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IMPACT OF AGGREGATE GRADATIONS ON MIXTURES PERFORMANCE

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16. Abstract

This project evaluated the impact of various gradations on the performance of asphalt concrete mixtures and identified the better performing mixtures for each aggregate source. A total of 64 mix designs were completed (60 at UNR, and four at NDOT) with various combinations of aggregate sources, aggregate gradations and binders. A laboratory testing program was conducted to grade the asphalt binders based on the Superpave performance based grading system and evaluated the temperature susceptibility, moisture sensitivity, tensile strength, permanent deformation, and low temperature performance of the mixtures. All the testing was done in accordance with American Society of Testing and Materials standards.

Based on the results of the laboratory tests and analysis presented in this study, the following conclusions were made: the results showed that the percentage of optimum binder was dependent on the type and gradation of the aggregate and grade of the binder the finer the gradation of the aggregate, the higher the optimum asphalt cement due to higher surface area.

It was recommended that properties of the selected mixtures should be evaluated under the Superpave mixture analysis and performance prediction system, involving the evaluation of the selected mixtures using the simple shear testing (SST) device for permanent deformation and there indirect tension (IDT) device for low temperature.

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IMPACT OF AGGREGATE GRADATIONS ON MIXTURES PERFORMANCE

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1.0 INTRODUCTION

Asphalt concrete mixtures are rather complex materials to design, asphalt contents in excess of optimum may lead to problems like flushing and insufficient air voids space may yield a reduction in stability. On the other hand, asphalt contents below the optimum will jeopardize the long term durability of the mix and will produce a harsh mix that complicates laydown and construction operations. In general poorly graded aggregate leads to a high air voids requiring higher percentage of asphalt, and normally producing a low stability mixture. The large surface area of particles that is present in fine-grained mixes may present a problem of selective absorption of the asphalt which may lead to early hardening or aging of the mix (1).

The basic strength properties of asphalt concrete mixtures are derived from the cohesive strength of the bituminous material, the frictional resistance between the aggregate particles, and the interlocking resistance due to the compacted structure of the aggregate. Therefore the basic strength properties are greatly influenced by aggregate characteristics such as size, gradation, surface texture and shape of the aggregate.

Aggregate gradation is perhaps the most important element of an asphalt concrete mixture, it affects almost all of the physical properties of the mix. A maximum density gradation would provide increased stability. However, sufficient air voids space must be provided to permit enough asphalt cement to be incorporated to ensure durability and to avoid bleeding and/or rutting.

The Strategic Highway Research Program's (SHRP) Superpave has recommended a restricted zone along the maximum density line on the Federal Highway Administration's (FHWA) 0.45 power graph as shown in Figure 1 (2). The control points of the restricted zone depend on the nominal maximum size of aggregate. According to Superpave any gradation that pass above or below the restricted zone, but within the relevant control points, is expected to produce a good performing mixture.

1.1 OBJECTIVE

The objective of this research program is to evaluate the impact of various gradations on the performance of asphalt concrete mixtures. The measured performance indicators of the mix included: resilient modulus as a function of temperature, tensile strength, moisture susceptibility, permanent deformation, and low temperature cracking.

1.2 SCOPE

The scope of this research includes four aggregate sources, five gradations, and five grades of asphalt cement. The five distinctly different gradations selected for the study are shown in Figures 2a and 2b. These gradations are slightly different from one source to another. Gradation No.1 represents the actual mix design for the specific project constructed by the Nevada Department of Transportation (NDOT). Gradations No.2 and No.3 are developed according to the Superpave recommendations. Gradation No.4 is developed by combining the aggregate using the Texas Department of Transportation's grading factor which has resulted in a coarser gradation. Gradation No.5 represents one of NDOT's gradations which has shown excellent long term performance.

2.0 BACKGROUND

The design of asphalt concrete mixtures has long been an empirical process. The Hveem (ASTM D1560), and Marshall (ASTM D1559) are the two major methods of mixture designs used extensively by the asphalt community. These methods are considered to be empirical, that is, they are based on test values that have been established on the basis of observed field performance. Research is currently in progress to develop a mechanistic design procedure which will relate mixture properties to field performance. However, the existing mixture design procedures have a long history of acceptance.

The following is a brief review of the findings by various researchers concerning the commonly occurring distresses in asphalt pavements.

Rutting

Several studies were conducted by various researchers to identify variables most responsible for rutting formation. Brown et al (3) studied five pavement sections out of which four were found to have rutting while the fifth was considered to have no rutting after 10 years of service. Straight line regressions were used to develop correlations between rutting and mixture properties. The test results showed that low air voids are the cause of most rutting in the sections evaluated. The low air voids were due to over compaction and lack of quality control of the asphalt mixture during construction. The Marshall flow appeared to be a good indicator of rutting potential whereas the resilient modulus and indirect tensile strength values didn't significantly relate to rutting potential. In some cases stripping of the asphalt mixture had contributed to rutting of the sections. It was concluded that the stripping and rutting would have been minimized if high quality crushed aggregates had been used.

In 1987, the National Center for Asphalt Technology (NCAT) had initiated a comprehensive study to determine mixture properties and to identify procedures necessary for construction of rut resistant HMA pavements (4). In the study, forty-two pavements were sampled from fourteen states. The overall testing program of the study is shown in Figure 3. Analysis of the data concluded that most of the rutting was observed in the top 3-4 inches of HMA, necessitating high quality material in the top layers. Mixtures with in-place air voids contents below approximately 3.0% had experienced premature rutting. The properties of the asphalt cements extracted from the mixture were not closely related to rutting. Also the results of the study indicated that the angularity of the aggregate as measured by percent of coarse aggregate with 2 or more crushed faces help resist rutting if the in-place air voids are above 2.5%.

A laboratory analysis of the effect of varying the maximum aggregate size on rutting potential and on other properties of HMA was performed by Brown et al. (5). The study included maximum aggregate sizes of 3/8", 1/2", 3/4", 1", 1.5" of 100 percent crushed limestone. The gradation specifications for each maximum size aggregate followed the FHWA's recommendations. The mix designs were done using Marshall method. Six-inch and four-inch specimens were used in the study. Analysis of the data indicated that the six-inch diameter specimens generally showed better permanent deformation characteristics as the maximum size of aggregate increases whereas the four-inch diameter specimens generally showed an opposite trends as shown in Figure 4.

Huber et al (6) conducted field study on 11 pavement sections to investigate the rutting problem. The study concluded that asphalt content and voids filled with asphalt were the most significant parameters that affected rutting. Binder characteristics such as penetration and viscosity did not prove to be significant factors on rutting.

Carpenter and Enockson (7) studied 32 overlay projects in Illinois. Their analysis indicated that the majority of the rutting problems can be attributed to the properties of the aggregate gradation. The tender mix resulting from a hump in the 0.45 power gradation curve was found to be contributing to rutting. The percentage passing No. 40 sieve and retained on No. 80 sieve was found to influence rutting. The mixture strength tests showed that resilient modulus and indirect tensile strength hold a strong correlation to rutting. The study recommended to have control on density, air voids, and VMA during construction to mitigate rutting.

Moisture damage

Kennedy et al (8) had investigated an asphalt concrete overlay which had developed premature distress in the form of rutting, shoving, and bleeding. The research showed that the failure was due to moisture damage of the mixture. The test results indicated that the average value of Voids Filled with Asphalt (VFA) was 57.5 percent which is less than the recommended values leaving the mixture susceptible to moisture damage, and ravelling. All the three mixtures used in the project were deficient in material passing the No.200 sieve. It was felt that this lack of minus No. 200 material could have contributed to the overall damage to these moisture susceptible mixtures. The fine material normally helps to fill the space between larger aggregate, thus impeding the permeation of moisture throughout the mixture by minimizing the extent of interconnected voids. The research concluded that the basic causes of the premature distress of the pavement are: a) all aggregate and the resulting aggregate-asphalt combinations were highly susceptible to moisture damage and b) the anti-stripping additive used in the mixture was not effective.

Santucci et al (9) in a case study of moisture damage to asphalt pavements have concluded that the water from external sources such as rain and melting snow, in combination with traffic result in early distress of asphalt pavements. The damage is especially high if the pavement has relatively high air voids allowing the water easy entrance into the pavement. Moisture from internal sources such as inadequately dried aggregate can also result in early pavement distress. High air voids contents in dense graded asphalt pavements accelerates the hardening of the asphalt binder, and hence affect the long term durability of the pavement.

Low temperature cracking

Kandhal (10) studied six pavement sections in Elk county, Pennsylvania. Two of the six pavements developed extensive low temperature non-load associated cracking during the first severe winter. The study revealed that stiffness modulus of asphalt concrete is a better indicator of the potential for low temperature cracking of the pavement. The two sections which developed cracking, had higher stiffness modulus values than the remaining four. Temperature susceptibilities of the asphalts as indicated by the Penetration Index values have changed drastically after 20 months of aging. However, the same properties expressed by the Penetration Viscosity Number values were essentially unchanged.

Fromm and Phang (11) had studied a total of 33 pavement sections in both Southern and Northern Ontario to characterize low temperature cracking of bituminous pavements. The study concluded that the stiffness modulus of the asphalt concrete at low temperature is the major factor governing the low temperature cracking. The gradation of the base and subbase material has a small effect. Asphalts of good flow properties at low temperatures lead to pavements which display fewer low temperature cracking.

Ruth et al (12) have reported that the viscosity and temperature susceptibility of the asphalts have the greatest effect on the low temperature cracking of asphalt pavements. The modulus of asphalt concrete increases substantially with increased asphalt viscosity. Asphalt viscosity increases due to reduction in temperature and age hardening. The tensile stresses produced by vehicular loads will increase as the viscosity increases. Therefore, it is essential that the thickness of the asphalt concrete pavements be increased to reduce stresses to an acceptable level. High viscosity asphalts will require greater thickness of asphalt concrete than low viscosity asphalts to achieve tensile stresses that will not promote early cracking of the pavement.

Summary

As seen from the literature review, the maximum size and size distribution of aggregate significantly influence the properties of hot mix asphalt concrete. A dense graded aggregate produces a mixture stiffer than that produced by an open-graded mixture. The tender mix resulting from a hump in the 0.45 power gradation curve was found to contribute to rutting. Also, angular and crushed aggregate help resist rutting if the in-place air voids are above 3%.

The mixtures with deficiency in material passing the No.200 sieve could contribute to moisture damage. It was observed that fine aggregates normally help fill the spaces between larger aggregates, thus minimizing the permeation of moisture and thereby moisture damage. It was also revealed that resilient modulus of asphalt concrete has correlated well with low temperature cracking. Mixtures with higher stiffness modulus values are prone to low temperature cracking. This implies that open graded mixtures and mixtures made with softer grade of asphalt binder should have better low temperature characteristics.

This research will evaluate various mixtures designed with different gradations and asphalts. Thus the impact of various gradations on mixture properties will be evaluated.

3.0 RESULTS AND ANALYSIS

This section of the report presents the analysis of the data generated from the laboratory tests designed to characterize the binders and aggregates used in the research and to determine the engineering properties of the mixtures.

3.1 Materials

The materials used in this laboratory investigation consists of four sources of aggregates and five sources of asphalt binders. The four sources of aggregates are all from the following Nevada pits:

1. Rural Pit: Granite Rye Patch and Wahsworth
2. Frehner Sloan Pit
3. Apex and Overton Pit
4. Las Vegas Paving Lone Mtn Pit

The five binders are: a)AC-20, b)AC-20P_1, c)AC-20P_2, d)AC-30, and e)AC-30P. The AC-20 binder will only be used with the rural pit in place of the AC-30 binder. As mentioned under the scope of this study, a total of five different gradations (figures 2a, 2b) will be evaluated for each aggregate source and binder type combination. In each case the first gradation, labeled as G1, represents the gradation that was used on the actual job. The first part of this study was completed during 1994 and the second part was completed during 1995. Table 1 summarizes the combinations for the evaluated mixtures.

3.1.1 Aggregate characterization and blending

The aggregates from all four sources were blended to meet the designed gradations. Summary of the percentages of stockpiles used for each gradation is shown in Table 2 for all the aggregate sources. Table 3 summarizes the aggregate properties. As per NDOT plant mix specifications, the maximum absorption capacity for aggregate (plus #4 sieve) is 4% and the minimum fractured faces is 60%. Both of these specification limits were met for all the aggregates used in this study. The percent fractured faces, flat and elongated, and uncompacted voids properties were measured during the 1995 program. The rural aggregates were not available for the 1995 program, therefore, their properties were not measured.

3.1.2 Asphalt binder characterization

The five binders (AC-20, AC-20P_1, AC-20P_2, AC-30, and AC-30P) used in the research have been graded based on the Superpave grading system. The first step in grading a given binder consists of checking its flash point for safety regulations and viscosity against the specification limits. The Superpave specification limits call for a minimum flash point of 230°C and a maximum viscosity of 3 Pa*s at 135°C.

Further the specified limit for the percentage weight loss after RTFOT is 1%. The flash point, viscosity, and percentage weight loss data given in Table 4 indicate that all the binders are within the specifications. The AC-30P binder has a high rotational viscosity relative to the other four binders but still within the Superpave specification limits.

The rheological properties of the binders are summarized in Tables 5 through 9. The final grades of the binders are as follows:

Binder	Grade
AC-20	PG 64-22
AC-20P$_1$	PG 64-28
AC-20P$_2$	PG 58-22
AC-30	PG 64-22
AC-30P	PG 70-22

The fact that the AC-20 and AC-30 binders are from the same supplier and still graded the same, was a big surprise. Also the AC-20P$_2$ having a low temperature grade similar to the AC-20, AC-30, and AC-30P binders is little bit unusual. In order to verify the grades, multiple replicates were tested from both binders by independent operators. Even with multiple replicates and multiple operators, the data still indicated the same grades. This represents one of the major issues that the implementation of the Superpave grading process will have to face.

3.2 Mixture Designs

The Hveem mix design presented in the Asphalt Institute's manual series number 2 was followed to arrive at the optimum percentage of asphalt content. The mix designs data are shown in Tables 10 through 13. The optimum asphalt contents have been selected based on the following NDOT criteria for Hveem mix design for hot mixed asphalt (HMA) mixtures:

Mixture Type	Min. Hveem Stab.	Air Voids	Min. VMA
Type 2 and Type 2C	35	3-6	12
Type 2C in Las Vegas	37	3-7	12
Type 2C on Interstate	37	3-7	12

The following mixtures were eliminated because an acceptable mix design could not be found:

Mixture	Failed Criteria
Rural-G5-AC-20	Stability
Sloan-G5-AC-20P_2	VMA
Sloan-G2-AC-30P	VMA
Apex-G4-AC-30	Stability
Apex-G1-AC-20P_2	VMA
Apex-G2-AC-20P_2	VMA
Apex-G5-AC-20P_2	VMA
Apex-G1-Ac-30P	VMA
Apex-G2-AC-30P	Air Voids
Vegas-G5-AC-30	Stability
Vegas-G2-AC-20P_2	VMA
Vegas-G3-AC-20P_2	Air Voids
Vegas-G5-AC-20P_2	Air Voids
Vegas-G1-AC-30P	Air Voids
Vegas-G3-AC-30P	Air Voids
Vegas-G5-AC-30P	Air Voids

The results show that the percentage of optimum binder is dependent on the type and gradation of the aggregate and the grade of asphalt cement. The finer the gradation of the aggregate, the higher the optimum asphalt content due to higher surface area.

3.3 Selection of Best Mixtures

Several selection criteria were established to select the best mixtures from each aggregate source. The selection process consisted of the following:

1. Select the set of mixtures that meet certain criteria for resilient modulus (Mr), Tensile strength (TS), and retained strength ratios.

2. Evaluate the selected mixtures from step 1 under the repeated load triaxial permanent deformation test. Base on the results of the permanent deformation test, recommend the best mixtures for the low temperature cracking test.

3. Evaluate the low temperature properties of the selected mixtures from step 2 using the thermal stress restrained specimen test (TSRST).

3.3.1 Selection of mixtures based on Mr, TS, and strength ratios

The selection criteria were selected based on the analysis of NDOT's mixtures properties data base as summarized in reference 13 and the current NDOT's mixtures specifications. The adopted criteria are as follows:

a. Minimum resilient modulus at 77°F of 215,000 psi for AC-20P's mixtures and 270,000 psi for all other mixtures.

b. Minimum resilient modulus at 104°F of 50,000 psi.

c. Minimum tensile strength at 77°F of 65 psi.

d. Minimum resilient modulus and tensile strength retained ratios of 70%.

Mr values can be used to evaluate the relative quality of the materials as well as to generate input for pavement design or pavement evaluation and analysis. Also one of the desired properties of a hot mix asphalt concrete is to have a low temperature susceptibility, i.e. less variation in the modulus values as a function of temperature.

Low moisture sensitivity of a mixture is desirable to eliminate stripping problems. For assessing the moisture damage, the resilient modulus and tensile strength are measured before and after moisture conditioning of samples to determine the retained strength as a percent of the original strength. A high number indicates that good performance is expected while a low number indicates that poor performance is expected.

The test results of Mr, TS, temperature and moisture susceptibility are compared with the above listed criteria. As mentioned earlier, the mixtures which meet the specification limits from each aggregate source are selected for further evaluation under the permanent deformation and TSRST.

Only one mixture have failed the resilient modulus criteria. The Vegas-G4-AC-30P mixture had a Mr at 77°F of 208,000 psi which is below the criteria of 270,000 psi.

Tables 14 through 17 summarize the Mr data for the selected mixtures.

None of the mixtures failed the tensile strength criteria. Tables 18 through 21 summarizes the tensile strength data for the selected mixtures. However, several mixtures have failed the strength ratios criteria:

Mixture	Failed Criteria
Rural-G1-AC-20P_1	Mr ratio
Rural-G3-AC-20P_1	Mr ratio
Rural-G4-AC-20P_1	Mr and TS ratios
Rural-G5-AC-20P_1	Mr ratio
Rural-G1-AC-20	Mr and TS ratio
Rural-G3-AC-20	Mr ratio
Rural-G4-AC-20	Mr and TS ratios
Sloan-G1-AC-20P_1	Mr and TS ratios
Sloan-G2-AC-20P_1	Mr ratio
Sloan-G5-AC-20P_1	TS ratio
Sloan-G2-AC-30	Mr and TS ratios
Sloan-G3-AC-30	Mr and TS ratios
Sloan-G4-AC-30	Mr and TS ratios
Sloan-G5-AC-30	Mr and TS ratios
Sloan-G4-AC-20P_2	Mr ratio
Apex-G1-AC-20P_1	Mr ratio
Apex-G1-AC-30	TS ratio
Apex-G5-AC-30	TS ratio
Vegas-G2-AC-30P	Mr ratio

Tables 22, 23, and 24 summarize the strength ratios for the mixtures that passed the moisture sensitivity criteria. At this point, all of the mixtures from the rural pit have been eliminated either through the mix design or the strength ratios criteria. As can be seen from the above data summary, the rural aggregates have problems satisfying both the Mr and TS ratios. This would indicate that mixtures produced from this source would be highly susceptible to moisture damage. It should be noted that all of the evaluated mixtures included 1.5% lime.

3.3.2 Selection of mixtures based on permanent deformation

The mixtures that made the cut through the strength values and strength ratios criteria were evaluated using the triaxial permanent deformation test at 104°F temperature under dry conditions. The test consists of subjecting the asphalt concrete sample (4"x8") to a constant confining pressure and a repeated deviator stress (0.1 sec duration and 0.5 sec rest period) and measuring the accumulated permanent vertical strain over the entire height of the specimen. Figure 5 shows a typical relationship between the permanent strain and number of load cycles. Two replicates were tested for each selected mixture. Table 25 summarizes the permanent strain data for the selected mixtures.

The permanent deformation criteria calls for a maximum allowable permanent strain of 1% under 12,000 cycles. The permanent deformation data in table 25 indicate that a total of six mixtures would perform well for the Sloan aggregates, eight mixtures would perform well for the Apex aggregates, and six mixtures would perform well for the Las Vegas aggregates.

The data in Table 25 indicate that the source and gradation of the aggregate plays a significant role on the resistance of the mixture to permanent deformation. In the case of Sloan aggregates, the AC-30P mixtures experienced 0.56% permanent strain with gradation G1 while it experienced 1.45% permanent strain with gradation G5. Also in the case of Las Vegas aggregates, the AC-20P_2 mixtures experienced 0.53% permanent strain with gradation G1 while it experienced 3.3% permanent strain with gradation G4. It should be noted that the G1 gradation represents the actual gradation that NDOT used on both projects.

When evaluating the impact of the aggregate source, it can be seen that the G5-AC-30P mixtures with sloan aggregates experienced 1.45% permanent strain while the same mixture (i.e. same binder and gradation) experienced 0.86% permanent strain with Apex aggregates.

The permanent deformation data also indicate that the AC-20P mixtures with the appropriate aggregate gradation would have the same resistance to rutting as the AC-30 and AC-30P mixtures. For example, the Sloan aggregates with G3-AC-20P_1 experienced 0.32% permanent strain while the same aggregate with AC-30 experienced a 0.30% permanent strain.

3.3.3 Selection of mixtures based on TSRST

The TSRST was used to predict the low temperature performance of the selected mixtures. The most important parameters measured during the test is the fracture temperature at the point of failure. Table 26 summarizes the TSRST test results. The mixtures were evaluated based on the premise that higher fracture stress and lower fracture temperature indicate better low temperature resistance.

There is no actual failure criteria for the TSRST. The results of the test indicate the lowest temperature under which the mixture is expected to perform without the development of low temperature cracks. Therefore, the lower the cracking temperature the better the mixture would be in resisting low temperature cracking.

Table 27 summarizes the fracture temperatures for each binder type for all aggregate sources and the selected gradations. The data in Table 27 leads to the following observations:

1. The fracture temperatures of the mixtures are lower than the binders low temperature grades.

2. The polymer modified mixtures showed lower fracture temperatures than the unmodified mixtures.

3. The AC-20P_1 mixtures showed the lowest fracture temperatures while the AC-20P_2 mixtures fracture temperatures were similar to the AC-30P mixtures. This strongly supports the reason why the AC-20P_2 has similar low temperature grade as the AC-30P binder.

4. The binder plays a major role in controlling the fracture temperature of the mixture regardless of the aggregate source and gradation. This is supported by the low coefficient of variations for the fracture temperatures (below 10%) for all binders. For example, mixtures made with the AC-20P_1 binders had a mean fracture temperature of -35.5°C and a standard deviation (STD) of 1.4°C when considering all aggregate sources and gradations combined. Such a low STD indicates that all

AC-20P$_1$ mixtures would crack at nearly the same temperatures.

3.4 Selection of the Most Desirable Mixtures

The most desirable properties of HMA mixtures consist of high resilient modulus at 77°F, high tensile strength retained ratio, good resistance to permanent deformation, and good resistance to low temperature cracking.

Using these criteria, the mixtures from each aggregate source were ranked for each category as shown in Tables 28, 29, and 30. It should be noted that the mixtures ranked in Tables 28, 29, and 30 are the ones that have passed the strength and performance criteria. The final step is to rank the mixtures based on their performance under all criteria combined. For this purpose, the sum column of Tables 28, 29, and 30 will be used where the mixture with the lowest sum will be ranked first while the one with the highest sum will be ranked last. The following ranking was obtained:

Aggregate Source	Mixture	Rank	Sum
Sloan	G3-AC-20P$_1$	1	8
	G3-AC-30P	2	9
	G1-AC-30	3	12
	G1-AC-30P	4	14
	G4-AC-30P	5	17
Apex	G2-AC-20P$_1$	1	9
	G3-AC-20P$_1$	2	11
	G3-AC-20P$_2$	3	15
	G5-AC-30P	3	15
	G3-AC-30P	4	16
	G4-AC-30P	5	18

Las Vegas	G1-AC-20P_1	1	7
	G1-AC-30	2	10
	G1-AC-20P_2	3	11
	G4-AC-30	4	12

Since it was already proven in this research that the low temperature behavior of the mixture is significantly controlled by the binder, another ranking system was established which excluded the fracture temperature criteria and directly assess the impact of aggregate gradations. The following mixtures were ranked based on the Mr at 77°F, TS ratio, and permanent deformation criteria:

Aggregate Source	Mixture	Rank	Sum
Sloan	G1-AC-30	1	7
	G3-AC-20P_1	1	7
	G3-AC-30P	1	7
	G1-AC-30P	2	11
	G4-AC-30P	3	13
Apex	G2-AC-20P_1	1	8
	G3-AC-20P_1	1	8
	G3-AC-20P_2	2	10
	G3-AC-30P	2	10
	G5-AC-30P	3	13
	G4-AC-30P	4	14
Las Vegas	G1-AC-20P_1	1	6
	G1-AC-30	2	7
	G4-AC-30	3	8
	G1-AC-20P_2	4	9

It can be seen that the elimination of the fracture temperature criteria only introduced minor adjustments in the ranking of the mixtures in favor of the G1 gradation which represents the one selected by NDOT for the specific project.

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary:

The objective of this research program is to evaluate the impact of various gradations on the performance of asphalt concrete mixtures and to identify the better performing mixtures for each aggregate source.

A total of 64 mix designs were completed (60 at UNR, and four at NDOT) with various combinations of aggregate sources, aggregate gradations and binders. A laboratory testing program was conducted to grade the asphalt binders based on the Superpave performance based grading system and to evaluate the temperature susceptibility, moisture sensitivity, tensile strength, permanent deformation, and low temperature performance of the mixtures.

All the testing was done in accordance with American Society of Testing and Materials standards.

4.2 Conclusions:

Based on the results of the laboratory tests and analysis presented in this study, the following conclusions can be made:

1. The results show that the percentage of optimum binder is dependent on the type and gradation of the aggregate and grade of the binder. The finer the gradation of the aggregate, the higher the optimum asphalt cement due to higher surface area.

2. A total of 16 mixtures failed the NDOT Hveem criteria. Three mixtures failed the stability criteria, six mixtures failed the air voids criteria, and seven mixtures failed the VMA criteria. The failed mixtures were not evaluated under the next part of the program.

3. All of the mixtures that made it through the mix design criteria except one (Las Vegas-G4-AC-30P) have passed the Mr at 77°F, Mr at 104°F, and TS at 77°F criteria.

4. Dense graded mixtures gave higher Mr values at different temperatures than the open graded (G4) mixtures. The Mr values are also influenced by the grade of asphalt (i.e. mixtures with the AC-20 and the AC-30 binders produced higher Mr values than the mixtures with the AC-20P binder).

5. The moisture susceptibility criteria have proven to be the most restricted criteria. A total of 19 mixtures have failed either the Mr or TS ratio criteria. The Las Vegas aggregate source showed the least problem with moisture sensitivity while the Rural and Sloan aggregates showed the worst problem. Eight mixtures failed the Mr ratio criteria, three mixtures failed the TS ratio criteria, and eight mixtures failed both the Mr and TS

ratio criteria. The most surprising observation was that the entire set of mixtures of the Rural aggregates was eliminated based on the moisture sensitivity criterion.

6. The permanent deformation data showed that only 3 out of 23 mixtures have failed the permanent deformation criterion. Two Sloan and one Las Vegas mixtures have failed the 1% permanent strain criterion. The two Sloan mixtures can be considered as borderline since only one of the two samples failed which made the average of the two samples above 1%. The low number of mixtures failing the permanent deformation criterion indicates that the Mr at 77°F and 104°F criteria can be adequately used to ensure good resistance to permanent deformation.

7. The TSRST data indicate that the binder is the main contributor to the mixture's resistance to low temperature cracking. The polymer modified mixtures have shown better resistance to low temperature cracking than the unmodified mixtures regardless of the aggregate source and gradation. Also the aggregate gradation has a minor impact on the low temperature cracking resistance of the mixture.

8. Based on the data generated from this project and the data analysis presented in this report, it is recommended

that NDOT uses the Mr and TS at 77°F, Mr at 104°F, and TS ratio properties to select the best gradation for a given aggregate source and rely on the selection of the binder to provide the resistance to low temperature cracking wherever it is needed. Following this recommendation, it was concluded that the G1 gradation that NDOT is currently using generates the best performance for the Sloan and Las Vegas aggregates. In the case of the Apex aggregate, NDOT should consider using the G3 gradation. The G3 gradation is very similar to the G1 gradation except the G3 is little coarser and it does go below the Superpave restricted zone while the G1 goes through the Superpave restricted zone. In the case of the Rural aggregates additional gradations should be investigated to ensure good performing mixtures.

9. The properties of the selected mixtures should be evaluated under the Superpave Mixture analysis and performance prediction system. This will involve the evaluation of the selected mixtures using the simple shear testing (SST) device for permanent deformation and the indirect tension (IDT) device for low temperature.

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Table 1: Combinations of gradations and binders used.

Year	Pit	Gradation	Binder
1994	Rural	G1, *, G3, G4, G5	AC-20, AC-20P$_1$
	Frehner Sloan	G1, G2, G3, G4, G5	AC-30, AC-20P$_1$
	Apex	G1, G2, G3, G4, G5	AC-30, AC-20P$_1$
	Las Vegas	G1, G2, +, G4, G5	AC-30, AC-20P$_1$
1995	Frehner Sloan	G1, G2, G3, G4, G5	AC-20P$_2$, AC-30P
	Apex	G1, G2, G3, G4, G5	AC-20P$_2$, AC-30P
	Las Vegas	G1, G2, +, G4, G5	AC-20P$_2$, AC-30P

$_1$- 1994 Conoco AC-20P
$_2$- 1995 Telfer Sheldon AC-20P
*- Gradation G2 coincides with gradation G5
+- Gradation G3 coincides with Gradation G4

Table 2 :Summary of percentages of stockpiles for all gradations of all aggregate sources.

Aggr.source	Stockpile (%)					
Rural pit	Gradation	1"	3/4"	3/8"	C.Fines	W.Sand
	G1	14	27	14	33	12
	G3	18	48	0	26	8
	G4	14	43	23	20	0
	G5	0	0	60	32.5	7.5
Frehner Sloan pit 1994	Gradation	Coarse	Inter.	W.C.Fines	W.C.Sand	x
	G1	25	15	45	15	x
	G2	28	10	27	35	x
	G3	39	16	22	23	x
	G4	33	30	27	10	x
	G5	0	33	50	17	x
Frehner Sloan pit 1995	Gradation	Coarse	Inter.	W.C.Fines	W.C.Sand	x
	G1	25	26	17.2	31.8	x
	G2	24	17.3	19.8	39	x
	G3	42	24	12	22	x
	G4	37	32	11	20	x
	G5	0	45	15	40	x
Apex pit	Gradation	Coarse	Inter.	C.Fines	A.Fines	O.Fines
	G1	26	22	31	15	6
	G2	22	12	36	30	0
	G3	28	24	23	25	0
	G4	30	33	16	21	0
	G5	0	38	40	22	0
Las vegas Paving pit	Gradation	3/4"	1/2"	C.Fines	N.Sand	x
	G1	25	10	45	20	x
	G2	21	10	29	40	x
	G4	30	26	29	15	x
	G5	0	35	40	25	x

Table 3: Aggregates Properties.

Pit	Property	G1		G2		G3		G4		G5	
		Fine	Co.	Fine	Co.	Fine	Co.	Fine	Co.	Fine	Co.
Rural	Bulk sp gr	2.573	2.680			2.596	2.692	2.601	2.713	2.563	2.673
	Bulk sp gr SSD	2.588	2.694			2.603	2.723	2.624	2.732	2.581	2.698
	Apparent sp gr	2.776	2.803			2.786	2.819	2.797	2.822	2.754	2.807
	Abs. Cap (%)	2.71	0.68			2.48	0.57	2.31	0.59	2.60	0.71
Frehner Sloan	Bulk sp gr	2.678	2.819	2.636	2.807	2.667	2.800	2.708	2.790	2.660	2.787
	Bulk sp gr SSD	2.709	2.827	2.698	2.824	2.720	2.813	2.757	2.805	2.720	2.803
	Apparent sp gr	2.732	2.832	2.810	2.856	2.816	2.836	2.819	2.837	2.831	2.822
	Abs. Cap (%)	2.51	0.59	2.36	0.61	1.98	0.47	1.83	0.63	2.27	0.71
	2 Fractured Faces (%)	-	93.1	-	93.2	-	93.5	-	93.1	-	91.0
	1 Fractured Face (%)	-	99.5	-	99.6	-	99.6	-	99.5	-	99.0
	Flat & Elongaed Particles (%)	-	0.0	-	0.0	-	0.0	-	0.0	-	0.0
	Uncompacted Void Content, U_1, (%)	50.4	-	49.2	-	49.8	-	50.8	-	49.5	-

Table 3 : Aggregates Poperties (continued).

Pit	Property	G1		G2		G3		G4		G5	
		Fine	Co.	Fine	Co.	Fine	Co.	Fine	Co.	Fine	Co.
Apex	Bulk sp gr	2.523	2.690	2.519	2.656	2.573	2.713	2.648	2.729	2.594	2.686
	Bulk sp gr SSD	2.593	2.710	2.584	2.673	2.631	2.724	2.680	2.737	2.676	2.703
	Apparent sp gr	2.697	2.734	2.693	2.702	2.730	2.744	2.734	2.759	2.827	2.733
	Abs. Cap (%)	2.71	0.68	2.56	0.63	2.24	0.42	1.7	0.50	3.20	0.64
	2 Fractured Faces (%)	-	97.1	-	97.3	-	97.1	-	96.9	-	96.0
	1 Fractured Face (%)	-	99.0	-	99.0	-	99.0	-	99.0	-	99.0
	Flat & Elongaed Particles (%)	-	0.9	-	1.0	-	0.9	-	0.9	-	0.5
	Uncompacted Void Content, U_r, (%)	49.22	-	50.4	-	51.4	-	52.8	-	51.7	-
Las Vegas	Bulk sp gr	2.599	2.791	2.595	2.746			2.603	2.821	2.593	2.780
	Bulk sp gr SSD	2.663	2.808	2.669	2.786			2.678	2.827	2.658	2.805
	Apparent sp gr	2.817	2.822	2.803	2.808			2.795	2.832	2.803	2.818
	Abs. Cap (%)	2.64	0.77	2.86	0.81			2.59	0.77	2.71	0.74
	2 Fractured Faces (%)	-	84.9	-	85.5			-	87.9	-	97.0
	1 Fractured Face (%)	-	93.2	-	93.5			-	94.5	-	98.6
	Flat & Elongaed Particles (%)	-	0.1	-	0.1			-	0.1	-	0.2
	Uncompacted Void Content, U_r, (%)	51.0	-	50.1	-			51.1	-	51.0	-

Table 4 : Flash point, viscosity, performance grade, and mass loss data of the binders.

Binder type	Flash point (°C)	Viscosity (Pa*sec)	% mass loss (RTFOT)	PG Grade
AC-20P[1]	266	0.642	0.21	64-28
AC-20P[2]	251	0.363	0.36	58-22
AC-20	288	0.367	0.17	64-22
AC-30	244	0.442	0.15	64-22
AC-30P	284	2.567	0.08	70-22*

[1]- 1994 Conoco AC-20P

[2]- 1995 Telfer Sheldon AC-20P

* - 0.7°C from being a PG 76-22

Table 5 : Rheological properties of the AC-20 binder.

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	G^*/sinδ kPa	Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	G^*/sinδ kPa
70	25	6	-	-	-	70	25	6	-	-	-
64	"	"	1.46	86.3	1.462	64	"	"	5.612	80.46	5.691
58	"	"	3.92	83.5	3.945	58	"	"	10.56	78.86	10.77
52	"	"	6.86	82.4	6.924	52	"	"	21.01	75.98	21.66

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G^*, MPa	Phase angle δ	G^*sinδ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1	2.232	44.9	1.576	-9.9	98	0.33	-	-	-
22	"	"	3.681	44.1	2.56	-19.8	289	0.26	-	-	-
19	"	"	6.623	38.7	4.14	-	-	-	-	-	-
16	"	"	13.73	35.5	7.965	-	-	-	-	-	-

1. Original: Tmax
   Temperature at which G^*/sinδ = 1.0 KPa = 67.5°C

2. RTFOT: Tmax
   Temperature at which G^*/sinδ = 2.2 KPa = 72.4°C

3. DSR-PAV: Tint
   Temperature at which G^*(sinδ) = 5.0 KPa = 18.3°C

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa = -20.4°C
   Temperature at which m = 0.30 = -14.4°C

Table 6 : Rheological properties of the 1994 AC-20P$_1$ binder.

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa	Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa
70	25	6	-	-	-	70	25	6	-	-	-
64	"	"	1.06	78.3	1.081	64	"	"	2.509	77.05	2.575
58	"	"	1.92	77.36	1.963	58	"	"	4.830	75.72	4.985
52	"	"	4.05	76.04	4.174	52	"	"	11.30	73.99	11.760

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G^*, MPa	Phase angle δ	$G^*\sin\delta$ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1	1.40	52.59	1.112	-10	66	0.38	-	-	-
22	"	"	2.43	50.46	1.870	-19.5	228	0.31	-	-	-
19	"	"	5.46	46.94	3.992	-	-	-	-	-	-
16	"	"	8.39	37.34	5.090	-	-	-	-	-	-

1. Original: Tmax
   Temperature at which $G^*/\sin\delta$ = 1.0 KPa = 64.4°C

2. RTFOT: Tmax
   Temperature at which $G^*/\sin\delta$ = 2.2 KPa = 64.7°C

3. DSR-PAV: Tint
   Temperature at which $G^*(\sin\delta)$ = 5.0 KPa = 16.7°C

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa = -23.7°C
   Temperature at which m = 0.30 = -20.86°C

Table 7 : Rheological properties of AC-30 binder.

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa	Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa
70	25	6	0.85	87.5	0.85	70	25	6	2.01	83.9	2.03
64	"	"	1.81	86.1	1.81	64	"	"	6.36	79.6	6.47
58	"	"	4.22	83.6	4.25	58	"	"	16.15	76.9	16.6
52	"	"	10.53	80.6	10.7	52	"	"	26.7	75.9	27.8

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G^*, MPa	Phase angle δ	$G^*\sin\delta$ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1	5.22	42.9	0.96	-5	60	0.35		-	-
22	"	"	9.38	39.7	5.99	-10	112	0.32		-	-
19	"	"	12.7	37.4	7.71					-	-
16	"	"	18.1	35.6	10.53					-	-

1. Original: Tmax
   Temperature at which $G^*/\sin\delta$ = 1.0 KPa = 67.9°C

2. RTFOT: Tmax
   Temperature at which $G^*/\sin\delta$ = 2.2 KPa = 73.5°C

3. DSR-PAV: Tint
   Temperature at which $G^*(\sin\delta)$ = 5.0 KPa = 19.7°C

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa = -17.8°C
   Temperature at which m = 0.30 = -13.3°C

Table 8 : Rheological properties of the 1995 AC-$20P_2$ binder.

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa	Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa
70	25	12.5	0.541	67.2	0.5864	70	25	10	1.275	85.9	1.2783
64	"	"	0.918	70.3	0.9745	64	"	"	2.645	83.8	2.6605
58	"	"	1.717	73.1	1.7946	58	"	"	5.749	84.1	5.8144
52	"	"	3.451	74.6	3.5770	52	"	"	12.82	79.0	12.8562

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G^*, MPa	Phase angle δ	$G^*\sin\delta$ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1	1.603	58.9	1.3725	-10	126	0.43	-	-	-
22	"	"	2.868	56.3	2.3852	-20	544	0.24	-	-	-
19	"	"	4.987	53.6	4.0124	-	-	-	-	-	-
16	"	"	8.635	49.8	6.5973	-	-	-	-	-	-

1. Original: Tmax
   Temperature at which $G^*/\sin\delta$ = 1.0 KPa = 63.8°C

2. RTFOT: Tmax
   Temperature at which $G^*/\sin\delta$ = 2.2 KPa = 64.9°C

3. DSR-PAV: Tint
   Temperature at which $G^*(\sin\delta)$ = 5.0 KPa = 17.7°C

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa = -15.9°C
   Temperature at which m = 0.30 = -16.0°C

Table 9 : Rheological properties of the AC-30P binder.

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G*, kPa	Phase angle δ	G*/sinδ kPa	Temp, C	Plate Diam., mm	Strain, %	G*, kPa	Phase angle δ	G*/sinδ kPa
70	25	6	1.60	82.8	1.61	70	25	6	3.96	79.4	4.02
64	"	"	3.21	80.0	3.26	64	"	"	6.71	75.5	6.93
58	"	"	5.50	76.1	5.66	58	"	"	11.35	72.3	11.92
52	"	"	9.20	72.2	9.66	52	"	"	-	-	-

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G*, MPa	Phase angle δ	G*sinδ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1	6.57	39.6	4.19	-10.4	218	0.32	-	-	-
22	"	"	9.55	37.9	5.87	-20.2	676	0.22	-	-	-
19	"	"	-	-	-	-	-	-	-	-	-
16	"	"	-	-	-	-	-	-	-	-	-

1. Original: Tmax
   Temperature at which G*/sinδ = 1.0 KPa = 75.3°C

2. RTFOT: Tmax
   Temperature at which G*/sinδ = 2.2 KPa =76.7°C

3. DSR-PAV: Tint
   Temperature at which G*(sinδ) = 5.0 KPa = 23.4°C

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa = -12.2°C
   Temperature at which m = 0.30 = -12.4°C

Table 10 : Mix design results of Rural pit aggregate mixtures.

Gradation	Binder Type	Opt. AC(%) Dry wt of agg	Stab. No.	Va (%)	Gsb	Gmb	VMA (%)	VFA (%)
G1	AC-20P[1]	4.7	49	4.3	2.64	2.367	14.4	70.1
G3	AC-20P[1]	4	41	4.2	2.68	2.363	15.2	72.4
G4	AC-20P[1]	3.8	37	5	2.701	2.34	16.5	69.8
G5	AC-20P[1]	4.8	35	5.8	2.663	2.32	16.9	65.6
G1	AC-20	4.8	37	4	2.64	2.351	15.0	73.4
G3	AC-20	4.1	35	4.2	2.68	2.365	15.2	72.4
G4	AC-20	3.8	35	5	2.701	2.342	16.5	69.6

Va = air voids, percent of total volume

Gsb = bulk sp. gr. of total aggregate

Gmb = bulk sp. gr. of compacted mixture

[1]- 1994 Conoco AC-20P

Table 11 : Mix design results of Frehner Sloan pit aggregate mixtures.

Gradation	Binder Type	Opt. AC(%) Dry wt of agg	Stab. No.	Va (%)	Gsb	Gmb	VMA (%)	VFA (%)
G1	AC-20P[1]	4.3	47	4.2	2.81	2.5	14.7	71.4
G2	AC-20P[1]	4.3	42	4	2.798	2.525	13.5	70.3
G3	AC-20P[1]	3.8	38	4.4	2.78	2.507	13.1	66.5
G4	AC-20P[1]	3.6	42	4.3	2.789	2.501	13.4	68.0
G5	AC-20P[1]	4.6	37	4.8	2.765	2.478	14.3	66.5
G1	AC-30	4.2	49	4.4	2.81	2.498	14.7	70.0
G2	AC-30	4.3	44	4	2.798	2.54	13.0	69.1
G3	AC-30	3.7	40	4	2.78	2.509	13.0	69.2
G4	AC-30	3.6	39	4	2.789	2.503	13.4	70.1
G5	AC-30	4.4	38	4.7	2.765	2.462	14.7	68.1
G1	AC-20P[2]	4.25	37	4	2.747	2.522	12	65
G2	AC-20P[2]	4.7	40	4	2.704	2.497	12	65
G3	AC-20P[2]	3.75	42	4	2.752	2.507	12.25	65
G4	AC-20P[2]	3.75	46	4	2.763	2.503	12	66
G1	AC-30P	5.25	41	4	2.747	2.59	13.8	72
G3	AC-30P	3.75	41	3.8	2.752	2.53	12	65
G4	AC-30P	3.75	49	3.75	2.763	2.467	14	57
G5	AC-30P	6	42	5.25	2.634	2.452	12.2	63

Va = air voids, percent of total volume

Gsb = bulk sp. gr. of total aggregate

Gmb = bulk sp. gr. of compacted mixture

[1]- 1994 Conoco AC-20P

[2]- 1995 Telfer Sheldon AC-20P

Table 12 : Mix design results of Apex pit aggregate mixtures.

Gradation	Binder Type	Opt. AC(%) Dry wt of agg	Stab. No.	Va (%)	Gsb	Gmb	VMA (%)	VFA (%)
G1	AC-20P$_1$	4	42	5.4	2.68	2.4	13.9	61.1
G2	AC-20P$_1$	4.1	43	4	2.65	2.423	12.2	67.1
G3	AC-20P$_1$	3.7	47	4	2.701	2.448	12.6	68.3
G4	AC-20P$_1$	3.6	36	4.3	2.726	2.44	13.6	68.4
G5	AC-20P$_1$	3.9	40	4	2.689	2.451	12.3	67.4
G1	AC-30	4	39	5.1	2.68	2.398	14.0	63.5
G2	AC-30	4.2	40	4	2.65	2.422	12.3	67.4
G3	AC-30	3.7	48	4	2.701	2.428	13.3	70.0
G5	AC-30	3.8	39	4	2.689	2.45	12.2	67.3
G3	AC-20P$_2$	3.8	43	4	2.651	2.432	12.1	65
G4	AC-20P$_2$	4.5	36	5.75	2.701	2.405	15.1	67
G3	AC-30P	3.75	38	4	2.651	2.388	12.75	65
G4	AC-30P	3.25	37	4	2.701	2.349	15.5	75
G5	AC-30P	5.2	42	4	2.633	2.342	15.4	70

Va = air voids, percent of total volume

Gsb = bulk sp. gr. of total aggregate

Gmb = bulk sp. gr. of compacted mixture

$_1$- 1994 Conoco AC-20P

$_2$- 1995 Telfer Sheldon AC-20P

Table 13 : Mix design results of Las Vegas pit aggregate mixtures.

Gradation	Binder Type	Opt. AC(%) Dry wt of agg	Stab. No.	Va (%)	Gsb	Gmb	VMA (%)	VFA (%)
G1	AC-20P[1]	4.3	37	4	2.78	2.477	14.6	72.6
G2	AC-20P[1]	4.4	41	4	2.722	2.48	12.7	68.6
G4	AC-20P[1]	3.8	38	4.7	2.829	2.478	15.6	69.9
G5	AC-20P[1]	4.4	34	4.3	2.679	2.477	14.3	70.0
G1	AC-30	4.5	39	4.2	2.78	2.463	15.2	72.4
G2	AC-30	4.5	38	4	2.722	2.493	12.4	67.6
G4	AC-30	3.7	37	4.6	2.829	2.47	15.8	70.9
G1	AC-20P[2]	4.7	44	3.9	2.684	2.478	12.7	65
G4	AC-20P[2]	4.8	37	4.2	2.733	2.463	14.2	66
G2	AC-30P	5.6	40	4	2.654	2.383	15	67
G4	AC-30P	5.8	37	4	2.733	2.4	17.1	78

Va = air voids, percent of total volume

Gsb = bulk sp. gr. of total aggregate

Gmb = bulk sp. gr. of compacted mixture

[1]- 1994 Conoco AC-20P

[2]- 1995 Telfer Sheldon AC-20P

Table 14 : Mr at different temperatures for the Rural pit aggregate mixtures.

Sample #	Mr at 77°F (dry)	Mr at 77°F (wet)	Mr at 104°F	Mr at 34°F
G1 AC-20P[1]	510	250	120	2467
G3 AC-20P[1]	450	215	109	2477
G4 AC-20P[1]	400	185	119	1754
G5 AC-20P[1]	428	202	123	2340
G1 AC-20	702	278	222	2886
G3 AC-20	706	278	120	3722
G4 AC-20	454	307	130	3317

[1]- 1994 Conoco AC-20P

* All Values in ksi

Table 15 : Mr at different temperatures for the Frehner Sloan pit aggregate mixtures.

Sample #	Mr at 77°F (dry)	Mr at 77°F (wet)	Mr at 104°F	Mr at 34°F
G1 AC-20P$_1$	363	170	92	3307
G2 AC-20P$_1$	541	313	119	2980
G3 AC-20P$_1$	381	307	102	2374
G4 AC-20P$_1$	310	243	83	1768
G5 AC-20P$_1$	318	267	119	2628
G1 AC-30	737	510	230	4296
G2 AC-30	860	328	199	5476
G3 AC-30	695	355	170	2361
G4 AC-30	429	211	121	2113
G5 AC-30	655	337	149	2724
G1 AC-20P$_2$	274	219	39	2427
G2 AC-20P$_2$	300	228	48	3388
G3 AC-20P$_2$	214	186	62	3282
G4 AC-20P$_2$	319	134	82	4284
G1 AC-30P	335	285	105	2872
G3 AC-30P	384	295	70	1578
G4 AC-30P	372	242	100	1891
G5 AC-30P	285	254	65	2070

$_1$- 1994 Conoco AC-20P
$_2$- 1995 Telfer Seldon AC-20P
* All Mr values in ksi.

Table 16 : Mr at different temperatures for the Apex pit aggregate mixtures.

Sample #	Mr at 77°F (dry)	Mr at 77°F (wet)	Mr at 104°F	Mr at 34°F
G1 AC-20P$_1$	498	301	106	3310
G2 AC-20P$_1$	623	525	141	3023
G3 AC-20P$_1$	478	657	142	3551
G4 AC-20P$_1$	346	466	95	2550
G5 AC-20P$_1$	542	598	119	3115
G1 AC-30	701	692	174	3668
G2 AC-30	880	640	169	3923
G3 AC-30	902	654	177	2880
G5 AC-30	994	833	220	4876
G3 AC-20P$_2$	248	269	72	2524
G3 AC-30P	296	368	112	1217
G4 AC-30P	247	241	113	1320
G5 AC-30P	394	374	122	2297

$_1$- 1994 Conoco AC-20P
$_2$- 1995 Telfer Sheldon AC-20P
* All values in ksi

Table 17 : Mr at different temperatures for the Las Vegas Paving pit aggregate mixtures.

Sample #	Mr at 77°F (dry)	Mr at 77°F (wet)	Mr at 104°F	Mr at 34°F
G1 AC-20P$_1$	436	474	106	2753
G2 AC-20P$_1$	324	328	97	2073
G4 AC-20P$_1$	283	279	107	2364
G5 AC-20P$_1$	470	288	147	2348
G1 AC-30	807	443	178	3534
G2 AC-30	746	651	201	3452
G4 AC-30	520	592	203	3271
G1 AC-20P$_2$	250	242	74	2217
G4 AC-20P$_2$	216	205	73	3095
G2 AC-30P	386	156	83	1918

$_1$- 1994 Conoco AC-20P
$_2$- 1995 Telfer Sheldon AC-20P
* All Mr values in ksi.

Table 18 : Tensile strength data of Rural pit aggregate mixtures.

Sample #	Tensile Strength (wet) in psi.	Tensile Strength (dry) in psi.
G1 AC-20P[1]	91	122
G3 AC-20P[1]	84	107
G4 AC-20P[1]	80	117
G1 AC-20	64	104
G3 AC-20	74	94
G4 AC-20	36	102

[1]- 1994 Conoco AC-20P

Table 19 : Tensile strength data of Frehner Sloan pit aggregate mixtures.

Sample #	Tensile Strength (wet) in psi.	Tensile Strength (dry) in psi.
G1 AC-20P1	69	114
G2 AC-20P1	113	135
G3 AC-20P1	93	112
G4 AC-20P1	71	102
G5 AC-20P1	63	104
G1 AC-30	111	153
G2 AC-30	67	130
G3 AC-30	77	127
G4 AC-30	53	99
G5 AC-30	71	130
G1 AC-20P2	103	111
G2 AC-20P2	117	110
G3 AC-20P2	100	105
G4 AC-20P2	111	124
G1 AC-30P	102	134
G3 AC-30P	103	109
G4 AC-30P	90	118
G5 AC-30P	93	94

1- 1994 Conoco AC-20P

2- 1995 Telfer Sheldon AC-20P

Table 20 : Tensile strength data of Apex pit aggregate mixtures.

Sample #	Tensile Strength (wet) in psi.	Tensile Strength (dry) in psi.
G1 AC-20P$_1$	99	125
G2 AC-20P$_1$	107	125
G3 AC-20P$_1$	109	145
G4 AC-20P$_1$	125	127
G5 AC-20P$_1$	141	120
G1 AC-30	106	147
G2 AC-30	88	137
G3 AC-30	126	129
G5 AC-30	149	182
G3 AC-20P$_2$	105	107
G4 AC-20P$_2$	86	97
G3 AC-30P	108	105
G4 AC-30P	90	101
G5 AC-30P	110	120

$_1$- 1994 Conoco AC-20P

$_2$- 1995 Telfer Sheldon AC-20P

Table 21 : Tensile strength data of Las Vegas paving pit aggregate mixtures.

Sample #	Tensile Strength (wet) in psi.	Tensile Strength (dry) in psi.
G1 AC-20P[1]	115	112
G2 AC-20P[1]	94	108
G4 AC-20P[1]	84	116
G1 AC-30	97	139
G2 AC-30	131	123
G4 AC-30	106	121
G1 AC-20P[2]	104	97
G4 AC-20P[2]	104	105
G2 AC-30P	92	119
G4 AC-30P	88	88

[1]- 1994 Conoco AC-20P
[2]- 1995 Telfer Sheldon AC-20P

Table 22 : Moisture susceptibility data of Frehner Sloan pit aggregate mixtures.

Sample #	Mr Ratio	Ten. St. Ratio
G3 AC-20P[1]	0.81	0.83
G4 AC-20P[1]	0.78	0.70
G1 AC-30	0.69	0.73
G1 AC-20P[2]	0.98	0.93
G2 AC-20P[2]	0.79	1.06
G3 AC-20P[2]	0.88	0.95
G1 AC-30P	0.70	0.76
G3 AC-30P	0.71	0.94
G4 AC-30P	0.69	0.77
G5 AC-30P	0.87	1.03

[1]- 1994 Conoco AC-20P
[2]- 1995 Telfer Sheldon AC-20P

Table 23 : Moisture susceptibility data of Apex pit aggregate mixtures.

Sample #	Mr Ratio	Ten. St. Ratio
G2 AC-20P[1]	0.84	0.75
G3 AC-20P[1]	1.37	0.98
G4 AC-20P[1]	1.34	1.17
G5 AC-20P[1]	1.10	0.72
G2 AC-30	0.73	0.98
G3 AC-30	0.73	0.89
G3 AC-20P[2]	0.98	0.99
G4 AC-20P[2]	0.87	0.88
G3 AC-30P	1.19	1.03
G4 AC-30P	1.02	0.89
G5 AC-30P	0.86	0.92

[1]- 1994 Conoco AC-20P

[2]- 1995 Telfer Sheldon AC-20P

Table 24: Moisture susceptibility data of Las Vegas Paving pit aggregate mixtures.

Sample #	Mr Ratio	Ten. St. Ratio
G1 AC-20P_1	1.08	1.03
G2 AC-20P_1	1.01	0.87
G4 AC-20P_1	0.99	0.72
G1 AC-30	0.55	0.70
G2 AC-30	0.87	1.06
G4 AC-30	1.13	0.87
G1 AC-20P_2	0.93	1.07
G4 AC-20P_2	0.96	0.99
G4 AC-30P	0.92	1.00

$_1$- 1994 Conoco AC-20P
$_2$- 1995 Telfer Sheldon AC-20P

Table 25 : Summary of plastic strain data for the selected mixtures.

Aggregate Source	Gradation and Binder	Specimen #	Air Voids (%)	Pl. Strain at 12000 cycles
Frehner Sloan pit	G3 AC-20P[1]	#1	8.7	0.40
		#2	8.2	0.24
		Avg.	8.5	0.32
	G1 AC-30	#1	8.1	0.30
		#2	8.9	0.30
		Avg.	8.5	0.30
	G1 AC-20P[2]	#1	7.3	1.56
		#2	7.0	0.92
		Avg.	7.2	1.24
	G2 AC-20P[2]	#1	7.0	0.90
		#2	7.7	1.23
		Avg.	7.4	1.07
	G3 AC-20P[2]	#1	6.7	1.09
		#2	6.4	0.62
		Avg.	6.6	0.86
	G1 AC-30P	#1	8.0	0.90
		#2	7.5	0.22
		Avg.	7.8	0.56
	G3 AC-30P	#1	7.3	0.46
		#2	5.8	1.14
		Avg.	6.6	0.80
	G4 AC-30P	#1	6.6	0.96
		#2	6.0	0.98
		Avg.	6.3	0.97
	G5 AC-30P	#1	5.5	0.75
		#2	7.1	2.14
		Avg.	6.3	1.45

[1] - 1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 25 :Summary of plastic strain data for the selected mixtures (continued).

Aggregate Source	Gradation and Binder	Specimen #	Air Voids (%)	Pl. Strain at 12000 cycles
Apex	G2 AC-20P[1]	#1	5.9	0.25
		#2	5.9	0.24
		Avg.	5.9	0.25
	G3 AC-20P[1]	#1	6.6	0.30
		#2	7.8	0.45
		Avg.	7.2	0.38
	G2 AC-30	#1	6.3	0.18
		#2	6.1	0.23
		Avg.	6.2	0.21
	G3 AC-30	#1	5.7	0.24
		#2	6.2	0.26
		Avg.	6.0	0.25
	G3 AC-20P[2]	#1	7.7	0.39
		#2	6.3	0.14
		Avg.	7.0	0.27
	G3 AC-30P	#1	7.1	0.51
		#2	7.5	0.76
		Avg.	7.3	0.64
	G4 AC-30P	#1	7.7	0.37
		#2	6.8	0.60
		Avg.	7.3	0.49
	G5 AC-30P	#1	7.0	0.83
		#2	7.2	0.89
		Avg.	7.1	0.86

[1] - 1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 25 :Summary of plastic strain data for the selected mixtures (continued).

Aggregate Source	Gradation and Binder	Specimen #	Air Voids (%)	Pl. Strain at 12000 cycles
Las Vegas	G1 AC-20P[1]	#1	7.8	0.19
		#2	7.0	0.17
		Avg.	7.4	0.18
	G1 AC-30	#1	7.0	0.24
		#2	7.3	0.37
		Avg.	7.2	0.31
	G2 AC-30	#1	6.5	0.42
		#2	6.8	0.27
		Avg.	6.7	0.35
	G4 AC-30	#1	6.5	0.30
		#2	6.9	0.36
		Avg.	6.7	0.33
	G1 AC-20P[2]	#1	6.6	0.65
		#2	7.3	0.40
		Avg.	7.0	0.53
	G4 AC-20P[2]	#1	7.5	4.48
		#2	8.0	2.12
		Avg.	7.8	3.30

[1] - 1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 26 :Low temperature performance indicators.

SAMPLE		Fracture Temperature (C)	Fracture Stress (psi)
F.Sloan pit G1 AC-20P[2]	#1	-30.1	165.8
	#2	-30.1	190.7
	Avg.	-30.1	178.25
F.Sloan pit G1 AC-30	#1	-28.8	301.1
	#2	-27	305.4
	Avg.	-27.9	303.25
F.Sloan pit G1 AC-30P	#1	-32.3	179.7
	#2	-32.3	178.3
	Avg.	-32.3	179
F.Sloan pit G2 AC-20P[2]	#1	-33.5	248.8
	#2	-30.3	176.8
	Avg.	-31.90	212.8
F.Sloan pit G3 AC-20P[1]	#1	-35	407.7
	#2	-32.5	230.6
	Avg.	-33.75	319.15
F.Sloan pit G3 AC-30P	#1	-32.7	74.4
	#2	-32.5	60.2
	Avg.	-32.6	67.3
F.Sloan pit G4 AC-30P	#1	-32.3	84.5
	#2	-27.8	41.7
	Avg.	-30.05	63.1

[1] -1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 26 :Low temperature performance indicators (continued).

SAMPLE		Fracture Temperature (C)	Fracture Stress (psi)
Apex pit G2 AC-20P[1]	#1	-33.6	226.1
	#2	-38.7	209.3
	Avg.	-36.15	217.7
Apex pit G3 AC-20P[1]	#1	-34.3	130.3
	#2	-35.2	149.6
	Avg.	-34.75	139.95
Apex pit G3 AC-20P[2]	#1	-31.8	155.2
	#2	-34.4	148.1
	Avg.	-33.1	151.65
Apex pit G3 AC-30P	#1	-32.7	104.8
	#2	-32.3	62.9
	Avg.	-32.5	83.85
Apex pit G4 AC-30P	#1	-35.5	40.7
	#2	-31.3	37.8
	Avg.	-33.4	39.25
Apex pit G5 AC-30	#1	-27.3	170.2
	#2	-26.2	205.3
	Avg.	-26.75	187.75
Apex pit G5 AC-30P	#1	-35.1	155.8
	#2	-36.7	175.3
	Avg.	-35.9	165.55

[1] -1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 26 :Low temperature performance indicators (continued).

SAMPLE		Fracture Temperature (C)	Fracture Stress (psi)
Las vegas pit G1 AC-20P[1]	#1	-34.4	286.6
	#2	-39.5	298.1
	Avg.	-36.95	292.35
Las vegas pit G1 AC-20P[2]	#1	-33.3	206.9
	#2	-30.5	166.5
	Avg.	-31.9	186.7
Las vegas pit G1 AC-30	#1	-28.9	301.2
	#2	-30.5	254.9
	Avg.	-29.7	278.05
Las vegas pit G4 AC-30	#1	-23.5	148.3
	#2	-25.6	213.1
	Avg.	-24.55	180.7

[1] -1994 Conoco AC-20P

[2] - 1995 Telfer Sheldon AC-20P

Table 27: TSRST fracture temperatures for each binder type.

Binder Type	**Mean (°C)**	**Standard Deviation (°C)**	**Coefficient of Variation (%)**
AC-20P$_1$ (PG64-28)	-35.5	1.4	4
AC-20P$_2$ (PG58-22)	-31.8	1.2	4
AC-30P (PG70-22)	-32.8	1.9	6
AC-30 (PG64-22)	-27.2	2.2	8

Table 28: Summary of the most desirable mixtures for Sloan aggregates.

	Ranking Criteria				
Mixture	**Mr at 77°F**	**TS Ratio**	**Permanent Deform.**	**Low Temp. Cracking**	**Sum of Ranks**
G1-AC-30	1	5	1	5	12
G1-AC-30P	5	3	3	3	14
G3-AC-20P$_1$	3	2	2	1	8
G3-AC-30P	2	1	4	2	9
G4-AC-30P	4	4	5	4	17

Table 29: Summary of the most desirable mixtures for Apex aggregates.

	Ranking Criteria				
Mixture	**Mr at 77°F**	**TS Ratio**	**Permanent Deform.**	**Low Temp. Cracking**	**Sum of Ranks**
G2-AC-20P_1	1	6	1	1	9
G3-AC-20P_1	2	3	3	3	11
G3-AC-20P_2	6	2	2	5	15
G3-AC-30P	4	1	5	6	16
G4-AC-30P	5	5	4	4	18
G5-AC-30P	3	4	6	2	15

Table 30: Summary of the most desirable mixtures for Las Vegas aggregates.

	Ranking Criteria				
Mixture	**Mr at 77°F**	**TS Ratio**	**Permanent Deform.**	**Low Temp. Cracking**	**Sum of Ranks**
G1-AC-20P_1	3	2	1	1	7
G1-AC-30	1	4	2	3	10
G1-AC-20P_2	4	1	4	2	11
G4-AC-30	2	3	3	4	12

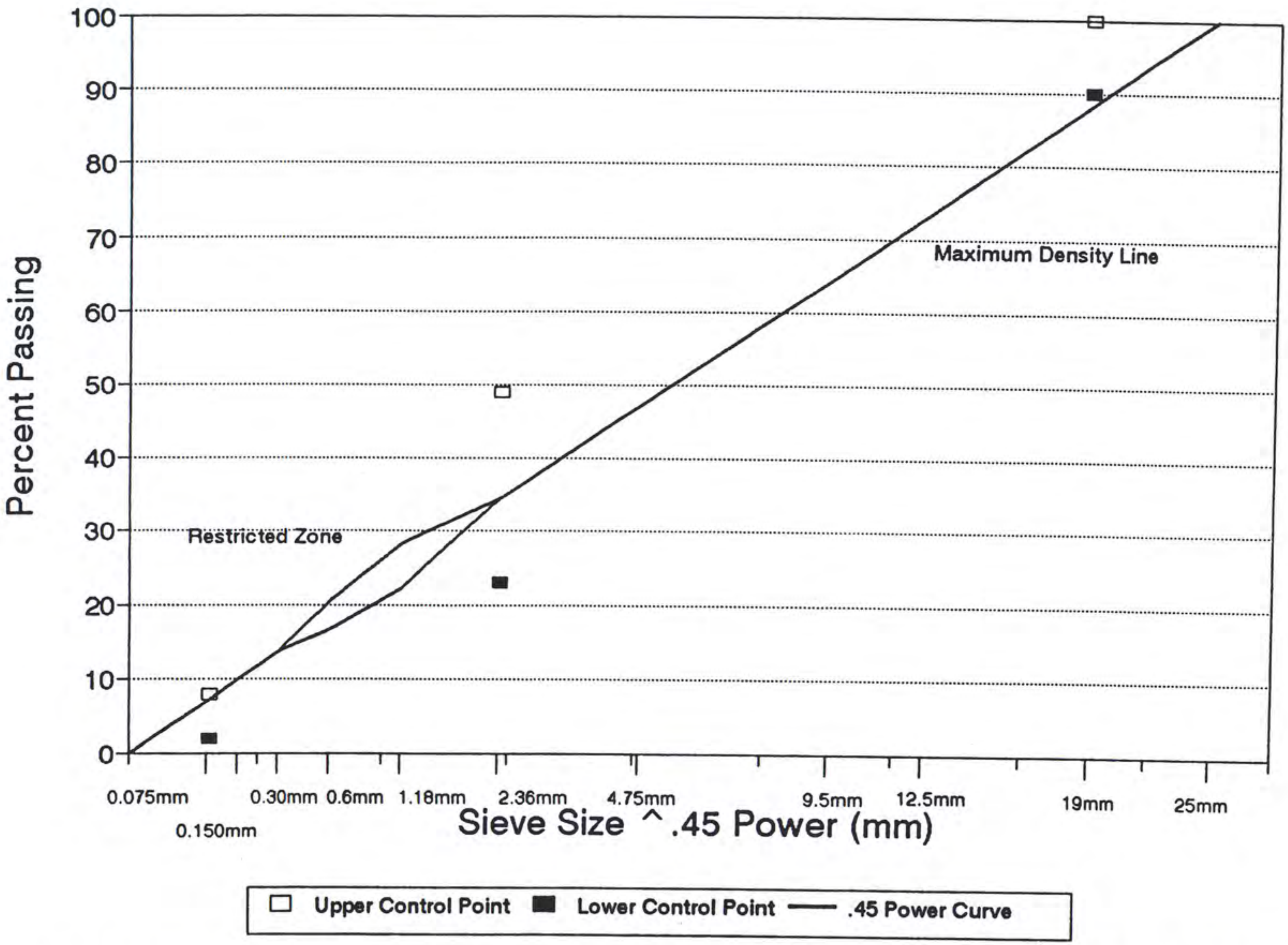

Figure 1. Superpave restricted zone and control points for 3/4" nominal maximum size aggregates.

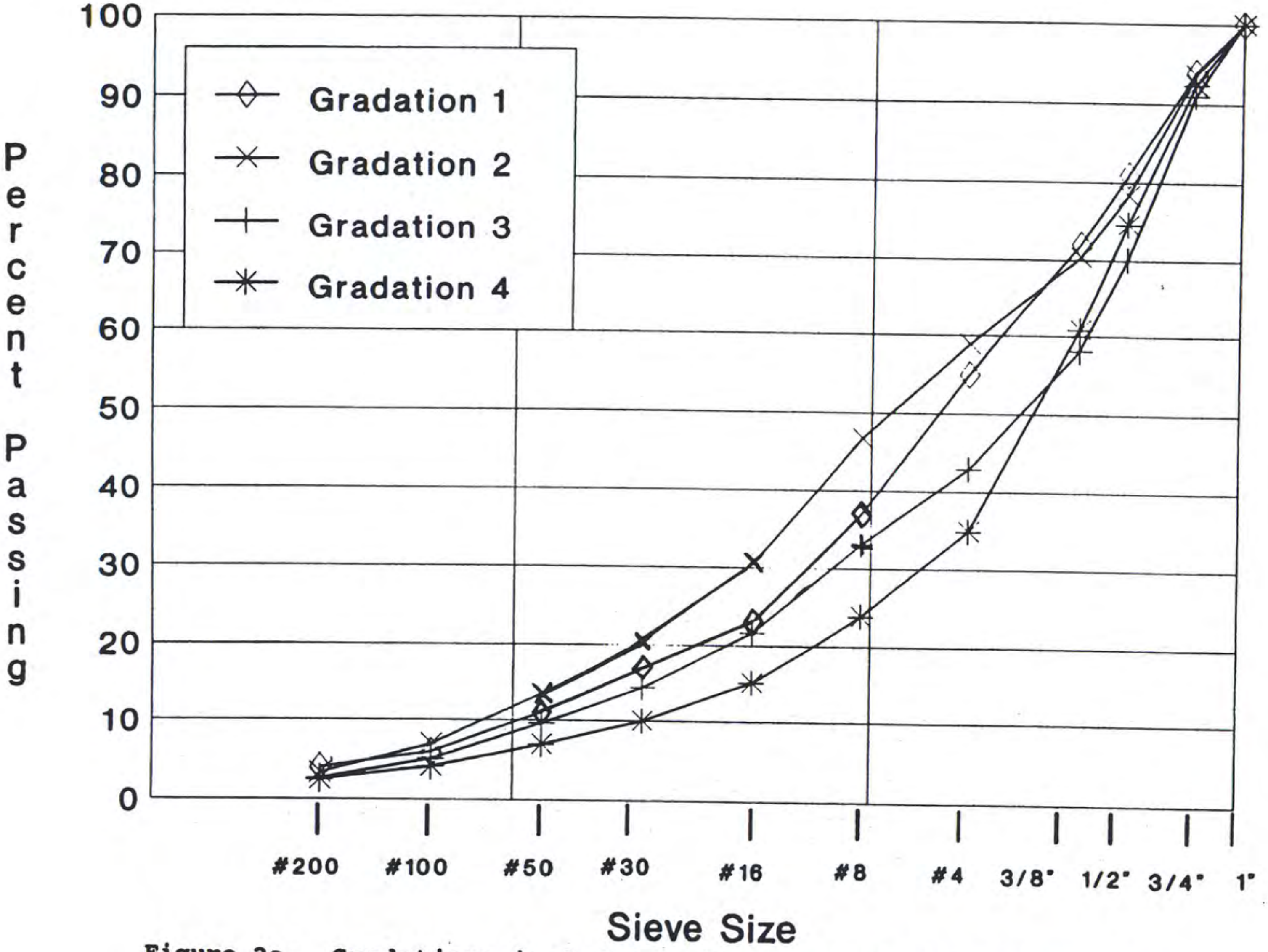

Figure 2a. Gradations included in the research (1" maximum size).

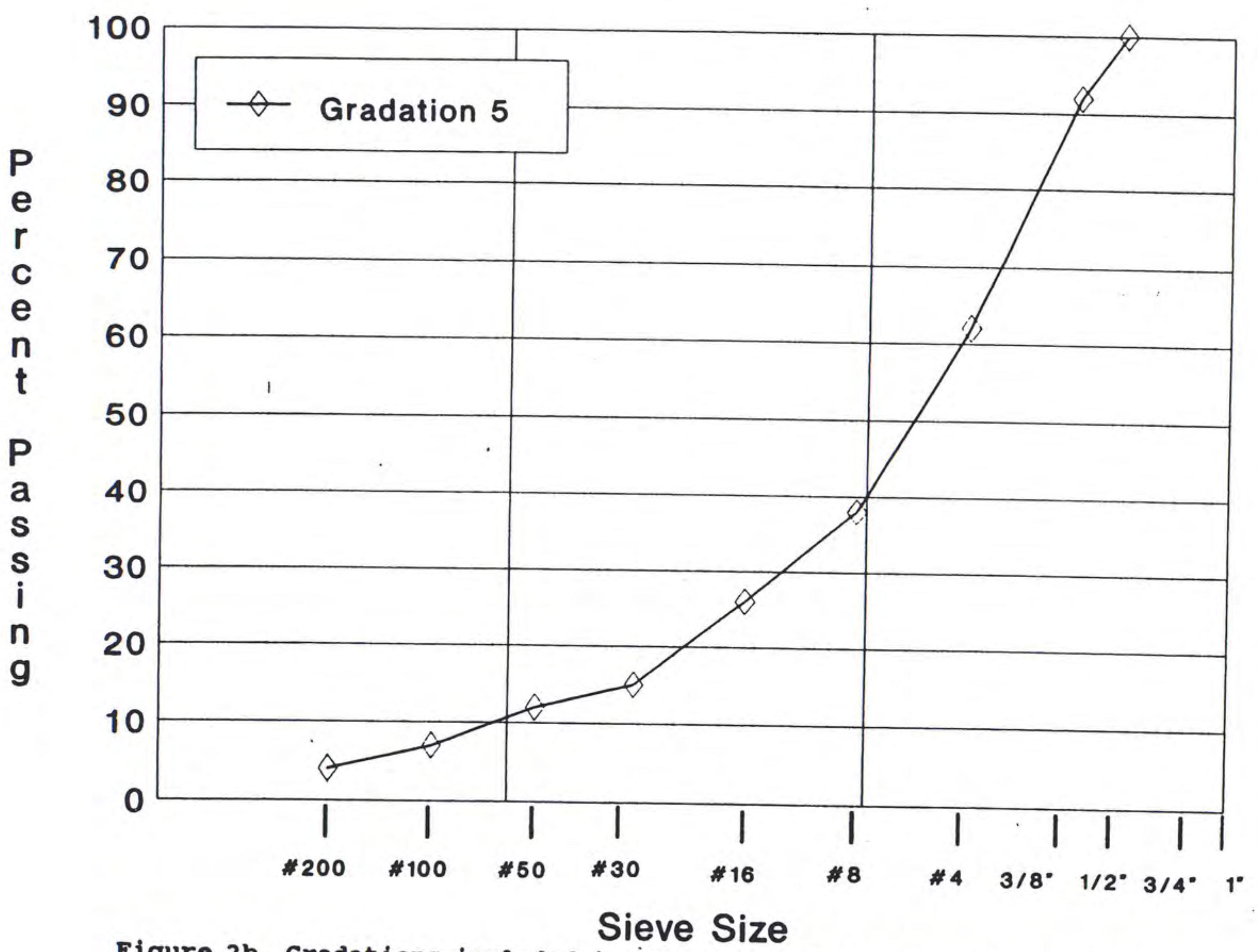

Figure 2b. Gradations included in the research (1/2" maximum size).

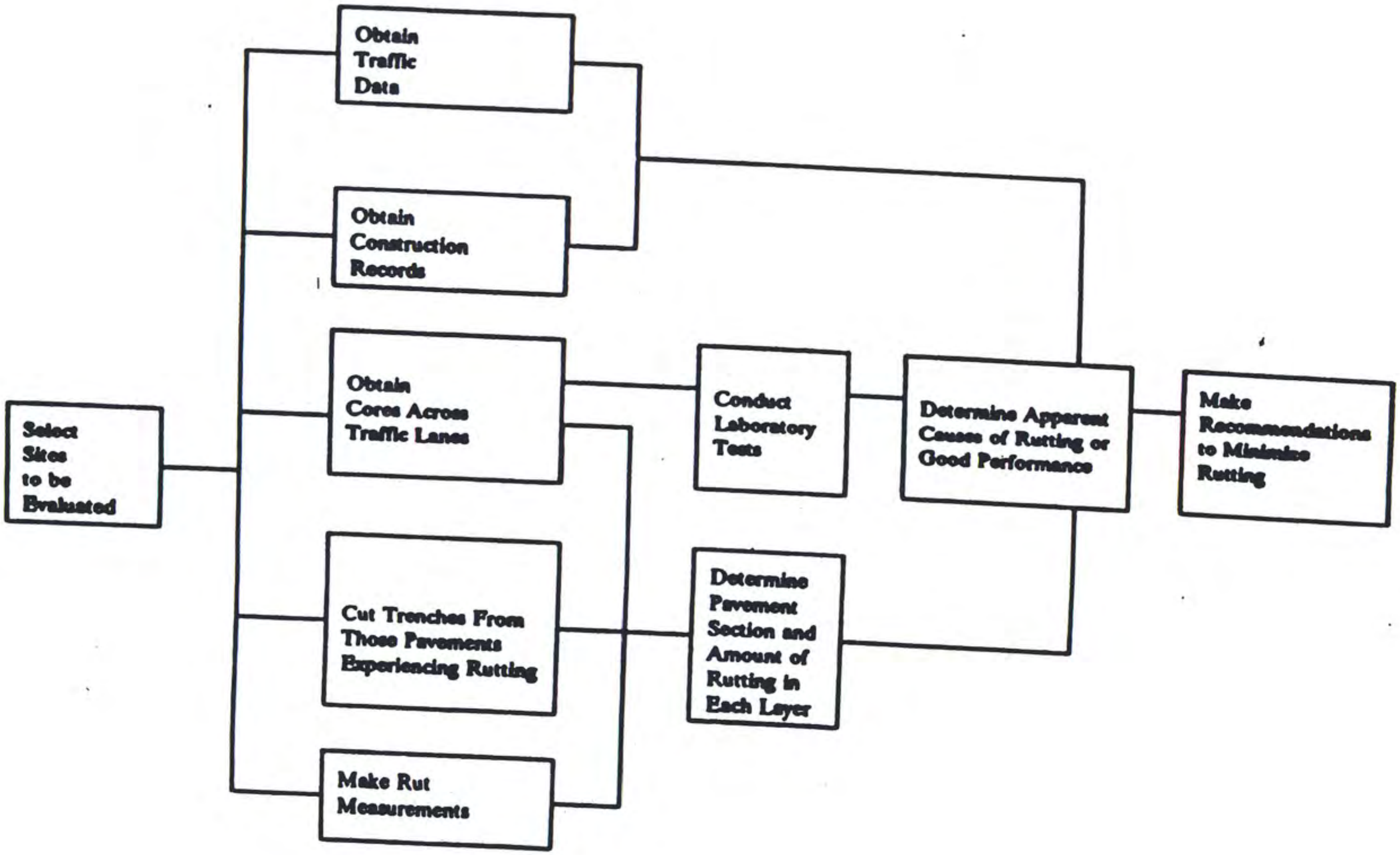

Figure 3. Overall testing program of NCAT study.

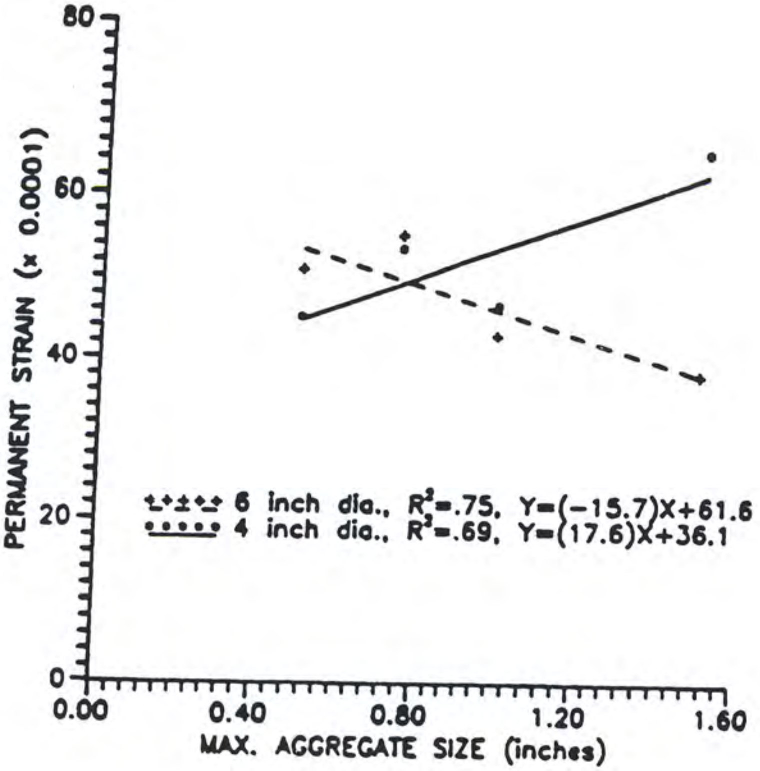

Figure 4. Effect of max. size of aggregate on rutting potential.

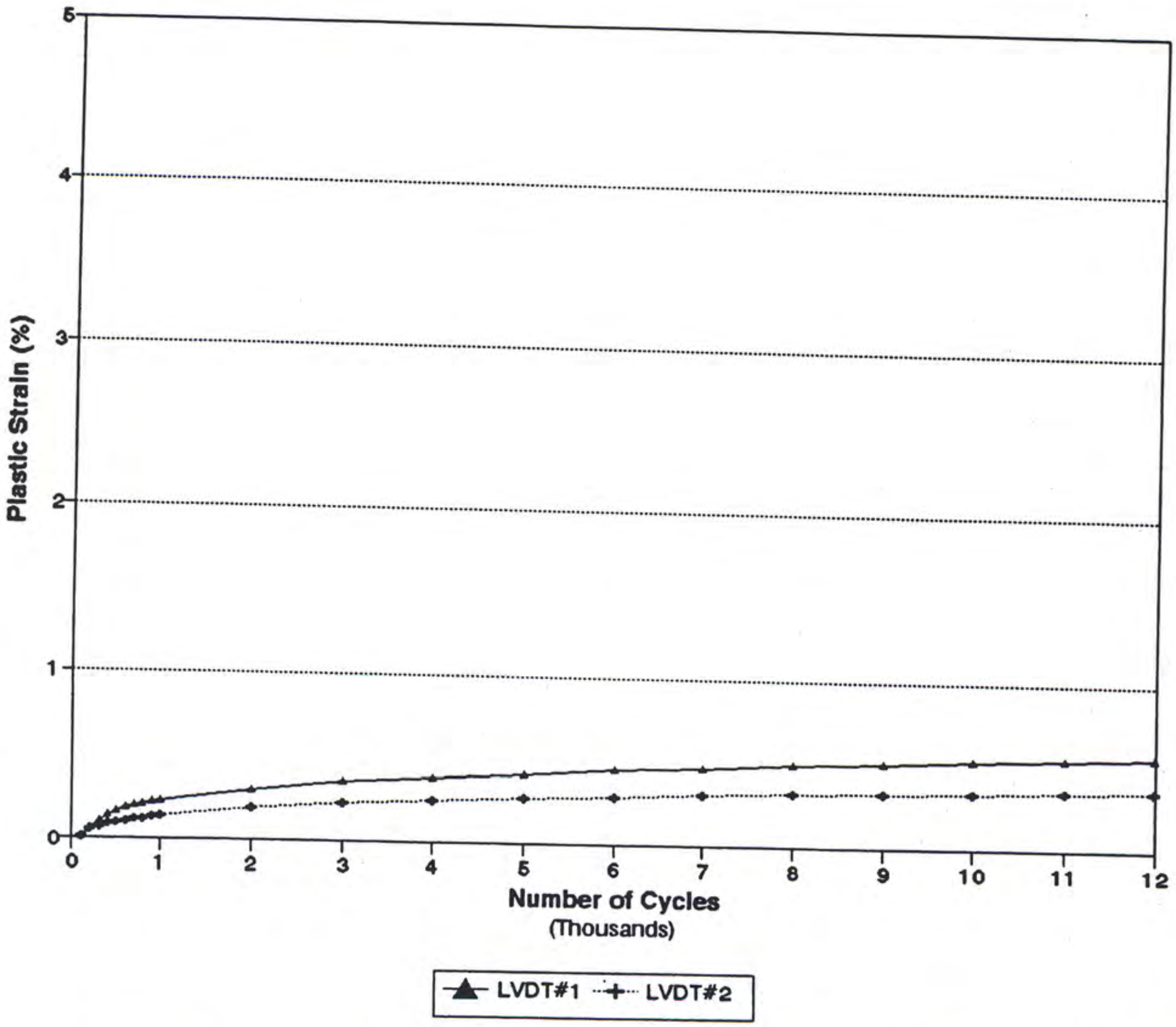

Figure 5. Typical permanent deformation characteristics of mixtures @ 104°F (dry).

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