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16. Abstract

Pavement cores were collected from rutting asphalt concrete pavements less than 2 years after last overlay. Tests were performed in an attempt to determine the cause(s) of rutting. Findings revealed common causes such as excessive asphalt, fine-grained aggregate and natural, rounded aggregate particles.

A laboratory test program was designed and initiated to quantify the contribution to rutting in asphalt concrete mixtures when increasing amounts of natural (uncrushed) aggregate particles are added. The objective is to generate supporting data and prepare specifications for maximum quantity of certain natural sands, minimum top-size aggregate and minimum voids in mineral aggregate in paving mixtures to be placed on high traffic volume roadways. Results to date have shown that susceptibility to plastic deformation increases dramatically when natural particles replace crushed particles in a given aggregate gradation.

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INVESTIGATION OF RUTTING
IN
ASPHALT CONCRETE PAVEMENTS

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Interim Report 1121-1
Research Study 2-8-87-1121

Prepared for
Texas State Department of Highways and Public Transportation
Federal Highway Administration
U.S. Department of Transportation

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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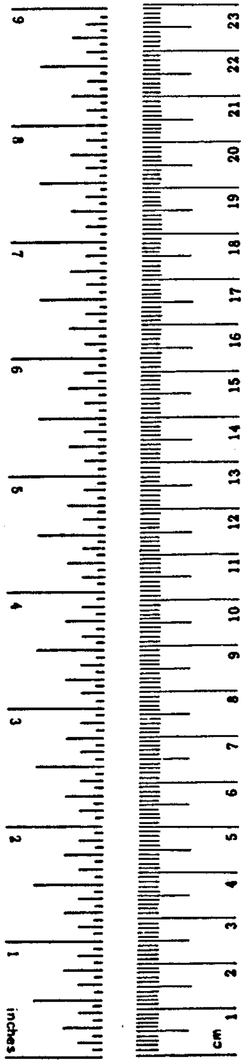
* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac

MASS (weight)

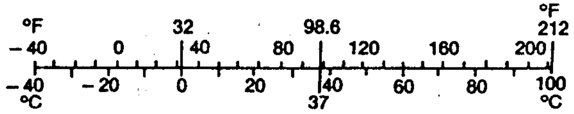
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

IMPLEMENTATION STATEMENT

Technology is available, and has been for many years, to build asphalt concrete pavement layers that will resist rutting under heavy traffic loads. Most highway engineers are very well aware of this. Problems associated with producing and placing rut-resistant asphalt paving mixtures are availability of quality materials, workability, compactibility, and of course, cost. In addition, some existing specifications encourage production of rut-susceptible paving mixtures.

The primary materials-related factor associated with plastic deformation (rutting) in asphalt concrete pavements is the characteristics of the aggregate. Rut-resistant mixtures are composed of large maximum size, crushed aggregate with little or no natural aggregate (sand and/or gravel). The gradation is designed to provide stone to stone contact to support shear stresses and resist plastic flow. Without the lubricating effects of field sand, these coarse, crushed aggregate mixtures are more difficult to place in a smooth-textured layer and more difficult to compact to acceptable air void levels. But once adequately compacted, these coarse, crushed stone asphalt mixtures will offer excellent resistance to plastic deformation. Of course, the more easily a mixture compacts, the more susceptible to rutting it will be.

In a properly designed rut-resistant aggregate for asphalt concrete, the viscosity characteristics of the asphalt will have minimal effects on the problem of rutting. The quantity of asphalt, on the other hand, may have significant influence on rutting. A rut-resistant aggregate system with adequate voids in the mineral aggregate (VMA) will be less sensitive to asphalt content than those mixtures containing rounded, smooth-textured, non-absorptive aggregate particles. A rut-susceptible aggregate will be more sensitive to asphalt quantity and viscosity.

A rut-resistant asphalt paving mixture contains a minimum VMA of about 15 percent (slightly less in the binder course), more than 90 percent (preferably 100 percent) crushed stone, a maximum aggregate size near 3/4-inch (1-inch for base mixes), and 5 to 8 percent in-place air voids. This type of mix will usually require more asphalt than similarly graded mixtures containing hard, nonabsorptive natural (uncrushed) aggregate particles. However, a larger maximum aggregate size will increase the volume concentration of aggregate and thus reduce the asphalt requirement when compared to finer graded mixtures. If rut resistance was the only consideration, more than 5 percent air voids may be advisable; however, a 3 to 5 percent air void range after traffic will usually provide acceptable resistance to rutting as well as stripping and oxidative aging.

The Asphalt Institute recommends that the maximum size aggregate used in the Hveem test not exceed 1-inch and, further, that oversize rock up to 25 percent may be screened out without marked effect on stabilometer values.

Compaction energy requirements for a rut-resistant paving mixture will likely be greater than those normally encountered. Therefore, more or heavier compaction equipment (as used in years past) or higher compaction temperatures may be required for adequate densification.

These types of rut-resistant mixes will be more expensive to produce and pavements will be more difficult (costly) to construct. Therefore, they may be cost effective only on high traffic-volume roadways. Use of these mixtures may not result in cost savings during the first year. Cost savings should be realized by extended pavement service life and reduced maintenance activities.

Presently, these guidelines are general in nature. However, it is the objective in the remainder of this study to develop more specific guidelines and specifications which can be readily implemented.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

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INTRODUCTION

In 1984, WASHTO (1) stated that in some states rutting in asphalt concrete pavements "is the most pressing issue presently facing the highway agencies." WASHTO further stated that "the State Materials Engineers do not feel that the present procedures and specifications fully address the rutting problem. The general feeling is that the present state-of-the-art in materials testing relating to rutting needs to be upgraded through basic research."

Many roadways are experiencing extensive, premature, high levels of rutting even when made with materials which, in the past, showed little propensity toward rutting. This brings into question the ability of current pavement and mixture design methods to adequately address permanent deformation and the ability of existing materials specifications to prevent premature pavement failure due to rutting under the increasing demands of traffic. Based on findings from research studies (2), and discussions with trucking industry personnel, tire manufacturers and legislative committees, there appears to be no hope that stresses applied to pavements will decrease. The highway engineer is, therefore, charged with the responsibility to develop pavement and mixture design methods and materials acceptance criteria that will accommodate these high tire pressures and heavy loads.

Aggregates that are predominantly rounded and smooth textured, contain excessive sand-sized particles or insufficient filler or consist of small top-size particles have been associated with rutting in asphalt concrete pavements. Excessive asphalt content, particularly in rounded, smooth-textured, nonabsorptive aggregates, will promote rutting. Asphalts that are too soft for a given climate, slow setting or highly temperature susceptible will contribute to rutting when marginal aggregates are used. Paving mixtures containing excessive air voids, voids in the mineral aggregate, moisture, or foreign materials (such as unburned liquid fuels or liquid antistripping additives), or mixtures that are water-susceptible are candidates for rutting. Other considerations include mixing plant operations, environmental and geographical factors and, of course, traffic.

The overall purpose of this study is to assemble and analyze existing information on rutting pavements and paving mixtures, conduct tests, develop methods to reduce the rutting problem and distribute this information to highway personnel in an understandable, implementable format. Specific objectives include:

1. Review existing information,
2. Conduct field investigations of asphalt concrete pavements experiencing rutting,
3. Perform laboratory tests to isolate the cause(s) of rutting,
4. Develop new materials specification to minimize rutting,
5. Recommend test methods that have a good probability of identifying rut-susceptible mixtures
6. Recommend mix designs to economically reduce rutting, and
7. Assist the Department in implementing the findings of this research.

The limited scope of this project did not permit a comprehensive study of the fundamental materials properties that produce rutting. A more applied approach was taken which involved identification of recurring factors which contribute to rutting, assessing the magnitude of these factors and developing specifications and/or guidelines to reduce their effects.

LITERATURE REVIEW AND COMMENTS

CAUSES OF RUTTING

Krugler, et al. (3) stated that the rutting problem identified in western states falls primarily into three categories:

1. Excessive traffic consolidation in the upper portion of the pavement,
2. Plastic deformation due to insufficient mixture stability, and
3. Instability caused by stripping of the asphalt below the riding surface.

Traffic volume most likely cannot be controlled. Traffic loads can only be controlled through legislation and strict enforcement of the load regulations to include heavy fines for noncompliance. Eliminating consolidation and plastic deformation by traffic will require the use of properly designed paving mixtures and structural systems as well as adequate construction quality control. Stripping can be reduced by minimizing the exposure of the mixture to moisture (compaction, sealing and drainage) and/or utilizing antistripping additives or non-stripping materials. The next step is to develop appropriate screening procedures to identify rut-susceptible materials in the laboratory and specifications to eliminate them.

More specifically, factors identified in New Mexico (4), Florida (5) and Wyoming (6) as the cause of rutting include:

1. Drum mix plants operated at relatively low temperatures,
2. Excessive permissible moisture in the mix,
3. Elimination of multiple stockpile requirements,
4. Excessive fines (sand-size particles) allowed in the mix,
5. Use of control-strip density requirement rather than reference type density requirement,
6. Temperature susceptible asphalt cement,
7. Rounded aggregates or insufficient crushed particles,
8. Excessive asphalt content, and
9. Cold weather paving which leads to low density.

In addition, a field study by Roberts (2) showed that tire inflation pressures are much higher than those typically used in design procedures. He stated that truck tire pressures average between 95 and 100 psi; whereas, 75-90 psi is typically used in pavement design procedures. More importantly, however, these higher truck tire inflation pressures translate to contact pressures 200 psi and greater! The distribution of hot tire pressure measurements taken across the country has recently been reported by FHWA (7). Pavement designers should note that approximately 65 percent of the tires checked during the survey were inflated to pressures in excess of those used in the AASHO Road Test (1958-60). In other words, pavement designers may be designing today's pavements for yesterday's loads. Incidentally, a Wyoming study (6) found that single and tandem axle loads were frequently applying damaging effects to their pavements 10 times that of the legal limit.

REDUCING RUTTING

In 1984, the Illinois Department of Transportation (8) moved rapidly to address rutting on their high traffic volume roadways. Their new interstate highway specification includes the following changes: (1) increased VMA from 11-13 percent to 15 percent minimum, (2) increased design air voids content from 2.5 percent to 4 percent, (3) replaced 100 percent of natural sand with coarser crushed sand size particles, (4) increased aggregate fines (-#200) from 0-6 percent to 0-8 percent, (5) changed asphalt grade from AC-10 to AC-20 and (6) changed from passing-retained gradation to percent passing gradation. Some of these changes may be unnecessarily costly, such as replacing 100 percent of the natural sand with crushed sand. Changing from AC-10 to AC-20 in the Illinois climate may be inviting a thermal cracking problem. These specification changes were made by a committee of high level Illinois DOT personnel in a short time period (3 months) based on recommendations from asphalt pavement experts and with little or no site specific data from a well-designed research program. Rutting on their interstate highways was virtually eliminated. It may be possible, however, to reduce these requirements somewhat and provide a more cost-effective and yet adequate specification to address rutting on high traffic volume roadways.

Large stone mixes (9-13) have recently been used to substantially reduce rutting on major highways in several states. These types of mixes are not new but neither have they been widely used in the U.S. Three types of large stone mixes have been evaluated in resisting rutting due to heavy loads and high tire pressures: (1) dense graded, (2) stone filled and (3) open graded.

The dense graded material (9) is an aggregate blend that primarily develops strength from aggregate interlock and viscosity of the binder (Figure 1). The introduction of the larger stone increases the volume concentration of aggregate (100-VMA) in the mix which, in turn, improves its bearing capacity. The mix is characterized by high stability and air void levels typically between 4 percent and 8 percent. Large stone asphalt-treated bases were the backbone of many state specifications, but over the years they have been replaced with finer mixtures. ASTM D3515 provides an example of typical grading envelopes for 1 1/2-inch nominal maximum size material.

A stone filled mixture (9) essentially consists of a properly designed small top size asphalt concrete mix combined with larger single sized stone (Figure 2) of up to 1 1/2-inch maximum size for base courses or a smaller size stone (1/2-inch) for surface mixtures. As shown in Figure 3, a stone matrix is formed by the large stones and the voids between the stones are filled by the asphalt concrete mix. Due to the bridging effect of the stone on stone, the mix is resistant to rutting and further densification under traffic. The introduction of higher proportions of top size stone and/or larger stone increases the volume concentration of aggregate, reduces aggregate surface areas, and reduces the optimum asphalt cement content by about 1 percent when compared to normal dense graded mixtures.

An open graded mix (9), as shown in Figure 4, consists of large top size crushed stone (up to 2 1/2-inch), low asphalt cement content (typically 2.0 percent) and voids in the 15 percent to 30 percent range. The mix develops strength from direct stone on stone contact which again resists both rutting and further densification. With the high permeability of this mix, it is essential that the layer is properly drained.

The objective (9) of using large stone mixture is to change the basic structure of the mix such that the traffic is supported by direct stone on stone contact and to ensure that the mix will not densify under traffic. These concepts are not new, but neither are they being routinely applied due to a variety of factors. In fact, it is interesting to look briefly at historical developments. Large stone penetration macadam, and later, plant mix macadam mixtures, were popular from the turn of the century through the 1950s. However, as we became more mechanized and production-oriented, we found that the finer (1/2-inch maximum) stone sizes were easier to handle. They did not wear the flights in the mixing facility as much, and they produced a uniform, smooth pavement. Frankly, contractors resisted the use of coarser, larger stone mixture because benefits could not be demonstrated under the traffic conditions at that time. It should also be noted that our standard mix design procedures (Marshall and Hveem) both use 4-inch diameter molds which cannot handle aggregates larger that 1-inch due to edge effects. This simple fact has probably limited us to 1-inch size materials to the extent that we may actually be designing the mix to fit the mold and not the pavement requirements (9).

Monroe (12), a bituminous engineer with the Iowa Department Of Transportation, in 1988, stated "I am confident that in the near future, when laws will again be changed to allow still heavier trucks and necessarily higher tire pressures, we will be required to go to still coarser mixes. We should be designing with these coarser mixes now, so we do not get caught with miles and miles of rutting pavement in the near future. We should not just be trying to catch up, but be ahead of the situation." He further stated, "I am also confident that in the future, agencies will be adopting gradations that have been coined 'stone filled' and contrary to nonexperienced opinion, very little segregation is encountered when actually placing these mixes."

Iowa (12) is presently having good success with the following specification for heavy wheel load interstate mixes: (1) 3/4-inch mix gradings, (2) laboratory air voids, minimum 3.5 percent, maximum 6.0

percent, (3) voids in mineral aggregate (VMA), minimum 13.5 percent, (4) Marshall compaction, 75 blows, (5) AC film thickness calculated, minimum 7.0 microns, (6) filler/bitumen ratio, maximum 1.2, (7) crushed particles, minimum 85 percent, (8) compaction on road, minimum 96 percent of laboratory density, (9) compaction voids, road 4 to 8 percent, and (10) Marshall laboratory stability, minimum 1,750.

Recent studies in Georgia (14) have shown the benefits of adding crushed fines and sand-size particles to mixtures that are prone to rut. Laboratory evaluations employed a loaded-wheel tester applying a load of 100 pounds at a contact pressure of 100 pounds per square inch, at 22 cycles per minute and 95°F. The load was applied by a rolling wheel to a 3x3x15-inch asphalt concrete beam. Rut depths in the specimens were measured and used to evaluate rutting potential of pavements made using these mixtures. Gradations of seven different mixtures were kept reasonably constant while the character of the sand-size particles and filler size particles were adjusted to include higher and lower percentages of crushed material. Results showed that generally the incorporation of 5 percent crushed fine aggregate particles into certain asphalt concrete mixtures will improve resistance to rutting, provided other mix design factors are adjusted accordingly. Findings also revealed the deficiency of the Marshall test in assessing rutting potential. The authors stated that the small sample size may have influenced the results and that the procedure as it exists is unsuitable for coarse-grained mixtures.

It is, in fact, well-established that aggregate gradation, shape, quality and asphalt grade are primary factors contributing to rutting resistance of asphalt concrete pavements (15-26). Other work has emphasized the importance of quality control during construction to insure adequate compaction (27).

In a current rutting study at the National Center for Asphalt Technology (NCAT), analysis of asphalt mixtures from rutted pavements showed that the single largest contributor to rutting is excessive asphalt content (28) resulting in insufficient air voids. The design asphalt content cannot be arbitrarily lowered in all asphalt mixtures since this would create other problems such as cracking or raveling. To prevent rutting, the mixture should be designed so that the in-place voids in the total mix under traffic will never fall below 4 percent. Most aggregates break down somewhat when processed through the asphalt plant. This break down produces more minus number 200 material in the blend, a condition which sometimes requires that asphalt content be lowered slightly to maintain mixture properties, such as voids in total mix, within specified values. Asphalt content should not be arbitrarily increased to facilitate compaction (achieve required density) because this will increase the probability of rutting under traffic.

Kamel and Miller (29) described the Petro-Canada pavement performance simulation test facility in which asphalt pavements are built from the subgrade up and tested under full-scale dynamic loads simulating heavy trucks. Rutting and other forms of distress are monitored over millions of load cycles at room temperature indicating the long-term pavement load-associated performance. The work also illustrates the importance of long-term tests in accurately predicting long-term performances. Test results of two investigations are given (9) illustrating use of the facility to compare pavement rutting performance of three 85-100 pen asphalt cements and to determine effects of inadequate or marginal compaction levels on long-term pavement performance. The results of the first investigation indicated that pavement rutting performance varied significantly from one asphalt cement to another even though all test asphalts were of the same penetration grade. Pavements incorporating asphalt cement with higher viscosity and lower temperature susceptibility provided the best performance; whereas, pavements incorporating asphalt with lower viscosity and higher temperature susceptibility provided the worst rutting performance under the same test conditions. (These mixtures contained 25 percent sand and were compacted to 3 percent air voids, both of which accentuated their sensitivity to asphalt viscosity.) The test results of the second investigation showed that construction quality has significant effects on long-term pavement performance. Severe pavement deformation and early failures developed in pavements with marginal/inadequate compaction levels of the hot mix and/or of the granular base layers.

FINDINGS

This section presents, first, findings from a field investigation of pavements including tests on cores and, second, findings from the investigation of laboratory prepared test specimens.

FIELD INVESTIGATION

The research study was initiated with a field investigation to provide an understanding of the primary contributors to the rutting problem in Texas and their magnitude. More rutting pavements were located than possible to analyze in this limited study. Therefore, the study was limited to pavements that were no more than two years old (with one exception) and experiencing rutting greater than 0.4-inch. Rutted and unrutted (or less rutted) pavements comprised of the same materials (whenever possible) were studied. Ten pavement sites were located, visually evaluated, and sampled in an effort to identify the cause(s) of the rutting. Five cores distributed across the pavement in and between the wheelpaths were drilled in order to ascertain the profile of the transverse cross section of the pavement. Cores were drilled in accordance with this scheme at each of five locations to obtain a total of 25 cores. The cores were tested in the laboratory to determine their properties. This subsection describes the field evaluations and materials characterizations resulting from this work.

Description of Test Pavements

Rutting pavements in Districts 4, 8, 10, 11, and 17 were selected for study (Figure 5). Pavements were selected only if rutting appeared to be occurring in the asphalt concrete layer; that is, rutting primarily in an untreated base or subgrade was not considered in this study. A visual condition survey of each pavement was conducted, rut depths were measured and photographs were taken. A summary of the test pavements is given in Table 1. Two sets of cores were collected from each site near Sweetwater, Fairfield, and Centerville which represented two levels of rutting (Table 1). All cores were collected from the travel lanes. Environmental and traffic data (presently unavailable) are included in Table 2.

Results of Tests on Pavement Cores

Testing of pavement cores consisted of visual inspection and measurement of air void content, resilient modulus at five temperatures, Hveem and Marshall stability, tensile properties, and resistance to moisture (Figure 6). Results of these tests are given in Tables 3 and 4. After extraction and recovery of the asphalt, both the aggregate and the asphalt were further characterized (Tables 5 and 6). Mixture design data are included in some of these tables to facilitate comparisons.

Mixture Properties. Mixtures from Sweetwater, Centerville, and Tyler contained average air void contents below the 3 percent level. These are dangerously low air void levels, particularly for mixtures placed on high volume interstate highways. Although, in most cases, air void contents were lower in the wheelpaths than between the wheelpaths (Table 7), the differences were not large. Voids in the mineral aggregate (VMA) appeared acceptable for all mixes except the surface mix from Sweetwater. However, acceptable VMA with low air voids is an indicator of excess asphalt (Centerville and Tyler).

Resilient modulus tests at 104F for mixtures from Sweetwater, Centerville, Tyler (surface), Lufkin, and Dumas yielded relatively low values when compared to those from the other sites and other data (15). Mixtures from Tyler (surface), Lufkin, and Dumas exhibited the lowest values of resilient modulus at all temperatures. Resilient modulus is an indicator of load carrying capacity or stiffness of the pavement layer.

Hveem stability of the pavement cores was measured following the Texas SDHPT procedure normally used on molded specimens (Table 3). The mixtures from Sweetwater, Lufkin, and Dumas exhibited values below 35, which is an indicator of unacceptable stability. Hveem stability is a measure of interparticle friction of the aggregate or a relative measure of the resistance of a compacted mix to lateral displacement under vertical loading (very short-term plastic deformation).

Marshall stability of the pavement cores was measured following the ASTM procedures normally used on molded specimens (Table 3). A value of 1800 is often used as a minimum value for Marshall stability for heavily trafficked roadways. If this criterion is applied here, the mixtures from Sweetwater, Fairfield, Lufkin, and Dumas appear unacceptable. With the exception of the mixture from Lufkin, those same mixtures exhibited Marshall flow values that exceeded 14, which is considered a maximum acceptable value for high traffic pavements.

Results from indirect tension tests (Table 4) show that, similarly, mixtures from Sweetwater, Lufkin, and Dumas yielded the lowest values of tensile strength. If 200 psi is arbitrarily selected as the minimum value, then Fairfield-site 2 and Tyler-surface also exhibit insufficient tensile strength. Tensile strength of a mixture is strongly influenced by the consistency of the asphalt cement which also influences rutting.

Indirect tension tests were also performed following an accelerated Lottman (30) moisture treatment procedure to facilitate computation of tensile strength ratios (TSR). If a minimum criterion of 70 is applied, then several of the mixtures indicate unacceptable sensitivity to moisture. This is particularly true when the exceptionally low air void contents of some of the mixtures are considered.

Aggregate Properties. Characteristics of the aggregate are the primary factors influencing rut-susceptibility of asphalt paving mixtures. All information available on the aggregates used in these mixtures has been assembled in Table 5. Gradations are plotted in Figures 7 through 17. All of the aggregate systems are dense graded. They contain from 12 to 50 percent natural, rounded particles (Table 5). Note that the surface mixture from Tyler and the mixture from Lufkin contain lightweight synthetic coarse aggregate. After extraction of the asphalt, the aggregate particles were visually examined and characterized regarding shape, texture and porosity. There seemed to be a natural break in aggregate properties at the number 40 sieve in several cases. Therefore, only the plus 40 and minus 40 results are shown in Table 5. Most of the mixtures contained a preponderance of smooth-surfaced, nonporous aggregate particles in the minus 40 portion. These particles, of course, were portions of the sands and gravels which are believed to have contributed significantly to the rutting problems in these mixes.

Asphalt Properties. Asphalts were extracted from the pavement cores and penetration and viscosity at two temperatures were measured (Table 6). The results were not unusual except for the asphalt from Fairfield-site 1 which had a viscosity at 140F of 10,700. There is presently no explanation for this anomaly. Those asphalts exhibiting viscosities at 140F of about 2000 were originally AC-10 grade, the others were originally AC-20 grade. Measurements of asphalt content revealed that the mixtures from Lufkin, Centerville-site 1, and Tyler surface contained asphalt contents at least 0.5 percent above optimum.

Interpretation of Results

Sweetwater. At Site 2 the asphalt content measured 0.7 percent less than Site 1 and, consequently, Site 2 exhibited less rutting (0.21-inch vs 0.72-inch). Although Hveem and Marshall stability yielded higher values for Site 2, the other materials properties were quite similar for sites 1 and 2. Both the base and the surface mixtures from Sweetwater contained extremely low air voids and, by comparison with the other mixtures studied, fairly low VMA. The 0.45 power gradation curves (Figures 8 and 9) are very near a straight line indicating a very dense gradation with little room for asphalt or air voids. An aggregate of this gradation may become unstable with a slight excess of asphalt. Although the sand content was quite low, the sand particles were very rounded, smooth and nonporous. These factors, along with the heavy IH 20 traffic, resulted in premature rutting in this pavement. In fact, at Site 1, two ruts were visible in each wheel path which were apparently caused by dual truck tires. Rutting in this pavement seems to have stabilized for the present time, since no notable increase was observed during the summer of 1988.

Fairfield. The Fairfield pavement exhibited reasonably high air voids and excellent VMA. However, this mixture contained 70 percent natural aggregate particles which likely contributed significantly to the rutting problem. In addition, the gradation plots (Figures 10 and 11) show a hump in the curve at the number 40 sieve indicating a critical mixture that becomes readily unstable with a slight excess of fluids. The mix at Site 1 contained 0.6 percent more asphalt than Site 2 yet exhibited less rutting

(0.22-inch vs 0.52-inch). No significant increase in rutting occurred during the long hot summer of 1988.

Centerville. This mix contained only 14 percent natural aggregate which was a very fine field sand (Table 5). Figures 12 and 13 reveal a large hump in the gradation curve at the number 40 sieve indicating the coarse aggregates had no particle-to-particle contact to resist shear stresses but were "free-floating" in the fines-plus-asphalt matrix. The air void profile (Table 7) indicates the Centerville pavement was compacted below the normally specified levels during construction. The other materials properties appear to be good, however, the pavement rutted more than 0.5-inches in 17 months (one summer). The mix at Site 1 contained 0.6 percent more asphalt than the mix at Site 2 and exhibited notably more rutting (0.55-inch vs 0.16-inch). Only a slight increase in rutting occurred during the summer of 1988.

Tyler. This pavement was placed as a fabric test section (31) in 1981 at a very high-traffic area of IH 20. Rutting began during the first summer and increased to about 0.5-inches within two summers. Rutting leveled off for four years and then, in the spring of 1987, it began to increase dramatically (Figure 18). The surface required milling and overlaying by July of 1987.

Based on examination of the cores, the materials properties of the mixtures appeared to be excellent. Air voids were slightly low, particularly in the base. The aggregate in the surface mix contained 50 percent natural sands and 50 percent lightweight coarse aggregate (Table 5). The aggregate in the base mix contained 34 percent natural particles. Most of these natural particles were very rounded, smooth textured and nonporous. Both the base and surface mixtures were gap graded and exhibited a notable hump in the gradation curve at the number 40 sieve (Figure 14). Apparently, compaction by traffic caused the mix to reach a certain critical air void level, then the mix became unstable under the dynamic traffic loads and began to fail rapidly. The resilient modulus test at 104F was the only laboratory procedure that indicated a problem. Although both the base and surface mixtures indicated severe moisture susceptibility, visual examination of the cores did not indicate that moisture had damaged the pavement layers. Flushing was very minor which is further evidence that little or no stripping had occurred.

Lufkin. The Lufkin mix contained acceptable air voids and excellent VMA. However, this mix contained 37 percent by weight natural sand particles with an asphalt content 1 percent above optimum design and, as a result, exhibited relatively low stability. The coarse material in this mixture was lightweight synthetic aggregate. The aggregate grading exhibited minus number 40 sieve size material in excess of that specified for Item 340, Type D. This may be due partially to aggregate degradation during plant operations, pavement service and coring. The mixture also exhibited sensitivity to moisture. This combination of factors in the presence of the incessant traffic of US 59 resulted in severe rutting after two summers. This pavement was milled off in the spring of 1988 to remove ruts near 1-inch deep.

Dumas. Tests on the Dumas cores showed relatively high air voids and a mixture of low stability and poor resistance to moisture damage. Table 7 shows significantly lower air voids in the wheelpaths than between or outside the wheelpaths indicating inadequate compaction during construction. Figure 17 indicates a very dense aggregate gradation which when adequately compacted should contain relatively low air voids. Visual examination of cores indicated stripping of asphalt from the large and intermediate size aggregate. Inadequate compaction may have provided permeable voids which enhanced stripping which in turn contributed to rutting. The design asphalt content is not known, but the actual content appears quite high. Another factor contributing to the rutting problem could be the low viscosity of the asphalt.

General Comments. Rutting occurs in two stages. The first stage of rutting is caused by densification of the mixture under traffic. If the mix is properly designed, this initial rutting rate decreases considerably as the maximum density for a particular mixture is attained. However, if the voids become overfilled with asphalt during the densification process, then the rate of rutting will increase. After this point is reached, the mixture becomes unstable and failure occurs rapidly. The steps to minimize rutting are to construct the pavement close to the final density that will be obtained under traffic, and design the mixture such that sufficient voids (typically 3-5 percent) are available in the mixture after traffic so that plastic flow does not occur during the design life of the pavement. This acceptable range of void contents may be narrow or not exist at all for mixtures with a preponderance of rounded aggregates. By comparison, an acceptable range of void contents may be much wider but more difficult to achieve for mixtures containing only crushed aggregate and a relatively large maximum size aggregate. If a mixture is difficult to compact, it will likely be difficult to rut.

LABORATORY INVESTIGATION

The field investigation indicated that the character and quantity of natural aggregate particles in the asphalt paving mixtures often contributed to rutting in Texas. A study of the literature from several other agencies indicated this problem is widespread and serious. As a result, a laboratory investigation was initiated to quantify mixture sensitivity to natural sand content with particular emphasis on plastic deformation. This work will address only a portion of this very complex subject of rutting, but the results should produce practical information useful in preparing materials acceptance criteria and possibly other specifications to reduce the problem.

Experiment Plan

The pilot laboratory test program (Figure 19) was designed to: (1) determine relative effects of natural sand on rutting, (2) quantify influence on resistance to rutting when natural sand is replaced or partially replaced by manufactured sand (crushed stone), and (3) evaluate the ability of the test procedures to predict field rutting. The test procedures included indirect tension, long-term static creep, unconfined compression, long-term dynamic creep, and Hveem Stability. Description of the tests will be given in the following pages, along with the material properties, test results obtained to date, and interpretation of the results.

The first phase of the laboratory program deals with the analysis of three different mixes (Table 8) using the tests previously mentioned and thoroughly described in a following section. Only laboratory prepared specimens were evaluated in this test program.

Materials

The asphalt used in preparing the asphalt concrete test specimens was Texaco AC-20 obtained from Port Neches, Texas. Asphalt properties are listed in Table 9.

The coarse aggregate (plus no. 10 sieve) was selected to be crushed limestone (obtained from Brownwood, Texas). The sand-size fraction is defined here as the material passing the No. 10 sieve. The natural sand was a siliceous, subrounded, smooth surfaced and nonporous aggregate. The manufactured sand was limestone screenings. These particles are angular in shape, rough in texture, and somewhat porous (absorbant).

An aggregate gradation (Figure 20) was selected based on typical gradations observed in the field. The gradation was designed to meet Texas SDHPT Type D specifications. The total aggregate mixture contained a blend of 60 percent crushed limestone and 40 percent natural field sand. Two additional aggregate mixtures were produced by replacing 50 percent and 100 percent of the natural field sand fraction with limestone screenings of a similar gradation (Table 8). Therefore, the three aggregate gradings used contained 40, 20 and 0 percent natural sand in crushed limestone. An asphalt concrete mix design (Table 10) was performed for the mixture containing 50 percent natural sand-50 percent manufactured sand, and the optimum asphalt content obtained (5.5 percent) was used for the other two mixtures tested. Mixture design procedures specified by the Texas State Department of Highways and Public Transportation (33) were followed.

Description of Tests

Several tests were used to characterize the mixtures: indirect tension, long-term static creep, unconfined compression, long-term dynamic creep, and Hveem stability.

Hveem stability tests were performed in accordance with Texas SDHPT test method Tex-208-F which is a modification of ASTM D1560.

The indirect tension test employs the indirect method of measuring mixture tensile properties (Figure 21)(34). The 2-inch high and 4-inch diameter cylindrical specimens were loaded diametrally at a constant rate of deformation until complete failure occurred. This loading configuration generates a uniform tensile stress perpendicular to and along the diametral plane. Deformation perpendicular to the loaded plane was monitored in order to quantify mixture stiffness. Tests were conducted at a temperature of 77°F and a deformation rate of 2 inches per minute. The specimens were compacted using the Texas Gyratory shear compactor.

Unconfined compression tests were performed on 4-inch diameter by 8-inch high cylindrical specimens. This test is a specific case of the triaxial compression test, where the confining pressure is zero. The main purpose of the test was to determine the shear strength of the mixture. The stability of the sample is represented by the general Coulomb equation:

$$s = c + \sigma \tan d$$

where:

c = cohesion
d = angle of internal friction
σ = compressive stress
s = shear strength

This Mohr-Coulomb theory will be applied to determine angle of internal friction and cohesion and, consequently, provide a means of comparing the different mix types.

In the long-term static creep test, cylindrical specimens were tested in axial unconfined compression at 104° F. Vertical deformations were measured by means of LVDT's (Figure 22)(35). This allowed a viscoelastic characterization of the asphalt mix.

The 8-inch high and 4-inch diameter cylindrical specimens were compacted using a Cox kneading compactor. Subsequently, they were capped with sulfur and stored in a 50°F environmental chamber to minimize any binder changes before the test was performed. All specimens were tested between 4 days and 15 days after fabrication. Just prior to testing, the samples were conditioned in the test temperature environment for at least 4 hours to achieve an homogeneous temperature distribution within the specimen. Once this temperature was achieved, the creep test was conducted under a constant static load until the sample reached failure within a reasonable long-term period of time (the target value was eight hours). Data were recorded throughout the test and plotted on a linear scale. Relative performance of the mixtures was evaluated and analyzed.

The setup for the long-term dynamic creep test was identical to the long-term static creep test. In this test, a repeated haversine load was applied to the specimen at the test temperature until the sample reached failure within a reasonable long-term period of time (at least 8 hours). The load for this test was the same load used for the long-term static creep test. Data were recorded periodically as deformation accumulated and plotted on a linear scale.

Test Results

At this stage of work, two test procedures have been completed: the indirect tension test and the long-term static creep test. Results from the indirect tensile test are presented in Table 11. After observing these results, the following general conclusions were formulated.

One would not expect the character of the sand-size particles in an asphalt concrete mixture to have a great effect on tensile properties. Tensile strength is primarily a function of the binder properties. Furthermore, with all other variables held constant, tensile strength will always vary inversely with air void content. Indirect tension test results exhibited a decrease in tensile strength as the proportion of manufactured sand increased. This was due partially to the corresponding increase in air void content. The goal was to produce low void specimens between 3 and 4 percent and high void specimens between 5 and 7 percent.

Another reason for the decrease in tensile strength with increasing manufactured sand content is the greater absorption capacity of the crushed limestone particles as compared to the siliceous sand. The specific surface area of the crushed material is also greater than the naturally weathered sand. With a fixed asphalt content, the film thickness on the crushed material will be less, thus providing less particle to particle adhesion or tensile strength.

To optimize tensile strength and equalize void content, a slight increase in asphalt content would be required as the crushed limestone particles replace the natural sand particles. Varying asphalt content, however, may have caused other difficulties in interpreting these data. Asphalt content will be varied in the second phase of this work. It is anticipated that the natural sand mixtures will exhibit greater sensitivity to asphalt content than the manufactured sand mixtures.

Results from the long-term static creep are shown in Figures 23 and 24, and Figures A1 through A6 in Appendix A. The applied stress was selected according to a trial and error procedure, based on long-term behavior. The temperature was selected to simulate realistic behavior under critical field conditions. Conclusions are summarized below:

1) Test results in Figures 23 and 24, taken directly from the data acquired, show for any duration of applied load, much more total deformation in the 100 percent natural sand mix than in those mixes containing manufactured sand.

2) Deformation upon static loading is strongly dependent on air void content. Samples having high air void contents failed much faster than samples having low air void contents.

3) A large gap in deformation trends is observed between the 50 percent natural sand-50 percent manufactured sand mix and the 100 percent manufactured sand mix. This indicates that 20 percent natural sand in the total mix is an excessive quantity for achieving low deformations during long periods of stress, for both low and high air void contents.

4) The data presented so far shows that the texture, shape and porosity of the fine aggregate are major factors related to total deformation. These factors will also be analyzed and compared with selected results obtained by other researchers using the dynamic permanent deformation test.

In previous work by Button, et al. (36), asphalt concrete mixture designs and characterizations were performed on two mixtures of the same aggregate gradation. However, one was composed of 100 percent subrounded, silicious river gravel; the other was composed of 100 percent crushed limestone. Both mixtures contained the same asphalt cement. Optimum asphalt content for the gravel mixture was 3.5 percent and for the limestone mixture, 4.5 percent. These were special laboratory mixtures which were composed of a very dense gradation. Selected findings from this study appear pertinent here. The mixture containing the rounded gravel consistently exhibited more sensitivity to asphalt content and temperature than the mixture containing crushed limestone. This has also been demonstrated by Kalcheff (37) and others. To illustrate the sensitivity of these mixtures to asphalt content, variations in mixture properties from 0.5 percent below optimum to 0.5 percent above optimum were compared (Table 12). In addition, temperature susceptibility (slope of curve) of these mixtures is compared in Figure 25.

Engineering properties of mixtures containing higher proportions of uncrushed particles (river gravel and/or field sand) are shown to be more dependent on the asphalt content and asphalt properties than mixtures containing crushed particles. Properly designed crushed stone mixtures transmit loads through the interlocked aggregate "skeleton." They depend less on the binder or mastic for shear strength.

Interpretation Of Laboratory Results

Some general conclusions have already been stated concerning the trends observed in the two laboratory tests completed at this time. Following is an interpretation of how the results obtained so far can relate to important factors such as mix design, pavement construction, performance and cost.

Replacement of natural sand particles by manufactured sand particles (crushed stone) increases the resistance of the asphalt pavement to permanent deformation, as observed from the long-term static creep test. This replacement implies changes in the final mix design. Some of these changes are summarized below:

- Increased asphalt content due to greater specific surface area and greater absorption of asphalt by some manufactured particles.
- Increased air void content of compacted mixtures due to the angular shape and surface texture of the manufactured particles.
- Increased VMA due to angularity of crushed material.

In terms of construction, the manufactured sand will affect the following factors:

- The manufactured sand mix is more resistant to compaction. This may require compaction of the mix at higher temperatures, reduce the time available for compaction, or necessitate more or heavier Compaction equipment.
- Workability will suffer but it may be possible to use other design and/or construction procedures to minimize this potential problem.

Earlier work (37, 38, 39) has also shown that when using manufactured sand in place of natural sand, rutting resistance of the asphalt paving mixture is greatly improved. Field performance corroborating this fact has been observed by Kandhal (40), Lai (14), Lynch and Tam (20) and many others.

Replacement of field sand with washed screenings will of course increase initial cost of the paving mixture but significant benefits in performance will be realized, particularly on high volume highways that carry heavy loads. Reduced maintenance cost of these high volume roadways can become very significant when measured in terms of user costs.

Four of the leading suppliers of crushed stone in Texas were contacted regarding the availability of manufactured sand should hot mix specifications be changed. All were confident of meeting the demand for washed screenings in the foreseeable future. These suppliers presently have stockpiles of manufactured sand (crushed screenings) ranging from 0.6 to 1.5 million tons. All suppliers contacted expressed their willingness to upgrade their facilities to meet the potential demand for washed screenings.

SUBSEQUENT PHASES OF WORK

Subsequent phases of this work relate to an expanded, more detailed test program which includes an analysis of the following points:

- Additional ratios of natural sand to manufactured sand within the mixture in order to obtain specific and applicable recommendations. These ratios will likely be 25 to 75 percent and 12 to 88 percent.
- Vary asphalt content for preselected mixes and measure their performance under creep testing to demonstrate that sensitivity of the mixture to asphalt content will decrease significantly as the natural sand is replaced with manufactured sand. That is, the addition of crushed particles will produce a more forgiving mixture.
- Triaxial creep tests with different confining pressures for selected mixes.
- Pavement rutting prediction using the ILLIPAVE computer program and the data obtained.
- Improved methodology for studying and evaluating the propensity of a mixture towards rutting.
- Proposed specifications for maximum natural sand content and acceptance criteria for manufactured replacements.
- A recommended traffic level for which the proposed specifications can be used in a cost-effective manner.
- Field tests to verify effectiveness of replacing natural aggregate particles with manufactured particles, larger aggregate surface mixtures, and higher VMA's and evaluate any difficulties in placing and compacting these mixtures.

TENTATIVE CONCLUSIONS

CONCLUSIONS

1. The field investigation indicated that the chief mixture deficiencies that contributed to rutting were excessive asphalt content, excessive fine aggregate (sand-size particles), and the round shape and smooth texture of the natural (uncrushed) aggregate particles.

2. The literature review revealed that rutting has been successfully addressed by using large top-size crushed aggregate (1 to 1½-inch), increasing voids in mineral aggregate requirements, (14-15 percent minimum), replacing most or all of natural sands with manufactured particles, increasing minimum allowable air voids in the laboratory compacted mix to 4 percent, and limiting the filler to bitumen ratio to about 1.2.

3. A properly designed asphalt paving mixture transmits loads through an interlocked aggregate "skeleton." It does not depend upon the asphalt binder or the mastic for shear strength.

4. For certain volumes and weights of traffic, stone-filled asphalt mixtures appear to be a viable solution to the rutting problem. Experience and careful quality control will likely be required to avoid unacceptable segregation of these type mixtures. In a mix of this type, resistance to rutting will be less dependent on the quality of the fine aggregate or the consistency of the asphalt cement.

5. More compactive effort will be required when rut-resistant asphalt paving mixtures are placed. More or larger rollers may be required to achieve adequate mixture density before the mat temperature drops below the specified level. Higher mixture temperatures may be required to facilitate densification and provide adequate time for compaction.

6. Results of the laboratory investigation show that, as crushed fine aggregate particles are replaced with natural (uncrushed) fine aggregate particles of the same gradation, the asphalt concrete mixture becomes significantly less resistant to permanent deformation.

RECOMMENDATIONS

1. Asphalt content of a paving mixture should not be arbitrarily increased to facilitate compaction or achieve the required density or because the mixture looks dry. Mixture design data should be carefully reviewed to estimate consequences of increasing asphalt content or, if warranted, a new mixture design should be developed.
2. In the interim, while specifications are being developed, the use of Type C mixtures in place of Type D mixtures for surface courses will help alleviate rutting on high volume roadways. Similarly, replacing Type C mixture with Type B mixtures for binder courses should also yield positive results. Use of excessive quantities (greater than 15 percent) of field sands in these mixes should be avoided.
3. A mandatory stripping test for individual aggregate types in the job mix formula should be instituted. All aggregate exhibiting 5 percent or more stripping should be pretreated. Field sands that exhibit stripping, as most do, should be limited to 10 percent of the mix even with pretreatment.
4. Certain natural sands with subangular particle shapes and or rough textures may be available in certain locations. These are much more desirable than those with rounded particle shapes. Examination of sand particles under the microscope and elimination of the undesirable materials from asphalt mixtures will reduce the potential for rutting.
5. Develop a specification for a rut-resistant mixture for high volume roadways carrying heavy traffic. The remaining portion of this study will be devoted to this task. The existing specification for Item 340 should be used for lower volume roadways.

TABLES

Table 1. Summary of Rutting Pavements Evaluated

	Location					
General Information	Sweetwater	Fairfield	Centerville	Tyler	Lufkin	Dumas
District No.	8	17	17	10	11	4
County	Nolan	Freestone	Leon	Gregg	Angelina	Sherman
Highway No.	IH 20	IH 45	IH 45	IH 20	US 59	US 287
Control-Section No.	6-3-84	675-2-18	-	495-6	176-3-81	-
Direction	East	North	North	East	South	
No. Lanes each Direction	2	2	2	2	2	-
Description of Pavement						
Existing Pavement						
Layer 1 (Top)	2 1/2″ Ty D	3/4″ Ty D	3/4″ Ty D	1 1/2″ Ty D	3″ Ty D	
Layer 2	8 1/2″ Recycle	3.75″Ty C	4.5″ Ty C*	2″ Ty B	Surf Trt.	
Layer 3	Lime Trt Base	Asp. Rub.	Asp. Rub.	Fabric	Conc. Pvt.	
Layer 4	-	8″ CRCP	8″ CRCP	8″ CRCP	-	
Date of last Const.	Sept 84	Sept 85	Oct 85	July 81	Nov 85	July 85
Date Cored	Mar 87	April 87	April 87	Sept 87	Dec 87	Nov 86
Rut Depth, in. (site 1)	0.72	0.22	0.55	0.73	0.75	0.41
Rut Depth, in. (site 2)	0.21	0.52	0.16	-	-	-

Table 2. Climatological Summary for Rutting Pavement Test Sites

Item	Sweetwater	Fairfield/ Centerville	Dumas	Lufkin	Tyler
Climate	Semiarid, mild winter, Lower humidity and hot summers	Subtropical with mild winter and hot humid summers	Short but severe winters, warm summer days, cool nights, low humidity	Humid, mild winters and hot summers	Humid, mild winters and hot summers
Temperature					
Mean* and Record Max F	95/111	96/111	92/109	94/108	94/108
Mean* and Record Min, F	31/-9	35/-3	19/-18	38/-2	33/2
No. Days/Year 9 F and Above	96	101	72	103	83
No. Days/Year 32 F and Below	55	45	129	35	57
Frost Penetration, inch	3	<3	>3	<3	<3
Precipitation					
Mean Annual Precip, inch	23	39	19	42	43
Mean Annual Ice/Snow, inch	0.8	0.8	16.2	0.8	1.9
Mean Heating Degree-days	2620	2150	3750	1930	2330

*Mean Daily maximum and minimum temperatures for the hottest or coldest month, respectively.

Table 3. Mixture Properties of Pavement Cores

Location	Air Void Content, percent[1]	VMA, percent[1]	Resilient Modulus, psi x 10^3					Hveem Stability[2]	Marshall Stab, lbs[2]	Marshall Flow, 0.01"[2]
			13 F[2]	33 F[2]	68 F[2]	77 F[1]	104 F[2]			
Sweetwater - 1	1.7	13.6[3]	1850	1396	489	344	37	8	650	17
Sweetwater - 2[4]	1.6	12.8[3]	2015	1364	601	551	63	20	850	15
Sweetwater - base	1.5	-	2000	1620	1040	729	343	17	1700	17
Fairfield - 1[4]	8.4	18.9	2110	1540	930	910	250	45	1450	16
Fairfield - 2	4.8	15.2	1940	1330	780	750	230	36	1500	16
Centerville - 1	2.2	16.1	2080	1650	804	560	84	44	3000	11
Centerville - 2[4]	1.0	14.5	1880	1650	880	680	140	44	2700	13
Tyler - base	3.1	17.5	2820	2220	1280	940	170	43	3700	9
Tyler - surface	2.6	22.1	1430	900	420	300	57	44	2600	13
Lufkin	3.5	16.0	1490	860	230	170	23	32	960	11
Dumas	6.9	22.0[3]	1600	1060	360	250	35	24	1900	16

[1] Average of 25 values

[2] Average of 6 values (3 in wheelpath, 3 outside wheelpath)

[3] Based on estimated value of bulk specific gravity of aggregate of 2.65

[4] Less rutted than other site near same location

Table 4. Tensile Properties of Cores Before and After Lottman Freeze-Thaw Moisture Treatment

	Before Moisture Treatment				After Moisture Treatment				
		Tensile Properties*				Tensile Properties*			
Location	Average Air Void Content, percent	Tensile Strength, psi	Strain @ Failure in/in	Secant Modulus, psi	Average Air Void Content, percent	Tensile Strength psi	Strain @ Failure, in/in	Secant Modulus, psi	Tensile Strength Ratio
Sweetwater - 1	1.7	142	0.0086	78,000	1.9	151	0.0013	82,000	106
Sweetwater - 2	1.6	175	0.0032	69,000	1.2	160	0.0023	64,000	91
Sweetwater - base	1.5	221	0.0031	71,000	-	170	0.0067	37,000	77
Fairfield - 1	8.4	200	0.0015	154,000	6.3	174	0.0017	103,000	87
Fairfield - 2	4.8	188	0.0013	147,000	5.9	116	0.0045	51,000	62
Centerville - 1	2.2	268	0.0028	97,000	1.0	275	0.0031	92,000	103
Centerville - 2	1.0	289	0.0025	132,000	1.1	181	0.0022	86,000	63
Tyler - base	2.6	251	0.0013	202,000	3.1	100	0.0021	47,000	40
Tyler - surface	3.1	175	0.0024	75,000	3.4	95	0.0050	19,000	54
Lufkin	2.2	119	0.0040	30,000	4.5	74	0.0044	18,000	62
Dumas	4.7	143	0.0017	58,000	9.9	74	0.0042	18,000	52

*Tensile tests were performed at 77 F and 2 inches per minute.

Table 5. Aggregate Characteristics

Pavement Location	Aggregate Type	Aggregate Blend	Particle Shape		Particle Texture		Porosity	
			+#40	-#40	+#40	-#40	+#40	-#40
Sweetwater (surface)	Limestone - 59% Martin Source	62% - 3/8" - #4, 30% - #4 - #10	Angular to Subangular	Angular to Subangular	Rough to Smooth	Smooth	Porous	Nonpouous
	Screenings - 29% Martin Source	13% - #4 - #10, 49% - #10 - #40, 24% - #80 - #200, 14% - #200						
	Sand ------12% J. H. Strain & Sons	5% - #10 - #40, 62% - #40 - #80 29% - #80 - #200, 4% - #200						
Sweetwater (base)	Recycle Asphalt Mix - 61%	49% - 1 1/4"- #4, 29% - #4 - #10, 22% - #10	Angular to Subangular	Subangular to Rounded	Rough	Smooth	Porous	Nonporous
	Martin Aggregate - 30%	57% - 1 1/4" - 7/8", 39% - 7/8" - #4, 4% - #4						
	Martin Base - 9%	-						
Fairfield (base)	Type C Rock - 30% D.P. Frost	17% -5/8", 67% - 3/8", 14% - #4	Angular to Subangular	Angular to Subangular	Rough to Smooth	Smooth	Porous and Nonporous	Nonporous
	Processed Gravel - 30% Grifford Hill	53% - #4, 44% - #10						
	Screenings - 30% D.P. Frost	42% - #40, 25% - #80, 19% - #200						
	Field Sand - 10% Bohler Field	69% - #80, 26% - #200						
Centerville (base)	Grade "3" rock - 25%	87% - 5/8" - 3/8", 11% - 3/8" - #4	Anglular to Subangular	Angular to Subangular	Rough	Smooth	Porous	Nonporous
	Type D Rock - 40%	52% - 3/8" - #4, 33% - #4 - #10						
	Screenings - 21% East Texas Stone	28% - #10 - #40, 42% - #40 - #80, 20% - #80 - #200						
	Harris Field Sand - 14%	46% - #40 - #80, 33% - #80 - #200 13% minus #200						
Tyler	Base							
	Coarse Crushed Limestone Stewart Bridgeport	-	Angular to Subangular	Angular to Subangular	Rough to Smooth	Rough to Smooth	Porous	Nonporous
	Medium Crushed Limestone Stewart Bridgeport	-						
	Field Sand Lone Star Gas - local	-						
	Field Sand Fair Pit - Local	-						
	Surface							
	Lightweight - 50% TXI Streetman	-	Subrounded to Rounded	Angular to Subangular	Rough to Smooth	Smooth	Porous	Nonporous
	Concrete Sand - 15% Norton Sand & Gravel	-						
	Field Sand - 18% J. Fair - local	-						
	Field Sand - 17% Lone Star Gas	-						
Lufkin	Lightweight Aggr. 62%	71% - 3/8" - #4, 24% - #4 - #10	Subangular	Angular	Rough	Smooth	Porous	Porous and Nonporous
	O & I Sand (coarse) 27%	13% - #10 - #40, 68% - #40 -#80						
	Elliot Sand 11%	70% - #40 - #80, 17% - #80 - #200 10% -minus #200.						
Dumas	-	-	Angular to Subangular	Subangular	Rough	Rough to Smooth	Porous to Nonporous	Nonporous

Table 6. Data for Asphalts Extracted from Pavement Cores

	Sweetwater Surface		Sweetwater Base	Fairfield		Centerville		Tyler		Lufkin	Dumas
Site No.	1	2	1	1	2	1	2	Base[1]	Surface[1]	1	1
Rut Depth[2]. in	0.72	0.21	-	0.22	0.52	0.55	0.16	-	0.73	0.75	0.41
Penetration											
77 F,100gm,5sec	37	36	31	27	44	27	36	32	72	56	65
39.2 F,200gm,60sec	10	11	3	13	15	5	3	-	-	21	19
Viscosity, poise											
140 F	2230	2330	4290	10,710	5170	6150	4210	4700	2520	4170	1800
275 F	3.20	3.3	4.24	5.63	3.61	5.05	4.26	5.19	-	4.90	5.39
Asphalt Content, percent	5.3	4.6	5.3	5.3	4.7	5.6	5.0	5.0	8.7	9.5	7.0
Design Asphalt Content	5.0	5.0	5.0	4.9	4.9	5.1	5.1	5.0	8.1	8.5	-

[1] Mixtures from same location: Type B base and Type D surface mixes.

[2] Average of about 10 measurements where cores were drilled.

Table 7. Summary of Air Voids In and Outside Wheelpaths

Pavement Location	Air Voids Content, Percent					
	Adjacent to Centerline	Wheelpath	Between Wheelpath	Wheelpath	Adjacent to Shoulder	Average
Sweetwater - site 1	2.5	1.6	1.7	1.2	1.5	1.7
Sweetwater - site 2*	1.6	0.9	3.1	0.9	1.2	1.5
Sweetwater (base)	1.1	2.2	0.2	1.6	2.5	1.5
Fairfield - site 1*	8.1	6.5	7.5	6.6	6.8	7.1
Fairfield - site 2	4.8	4.1	5.7	5.4	5.8	5.2
Centerville - site 1	2.4	1.3	1.2	1.0	1.9	1.6
Centerville - site 2*	3.9	1.1	1.0	2.1	2.0	2.0
Tyler - base	4.3	2.5	3.3	3.0	3.8	3.4
Tyler - surface	2.1	2.8	2.7	2.9	2.7	2.6
Lufkin	3.3	2.8	3.7	3.5	4.0	3.5
Dumas	9.9	4.1	6.9	4.7	6.5	6.4
Overall Average	4.0	2.7	3.4	3.0	3.5	

*Less rutting than other site near same location

Table 8. Pilot Laboratory Program

Coarse Aggregate (> #10 sieve) = Crushed Limestone for all mixtures

Asphalt Type and Grade = Texaco AC-20

Sand Type (< #10 sieve) = Mix 1: 100% Natural Sand *

Mix 2: 50% Natural Sand +
50% Manufactured Sand *

Mix 3: 100% Manufactured Sand *

Air Void Contents = High (5-7%) and Low (3-4%)**

---

* Natural sand content is the mixture variable.
** Air void content is the specimen fabrication variable.

Table 9. Properties of Asphalt

Asphalt Source Grade	Texaco AC-20
Specific gravity at 77°F	1.029
Viscosity at 140°F, P	2040
Viscosity at 275°F, cSt	398
Penetration at 77°F, 100 g, 5 s	75
Penetration at 39.2°F, 100 g, 5 s	8
Penetration at 39.2°F, 200 g, 60 s	28
Softening point, °C	51.8
Softening point, °F	125
Temperature susceptibility[1] 140° to 275°F	-3.52
PVN[2]	-0.6
P.I.[3] from penetration at 39.2°F and 77°F	-1.0
P.I. from penetration at 77°F and softening point	+0.3

---

[1] Temperature susceptibility = $(\log\log \eta_2 - \log\log \eta_1)/(\log T_2 - \log T_1)$ where η = viscosity in cP, T = absolute temperature.

[2] Determined from penetration at 77°F and viscosity at 275°F (McLeod, 1976).

[3] P.I. = $(20 - 500\alpha/(1 + 50\alpha)$:

$\alpha = [\log(\text{pen}_2) - \log(\text{pen}_1)]/(T_2 - T_1)$, or
$[\log 800 - \log(\text{pen}_{25°C})]/(T_{SP} - 25)$, where T = temperature, °C.

(After Reference 32)

Table 10. Design Data for Mix Containing 20 percent Natural Sand in Total Aggregate Blend (50-50 mix)

Mix 1	Asphalt Content, percent	Density, percent	Hveem Stability	Marshall Stability, lbs	Unit Weight, lbs/ft3
1	4.0	93.2	41.3	1715	146.8
2	4.5	93.5	42.8	2025	147.5
3	5.0	95.0	41.3	2150	148.9
4	5.5	96.7	38.7	2135	150.1
5	6.0	97.6	34.4	2040	149.5

Optimum Asphalt Content: 5.5%

Mix Type: < #10 Sieve: 50% Natural Sand - 50% Manufactured Sand

> #10 Sieve: Crushed Limestone

Table 11. Indirect Tensile Test Results

Mixture Type	Low Air Void Specimens			High Air Void Specimens		
	Tensile Strength, psi	Strain, in/in	Air Voids, percent	Tensile Strength, psi	Strain, in/in	Air Voids, percent
100% Natural	151	0.40	2.6	94	0.60	5.0
Sand	165	0.49	3.0	95	0.55	5.1
	147	0.42	3.4	103	0.55	5.5
Avg.	154	0.44	3.0	97	0.57	5.2
50% Natural Sand	120	0.49	3.6	96	0.47	6.6
50% Manufactured	112	0.46	3.9	100	0.49	6.7
Sand	109	0.56	4.4	85	0.57	7.3
Avg.	114	0.50	4.0	94	0.51	6.9
100% Manufactured	111	0.34	3.5	88	0.41	6.7
Sand	108	0.39	4.0	99	0.35	6.8
	92	0.40	4.3	87	0.42	7.2
Avg.	104	0.38	3.9	91	0.39	6.9

Table 12. Variation in Engineering Properties of Asphalt Concrete Mixtures Containing Rounded Gravel and Crushed Limestone

Property Measured	Variation in Properties of Asphalt Concrete when Asphalt Content varies ±0.5 percent around optimum.		Variation Expressed in Percent	
	Rounded Gravel	Crushed Limestone	Rounded Gravel	Crushed Limestone
Hveem Stability[1]	6.2	4.9	23	9
Air Void Content[1]	3.0	2.0	77	77
Voids in Mineral Aggregate[1]	1.0	0.3	10	4
Resilient Modulus[1]	80,000	50,000	15	8
Marshall Stability[2]	130	175	11	7

[1] Mixtures compacted using Texas gyratory shear device.

[2] Mixtures compacted using Marshall hammer.

FIGURES

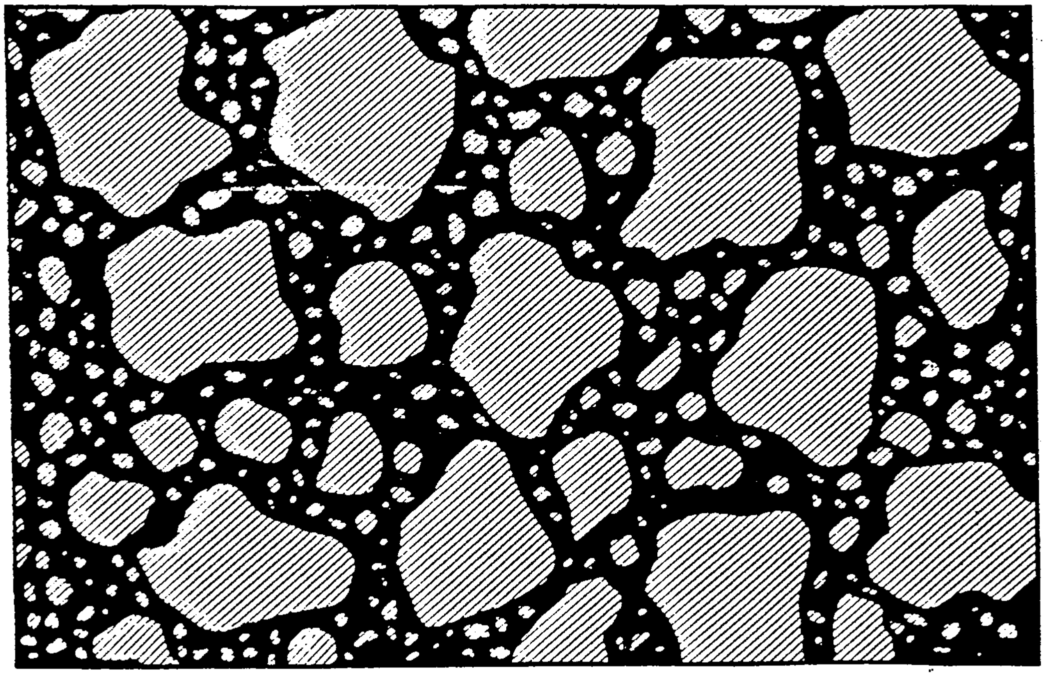


Figure 1. Dense Graded Mix Structure (after Reference 9).

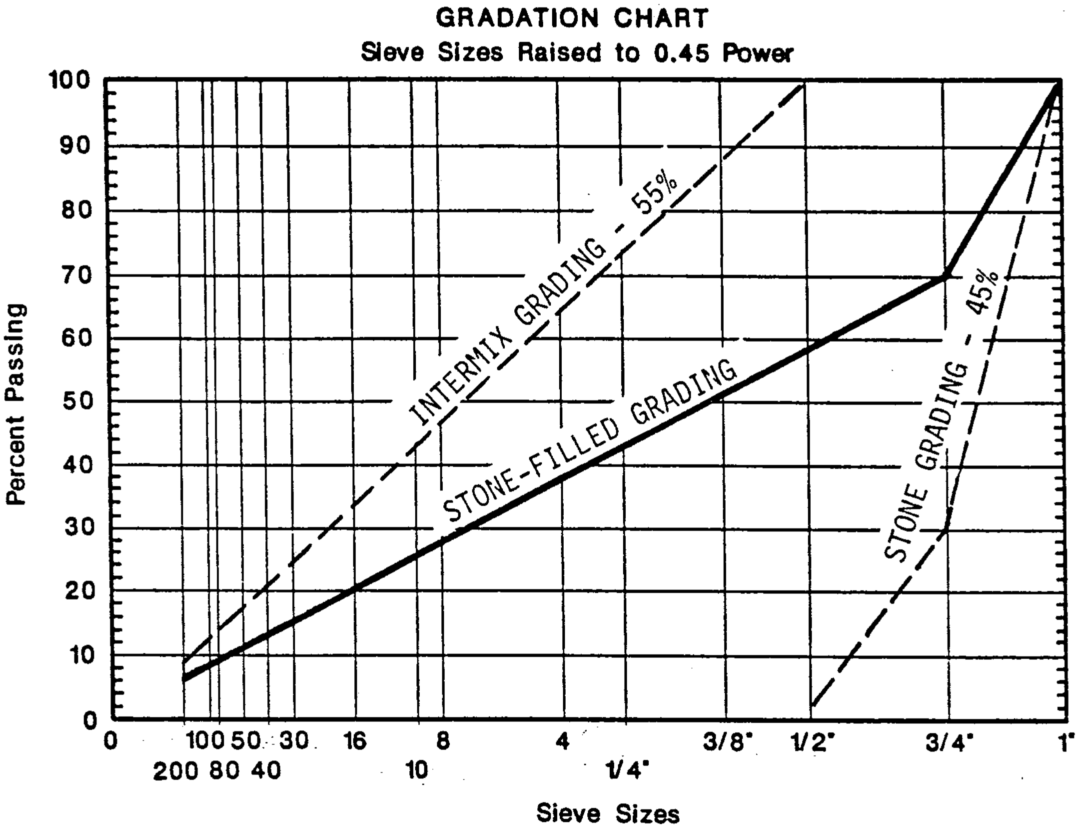


Figure 2. Stone Added to Intermix Grading (after Reference 12).

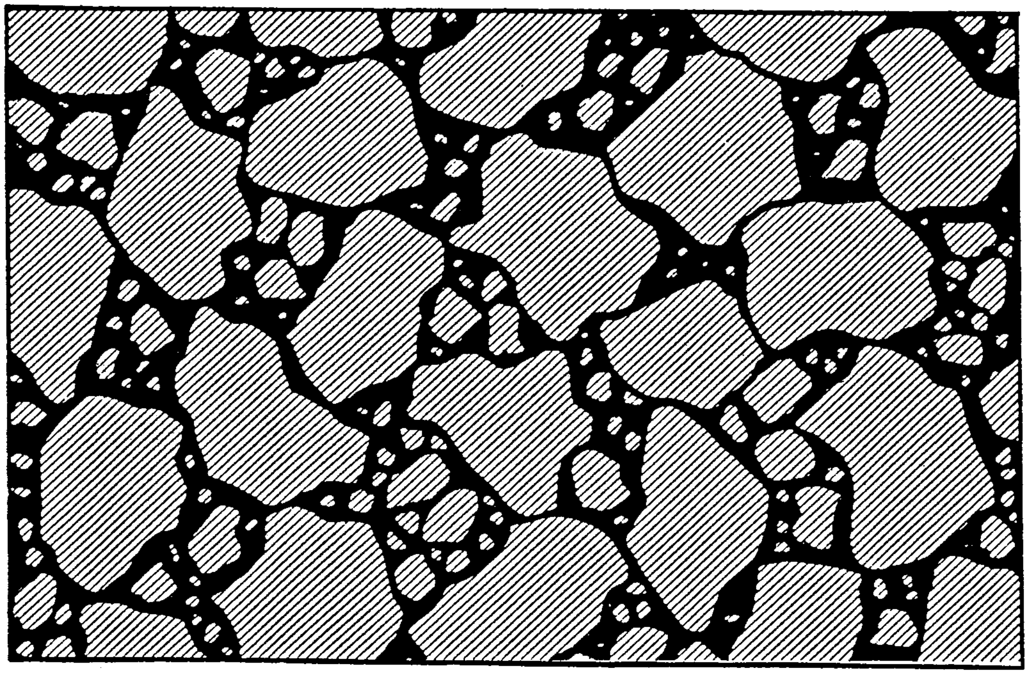


Figure 3. Stone Filled Mix Structure (after Reference 9).

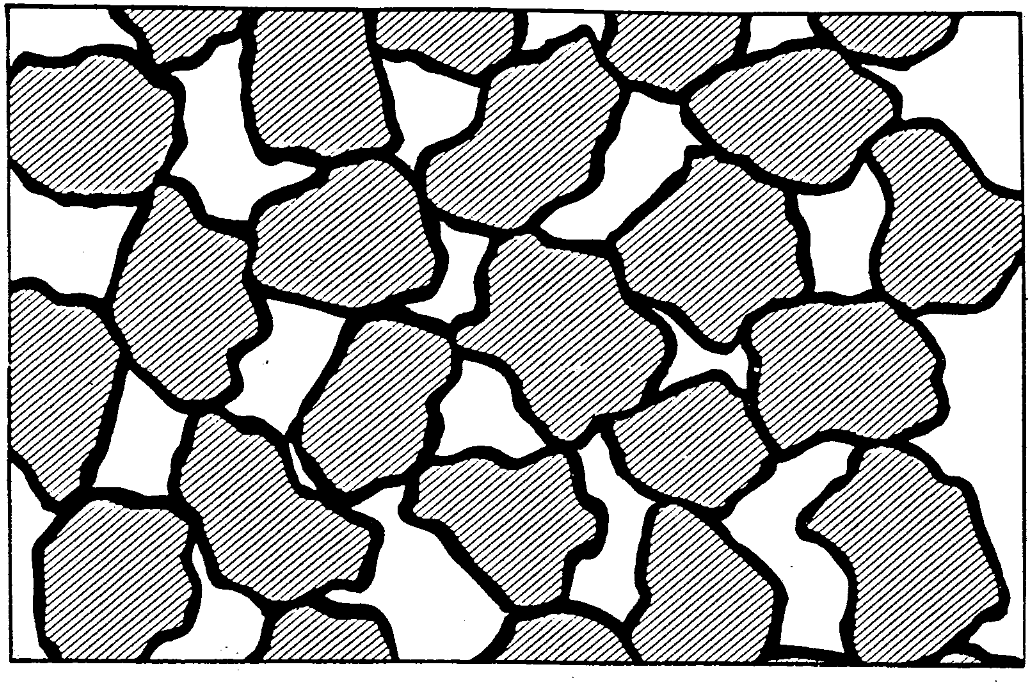


Figure 4. Open Graded Mix Structure (after Reference 9).

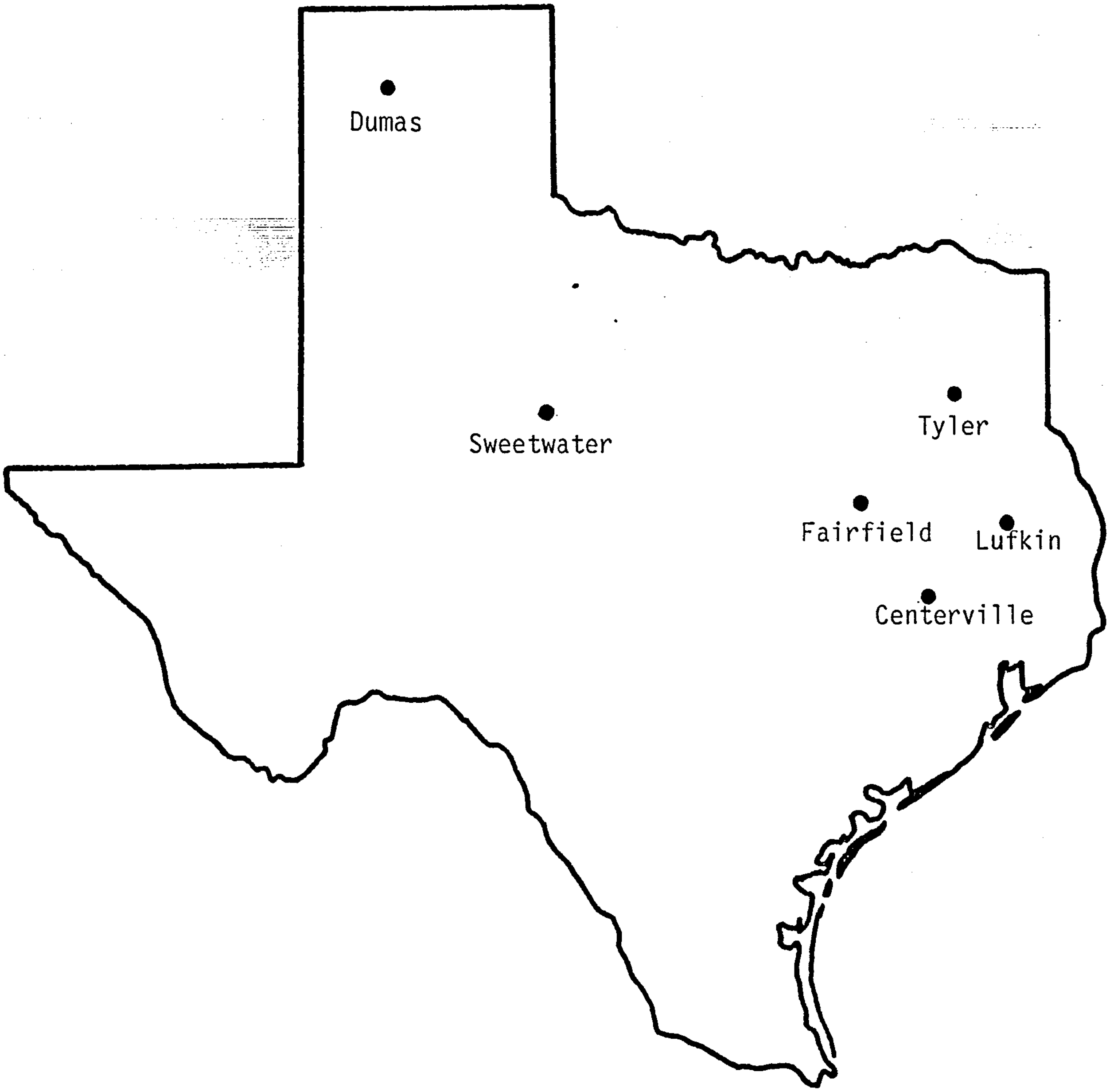


Figure 5. Location of Field Test Sites for Rutting Pavements.

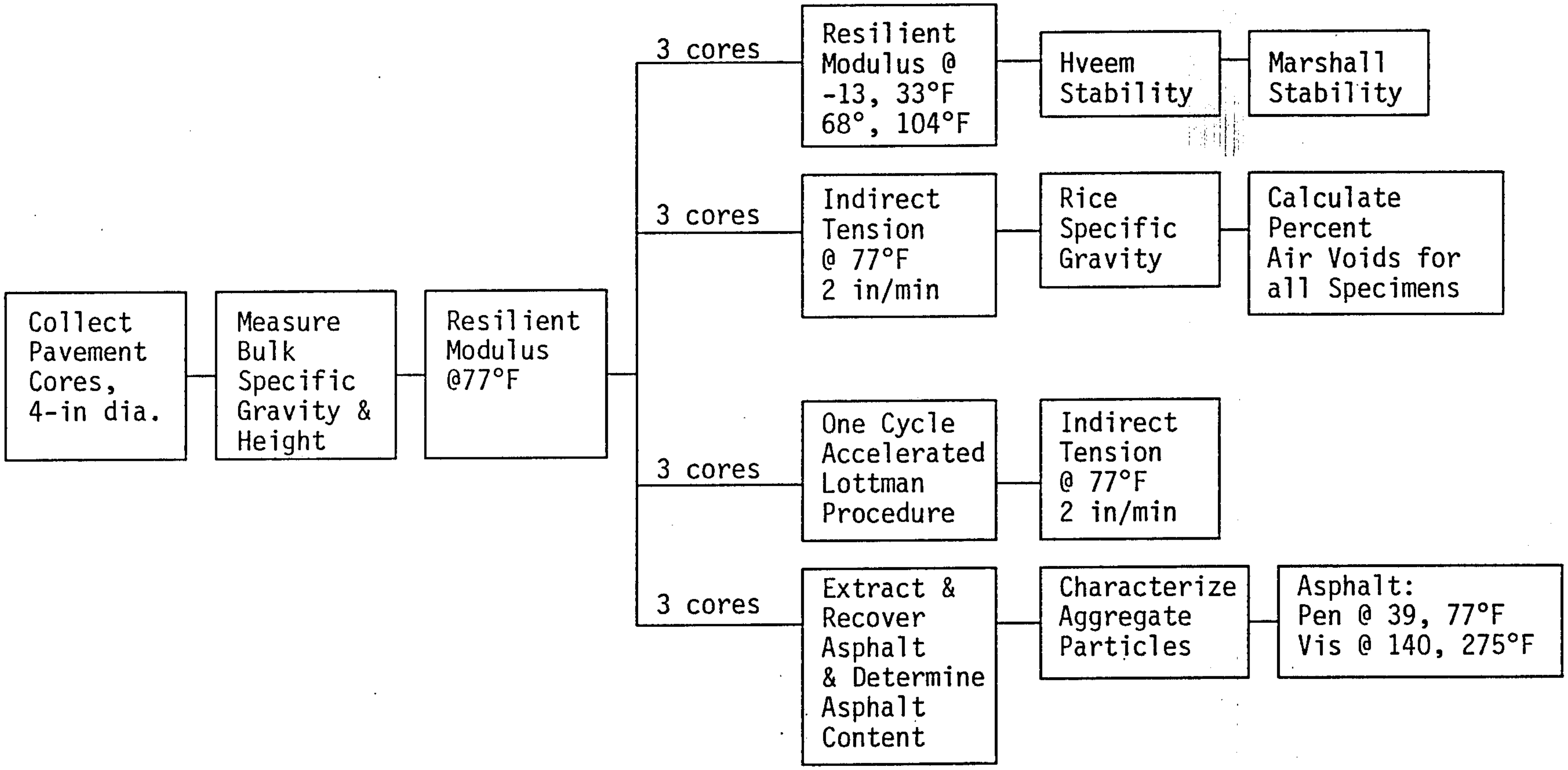


Figure 6. Laboratory Test Program for Paving Mixtures.

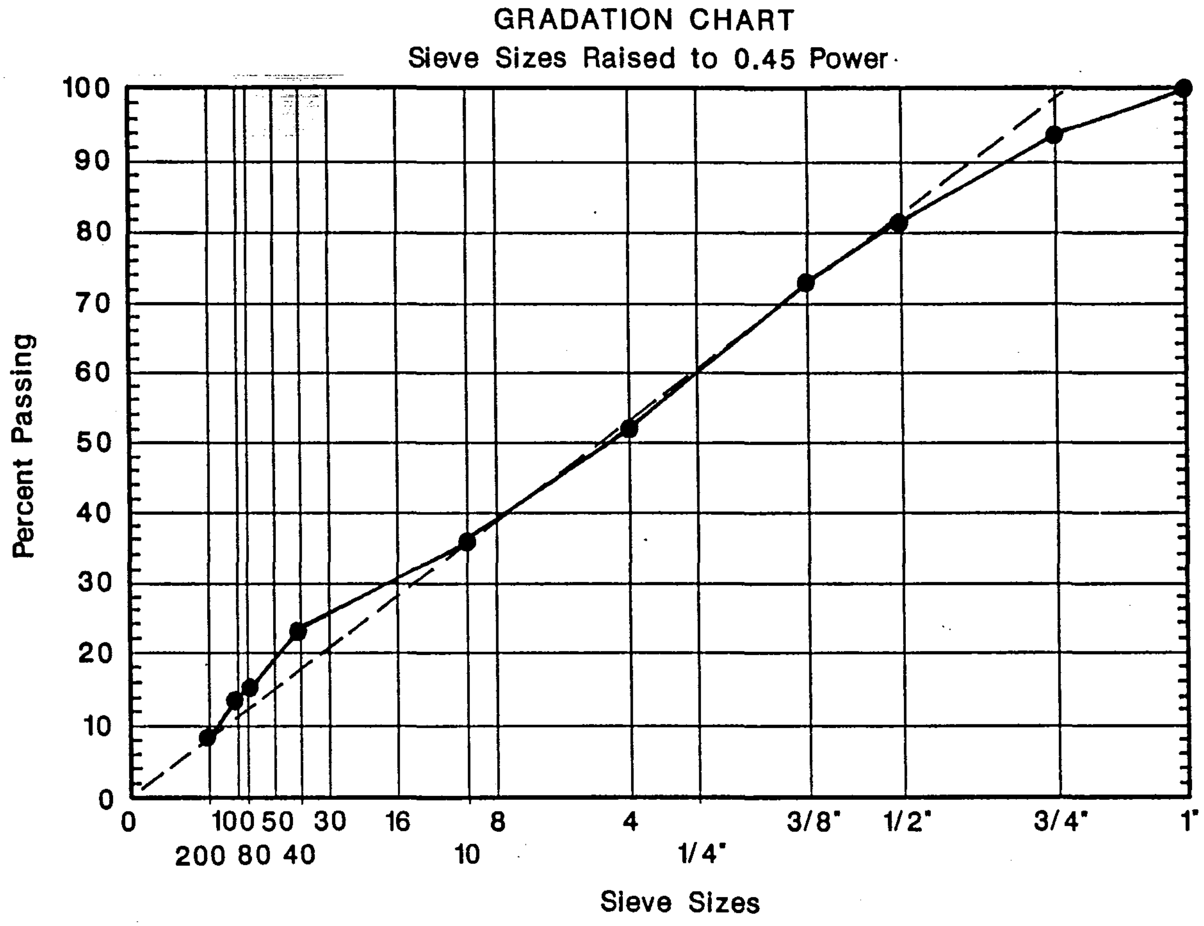


Figure 7. Gradation of Aggregate from cores - Sweetwater recycled base.

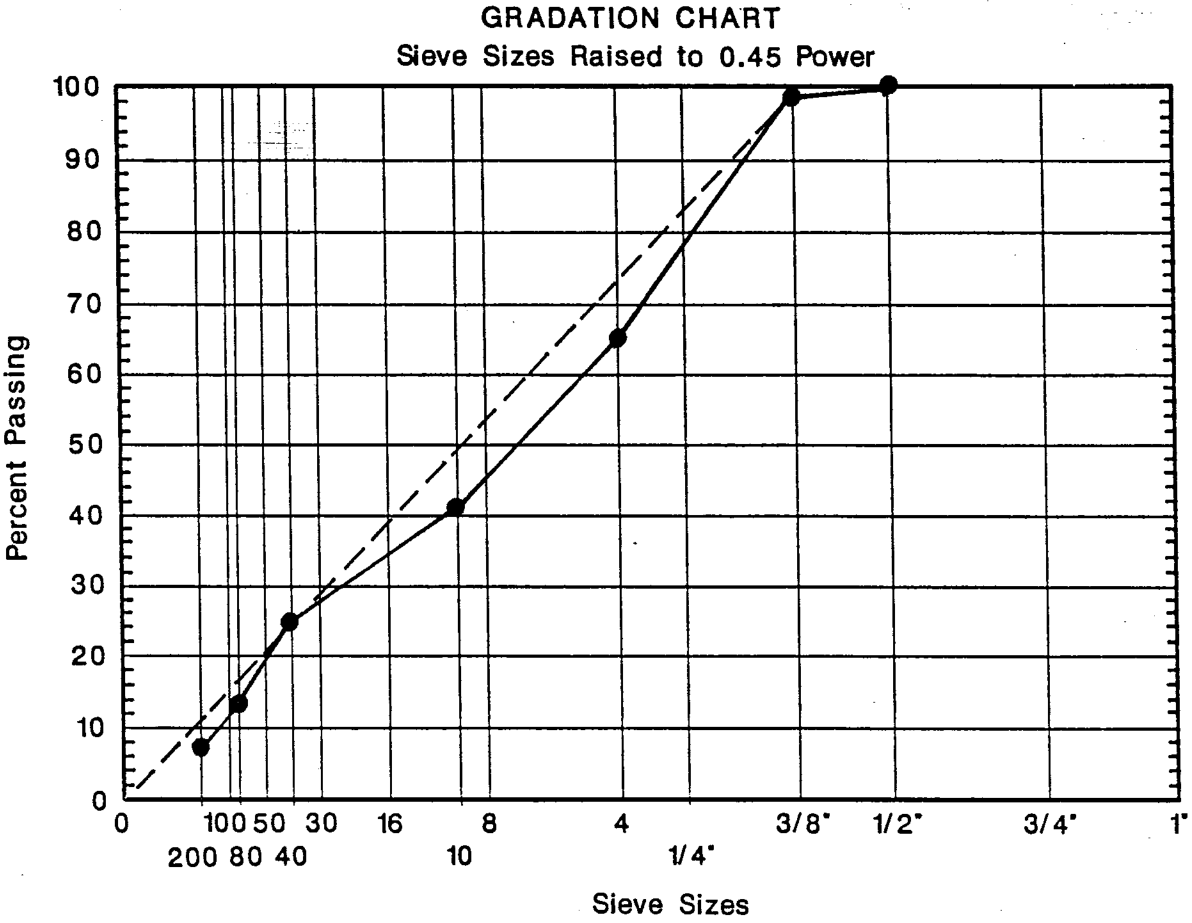


Figure 8. Gradation of Aggregate from cores - Sweetwater, site 1.

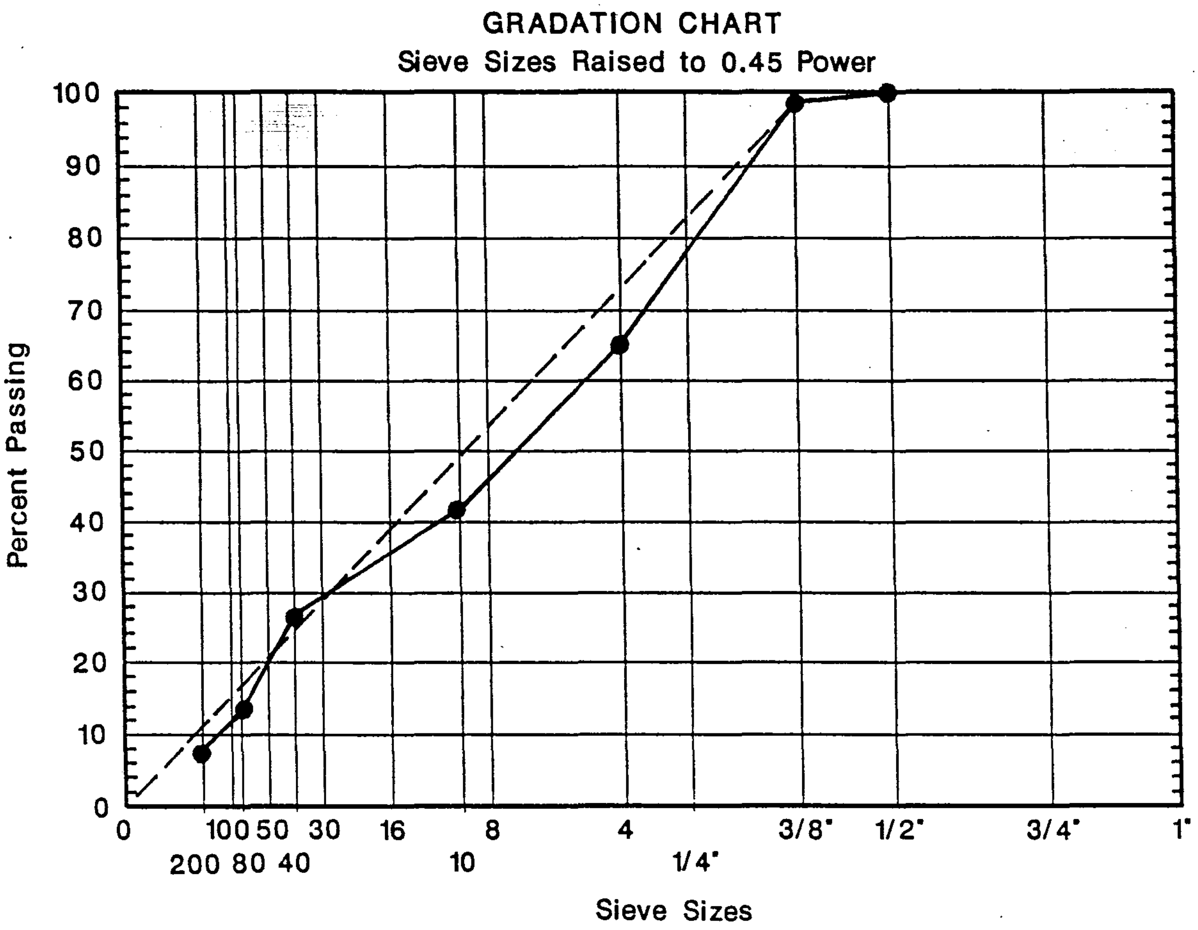


Figure 9. Gradation of Aggregate from cores - Sweetwater, site 2.

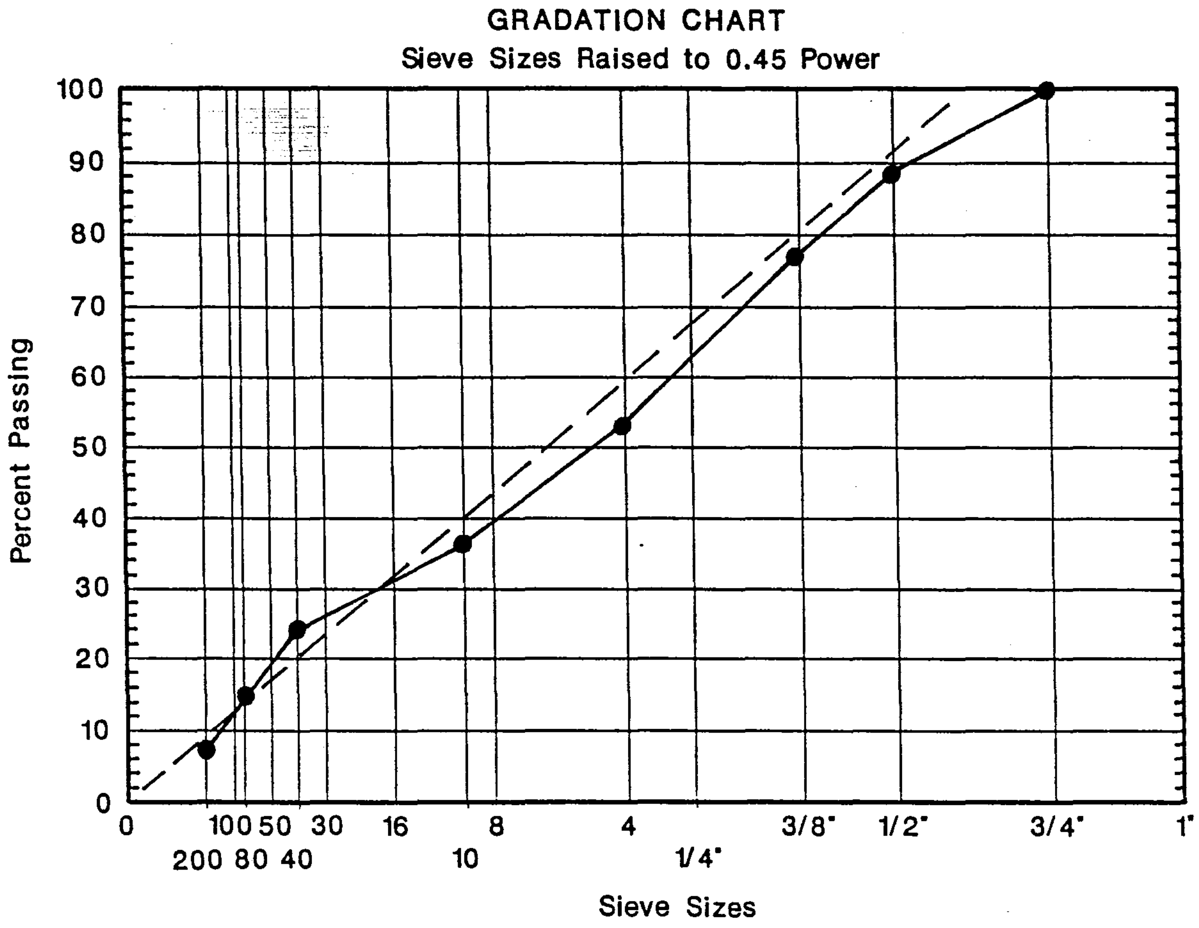


Figure 10. Gradation of Aggregate from cores - Fairfield, site 1.

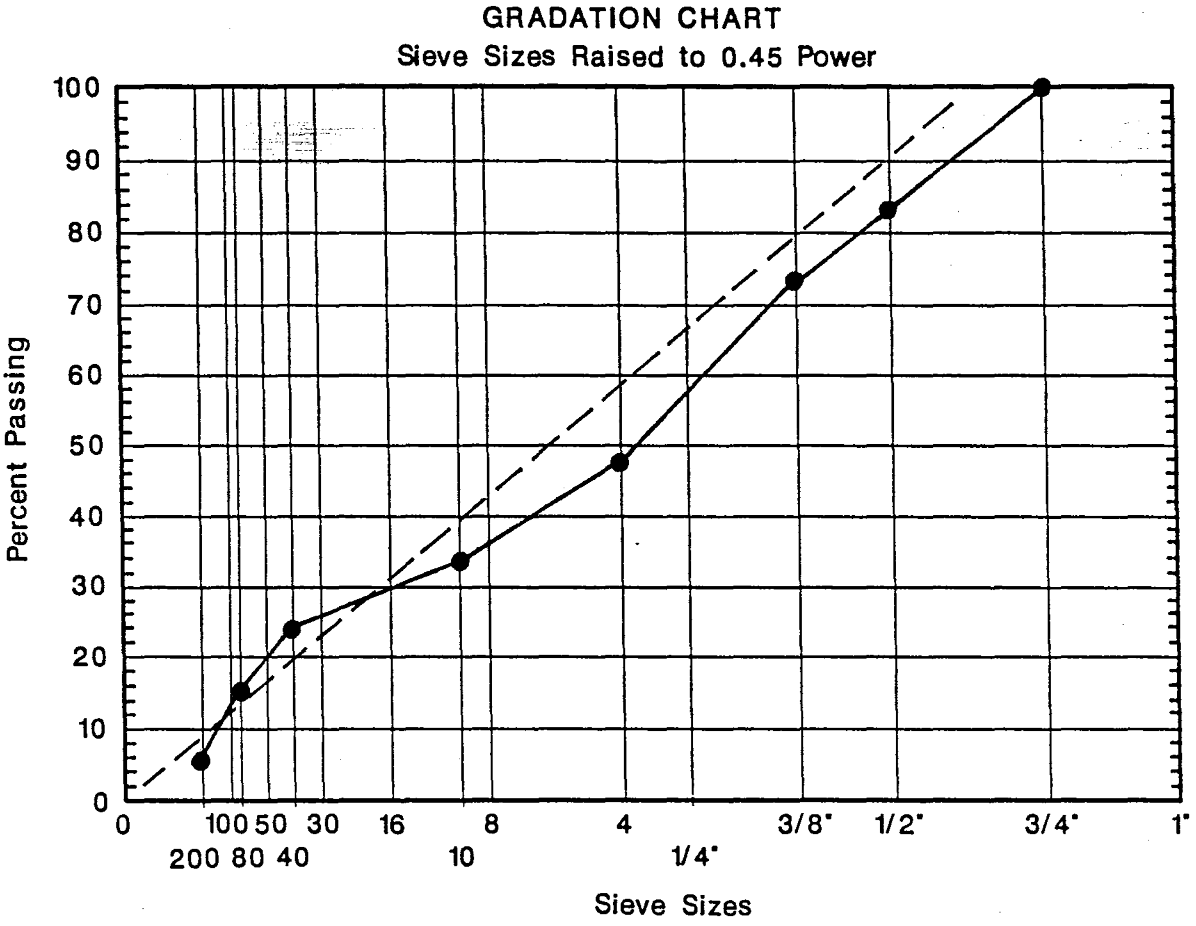


Figure 11. Gradation of Aggregate from cores - Fairfield, site 2.

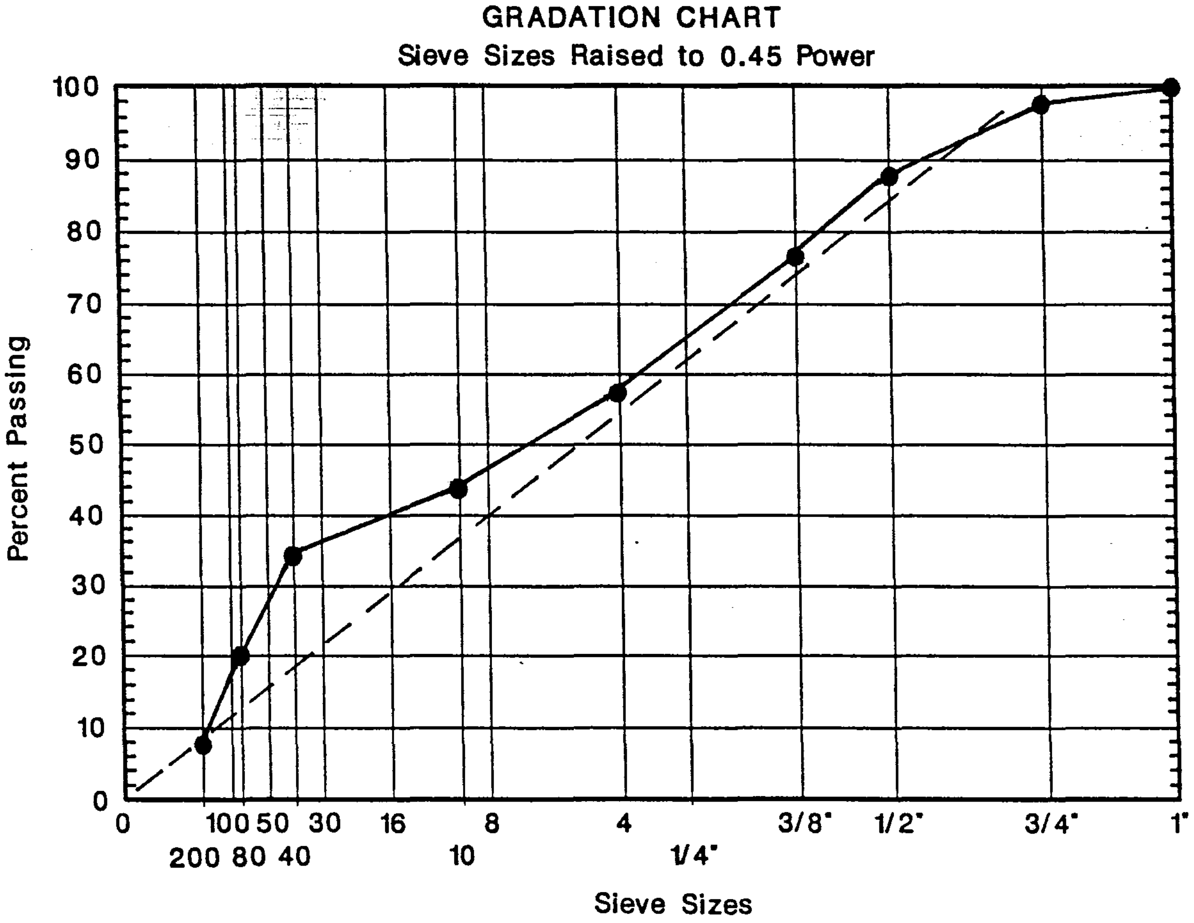


Figure 12. Gradation of Aggregate from cores - Centerville, site 1.

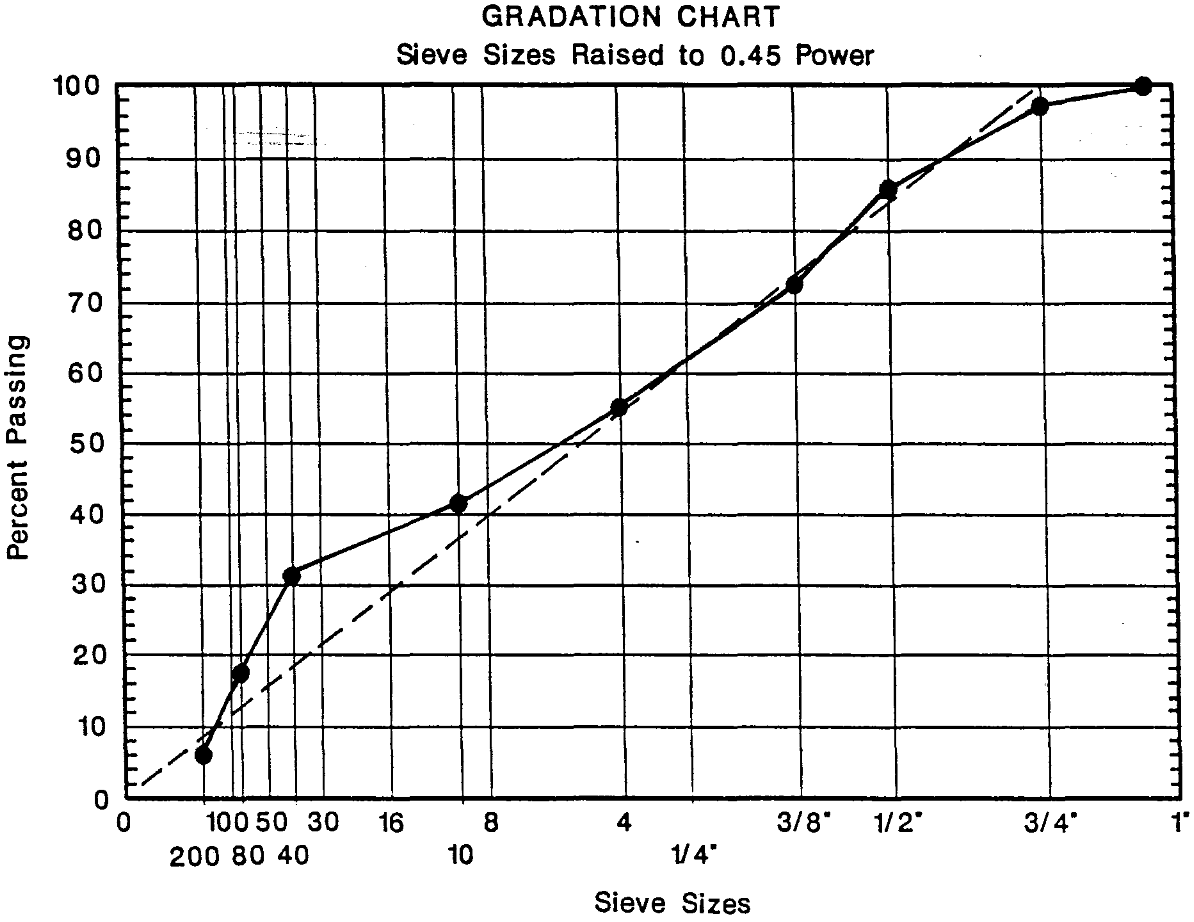


Figure 13. Gradation of Aggregate from cores - Centerville, site 2.

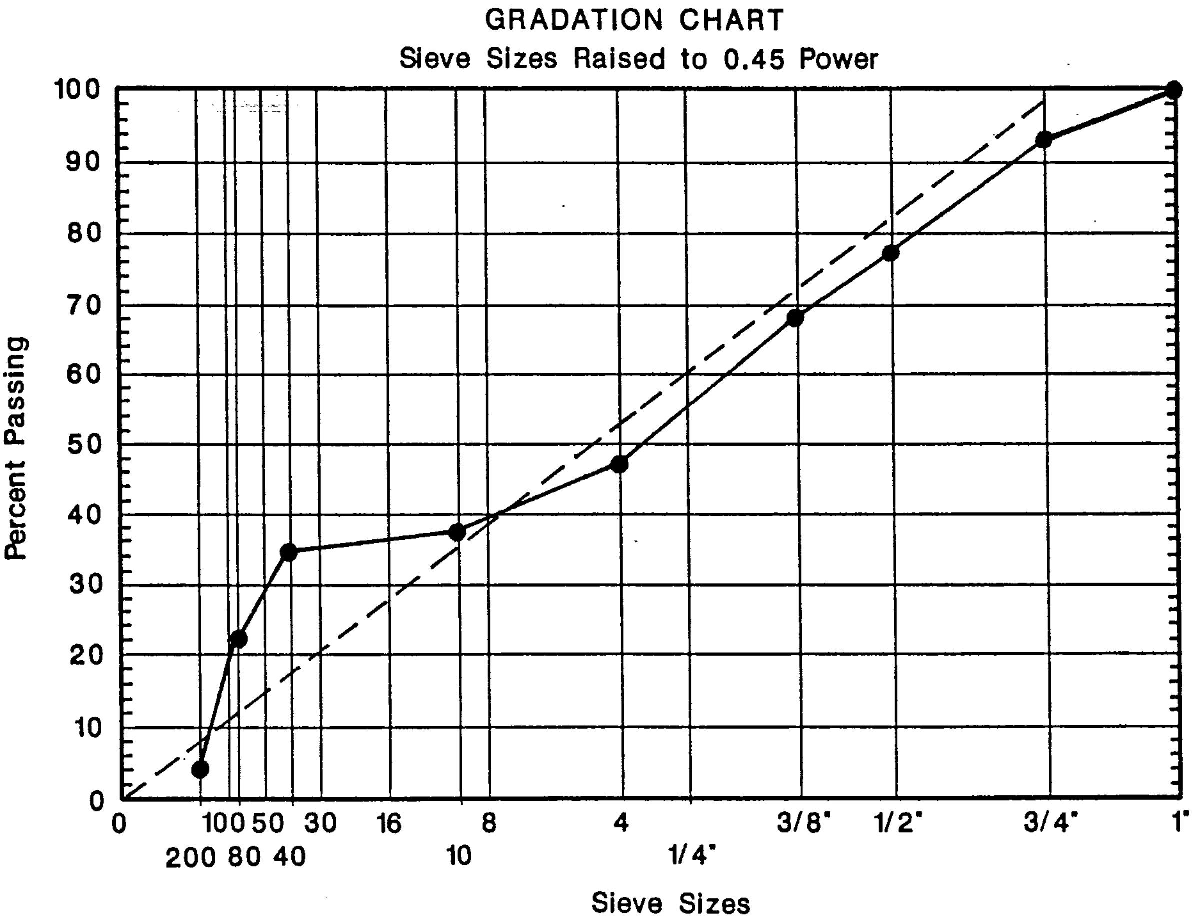


Figure 14. Gradation of Aggregate from cores - Tyler base.

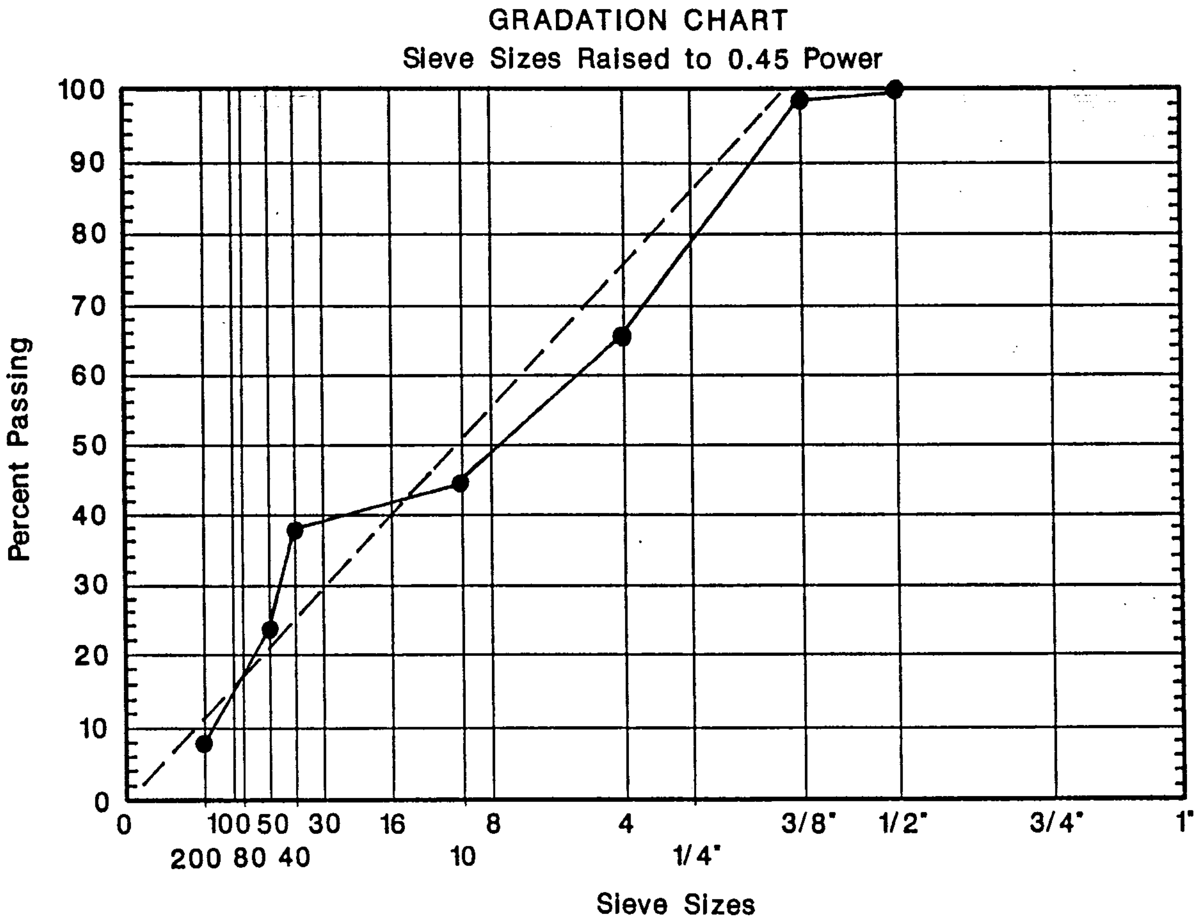


Figure 15. Gradation of Aggregate from cores - Tyler surface course.

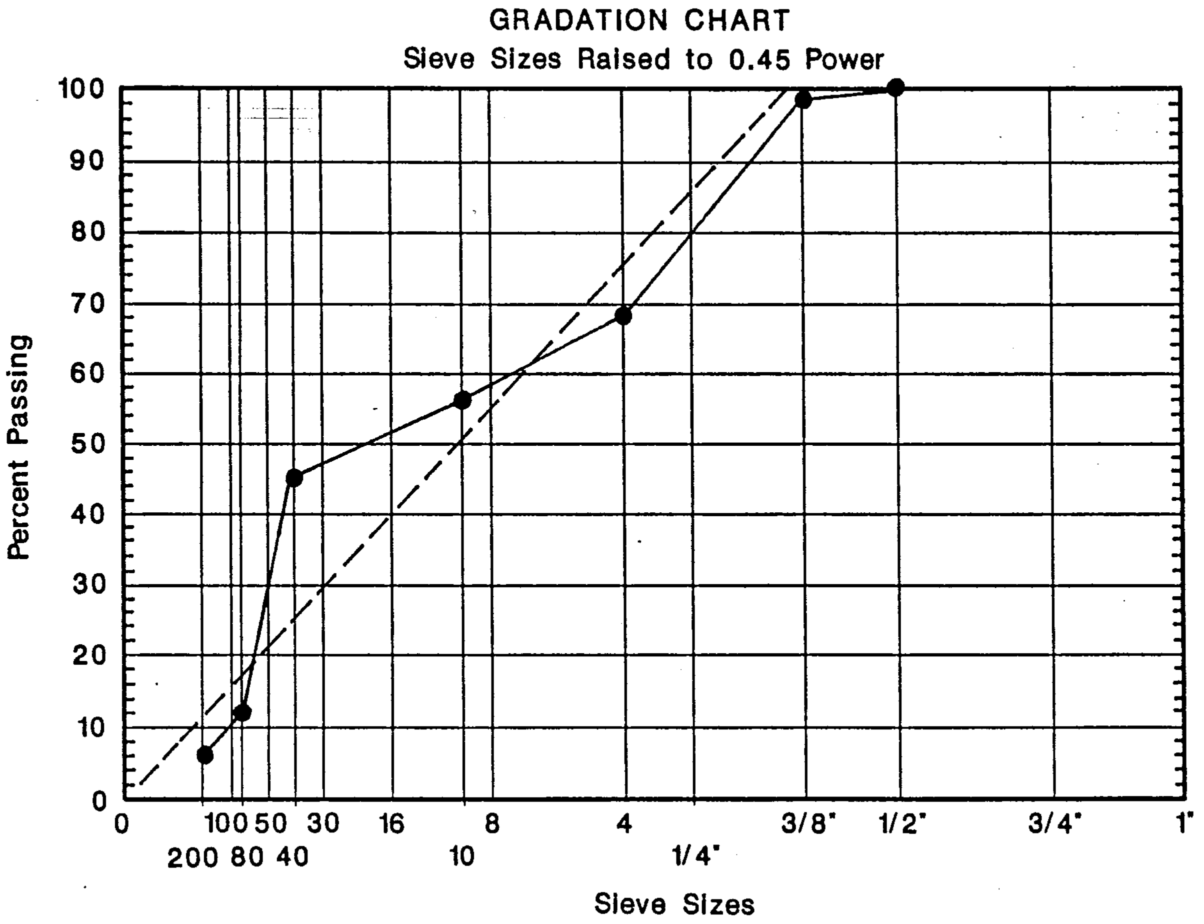


Figure 16. Gradation of Aggregate from cores - Lufkin

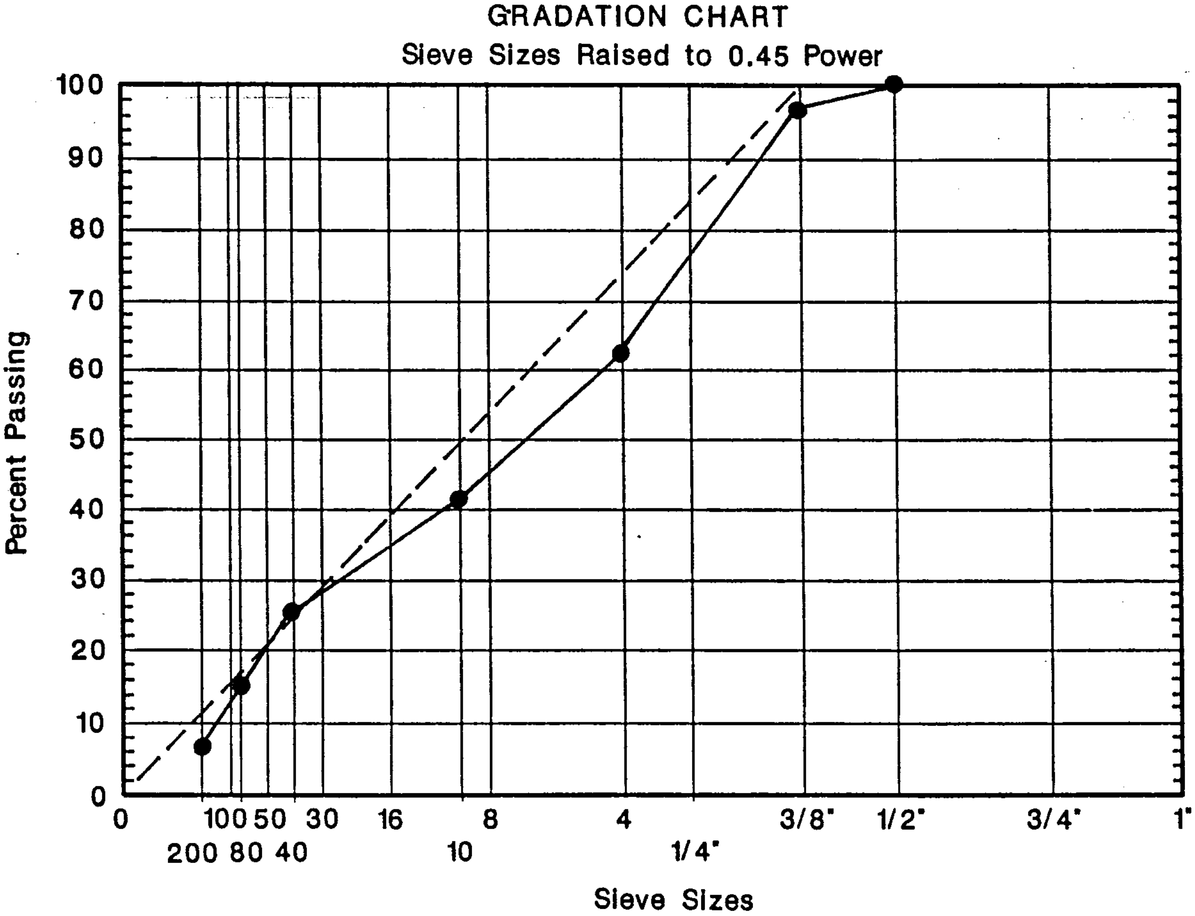


Figure 17. Gradation of Aggregate from cores - Dumas.

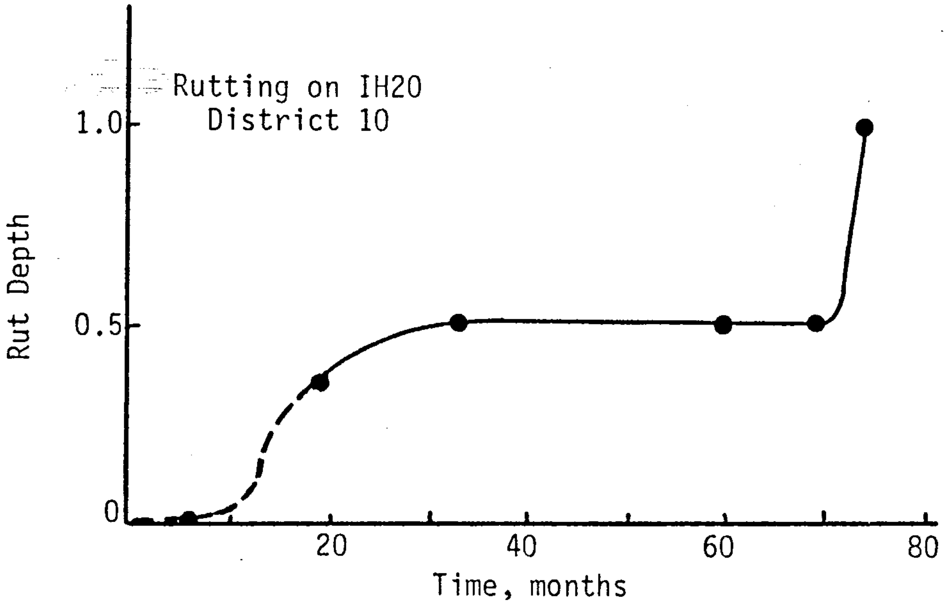


Figure 18. Rutting History of Pavement on IH20 near Tyler, Texas.

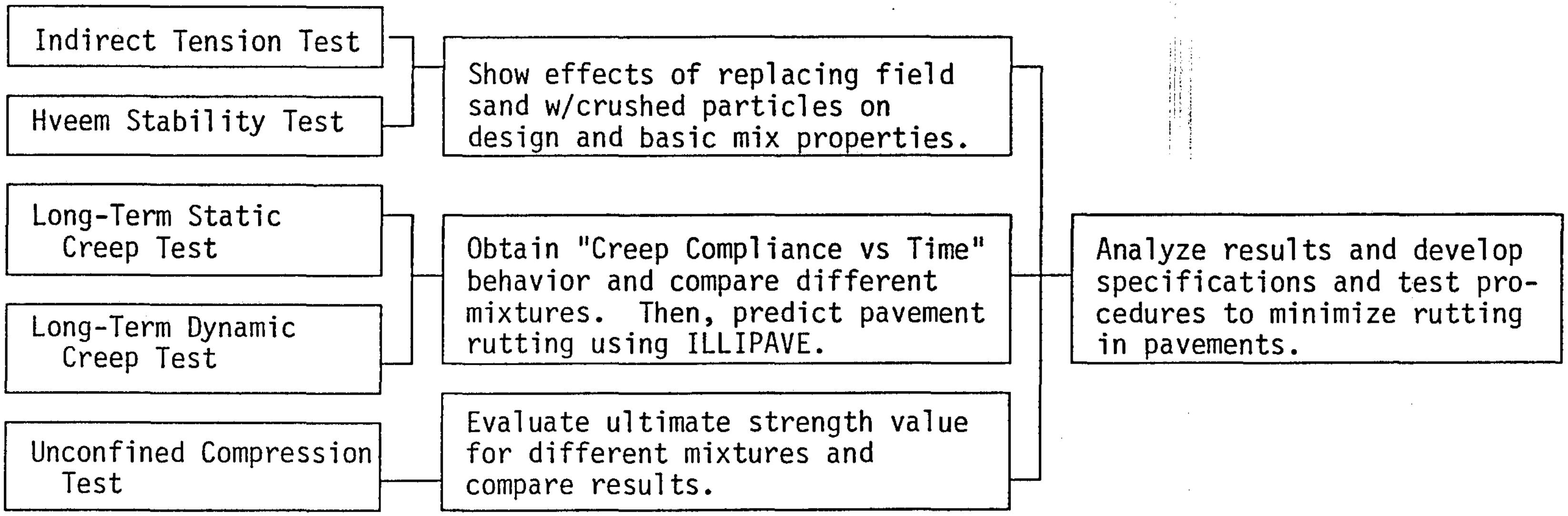
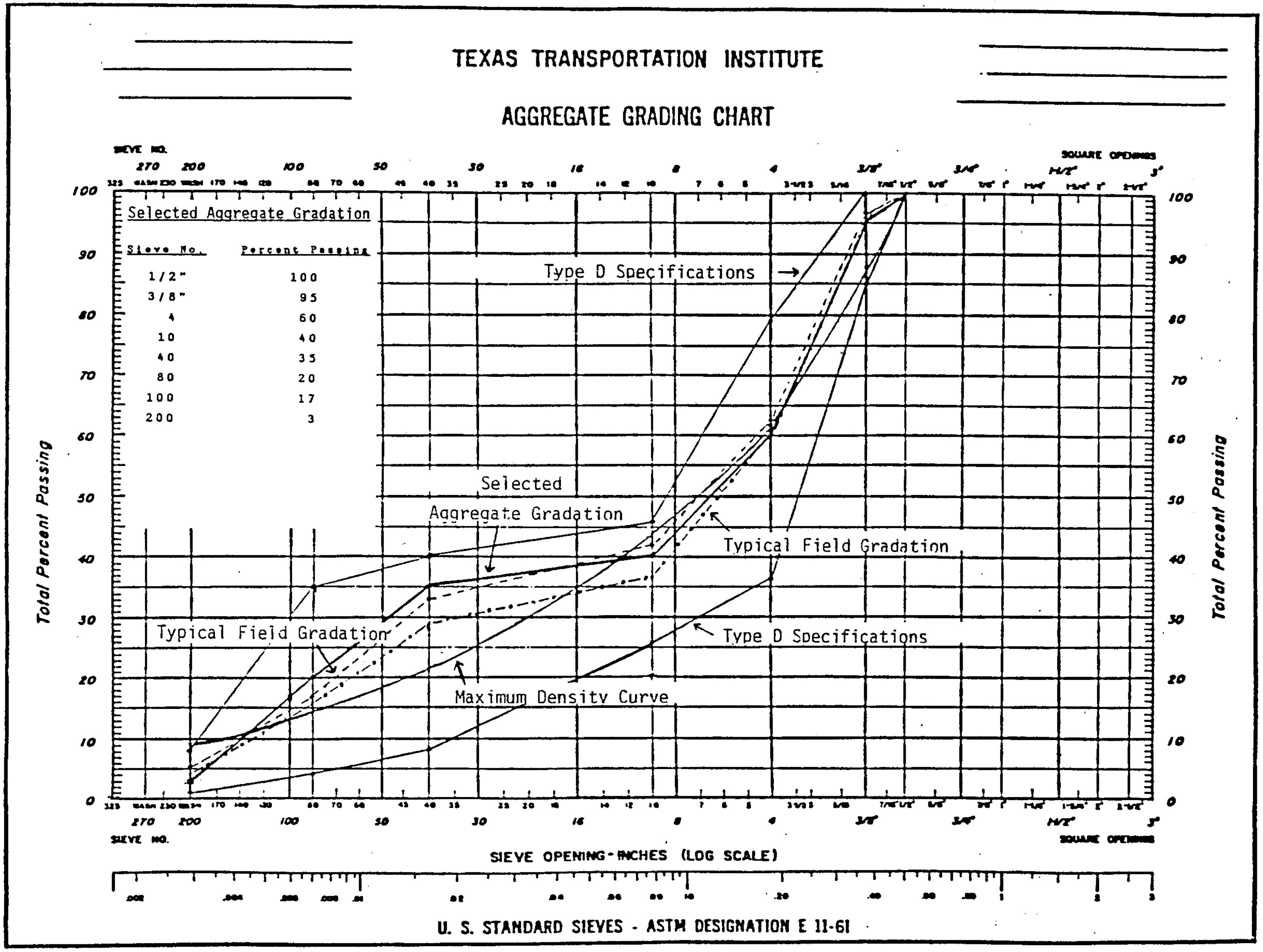


Figure 19. Sequenced Laboratory Test Program.



Selected Aggregate Gradation

Sieve No.	Percent Passing
1/2"	100
3/8"	95
4	60
10	40
40	35
80	20
100	17
200	3

Figure 20. Aggregate Gradation and Specifications.

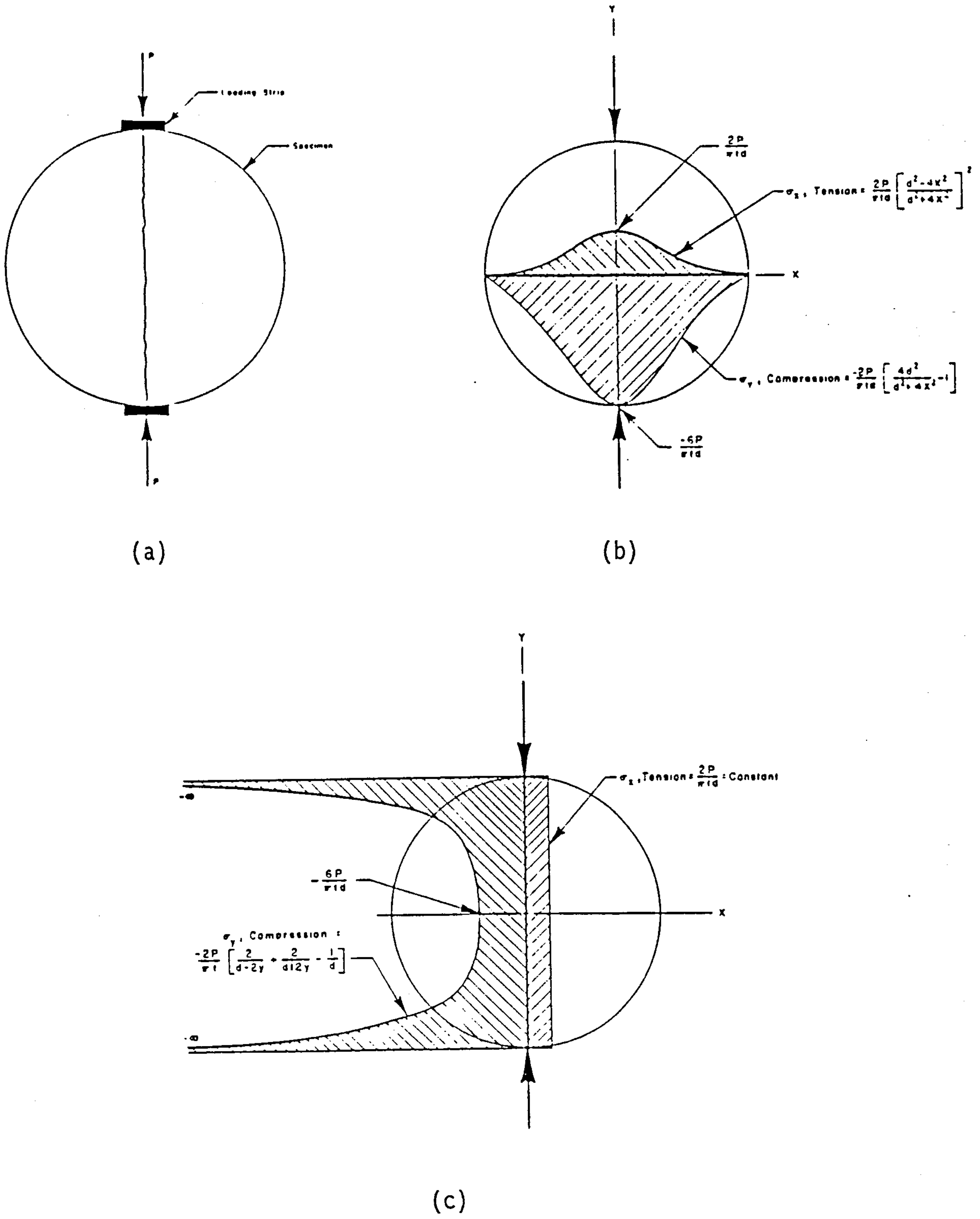


Figure 21 - a) Indirect Tensile Test b) Stress distributions along x-axis
c) Stress distributions along y-axis (After Reference 34).

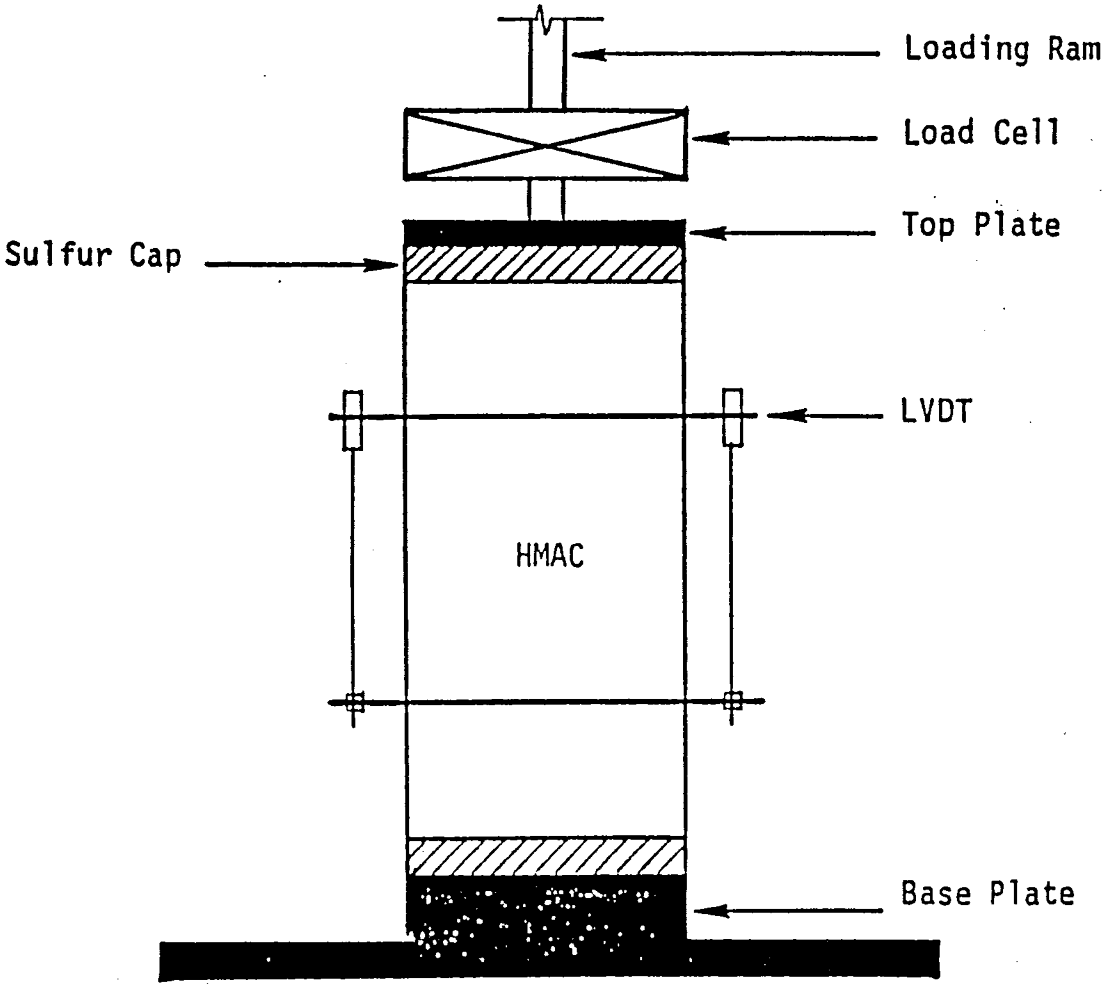


Figure 22 - Setup for Creep Test (After Reference 35).

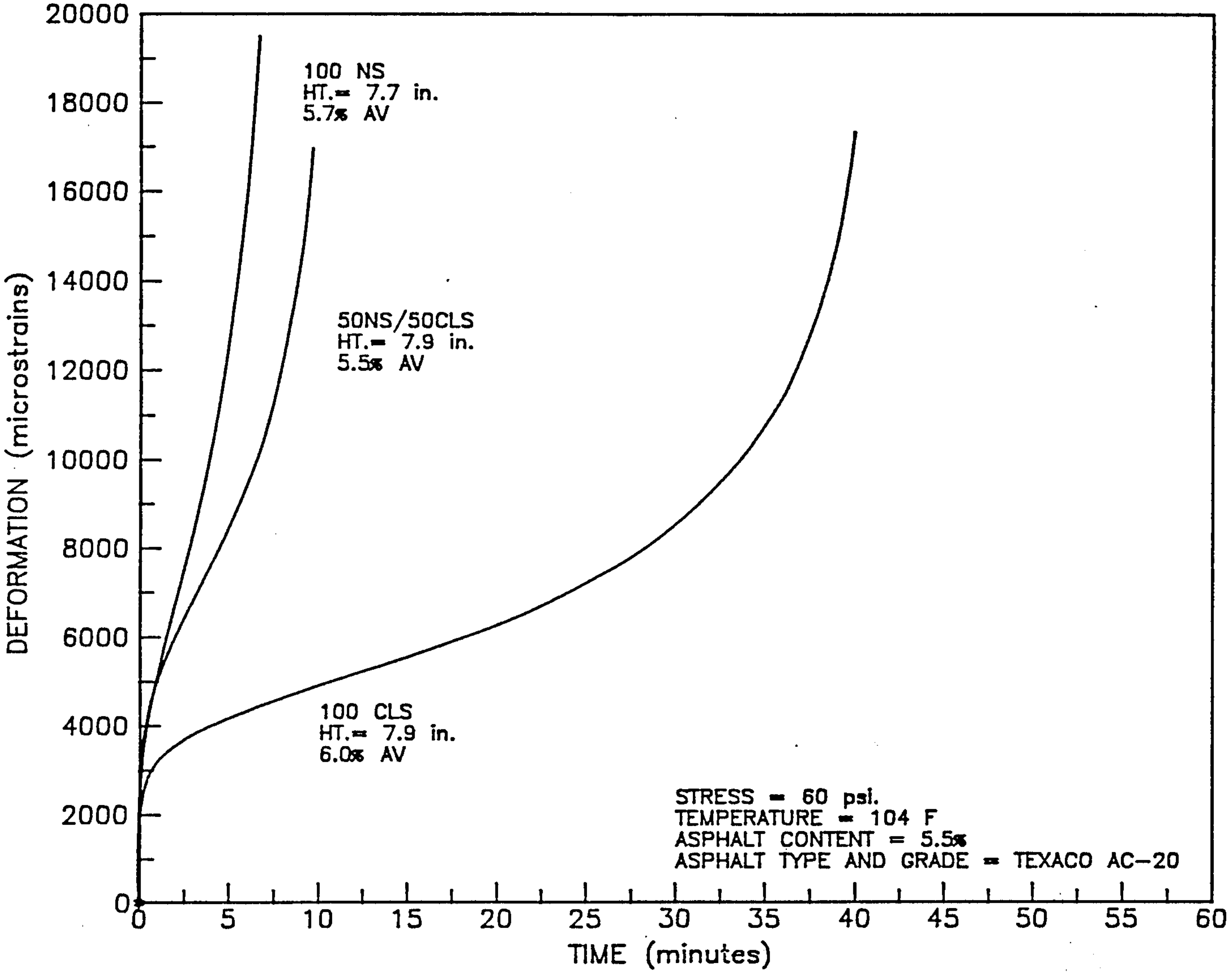


Figure 23. Response to Static Creep for Three Different Mixtures at High Air Void Content.

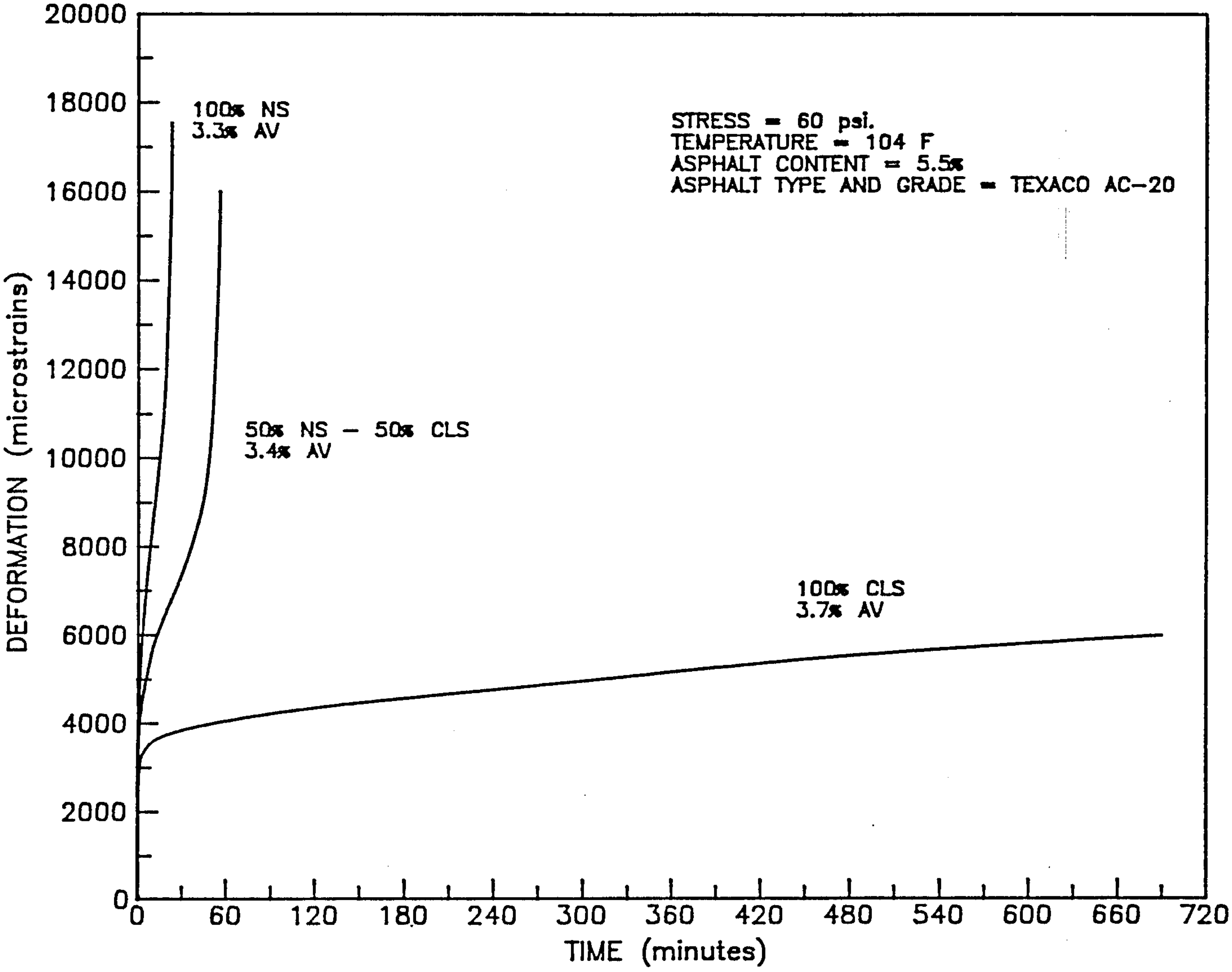


Figure 24. Response to Static Creep for Three Different Mixtures at Low Air Void Content.

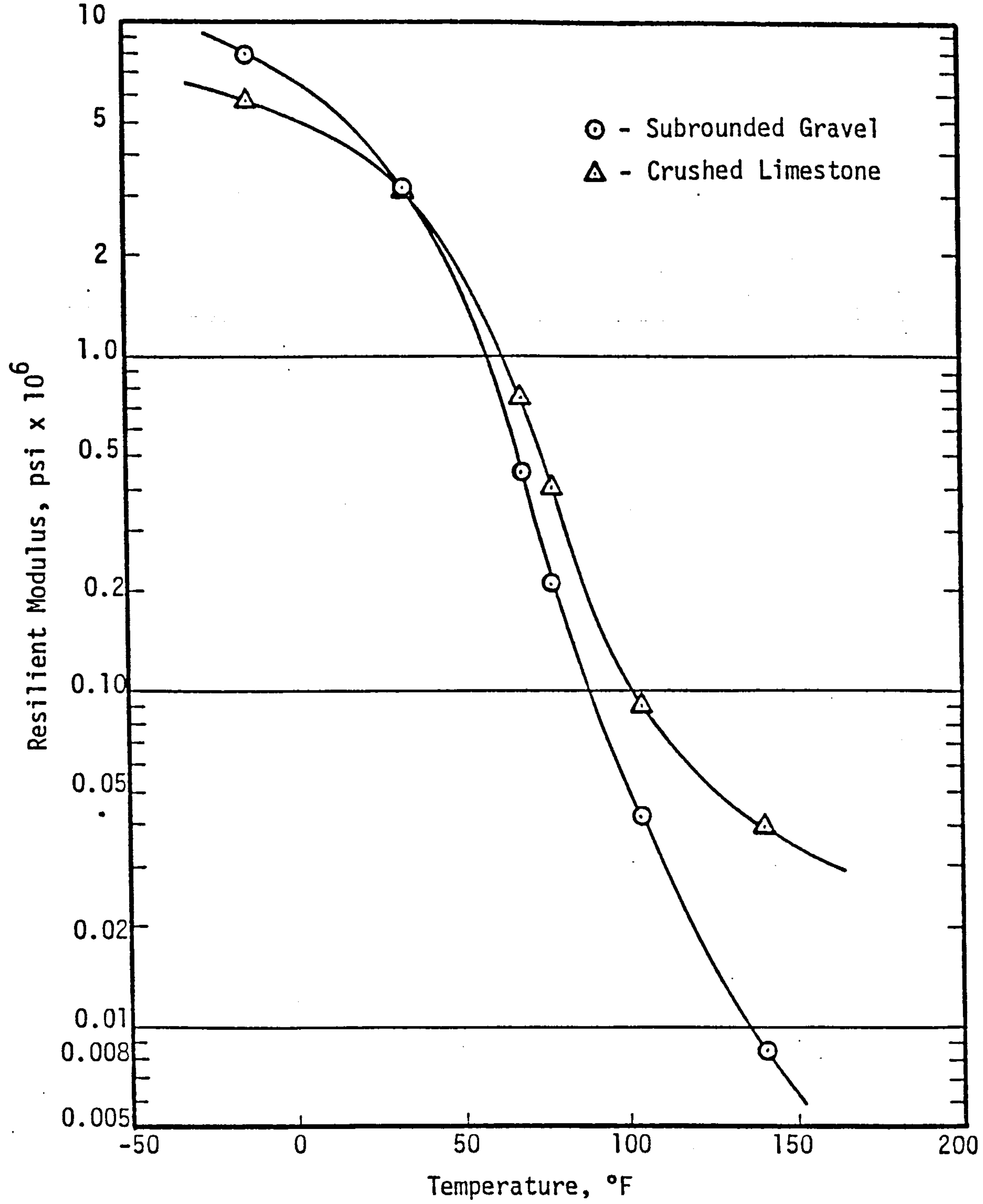


Figure 25. Resilient Modulus of Laboratory Compacted Specimens as a Function of Temperature.

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APPENDIX A

Static Creep Results

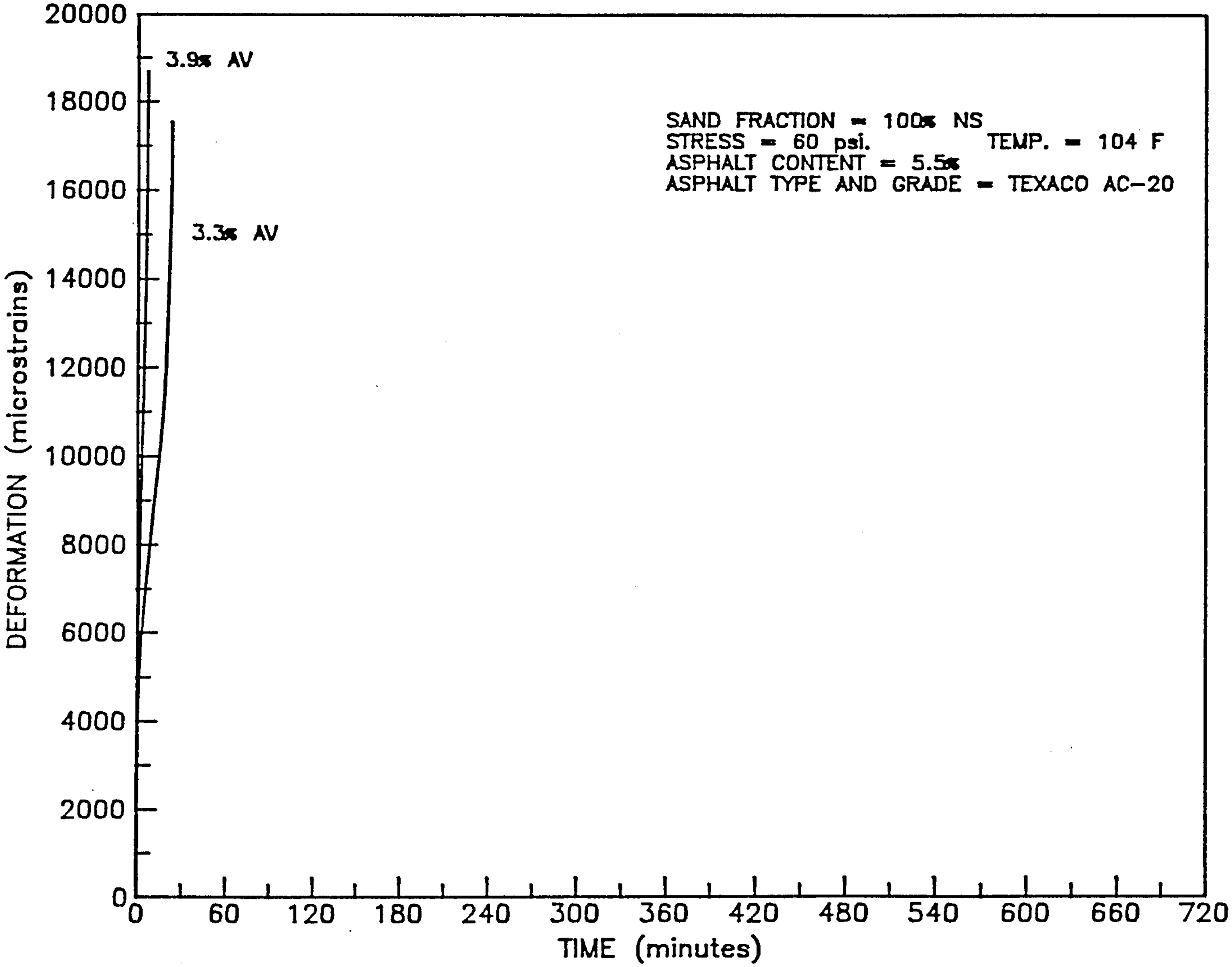

Figure A1. Response to Static Creep for Low Air Void Specimens Containing 40 Percent Natural Sand.

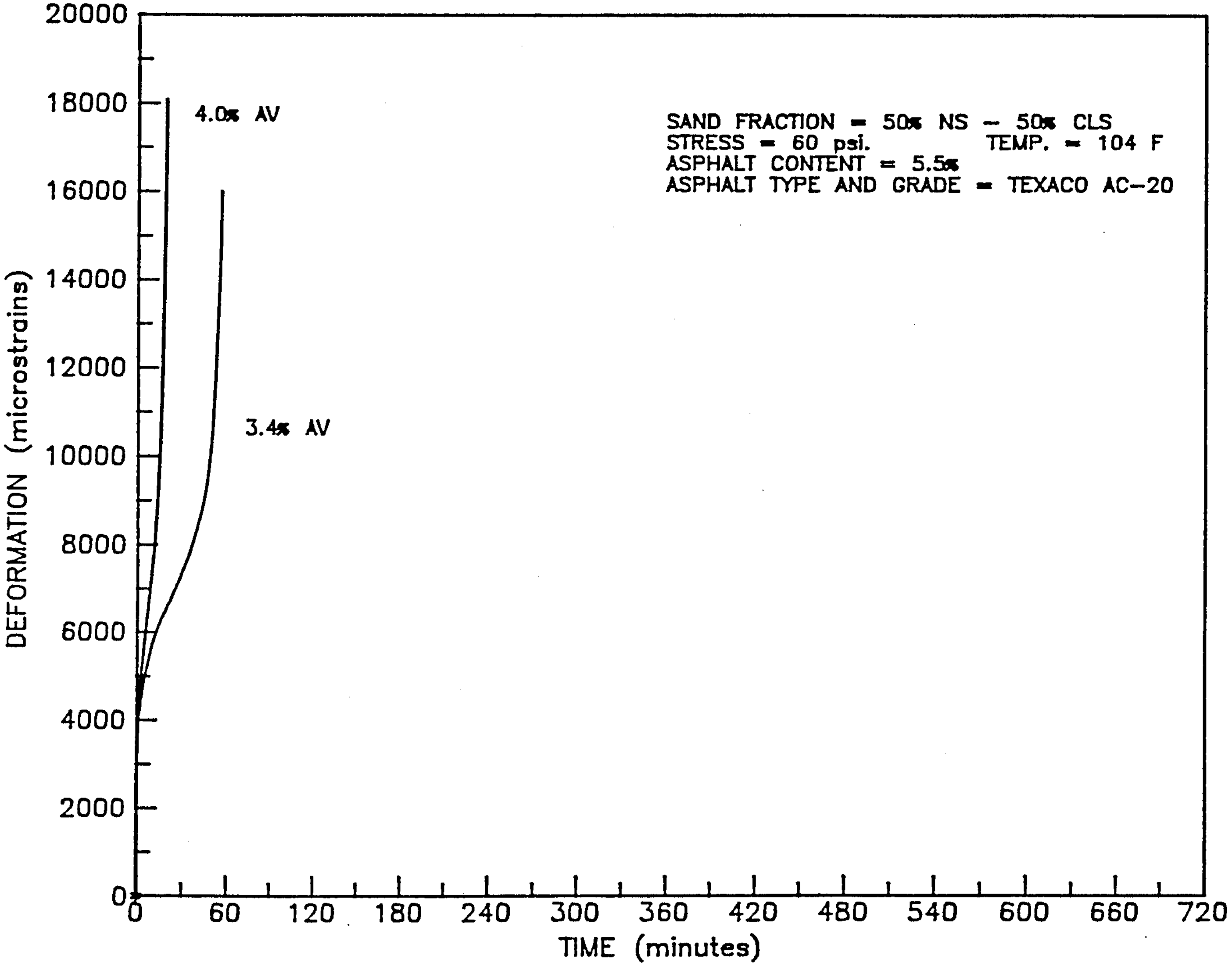

Figure A2. Response to Static Creep for Low Air Void Specimens Containing 20 Percent Natural Sand and 20 Percent Manufactured Sand.

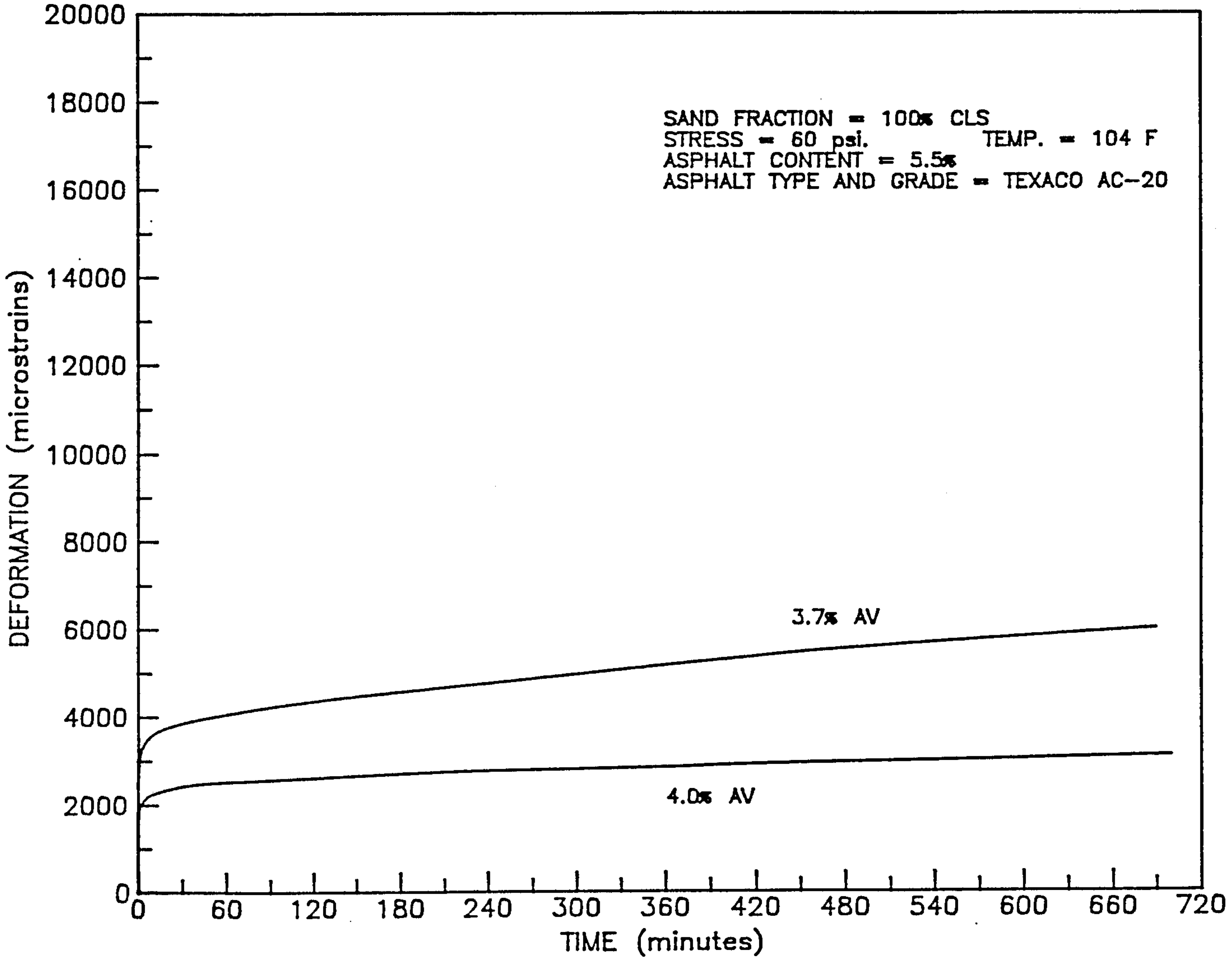

Figure A3. Response to Static Creep for Low Air Void Specimens Containing 40 Percent Manufactured Sand.

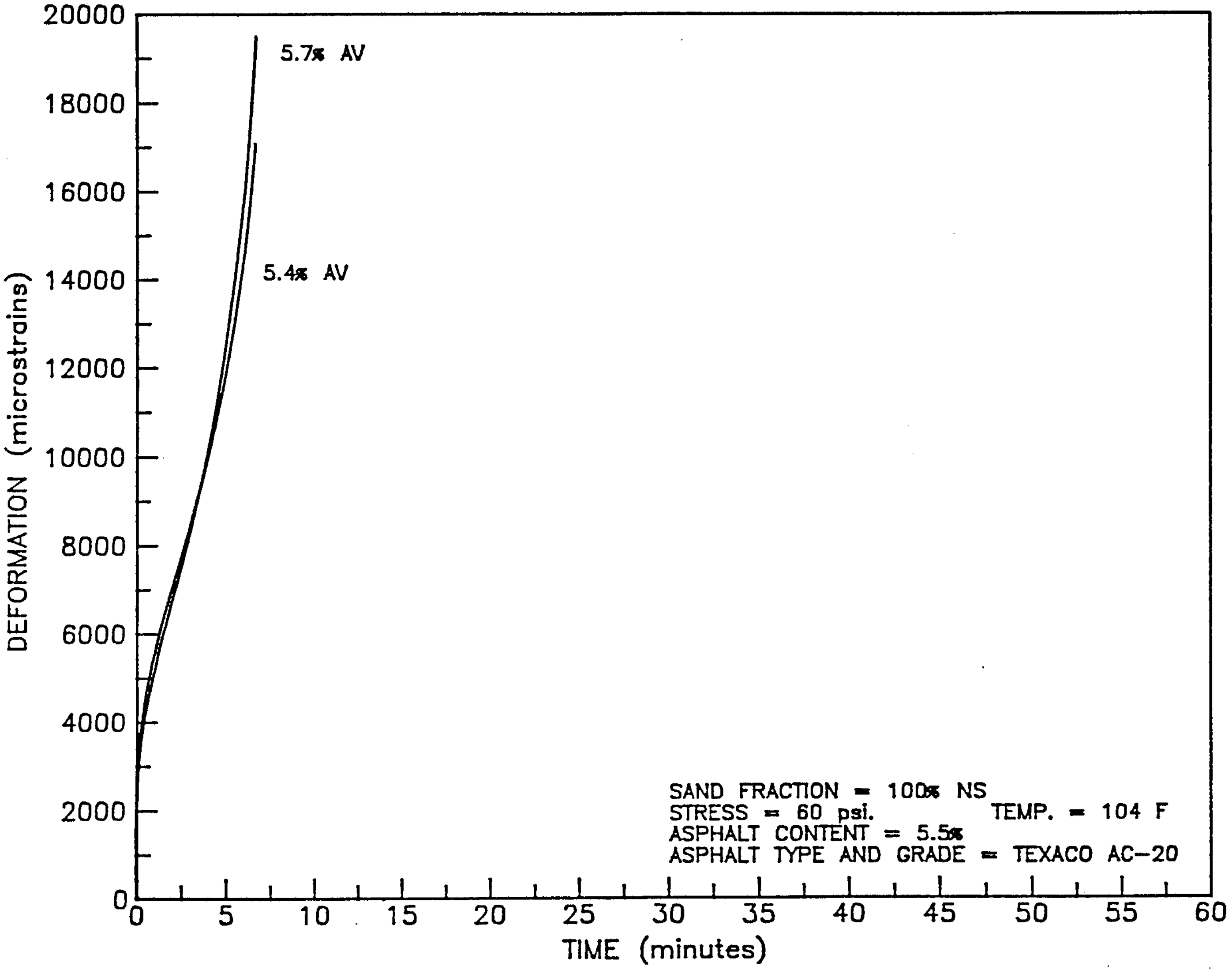

Figure A4. Response to Static Creep for High Air Void Specimens Containing 40 Percent Natural Sand.

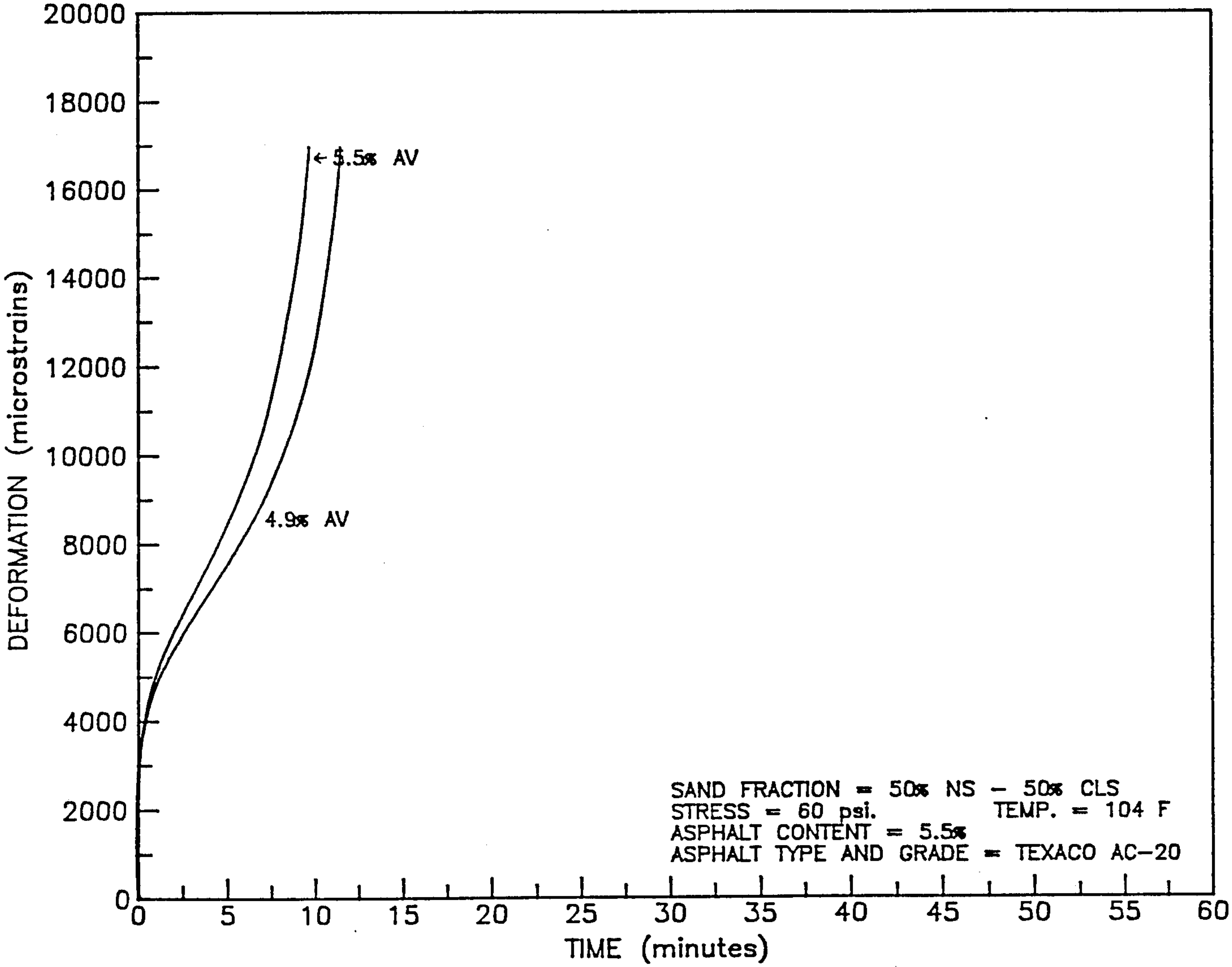

Figure A5. Response to Static Creep for High Air Void Specimens Containing 20 Percent Natural Sand and 20 Percent Manufactured Sand.

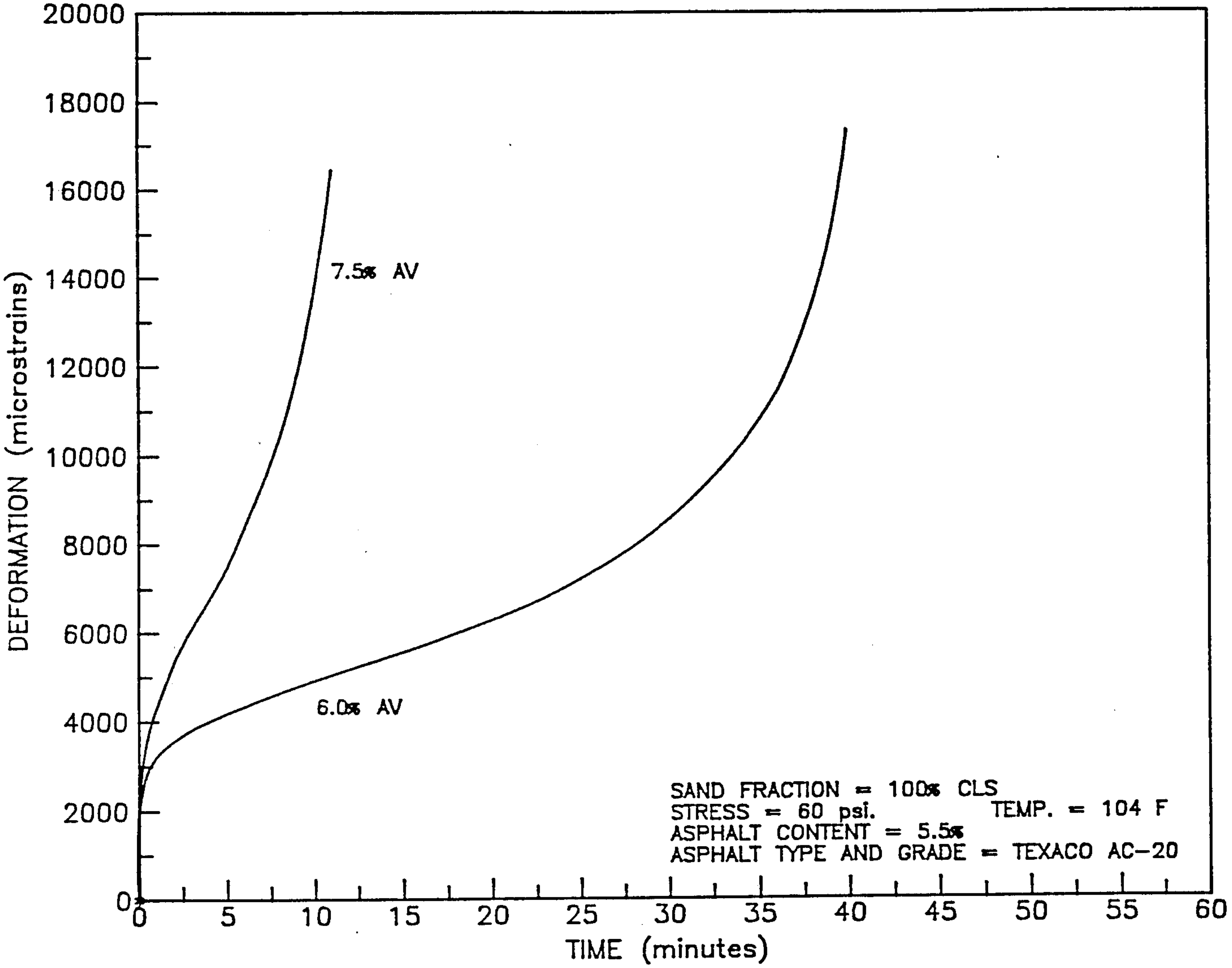

Figure A6. Response to Static Creep for High Air Void Specimens Containing 40 Percent Manufactured Sand.