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EFFECTS OF SEGREGATION ON MIX PROPERTIES OF HOT MIX ASPHALT

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16. **Abstract**

Segregation of hot mix asphalt is a recurring problem in the paving industry. There is little documented research that quantifies the effect of segregation on mix properties and pavement performance. Many state highway agencies are embracing performance based quality control/quality assurance (QC/QA) programs but only a few states have performed studies to quantify the effect of segregation on pavement performance.

This study was conducted on four newly constructed pavements which had noticeable spots of segregation. Cores were obtained from both segregated and non-segregated sections of the four pavements. The unit weights of the pavements were determined using a thin-lift nuclear gauge. The change in gradation on the 4.75 mm sieve was compared with asphalt content, nuclear gauge unit weight, core unit weight, and macro texture to determine if an indicator test could quantify segregation. The cores were tested for moisture sensitivity, fatigue life, and indirect tensile strength to determine the effect of segregation on performance. The results indicated that asphalt content was the best indicator of segregation and macro texture the best nondestructive indicator of segregation. Core unit weight is the best indicator test to predict pavement performance.

Based on the gradations, asphalt contents, and VTM of the field cores, four levels of segregation were defined. The pavement materials (asphalt cement and aggregates) used in the construction of two of the four pavements were obtained and laboratory samples were prepared to simulate the four levels of segregation obtained from field cores.

The laboratory samples were tested to evaluate the effects of segregation on mix properties and performance. The results of this study indicate that segregation causes a drop in unit weight, indirect tensile strength, moisture resistance, and fatigue life, as well as an increase in permeability of asphalt mixes. The coarse-graded mix was more affected by segregation than the mix with a gradation closer to the maximum density line.

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PREFACE

This research project was funded by the Kansas Department of Transportation K-TRAN research program. The Kansas Transportation Research and New-Developments (K-TRAN) Research Program is an ongoing, cooperative and comprehensive research program addressing transportation needs of the State of Kansas utilizing academic and research resources from the Kansas Department of Transportation, Kansas State University and the University of Kansas. The projects included in the research program are jointly developed by transportation professionals in KDOT and the universities.

NOTICE

DISCLAIMER

ABSTRACT

Segregation of hot mix asphalt is a recurring problem in the paving industry. There is little documented research that quantifies the effect of segregation on mix properties and pavement performance. Many state highway agencies are embracing performance-based quality control/quality assurance (QC/QA) programs but only a few states have performed studies to quantify the effect of segregation on pavement performance.

This study, funded by the Kansas Department of Transportation, was conducted on four newly constructed pavements which had noticeable spots of segregation. Cores were obtained from both segregated and non-segregated sections of the four pavements. The unit weights of the pavements were determined using a thin-lift nuclear gauge. The change in gradation on the 4.75 mm sieve was compared with asphalt content, nuclear gauge unit weight, core unit weight and macro texture to determine if an indicator test could quantify segregation. The cores were tested for moisture sensitivity, fatigue life and indirect tensile strength to determine the effect of segregation on performance. The results indicated that asphalt content was the best indicator of segregation and macro texture the best nondestructive indicator of segregation. Core unit weight is the best indicator test to predict pavement performance.

Based on the gradations, asphalt contents, and VTM of the field cores, four levels of segregation were defined. The pavement materials (asphalt cement and aggregates) used in the construction of two of the pavements were obtained and laboratory samples were prepared to simulate the four levels of segregation obtained from the field cores.

The laboratory samples were tested to evaluate the effects of segregation on mix properties and performance. The results of this study indicate that segregation causes a drop in the unit weight, indirect tensile strength, moisture resistance, and fatigue life, as well as an increase in permeability of asphalt mixes. The coarse-graded mix was more affected by segregation than the mix with a gradation closer to the maximum density line.

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CHAPTER 1

INTRODUCTION

GENERAL PROBLEM STATEMENT

Segregation of hot mix asphalt (HMA) is a recurring problem that has caused concern in the paving industry for decades. Segregation in HMA pavements occurs when coarse aggregates congregate at one spot in the pavement (1). These coarse spots exhibit open textures and low densities (1,2). This allows the ingress of water and air into the pavement, resulting in durability-related damage such as raveling, cracking and stripping. The overall effect is a substantial reduction in pavement performance and increased maintenance.

In an effort to achieve stability and reduce rutting in HMA pavements, engineers in recent years have reduced the asphalt content, increased the maximum aggregate size, and increased the use of gap-graded mixes. These mixes mentioned above are prone to segregation (2).

Visual observations of the HMA pavement surface texture are usually used to identify segregation. However, these observations are subjective and could lead to many disagreements between contracting parties. Establishing appropriate procedures for detecting and measuring segregation are needed.

There is little documented research that quantifies the effect of segregation on mix properties and pavement performance. Many state highway agencies (SHA) are embracing performance-based quality control/quality assurance (QC/QA) programs instead of method specifications. By determining the effect of segregation on the mix properties and performance of HMA pavements, transportation agencies will have data available to adopt defensible performance-based specifications.

PROJECT OBJECTIVES

The objectives of this project were to 1) determine if an indicator test such as asphalt content, pavement macro texture or unit weight from either a nuclear gauge or cores, could be used to quantify segregation, 2) determine the effects of a change in gradation from the job mix formula (JMF) on mix and material properties of laboratory and field samples, and 3) estimate the effects of that change on pavement performance.

Field cores from segregated pavements in Kansas were obtained and void properties, mix and material properties and extracted aggregate gradations were determined. By duplicating the extracted gradations, representative laboratory segregated samples were made allowing the determination of the effect of a change in gradation from the JMF on mix properties. A portion of the laboratory prepared samples were aged using the SHRP aging methods to determine the long term effects of segregation on mix properties.

SCOPE

This study was funded by the Kansas Department of Transportation (KDOT) and was conducted on four recently constructed pavements in Kansas which had noticeable spots of segregation. Cores were obtained from both noticeably segregated and non-segregated areas on the selected pavements. The segregated areas were identified as open textured spots and the non-segregated areas as uniformly textured spots. All cores were sent to the Bituminous Materials Laboratory at the University of Kansas for detailed testing and evaluation. The void properties, asphalt content, and gradations were determined for each core. The aggregates and asphalt cements used in the production of the four mixes were obtained from KDOT.

Laboratory samples were prepared to simulate the field cores by using the same materials, gradation, asphalt content, and voids. The laboratory samples were tested to determine the effects of segregation on HMA mix properties and performance. The effects of aging on performance of the laboratory samples were also investigated.

WORK PLAN

Task 1. Review of Available Literature

A review of the available literature was conducted. This review covered available work relevant to the scope of this study such as the work carried out by the National Center for Asphalt Technology, the University of Arkansas and the Missouri Highway and Transportation Department. Available literature from KDOT studies was reviewed as well.

Task 2. Selection, Sampling and Field Evaluation of Segregated Pavements

Four projects exhibiting various degrees and/or severity of segregation were selected by KDOT in consultation with the Principal Investigator. Two of the segregated pavements were BM-1B mixes and the other two pavements a BM-2 and an HR-2C mix. Four to five segregated and non-segregated locations from each of the four pavements were sampled. A minimum of three cores per segregated area was obtained. The exact sampling locations and the number of cores obtained were determined by the principal investigator and the project monitor. All core drilling and traffic control was the responsibility of KDOT. All cores were supplied to the principal investigator for further testing. If possible, nuclear density meter testing was performed by KDOT at the locations of the cores and the results tied to each core location. When available, KDOT supplied the combined cold feed gradations, Marshall mix designs, samples of the asphalt cement and aggregates utilized and any field test results from the sampled areas of the selected projects.

Task 3. Tests on Pavement Cores

The cores obtained from Task 2 were returned to the laboratory and the top lift removed for further testing. The following tests were performed on the top lift: 1) voids analysis, 2) air permeability, 3) macro texture, 4) moisture sensitivity, 5) indirect tensile strength, and 6) fatigue life. After completion of the above testing the maximum specific gravity, asphalt content and extracted gradation of selected cores were determined. Segregation was quantified based on the deviation from the JMF.

Task 4. Laboratory Evaluation of Segregation

Based on the results from Task 3, four representative gradations for the BM-1B and BM-2 mixes were selected to cover the full range of segregation and compaction found on the projects. Laboratory compacted samples were made from materials utilized on the projects sampled in Task 2. Samples were compacted on KDOT's U.S. Army Corps of Engineers Gyratory Testing Machine (GTM). Where appropriate, one set of samples was tested without aging, one set was short term aged and one set long term aged, as defined by SHRP. The following tests were performed on some or all of the samples: 1) voids analysis, 2) air permeability (ASTM D3637), 3) moisture sensitivity (AASHTO T283), 4) indirect tensile strength (ASTM D4123) and 5) fatigue life (ASTM D4123).

CHAPTER 2

REVIEW OF LITERATURE

(Task 1)

INTRODUCTION

Early HMA pavement distress such as cracking, rutting, and stripping, has been associated with asphalt mix segregation (1,2). These distress affect the performance, serviceability, and structural capacity of the affected pavement (3). Segregation is identified as a non-uniform distribution of various aggregate sizes throughout the mixture. Segregation has typically been quantified as a change in gradation on the 4.75 mm sieve (4). There have been many articles on the causes of and remedies for segregation (1,2,4-7), but the problem still exists on many newly constructed pavements. Little research has been performed to establish procedures to quantify segregation and evaluate the effects of segregation on HMA properties and performance.

PREVIOUS STUDIES

The following states have performed research on identifying segregation and determining the effects of segregation on HMA properties and performance: Alabama, Arkansas, Georgia, Indiana and Missouri. A summary of the research from these states is discussed below.

Alabama

Cross and Brown (4) conducted a study on segregation of five pavements in Alabama. The authors were interested in determining if segregation and raveling could be quantified using an indicator test, such as the pavement macro texture or thin-lift nuclear gauge. Cores were obtained from segregated and non-segregated areas of the pavement and the unit weight and macro texture of the pavement surface determined. Some of the conclusions made by the authors are listed below.

1) The measured change in gradation on the 4.75-mm sieve was selected to quantify segregation and raveling.

2) A variation more than 8 to 10% passing the 4.75-mm can result in raveling.

3) Pavement macro texture correlated to the amount of raveling. A change in macro texture of 0.50 mm or greater would result in raveling.

4) Visual observations could detect the lateral extent of segregation.

5) The measured asphalt content decreased as the mix got coarser and was highly correlated to the change in percent passing the 4.75-mm sieve.

Arkansas

Elliott et al. (8) reported on the effects of aggregate gradation variation on asphalt mix properties. Laboratory samples were made based on the extreme gradation variation normally found in construction. The asphalt content used was maintained at the job mix design content. This is the fallacy of this project. The method used contradicted with the findings by other researchers (3,4,9,10) which indicated that segregation changes the asphalt content of the mixes. The objectives of the study were to determine the effect of gradation variation on: 1) creep behavior as a measure of rutting resistance, 2) split tensile strength as an indicator of fatigue resistance potential, 3) Marshall mix properties of stability, flow, air voids, and voids in mineral aggregate as a measure of mix acceptability, and 4) resilient modulus as the parameter controlling the structural layer coefficient in the AASHTO thickness design procedure.

Some of the conclusions drawn by the authors are listed below.

1) Finer coarse aggregate and coarser fine aggregate gradation variations result in the highest Marshall air voids and VMA but lowest Marshall flow.

2) Coarser coarse aggregate and finer fine aggregate gradation variations resulted in the lowest Marshall air voids and VMA but highest Marshall flow.

3) Creep stiffness of the control, coarse and fine gradations were higher than any other aggregate combinations.

4) Coarser gradation variations produce the lowest tensile strength.

5) Tensile strength is more a function of air void content (i. e. compaction) than it is gradation variation.

Indiana

Khedawyi and White (3) conducted a study on the development and analysis of laboratory techniques for simulating segregation. Five mixes with varying degrees of segregation were evaluated. A median gradation binder mix at 4.5 percent asphalt content was used as a control mix. This mixture was heated and sieved over a 9.5 mm sieve creating coarse (retained) and fine (passing) fractions representing the extremes of segregation. Two other mixtures with intermediate degrees of segregation were produced by combining percentages of the coarse and fine materials. The US Army Corps of Engineers gyratory testing machine (GTM) was utilized to compact and test the five mixtures. The unit weight, the gyratory stability index (GSI), the gyratory compactability index (GCI) and the percent air voids were determined for each compacted mix. The indirect tensile strength test was performed on samples prepared with the GTM. The PURwheel tracking device test was conducted on compacted slab samples to evaluate the resistance to permanent deformation and moisture damage. The following conclusions were drawn based on the results of this study.

1) As a result of segregation, the combination of the fine material and excess of asphalt created a potential for rutting.

2) Air voids were low for segregated fine mixtures and high for segregated coarse mixtures.

3) Indirect tensile strength increased and then decreased with increasing amounts of coarse aggregate.

4) GSI and GCI decreased with the increasing amount of coarse aggregate.

The effect of segregation on fatigue performance of HMA was also studied by Khedawyi and White (11). The same five mixes used in the above study (3) were evaluated. A constant strain flexural fatigue test was performed on beam specimens cut from slabs. The analysis of results revealed the followings.

1) Results for the five mixes indicated a linear relation between log ϵ and log N_f.

2) The use of more coarse aggregate in the asphalt mix generally led to shorter fatigue life.

3) For a given strain level, shorter fatigue life was obtained as the relative volume of asphalt decreased.

4) The combination of large aggregate and low asphalt content in HMA caused higher fatigue potential.

5) As the density of HMA decreased, the fatigue life decreased.

Williams et al. (5) studied the measurement and effects of segregation on HMA properties. The laboratory techniques for simulating segregation used by Khedawyi and White (3) were adopted in this study. The authors were interested in knowing if a nondestructive test, such as an air permeameter, nuclear moisture/density gauge or thermal imaging, could be used to detect segregation. The PURwheel tracking device was also used to determine the effects of segregation on performance. The following conclusions were made by the authors.

1) The asphalt content increases from very coarse to very fine segregation.

2) The density of segregated mixes decreases compared to design mix.

3) The air voids increase from very fine to very coarse segregation.

4) The air permeameter could only be used to detect very coarse segregation.

5) Nuclear density and asphalt content could be used in combination to identify segregation.

6) Significant loss in performance could be found in segregated mixtures when tested with the PURwheel tracking device.

Missouri

Webb (12), from the Missouri Highway and Transportation Department (MHTD), performed a study to determine the suitability of using a "continuous density system" to identify and quantify the presence of segregation in bituminous overlays. This study concluded that the Troxler 4545 continuous system did not provide satisfactory results in identifying and quantifying areas of segregation.

SUMMARY

The review of the literature indicated that there is still no standard procedure available to detect segregation or to quantify the effect of segregation on HMA properties and performance. The review of the literature also showed that very few highway agencies have performed segregation studies. Since most agencies are implementing QC/QA programs, the segregation problem has been given special attention. With the ongoing research on HMA segregation, a standard method could be developed to measure segregation and to evaluate its effects on HMA pavement performance.

CHAPTER 3

FIELD OBSERVATIONS & TEST PLAN

(Task 2)

SITE SELECTION AND DESCRIPTIONS

Four sites were selected for sampling and evaluation by Rodney Maag, KDOT Field Engineer, with input from the principal investigator. For each site, areas which had signs of segregation (non-uniform surface texture) and non-segregated (uniform surface texture) were visually identified and groups of 3 cores were obtained from each area. The location of the four sites, and the mix sampled are shown in Table 1. A brief description of each site follows.

Table 1. Location of Test Sites.

Site No.	Route	County	Mix Sampled
1	US 281	Barber	BM-2
2	US 183	Phillips	BM-1B
3	US 183	Phillips	HR-2C
4	US 36	Nemaha	BM-1B

Site 1. US 281

Site 1 (281-4-K 4051-01) was located on US 281 in Barber County. The mix sampled was a KDOT BM-2 mix which had been utilized as a wearing course over the winter. A permanent wearing surface was being placed over the BM-2 mix at the time the site was sampled. The BM-2 mix had been opened to traffic for eight months at the time of sampling. The BM-2 mix is a dense graded, 12.5 mm nominal size aggregate, mix which is finer than a BM-1B mix and typically lies above the maximum density line. The binder utilized was a Coastal AC-10.

Site 2. US 183

Site 2 (183-74-K 4062-01) was located on US 183 in Phillips County. The mix sampled was a KDOT BM-1B mix which was utilized as the wearing course. The mix had not been opened to traffic at the time of sampling. The BM-1B mix is a dense graded, 12.5 mm nominal size mixture. The gradation typically falls below the maximum density line. The BM-1B mix used a Coastal AC-20 as the binder.

Site 3. US 183

Site 3 (183-74-K 3370-01) was located on US 183 in Phillips County and was the binder mix for this pavement. The mix sampled was a KDOT HR-2C mix which contained RAP in the mix. The mix had been opened to traffic at the time of sampling. The HR-2C mix is a dense graded, 19 mm nominal size aggregate, mix which lies below the maximum density line. The asphalt cement was Sinclair AC-10.

Site 4. US 36

Site 4 (36-66 K-3328-01) was located on US 36 in Nemaha County. The mix sampled was a KDOT BM-1B mix which was utilized as the wearing course. The BM-1B mix had been opened to traffic for some time when sampled. The BM-1B mix is a dense graded, 12.5 mm nominal size mixture with a gradation that typically falls below the maximum density line. The binder utilized was a Coastal AC-10. The mixture was difficult to core due to sample disintegration and the mix appeared to suffer from a large percentage of aggregate breakdown.

FIELD TESTING

The field testing was conducted by the principal investigator, Rodney Maag, KDOT Field Engineer, and KDOT District construction personnel. For each site, areas which had signs of segregation (non-uniform surface texture) and non segregation (uniform surface texture) were visually identified. Sets of three 100 mm diameter cores were obtained from coarse textured (segregated) areas and sets of three cores were obtained from uniform textured (non-segregated) areas. The non-segregated core sets were obtained within 15 to 30 m of the segregated core sets and the individual cores within each set were obtained within 150 mm of each other. A nuclear gauge was utilized to determine the unit weight of the surface mix for each set. Sand was used to fill surface voids for nuclear gauge testing. The cores were returned to the Bituminous Materials Laboratory at the University of Kansas for further testing.

LABORATORY TESTING

Cores

A water-cooled, diamond saw was used to separate the surface layer from the remainder of the core. The thickness of the surface layer was measured and recorded and the cores were then air-dried to a constant weight. The macro texture of each core was determined in general accordance with ASTM E 965. Ottawa sand was utilized since it met the gradation requirements of passing a 0.3 mm sieve and retained on a 0.15 mm sieve. The weight of the sand covering the surface of the core was measured. The macro texture depth was determined by dividing the volume of the sand by the surface area of the core.

The bulk specific gravity was determined in accordance with ASTM D 2726. If the core absorbed more than 2 percent water, Parafilm was used to determine the bulk specific gravity according to ASTM D 1188. Next, the indirect tensile strength of one core from each set was determined in accordance with ASTM D 4123. The tests were conducted at 25°C. The load and deformation at failure were measured and the stress and strain were calculated.

The moisture sensitivity was evaluated using AASHTO T 283. This method is intended for mixes compacted to 7 ± 1 percent air voids. One core from each set was subjected to vacuum saturation followed by a freeze cycle, a warm water soaking cycle, and then tested for indirect tensile strength. The conditioned indirect tensile strength was compared to unconditioned indirect tensile strength previously determined and the Tensile Strength Ratio (TSR) calculated.

The fatigue testing was performed on one core from each set in general accordance with ASTM D 4123. A haversine pulse-load was applied for 0.1 second with a 0.9 second rest at a frequency of one cycle per second. The test was conducted in constant stress at 7.5 % of the indirect tensile strength. The number of load repetitions to failure was recorded.

The cores used in the indirect tensile test were used to determine the theoretical maximum density (TMD). The cores were warmed at 105 °C until the material could be separated then allowed to cool prior to determining the TMD in accordance with ASTM D 2041. A type E pycnometer was used for samples weighing more than 1000 g and a calibrated 1000 ml Erlenmeyer flask was used for samples weighing less than 1000 g. From the bulk specific gravity and TMD results, the percent air voids were determined according to ASTM D 3203.

All cores obtained from either the TMD, fatigue or moisture sensitivity tests were dried in an oven at 105 °C to a constant weight. The asphalt content of the samples was then determined by the ignition method. At present, there is no standard procedure to determine the asphalt content by ignition. Thus, the method used by the National Center for Asphalt Technology (NCAT) was followed. A correction for factor was not applied to the asphalt content.

A washed sieve analysis was performed on the materials remaining from the ignition test in accordance with ASTM C 117 and C 136. A dust correction from the ignition test was not applied to the gradation analysis.

Laboratory Compacted Samples

Two mixes were selected for laboratory testing, the BM-1B from Site 1 and the BM-2 mix from Site 2. The original mix design used at each site was identified and the information on aggregate sources, percentage of each component, component and combined aggregate gradations, optimum asphalt content, and asphalt cement source and grade was obtained from KDOT. Based on the source of material, asphalt content, gradation, and air voids from the field cores, 102 mm diameter laboratory samples were prepared. The parent materials used in the production of the field cores were the same materials used in simulating the laboratory samples.

Laboratory Preparation and Aging

Four levels of segregation were defined based on gradation, asphalt content, and air voids of the field cores and laboratory samples made based on the gradations determined from the cores. The samples were batched at 0%, 5%, 10% and 20% levels of segregation, representing 0,5,10 and 20 percent coarser on the 4.75mm sieve, and then sent to the KDOT Materials and Research Laboratory for compaction.

Eight out of the twelve samples at each level of segregation were short-term oven-aged (STOA) and the other four samples were compacted without any aging. All samples were compacted using the US Army Corps of Engineers Gyratory Testing Machine (GTM) at the KDOT Materials and Research Laboratory. All samples were compacted to a targeted compacted density based on the percent air voids and asphalt content from the field cores. After compaction six out of the eight STOA samples at each level of segregation were long-term oven-aged (LTOA) by placing the compacted samples in an oven at 80°C for 2 days. This procedure simulates the aging an HMA pavement will undergo after 10 years of service.

Testing of Laboratory Samples

After aging the bulk specific gravity of all samples were determined in accordance with ASTM D 2726. The bulk specific gravity of all 10% and 20% level of segregation samples were redetermined according to ASTM D 1188 using Parafilm. The TMD was determined on samples of loose mix in accordance with ASTM D 2041 and the percent air voids determined for each sample.

Three samples were selected from each level of segregation and the absolute air permeability determined in accordance with procedure C of ASTM D 3637. The indirect tensile strength was determined on a set of two non-aged and two LTOA samples at each level of segregation. The test was performed at 25°C in accordance with ASTM D 4123. The load and deformation at failure were measured and the stress and strain calculated.

The moisture sensitivity test was performed on a set of two non-aged and two LTOA samples at each segregation level. AASHTO T 283 was generally followed for the moisture sensitivity test. This method is intended for mixes compacted to 7 ± 1% air voids. However, the samples tested were compacted to predetermined air voids rather than the 7% specified in the procedure. The saturation of the samples was obtained by holding a 610-mm Hg vacuum for 30 minutes on each sample tested. This test variation is the Colorado method (13). The saturated samples were subjected to a freeze-thaw cycle and then tested for indirect tensile strength. The conditioned indirect tensile strength was compared to unconditioned indirect tensile strength and the TSR calculated.

Fatigue testing was performed on a set of two STOA and two LTOA samples at each level of segregation in accordance with ASTM D 4123. A haversine pulse-load was applied for 0.1 second with a 0.9 second rest at a frequency of 1 cycle per second. The test was conducted in a constant stress mode and the stress level was 5% of the control (non-aged) tensile strength. The number of load repetitions to failure was recorded.

CHAPTER 4

FIELD AND CORE TEST RESULTS & ANALYSIS

(Task 3)

FIELD AND PAVEMENT CORE TEST RESULTS

Aggregate Gradations

Gradation analysis was performed on each core from each site in accordance with ASTM C117 and C136. The gradation analysis was performed on the aggregate remaining from the asphalt ignition test. The results of the gradation analysis and JMF for the four sites are shown in Tables 2 thru 5, respectively.

Indicator Tests

One of the objectives of this study was to determine if an indicator test could be used to detect segregation. The indicator tests were asphalt content from an ignition test, unit weight from a nuclear gauge and cores, air void content, and pavement macro texture. The results of the indicator tests for the four sites are shown in Tables 6 thru 9, respectively.

Performance Tests

The cores obtained from the field study were tested in the laboratory to determine the effects of segregation on performance. The performance tests were indirect tensile strength

Table 2. Asphalt Content & Gradation Analysis for Site 1, US 281, BM-2 Mix.

LOCATION	CORE	VISUALLY SEG.	ASPHALT CONTENT (%)	SIEVE SIZE (mm) 19	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075
				PERCENT RETAINED									
Job Mix Formula				0.0	8.0	21.0	38.0	49.0	61.0	74.0	88.0	94.0	95.0
3	A	NO	5.85	0.0	6.7	16.0	33.8	45.5	56.5	69.2	84.3	90.9	92.9
3	B	NO	5.87	0.0	5.5	15.3	33.8	45.7	56.4	69.3	84.5	90.9	93.0
3	C	NO	5.82	0.0	7.8	16.7	33.7	45.3	56.6	69.1	84.1	90.9	92.8
6	A	NO	5.84	0.0	5.7	13.7	31.7	43.4	54.4	68.5	85.0	91.7	93.6
6	B	NO	5.99	0.0	7.2	13.9	30.3	42.0	53.6	67.3	83.7	91.0	92.9
6	C	NO	5.94	0.0	4.1	12.1	29.9	42.6	54.1	68.4	84.8	91.6	93.6
8	A	NO	5.97	0.0	5.1	12.5	29.0	41.6	53.2	67.5	84.5	91.5	93.5
8	B	NO	5.93	0.0	6.5	14.2	29.9	42.2	53.8	67.8	84.4	91.5	93.4
8	C	NO	5.88	0.0	7.9	15.9	30.7	42.8	54.5	68.1	84.4	91.6	93.4
1	A	YES	4.14	0.0	8.6	19.2	41.1	52.1	61.0	72.3	85.9	91.8	93.6
1	B	YES	3.91	0.0	16.0	28.3	48.1	57.5	65.4	74.7	86.3	91.9	93.5
1	C	YES	4.03	0.0	12.3	23.8	44.6	54.8	63.2	73.5	86.1	91.8	93.5
4	A	YES	5.77	0.0	7.2	18.8	37.9	49.7	59.6	71.3	85.1	91.1	93.1
4	B	YES	5.90	0.0	9.1	19.1	36.9	48.9	59.0	70.6	84.5	90.9	92.9
4	C	YES	6.02	0.0	11.0	19.4	36.0	48.0	58.3	69.9	84.0	90.7	92.6
5E	A	YES	6.24	0.0	7.6	17.1	31.4	43.0	54.5	68.0	85.0	92.1	94.0
5E	B	YES	6.33	0.0	7.1	15.8	31.6	42.4	53.7	68.2	85.2	91.9	93.7
5E	C	YES	6.19	0.0	7.7	14.7	30.6	42.1	53.6	68.2	85.1	91.8	93.7
5W	A	YES	6.42	0.0	7.4	15.9	32.4	43.0	54.2	68.4	85.1	91.7	93.5
5W	B	YES	6.37	0.0	12.8	18.8	34.4	44.9	56.2	69.6	85.6	92.4	94.1
5W	F	YES	6.13	0.0	5.1	14.4	31.0	42.6	54.3	68.9	85.6	92.1	93.9
7	A	YES	5.80	0.0	9.3	16.8	32.4	44.2	55.6	68.3	84.3	91.4	93.2
7	B	YES	5.70	0.0	8.7	17.5	34.0	45.4	56.0	69.1	84.9	91.5	93.4
7	C	YES	5.75	0.0	7.2	17.0	31.7	43.9	55.1	68.8	85.2	91.8	93.7

Table 3. Asphalt Content & Gradation Analysis for Site 2, US 183, BM-1B Mix.

LOCATION	CORE	VISUALL SEG.	ASPHALT CONTENT (%)	19.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075
				SIEVE SIZE (mm) PERCENT RETAINED									
Job Mix Formula				0.0	8.0	19.0	54.0	71.0	81.0	85.0	89.0	94.0	95.5
30	A	NO	5.19	0.0	6.5	16.9	48.3	66.9	76.0	79.3	83.7	90.3	93.6
30	B	NO	5.29	0.0	6.5	16.0	47.5	66.9	76.2	79.6	84.0	90.6	93.9
30	C	NO	5.29	0.0	7.6	17.1	46.9	66.7	76.5	79.6	83.8	90.6	93.7
32	A	NO	5.35	0.0	6.5	15.1	46.7	66.5	76.1	79.1	83.3	90.2	93.4
32	B	NO	5.47	0.0	4.9	12.9	45.3	65.5	75.3	78.6	83.1	90.0	93.5
32	C	NO	5.51	0.0	4.5	14.9	45.8	65.7	75.2	78.6	83.1	90.0	93.5
34	A	NO	5.37	0.0	6.9	15.9	48.9	68.4	77.2	80.4	84.6	90.8	93.9
34	B	NO	5.38	0.0	5.8	15.8	48.7	68.1	77.5	80.4	84.3	90.8	93.8
34	C	NO	5.55	0.0	6.0	15.4	48.2	68.2	77.3	80.4	84.5	90.8	93.9
36	A	NO	5.28	0.0	8.9	19.7	51.9	68.7	76.5	79.5	83.8	90.5	93.7
36	B	NO	5.48	0.0	6.5	16.7	51.2	68.5	76.8	79.9	84.1	90.6	93.8
36	C	NO	5.42	0.0	8.7	19.6	51.6	69.3	78.1	80.9	84.9	91.2	94.1
38	A	NO	5.23	0.0	6.0	17.8	52.2	70.4	79.5	82.3	86.0	91.8	94.4
38	B	NO	5.21	0.0	7.2	17.8	52.8	70.5	78.7	81.8	85.7	91.4	94.3
38	C	NO	5.23	0.0	6.8	18.1	52.9	70.6	79.2	82.2	86.0	91.6	94.3
29	A	YES	5.08	0.0	7.5	20.9	52.8	70.0	78.0	80.7	84.6	91.1	94.0
29	B	YES	5.01	0.0	7.1	19.3	54.5	70.4	77.6	80.3	84.5	90.8	93.9
29	C	YES	5.18	0.0	7.3	16.2	49.6	68.1	76.8	79.9	84.2	90.6	93.8
31	A	YES	4.92	0.0	9.1	24.1	56.7	71.8	78.5	81.1	85.1	91.2	94.2
31	B	YES	5.15	0.0	7.8	19.4	52.9	69.7	77.7	80.4	84.3	90.8	93.8
31	C	YES	5.25	0.0	6.2	16.5	49.8	68.1	76.7	79.8	84.2	90.7	93.8
33	A	YES	4.54	0.0	17.9	32.3	63.8	75.5	80.3	82.5	86.1	91.6	94.2
33	B	YES	4.37	0.0	17.8	38.3	67.3	76.7	80.7	82.6	86.1	91.9	94.7
33	C	YES	4.32	0.0	17.6	37.3	66.9	76.8	81.2	83.1	86.4	91.9	94.5
35	A	YES	4.38	0.0	21.7	40.6	68.2	77.1	81.5	83.5	86.8	92.1	94.7
35	B	YES	4.10	0.0	20.5	42.0	69.1	77.4	81.4	83.4	87.0	92.2	94.8
35	C	YES	4.27	0.0	23.2	43.6	69.8	77.8	81.4	83.4	86.9	92.1	94.7
37	A	YES	4.84	0.0	13.0	27.1	62.0	75.8	82.0	84.5	87.8	92.6	95.0
37	B	YES	4.92	0.0	14.7	27.2	60.4	75.2	81.8	84.2	87.5	92.5	94.7
37	C	YES	4.73	0.0	10.9	25.6	62.7	76.1	82.3	84.8	88.1	92.7	95.0

Table 4. Asphalt Content and Gradation Analysis for Site 3, US 183, HR-2C Mix.

LOCATION	CORE	VISUALLY SEG.	ASPHALT CONTENT (%)	25.0 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
				SIEVE SIZE PERCENT RETAINED										
Job Mix Formula				0.0	1.0	19.0	35.0	60.0	72.0	81.0	88.0	92.0	94.0	96.0
27	A	NO	4.95	0.0	1.9	12.6	27.1	50.1	63.7	75.0	81.2	87.2	92.0	94.0
27	B	NO	4.83	0.0	0.8	13.1	26.3	49.5	63.5	74.5	81.3	87.4	92.0	94.2
25	A	YES	4.74	0.0	0.0	14.6	28.3	53.1	65.6	76.1	82.1	88.0	92.4	94.2
25	B	YES	4.62	0.0	0.0	16.9	30.5	53.3	66.4	76.8	83.3	89.1	93.0	94.8
26	A	YES	4.42	0.0	0.0	19.9	32.8	57.7	68.8	77.4	83.2	88.8	92.9	94.7
26	B	YES	4.34	0.0	0.0	18.3	34.8	57.6	68.0	76.4	81.5	87.1	92.0	94.1
28	A	YES	4.81	0.0	0.5	15.6	29.3	53.1	66.0	75.7	82.0	87.9	92.3	94.3
28	B	YES	4.63	0.0	0.0	13.4	29.0	55.0	67.3	76.8	82.4	88.0	92.5	94.4

Table 5. Asphalt Content and Gradation Analysis for Site 4, US 36, BM-1B Mix.

LOCATION	CORE	VISUALL SEG.	ASPHALT CONTENT (%)	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm	0.075 mm
				SIEVE SIZE PERCENT RETAINED									
Job Mix Formula				0.0	5.0	21.0	50.0	65.0	76.0	85.0	91.0	94.0	94.0
3	A	NO	5.27		4.9	10.3	39.9	59.0	70.9	79.8	87.9	91.6	93.0
5	B	NO	5.86	0.0	3.3	12.0	41.0	60.3	71.7	80.6	88.3	91.6	92.7
7	B	NO	5.71	0.0	9.1	15.9	41.9	62.3	73.6	82.0	89.3	92.5	93.6
4	E	YES	5.73	0.0	3.0	10.4	37.4	57.0	69.4	79.0	87.2	90.7	92.0
41	A	YES	5.79	0.0	2.7	8.2	35.6	56.5	69.1	79.0	87.4	90.9	92.3
6	A	YES	5.25	0.0	4.3	13.0	40.9	61.0	73.1	81.7	88.9	92.1	93.3
61	B	YES	5.10	0.0	6.6	14.8	40.3	60.6	72.7	81.5	88.9	92.2	93.4

Table 6. Results of Indicator Tests for Site 1, US 281, BM-2 Mix.

LOCATION	CORE	SEG.	MACRO-TEXTUR (mm)	AIR VOIDS (%)	ASPHALT CONTENT (%)	CORE UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
3	A	No	0.159	6.3	5.85	22.23	*
3	B	No	0.193	6.1	5.87	22.28	21.96
3	C	No	0.208	5.9	5.82	22.32	*
6	A	No	0.246	9.6	5.84	21.58	*
6	B	No	0.237	10.1	5.99	21.46	21.72
6	C	No	0.213	10.4	5.94	21.40	*
8	A	No	0.161	6.9	5.97	22.23	*
8	B	No	0.199	6.5	5.93	22.33	22.15
8	C	No	0.184	6.4	5.88	22.35	*
1	A	Yes	0.565	12.2	4.14	21.56	*
1	B	Yes	0.520	11.7	3.91	21.67	21.89
1	C	Yes	0.508	11.8	4.03	21.65	*
4	A	Yes	0.343	6.3	5.77	22.17	*
4	B	Yes	0.210	6.4	5.90	22.14	22.37
4	C	Yes	0.176	6.0	6.02	22.23	*
5E	A	Yes	0.547	15.2	6.24	20.23	*
5E	B	Yes	0.349	15.4	6.33	20.19	20.75
5E	C	Yes	0.380	15.5	6.19	20.15	*
5W	A	Yes	0.366	12.3	6.42	20.81	*
5W	B	Yes	0.453	12.0	6.37	20.86	20.49
5W	F	Yes	0.399	13.3	6.13	20.57	*
7	A	Yes	0.445	11.2	5.80	21.22	*
7	B	Yes	0.893	11.1	5.70	21.24	21.58
7	C	Yes	0.391	8.5	5.75	21.86	*

* = One Test per Location.

Table 7. Results of Indicator Tests for Site 2, US 183, BM-1B Mix.

LOCATION	CORE	SEG.	MACRO-TEXTURE (mm)	AIR VOIDS (%)	CORE UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
30	A	No	0.253	8.9	21.98	*
30	B	No	0.293	8.6	22.03	23.57
30	C	No	0.240	8.6	22.05	*
32	A	No	0.226	8.2	22.16	*
32	B	No	0.236	8.6	22.08	23.02
32	C	No	0.289	8.3	22.15	*
34	A	No	0.336	13.7	20.83	*
34	B	No	0.273	13.3	20.92	22.42
34	C	No	0.345	15.2	20.46	*
36	A	No	0.242	8.1	22.20	*
36	B	No	0.282	8.6	22.09	23.05
36	C	No	0.306	8.4	22.13	*
38	A	No	0.299	9.0	22.05	*
38	B	No	0.279	8.5	22.17	23.12
38	C	No	0.258	8.6	22.14	*
29	A	Yes	0.442	15.4	20.50	*
29	B	Yes	0.492	18.6	19.73	22.08
29	C	Yes	0.463	14.2	20.79	*
31	A	Yes	0.460	15.8	20.39	*
31	B	Yes	0.528	14.6	20.67	21.17
31	C	Yes	0.416	12.1	21.27	*
33	A	Yes	0.738	19.4	19.77	*
33	B	Yes	0.880	21.0	19.37	21.90
33	C	Yes	0.757	21.5	19.25	*
35	A	Yes	0.961	16.9	20.38	*
35	B	Yes	0.872	18.0	20.10	22.02
35	C	Yes	0.915	17.5	20.22	*
37	A	Yes	0.491	15.3	20.62	*
37	B	Yes	0.450	14.8	20.73	22.33
37	C	Yes	0.506	15.1	20.65	*

* = One Test per Location.

Table 8. Results of Indicator Tests for Site 3, US 183, HR-2C Mix.

LOCATION	CORE	SEG.	MACRO-TEXTUR (mm)	AIR VOIDS (%)	ASPHALT CONTENT (%)	CORE UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
27	A	No	0.214	7.3	4.95	22.47	
27	B	No	0.191	6.4	4.80	22.69	N/A
27	C	No	0.099	6.1		22.77	
27	D	No	0.176	5.5		22.91	
25	A	Yes	0.188	7.4	4.73	22.39	
25	B	Yes	0.216	6.9	4.59	22.50	N/A
25	C	Yes	0.358	6.3		22.67	
26	A	Yes	0.388	10.0	4.32	22.00	
26	B	Yes	0.500	10.1		21.99	
26	C	Yes	0.577	10.6	4.36	21.87	N/A
26	D	Yes	0.617	10.0		22.02	
26	E	Yes	0.61	9.0		22.27	
28	A	Yes	0.379	6.4	4.79	22.68	
28	B	Yes	0.373	6.9	4.68	22.56	N/A
28	C	Yes	0.303	6.6		22.63	

N/A = Data Not Available.

Table 9. Results of Indicator Tests for Site 4, US 36, BM-1B Mix.

LOCATION	CORE	SEG.	MACRO-TEXTUR (mm)	AIR VOIDS (%)	CORE UNIT WEIGHT (kN/m^3)	NUCLEAR GAUGE UNIT WEIGHT (kN/m^3)
3	A	No	0.246	11.9	21.24	*
3	B	No		12.9	21.00	21.40
3	C	No	0.219	11.7	21.28	*
5	A	No	0.307	11.5	20.96	*
5	B	No	0.328	11.7	20.91	21.72
5	C	No	0.371	11.6	20.93	*
7	A	No	0.225	10.9	21.01	*
7	B	No	0.358	10.8	21.03	21.45
7	C	No	0.248	10.6	21.08	*
4	A	Yes	0.303	12.0	21.00	*
4	B	Yes	0.433	12.2	20.95	*
4	C	Yes	0.410	11.7	21.07	21.67
4	D	Yes		11.2	21.19	*
4	E	Yes	0.340	11.9	21.03	*
41	A	Yes	0.355	11.6	21.07	*
41	B	Yes	0.475	12.0		21.86
41	C	Yes	0.495	12.1	20.95	*
6	A	Yes	0.449	12.0	21.23	*
6	B	Yes	0.506	13.4	20.89	22.15
6	C	Yes				*
61	A	Yes	0.416	12.1	21.13	*
61	B	Yes	0.399	11.3	21.34	22.07
61	C	Yes	0.409	11.4	21.31	*

* = One Test per Location.

(ASTM D4123), moisture sensitivity (AASHTO T283), and fatigue life. The results for the four sites are shown in Tables 10 thru 13, respectively.

ANALYSIS OF DATA

Visual Identification

Cross and Brown (4) showed that visual observations could adequately detect segregation in Alabama mixtures. Areas of coarse surface texture were identified and cores were obtained from these areas as well as from uniform areas. The macro texture test was used to quantify the surface texture of each location. Figures 1 thru 4 shows the average macro texture of the uniform surface textured cores and the average macro texture of each coarse textured area. The 95% confidence limit, 95% probability that a sample is coarser than the average macro texture of the pavement, is shown as well.

Figure 1 shows that 4 of 5 coarse textured areas were actually coarser than the average with location 4 being coarser than the average at the 90% confidence limit. Figures 2 and 3 show that all locations identified as segregated at sites 2 and 3 were coarser than the average pavement macro texture at a 95% confidence limit. Figure 4 shows that 3 of 4 coarse textured locations were coarser than the average at a 95% confidence limit. Location 4 was not significantly coarser than the average. The results of the visual observations show that 16 of 18 locations identified as having a coarse surface texture were coarser than the average at a 95% confidence limit and 17 of 18 were coarser at a 90% confidence limit indicating that visual observations can identify non-uniform surface texture.

Table 10. Results of Performance Tests for Site 1, US 281, BM-2 Mix.

LOCATION	CORE	SEG.	FATIGUE LIFE (Nf)	INDIRECT TENSILE STRENGTH CONTROL (kPa)	INDIRECT TENSILE STRENGTH CONDITIONED (kPa)	TENSILE STRENGTH RATIO (TSR)
3	A	No	2940	*	*	*
3	B	No	*	*	706.7	0.74
3	C	No	*	962.5	*	*
6	A	No	2503	*	*	*
6	B	No	*	846.7	*	*
6	C	No	*	*	428.9	0.51
8	A	No	*	*	636.4	0.68
8	B	No	3377	*	*	*
8	C	No	*	947.4	*	*
1	A	No	*	*	379.9	0.53
1	B	No	*	712.9	*	*
1	C	No	1938	*	*	*
4	A	No	*	*	646.8	0.58
4	B	No	3695	*	*	*
4	C	No	*	1114.2	*	*
5E	A	Yes	*	410.9	*	*
5E	B	Yes	231	*	*	*
5E	C	Yes	*	*	144.8	0.35
5W	A	Yes	*	*	203.4	0.39
5W	B	Yes	*	527.5	*	*
5W	F	Yes	549	*	*	*
7	A	Yes	*	570.2	*	*
7	B	Yes	*	*	401.3	0.70
7	C	Yes	3130	*	*	*

* = Not Tested.

Table 11. Results of Performance Tests for Site 2, US 183, BM-1B Mix.

LOCATION	CORE	SEG.	FATIGUE LIFE (Nf)	INDIRECT TENSILE STRENGTH CONTROL (kPa)	INDIRECT TENSILE STRENGTH CONDITIONED (kPa)	TENSILE STRENGTH RATIO (TSR)
30	A	No	*	*	405.5	0.78
30	B	No	2202	*	*	*
30	C	No	*	519.9	*	*
32	A	No	*	531.6	*	*
32	B	No	2107	*	*	*
32	C	No	*	*	414.7	0.78
34	A	No	*	*	376.6	0.83
34	B	No	*	453.7	*	*
34	C	No	830	*	*	*
36	A	No	*	*	423.5	0.75
36	B	No	2086	*	*	*
36	C	No	*	564.7	*	*
38	A	No	*	446.1	*	*
38	B	No	*	*	423.8	0.95
38	C	No	3610	*	*	*
29	A	Yes	*	361.3	*	*
29	B	Yes	547	*	*	*
29	C	Yes	*	*	397.4	1.10
31	A	Yes	842	*	*	*
31	B	Yes	*	395.1	*	*
31	C	Yes	*	*	367.4	0.93
33	A	Yes	*	*	192.2	0.82
33	B	Yes	212	*	*	*
33	C	Yes	*	234.4	*	*
35	A	Yes	*	306.1	*	*
35	B	Yes	670	*	*	*
35	C	Yes	*	*	244.9	0.80
37	A	Yes	695	*	*	*
37	B	Yes	*	428.9	*	*
37	C	Yes	*	*	283.1	0.66

* = Not Tested.

Table 12. Results of Performance Tests for Site 3, US 183, HR-2C Mix.

LOCATION	CORE	SEG.	FATIGUE LIFE (Nf)	INDIRECT TENSILE STRENGTH CONTROL (kPa)	INDIRECT TENSILE STRENGTH CONDITIONED (kPa)	TENSILE STRENGTH RATIO (TSR)
27	A	No	*	466.7	*	*
27	B	No	*	*	491.6	1.05
27	C	No	*	*	*	*
			*	*	*	*
25	A	Yes	*	597.9	*	*
25	B	Yes	*	*	479.2	0.80
25	C	Yes	*	*	*	*
			*	*	*	*
26	A	Yes	*	*	182.0	0.69
26	B	Yes	*	*	*	*
26	C	Yes	*	263.9	*	*
			*	*	*	*
28	A	Yes	*	*	441.3	0.85
28	B	Yes	*	522.2	*	*
28	C	Yes	*	*	*	*

* = Not Tested.

Table 13. Results of Performance Tests for Site 4, US 36, BM-1B Mix.

LOCATION	CORE	SEG.	FATIGUE LIFE (Nf)	INDIRECT TENSILE STRENGTH CONTROL (kPa)	INDIRECT TENSILE STRENGTH CONDITIONED (kPa)	TENSILE STRENGTH RATIO (TSR)
3	A	No	N/T	567.6	N/T	0.78
3	B	No	N/T	*	N/T	*
3	C	No	N/T	*	N/T	*
5	A	No	N/T	*	N/T	N/T
5	B	No	N/T	449.6	N/T	N/T
5	C	No	N/T	*	N/T	N/T
						N/T
7	A	No	N/T	*	N/T	N/T
7	B	No	N/T	423.6	N/T	N/T
7	C	No	N/T	*	N/T	N/T
						N/T
4	A	Yes	N/T	*	N/T	N/T
4	B	Yes	N/T	*	N/T	N/T
4	E	Yes	N/T	423.4	N/T	N/T
						N/T
41	A	Yes	N/T	430.8	N/T	N/T
41	B	Yes	N/T	*	N/T	N/T
41	C	Yes	N/T	*	N/T	N/T
6	A	Yes	N/T	453.1	N/T	N/T
6	B	Yes	N/T	*	N/T	N/T
6	C	Yes	N/T	*	N/T	N/T
61	A	Yes	N/T	*	N/T	N/T
61	B	Yes	N/T	438.0	N/T	N/T
61	C	Yes	N/T	*	N/T	N/T

N/T = Damaged Core, Not Tested.
* = Not Tested.

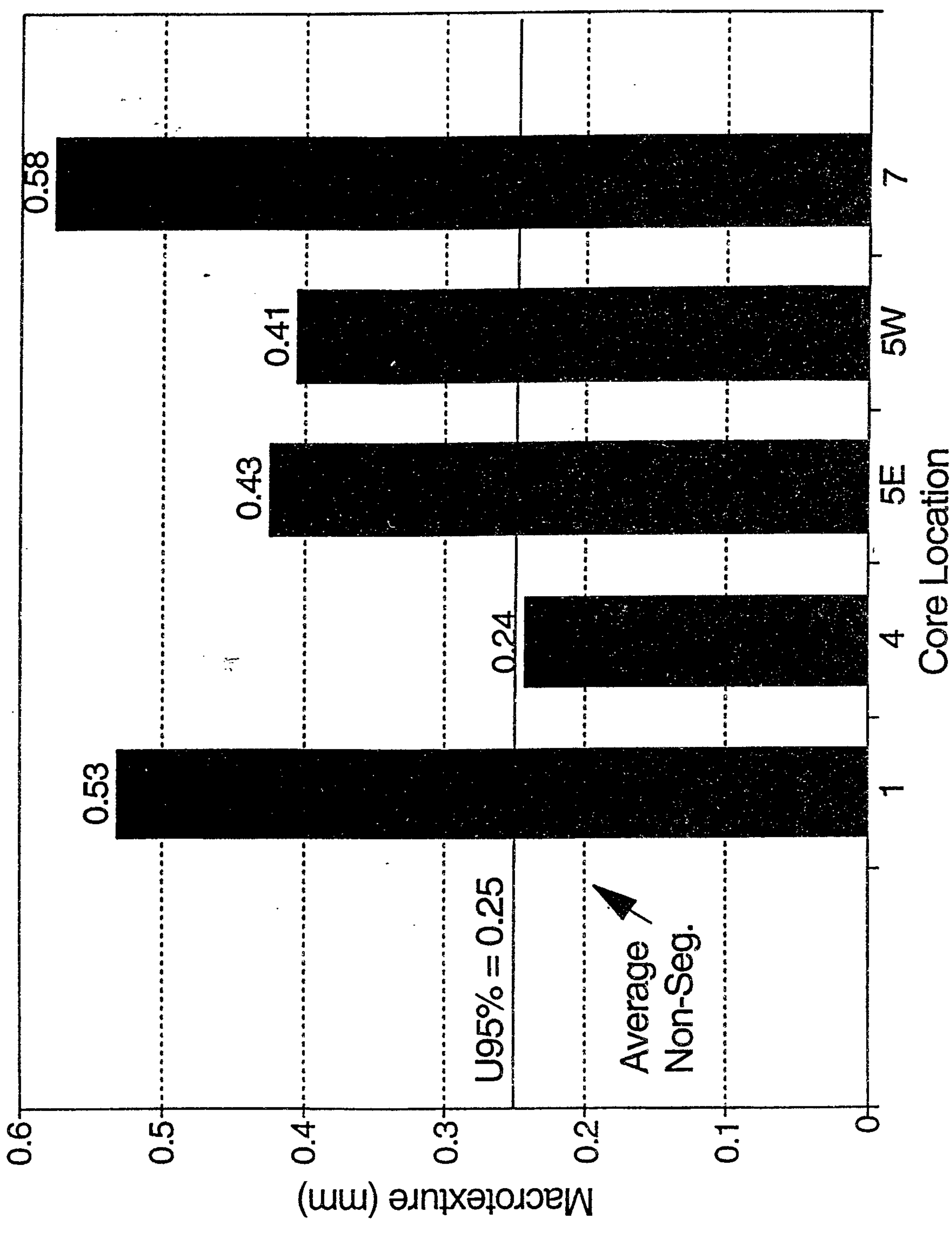

Figure 1. Coarse Surface Texture vs Average Texture, Site 1.

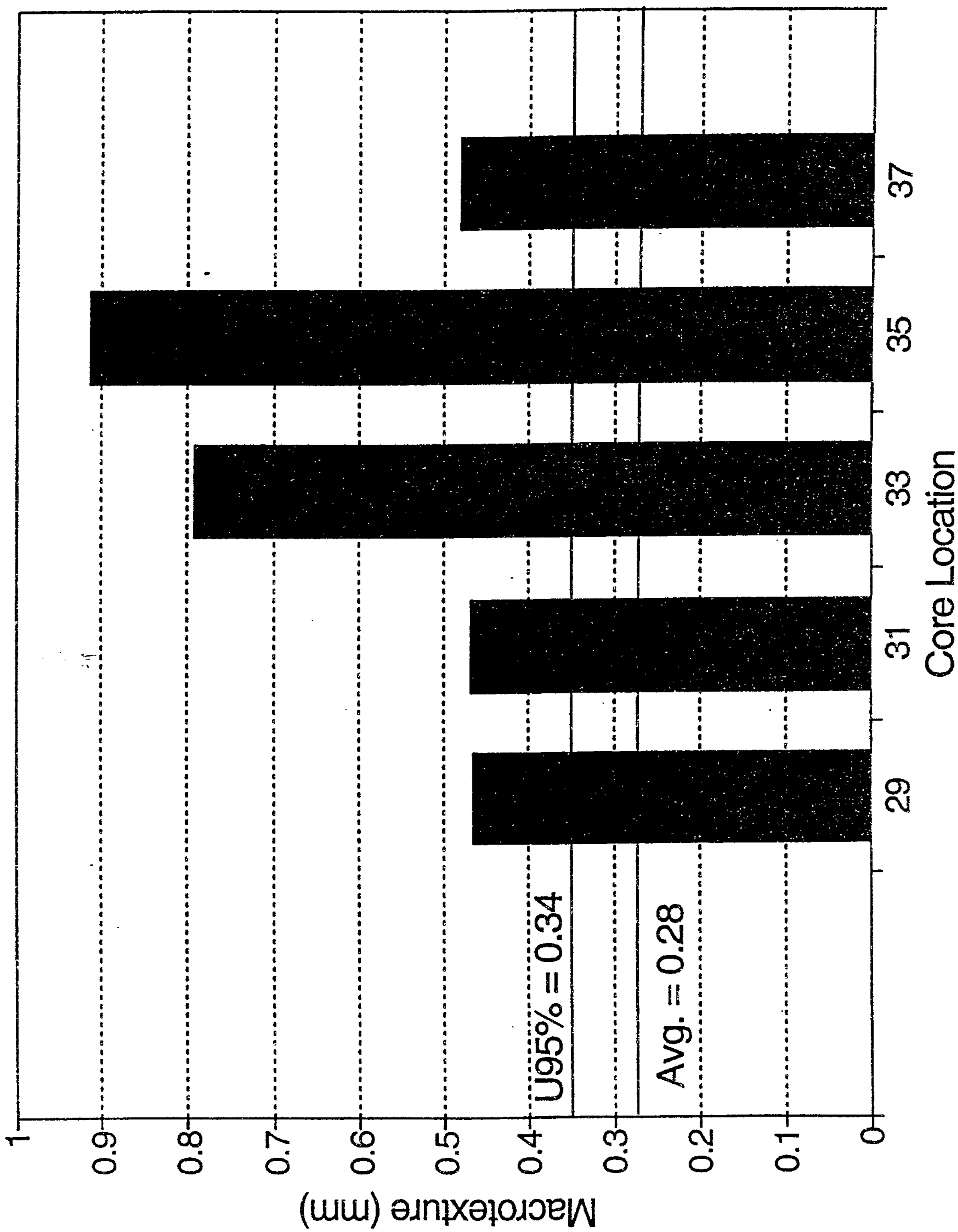

Figure 2. Coarse Surface Texture vs Average Texture, Site 2.

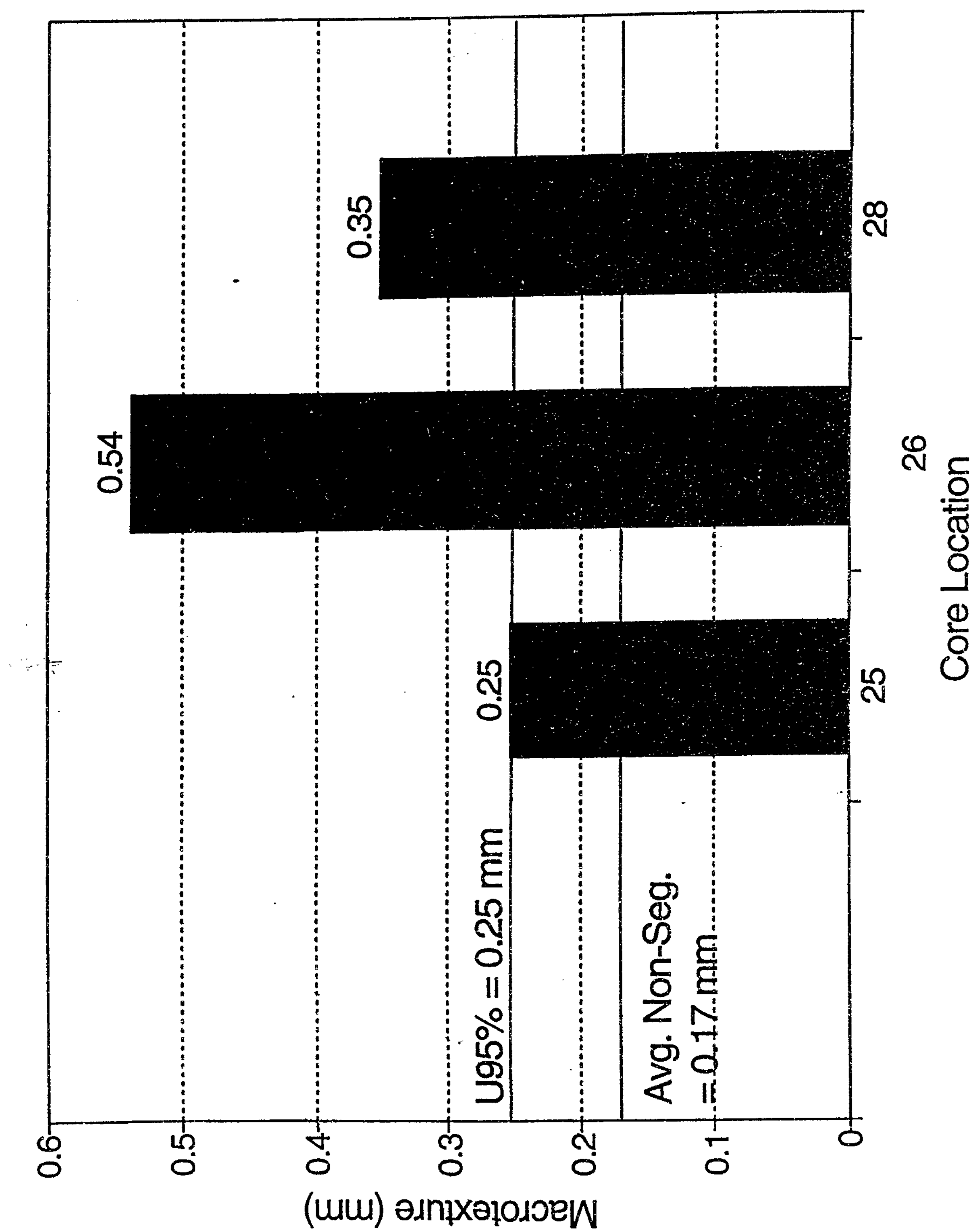

Figure 3. Coarse Surface Texture vs Average Texture, Site 3.

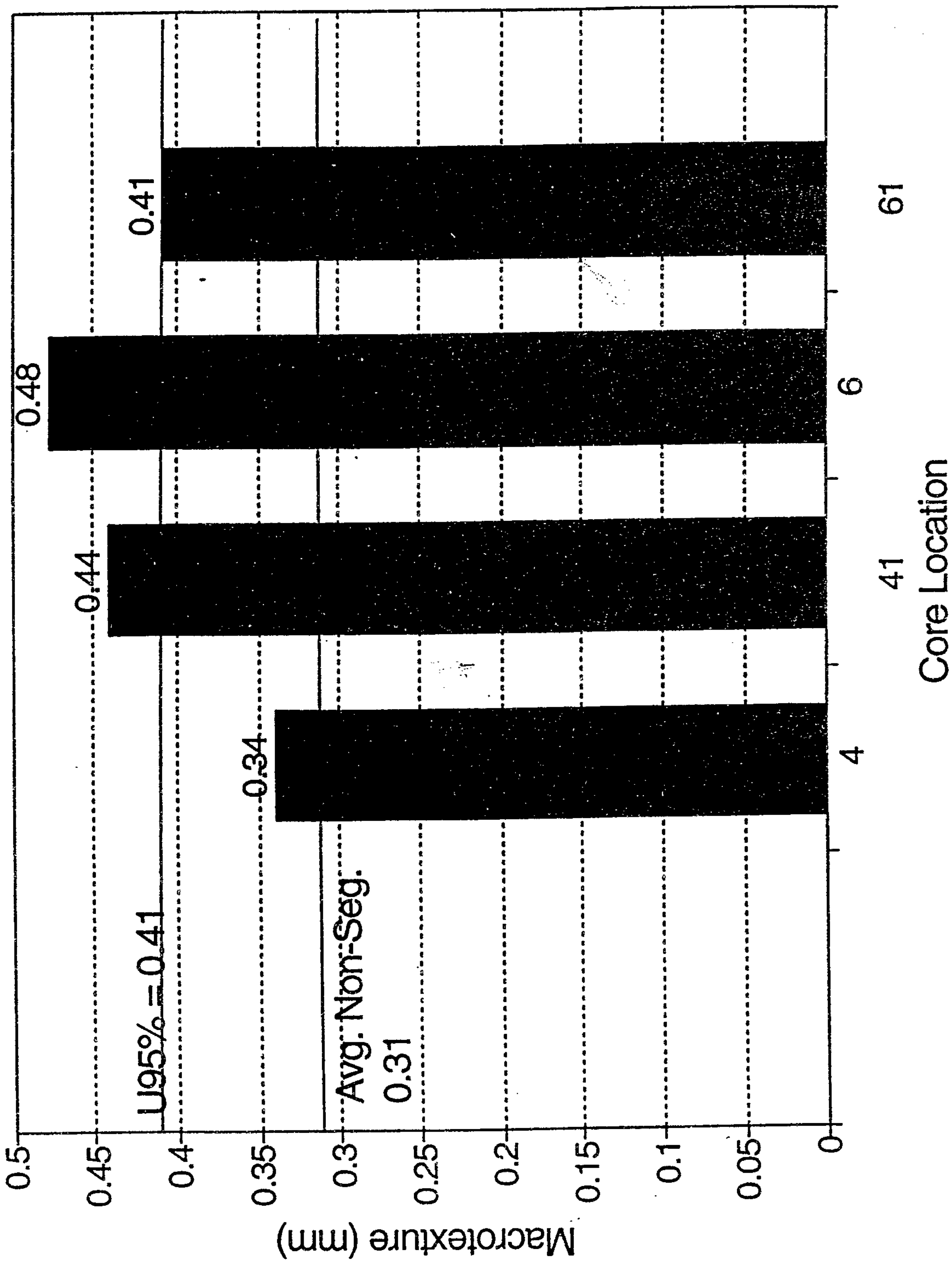

Figure 4. Coarse Surface Texture vs Average Texture, Site 4.

Segregation

Segregation has typically been quantified as a measured change in gradation on the 4.75 mm sieve. A location was considered segregated if the percent retained on the 4.75 mm sieve was significantly coarser than the average gradation of the uniform textured cores at a confidence limit of 95%. Figures 5,8,11 & 13 show the average percent retained of the uniform surface textured cores and the average percent retained of each coarse textured area. The 95% confidence limit, 95% probability that the gradation is coarser on the 4.75 mm sieve than the average is shown as well.

__Site 1__

Figure 5 shows that only 2 of 5 locations at site 1 identified as having a coarse surface texture were segregated, based on the 4.75 mm sieve. The average percent retained for the 4.75 mm sieve for the uniform surface textured cores is 31.4 %, which is 6.6 % finer than the JMF. The corresponding standard deviation is 1.9 %. The KDOT specified the tolerance limit for one test on the 4.75 mm sieve for a BM-2 mix is ± 6 %. Figures 6 and 7 shows the variation in gradation of the coarse textured cores from the average of the uniform textured cores. Sites 5E, 5W and 7 are not significantly coarser than the average at a confidence limit of 95%. As shown in Table 6, locations 1, 5E, 5W and 7 had high average air voids, 11.9%, 15.4 %, 12.5% and 10.3 %, respectively, compared to an average of 7.5 % for the uniform textured cores. The cores from locations 5E, 5W and 7 were not segregated on the 4.75 mm sieve, but had high air void contents. The high voids resulted in a coarse surface texture which was mistaken for a change in gradation. Location 4 was also identified as segregated, however, it

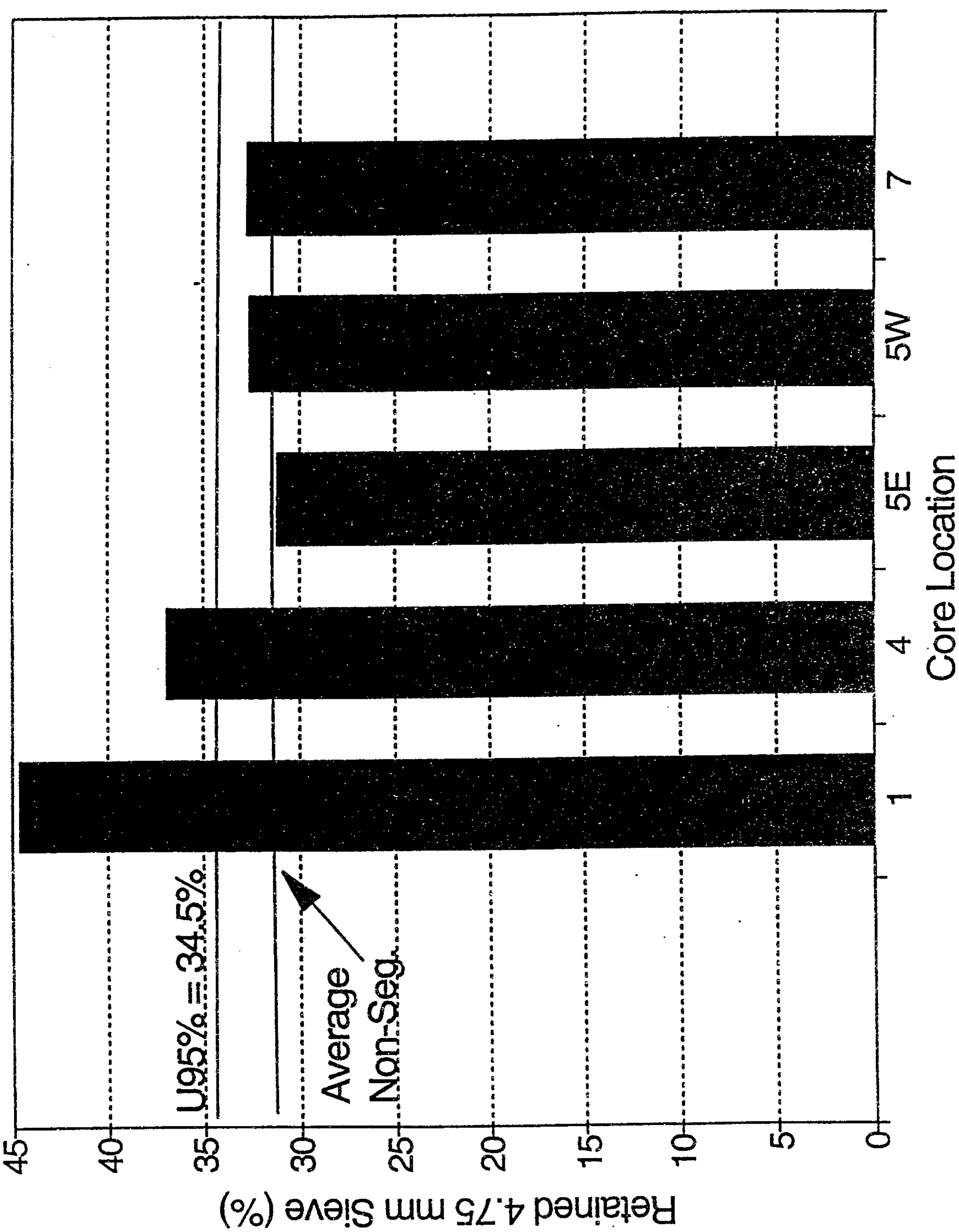

Figure 5. Percent Retained 4.75-mm Sieve vs Average Percent Retained, Site 1.

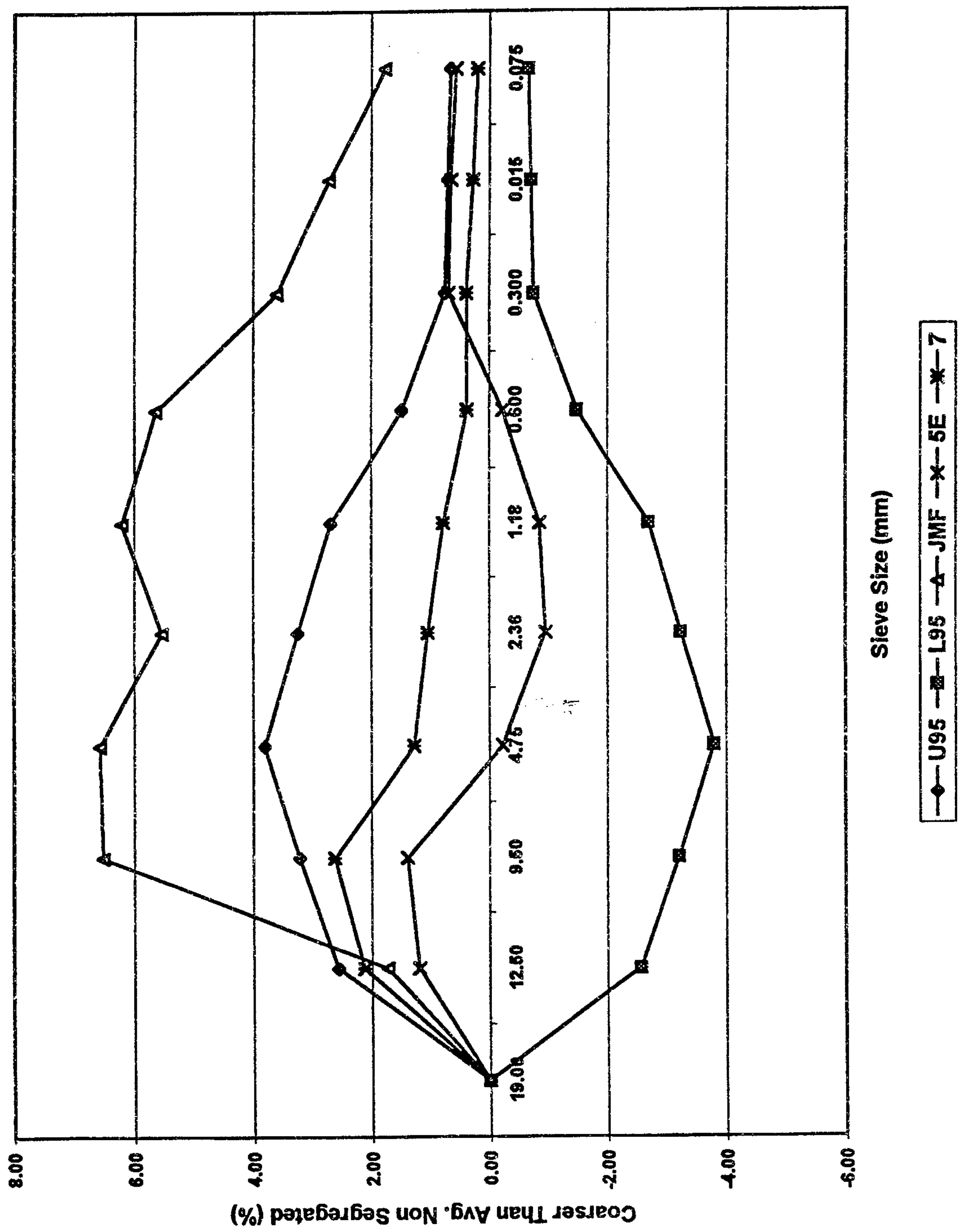

Figure 6. Change in Gradation vs Average Gradation, Site 1 (Loc. 5E & 7)

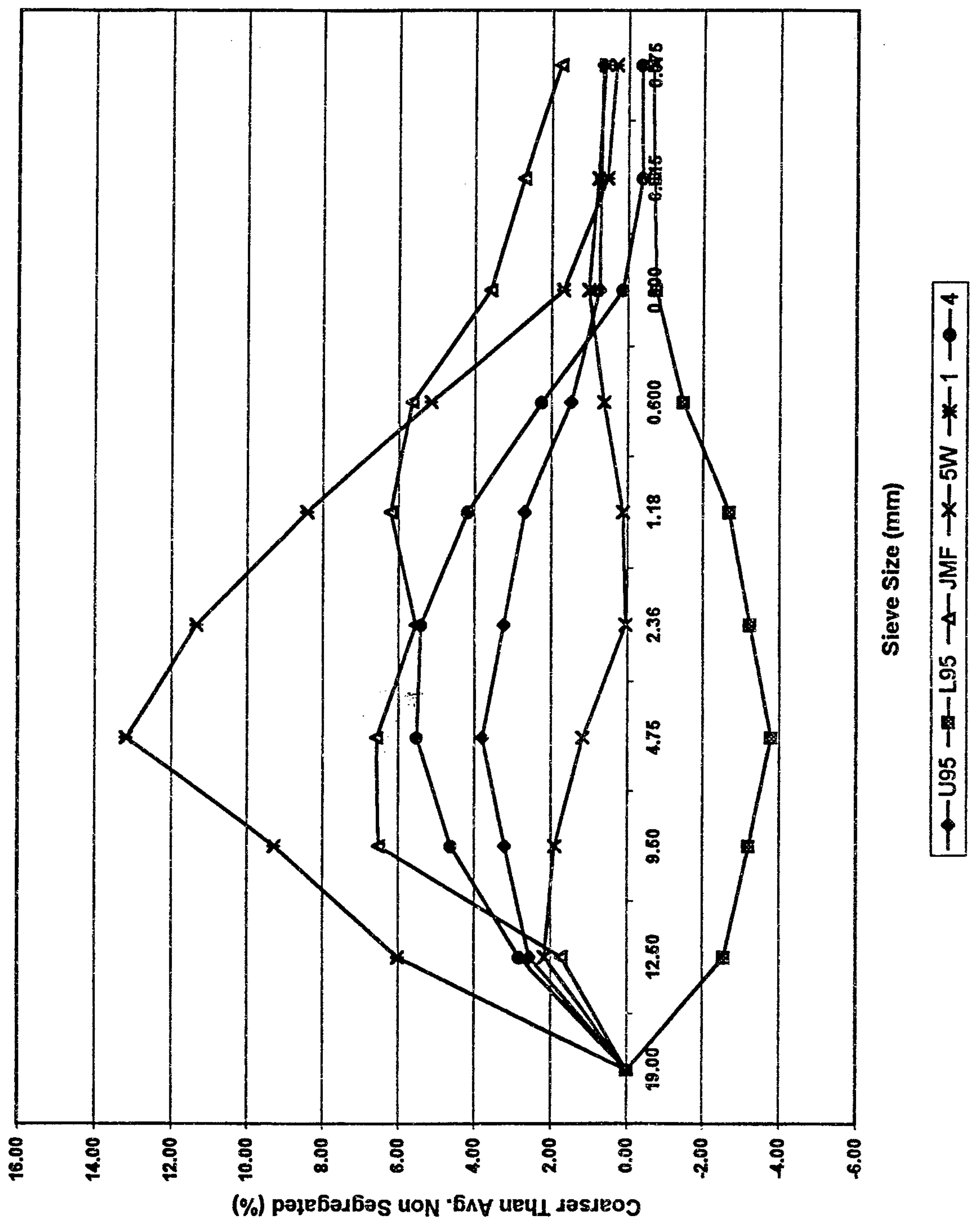

Figure 7. Change in Gradation vs Average Gradation, Site 1 (Loc. 5W, 1, & 4)

had an average gradation within the KDOT specified tolerance limit and had a low air void content, 6.2 %. Thus, only one of five areas identified as segregated, location 1, was outside the specifications on the 4.75 mm sieve (segregated).

Site 2

Figure 8 shows that only 3 of 5 locations at site 2 identified as having a coarse surface texture was segregated, based on the 4.75 mm sieve. Locations 29 and 31 were not coarser than the average at a confidence limit of 95%. Table 3 shows the gradation analysis of Site 2 (BM-1B mix) and Table 7 shows the results of the indicator tests. The average percent retained on the 4.75 mm sieve for the uniform surface texture cores is 49.3 %, which is 4.7 % finer than the JMF. The corresponding standard deviation for the uniform surface texture cores is 2.6 %. The KDOT specified tolerance limits on the 4.75 mm sieve for a BM-1B mix are ± 6 %. Figures 9 and 10 show the variation in gradation of the coarse textured cores from the average of the uniform textured cores. Locations 33, 35 and 37 were outside the tolerance limit on the 4.75 mm sieve and significantly coarser than the average at a 95% confidence limit. Locations 29 and 31 were outside the specification limits and coarser than the average at a confidence limit of 95%. As shown in Table 7 locations 29 and 31 had high average air void contents, 16.1 % and 14.2 %, respectively, compared to an average of 9.6 % for the uniform textured cores. The cores from these locations were not segregated and the high air void contents resulting in a coarse surface texture which was mistaken for segregation.

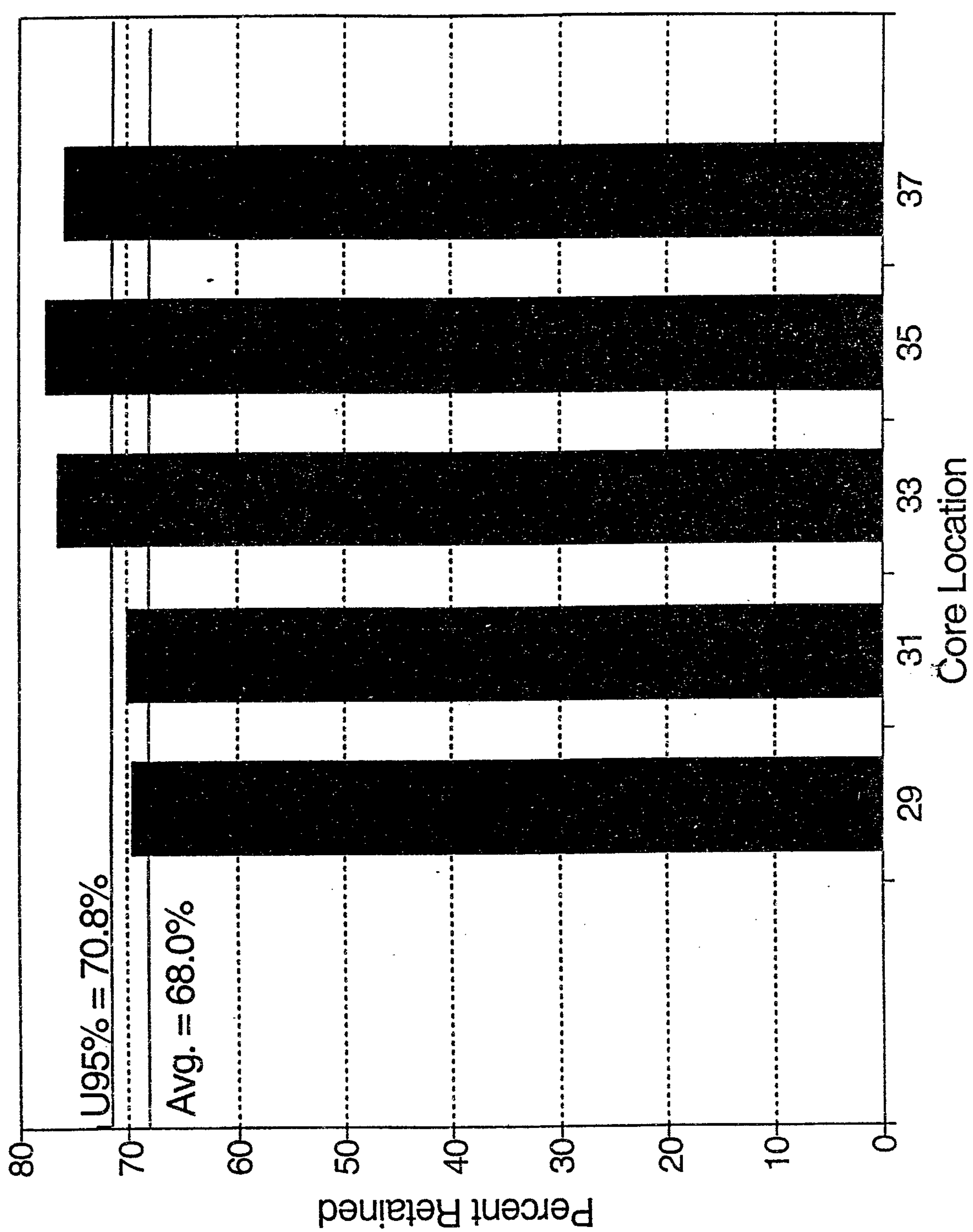

Figure 8. Percent Retained 4.75-mm Sieve vs Average Percent Retained, Site 2.

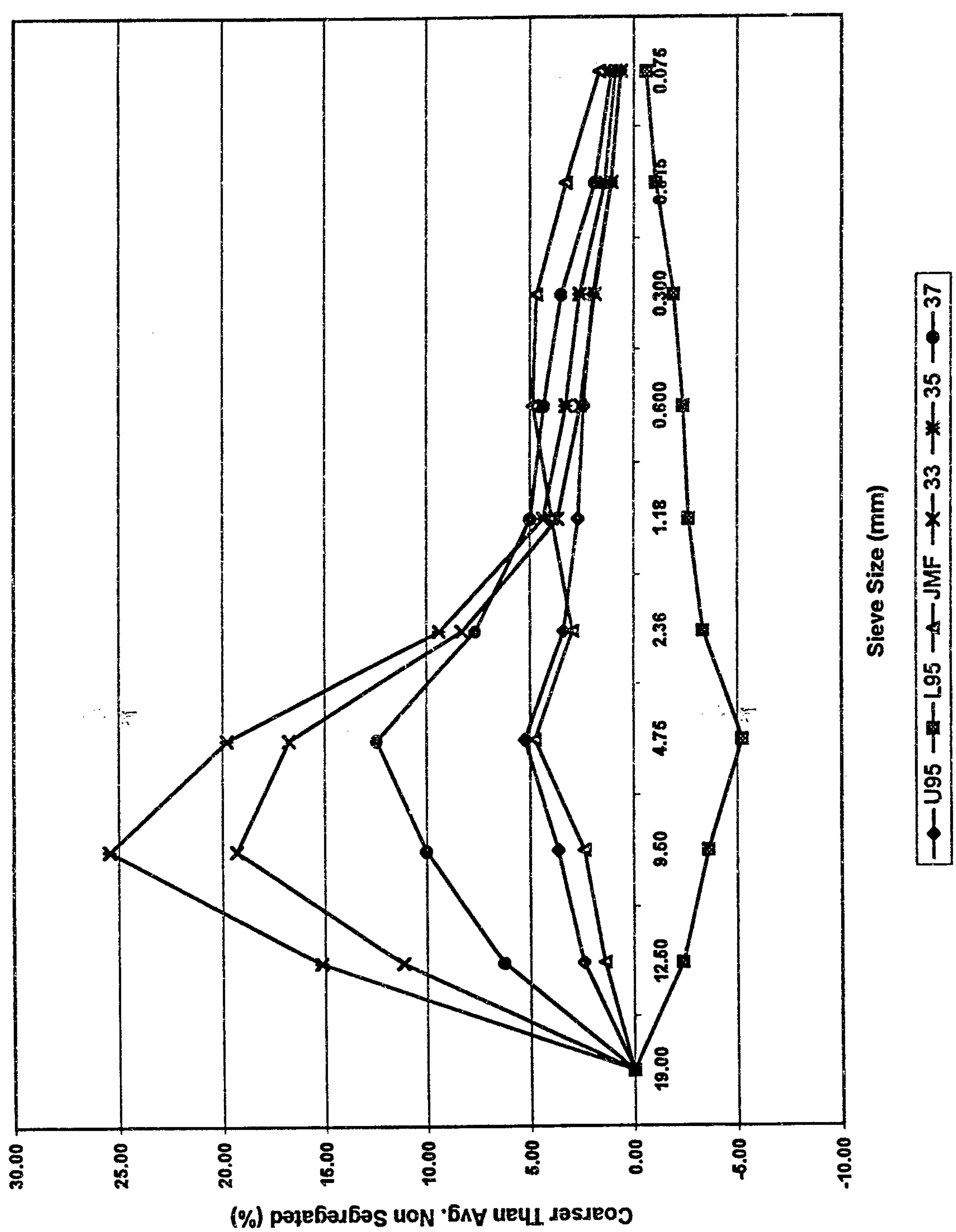

Figure 9. Change in Gradation vs Average Gradation, Site 2 (Loc. 33, 35, & 37)

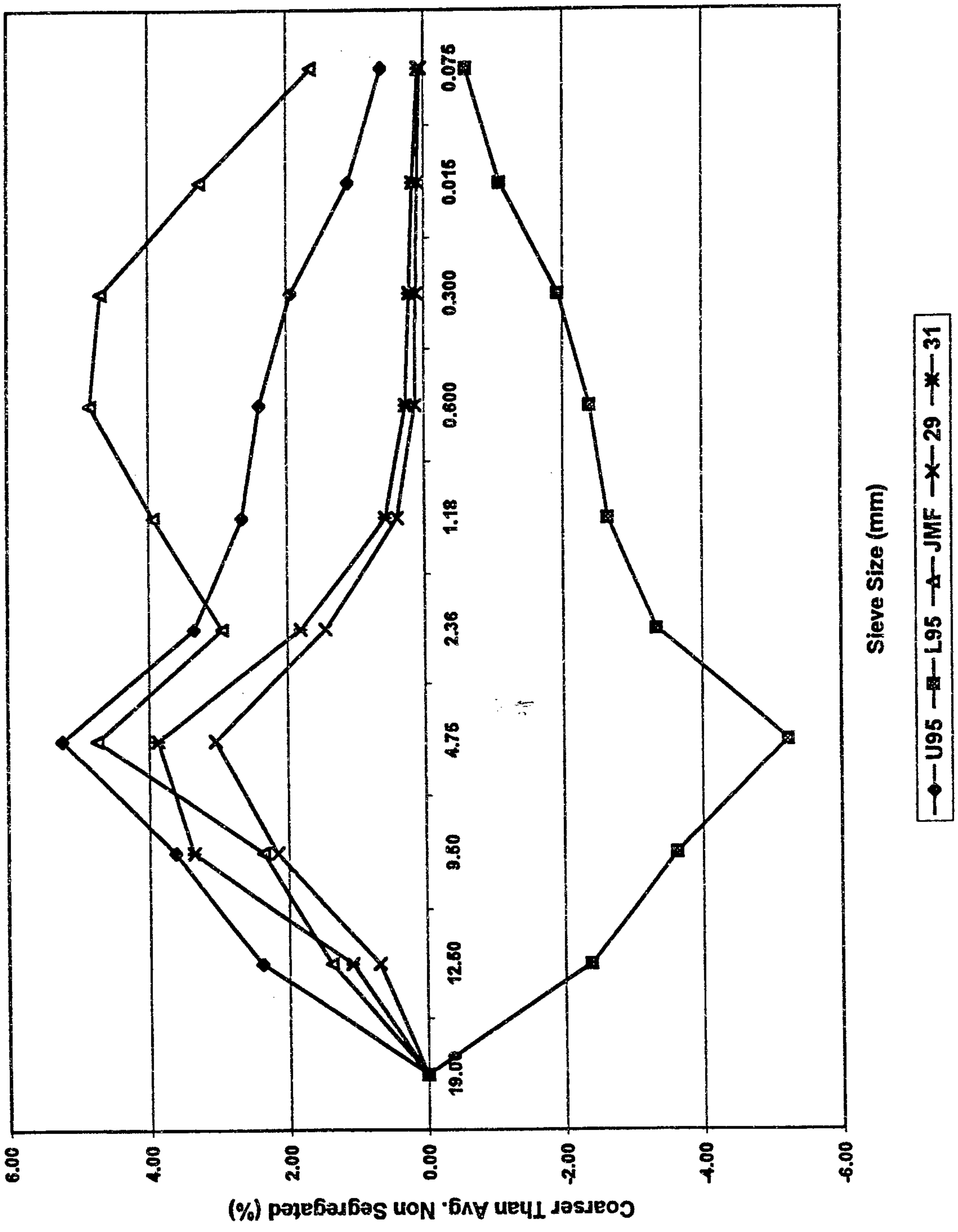

Figure 10. Change in Gradation vs Average Gradation, Site 2 (Loc. 29 & 31)

Site 3

Figure 11 shows that all locations identified as coarser than the average were segregated, based on the 4.75 mm sieve. Table 4 shows the gradation analysis and JMF from Site 3 (HR-2C mix) and Table 8 the results of the indicator tests. Figure 12 shows the variation in gradation of the coarse textured cores from the gradation of the uniform textured cores. The average percent retained on the 4.75 mm sieve for the uniform textured cores is 49.8 %, which is 10.2% finer than the JMF. The tolerance limits for a single test on the 4.75 mm sieve for a BM-2C mix is ± 6%. All locations were outside the specification limit except location 26, indicating that either the JMF was changed or the gradation of the mix or RAP changed during production. Virgin aggregate gradation quality control tests were performed by KDOT on the cold feeds and this would not identify a change in the combined recycle mix occurring during production.

Site 4

Figure 13 shows that all locations identified as coarser than the average were not segregated, based on the 4.75 mm sieve. Table 5 shows the gradation analysis and JMF from Site 4 (BM-1B mix) and Table 9 the results of the indicator tests. Figure 14 shows the variation in gradation of the coarse textured cores from the average of the uniform textured cores. The average percent retained on the 4.75 mm sieve for the uniform textured cores is 40.8 %, which is 9.1% finer than the JMF. All locations were considerably finer than the specification limits. Visual observations of the cores from site 4 indicated considerable aggregate

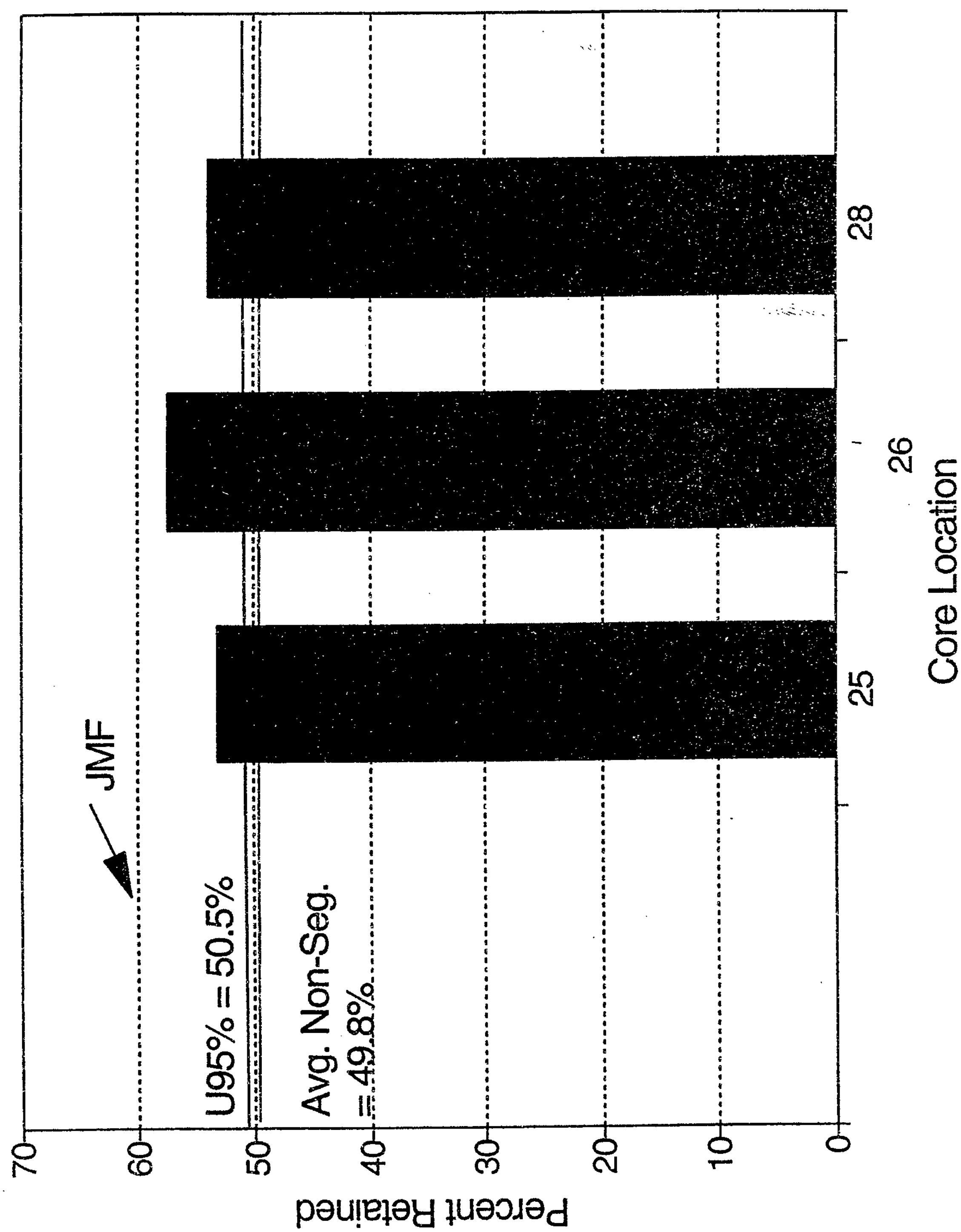

Figure 11. Percent Retained 4.75-mm Sieve vs Average Percent Retained, Site 3.

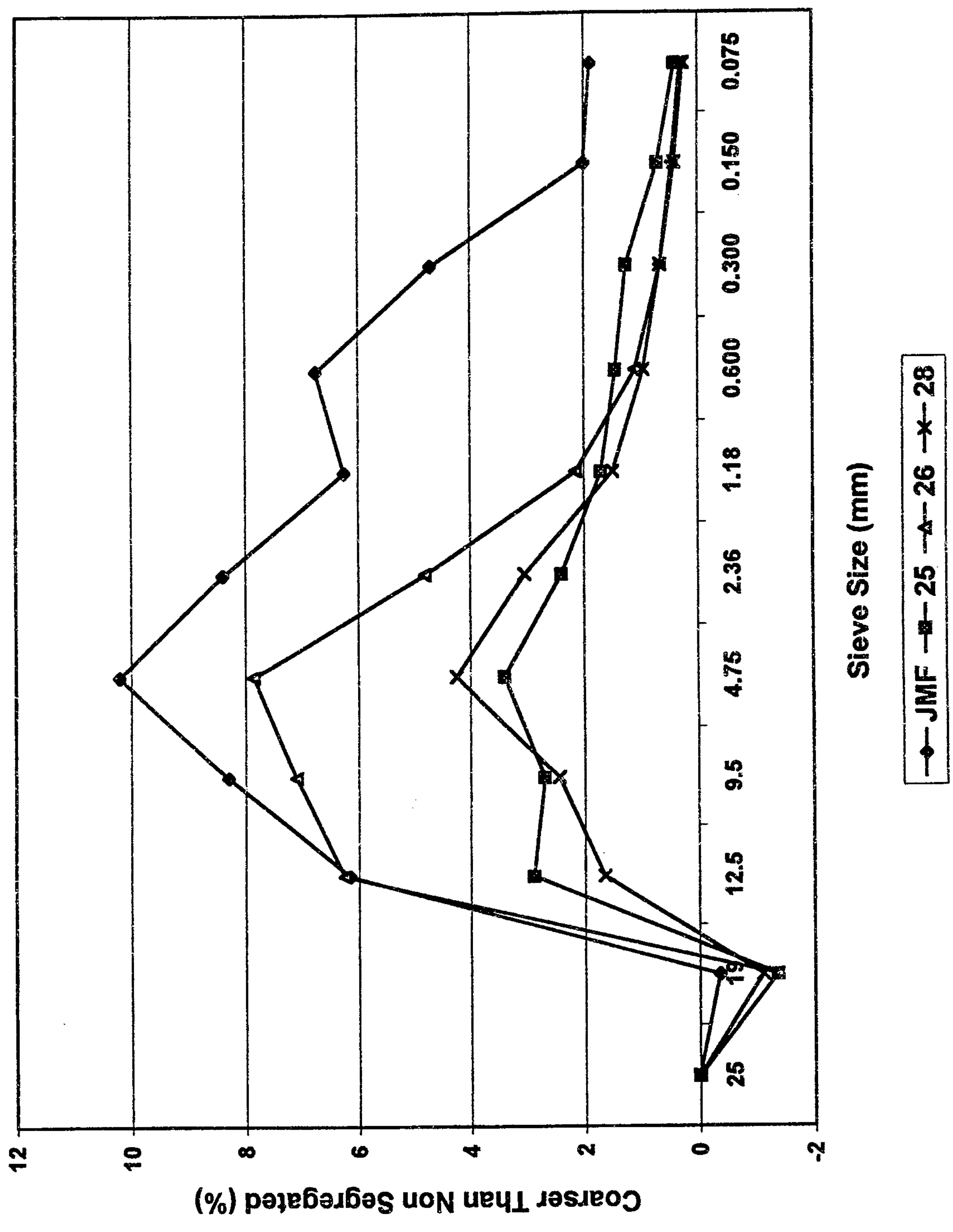

Figure 12. Change in Gradation vs. Average Gradation, Site 3.

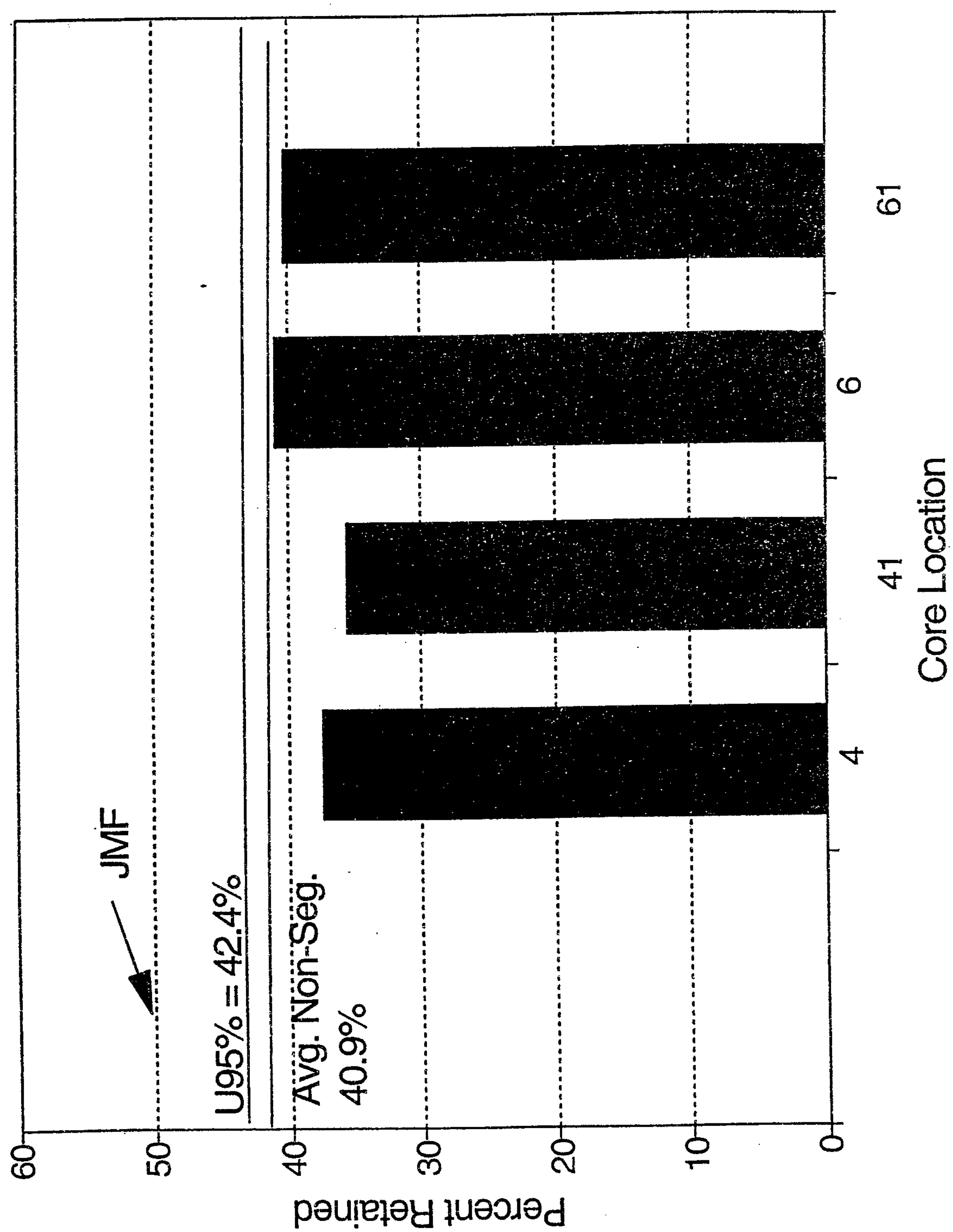

Figure 13. Percent Retained 4.75-mm Sieve vs Average Percent Retained, Site 4.

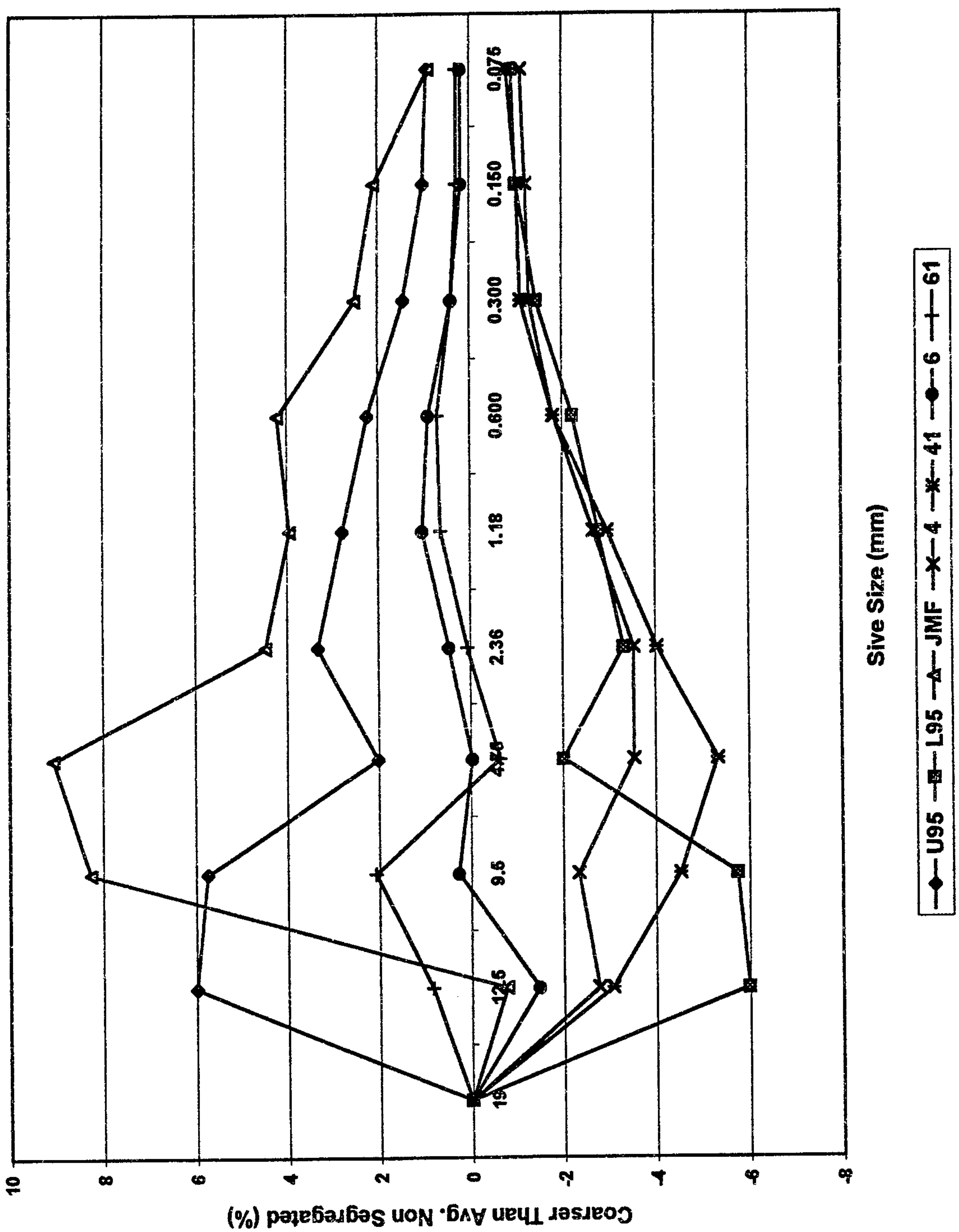

Figure 14. Change in Gradation vs. Average Gradation, Site 4.

breakdown. Due to the excessive aggregate breakdown resulting in a significantly finer mix being placed, site 4 was removed from further analysis.

Indicator Tests

One of the objectives of this study was to determine if an indicator test could be used to detect either a coarse surface texture or segregation. Visual observation was shown to be the best indicator of coarse surface texture but could not indicate a change in gradation on the 4.75 mm sieve. Segregation was quantified as percent retained on the 4.75 mm sieve and surface texture as macro texture. The indicator tests were asphalt content from an ignition test, unit weight from a nuclear gauge and unit weight from cores. The results of correlation analysis to detect segregation and pavement surface texture are shown in Tables 14 and 15, respectively. The significant correlations are discussed below.

Asphalt Content

End of the load segregation is typically associated with lower measured asphalt contents (9,10). Figure 15 shows the relationship between asphalt content and percent retained on the 4.75 mm sieve for sites 1, 2 and 3. The relationships have R^2's ranging from 0.73 to 0.92 and indicate that as the amount of segregation (coarseness) increases, the asphalt content decreases. The slopes of the lines for sites 2 (BM-1B) and 3 (HR-2C) are similar. Both mixes generally have the same shape on a grain-size distribution curve. The relationship between the change in asphalt content from the average and the change in percent passing from the average (normalized data) for sites 2 and 3 are shown in Figure 16. The relationship has an R^2

of 0.93 and indicates that a change in asphalt content of 0.28 % indicates a change in percent retained of 5 %. The relationships agree with the results by Brown et al. (10) and Kandhal (9) and confirms that the type of segregation observed was end of the load segregation. Of the indicator tests evaluated, the asphalt content was the best indicator of segregation.

Table 14. Summary of Correlation Analysis with Segregation.

		Site 1	Site 2	Site 3	All*
Macrotexture	R	0.377	0.913	0.816	0.640
	Alpha	0.0069	0.0001	0.0135	0.0001
	n	24	30	8	36
Asphalt Content	R	-0.856	-0.959	-0.919	-0.551
	Alpha	0.0001	0.0001	0.0013	0.0005
	n	24	30	8	36
Nuclear Gauge Unit Weight	R	0.187	-0.534	N/A	0.551
	Alpha	0.3978	0.1118	N/A	0.0986
	n	24	10	N/A	10
Core Unit Weight	R	0.181	-0.727	-0.798	-0.333
	Alpha	0.3978	0.0001	0.0177	0.0474
	n	24	30	8	36
Voids Total Mix	R	0.036	0.774	0.802	0.491
	Alpha	0.8667	0.0001	0.0167	0.0024
	n	24	30	8	36

* Normalized data, segregated cores only.
N/A = Data not available.

Table 15. Summary of Correlation Analysis with Pavement Surface Texture.

		Site 1	Site 2	Site 3	All*
Percent Retained 4.75 mm Sieve	R	0.377	0.913	0.816	0.640
	Alpha	0.069	0.0001	0.0135	0.0001
	n	24	30	8	36
Asphalt Content	R	-0.362	-0.933	-0.781	-0.424
	Alpha	0.0815	0.0001	0.0130	0.0089
	n	24	30	9	37
Nuclear Gauge Unit Weight	R	-0.304	-0.664	N/A	0.032
	Alpha	0.4647	0.0364	N/A	0.9303
	n	8	10	N/A	10
Core Unit Weight	R	-0.500	-0.809	-0.749	-0.426
	Alpha	0.0128	0.0001	0.0013	0.0055
	n	24	30	15	41
Voids Total Mix	R	0.609	0.846	0.793	0.580
	Alpha	0.0016	0.0001	0.0004	0.0003
	n	24	30	15	41

* Normalized data, segregated cores only.
N/A = Data not available.

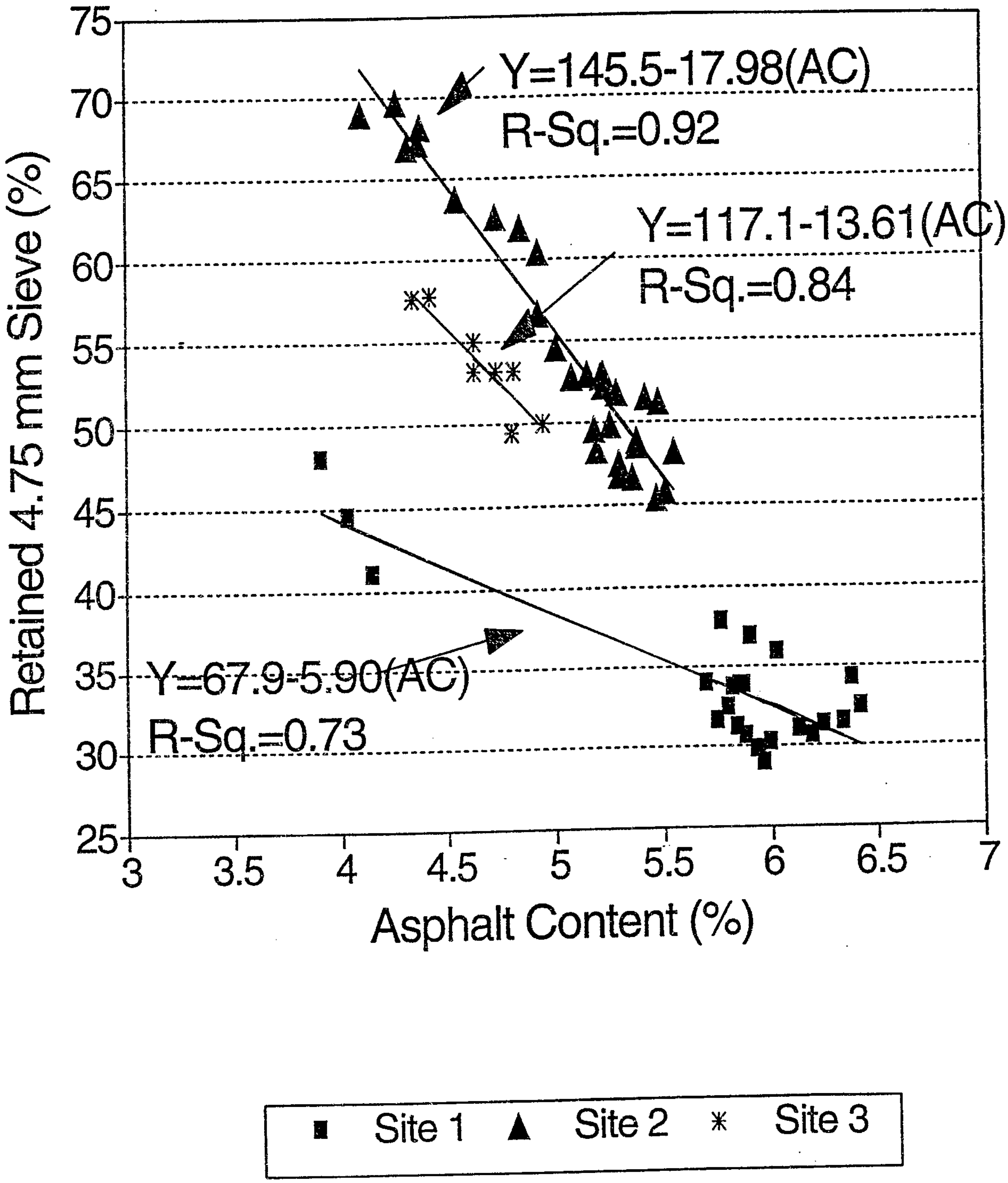

Figure 15. Asphalt Content vs Retained 4.75-mm Sieve.

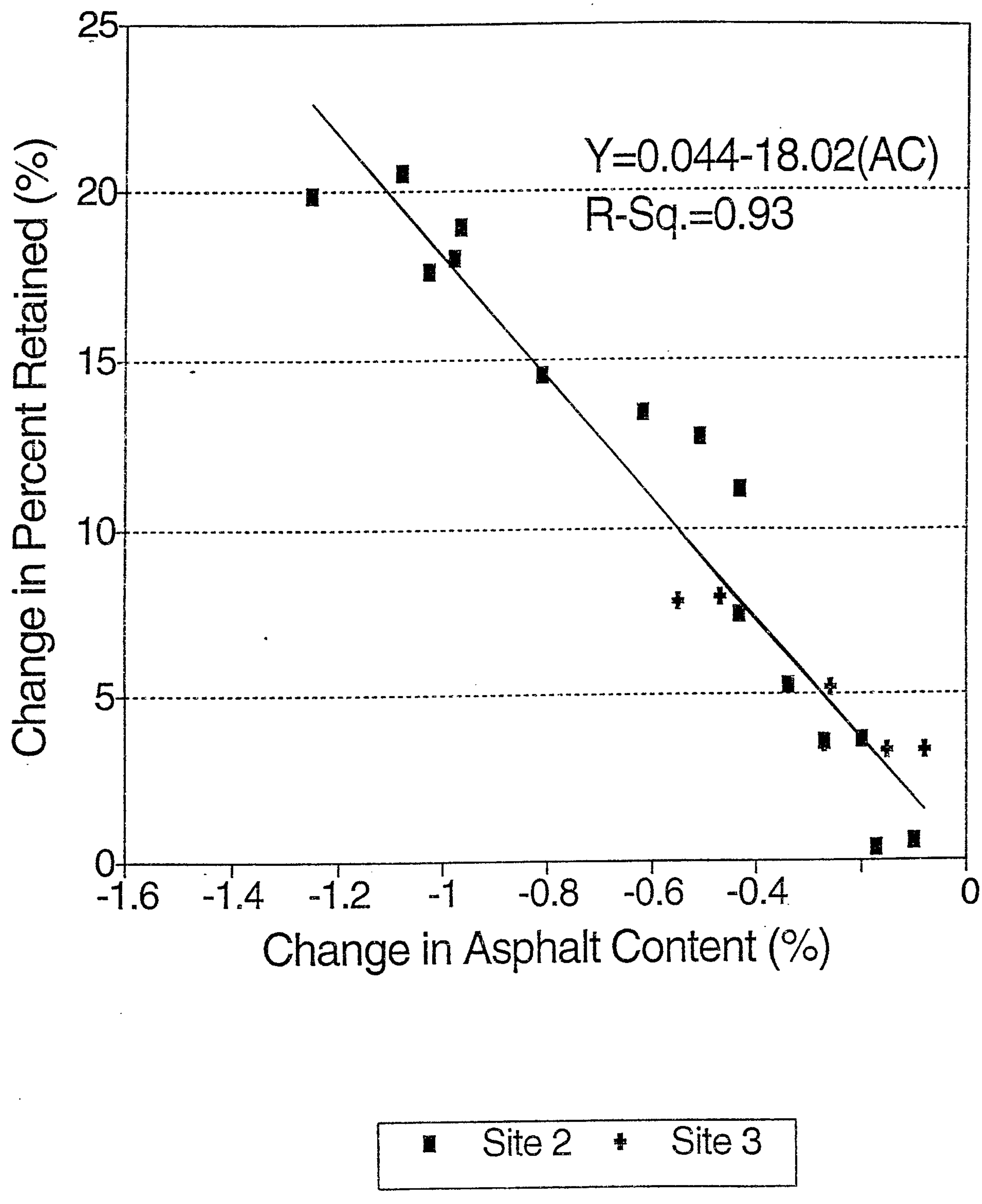

Figure 16. Change in Asphalt Content vs. Change in 4.75 mm Sieve.

The relationships between asphalt content and pavement surface texture (macro texture) are shown in Figures 17 and 18. The relationships for site 1-3 have R^2's of 0.13, 0.87 and 0.61, respectively. The more segregated the site, based on the 4.75 mm sieve, the higher the R^2. The normalized data for sites 2 and 3 are shown in Figure 18. The results indicate that the relationship is not mix specific, with an R^2 of 0.80. A change in asphalt content of 0.2 % from the average would indicate a change in macro texture of 0.05 mm.

Nuclear Gauge Unit Weight

The unit weights of the pavement at the core locations were determined using a nuclear gauge. One test was performed at each location and the unit weight compared to the average gradation from the cores at that location. The relationships were not significant, indicating that using the nuclear gauge at only one location could not identify either segregation or a non-uniform surface texture. The nuclear gauge does a poor job of detecting segregation when testing at one location. This agrees with the work performed by the Missouri Highway and Transportation Department (13) where they could not fully identify segregated areas of the pavement using a continuous density profile. Cross and Brown (4) also found that nuclear gauge unit weight was not one of the better indicators of segregation. Tables 6 through 9 indicate that segregated areas have lower unit weights than non-segregated areas. However, there are many other factors besides segregation that could contribute to low unit weight.

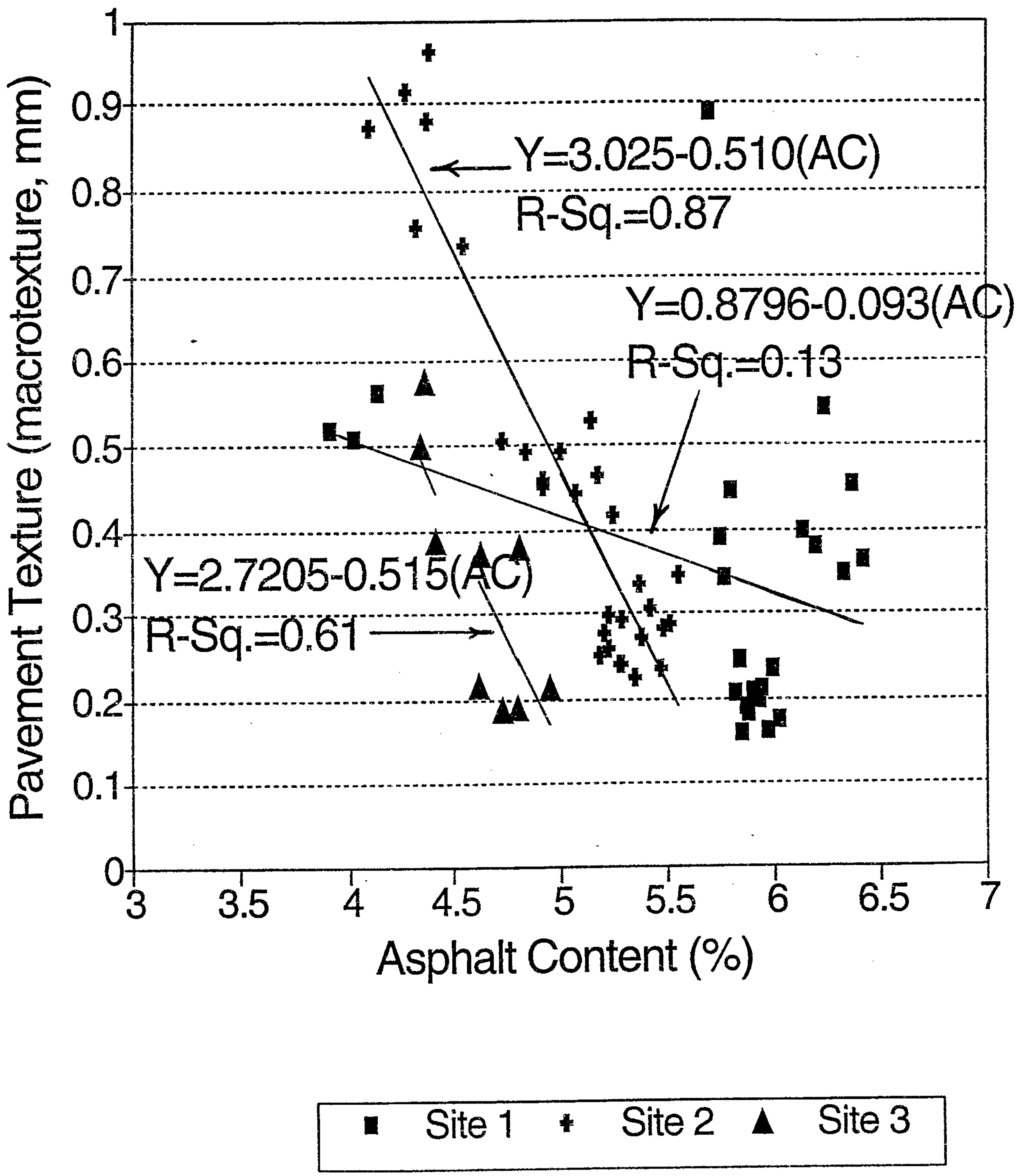

Figure 17. Asphalt Content vs Pavement Surface Texture.

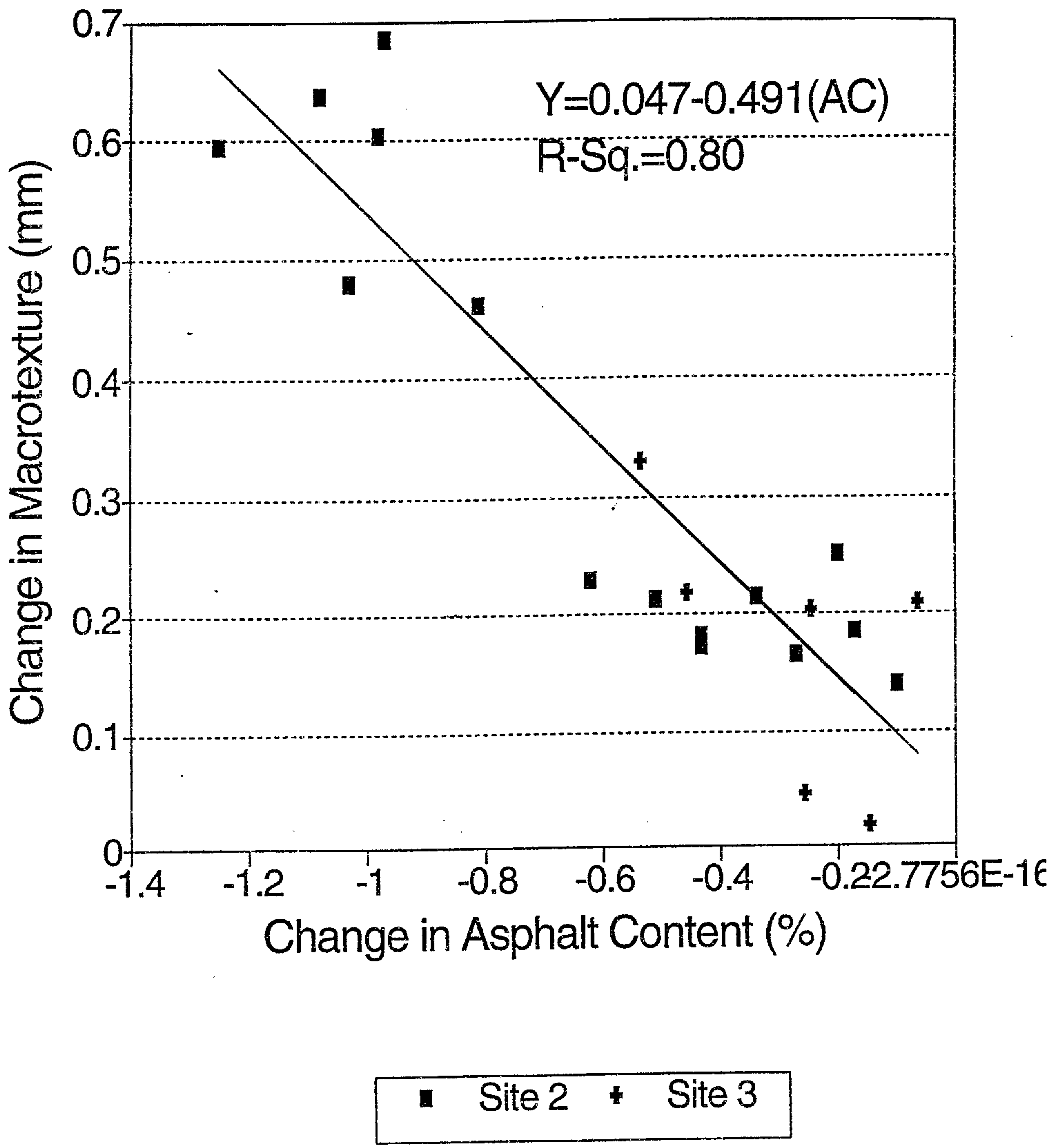

Figure 18. Change in Asphalt Content vs. Change in Surface Texture.

Core Unit Weight

Cores were obtained from the segregated and non-segregated areas. The analysis of the data was performed on the VTM as an indication of percent compaction as the magnitude of the unit weight is a function of the specific gravity of the aggregates. Figure 19 shows the relationship between VTM and percent retained on the 4.75 mm sieve. The relationships have R^2's of 0.60 for site 2 and 0.64 for site 3. The relationship was not significant for site 1. Site 1 had only one location that was segregated. The normalized relationship is shown in Figure 20. The relationship has an R^2 of 0.52 indicating that the relationship is somewhat mix specific. The relationships indicate that a change in VTM or unit weight indicates a change in gradation. However, there are many other factors besides segregation that could contribute to high VTM or low unit weight.

The relationship between VTM and pavement surface texture is shown in Figures 21 and 22. The relationships have R^2's of 0.37, 0.72 and 0.59 for sites 1-3, respectively. The more segregated the site the better the relationship. The normalized relationship is shown in Figure 22 for sites 2 and 3. The relationship has an R^2 of 0.34 indicating that the relationship is mix specific.

Macro Texture

The macro texture test could be used as an indicator test for segregation. The test was performed on each core in general accordance with ASTM E965. The results are shown in Tables 6-9. Figure 23 shows the relationship between macro texture and percent retained on the 4.75 mm sieve for sites 1 through 3. The relationships have R^2's of 0.14, 0.83 and

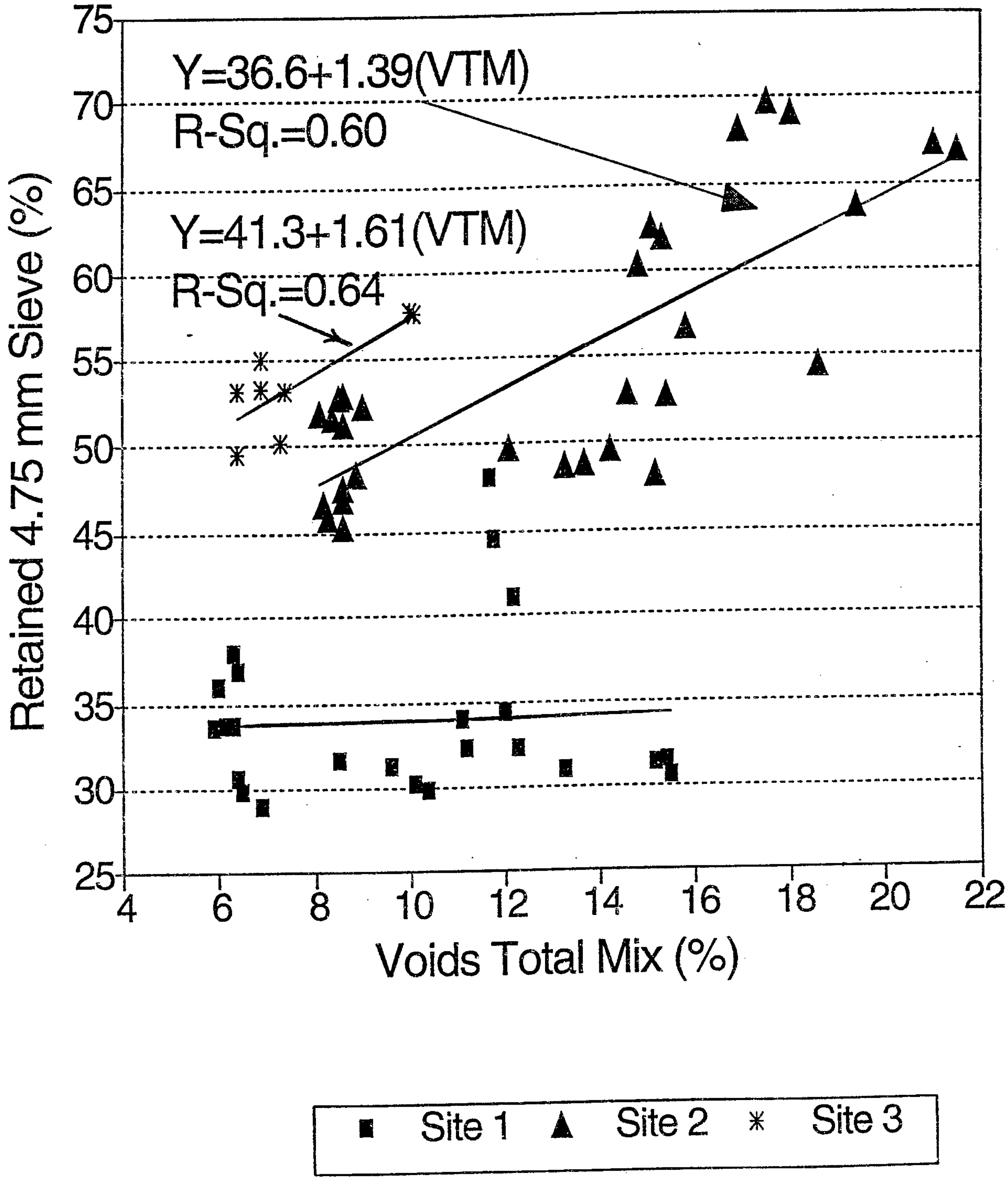

Figure 19. VTM vs Retained 4.75-mm Sieve.

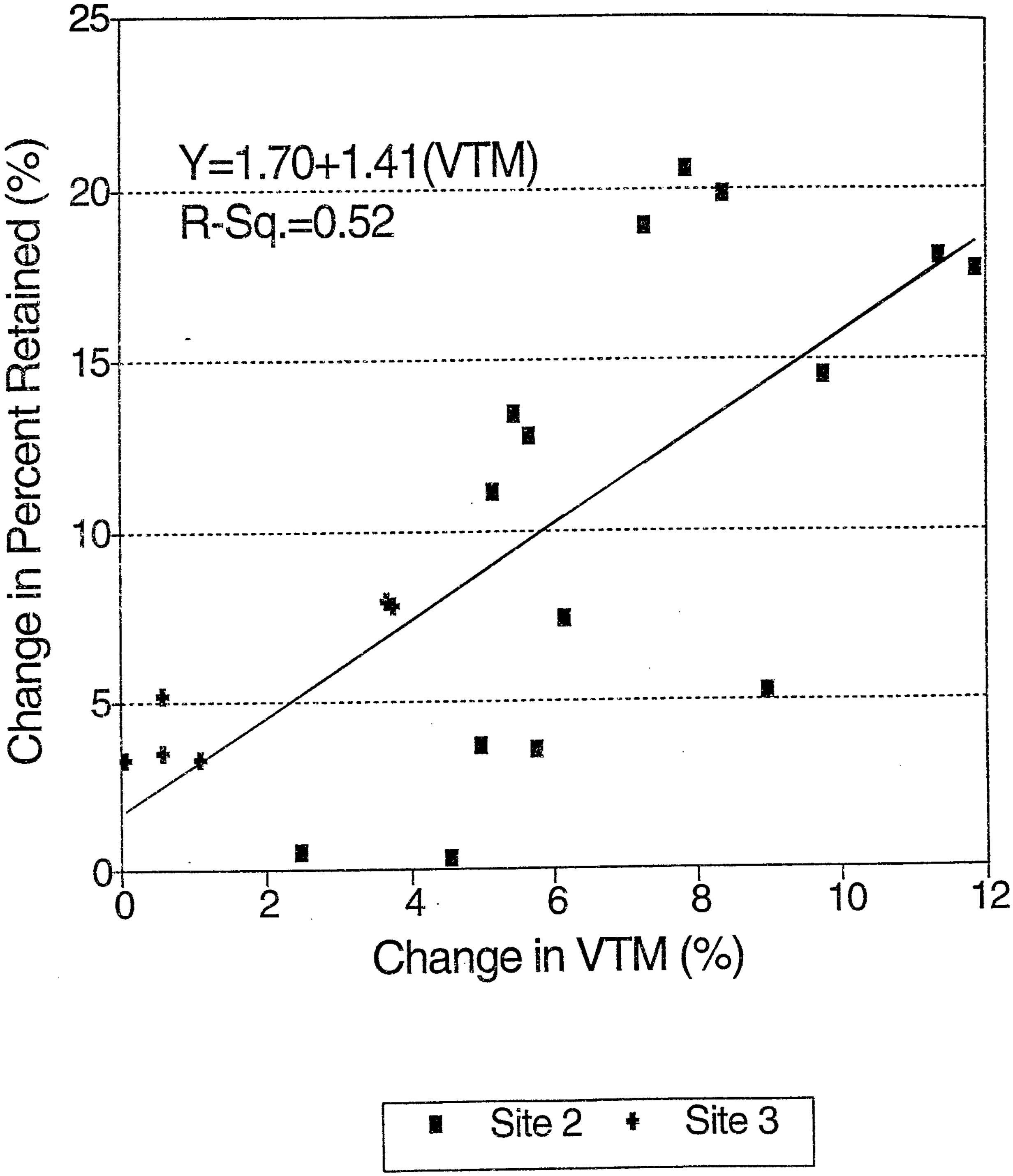

Figure 20. Change in VTM vs. Change in Percent Retained.

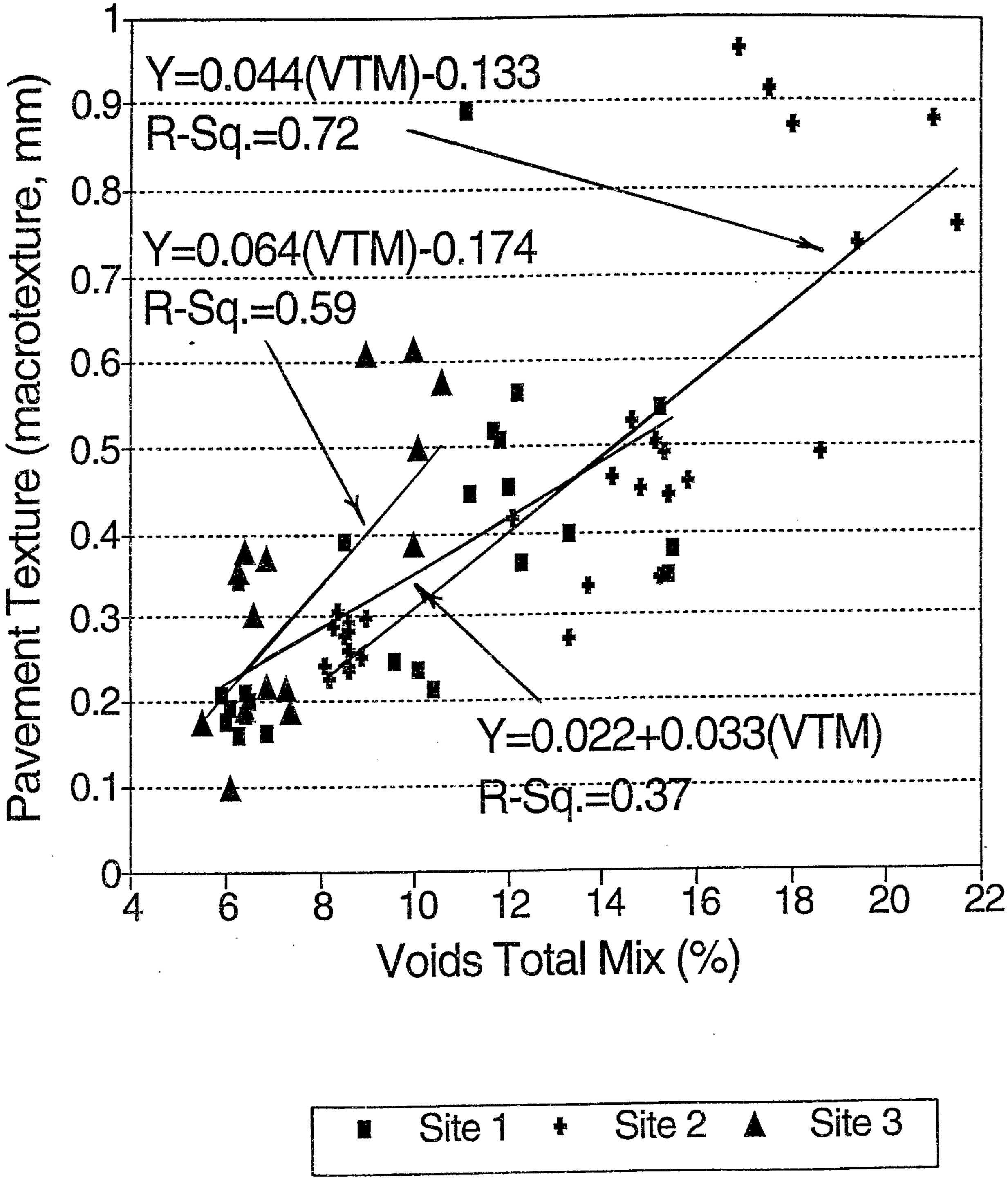

Figure 21. VTM vs Pavement Surface Texture.

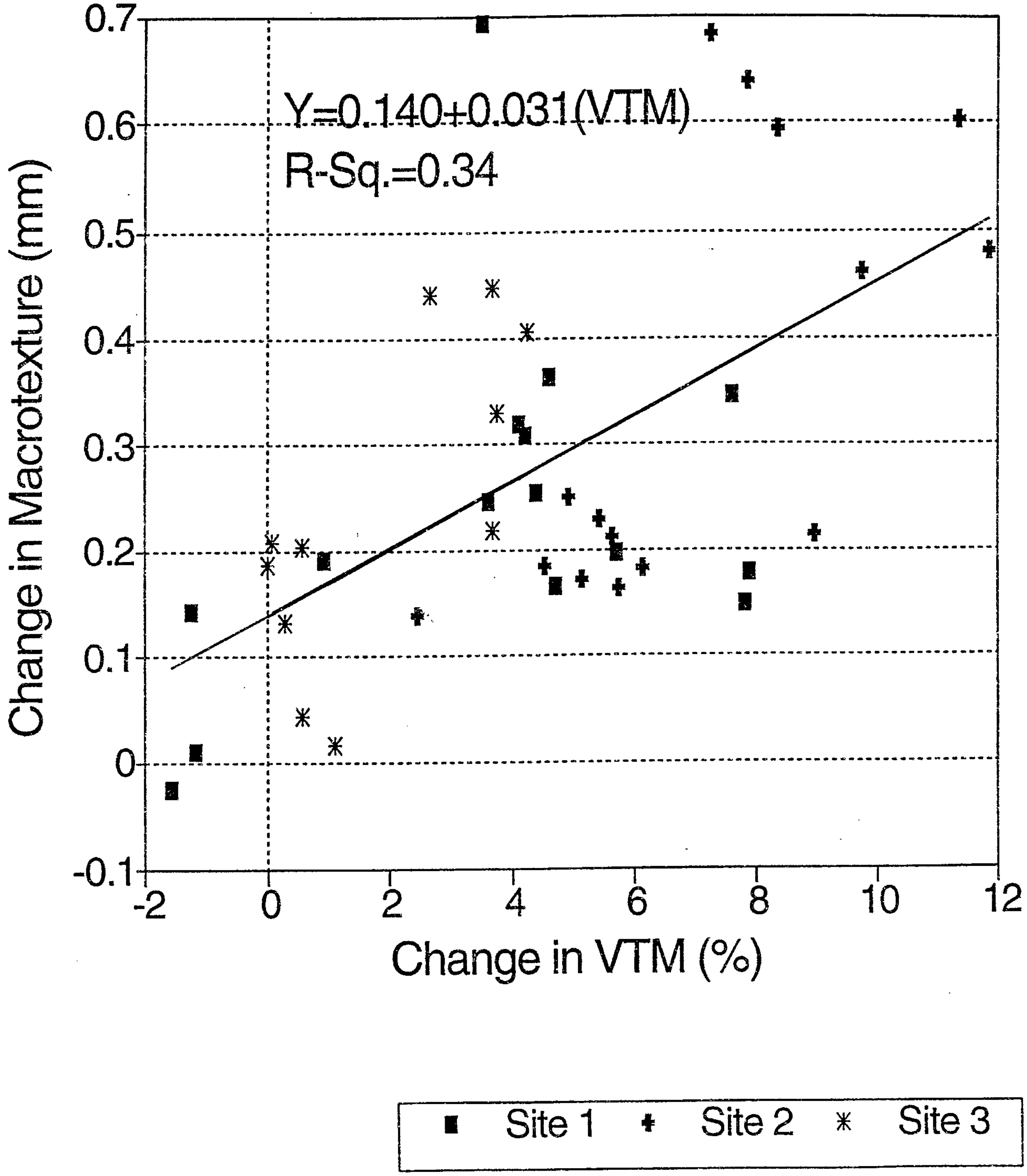

Figure 22. Change in VTM vs. Change in Surface Texture.

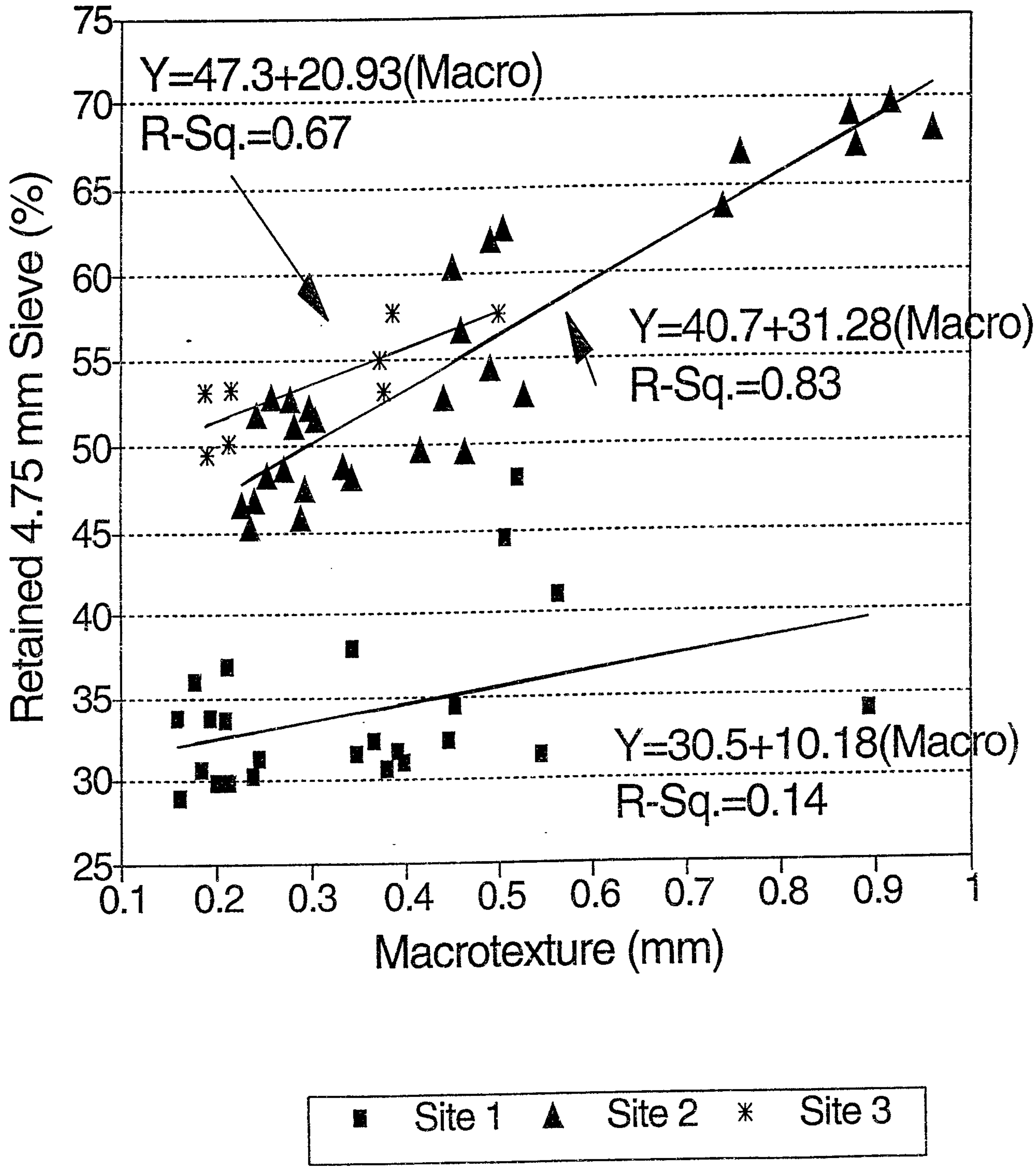

Figure 23. Macrotexture vs Retained 4.75-mm Sieve.

0.67 for sites 1through 3, respectively. Again, the more segregated the site the better the fit. The results of the normalized data for sites 2 and 3 are shown in Figure 24. The relationship has an R^2 of 0.75 and indicates that as the macro texture increases the amount of segregation increases. A change in macro texture of 0.15 mm indicates a change in gradation of 5 % on the 4.75 mm sieve. The pavement macro texture was the best nondestructive indicator test for segregation. The relationship between pavement macro texture and segregation agrees with the findings by Cross and Brown (4) who also reported that macro texture was the best indicator of segregation.

EFFECT OF SEGREGATION ON PERFORMANCE

The cores obtained from the field were tested in the laboratory to determine the effects of segregation on performance. Performance tests were performed on all sites. Based on the gradation analysis, Site 2 was the only site that had more than 6 % segregation, and would be out of specification tolerances on the 4.75 mm sieve. Therefore, the discussion of the analysis of test cores on performance is limited to Site 2 only.

Indirect Tensile Strength

The results of the indirect tensile strength test for Site 2 are shown in Table 11. Figure 25 is a plot of indirect tensile strength versus segregation. The relationship has an R^2 of 0.66 and indicates that as the amount of segregation increases the tensile strength decreases. The average tensile strength of the non segregated cores was 503 kPa. A change in gradation of 6% on the 4.75 mm sieve corresponds to a change of 63 kPa or a 12.5% drop in tensile.

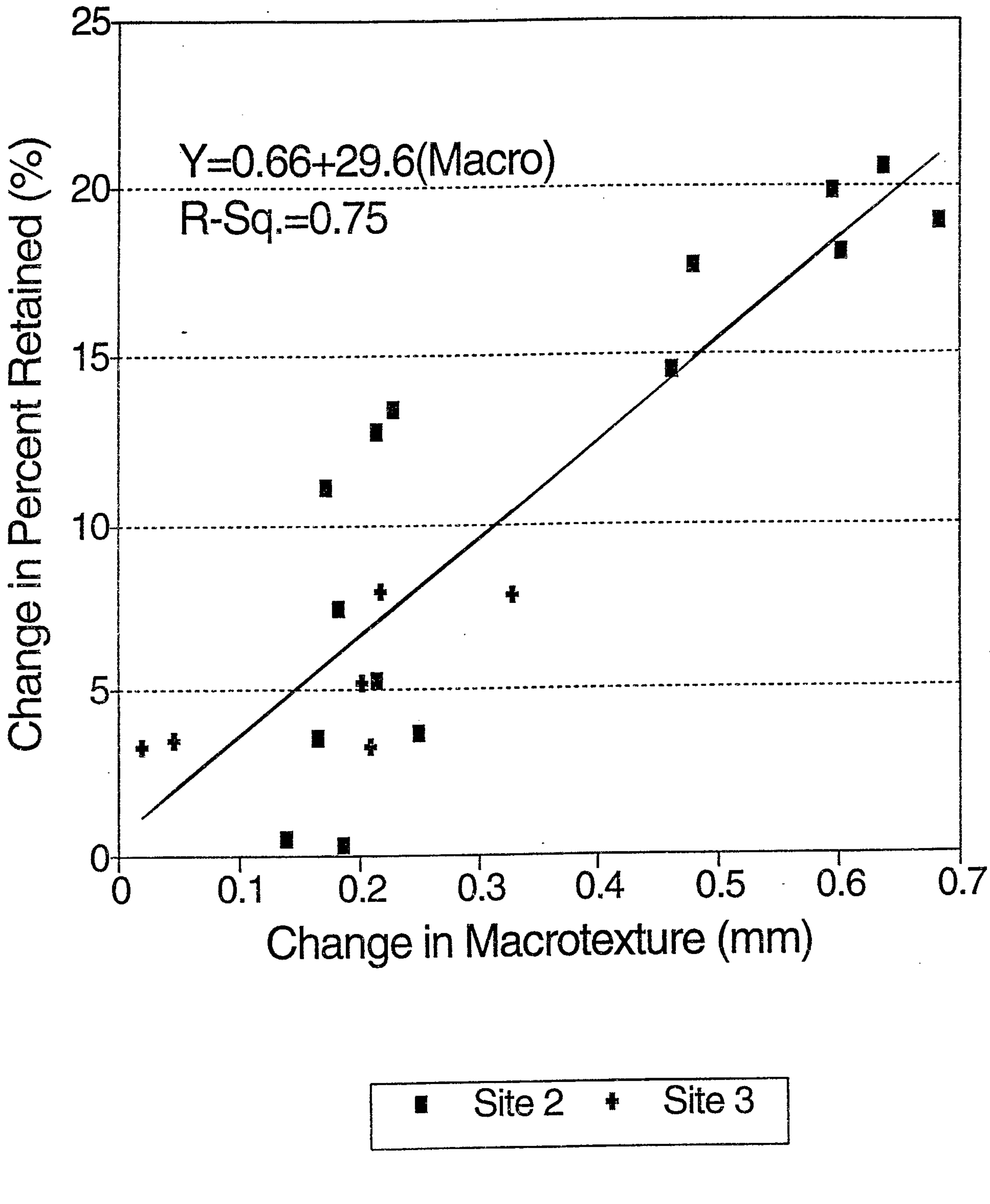

Figure 24. Change in Macrotexture vs. Change in Percent Retained.

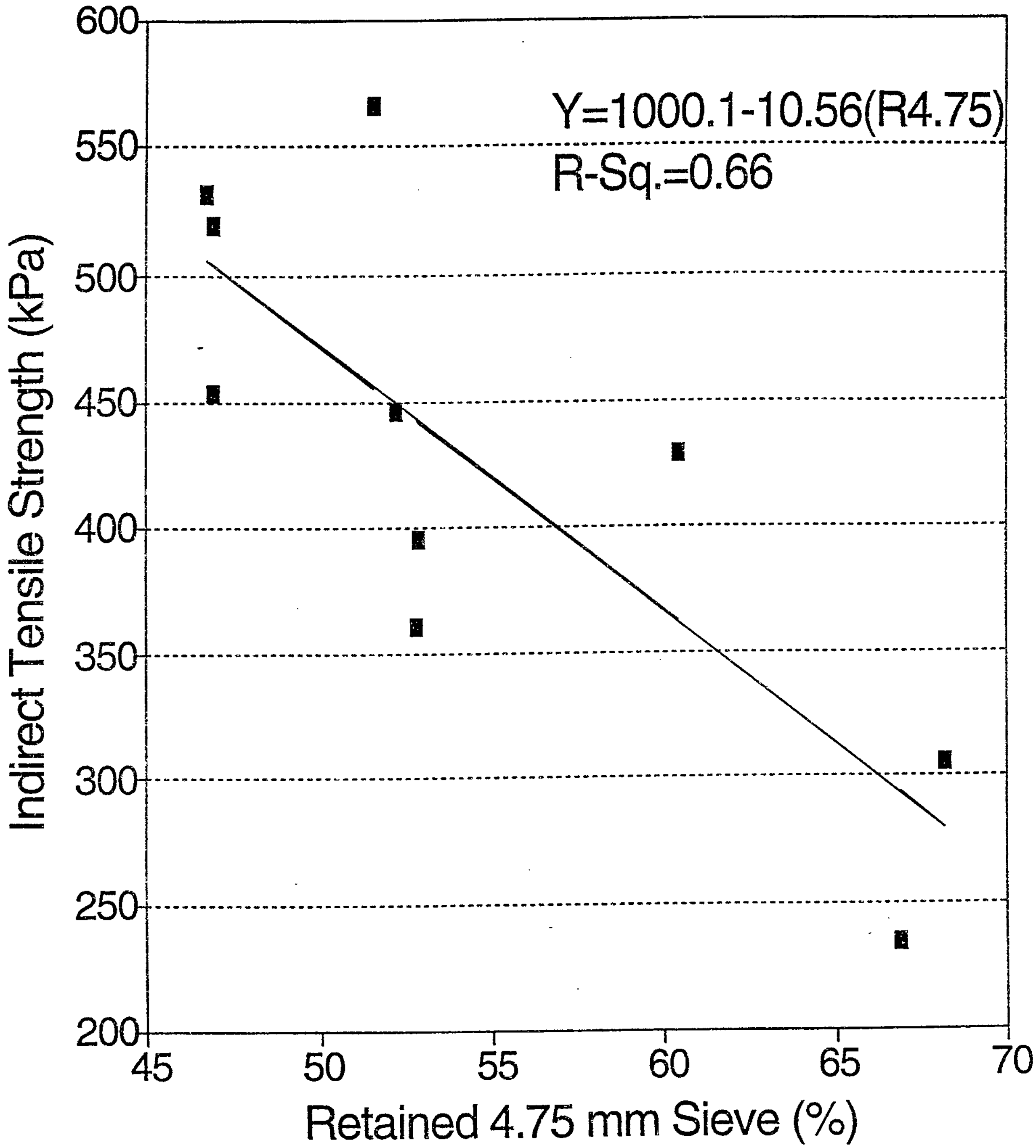

Figure 25. Indirect Tensile Strength vs. Segregation, Site 2.

strength. Figure 26 shows the relationship between the indirect tensile strength and VTM. The relationship has an R^2 of 0.89 which shows that the VTM or percent compaction has a stronger effect on indirect tensile strength than a change in gradation.

Moisture Sensitivity

The cores were tested for moisture sensitivity using AASHTO T 283 with the optional freeze cycle. Figure 27 is a plot of TSR versus segregation from site 2. The air void contents of the cores varied from 8.1 % to 21.5 %. Cores with high air void contents attained 55 - 80 % saturation in a matter of seconds compared to 15 - 20 minutes for some of the non-segregated cores. AASHTO T 283 is intended for laboratory samples compacted to 7 ± 1 % air void contents and it did not work well using field cores.

The results of the conditioned indirect tensile strength test for Site 2 are shown in Table 11. The effect of segregation on conditioned indirect tensile strength is shown in Figure 28. The relationship has an R^2 of 0.83 and indicates that as the amount of segregation increases the conditioned tensile strength decreases. The average conditioned tensile strength of the non segregated cores was 409 kPa. A change in gradation of 6% on the 4.75 mm sieve corresponds to a change of 57 kPa or a 14% drop in conditioned tensile strength. This is approximately the same drop as seen in indirect tensile strength (control). Figure 29 is a plot of conditioned indirect tensile strength versus VTM. The relationship has an R^2 of 0.74 which shows that the conditioned indirect tensile strength is as much a function of VTM (percent compaction) as segregation.

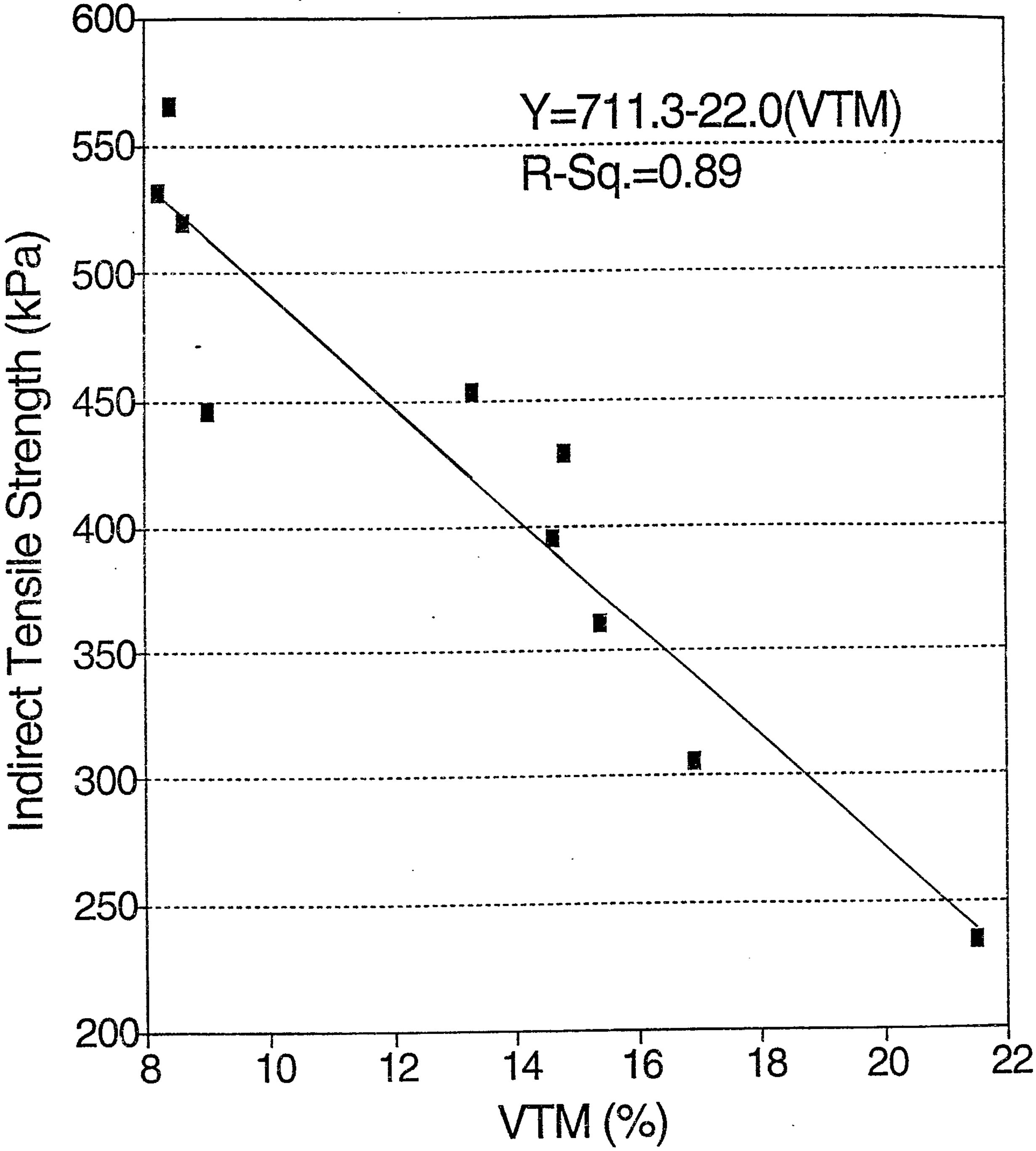

Figure 26. Indirect Tensile Strength vs. VTM, Site 2

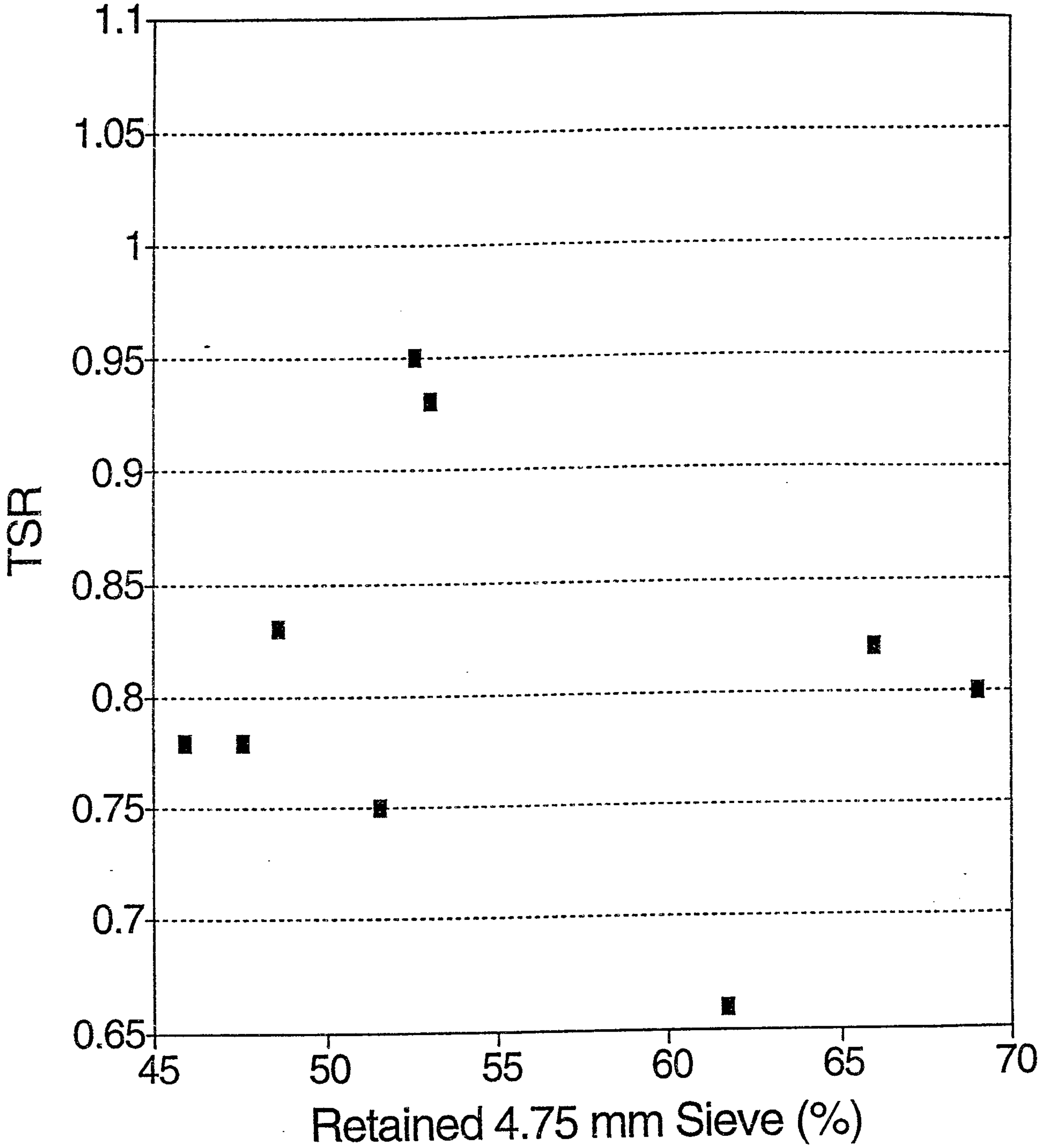

Figure 27. Tensile Strength Ratio vs. Segregation, Site 2.

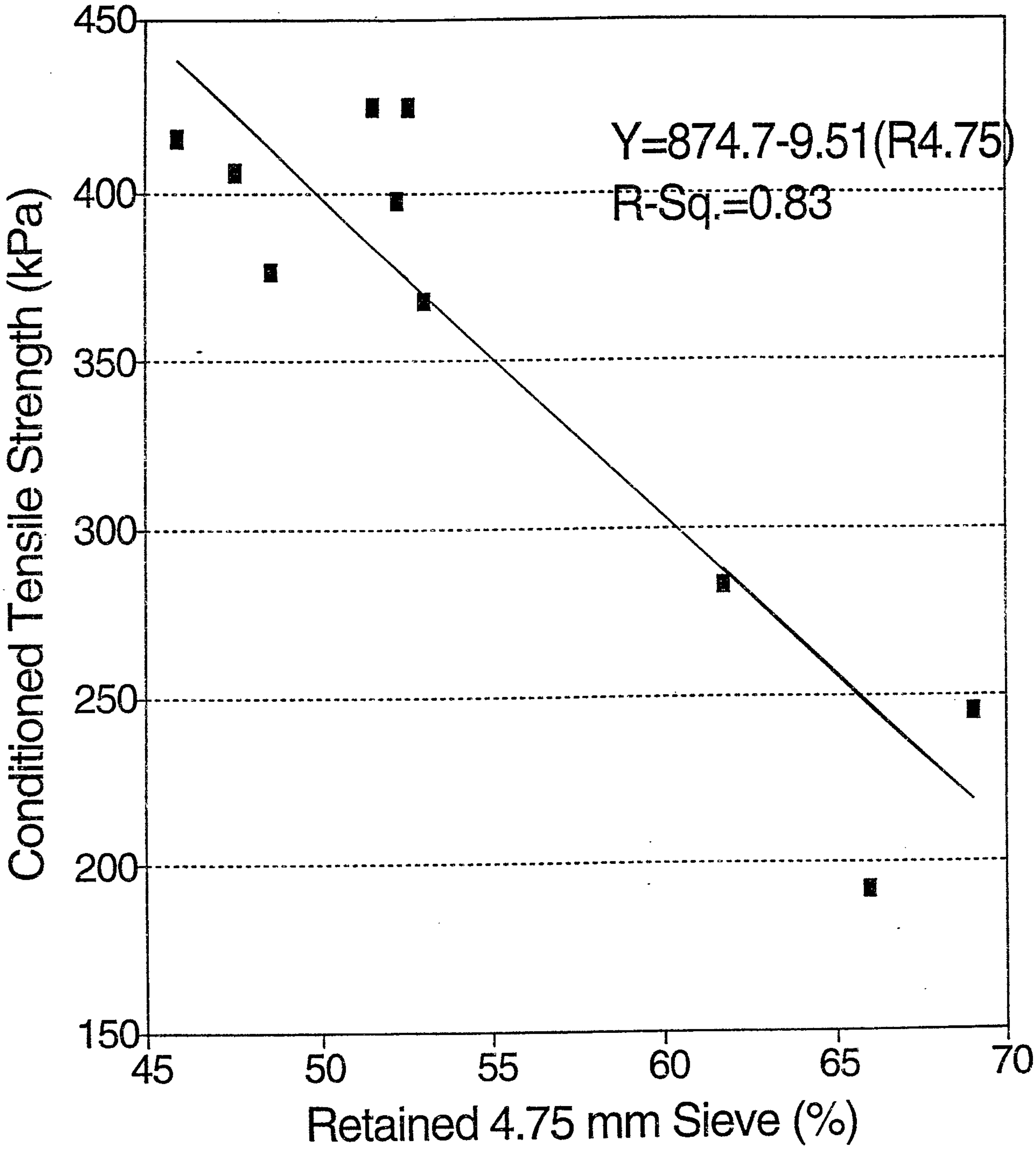

Figure 28. AASHTO T283 Conditioned Tensile Strength vs. Segregation, Site 2.

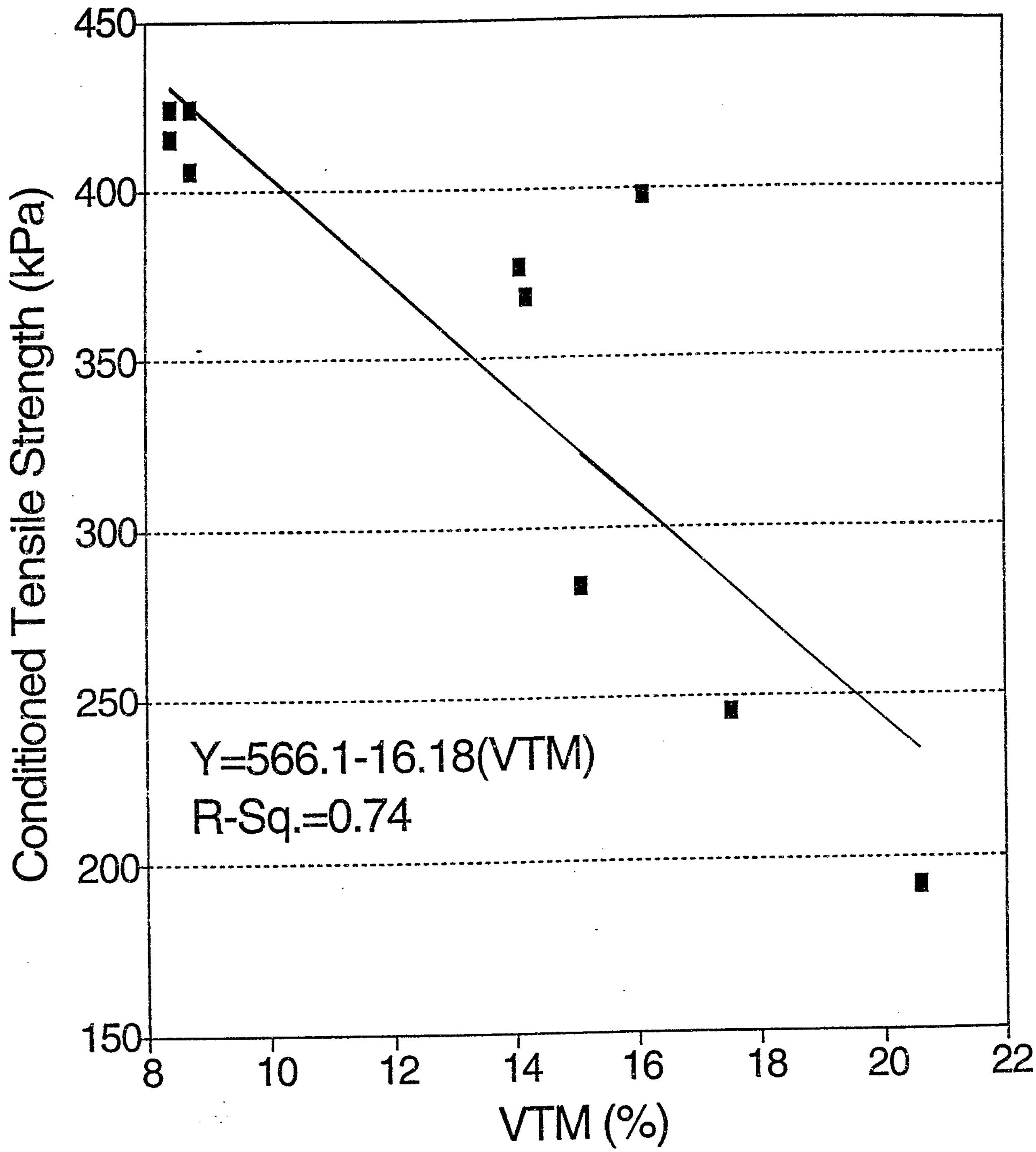

Figure 29. AASHTO T283 Conditioned Tensile Strength vs. VTM, Site 2.

Fatigue Life

The fatigue test was performed in constant stress at 7.5 % of the indirect tensile strength. The results of the fatigue life for Site 2 are shown in Table 12. Figure 30 is a plot of fatigue life versus segregation. The relationship has an R^2 of 0.50 and indicates that the fatigue life decreases as the amount of segregation increases. From the regression model, it can be predicted that a change in gradation of 5 %, 10 % and 20 % on the 4.75 mm sieve would correspond to a loss of 28 %, 50 % and 76 %, respectively, in fatigue life. The effect of VTM on the fatigue life is shown in Figure 31. The relationship has an R^2 of 0.92 which shows that the fatigue life is also more a function of VTM (percent compaction) than gradation.

Summary

The limited performance data obtained from site 2 indicate that segregation has a detrimental effect on performance as measured by indirect tensile strength and fatigue life. However, the data also indicated that the air void content has as strong an effect on performance as segregation. The data indicates that a drop in unit weight (increase in VTM) has a detrimental effect on performance. It did not matter whether the change in unit weight was a result of a change in gradation (segregation) or some other factor.

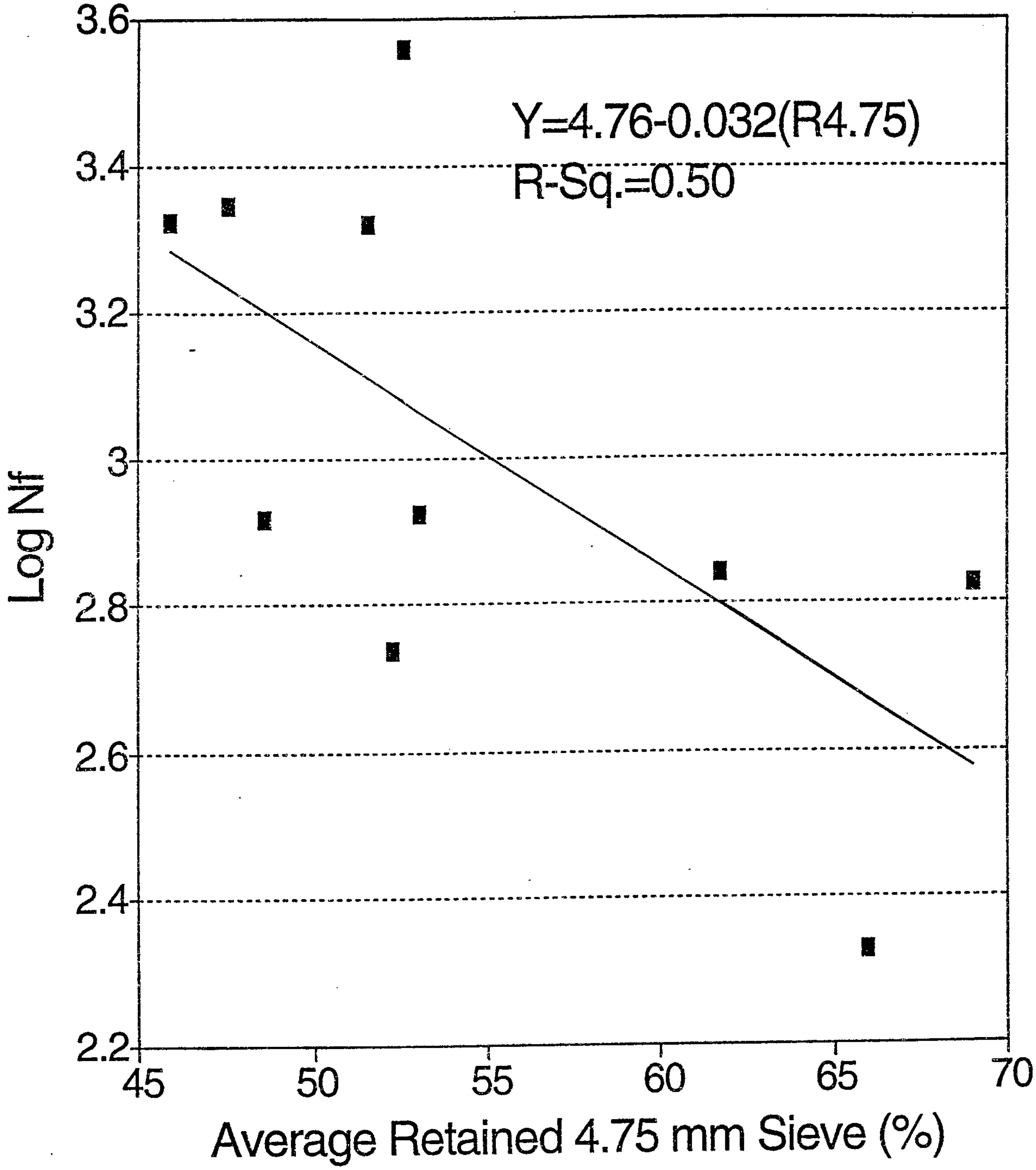

Figure 30. Fatigue Life vs. Segregation, Site 2.

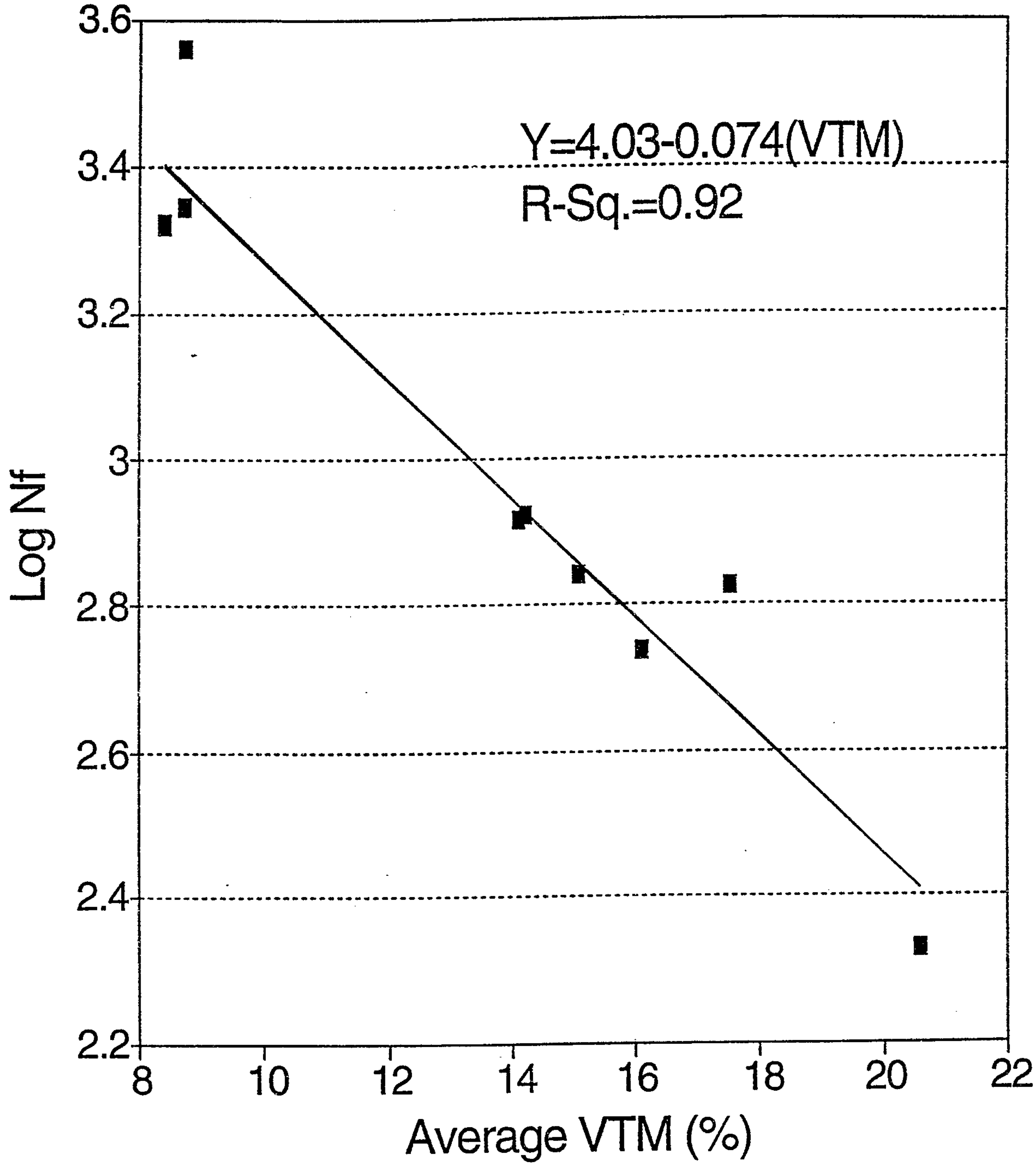

Figure 31. Fatigue Life vs. VTM, Site 2.

CHAPTER 5

EFFECT OF SEGREGATION ON PERFORMANCE

(Task 4)

To determine the effects of segregation on pavement performance, laboratory compacted samples were prepared to simulate the field cores previously obtained. Two mixes were evaluated, a BM-2 mix simulating the gradations from site 1 and a BM-1B mix simulating the gradations from site 2.

LABORATORY SIMULATION OF FIELD SAMPLES

The original mix design used at each site was identified and obtained from KDOT. Information on aggregate sources, percentage of each component, component and combined aggregate gradations, optimum asphalt content, asphalt cement source and grade were obtained as well. Based on the source of material, asphalt content, gradation, and air voids in the field cores, 102 mm diameter laboratory samples were prepared. The parent materials used in the production of the field cores were the same materials used in simulating the laboratory samples. Table 16 shows the source of aggregates used in the production of both mixes and the individual aggregate single point and the blended job mix gradations. Table 17 is the Marshall job mix formula for both mixes.

Table 16. Aggregate Source, Blend and Single Point Gradation.

Aggregate Type	Percent in Blend	Producer	County	Sieve Size (mm) Percent Retained 19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
							BM-1B Mix						
CS-1	23	Quartzite Stone Co.	Lincoln	0	32	67	96	97	98	98	98	98	98
CS-1B	27	Quartzite Stone Co.	Lincoln	0	0	10	96	97	98	98	98	98	98
CS-2	25	Quartzite Stone Co.	Lincoln	0	0	0	5	30	43	51	63	80	87
SSG-3	25	Olson Sand	Franklin	0	1	4	24	59	87	94	97	99	99
JMF	100			0	8	19	55	71	82	85	89	94	96
							BM-2 Mix						
CS-1	28	Martin Mariett	Elk	0	25	60	90	97	98	98	98	98	98
CS-2A	15	Martin Mariett	Elk	0	0	8	40	61	72	78	83	86	89
CS-2	7	Martin Mariett	Elk	0	0	0	0	2	21	40	55	63	70
SSG-1	50	Whitefield Sand Co.	Pratt	0	3	8	18	25	43	63	89	99	99
JMF	100			0	9	22	40	49	61	73	88	94	95

Levels of Segregation

Four severity levels of segregation were defined based on the gradations of the field cores. The four levels of segregation were 0%, 5%, 10%, and 20% segregation. The amount of segregation was quantified by subtracting the percent retained on the 4.75 mm sieve of each segregated core from the average percent retained on the 4.75 mm sieve of the non-segregated cores. The average gradation, from the uniform textured cores, was designated 0% segregation and the mixes increase in levels of segregation from 5% segregation to 20% segregation. Table 18 shows the gradation for the four levels of segregation defined for both BM-1B and BM-2 mixes as well as the JMF.

Gradation

Figures 32 and 33 show the gradation of the JMF and the levels of segregation for both BM-1B and BM-2 mixes, respectively, on a 0.45 power chart. These figures also show the maximum density curve. The 0% and 5% segregated gradations have a 12.5 mm nominal size and their maximum density curve is different from 10% and 20% segregated gradations, which have a 19 mm nominal size.

From Figure 32, all BM-1B mix gradations deviate to the coarse side of their respective maximum density line. The gradation of both the 0% and 5% segregated BM-1B mix samples satisfy the KDOT gradation band. The gradations of the 10% and 20% segregated BM-1B mixes fall outside the KDOT specification band and are on the coarse side of the JMF. The 0% segregated mix falls on the fine side of the JMF gradation and the 5% segregated mix, which is closer to the JMF, falls on the coarse side.

Table 17. Marshall Mix Design Values.

Asphalt Grade	Asphalt Content (%)	VTM (%)	VMA (%)	VFA (%)	Unit Weight (kN/m^3)	Marshall Stability (N)
BM-1B Mix						
AC-10	5.1	3.9	14.5	73.1	23.17	9021
BM-2 Mix						
AC-20	5.0	4.4	14.9	70.4	22.84	4951

Table 18. Levels of Segregation and JMF.

Sieve Size (mm)	JMF	Levels of Segregation 0 (Percent Retained)	5	10	20
BM-1B Mix					
19	0	0	0	0	0
12.5	8	7	10	13	19
9.5	19	17	22	27	37
4.75	54	49	54	58	66
2.36	70	68	72	74	76
1.18	81	77.5	80.5	81.5	81.5
0.600	85	80.5	83.5	83.5	83.5
0.300	89	84.5	86.5	86.5	86.5
0.150	94	91	92	92	92
0.075	96	94	95	95	95
BM-2 Mix					
19	0	0	0	0	0
12.5	8	7	10	12	16
9.5	22	15	19	23	31
4.75	40	32	36	42	52
2.36	49	44	48	52	61
1.18	61	55	58	61	68
0.600	73	68	70	73	79
0.300	88	84	84	85	87
0.150	94	91	91	92	93
0.075	95	93	93	94	95

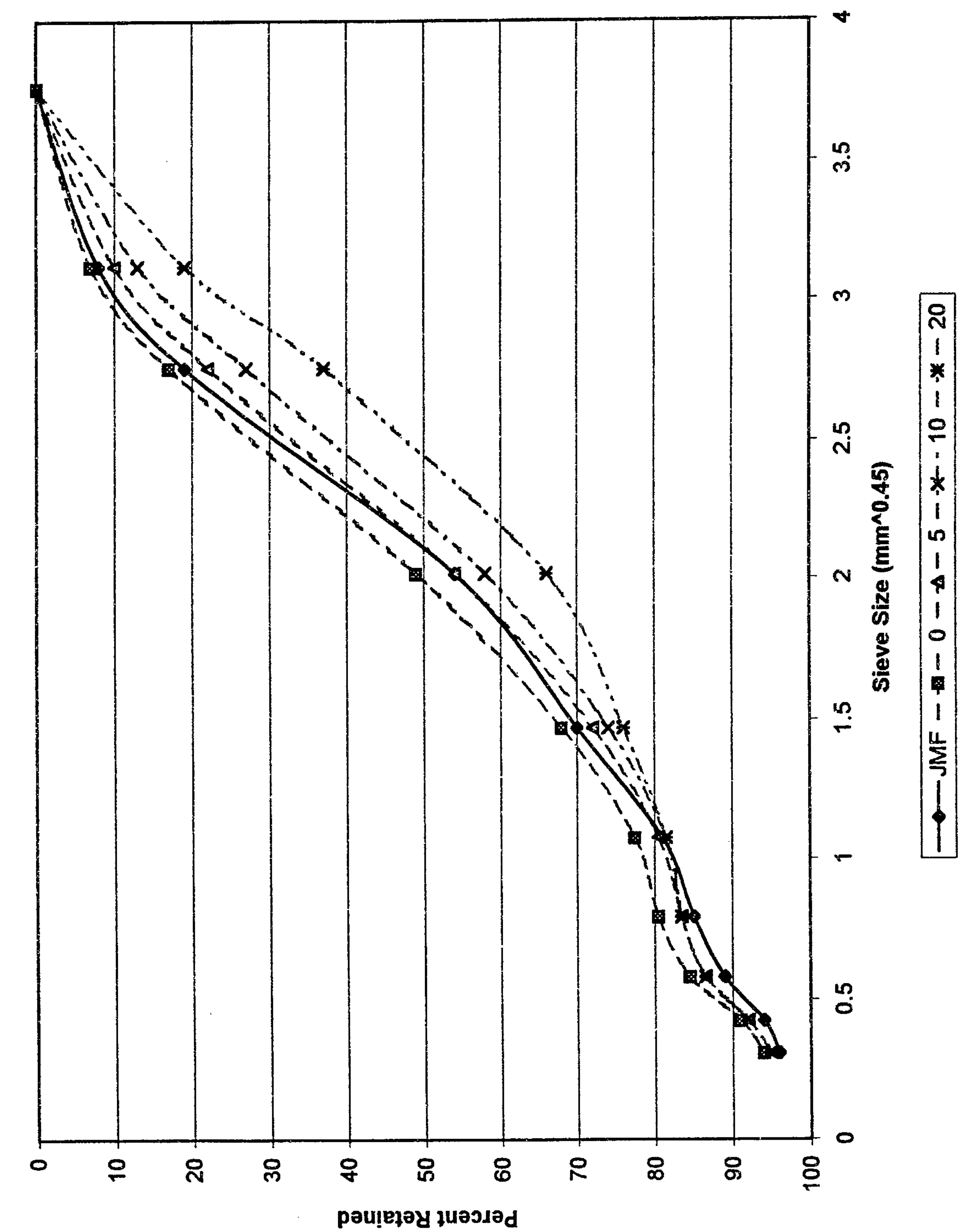

Figure 32. Gradations of BM-1B Mix.

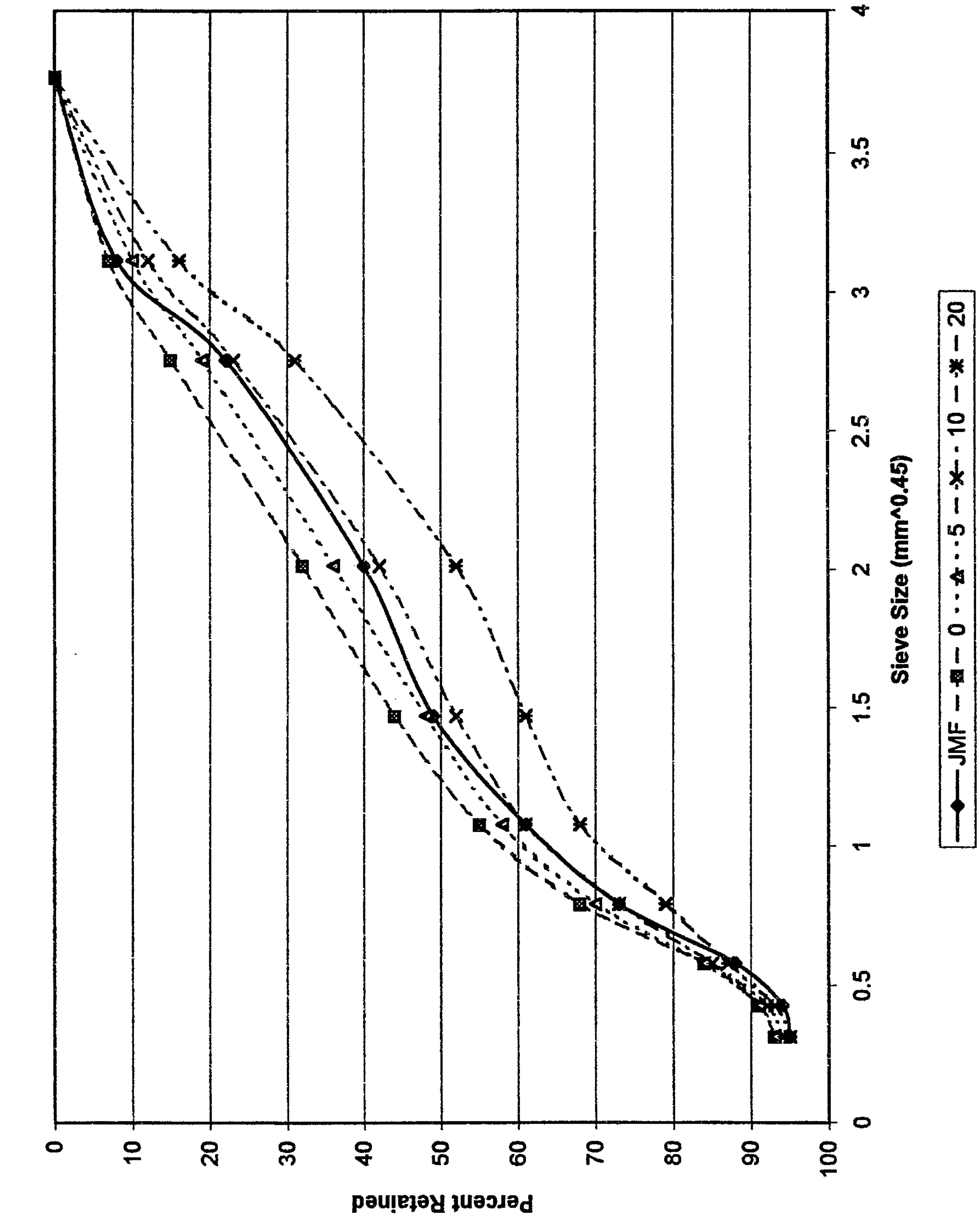

Figure 33. Gradations of BM-2 Mix.

From Figure 33, the gradations of the BM-2 mixes show a different trend. All BM-2 mix gradations deviate to the fine side of the maximum density gradation and the deviations are less pronounced than the BM-1B mixes. BM-2 mix samples are, therefore, expected to pack closer and give less voids than the BM-1B mixes. The gradation of the 0% segregated samples did not meet the KDOT specification band on the 2.36 mm and 4.75 mm sieves.

Aggregate Batching

Since gradation controls the level of segregation, the individual aggregates in both mixes were obtained and shaken down to the 0.150 mm sieve to ensure controlled batching. Twelve samples were batched for each of the four levels of segregation and sent to KDOT for compaction on the GTM.

Table 19 shows the average in-situ VTM and percent asphalt content by weight of mix obtained from the field cores at all levels of segregation for both mixes. Also included in Table 19 are the targeted VTM and unit weight as well as the average VTM and unit weight obtained upon compaction. The in-situ VTM values were lowered on average by 4% for BM-1B mixes and 2% for BM-2 mixes at all levels of segregation to obtain the targeted values. This was to simulate densification by traffic since the cores were obtained from newly constructed pavements. The unit weights obtained upon compaction were higher than the targeted values for all mixes, even after reducing the in-situ VTM values.

Table 19. Average, In-Situ, Targeted and Obtained Properties.

Level of Segregation	In-Situ VTM (%)	Asphalt Content (%)	Targeted Unit Weight (kN/m^3)	Targeted VTM (%)	Average Unit Weight Obtained (kN/m^3)	Average VTM Obtained (%)
			BM-1B Mix			
0	8.0	5.0	23.20	4.0	23.28	4.3
5	11.4	4.8	22.42	7.5	23.50	3.6
10	14.3	4.6	21.87	10.0	22.58	7.6
20	20.0	4.2	20.52	16.0	21.44	12.8
			BM-2 Mix			
0	6.0	5.3	22.83	4.0	23.28	2.2
5	8.0	4.8	22.50	6.0	23.16	3.4
10	9.8	3.9	22.29	8.0	22.72	5.7
20	13.5	3.4	21.59	11.5	22.10	9.6

ANALYSIS OF DATA

Unit Weight

The bulk specific gravity (G_{mb}) of all samples was determined by the saturated surface dry method as outlined in ASTM D2726. The bulk specific gravity of all 10% and 20% segregated samples were redetermined using Parafilm in accordance with ASTM D1188. The results are shown in Tables 20 and 21 for the BM-1B and BM-2 mixes, respectively. Based on the effective specific gravity of the aggregate and asphalt content, the theoretical maximum density was computed and the percent air voids determined for each sample. Although all the samples prepared in the laboratory had less than 2% water absorption, the VTM values of the 10% and 20% segregated samples obtained from ASTM D2726 were high enough to consider ASTM D1188. At high VTM's, the air voids in the samples are interconnected and water can easily enter and drain out of the sample resulting in a lower measured volume and higher computed bulk specific gravity. The purpose of the Parafilm is to correct this situation.

From Tables 20 and 21, G_{mb} values determined from ASTM D2726 are higher than those using Parafilm (ASTM D1188). A student t-test was performed on the SSD and Parafilm unit weights to determine if the difference is significant. A summary of the t-test is shown in Table 22 and indicates that the difference is significant at the 99% level of confidence. Therefore, for 10% and 20% segregated samples, G_{mb} values obtained from the Parafilm test (ASTM D1188) were used for further analysis.

Table 20. Unit Weight and Void Properties, BM-1B Mix.

Mix Type	Specimen	Percent Seg.	Aging	% AC	Bulk Specific Gravity SSD	Bulk Specific Gravity Parafilm	VTM %	VMA %	VFA %
BM-1B	0-N-1	0	NA	4.76	2.390	*	3.57	13.75	74.04
BM-1B	0-N-2	0	NA	4.76	2.388	*	3.65	13.82	73.60
BM-1B	0-N-3	0	NA	4.76	2.371	*	4.35	14.45	69.89
BM-1B	0-N-4	0	NA	4.76	2.370	*	4.37	14.47	69.78
BM-1B	0-A-1	0	LTOA	4.76	2.371	*	4.36	14.46	69.87
BM-1B	0-A-2	0	LTOA	4.76	2.375	*	4.19	14.30	70.74
BM-1B	0-A-3	0	LTOA	4.76	2.372	*	4.33	14.43	70.02
BM-1B	0-A-4	0	LTOA	4.76	2.351	*	5.17	15.19	65.94
BM-1B	0-A-5	0	LTOA	4.76	2.369	*	4.45	14.54	69.38
BM-1B	0-A-6	0	LTOA	4.76	2.379	*	4.03	14.16	71.57
BM-1B	0-A-7	0	STOA	4.76	2.369	*	4.44	14.53	69.46
BM-1B	0-A-8	0	STOA	4.76	2.374	*	4.22	14.34	70.54
BM-1B	5-N-1	5	NA	4.58	2.394	*	3.71	13.46	72.46
BM-1B	5-N-2	5	NA	4.58	2.382	*	4.18	13.89	69.87
BM-1B	5-N-3	5	NA	4.58	2.405	*	3.26	13.06	75.03
BM-1B	5-N-4	5	NA	4.58	2.395	*	3.65	13.41	72.75
BM-1B	5-A-1	5	LTOA	4.58	2.407	*	3.15	12.96	75.67
BM-1B	5-A-2	5	LTOA	4.58	2.384	*	4.11	13.82	70.28
BM-1B	5-A-3	5	LTOA	4.58	2.406	*	3.22	13.02	75.26
BM-1B	5-A-4	5	LTOA	4.58	2.398	*	3.54	13.30	73.42
BM-1B	5-A-5	5	LTOA	4.58	2.391	*	3.81	13.55	71.91
BM-1B	5-A-6	5	LTOA	4.58	2.396	*	3.61	13.37	72.99
BM-1B	5-A-7	5	STOA	4.58	2.398	*	3.54	13.31	73.38
BM-1B	5-A-8	5	STOA	4.58	2.401	*	3.42	13.20	74.07
BM-1B	10-N-1	10	NA	4.40	2.340	2.305	7.50	16.47	54.43
BM-1B	10-N-2	10	NA	4.40	2.354	2.323	6.78	15.81	57.11
BM-1B	10-N-3	10	NA	4.40	2.335	2.304	7.57	16.53	54.19
BM-1B	10-N-4	10	NA	4.40	2.336	2.297	7.84	16.77	53.26
BM-1B	10-A-1	10	LTOA	4.40	2.338	2.299	7.76	16.70	53.52
BM-1B	10-A-2	10	LTOA	4.40	2.335	2.302	7.63	16.58	53.97
BM-1B	10-A-3	10	LTOA	4.40	2.340	2.304	7.56	16.52	54.23
BM-1B	10-A-4	10	LTOA	4.40	2.342	2.298	7.81	16.74	53.36
BM-1B	10-A-5	10	LTOA	4.40	2.337	2.298	7.80	16.73	53.39
BM-1B	10-A-6	10	LTOA	4.40	2.337	2.299	7.75	16.68	53.58
BM-1B	10-A-7	10	STOA	4.40	2.340	2.298	7.80	16.74	53.37
BM-1B	10-A-8	10	STOA	4.40	2.337	2.299	7.78	16.72	53.44
BM-1B	20-N-1	20	NA	4.03	2.304	2.154	14.04	21.61	35.02
BM-1B	20-N-2	20	NA	4.03	2.314	2.180	13.04	20.69	37.00
BM-1B	20-N-3	20	NA	4.03	2.310	2.181	12.98	20.64	37.12
BM-1B	20-N-4	20	NA	4.03	2.298	2.180	13.01	20.67	37.06
BM-1B	20-A-2	20	LTOA	4.03	2.312	2.183	12.90	20.57	37.28
BM-1B	20-A-3	20	LTOA	4.03	2.329	2.205	12.01	19.76	39.22
BM-1B	20-A-4	20	LTOA	4.03	2.314	2.188	12.70	20.38	37.71
BM-1B	20-A-5	20	LTOA	4.03	2.301	2.188	12.70	20.39	37.69
BM-1B	20-A-6	20	STOA	4.03	2.300	2.187	12.74	20.42	37.62
BM-1B	20-A-8	20	STOA	4.03	2.318	2.195	12.43	20.14	38.29
BM-1B	20-A-9	20	LTOA	4.03	2.315	2.197	12.36	20.07	38.45
BM-1B	20-A-10	20	LTOA	4.03	2.330	2.200	12.23	19.96	38.71

***= Not Tested.** **STOA= SHRP Short Term Oven Aging.**
NA= Not Aged. **LTOA= SHRP Long Term Oven Aging.**

Table 21. Unit Weight and Void Properties, BM-2 Mix.

Mix Type	Specimen	Percent Seg.	Aging	% AC	Bulk Specific Gravity SSD	Bulk Specific Gravity Parafilm	VTM %	VMA %	VFA %
BM-2	B2-0-N-1	0	NA	5.03	2.340	*	3.59	14.75	75.65
BM-2	B2-0-N-2	0	NA	5.03	2.374	*	2.16	13.48	83.97
BM-2	B2-0-N-3	0	NA	5.03	2.378	*	2.00	13.34	85.01
BM-2	B2-0-N-4	0	NA	5.03	2.370	*	2.33	13.64	82.88
BM-2	B2-0-A-1	0	LTOA	5.03	2.381	*	1.87	13.23	85.85
BM-2	B2-0-A-2	0	LTOA	5.03	2.377	*	2.05	13.38	84.71
BM-2	B2-0-A-3	0	LTOA	5.03	2.381	*	1.90	13.26	85.64
BM-2	B2-0-A-4	0	LTOA	5.03	2.376	*	2.08	13.41	84.47
BM-2	B2-0-A-5	0	STOA	5.03	2.376	*	2.11	13.44	84.31
BM-2	B2-0-A-6	0	LTOA	5.03	2.381	*	1.91	13.26	85.63
BM-2	B2-0-A-7	0	LTOA	5.03	2.380	*	1.95	13.30	85.32
BM-2	B2-0-A-8	0	STOA	5.03	2.377	*	2.07	13.41	84.53
BM-2	B2-5-N-1	5	NA	4.58	2.359	*	3.46	13.61	74.58
BM-2	B2-5-N-2	5	NA	4.58	2.351	*	3.77	13.88	72.86
BM-2	B2-5-N-3	5	NA	4.58	2.357	*	3.52	13.66	74.26
BM-2	B2-5-N-4	5	NA	4.58	2.356	*	3.57	13.71	73.93
BM-2	B2-5-A-1	5	STOA	4.58	2.358	*	3.49	13.63	74.41
BM-2	B2-5-A-2	5	LTOA	4.58	2.368	*	3.07	13.26	76.85
BM-2	B2-5-A-3	5	LTOA	4.58	2.364	*	3.24	13.41	75.82
BM-2	B2-5-A-4	5	STOA	4.58	2.359	*	3.45	13.60	74.64
BM-2	B2-5-A-5	5	LTOA	4.58	2.362	*	3.30	13.47	75.48
BM-2	B2-5-A-6	5	LTOA	4.58	2.365	*	3.21	13.38	76.01
BM-2	B2-5-A-7	5	LTOA	4.58	2.367	*	3.12	13.30	76.54
BM-2	B2-5-A-8	5	LTOA	4.58	2.356	*	3.57	13.70	73.97
BM-2	B2-10-N-1	10	NA	4.21	2.335	2.322	5.47	14.59	62.50
BM-2	B2-10-N-2	10	NA	4.21	2.329	2.319	5.59	14.70	61.95
BM-2	B2-10-N-3	10	NA	4.21	2.325	2.317	5.69	14.79	61.53
BM-2	B2-10-N-4	10	NA	4.21	2.343	2.325	5.34	14.47	63.12
BM-2	B2-10-A-1	10	LTOA	4.21	2.339	2.325	5.34	14.47	63.09
BM-2	B2-10-A-2	10	LTOA	4.21	2.331	2.322	5.48	14.60	62.47
BM-2	B2-10-A-3	10	LTOA	4.21	2.345	2.321	5.49	14.61	62.41
BM-2	B2-10-A-4	10	LTOA	4.21	2.323	2.308	6.02	15.09	60.09
BM-2	B2-10-A-5	10	STOA	4.21	2.328	2.312	5.88	14.96	60.71
BM-2	B2-10-A-6	10	LTOA	4.21	2.335	2.311	5.93	15.00	60.49
BM-2	B2-10-A-7	10	STOA	4.21	2.328	2.309	6.00	15.07	60.16
BM-2	B2-10-A-8	10	LTOA	4.21	2.330	2.314	5.78	14.87	61.12
BM-2	B2-20-N-1	20	NA	3.19	2.294	2.271	8.93	15.49	42.35
BM-2	B2-20-N-2	20	NA	3.19	2.284	2.255	9.60	16.12	40.41
BM-2	B2-20-N-3	20	NA	3.19	2.268	2.242	10.12	16.60	39.01
BM-2	B2-20-N-4	20	NA	3.19	2.279	2.250	9.79	16.29	39.91
BM-2	B2-20-A-1	20	LTOA	3.19	2.278	2.253	9.66	16.17	40.25
BM-2	B2-20-A-2	20	LTOA	3.19	2.272	2.246	9.93	16.42	39.53
BM-2	B2-20-A-3	20	LTOA	3.19	2.283	2.254	9.63	16.14	40.35
BM-2	B2-20-A-4	20	LTOA	3.19	2.276	2.254	9.61	16.12	40.39
BM-2	B2-20-A-5	20	STOA	3.19	2.276	2.245	9.97	16.45	39.43
BM-2	B2-20-A-6	20	STOA	3.19	2.288	2.262	9.32	15.85	41.22
BM-2	B2-20-A-7	20	LTOA	3.19	2.286	2.259	9.41	15.94	40.95
BM-2	B2-20-A-8	20	LTOA	3.19	2.282	2.255	9.58	16.10	40.47

***= Not Tested.**
NA= Not Aged.

STOA= SHRP Short Term Oven Aging.
LTOA= SHRP Long Term Oven Aging.

Table 22. Summary of Student t-Test for ASTM D2726 and D1188.

	BM -1B Mix				BM- 2 Mix			
	10% Segregated		20% Segregated		10% Segregated		20% Segregated	
	ASTM D2726	ASTM D1188	ASTM D2726	ASTM D1188	ASTM D2726	ASTM D1188	ASTM D2726	ASTM D1188
Observations	12	12	12	12	12	12	12	12
Mean (kN/m^3)	22.95	22.59	22.69	21.44	22.89	22.73	22.37	22.10
t-value	14.47		26.18		5.76		8.76	
t-critical	2.82		2.82		2.82		2.82	

Figure 34 shows the change in average unit weight with respect to percent change on the 4.75 mm sieve (level of segregation) for both BM-1B and BM-2 mixes. Generally, an increase in the level of segregation results in a decrease in the unit weight for both mixes. The unit weight decreases steadily with an increase in the level of segregation for the BM-2 mix. However, for the BM-1B mix, there is a hump at the 5% level of segregation. An increase in the segregation from 0% to 5% for the BM-1B mix resulted in a denser mix and the average unit weight increased by about 1%. From Figure 34, a linear regression analysis on unit weight and level of segregation yielded an R^2 of 0.96 for the BM-2 mix, showing a strong relationship between unit weight and level of segregation. For the BM-1B, a linear regression analysis on unit weight and all levels of segregation yielded an R^2 of 0.88. Treating the 0% segregated samples as outliers to remove the hump, an R^2 of 0.97 was obtained. Opposite trends were observed for VTM and VMA as shown in Figures 35-36 since they are reciprocates of unit weight. The slope of unit weight versus segregation for BM-1B is steeper

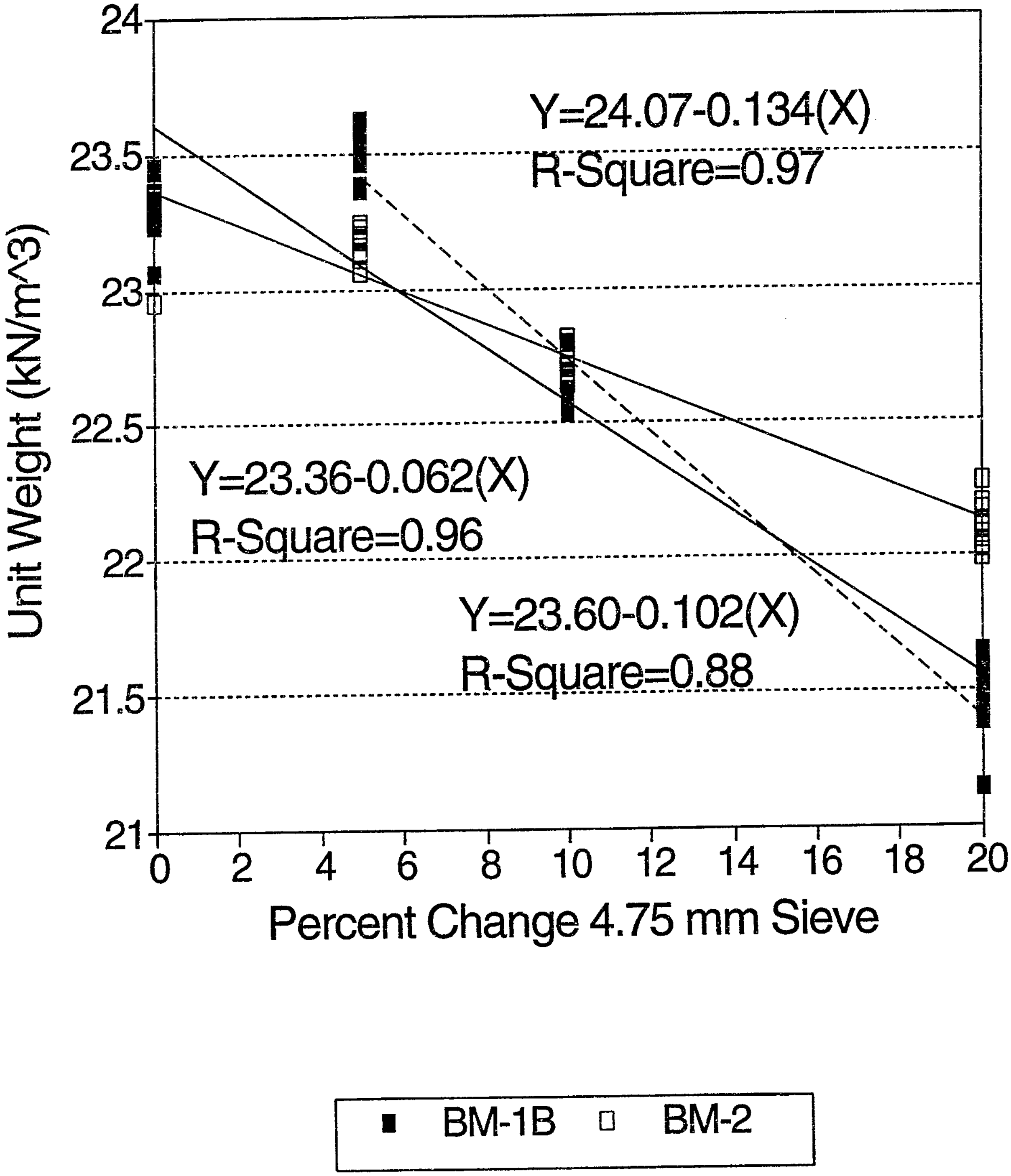

Figure 34. Average Unit Weight vs. Segregation.

than that for the BM-2 mix and thus the unit weight of BM-1B mix is more sensitive to segregation than BM-2 mix. This is due to the fact that the BM-2 mix gradations are finer and closer to the maximum density line than that of BM-1B mix which is coarser and more prone to segregation.

Air Permeability

Three samples at each level of segregation were selected and tested for absolute air permeability in accordance with ASTM D3637. The results are shown in Table 23. Most HMA mixtures are designed and constructed to be impermeable. A permeable HMA will allow the ingress of water and air into the pavement structure resulting in subgrade weakness, water damage, oxidation, raveling, and cracking. Permeability is generally expressed as either, relative permeability (k) or absolute permeability (K). The units for the former are in cm/s and the latter are expressed in cm^2. Absolute permeability (K) was measured during this study. KDOT classifies absolute permeability in 10^{-10} cm^2 as:

- over 1,000 - high
- 500 - 1,000 - medium
- 100 - 500 - low
- 0 - 100 - very low

Figure 37 shows a plot of absolute permeability versus level of segregation. The permeability of the BM-2 mix, which is finer, was not sensitive to segregation and recorded very low to medium permeabilities. The BM-1B mix recorded medium permeability values at 0% and 5% segregation but the permeability increased rapidly from 10% to 20%

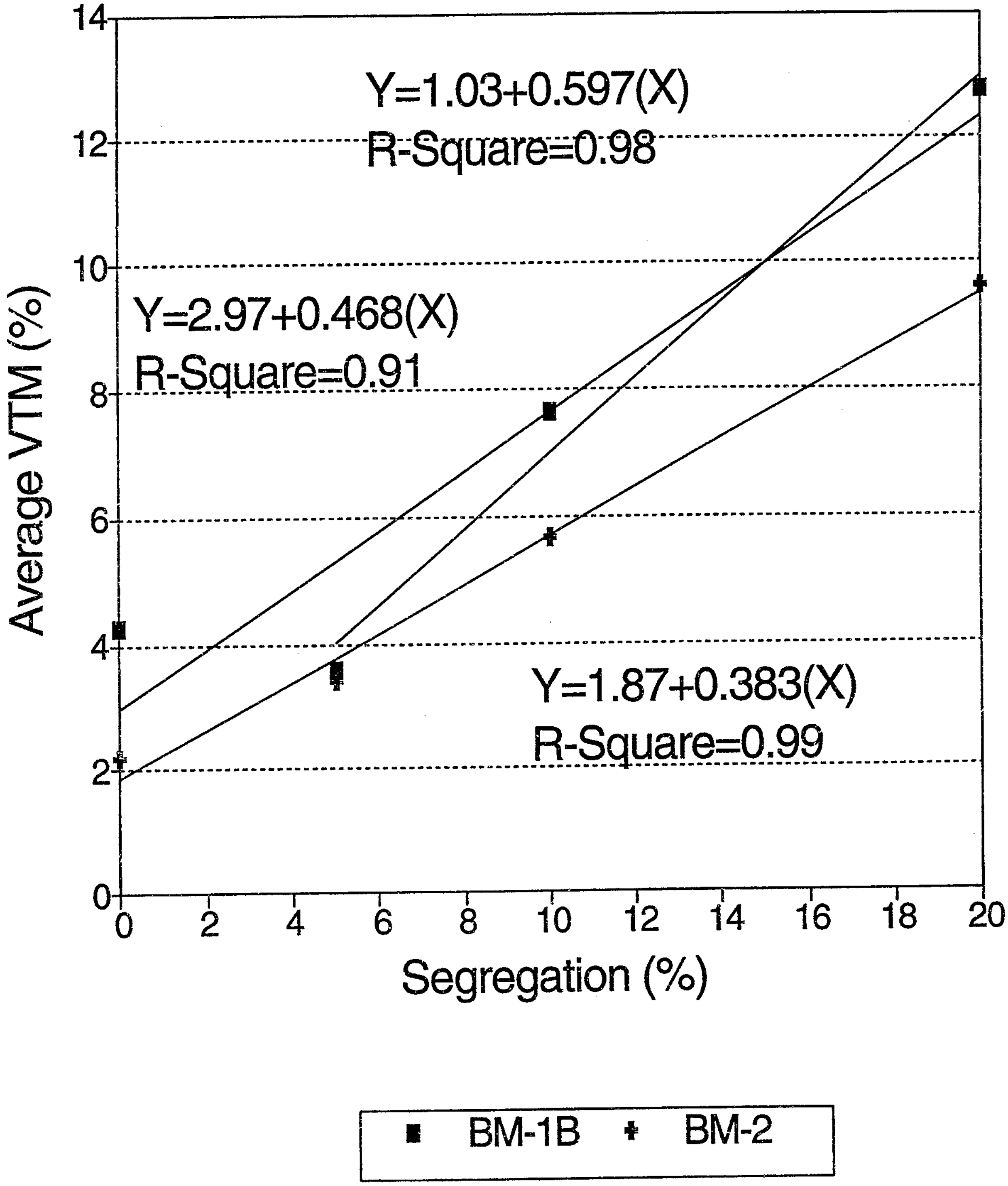

Figure 35. Average VTM vs. Segregation.

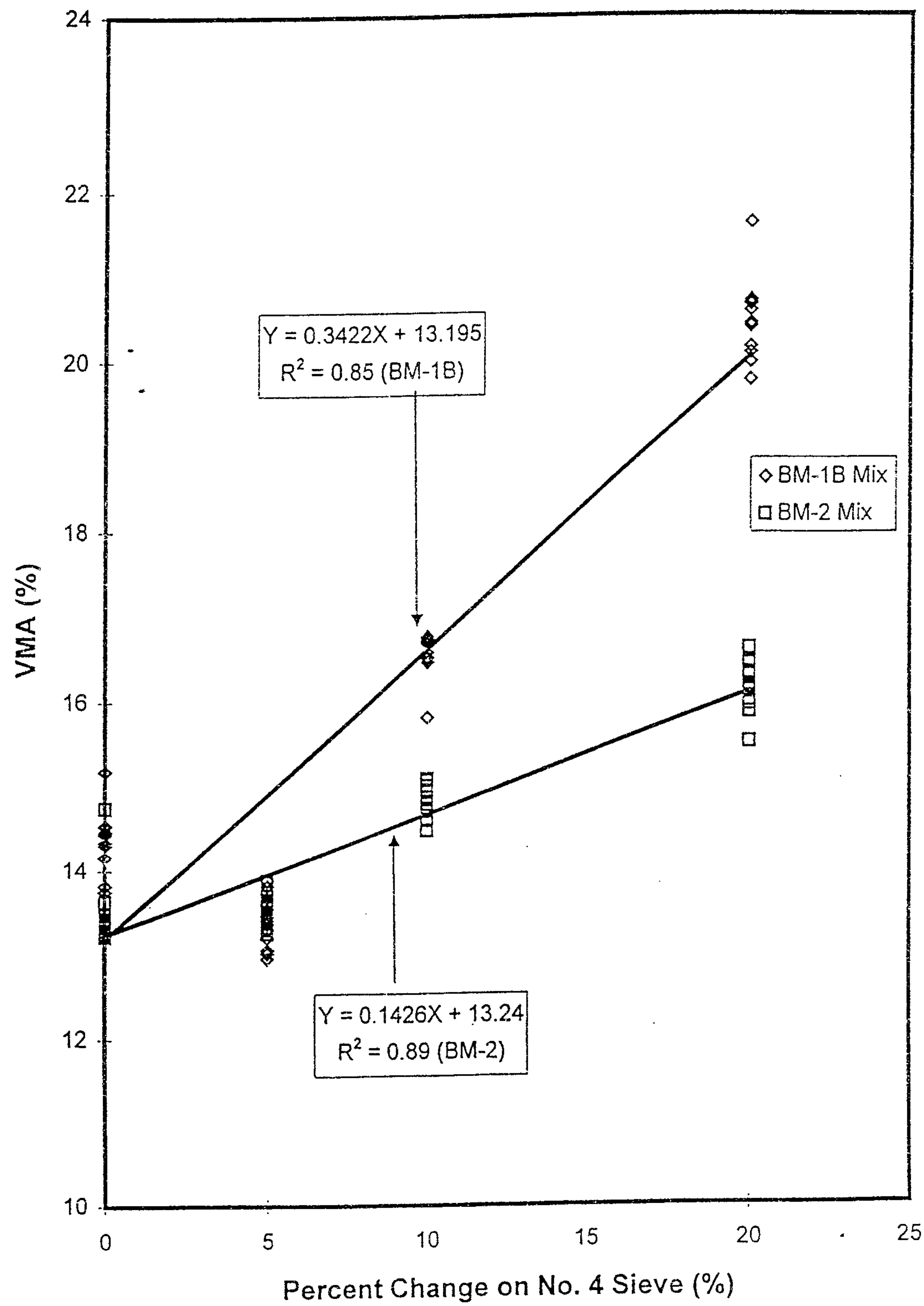

Figure 36. VMA vs. Segregation.

Table 23. Absolute Air Permeability.

Sample ID	Mix Typ	Percent Seg.	Aging	VTM (%)	Unit Weight (kN/m^3)	Absolute Air Permeability (10^-10 cm^2)
0-N-3	BM-1B	0	NA	4.35	23.26	734.3
0-N-4	BM-1B	0	NA	4.37	23.25	1303.6
0-A-1	BM-1B	0	LTOA	4.36	23.26	823.2
5-N-1	BM-1B	5	NA	3.71	23.48	1604.1
5-N-4	BM-1B	5	NA	3.65	23.49	901.8
5-A-7	BM-1B	5	STOA	3.54	23.52	1454.9
10-N-1	BM-1B	10	NA	7.50	22.62	2546.8
10-N-3	BM-1B	10	NA	7.57	22.60	3450.9
10-A-2	BM-1B	10	LTOA	7.63	22.59	4771.8
20-N-3	BM-1B	20	NA	12.98	21.40	49138.8
20-N-4	BM-1B	20	NA	13.01	21.39	42061.3
20-A-6	BM-1B	20	STOA	12.74	21.46	44485.3
						0.0
B2-0-N-2	BM-2	0	NA	2.16	23.29	238.6
B2-0-N-4	BM-2	0	NA	2.33	23.25	192.9
B2-0-A-5	BM-2	0	STOA	2.11	23.31	218.0
B2-5-N-1	BM-2	5	NA	3.46	23.14	227.7
B2-5-N-3	BM-2	5	NA	3.52	23.12	207.4
B2-5-A-1	BM-2	5	STOA	3.49	23.13	269.5
B2-10-N-2	BM-2	10	NA	5.59	22.75	275.0
B2-10-N-3	BM-2	10	NA	5.69	22.73	276.0
B2-10-A-2	BM-2	10	LTOA	5.48	22.78	321.1
B2-20-N-2	BM-2	20	NA	9.60	22.12	1073.3
B2-20-N-4	BM-2	20	NA	9.79	22.07	644.8
B2-20-A-8	BM-2	20	LTOA	9.58	22.12	2076.2

NA= Not Aged.
STOA= SHRP Short term Oven Aging.
LTOA= SHRP Long Term Oven Aging.

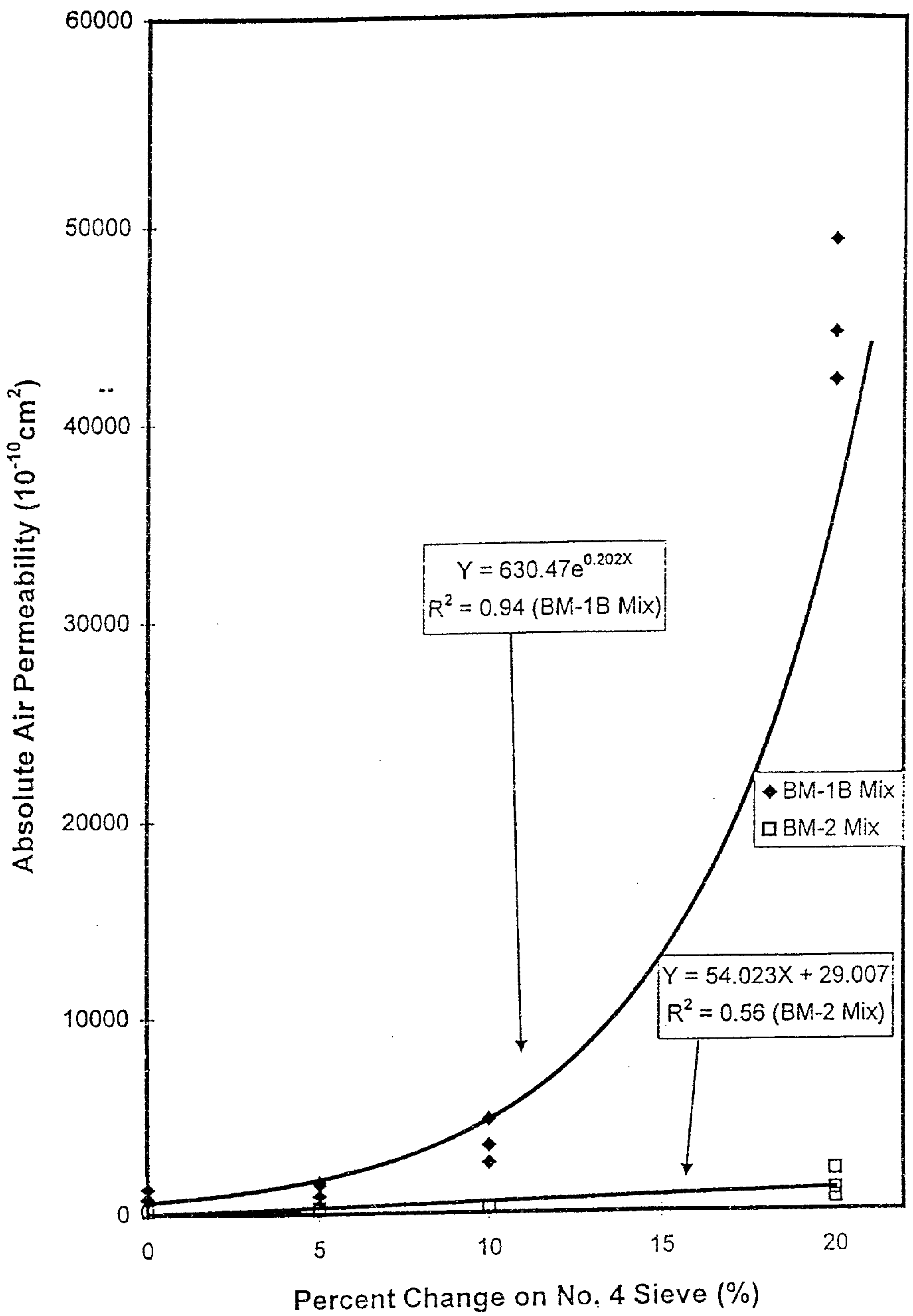

Figure 37. Absolute Air Permeability vs. Segregation.

segregation. As seen in Figure 38, this rapid increase in permeability occurred after an average VTM of 7.5%. This trend is similar to a study of segregated mixes in Georgia by Brown et al. (10) where they reported a rapid increase in relative permeability at 8% VTM.

Indirect Tensile Strength

The indirect tensile strength was determined on a set of two non-aged and two LTOA samples at each level of segregation. The test was performed at 25°C in accordance with ASTM D4123. The load and deformation at failure were measured, the stress and strain calculated, and the results are shown in Table 24. The tensile strength obtained was used as the control strength for moisture sensitivity and fatigue testing as well as to evaluate the cracking potential of the mix. However, the tensile strain at failure is more useful for predicting cracking potential. Mixes that can accommodate high strains prior to failure are more likely to resist cracking than mixes that cannot withstand high strains. The tensile strains at failure were computed from the recorded vertical deformations using a Poisson's ratio of 0.35.

The change in indirect tensile strength with level of segregation is shown in Figures 39 and 40. Generally, an increase in segregation results in a decrease in tensile strength. As with unit weight, there is a slight hump at the 5% level of segregation for the BM-1B mix. A linear regression analysis yielded an R^2 of 0.95 and 0.90 for the LTOA and non-aged samples, receptively. The BM-2 mix yielded an R^2 of 0.83 for the LTOA samples and 0.85 for the non-aged samples. The results show that there is a strong relationship between indirect tensile strength and level of segregation. The LTOA curves are steeper than the

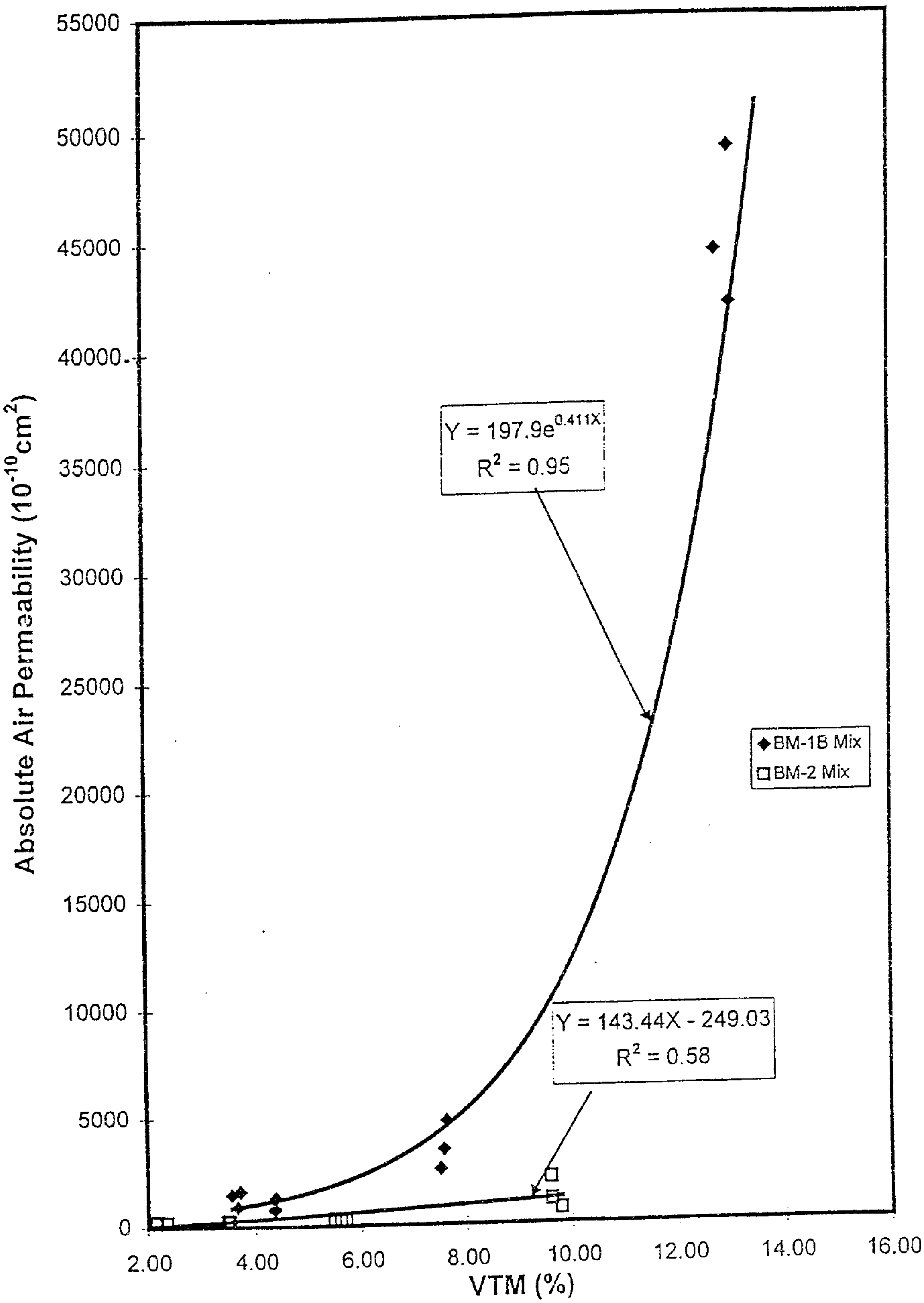

Figure 38. Absolute Air Permeability vs. VTM.

Table 24. Results of Tensile Strength Testing.

Sample ID	Mix Type	Percent Seg.	Aging	Unit Weight (kN/m^3)	VTM (%)	Indirect Tensile Strength (kPa)	Indirect Tensile Strain (mm/mm)
0-N-3	BM-1B	0	NA	23.26	4.35	113.6	0.0274
0-N-4	BM-1B	0	NA	23.25	4.37	116.9	0.0274
0-A-3	BM-1B	0	LTOA	23.27	4.33	160.2	0.0242
0-A-4	BM-1B	0	LTOA	23.06	5.17	163.7	0.0274
5-N-1	BM-1B	5	NA	23.48	3.71	112.7	0.0242
5-N-4	BM-1B	5	NA	23.49	3.65	122.3	0.0242
5-A-1	BM-1B	5	LTOA	23.62	3.15	159.3	0.0226
5-A-2	BM-1B	5	LTOA	23.38	4.11	151.4	0.0242
10-N-1	BM-1B	10	NA	22.62	7.50	100.4	0.0258
10-N-3	BM-1B	10	NA	22.60	7.57	95.5	0.0258
10-A-3	BM-1B	10	LTOA	22.60	7.56	128.2	0.0290
10-A-4	BM-1B	10	LTOA	22.54	7.81	121.9	0.0258
20-N-3	BM-1B	20	NA	21.40	12.98	70.5	0.0322
20-N-4	BM-1B	20	NA	21.39	13.01	70.3	0.0322
20-A-3	BM-1B	20	LTOA	21.64	12.01	89.5	0.0339
20-A-10	BM-1B	20	LTOA	21.58	12.23	99.2	0.0290
				0.00			
B2-0-N-2	BM-2	0	NA	23.29	2.16	137.7	0.0242
B2-0-N-4	BM-2	0	NA	23.25	2.33	149.3	0.0258
B2-0-A-1	BM-2	0	LTOA	23.36	1.87	222.7	0.0210
B2-0-A-3	BM-2	0	LTOA	23.35	1.90	213.5	0.0242
B2-5-N-1	BM-2	5	NA	23.14	3.46	132.3	0.0242
B2-5-N-3	BM-2	5	NA	23.12	3.52	129.1	0.0242
B2-5-A-7	BM-2	5	LTOA	23.22	3.12	228.7	0.0210
B2-5-A-8	BM-2	5	LTOA	23.11	3.57	201.6	0.0242
B2-10-N-2	BM-2	10	NA	22.75	5.59	121.2	0.0242
B2-10-N-3	BM-2	10	NA	22.73	5.69	124.6	0.0226
B2-10-A-3	BM-2	10	LTOA	22.77	5.49	202.4	0.0193
B2-10-A-4	BM-2	10	LTOA	22.65	6.02	192.4	0.0226
B2-20-N-2	BM-2	20	NA	22.12	9.60	116.1	0.0210
B2-20-N-4	BM-2	20	NA	22.07	9.79	101.6	0.0226
B2-20-A-2	BM-2	20	LTOA	22.04	9.93	137.7	0.0193
B2-20-A-3	BM-2	20	LTOA	22.11	9.63	161.7	0.0210

NA= Not Aged.
LTOA= SHRP Long Term Oven Aging.

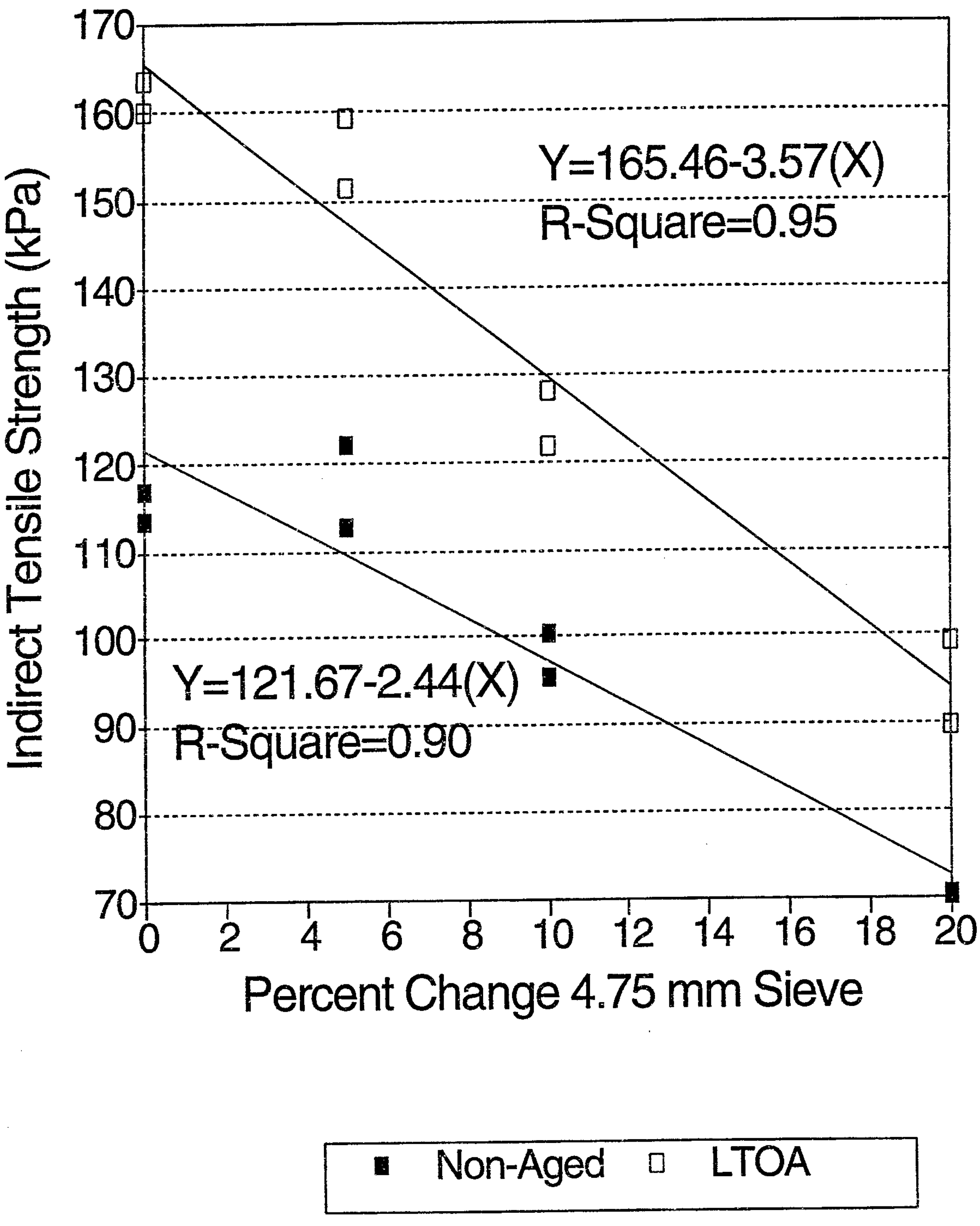

Figure 39. Indirect Tensile Strength vs. Segregation, BM-1B Mix.

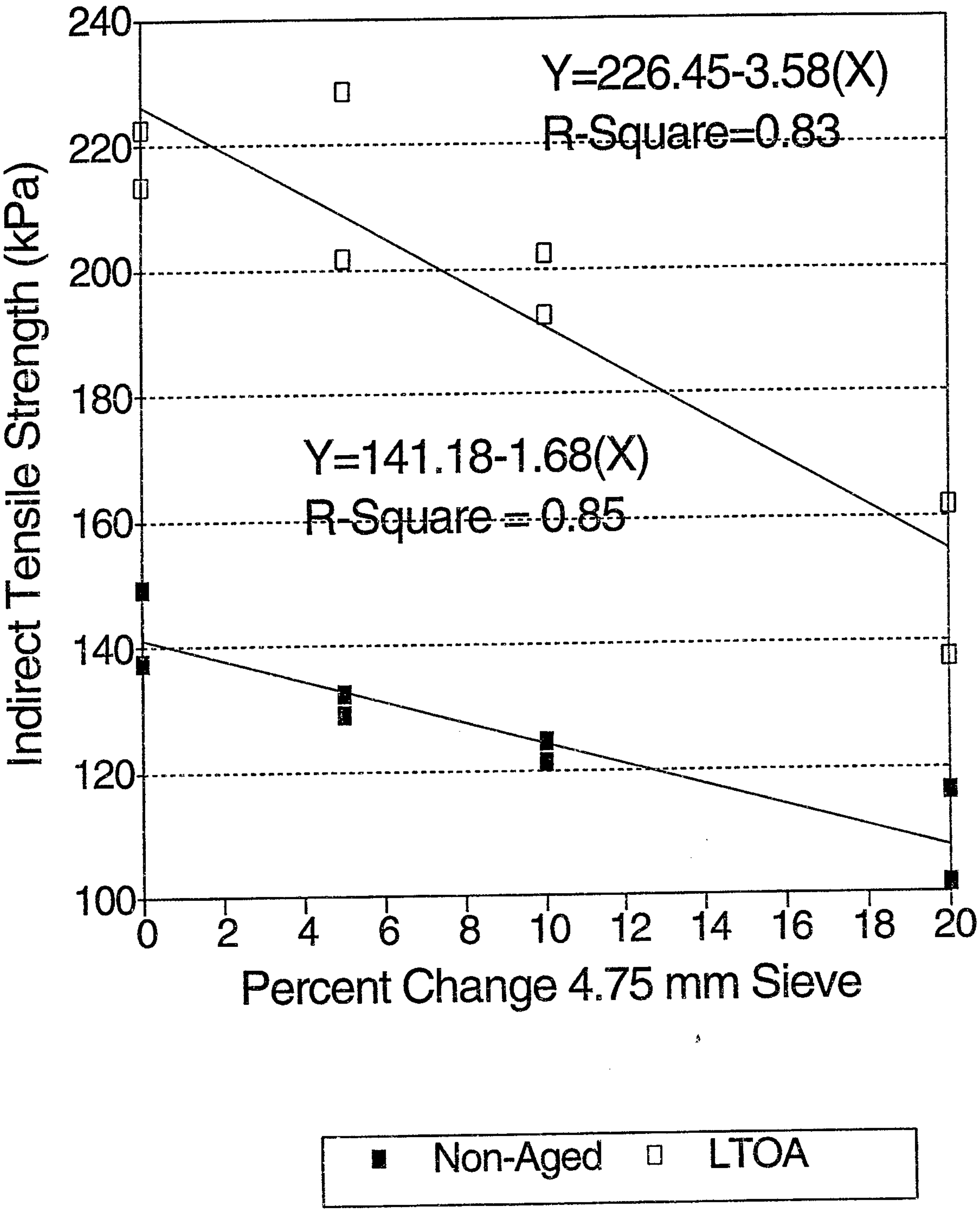

Figure 40. Indirect Tensile Strength vs. Segregation, BM-2 Mix.

non-aged curves suggesting that aging increases the rate at which indirect tensile strength drops with segregation.

Since the indirect tensile strength followed the same trend as the unit weight, a linear regression analysis was performed on indirect tensile strength and unit weight. Strong relationships were observed between the two as shown in Figure 41. The figure suggests that indirect tensile strength is mix specific. As shown in Figures 39 and 40, the LTOA and BM-2 mix samples recorded higher indirect tensile strengths than the non-aged and BM-1B mix samples. However, this does not mean that the BM-2 mix and LTOA samples will perform better in cracking. The higher indirect tensile strengths for the BM-2 mix and LTOA samples were due to their higher stiffness. The asphalt binder for the BM-2 mix is an AC-20 and, therefore, stiffer than the BM-1B mix which has an AC-10 as binder. Also, the LTOA hardened the asphalt, stiffening the mixes. The aged mixes are expected to fail at lower strain values. This is illustrated in Figure 42 by the computed tensile strains. From Figure 42, non-aged and BM-1B mix samples generally recorded higher strains and should better resist cracking.

Moisture Sensitivity

AASHTO T283 was generally followed to investigate the effects of segregation on moisture damage to HMA. Two samples each of non-aged and LTOA were tested for moisture susceptibility at all levels of segregation for both mixes. AASHTO T283 is intended for mixes compacted to 7 ±1% air voids, but as mentioned earlier, the samples tested were compacted to predetermine air voids based on the air voids of the field cores. Each

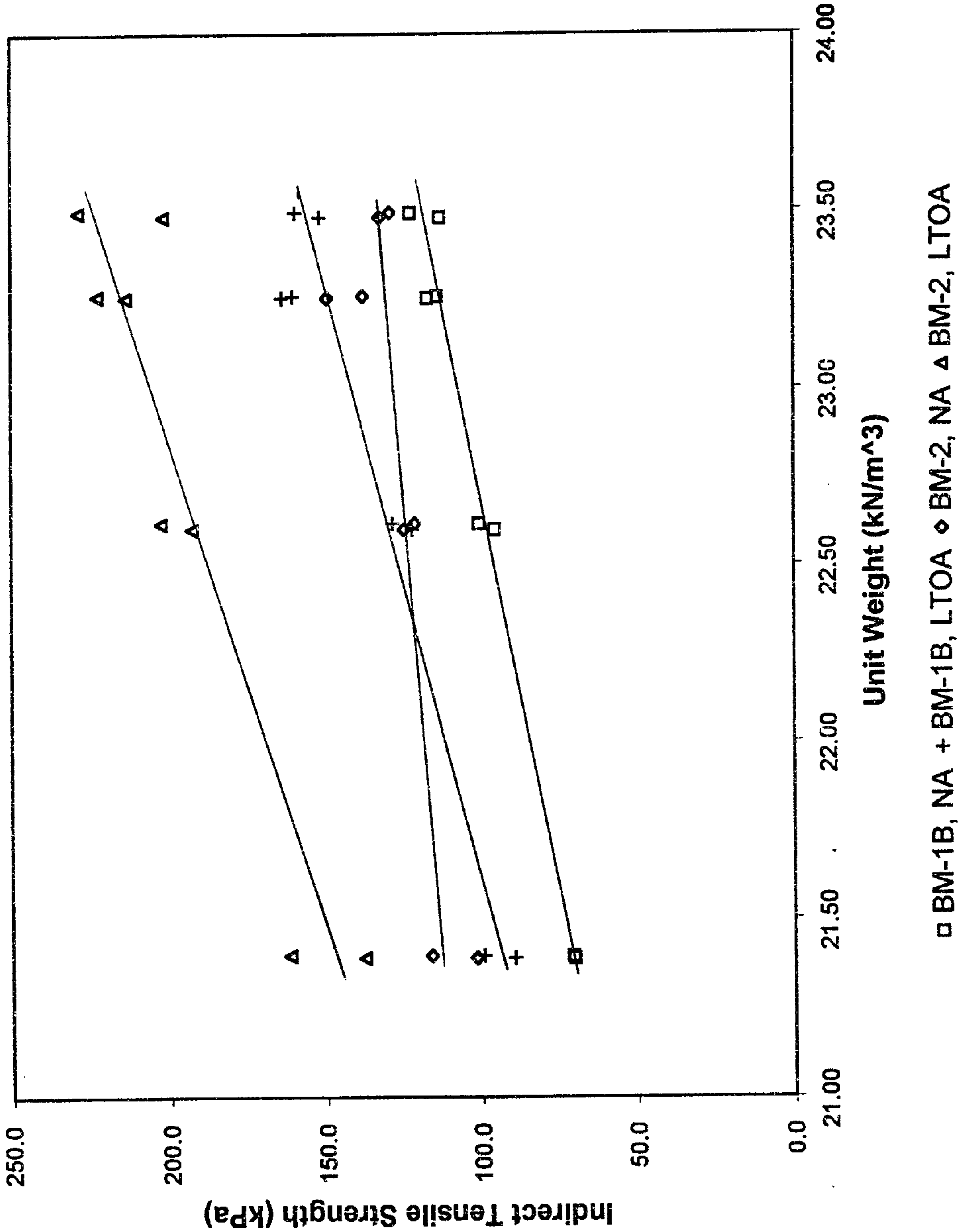

Figure 41. Indirect Tensile Strength vs. Unit Weight.

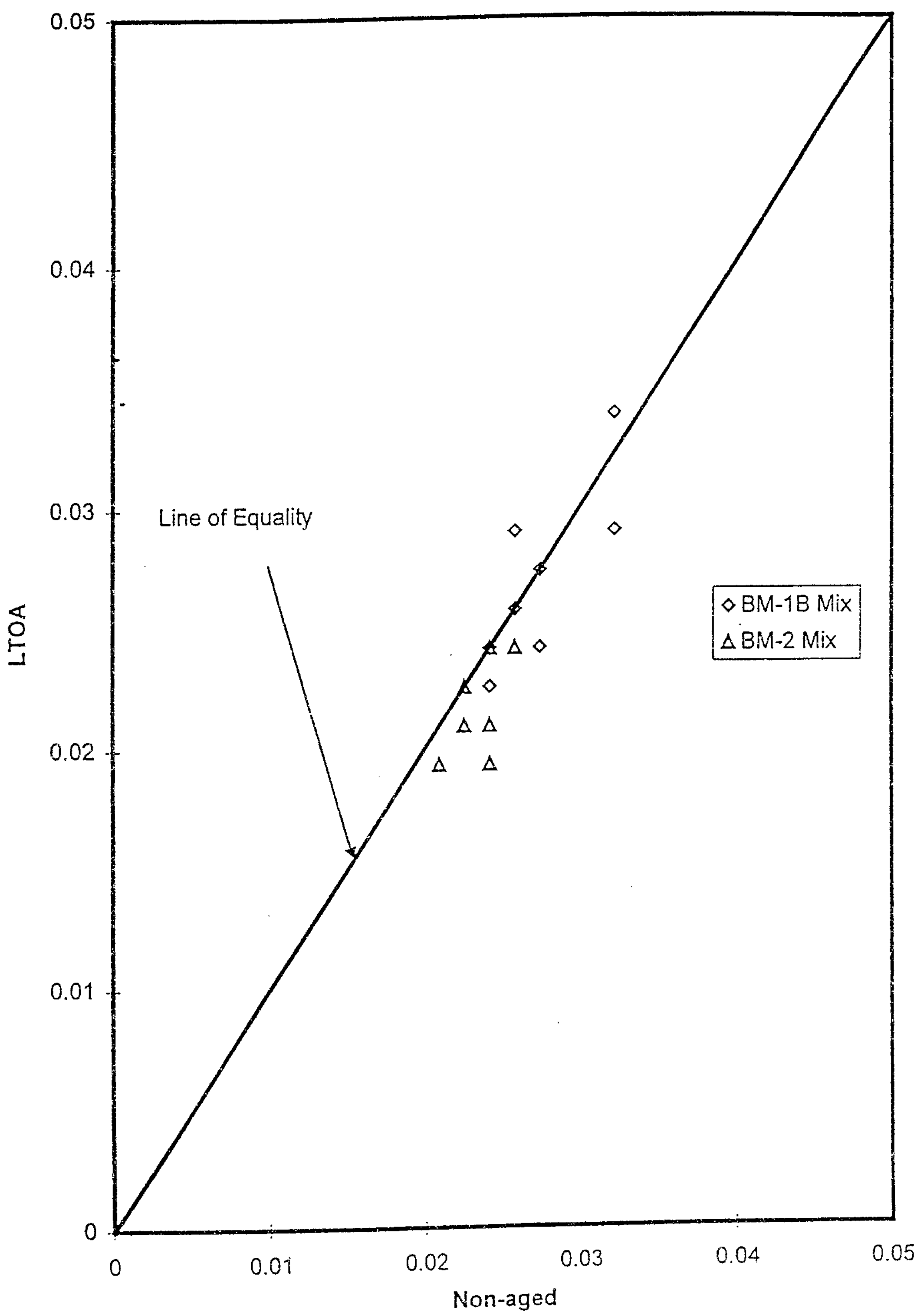

Figure 42. Indirect Tensile Strain for Non-Aged and LTOA Samples.

sample tested for moisture sensitivity was subjected to a 610-mm Hg vacuum for 30 minutes during saturation. Aschenbrener and McGennis (13) reported that the 610-mm Hg vacuum for 30 minutes saturation variation to AASHTO T283 better discriminated moisture susceptible mixes in Colorado. The variation also ensures that all samples are subjected to the same conditions during saturation. The degree of saturation obtained ranged from 32% to 92%, depending on the air voids. The results are shown in Table 25.

After saturation, the samples were subjected to a freeze cycle for 24 hours at -18°C followed by a hot water soaking for 24 hours at 60°C to obtain the conditioned samples. Conditioned, non-aged, indirect tensile strengths were compared too unconditioned, non-aged, non-segregated indirect tensile strengths while conditioned, LTOA, indirect tensile strengths were compared to unconditioned, LTOA, non-segregated indirect tensile strengths. The unconditioned indirect tensile strengths were obtained from the indirect tensile strength test mentioned in the preceding section.

Figures 43 and 44 are plots of TSR versus percent change on the 4.75 mm sieve for BM-1B and BM-2 mixes, respectively. Linear regression analysis yielded R^2s of 0.95 (BM-1B mix non-aged), 0.87 (BM-1B mix LTOA), 0.86 (BM-2 mix non-aged), and 0.95 (BM-2 mix, LTOA). These strong relationships indicate that an increase in level of segregation results in a decrease in TSR.

Because a significant component of HMA tensile strength is contributed by asphalt stiffness, the LTOA samples recorded higher TSR values than the non-aged samples. From Figures 43 and 44, the slopes of the TSR versus segregation lines did not change significantly after LTOA. Thus, LTOA did not significantly affect the sensitivity of

Table 25. Results of AASHTO T283 Testing.

Sample ID	Mix Type	Percent Seg.	Aging	Unit Weight (kN/m^3)	TSR (%)	Saturation (%)
0-N-1	BM-1B	0	NA	23.45	82.5	47.5
0-N-2	BM-1B	0	NA	23.43	74.8	48.9
0-A-1	BM-1B	0	LTOA	23.26	84.9	61.0
0-A-2	BM-1B	0	LTOA	23.30	86.6	59.5
5-N-2	BM-1B	5	NA	23.36	77.1	60.1
5-N-3	BM-1B	5	NA	23.59	71.2	39.8
5-A-3	BM-1B	5	LTOA	23.60	91.7	46.2
5-A-4	BM-1B	5	LTOA	23.52	88.2	31.5
10-N-2	BM-1B	10	NA	22.79	58.0	52.3
10-N-4	BM-1B	10	NA	22.54	55.0	51.0
10-A-1	BM-1B	10	LTOA	22.55	70.0	59.4
10-A-2	BM-1B	10	LTOA	22.59	69.5	56.0
20-N-1	BM-1B	20	NA	21.14	37.6	40.3
20-N-2	BM-1B	20	NA	21.38	39.6	40.6
20-A-2	BM-1B	20	LTOA	21.42	54.2	39.2
20-A-4	BM-1B	20	LTOA	21.47	51.5	42.6
B2-0-N-1	BM-2	0	NA	22.95	53.3	77.8
B2-0-N-3	BM-2	0	NA	23.33	80.2	42.2
B2-0-A-2	BM-2	0	LTOA	23.32	83.5	68.2
B2-0-A-6	BM-2	0	LTOA	23.35	83.9	56.8
B2-5-N-2	BM-2	5	NA	23.06	65.0	66.3
B2-5-N-4	BM-2	5	NA	23.11	64.7	59.7
B2-5-A-2	BM-2	5	LTOA	23.23	73.4	91.5
B2-5-A-6	BM-2	5	LTOA	23.20	70.3	81.4
B2-10-N-1	BM-2	10	NA	22.78	43.6	72.3
B2-10-N-4	BM-2	10	NA	22.81	47.6	62.3
B2-10-A-1	BM-2	10	LTOA	22.81	45.6	77.8
B2-10-A-8	BM-2	10	LTOA	22.70	43.2	75.9
B2-20-N-1	BM-2	20	NA	22.28	17.0	87.9
B2-20-N-3	BM-2	20	NA	21.99	17.8	73.5
B2-20-A-7	BM-2	20	LTOA	22.16	22.8	75.7
B2-20-A-8	BM-2	20	LTOA	22.12	29.0	70.7

NA= Not Aged.
LTOA= SHRP Long Term Oven Aging.

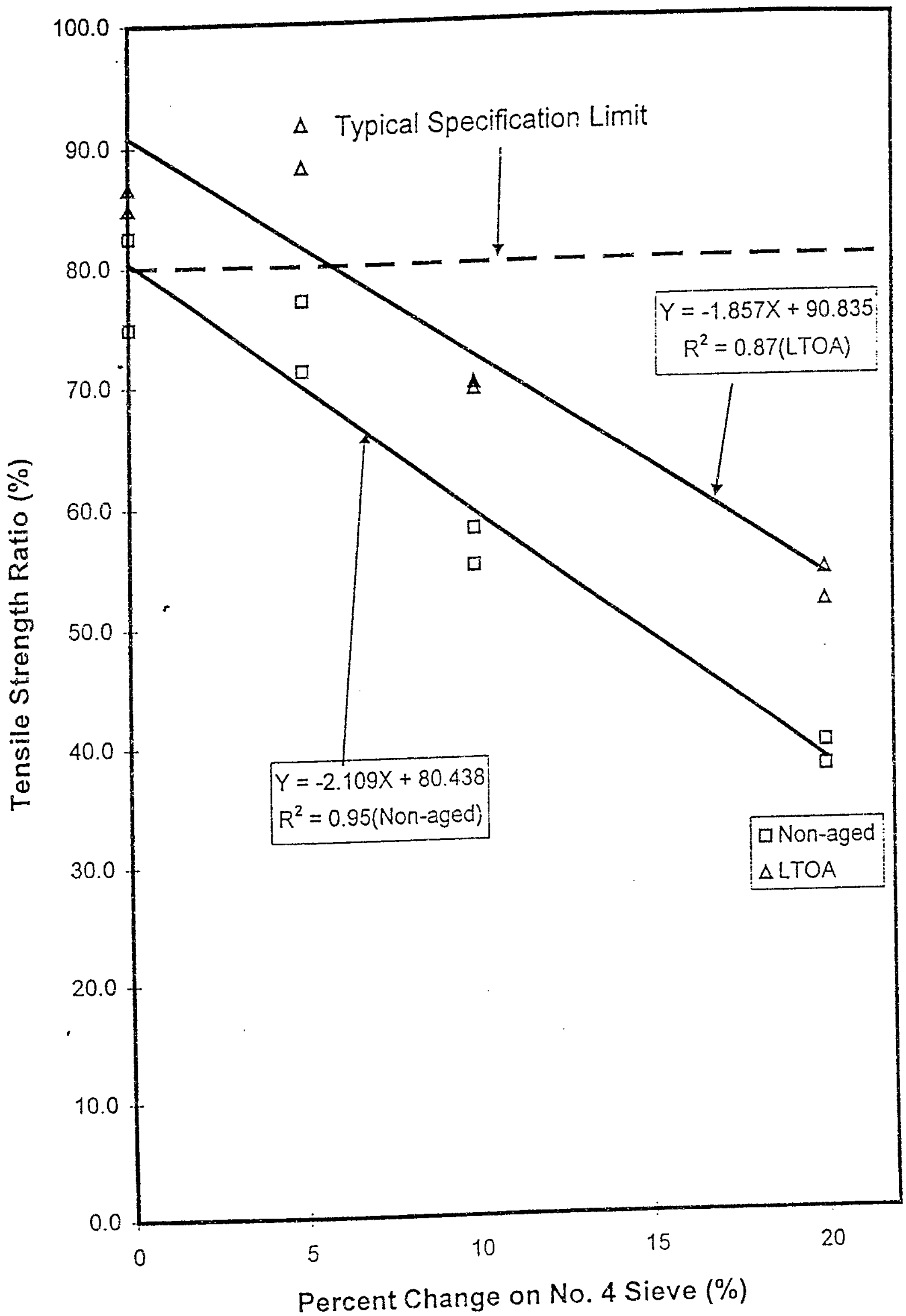

Figure 43. TSR vs. Segregation, BM-1B Mix.

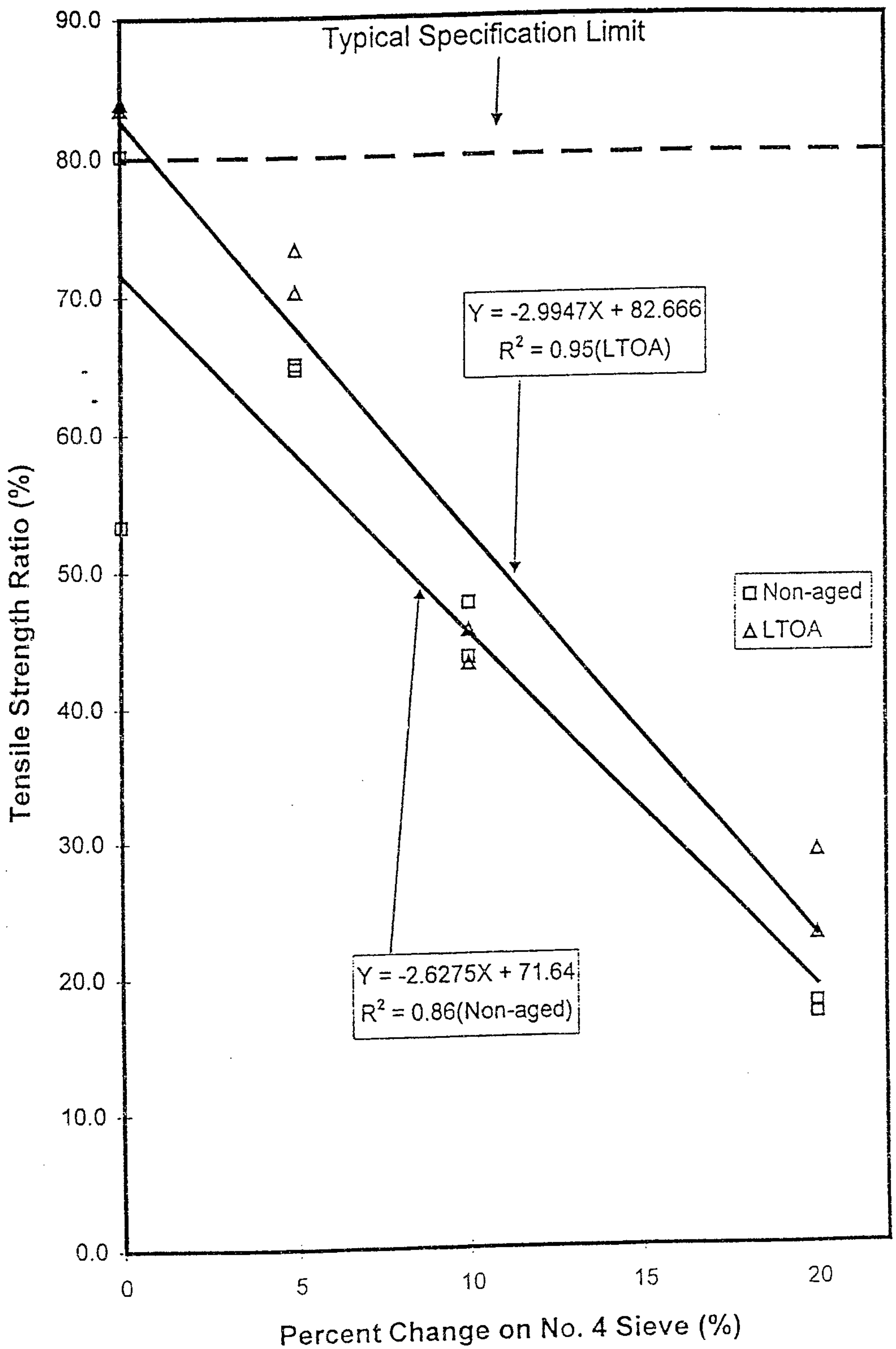

Figure 44. TSR vs. Segregation, BM-2 Mix.

moisture damage to segregation. Using a typical TSR specification of 80%, only the non-segregated samples would be acceptable as segregation resulted in a rapid reduction in the resistance to moisture damage.

Figure 45 is a plot of TSR versus unit weight. Regression analysis yielded R^2s of 0.81 and 0.94 for BM-1B and BM-2 mixes, respectively. The strong relationships indicate that a decrease in unit weight as a result of segregation increases the moisture susceptibility of the mixes. Also, the different slopes suggest that the variation in TSR with unit weight is mix specific.

Fatigue

Fatigue testing was performed on two sets each of STOA and LTOA samples at all levels of segregation. The fatigue testing was performed in general accordance with ASTM D4123. A haversine pulse-load was applied for 0.1 second with a 0.9 second rest for a frequency of 1 cycle per second. The test was conducted in constant stress at 5% of the control (non-aged) indirect tensile strength. The number of repetitions to failure (N_f) was recorded and the results shown in Table 26.

Figure 46 is a plot of Log N_f versus percent segregation for both mixes. For the BM-1B mixes, regression analysis yielded an R^2 of 0.80 and 0.92 for LTOA and STOA samples, respectively. For the BM-2 mixes, an R^2 of 0.92 (LTOA) and 0.95 (STOA) were obtained. The relationships in Figure 46 indicate that an increase in the level of segregation results in a decrease in fatigue life. The BM-1B mixes performed better in fatigue than the BM-2 mixes.

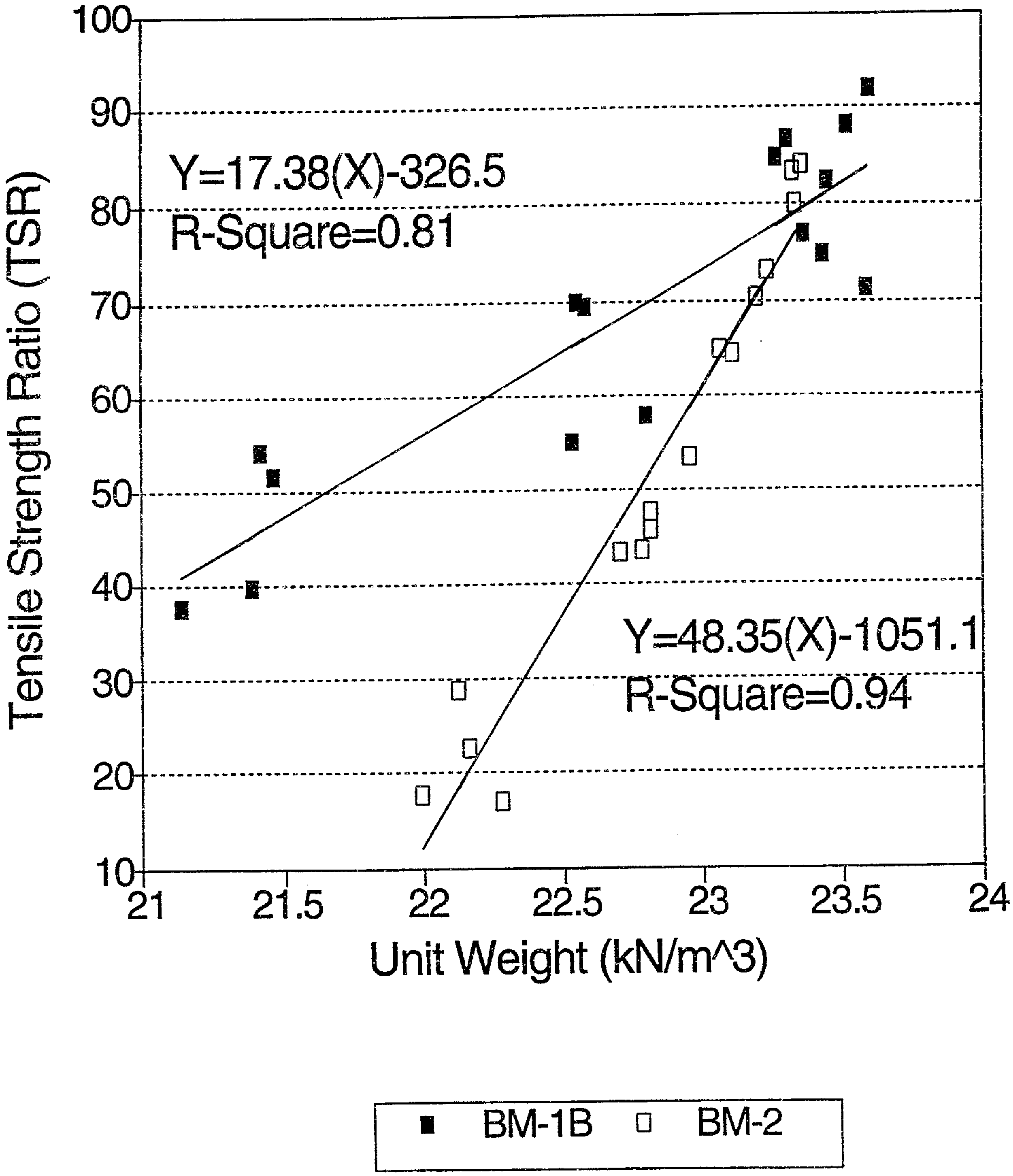

Figure 45. TSR vs. Unit Weight.

Table 26. Results From Fatigue Testing.

Sample ID	Mix Type	Percent Seg.	Aging	Repetitions to Failure (Nf)	Unit Weight (kN/m^3)
0-A-5	BM-1B	0	LTOA	130325	23.24
0-A-6	BM-1B	0	LTOA	166274	23.34
0-A-7	BM-1B	0	STOA	47832	23.24
0-A-8	BM-1B	0	STOA	51627	23.29
5-A-5	BM-1B	5	LTOA	14141	23.46
5-A-6	BM-1B	5	LTOA	10140	23.50
5-A-8	BM-1B	5	STOA	5863	23.55
10-A-5	BM-1B	10	LTOA	1923	22.55
10-A-6	BM-1B	10	LTOA	2397	22.56
10-A-7	BM-1B	10	STOA	620	22.54
10-A-8	BM-1B	10	STOA	424	22.55
20-A-5	BM-1B	20	LTOA	275	21.46
20-A-8	BM-1B	20	STOA	398	21.53
20-A-9	BM-1B	20	LTOA	303	21.55
B2-0-A-4	BM-2	0	LTOA	73	23.31
B2-0-A-5	BM-2	0	STOA	52	23.31
B2-0-A-7	BM-2	0	LTOA	53	23.34
B2-0-A-8	BM-2	0	STOA	57	23.31
B2-5-A-1	BM-2	5	STOA	50	23.13
B2-5-A-3	BM-2	5	LTOA	41	23.19
B2-5-A-4	BM-2	5	STOA	46	23.14
B2-5-A-5	BM-2	5	LTOA	45	23.18
B2-10-A-2	BM-2	10	LTOA	38	22.78
B2-10-A-5	BM-2	10	STOA	38	22.68
B2-10-A-6	BM-2	10	LTOA	33	22.67
B2-10-A-7	BM-2	10	STOA	30	22.65
B2-20-A-1	BM-2	20	LTOA	16	22.10
B2-20-A-4	BM-2	20	LTOA	22	22.12
B2-20-A-5	BM-2	20	STOA	14	22.03
B2-20-A-6	BM-2	20	STOA	14	22.19

STOA = SHRP Short Term Oven Aging.
LTOA= SHRP Long Term Oven Aging.

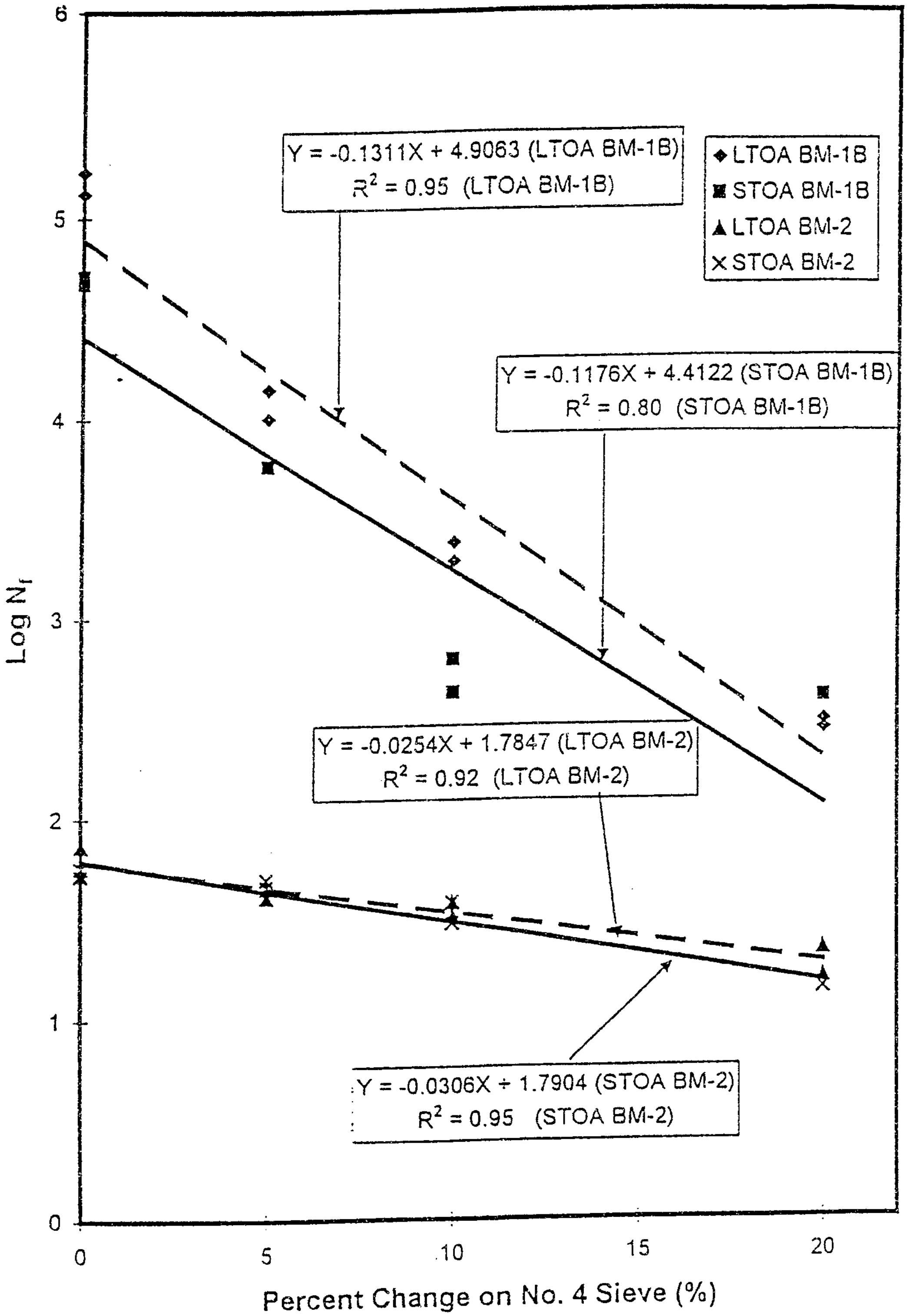

Figure 46. Log N_f vs. Segregation.

The LTOA samples recorded higher fatigue life than STOA samples. However, this does not mean that long term aging improves the fatigue life of asphalt mixes. Long term aging stiffened the mixes and recorded higher fatigue life because the fatigue test was performed in constant stress. Although LTOA samples generally recorded higher N_f, long term aging did not significantly affect the fatigue life of BM-2 mixes. This is evident from the similar STOA and LTOA fatigue curves obtained for BM-2 mix. The fatigue life of the BM-1B mix was more sensitive to segregation than the BM-2 mix.

Figure 47 is plot of Log N_f versus unit weight for both mixes. An R^2 of 0.68 and 0.91 were obtained for BM-1B and BM-2 mixes, respectively. The relationships indicate that a decrease in unit weight generally results in a decrease in fatigue life. Although fatigue life has a strong relationship with unit weight, it is mix specific as evident in the different slopes for both mixes (Figure 47).

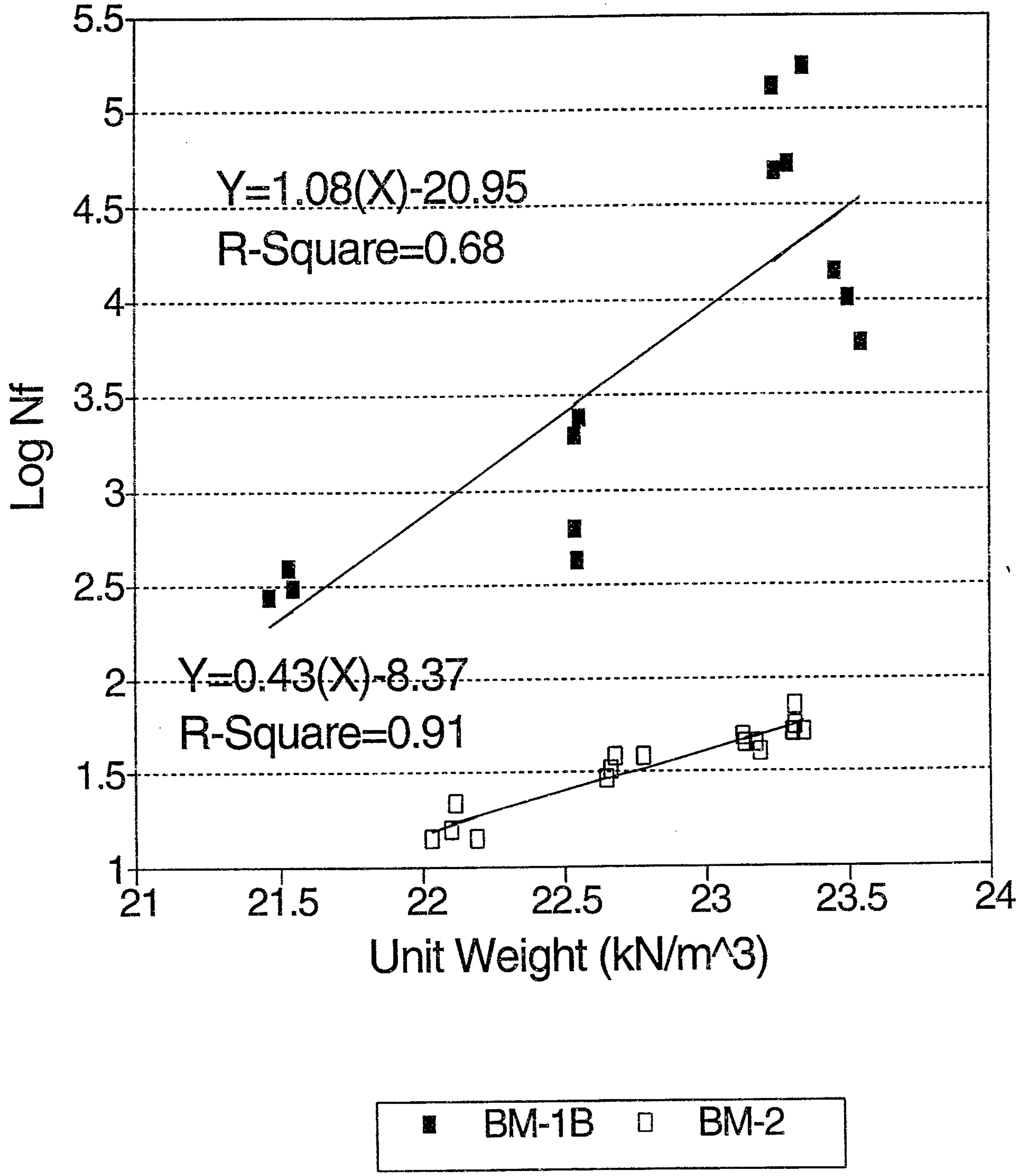

Figure 47. Log N_f vs. Unit Weight.

CHAPTER 6

CONCLUSIONS

Based on the results of this study the following conclusions are warranted.

1. Cold feed gradations do not adequately control the gradation of the mix. From the cold feed gradations provided by KDOT, all four of the mixtures were within specification tolerances. However, the non-segregated cores were typically outside the specification tolerances on at least one sieve.
2. Visual observations could adequately identify non-uniform surface texture.
3. Of the indicator tests evaluated, asphalt content was the best indicator of segregation. For the BM-1B mix, a change in asphalt content of 0.28% corresponded to a change in gradation of 5% on the 4.75 mm sieve, KDOT's tolerance limit.
4. The macro texture was the best nondestructive indicator of segregation. For the BM-1B mix, a change in macro texture of 0.160 mm corresponded to a change in gradation of 5% on the 4.75 mm sieve.
5. Segregation had a great effect on pavement performance as measured by the pavement cores. A change in gradation of 5% on the 4.75 mm sieve corresponded to a 10% drop in control or conditioned indirect tensile strength. A change in gradation of 5%, 10% and 20% on the 4.75 mm sieve corresponded to a loss of 28%, 50% and 76%, respectively, in fatigue life. Each of the performance tests had a better correlation with unit weight than segregation.

6. The results of the indicator tests versus performance showed that the loss in pavement performance was a function of unit weight, whether by segregation or other means. The unit weight, either by nuclear density gauge or cores could not differentiate between a coarse surface texture caused by gradation change (segregation) or from high air voids. Therefore, the unit weight is not a good indicator of segregation.

7. The results from the pavement cores revealed that the relationships between indicator tests and performance were mix specific.

For the laboratory compacted samples the following conclusions can be drawn.

1. Segregation causes a drop in the unit weight. This drop in unit weight is associated with an increase in VTM and VMA.

2. Segregation results in a porous asphalt mix. The increase in permeability, as a result of segregation, was more pronounced in the BM-1B mix (coarse-graded) than the BM-2 mix. Segregation of the BM-2 mix, with an aggregate gradations closer to the maximum density line, did not significantly affect permeability.

3. Segregation causes a decrease in the indirect tensile strength. This drop in indirect tensile strength could cause a drop in cracking resistance. Aging increases the rate at which indirect tensile strength drops with level of segregation. For the mixes considered in this study, a 5% increase in segregation caused a 10% drop in indirect tensile strength for non-aged BM-1B mixes, and a 5% increase in segregation caused a 6% drop in indirect tensile strength for non-aged BM-2 mixes.

4. Segregation leads to moisture susceptible asphalt mixes and aging does not significantly affect the moisture sensitivity.

5. Segregation causes a reduction in fatigue life of asphalt mixes. In this study, segregation of the BM-1B (coarse-graded) mix was more sensitive to a loss in fatigue life than the BM-2 (fine-graded) mix.

6. The effect of segregation on permeability, tensile strength, moisture sensitivity and fatigue life are mix specific.

7. Permeability, tensile strength, moisture sensitivity, and fatigue life correlates with unit weight.

CHAPTER 7

RECOMMENDATIONS

Based on the results of this study the following recommendations are made:

1. Asphalt content was the best indicator of segregation. A change in asphalt content of 0.28 % could be used to indicate a mix out of tolerance on the 4.75 mm sieve.

2. Macro texture was the best nondestructive indicator of segregation. An increase in macro texture of 0.160 mm could be used to indicate a mix out of tolerance on the 4.75 mm sieve.

3. Unit weight from a nuclear density gauge taken at one location could not identify either segregation or a non-uniform surface texture. The macro texture test is hard to perform and time consuming. Asphalt content is not a nondestructive test. However, most nuclear gauges can measure asphalt content. Further study is recommended on combining two indicator tests, such as asphalt content and unit weight, which could help differentiate between high air voids and segregation. The ability of a nuclear gauge using asphalt content, with its high correlation, and unit weight, with its low correlation, should be evaluated to determine if the nuclear gauge could reliably detect segregation.

For segregated sections on a road, a seal coat can be applied to prevent the ingress of water and air into the pavement structure. This seal coat will decrease the permeability of the mix and improve the moisture sensitivity of the affected pavement. However, segregation also causes a drop in the indirect tensile strength and fatigue life of the affected pavement and as such, an overlay or patching must be applied before the seal coat to improve the structural capacity of the affected pavement.

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