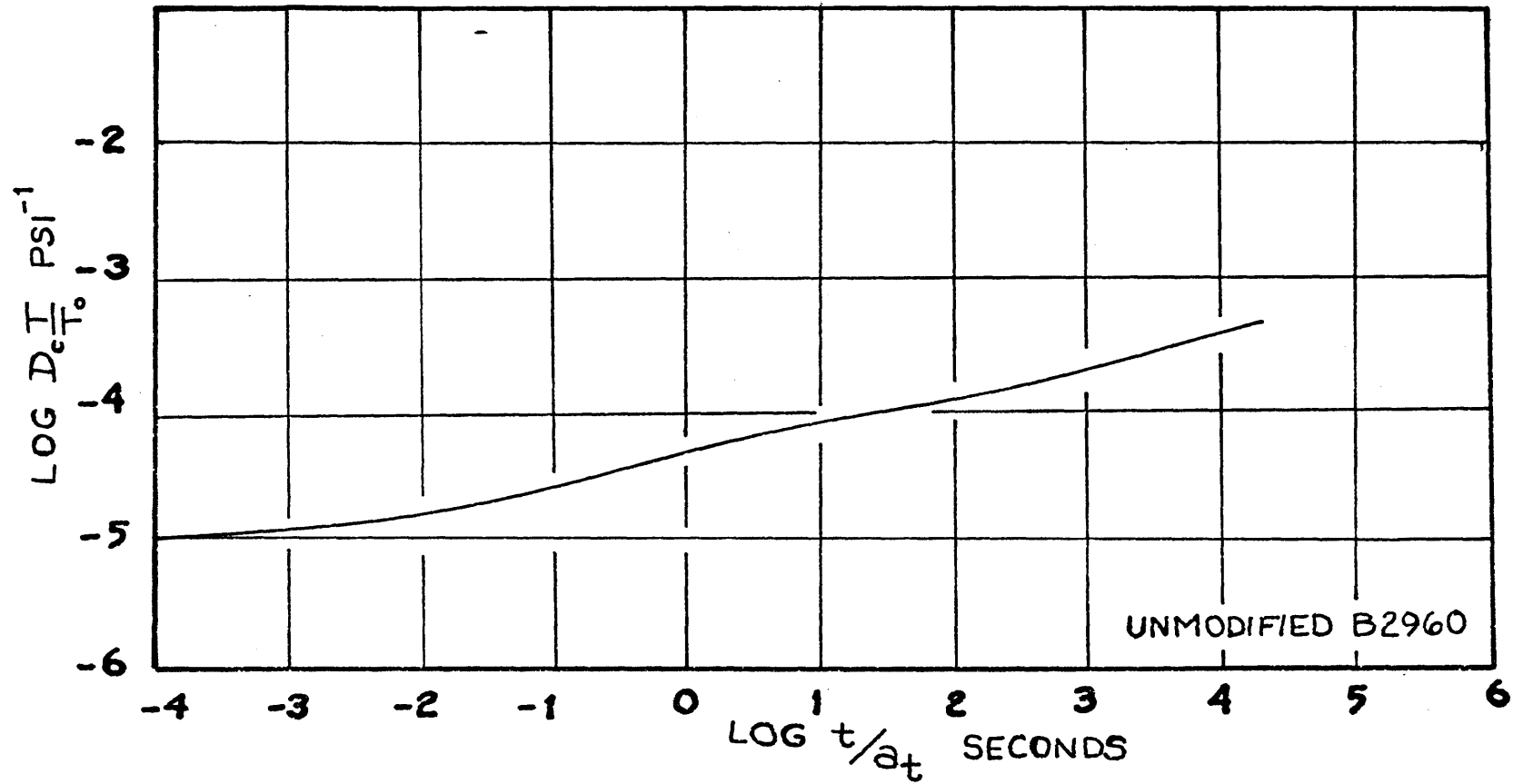
FIGURE(7)CREEP COMPLIANCE MASTER CURVE REDUCED AT $T_o = 293°K$
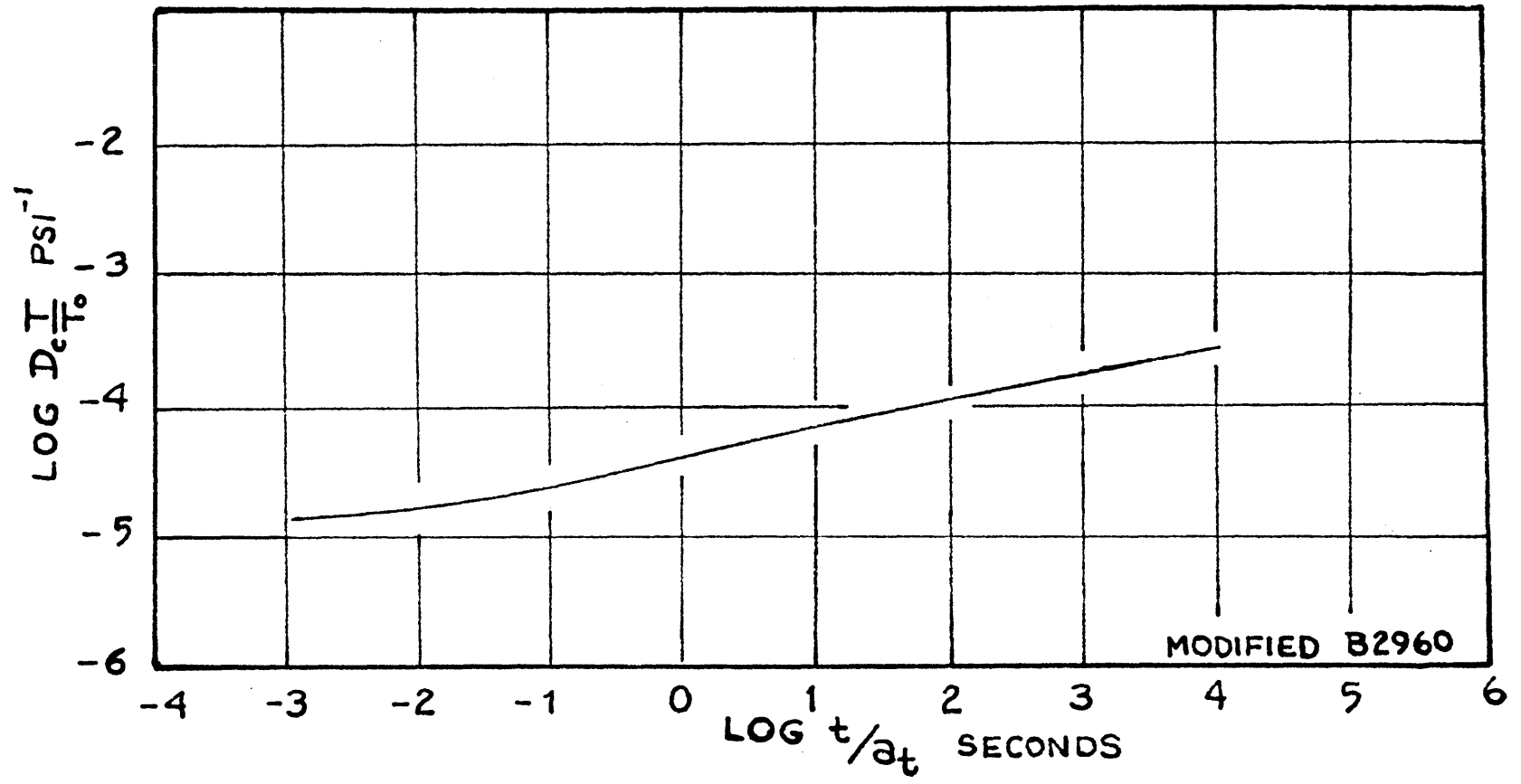
FIGURE (8) CREEP COMPLIANCE MASTER CURVE REDUCED AT $T_o = 293°K$
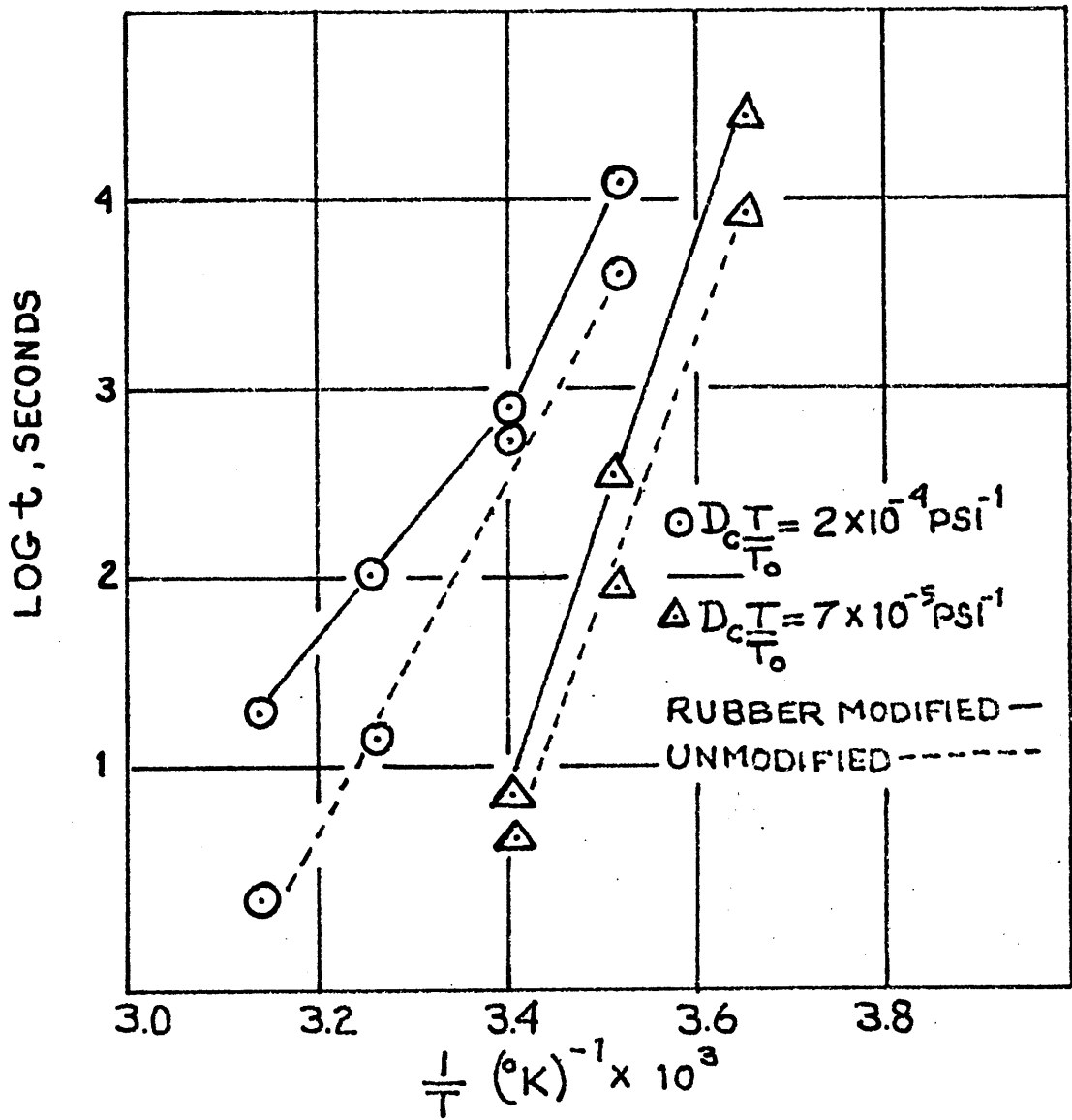
FIGURE (9) LOG t VERSUS $\frac{1}{T}$ FOR CONSTANT

REDUCED CREEP COMPLIANCE

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According to the time-temperature superposition principle a
shift along the log time axis on a reduced creep compliance versus
log time plot is equivalent to changing the test temperature. The
slope of the log t versus $\frac{1}{T}$ plot is an indication of the amount
of shift necessary or the sensitivity of the creep response of the
material to changes in temperature. Examination of figure (9)
reveals that above 20°C $\left(\frac{1}{T} < 3.41 \times 10^{-3} \, °K^{-1} \right)$ the plot for un-
modified asphalt has a steeper slope than that for rubber modified
asphalt which suggests that in this temperature range unmodified
asphalt is more susceptible to temperature change while below 20°C
both materials display about the same sensitivity to changes in
temperature. In addition the time necessary to reach some
arbitrary creep compliance is less for the unmodified mix which
suggests that it is the weaker of the two materials.

Relaxation Tests

The effects of repetition of straining were similar to the
effects of repetition of loading experienced in creep. A precondi-
tioning of three or four cycles of straining to .3% followed by
5 minute periods of relaxation was found to produce consistant
response from specimen to specimen.

Again as in the creep tests because of inertia effects and
equipment limitations it was impractical to apply a step strain
input as called for in an ideal relaxation test. Because of this

finite loading time some relaxation takes place in the material before the material is completely loaded. No attempt was made to account for this effect in plotting relaxation modulus versus log time. However when these plots were used to construct master relaxation curves data taken at times less than ten seconds were found to lie off the master curves generated. By ignoring data taken at less than ten seconds plots of reduced relaxation modulus versus log time were found to superimpose very well and produce smooth master curves of relaxation modulus.

Relaxation Modulus

The results of relaxation tests conducted on rubber modified and unmodified sand asphalt mixes at 293°K are presented in figure (10). Tests conducted at other temperatures are contained in the Appendix. Examination of these figures reveals that the rubber modified mix appears to relax faster than the unmodified mix but arrives at a steady state modulus which is higher than that of the unmodified mix.

Time-Temperature Superposition Principle

The time-temperature superposition principle was applied to relaxation modulus versus log time plots made at different temperatures in order to produce master relaxation curves. These curves are presented in figures (13) and (14). As discussed before data taken at less than ten seconds were ignored in the construction of these

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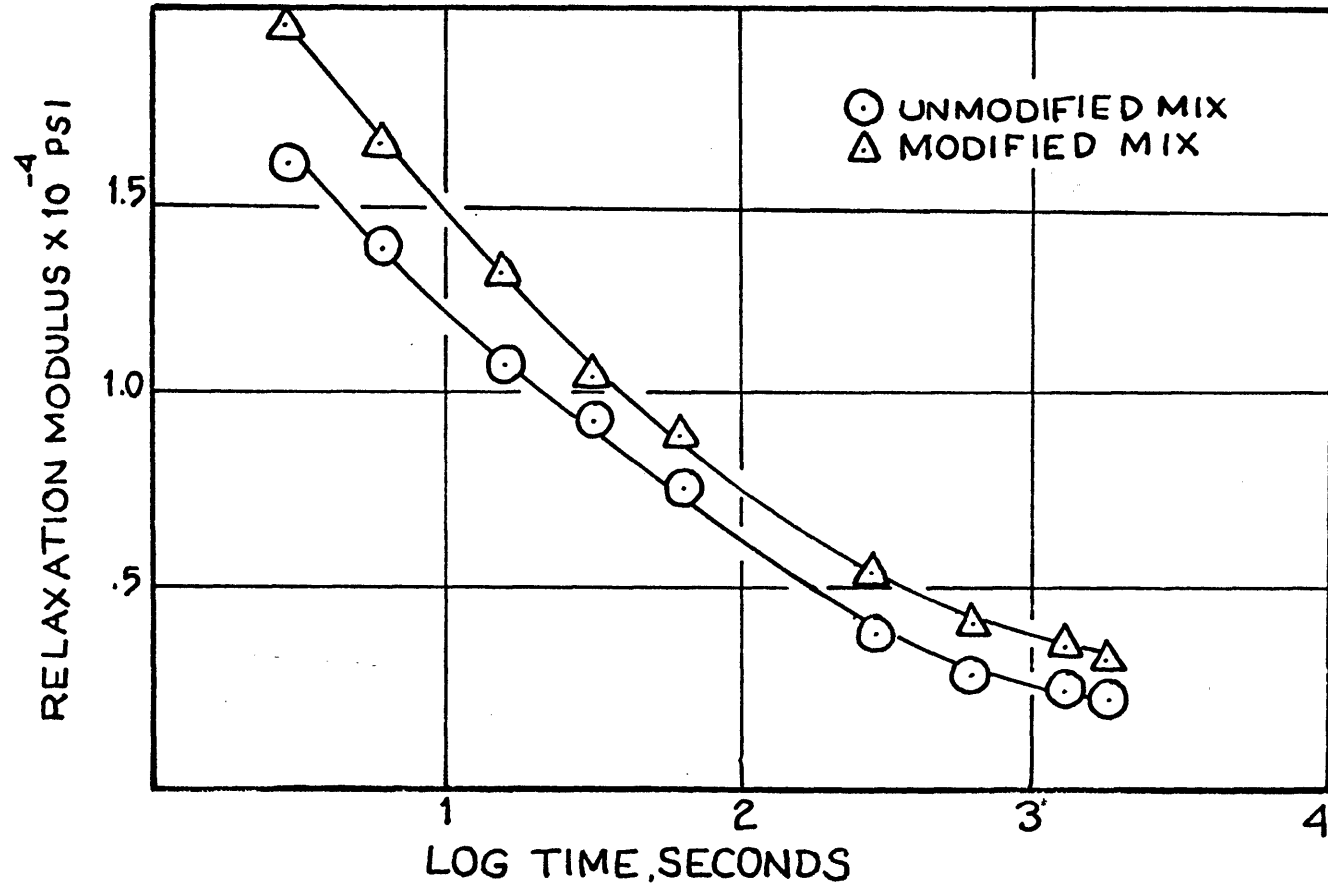
FIGURE(10) RELAXATION MODULI AT 293°K
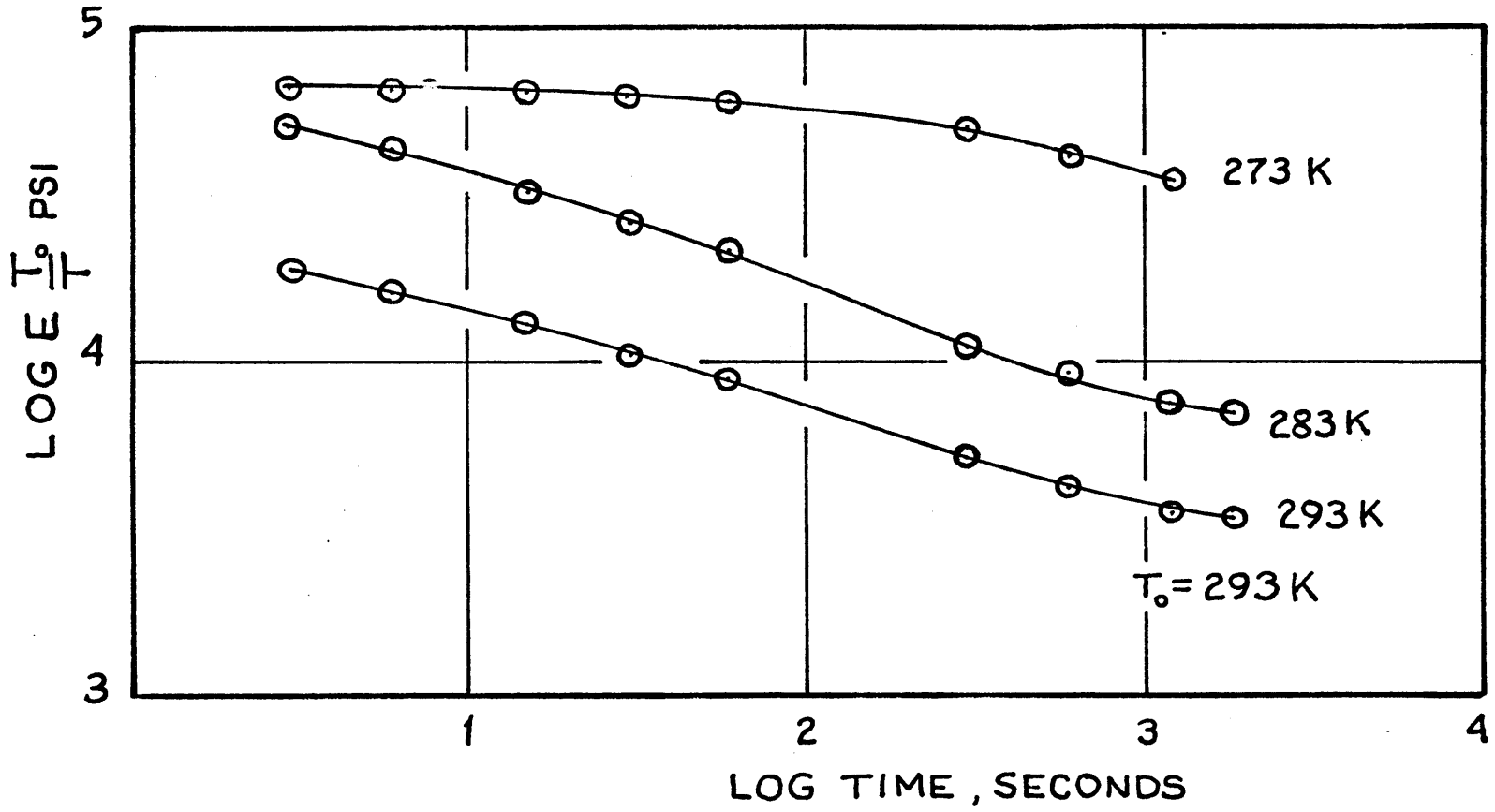
FIGURE (11) REDUCED RELAXATION MODULI FOR RUBBER
MODIFIED MIX AT VARIOUS TEMPERATURES
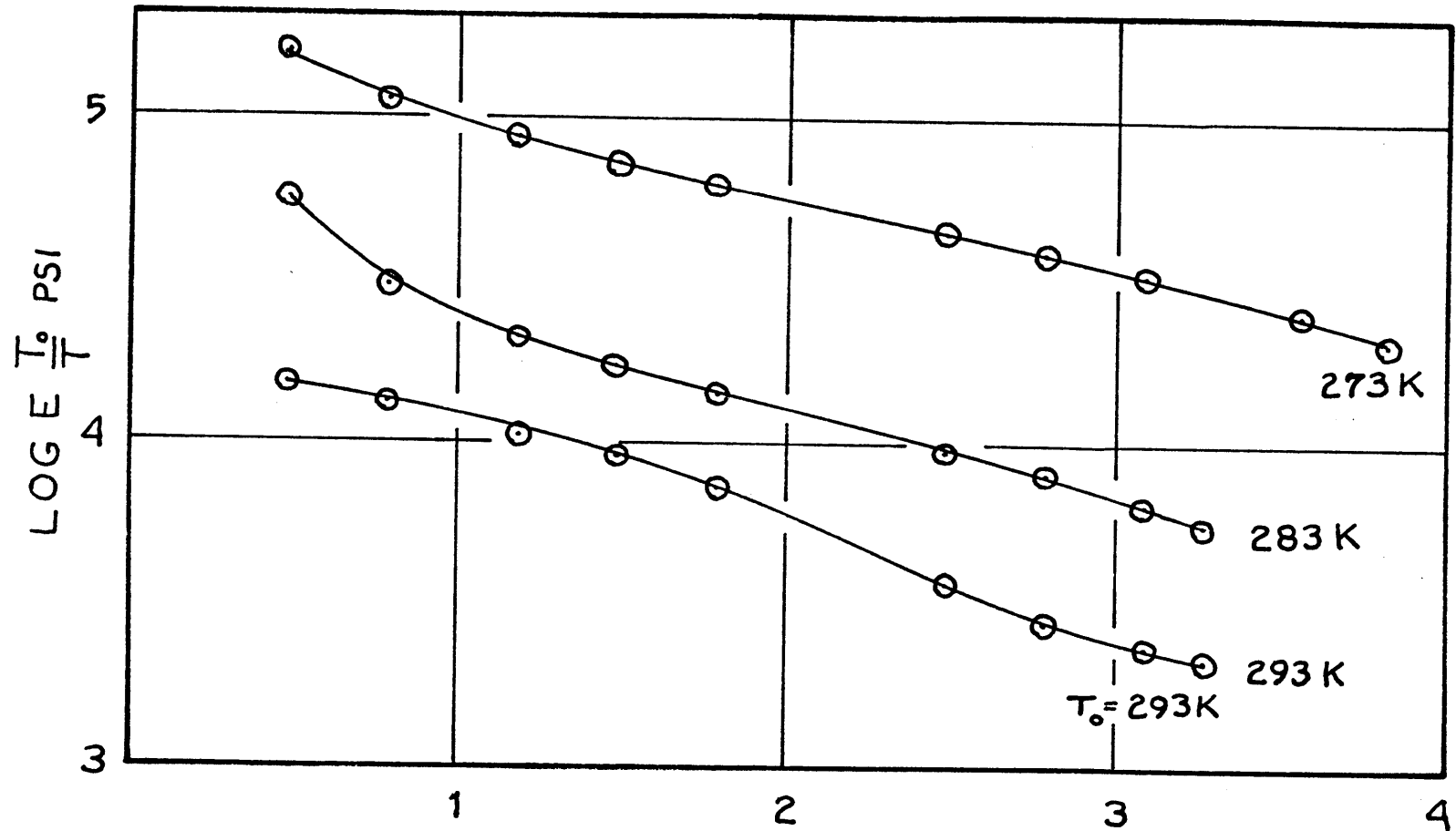
FIGURE (12) REDUCED RELAXATION MODULI FOR UNMODIFIED MIX AT VARIOUS TEMPERATURES
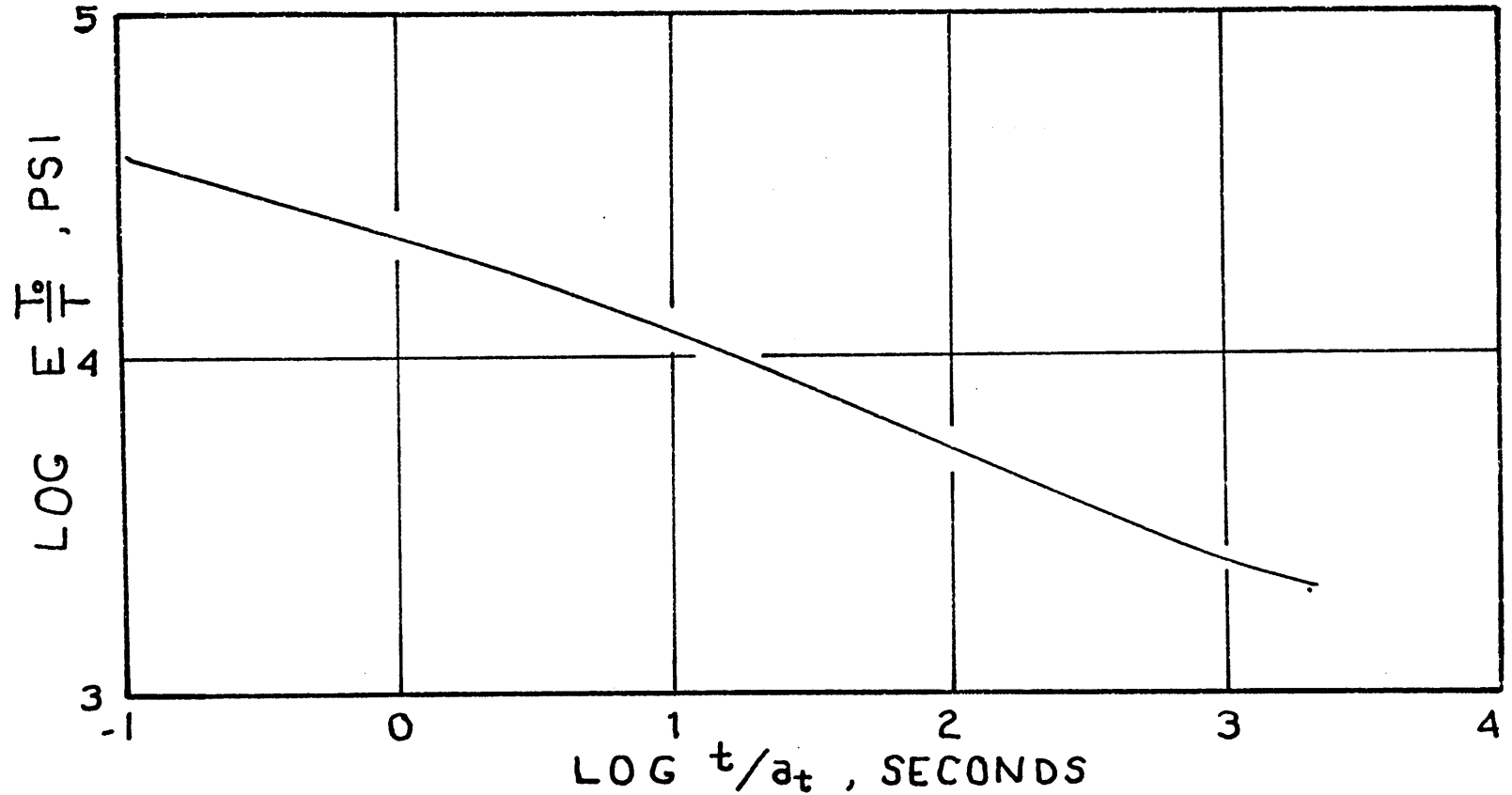
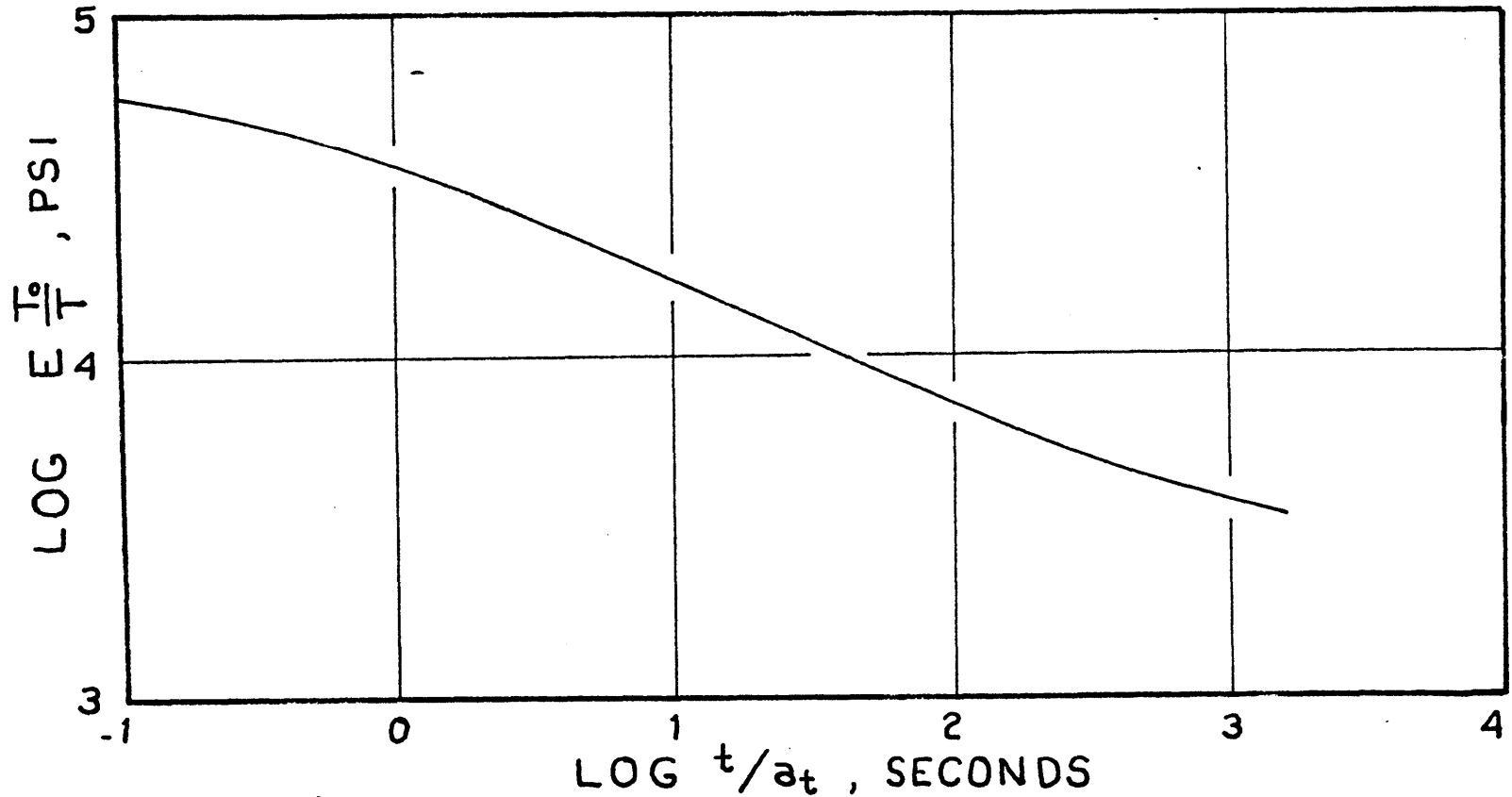FIGURE (13) RELAXATION MODULUS MASTER CURVE FOR UNMODIFIED MIX REDUCED AT 293°K

FIGURE (14) RELAXATION MODULUS MASTER CURVE FOR RUBBER
MODIFIED MIX REDUCED AT 293°K

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curves. These plots indicate that rubber modified sand asphalt has
a higher modulus at all times which simply means that the rubber
modified mix is a stronger material. The shorter relaxation times
of rubber modified mixes are not reflected in the master relaxation
curve at 293°K because this effect seems to be associated with
temperatures lower than 293°K. To better characterize the short time
response of these mixes one should use dynamic tests ran at different
frequencies. Relaxation tests conducted at more and lower temper-
atures could better characterize the short time relaxation response
of these materials.

Constant Strain-Rate Tests

In conjunction with the relaxation tests constant strain rate
tests were conducted at 0°C using the same apparatus as used in the
relaxation tests. Specimens were conditioned by several cycles of
strain to .5%. Three specimens at each strain rate were tested.
The Instron testing machine was used at cross-head speeds of .02,
.05, and .1 in/min. Results of these tests are presented in Table (4).
These results indicate that the rubber modified mix had a higher
modulus than the unmodified at all strain rates. Both materials
exhibited increasing modulus with increasing strain rate.

Shift Factors for Creep and Relaxation

A plot of log a_t versus $\frac{1}{T}$ is presented in figure (15).
This plot reflects the amount of shift along the horizontal axis

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STRAIN RATE	RUBBER MODIFIED			UNMODIFIED	
IN/IN PERMIN	MAXIMUM STRESS PSI	STRAIN AT MAX STRESS $\frac{IN}{IN}$		MAXIMUM STRESS PSI	STRAIN AT MAX STRESS $\frac{IN}{IN}$
.0066	$.92 \times 10^5$	.004		$.65 \times 10^5$	.007
.0166	1.0×10^5	.021		$.72 \times 10^5$	.036
.033	1.2×10^5	.025		$.80 \times 10^5$	.036

TABLE (4) RESULTS OF CONSTANT STRAIN RATE TESTS AT 0°C
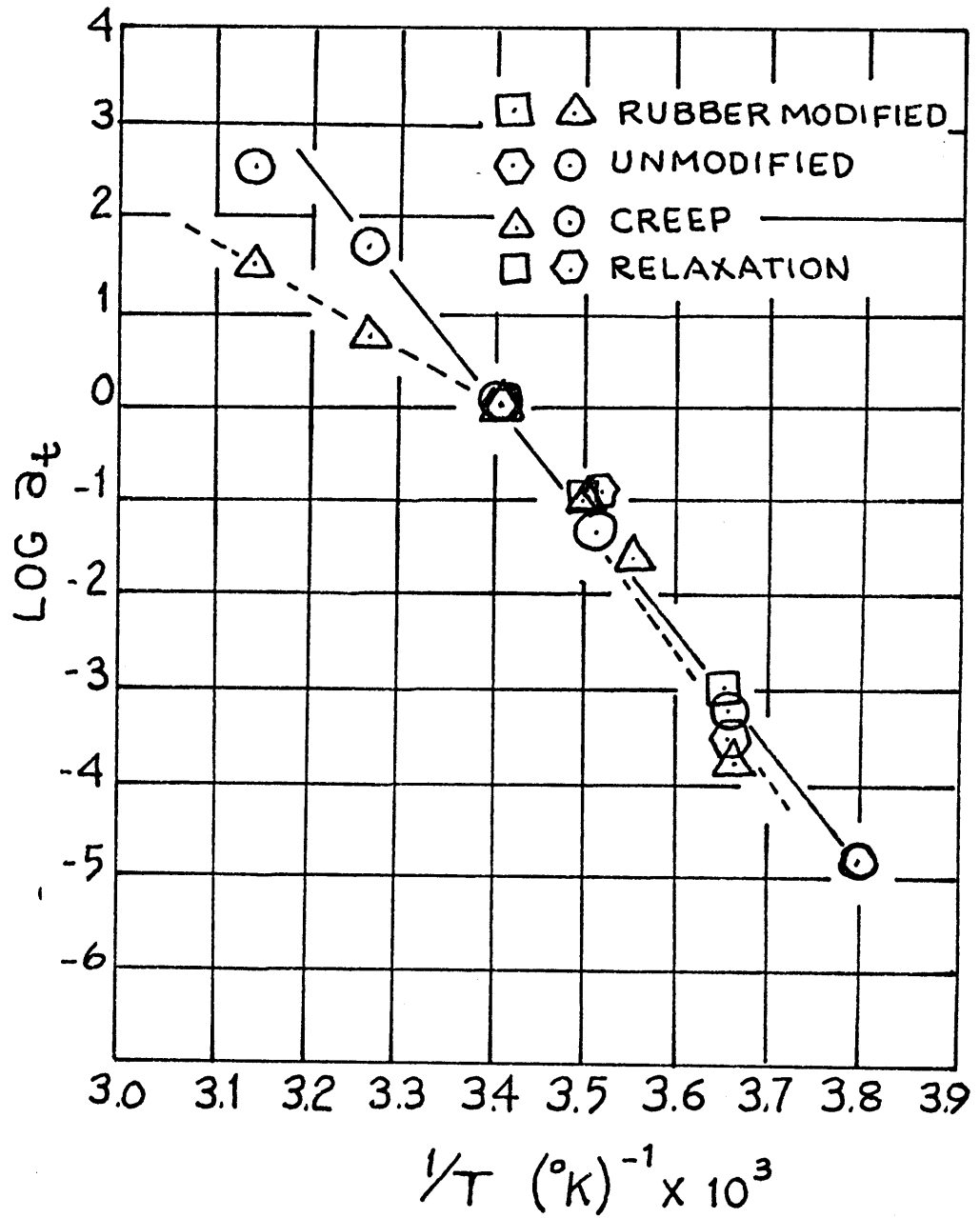
FIGURE (15)   SHIFT FACTORS VS. $\frac{1}{T}$

necessary to superimpose plots of reduced creep compliance or reduced relaxation modulus made at different temperatures. The slope of this plot is an indication of a materials sensitivity to temperature change. This plot indicates that above 20°C or 293°K the properties of rubber modified and asphalt are less sensitive to temperature change than the unmodified mix. It also indicates that both materials are equally sensitive to temperature change below 293°K. From this we would expect the reductions in strength due to high service temperatures to be less in the case of the rubber modified mix.

The smoothness or continuity of this plot together with the successful application of the time-temperature superposition principle indicates that both the rubber modified and unmodified sand asphalt mixes are thermorheologically simple materials.

Notched Beam Tests

Notched beam tests were conducted in order to examine the influence of rubber modification on brittle fracture at low temperatures. Tests were conducted at a constant deformation rate of .1 in/min. The results of these tests are presented in Table (5) and Figure (16). The rubber modified specimens exhibited a greater G_c or critical strain energy release rate at each temperature tested. Both materials exhibited an increase in G_c with increasing temperature. The failure of beams tested at -10°C was not truly
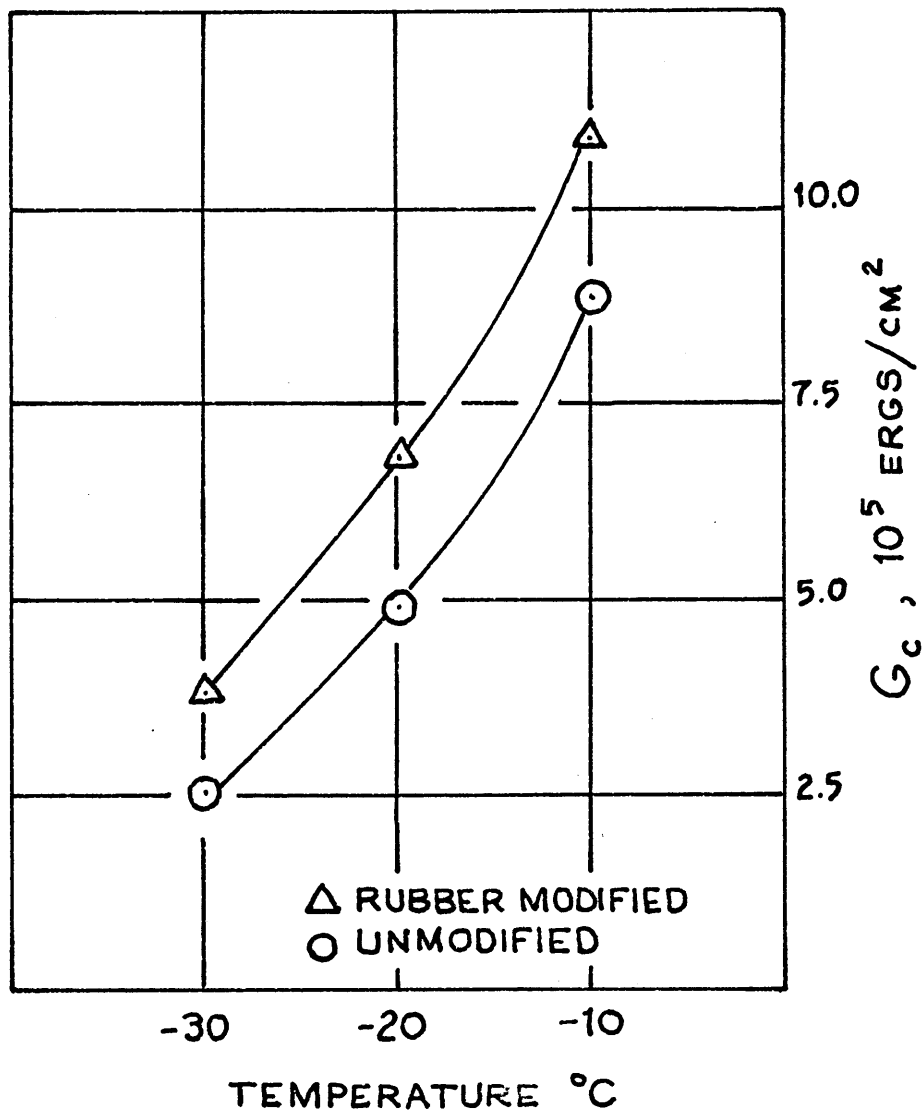
FIGURE (16) G_c VERSUS TEMPERATURE

TEMP °C	RUBBER MODIFIED		UNMODIFIED	
	$E, 10^{10} \frac{DYNES}{CM^2}$	$G_c, 10^5 \frac{ERGS}{CM^2}$	$E, 10^{10} \frac{DYNES}{CM^2}$	$G_c, 10^5 \frac{ERGS}{CM^2}$
-10	1.2	10.2	1.2	8.8
-20	1.4	6.8	1.4	4.9
-30	2.1	3.7	2.3	2.6

TABLE (5) RESULTS OF NOTCHED BEAM TESTS

brittle which would make doubtful the designation of G_c at that temperature, as a material property. However it should still serve as a measure of the relative resistance of the two materials to fracture at that temperature. The implication of these results is that the rubber modified mix would provide a paving surface more resistant to cracking under low temperature service conditions with ultimate reductions in the cost of highway maintenance.

These results follow the same trend as those previously obtained in notched beam tests conducted on rubber modified and unmodified binders (2). However there is at least an order of magnitude increase in both modulus and G_c as a result of the addition of the aggregate as used in this study. This was to be expected since the addition of 75% mineral filler in this previous study significantly increased both G_c and the modulus of the binders tested.

Impact Tests

Izod type impact tests were conducted to examine the influence of rubber modification on impact strengths of sand asphalt mixes at -37, -20, and 0°F. This test was chosen because of the relative degree of ease with which it is conducted. Results from such a test are qualitative versus quantitative. To date no complete analysis of the Izod test has been forthcoming. One should be suspect of data comparing the impact response of materials unless

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there is a significant difference between the response of materials. The results of Izod impact tests conducted in this study are presented in Figure (17). These results indicate that the rubber modified sand asphalt mix possesses greater resistance to high speed brittle fracture at low temperatures. However due to the degree of scattering of data experienced in these tests it is felt that further tests are necessary to validate these results.
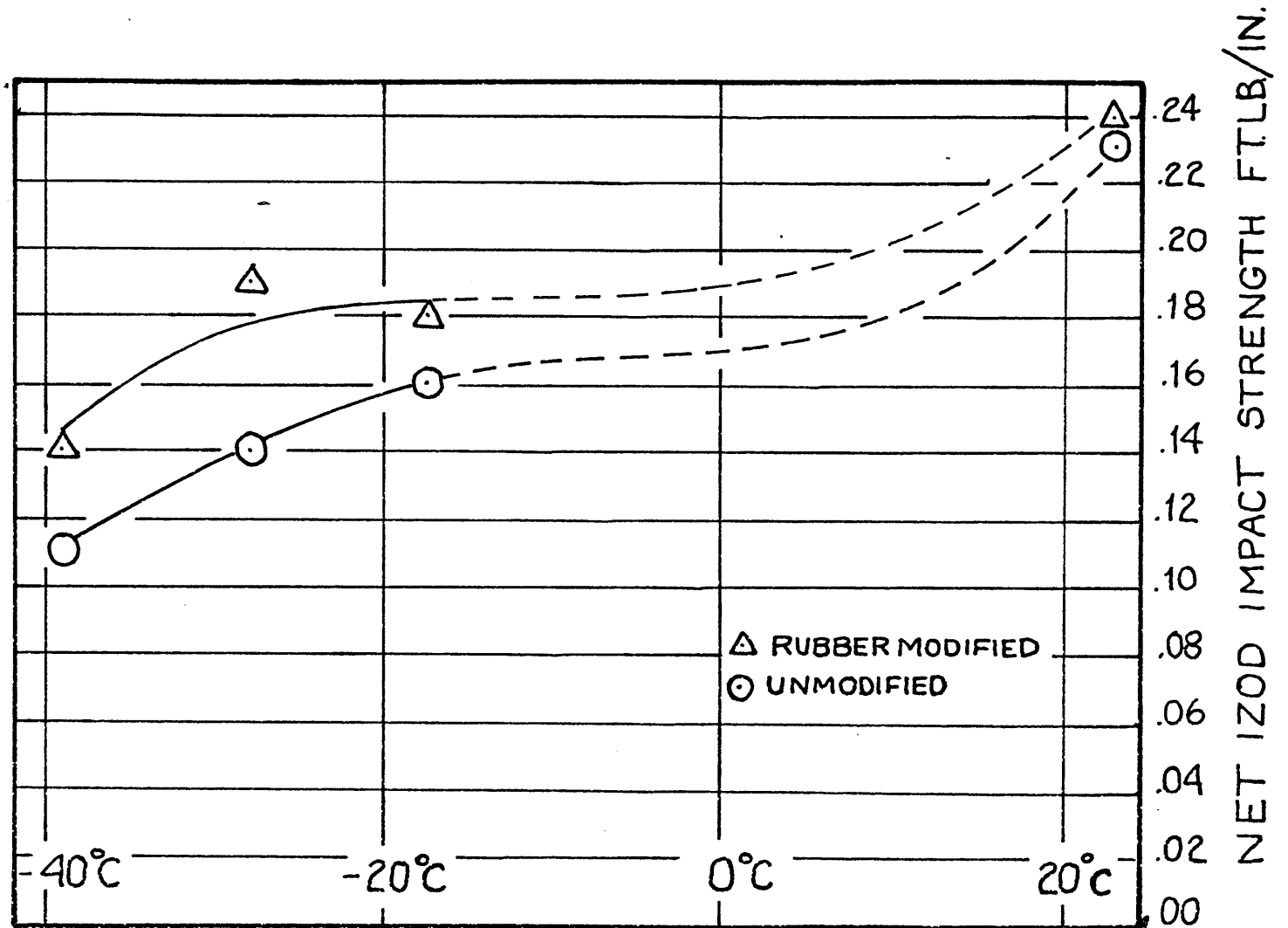
FIGURE (17) IMPACT STRENGTH VERSUS TEMPERATURE

V CONCLUSIONS

In this study various tests were conducted to compare the
properties of sand asphalt mixes made with binders consisting
of unmodified B2960 asphalt and B2960 asphalt modified by the
addition of 4.5% Pliopave L170, a rubber pavement additive manufac-
tured by Goodyear Tire and Rubber Company.

Creep, relaxation and constant strain-rate compression tests
were conducted to evaluate the viscoelastic response of the
materials. Notched-beam and impact tests were used to compare the
resistance of the materials to brittle fracture at low temperatures.
From the results of these tests the following conclusions are drawn.

1. The time-temperature superposition principle can be
applied successfully to the creep and relaxation response of
sand asphalt mixes if strains are restricted to very small values.

2. The temperature susceptibility of mixes made with rubber
modified binder is less than that of mixes made with unmodified B2960
asphalt binder in the temperature range above 20°C. This means
that changes in temperature would have less effect on the properties
of a rubber modified asphalt pavement than on a conventional
pavement of the same mix design. At any service temperature above
20°C one would expect less shove and other high temperature
damage in a rubber modified pavement.

3. At sufficiently low temperatures the techniques of

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fracture mechanics can be applied to sand asphalt mixes.

4. The critical strain energy release rates of sand asphalt mixes are temperature dependent and increase with increasing temperature in the range of $-30°C$ to $-10°C$.

5. The critical strain energy release rates for rubber modified sand asphalt mixes are 20 to 40 per cent higher than those for unmodified sand asphalt mixes in the range of temperatures examined in this study. Accordingly a pavement constructed of rubber modified mix should be less susceptible to cracking than a conventional mix when subjected to the same low temperature service environment.

Suggestions for Future Work

In light of the results of this study the following areas of research seem to warrant investigation

1) Dynamic tests should be conducted to characterize the creep and relaxation response for very short loading times.

2) The effects of accelerated aging on creep, relaxation, and brittle fracture should be investigated.

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APPENDICES

DEFINITION OF SYMBOLS

σ stress

ε strain

γ surface energy of material per unit area

c half crack length

γ_p fracture surface work of material per unit area

U elastic strain energy of system

G_c critical strain energy release rate

ν Poisson's ratio

σ_n nominal bending stress at tip of notch

h net depth of beam at the notch

$f(c/d)$ function of notch depth ratio

D_c Creep Compliance

E Relaxation Modulus

$D_c \dfrac{T}{T_0}$ Reduced Creep Compliance

$E \dfrac{T_0}{T}$ Reduced Relaxation Modulus

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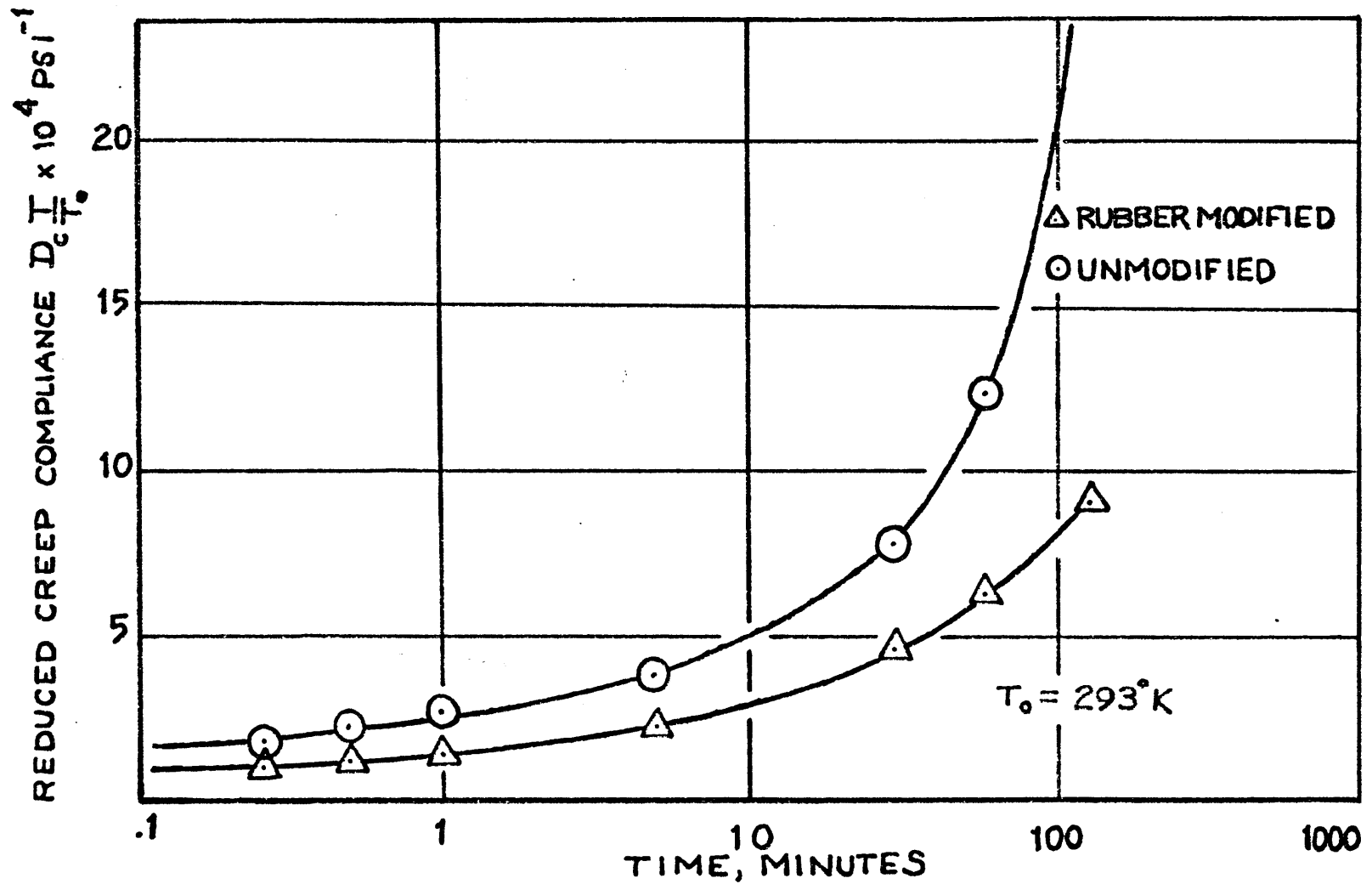FIGURE (18) REDUCED CREEP COMPLIANCE AT 283°K

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FIGURE (19) REDUCED CREEP COMPLIANCE AT 293° K
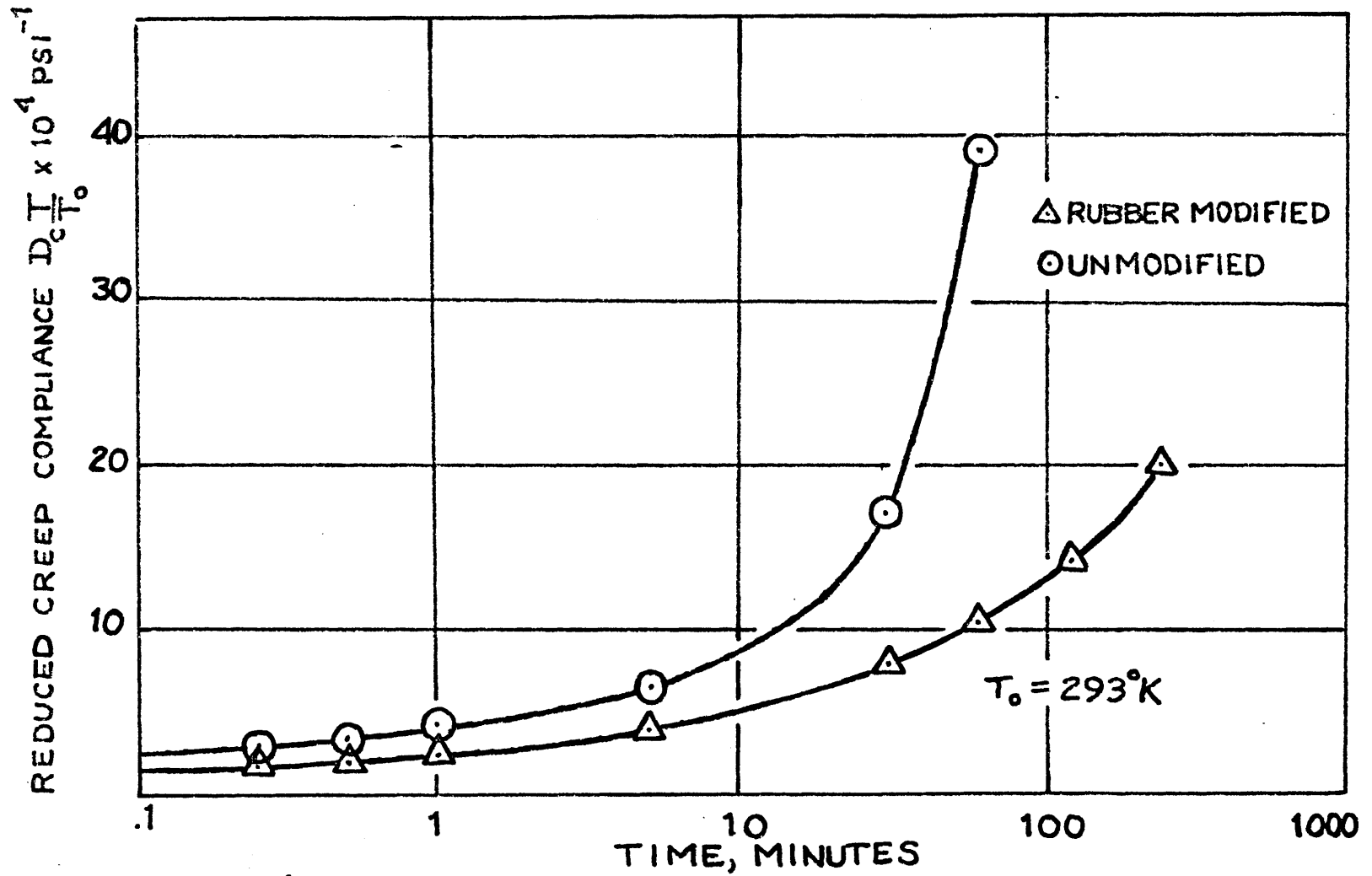
FIGURE (20) REDUCED CREEP COMPLIANCE AT 308°K

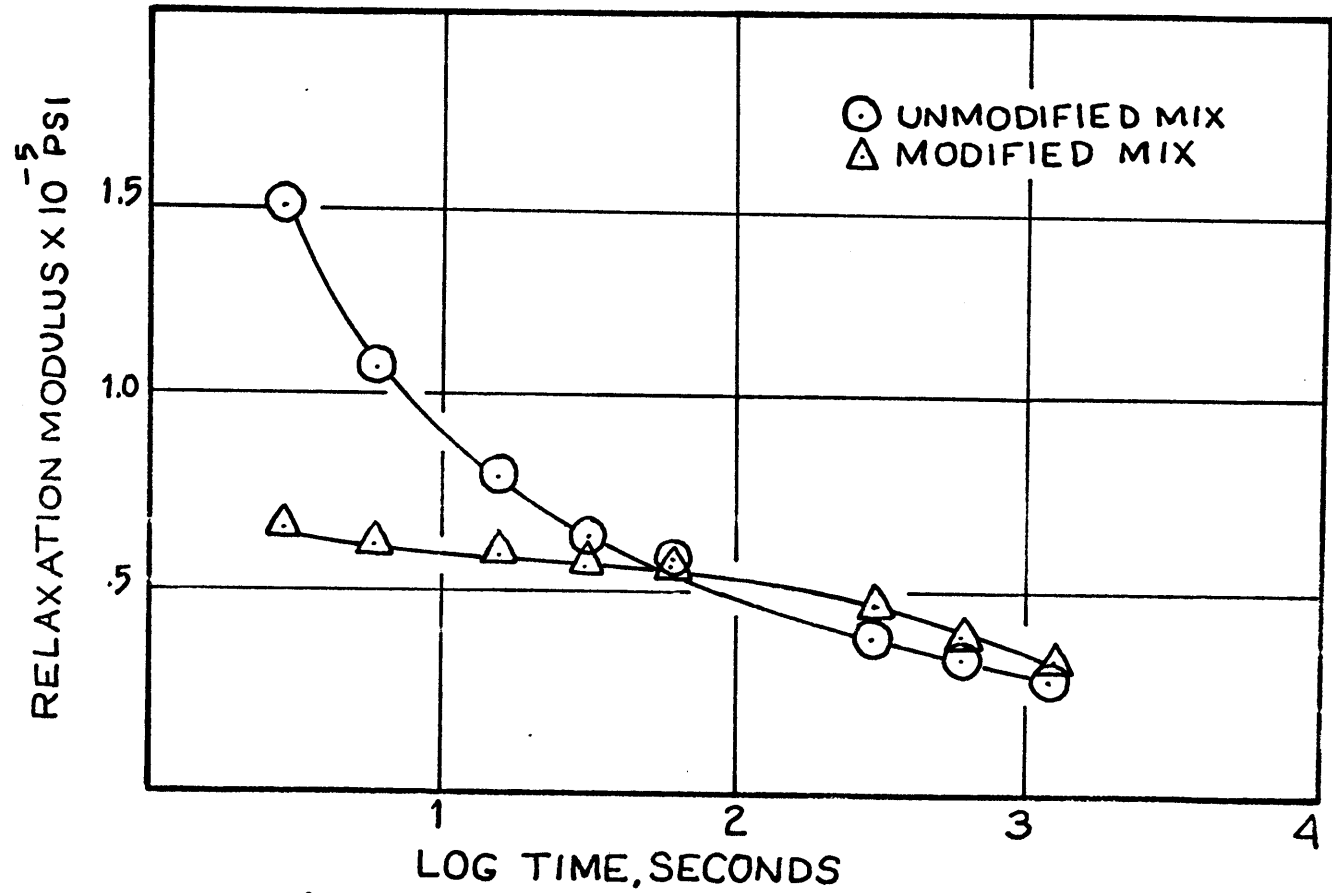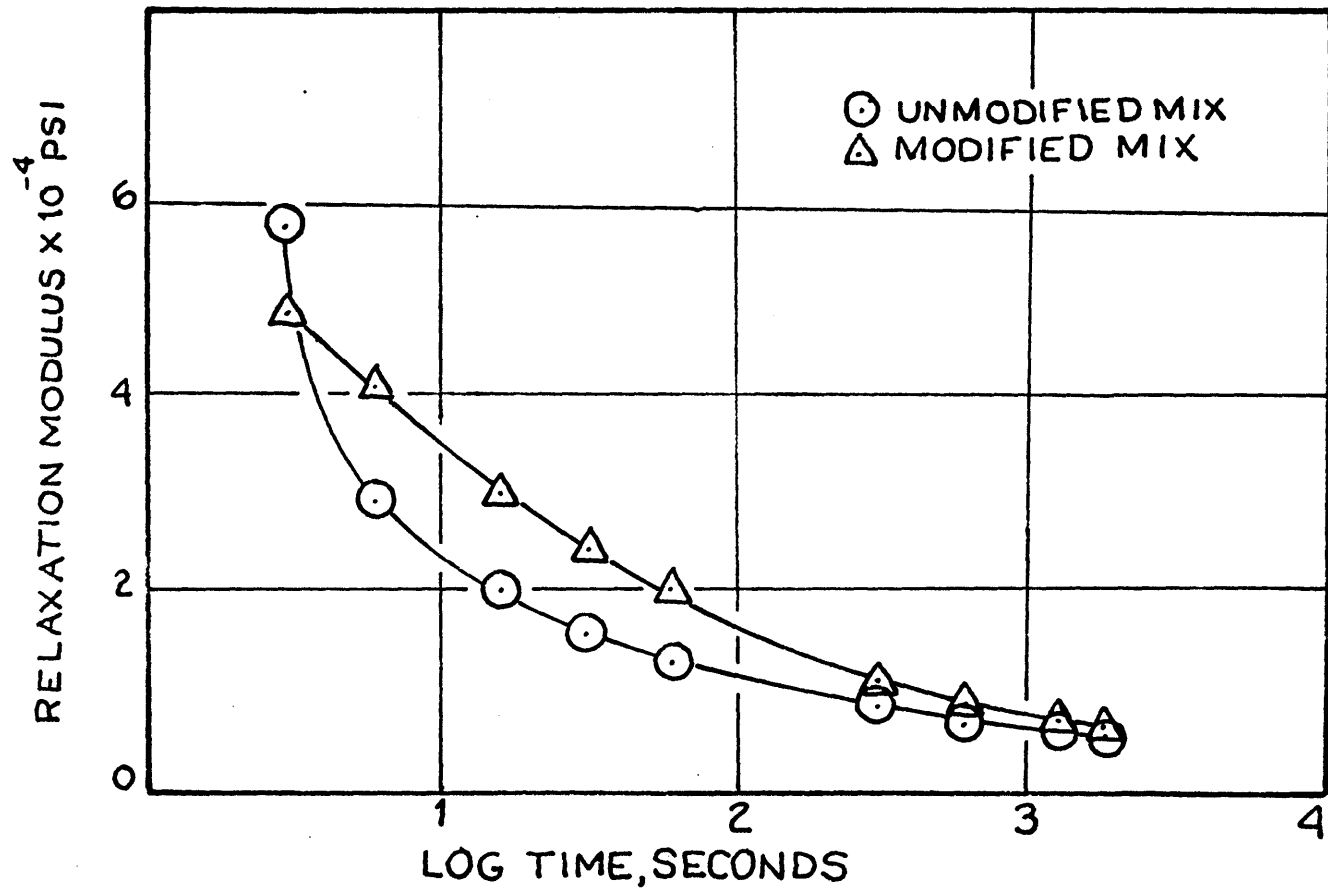FIGURE (21) REDUCED CREEP COMPLIANCE AT 318°K

FIGURE (22) RELAXATION MODULI AT 273°K

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FIGURE(23) RELAXATION MODULI AT 283°K