



KTC-90-12

LARGE-STONE MIXES FOR REDUCING RUTTING

**Southeastern Consortium of University Transportation Centers
(SECUTC)
Kentucky Transportation Center
University of Kentucky**

Final Report

by

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EXECUTIVE SUMMARY

Large-stone mixes are becoming a very popular means for reducing rutting in flexible pavements. Aggregate interlock in large-stone mixes provides for very efficient dissipation of compressive and shear stresses that are known to be responsible for rutting and shoving in flexible pavements. This report documents mix design procedures and laboratory testing for characterization of rutting potential of large-stone asphalt mixes (LSAM) in Kentucky and particularly the Louisa Bypass project.

~~A series of~~ large-stone aggregate gradations were studied. A promising aggregate gradation was selected in cooperation with Kentucky Department of Highway officials and representatives of the asphalt industry. Based upon the findings of this study, several test sections were constructed on coal-haul corridors throughout the Commonwealth of Kentucky. LSAM sections have been in service for less than one year, and conclusions on the performance of these mixes would be premature. It is important, however, to note that conventional asphalt mixtures on pavements subjected to heavy truck traffic in Kentucky usually exhibit severe rutting after only a few months in service. In this respect, one may conclude that LSAM projects have performed well. Performance-oriented laboratory test results indicate that higher levels of structural capacity and rutting resistance, as compared to conventional hot mix asphalt, may be achieved by using the LSAM in flexible pavements. A field trial followed the laboratory investigations. Construction of the Louisa Bypass, which is located in the mountainous region of eastern Kentucky, was studied. Recommendations presented in this report for construction of Large-stone mixes in heavy haul roads are based upon information obtained from the Louisa Bypass.

INTRODUCTION

Today, pavement engineers are challenged to use conventional methods to design cost effective pavements that are expected to withstand unconventional wheel loads and tire pressures. Additional emphasis by many state agencies on post construction ride quality, as a check for quality control, has contributed to contractors' high regard for mixture handling and workability rather than long-term mixture performance. One may ask the following question: are we designing asphalt mixtures that are easy to handle so we may mold them in the laboratory using the available equipment, or are we designing our mixtures for performance while maintaining an open attitude for progress with regard to some of our conventional design methods?

Highway agencies are faced with the challenge of designing asphalt pavements using traditional design methodologies that do not account for heavy truck loads and high tire pressures.

Large-stone asphalt mixtures (LSAM) are gaining popularity among highway agencies that are charged with designing heavy duty asphalt pavements. LSAM develops strength by the stress bridging effect of larger aggregate and stone-to-stone contact.

Pavement designers in Kentucky accepted the challenge of designing and constructing a mix that would accommodate heavy and severe highway loads. A task force was formed to address the design and construction of a heavy duty hot mix. That task force was composed of representatives of the Kentucky Department of Highways (DOH), Kentucky Plantmix Asphalt Industry, Kentucky Transportation Center at the University of Kentucky, Asphalt Institute, National Asphalt Pavement Association, Chevron USA Inc., and Ashland Oil Co.

The task force recommended that alterations in the aggregate gradations could provide more stone-to-stone contact, higher stress resistance (especially shear stress), and thereby yield needed improvements in rutting and shoving resistance.

AGGREGATE GRADATION ANALYSES

The coarse aggregates used in this study were obtained from Plum Run, Ohio. All aggregates were crushed limestone from the same quarry. The average gradations for these aggregates were supplied by the quarry and are listed in Table 1. Unless otherwise noted, the aggregate gradation data are based on dry-sieve analyses. Two sand fractions were used in these analyses. The first was a natural washed sand from Plum Run, Ohio. The second sand was a crushed limestone sand from Kenmore, Kentucky.

Initially, eleven gradations were considered for laboratory testing. Each gradation was made by blending two or three coarse aggregates and one sand fraction. The

blended gradations were within the Kentucky Class K specification limits. Figure 1 illustrates the Kentucky specification limits (1) for Class K large-stone mix.

After a thorough review of the literature and the state-of-the-art on design and construction of LSAM (2-8), several discussions were held with representatives of the asphalt industry and personnel of Kentucky Department of Highways (DOH). It was decided to test only Blends 1, 1a, 2a, and 5a. Gradation distribution of those blends are depicted in Figure 2. Aggregate blends were selected to represent two groups: aggregate blends containing all crushed sand (Blends: 1a, 2a, and 5a) and an aggregate blend containing all natural sand (Blend: 1). The following sections present results of a detailed mixture study that was conducted on the Louisa Bypass project.

MARSHALL MIX DESIGN

In order to accommodate LSAM's aggregate size, 6-inch diameter modified Marshall specimens were compacted in the laboratory using a 22.5-lb hammer. This was partially based upon earlier work conducted by the Pennsylvania Department of Transportation (9) using 3.75 inches as the target height. Based upon the ratio of volume to compactive effort, 112 blows of a 22.5-lb hammer on a 6-inch diameter specimen is equivalent to 75 blows of a 10-lb hammer on a 4-inch diameter specimen, and this was used as an interim guide for laboratory compaction of LSAM by the Kentucky DOH.

A comparison of density and air voids data obtained from LSAM cores (6-inch diameter by 12-inch height) and the laboratory compacted specimens (6-inch diameter by 3.75-inch height, and 6-inch diameter by 12-inch height) was made to verify the compaction efficiency of the modified 6-inch Marshall method. The 6-inch diameter by 12-inch high LSAM specimens were compacted in three 4-inch lifts based on weight/volume relationships and a sufficient number of 22.5-lb blows to yield densities similar to the 6-inch diameter by 3.75-inch high specimens. Results are presented in Figures 3 and 4 which demonstrate that target densities and air voids may be readily achieved using the modified 6-inch Marshall method. The laboratory compaction procedures produced higher densities and lower air voids. The 6-inch diameter by 12-inch high pavement cores and laboratory manufactured specimens were later tested for creep and permanent deformation.

The first trial specimen was compacted at 135 blows per side in an effort to obtain high stability. Compaction was equivalent to 88 blows per side on a 4-inch diameter standard Marshall specimen which resulted in a relatively high density (approximately 150 pounds per cubic foot) and a low void content; however, considerable particle crushing occurred. All remaining 6-inch diameter specimens were compacted at 112 blows per side. Marshall mix design data are summarized in Table 2. From the mixture stability point of view, Blend 1a was recommended as the gradation of choice for large-stone construction in Kentucky (10).

One can say the 6-inch Marshall should not include particles that are larger than 1.125 inches when considering similitude of the standard 4-inch Marshall specimen that may contain top-size aggregate of 0.75 inch, which may appear as a point of concern regarding the type of LSAM that was used in Kentucky (Class K top-size: 1.5-inch). This is a minor concern since at least 95 percent of the Class K particles pass the 1.5-inch sieve.

Realizing that not all bituminous laboratories have 6-inch diameter Marshall molds and testing capabilities, the U.S. Corps of Engineers (11) recommended a procedure by which large particles (larger than 1-inch diameter) are removed from the gradation and replaced with particles ranging from 3/4-inch and up to 1-inch. This procedure was used on both 4-inch and 6-inch diameter specimens and results are presented in Table 3. These data suggest that mix variables such as density, air voids, voids in the mineral aggregate (VMA), and flow were only slightly affected by this procedure. The mixture stability, however, exhibited a pronounced sensitivity to the Corps of Engineers large aggregate replacement procedure. It is therefore recommended not to alter the gradation of LSAM in order to satisfy the requirements of the 4-inch diameter Marshall test, unless verifiable stability correlations are available for the Corps of Engineers gradation adjustment procedure.

COMPRESSIVE STRENGTH

In addition to the conventional stability and flow tests, a series of mechanistic tests were conducted in order to obtain data for defining the fundamental mechanical deformation characteristics of LSAM. Tests included compressive strength, creep and permanent deformation, and resilient modulus.

It was decided to conduct a limited sensitivity study since there was a lack of sufficient data on the effectiveness of the modified Marshall mix design procedure as compared to other mix design procedures. The objective of this limited study was to quantify the sensitivity of the strength and deformation characteristics of the Kentucky Class K mix to variations in asphalt content and method of compaction. Three methods of compaction used were: 6-inch modified Marshall, vibratory, and kneading.

The unconfined compression test is often used as an index test for determining the resistance of an asphaltic mixture to shear flow and permanent deformation; i.e, rutting and shoving. In this study, the compressive strength tests were conducted by personnel at the Asphalt Institute. Specimens were 6 inches in diameter and 6 inches in height. Unconfined compressive tests were conducted at 77°F and 0.05 inch per minute rate of loading. These data are presented in Figure 5. The data suggest that the method of laboratory compaction has a significant influence on the compressive strength of LSAM.

It is clear that the modified Marshall compacted specimens were sensitive to variations in asphalt content. That attribute is desirable for mix design purposes. A moderate peak in the LSAM compressive strength occurs in the neighborhood of the optimum asphalt content.

RESILIENT MODULUS

Elastic modulus is a measure of a material's response to load and deformation. Modulus of elasticity relates the forces causing deformation to actual deformation. In pavement technology, the resilient modulus has long been used as a surrogate parameter for elastic modulus because it lends itself to relatively simple testing procedures. For pavement design and analysis purposes, generally, higher moduli indicate more resistance to deformation, deflection, and longer pavement life. A high modulus surface and/or base layer will also protect the subgrade from being overstressed, should reduce the probability of subgrade failure.

Characterization of the LSAM from a structural point of view was of great interest to Transportation Cabinet officials. Resilient modulus tests were conducted at various temperatures to better understand the potential structural benefits of the LSAM. Chevron U.S.A., Inc., in Richmond, California, participated in the resilient modulus testing program. The resilient modulus data for a range of temperatures are summarized in Figure 6. The data indicate that an LSAM pavement layer offers a higher level of structural capacity as compared to a conventional hot mix asphalt (HMA) layer of the same thickness. Large-stone mixes may be very cost competitive in terms of their added structural capacity combined with their lower optimum asphalt content.

STATIC AND DYNAMIC CREEP

The Kentucky Transportation Center at University of Kentucky conducted several creep tests on 6-inch diameter by 12-inch high pavement cores and laboratory compacted specimens of the same dimensions at 104°F. This mechanistic methodology is often used for characterizing permanent deformation. Both static and dynamic (cyclic repeated-load) creep tests were conducted at 29 psi. The static creep test consisted of monitoring the creep strain for one hour under a constant load of 29 psi. Dynamic creep tests were conducted under repeated-load, square-shaped pulses at 1-Hertz. The resilient and permanent components of deformation were recorded. The data from both static and dynamic tests were merged in order to study permanent deformation characteristics of LSAM under static and dynamic modes. This was possible under the assumption of linear viscoelasticity. For example, the cumulative creep deformation caused by a set of ten, 1-Hertz, load pulses was assumed to be equivalent to the creep deformation caused by ten seconds of static creep load. The merged data are presented in Figure 7. The trends in Figure 7 indicate that laboratory specimens which were compacted using the modified Marshall hammer are less prone to permanent deformation than the LSAM

pavement cores. This is due to the fact that higher densities are more readily achievable under laboratory conditions. The large-stone Class K was less susceptible to permanent deformation than the conventional Class I mix.

The stone-to-stone contact of aggregate particles in the LSAM reduces the probability of plastic flow due to low air voids and/or high densities. Mix design criteria that are commonly applied to conventional HMA should be re-examined before extrapolating them to LSAM design situations. The observation that the method of laboratory compaction significantly influences the mechanical behavior of the LSAM is consistent with the compressive strength data presented in Figure 5.

CONSTRUCTION OF THE LOUISA BYPASS

The Kentucky Department of Highways selected several coal haul sections for field testing of an experimental LSAM.

The Louisa Bypass on U.S. 23 in Lawrence County (3.7 miles, 4 lanes) is a newly constructed pavement located deep within the heart of coal country in eastern Kentucky. The original subgrade (CBR 4) was modified and upgraded with eight inches of granular subbase for half of the project's length, and shale subbase was used for the remaining half. Shale was used due to an on site shortage of rock during the subgrade and subbase construction. The variation in the subbase material provides an opportunity to evaluate long-term performance variation due to the structural arrangement. The pavement was originally intended to be a Full Depth Asphalt structure; however, due to the presence of shale in the subgrade, which is prone to rapid strength deterioration, it was decided to include a granular subbase layer. The subbase layer consisted of four inches of dense-graded aggregate (DGA) covered with four inches of an open graded, large-stone drainage layer.

Twelve inches of LSAM base was constructed on top of the subbase layer in three 4-inch lifts. A one-inch surface wearing course completed the project. Asphalt grade AC-20 was used for half of the project and the asphalt in the surface wearing course was modified with a polymer. The other half had a polymerized surface wearing course. The use of polymerized asphalt was part of the Transportation Cabinet's experiments with modified asphalts.

The following items are the result of numerous observations that were made during construction of the LSAM. Some of these points may apply to all types of hot mix asphalt (HMA) construction; however, in many instances, large-stone mixes are more sensitive to construction errors than their conventional counterparts (12). It is extremely important to maintain close technical supervision over mix design, plant mixing, mix laydown, and compaction operations during the construction of LSAM.

Mix Design

The 6-inch diameter by 3.75-inch thick modified Marshall method of mix design (9) was adopted by the Kentucky DOH. There are several factors that contribute to a successful LSAM mix design.

- 1- Adequate asphalt film thickness (9-11 microns) is necessary for workability and durability. This is controlled by the asphalt content and percent mineral filler in the aggregate. In conventional HMA construction, asphalt film thickness ranges from 6 to 8 microns and fine materials act as asphalt extenders (13). A thicker film thickness is desirable to assist compaction of rather harsh LSAM mixtures.
- 2- Percent voids in the mineral aggregate (VMA) must be sufficient to accommodate the desired film thickness at maximum field density without excessive reduction in air voids. The VMA of Kentucky LSAM was 11.5 percent which is consistent with the widely accepted criterion set by the Asphalt Institute (14) and the National Asphalt Pavement Association (3).
- 3- Laboratory compaction of 6-inch diameter by 3.75-inch high Marshall specimens may be achieved at 112 blows per side using a 22.5-pound Marshall hammer (9, 15, 16). Densities achieved in the laboratory may be closely duplicated in construction, see Figure 3.
- 4- Air voids should be in the range of 3.5 to 5.5 percent with the average being 4.5 percent. This range will minimize both air and water permeabilities. Figure 4 illustrates the variations in the air void content of laboratory and field specimens.

Plant Mixing

- 1- Plant mixing time may need to be adjusted slightly for LSAM. A longer mixing time, as compared to conventional HMA, may be necessary to assure coating of larger aggregate particles.
- 2- Mixing the LSAM did not induce unusual wear upon the plant mixing equipment.
- 3- Careful attention to aggregate feeding and mixture handling to avoid segregation is essential. Cone formation and the resulting segregation of aggregate and mixture may be avoided by multiple material drops; this will minimize segregation.

Laydown Operations

There are several important laydown operational details that may be used to minimize segregation in the LSAM.

- 1- Coarse particles accumulating in the paver wings should be discarded and never be incorporated into the flow of mix to the screen hopper.
- 2- Mixture in the receiving hopper bed should be maintained at a minimum depth of 18 to 24 inches to prevent accumulated coarse particles from reaching the slat conveyor.
- 3- The receiving hopper gates should be set to provide as nearly continuous flow of the mixture as possible. A continuous operation of the distribution augers at full capacity is required to ensure mass movement of material for the entire screed.
- 4- Paver speed should be regulated to accommodate the mixture production and transport rates. Avoiding "stop-and-go" in the paver operation reduces segregation, improves the texture of spread, and eliminates any tendency for screed settlement (15-17).
- 5- A minimum lift thickness of 3.5 inches will minimize the effect of large aggregate boundary restrictions.

Compaction Operations

- 1- Although most LSAM gradations are very coarse graded and tend to be harsh, required density may readily be achieved through proper use of a variety of suitable conventional compaction equipment (15-16).
- 2- Primary compaction should commence immediately after mixture spreading. Density may readily be achieved at compaction temperatures ranging from 250°F to 300°F. Compaction at lower temperatures requires considerable increase in roller coverage and is not recommended. Lateral displacement of this rather harsh mix was not a problem. A successful compaction sequence included the following: (a) two passes of a vibratory roller in the static mode for breakdown rolling, (b) six passes of a vibratory roller at high frequency and low amplitude for primary compaction, (c) four passes of a pneumatic roller to complete compaction, and (d) two passes of a static roller to smooth the surface.

- 3- Since the stone-to-stone contact structure of LSAM may produce high point stresses of large aggregate particles during compaction, the frequency and amplitude of the vibratory roller may need to be adjusted to reduce particle breakage and optimize compaction. This is especially true whenever relatively rigid bases (Kentucky Mountain Parkway LSAM overlay on broken and seated portland cement concrete project) are encountered.

Quality Control

- 1- Quality control should be used in the construction of LSAM in order to ensure adherence to design parameters such as aggregate gradation, asphalt content, density, and air void content. Moving averages should be maintained and used as the basis for evaluating variability of mixture parameters. A schematic of the concept of moving averages that is recommended for quality control is presented in Figure 8.
- 2- Asphalt extraction and gradation tests should be conducted on as large quantities of LSAM material as equipment will permit so that samples will be representative of the bulk material. Total daily mixture output of the plant and asphalt cement tonnage is a convenient and relatively accurate way of determining the average daily asphalt content in lieu of time consuming extraction tests.
- 3- Compaction pattern is a function of equipment that is available at the site. The pattern should be established initially by construction of a test section (at least 500-ft long and 12-ft wide). Construction of a control strip is also useful for detecting potential segregation problems. Rolling patterns and coverages that are required to produce the desired density should be maintained throughout the job. Target density on the job was based upon 93 to 94 percent of solid volume (i.e. 6 to 7 percent air void). Control range was set at 92 to 97 percent of solid volume.
- 4- Field density evaluations should be made frequently to assure that the compaction procedure is adequate. If the desired density is not being achieved, adjustments to roller coverage should be made. If large adjustments are required, a new test section should be constructed.

LONG-TERM PERFORMANCE MONITORING

The Louisa Bypass has been in service for approximately six months. Plans have been made to monitor the long-term performance of this projects under Project KYHPR-85-107, Subtask 19. Figure 9 is a schematic of the Louisa Bypass. Several inter-layer thin metal strips were placed between the 4-inch LSAM lifts. Borescope holes will be drilled at those locations each year and contribution of each layer to the overall rutting will be measured.

IMPLEMENTATION

Findings of this study have been implemented on an interim basis by Kentucky Transportation Cabinet in the form of tentative specifications for design of Class K large-stone asphalt mixtures.

CONCLUSIONS AND RECOMMENDATIONS

Large-stone asphalt mixes (LSAM) offer a number of desirable properties for heavy duty asphalt pavements. The LSAM properties that receive high marks include stability, compressive strength, resilient modulus, and creep, all of which contribute to a more rut resistant asphalt mixture. Large-stone mixes offer higher structural capacity at lower optimum asphalt content compared to conventional mixes rendering them cost competitive. It was demonstrated that desired densities and air voids could be readily achieved using a modified Marshall laboratory compaction procedure.

It is recommended that large-stone gradations, such as Kentucky Class K, be used in heavy duty hot mix asphalt (HMA) construction. The laboratory method of compaction has a significant influence upon the mechanical properties of HMA. A standard method of laboratory compaction which would simulate the field compaction is needed.

Experience in Kentucky indicates that large stone asphalt mixes (LSAM) may be designed and constructed with minimum modification to the existing design and construction procedures. Special attention should be devoted to plant and paver operations for reducing the probability of segregation. Lift thickness should not be reduced below 3.5 inches (for 1.5-inch top size gradation) in order to insure adequate degrees of freedom for particle reorientation during compaction. Current construction equipment and procedures are appropriate for LSAM. Careful attention to production and construction details is essential to providing a uniform mixture and an effectively constructed LSAM pavement layer.

Mix design and construction procedures for LSAM are not been fully developed yet. Additional work based upon the 6-inch diameter modified Marshall procedure is needed to standardize laboratory procedures for specimen preparation and testing.

ACKNOWLEDGMENT

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TABLE 1. AGGREGATE GRADATION.

Source	Percent Passing				
	Plum Run				Kenmore ¹
Sieve	No. 4	No. 56	No. 78	Sand	Sand
2"	100				
1 1/2"	95	100			
1"	26	87			
3/4"	9	61	100		
1/2"	2	25	94		
3/8"	1	7	70		
4		3	11	100	92
8			3	88	72
16				58	52
30				34	44
50				19	36
100				8	25
200				4	16

(1) Wet Sieve Analysis.

**TABLE 2. MIX DESIGN PARAMETERS FOR TWO KENTUCKY LSAM PROJECTS:
LOUISA BYPASS AND MOUNTAIN PARKWAY.**

Mix Parameter¹	Louisa Bypass	Mountain Parkway	Criteria
Stability, lb.	5,300	5,900	3,000 (min)
Flow, 0.01 in.	16	19	28 (max)
Air Voids, %	3.6	4.4	3.5-5.5
VMA, %	13.1	13.0	11.5 (min)
Retained Tensile Strength, %	Pass	Pass	70

- (1) Data are based upon 6 inch diameter by 3.75 inch thick modified Marshall, specimens were compacted at 112 blows per side using a 22.5-lb. hammer.

TABLE 3. SUMMARY OF MARSHALL MIX DESIGN DATA.

Mix Parameter	Aggregate Blends					
	1	1a	2a	5a	1a ²	1a ³
Stability, lb.	5,100	5,000	5,200	4,500	4,100	2,850
Flow, 0.01 in.	22	20.5	26.5	23	20	14
Air Voids, %	5	4.7	4.3	4	4.3	4.5
VMA, %	12.6	11.5	12.2	14.5	12.4	13.2

- (1) Data are based on 6-inch diameter by 3.75-inch thick modified Marshall specimens compacted at 112 blows per side using a 22.5-lb. hammer, unless otherwise indicated.
- (2) U.S. Army Corps of Engineers, Method 103 (11), 6-inch mold, 112 blows.
- (3) U.S. Army Corps of Engineers, Method 103 (11), 4-inch mold, 112 blows.

GRADATION OF CLASS K BASE

SIEVE SIZES RAISED TO 0.45 POWER

..... Lower Limit — Upper Limit

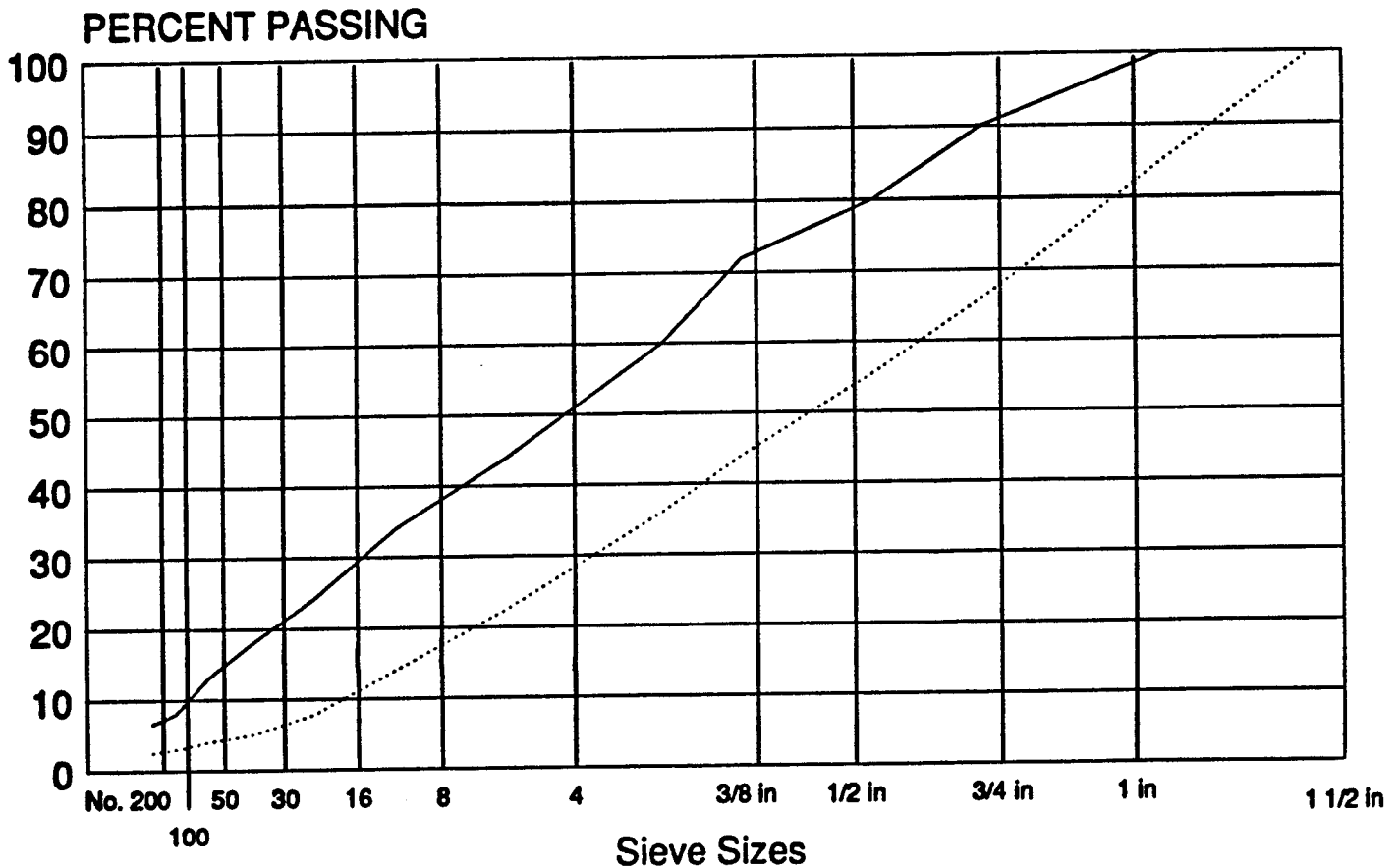


FIGURE 1. GRADATION SPECIFICATION LIMITS FOR KENTUCKY CLASS K.

GRADATION OF LAB TEST MIXTURES

SIEVE SIZES RAISED TO 0.45 POWER

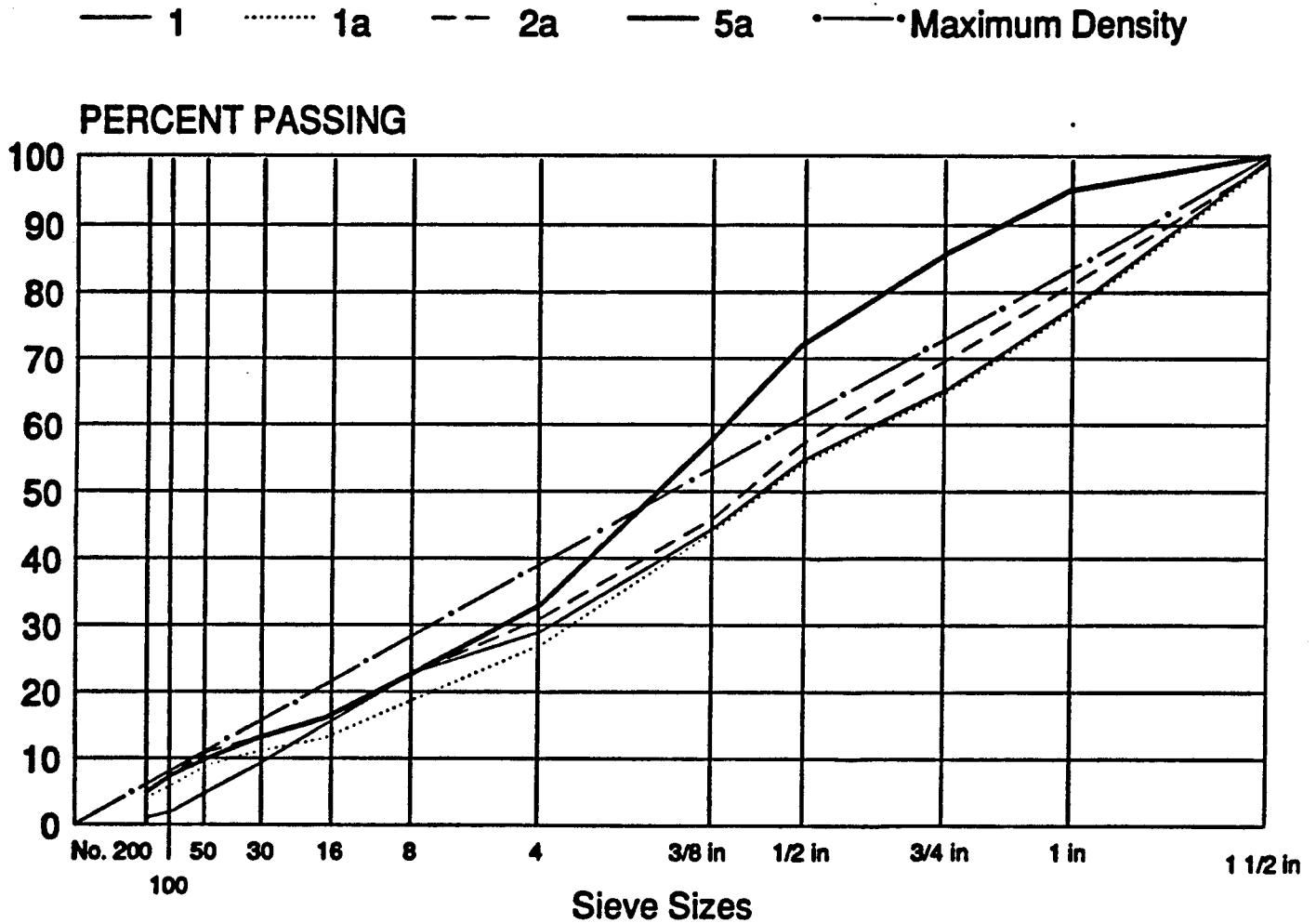


FIGURE 2. TRIAL LARGE-STONE GRADATIONS.

DENSITY

Core Versus Marshall

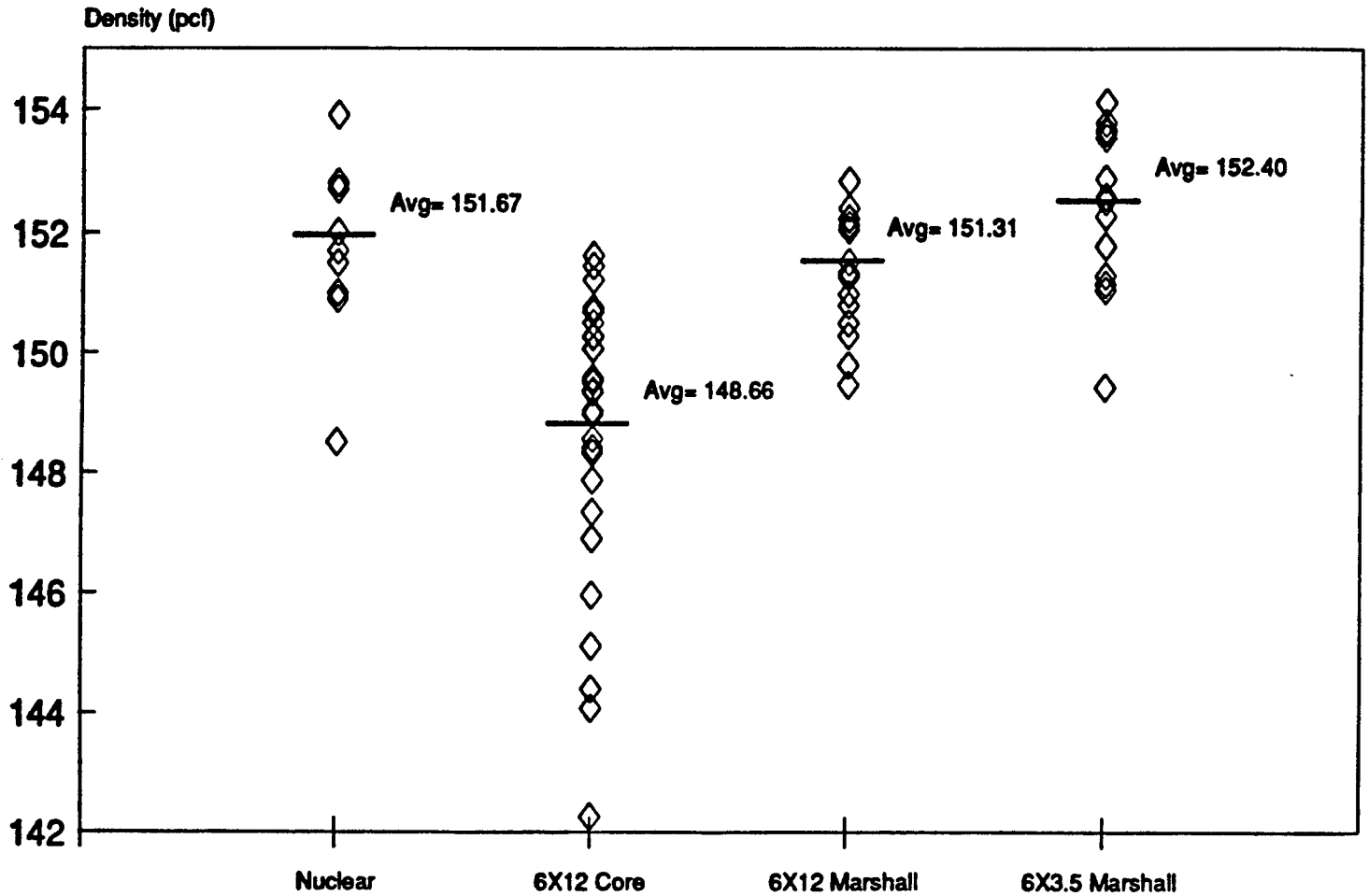


FIGURE 3. LABORATORY AND FIELD DENSITY DATA FOR LARGE-STONE MIXES.

PERCENT AIR VOID

CORE VERSUS MARSHALL

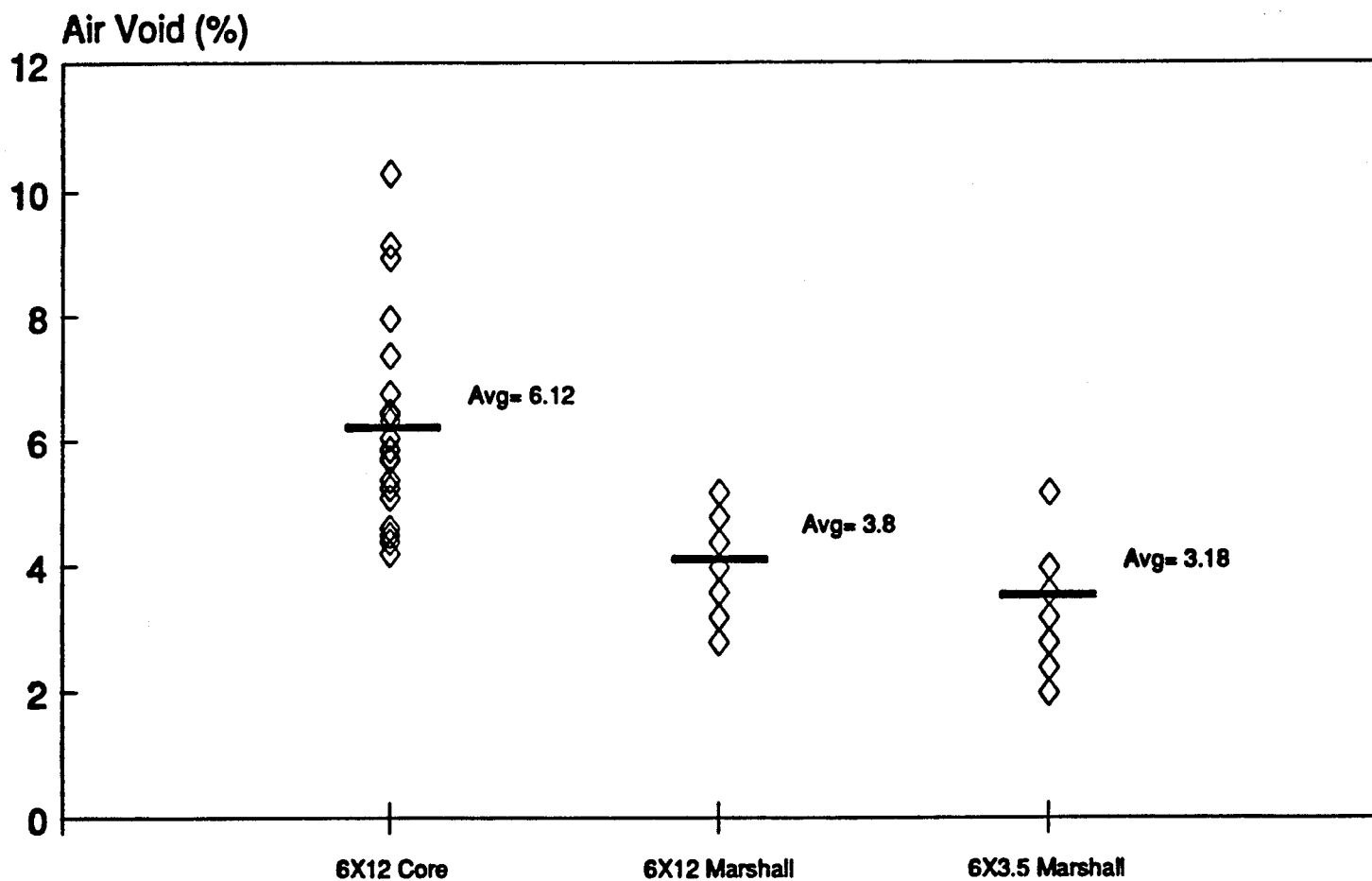


FIGURE 4. LABORATORY AND FIELD AIR VOIDS DATA FOR LARGE-STONE MIXES.

COMPRESSIVE STRENGTH AND METHOD OF COMPACTION

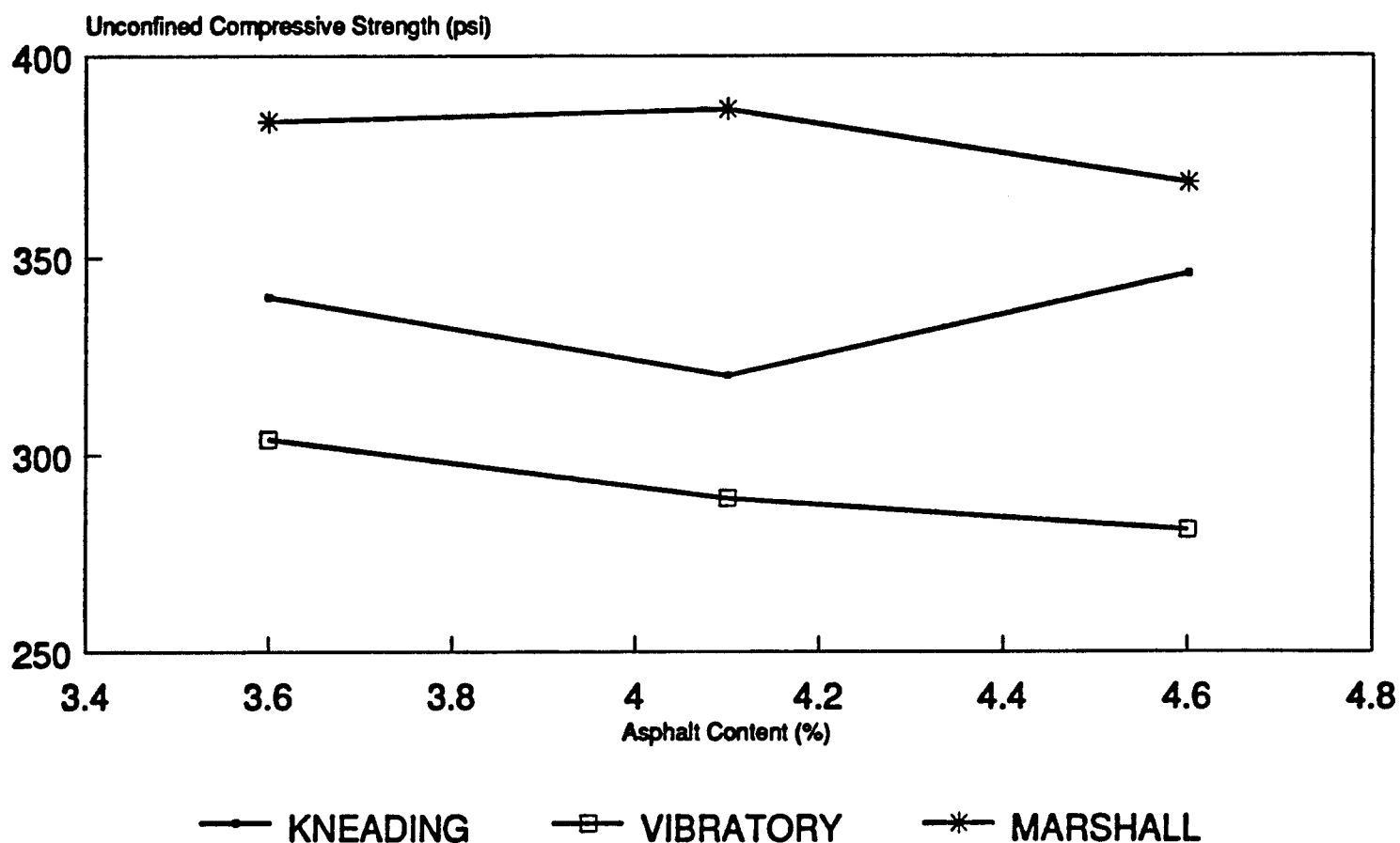


FIGURE 5. COMPRESSIVE STRENGTH AS A FUNCTION OF ASPHALT CONTENT AND METHOD OF COMPACTION FOR LARGE-STONE ASPHALT MIXES.

RESILIENT MODULUS

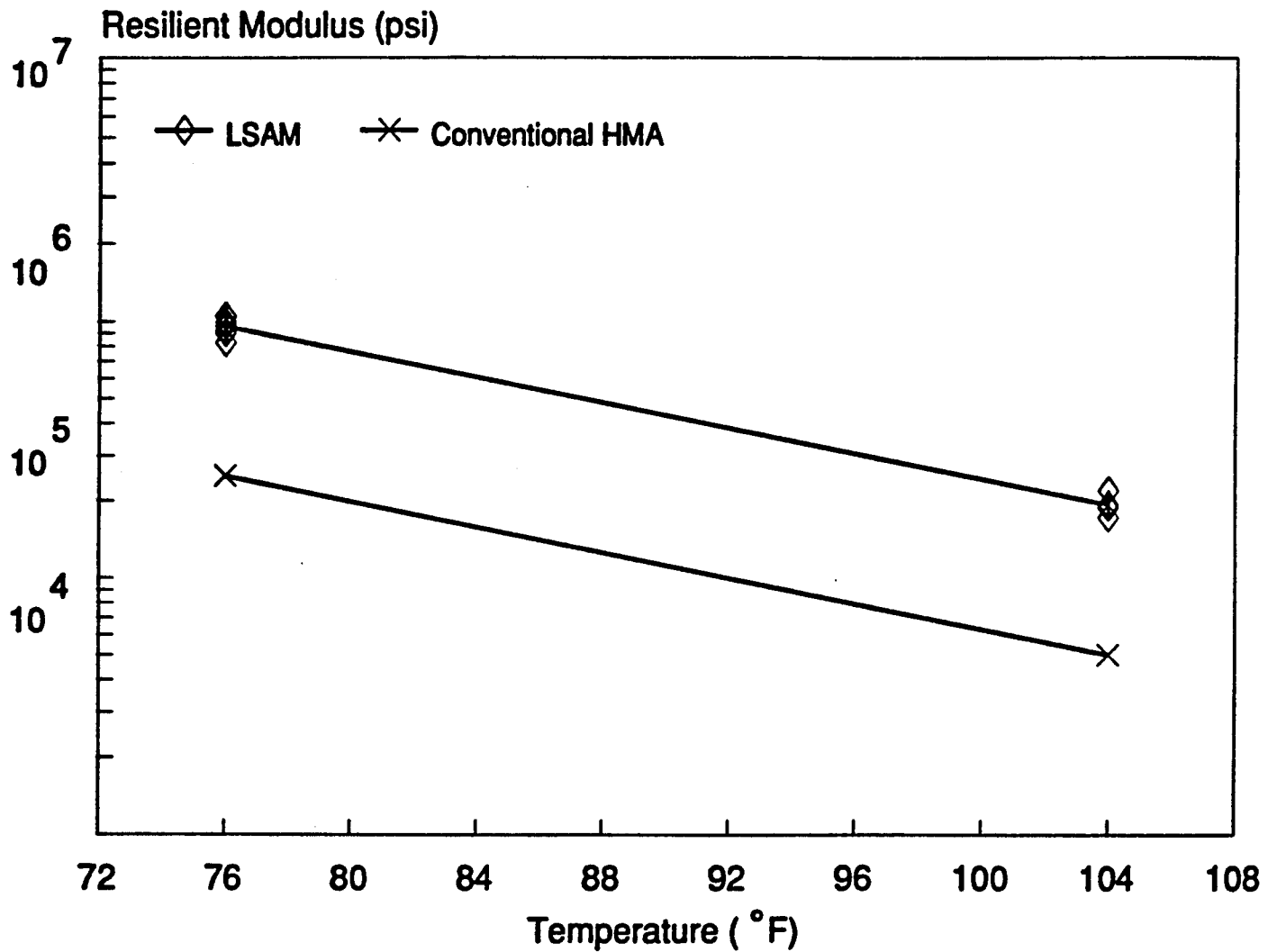


FIGURE 6. RESILIENT MODULUS AS A FUNCTION OF TEMPERATURE.

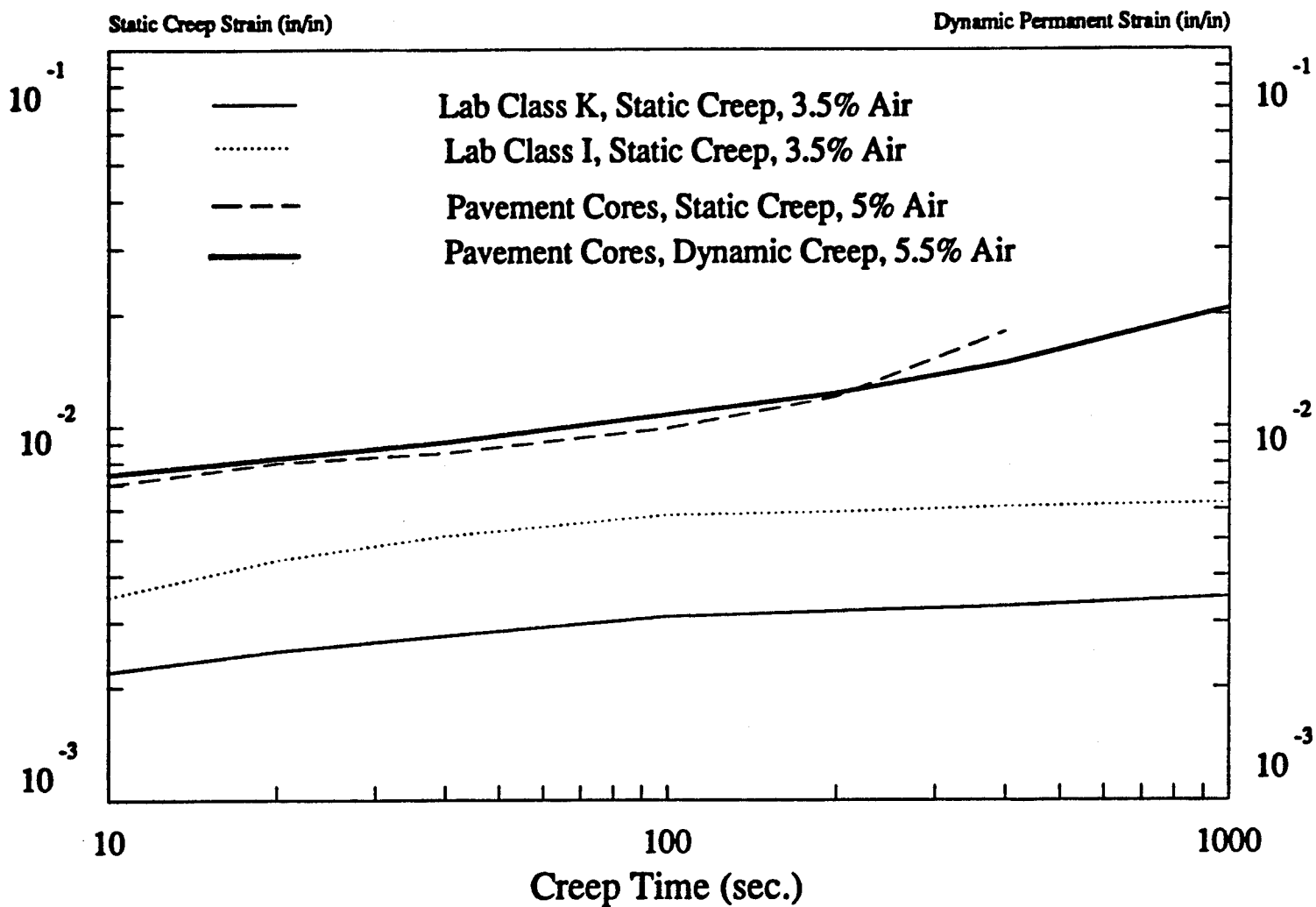


FIGURE 7. CREEP AND PERMANENT DEFORMATION DATA FOR LABORATORY AND FIELD SPECIMENS AT 104°F.

MOVING AVERAGE

QUALITY CONTROL PARAMETER

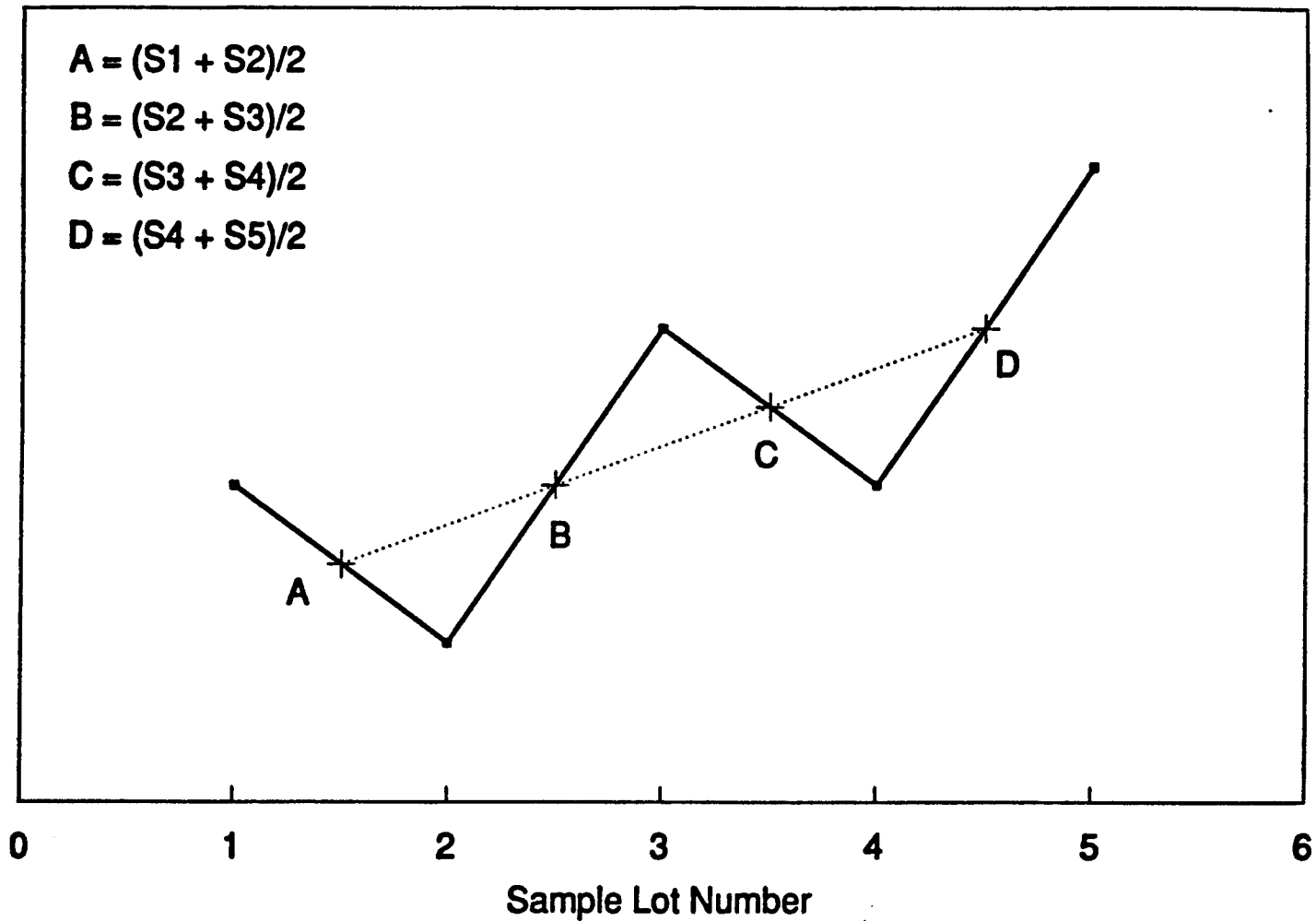


FIGURE 8. SCHEMATIC REPRESENTATION OF THE MOVING AVERAGE CONCEPT.

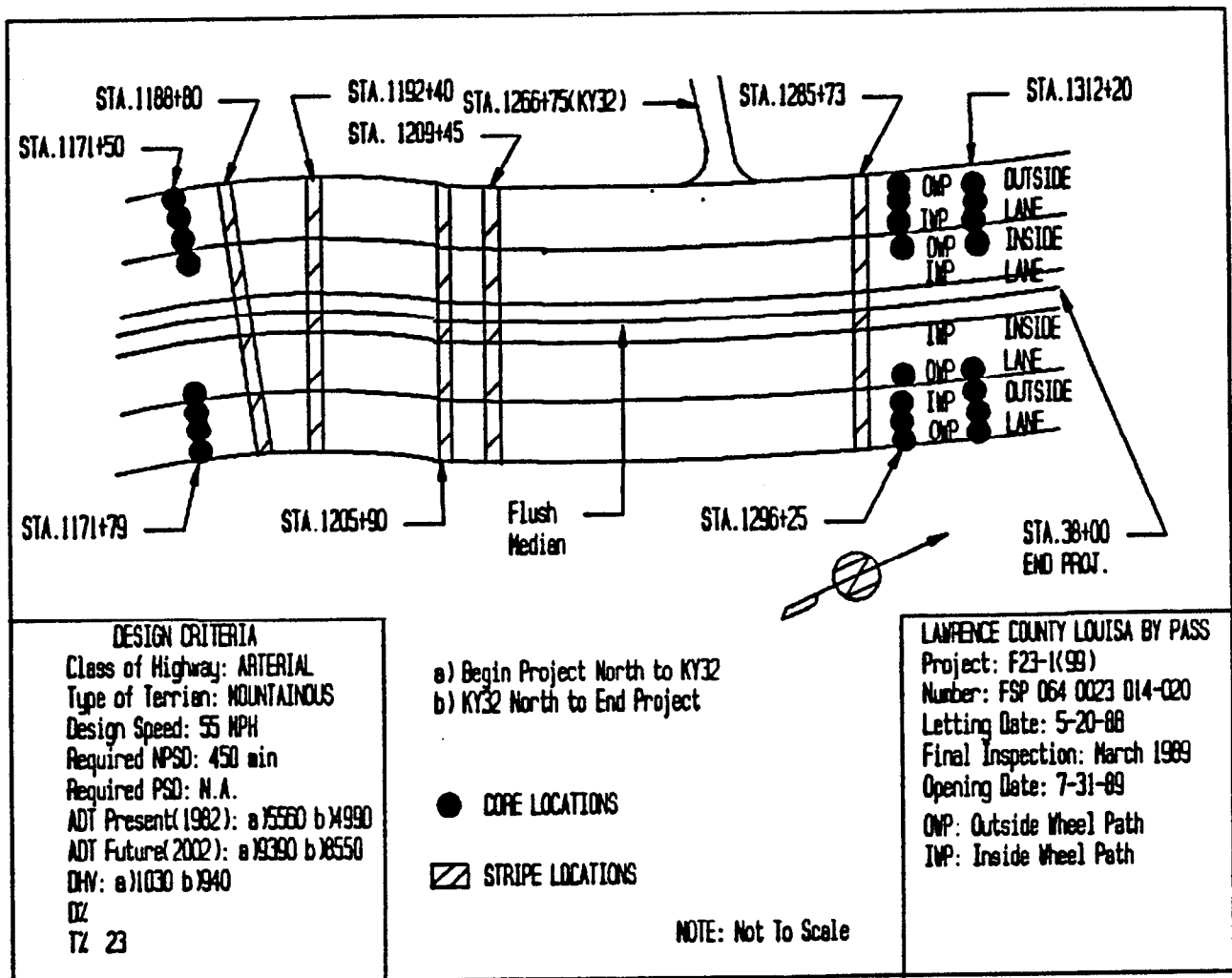


FIGURE 9. SCHEMATIC OF THE LOUISA BYPASS PROJECT.