Influence of Aggregate on Rutting in Asphalt Concrete Pavements

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Pavement cores were collected from rutting asphalt concrete pavements less than 2 years old. Laboratory tests revealed common causes of rutting, such as excessive asphalt content, excessive fine-grained aggregate, and high percentages of natural, rounded aggregate particles. A test program was designed and initiated to quantify the contribution to plastic deformation in laboratory-prepared asphalt concrete mixtures when increasing amounts of natural (uncrushed) aggregate particles are added to replace crushed particles. 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. Tests on asphalt mixtures included unconfined compression, static and dynamic creep, and indirect tension; the particle index test was used on the aggregate. Results to date have indicated that susceptibility to plastic deformation increases dramatically when natural fine aggregate particles replace crushed particles in a given aggregate gradation. A new theoretical approach that includes the aggregate's influence on rutting is being considered. In this analysis the aggregate's characteristics are studied by using a factor in the creep-recovery performance of the mixture.

In 1984, the Western Association of State Highway and Transportation Officials (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 that, in the past, showed little propensity to 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. On the basis of 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.

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 aware of this. Problems associated with producing and placing rut-resistant asphalt paving mixtures are workability, compactibility, and, of course, cost. In addition, some existing state highway specifications encourage production of rut-susceptible paving mixtures.

The overall purpose of this ongoing 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 and implementable format. Specific objectives are to

1. Conduct field investigations of asphalt concrete pavements experiencing rutting,
2. Perform laboratory tests to isolate the causes of rutting, and
3. Recommend methods to minimize rutting.

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 that involved identification of recurring factors that contributed to rutting, assessment of the magnitude of these factors, and development of guidelines to reduce their effects. An existing computer simulation program was modified such that the influence of the aggregate was considered in the rutting model.

This study (*3*) was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) in cooperation with the Federal Highway Administration of the U.S. Department of Transportation.

LITERATURE REVIEW AND COMMENTS

Causes of Rutting

Krugler et al. (*4*) 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

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enforcement of the load regulations to include heavy fines for noncompliance. Elimination of 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 by utilizing antistripping additives or nonstripping materials. The next step is to develop appropriate screening procedures to identify rut-susceptible materials in the laboratory and specifications to eliminate them.

Factors identified in New Mexico (*5*), Florida (*6*), and Wyoming (*7*) 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 leading to low density.

In addition, a field study by Roberts et al. (*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 to 90 psi is typically used in pavement design procedures. More important, 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 (*8*). 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 (1958–1960). A Wyoming study (*7*) found that single and tandem axle loads frequently applied damaging effects to their pavements 10 times that of the legal limit. In other words, pavement designers may be designing today's pavements for yesterday's loads.

Reducing Rutting

Large stone mixes 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 United States. Three types of large stone mixes have been evaluated in resisting rutting caused by heavy loads and high tire pressures: dense graded, stone filled, and open graded.

The dense graded material is an aggregate blend that, according to Acott (*9*),

> primarily develops strength from aggregate interlock and the 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% and 8%.
>
> 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 1½-in. nominal maximum size material.

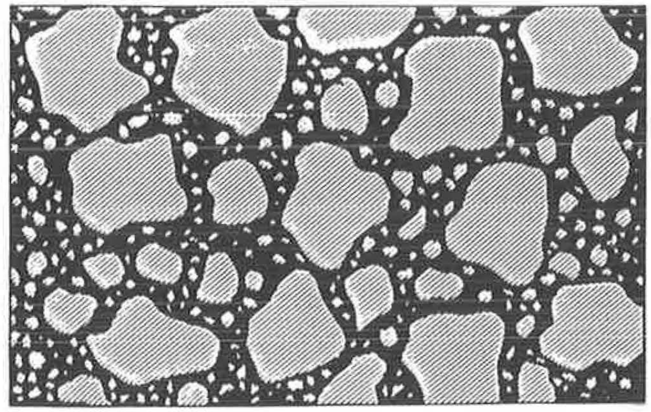

FIGURE 1 Dense graded mix structure (*9*).

Acott (*9*) cites work by Drake, describing a stone-filled mixture as essentially . . .

> a small top size asphalt concrete mix combined with larger single sized stone [Figure 2] of up to 1½-in. maximum size for base courses or a smaller size stone (½ in.) for surface mixtures.
>
> As shown in Figure 3, a stone matrix is formed by the stone and the voids between the stone 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% [when compared with normal dense graded mixtures].

An open graded mix, as shown in Figure 4, consists of large top size crushed stone (up to 2½ in.), low asphalt cement content (typically 2.0 percent) and voids in the 15 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 be properly drained.

As described by Acott (*9*),

> The objective [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 they are not being applied currently due to various factors. In fact, it is interesting to look briefly at the history of developments. Large stone penetration macadam, and later, plant mix macadam mixtures, were popular from the turn of the century through to the 1950s.
>
> However, as we became more mechanized and production-oriented, we found that the finer (½-in. maximum stone sizes) were easier to handle. They didn't 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-in.-diam. molds which cannot handle aggregates larger than 1 in. due to edge effects. This simple fact has probably limited us to 1-in. size

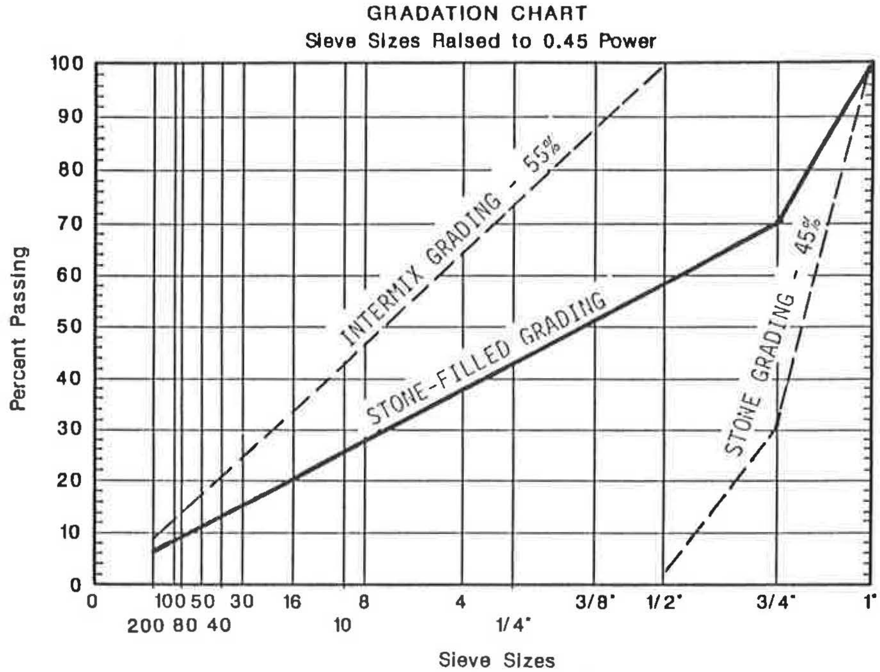

FIGURE 2 Stone added to intermix grading (*21*).

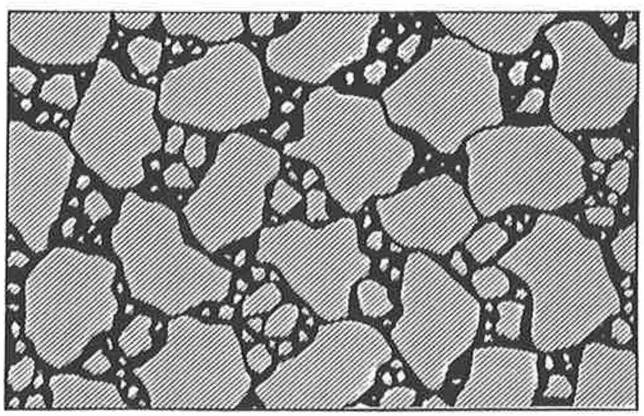

FIGURE 3 Stone-filled mix structure (*9*).

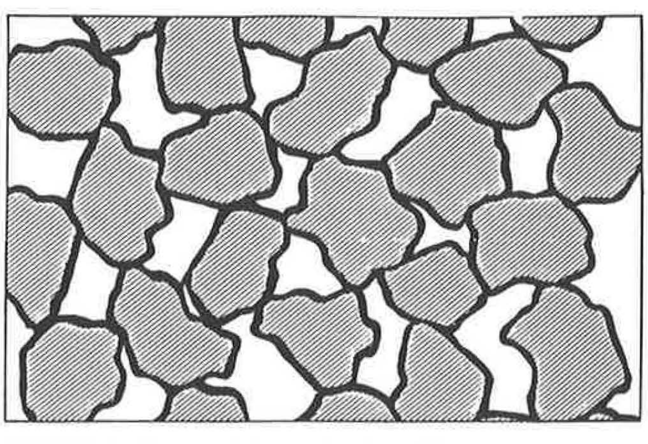

FIGURE 4 Open graded mix structure (*9*).

materials to the extent that we may actually be designing the mix to fit the mold and not the pavement [requirements].

FINDINGS

Field Investigation

The research study (*3*) 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 could be analyzed in this limited study. Therefore, the study was limited to pavements that were no more than 2 years old (with one exception) and experiencing rutting greater than 0.4 in. Rutted and unrutted (or less rutted) pavements composed of the same materials (whenever possible) were studied. Ten pavement sites were located and visually evaluated and sampled in an effort to identify the causes of the rutting. Five cores distributed across the pavement in and between the wheel paths were drilled 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 section describes the field evaluations and materials characterizations resulting from this work.

Description of Test Pavements

Pavements were selected only if rutting appeared to be occurring in the asphalt concrete surface layer; that is, rutting primarily in the untreated base or subgrade was not considered in this study. A visual condition survey of each pavement was conducted, and rut depths were measured. 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.

Results of Tests on Pavement Cores

Results of these tests are given in Tables 2 and 3. After extraction and recovery of the asphalt, both the aggregate and the asphalt were further characterized (Table 4). Mixture design data are included for most of these asphalts 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

TABLE 1 SUMMARY OF RUTTING PAVEMENTS EVALUATED

	Location					
	Sweetwater	Fairfield	Centerville	Tyler	Lufkin	Dumas
Highway No.	IH 20	IH 45	IH 45	IH 20	US 59	US 287
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	Subgrade	8" CRCP	8" CRCP	8" CRCP	Subgrade	
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 MIXTURE PROPERTIES OF PAVEMENT CORES

Location	Air Void Content, percent[1]	VMA, percent[1]	Resilient Modulus, psi x 10^3 13°F[2]	33°F[2]	68°F[2]	77°F[1]	104°F[2]	Hveem Stability[2]	Marshall Stab, lbs[2]	Marshall Flow, 0.01"[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 3 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 4 DATA FOR ASPHALTS EXTRACTED FROM PAVEMENT CORES

	Sweetwater							Tyler			
	Surface		Base	Fairfield		Centerville		Base	Surface	Lufkin	Dumas
Site number	1[a]	2	1	3	4	5	6	7	7	8	9
Penetration											
77°F, 100gm, 5 sec	37	36	31	27	44	27	36	32	72	56	65
39.2°F, 200gm, 60 sec	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	Unknown

[a]Numbers in this row refer to site numbers.

lower in the wheel paths than between the wheel paths, 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 104°F for mixtures from Sweetwater, Centerville, Tyler (surface), Lufkin, and Dumas yielded relatively low values when compared with those from the other sites and other data (*10*). 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 2). The mixtures from Sweetwater, Lufkin, and Dumas exhibited values below the normally specified value of 35.

A Marshall stability value of 1800 is often used as a minimum value 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 3) show that, similarly, mixtures from Sweetwater, Lufkin, and Dumas yielded the lowest values of tensile strength. Tensile strength of a mixture is strongly influenced by the consistency of the asphalt cement, which can influence rutting.

Indirect tension tests were also performed following an accelerated Lottman moisture treatment procedure (*11*) 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 materials quality factors influencing rut susceptibility of asphalt paving mixtures. All of the aggregate systems were dense graded. Natural aggregate contents of the surface mixtures are as follows: Sweetwater, 12 percent; Fairfield, 40 percent; Centerville, 14 percent; Tyler, 50 percent; and Lufkin, 38 percent. The surface mixture from Tyler and the mixture from Lufkin contained 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 No. 40 sieve in several cases. 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 most of these mixes. Gradations from Centerville, Tyler, and Lufkin exhibited a significant hump at the No. 40 sieve.

Asphalt Properties Asphalts were extracted from the pavement cores, and penetration and viscosity at two temperatures were measured. The results were not unusual except for the asphalt from Fairfield—Site 1, which had a viscosity at 140°F of 10,700. There is presently no explanation for this anomaly. Those asphalts exhibiting viscosities at 140°F 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.

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 that this problem is widespread and serious. As a result, a laboratory investigation (*3*) was initiated to quantify mixture sensitivity to natural sand content with particular emphasis on plastic deformation. This work will address only a portion of the 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.

Materials

The asphalt used in preparing the asphalt concrete test specimens was Texaco AC-20 obtained from Port Neches, Texas.

The coarse aggregate (plus No. 10 sieve) was crushed limestone (obtained from Brownwood, Texas). The sand-size fraction is defined here as the material passing the No. 10 sieve and retained on the No. 200 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 (absorbent).

An aggregate gradation was selected based on typical gradations observed in the field. The gradation was designed to meet Texas SDHPT Type D (⅜ in. maximum size) specifications. The total aggregate mixture contained a blend of 60 percent crushed limestone and 40 percent natural field sand. Four additional aggregate mixtures were produced by replacing 50, 75, 88, and 100 percent of the natural field sand fraction with clean limestone screenings of a similar gradation. Therefore, the five aggregate gradings used contained 40, 20, 10, 5, and 0 percent natural sand in crushed limestone. An asphalt concrete mix design was performed for the mixture containing 50 percent natural sand and 50 percent manufactured sand, and the optimum asphalt content obtained (5.5 percent) was used for the other four mixtures tested. Mixture design procedures specified by the Texas SDHPT (*12*) were followed.

Experiment Plan

The laboratory test program (Figure 5) was designed to (a) determine the relative effects of natural sand on permanent deformation, (b) quantify the influence on resistance to plastic deformation when natural sand is replaced or partially replaced by manufactured sand (crushed stone), and (c) attempt to relate test results to pavement rutting.

Particle Index The particle index test provides a quantifiable measure of the shape and texture characteristics of the aggregate. The test was originally developed by Huang (*13*) and has been used considerably in research following its standardization by ASTM.

Test results indicate that particle index values increase as the amount of natural sand in the mix decreases (see the following table). Although this is expected, it is also a measure that can be used in comparing the performance of the different mixes.

Natural Sand (%)	*Particle Index*
0	13.5
5	13.2
10	13.0
20	12.4
40	11.3

Mixture Characterization Tests used to characterize the mixtures at this stage of the work include Hveem stability, indirect tension, unconfined compression, static creep (long and short term), and dynamic creep (long and short term). Unconfined compression and creep tests were performed on 4-in.-diameter by 8-in.-high cylindrical specimens.

In the creep tests, cylindrical specimens were tested in axial unconfined compression. A haversine load pulse of 0.1 sec

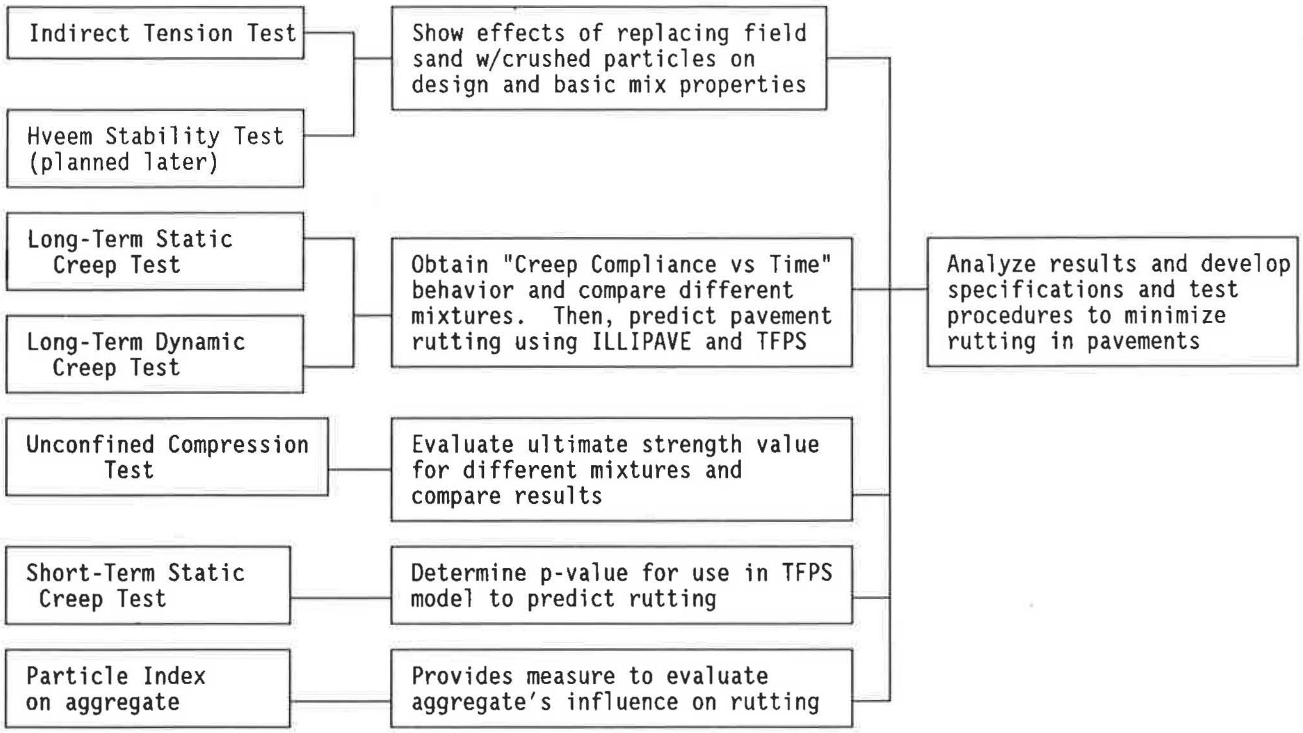

FIGURE 5 Sequenced laboratory test program.

duration (per cycle) was used for the dynamic creep test. Both creep tests (static and dynamic) were conducted at 104°F until the sample reached failure within a reasonable long-term period (the target value was 8 hr). The applied stress was selected by using a trial and error procedure based on specimen behavior.

***p*-Value** A new concept, introduced in the theoretical analysis of rutting, which accounts for the aggregate's role in the performance of the mixture, is *p*-value. The value itself is used in describing the creep and recovery response of a mixture as follows (Figure 6):

$$D(t) = \frac{D_o + D_m a t^{\gamma}}{1 + a t^{\gamma}} \tag{1}$$

$$R(t) = \eta \left[\frac{D_o + D_m b t^{\gamma p}}{1 + b t^{\gamma p}} \right] \tag{2}$$

where

D_o = initial compliance,
D_m = maximum compliance,
a, b = constants,
p = p-value, which accounts for the aggregate's influence,
γ = slope factor, and
η = efficiency factor.

The new compliance equations for both creep and recovery are designed to be used in the rutting model of the Texas Flexible Pavement System (TFPS) program developed at Texas Transportation Institute. In this rutting model, the strain response due to loading and unloading is decomposed into ε_e, elastic (resilient) strain, and ε_p, permanent strain. In the analysis, the elastic strain is assumed to remain constant throughout the life of the pavement. The permanent strain, on the other hand, behaves in the following manner:

$$\frac{\partial \varepsilon_p}{\partial N} = \varepsilon_e \cdot \mu \cdot N^{-\alpha} \tag{3}$$

where

μ, α = parameters determined from Equations 1 and 2 through theoretical analyses,
N = number of cycles, and
ε_e = elastic strain.

Part of the laboratory investigation consists of determining the unknown parameters in Equations 1 and 2, including the p-value, from creep-recovery tests for different mixes. The procedure can be described in the following steps:

1. Precondition the sample (using Shell's recommendations: 1.45 psi for 30 min).
2. Load and unload the sample for 1,000 sec, respectively, measuring deformation versus time.
3. Plot and analyze compliance versus time, using Equations 1 and 2.

The results to date have shown considerable success in the sense that the influence of the aggregate seems to be strongly related to the p-value. For 0 percent natural sand, p-values have been found to be between 0.75 and 0.95. For 40 percent natural sand, p-values lie between 0.35 and 0.50.

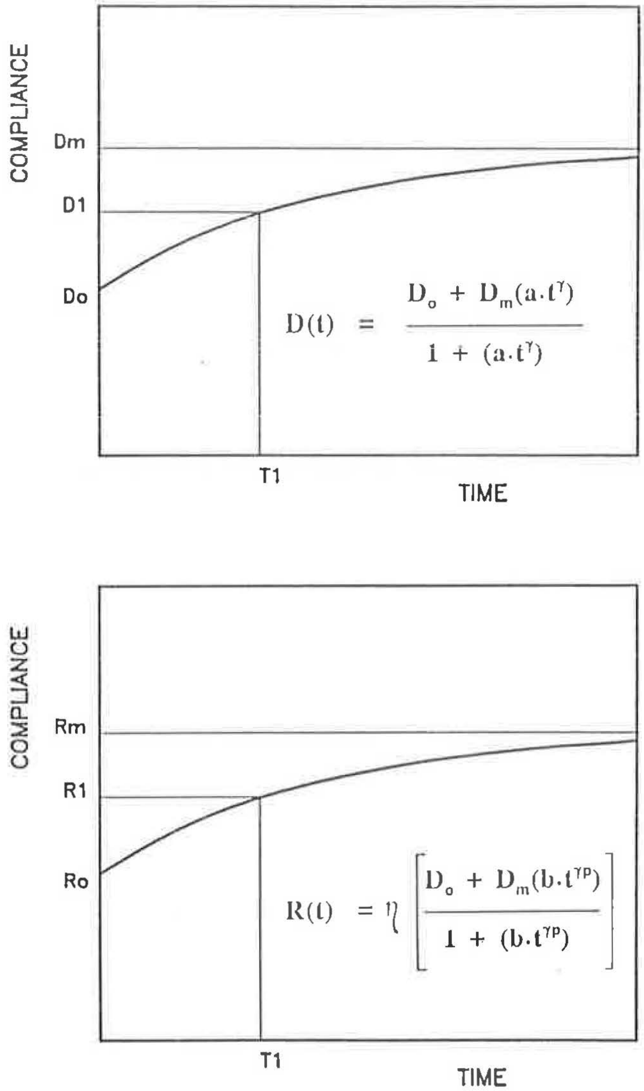

FIGURE 6 Creep-recovery curves for analyzing the *p*-value.

Test Results

One would not expect the character of the sand-size particles in an asphalt concrete mixture to have a great effect on tensile properties (Table 5). 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 compared with 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 was 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.

Results are shown in Figures 7 through 10. Conclusions are summarized as follows:

1. Test results in Figures 7 through 9 show, for any duration of applied load, significantly more total deformation as the percent natural sand in the mixture increases.
2. Deformation on static and dynamic 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 mixtures containing 0 and 20 percent natural sand. This indicates that 20 percent natural sand in this particular mix is an excessive quantity for achieving low deformations during long periods of stress for both low and high air void contents.
4. The texture, shape, and porosity of the fine aggregate are major factors related to plastic deformation.
5. Figure 10 shows how the ultimate unconfined compressive strength is improved by reducing the amount of natural sand in the design mixture, under a constant air void content.

In previous work by Button et al. (*14*), asphalt concrete mixture characterizations were performed on two mixtures of the same aggregate gradation. However, one was composed of 100 percent subrounded, siliceous river gravel, and the other was composed of 100 percent crushed limestone. Both mixtures contained the same asphalt cement. Optimum asphalt

TABLE 5 SUMMARY OF INDIRECT TENSION TEST RESULTS

	Low Air Void Specimens			High Air Void Specimens		
Mixture Type	Tensile Strength, psi	Strain, in/in	Air Voids, percent	Tensile Strength, psi	Strain, in/in	Air Voids, percent
40% Natural Sand	154	0.44	3.0	97	0.57	5.2
20% Natural Sand	114	0.50	4.0	94	0.51	6.9
0% Natural Sand	104	0.38	3.9	91	0.39	6.9

NOTE: Each value represents an average of three tests.

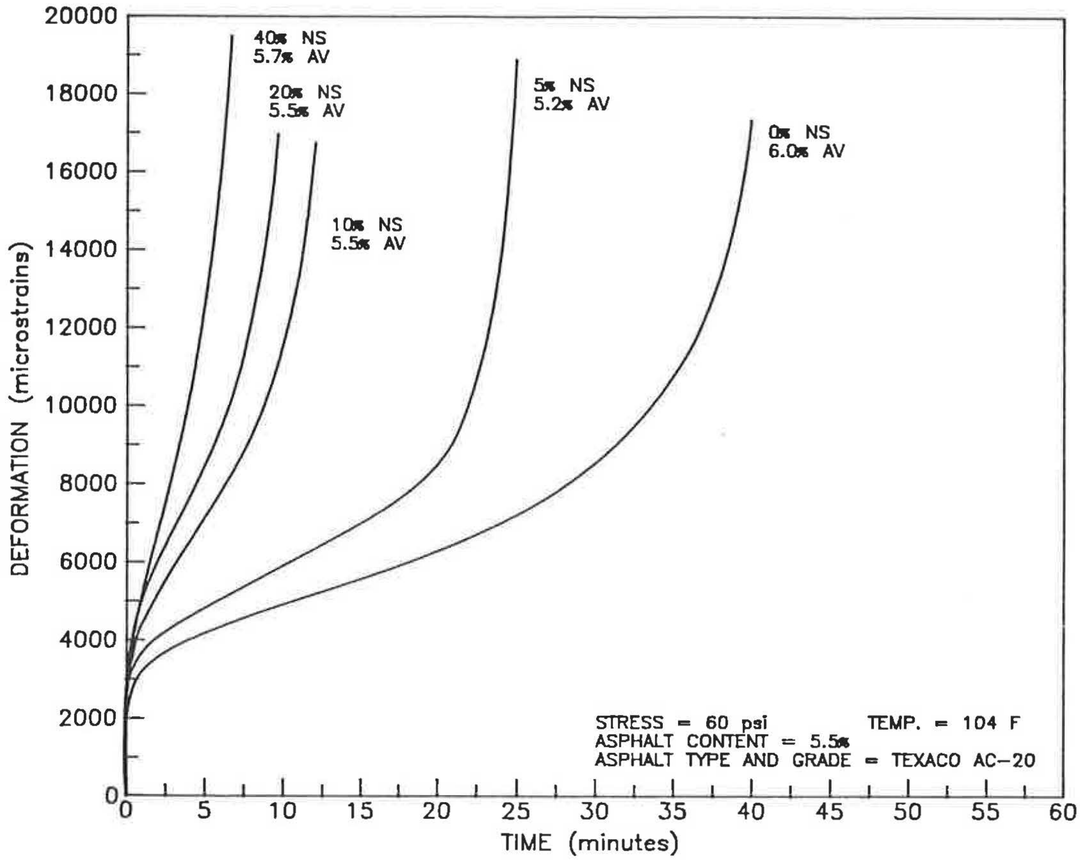

FIGURE 7 Response to static creep for five different mixtures at high air void content (NS, natural sand; AV, air voids).

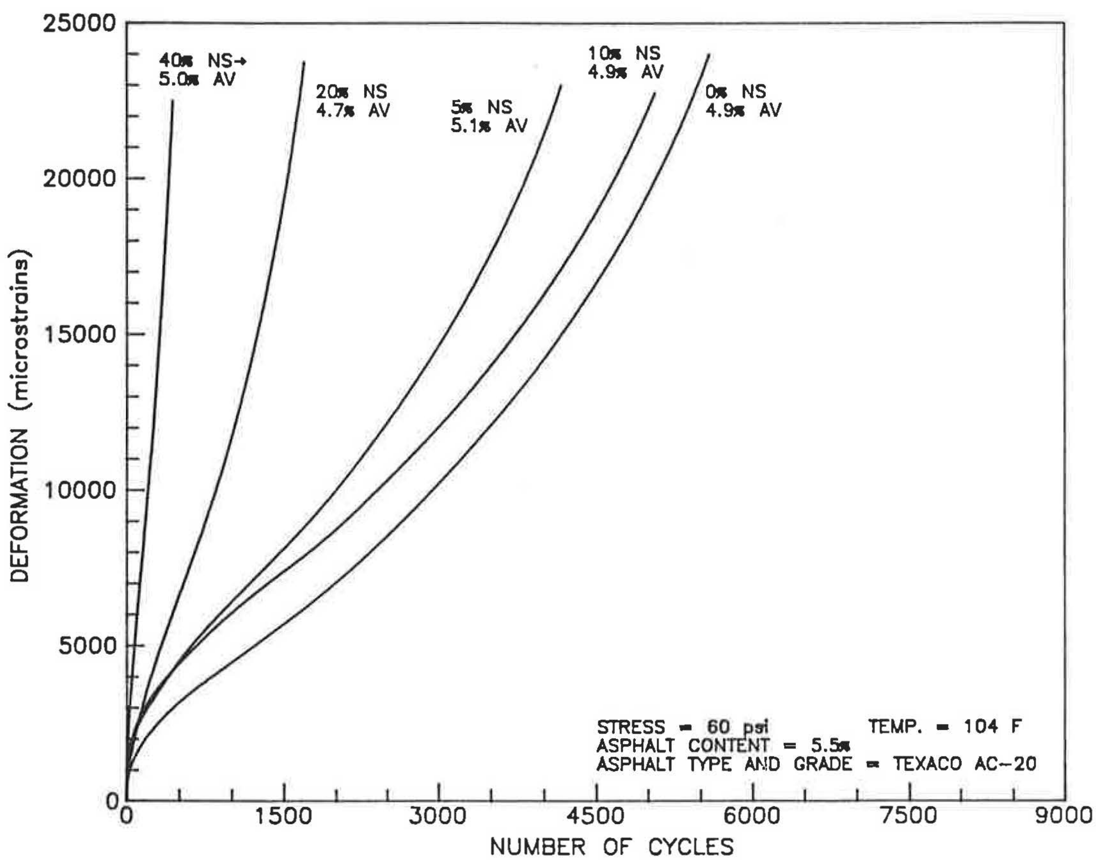

FIGURE 8 Response to permanent deformation (dynamic test) for five different mixes at high air void content (NS, natural sand; AV, air voids).

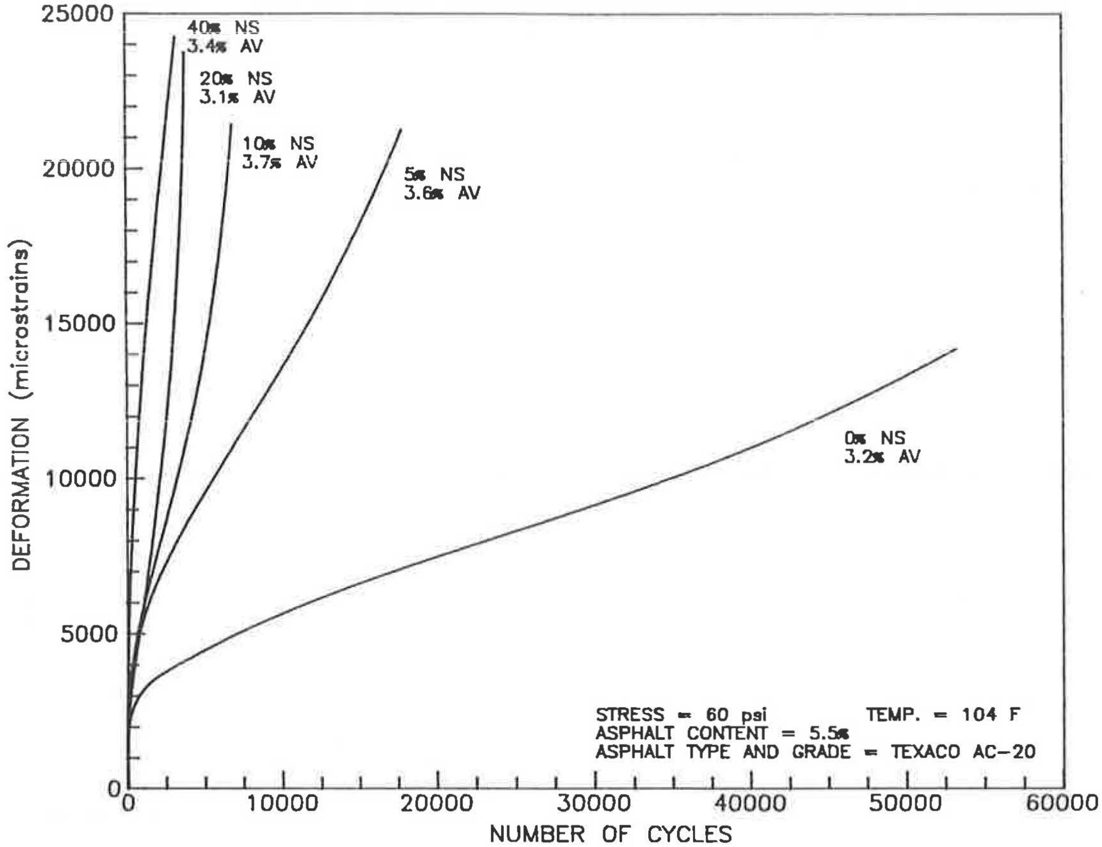

FIGURE 9 Response to permanent deformation (dynamic test) for five different mixes at low air void content (NS, natural sand; AV, air voids).

content for the gravel mixture was 3.5 percent and for the limestone mixture was 4.5 percent. These were special laboratory mixtures, which were composed of a very dense gradation. The mixture containing the rounded gravel consistently exhibited more sensitivity to asphalt content and temperature changes than the mixture containing crushed limestone. This has also been demonstrated by Kalcheff (*15*) and others.

Engineering properties of mixtures containing higher proportions of uncrushed particles (river gravel and 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 "framework." They depend less on the binder or mastic for shear strength.

Interpretation of Laboratory Results

Replacement of natural sand particles by manufactured sand particles (crushed stone) increases the resistance of the asphalt pavement to permanent deformation. This replacement implies changes in the final mix design. Some of these changes are (a) increased asphalt content owing to greater specific surface area and greater absorption of asphalt by some manufactured particles and (b) increased air void content and VMA of compacted mixtures owing to the angular shape and surface texture of the manufactured particles.

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

1. 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.
2. Workability will suffer, but it may be possible to use other design or construction procedures, or both, to minimize this potential problem.

Earlier work (*15–17*) has also indicated 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 (*18*), Lai (*19*), Tam and Lynch (*20*), and many others.

Replacement of field sand with washed screenings will, of course, increase the 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.

CONCLUSIONS

1. The field investigation indicated that the chief mixture deficiencies contributing to rutting were excessive asphalt con-

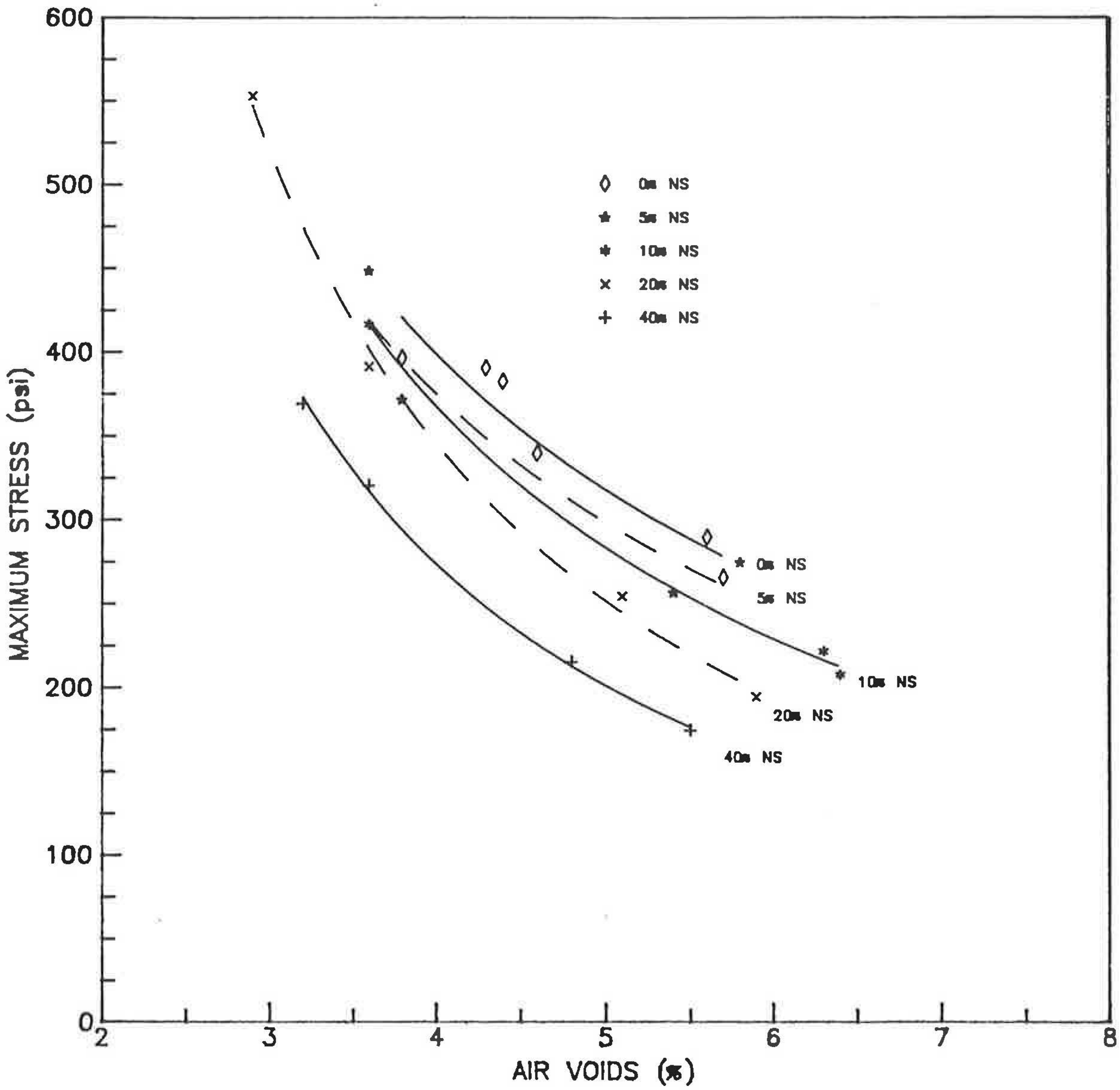

FIGURE 10 Response to unconfined compression testing for five different mixes as a function of air void content (NS, natural sand; AV, air voids).

tent, excessive fine aggregate (sand-size particles), and the round shape and smooth texture of the natural (uncrushed) aggregate particles.

2. Asphalt content of a paving mixture should not be arbitrarily increased to facilitate compaction or achieve the required density.

3. Results of the laboratory investigation (Figures 6 through 8) indicate that the asphalt mixtures containing some natural (rounded) sands plastically deform under static or dynamic loads much more readily than similarly graded mixtures containing only manufactured (crushed) particles. Certain natural sands with subangular particle shapes or rough surface textures, or both, may be available in certain locations. These are much more desirable than those with rounded, smooth particles. Examination of sand particles under the microscope and elimination of the undesirable materials from asphalt mixtures will reduce the potential for rutting.

4. The *p*-value represents a new approach in which the aggregate properties are included in the theoretical analysis of the creep-recovery test.

5. Particle index mix values indicate a significant influence on the performance of the mixture under permanent deformation tests, providing a direct measure of mixture susceptibility to rutting.

6. Highway-specifying agencies should consider limiting the natural (uncrushed) particle content of asphalt mixes in high volume pavement facilities to about 10 to 15 percent, depending on other characteristics of the mix.

7. The literature review revealed that rutting has been successfully addressed by using large top-size crushed aggregate (1 to 1½ in.), increasing voids in mineral aggregate requirements (14 to 15 percent minimum), replacing most or all 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. A properly designed asphalt paving mixture transmits loads through an interlocked aggregate framework. It does not depend on the asphalt or the mastic for shear strength.

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