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# Marginal Aggregates in Flexible Pavements: Laboratory Evaluation

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Final Report

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The U.S. Army Engineer Waterways Experiment Station conducted this study as part of the Inter-Agency Agreement Project "Durability Criteria for Airport Pavements." The FAA William J. Hughes Technical Center COTR: Dr. Xiaogong Lee

**16. Abstract**


The purpose of this project was to evaluate the utilization of substandard or marginal aggregates in flexible airport pavement construction. This investigation was undertaken to evaluate the effects of using lower quality aggregates such as rounded uncrushed gravels and sands on the rutting of flexible pavements. The scope of this research project included a review of available literature and existing data (Part I), a laboratory evaluation organized to determine the effects of marginal aggregates and potential techniques to upgrade these substandard materials (Part II), and a field evaluation of these upgraded marginal aggregate asphalt mixtures (Part III).

This report summarizes the laboratory evaluation, Part II of the project. The laboratory investigation focused on three areas: (1) aggregate characterization, (2) evaluation of asphalt mixture properties affecting rutting potential and pavement performance, and (3) upgrading marginal aggregate asphalt mixtures with hard asphalt cements and various asphalt modifications.

The findings of this laboratory evaluation indicated that several test methods including the Particle Index, Uncompacted Void Content of Fine Aggregate, Unit Weight and Voids in Aggregate, and Gyratory Elasto-Plastic Index could be used to quantitatively characterize aggregate shape and texture. This laboratory study also demonstrated that the confined repeated load deformation (triaxial creep) test was successful in evaluating the rutting characteristics of asphalt mixtures. The laboratory data demonstrated that asphalt modification could improve the rutting characteristics of asphalt mixtures with marginal aggregates.


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# PREFACE

This report was sponsored by the U.S. Department of Transportation, Federal Aviation Administration (FAA) under Inter-Agency Agreement No. DTFA01-90-Z-02069, "Durability Criteria for Airport Pavements." The study was performed by the Airfields and Pavements Division (APD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, during the period October 1990 to August 1994. Dr. Xiaogong Lee was the FAA William J. Hughes Technical Center Technical Monitor.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL; and Dr. G. M. Hammitt II, former Chief, APD. This report was prepared under the direct supervision of Mr. T. W. Vollor, Chief, Materials Analysis Branch, APD. APD personnel engaged in the laboratory testing included Messrs. Bill Burke, Jerry Duncan, Roosevelt Felix, Herbert McKnight, and Joey Simmons. Instrumentation Services Division (ISD) support was provided by Mr. Tommy Carr and Ms. August Williamson. The project's Principal Investigator and author of this report was Dr. Randy C. Ahlrich.

The Director of WES during the preparation and publication of this report was Dr. Robert W. Whalin. The Commander and Deputy Director was COL Bruce K. Howard, EN.

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## EXECUTIVE SUMMARY

High-quality aggregates are becoming increasingly scarce and expensive in many areas. Current airport flexible pavement specifications require high-quality aggregates in asphalt concrete mixtures. In an increasing number of cases, locally available aggregates are not meeting applicable specifications, and high-quality aggregates that meet the specifications are being imported to the construction site.

The use of marginal aggregates in flexible pavement construction is one of the possible answers to the lack of high-quality aggregate sources. This research study determined in engineering terms the impact of using marginal aggregates in asphalt concrete mixtures for airport pavements.

The purpose of this study was to evaluate the utilization of marginal aggregate asphalt mixtures and to determine if poor-quality aggregates could be improved to provide equivalent and acceptable pavement performance.

This report summarizes the laboratory evaluation that was conducted to determine the effects of aggregate shape, texture, and gradation on the performance of asphalt concrete mixtures. The laboratory investigation focused on three areas: (1) aggregate characterization tests, (2) evaluation of asphalt mixture properties effecting rutting potential, and (3) upgrading marginal aggregate asphalt mixtures with asphalt modification.

The findings of the laboratory evaluation indicated that several test methods including the Particle Index (ASTM D 3398), Uncompacted Void Content for Fine and Coarse Aggregates (NAA Method), Unit Weight and Voids in Aggregate (ASTM C29), and Gyratory Elasto-Plastic Index (ASTM D 3397) could be used to quantitatively characterize aggregate shape and texture. This laboratory study also demonstrated that the confined repeated load deformation (triaxial creep) test was successful in evaluating the rutting characteristics of asphalt mixtures. The laboratory data also demonstrated that asphalt modification could improve rutting characteristics of asphalt mixtures with marginal aggregates.

Based on the findings of this laboratory investigation, the following recommendations were made: (1) current FAA specifications could be improved by implementing performance-related aggregate characterization properties determined by Particle Index test and the NAA and modified NAA particle shape and texture tests, (2) current FAA specifications should be modified and shifted to include finer gradations, (3) the confined repeated load deformation test should be used in conjunction with current FAA specifications to analyze rutting potential of asphalt mixtures, and (4) asphalt modification can be used to improve rutting characteristics of asphalt mixtures.

# INTRODUCTION

## BACKGROUND.

High-quality aggregates are becoming increasingly scarce and expensive in many localities. Traditional flexible pavement specifications require high-quality aggregates in asphalt concrete mixtures for airport flexible pavements. In an increasing number of cases, locally available aggregates are not meeting applicable specifications, and aggregates that meet the specifications must be imported to the site at considerable expense [1].

The use of marginal aggregates in flexible pavement construction is one of the possible answers to high pavement construction costs and a lack of quality aggregate sources. A broad definition of a marginal aggregate is "any aggregate that is not normally usable because it does not have the characteristics required by the specification, but could be used successfully by modifying normal pavement design and construction procedures" [2]. For this study, marginal or substandard aggregates are defined as aggregates that do not meet the Federal Aviation Administration's (FAA) specification requirements for airport pavements.

Using local available marginal materials is often very tempting, but the decision to use or reject these materials should be made only after a complete evaluation. The decision should be based on an evaluation of the material characteristics and how these characteristics will affect the design, performance, and construction of the pavement. Potential problem areas must be clearly identified or any expected cost savings will be lost [3].

Current FAA specifications were developed at times when high quality aggregates were readily available. However, this is no longer the case in many areas. This study will attempt to define in engineering terms the impact of using marginal aggregates in asphalt concrete mixtures for flexible pavements. Strategies for improving the performance of marginal aggregates to equal that of standard aggregates will be evaluated.

## PURPOSE.

The purpose of the research study was to evaluate the utilization of marginal aggregates in flexible pavement construction for airport pavements. Marginal aggregates have been defined as aggregates that do not meet FAA specification requirements. The current FAA guidance for airport pavement construction is provided in FAA Advisory Circular AC-150/5370-10A, "Standards for Specifying Construction of Airports" [4]. Specific requirements for asphalt concrete mixtures are provided in Item P-401 (Plant Mix Bituminous Pavements). Marginal aggregates can have one or more of the following deficiencies: improper gradation, lack of fractured faces, flat and elongated particles, high natural sand content, high Los Angeles (LA) abrasion and soundness values, and excessive amounts of No. 200 material. This research will determine if marginal aggregates can provide equivalent or acceptable pavement performance with an emphasis on pavement deformation and rutting.

OBJECTIVES.

The research documented in this report was executed to achieve the following objectives:

1. Evaluate and determine suitable methods or tests to characterize aggregate shape and texture to improve aggregate specifications as it relates to pavement rutting.

2. Determine boundaries for aggregate gradation bands, limits for percent crushed particles, and maximum amounts of natural sand materials.

3. Evaluate laboratory asphalt mixture tests and procedures to determine effects of aggregate quality on asphalt mixture performance.

4. Determine potential of hard asphalt cement and asphalt modifiers to upgrade marginal aggregate asphalt mixtures to produce equivalent, acceptable pavement performance.

SCOPE.

The overall research study for marginal aggregates in flexible pavements was conducted in three phases. Part I was a review of available literature and existing data. Based on the literature review, a laboratory study (Part II) was conducted using poor quality aggregates that do not meet FAA requirements. The marginal aggregates were compared to proven, accepted aggregate to evaluate the effectiveness of these materials in asphalt concrete mixtures for flexible pavements. The final phase, Part III, took the concepts and techniques using marginal aggregates that had the greatest potential and evaluated these materials in field test sections. These field test sections were trafficked with aircraft loads and tire pressures, monitored, and evaluated to determine the performance of the marginal aggregates.

This report summarizes the laboratory evaluation (Part II) that was conducted to determine the effects of aggregate shape, texture, and gradation on the performance of asphalt concrete mixtures for airport pavements. The laboratory investigation focused on three areas: (1) aggregate characterization, (2) evaluation of asphalt mixture properties effecting rutting potential and pavement performance, and (3) upgrading marginal aggregate asphalt mixtures with a hard asphalt cement and asphalt modification. The details of laboratory evaluation are presented and discussed in the "Experimental Plan" section.

## EXPERIMENTAL PLAN

This study attempted to define in engineering terms the impact of using marginal aggregates in asphalt concrete mixtures for flexible airport pavements. Basically, the laboratory study determined how much the asphalt concrete mixture's strength had been reduced by using marginal aggregates and determined the success of strategies to improve the performance of these mixtures with marginal aggregates to equal that of accepted standard mixtures. As directed by the FAA, the major emphasis was on the use of marginal aggregates in asphalt concrete mixtures and the potential of upgrading these mixtures with stiffer, modified asphalt binders.

Item P-401 (Plant Mix Bituminous Pavements) provides the FAA requirements for asphalt concrete mixtures. This specification requires a high quality, durable, clean, well-graded, crushed aggregate. The laboratory testing considered the effects of departure from the requirements of the specification for the standard 3/4 inch maximum aggregate size gradation, the percentage of crushed aggregate particles, the amount of natural sand, and the amount of material smaller than the No. 200 sieve. The other standard aggregate requirements that are specified by Item P-401, LA Abrasion (ASTM C 131), sulfate soundness (ASTM C 88) and flat and elongated (ASTM D 4791) tests, were not examined because these tests do not correlate particularly well with pavement deformation or rutting and field performance [5, 6]. Previous laboratory research and field investigations have indicated that poorly graded aggregate gradations, uncrushed particles, too much natural sand and excessive amounts of material smaller than the No. 200 sieve produce less than acceptable asphalt concrete mixtures and are susceptible to pavement deformation [7, 8, 9, 10].

The aggregate sources for this laboratory evaluation included limestone, crushed and uncrushed gravel and sand materials. The limestone aggregate met the requirements of Item P-401 and served as the accepted high-quality aggregate. Uncrushed gravel and sand materials were used as the low-quality, marginal aggregate. All lab stock aggregate materials were evaluated with the following tests:

- Percent Crushed Particles.
- Gradation.
- Absorption.
- Specific Gravity.

The aggregates from each source were processed by screening to develop laboratory stock. These processed materials were used to fabricate the specific test gradations. These test gradations were selected to determine the effects of variation in aggregate gradation (shape of gradation curve), amount of crushed particles in coarse aggregate (0, 30, 50, 70, 100 percent), and the amount of natural sand material in the aggregate blend (0, 10, 20, 30, 40 percent). The description and designation of the test gradations evaluated in the marginal aggregate laboratory study are listed in table 1. The numerical values for these test gradations are presented in table 2 and shown graphically on semi-log and 0.45 power maximum density gradation curves in appendix A.

TABLE 1. DESCRIPTION AND DESIGNATION OF MARGINAL AGGREGATE BLENDS

| Mix Designation | Description |
|---|---|
| Mix 1 | Center of FAA gradation band/Crushed limestone |
| Mix 2 | Coarse side (lower limit) of FAA band/Crushed limestone and fine sand |
| Mix 3 | Fine side (upper limit) of FAA band/Crushed limestone and fine sand |
| Mix 4 | Poorly graded No. 1/Crushed limestone and fine sand |
| Mix 5 | Finely graded No. 1/Crushed limestone, fine sand and coarse sand |
| Mix 6 | Excessive Fines No. 1/Crushed limestone and fine sand |
| Mix 7 | Poorly graded No. 2/Crushed limestone and fine sand |
| Mix 8 | Poorly graded No. 3/Crushed limestone and fine sand |
| Mix 9 | Crushed gravel with 10% coarse sand |
| Mix 10 | Crushed gravel with 20% coarse sand |
| Mix 11 | Crushed gravel with 30% coarse sand |
| Mix 12 | Crushed gravel with 40% coarse sand |
| Mix 13 | Center of FAA gradation band/Crushed gravel |
| Mix 14 | Center of FAA gradation band/Uncrushed gravel |
| Mix 15 | Uncrushed gravel with 10% coarse sand |
| Mix 16 | Uncrushed gravel with 20% coarse sand |
| Mix 17 | Uncrushed gravel with 30% coarse sand |
| Mix 18 | Uncrushed gravel with 40% coarse sand |
| Mix 19 | Center of FAA gradation band - gravel/Coarse (uncrushed)/Fine (crushed) |
| Mix 20 | Center of FAA gradation band - gravel/<br>Coarse (70% crushed - 30% uncrushed)/Fine (crushed) |
| Mix 21 | Center of FAA gradation band - gravel/<br>Coarse (50% crushed - 50% uncrushed)/Fine (crushed) |
| Mix 22 | Center of FAA gradation band - gravel/<br>Coarse (30% crushed - 70% uncrushed)/Fine (crushed) |

TABLE 2. AGGREGATE GRADATIONS FOR MARGINAL AGGREGATE LABORATORY STUDY

| Mix Number | Sieve sizes (percent passing) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3/4 in. | 1/2 in. | 3/8 in. | No. 4 | No. 8 | No. 16 | No. 30 | No. 50 | No. 100 | No. 200 |
| 1 | 100 | 89.9 | 77.4 | 57.0 | 44.5 | 28.3 | 23.0 | 15.6 | 8.4 | 5.6 |
| 2 | 100 | 79.8 | 62.4 | 42.7 | 32.2 | 18.0 | 14.0 | 9.1 | 5.2 | 2.6 |
| 3 | 100 | 99.1 | 87.6 | 67.8 | 56.0 | 39.0 | 32.9 | 23.9 | 13.9 | 6.9 |
| 4 | 100 | 80.7 | 67.9 | 48.1 | 43.3 | 38.0 | 31.0 | 22.3 | 13.0 | 4.8 |
| 5 | 100 | 94.1 | 88.4 | 76.7 | 66.5 | 50.3 | 42.0 | 27.3 | 13.8 | 7.4 |
| 6 | 100 | 99.1 | 87.6 | 67.7 | 55.3 | 37.9 | 31.3 | 20.9 | 14.7 | 10.7 |
| 7 | 100 | 69.9 | 64.1 | 63.9 | 54.8 | 38.0 | 31.7 | 22.7 | 13.0 | 6.3 |
| 8 | 100 | 79.8 | 62.4 | 42.8 | 35.3 | 25.6 | 22.7 | 21.2 | 16.2 | 5.8 |
| 9 | 100 | 88.7 | 77.7 | 58.1 | 42.1 | 33.1 | 24.5 | 13.1 | 9.0 | 4.0 |
| 10 | 100 | 88.7 | 77.6 | 57.8 | 42.2 | 35.4 | 28.9 | 13.0 | 8.6 | 3.7 |
| 11 | 100 | 88.7 | 77.6 | 57.5 | 43.9 | 39.7 | 33.7 | 12.9 | 8.2 | 3.5 |
| 12 | 100 | 88.7 | 77.6 | 57.3 | 44.8 | 42.1 | 36.6 | 11.0 | 6.8 | 3.4 |
| 13 | 100 | 88.7 | 77.7 | 58.4 | 42.1 | 30.7 | 23.2 | 15.9 | 10.8 | 4.6 |
| 14 | 100 | 89.2 | 78.2 | 57.5 | 44.0 | 26.3 | 24.2 | 14.7 | 9.5 | 4.0 |
| 15 | 100 | 89.2 | 78.2 | 57.3 | 44.7 | 31.9 | 29.2 | 13.4 | 8.7 | 4.2 |
| 16 | 100 | 89.2 | 78.1 | 57.0 | 44.7 | 37.6 | 34.3 | 15.3 | 9.5 | 3.4 |
| 17 | 100 | 89.2 | 78.1 | 56.7 | 44.9 | 40.4 | 36.0 | 14.1 | 8.6 | 3.4 |
| 18 | 100 | 89.2 | 78.1 | 56.5 | 46.7 | 44.6 | 39.1 | 13.1 | 8.4 | 3.2 |
| 19 | 100 | 88.5 | 77.9 | 58.0 | 42.0 | 30.7 | 23.2 | 15.9 | 10.8 | 4.6 |
| 20 | 100 | 88.5 | 77.9 | 58.0 | 42.0 | 30.7 | 23.2 | 15.9 | 10.8 | 4.6 |
| 21 | 100 | 88.5 | 77.9 | 58.0 | 42.0 | 30.7 | 23.2 | 15.9 | 10.8 | 4.6 |
| 22 | 100 | 88.5 | 77.9 | 58.0 | 42.0 | 30.7 | 23.2 | 15.9 | 10.8 | 4.6 |
| FAA limits | 100 | 79-99 | 68-88 | 48-68 | 33-53 | 20-40 | 14-30 | 9-21 | 6-16 | 3-6 |

The marginal aggregate laboratory study included three phases, as outlined below and illustrated by the flow chart in figure 1.

1. Phase I—Aggregate characterization of coarse and fine aggregate fractions for each of the twenty-two selected aggregate blends.

2. Phase II—Preparation and evaluation of twenty-two asphalt mixtures produced with AC-20.

3. Phase III—Preparation and evaluation of ten selected aggregate blends produced with AC-40, AC-20 modified with styrene-butadiene-styrene (SBS), and AC-20 modified with low-density polyethylene (LDPE) (total of thirty mixtures).

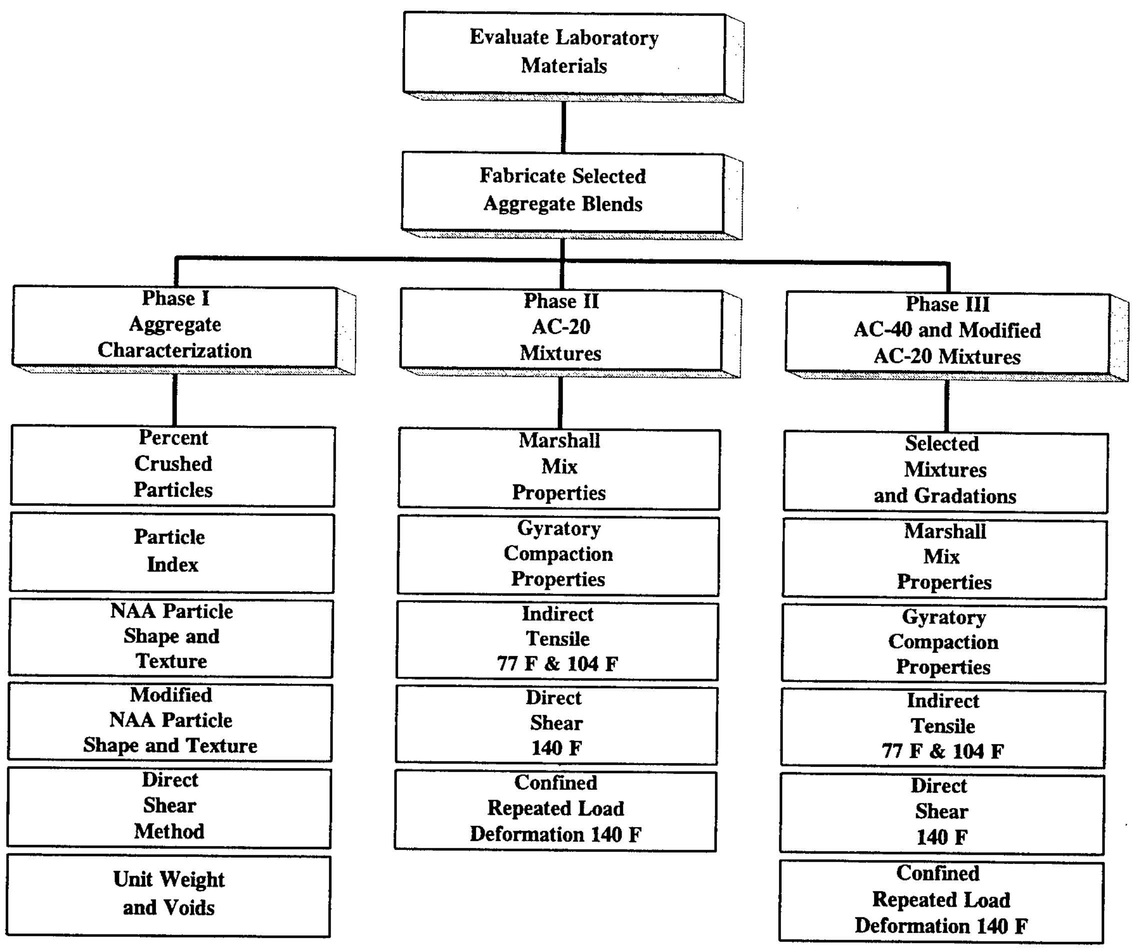


FIGURE 1. MARGINAL AGGREGATE LABORATORY STUDY TEST PLAN

PHASE I—AGGREGATE CHARACTERIZATION.

After the lab stock materials were tested and fabricated to meet the desired test aggregate gradations, each blend was evaluated to characterize the particle shape and surface texture. Each blend was separated on the No. 4 sieve so that the coarse and fine aggregate fractions could be evaluated. The following tests were conducted on each of the 22 aggregate blends:

- Coarse Aggregate (+ No. 4)
  - Percent Crushed Particles
  - Particle Index - ASTM D3398
  - Unit Weight and Voids - ASTM C29
  - Modified NAA Particle Shape and Texture

- Fine Aggregate (- No. 4)
  - Percent Crushed Particles
  - Particle Index - ASTM D3398
  - Direct Shear - EM 1110-2-1906
  - NAA Particle Shape and Texture

PHASE II—AC-20 MIXTURES.

This phase involved the preparation and testing of asphalt mixtures produced with AC-20. A Marshall mix design was conducted on each test gradation aggregate blend and an optimum asphalt content was selected at 4 percent air voids using a gyratory compactive effort equivalent to a 75 blow compactive effort. The details of the gyratory compaction are discussed in the following section. The following laboratory tests were conducted to evaluate engineering properties of each asphalt concrete mixture at the optimum asphalt content:

- Marshall Mix Properties.
- Gyratory Compaction Properties.
- Indirect Tensile (77°F and 104°F).
- Direct Shear (140°F).
- Confined Repeated Load Deformation (140°F).

Details and descriptions of each test procedure are presented and discussed in the following section. This laboratory testing determined the range of mix properties that would be expected using material meeting the P-401 specification and the impact of deviations on engineering properties by using marginal aggregates.

PHASE III—AC-40 AND MODIFIED AC-20 MIXTURES.

This phase involved the preparation and testing of ten selected aggregate blends with an AC-40 and two AC-20 modified asphalts. The asphalt modifiers used in this laboratory study were a

SBS and a LDPE. A Marshall mix design was conducted for each mixture in order to select an optimum asphalt at 4 percent air voids. The same engineering property tests that were conducted in Phase II were also conducted on these specimen. This phase of laboratory testing would determine the effectiveness of stiffer asphalt cements and asphalt modification to improve the strength or rutting characteristics of asphalt mixtures with marginal aggregates.

## MATERIALS, TEST EQUIPMENT, AND PROCEDURES

### MATERIALS.

The primary objectives of this study were to quantify the aggregate particle characteristics, to evaluate the relationship between these aggregate properties and the rutting potential of marginal aggregate asphalt mixtures, and to determine the potential of asphalt modification to improve the rutting characteristics of marginal aggregate asphalt mixtures. In order to achieve these goals, this laboratory testing program had to include several variables:

- Aggregate gradation.
- Type of aggregate.
- Type of asphalt binder.
- Percentage of crushed particles.
- Percentage of natural sand.
- Type of aggregate characterization test.
- Type of asphalt concrete mixture test.

AGGREGATES. This laboratory study incorporated the use of three coarse aggregates (crushed limestone, crushed gravel, and uncrushed gravel) and five fine aggregates (crushed limestone, crushed gravel, uncrushed gravel, coarse natural sand, and fine natural sand). Each of these aggregate materials, except for the natural sand materials were processed by screening into individual sieve sizes in order to accurately fabricate the desired test gradations. Each aggregate type was considered nonabsorptive and had low average absorption values (limestone - 0.2 percent, gravel - 1.4 percent, and natural sands - 0.5 percent). The aggregate materials used in this laboratory study had been previously used and evaluated in other research studies. The test results for LA Abrasion, soundness, and flat and elongated particles meet the Item P-401 requirements.

ASPHALT BINDERS. This laboratory study incorporated the use of four asphalt binder materials. Since the primary goal or objective of Phase II of this laboratory study was to investigate the influence of aggregate gradation and particle shape on the strength and rutting characteristics of asphalt concrete mixtures, an AC-20 asphalt cement was selected because it is very common asphalt cement and would not interfere with evaluating the aggregate properties. The physical properties for the AC-20 asphalt cement are presented in table 3. The primary purpose of Phase III of this laboratory study was to determine the effectiveness of harder asphalt cements and modified binders to improve the strength and rutting characteristics of asphalt concrete mixtures with marginal aggregates. For this phase of the laboratory study, an AC-40, an AC-20 modified with 5 percent SBS, and an AC-20 modified with 6 percent LDPE were mixed with ten selected aggregate blends. The physical properties of these materials are also presented in table 3.

TABLE 3. PHYSICAL PROPERTIES OF ASPHALT BINDER MATERIALS

| Test | AC-20 | AC-40 | AC-20 + SBS | AC-20 + LDPE |
|---|---|---|---|---|
| Viscosity - absolute, 140°F, P | 2246 | 3595 | 25,963 | 11,016 |
| Viscosity - kinematic, 275°F, cSt | 492 | 346 | 1878 | 731 |
| Penetration - 77°F, 100 g, 5 sec, 0.1 mm | 75 | 30 | 48 | 56 |
| Flash point - Cleveland Open Cup, °F | 550 | 547 | 534 | 547 |
| Test on residue from thin film oven test | | | | |
| Percent weight loss | 0.48 | 0.00 | 0.11 | 0.13 |
| Viscosity - 140°F, P | 6602 | 6907 | 21,820 | 13,251 |
| Ductility - 77°F, 5 cm/min, cm | 71 | 150 | 143 | 39 |

## TESTS FOR CHARACTERIZING AGGREGATES.

Characterization of aggregate particles has been done by various tests and methods in the past. The characterization of aggregate shape (angularity) and surface texture (roughness) is essential in selecting aggregates to produce high quality asphalt mixtures for heavy duty pavements. Based on the findings from the literature review [11], the test methods and procedures used to evaluate and characterize the coarse and fine aggregates of each aggregate blend are listed in table 4. The laboratory equipment and test procedures used in this laboratory study are described and discussed in the following paragraphs.

TABLE 4. AGGREGATE CHARACTERIZATION TESTS

| Coarse Aggregate | Fine Aggregate |
|---|---|
| Percent crushed particles | Percent crushed particles |
| Index of aggregate particle shape and texture | Index of aggregate particle shape and texture |
| Unit weight and voids | Direct shear |
| Modified NAA particle shape and texture | NAA particle shape and texture |

PERCENT CRUSHED PARTICLES. This test method is a procedure for determining the percentage of crushed or fractured particles in an aggregate sample by visual inspection. This method is currently being proposed as an American Society for Testing and Materials (ASTM) standardized test method. This method involves subjectively separating crushed or fractured aggregate particles from uncrushed aggregate particles. The percentage of crushed particles is expressed by weight or count. A crushed particle is defined as an aggregate particle that has at least two mechanically induced fractured faces.

The lab stock materials used in this laboratory study were either 100 percent crushed limestone and crushed gravel or 100 percent uncrushed gravel and uncrushed natural sand. Since each aggregate blend was fabricated with individual sieve sizes of these lab stock materials, the percent crushed particles (composite, coarse, fine) and natural sand contents could be determined from batch weights instead of by visual inspection. Calculating the percent crushed particles in this matter eliminated the human error by eliminating the subjectivity and personal judgment.

INDEX OF AGGREGATE PARTICLE SHAPE AND TEXTURE. The Particle Index test was originally developed by Huang for the evaluation of coarse aggregates for a soil-aggregate material [12]. This test was based on the concept that the aggregate void characteristics would indicate the characteristics of the aggregate's shape, angularity, and surface texture for a one-sized aggregate. The original test procedure and equipment have been modified and standardized by ASTM in Test Method D 3398 [13].

The equipment required is simple consisting of cylindrical steel molds ranging in diameters from 2 to 8 in. depending on the aggregate size. This test method requires that the aggregate sample be separated into individual sieve fractions and washed and oven-dried. Each size fraction is separately compacted in three equal lifts in the cylindrical mold using a tamping rod. This compaction is applied with two efforts, 10 and 50 drops per layer. Each tamp is dropped from a height of 2 in. above the surface of the layer being compacted. The percent voids in the aggregates for each compactive effort is calculated using the weight of the aggregate in the cylindrical mold and the bulk gravity of the aggregate. Based on the percentages of voids at 10 and 50 drops, the Particle Index value of an aggregate is calculated using the following equation:

$$Ia = 1.25\, V_{10} - 0.25\, V_{50} - 32.0 \tag{1}$$

where

$Ia$ = Particle Index value
$V_{10}$ = percent voids with 10 drops per layer
$V_{50}$ = percent voids with 50 drops per layer

The weighted Particle Index value for an aggregate blend having multiple aggregate sizes is computed on the basis of the weight percentage of each size fraction in the aggregate gradation. In the case where a sieve size is represented by less than 10 percent of the grading, the average Particle Index value for the next coarser and finer size is used.

NAA PARTICLE SHAPE AND TEXTURE. This test method has recently been adopted by ASTM (Test Method C 1252) but was developed by the National Aggregate Association (NAA) as a simple practical routine test to measure aggregate particle shape and surface texture of fine aggregate (material smaller than the Number 4 sieve) [14]. This test method determines the loose uncompacted void content of fine aggregate by allowing the fine aggregate particles to fall loosely from a specified height through the orifice of a funnel into a calibrated cylinder. The excess material is struck off and the aggregate in the cylinder is weighed. The uncompacted void content of the fine aggregate sample is calculated using the weight of aggregate and the bulk specific gravity of the aggregate. The test equipment dimensions are summarized in table 5 and the test apparatus is shown in figure 2.

Three methods are included in the NAA test method for measurement of void content using graded fine aggregate (standard grading or as-received grading) or through the use of several individual size fractions. Method A uses a standard fine aggregate grading of 190 grams that can be obtained from individual sieve fractions. The standard grading consists of the following sizes and weights:

| Sieve Size Fraction | Mass, g |
|---|---|
| No. 8 to No. 16 | 44 |
| No. 16 to No. 30 | 57 |
| No. 30 to No. 50 | 72 |
| No. 50 to No. 100 | 17 |
| Total | 190 |

Method B uses 190 grams of three individual aggregate size fractions: No. 8 to No. 16, No. 16 to No. 30, and No. 30 to No. 50. Each size fraction is tested separately and the uncompacted void content for the fine aggregate is computed as the average of the three size fractions.

Method C uses 190 grams of as-received material that passes the No. 4 sieve. The uncompacted void content of a fine aggregate for this test method is calculated using the following equation:

$$UCV = \frac{Vol - \left(\frac{Mass}{Bulk}\right)}{Vol} \times 100 \qquad (2)$$

where

UCV = uncompacted voids in fine aggregate, percent
Mass = mass of aggregate in cylinder, grams
Bulk = bulk specific gravity of fine aggregate
Vol = volume of cylinder, cubic centimeters

MODIFIED NAA PARTICLE SHAPE AND TEXTURE. The NAA particle shape and texture apparatus was modified in order to test and evaluate larger coarser aggregate particles (No. 4 to 3/4 in.) with the same concept of uncompacted voids. The basic differences in the test apparatus was the size of the funnel orifice and the volume of the cylinder. These dimensions were enlarged to account for the larger coarser aggregate particles and to have the approximate same aggregate size to orifice opening ratio. The modified test apparatus dimensions are very similar to the dimensions specified for the Pouring Test developed by Ishai and Gelber [15]. The height of aggregate fall was kept constant to insure the energy levels were consistent for both test methods. The dimensions of the modified test apparatus are summarized in table 5 and the test apparatus is shown in figure 2.

TABLE 5. NAA AND MODIFIED NAA TEST APPARATUS DIMENSIONS

| Parameters | NAA Test Apparatus | Modified NAA Test Apparatus |
|---|---|---|
| Aggregate size | No. 4 to No. 100 | 3/4 in. to No. 4 |
| Bin diameter, in. | 4.0 | 6.0 |
| Orifice diameter, in. | 0.5 | 4.0 |
| Drop distance, in. | 4.5 | 4.5 |
| Volume of cylinder, $in.^3$ | 6.1 | 171 |

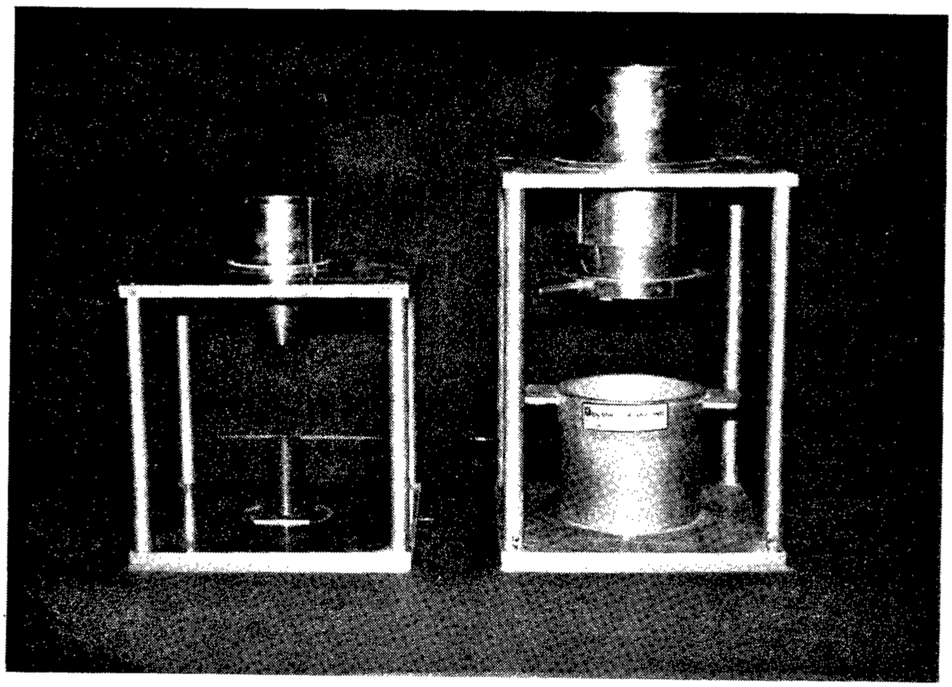

FIGURE 2. NAA AND MODIFIED NAA PARTICLE SHAPE AND TEXTURE TEST APPARATUS

The measurement of the uncompacted void content for coarse aggregate particles is conducted using two gradings. Method 1 uses 5,000 grams of as-received material that passes the 3/4 in. sieve but is retained on the No. 4 sieve. The uncompacted void content is calculated using equation 2. Method 2 uses 5,000 grams of individual aggregate size fractions: 3/4 to 1/2 in., 1/2 to 3/8 in., and 3/8 in. to No. 4. Each size fraction is tested separately and the uncompacted void content for each size fraction is determined. The uncompacted void content for the coarse aggregate particles is calculated as an average of the three individual size fractions or by weighted average using the weight percentage of each size fraction in the coarse aggregate gradation.

DIRECT SHEAR. This test method is used to determine the shear strength and angle of internal friction (Ø) of fine aggregate materials under different normal stress conditions. The shear strength of a fine aggregate is controlled by the angle of internal friction and the normal effective stress. The shear failure of a fine aggregate is determined by two major factors, rolling and slipping. The sliding resistance of aggregate particles for a given normal stress is determined by the angle of internal friction, particle shape, angularity, and texture. Theoretically, this concept should produce a valid relationship between the angle of internal friction and the characteristics of aggregate shape, angularity, and surface texture.

The direct shear test (EM 1110-2-1906, Appendix IX) [16] is performed on an oven-dried sample of approximately 140 grams of fine aggregate. The fine aggregate sample is placed in a square box in which the top half can slide over the bottom half (figure 3). The box dimensions are 3.0 by 3.0 in. and 0.5 in. thick. The fine aggregate is placed into the shear box at a uniform density for each aggregate blend. A normal force or stress is applied to the top of the box while a horizontal shearing force is applied so that the failure will occur along a horizontal plane at the midheight of the sample. This shear test was conducted at three normal stress levels (1TSF, 2TSF, and 3TSF) of each aggregate blend. The angle of internal friction was determined by plotting shear stress versus normal stress and constructing a "best fit" line through the data points. The angle of internal friction is the angle between the constructed best fit line and the horizontal (x) axis.

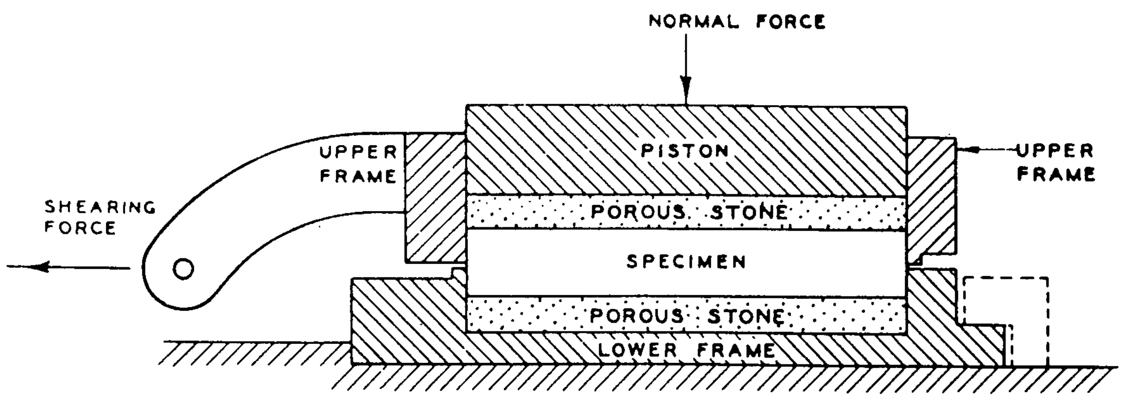


FIGURE 3. SCHEMATIC DIAGRAM OF DIRECT SHEAR BOX [16]

UNIT WEIGHT AND VOIDS IN AGGREGATE. This test method (ASTM C29) determines the unit weight of fine, coarse, or mixed aggregate blends in a compacted or loose condition and calculates the voids in the aggregate matrix based on the unit weight. The voids calculated with this method are the space between the aggregate particles not occupied by solid mineral matter. These voids do not include any voids within the aggregate particles, either permeable or impermeable [17].

The test method is basically simple and straightforward and requires approximately 5,000 grams of oven-dried aggregate to be placed in a specified cylinder (0.1 $ft^3$ for aggregates smaller than

1/2 in.) in a compacted or loose condition. ASTM C29 test method allows three procedures for determining the unit weight of an aggregate: rodding, jigging, and shoveling. The rodding and jigging procedures produce compacted samples while the shoveling procedure produces a loose sample. The rodding procedure specifies that the aggregate material be compacted in three equal lifts with 25 strokes of a tamping rod evenly distributed over the surface. The shoveling procedure requires that the aggregate be discharged from a shovel or scoop not more than 2 in. above the cylinder. After each procedure is completed, the excess aggregate particles are leveled off with a straightedge and the weight of aggregate is determined. The void content of the aggregate matrix is calculated using equation 2.

## TESTS FOR EVALUATING ASPHALT CONCRETE MIXTURES.

In order to complete the objectives of this laboratory study, several test procedures and types of testing equipment were used to determine the effects of marginal aggregates on the engineering properties (strength and rutting characteristics) of asphalt concrete mixtures. Current, state-of-the-art testing equipment and procedures were used in addition to standard laboratory procedures generally used to conduct Marshall mix designs. The modern tests included the Corps of Engineers Gyratory Testing Machine (GTM) and the indirect tensile, direct shear, and confined repeated load deformation (triaxial cyclic creep) test equipment. The laboratory equipment and test procedures that were used in this laboratory study are described and discussed in the following paragraphs.

MARSHALL MIX PROPERTIES. The Marshall mix design was used to determine the optimum asphalt contents for all asphalt concrete mixtures. The compactive effort was modified and the gyratory compaction process was used instead of the Marshall impact hammer (ASTM D 1559) [18]. The optimum asphalt content was selected at 4 percent air voids (voids total mix) to reduce the effect of the asphalt content on the mix properties and to enhance the influence of aggregate gradation and particle shape and texture. The Marshall mix properties which include void parameters, Marshall stability, and flow were determined for each asphalt concrete mixture at its optimum asphalt content.

The quality of an asphalt concrete mixture or its ability to handle traffic loads is measured by the Marshall stability and flow values [19]. The Marshall stability of an asphalt mixture is an indicator of the mix strength defined as the resistance to deformation or plastic flow under a load. Stability has also been defined as a measurement of the mass viscosity of an asphalt-aggregate mixture and is affected by aggregate shape and texture and the viscosity or stiffness of the asphalt cement [20]. The flow value is an indicator of mix plasticity measured as the deformation at failure or maximum load of the stability test. The Marshall stability and flow test was conducted according to ASTM D 1559 using a Marshall testing machine which was equipped with an automatic plotting device for graphing stability curves.

GYRATORY TESTING MACHINE. Compaction of asphalt concrete mixtures using the gyratory method applies normal forces to both the top and bottom faces of the material confined in cylindrically-shaped molds (ASTM D 3387) [21]. Normal forces at designated pressures are supplemented with a kneading action or gyratory motion to compact the asphalt concrete material into a denser configuration with aggregate particle orientation more consistent with in-place pavements. The U.S. Army Corps of Engineers has developed a method, procedure, and equipment using this compaction procedure [22, 23, 24].

The gyratory compaction method (ASTM D 3387) involves placing asphalt concrete material into a 4-in.-diameter mold and loading into the GTM at a prescribed normal stress level which represents anticipated traffic contact pressure. The asphalt concrete material and mold are then rotated through a 1-degree gyration angle for a specified number of revolutions of the roller assembly. This compaction process produces stress-strain properties that are representative of those in field compacted specimens.

Model 4C and Model 8A/6B/4C GTM's (figure 4) were used to compact all laboratory specimen in the marginal aggregate laboratory study. Previous research with the GTM has suggested that the laboratory tests will simulate field behavior and performance under traffic when asphalt concrete mixtures are compacted at stress levels similar to anticipated field traffic conditions [25, 26]. The gyratory compactive effort used in this laboratory study was a 200 psi normal stress level, 1-degree gyration angle, and 30 revolutions of the roller assembly which is equivalent to the standard 75-blow Marshall hand hammer effort [19]. This compaction effort produced asphalt concrete specimen that satisfy the Marshall specimen dimensions of 4 in. in diameter and 2 1/2 in. thick.

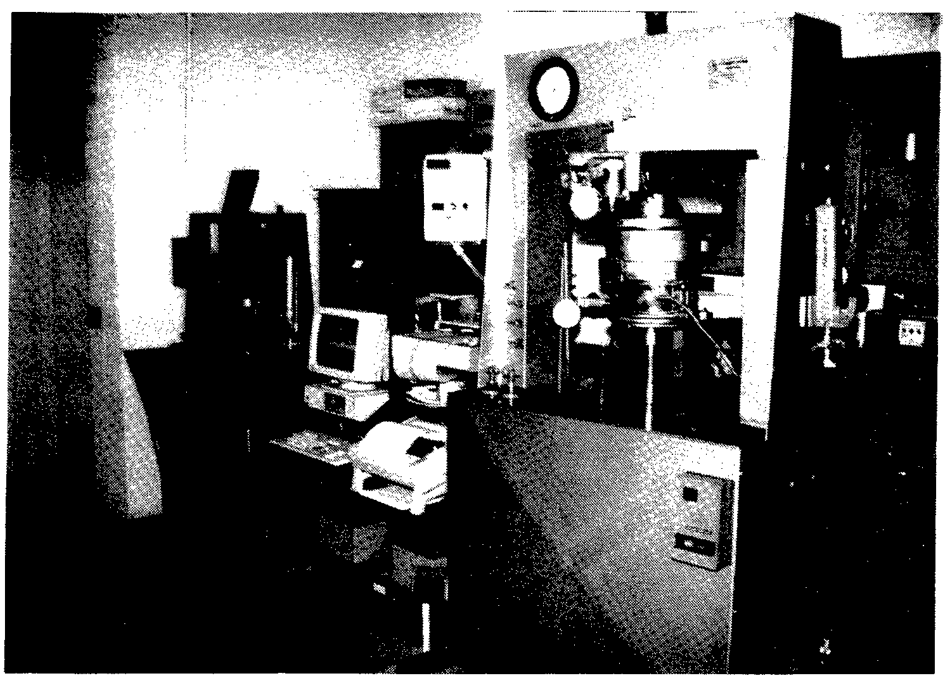

FIGURE 4. WES MODEL 4C AND 8A/6B/4C GYRATORY TESTING MACHINES

The gyratory compaction method using the GTM produces a gyratory graph or gyrograph that can be used to evaluate the asphalt concrete mixture behavior during compaction (figure 5). The gyrograph indicates the relative stability or plastic behavior of the mixture during the compactive effort. The gyrograph indicates an unstable mixture when the gyrograph spreads or widens. A gyrograph that does not spread is considered stable under that loading condition. The gyrograph also produces two indices that describe the relative stability of an asphalt concrete mixture. The ratio of the final width to the intermediate width of the gyrograph is called the Gyratory Stability Index (GSI). A GSI value greater than 1.0 indicates an unstable plastic mixture with a high asphalt content. The ratio of the intermediate width to the initial width is called the Gyratory Elasto-Plastic Index (GEPI). The GEPI value is an indicator of the quality of the aggregate. The GEPI is a measure of the shear strain experienced by the mixture and is an index of the angle of internal friction of the aggregate [22, 23].

INDIRECT TENSILE. The indirect tensile test was developed to indirectly determine the tensile strengths of materials by placing a cylinder of material horizontally between two loading plates and loading the specimen across its diameter until failure. This loading configuration subjects the center plane between the loading plates to a nearly uniform tensile stress which results in a tensile failure of the material. This test procedure has been used to test soils, concrete, and asphalt materials and has been used by engineers to compute fundamental properties of materials [27].

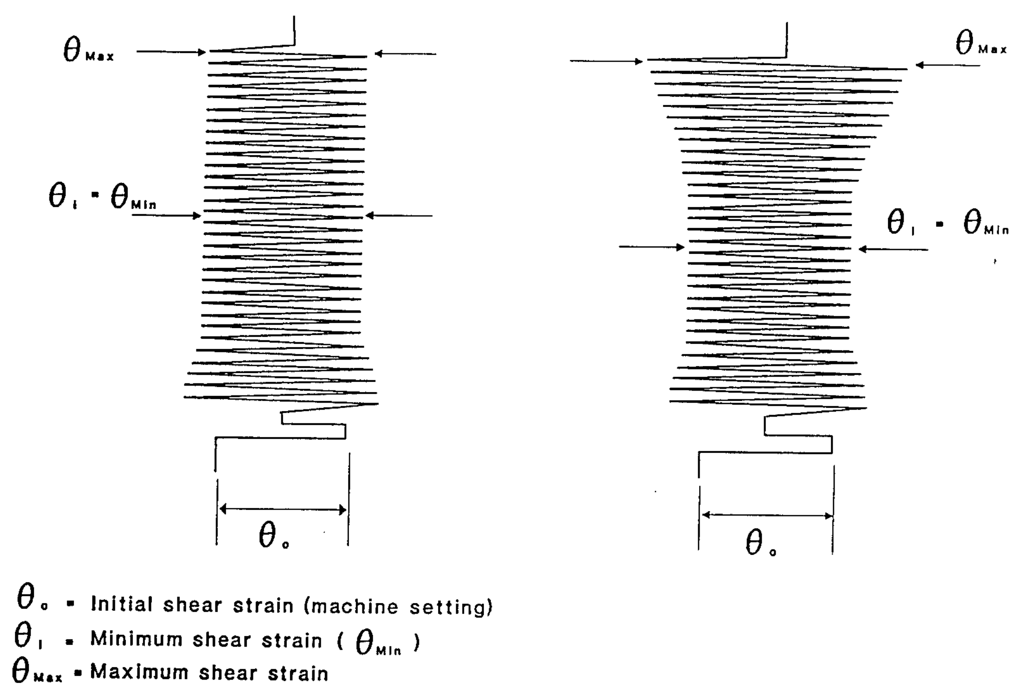


FIGURE 5. TYPICAL GYROGRAPH [23]

ASTM Method D 4123 provides guidance on indirect tensile testing of asphalt concrete mixtures [28]. This test procedure was conducted on specimen produced at optimum asphalt content for all marginal aggregate asphalt mixtures. This test procedure is considered straightforward and generally produces consistent results. The indirect tensile test was conducted on specimen at two test temperatures, 77 and 104°F. These specimens were cured in an oven at the appropriate temperature for 2 hours before testing. The indirect tensile test requires that the specimen be positioned so that the loading plates are centered and the load is applied across the diameter of the specimen (figure 6). The vertical load is applied at a constant deformation rate of 2 in. per minute until failure. The ultimate load is recorded at failure and is used to calculate the tensile strength. The tensile strength is calculated according to ASTM D 4123 with the following equation:

$$TS = 2P/\pi t D \tag{3}$$

where

TS = tensile strength, psi
P = ultimate load required to fail specimen, lbs.
t = thickness of specimen, in.
D = diameter of specimen, in.

This testing procedure was conducted on a minimum of three specimen for each of the 52 marginal aggregate asphalt mixtures at both temperatures.

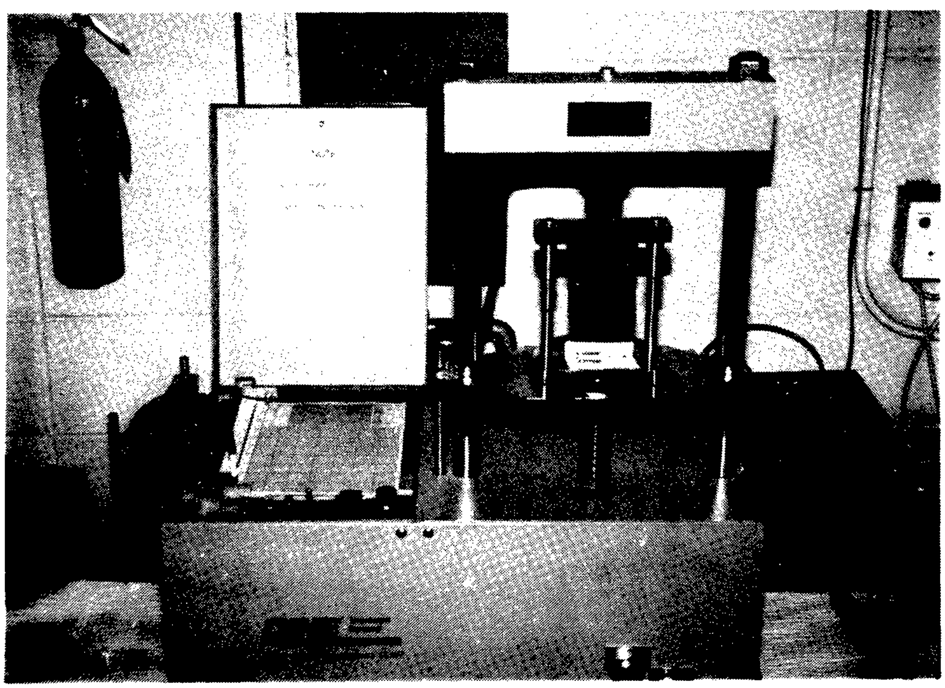

FIGURE 6. INDIRECT TENSILE TEST

DIRECT SHEAR. The direct shear test is used to determine the angle of internal friction (Ø) and the shear strength of asphalt mixture under different normal stress conditions. The shear strength of an asphalt mixture is controlled by the cohesion of the asphalt binder, the angle of internal friction, and the effective normal stress. For a given normal stress and asphalt binder type, the shear strength of an asphalt concrete mixture is determined by the aggregate properties (i.e., gradation, angularity, shape, and surface texture).

The direct shear test for asphalt concrete mixtures was conducted in the device shown in figure 7. A standard Marshall specimen (4 in. diameter and 2.5 in. thick) was placed in the shearing apparatus and tested at 140°F. The simple shear assembly was placed in the Instron machine which applied and measured the shear load and displacement during the test. The shear load was applied at a rate of 1/2 in. per minute. The direct shear test was conducted at three normal stress levels, 100, 200, and 300 psi. Two test replicates were conducted for each test condition. The angle of internal friction and cohesion (shear strength at normal stress equal to zero) were determined by plotting shear stress versus normal stress and constructing a best fit line through the data points. The angle of internal friction is the angle between the constructed best fit line and the horizontal (x) axis and the cohesion value is the intercept of the vertical (y) axis.

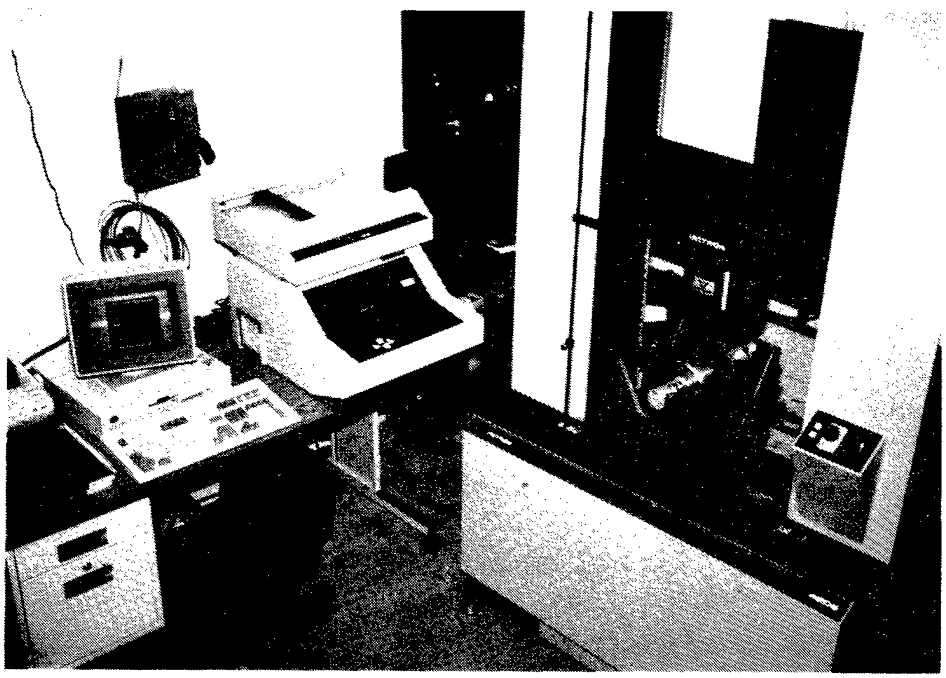

FIGURE 7. DIRECT SHEAR TEST APPARATUS

CONFINED REPEATED LOAD DEFORMATION. The confined repeated load deformation (triaxial cyclic creep) test was used to evaluate the rutting potential of marginal aggregate asphalt mixtures and to determine the effectiveness of stiffer asphalt binders to improve the rutting characteristics of these mixes. This test equipment and evaluation was developed by U.S. Army Engineer Waterways Experiment Station (WES) specifically for this research on the basis of recent work conducted at the National Center for Asphalt Technology (NCAT) at Auburn

University. This work showed the confined repeated load deformation test provided an accurate laboratory indication of rutting [29, 30].

The confined repeated load deformation tests were performed on individual Marshall specimen that were 2.5 in. thick and 4 in. in diameter in the test apparatus shown in figure 8. The specimens were placed in the triaxial chamber with smooth, dense-graded paper on each end and a rubber membrane around the sides. The triaxial chamber was then placed in an environmental chamber at 140°F for a minimum of 2.5 hours. The triaxial chamber was pressurized with a confining pressure of 40 psi for 5 minutes. Each specimen was preconditioned with a 1.5 psi axial preload and then a 10 psi cyclic axial stress was applied for 30 cycles. The cyclic or repeated load was applied with a 0.1 second load application and a 0.9 second rest period.

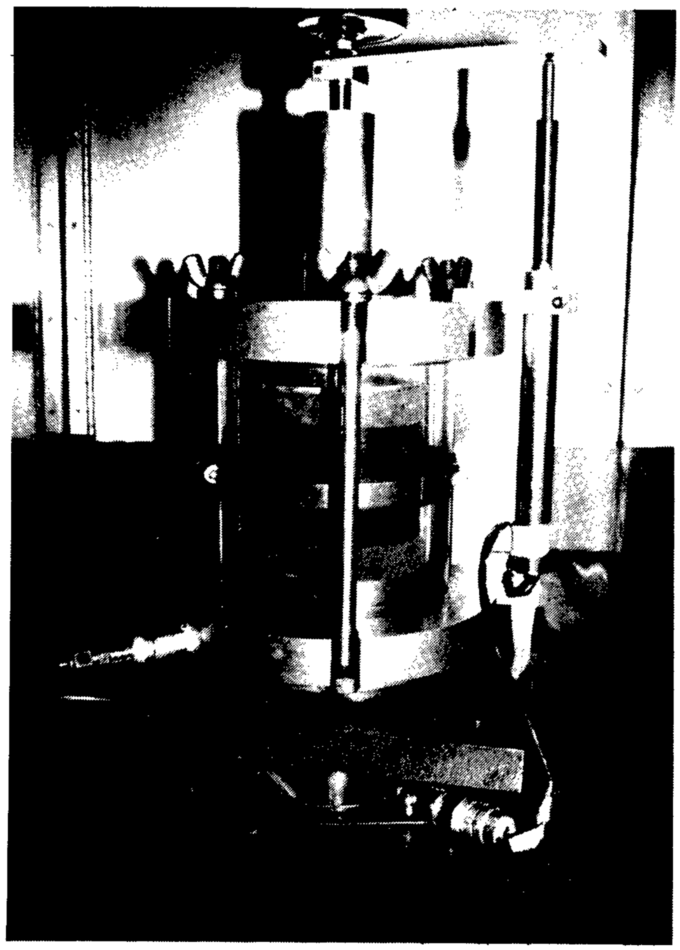

FIGURE 8. CONFINED REPEATED LOAD DEFORMATION TEST

The loading portion of the test applied a repeated cyclic load for 60 minutes and then the loading was released for 15 minutes for the rebound phase. The applied axial stress was 240 psi with a deviator stress of 200 psi. The deformations and loads were recorded at various times during the creep and rebound phases. These measurements were used to calculate stresses and strains and then converted into a creep modulus and permanent deformation values. The continued repeated load deformation test was conducted at 140°F which was considered a typical maximum pavement temperature.

The results of the confined repeated load deformation test can be used in several ways to evaluate asphalt concrete mixtures. The amount of deformation after the creep and rebound phases of the test indicates the asphalt mixture's potential for permanent deformation. Smaller axial deformations and lower creep deformation values indicate a stable asphalt mixture. The creep modulus value indicates the asphalt mixture's stiffness. High creep modulus values should indicate minimum potential permanent deformation. The creep modulus value is calculated using the following equation:

$$CM = S x H / D \qquad (4)$$

where

CM = creep modulus value, psi
S = vertical stress - load/contact area, psi
H = height of specimen, in.
D = axial deformation, in.

Another test result that can be used to evaluate the rutting potential of an asphalt concrete mixture is the slope of the steady state portion of the creep deformation curve. This slope was determined from the creep deformation curve plotted on log-log scale. The higher the slope value, the greater the potential for rutting in the asphalt concrete mixture [31, 32].

## PHASE I— AGGREGATE CHARACTERIZATION

This section presents and discusses the results of the aggregate particle characterization tests conducted on the fabricated test aggregate gradations. The laboratory testing program for this marginal aggregate study was focused around the effects of departing from the Item P-401 Specification for the standard 3/4 in. maximum aggregate size gradation and the percentage of crushed particles (coarse and fine) in the aggregate blend. The aggregate characterization tests were conducted to determine the effect of the shape of the aggregate gradation curve and to quantify the characteristics of the aggregate particle shape and texture. Analysis of these test results included a graphical analyses of the shape of the aggregate gradation curve with standard semi-log and 0.45 power maximum density gradation curves and correlation of individual aggregate characterization tests with the percentage of crushed particles for composite (total), coarse, and fine fractions. This analysis was conducted to achieve two of the stated objectives of this study: (1) evaluate and determine suitable methods or tests to characterize aggregate particle shape and texture to improve aggregate specifications as it relates to pavement rutting and (2) to determine boundaries for aggregate gradation, limits for percent crushed particles, and maximum amounts of natural sand materials.

AGGREGATE GRADATIONS.

The fabricated test gradations were produced to determine the effects of variation from the 3/4 in. maximum aggregate gradation specified in Item P-401. Mixes 1-8 were fabricated with crushed limestone materials so that the effect of gradation could be evaluated with high quality aggregates and that the effects of particle shape would be minimized. These test gradations were designed to evaluate the general shape of the aggregate gradation curve as the gradations varied from the maximum limits of the FAA specification, contained excessive fine materials and were poorly gap-graded. Mixes 9-18 were fabricated with crushed and uncrushed gravel with varying amounts of coarse natural sand materials. These test gradations were designed to evaluate the effect the fine aggregate portion (material smaller than the No. 4 sieve) of the gradation curve.

Graphical analysis is the best way to evaluate an aggregate gradation if asphalt concrete mixture data or field performance data are not available. The graphical analysis involves plotting the aggregate curve against proven specification bands or plotting the gradation curve on a 0.45 power maximum density gradation curve. Comparison of the test gradation to these established specifications is a good indicator of relative performance but not an absolute predictor of asphalt concrete performance.

Of the 18 test gradations designed to evaluate the aggregate gradation characteristics of asphalt concrete mixture, only six aggregate blends (Mixes 1, 9, 10, 13, 14, and 15) would fall inside the specified FAA limits listed in table 2. Mixes 1, 9, 10, and 13 are the only aggregate blends that would meet all the Item P-401 aggregate requirements. This means the other 14 aggregate blends would be classified as marginal aggregate mixtures. Each of the aggregate test gradations are plotted with the FAA specification limits on standard semi-log gradation curves in figures A-1-A-19.

Previous research studies have indicated that plotting aggregate gradations with a 0.45 power maximum density gradation curve can indicate the quality of the aggregate blend [33, 34, 35] Aggregate gradations that produce a hump between the No. 4 and No. 100 sieve sizes generally produce a tender or unstable asphalt concrete mixture. This hump is generally around the No. 30 sieve and is produced by an excess amount of middle-sized sand particles.

This hump was evident in several aggregate gradations fabricated for this laboratory study (Mixes 10-12, 14-18). As the percentage of natural sand material increased, the hump at the No. 30 sieve increased. Based on previous laboratory and field studies [36, 37, 38], these aggregate blends should produce sensitive, tender asphalt concrete mixtures. The test aggregate gradation curves are plotted with the 0.45 power maximum density line in figures A-20-A-38.

The evaluation and analysis of the effect of the general shape of an aggregate gradation can best be conducted by comparing the gradations with the asphalt concrete properties. This analysis is presented and discussed in Phases II and III.

AGGREGATE PARTICLE SHAPE AND SURFACE TEXTURE.

The aggregate particle characterization tests were conducted to quantify the shape and surface texture of the aggregates in each aggregate blend and to correlate these aggregate characteristics to the percentage of crushed particles and to the amount of natural sand in the aggregate blend. Currently, Item P-401 controls the quality of the aggregate shape and surface texture by specifying minimum values for crushed particles (70 percent coarse and fine) and the maximum amount of natural sand (20 percent by total aggregate weight). The analysis also included a correlation of aggregate characterization tests to the Particle Index value which is the only standardized test method for aggregate characterization for asphalt concrete mixtures. The particle characteristics will also be correlated with asphalt mixture properties including mix strength values and rutting characteristics. This analysis will determine the relationship between and the influence of aggregates on the performance of asphalt concrete mixtures. This analysis is discussed in detail in Phases II and III.

PERCENT CRUSHED PARTICLES. A crushed particle is defined as an aggregate particle that has at least two mechanically induced fractured faces. The lab stock materials used to fabricate the test aggregate blends were composed of 100 percent crushed limestone and crushed gravel or 100 percent uncrushed gravel and uncrushed natural sand. Since each aggregate blend was fabricated with individual sieve sizes of each lab stock material, the percentage of crushed particles for the composite gradation, coarse aggregate fraction and fine aggregate fraction, and the amount of natural sand material were determined from the batch weight percentages instead of by visual inspection. Using the batch weight percentages eliminated the human error and bias produced by subjectivity and personal judgment which is required by the visual inspection procedure. The percent crushed particle values and the natural sand content for each aggregate blend are listed in table 6.

INDEX OF AGGREGATE PARTICLE SHAPE AND TEXTURE. The Particle Index test (ASTM D 3398) is based on the concept that aggregate void characteristics for a one-sized aggregate compacted in a standard mold would indicate the characteristics of aggregate shape, angularity, and surface texture. Numerous studies have indicated that the Particle Index value is larger for aggregates that are more irregular, angular, and rougher. These studies concluded that aggregates with rounded particles and smooth surface textures have a Particle Index of 6 to 7 or less, while aggregate with highly crushed particles with rough textures have a Particle Index value of 15 to 20 or more. A Particle Index value of 14 has also been found to separate uncrushed natural sands from manufactured sands [39, 40, 41].

The Particle Index test was conducted on each size fraction of each lab stock material. The Particle Index values for these lab stock materials are presented in table 7. The weighted Particle Index for each aggregate blend was calculated on the basis of the weight percentage of each size fraction in the aggregate gradation. The weighted Particle Index values for the composite gradation, coarse aggregate fraction, and fine aggregate fraction are listed in table 8. To simply and shorten this method, the Particle Index value was determined for the major sieve fraction and the major plus second major sieve fractions. These Particle Index values are also listed in table 8.

## TABLE 6. PERCENT CRUSHED PARTICLES AND NATURAL SAND CONTENT

| | Percent Crushed Particles | | | |
|---|---|---|---|---|
| Mix Number | Composite Gradation | Coarse Aggregate Fraction | Fine Aggregate Fraction | Natural Sand Content |
| 1 | 100 | 100 | 100 | 0 |
| 2 | 92 | 100 | 75 | 8 |
| 3 | 88 | 100 | 79 | 12 |
| 4 | 90 | 100 | 77 | 10 |
| 5 | 91 | 100 | 86 | 9 |
| 6 | 90 | 100 | 82 | 10 |
| 7 | 88 | 100 | 78 | 12 |
| 8 | 85 | 100 | 58 | 15 |
| 9 | 90 | 100 | 76 | 10 |
| 10 | 80 | 100 | 53 | 20 |
| 11 | 70 | 100 | 32 | 30 |
| 12 | 60 | 100 | 11 | 40 |
| 13 | 100 | 100 | 100 | 0 |
| 14 | 0 | 0 | 0 | 11 |
| 15 | 0 | 0 | 0 | 10 |
| 16 | 0 | 0 | 0 | 20 |
| 17 | 0 | 0 | 0 | 30 |
| 18 | 0 | 0 | 0 | 40 |
| 19 | 42 | 0 | 100 | 0 |
| 20 | 83 | 70 | 100 | 0 |
| 21 | 71 | 50 | 100 | 0 |
| 22 | 59 | 30 | 100 | 0 |

## TABLE 7. PARTICLE INDEX VALUES FOR LAB STOCK MATERIALS

| Sieve Size | Crushed Limestone | Crushed Gravel | Uncrushed Gravel |
|---|---|---|---|
| 1/2 in. | 15.0 | 12.8 | 8.7 |
| 3/8 in. | 15.5 | 14.0 | 8.8 |
| No. 4 | 16.3 | 13.5 | 8.0 |
| No. 8 | 17.2 | 15.6 | 8.8 |
| No. 16 | 17.2 | 16.6 | 7.8 |
| No. 30 | 15.9 | 16.6 | -- |
| No. 50 | 15.7 | 13.4 | 6.4 |
| No. 100 | 14.7 | 14.2 | 9.7 |
| No. 200 | 15.4 | 19.9 | 9.4 |
| Fine Aggregates | | | |
| Coarse natural sand | 5.9 | | |
| Fine natural sand | 9.0 | | |
| Limestone dust | 16.0 | | |

TABLE 8. PARTICLE INDEX VALUES FOR AGGREGATE BLENDS

| Mix Number | Composite Particle Index | Coarse Aggregate Particle Index | Fine Aggregate Particle Index | Major Fraction Particle Index | Major + 2nd Major Particle Index |
|---|---|---|---|---|---|
| 1 | 16.2 | 16.2 | 16.2 | 16.3 | 16.7 |
| 2 | 15.3 | 15.8 | 13.8 | 15.0 | 15.3 |
| 3 | 15.3 | 16.5 | 14.1 | 16.3 | 16.8 |
| 4 | 15.1 | 15.9 | 13.9 | 15.0 | 15.7 |
| 5 | 15.4 | 16.6 | 14.6 | 17.2 | 16.8 |
| 6 | 15.4 | 16.5 | 14.3 | 16.3 | 16.8 |
| 7 | 15.0 | 15.8 | 14.2 | 15.0 | 16.1 |
| 8 | 14.8 | 15.7 | 12.7 | 15.0 | 15.5 |
| 9 | 13.8 | 14.0 | 13.5 | 13.5 | 13.2 |
| 10 | 12.8 | 13.9 | 11.2 | 5.9 | 9.7 |
| 11 | 11.9 | 13.9 | 9.3 | 5.9 | 9.7 |
| 12 | 11.1 | 13.9 | 7.8 | 5.9 | 9.7 |
| 13 | 14.8 | 14.1 | 15.9 | 13.5 | 13.2 |
| 14 | 8.3 | 8.4 | 8.1 | 8.0 | 7.9 |
| 15 | 8.2 | 8.4 | 7.9 | 8.0 | 7.9 |
| 16 | 8.2 | 8.6 | 7.7 | 8.0 | 7.9 |
| 17 | 8.0 | 8.5 | 7.3 | 5.9 | 7.0 |
| 18 | 7.8 | 8.5 | 7.1 | 5.9 | 7.0 |
| 19 | 11.3 | 8.5 | 15.6 | 8.0 | 8.4 |
| 20 | 13.6 | 12.3 | 15.6 | 13.5 | 14.5 |
| 21 | 13.1 | 11.5 | 15.6 | 16.6 | 15.0 |
| 22 | 12.4 | 10.3 | 15.6 | 8.0 | 8.4 |

NAA PARTICLE SHAPE AND TEXTURE. This aggregate characterization test was developed as a simple routine test to measure the aggregate particle shape and surface texture using the loose uncompacted void content of a fine aggregate. Several studies concluded that decreasing aggregate angularity and smoother surface textures will decrease the loose uncompacted void content. These studies have found that this test method can distinguish the difference between aggregate shapes and surface textures of fine aggregate, but the three methods (A, B, C) produce different void levels for the same aggregate because of different aggregate gradings [41, 42, 43].

For this laboratory study, Methods A and C were used to characterize each aggregate blend. Method A uses a standard fine aggregate grading of 190 grams that can be obtained from individual sieve fractions. The standard grading and weights were previously presented. Method C uses 190 grams of as-received material that passes the No. 4 sieve. Conducting the flow test with this material was more difficult due to the clogging of the funnel by the plus No. 8 material. The clogging of the funnel interrupted the free flow of the fine aggregate through the funnel orifice. Slight tamping of the funnel was required to unclog the larger particles. The calculated uncompacted void contents for Methods A and C are presented in table 9.

TABLE 9. NAA PARTICLE SHAPE AND TEXTURE VALUES

| Mix Number | Method A | Method C |
|---|---|---|
| 1 | 47.1 | 39.3 |
| 2 | 46.4 | 39.3 |
| 3 | 47.2 | 38.1 |
| 4 | 45.8 | 41.0 |
| 5 | 46.6 | 40.0 |
| 6 | 46.8 | 40.5 |
| 7 | 47.4 | 39.2 |
| 8 | 44.2 | 36.4 |
| 9 | 44.1 | 37.4 |
| 10 | 43.1 | 35.7 |
| 11 | 41.2 | 36.1 |
| 12 | 39.9 | 36.2 |
| 13 | 45.9 | 39.0 |
| 14 | 38.4 | 33.4 |
| 15 | 41.3 | 35.3 |
| 16 | 40.6 | 33.5 |
| 17 | 39.6 | 34.6 |
| 18 | 40.2 | 34.7 |
| 19 | 45.9 | 37.6 |
| 20 | 46.2 | 37.3 |
| 21 | 46.2 | 37.6 |
| 22 | 44.3 | 36.6 |

MODIFIED NAA PARTICLE SHAPE AND TEXTURE. The NAA particle shape and texture apparatus was modified and enlarged to test and evaluate larger coarser aggregate particles (No. 4 to 3/4 in.). This test apparatus was used to determine the shape and surface texture of coarse aggregate particles using the loose uncompacted void content. Since the concept of using void contents to characterize aggregate shape and surface texture had been successful with other test methods, enlarging the NAA flow test apparatus to quantify the coarse aggregate shape and texture seemed to be a valid and practical idea.

Since there was no established procedure for testing coarse aggregate in this manner, two methods were established that simulated the fine aggregate test requirements. The primary difference in these two methods is the gradation of the aggregates. Method 1 uses the as-received material that passes the 3/4 in. sieve but was retained on the No. 4 sieve. Method 2 tests the individual aggregate size fractions (3/4 to 1/2 in., 1/2 to 3/8 in., and 3/8 in. to No. 4 sieve). The uncompacted void content for Method 2 is calculated as an average of the three individual size fractions and by weighted average using the weight percentages of each size fraction in the coarse aggregate gradation. The calculated uncompacted void contents for the modified NAA test apparatus are presented in table 10.

TABLE 10. UNCOMPACTED VOID CONTENTS FOR MODIFIED NAA TEST APPARATUS

| Mix Number | Method 1 As-Received Material | Method 2 Average of Individual Sizes | Method 2 Weighted Average |
|---|---|---|---|
| 1 | 47.0 | 49.2 | 49.4 |
| 2 | 46.4 | 49.2 | 49.2 |
| 3 | 47.4 | 49.2 | 49.4 |
| 4 | 46.4 | 49.2 | 49.5 |
| 5 | 47.4 | 49.2 | 49.7 |
| 6 | 47.7 | 49.2 | 49.4 |
| 7 | 49.1 | 49.2 | 49.1 |
| 8 | 46.8 | 49.2 | 49.2 |
| 9 | 45.9 | 47.7 | 47.6 |
| 10 | 45.9 | 47.7 | 47.6 |
| 11 | 45.9 | 47.7 | 47.6 |
| 12 | 45.9 | 47.7 | 47.6 |
| 13 | 45.9 | 47.7 | 47.6 |
| 14 | 39.9 | 42.2 | 42.2 |
| 15 | 39.9 | 42.2 | 42.2 |
| 16 | 39.9 | 42.2 | 42.2 |
| 17 | 39.9 | 42.2 | 42.2 |
| 18 | 39.9 | 42.2 | 42.2 |
| 19 | 40.3 | 42.2 | 42.2 |
| 20 | 43.7 | 45.0 | 46.0 |
| 21 | 42.9 | 45.0 | 45.0 |
| 22 | 41.6 | 45.0 | 43.9 |

DIRECT SHEAR. The direct shear test was used to determine the shear strength and the angle of internal friction of the fine aggregate for each aggregate blend. Theoretically, this test method should produce a valid relationship between the angle of internal friction and the aggregate shape and surface texture, but conflicting results have been reported. Winford [41] reported that the angle of internal friction values separated the natural sand materials from the manufactured sand materials while Sturat [44] concluded that the direct shear method was not a good indicator of sand shape and texture.

The direct shear test was conducted on the material smaller than the No. 4 sieve material of each aggregate blend. The test was conducted using three normal stress levels, 1TSF, 2TSF, and 3TSF. The angle of internal friction was determined by plotting shear stress versus normal stress and analytically determining the angle produced by the best fit line through the data points. The angle of internal friction values for each aggregate blend are presented in table 11.

TABLE 11. ANGLE OF INTERNAL FRICTION VALUES FOR FINE AGGREGATE

| Mix Number | Angle of Internal Friction |
|---|---|
| 1 | 42.5 |
| 2 | 46.0 |
| 3 | 41.5 |
| 4 | 41.5 |
| 5 | 42.0 |
| 6 | 42.5 |
| 7 | 41.0 |
| 8 | 40.5 |
| 9 | 41.0 |
| 10 | 39.0 |
| 11 | 40.5 |
| 12 | 36.5 |
| 13 | 41.5 |
| 14 | 39.5 |
| 15 | 39.5 |
| 16 | 36.5 |
| 17 | 36.0 |
| 18 | 36.0 |
| 19 | 42.5 |
| 20 | 43.5 |
| 21 | 42.5 |
| 22 | 41.5 |

UNIT WEIGHT AND VOIDS IN AGGREGATE. This test method (ASTM C29) is used to determine the unit weight and void content in an aggregate matrix for fine, coarse, and mixed aggregate blends. The unit weight and void content can be calculated in a loose or compacted condition. This test procedure was developed to select proportions for concrete mixtures, but the determination of void contents in an aggregate matrix has been proven to be a valid method of characterizing aggregate particle shape and surface texture.

For this laboratory study, the coarse aggregate fraction of each aggregate blend was tested. The rodding procedure which produces a compacted sample and the shoveling procedure which produces a loose sample were used to evaluate the shape and surface texture characteristics of the coarse aggregate fraction. The void content was determined for two gradings of each coarse aggregate fraction, as-received and individual sieve size fractions. The void content for this second grading was calculated using an average value of three size fractions and by weighted average according to the percentages in the coarse aggregate gradation. The calculated void contents for each aggregate blend are presented in table 12.

TABLE 12. VOID CONTENTS FROM ASTM C29 METHOD

| Mix Number | Rodding Procedure: As-Received Material | Rodding Procedure: Average of Individual Sizes | Rodding Procedure: Weighted Average | Shoveling Procedure: As-Received Material | Shoveling Procedure: Average of Individual Sizes | Shoveling Procedure: Weighted Average |
|---|---|---|---|---|---|---|
| 1 | 41.3 | 43.3 | 43.5 | 45.9 | 48.6 | 48.9 |
| 2 | 41.3 | 43.3 | 43.3 | 46.0 | 48.6 | 48.6 |
| 3 | 42.1 | 43.3 | 43.4 | 46.3 | 48.6 | 48.9 |
| 4 | 41.2 | 43.3 | 43.5 | 45.7 | 48.6 | 49.0 |
| 5 | 41.2 | 43.3 | 43.7 | 46.3 | 48.6 | 49.2 |
| 6 | 41.2 | 43.3 | 43.4 | 46.4 | 48.6 | 48.9 |
| 7 | 43.6 | 43.3 | 43.5 | 48.8 | 48.6 | 48.7 |
| 8 | 41.0 | 43.3 | 43.3 | 45.8 | 48.6 | 48.6 |
| 9 | 40.7 | 42.5 | 42.4 | 44.6 | 46.7 | 46.6 |
| 10 | 40.7 | 42.5 | 42.4 | 44.6 | 46.7 | 46.6 |
| 11 | 40.7 | 42.5 | 42.4 | 44.6 | 46.7 | 46.6 |
| 12 | 40.7 | 42.5 | 42.4 | 44.6 | 46.7 | 46.6 |
| 13 | 40.7 | 42.5 | 42.4 | 44.6 | 46.7 | 46.6 |
| 14 | 35.9 | 38.2 | 38.1 | 38.6 | 41.1 | 41.0 |
| 15 | 35.9 | 38.2 | 38.1 | 38.6 | 41.1 | 41.0 |
| 16 | 35.9 | 38.2 | 38.1 | 38.6 | 41.1 | 41.0 |
| 17 | 35.9 | 38.2 | 38.1 | 38.6 | 41.1 | 41.0 |
| 18 | 35.9 | 38.2 | 38.1 | 38.6 | 41.1 | 41.0 |
| 19 | 35.4 | 38.2 | 38.2 | 38.6 | 41.1 | 41.1 |
| 20 | 38.5 | 40.4 | 41.2 | 42.5 | 43.9 | 45.0 |
| 21 | 37.8 | 40.4 | 40.3 | 41.9 | 43.9 | 43.9 |
| 22 | 37.3 | 40.4 | 39.5 | 40.8 | 43.9 | 42.8 |

## ANALYSIS AND DISCUSSION OF DATA.

AGGREGATE PARTICLE SHAPE AND SURFACE TEXTURE. The aggregate particle characterization tests were conducted to quantify the particle shape and surface texture of the aggregates in each aggregate blend. The analysis of these aggregate particle characterization tests consisted of correlations between test results for the composite blend, coarse aggregate fraction and fine aggregate fraction with the percentage of crushed particles in the aggregate blends (Mixes 1-22). The analysis also included a correlation of the characterization test results for the fine aggregate fractions with the amount of natural sand material in the aggregate blend (Mixes 9-18). The final correlation of the aggregate characterization tests involved the nonstandard aggregate characterization tests with the Particle Index test results. These correlations were conducted to determine if aggregate particle characterization tests could be used to improve aggregate specifications by replacing the current requirements of percent crushed particles for the coarse and fine aggregate fractions and the maximum limits for natural sand materials.

## CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH PERCENT CRUSHED PARTICLES.

The Particle Index Test (ASTM D 3398). The Particle Index test has been used in several laboratory studies to evaluate the particle shape and surface texture of aggregates. This method has been effective in characterizing aggregate shape and texture but because this method is tedious and time-consuming, this method has only been used as a research tool. A summary of these previous studies indicates that angular, rough aggregates have a Particle Index value greater than 14 while round, smooth aggregates have a Particle Index value less than 12. The test results from this laboratory study (table 8) agree with the findings in the literature. Mix 1 (crushed limestone) and Mix 13 (crushed gravel) had Particle Index values of 16.2 and 14.8, respectively, while Mix 14 (uncrushed gravel) had a Particle Index value of 8.3.

Correlations between the Particle Index values for the composite blend, coarse aggregate fraction, and fine aggregate fraction and the percent crushed particles for each fraction were conducted using linear regression. The coefficient of determination ($R^2$) was used to determine how strong the correlation was between the data points and the regression equation. A strong correlation or relationship was found between the Particle Index values and the percent crushed particles. The results of these correlations are shown in figure 9. The $R^2$ values for these correlations were extremely high (0.945-composite, 0.924-coarse, 0.984-fine) and indicate there is a strong linear relationship between Particle Index values and the percent of crushed particles in an aggregate blend.

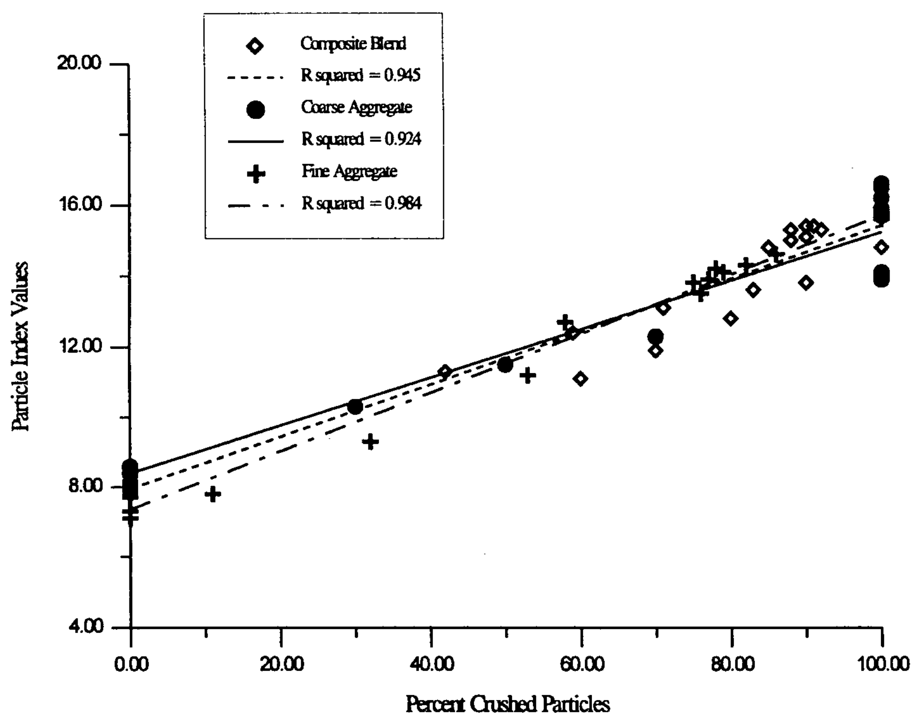


FIGURE 9. PARTICLE INDEX VALUES VERSUS PERCENT CRUSHED PARTICLES

In order to shorten this time-consuming test procedure, correlations were conducted between Particle Index values for the major sieve size fraction and the major fraction plus the 2nd major sieve size fractions and the percent crushed particles. These correlations were not as strong as with the weighted composite Particle Index values. The $R^2$ value for the major sieve fraction was 0.520 while the $R^2$ value for the major plus 2nd major sieve fraction was 0.718. These results indicate that several sieve size fractions are required to produce as strong a correlation as did the weighted composite Particle Index values.

The Modified NAA Particle Shape and Texture Test. This test was used to characterize aggregate shape and texture of coarse aggregates using the loose uncompacted void content. The uncompacted voids contents for this test method are presented in table 10. The void contents determined for Method 2 are basically the same; the void contents were not affected by calculating the void content using a straight average or a weighted average of the individual aggregate sizes. However, there was a difference in void contents for Methods 1 and 2. The void contents for Method 1 (as-received) were approximately 2 percent lower than for Method 2 (weighted average). This difference is due to the gradation difference in the aggregates tested. Individual aggregate sizes should produce higher void contents than graded samples.

An extremely strong correlation was determined for the uncompacted void contents determined using this modified NAA method and the percent crushed particles. The results of these correlations are shown in figure 10. The $R^2$ values for Method 1 and Method 2 are 0.941 and 0.945, respectively. This data indicates this test method can be conducted on blended aggregate samples or individual size samples with equal confidence. This method provides flexibility and is an excellent indicator of crushed coarse particles.

The Unit Weight and Voids in Aggregate Test Method (ASTM C29). This test is primarily used for concrete mixture designs but because this method determines void contents of aggregates, this method was evaluated as an aggregate characterization test for the coarse aggregate fraction. The rodding procedure which produces a compacted sample and the shoveling procedure which produces a loose sample were used to evaluate the coarse aggregate shape characteristics. The uncompacted void contents for each procedure are presented in table 12. As expected, the rodding procedure produced void contents approximately 4 percent lower than the shoveling procedure. The difference between the average and weighted average of individual aggregate sizes was negligible for both procedures. The difference in void contents between the as-received material and the weighted average was evident with the as-received material producing the lower void contents. The effect of gradation influenced the test results as it did in the Modified NAA test method.

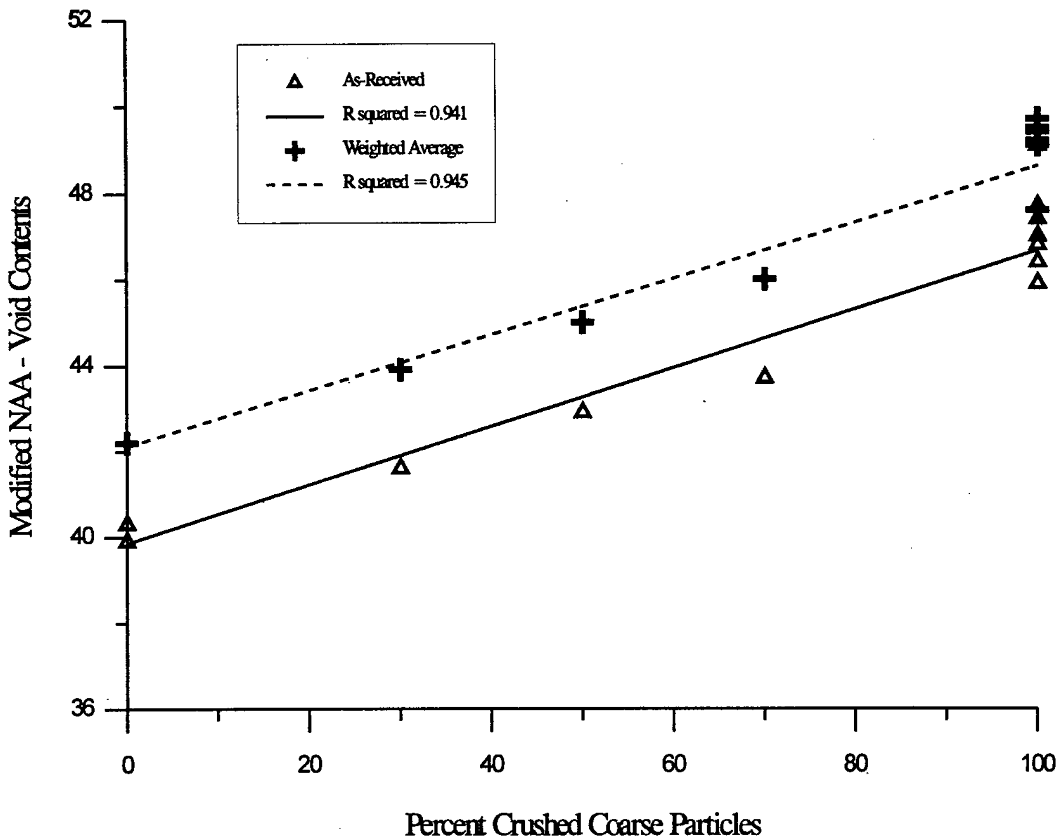


FIGURE 10. MODIFIED NAAP PARTICLE SHAPE AND TEXTURE VOID CONTENTS VERSUS PERCENT CRUSHED COARSE PARTICLES

An extremely strong correlation was determined for the uncompacted void contents determined using the rodding and shoveling procedures and the percent crushed coarse aggregate particles. The results of these correlations are shown in figure 11. The $R^2$ values for the rodding procedure with as-received materials and weighted average of individual sizes are 0.930 and 0.966 respectively. The $R^2$ values for the shoveling procedure with as-received materials and weighted average of individual sizes are 0.922 and 0.925 respectively. These results indicate that either procedure (rodding or shoveling) could be used to determine the percent of crushed coarse particles in an aggregate blend.

The NAA Particle Shape and Texture Test Method. This test was used to measure the fine aggregate particle shape and surface texture using uncompacted void contents. Methods A and C were used in this laboratory evaluation and the results are presented in table 9. The computed void contents for Method A are 4 to 8 percent higher than Method C void contents for the same aggregate blend. The difference between these results are due to the difference in aggregate grading. Method C is the as-received material which contains more fine material than Method A.

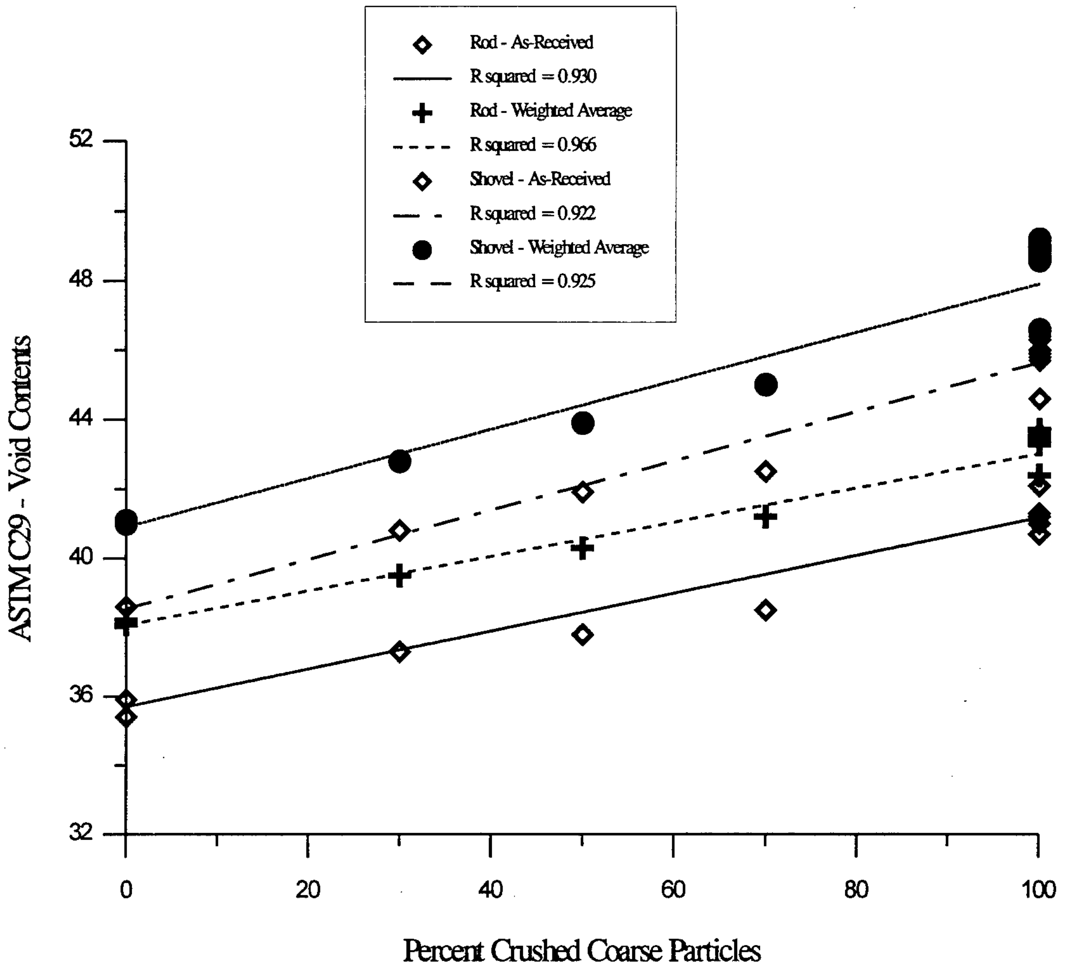


FIGURE 11. VOID CONTENTS FROM ASTM C29 METHOD VERSUS PERCENT CRUSHED COARSE PARTICLES

The Method A test procedure has been used by several researchers to characterize fine aggregate shape and texture. A review of these recent studies indicated that angular, rough, fine aggregate have void contents greater than 45 and round, smooth, fine aggregate have void contents below 43. The test results from this laboratory study agree with the test results presented in the literature. Mix 1 (crushed limestone) and Mix 13 (crushed gravel) had void contents of 47.1 and 45.9, respectively, while Mix 13 (uncrushed gravel) had a void content of 38.4.

The correlations for void contents determined using NAA Methods A and C with percent crushed fine particles are shown in figure 12. The correlation for Method C ($R^2 = 0.606$) was not as strong as the correlation for Method A ($R^2 = 0.845$). Based on this data, Method A (standard grading) is a better indicator of percent crushed fine particles than Method C (as-received material).

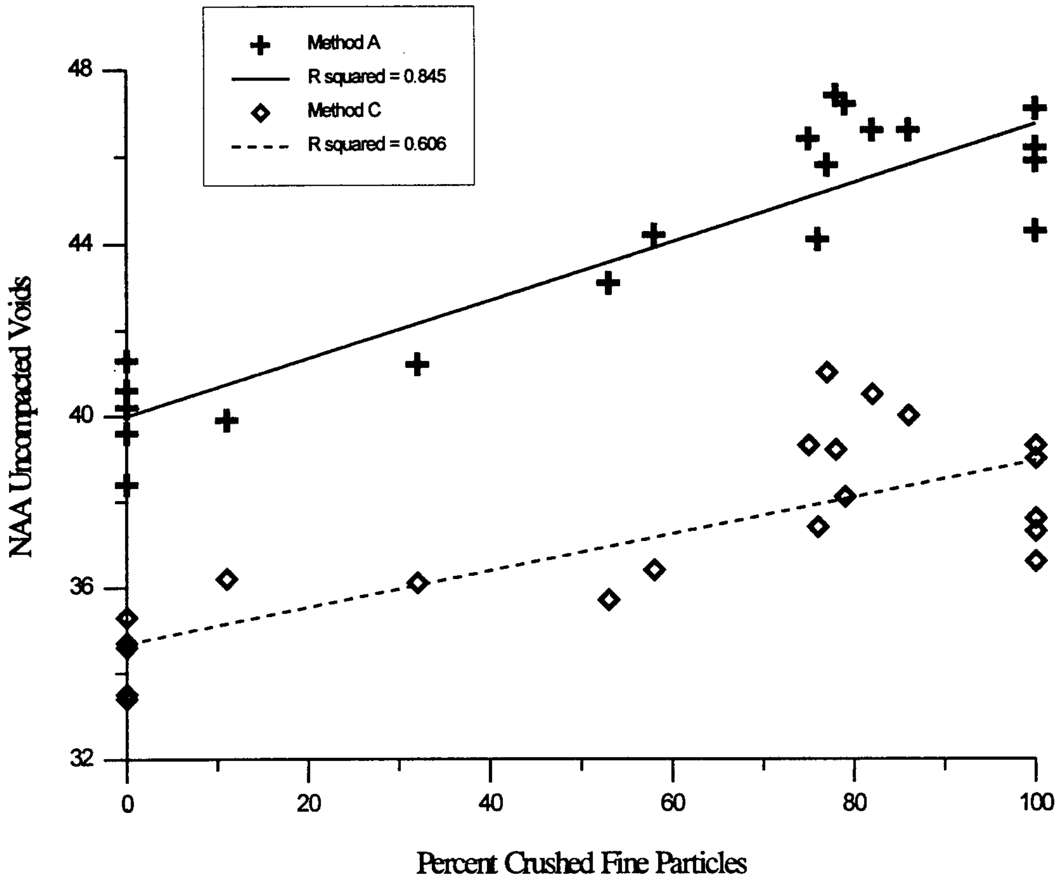


FIGURE 12. NAA PARTICLE SHAPE AND TEXTURE VOID CONTENTS VERSUS PERCENT CRUSHED FINE PARTICLES

The Direct Shear Test. The direct shear test was conducted to determine the angle of internal friction (Ø) of the fine aggregate. Theoretically, this method should produce a valid relationship between aggregate shape and texture and the angle of internal friction. A review of the literature produced conflicting results about the ability of this method to produce a strong relationship between aggregate shape and texture and the angle of internal friction. The test results for the material smaller than the No. 4 sieve of each aggregate blend are presented in table 11.

The correlation for angle of internal friction and percent crushed fine particles was not as strong as the previous aggregate characterization tests. The correlation for the direct shear test is shown in figure 13. The $R^2$ value for this correlation was 0.674, the lowest for any test method.

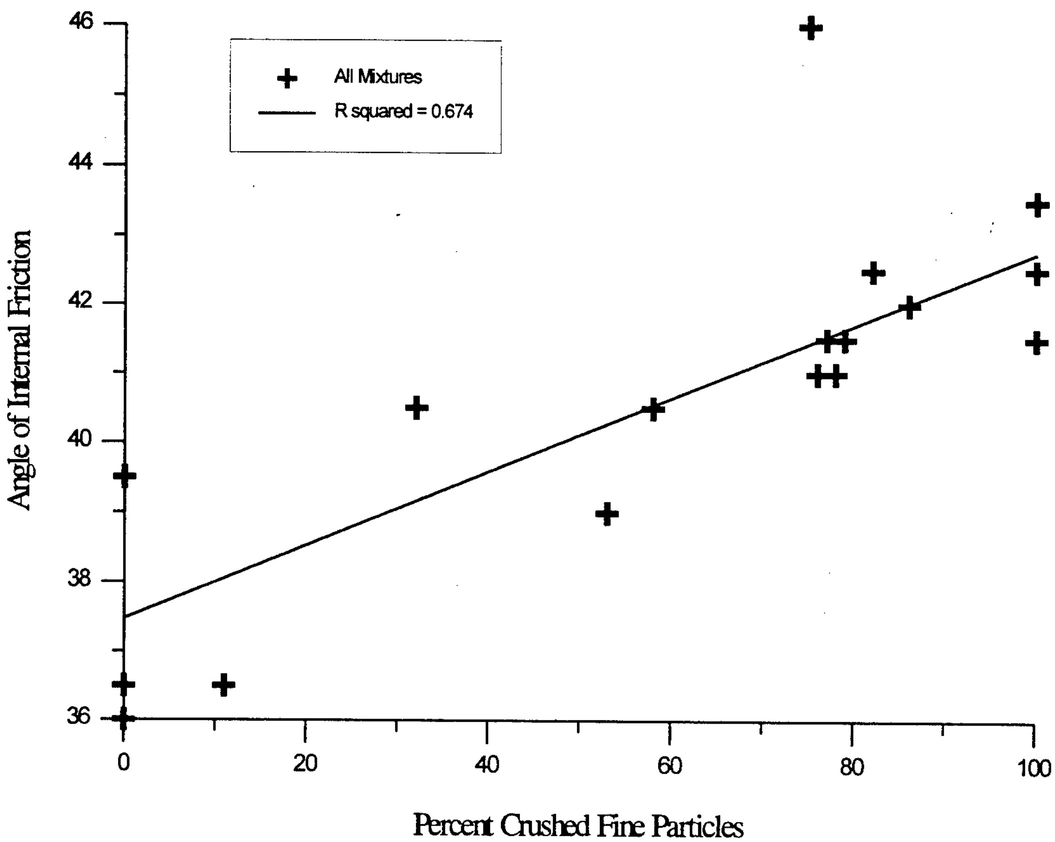


FIGURE 13. ANGLE OF INTERNAL FRICTION FROM DIRECT SHEAR TEST VERSUS PERCENT CRUSHED FINE PARTICLES

Summary of Coefficients of Determination. A summary of coefficients of determination for the aggregate particle characterization tests and percent crushed particles is presented in table 13. The Particle Index test produced extremely high correlations with percent crushed particles for composite blends, coarse aggregate fractions, and fine aggregate fractions. The idea of shortening the test procedure to one or two aggregate sizes did not produce good correlations. The Modified NAA test and ASTM C29 both did an excellent job correlating void contents with percent crushed coarse aggregate. The NAA particle shape and texture test produced a very good correlation with percent crushed fine aggregate. The direct shear test produced the worst correlation of any aggregate characterization test with percent crushed particles. Based on this data, the Particle Index test, NAA particle shape and texture, Modified NAA test, and ASTM C29 methods would all be viable alternatives to characterize aggregate shape instead of percent crushed particles.

TABLE 13. CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH PERCENT CRUSHED PARTICLES

| Aggregate Size | Aggregate Particle Characterization Test | Coefficient of Determination ($R^2$) |
|---|---|---|
| Composite Blend | Particle Index | 0.945 |
| | Major Fraction Particle Index Value | 0.520 |
| | Major plus 2nd Major Fraction Particle Index Value | 0.718 |
| Coarse Aggregate | Particle Index | 0.924 |
| | Modified NAA, As-Received | 0.941 |
| | Modified NAA, Weighted Average | 0.945 |
| | ASTM C29 (Rod), As-Received | 0.930 |
| | ASTM C29 (Rod), Weighted Average | 0.966 |
| | ASTM C29 (Shovel), As-Received | 0.922 |
| | ASTM C29 (Shovel), Weighted Average | 0.925 |
| Fine Aggregate | Particle Index | 0.984 |
| | NAA, Method A | 0.845 |
| | NAA, Method C | 0.606 |
| | Direct Shear | 0.674 |

CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH NATURAL SAND CONTENT.

The Particle Index Test. The Particle Index test was used to characterize the fine aggregate fraction and to determine if there is a correlation between Particle Index values and the natural sand content. Previous research indicated that this test method could separate natural and manufactured sands. A Particle Index value of 14 appeared to be the value that separated round sands from angular sands.

An extremely strong correlation was determined for the Particle Index value and the amount of natural sand in the aggregate blend. The result of this correlation is shown in figure 14. The $R^2$ value for this linear correlation was 0.995. This correlation is approximately the same as the Particle Index correlation with percent crushed fine aggregate. The Particle Index test is an excellent indicator of the amount of natural sand in the aggregate blend.

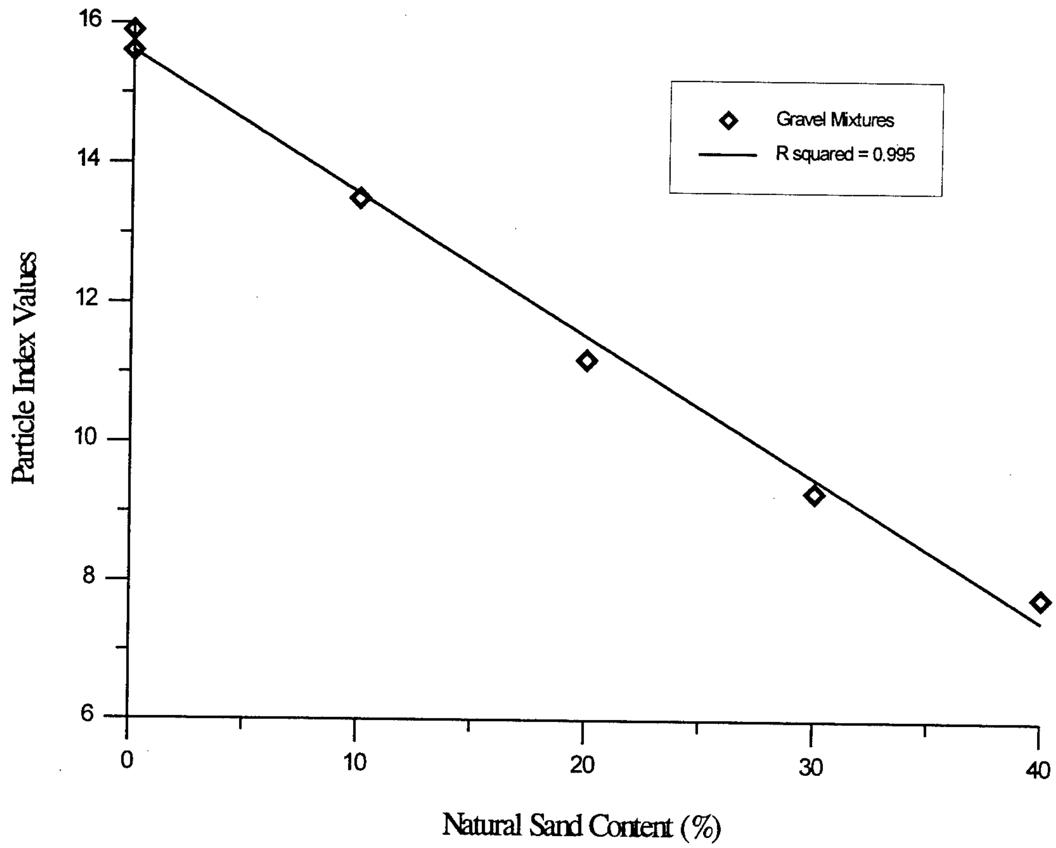


FIGURE 14. PARTICLE INDEX VALUES VERSUS NATURAL SAND CONTENT

NAA Particle Shape and Texture Test. The NAA particle shape and texture test was developed originally to measure the aggregate shape and texture of sand-sized materials. Several laboratory studies have evaluated this test method and found that this method can distinguish between round, smooth aggregates and angular, rough aggregates. An uncompacted void content of 44 to 45 is the separation of natural and manufactured sands for Method A. The test results from this study indicated that as the amount of natural sand increases the void contents decrease.

The correlations for void contents determined using NAA Methods A and C with the natural sand content are shown in figure 15. The correlation for Method A is extremely strong ($R^2 = 0.937$) while the correlation for Method C is not very strong ($R^2 = 0.481$). Based on this data, Method C should not be used to determine the natural sand content of an aggregate blend.

As previously reported, the direct shear test should produce a valid relationship between aggregate shape and texture and the angle of internal friction but fails to do so in many cases. The correlation of angle of internal friction to natural sand content is somewhat strong with a $R^2 = 0.780$. This correlation is shown in figure 16.

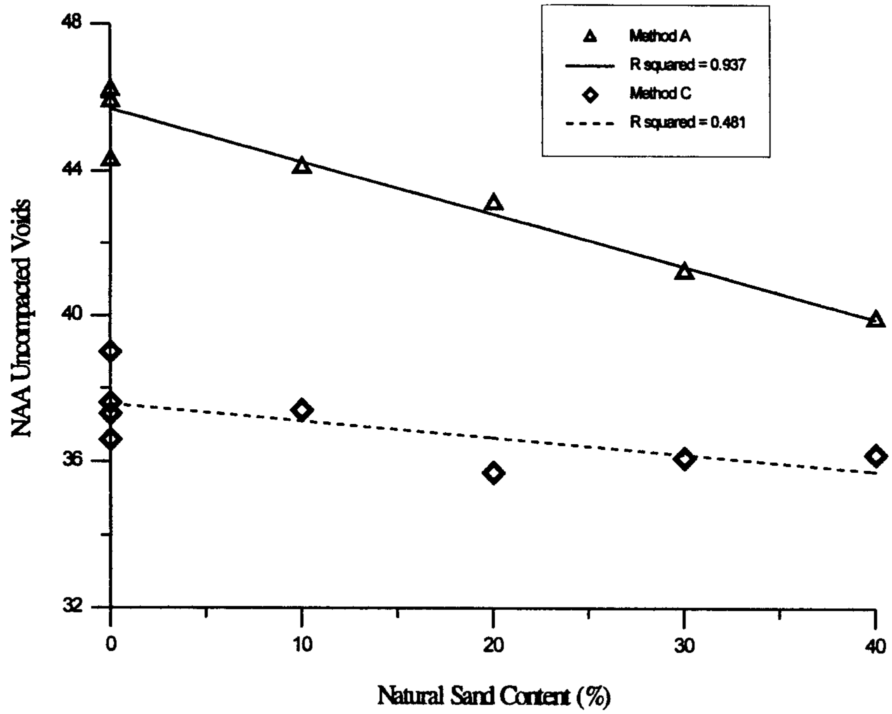


FIGURE 15. NAAP PARTICLE SHAPE AND TEXTURE VOID CONTENTS VERSUS NATURAL SAND CONTENT

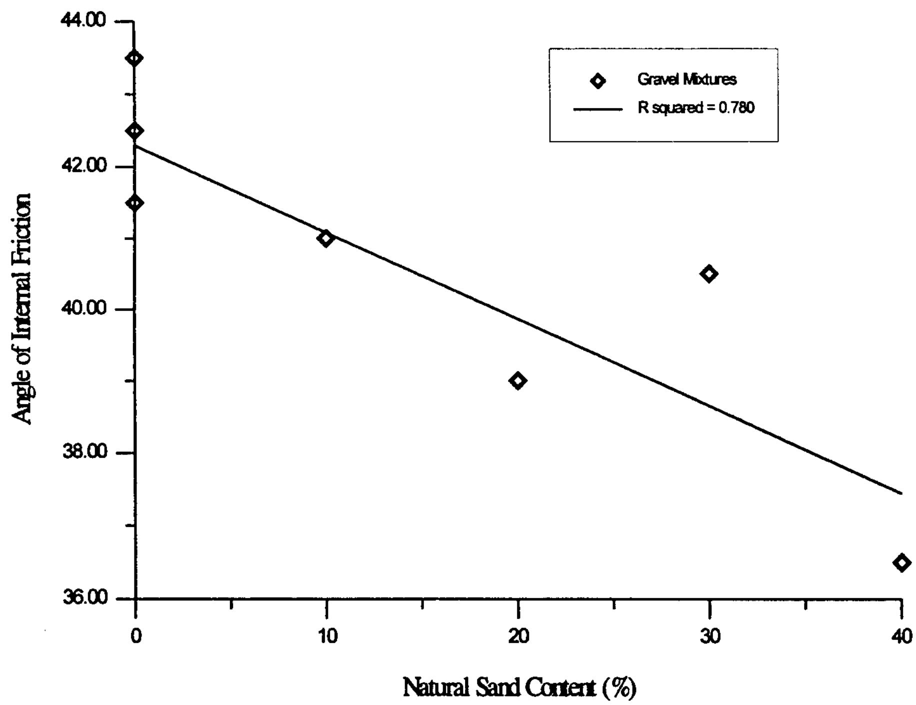


FIGURE 16. ANGLE OF INTERNAL FRICTION FROM DIRECT SHEAR TEST VERSUS NATURAL SAND CONTENT

Summary of Coefficients of Determination. A summary of coefficients of determination for aggregate particle characterization tests and the natural sand content is presented in table 14. The Particle Index test produced an extremely high correlation with the natural sand content which corresponds to the strong correlation the Particle Index test had with percent crushed particles. The two methods of the NAA procedure produced significantly different correlations. Method A produced a very strong correlation while Method C produced a below average correlation. The direct shear test produced an above average correlation with natural sand content but was not as effective as the Particle Index and NAA particle shape and texture tests.

TABLE 14. CORRELATION OF FINE AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH NATURAL SAND CONTENT

| Fine Aggregate Particle Characterization Test | Coefficient of Determination ($R^2$) |
|---|---|
| Particle Index | 0.995 |
| NAA - Method A | 0.937 |
| NAA - Method C | 0.481 |
| Direct Shear | 0.780 |

CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH PARTICLE INDEX TEST. As discussed earlier in this report, the Particle Index test has proven to correlate extremely well with aggregate particle shape and surface texture. This test method is proven and standardized, but due to the sample preparation time and time required to perform the test, this method is primarily used in research studies. Simpler, quicker test methods that correlate well to Particle Index test would be a viable alternative for specifications to characterize aggregate particle shape and surface texture. Analyses were conducted to establish relationships between the Particle Index test and the Modified NAA test, ASTM C29, NAA test, and direct shear test methods.

A summary of coefficients of determination for the aggregate particle characterization tests and the Particle Index test is presented in table 15. The results of these correlations are shown in figures 17-20. These correlations are separated into coarse and fine aggregate fractions. The Modified NAA test and ASTM C29 test methods were evaluated for the coarse aggregate fraction. Each of these correlations has an extremely strong linear correlation with the Particle Index values. The difference in these relationships is extremely small which means any of these test methods could be used to characterize coarse aggregate shape and texture.

The Particle Index values for fine aggregation fraction were correlated with the NAA test and direct shear test methods. The NAA test method produced a stronger correlation with Particle Index than did the direct shear test. Based on this data, the NAA particle shape and texture test could be used to characterize fine aggregate shape and texture.

TABLE 15. CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH PARTICLE INDEX VALUES

| Aggregate Size | Aggregate Particle Characterization Tests | Coefficient of Determination ($R^2$) |
|---|---|---|
| Coarse | Modified NAA, As-Received | 0.964 |
| | Modified NAA, Weighted Average | 0.996 |
| | ASTM C29 (Rod), As-Received | 0.935 |
| | ASTM C29 (Rod), Weighted Average | 0.988 |
| | ASTM C29 (Shovel), As-Received | 0.959 |
| | ASTM C29 (Shovel), Weighted Average | 0.997 |
| Fine | NAA, Method A | 0.865 |
| | NAA, Method C | 0.610 |
| | Direct Shear | 0.700 |

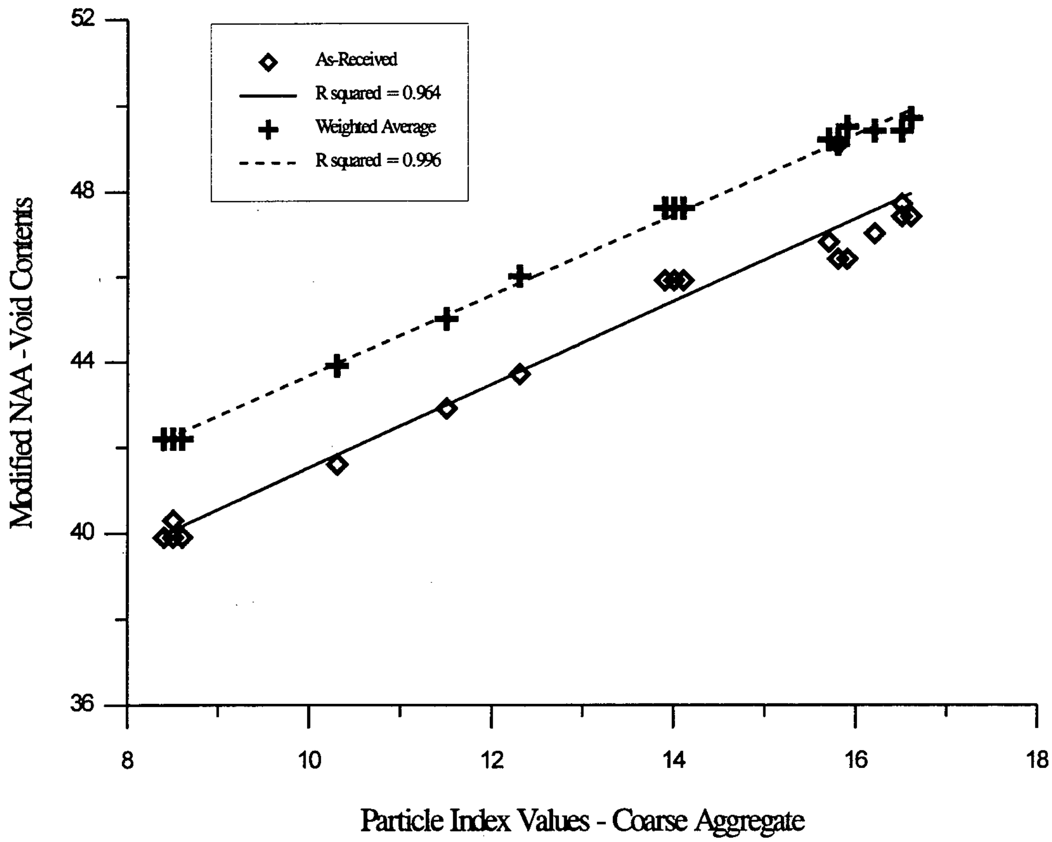


FIGURE 17. MODIFIED NAA PARTICLE SHAPE AND TEXTURE VOID CONTENTS VERSUS PARTICLE INDEX VALUES

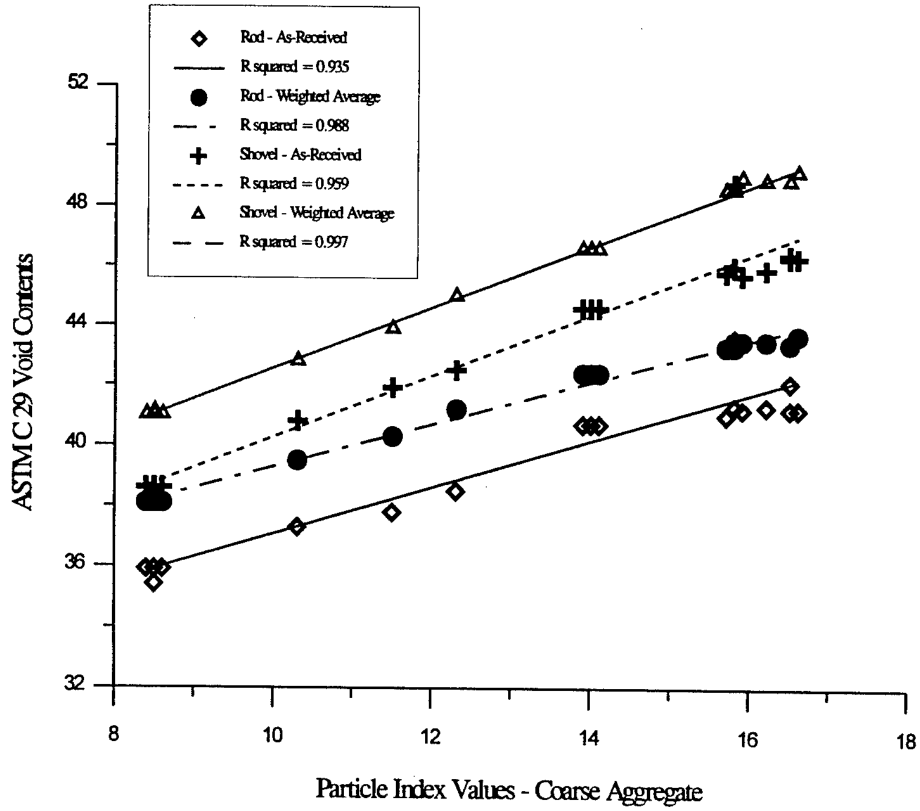


FIGURE 18. VOID CONTENTS FROM ASTM C29 METHOD VERSUS PARTICLE INDEX VALUES

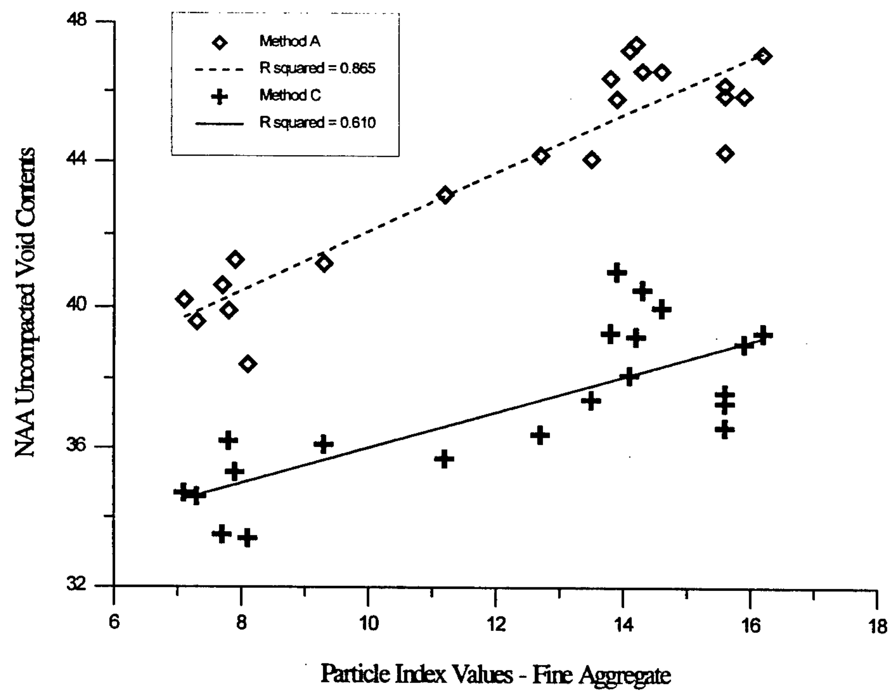


FIGURE 19. NAA PARTICLE SHAPE AND TEXTURE VOID CONTENTS VERSUS PARTICLE INDEX VALUES

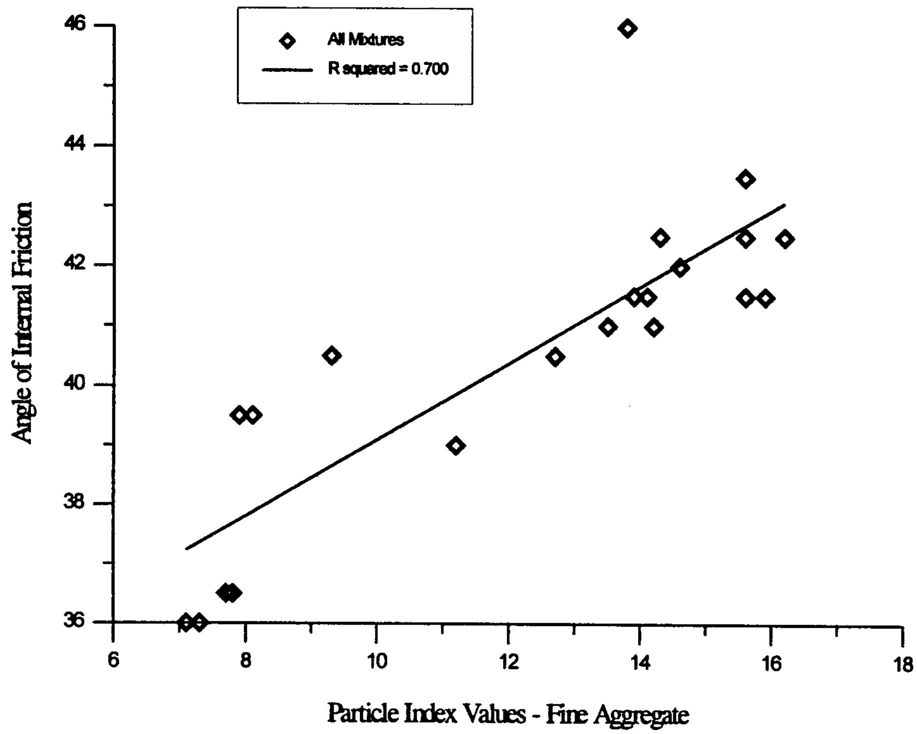


FIGURE 20. ANGLE OF INTERNAL FRICTION FROM DIRECT SHEAR TEST VERSUS PARTICLE INDEX VALUES

## PHASE II—AC-20 MIXTURES

This section presents and discusses the results of the preparation and testing of the 22 asphalt concrete mixtures produced with an AC-20 asphalt cement. This phase of the laboratory study was designed to determine the range of asphalt mixture properties that would be expected using material meeting the Item P-401 specification and the impact of deviations on the engineering properties (strength values and rutting characteristics) by using marginal or substandard aggregates. The test aggregate gradations were selected to determine the effects of variation in the shape of an aggregate gradation curve, the percentage of crushed coarse aggregates, and the amount of natural sand material in the aggregate blend. The AC-20 asphalt cement was used in this phase because this type of asphalt binder is the most common asphalt cement in the United States and would not interfere with the investigation of the influence of aggregate properties on the quality of the asphalt concrete mixtures.

Marshall mix designs were conducted for the aggregate blends to determine an optimum asphalt content at 4 percent air voids (voids total mix). In order to insure that the asphalt content did not influence the strength properties and rutting characteristics of the various mixtures, this void criteria was selected and held constant throughout the laboratory testing. All specimens were compacted with the Gyratory Testing Machine. The asphalt mixture's strength properties and rutting characteristics were evaluated with the Marshall mix properties, gyratory compaction properties, indirect tensile test, direct shear test, and the confined repeated load deformation test.

Analysis of the test results involved determining the amount of variation of asphalt mixture properties when marginal aggregates were substituted for high quality aggregates and correlating the aggregate characterization tests to the asphalt mixture properties with an emphasis on pavement deformation and rutting potential.

## MARSHALL MIX PROPERTIES.

The Marshall mix design with the modification of the compactive effort (gyratory compaction) was used to determine the optimum asphalt content for all asphalt concrete mixtures in Phase II. The design criteria specified in Item P-401 for asphalt mixtures designed for tire pressures greater than 100 psi is presented in table 16.

A summary of the average Marshall mix properties for the AC-20 mixtures is presented in table 17. The test results include unit weight, theoretical specific gravity, air voids, voids in mineral aggregates, voids filled with asphalt, and the Marshall stability and flow values. The void parameters and gravity values are an average of 24 specimens while the stability and flow values are an average of three to five specimens.

TABLE 16. DESIGN CRITERIA FOR ASPHALT CONCRETE MIXTURES—ITEM P-401

| Test | FAA Specification Requirement |
|---|---|
| Compactive effort, blows | 75 |
| Stability, lbs (minimum) | 2150 |
| Flow, 0.01 in. | 10-14 |
| Air voids, % | 2.8-4.2 |
| Voids in mineral aggregate, % (minimum) | 14 |
| Voids filled, % | 65-75 |

## GYRATORY COMPACTION PROPERTIES.

The Gyratory Testing Machine was used to compact all specimen for this laboratory study. The gyratory compactive effort used in this study was a 200 psi normal pressure, 1-degree gyration angle, and 30 revolutions of an oil-filled roller assembly. This compactive effort is equal to the 75-blow hand hammer effort that is normally used for heavy duty pavements. This compaction process was selected because the kneading action produces compacted specimen that have aggregate particle orientation similar to in-place pavements. The Gyratory Testing Machine also produces stress-strain measurements for each compacted specimens that can be used to evaluate the quality of an asphalt concrete mixture.

A summary of the average gyratory compaction properties for the AC-20 mixtures is presented in table 18. These test results include the GSI, GEPI, gyratory shear strength, and gyratory shear factors (GSF) values. The gyratory shear strength value is the shear strength of the compacted specimen determined from the static roller pressure readings and the GSF value is a ratio of the measured shear strength to the applied shear stress. The gyratory compaction properties are an average of six specimens for each mixture.

TABLE 17. SUMMARY OF MARSHALL MIX PROPERTIES AT OPTIMUM ASPHALT CONTENT FOR AC-20 MIXTURES

| Mix Number | Optimum Asphalt Content (%) | Bulk Specific Gravity | Theoretical Specific Gravity | Voids Total Mix (%) | Voids in Mineral Aggregate (%) | Voids Filed (%) | Unit Weight (pcf) | Stability (lbs) | Flow (0.01 in.) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.7 | 2.530 | 2.636 | 4.0 | 15.5 | 74.1 | 157.9 | 2017 | 11.8 |
| 2 | 5.2 | 2.503 | 2.598 | 3.7 | 16.2 | 77.4 | 156.2 | 1524 | 12.6 |
| 3 | 5.0 | 2.500 | 2.601 | 3.9 | 15.9 | 75.6 | 156.0 | 2232 | 12.3 |
| 4 | 4.9 | 2.510 | 2.608 | 3.8 | 15.6 | 76.0 | 156.6 | 2125 | 11.3 |
| 5 | 5.6 | 2.481 | 2.582 | 3.9 | 17.3 | 77.4 | 154.8 | 2145 | 11.3 |
| 6 | 4.3 | 2.523 | 2.633 | 4.2 | 14.6 | 71.4 | 157.4 | 2014 | 12.9 |
| 7 | 4.6 | 2.500 | 2.614 | 4.4 | 15.5 | 71.7 | 156.0 | 1872 | 10.7 |
| 8 | 4.0 | 2.530 | 2.636 | 4.0 | 13.8 | 70.9 | 157.9 | 1851 | 10.8 |
| 9 | 6.5 | 2.295 | 2.387 | 3.8 | 18.2 | 78.9 | 143.2 | 1554 | 11.1 |
| 10 | 6.0 | 2.314 | 2.406 | 3.8 | 17.2 | 77.8 | 144.4 | 1610 | 10.2 |
| 11 | 5.8 | 2.320 | 2.415 | 3.9 | 16.9 | 76.7 | 144.8 | 1370 | 9.4 |
| 12 | 5.6 | 2.328 | 2.426 | 4.1 | 16.6 | 75.6 | 145.2 | 1107 | 8.0 |
| 13 | 7.0 | 2.277 | 2.368 | 3.8 | 19.2 | 80.0 | 142.1 | 2035 | 13.0 |
| 14 | 4.7 | 2.348 | 2.437 | 3.7 | 14.3 | 74.1 | 146.5 | 1192 | 8.9 |
| 15 | 4.6 | 2.356 | 2.447 | 3.7 | 14.1 | 73.9 | 147.0 | 1147 | 8.8 |
| 16 | 4.8 | 2.355 | 2.445 | 3.7 | 14.6 | 74.7 | 146.9 | 1074 | 8.4 |
| 17 | 4.8 | 2.353 | 2.449 | 3.9 | 14.8 | 73.5 | 146.8 | 1031 | 8.3 |
| 18 | 4.9 | 2.345 | 2.449 | 4.3 | 15.3 | 72.2 | 146.3 | 916 | 7.1 |
| 19 | 6.2 | 2.291 | 2.389 | 4.1 | 17.8 | 76.8 | 142.9 | 1454 | 10.4 |
| 20 | 6.7 | 2.277 | 2.376 | 4.2 | 18.8 | 78.0 | 142.1 | 1610 | 11.8 |
| 21 | 6.7 | 2.285 | 2.375 | 3.8 | 18.5 | 79.8 | 142.6 | 1523 | 11.4 |
| 22 | 6.3 | 2.294 | 2.387 | 4.0 | 17.9 | 77.7 | 143.0 | 1525 | 11.3 |

TABLE 18. SUMMARY OF GYRATORY COMPACTION PROPERTIES FOR AC-20 MIXTURES

| Mix Number | Thickness (in.) | Gyratory Stability Index (GSI) | Gyratory Elasto-Plastic Index (GEPI) | Gyratory Shear Strength (psi) | Gyratory Shear Factor (GSF) |
|---|---|---|---|---|---|
| 1 | 2.458 | 1.01 | 1.24 | 104 | 1.62 |
| 2 | 2.509 | 0.99 | 1.28 | 115 | 1.80 |
| 3 | 2.470 | 0.99 | 1.24 | 130 | 2.03 |
| 4 | 2.460 | 0.99 | 1.22 | 110 | 1.72 |
| 5 | 2.477 | 0.99 | 1.29 | 111 | 1.73 |
| 6 | 2.451 | 1.00 | 1.24 | 124 | 1.94 |
| 7 | 2.453 | 1.00 | 1.19 | 120 | 1.87 |
| 8 | 2.469 | 0.99 | 1.24 | 172 | 2.69 |
| 9 | 2.677 | 0.99 | 1.45 | 200 | 3.13 |
| 10 | 2.653 | 0.99 | 1.50 | 179 | 2.80 |
| 11 | 2.624 | 0.99 | 1.54 | 203 | 3.17 |
| 12 | 2.602 | 0.99 | 1.56 | 213 | 3.34 |
| 13 | 2.705 | 1.00 | 1.46 | 159 | 2.49 |
| 14 | 2.542 | 0.99 | 1.67 | 164 | 2.56 |
| 15 | 2.535 | 1.00 | 1.63 | 160 | 2.50 |
| 16 | 2.545 | 1.00 | 1.70 | 184 | 2.87 |
| 17 | 2.549 | 0.98 | 1.70 | 160 | 2.50 |
| 18 | 2.535 | 0.99 | 1.74 | 180 | 2.81 |
| 19 | 2.613 | 1.00 | 1.55 | 149 | 2.35 |
| 20 | 2.690 | 0.99 | 1.50 | 191 | 2.98 |
| 21 | 2.690 | 0.99 | 1.52 | 197 | 3.08 |
| 22 | 2.677 | 0.99 | 1.55 | 206 | 3.22 |

As discussed earlier in this report, the GEPI index is a value that indicates the quality (shape and surface texture) of the aggregate in a compacted asphalt mixture. This value was considered to be an aggregate particle characterization test conducted on the asphalt-aggregate mixture. The analysis of this aggregate particle characterization test included correlations with percent crushed particles, amount of natural sand material, and the other aggregate characterization tests that had correlated well with the aggregate shape and texture properties.

A summary of the correlations for the GEPI index and the aggregate particle characterization tests is presented in table 19. These correlations are separated into composite, coarse, and fine aggregate fractions. The percentage of crushed particles and the Particle Index test were evaluated for the composite blend. The $R^2$ value for the correlation with the Particle Index test was very strong ($R^2 = 0.855$). The Particle Index test and the Modified NAA particle shape and texture test for the coarse aggregate fraction correlated very well with the GEPI values, 0.832 and 0.811 respectively. The correlations for the GEPI values and the fine aggregate particle characterization tests were not very strong and indicated the GEPI value was influenced by the total aggregate blend. These data also indicated that the GEPI values had a stronger relationship with other aggregate particle characterization tests than with the percentage of crushed particles in the aggregate blend.

TABLE 19. CORRELATION OF GYRATORY ELASTO-PLASTIC INDEX VALUES WITH AGGREGATE PARTICLE CHARACTERIZATION TESTS

| Aggregate Size | Aggregate Particle Characterization Test | Coefficient of Determination ($R^2$) |
|---|---|---|
| Composite | Percent Crushed Particles | 0.707 |
| | Particle Index | 0.855 |
| Coarse Aggregate | Percent Crushed Particles | 0.638 |
| | Particle Index | 0.832 |
| | Modified NAA-Weighted Avg | 0.811 |
| Fine Aggregate | Percent Crushed Particles | 0.450 |
| | Natural Sand Content | 0.461 |
| | Particle Index | 0.450 |
| | NAA-Method A | 0.659 |

Several observations and trends were observed from the GEPI values. In evaluating the effect of the shape of aggregate gradation curve, the GEPI value did not vary significantly for Mixes 1-8. These results were expected because the same aggregate type (crushed limestone) was used in all these mixtures. In evaluating the effect of the percentage of crushed coarse aggregate, the GEPI value did distinguish between the difference in percent crushed coarse particles, as the percentage of uncrushed coarse aggregate increased, the GEPI value increased. Mix 13 (crushed coarse aggregate) had a GEPI value of 1.46 while Mix 19 (uncrushed coarse aggregate had a GEPI value of 1.55. The amount of natural sand material had the same effect on the GEPI value as did the percentage of crushed coarse aggregate. The GEPI value increased as the amount of natural sand increased. The GEPI values ranged from 1.46 for Mix 13 (crushed fine aggregate) to 1.56 for Mix 12 (40 percent natural sand).

INDIRECT TENSILE.

The indirect tensile test was conducted to determine the tensile strengths of the various marginal aggregate asphalt mixtures. This test was conducted on a minimum of three specimens at two test temperatures, 77 and 104°F. These test temperatures were selected to evaluate the various aggregate properties at medium and high pavement temperatures where most pavement rutting occurs. The tensile strengths calculated according to ASTM D 4123 are summarized in table 20 for the AC-20 mixtures. Six specimen were tested for each AC-20 mixture.

TABLE 20. SUMMARY OF INDIRECT TENSILE VALUES FOR AC-20 MIXTURES

| Mix Number | Tensile Strength at 77°F (psi) | Tensile Strength at 104°F (psi) |
|---|---|---|
| 1 | 97.5 | 35.8 |
| 2 | 68.8 | 31.0 |
| 3 | 99.6 | 42.7 |
| 4 | 93.7 | 48.7 |
| 5 | 93.0 | 45.9 |
| 6 | 102.2 | 45.4 |
| 7 | 100.6 | 44.0 |
| 8 | 99.3 | 45.6 |
| 9 | 56.7 | 30.2 |
| 10 | 61.9 | 31.2 |
| 11 | 75.4 | 32.3 |
| 12 | 67.6 | 25.7 |
| 13 | 70.9 | 29.5 |
| 14 | 84.4 | 38.7 |
| 15 | 98.6 | 39.6 |
| 16 | 111.4 | 39.1 |
| 17 | 109.3 | 36.2 |
| 18 | 76.2 | 23.2 |
| 19 | 78.0 | 24.3 |
| 20 | 91.3 | 22.5 |
| 21 | 83.2 | 28.4 |
| 22 | 102.5 | 31.2 |

## DIRECT SHEAR.

The direct shear test was conducted to determine the angle of internal friction and the shear strength of asphalt concrete mixtures under several normal stress conditions. A standard Marshall specimen (4 in. diameter and 2.5 in. thick) was sheared at 140°F in the simple shear test device. The shear load was applied at a constant rate until failure. At failure, the maximum shear load and displacement were recorded. The shear strength values were determined for three normal stress levels (100, 200, and 300 psi). The calculated shear strength values and the analytically determined angle of internal friction and cohesion values are presented in table 21 for the AC-20 mixtures. Six specimens were tested for each AC-20 mixture.

TABLE 21. SUMMARY OF DIRECT SHEAR DATA FOR AC-20 MIXTURES

| Mix Number | Angle of Internal Friction (Ø) | Cohesion-Y-Axis Intercept (psi) | Shear Strengths at Normal Stress Levels | | |
|---|---|---|---|---|---|
| | | | 100 psi | 200 psi | 300 psi |
| 1 | 21.6 | 42.8 | 78.0 | 130.8 | 157.1 |
| 2 | 19.3 | 46.5 | 84.5 | 110.3 | 154.4 |
| 3 | 22.8 | 33.2 | 76.2 | 115.5 | 160.5 |
| 4 | 18.2 | 67.9 | 94.3 | 146.5 | 160.1 |
| 5 | 17.9 | 53.9 | 84.8 | 121.1 | 149.3 |
| 6 | 19.2 | 62.7 | 94.5 | 138.1 | 164.0 |
| 7 | 18.1 | 59.6 | 86.6 | 136.5 | 151.9 |
| 8 | 14.5 | 71.9 | 97.1 | 125.3 | 148.9 |
| 9 | 11.5 | 52.7 | 72.8 | 94.2 | 113.6 |
| 10 | 14.7 | 45.7 | 70.9 | 100.1 | 123.3 |
| 11 | 16.0 | 39.6 | 69.3 | 95.2 | 126.8 |
| 12 | 16.2 | 32.4 | 63.8 | 86.0 | 122.1 |
| 13 | 15.6 | 46.9 | 73.5 | 105.2 | 129.2 |
| 14 | 15.0 | 28.3 | 55.6 | 80.6 | 109.1 |
| 15 | 12.0 | 50.3 | 71.6 | 93.0 | 114.3 |
| 16 | 14.2 | 42.0 | 67.8 | 91.2 | 118.3 |
| 17 | 11.6 | 31.3 | 54.5 | 67.3 | 95.7 |
| 18 | 11.4 | 45.7 | 70.0 | 78.0 | 110.4 |
| 19 | 13.7 | 53.3 | 68.6 | 120.3 | 117.5 |
| 20 | 13.7 | 40.8 | 67.0 | 86.0 | 115.9 |
| 21 | 7.7 | 74.7 | 91.4 | 95.5 | 118.5 |
| 22 | 13.9 | 43.7 | 66.4 | 97.6 | 116.0 |

CONFINED REPEATED LOAD DEFORMATION.

The confined repeated load deformation test was conducted to evaluate and determine the rutting characteristics of these AC-20 mixtures. The confined repeated load deformation test is considered to be one of the best laboratory test procedures to evaluate asphalt concrete mixtures for rutting potential. The test temperature of 140°F was used to simulate maximum pavement temperatures and to enhance the influence of aggregate properties on the mixture's behavior. A summary of the confined repeated load deformation tests is presented in table 22. These test results include deformation or strain values, creep modulus or stiffness values, and the slope of the steady state portion of the creep curve plotted on a log scale. The confined repeated load deformation test was conducted on a minimum of four specimens for each mixture.

TABLE 22. SUMMARY OF CONFINED REPEATED LOAD DEFORMATION TEST DATA FOR AC-20 MIXTURES

| Mix Number | Thickness (in.) | Voids Total Mix (%) | Total Strain (in/in.) | Permanent Strain (in/in.) | Resilient Strain (in/in.) | Creep Modulus Based on Axial Stress (psi) | Creep Modulus Based on Deviator Stress (psi) | Slope of Log Curve |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.446 | 4.0 | 0.0211 | 0.0211 | 0.0000 | 11423 | 9519 | 0.109 |
| 2 | 2.546 | 3.8 | 0.0284 | 0.0283 | 0.0001 | 8769 | 7326 | 0.212 |
| 3 | 2.479 | 3.9 | 0.0206 | 0.0205 | 0.0001 | 12041 | 10077 | 0.093 |
| 4 | 2.475 | 3.7 | 0.0148 | 0.0146 | 0.0002 | 16522 | 13998 | 0.121 |
| 5 | 2.478 | 3.9 | 0.0205 | 00200 | 0.0005 | 11782 | 10061 | 0.085 |
| 6 | 2.468 | 4.3 | 0.0270 | 0.0266 | 0.0004 | 9069 | 7672 | 0.171 |
| 7 | 2.473 | 4.4 | 0.0151 | 0.0145 | 0.0006 | 15926 | 13900 | 0.105 |
| 8 | 2.478 | 4.1 | 0.0232 | 0.0230 | 0.0002 | 10343 | 8699 | 0.115 |
| 9 | 2.677 | 4.1 | 0.0355 | 0.0350 | 0.0005 | 6828 | 5795 | 0.214 |
| 10 | 2.638 | 4.0 | 0.0387 | 0.0386 | 0.0001 | 6265 | 5235 | 0.253 |
| 11 | 2.606 | 3.7 | 0.0394 | 0.0384 | 0.0010 | 6303 | 5413 | 0.195 |
| 12 | 2.614 | 4.1 | 0.0400 | 0.0399 | 0.0001 | 6027 | 5026 | 0.259 |
| 13 | 2.737 | 4.3 | 0.0352 | 0.0352 | 0.0001 | 6912 | 5771 | 0.243 |
| 14 | 2.507 | 3.7 | 0.0849 | 0.0843 | 0.0006 | 2828 | 2373 | 0.365 |
| 15 | 2.535 | 3.6 | 0.0574 | 0.0574 | 0.0000 | 4240 | 3538 | 0.320 |
| 16 | 2.538 | 3.9 | 0.0665 | 0.0664 | 0.0001 | 3792 | 3165 | 0.328 |
| 17 | 2.563 | 3.9 | 0.0897 | 0.0890 | 0.0007 | 2714 | 2277 | 0.356 |
| 18 | 2.574 | 4.2 | 0.1022 | 0.1020 | 0.0003 | 2378 | 1986 | 0.415 |
| 19 | 2.639 | 4.1 | 0.0495 | 0.0495 | 0.0000 | 4900 | 4085 | 0.247 |
| 20 | 2.704 | 4.2 | 0.0408 | 0.0407 | 0.0001 | 5931 | 4950 | 0.213 |
| 21 | 2.651 | 3.9 | 0.0453 | 0.0452 | 0.0001 | 5310 | 4432 | 0.238 |
| 22 | 2.674 | 3.9 | 0.0447 | 0.0445 | 0.0002 | 5413 | 4527 | 0.248 |

## ANALYSIS AND DISCUSSION OF DATA.

This phase of the laboratory study was conducted to evaluate the engineering properties (strength values and rutting characteristics) of each asphalt concrete mixture produced with an AC-20 asphalt binder. This laboratory testing determined the range of properties that would be expected using aggregates meeting the P-401 specification and the impact of deviations on engineering properties by using marginal aggregates. The analysis of the test results involved determining the amount of variation of asphalt mixture properties when marginal, substandard aggregates were substituted for high quality aggregates and correlating the aggregate particle characterization tests to the permanent deformation properties. An additional analysis was conducted to correlate the relationship of asphalt mixture properties with the rutting characteristic test results of the confined repeated load deformation test.

The test aggregate gradations were selected and designed to determine the effects of variation in the shape of an aggregate gradation curve (Mixes 1-8), the percentage of crushed coarse aggregate (Mixes 13, 19-22), and the amount of natural sand material in the aggregate blend (Mixes 9-18).

IMPACT OF DEVIATION FROM P-401 SPECIFICATION. The asphalt mixture tests were conducted to characterize and quantify the mixture strength and rutting characteristics of each aggregate blend. In order to determine variation or percent difference, an accepted standard or control mixture was established. Mix 1 (crushed limestone) and Mix 13 (crushed gravel) were selected as the control mixtures for their respective aggregate types. Mix 1 was the control mixture for the evaluation of the shape of the aggregate gradation curve and Mix 13 was the control mixture for the evaluation of the percentage of crushed coarse aggregate and the amount of natural sand in the aggregate blend.

Variation in Shape of Aggregate Gradation Curve. As discussed earlier in this report, the best way to determine the effect of the general shape of the aggregate gradation curve is to compare asphalt mixture properties for proven field tested gradations to mixtures produced with substandard gradations. The asphalt mixture properties were determined using Marshall mix design, gyratory compaction process, indirect tensile test, direct shear test, and the confined repeated load deformation test.

Several observations and trends were observed from the Marshall mix properties for Mixes 1-8. The optimum asphalt content varied from 4.0 to 5.6 percent. Mix 1 (control) which had the maximum density aggregate gradation had an optimum asphalt content of 4.7 percent. The dense-graded mixtures that had either a coarser or finer gradation than the control mixture (Mixes 2, 3, and 5) had a higher optimum asphalt content (5.0 to 5.6 percent). Mix 6 which contained an excessive amount of material smaller than the No. 200 sieve had a lower optimum asphalt content (4.3 percent). The poorly-graded gap mixtures (Mixes 4, 7, and 8) had variable optimum asphalt contents at 4 percent air voids.

The voids in mineral aggregate (VMA) values for these mixtures ranged from 13.8 to 17.3 percent. Only Mix 8 had a VMA value below the minimum requirement of 14. The VMA values followed the same trends as the optimum asphalt content values. Mix 5 had the highest VMA and optimum asphalt content values while Mix 8 had the lowest VMA and optimum asphalt content values.

The Marshall stability values for Mixes 1-8 ranged from 1524 to 2232 lbs. Only Mix 3 met the minimum FAA requirement of 2150 lbs. The remaining mixtures except for Mix 2 produced Marshall stability values greater than 1800 lbs. The Marshall stability value for Mix 2 (1524 lbs) was extremely low and would not be accepted for a heavy duty asphalt pavement. The Marshall flow values for each mixture met the FAA specification requirements (10-14). The flow values ranged from 10.7 to 12.9.

The changes in Marshall mix properties between the control mix (Mix 1) and the remaining mixtures due to variations in the shape of aggregate gradation are presented in table 23 and shown graphically in figure 21. The Marshall stability values indicate that the shape of the aggregate gradation curve does affect this mixture property. The control mixture (Mix 1) had an average stability of 2017 lbs. This value is slightly below the minimum FAA requirement, but is above the typically accepted minimum value of 1800 often specified for heavy-duty pavements. Mixes 3, 4, and 5 produced stability values that were greater than the control mixture. These stability values ranged from 2125 to 2232 lbs, or a moderate increase of 5.4 to 10.7 percent. The largest reduction in Marshall stability values was produced by Mix 2, a 24.4 percent decrease. The Marshall flow values obtained in this study did not produce large deviations between mixtures. The Marshall stability/flow ratio has been used as an index for mixture stiffness [45]. Mixes 3, 4, 5, and 7 produced a positive increase in the stability/flow ratio that ranged from 2.3 to 11.1 percent. The largest decrease in this ratio was produced by Mix 2, a 29.2 percent decrease.

TABLE 23. MARSHALL MIX PROPERTIES FOR AC-20 MIXTURES EVALUATING THE SHAPE OF AGGREGATE GRADATION CURVE

| Mix Number | Marshall Stability (lbs) | Percent Difference[1] | Marshall Flow (0.01 in.) | Percent Difference[1] | Stability/ Flow Ratio | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 1 | 2017 | ---- | 11.8 | ---- | 171 | ---- |
| 2 | 1524 | -24.4 | 12.6 | +6.8 | 121 | -29.2 |
| 3 | 2232 | +10.7 | 12.3 | +4.2 | 182 | +6.4 |
| 4 | 2125 | +5.4 | 11.3 | -4.2 | 188 | +9.9 |
| 5 | 2145 | +6.4 | 11.3 | -4.2 | 190 | +11.1 |
| 6 | 2014 | -0.2 | 12.9 | +9.3 | 156 | -8.8 |
| 7 | 1872 | -7.2 | 10.7 | -9.3 | 175 | +2.3 |
| 8 | 1851 | -8.2 | 10.8 | -8.5 | 171 | 0.0 |

[1] Relative to control mix (Mix 1)

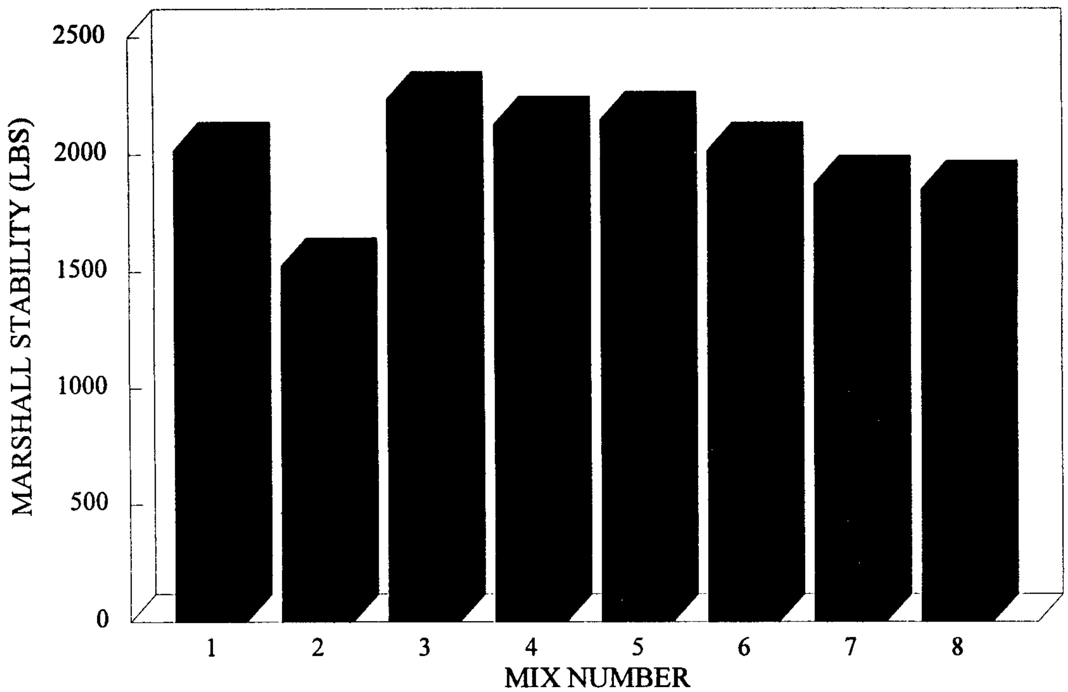


FIGURE 21. EFFECT OF SHAPE OF AGGREGATE GRADATION ON MARSHALL STABILITY VALUES FOR AC-20 MIXTURES

The gyratory compaction property that relates to mixture strength and stiffness is the gyratory shear strength value. The gyratory shear strength values presented in table 18 were inconsistent and produced no conclusive trends with the shape of the aggregate gradation curve.

Indirect tensile strength values are primarily dependent on the type of asphalt binder and the temperature of testing. The test results in table 20 indicate that the test temperature had a significant affect on the tensile strength values. The tensile strength values for these mixtures indicated that the tensile strength is reduced by 50 to 60 percent when the test temperature was raised from 77 to 104°F. However, the indirect tensile strength values were inconsistent when evaluating the shape of the aggregate gradation curve.

The direct shear strength test results presented in table 21 showed that the variation for direct shear strengths at the 200 psi normal stress level were not significant. The shear strength values are inconsistent and produced no conclusive trends with the shape of the aggregate gradation curve.

Several observations and trends were observed from the confined repeated load deformation test results. The effect of the shape of the aggregate gradation curve was evident in the permanent strain values, creep modulus values, and the slope of the log deformation curve. The mixtures that produced the better rutting characteristics were the aggregate gradations finer than the maximum density line (Mixes 3 and 5) and two poorly graded gap gradations (Mixes 4 and 7).

The differences in the confined repeated load deformation test results are presented in table 24 and shown graphically in figures 22-24. The permanent strain value for the control mixture was 0.0211 in/in. Mixes 3, 4, 5, and 7 produced strain values lower than the control mixture by 2.8 to 31.3 percent. Mixes 4 and 7 produced almost a third less permanent deformation which was considered a significant amount. Mixes 2 and 6 produced permanent deformation values 26.1 and 34.1 percent greater than the control mixture. The trends for the creep modulus values followed the trends for the permanent strain values. The slope values indicated that Mixes 3, 5 and 7 produced the lowest rate of rutting while Mixes 2 and 6 produced the highest rate of rutting. The percent difference (increase) in rate of rutting for Mixes 2 and 6 was significantly large, 94.5 and 56.9 percent, respectively.

TABLE 24. CONFINED REPEATED LOAD DEFORMATION TEST RESULTS FOR AC-20 MIXTURES EVALUATING THE SHAPE OF THE AGGREGATE GRADATION CURVE

| Mix Number | Permanent Strain (in/in.) | Percent Difference[1] | Creep Modulus (psi) | Percent Difference[1] | Slope of Log Curve | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 1 | 0.0211 | -- | 11423 | -- | 0.109 | -- |
| 2 | 0.0283 | +34.1 | 8769 | -23.2 | 0.212 | +94.5 |
| 3 | 0.0205 | -2.8 | 12041 | +5.4 | 0.093 | -14.7 |
| 4 | 0.0146 | -30.8 | 16522 | +44.6 | 0.121 | +11.0 |
| 5 | 0.0200 | -5.2 | 11782 | +3.1 | 0.085 | -22.0 |
| 6 | 0.0266 | +26.1 | 9069 | -20.6 | 0.171 | +56.9 |
| 7 | 0.0145 | -31.3 | 15926 | +39.4 | 0.105 | -3.7 |
| 8 | 0.0230 | +9.0 | 10343 | -9.5 | 0.115 | +5.5 |

[1] Relative to control mix (Mix 1)

Percentage of Crushed Coarse Aggregate. The effect of the percentage of crushed coarse aggregates was evaluated in Mixes 13, 19, and 20. The asphalt mixture properties were determined using the Marshall stability and flow test, gyratory shear strength, indirect tensile test, direct shear test, and confined repeated load deformation test. Due to the inconsistency and lack of significant conclusive trends with aggregate properties, the gyratory shear strength, indirect tensile strengths, and direct shear strength will only be presented and not discussed.

Several observations and trends were observed from the Marshall mix properties for Mixes 13 and 19-22. The optimum asphalt content values for these mixtures ranged from 6.2 to 7.0 percent. The optimum asphalt content value decreased as the percentage of uncrushed coarse aggregate increased. A significant decrease in optimum asphalt occurred between the 50 percent and 30 percent crushed coarse aggregate mixtures. The voids in mineral aggregate (VMA) values for these mixtures were all above the minimum FAA specification requirement of 14. The VMA values ranged from 17.8 to 19.2 percent. These VMA values decreased with an increase in the percentage of uncrushed coarse aggregate. The Marshall stability values for these mixtures did not meet the minimum value of 2150 lbs. Only Mix 13 (control mix) was close to the minimum requirement with a value for 2035 lbs. The remaining mixtures produced Marshall stability values near 1600 lbs and lower. These stability values are not acceptable for airport pavements. The flow values for each of these mixtures were acceptable but the trend was to decrease with an increase in uncrushed coarse aggregate.

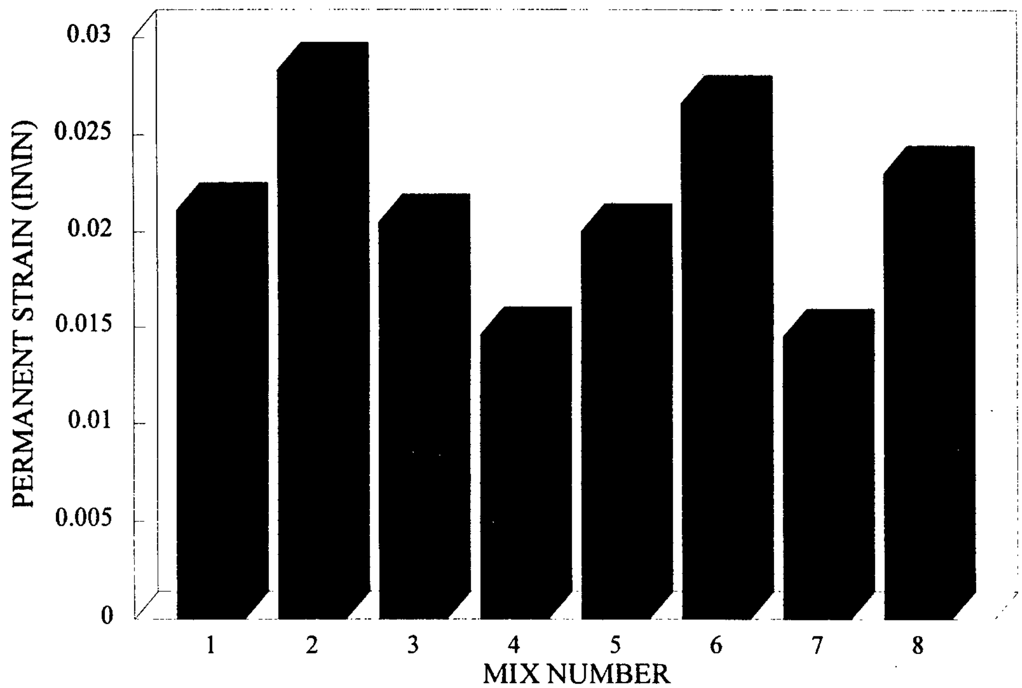


FIGURE 22. EFFECT OF SHAPE OF AGGREGATE GRADATION ON PERMANENT STRAIN VALUES FOR AC-20 MIXTURES

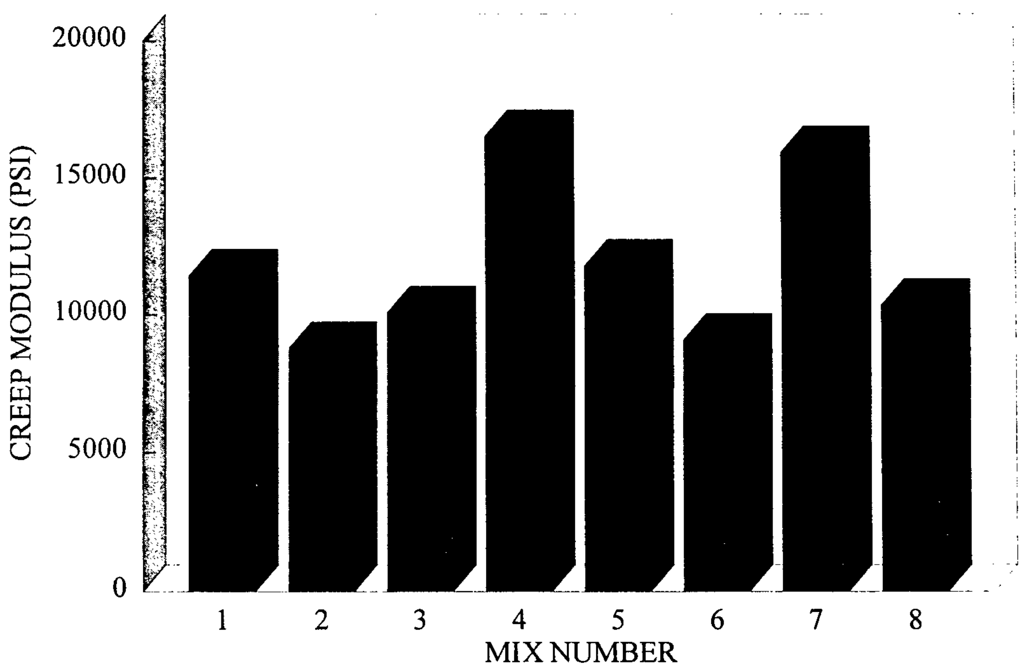


FIGURE 23. EFFECT OF SHAPE OF AGGREGATE GRADATION ON CREEP MODULUS VALUES FOR AC-20 MIXTURES

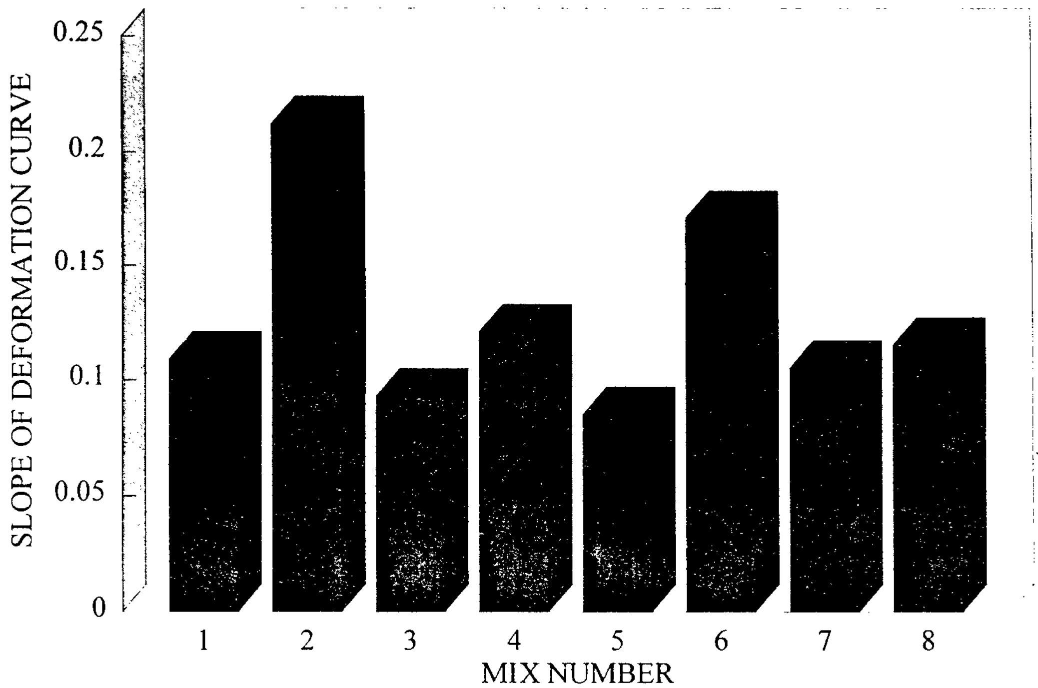


FIGURE 24. EFFECT OF SHAPE OF AGGREGATE GRADATION ON SLOPE OF DEFORMATION CURVE FOR AC-20 MIXTURES

The changes in the Marshall mix properties are presented in table 25 and shown graphically in figure 25. The Marshall stability values indicate that the percentage of crushed coarse aggregate significantly effects this mixture properly. The control mixture (Mix 13) had an average Marshall stability of 2035 lbs. while the remaining mixtures produced stability values much lower (1454 to 1610 lbs.). The stability values decreased as the percentage of uncrushed coarse aggregate increased. This data indicated a large decrease in stability when the percent crushed coarse aggregate was reduced from 100 percent crushed (Mix 13) to 70 percent crushed (Mix 20). The Marshall stability/flow ratio also showed the identical trend, as the percentage of uncrushed coarse aggregate increased, the ratio decreased.

TABLE 25. MARSHALL MIX PROPERTIES FOR AC-20 MIXTURES EVALUATING THE PERCENTAGE OF CRUSHED COARSE AGGREGATE

| Mix Number | Marshall Stability (lbs) | Percent Difference[1] | Marshall Flow (0.01 in.) | Percent Difference[1] | Stability/ Flow Ratio | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 13 | 2035 | -- | 13.0 | -- | 157 | -- |
| 19 | 1454 | -28.6 | 10.4 | -20.0 | 140 | -10.8 |
| 20 | 1610 | -20.9 | 11.8 | -9.2 | 136 | -13.4 |
| 21 | 1523 | -25.2 | 11.4 | -12.3 | 134 | -14.7 |
| 22 | 1525 | -25.1 | 11.3 | -13.1 | 135 | -14.0 |

[1] Relative to control mix (Mix 13)

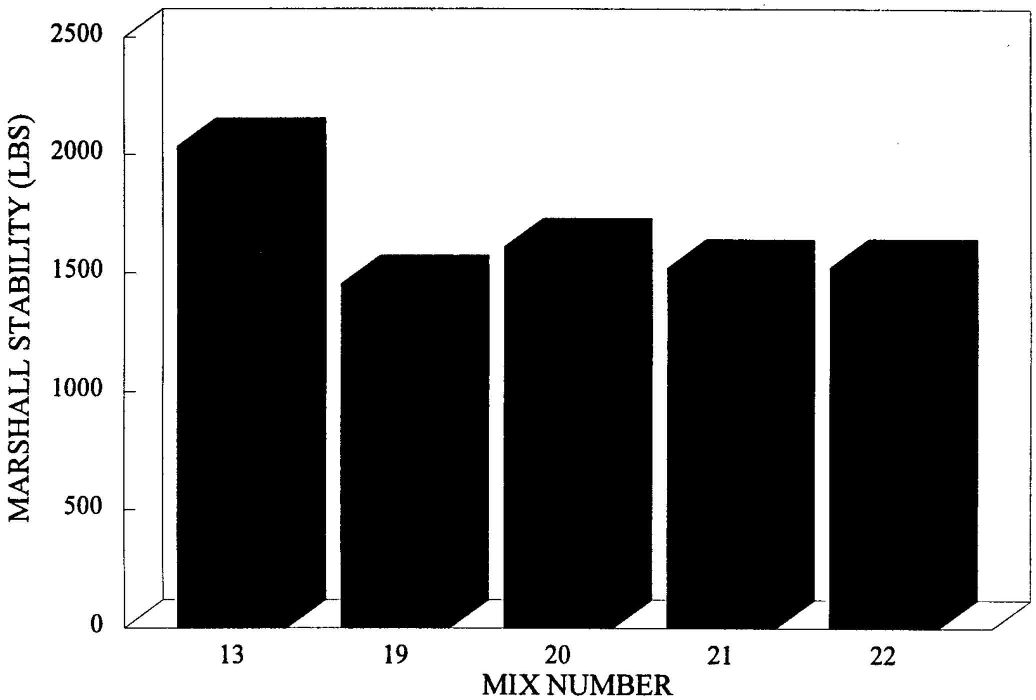


FIGURE 25. EFFECT OF CRUSHED COARSE AGGREGATE ON MARSHALL STABILITY VALUES FOR AC-20 MIXTURES

The confined repeated load deformation test results indicated that the percentage of crushed coarse aggregate did affect the rutting characteristics of these mixtures. The overall trend was as the percentage of crushed coarse aggregate decreased, the rutting potential for the mixtures increased. The calculated percent difference for these test results are presented in table 26 and shown graphically in figures 26 and 27.

TABLE 26. CONFINED REPEATED LOAD DEFORMATION TEST RESULTS FOR AC-20 MIXTURES EVALUATING THE PERCENTAGE OF CRUSHED COARSE AGGREGATE

| Mix Number | Permanent Strain (in/in.) | Percent Difference[1] | Creep Modulus (psi) | Percent Difference[1] | Slope of Log Curve | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 13 | 0.0352 | -- | 6912 | -- | 0.243 | -- |
| 19 | 0.0495 | +40.6 | 4900 | -29.1 | 0.247 | +1.7 |
| 20 | 0.0407 | +15.6 | 5931 | -14.2 | 0.213 | -12.4 |
| 21 | 0.0452 | +28.4 | 5310 | -23.2 | 0.238 | -2.1 |
| 22 | 0.0445 | +26.4 | 5413 | -21.7 | 0.248 | +2.1 |

[1] Relative to control mix (Mix 13)

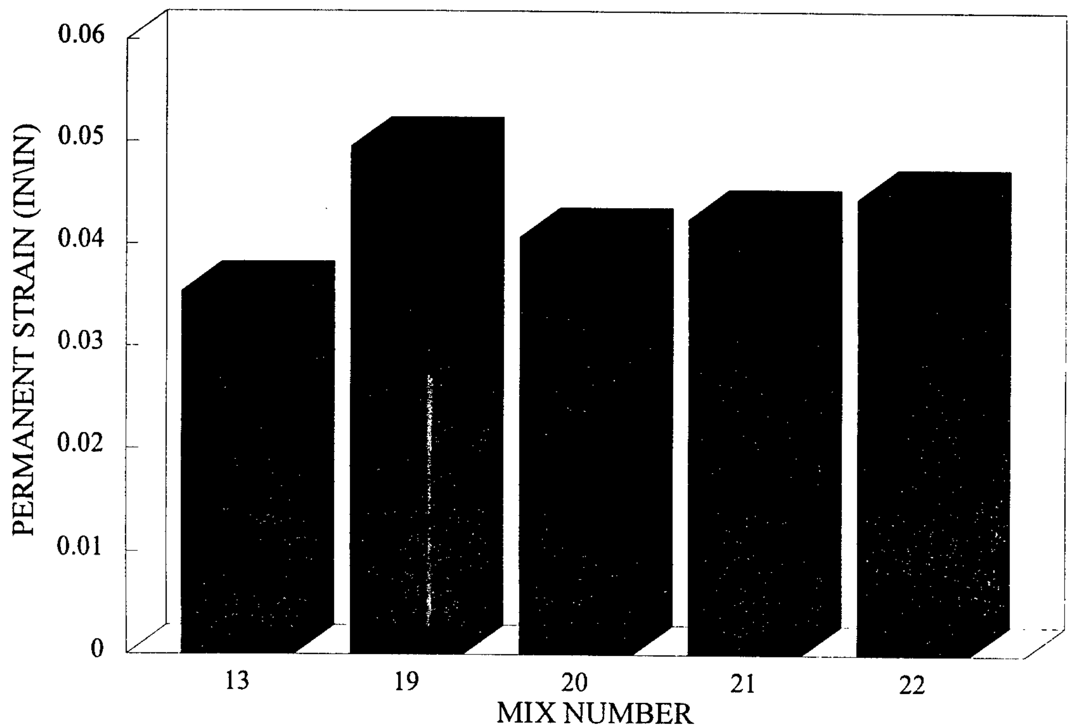


FIGURE 26. EFFECTIVE OF CRUSHED COARSE AGGREGATE ON PERMANENT STRAIN VALUES FOR AC-20 MIXTURES

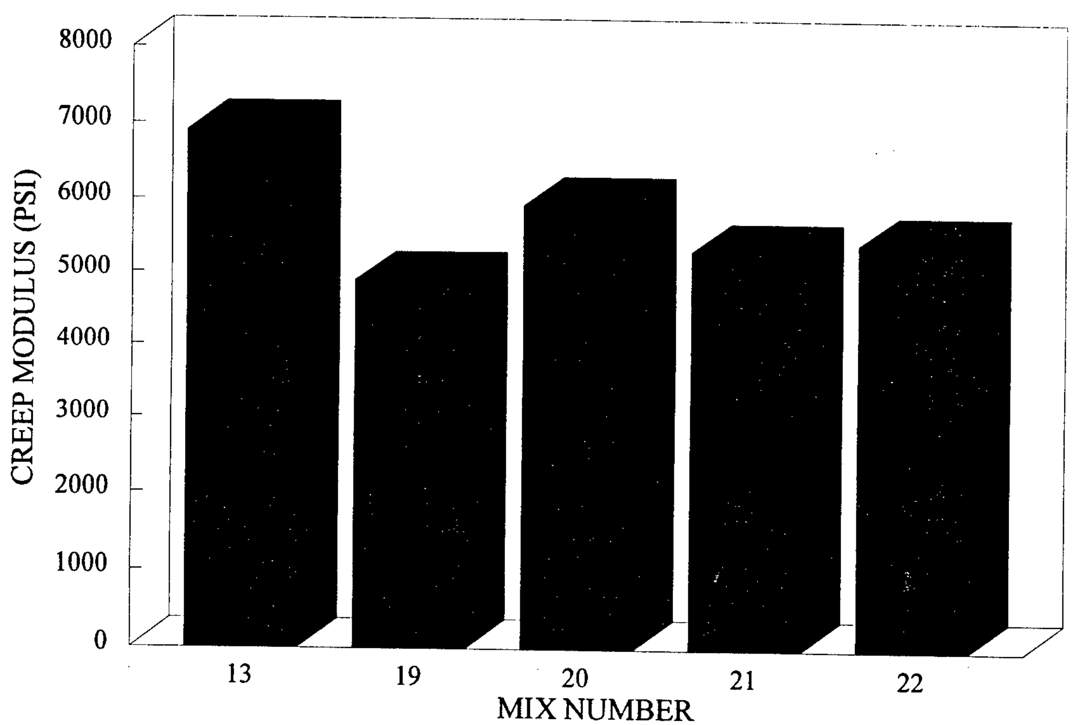


FIGURE 27. EFFECT OF CRUSHED COARSE AGGREGATE ON CREEP MODULUS VALUES FOR AC-20 MIXTURES

Amount of Natural Sand Material. The effect of the amount of natural sand material was evaluated in Mixes 9-18. Mixes 9-13 were fabricated with crushed gravel while Mixes 14-18 were fabricated with uncrushed gravel. Mixes 14-18 were tested and evaluated only to verify the aggregate characterization tests and mixture tests with extremely low-quality materials. Because these materials were so substandard for heavy-duty pavements, the results for Mixes 14-18 will only be presented and not discussed.

Expected trends were observed from the Marshall mix properties for Mixes 9-13. The optimum asphalt content values decreased as the amount of natural sand increased. The optimum asphalt content for Mix 13 (0 percent natural sand) was 7.0 percent compared to 5.6 percent for Mix 12 (40 percent natural sand). This large reduction in asphalt will produce a less durable asphalt mixture. The voids in mineral aggregate values for these mixtures are significantly higher than the minimum value of 14. The VMA values ranged from 16.6 to 19.2 percent. The trend is for VMA values to decrease as the amount of natural sand material increases. The Marshall stability values for these mixtures did not meet the minimum requirement of 2150 lbs. Mixes 9-12 which contained 10 to 40 percent natural sand had stability values of 1610 lbs and lower. The general trend for the Marshall stability value to decrease as the amount of natural sand increased. The amount of natural sand had a significant affect on the flow values (8.0 to 13.0). Mixes with 30 and 40 percent natural sand had flow values that did not meet FAA requirements.

The changes in the Marshall mix properties are presented in table 27 and shown graphically in figure 28. The amount of natural sand material in an aggregate blend significantly affects the Marshall stability values. The Marshall stability value decreases between 20 and 50 percent with the addition of 10 to 40 percent natural sand. The Marshall stability/flow ratio follows a similar trend and stiffness ratio reduces approximately 10 percent.

TABLE 27. MARSHALL MIX PROPERTIES FOR AC-20 MIXTURES EVALUATING THE AMOUNT OF NATURAL SAND MATERIAL

| Mix Number | Marshall Stability (lbs) | Percent Difference[1] | Marshall Flow (0.01 in.) | Percent Difference[1] | Stability/ Flow Ratio | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 9 | 1554 | -23.6 | 11.1 | -14.6 | 140 | -10.8 |
| 10 | 1610 | -20.9 | 10.2 | -6.2 | 158 | +0.6 |
| 11 | 1370 | -32.7 | 9.4 | -27.7 | 146 | -7.0 |
| 12 | 1107 | -45.6 | 8.0 | -38.5 | 138 | -12.1 |
| 13 | 2035 | -- | 13.0 | -- | 157 | -- |
| 14 | 1192 | -41.4 | 8.9 | -31.5 | 134 | -14.7 |
| 15 | 1147 | -43.6 | 8.8 | -32.3 | 130 | -17.2 |
| 16 | 1074 | -47.2 | 8.4 | -35.4 | 128 | -18.5 |
| 17 | 1031 | -49.3 | 8.3 | -36.2 | 124 | -21.0 |
| 18 | 916 | -55.0 | 7.1 | -45.4 | 129 | -17.8 |

[1] Relative to control mix (Mix 13)

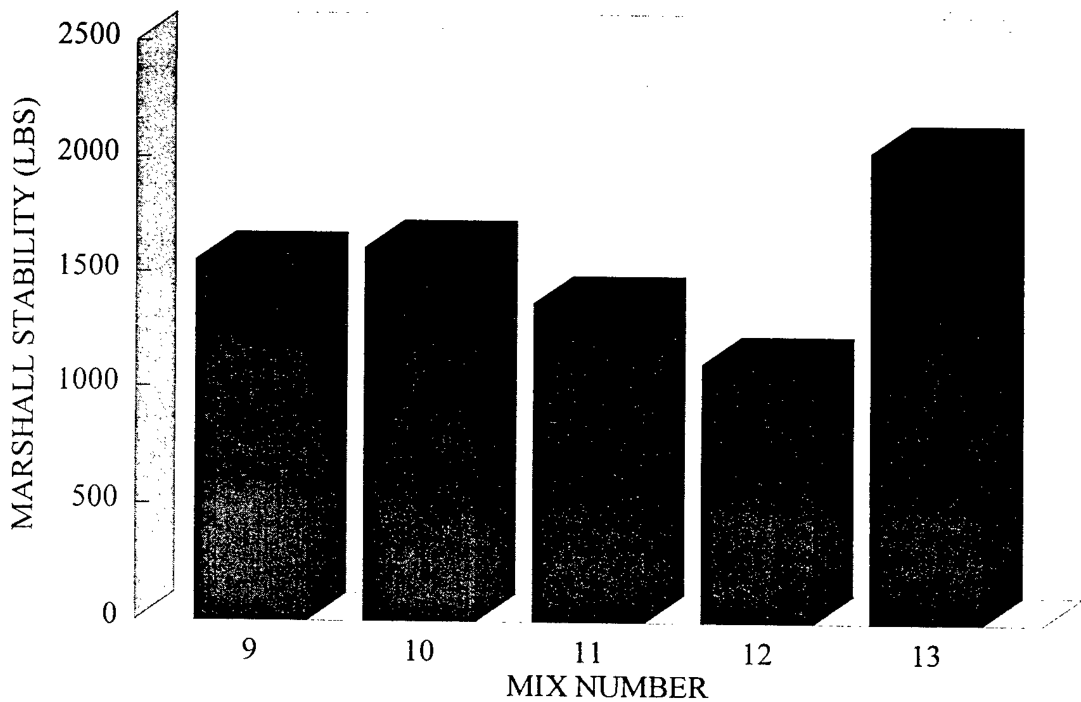


FIGURE 28. EFFECT OF NATURAL SAND CONTENT ON MARSHALL STABILITY VALUES FOR AC-20 MIXTURES

The confined repeated load deformation test results indicated that the amount of natural sand in the asphalt mixture did affect the rutting characteristics. The primary trend for the permanent strain value was to increase as the amount of natural sand increased while creep modulus decreased in value with an increase in the amount of natural sand material. The slope of the deformation curve varied insignificantly with the amount of natural sand. The calculated percent difference for these test results are presented in table 28 and shown graphically in figures 29 and 30.

TABLE 28. CONFINED REPEATED LOAD DEFORMATION TEST RESULTS FOR AC-20 MIXTURES EVALUATING THE AMOUNT OF NATURAL SAND MATERIAL

| Mix Number | Permanent Strain (in/in.) | Percent Difference[1] | Creep Modulus (psi) | Percent Difference[1] | Slope of Log Curve | Percent Difference[1] |
|---|---|---|---|---|---|---|
| 9 | 0.0350 | -0.6 | 6828 | -1.2 | 0.214 | -11.9 |
| 10 | 0.0386 | +9.7 | 6265 | -9.4 | 0.253 | +4.1 |
| 11 | 0.0384 | +9.1 | 6303 | -8.8 | 0.195 | -19.8 |
| 12 | 0.0399 | +13.4 | 6027 | -12.8 | 0.259 | +6.5 |
| 13 | 0.0352 | -- | 6912 | -- | 0.243 | -- |
| 14 | 0.0843 | +139.5 | 2828 | -59.1 | 0.365 | +50.2 |
| 15 | 0.0574 | +63.1 | 4240 | -38.7 | 0.320 | +31.7 |
| 16 | 0.0664 | +88.6 | 3792 | -45.1 | 0.328 | +35.0 |
| 17 | 0.0890 | +152.8 | 2714 | -60.7 | 0.356 | +46.5 |
| 18 | 0.1020 | +189.8 | 2378 | -65.6 | 0.415 | +70.8 |

[1] Relative to control mix (Mix 13)

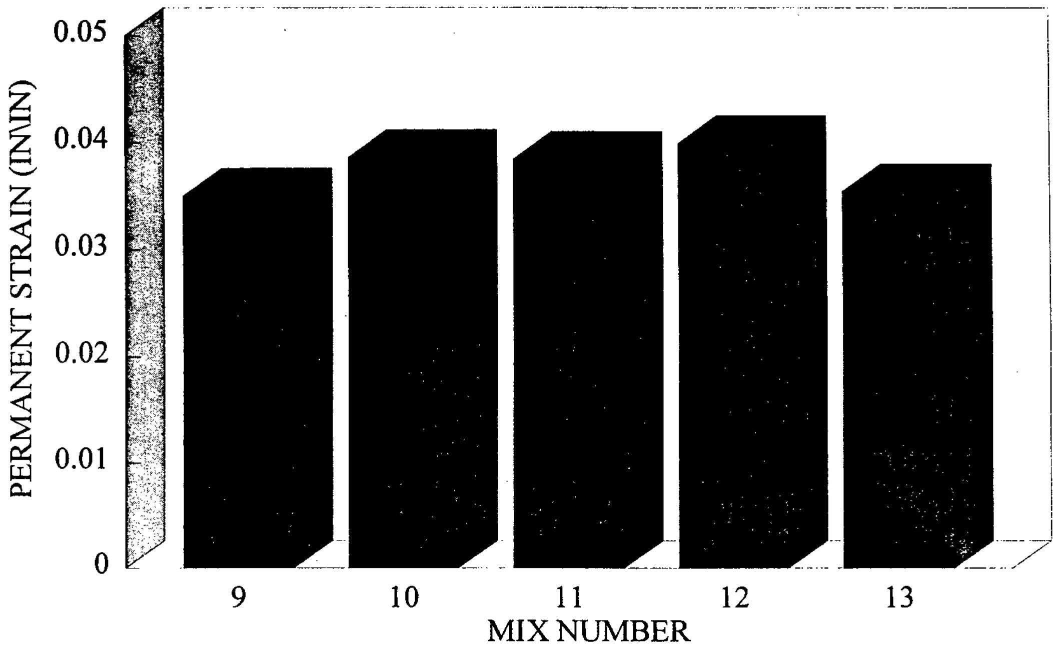


FIGURE 29. EFFECT OF NATURAL SAND CONTENT ON PERMANENT STRAIN VALUES FOR AC-20 MIXTURES

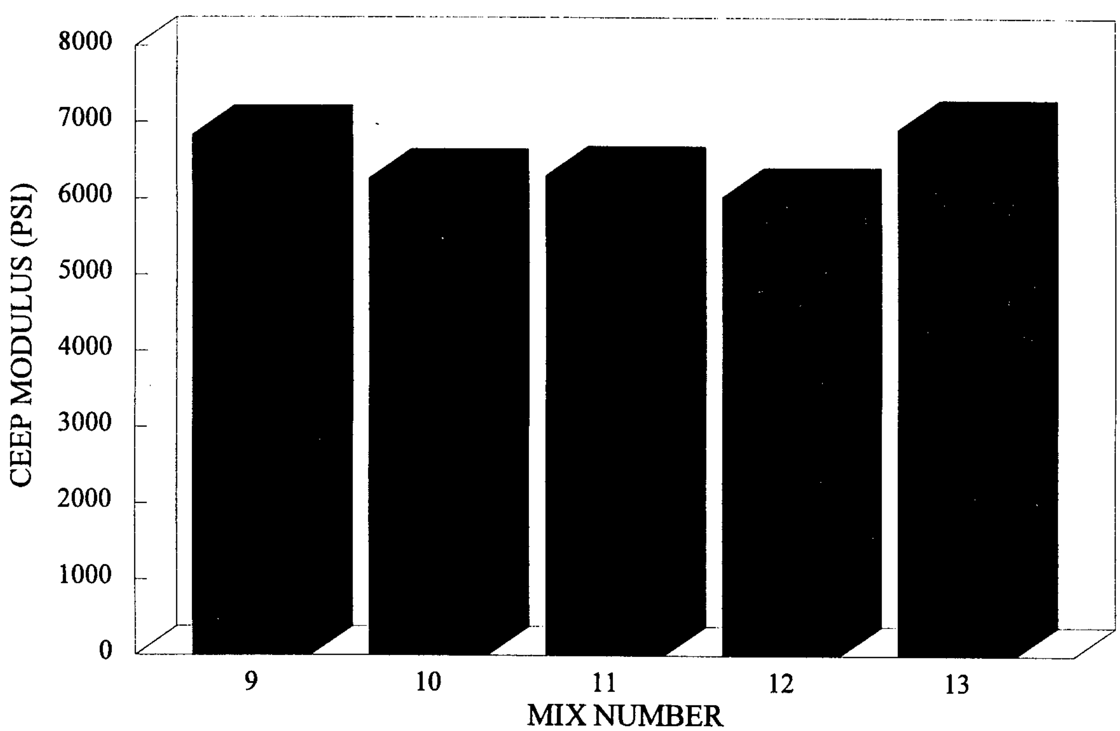


FIGURE 30. EFFECT OF NATURAL SAND CONTENT ON CREEP MODULUS VALUES FOR AC-20 MIXTURES

CORRELATION OF AGGREGATE PARTICLE CHARACTERIZATION TESTS WITH PERMANENT DEFORMATION PROPERTIES. Based on the findings for the aggregate particle characterization tests, six methods were selected to be correlated with the permanent deformation properties. The characterization for the aggregate particles was divided into three aggregate fractions: composite, coarse, and fine. The composite aggregate fraction was characterized with percent crushed particles, Particle Index, and GEPI values. The coarse aggregate fraction was characterized with percent crushed coarse particles, Particle Index, and Modified NAA particle shape and texture values. The fine aggregate fraction was characterized with percent crushed fine particles, natural sand content, Particle Index, and NAA particle shape and texture values. The permanent deformation properties selected for evaluation were permanent strain, creep modulus, and slope of the deformation curve.

A summary of the coefficients of determination for the aggregate particle characterization tests and the permanent deformation properties is presented in table 29. The results of the stronger correlations are shown in figures 31-33. The correlations for permanent strain values indicated that the composite blend aggregate characterization tests had the highest correlations. The $R^2$ values for the Particle Index, percent crushed particles, and GEPI were 0.841, 0.816, and 0.812, respectively. The highest correlation for creep modulus values with the aggregate characterization tests was with the GEPI values ($R^2$ = 0.839). The correlations for the slope of deformation curve were best explained with the GEPI and composite Particle Index values, $R^2$ = 0.867 and 0.819 respectively.

TABLE 29. CORRELATIONS OF AGGREGATE CHARACTERIZATION TESTS WITH PERMANENT DEFORMATION PROPERTIES FOR AC-20 MIXTURES

| | Coefficients of Determination ($R^2$) | | |
|---|---|---|---|
| Aggregate Characterization Tests | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
| PCP[1] - Composite | 0.816 | 0.522 | 0.724 |
| PCP - Coarse | 0.730 | 0.516 | 0.637 |
| PCP - Fine | 0.497 | 0.268 | 0.465 |
| PI[2] - Composite | 0.843 | 0.635 | 0.819 |
| PI - coarse | 0.782 | 0.676 | 0.777 |
| PI - Fine | 0.499 | 0.291 | 0.477 |
| Natural Sand Content | 0.580 | 0.295 | 0.516 |
| NAA - Method A | 0.626 | 0.479 | 0.629 |
| Modified NAA | 0.784 | 0.673 | 0.762 |
| GEPI | 0.812 | 0.839 | 0.867 |

[1] PCP - Percent Crushed Particles.
[2] PI - Particle Index.

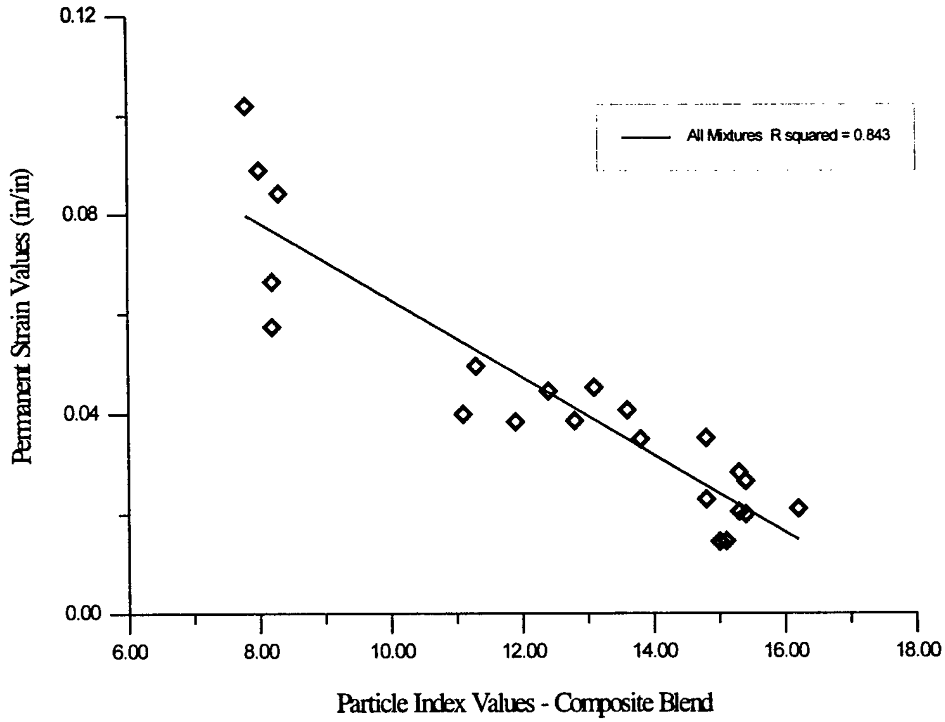


FIGURE 31. PERMANENT STRAIN VALUES FOR AC-20 MIXTURES VERSUS PARTICLE INDEX VALUES—COMPOSITE BLEND

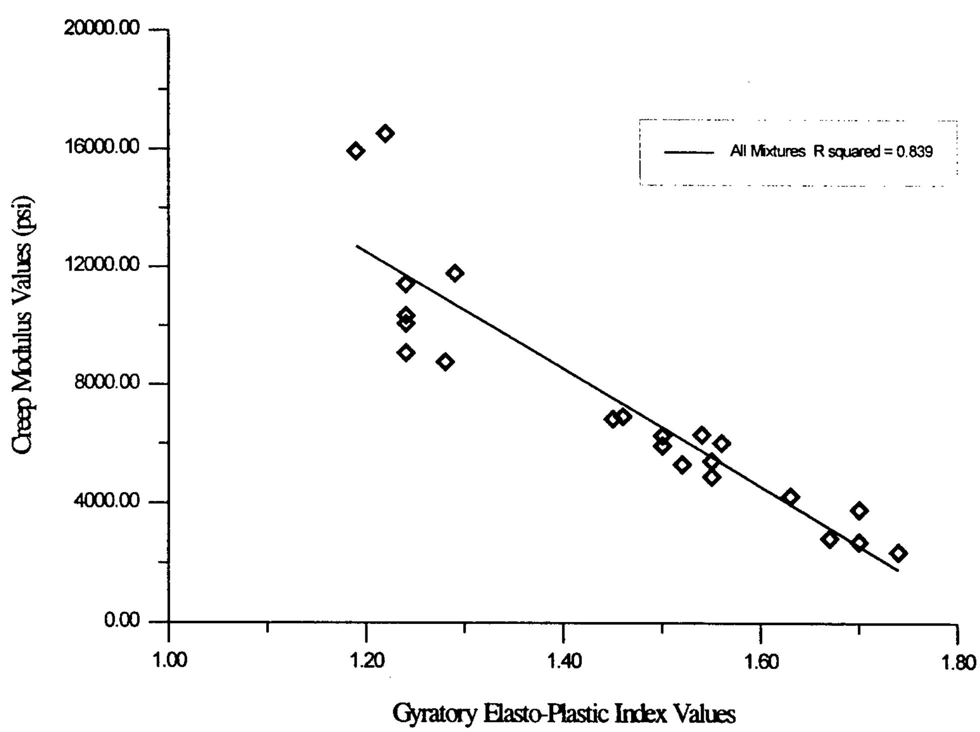


FIGURE 32. CREEP MODULUS VALUES FOR AC-20 MIXTURES VERSUS GEPI VALUES

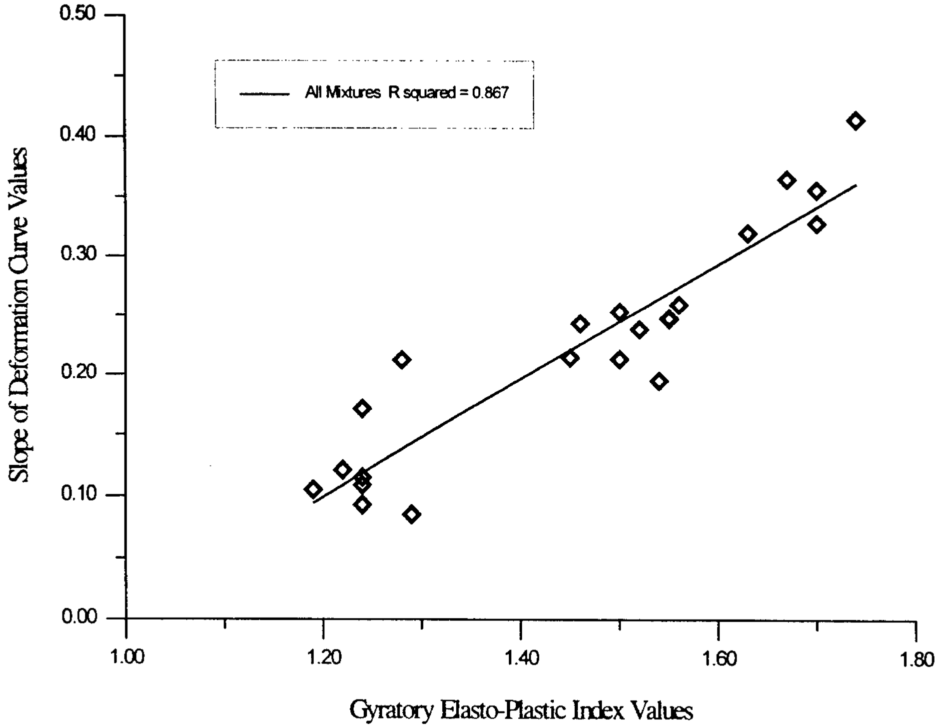


FIGURE 33. SLOPE OF DEFORMATION CURVE VALUES FOR AC-20 MIXTURES VERSUS GEPI VALUES

Based on the linear regression analyses, the aggregate particle characterization tests were ranked according to the highest correlations for each permanent deformation property. These rankings are presented in table 30. These rankings indicated that the composite aggregate blend and coarse aggregate fraction characterization tests evaluate the permanent deformation properties the best. Of these tests, the GEPI and composite Particle Index produce the strongest relationships. This ranking also indicated that the fine aggregate fraction tests have the weakest relationship to the permanent deformation properties.

TABLE 30. RANKINGS FOR CORRELATIONS OF AGGREGATE CHARACTERIZATION TESTS WITH PERMANENT DEFORMATION PROPERTIES FOR AC-20 MIXTURES

| Rank | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
|---|---|---|---|
| 1 | PI[1] - Composite | GEPI | GEPI |
| 2 | PCP[2] - Composite | PI - Coarse | PI - Composite |
| 3 | GEPI | Modified NAA | PI - Coarse |
| 4 | Modified NAA | PI - Composite | Modified NAA |
| 5 | PI - Coarse | PCP - Composite | PCP - Composite |
| 6 | PCP - Coarse | PCP - Coarse | PCP - Coarse |
| 7 | NAA - Method A | NAA - Method A | NAA - Method A |
| 8 | NSC[3] | NSC | NSC |
| 9 | PI - Fine | PI - Fine | PI - Fine |
| 10 | PCP - Fine | PCI-Fine | PCP-Fine |

[1] PI - Particle Index. [3] NSC - Natural Sand Content.
[2] PCP - Percent Crushed Particles.

CORRELATION OF AC-20 ASPHALT MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES. As discussed earlier in this section, the AC-20 asphalt mixture strength properties were determined using the Marshall stability and flow test, gyratory compaction process, indirect tensile test, and direct shear test. The permanent deformation properties determined from the confined repeated load deformation test were permanent strain, creep modulus, and slope of deformation curve.

A summary of the linear regression analyses for the AC-20 asphalt mixtures and permanent deformation properties is presented in table 31. The correlations for the Marshall stability and direct shear strength tests were the strongest for each permanent deformation property. These tests ranked either first or second for all three permanent deformation properties (table 32). The Marshall stability values had the highest correlation for permanent strain ($R^2 = 0.715$) and slope of deformation curve ($R^2 = 0.787$). The direct shear strength values produced the highest correlation for creep modulus ($R^2 = 0.769$). The results of these strong correlations are shown in figures 34-36.

TABLE 31. CORRELATIONS OF AC-20 MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES

| Asphalt Mixture Properties | Coefficients of Determination ($R^2$) | | |
|---|---|---|---|
| | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
| Marshall Stability | 0.715 | 0.652 | 0.787 |
| Marshall Flow | 0.561 | 0.298 | 0.486 |
| Gyratory Shear Strength | 0.187 | 0.454 | 0.277 |
| Indirect Tensile Strength - 77°F | 0.042 | 0.112 | 0.124 |
| Indirect Tensile Strength - 104°F | 0.164 | 0.389 | 0.260 |
| Angle of Internal Friction | 0.374 | 0.430 | 0.430 |
| Direct Shear Strength | 0.646 | 0.769 | 0.670 |

TABLE 32. RANKINGS FOR CORRELATIONS OF AC-20 MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES

| Rank | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
|---|---|---|---|
| 1 | Marshall Stability | Direct Shear Strength | Marshall Stability |
| 2 | Direct Shear Strength | Marshall Stability | Direct Shear Strength |
| 3 | Marshall Flow | Gyratory Shear Strength | Marshall Flow |
| 4 | Angle of Internal Friction | Angle of Internal Friction | Angle of Internal Friction |
| 5 | Gyratory Shear Strength | Indirect Tensile - 104°F | Gyratory Shear Strength |
| 6 | Indirect Tensile - 104°F | Marshall Flow | Indirect Tensile - 104°F |
| 7 | Indirect Tensile - 77°F | Indirect Tensile - 77°F | Indirect Tensile - 77°F |

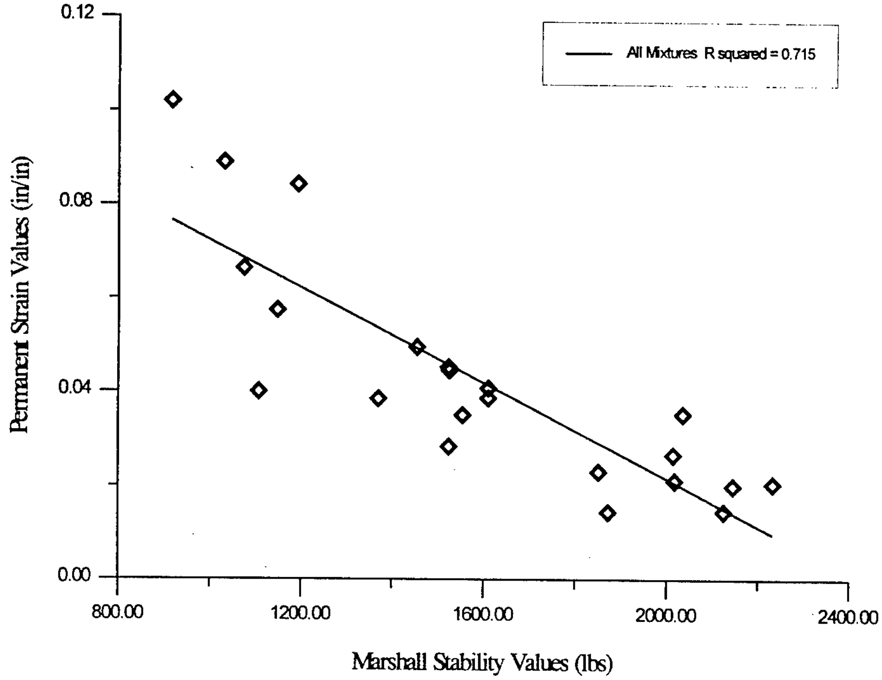


FIGURE 34. PERMANENT STRAIN VALUES FOR AC-20 MIXTURES VERSUS MARSHALL STABILITY VALUES

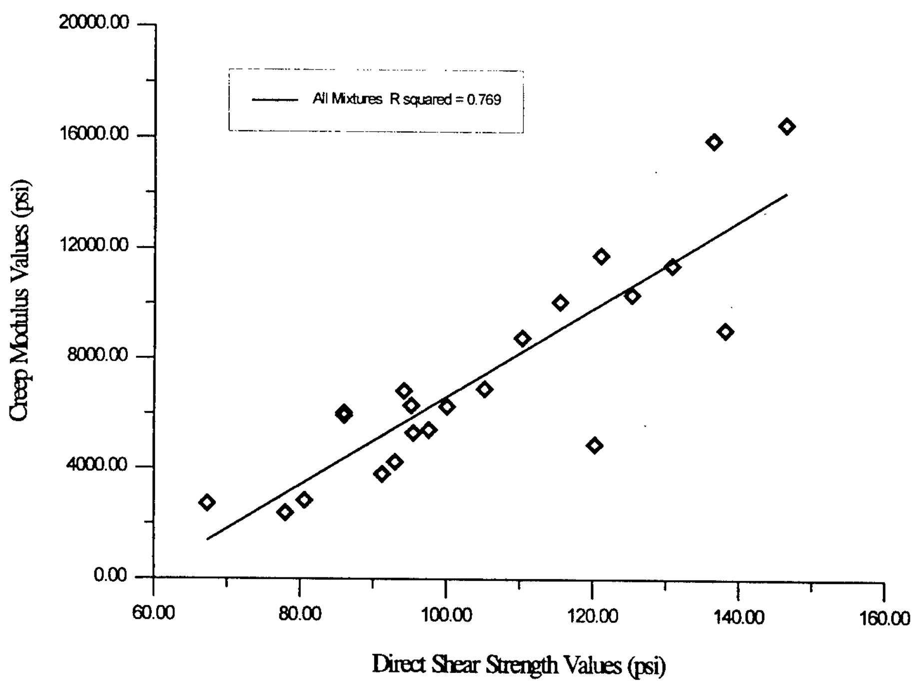


FIGURE 35. CREEP MODULUS VALUES FOR AC-20 MIXTURES VERSUS DIRECT SHEAR STRENGTHS

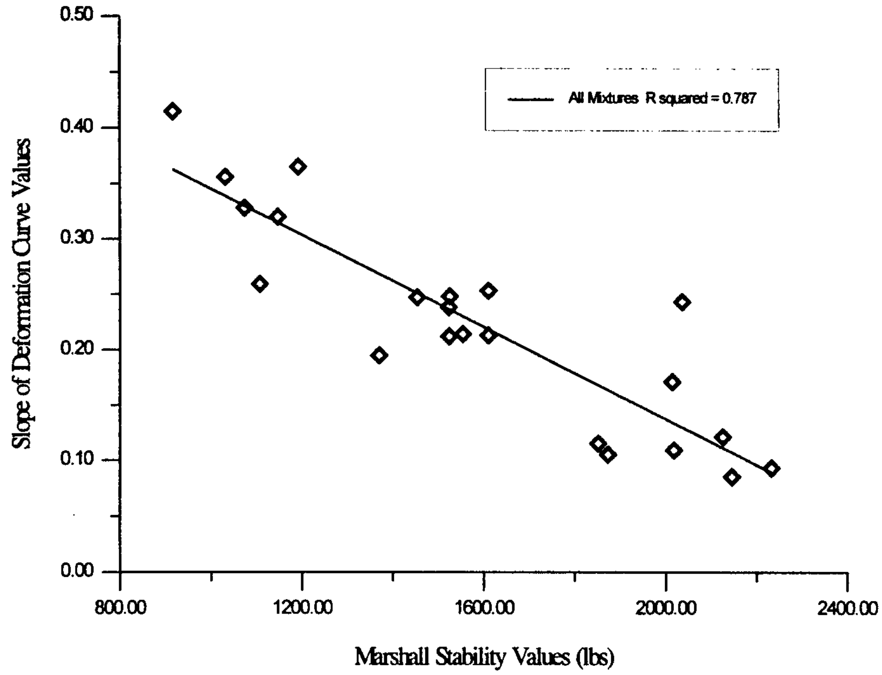


FIGURE 36. SLOPE OF DEFORMATION CURVE VALUES FOR AC-20 MIXTURES VERSUS MARSHALL STABILITY VALUES

## PHASE III—AC-40 AND MODIFIED AC-20 MIXTURES

This section presents and discusses the results of the preparation and testing of ten selected aggregate blends produced with a stiff asphalt cement (AC-40) and two polymer-modified AC-20 materials. This phase of the laboratory testing was designed to determine the effectiveness of stiffer asphalt binders to improve mixture strength and rutting characteristics of asphalt mixtures produced with marginal aggregates. The selected aggregate blends were chosen to determine the benefits of stiffer asphalt binders on aggregate type (limestone, gravel), gradation (shape), and percent crushed particles (coarse and fine). The primary emphasis of this phase was to determine if stiffer asphalt binders could improve marginal aggregate asphalt mixtures to provide equivalent or acceptable pavement performance.

The ten selected aggregate blends and their description are listed in table 33. A Marshall mix design with gyratory compaction was conducted for each aggregate blend and asphalt binder material (total of 30 mix designs). The optimum asphalt content for each mixture was selected at 4 percent air voids as was done with the AC-20 mixtures. The asphalt concrete mixture's strength properties and rutting characteristics were determined by the Marshall mix properties, gyratory compaction properties, indirect tensile test, direct shear test, and confined repeated load deformation test.

This section is organized to present and discuss the results of the AC-40, SBS modified AC-20, and LDPE modified AC-20 mixtures. Analysis of these test results involved determining the benefits or improvements of the stiffer asphalt binders and correlating the asphalt mixture properties with the permanent deformation properties.

TABLE 33. SELECTED AGGREGATE BLENDS FOR PHASE III

| Mix Number | Description |
|---|---|
| 1 | Center of FAA gradation band<br>Crushed limestone |
| 3 | Fine side (upper limit) of FAA band<br>Crushed limestone and fine sand |
| 6 | Excessive fines<br>Crushed limestone and fine sand |
| 12 | Crushed gravel with 40% coarse sand |
| 13 | Center of FAA gradation band<br>Crushed gravel |
| 14 | Center of FAA gradation band<br>Uncrushed gravel |
| 16 | Uncrushed gravel with 20% coarse sand |
| 18 | Uncrushed gravel with 40% coarse sand |
| 19 | Center of FAA gradation band - gravel<br>Coarse (uncrushed) Fine (crushed) |
| 21 | Center of FAA gradation band - gravel<br>Coarse (50% crushed-50% uncrushed) Fine (Crushed) |

## MARSHALL MIX PROPERTIES.

The Marshall mix design was used to determine the optimum asphalt content for the Phase III mixtures. The compaction temperature for the two AC-20 modified material was increased to 290°F to insure an adequate viscosity of the asphalt materials for coating the aggregate particles. A summary of the Marshall mix properties of the Phase III mixtures is presented in tables 34-36. These test results include unit weight, theoretical specific gravity, air voids, voids in mineral aggregates, voids filled with asphalt, and the Marshall stability and flow values. The void parameters and gravity values are an average of 24 specimens while the stability and flow values are an average of three to five specimens.

## GYRATORY COMPACTION PROPERTIES.

The gyratory compaction process was used to compact all the specimens for Phase III. This compactive effort and testing equipment was used to produce samples that better represented field conditions and produced valuable stress-strain measurements of each compacted specimen that can be used to evaluate the quality of the asphalt concrete mixture. A summary of the gyratory compaction properties for these mixtures is presented in table 37. The test results include GSI, GEPI, gyratory shear strength, and GSF values. The gyratory compaction properties are an average of 6 to 24 specimens.

## TABLE 34. SUMMARY OF MARSHALL MIX PROPERTIES AT OPTIMUM ASPHALT CONTENT FOR AC-40 MIXTURES

| Mix Number | Optimum Asphalt Content (%) | Bulk Specific Gravity | Theoretical Specific Gravity | Voids Total Mix (%) | Voids in Mineral Aggregate (%) | Voids Filled (%) | Unit Weight (pcf) | Stability (lbs) | Flow (0.01 in.) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.7 | 2.494 | 2.630 | 3.8 | 15.5 | 75.4 | 157.9 | 2296 | 13.5 |
| 3 | 4.8 | 2.503 | 2.603 | 3.8 | 15.6 | 75.4 | 156.2 | 2674 | 12.0 |
| 6 | 4.2 | 2.533 | 2.632 | 3.8 | 14.2 | 73.3 | 158.0 | 2518 | 13.5 |
| 12 | 5.5 | 2.328 | 2.424 | 4.0 | 16.5 | 76.1 | 145.3 | 1342 | 9.7 |
| 13 | 6.7 | 2.282 | 2.370 | 3.7 | 18.7 | 80.1 | 142.4 | 2153 | 14.5 |
| 14 | 4.5 | 2.356 | 2.442 | 3.6 | 14.0 | 74.4 | 147.0 | 1205 | 9.0 |
| 16 | 4.5 | 2.350 | 2.450 | 4.1 | 14.5 | 71.6 | 146.6 | 1108 | 8.7 |
| 18 | 4.9 | 2.348 | 2.444 | 3.9 | 15.2 | 74.2 | 146.5 | 850 | 8.5 |
| 19 | 5.9 | 2.300 | 2.393 | 3.9 | 17.2 | 77.4 | 143.5 | 1533 | 11.3 |
| 21 | 6.2 | 2.287 | 2.385 | 4.1 | 18.0 | 77.2 | 142.7 | 1804 | 13.0 |

## TABLE 35. SUMMARY OF MARSHALL MIX PROPERTIES AT OPTIMUM ASPHALT CONTENT FOR SBS-MODIFIED AC-20 MIXTURES

| Mix Number | Optimum Asphalt Content (%) | Bulk Specific Gravity | Theoretical Specific Gravity | Voids Total Mix (%) | Voids in Mineral Aggregate (%) | Voids Filled (%) | Unit Weight (pcf) | Stability (lbs) | Flow (0.01 in.) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.7 | 2.527 | 2.627 | 3.8 | 15.6 | 75.5 | 157.7 | 2323 | 14.2 |
| 3 | 5.0 | 2.493 | 2.591 | 3.8 | 16.2 | 76.6 | 155.6 | 2444 | 13.0 |
| 6 | 4.3 | 2.523 | 2.625 | 3.9 | 14.6 | 73.5 | 157.5 | 2794 | 13.3 |
| 12 | 5.6 | 2.325 | 2.417 | 3.8 | 16.7 | 77.1 | 145.0 | 1508 | 10.7 |
| 13 | 6.7 | 2.273 | 2.367 | 4.0 | 19.0 | 79.3 | 141.9 | 2350 | 18.0 |
| 14 | 4.3 | 2.357 | 2.455 | 4.0 | 14.0 | 71.6 | 147.1 | 1302 | 10.0 |
| 16 | 4.5 | 2.354 | 2.450 | 3.9 | 14.4 | 72.7 | 146.9 | 1495 | 9.0 |
| 18 | 4.9 | 2.347 | 2.441 | 3.9 | 15.2 | 74.8 | 146.5 | 1247 | 9.2 |
| 19 | 5.9 | 2.296 | 2.390 | 3.9 | 17.4 | 77.4 | 143.3 | 2293 | 13.3 |
| 21 | 6.4 | 2.277 | 2.374 | 4.1 | 18.5 | 77.9 | 142.1 | 1906 | 13.5 |

## TABLE 36. SUMMARY OF MARSHALL MIX PROPERTIES AT OPTIMUM ASPHALT CONTENT FOR LDPE-MODIFIED AC-20 MIXTURES

| Mix Number | Optimum Asphalt Content (%) | Bulk Specific Gravity | Theoretical Specific Gravity | Voids Total Mix (%) | Voids in Mineral Aggregate (%) | Voids Filled (%) | Unit Weight (pcf) | Stability (lbs) | Flow (0.01 in.) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.7 | 2.526 | 2.632 | 4.0 | 15.6 | 74.2 | 157.6 | 2495 | 15.2 |
| 3 | 4.8 | 2.504 | 2.605 | 3.9 | 15.6 | 75.2 | 156.2 | 2596 | 14.5 |
| 6 | 4.2 | 2.530 | 2.633 | 3.9 | 14.3 | 72.6 | 157.9 | 3137 | 13.8 |
| 12 | 5.5 | 2.332 | 2.426 | 3.9 | 16.4 | 76.4 | 145.5 | 1411 | 10.2 |
| 13 | 6.5 | 2.277 | 2.379 | 4.3 | 18.7 | 77.1 | 142.1 | 2089 | 14.2 |
| 14 | 4.3 | 2.365 | 2.459 | 3.8 | 13.7 | 72.2 | 147.6 | 1680 | 10.2 |
| 16 | 4.5 | 2.356 | 2.454 | 4.0 | 14.3 | 72.2 | 147.0 | 1425 | 9.5 |
| 18 | 4.8 | 2.351 | 2.449 | 4.0 | 15.0 | 73.3 | 146.7 | 958 | 9.2 |
| 19 | 5.9 | 2.300 | 2.395 | 4.0 | 17.2 | 76.8 | 143.5 | 1725 | 12.7 |
| 21 | 6.2 | 2.292 | 2.387 | 4.0 | 17.8 | 77.7 | 143.0 | 1974 | 14.5 |

TABLE 37. SUMMARY OF GYRATORY COMPACTION PROPERTIES FOR AC-40 AND MODIFIED AC-20 MIXTURES

| Asphalt Binder Type | Mix Number | Thickness (in.) | Gyratory Stability Index (GSI) | Gyratory Elasto-Plastic Index (GEPI) | Gyratory Shear Strength (psi) | Gyratory Shear Factor (GSF) |
|---|---|---|---|---|---|---|
| AC-40 | 1 | 2.446 | 0.99 | 1.20 | 121 | 1.90 |
| | 3 | 2.442 | 1.00 | 1.20 | 127 | 1.98 |
| | 6 | 2.403 | 1.04 | 1.21 | 97 | 1.52 |
| | 12 | 2.620 | 0.97 | 1.51 | 173 | 2.71 |
| | 13 | 2.687 | 0.99 | 1.40 | 155 | 2.41 |
| | 14 | 2.554 | 0.99 | 1.57 | 158 | 2.47 |
| | 16 | 2.542 | 0.98 | 1.51 | 154 | 2.40 |
| | 18 | 2.540 | 0.98 | 1.58 | 145 | 2.26 |
| | 19 | 2.645 | 0.97 | 1.51 | 160 | 2.50 |
| | 21 | 2.663 | 0.97 | 1.50 | 160 | 2.50 |
| AC-20 + SBS | 1 | 2.430 | 0.99 | 1.20 | 131 | 2.05 |
| | 3 | 2.432 | 0.99 | 1.25 | 135 | 2.11 |
| | 6 | 2.412 | 1.01 | 1.24 | 117 | 1.83 |
| | 12 | 2.574 | 0.99 | 1.48 | 181 | 2.83 |
| | 13 | 2.669 | 0.99 | 1.42 | 168 | 2.61 |
| | 14 | 2.545 | 0.99 | 1.46 | 164 | 2.56 |
| | 16 | 2.515 | 0.98 | 1.51 | 161 | 2.53 |
| | 18 | 2.542 | 0.98 | 1.56 | 168 | 2.62 |
| | 19 | 2.635 | 0.99 | 1.48 | 169 | 2.65 |
| | 21 | 2.671 | 0.99 | 1.41 | 164 | 2.57 |
| AC-20 + LDPE | 1 | 2.429 | 0.99 | 1.20 | 116 | 1.82 |
| | 3 | 2.418 | 1.00 | 1.21 | 131 | 2.04 |
| | 6 | 2.406 | 1.02 | 1.19 | 111 | 1.73 |
| | 12 | 2.558 | 0.97 | 1.47 | 181 | 2.82 |
| | 13 | 2.682 | 0.98 | 1.41 | 149 | 2.33 |
| | 14 | 2.525 | 0.98 | 1.53 | 155 | 2.42 |
| | 16 | 2.519 | 0.99 | 1.47 | 163 | 2.54 |
| | 18 | 2.520 | 0.98 | 1.63 | 154 | 2.40 |
| | 19 | 2.617 | 0.98 | 1.45 | 162 | 2.53 |
| | 21 | 2.638 | 0.99 | 1.43 | 152 | 2.38 |

## INDIRECT TENSILE.

The indirect tensile test was conducted to determine the tensile strengths of the selected aggregate blends produced with the stiffer asphalt binders. This test was conducted on three specimens at two temperatures, 77 and 104°F. These tests were conducted to evaluate the improvement of tensile strengths due to stiffer asphalt binders. The effectiveness of the stiffer asphalt binders was evaluated at the higher temperatures where rutting occurs. A summary of the tensile strengths is presented in table 38.

TABLE 38. SUMMARY OF INDIRECT TENSILE VALUES FOR AC-40 AND MODIFIED AC-20 MIXTURES

| Asphalt Binder Type | Mix Number | Tensile Strength at 77°F (psi) | Tensile Strength at 104°F (psi) |
|---|---|---|---|
| AC-40 | 1 | 329.1 | 47.1 |
| | 3 | 302.7 | 71.4 |
| | 6 | 287.7 | 82.7 |
| | 12 | 281.7 | 40.0 |
| | 13 | 272.1 | 33.1 |
| | 14 | 267.9 | 37.2 |
| | 16 | 299.3 | 43.6 |
| | 18 | 261.5 | 41.7 |
| | 19 | 233.9 | 48.2 |
| | 21 | 226.2 | 47.1 |
| AC-20 + SBS | 1 | 262.3 | 97.7 |
| | 3 | 269.4 | 99.5 |
| | 6 | 280.2 | 122.3 |
| | 12 | 264.6 | 77.4 |
| | 13 | 208.3 | 56.0 |
| | 14 | 237.9 | 62.2 |
| | 16 | 269.3 | 71.2 |
| | 18 | 245.5 | 63.0 |
| | 19 | 230.0 | 66.9 |
| | 21 | 240.0 | 73.5 |
| AC-20 + LDPE | 1 | 304.0 | 67.8 |
| | 3 | 384.3 | 94.3 |
| | 6 | 349.8 | 101.3 |
| | 12 | 327.2 | 59.7 |
| | 13 | 274.2 | 36.3 |
| | 14 | 352.4 | 58.7 |
| | 16 | 320.6 | 60.1 |
| | 18 | 265.2 | 44.5 |
| | 19 | 277.0 | 52.9 |
| | 21 | 270.9 | 50.7 |

DIRECT SHEAR.

The direct shear test was conducted to determine the benefits of stiffer asphalt binders on the shear strength and angle of internal friction of asphalt concrete mixtures. The standard Marshall specimens were tested at 140°F at three normal stress levels. The shear strength or stress was calculated based on the maximum load to failure. The calculated shear strength values and the analytically determined angle of internal friction and cohesion values are presented in table 39.

TABLE 39. SUMMARY OF DIRECT SHEAR DATA FOR AC-40 AND MODIFIED AC-20 MIXTURES

| Asphalt Binder Type | Mix Number | Angle of Internal Friction (Ø) | Cohesion Y-axis Intercept (psi) | Shear Strength at Normal Stress Levels | | |
|---|---|---|---|---|---|---|
| | | | | 100 psi (psi) | 200 psi (psi) | 300 psi (psi) |
| AC-40 | 1 | 12.3 | 155.8 | 177.1 | 200.5 | 220.8 |
| | 3 | 15.0 | 120.5 | 142.0 | 184.4 | 195.5 |
| | 6 | 22.9 | 98.2 | 139.7 | 184.3 | 224.1 |
| | 12 | 8.7 | 83.5 | 97.9 | 116.2 | 128.7 |
| | 13 | 11.5 | 90.0 | 106.2 | 139.5 | 147.0 |
| | 14 | 10.5 | 75.6 | 95.4 | 110.2 | 132.5 |
| | 16 | 11.0 | 73.0 | 89.1 | 118.2 | 127.4 |
| | 18 | 9.3 | 86.6 | 103.5 | 118.2 | 136.3 |
| | 19 | 7.9 | 116.6 | 129.3 | 145.9 | 157.7 |
| | 21 | 10.0 | 111.4 | 131.3 | 142.1 | 166.5 |
| AC-20 + SBS | 1 | 17.8 | 64.3 | 96.0 | 129.7 | 160.4 |
| | 3 | 13.5 | 82.8 | 109.4 | 125.4 | 157.4 |
| | 6 | 13.5 | 82.4 | 104.5 | 134.3 | 152.5 |
| | 12 | 15.6 | 37.1 | 64.1 | 94.4 | 119.9 |
| | 13 | 19.2 | 34.9 | 70.5 | 103.1 | 140.3 |
| | 14 | 16.6 | 28.9 | 59.7 | 86.2 | 119.2 |
| | 16 | 10.8 | 61.8 | 76.6 | 108.5 | 114.6 |
| | 18 | 13.5 | 40.0 | 65.3 | 85.8 | 113.4 |
| | 19 | 14.7 | 47.4 | 72.1 | 102.7 | 124.5 |
| | 21 | 17.8 | 38.4 | 71.1 | 101.7 | 135.2 |
| AC-20 + LDPE | 1 | 16.9 | 65.2 | 92.2 | 133.1 | 153.2 |
| | 3 | 10.4 | 92.4 | 112.0 | 126.5 | 148.5 |
| | 6 | 19.9 | 82.4 | 120.1 | 151.9 | 192.5 |
| | 12 | 8.0 | 83.2 | 94.5 | 116.8 | 122.6 |
| | 13 | 15.4 | 87.6 | 114.2 | 144.3 | 169.2 |
| | 14 | 8.8 | 84.6 | 102.2 | 111.1 | 133.1 |
| | 16 | 12.5 | 64.2 | 88.3 | 104.5 | 132.5 |
| | 18 | 6.4 | 93.7 | 104.0 | 117.8 | 126.3 |
| | 19 | 18.9 | 54.1 | 88.2 | 122.9 | 156.5 |
| | 21 | 14.6 | 88.9 | 114.5 | 142.3 | 166.7 |

## CONFINED REPEATED LOAD DEFORMATION.

The confined repeated load deformation test was conducted on Phase III mixtures to determine the improvements of stiffer asphalt binders on the rutting characteristics of these mixtures. Theoretically, the stiffer asphalt binders should decrease the rutting potential of asphalt mixtures when tested at 140°F. A summary of the confined repeated load deformation tests is presented in tables 40-42. These test results include deformation or strain values, creep modulus or stiffness values, and the slope of the steady state portion of the deformation curve plotted on a log-log scale. The confined repeated load deformation test was conducted on a minimum of four specimens for each mixture in Phase III.

## TABLE 40. SUMMARY OF CONFINED REPEATED LOAD DEFORMATION TEST DATA FOR AC-40 MIXTURES

| Mix Number | Thickness (in.) | Voids Total Mix (%) | Total Strain (in/in.) | Permanent Strain (in/in.) | Resilient Strain (in/in.) | Creep Modulus Based on Axial Stress (psi) | Creep Modulus Based on Deviator Stress (psi) | Slope of Log Curve |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.451 | 3.8 | 0.0241 | 0.0240 | 0.0001 | 9999 | 8363 | 0.115 |
| 3 | 2.461 | 3.9 | 0.0208 | 0.0207 | 0.0001 | 11851 | 9894 | 0.094 |
| 6 | 2.452 | 3.9 | 0.0290 | 0.0289 | 0.0001 | 8336 | 6961 | 0.179 |
| 12 | 2.611 | 3.9 | 0.0478 | 0.0477 | 0.0001 | 5200 | 4337 | 0.217 |
| 13 | 2.690 | 3.9 | 0.0394 | 0.0393 | 0.0001 | 6210 | 5191 | 0.234 |
| 14 | 2.559 | 3.7 | 0.0774 | 0.0774 | 0.0000 | 3235 | 2696 | 0.350 |
| 16 | 2.564 | 4.1 | 0.0900 | 0.0900 | 0.0000 | 2796 | 2331 | 0.311 |
| 18 | 2.564 | 3.9 | 0.1183 | 0.1183 | 0.0000 | 2103 | 1753 | 0.315 |
| 19 | 2.665 | 4.0 | 0.0625 | 0.0625 | 0.0000 | 3995 | 3329 | 0.212 |
| 21 | 2.684 | 4.0 | 0.0457 | 0.0456 | 0.0001 | 5651 | 4717 | 0.240 |

## TABLE 41. SUMMARY OF CONFINED REPEATED LOAD DEFORMATION TEST DATA FOR SBS-MODIFIED AC-20 MIXTURES

| Mix Number | Thickness (in.) | Voids Total Mix (%) | Total Strain (in/in.) | Permanent Strain (in/in.) | Resilient Strain (in/in.) | Creep Modulus based on Axial Stress (psi) | Creep Modulus based on Deviator Stress (psi) | Slope of Log Curve |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.424 | 4.0 | 0.0219 | 0.0219 | 0.0000 | 11135 | 9281 | 0.081 |
| 3 | 2.427 | 3.9 | 0.0218 | 0.0218 | 0.0000 | 11150 | 9281 | 0.077 |
| 6 | 2.412 | 4.2 | 0.0226 | 0.0226 | 0.0000 | 10713 | 8946 | 0.096 |
| 12 | 2.581 | 4.0 | 0.0361 | 0.0361 | 0.0000 | 7083 | 5909 | 0.148 |
| 13 | 2.673 | 4.0 | 0.0212 | 0.0212 | 0.0000 | 11482 | 9568 | 0.156 |
| 14 | 2.536 | 3.9 | 0.0429 | 0.0426 | 0.0003 | 5603 | 4700 | 0.199 |
| 16 | 2.521 | 4.1 | 0.0454 | 0.0454 | 0.0000 | 5445 | 4544 | 0.243 |
| 18 | 2.549 | 4.0 | 0.0774 | 0.0774 | 0.0000 | 3655 | 3048 | 0.260 |
| 19 | 2.640 | 4.1 | 0.0341 | 0.0341 | 0.0000 | 7329 | 6107 | 0.156 |
| 21 | 2.672 | 4.2 | 0.0259 | 0.0258 | 0.0001 | 9977 | 8327 | 0.157 |

TABLE 42. SUMMARY OF CONFINED REPEATED LOAD DEFORMATION TEST DATA FOR LDPE-MODIFIED AC-20 MIXTURES

| Mix Number | Thickness (in.) | Voids Total Mix (%) | Total Strain (in/in.) | Permanent Strain (in/in.) | Resilient Strain (in/in.) | Creep Modulus Based on Axial Stress (psi) | Creep Modulus Based on Deviator Stress (psi) | Slope of Log Curve |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.442 | 4.2 | 0.0193 | 0.0193 | 0.0000 | 12462 | 10385 | 0.095 |
| 3 | 2.417 | 3.9 | 0.0223 | 0.0223 | 0.0000 | 11011 | 9191 | 0.080 |
| 6 | 2.412 | 4.0 | 0.0295 | 0.0295 | 0.0000 | 8159 | 6806 | 0.100 |
| 12 | 2.584 | 3.9 | 0.0412 | 0.0411 | 0.0001 | 5912 | 4935 | 0.185 |
| 13 | 2.677 | 4.2 | 0.0392 | 0.0389 | 0.0003 | 6431 | 5414 | 0.128 |
| 14 | 2.521 | 3.8 | 0.0699 | 0.0699 | 0.0000 | 3541 | 2948 | 0.307 |
| 16 | 2.533 | 3.9 | 0.0703 | 0.0703 | 0.0000 | 3681 | 3067 | 0.170 |
| 18 | 2538 | 4.0 | 0.0835 | 0.0835 | 0.0000 | 2874 | 2395 | 0.268 |
| 19 | 2.597 | 4.0 | 0.0500 | 0.0500 | 0.0000 | 4875 | 4065 | 0.141 |
| 21 | 2.643 | 4.2 | 0.0331 | 0.0330 | 0.0001 | 7321 | 6111 | 0.083 |

## ANALYSIS AND DISCUSSION OF DATA.

This phase of the laboratory study was designed to determine the effectiveness of stiffer asphalt binders to improve the asphalt mixture's strength and rutting characteristics when produced with marginal aggregates. The purpose of these tests was to determine if stiffer asphalt binders could improve marginal aggregate asphalt mixtures enough to provide an equivalent or acceptable level of pavement performance. The analysis of the test results involved determining the benefits or improvements (percent difference from the AC-20 mixtures) produced by the stiffer asphalt binders. The criteria for improvement was an increase in mixture strength and/or improving the rutting characteristics of the marginal aggregate mixtures. Improvement was also considered if a marginal aggregate mixture with a stiff asphalt binder produced results equal to or better than that of a control mixture with a AC-20 asphalt binder. The analysis also included correlating the asphalt mixture properties with the permanent deformation properties.

BENEFITS OF STIFFER ASPHALT BINDERS. The benefits or improvements produced by the stiffer asphalt binders were determined using the asphalt mixture's strength values and permanent deformation properties. The asphalt mixture's strength was evaluated with Marshall stability and flow values, gyratory compaction properties, indirect tensile strengths, and direct shear strengths. The rutting characteristics were determined from the results of the confined repeated load deformation test.

Several observations and trends were observed from the Marshall stability and flow values. All mixtures produced with crushed limestone (Mixes 1, 3, and 6) had an increase in Marshall stability with the addition of stiffer asphalt binders. All these Marshall stability values exceeded the minimum FAA requirement of 2,150 lbs. The control mixture for the gravel mixtures (Mix 13) was also improved to meet the minimum FAA stability requirement with the AC-40 and SBS modified AC-20 binders. Mix 21 (50 percent uncrushed coarse aggregate) was also improved by the stiffer asphalt binders. The increase in stability values ranged from 18.5 to 29.6 percent with values above 1,800 lbs. The stiffer asphalt binders increased the stability values for all mixtures, even the low quality marginal mixtures (Mixes 12, 14, 16, 18, and 19). The overall trend for the flow values was to increase with the stiffer asphalt binders. The variation in Marshall stability values for the stiff asphalt binders is presented in table 43 and shown graphically in figure 37.

TABLE 43. MARSHALL STABILITY VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 2017 | 2296 | 13.8 | 2323 | 15.2 | 2495 | 23.7 |
| 3 | 2232 | 2674 | 19.8 | 2444 | 9.5 | 2596 | 16.3 |
| 6 | 2014 | 2518 | 25.0 | 2794 | 38.7 | 3137 | 55.8 |
| 12 | 1107 | 1342 | 21.2 | 1508 | 36.2 | 1411 | 27.5 |
| 13 | 2035 | 2153 | 5.8 | 2350 | 15.5 | 2089 | 2.7 |
| 14 | 1192 | 1205 | 1.1 | 1302 | 9.2 | 1680 | 40.9 |
| 16 | 1074 | 1108 | 3.2 | 1495 | 39.2 | 1425 | 32.7 |
| 18 | 916 | 850 | -7.2 | 1247 | 36.1 | 958 | 4.6 |
| 19 | 1454 | 1533 | 5.4 | 2293 | 57.7 | 1725 | 18.6 |
| 21 | 1523 | 1804 | 18.5 | 1906 | 25.1 | 1974 | 29.6 |
| [1] Relative to AC 20 mixtures | | | | | | | |

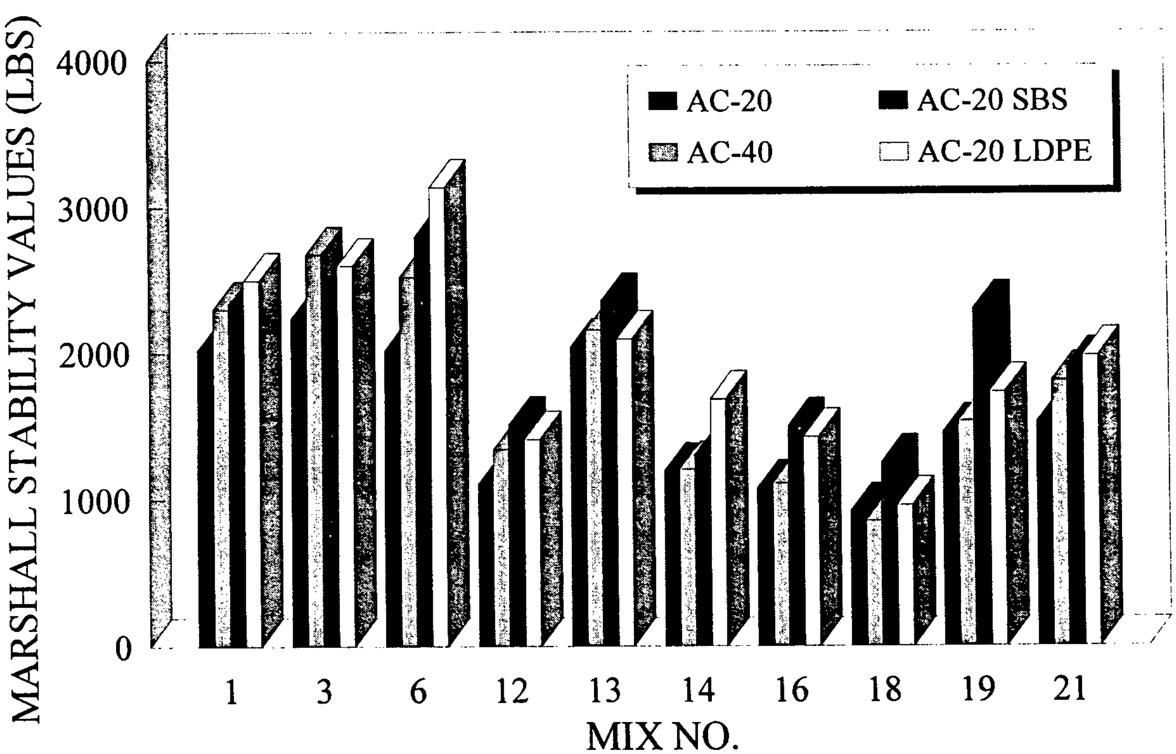


FIGURE 37. EFFECT OF STIFF ASPHALT BINDERS ON MARSHALL STABILITY VALUES

The gyratory compaction properties for the Phase III mixture produced mixed results. The GEPI values indicated consistent trends while the gyratory shear strength values were inconsistent. The GEPI values for these mixtures were lower than the GEPI values for the same aggregate blend with an AC-20 binder. The reduction in GEPI value indicates that the stiffer asphalt binders are improving the asphalt mixture's strength. Reducing the GEPI with stiff binders has the same effect as improving the quality of the aggregate's shape and texture. The changes in GEPI values caused by the stiffer asphalt binders are presented in table 44 and shown graphically in figure 38.

TABLE 44. GYRATORY ELASTO-PLASTIC INDEX (GEPI) VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 1.24 | 1.20 | -3.2 | 1.20 | -3.2 | 1.20 | -3.2 |
| 3 | 1.24 | 1.20 | -3.2 | 1.25 | 0.8 | 1.21 | -2.4 |
| 6 | 1.24 | 1.20 | -3.2 | 1.24 | 0.0 | 1.19 | -4.0 |
| 12 | 1.56 | 1.51 | -3.2 | 1.48 | -5.1 | 1.47 | -5.8 |
| 13 | 1.46 | 1.40 | -4.1 | 1.42 | -2.7 | 1.41 | -3.4 |
| 14 | 1.67 | 1.57 | -6.0 | 1.46 | -12.6 | 1.53 | -8.4 |
| 16 | 1.70 | 1.51 | -11.2 | 1.51 | -11.2 | 1.47 | -13.5 |
| 18 | 1.74 | 1.58 | -9.2 | 1.56 | -10.3 | 1.63 | -6.3 |
| 19 | 1.55 | 1.51 | -2.6 | 1.48 | -4.5 | 1.45 | -6.5 |
| 21 | 1.52 | 1.50 | -1.3 | 1.41 | -7.2 | 1.43 | -5.9 |

[1] Relative to AC 20 mixtures

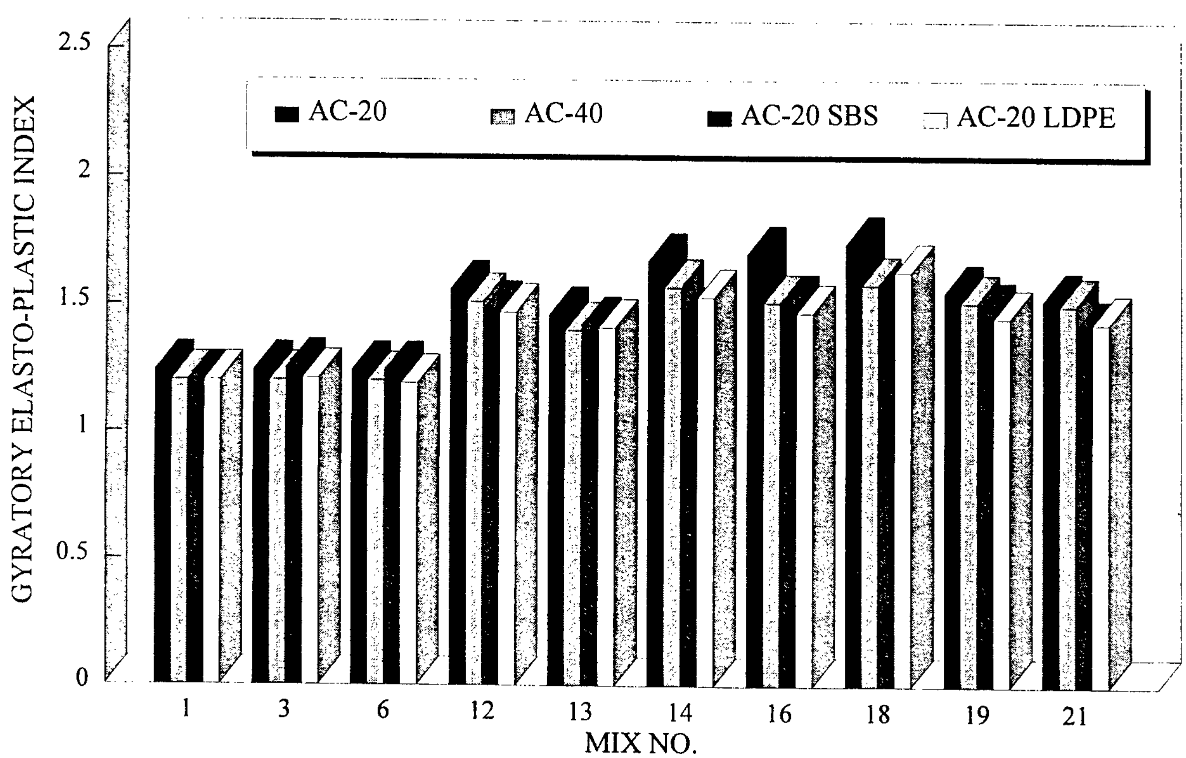


FIGURE 38. EFFECT OF STIFF ASPHALT BINDERS ON GEPI VALUES

As stated earlier in this report, the indirect tensile strength values are primarily dependent on the asphalt binder and the test temperature. The test results from the Phase III mixtures indicated the validity of this statement. The indirect tensile strengths for the 104°F test temperature are much lower (30 percent less) than the indirect tensile strengths for the 77°F test temperature. Since the primary focus of this study was on rutting, the 104°F test temperature test results will be discussed. The overall trend was that stiffer asphalt binders increased the tensile strength values (11.5 to 201.2 percent). The SBS-modified AC-20 binder produced the higher overall indirect tensile strength values. The changes in tensile strengths caused by stiffer asphalt binders are presented in table 45 and shown in figure 39.

TABLE 45. INDIRECT TENSILE STRENGTH VALUES AT 104°F FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 35.8 | 47.1 | 31.6 | 97.7 | 172.9 | 67.8 | 89.4 |
| 3 | 42.7 | 71.4 | 67.2 | 99.5 | 133.0 | 94.3 | 120.8 |
| 6 | 45.4 | 82.7 | 82.2 | 122.8 | 169.4 | 101.3 | 123.1 |
| 12 | 25.7 | 40.0 | 55.6 | 77.4 | 201.2 | 59.7 | 132.3 |
| 13 | 29.5 | 33.1 | 12.2 | 56.0 | 89.8 | 36.3 | 23.1 |
| 14 | 38.7 | 37.2 | -3.9 | 62.2 | 60.7 | 58.7 | 51.7 |
| 16 | 39.1 | 43.6 | 11.5 | 71.2 | 82.1 | 60.1 | 53.7 |
| 18 | 23.2 | 41.7 | 79.7 | 63.0 | 171.6 | 44.5 | 91.8 |
| 19 | 24.3 | 48.2 | 98.4 | 66.9 | 175.3 | 52.9 | 117.7 |
| 21 | 28.4 | 47.1 | 65.8 | 73.5 | 158.8 | 50.7 | 78.5 |

[1] Relative to AC 20 mixtures

The direct shear strength values at a 200 psi normal stress level were affected by the stiffer asphalt binders. Each asphalt binder type increased the direct shear strength values; the AC-40 binder increased the shear strength values from 29.6 to 59.7 percent, the SBS modified AC-20 binder increased the shear strength from 3.5 to 47.9 percent, and the LDPE-modified AC-20 binder increased the strength values from 17.1 to 74.6 percent. The positive changes in direct shear strength values produced with stiffer asphalt binders are presented in table 46 and shown graphically in figure 40.

The benefits or improvements of the stiffer asphalt binders on the rutting characteristics of the Phase III mixtures were evident in the permanent strain values, creep modulus values, and the slope of the deformation curve. The test results indicated that the AC-40 binder did not have much of a significant effect on the rutting characteristics as did the two polymer modified AC-20 binders. Overall, the SBS-modified AC-20 binder produced the greatest improvements in these asphalt mixtures.

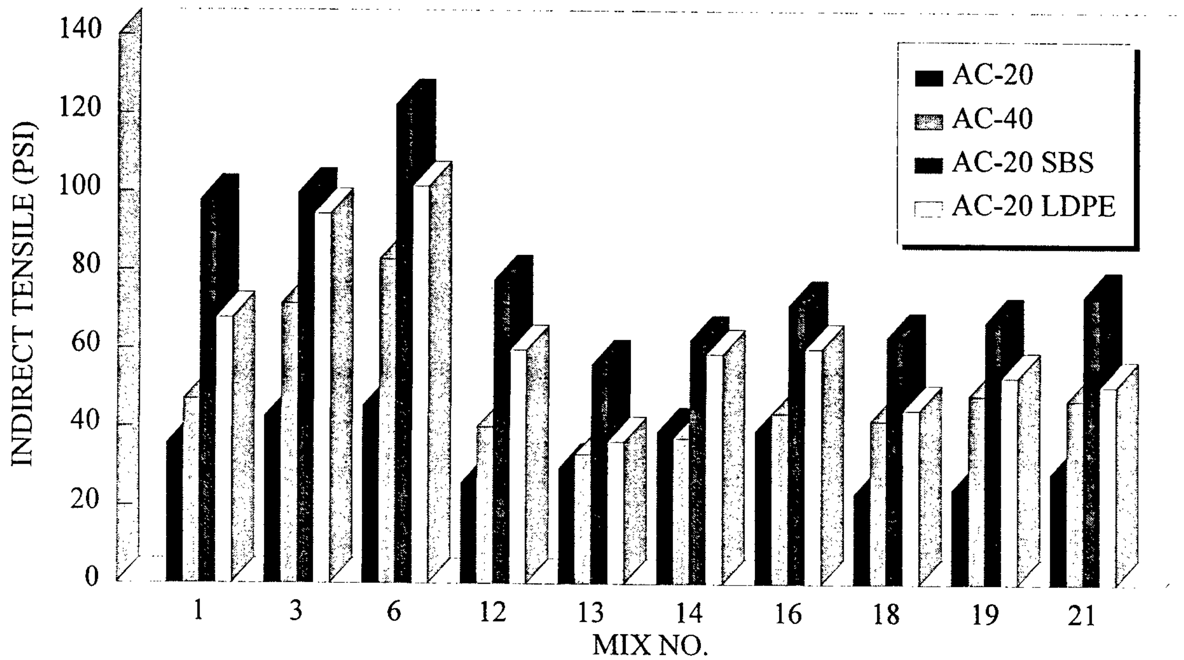


FIGURE 39. EFFECT OF STIFF ASPHALT BINDERS ON INDIRECT TENSILE STRENGTH VALUES AT 104°F

TABLE 46. DIRECT SHEAR STRENGTH VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 130.8 | 200.5 | 53.3 | 160.4 | 22.6 | 153.2 | 17.1 |
| 3 | 115.5 | 184.4 | 59.7 | 157.4 | 36.3 | 148.5 | 28.6 |
| 6 | 138.1 | 184.3 | 33.5 | 152.5 | 10.4 | 192.5 | 39.4 |
| 12 | 86.0 | 116.2 | 35.1 | 119.9 | 39.4 | 122.6 | 42.6 |
| 13 | 105.2 | 139.5 | 32.6 | 140.3 | 33.4 | 169.2 | 60.8 |
| 14 | 80.6 | 110.2 | 36.7 | 119.2 | 47.9 | 133.1 | 65.1 |
| 16 | 91.2 | 118.2 | 29.6 | 114.6 | 25.7 | 132.5 | 45.3 |
| 18 | 78.0 | 118.2 | 51.5 | 113.4 | 45.3 | 126.3 | 61.9 |
| 19 | 120.3 | 145.9 | 21.3 | 124.5 | 3.5 | 156.5 | 30.1 |
| 21 | 95.5 | 142.1 | 48.8 | 135.2 | 41.6 | 166.7 | 74.6 |

[1] Relative to AC 20 mixtures

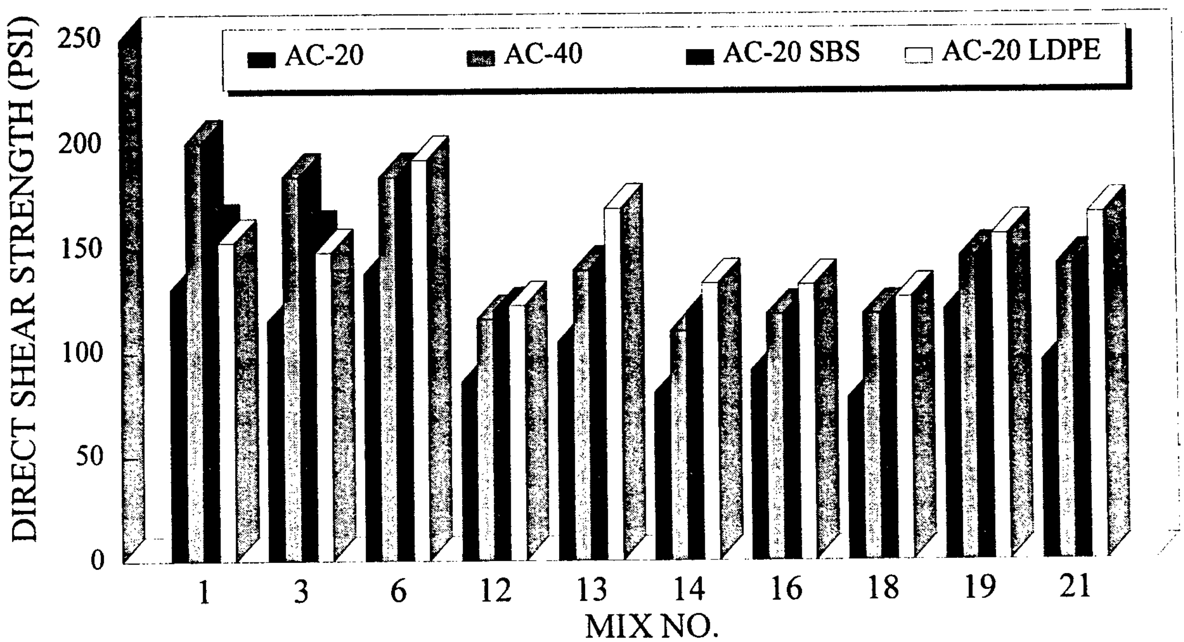


FIGURE 40. EFFECT OF STIFF ASPHALT BINDERS ON DIRECT SHEAR STRENGTH VALUES

The changes in the permanent strain values caused by the stiffer asphalt binders are presented in table 47 and shown graphically in figure 41. The permanent strain values for the SBS-modified mixtures improved for all the mixtures except Mixes 1 and 3. The SBS-modified mixtures produced a reduction in permanent strain values ranging from 9.5 to 49.5 percent when compared to AC-20 mixtures. Mix 13 (crushed gravel) was improved enough by the SBS modification to equal the strain values produced by Mix 1 (crushed limestone).

Mixes 12, 19, and 21 were also improved by SBS modification to approximately equal strain levels produced in the AC-20 control mixtures (Mix 13). The LDPE modified AC-20 binder also improved Mix 21 so that this mixture had lower strain levels than Mix 13 with AC-20.

The changes produced by stiffer asphalt binders on the creep modulus values are presented in table 48 and shown graphically in figure 42. As with the permanent strain values, the SBS modified AC-20 binder produced the greatest improvements in creep modulus values. These improvements in the creep modulus values ranged from 17.5 to 125.1 percent. Mix 13 was improved enough to equal Mix 1. Mixes 19 and 21 were improved enough by the SBS modification to equal or surpass the control mixture (Mix 13) with values of 7329 and 9927 psi, respectively. Mix 21 modified with the LDPE binder was also improved enough to surpass the control mixture (Mix 13) with a creep modulus value of 7321 psi.

TABLE 47. PERMANENT STRAIN VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 0.0211 | 0.0240 | 13.7 | 0.0219 | 3.8 | 0.0193 | -8.5 |
| 3 | 0.0205 | 0.0207 | 1.0 | 0.0218 | 6.3 | 0.0223 | 8.8 |
| 6 | 0.0266 | 0.0289 | 8.6 | 0.0226 | -15.0 | 0.0295 | 10.9 |
| 12 | 0.0399 | 0.0477 | 19.5 | 0.0361 | -9.5 | 0.0411 | 3.0 |
| 13 | 0.0352 | 0.0393 | 11.6 | 0.0212 | -39.8 | 0.0389 | 10.5 |
| 14 | 0.0843 | 0.0774 | -8.2 | 0.0426 | -49.5 | 0.0699 | -17.1 |
| 16 | 0.0664 | 0.0900 | 35.5 | 0.0454 | -31.6 | 0.0703 | 5.9 |
| 18 | 0.1020 | 0.1183 | 16.0 | 0.0774 | -24.1 | 0.0835 | -18.1 |
| 19 | 0.0495 | 0.0625 | 26.3 | 0.0341 | -31.1 | 0.0500 | 1.0 |
| 21 | 0.0452 | 0.0465 | 0.9 | 0.0258 | -41.9 | 0.0330 | -27.0 |

[1] Relative to AC 20 mixtures

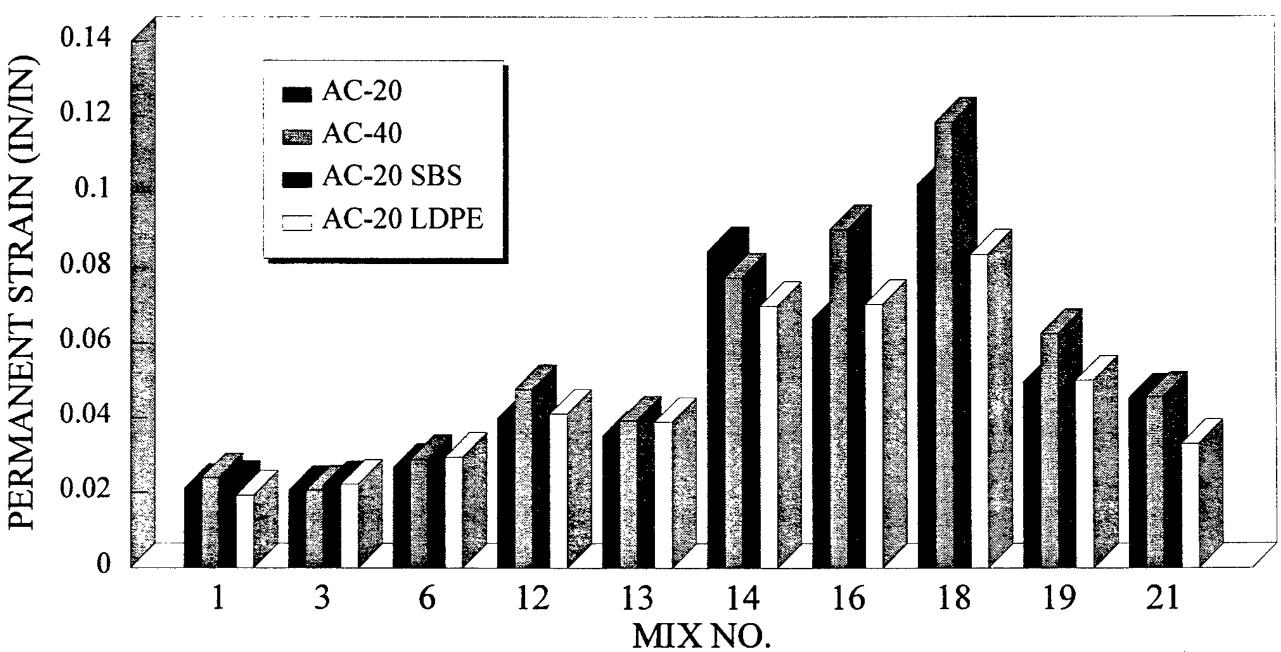


FIGURE 41. EFFECT OF STIFF ASPHALT BINDERS ON PERMANENT STRAIN VALUES

TABLE 48. CREEP MODULUS VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 11423 | 9999 | -12.5 | 11135 | -2.5 | 12462 | 9.1 |
| 3 | 12041 | 11851 | -1.6 | 11150 | -7.4 | 11011 | -8.6 |
| 6 | 9069 | 8336 | -8.1 | 10713 | 18.1 | 8159 | -10.0 |
| 12 | 6027 | 5200 | -13.7 | 7083 | 17.5 | 5912 | -1.9 |
| 13 | 6912 | 6210 | -10.2 | 11482 | 66.1 | 6431 | -7.0 |
| 14 | 2828 | 3235 | 14.4 | 5603 | 98.1 | 3541 | 25.2 |
| 16 | 3792 | 2796 | -26.3 | 5445 | 43.6 | 3681 | -2.9 |
| 18 | 2378 | 2103 | -11.6 | 3655 | 53.7 | 2874 | 20.9 |
| 19 | 4900 | 3995 | -18.5 | 7329 | 49.6 | 4875 | -0.5 |
| 21 | 4432 | 5651 | 27.5 | 9977 | 125.1 | 7321 | 65.2 |

[1] Relative to AC 20 mixtures

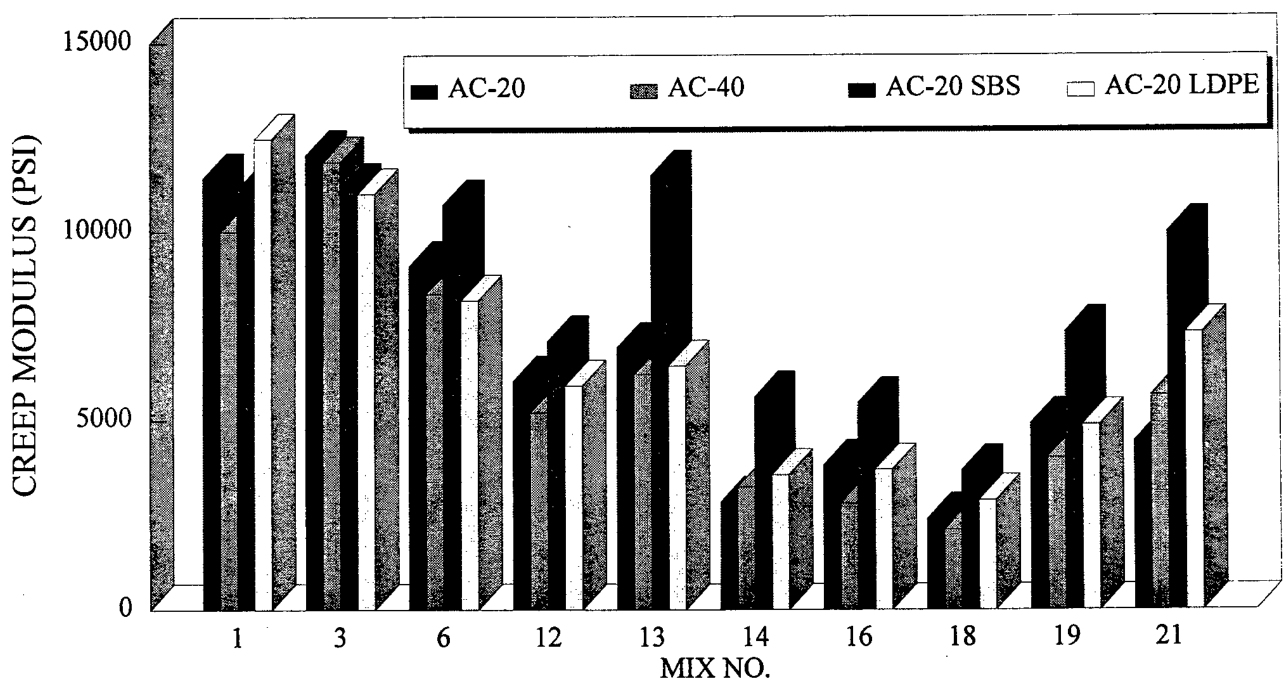


FIGURE 42. EFFECT OF STIFF ASPHALT BINDERS ON CREEP MODULUS VALUES

The slope of the deformation curve or the rate of rutting value was affected by all the stiff asphalt binders. The AC-40 binder had some effect on some of the mixtures, but the SBS and LDPE modified AC-20 binders significantly reduced the value for slope of the deformation curve for each mixture. The positive reduction in slope values caused by the stiff asphalt binders is presented in table 49 and shown graphically in figure 43. It is evident from this data that the modified AC-20 mixtures had a lower rate of potential rutting than the unmodified AC-20 mixtures of the same aggregate type and gradation.

TABLE 49. SLOPE OF DEFORMATION CURVE VALUES FOR PHASE III ASPHALT MIXTURES

| Mix Number | AC-20 | AC-40 | Percent Difference[1] | AC-20+ SBS | Percent Difference[1] | AC-20+ LDPE | Percent Difference[1] |
|---|---|---|---|---|---|---|---|
| 1 | 0.109 | 0.115 | 5.5 | 0.081 | -25.7 | 0.095 | -12.8 |
| 3 | 0.093 | 0.094 | 1.1 | 0.077 | -17.2 | 0.080 | -14.0 |
| 6 | 0.171 | 0.179 | 4.7 | 0.096 | -43.9 | 0.100 | -41.5 |
| 12 | 0.259 | 0.217 | -16.2 | 0.148 | -42.9 | 0.185 | -28.6 |
| 13 | 0.243 | 0.234 | -3.7 | 0.156 | -35.8 | 0.128 | -47.3 |
| 14 | 0.365 | 0.350 | -4.1 | 0.199 | -45.5 | 0.307 | -15.9 |
| 16 | 0.328 | 0.311 | -5.2 | 0.243 | -25.9 | 0.107 | -67.4 |
| 18 | 0.415 | 0.315 | -24.1 | 0.260 | -37.3 | 0.268 | -35.4 |
| 19 | 0.247 | 0.212 | -14.2 | 0.156 | -36.8 | 0.141 | -42.9 |
| 21 | 0.238 | 0.240 | 0.8 | 0.157 | -34.0 | 0.083 | -65.1 |

[1] Relative to AC 20 mixtures

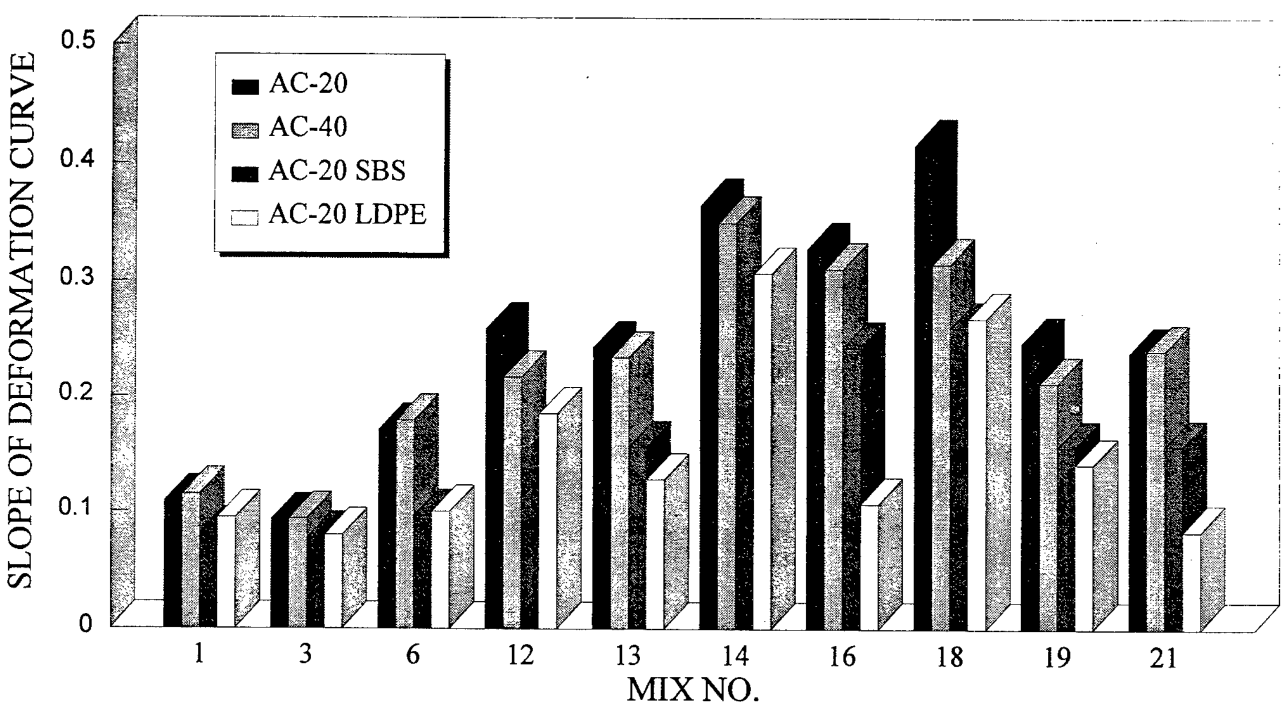


FIGURE 43. EFFECT OF STIFF ASPHALT BINDERS ON SLOPE OF DEFORMATION CURVE VALUES

CORRELATIONS OF PHASE III ASPHALT MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES. As discussed earlier in this section, the Phase III asphalt mixtures were tested to determine the effects of stiffer asphalt binders on the asphalt mixture's strength and permanent deformation properties. These mixture properties were analyzed and correlated using linear regression analyses. A summary of these correlations ($R^2$ values) is presented in table 50. The Marshall mix properties and the GEPI values produced the strongest relationships with the permanent deformation properties. These mixture properties ranked as the top three for all three permanent deformation properties (table 51). The Marshall stability values had the highest correlation with permanent strain values ($R^2$ = 0.683). The GEPI values produced the highest correlations for the creep modulus values ($R^2$ = 0.739) and the slope of the deformation curve values ($R^2$ = 0.599). The results of these correlations are shown graphically in figures 44-46.

TABLE 50. CORRELATIONS OF PHASE III ASPHALT MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES

| | Coefficients of Determination ($R^2$) | | |
|---|---|---|---|
| Asphalt Mixture Properties | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
| Marshall Stability | 0.683 | 0.712 | 0.560 |
| Marshall Flow | 0.602 | 0.607 | 0.444 |
| GEPI | 0.597 | 0.739 | 0.599 |
| Gyratory Shear Strength | 0.130 | 0.281 | 0.170 |
| Indirect Tensile Strength - 77°F | 0.007 | 0.012 | 0.048 |
| Indirect Tensile Strength - 104°F | 0.298 | 0.386 | 0.353 |
| Angle of Internal Friction | 0.305 | 0.291 | 0.277 |
| Direct Shear Strength | 0.342 | 0.354 | 0.438 |

TABLE 51. RANKINGS FOR CORRELATIONS OF PHASE III ASPHALT MIXTURE PROPERTIES WITH PERMANENT DEFORMATION PROPERTIES

| Rank | Permanent Strain | Creep Modulus | Slope of Deformation Curve |
|---|---|---|---|
| 1 | Marshall Stability | GEPI | GEPI |
| 2 | Marshall Flow | Marshall Stability | Marshall Stability |
| 3 | GEPI | Marshall Flow | Marshall Flow |
| 4 | Direct Shear Strength | Indirect Tensile - 104°F | Direct Shear Strength |
| 5 | Angle of Internal Friction | Direct Shear Strength | Indirect Tensile - 104°F |
| 6 | Indirect Tensile - 104°F | Angle of Internal Friction | Angle of Internal Friction |
| 7 | Gyratory Shear Strength | Gyratory Shear Strength | Gyratory Shear Strength |
| 8 | Indirect Tensile - 77°F | Indirect Tensile - 77°F | Indirect Tensile - 77°F |

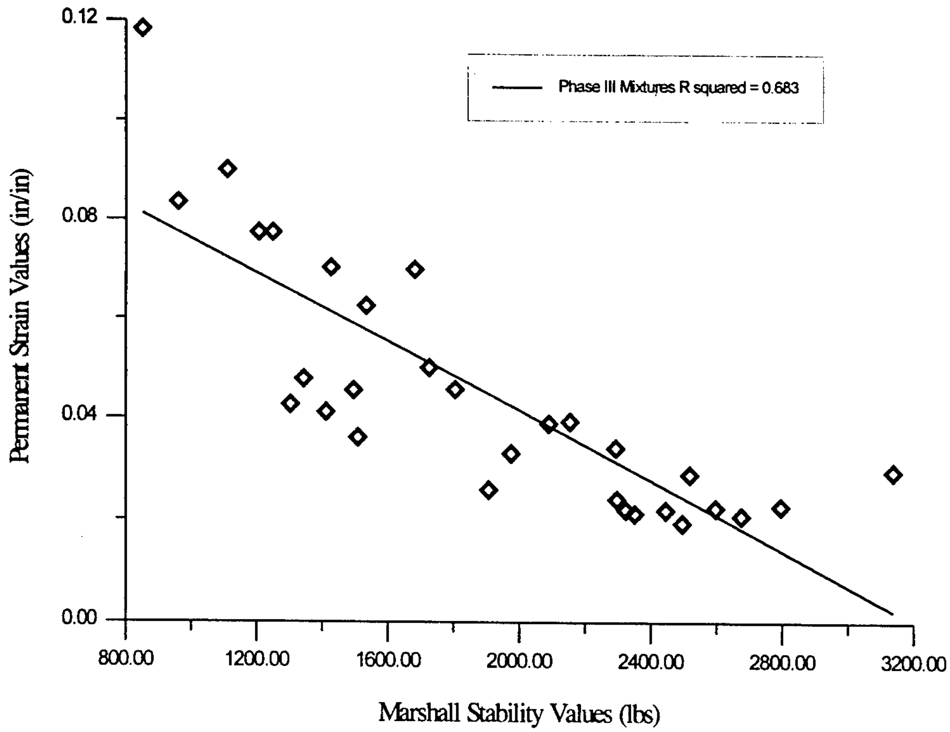


FIGURE 44. PERMANENT STRAIN VALUES FOR PHASE III ASPHALT MIXTURES VERSUS MARSHALL STABILITY VALUES

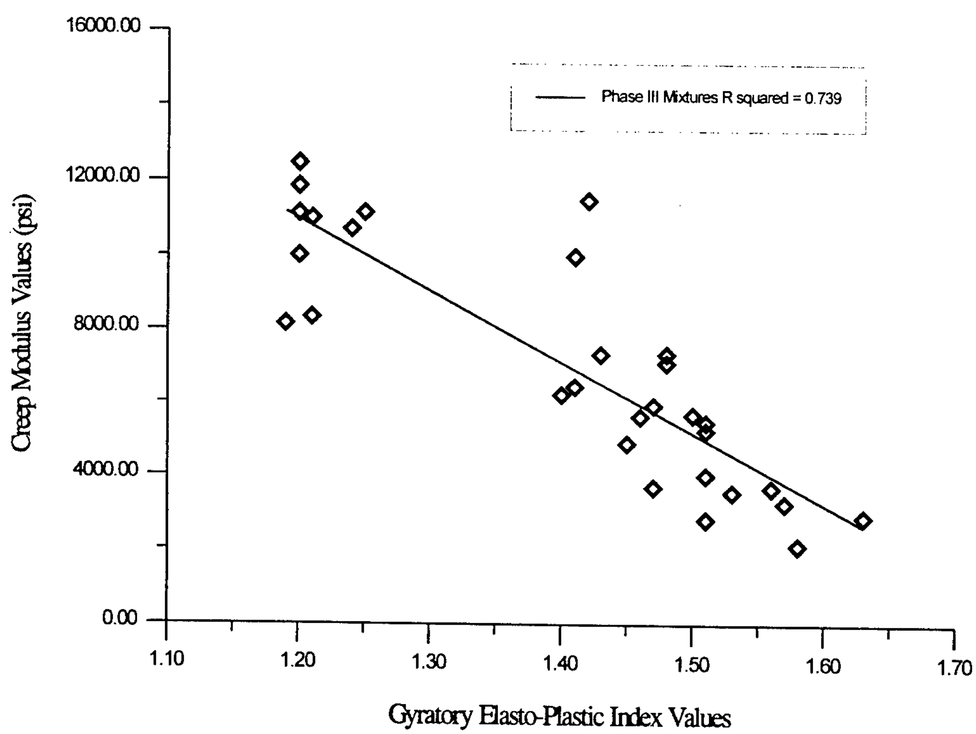


FIGURE 45. CREEP MODULUS VALUES FOR PHASE III ASPHALT MIXTURES VERSUS GEPI VALUES

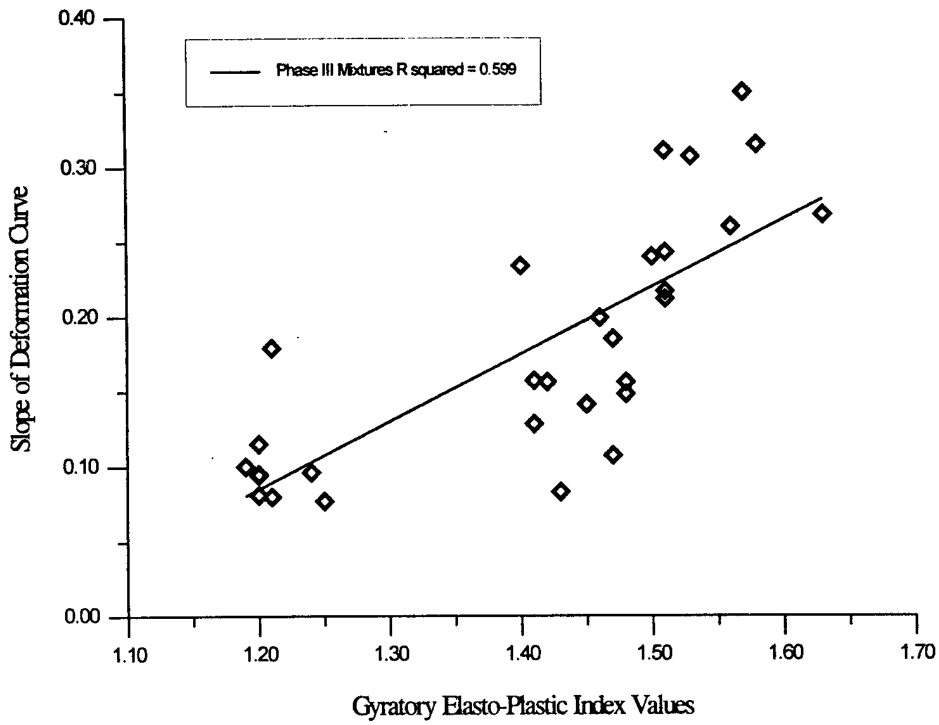


FIGURE 46. SLOPE OF DEFORMATION CURVE VALUES FOR PHASE III ASPHALT MIXTURES VERSUS GEPI VALUES

## CONCLUSIONS

The purpose of this research study was to evaluate the utilization of marginal aggregates in asphalt concrete layers for airport pavements. Marginal aggregates were defined as aggregates that do not meet current FAA specification requirements (Item P-401). This research study focused on aggregate particle and asphalt mixture characterization and whether marginal mixtures could provide or be improved to provide equivalent pavement performance with an emphasis on pavement deformation or rutting. The following conclusions were derived from the analysis of test results for this laboratory study.

1. The Particle Index test characterized the shape and texture of the aggregate blends very effectively. The Particle Index test results produced extremely strong, almost linear relationships, with percent crushed particles (composite, coarse, fine) and the amount of natural sand material. The short-cut versions of this test method, major sieve and 2nd major sieve fractions, did not produce strong correlations when compared to the composite Particle Index values. A Particle Index value greater than 14 would insure that the aggregate blend had at least 70 percent crushed particles.

2. The modified NAA particle shape and texture test produced extremely high correlations with percent crushed coarse aggregate. Method 1 (as-received) produced a $R^2$ value of

0.941, while Method 2 (weighted average) produced a $R^2$ value of 0.945. The uncompacted void contents for Method 1 were approximately 2 percent lower than for Method 2. The void contents for Methods 1 and 2 required to insure 70 percent crushed coarse particles were 45 and 47 percent, respectively.

3. Both the rodding and shoveling procedures of ASTM C29 produced excellent correlations with percent crushed coarse particles. The rodding procedure produced void contents approximately 4 percent lower than the shoveling procedure. To insure 70 percent crushed coarse particles, the void contents for the rodding procedure had to be at least 40 (as-received) and 42 (weighted average) percent, while the void contents for the shoveling procedure had to be at least 44 (as-received) and 46 (weighted) percent.

4. Method A of the NAA particle shape and texture test produced stronger relationships with percent crushed fine particles and the amount of natural sand material than did Method C. An uncompacted void content for Method A of 45 percent would insure 70 percent crushed fine particles an less than 10 percent natural sand material.

5. The direct shear test method for fine aggregates did not correlate well with percent crushed fine particles and the amount of natural sand material in the aggregate blend.

6. The GEPI values produced strong correlations with the composite aggregate blend and the coarse aggregate fraction characterization test results. These strong correlations indicated that the GEPI value did measure the aggregate quality in an asphalt-aggregate mixture. A GEPI value of 1.36 corresponds to a Particle Index value of 14 which corresponds to at least 70 percent crushed particles in the aggregate blend.

7. Based on strong correlations and simple test procedures, the best alternatives for specification requirements to characterize aggregate particle shape and texture are modified NAA particle shape and texture test for coarse aggregate fraction and the NAA particle shape and texture test for fine aggregate fraction. The Particle Index test and the GEPI value could be used to specify the aggregate characterization properties for the composite aggregate blend.

8. The shape of the aggregate gradation curve had a significant effect on permanent deformation properties. The asphalt-aggregate mixtures that produced the better rutting characteristics were with aggregate gradations finer than the maximum density line (Mixes 3 and 5) and two poorly-graded gradations (Mixes 4 and 7). Each of these mixtures produced better rutting characteristics than the mixture produced with an aggregate gradation falling on the center of the FAA gradation band. The two poorly-graded gradations both have large percentages of material retained on the No. 4 sieve with sufficient fine material (similar to stone mastic asphalt (SMA) mixtures) which can produce stone on stone contact.

9. Aggregate gradations plotted on a 0.45 power gradation curve amplified the presence of too much natural sand material in the aggregate blend.

10. The percentage of crushed coarse particles also had a significant effect on permanent deformation properties. As the percentage of crushed coarse particles decreased, the rutting potential of the asphalt mixtures increased. Asphalt mixtures containing less than 70 percent crushed coarse aggregate would be susceptible to rutting.

11. An increase in the amount of natural sand material did have an adverse effect on the permanent deformation properties. Asphalt mixtures with greater than 10 percent by weight produced results that indicated increased rutting potential. Asphalt mixtures with 20 percent and greater natural sand contents are suspect to being tender and unstable.

12. The Marshall stability test, direct shear strength test, gyratory compaction properties, and the confined repeated load deformation test were all sensitive to aggregate property changes and could be used to evaluate the effects of aggregate properties on asphalt mixtures.

13. The stiff asphalt binders (AC-40, SBS modified AC-20, and LDPE modified AC-20) did improve some of the marginal mixtures to the minimum FAA standards. Each stiff asphalt binder improved the Marshall stability values, the GEPI values, the indirect tensile strength values, and the direct shear strength values with varying success. The AC-40 binder was the least effecting while the SBS-modified AC-20 binder had the greatest positive effect on mixture strength.

14. All of the stiff asphalt binders reduced the GEPI values which has the same effect as improving the quality of the aggregates shape and texture.

15. AC-40 binder did not improve permanent deformation properties as significantly as the two polymer-modified AC-20 binders. Overall, the SBS-modified AC-20 binder produced the greatest improvements in these asphalt mixtures.

16. The SBS-modified AC-20 binder improved Mix 13 (crushed gravel) enough to equal Mix 1 (crushed limestone) with AC-20 binder. The SBS-modified AC-20 binder also improved Mixes 12, 19, and 21 enough to equal Mix 13 (control mix) produced with AC-20 binder. The LDPE-modified AC-20 improved Mix 21 enough to equal Mix 13 with AC-20 binder.

17. The SBS and LDPE-modified AC-20 mixtures significantly reduced the slope of the deformation curve values for all asphalt mixtures.

## RECOMMENDATIONS

Based on the conclusions derived from the results of this laboratory study, the following recommendations were made:

1. Current FAA aggregate specifications could be improved by implementing performance-based quantitative aggregate characterization properties determined by the Particle Index test and the NAA and modified NAA particle shape and texture tests. Initial preliminary guidance and criteria could be implemented based on values determined in this laboratory study, but final criteria should be verified based on additional research involving a variety of aggregate types and sources.

2. Current FAA gradation bands should be modified and shifted to include finer gradations. The coarse limit of the current specification produced a very low quality mixture. Mixtures finer than the current specification produced very low rut susceptible mixtures. A new gradation band for surface course mixtures is presented in table 52.

3. Additional research is needed to fully evaluate the poorly-graded mixtures and the potential of large aggregate mixtures and SMA mixtures.

4. Current FAA requirements for percent crushed particles and amount of natural sand material in the aggregate blend may allow rut susceptible asphalt mixtures to be used. The confined repeated load deformation test should be used in conjunction with the Marshall procedure to analyze the rutting potential of the asphalt mixture.

5. Modified asphalt binders can improve the rutting characteristics of marginal aggregate mixtures. Further research is needed to evaluate new and different asphalt modification techniques and to establish criteria for selecting the modifier type and dosage rate.

6. Analysis of field tests should be conducted to verify performance with laboratory data.

TABLE 52. NEW AGGREGATE GRADATION BANDS

| Sieve Size | 1 in. Max. | 3/4 in. Max. | 1/2 in. Max |
|---|---|---|---|
| 1 in. | 100 | --- | --- |
| 3/4 in. | 76-96 | 100 | --- |
| 1/2 in. | 66-88 | 78-96 | 100 |
| 3/8 in. | 58-82 | 69-89 | 78-96 |
| No. 4 | 43-67 | 51-73 | 58-78 |
| No. 8 | 30-54 | 36-60 | 38-60 |
| No. 16 | 24-44 | 24-48 | 26-48 |
| No. 30 | 15-35 | 18-38 | 18-38 |
| No. 50 | 9-25 | 11-27 | 11-27 |
| No. 100 | 6-18 | 6-18 | 6-18 |
| No. 200 | 3-6 | 3-6 | 3-6 |

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APPENDIX A: AGGREGATE GRADATION CURVES
(SEMI-LOG AND 0.45 POWER CURVE)

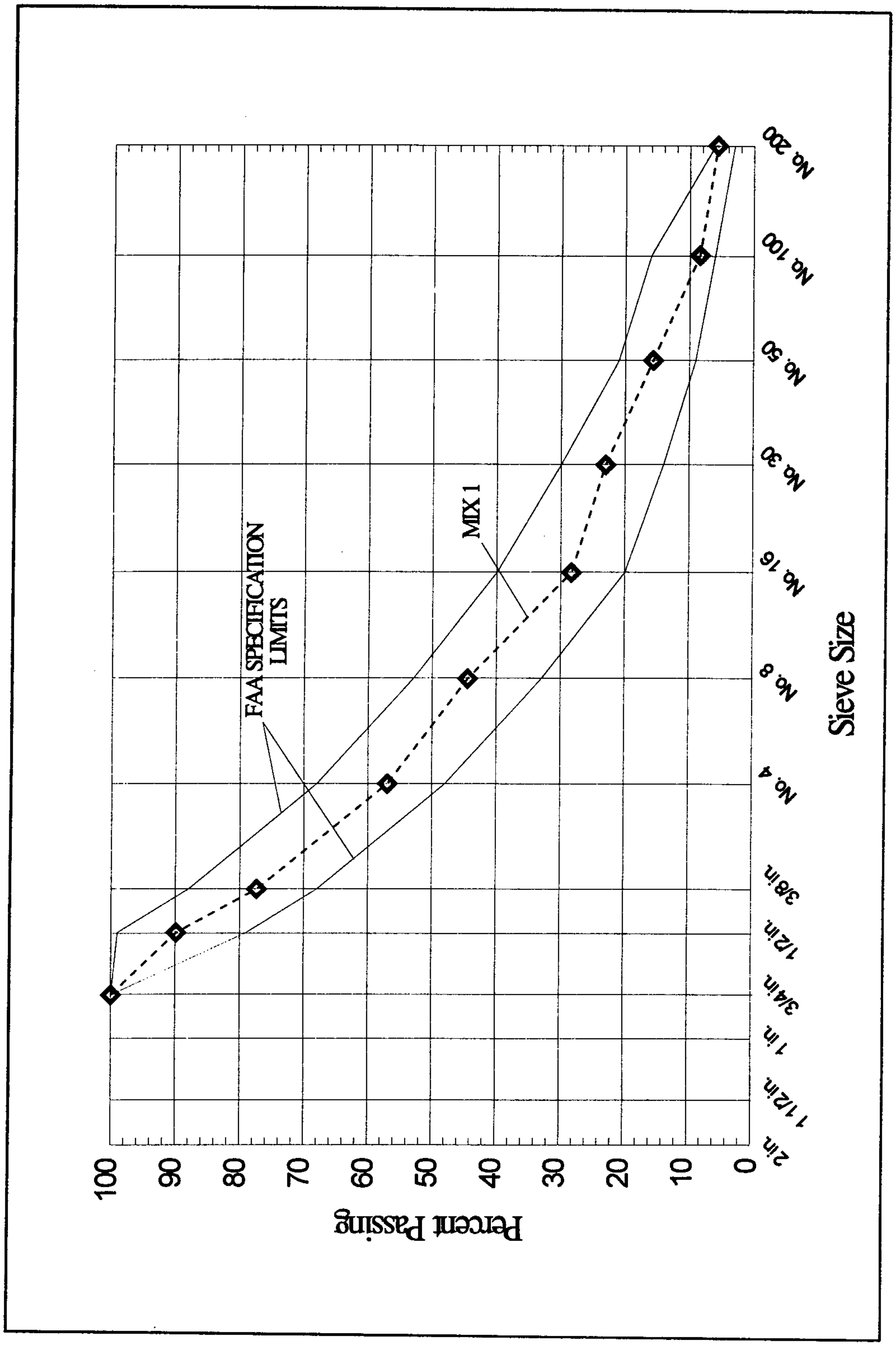


FIGURE A-1. AGGREGATE GRADATION FOR MIX 1

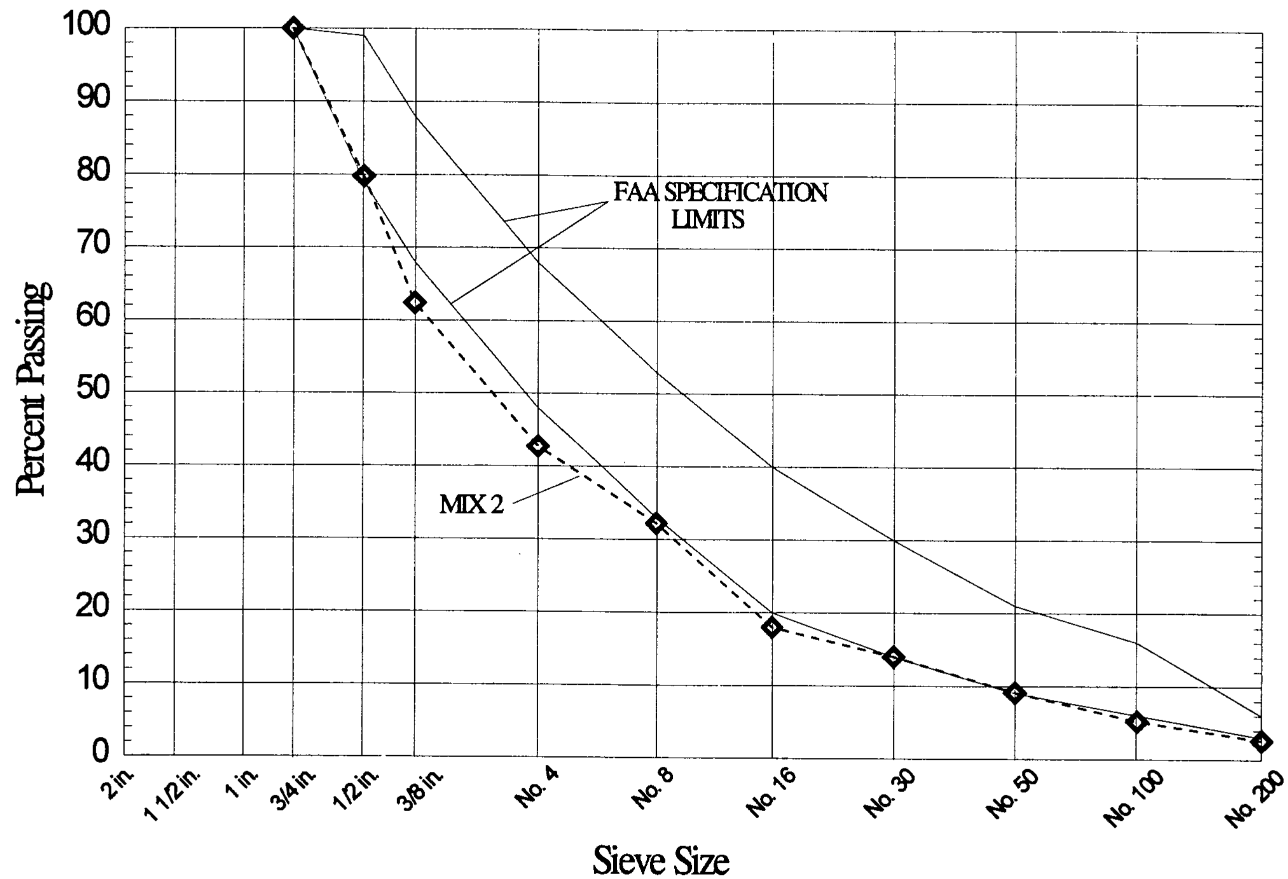


FIGURE A-2. AGGREGATE GRADATION FOR MIX 2

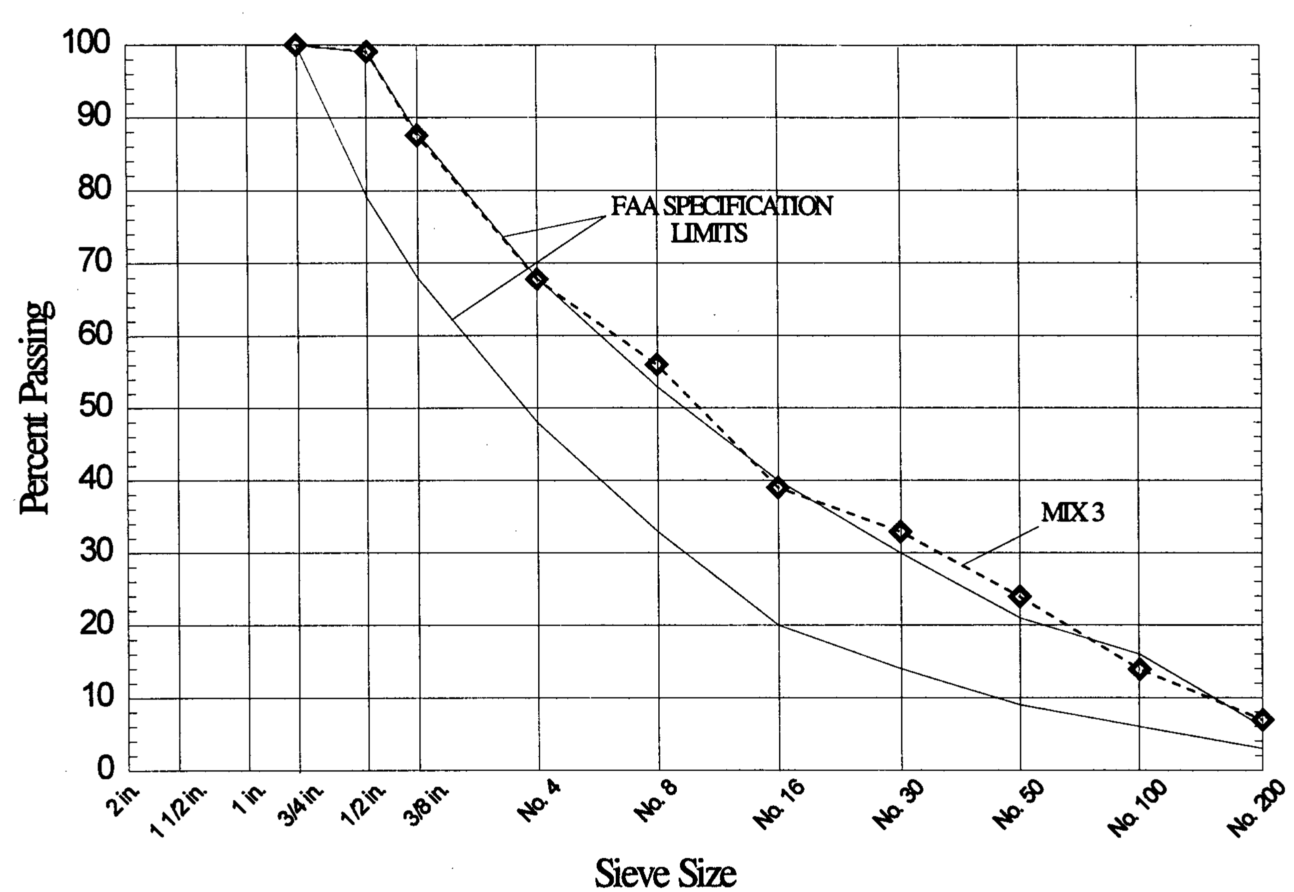


FIGURE A-3. AGGREGATE GRADATION FOR MIX 3

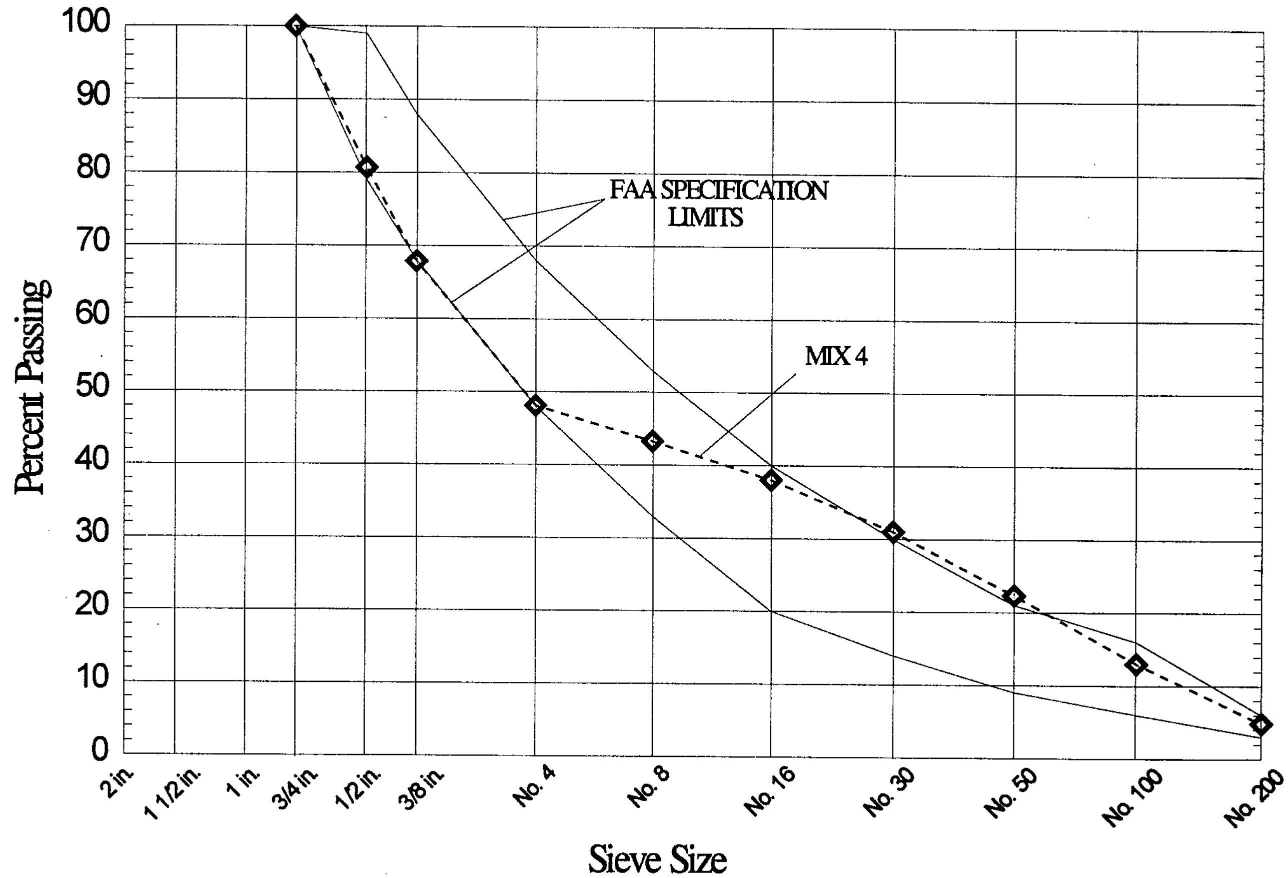


FIGURE A-4. AGGREGATE GRADATION FOR MIX 4

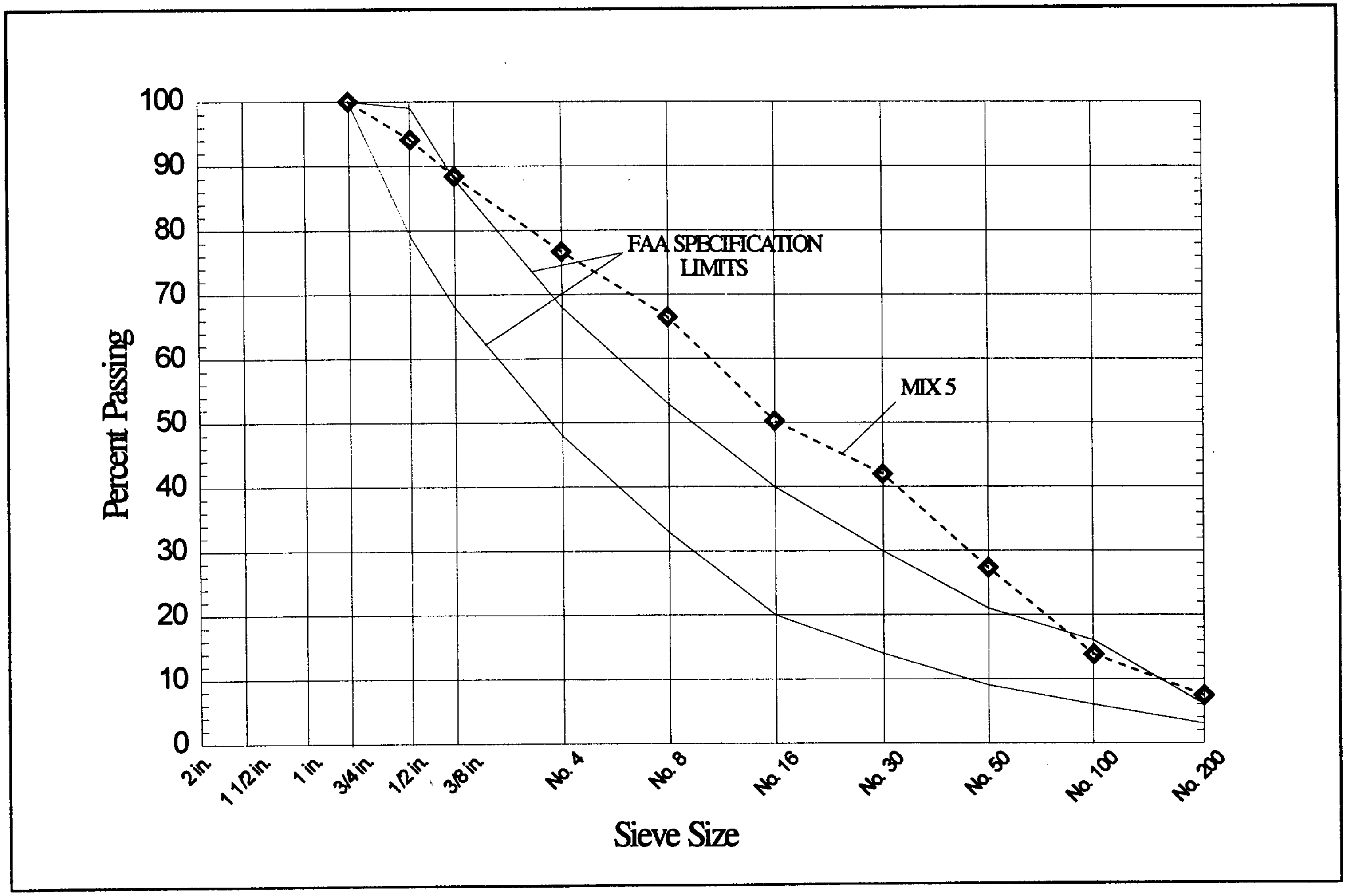


FIGURE A-5. AGGREGATE GRADATION FOR MIX 5

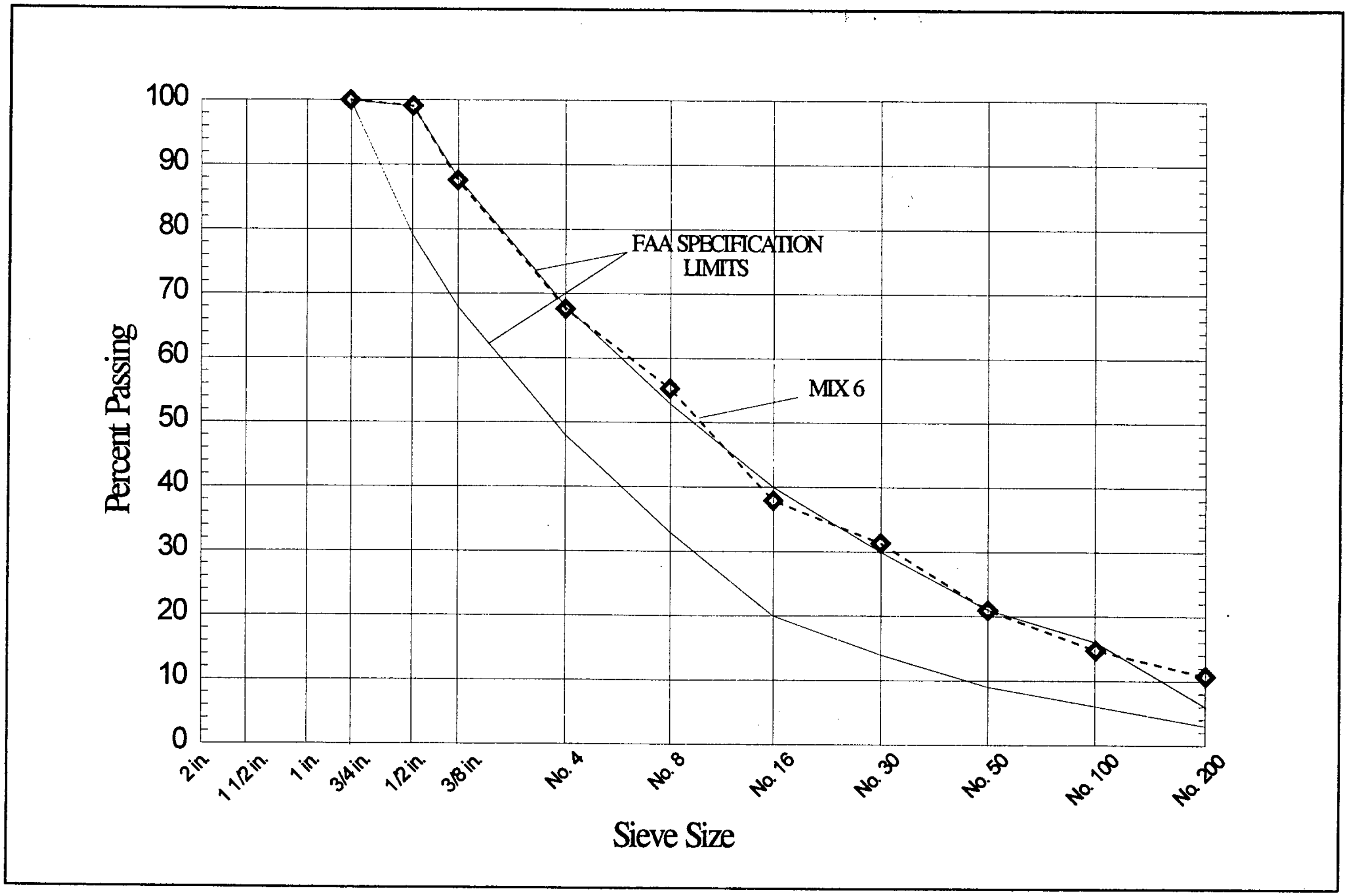


FIGURE A-6. AGGREGATE GRADATION FOR MIX 6

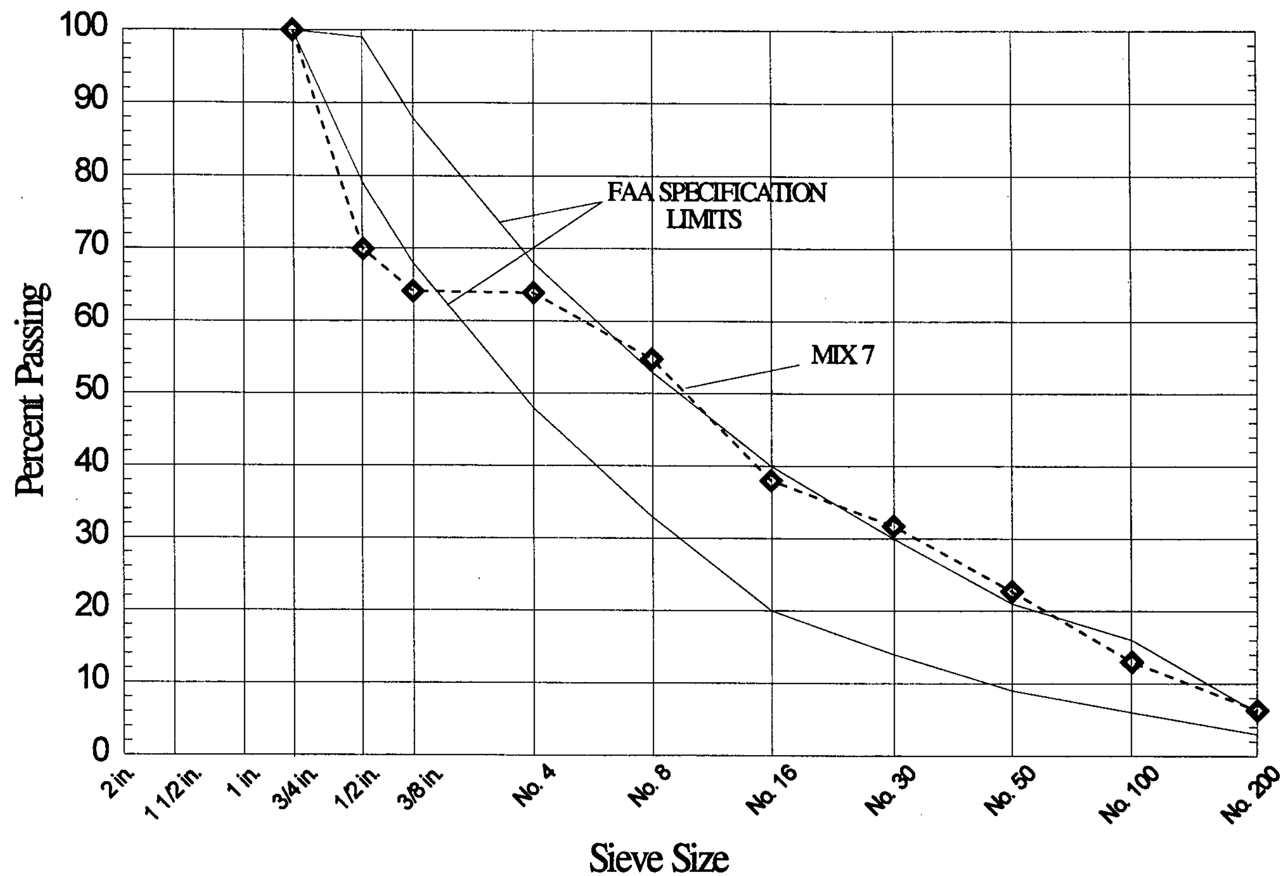


FIGURE A-7. AGGREGATE GRADATION FOR MIX 7

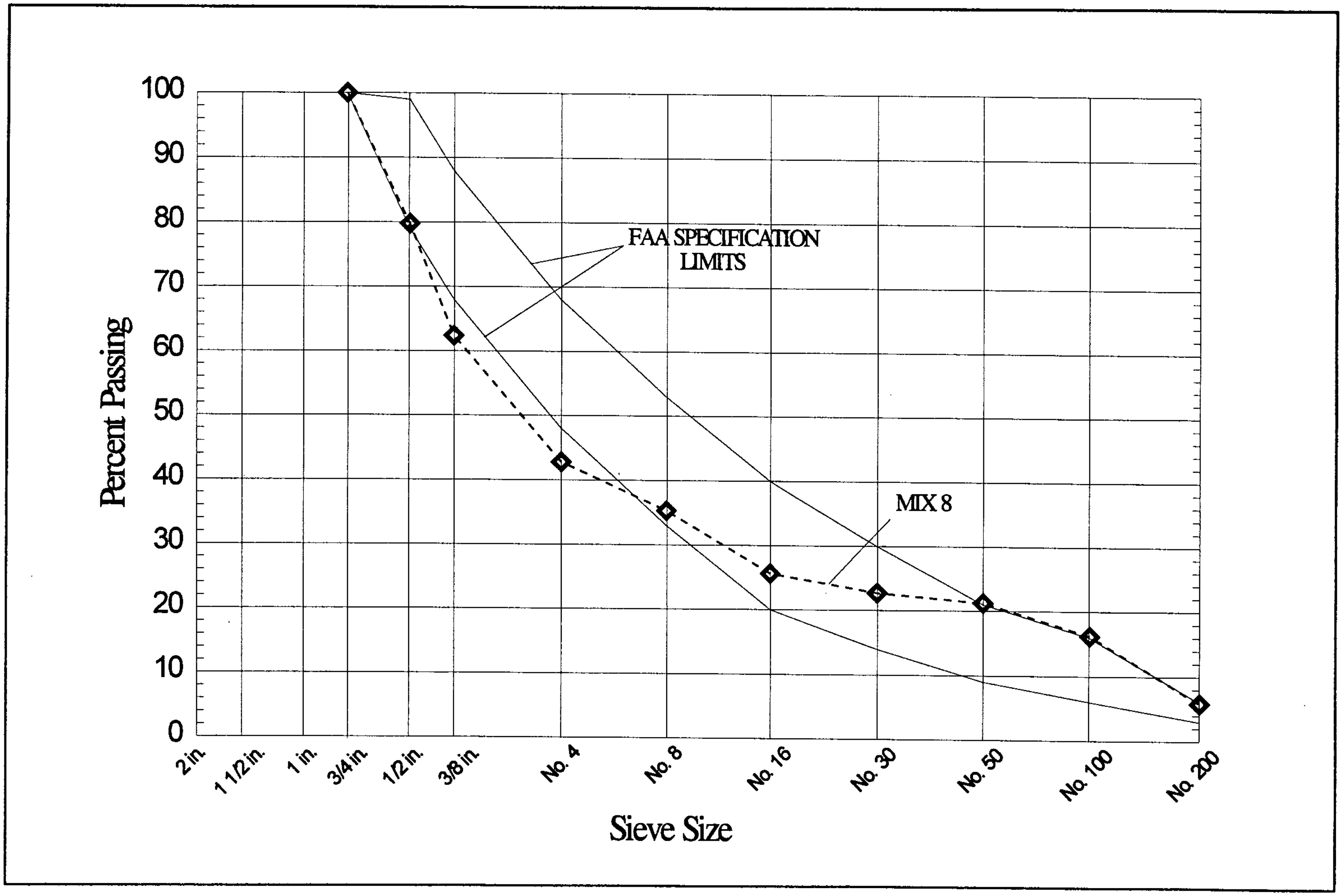


FIGURE A-8. AGGREGATE GRADATION FOR MIX 8

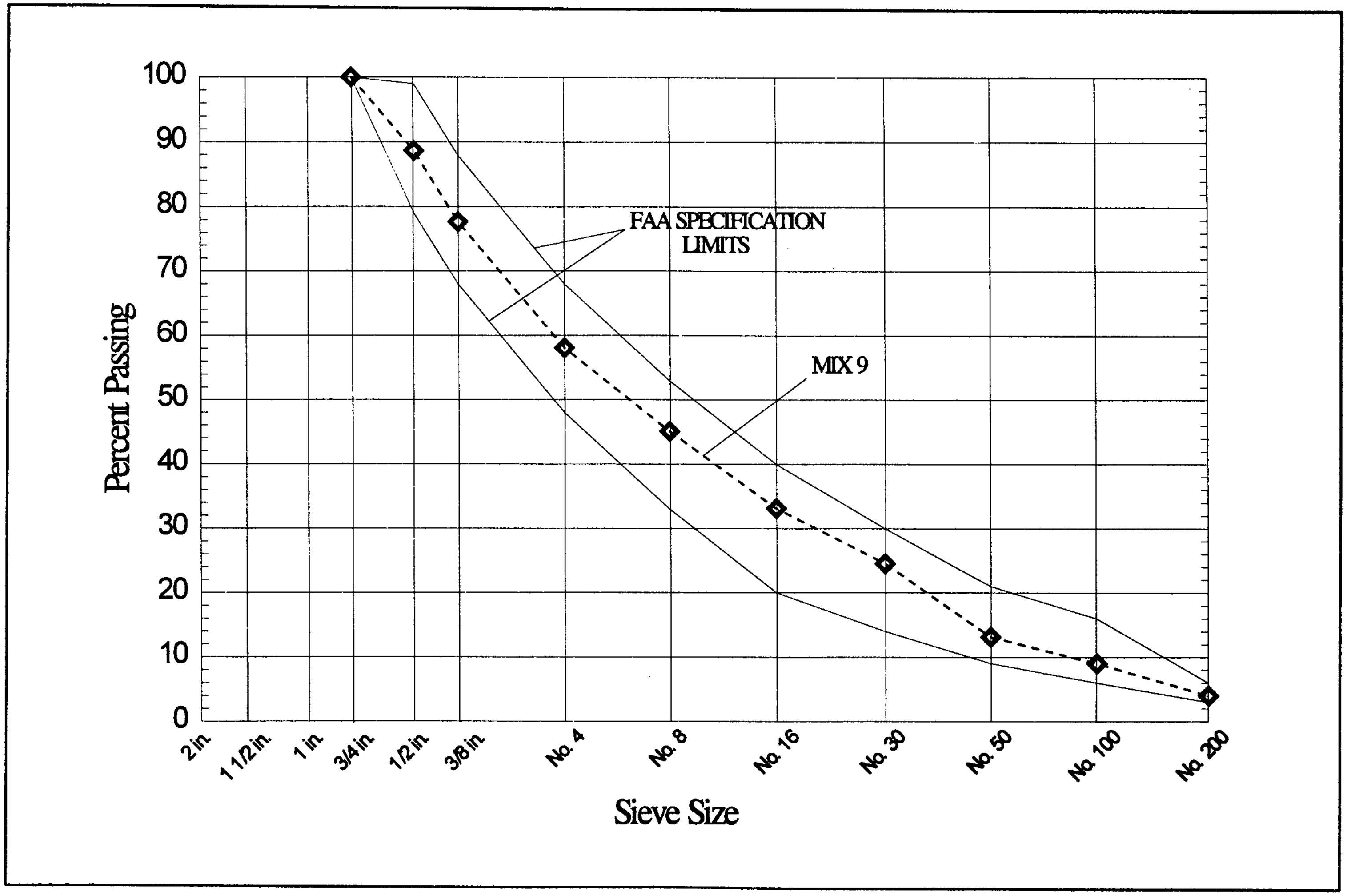


FIGURE A-9. AGGREGATE GRADATION FOR MIX 9

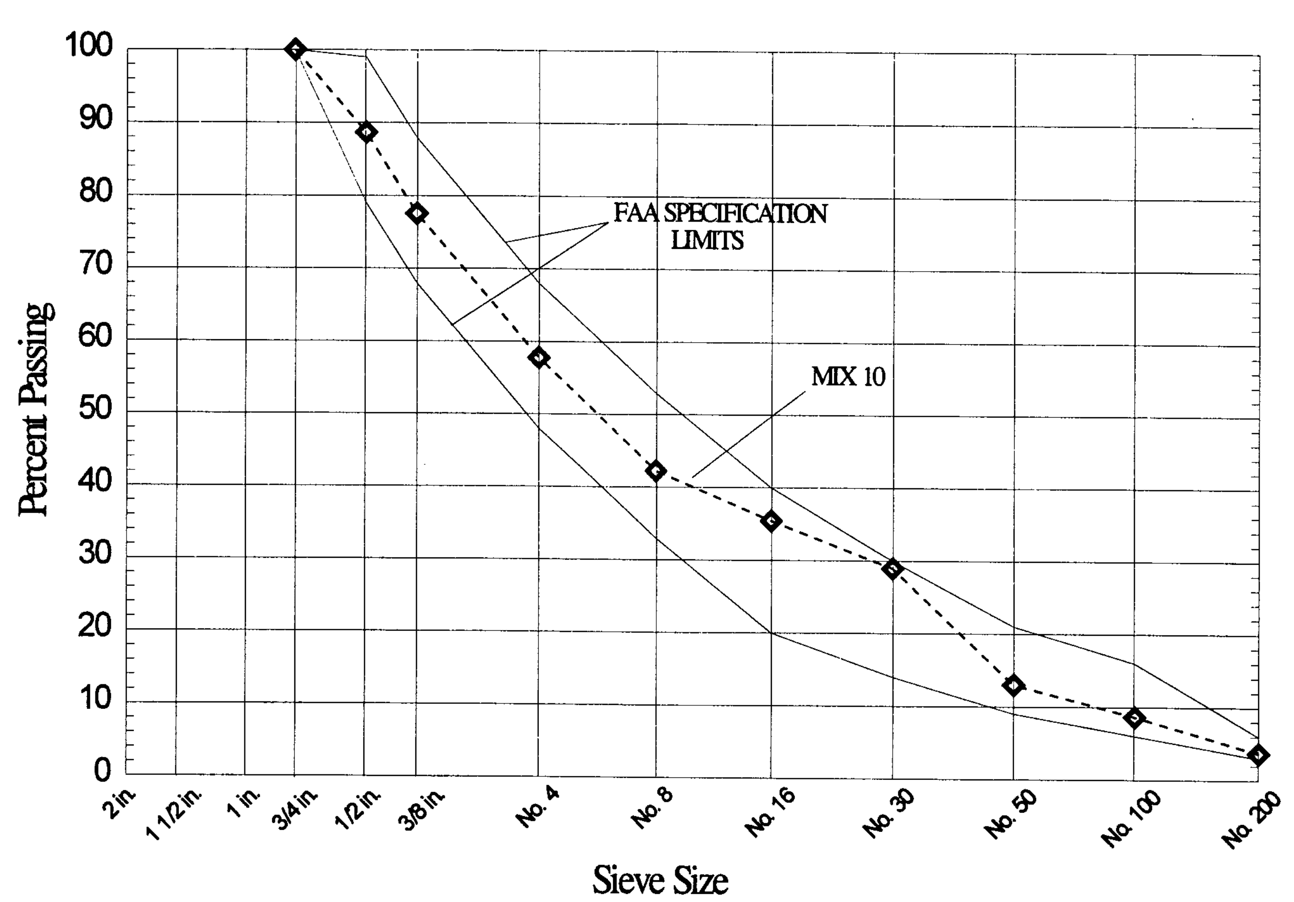


FIGURE A-10. AGGREGATE GRADATION FOR MIX 10

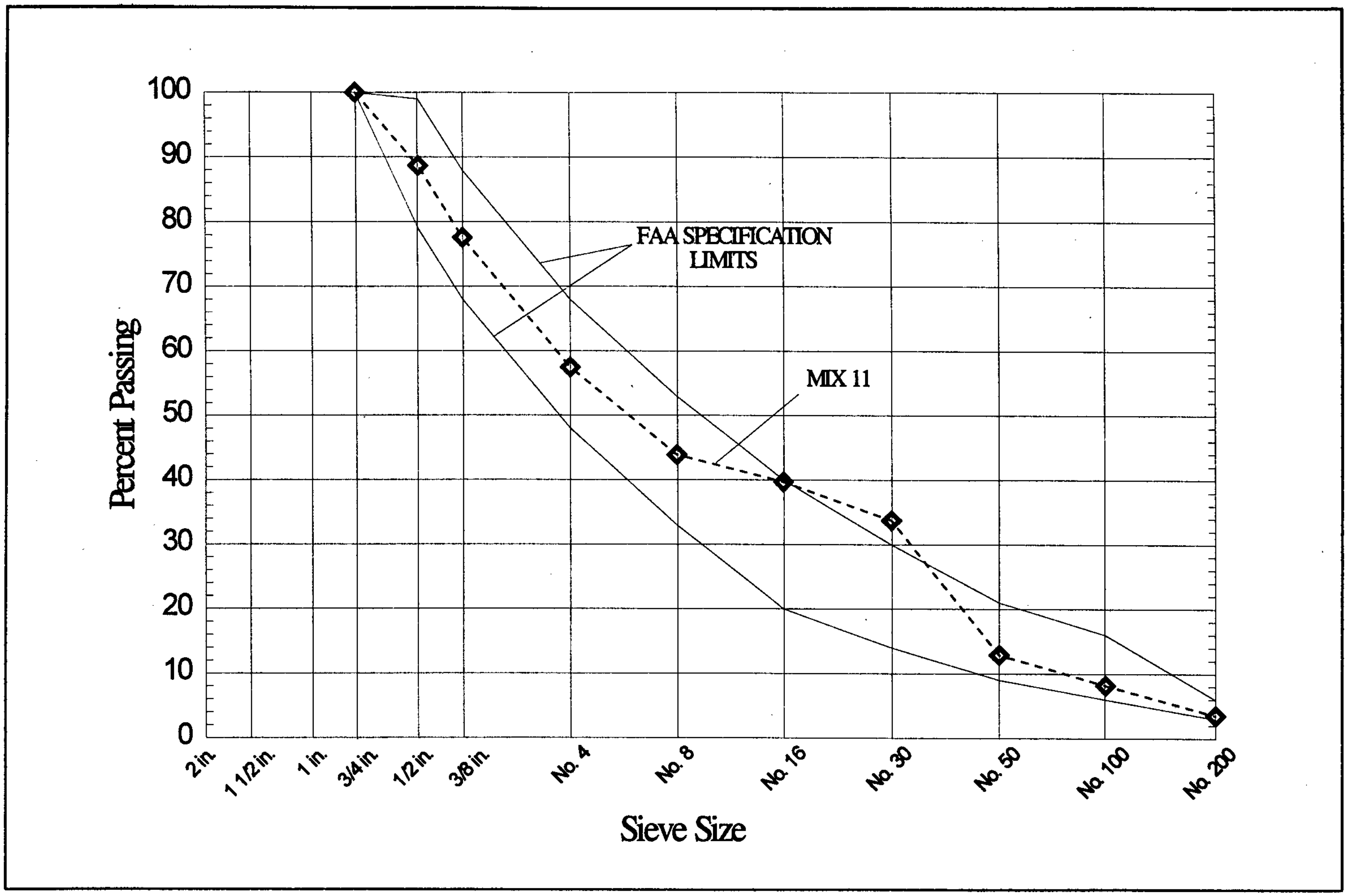


FIGURE A-11. AGGREGATE GRADATION FOR MIX 11

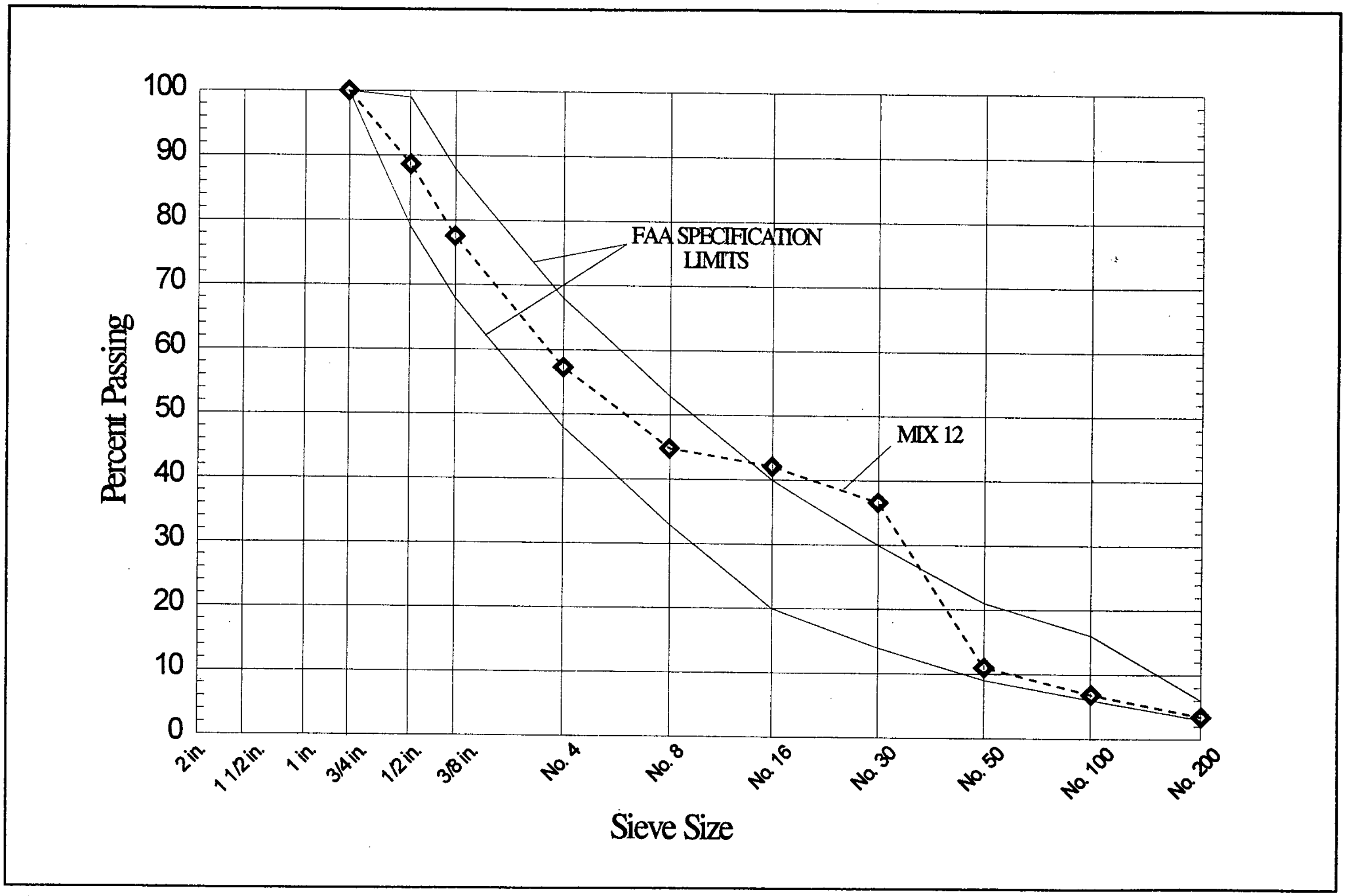


FIGURE A-12. AGGREGATE GRADATION FOR MIX 12

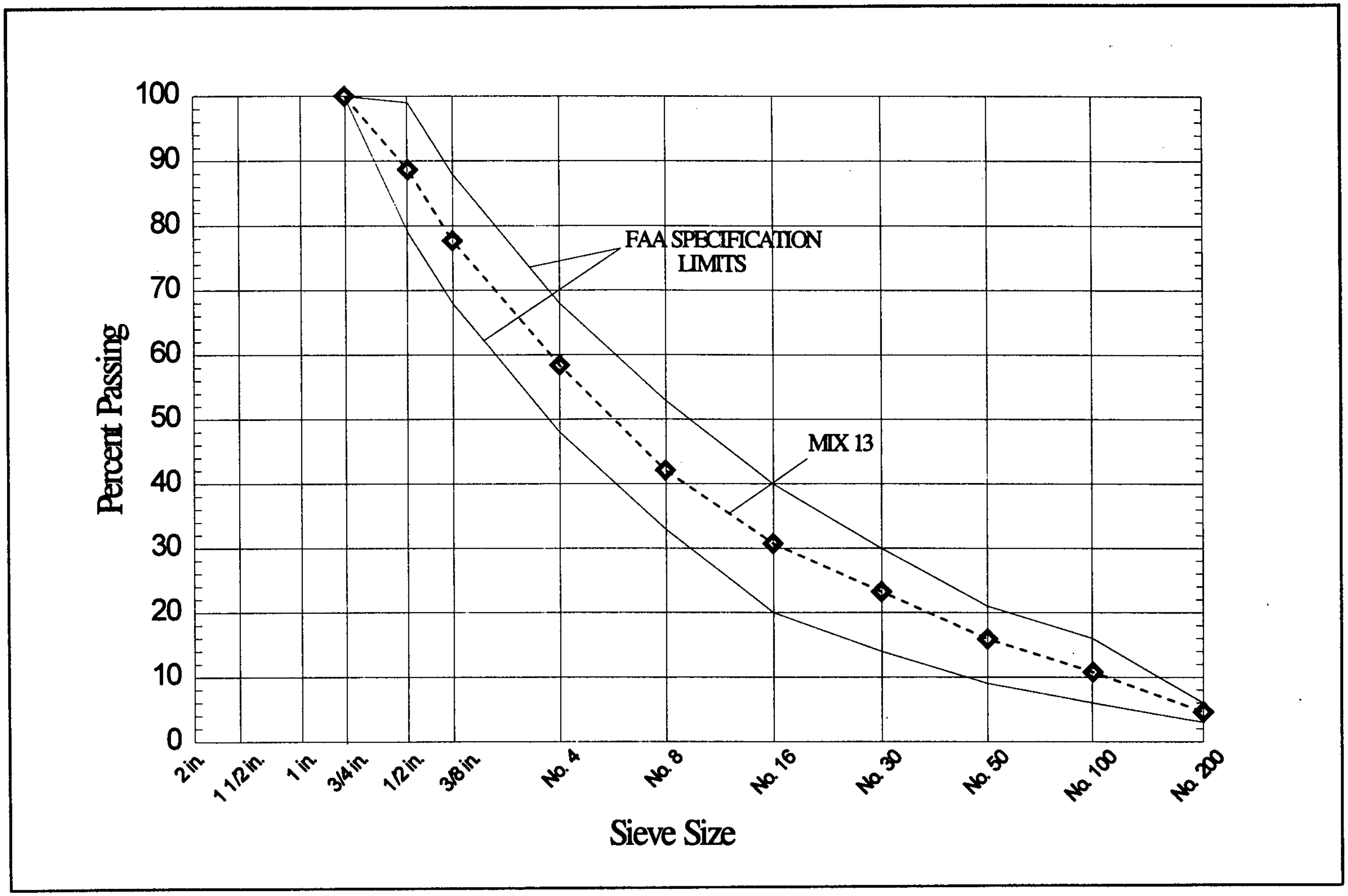


FIGURE A-13. AGGREGATE GRADATION FOR MIX 13

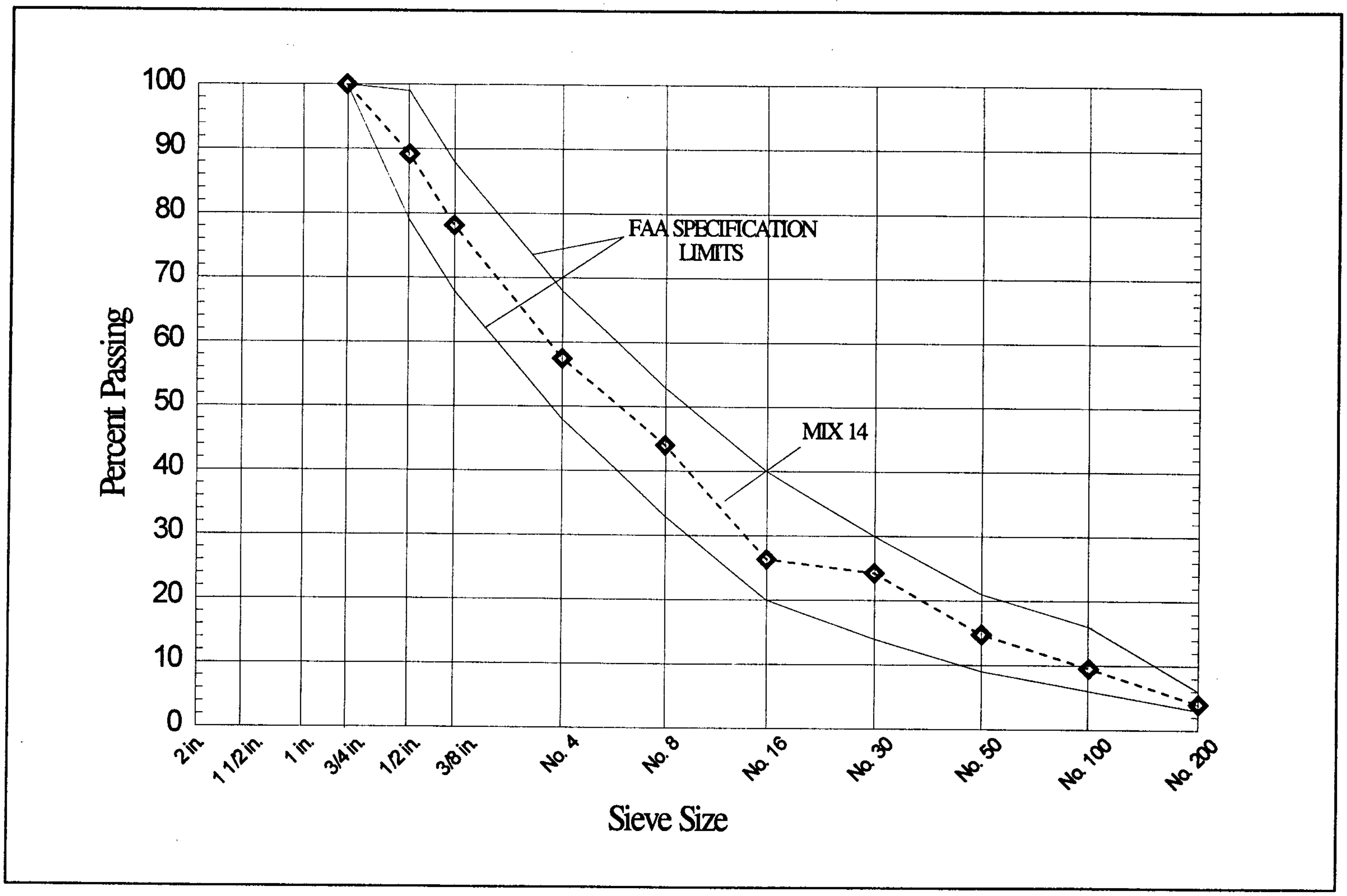


FIGURE A-14. AGGREGATE GRADATION FOR MIX 14

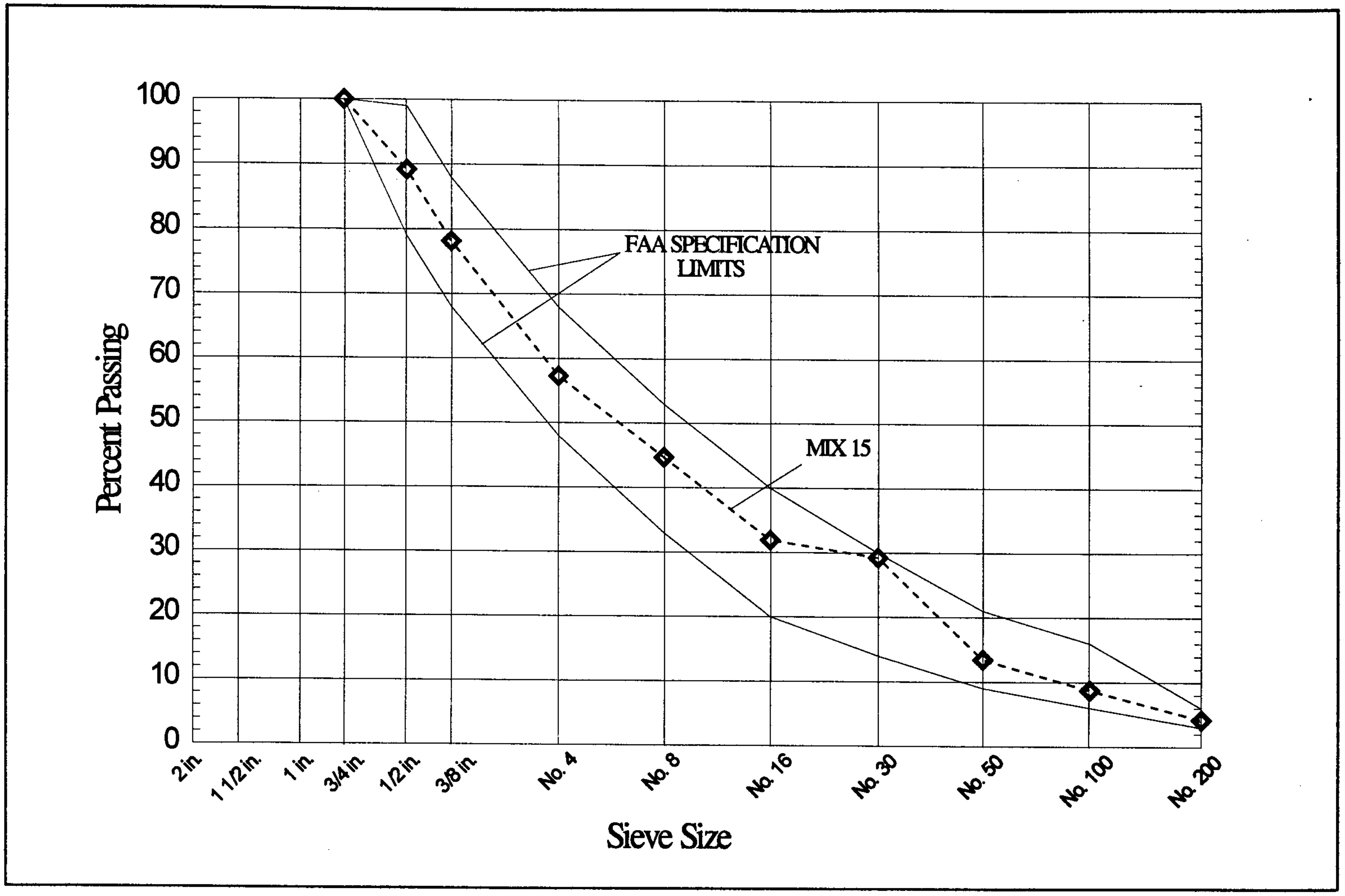


FIGURE A-15. AGGREGATE GRADATION FOR MIX 15

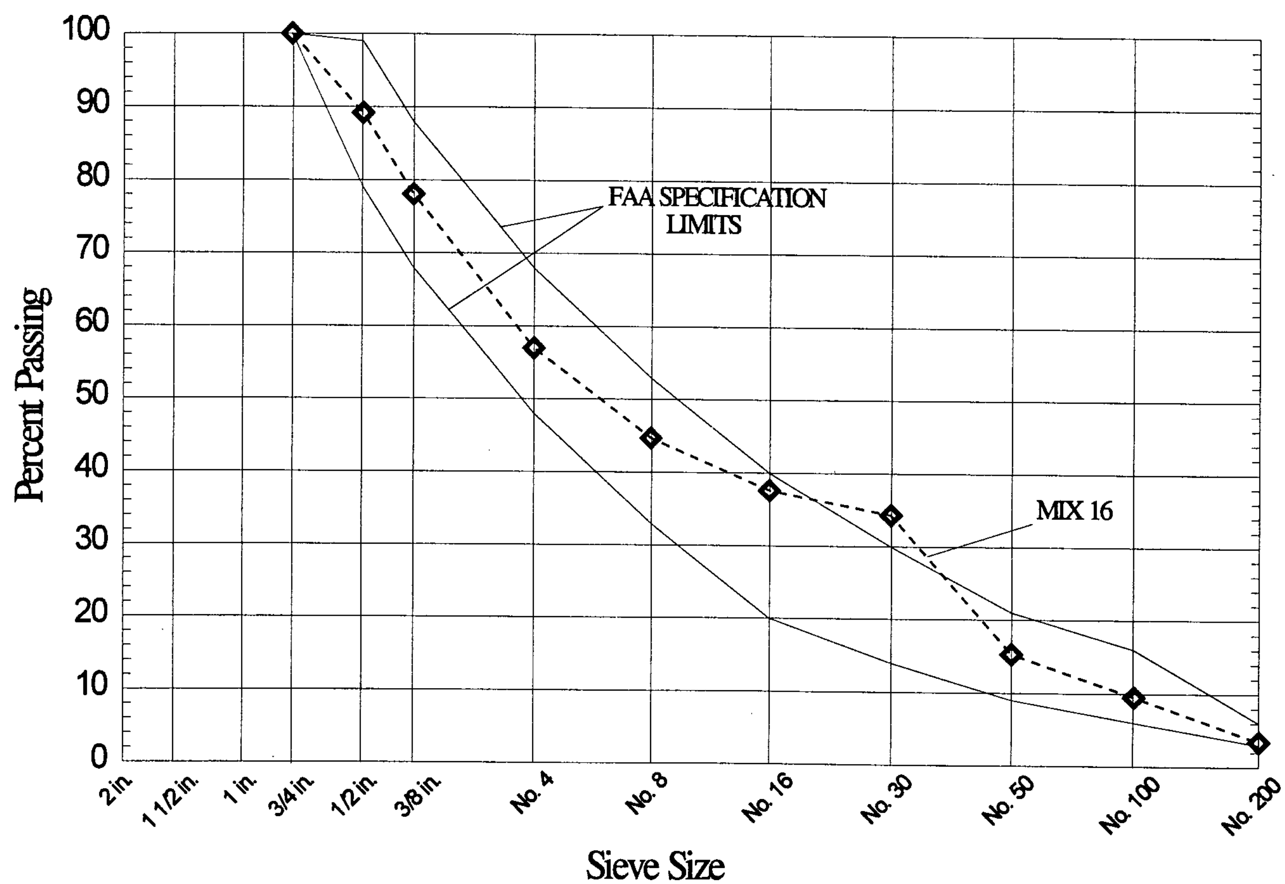


FIGURE A-16. AGGREGATE GRADATION FOR MIX 16

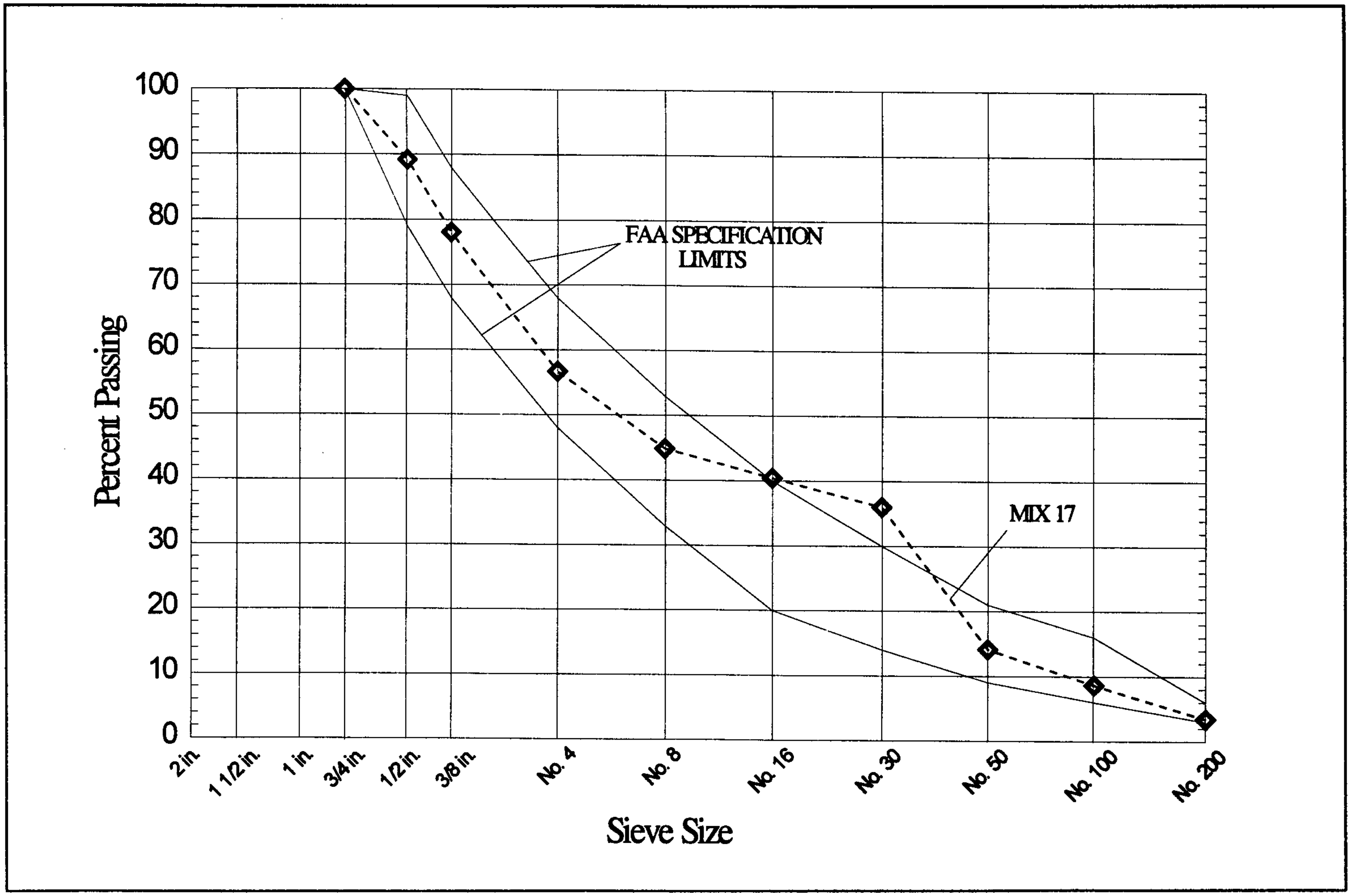


FIGURE A-17. AGGREGATE GRADATION FOR MIX 17

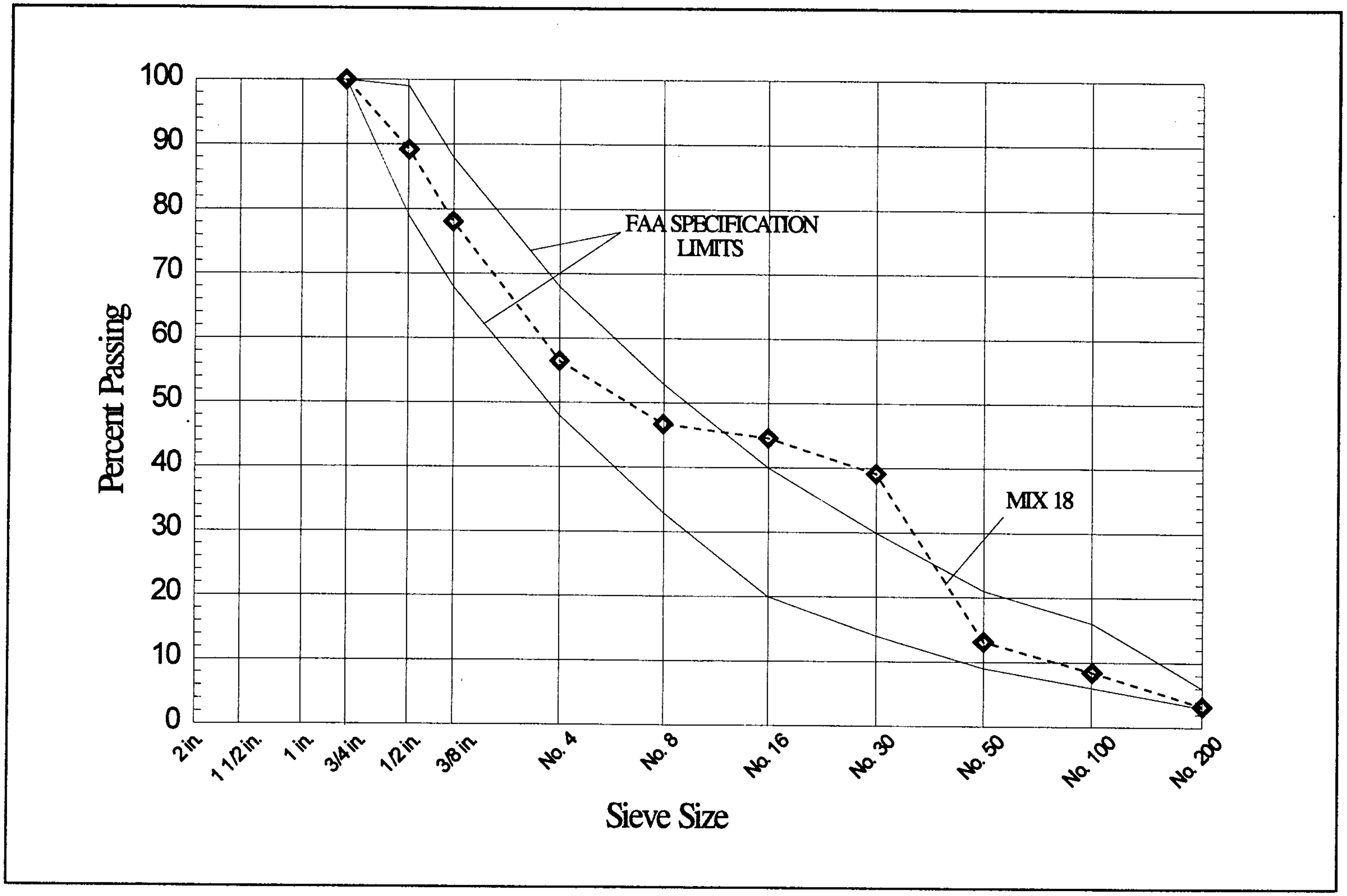


FIGURE A-18. AGGREGATE GRADATION FOR MIX 18

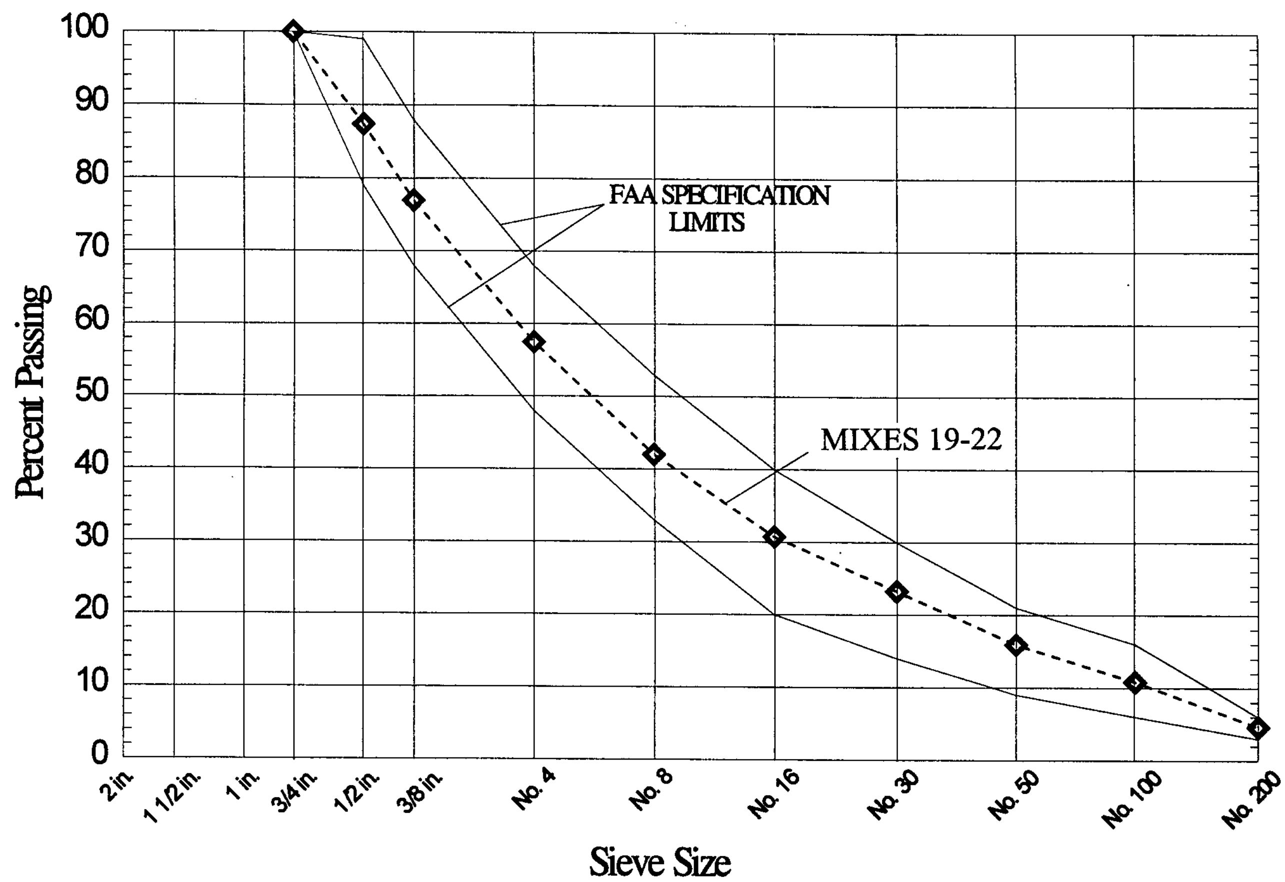


FIGURE A-19. AGGREGATE GRADATIONFOR MIXES 19-22

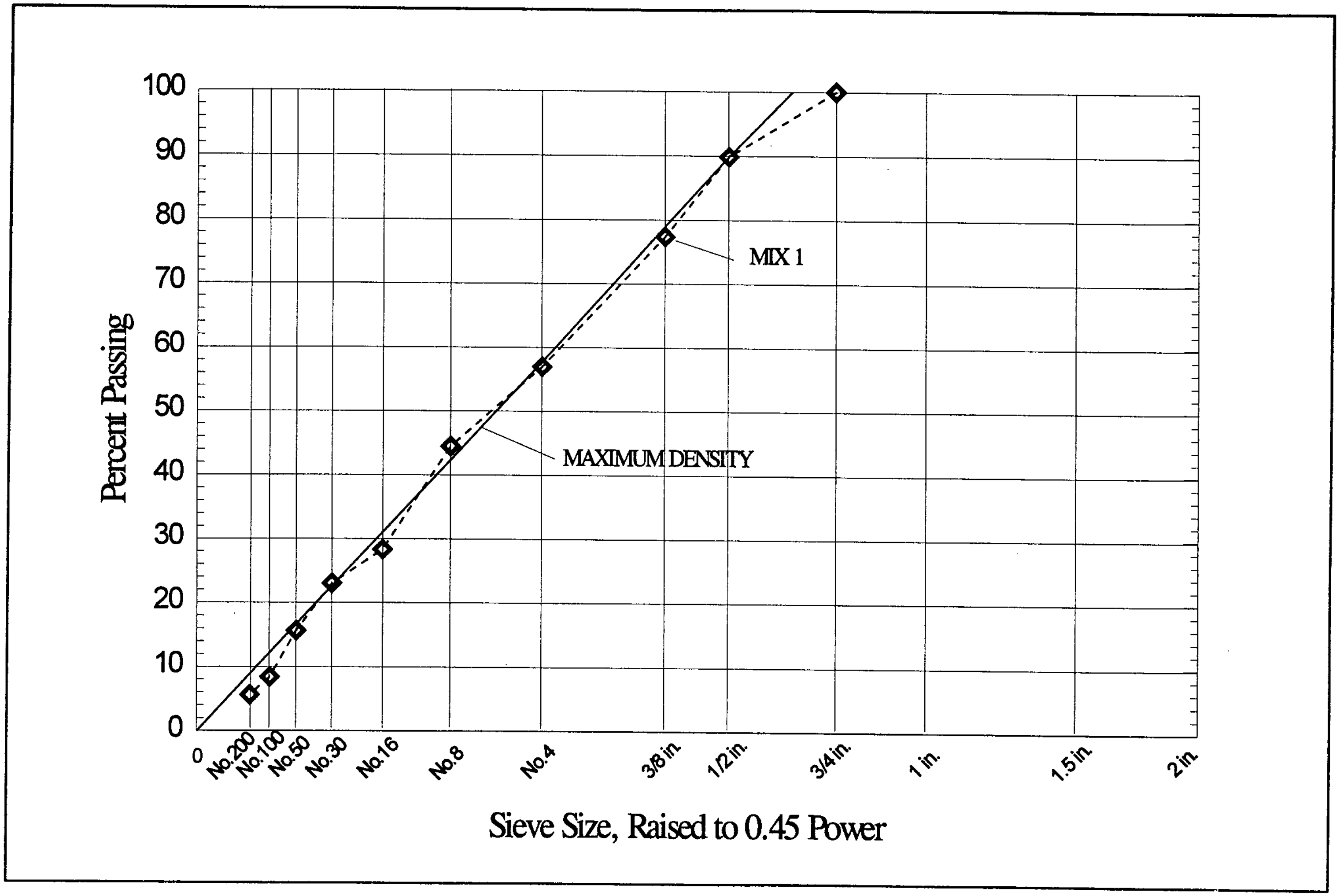


FIGURE A-20. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 1

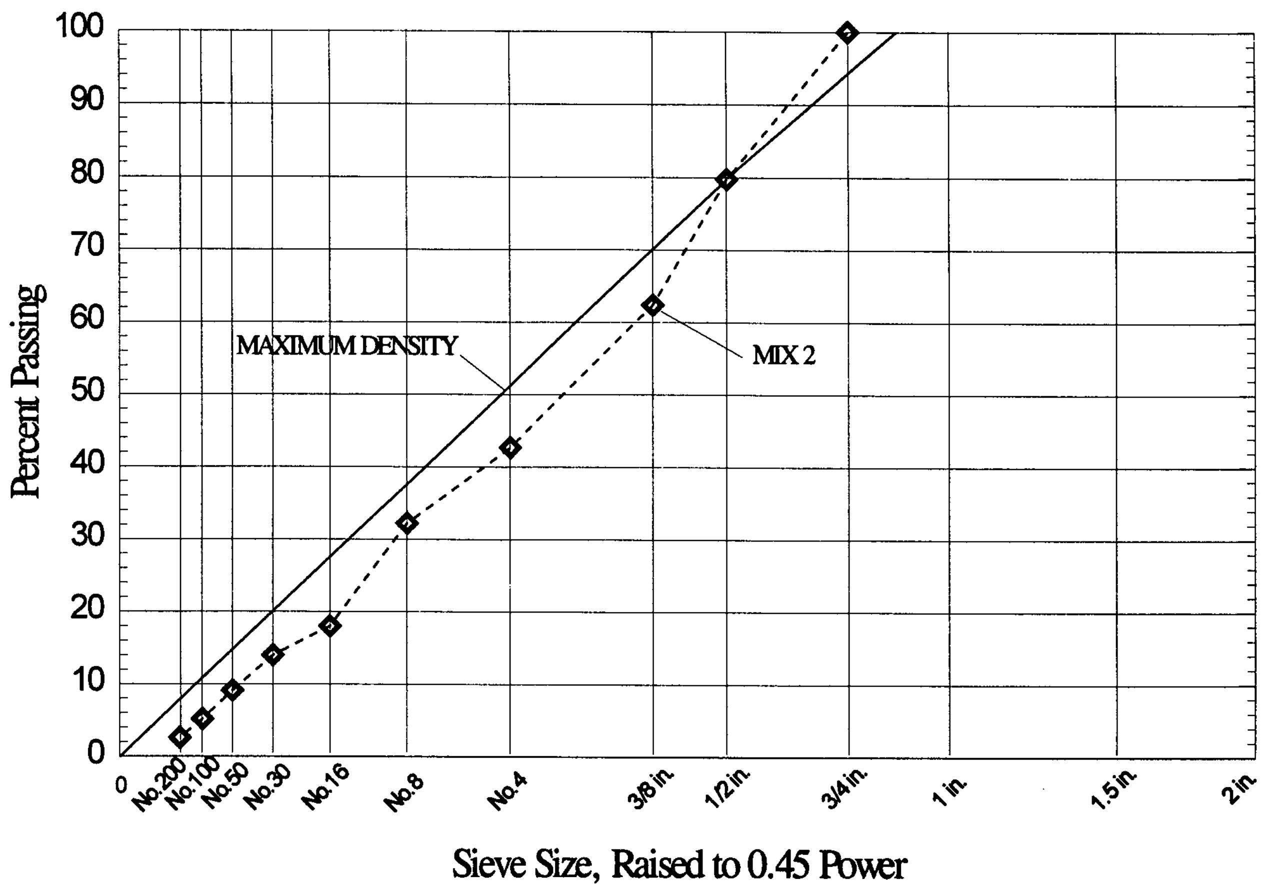


FIGURE A-21. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 2

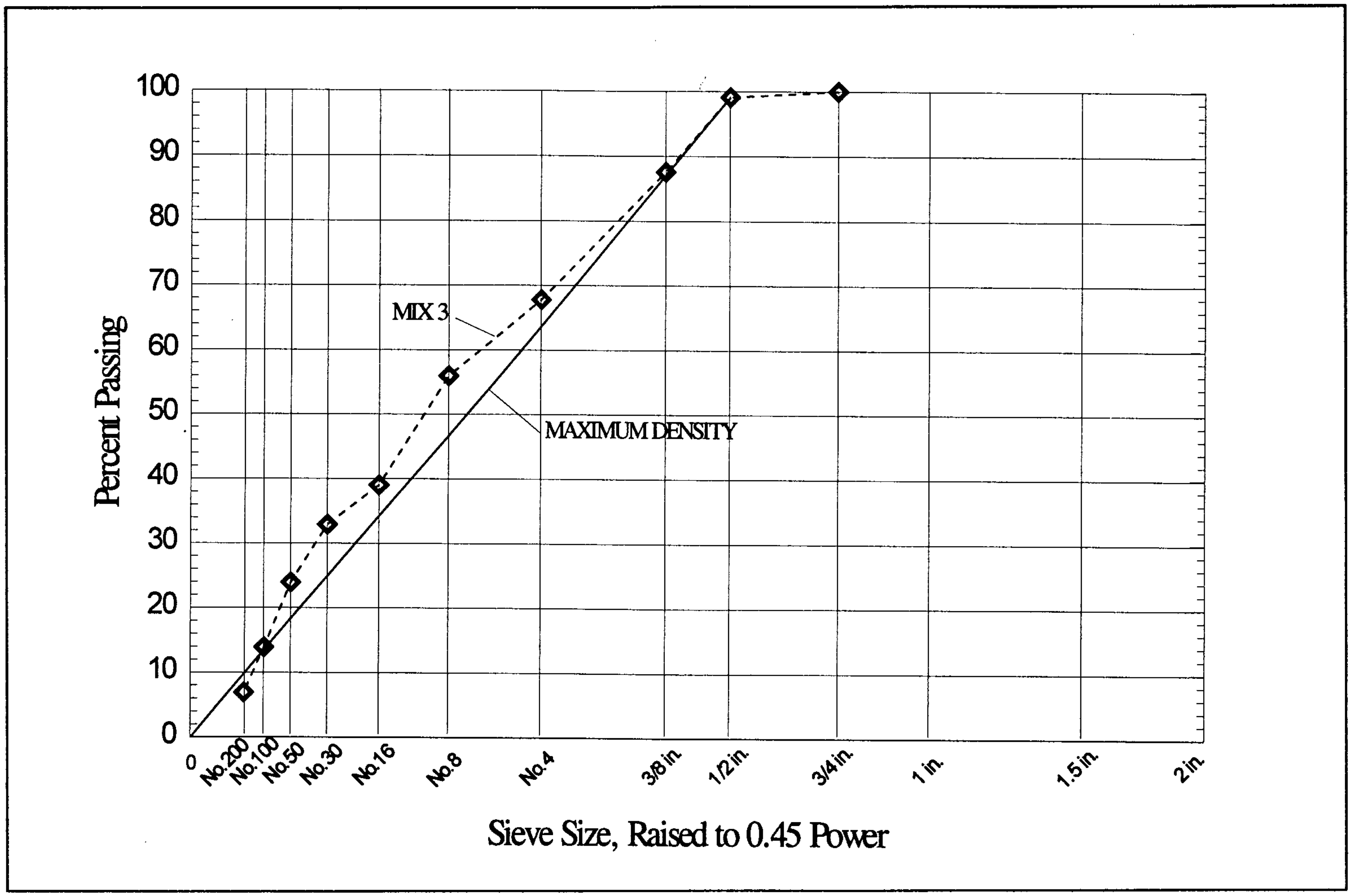


FIGURE A-22. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 3

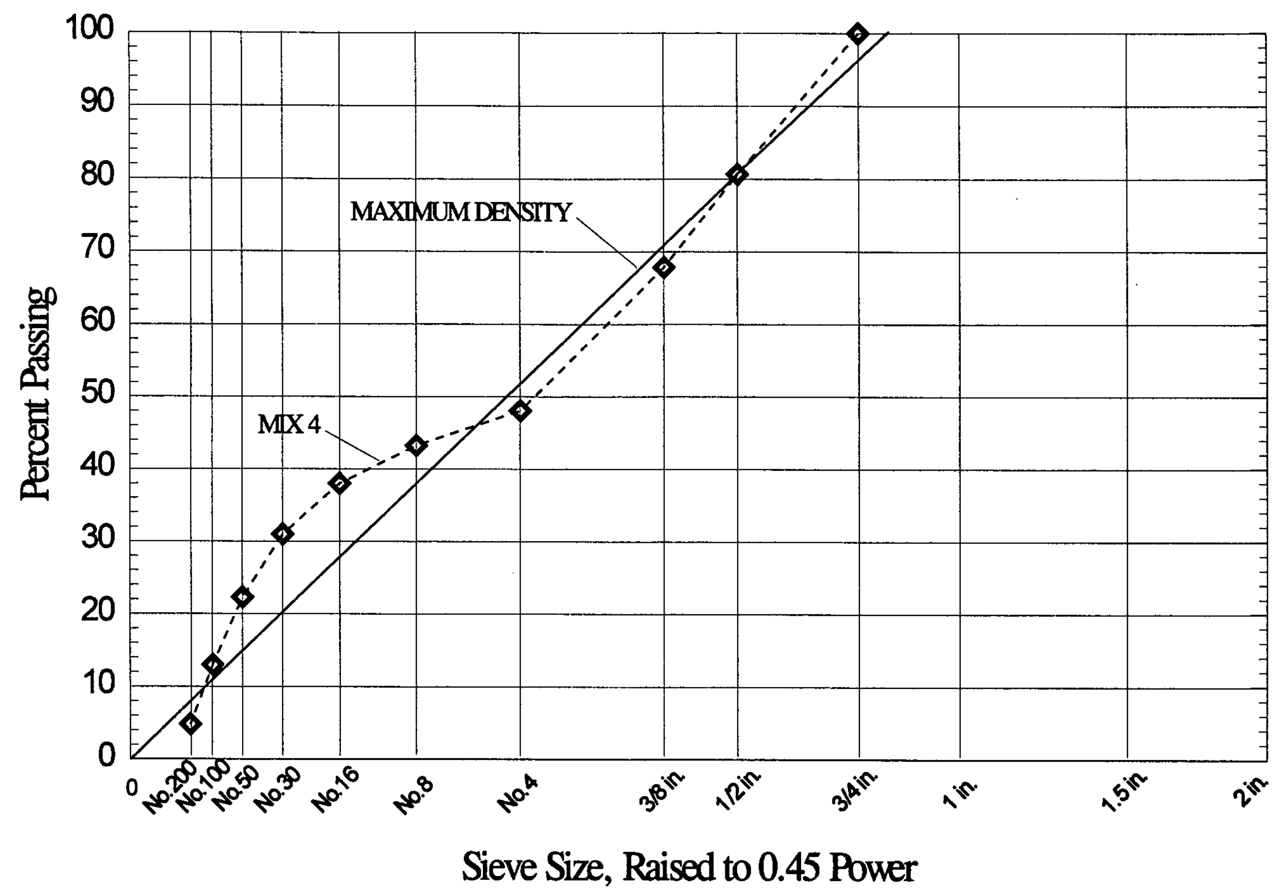


FIGURE A-23. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 4

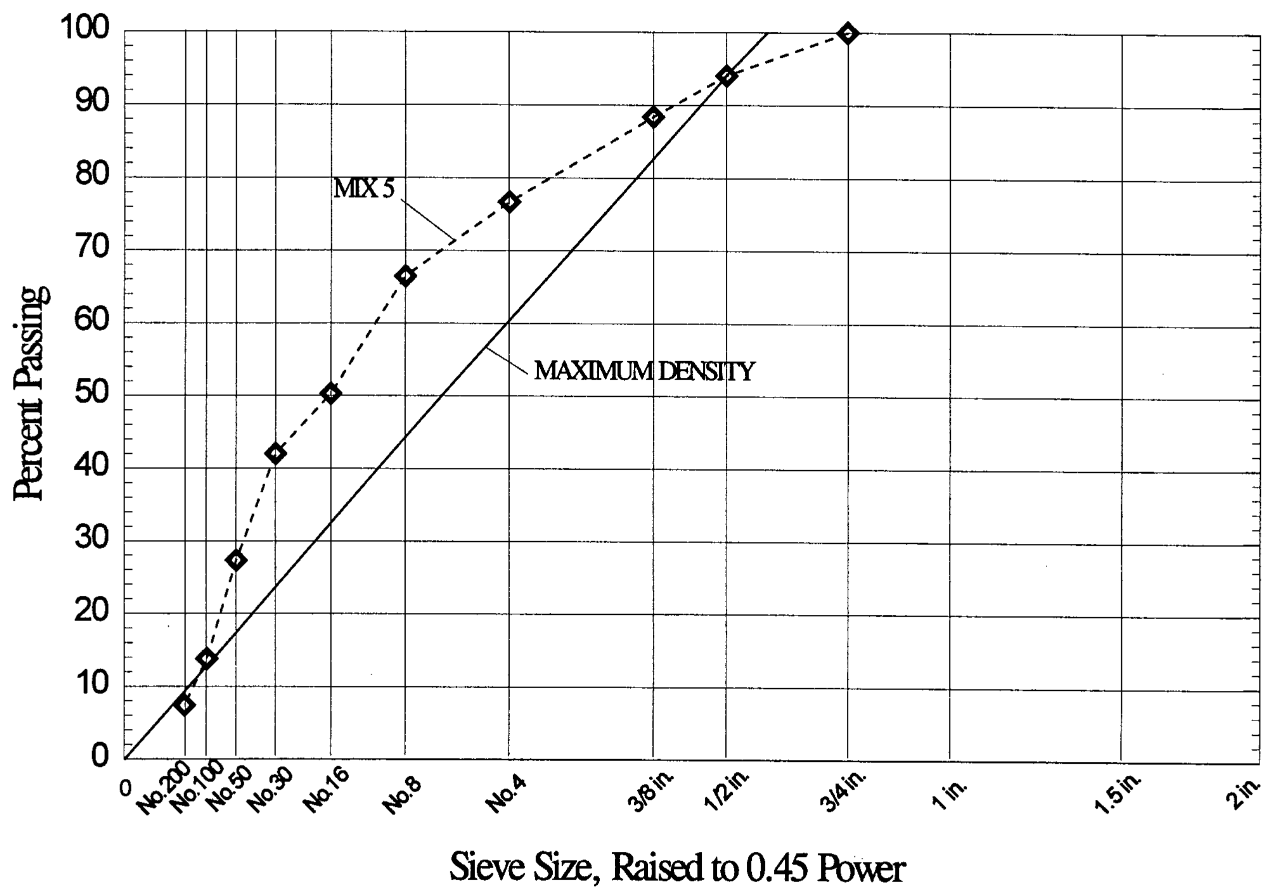


FIGURE A-24. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 5

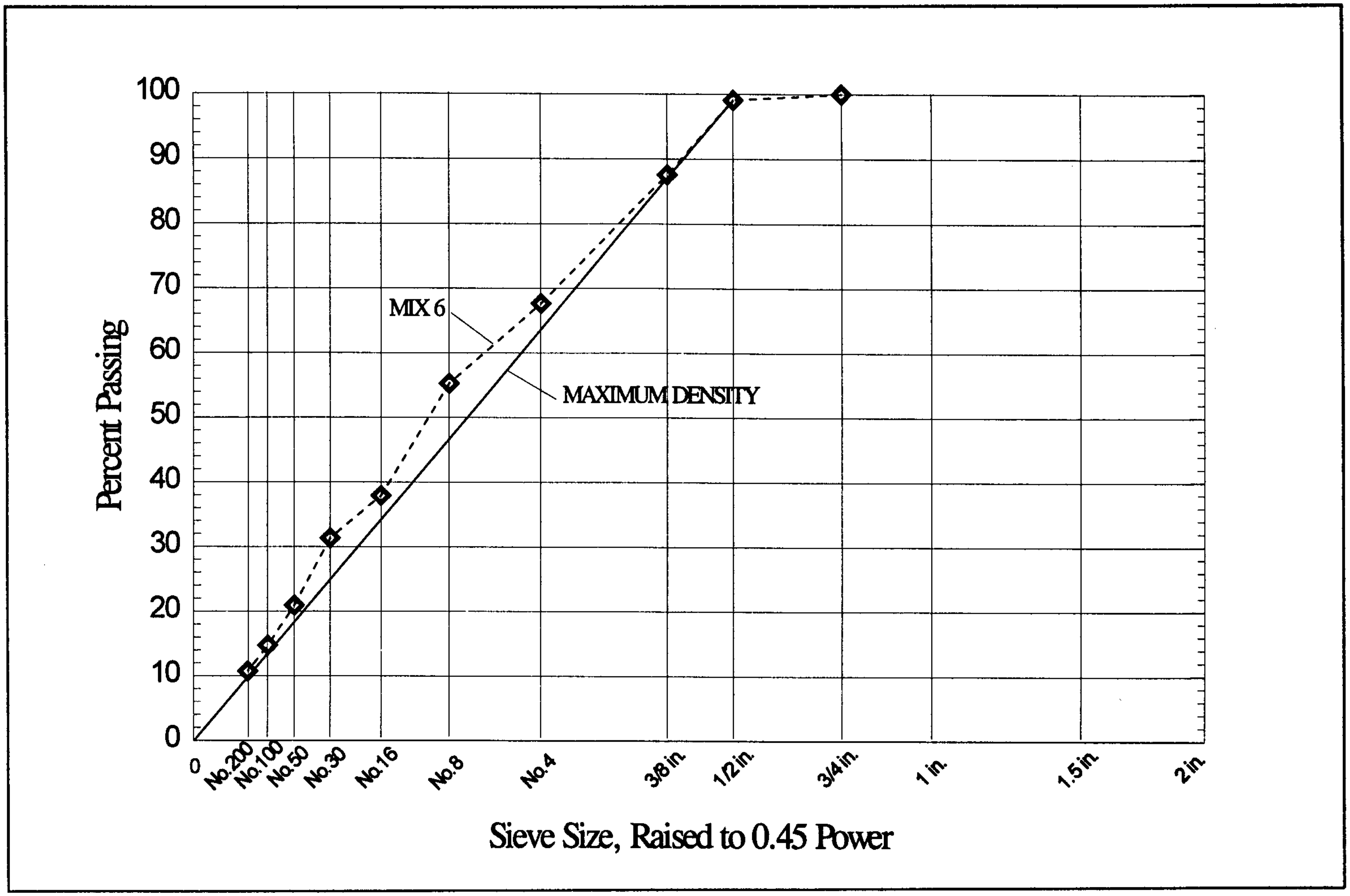


FIGURE A-25. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 6

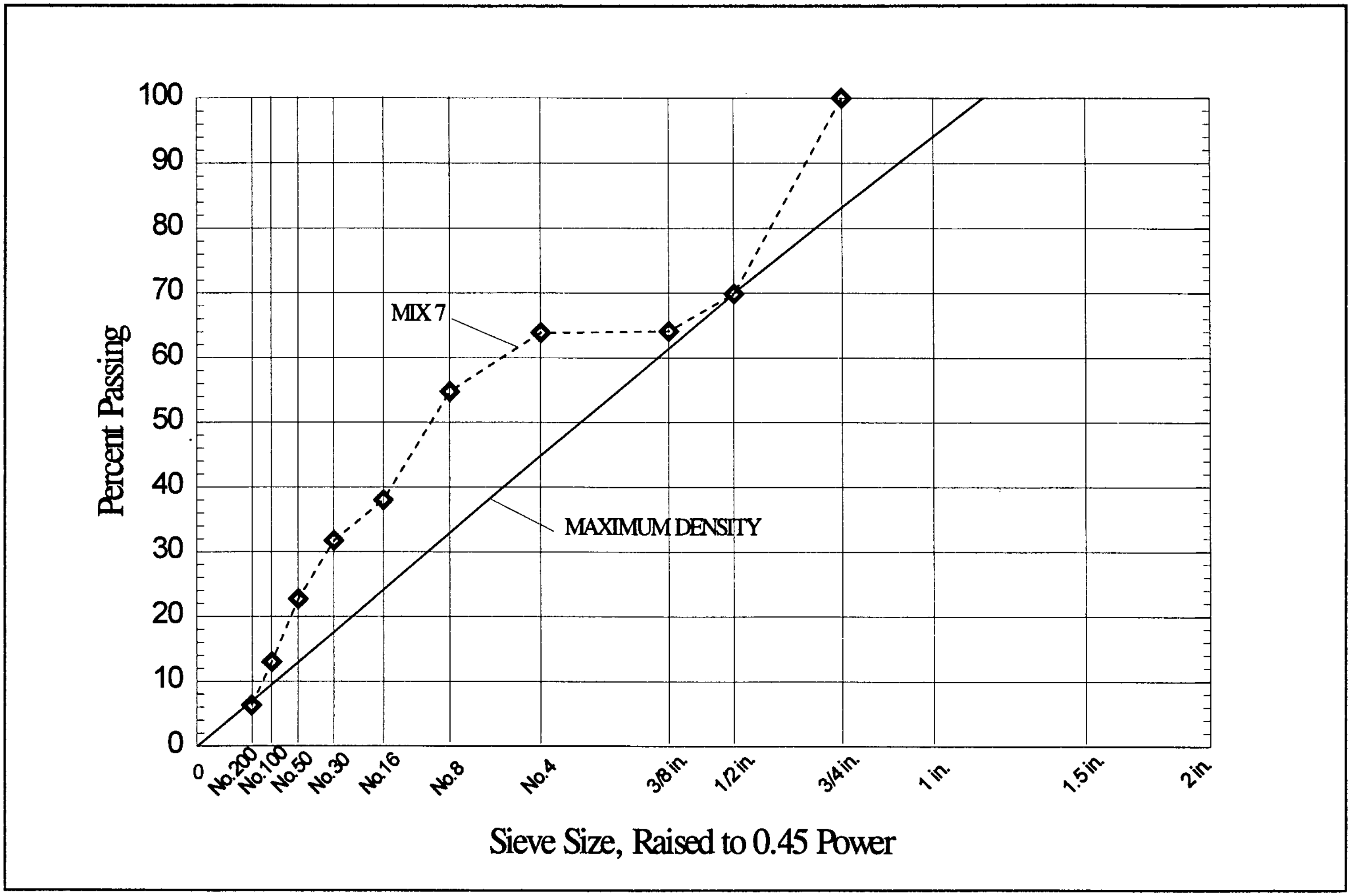


FIGURE A-26. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 7

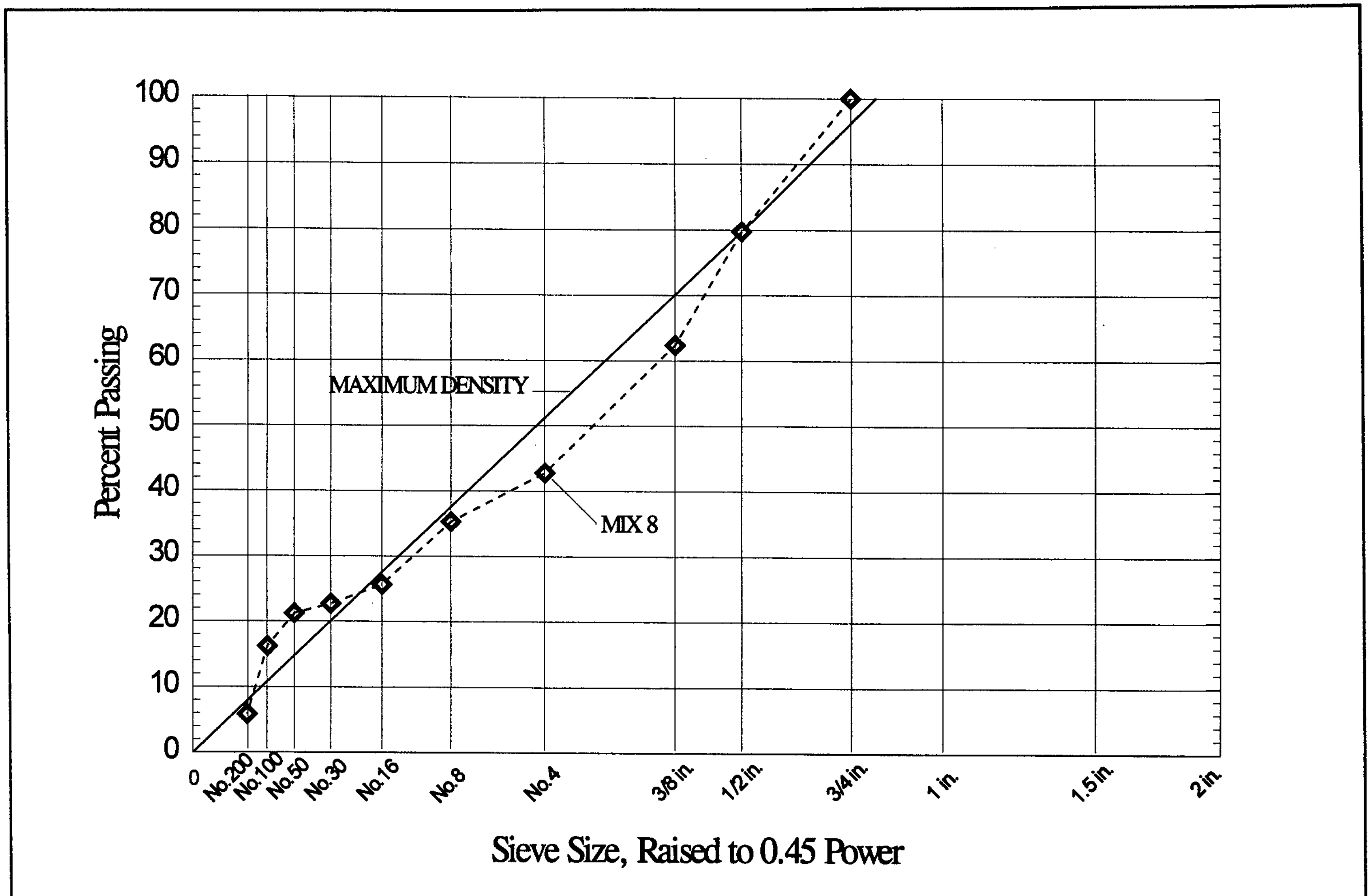


FIGURE A-27. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 8

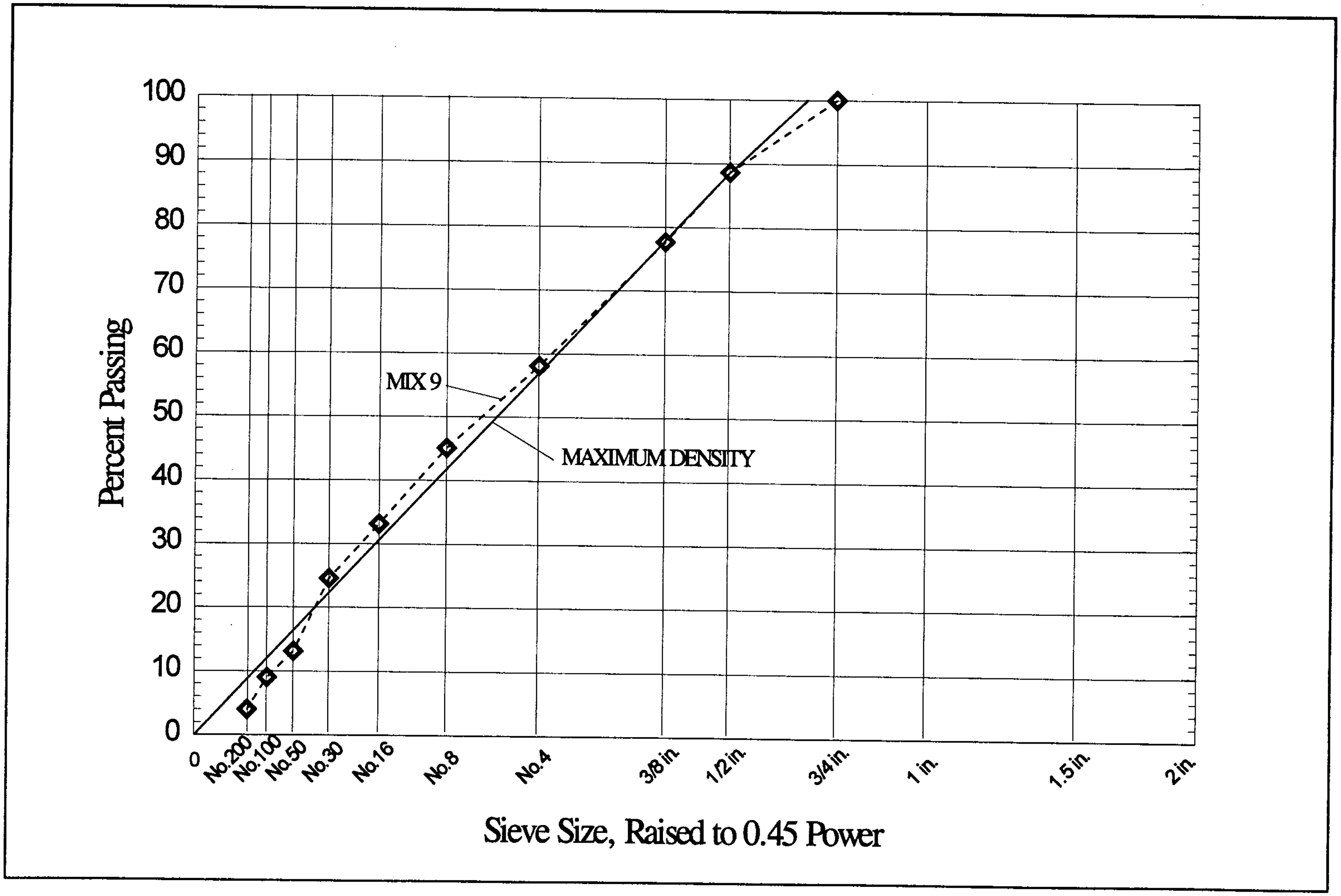


FIGURE A-28. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 9

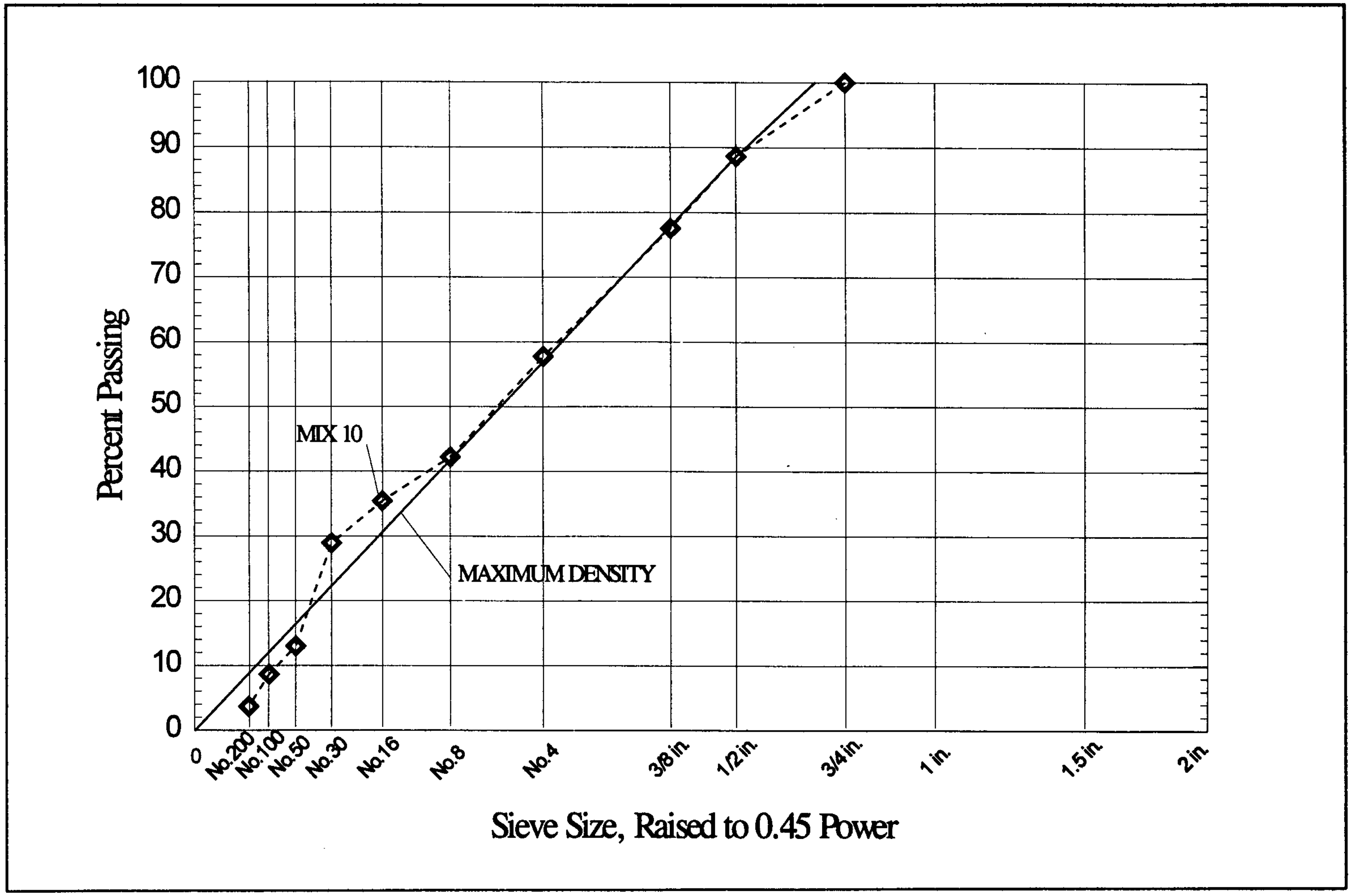


FIGURE A-29. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 10

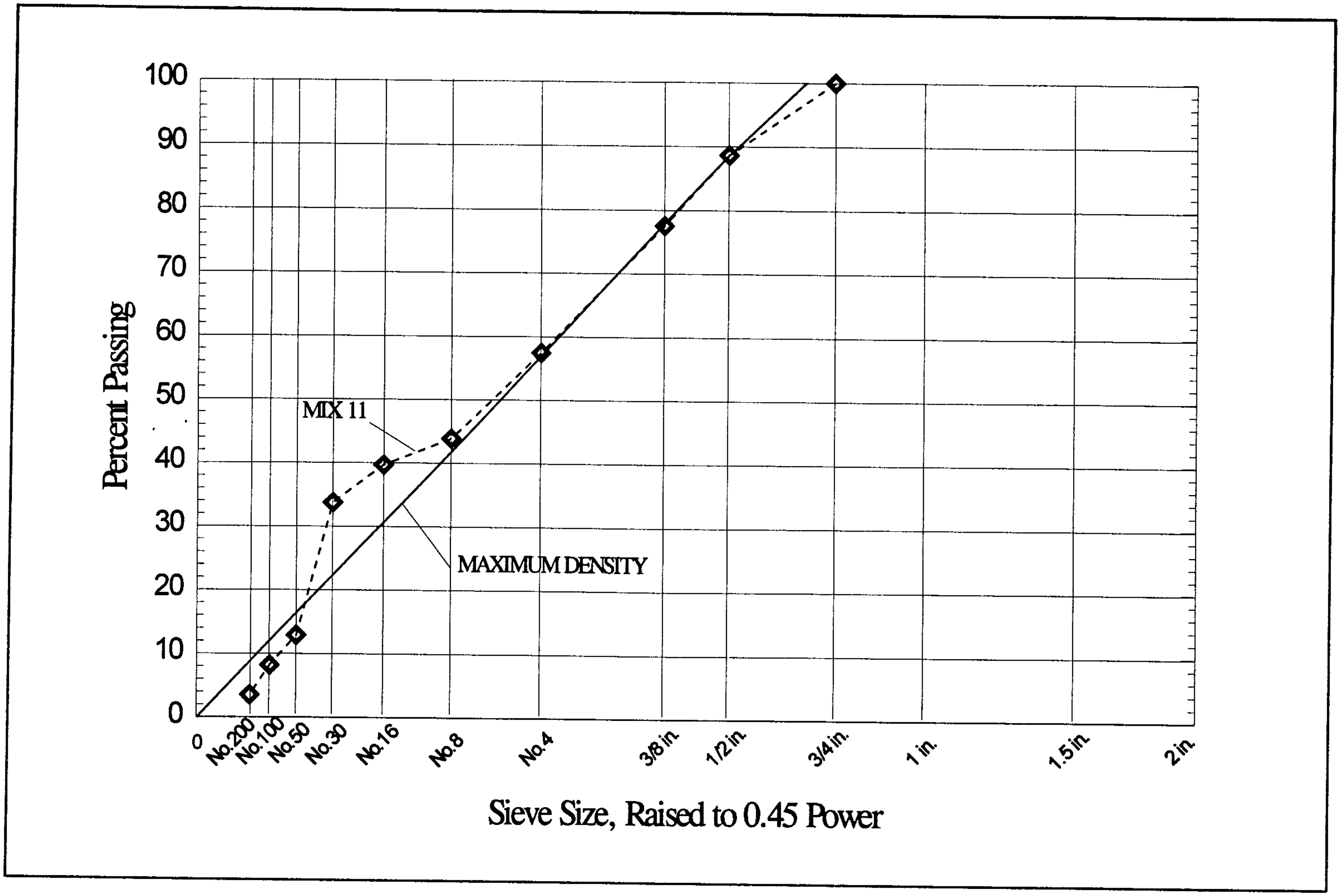


FIGURE A-30. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 11

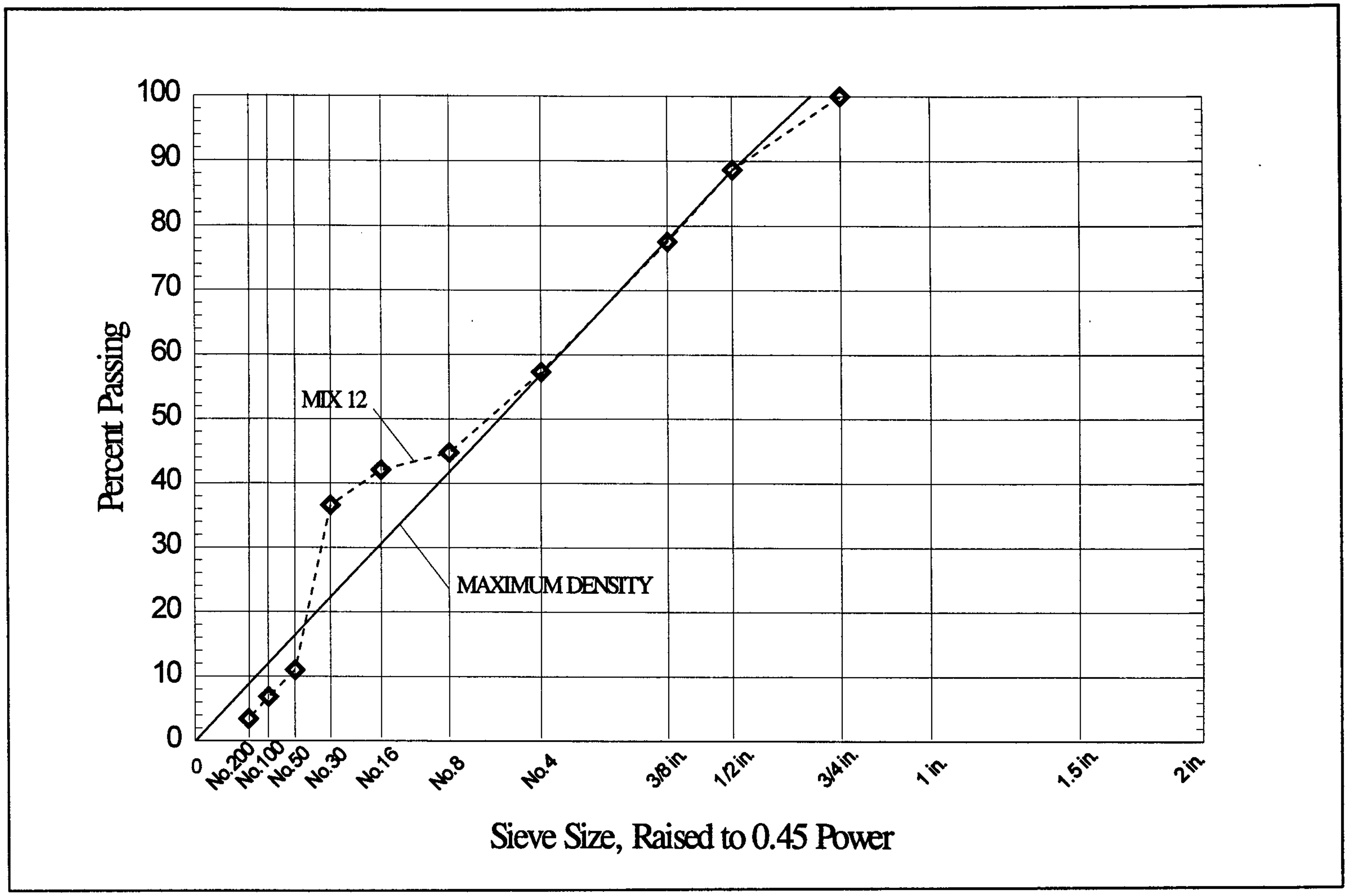


FIGURE A-31. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 12

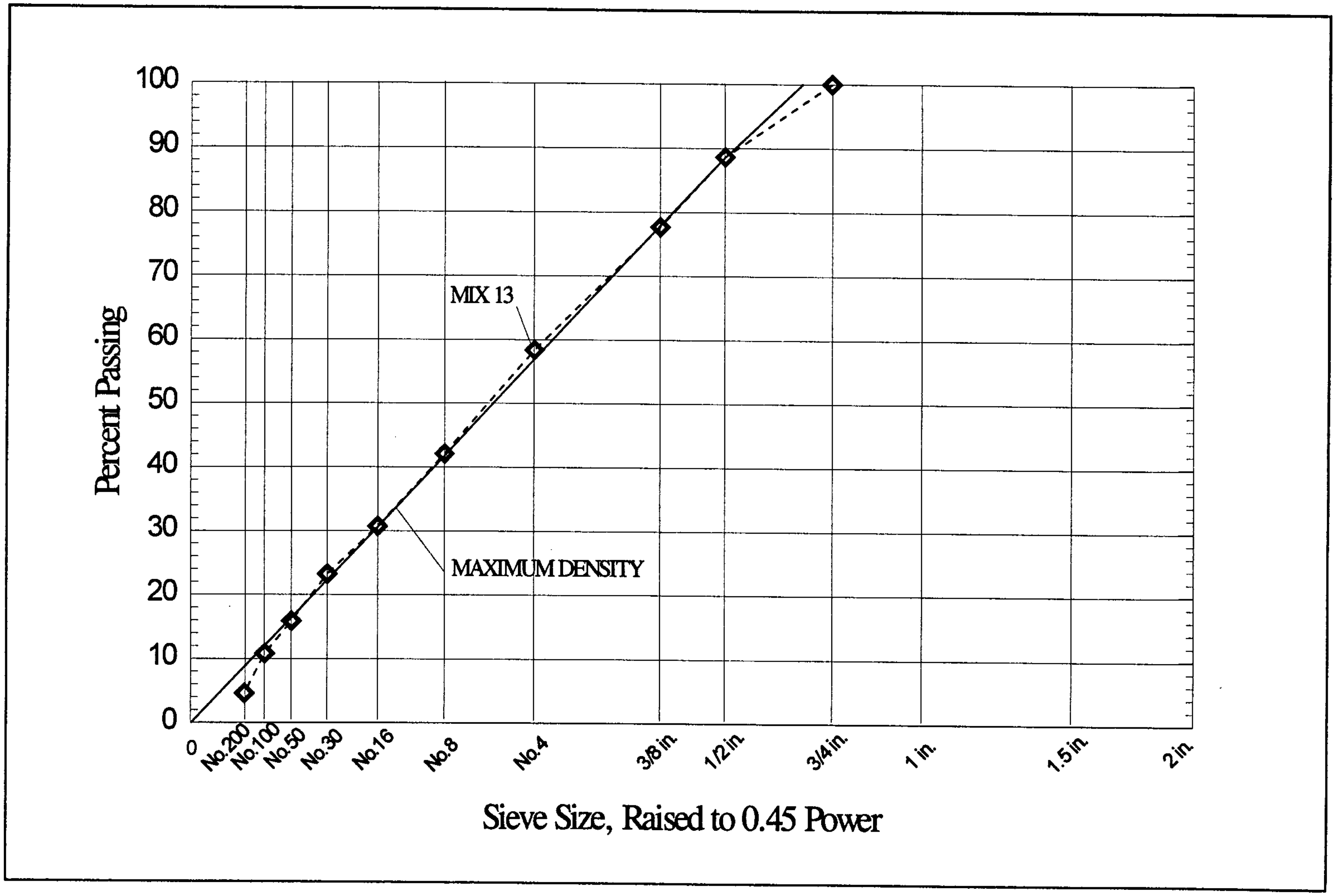


FIGURE A-32. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 13

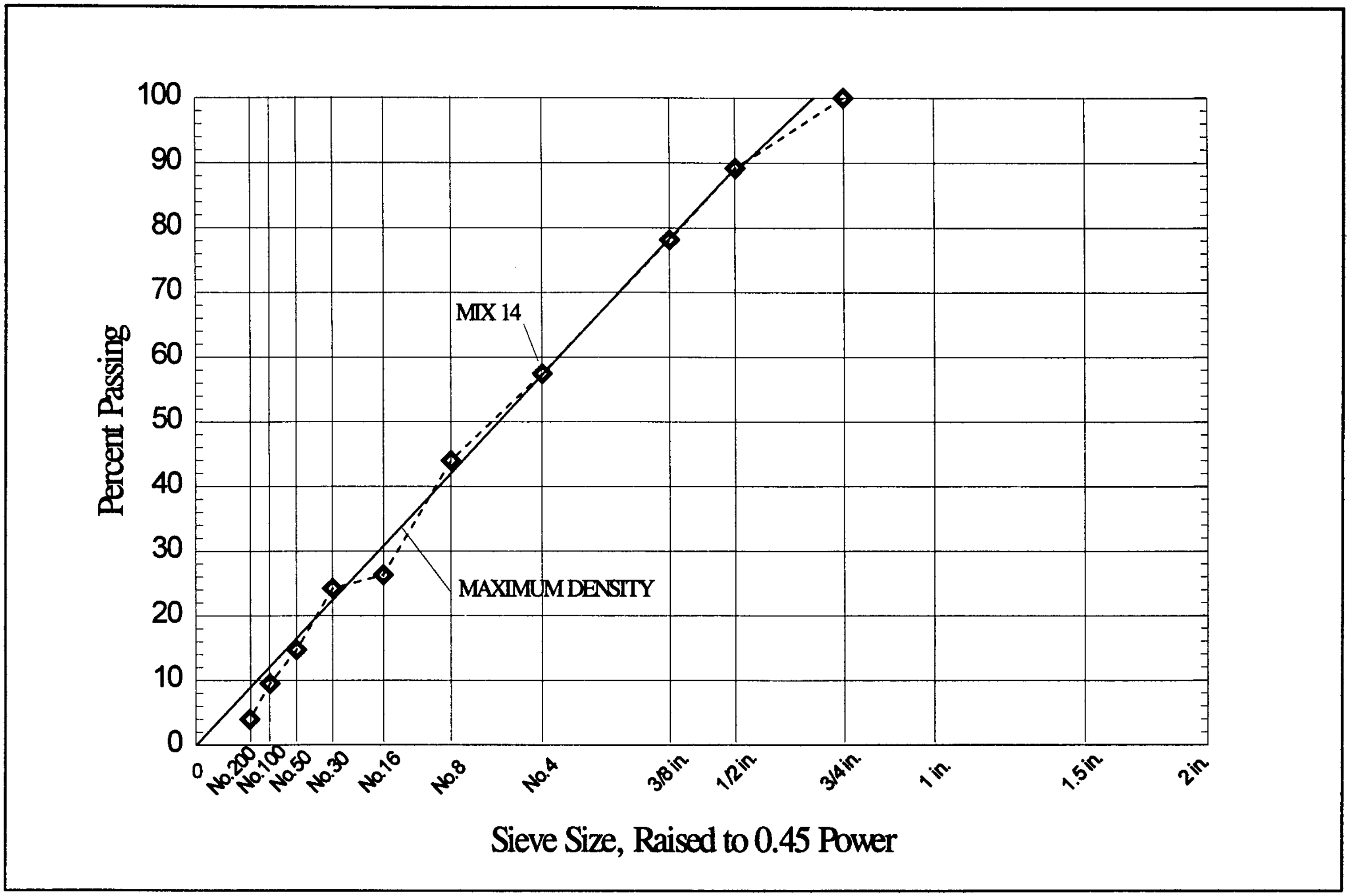


FIGURE A-33. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 14

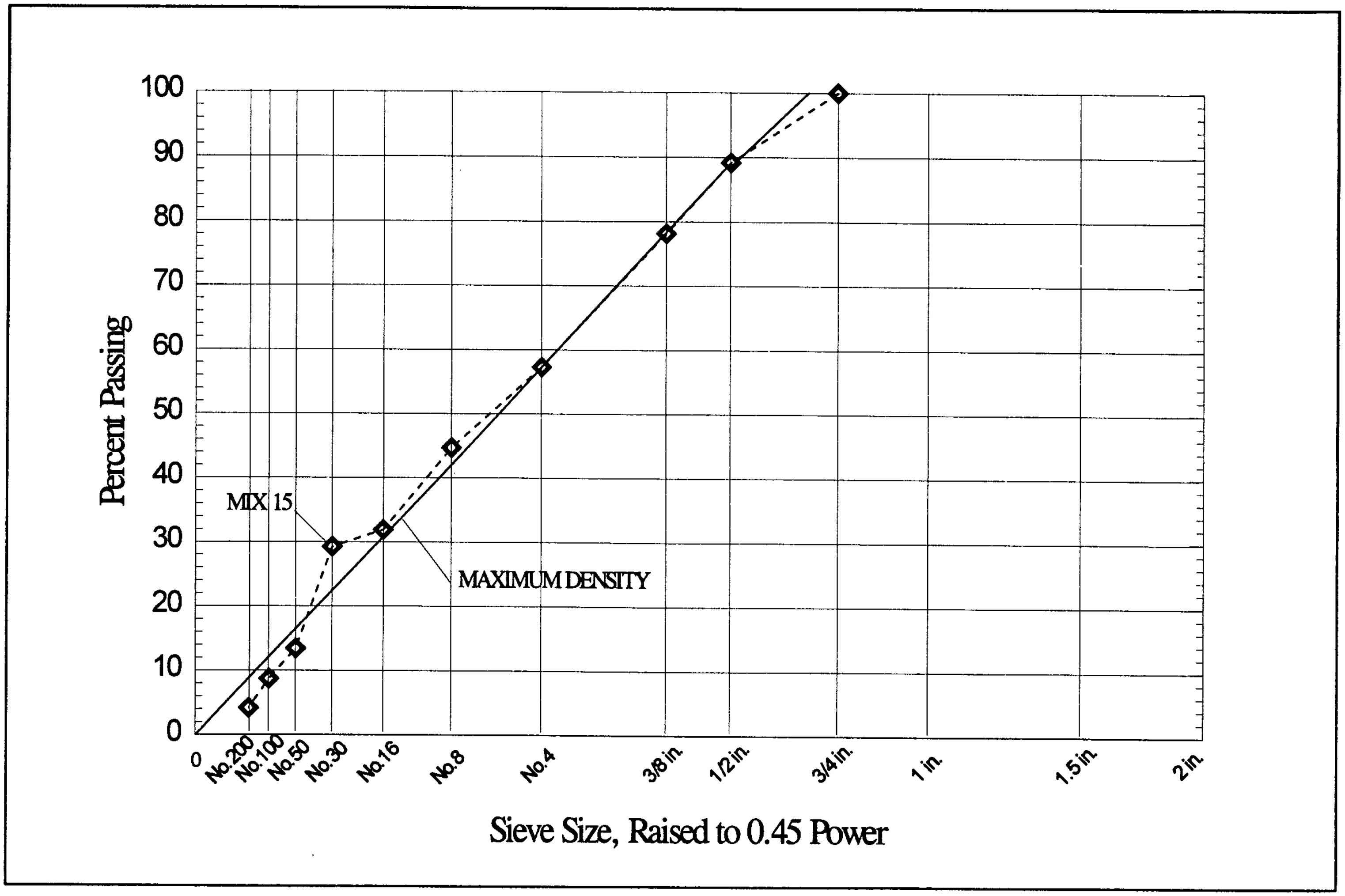


FIGURE A-34. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 15

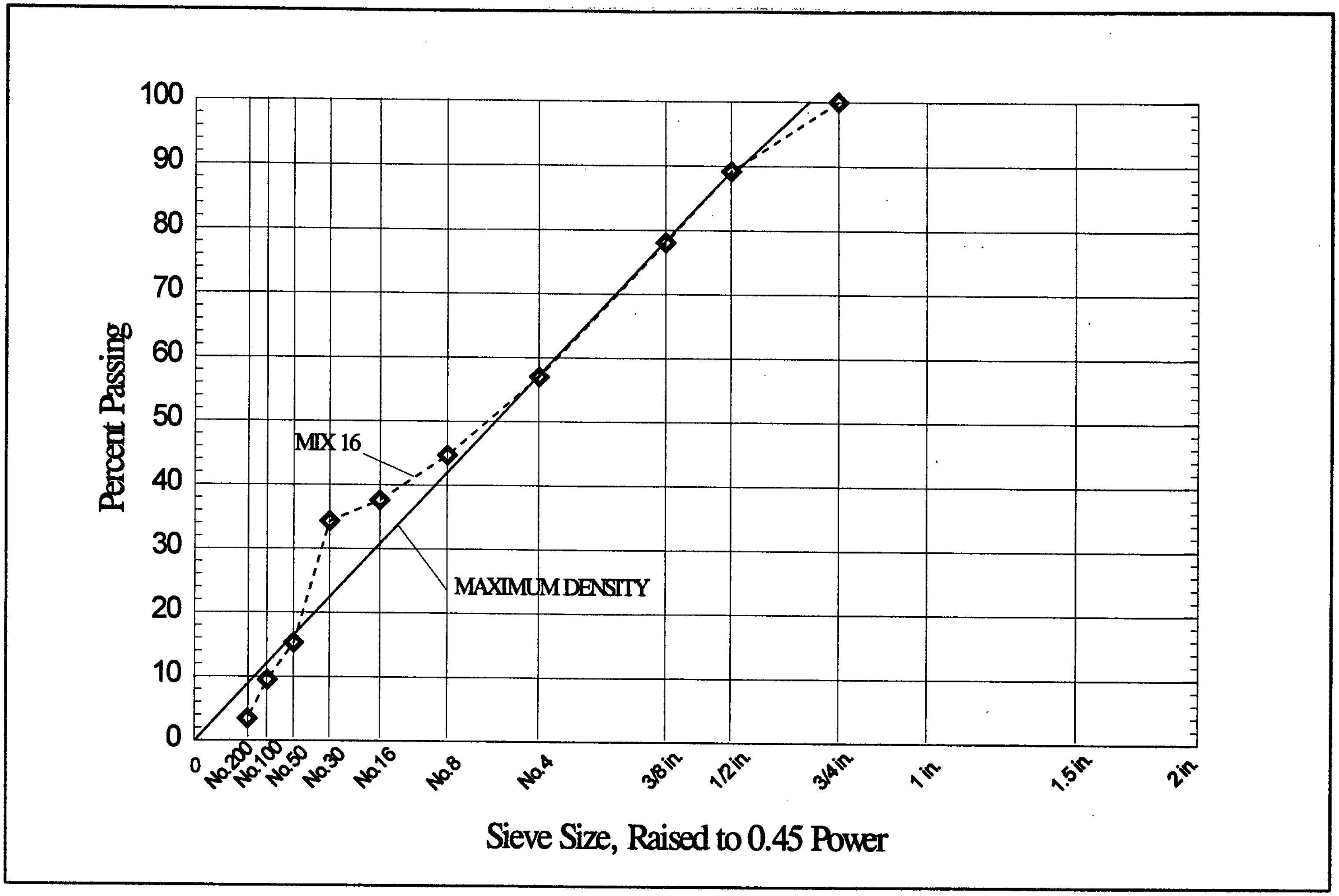


FIGURE A-35. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 16

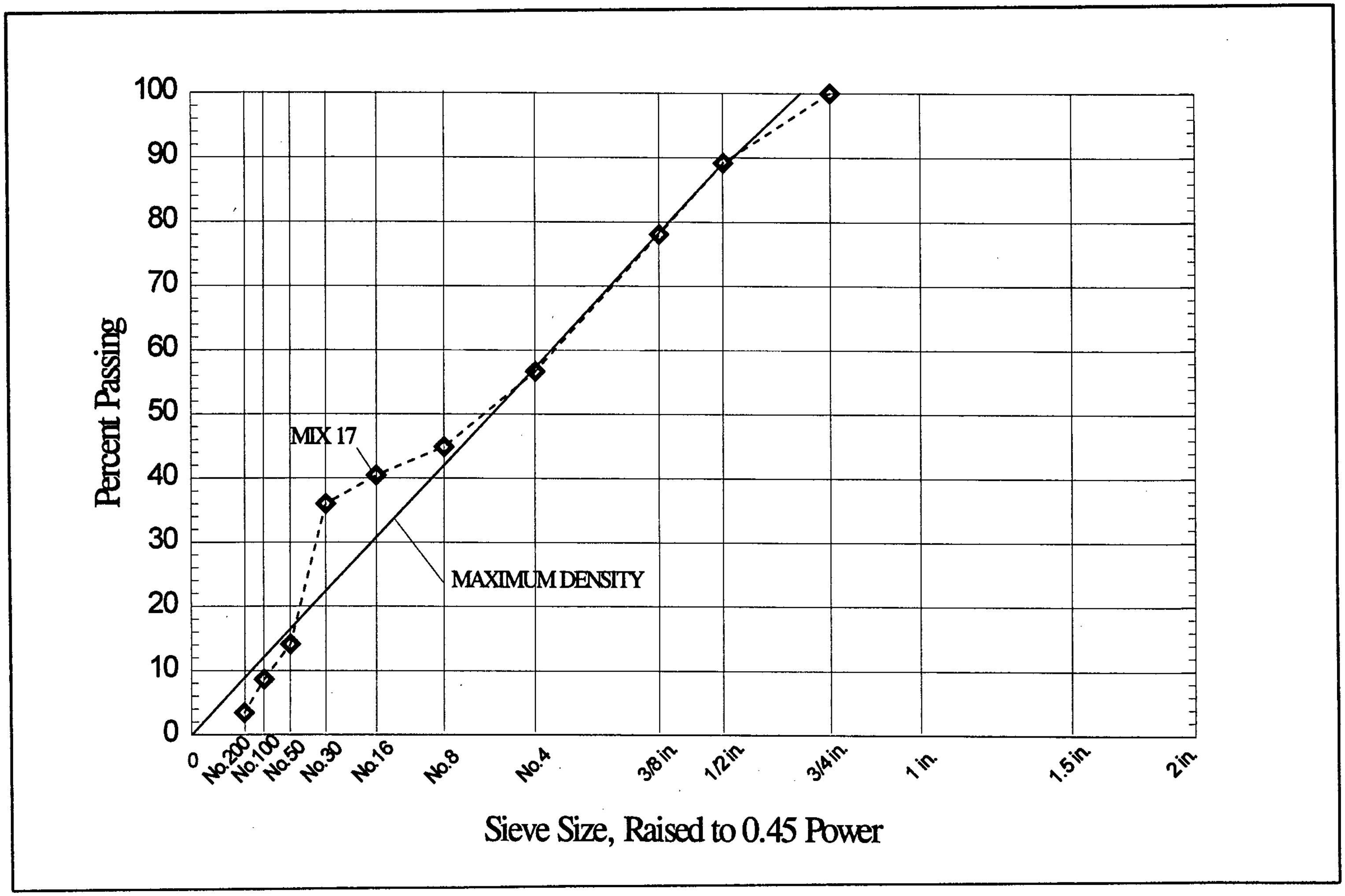


FIGURE A-36. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 17

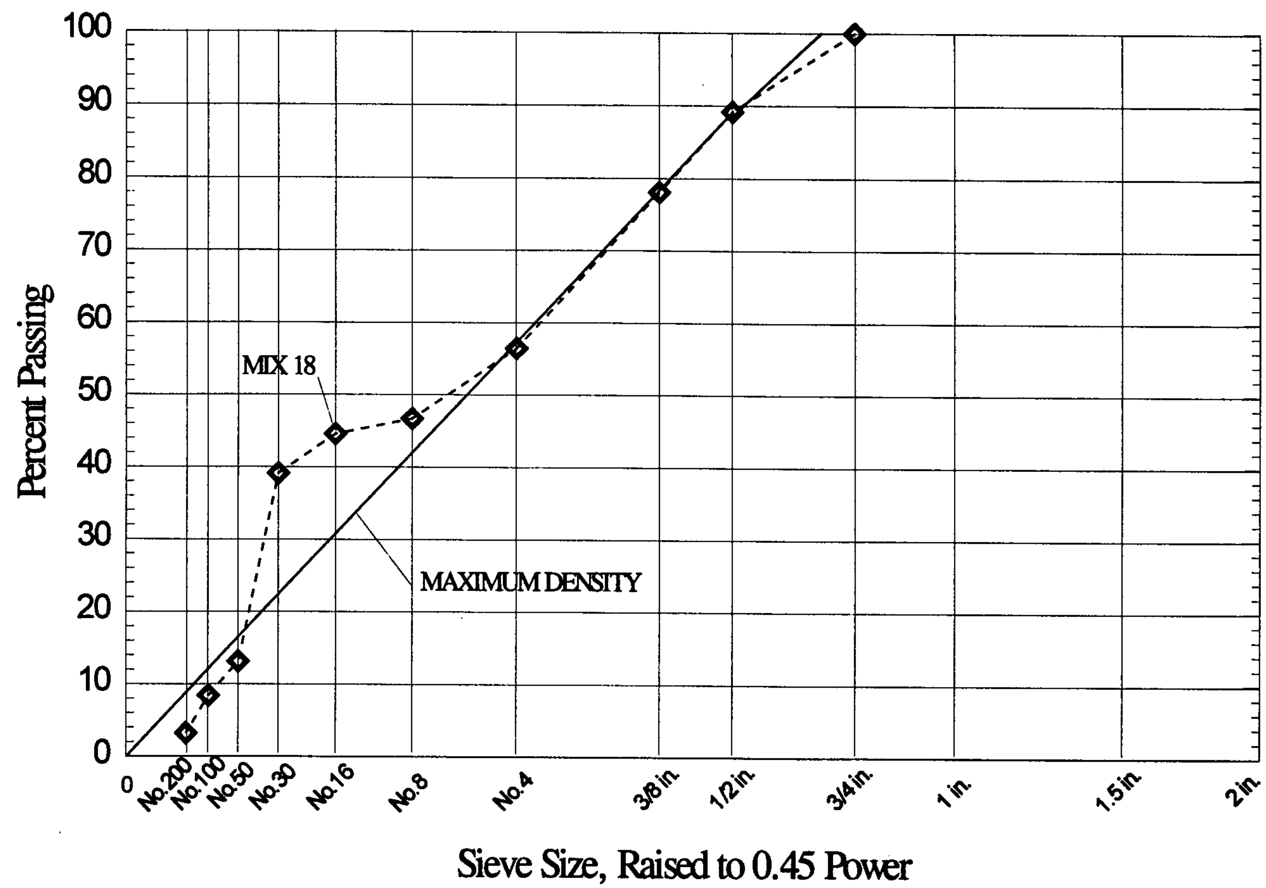


FIGURE A-37. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIX 18

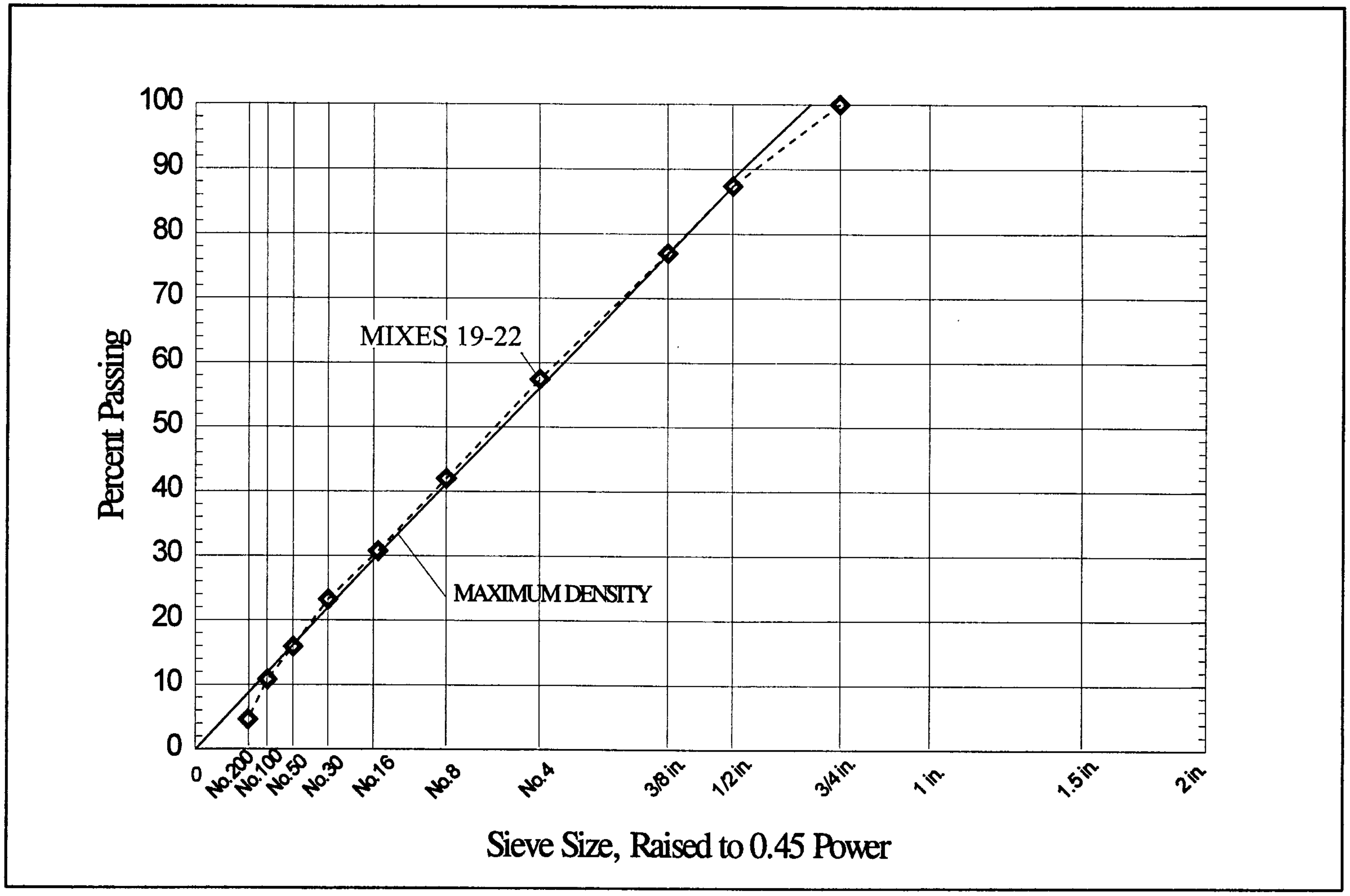


FIGURE A-38. AGGREGATE GRADATION RAISED TO 0.45 POWER CURVE FOR MIXES 19-22