Louisiana Highway Research

EVALUATION OF THE GYRATORY COMPACTOR FOR USE IN DESIGNING ASPHALTIC CONCRETE MIXTURES

Louisiana Department of Highways – Research & Development Section

EVALUATION OF THE GYRATORY COMPACTOR FOR USE IN DESIGNING ASPHALTIC CONCRETE MIXTURES

by

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TABLE OF CONTENTS

SYNOPSIS

The primary objective of this study was to evaluate the gyratory kneading compactor and to investigate the possibilities and capabilities of this type of equipment.

Curves were developed for six different asphaltic concrete mixes with varying compactive efforts and asphalt contents. These curves indicated that a wide range of compactive efforts can be applied by the gyratory compactor which would be a definite advantage over the presently used Marshall impact hammer.

Results showed that the optimum asphalt content can be obtained by means of the gyrographs which indicate whether or not the asphalt content for a mix at a given compactive effort is excessive.

Results of cores taken after 6 months of service showed that the void contents had decreased below the 75 blow laboratory design, indicating the need for a higher compactive effort in the laboratory, which may be beneficial in extending the service life of pavements.

The test results discussed herein deal with the gyratory machine as a compaction machine only. However, it is anticipated to supplement this study to evaluate the shear and bearing resistance of asphaltic concrete mixes in the laboratory using the gyratory machine, and attempt to correlate these results with similar mixes in the field.

INTRODUCTION

During the past several years the Louisiana Department of Highways, through necessity, had to increase the intensity of the pneumatic rollers for compacting asphaltic concrete pavements. This, consequently, made it necessary to increase the compactive effort of the laboratory design of asphaltic concrete mixtures. The need for this increase had become critical due to the excessive rutting and shoving observed on asphaltic concrete pavements after being subjected to traffic.

In an attempt to remedy this problem, high intensity pneumatic rollers capable of exerting contact pressures of up to 90 psi were incorporated into the specifications. To supplement this, the laboratory design compactive efforts were increased from 50 blows to 75 blows on both sides of a 4 inch diameter specimen using a standard Marshall impact hammer.

Although these modifications have shown a vast improvement in asphaltic concrete pavements in Louisiana, it again appears that an additional increase in design compactive effort is essential in obtaining maximum design life, due to the rapid increase of traffic volume encountered on the highways.

One of the objectives of this study then, is to establish an adequate laboratory compactive effort for design of asphaltic concrete by use of the gyratory compactor.

The gyratory compactor has several advantages that cannot be matched by the Marshall method as follows:

(1) It produces test specimens by a kneading compaction process which has stress-strain properties that are more representative of pavement compaction.

(2) It has the capability of indicating high plasticity by the aid of a gyrograph which shows whether or not a mix has an excess of voids filled with asphalt due to densification or due to an excessive asphalt content for a given mix at a given compactive effort.

(3) It is capable of producing a very large range of compactive efforts by the use of repetitive loading, or increase in gyrations, at a given vertical pressure from 0 to 300 psi.

(4) Optimum asphalt contents for a given compactive effort can be obtained using the gyrographs during the molding procedure and before actual testing of the specimens.

With these advantages, the gyratory compactor could very well be an essential piece of equipment for designing bituminous mixtures at higher compactive efforts.

Although the gyratory machine will be referred to in this report as a compaction apparatus, it is also an excellent testing machine. It is capable of determining the allowable shear stress for a given mix subjected to various contact pressures due to traffic at any desired temperature. It can also be used in evaluating mix designs that may vary in asphalt content, type of aggregate, proportioning of aggregate and mineral fillers. This report, however, will be confined to using the gyratory as a compaction machine only.

FUNDAMENTALS OF THE GYRATORY COMPACTOR

The compactive effort, is controlled mainly by three components.

(1) The gyratory angle used in compacting the specimen. This was limited to only 1° for this study, as suggested by the manufacturer, because the strain is believed to be closely related to the field strain.

(2) The vertical pressure applied to the specimen during compaction.

(3) The number of gyrations or revolutions used to compact the specimen.

The gyratory angle represents the percent strain applied to the specimen. The higher the angle the higher is the percent strain. The 1° angle seems to be the most satisfactory for design purpose at this time.

The vertical pressure ranges from 0 to 300 psi which is a large enough range to design mixes for any anticipated contact pressures that might be encountered on highways. The number of gyrations can be varied without limitations to the compactive effort desired on a particular design.

Figure 1, photograph A, shows the front view of the compaction assembly for the gyratory compactor used in this study. Photograph B shows the rear view of the assembly and also a close up of the gyrograph mechanism.

To better understand the operation of the gyratory compactor, a schematic of the gyratory assembly is shown in Figure 2.

In this figure, mold A, containing a test specimen, is clamped in position in the flanged mold chuck B. Vertical pressure on the test specimen is maintained by

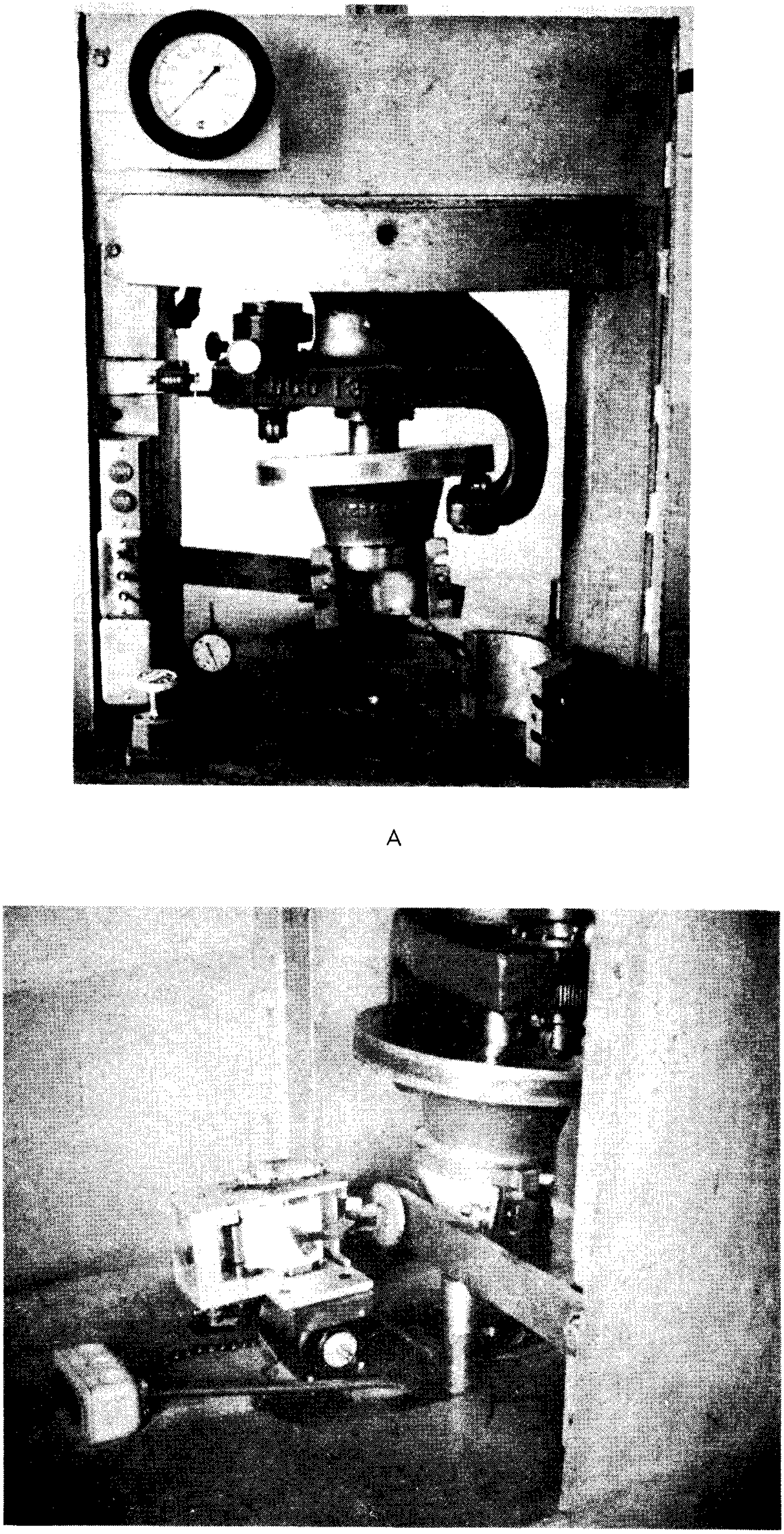

Figure 1 - Photographs of the working mechanisms of the Gyratory Compactor.
A. Front View of the Compaction Assembly.
B. Rear View of the Compaction Assembly and close up of the gyrograph mechanism.

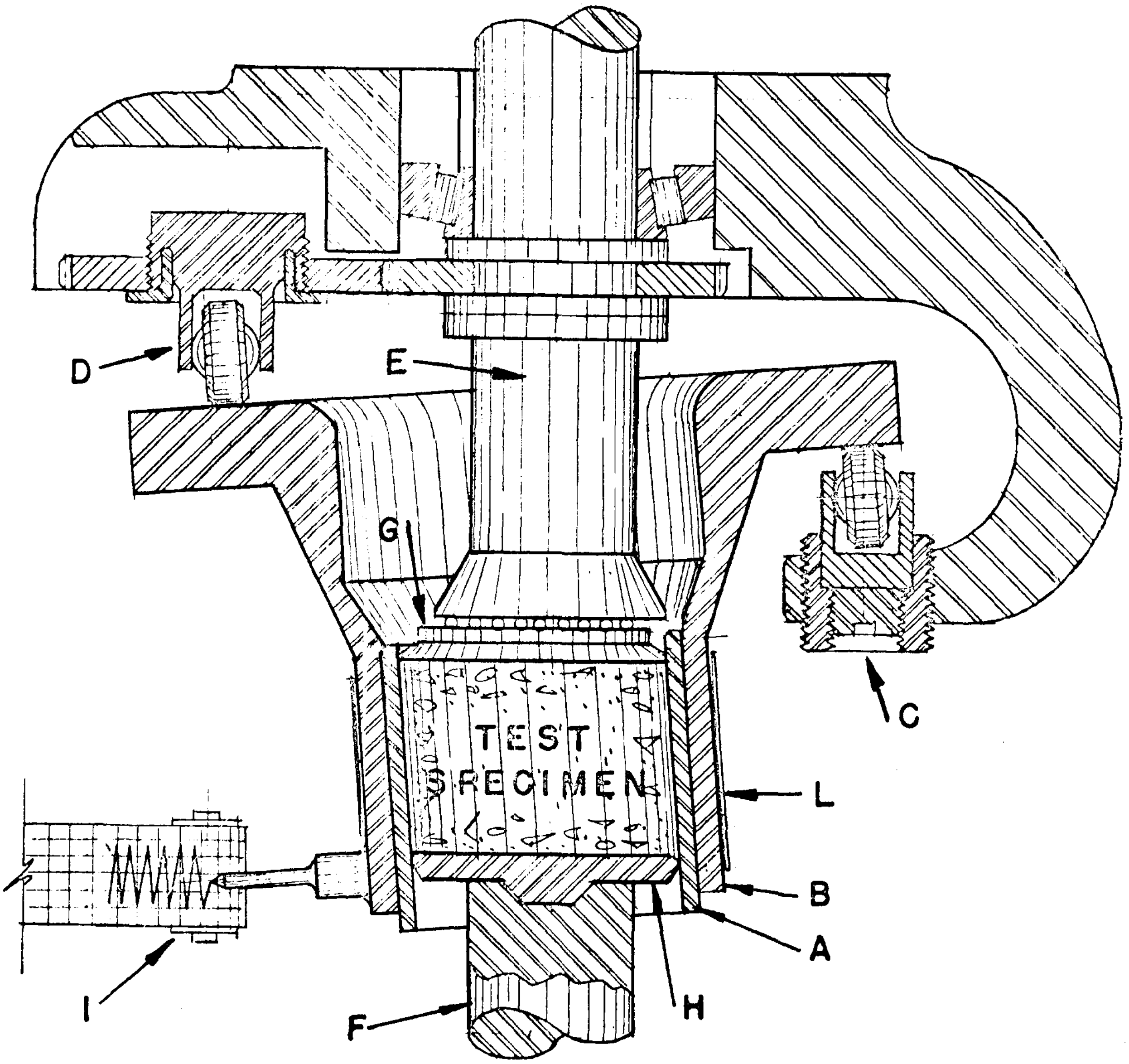

Figure 2 - Schematic Section through Gyrating Mechanism.

the upper and lower ram E and F acting against heads G and H respectively. A gyratory motion is imparted to mold chuck B by rollers C and D as they travel around the flange portion of the chuck, with the flanged portion of the chuck at an angle between rollers C and D.

The gyrograph is identified by the letter **I in the figure**. When the chuck gyrates, the pen on the side of the chuck records the angle maintained by the chuck in compacting the specimen. When the specimen has been compacted to a maximum density at a given asphalt content, any additional compaction applied will result in a reduction of density which increases the angle made by the chuck causing widening of the recordings on the gyrograph. Each division on the gyrograph is equal to approximately 7.5 minutes. If the asphalt content it too high for a given compactive effort, widening of the gyrograph will also occur. This is illustrated by the two gyrographs at the bottom of Figure 2. An asphalt content of 4.0 percent gives a uniform angle indicating that the specimen is not flushing and that higher density is being obtained with each revolution. The gyrograph representing 5.0 percent asphalt content shows a widening of the chart indicating that a maximum density has been reached and the additional revolutions of the machine are causing a decrease in density due to flushing of the asphalt or excessive asphalt for that compactive effort.

It is evident then that an optimum asphalt content can be obtained at a given compactive effort if specimens are molded at asphalt contents of 0.5 percent increments. When flushing or widening of the gyrograph first appears it will indicate that the optimum asphalt content for that compactive effort is less than the asphalt content that showed flushing.

SCOPE

This study was initiated in April, 1961 as a research project in cooperation with the Bureau of Public Roads, and consists of two phases.

Phase I consists of molding six different mixes at various compactive efforts and asphalt contents using the gyratory compactor and the Marshall impact hammer and analyzing the physical properties of the specimens.

Phase II consists of establishing an adequate compactive effort for the gyratory compactor, which could be used for design of the asphaltic concrete mixes and which would possibly aid in increasing the life of bituminous concrete pavements.

METHODOLOGY

A. Mixes Used

Six different mixes were used in this study to determine the effects the gyratory compactor has on each in varying the composition of the asphalt aggregate and the compactive effort.

The mixes are designated as Mix 1 through Mix 6 inclusive, and are composed of the following materials.

Mixes 1, 2 and 3 - Crushed siliceous gravel and a combination of sand and mineral filler.

Mix 4 - Crushed limestone, coarse sand, fine sand and mineral filler.

Mix 5 - Limestone rock asphalt and coarse sand.

Mix 6 - Expanded clay aggregate, coarse sand, fine sand, and mineral filler.

The majority of asphaltic concrete mixes used in Louisiana are crushed siliceous gravel, sand, and mineral filler. Mixes 1, 2 and 3 are composed of gravel obtained from three different hot mix plants in the state having similar characteristics. The composition and proportion of the various mix designs are shown in Table 1 of the Appendix.

B. Test Procedure

Specimens were molded on each of the above mentioned mixes, varying the compactive effort from a minimum of 50 blows with the Marshall hammer to a maximum of to 250 psi, 60 gyrations with the gyratory compactor. The physical properties of these mixes are given in the Appendix in Tables 2 through 7. In order to evaluate the different mixes along with effects of the compactive effort, curves were developed for each mix plotting percent bitumen versus percent voids, Marshall stability and density. The curves are shown in the Appendix. The tests performed were in accordance with the followings test procedures

(1) Specific gravity of compressed bituminous mixture LDH TR 304

(2) Marshall stability and flow LDH TR 305

The design laboratory compactive effort selected from this study was 100 psi, 60 gyrations which appears to be practical, especially on gravel mixes, from a construction standpoint. This compactive effort will probably vary for other areas depending on the aggregate type, asphalt cement, location, traffic volume and method of obtaining void contents. The theoretical specific gravity, as used in computing void contents in this study, was obtained by the apparent specific gravity method which is presently being used in Louisiana.

The formula for calculating the theoretical gravity along with the Louisiana Department of Highways mix design criteria for determining optimum asphalt content by the Marshall procedure are found in Table 9 of the Appendix.

TEST RESULTS

Phase I

The gravel mixes, represented by Figures 4 through 9 of the Appendix, indicate that as the compactive effort is increased, density and Marshall stability is increased and the void content is reduced. Also it appears that the higher the compactive effort the lower the optimum asphalt content.

At the bottom of each of the density curves are the gyrographs for each respective compactive effort and asphalt content. Using Mix No. 1 as an example, the gyrograph at 100 psi, 30 gyrations, from Figure 4 showed flushing of the asphalt (widening of the gyrograph) at 6.0 percent bitumen, whereas, at an effort of 250 psi, 60 gyrations flushing started at 5.0 percent bitumen. In addition to the void content, Marshall stability, and density results shown on the curves in Figures 4 and 5 the gyrographs also indicate that an increase of compactive effort decreases the optimum asphalt content.

It is also interesting to note that, in most cases, the gyrograph that did not show flushing preceding the gyrograph that did flush is usually very near the optimum asphalt content. An example of this is shown in Figure 4 Mix No. 1 at 100 psi, 60 gyrations. As shown by the gyrograph, flushing began at an asphalt content of 5.5 percent. The Marshall stability at that asphalt content was 1580 lbs., void content 4.1 percent, and density 146 lbs/ cu.ft. The gyrograph that did not show flushing at 5.0 percent bitumen had a Marshall stability of 1839 lbs, void content 4.6 percent, and density of 145.8 lbs/cu.ft. This indicates that 5.0 percent bitumen would be the optimum asphalt content. Results for gravel Mixes 2 and 3 are represented by Figures 6 through 9 and show very similar characteristics as Mix 1.

Figures 10 and 11 show curves for Mix No. 4 which was composed of crushed limestone aggregate. The characteristics mentioned for the gravel mixes were also very similar for the limestone mixes with the exception that these mixes gave much higher densities and Marshall stabilities and lower void contents.

Figures 12 and 13 represent curves for Mix No. 5 composed of limestone rock asphalt. The limestone rock asphalt contained approximately 4 percent natural asphalt and had an apparent specific gravity of 2.54. Again, the trend of the curves were similar to the gravel and limestone mixes. The stabilities, as seen by the curve in Figure 13, were extremely higher than any of the other mixes, going as high as 4817 lbs. at 3.0 percent additional asphalt and 250 psi, 60 gyrations compactive effort.

Figures 14 and 15 represent curves for Mix No. 6 composed of expanded clay aggregate, sand, and mineral filler. The apparent specific gravity of the expanded clay aggregate is approximately 1.30 depending on the size of the aggregate. This is a very light material and, consequently, results in low density as seen on the curve. The expanded clay mixes are somewhat different from others in that they can absorb a large quantity of asphalt without signs of flushing. As shown by the gyrographs, flushing has not occurred on any of the expanded clay mixes.

Due to the fact that the expanded clay does absorb a large quantity of asphalt without showing signs of flushing, it becomes more difficult to obtain an optimum asphalt content. It has been indicated by the curves that the Marshall stability results are probably the most appropriate to use to obtain the optimum asphalt content, because as the asphalt is increased the density will increase and voids will decrease to a point where the Marshall stability will have a very low value indicating that the density percent void curves alone would be misleading in obtaining optimum asphalt content. The optimum asphalt content cannot be obtained by the gyrograph due to the fact the gyrograph will not show flushing until the asphalt content is exceptionally high. For example, in Figure 14 at 250 psi, 60 gyrations the density appears to be rising at 6.5 percent bitumen just as the percent voids in Figure 15 are decreasing at that same bitumen content. The Marshall stability shows a peak at approximately 6.0 percent bitumen and has a definite drop at 6.5 percent bitumen, indicating that an additional increase in bitumen content would be a decrease in Marshall stability which would, therefore, be detrimental to the mix. For this reason, it appears that for expanded clay mixes, the optimum asphalt content should be based primarily on the Marshall stability curve, but in conjunction with density and percent voids.

The first phase of this study, as discusssed, is to determine what affect the gyratory compactor would have on the various mixes when varying the compactive effort and the asphalt content, and to compare the results with that obtained by the Marshall compaction hammer. This has been accomplished as discussed and as shown by the tabulated results in Tables 2 through 7 in the Appendix.

Phase II

This phase consists of establishing an adequate compactive effort for use with the gyratory compactor, through the aid of the results obtained in Phase I, for increasing the design life of asphaltic concrete pavements.

This study was initiated to supplement a previous study by the Louisiana Department of Highways (1)*. In that study it was concluded that the asphaltic concrete pavements constructed in the 1950's were showing excessive rutting, flushing,

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* Number in parenthesis refer to list of references at the end of report.

and lack of densification at the end of five years or equivalent to an estimated total traffic volume of 10 million vehicles. The anticipated design life of these pavements was 15 years or a traffic volume of approximately 30 million vehicles. From the findings (1) the actual life of the pavement was only one-third the design life anticipated.

It was also established in that study that after five years the void content was reduced to two percent in which the pavement showed shoving, rutting and cracking. It is known that hot mix pavement containing low density and high void contents immediately after compaction are much more susceptible to hardening or oxidation of the asphalt in addition to the rutting that will occur due to traffic densification.

It is believed that the reason for the deterioration after five years of service was not due to the void content approaching two percent voids, but due to the low compactive effort applied in the laboratory and in the field, giving a high initial void content and causing rapid oxidation of the asphalt due to weathering. This was also the reason for the excessive rutting after five years of service.

At the time these projects were being constructed the laboratory design method for asphaltic concrete mixes required 50 blow Marshall compaction. In the field the hot mix pavement was being compacted using a pneumatic roller with a 55 psi contact pressure. It has been proven since that time, that higher contact pressures are essential in obtaining higher densities and lower initial void contents, thereby minimizing rutting and cracking of the mix.(2) (3) In that report, results indicated that the test sections rolled at 85 psi contact pressure with the pneumatic roller showed less rutting after 3 years than did the test sections rolled at 55 psi contact pressure. It was also necessary to increase the compactive effort in the laboratory to the presently used 75 blow of the Marshall compaction effort.

In order to increase the design life of hot mix pavements, it was first thought that by using the gyratory compactor and varying the number of gyrations or repetitive loads at a certain vertical pressure, the mix could be densified to give two percent air voids or equivalent to 10 million vehicles as obtained in the Pavement Survey Study(1). After this was accomplished the number of gyrations equivalent to 30 million vehicles could be computed. Specimens would then be compacted using this computed value for the number of gyrations and vertical pressure and the data evaluated for percent voids using a different design compactive effort. However, this approach to the problem proved to be futile, due to the fact that in the laboratory the asphalt and the mixing and compaction temperatures remains fairly constant, whereas, the repetitive load in the field occures over a period of five years or more during which time the asphalt changes due to oxidation and weathering and the temperatures at the time of these loads change with the season and also the time of day.

To increase the design life of asphaltic concrete pavements, it is necessary first of all to start with the laboratory design which should result in the void content in a hot mix pavement after final rolling being adequate to minimize oxidation of the asphalt and eliminate excessive rutting due to traffic. In attempting to do this, a compactive effort of 100 psi, 60 gyrations with the gyratory compactor was chosen as a laboratory design. A vertical pressure of 100 psi was chosen mainly because it is very close to the contact pressures used by the pneumatic rollers and also the contact pressures applied to the finished pavements by the heavy truck traffic encountered.

In establishing a reasonable number of gyrations for design purposes, specimens were molded on the gyratory compactor using Mix No. 2 which had the same aggregate and mix design as that used in the compaction study. (2) (3) A vertical pressure of 100 psi was used on these specimens and the gyrations were varied from 10 to 70. The asphalt content was 5.8 percent, the same used on the roadway.

Figure 3 illustrates the curve obtained from these specimens plotting percent voids versus number of gyrations. The void content goes from a maximum of 7.8 percent for 10 gyrations to 3.5 percent for 70 gyrations at a constant pressure of 100 psi. Note that the design void content for this project was at 5.9 percent voids shown as 75 blow plant (mechanical) on the curve. Roadway results were obtained immediately after completion (designated original) then at 6, 15, and 36 months. It is interesting to note that only 6 months after completion of the project the void content had already decreased below the laboratory design indicating a need for higher compactive efforts in the mix design.

The curve also shows that cores taken after 36 months gave a void content of 4.0 percent. Had the mix been designed by the gyratory compactor at 100 psi, 60 gyrations, a design void content of 3.7 percent would have been obtained at 5.8 percent asphalt.

As also shown by the curve, as the number of gyrations approach 50 the void content begins to level off and shows very little change from 50 gyrations to 70 gyrations. It is believed that similar results are obtained on the roadway. That is, if a mix is designed for lower initial voids, and if a certain percentage of this design is required in the field, then the void content will change at a slower rate with time and traffic thus eliminating excessive rutting, oxidation of the asphalt, and providing a longer design life.

It should be mentioned that although the void content at 60 gyrations was 3.7 for Mix 2, (at 5.8 percent asphalt) had this mix been designed originally with the gyratory compactor at 100 psi, 60 gyrations the optimum asphalt content would have been lower because of the increase of laboratory compactive effort over the 75 blow design. This can be seen in Figures 6 and 7 on Phase I of this study.

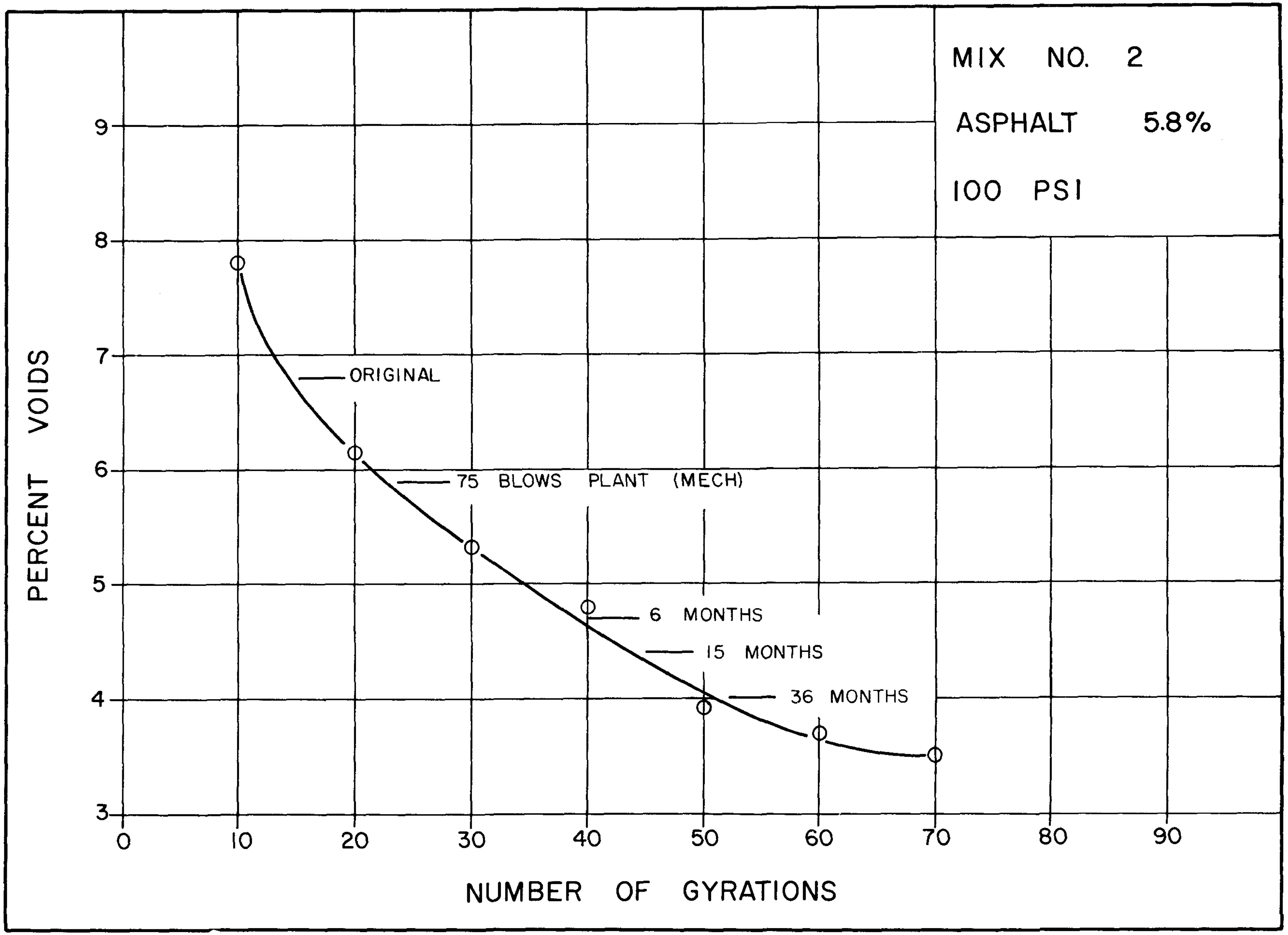

Figure 3 - Comparison of the Percent Voids, number of Gyrations Curve to the void content of roadway specimens from the original to 36 months.

At 100 psi, 60 gyrations for Mix No. 2, the optimum asphalt content appears to be approximately 5.2 to 5.5 percent. This shows a design void content of 4.0 percent.

In choosing a design compactive effort at 100 psi, specimens were molded on each of the six mix designs varying the number of gyrations from 10 to 60. The asphalt content used on these mixes was that which appeared to be optimum from the curves in Phase I at 100 psi, 60 gyrations. All test results are compiled in Table 8 of the Appendix.

Figure 16 through 21 represent the curves for Marshall stability and void content versus number of gyrations on each of the six mixes. As indicated by the curves, as the number of gyrations increases the void contents decreases and at 60 gyrations begins to level off with the exception of Figure 21 Mix No. 6. It was mentioned previously that due to the absorptive characteristics and the high void content of the expanded clay it became very difficult to base optimum conditions on void content or density alone.

This again is seen in Figure 21 which shows an irregular percent voids versus number of gyration curve, however, the Marshall stability shows a high value at 60 gyrations indicating an optimum condition.

Based on the results discussed in Phases I and II, it is believed that a compactive effort of 100 psi, 60 gyrations would be a superior design than the 75 blow Marshall hammer and would require a maximum effort in the field thus providing a longer design life of asphaltic concrete pavements.

CONCLUSIONS

The results from this study warrant the following conclusions and are confined to the materials and equipment studied herein:

(1) For the 75 blow Marshall method of design, the void content on the roadway after 6 months of traffic had already decreased below that obtained in the laboratory. This indicates a need for higher compactive efforts in the laboratory.

(2) As the void content approached 4 percent for a gravel mix at optimum asphalt content, any additional compactive effort applied would decrease the voids very little thus indicating that a mix compacted in the field near 4 percent voids may remain fairly constant over a period of years which would definitely increase the life of the pavement.

(3) Higher compactive efforts in the laboratory would naturally result in higher standards to be met in the field which would give higher densities, lower void contents and would minimize rutting and hardening of the asphalt obtained with time.

(4) It was confirmed that optimum asphalt contents can be predicted from the gyrographs at a given compactive effort and excessive asphalt can be detected by widening of the gyrograph which indicates flushing of the asphalt.

(5) For highly absorptive aggregate such as expanded clay the gyrograph will not show flushing even though the asphalt content is in excess of the amount needed to obtain suitable stability values. Therefore, the Marshall stability is probably the best means of obtaining optimum asphalt contents on expanded clay mixes at this time.

(6) The gyratory compactor is capable of producing a large range of compactive effort and when correlated with field results, this method of design would be a more meaningful and possibly a necessary means in extending the design life of asphalt concrete pavements. The time required to compact the specimens is approximately the same as the Marshall method.

RECOMMENDATIONS

Because of the advanced technical data now available through the manufacturer*, it is recommended that future studies be undertaken to further evaluate the gyratory machine as a testing apparatus. Field trials should be made in conjunction with additional laboratory studies to develope the most suitable design criteria.

The gyratory apparatus is capable of obtaining shear strengths, bearing resistance and strain data on asphaltic concrete mixtures. This data correlated with field conditions could be very important in predicting the performance of asphaltic concrete pavements.

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* Edco Engineering Developments Company Inc. Vicksburg, Mississippi

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(3) S. C. Shah, "Compaction of Asphaltic Concrete Pavement with High Intensity Pneumatic Roller", Part II, Densification Due to Traffic. Louisiana Department of Highways Research Report No. 19, October 1965

(4) Operators manual for the Gyratory Testing Machine, Engineering Development Company, Inc. Vicksburg, Mississippi

APPENDIX

TABLE 1

COMPOSITION AND PROPORTIONS OF THE VARIOUS MIX DESIGNS

MIX 1

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.650	45
2	2.650	35
3	2.640	15
Mineral Filler (Silica)	2.670	5
60-70 Pen (Shell Oil Co.)	1.030	Varied

MIX 2

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.629	48
2	2.634	27
3	2.627	20
Mineral Filler (Silica)	2.656	5
80-100 Pen (Shell Oil Co.)	1.020	Varied

GRADATION

U.S. Sieve	Per Cent Passing				
	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"					100
1/2"		100	100		100
3/8"		99	57		93
No. 4	100	36	1		63
No. 10	85	6			45
No. 40	52	1		100	29
No. 80	29			99	18
No. 200	11			98	10

U.S. Sieve	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"			100		100
1/2"			99		99
3/8"		100	49		90
No. 4	100	43	14		68
No. 10	86	22	4		52
No. 40	49	9	2	100	31
No. 80	24	3	2	99	17
No. 200	13	1	1	81	10

TABLE 1 (Cont.)

MIX 3

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.646	50
2	2.633	36
3	2.628	10
Mineral Filler (Limestone)	2.734	4
60-70 Pen (Shell Oil Co.)	1.030	Varied

MIX 4

Composed of Crushed Limestone, Coarse Sand, fine Sand and mineral filler

Aggregate Size	Specific Gravity	Proportions-%
1"-3/4" Limestone	2.718	15
3/4"-1/2" Limestone	2.718	17
1/2"-No. 4 Limestone	2.735	20
Pass No. 4 Limestone	2.700	4
Coarse Sand	2.620	30
Fine Sand	2.635	11
Mineral filler (Limestone Dust)	2.699	3
60-70 Pen (Esso)	1.030	Varied

GRADATION

U.S. Sieve	Per Cent Passing				
	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"					
1/2"		100	100		100
3/8"		99	57		95
No. 4	100	12	2		59
No. 10	85	1			48
No. 40	59			100	35
No. 80	40			96	24
No. 200	17			81	12

U.S. Sieve	Per Cent Passing				
	Limestone	Coarse Sand	Fine Sand	Mineral filler	Composite
1"					100
3/4"	Graded in individual				85
1/2"	sizes as shown above				68
No. 4		100			48
No. 10		90			39
No. 40		20	100		19
No. 80		1	98	100	14
No. 200		0	28	88	6

TABLE 1 (Cont.)

MIX 5

Composed of Limestone Rock Asphalt, Coarse Sand

Aggregate	Specific Gravity	Proportions-%
(Limestone Rock Asphalt)	2.542	65
(Coarse Sand)	2.656	35
60-70 Pen (Texaco)	1.030	Varied

MIX 6

Composed of Expanded Clay, Coarse Sand, Fine Sand and mineral filler

Aggregate Size	Specific Gravity	Proportions-%
3/4"-1/2"	1.243	15
1/2"-No. 4	1.312	20
Coarse Sand	2.644	50
Fine Sand	2.635	10
Mineral filler (Limestone Dust)	2.699	5
60-70 Pen (Esso)	1.030	Varied

GRADATION

U.S. Sieve	Limestone Rock Asphalt	Coarse Sand	Composite
3/4"			
1/2"			
3/8"	100	100	100
No. 4	93	99	95
No. 10	73	88	78
No. 40	40	54	45
No. 80	25	14	21
No. 200	14	3	10

U.S. Sieve	Expanded Clay	Coarse Sand	Fine Sand	Mineral filler	Composite
3/4"					100
1/2"	Graded in individual sizes as shown above	100			85
No. 4		98			64
No. 10		89	100		60
No. 40		47	99		39
No. 80		10	97	100	20
No. 200		0	29	87	7

TABLE 2

PHYSICAL PROPERTIES OF MIX NO. 1 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs/ cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.0% Theoretical Gravity - 2.49							
250 PSI 60 Gyrations	2.328	93.5	6.5	58.4	145.3	2423	9
Asphalt Content - 4.5% Theoretical Gravity - 2.47							
50 Blow Manual Hammer	2.292	92.8	7.2	59.1	143.0	1572	8
50 Blow Mechanical Hammer	2.282	92.4	7.6	55.7	142.4	1295	8
75 Blow Manual Hammer	2.316	93.8	6.2	63.0	144.5	1775	10
75 Blow Mechanical Hammer	2.293	92.8	7.2	59.1	143.1	1501	6
100 PSI 30 Gyrations	2.289	92.7	7.3	58.0	142.8	1306	10
100 PSI 45 Gyrations	2.309	93.5	6.5	61.1	144.1	1527	7
100 PSI 60 Gyrations	2.320	93.9	6.1	62.7	144.8	1749	9
200 PSI 30 Gyrations	2.302	93.2	6.8	59.9	143.6	1696	9
200 PSI 45 Gyrations	2.330	94.3	5.7	64.3	145.4	2166	7
200 PSI 60 Gyrations	2.336	94.6	5.4	65.6	145.8	2433	8
250 PSI 30 Gyrations	2.329	94.3	5.7	64.3	145.3	1622	10
250 PSI 45 Gyrations	2.341	94.8	5.2	66.5	146.1	2230	9
250 PSI 60 Gyrations	2.347	95.0	5.0	67.4	146.5	2493	8
Asphalt Content - 5.0 % Theoretical Gravity - 2.45							
50 Blow Manual Hammer	2.317	94.6	5.4	67.9	144.6	1574	10
50 Blow Mechanical Hammer	2.289	93.6	6.6	61.6	142.8	1504	8
75 Blow Manual Hammer	2.322	94.8	5.2	68.6	144.9	1638	10
75 Blow Mechanical Hammer	2.306	94.1	5.9	65.7	143.9	1617	7
100 PSI 30 Gyrations	2.317	94.6	5.4	67.9	144.6	1459	9
100 PSI 45 Gyrations	2.332	95.2	4.8	70.4	145.5	1633	7
100 PSI 60 Gyrations	2.336	95.4	4.6	70.9	145.8	1839	9
200 PSI 30 Gyrations	2.329	95.1	4.9	70.0	145.3	2028	9
200 PSI 45 Gyrations	2.333	95.2	4.8	70.4	145.6	2107	8
200 PSI 60 Gyrations	2.347	95.8	4.2	73.2	146.5	2051	9
250 PSI 30 Gyrations	2.333	95.2	4.8	70.4	145.6	2017	7
250 PSI 45 Gyrations	2.339	95.5	4.5	7.18	146.0	2301	7
250 PSI 60 Gyrations	2.346	95.8	4.2	73.2	146.4	2191	9
Asphalt Content - 5.5 % Theoretical Gravity - 2.44							
50 Blow Manual Hammer	2.310	94.7	5.3	70.2	144.1	1206	13
50 Blow Mechanical Hammer	2.304	94.4	5.6	68.9	143.8	1362	11
75 Blow Manual Hammer	2.318	95.0	5.0	71.4	144.6	1290	12
75 Blow Mechanical Hammer	2.309	94.6	5.4	69.7	144.1	1559	12
100 PSI 30 Gyrations	2.331	95.5	4.5	73.6	145.3	1385	11
100 PSI 45 Gyrations	2.337	95.8	4.2	78.8	145.8	1443	10
100 PSI 60 Gyrations	2.340	95.9	4.1	79.3	146.0	1580	11
200 PSI 30 Gyrations	2.337	95.8	4.2	78.8	145.8	1227	11
200 PSI 45 Gyrations	2.341	95.9	4.1	79.3	146.1	1911	11
200 PSI 60 Gyrations	2.345	96.1	3.9	76.4	146.3	1565	12
250 PSI 30 Gyrations	2.337	95.8	4.2	75.0	145.8	1612	9
250 PSI 45 Gyrations	2.347	96.2	3.8	76.9	146.5	1791	11
250 PSI 60 Gyrations	2.346	96.1	3.9	68.2	146.4	1800	11
Asphalt Content - 6.0% Theoretical Gravity - 2.42							
50 Blow Manual Hammer	2.301	95.1	4.9	73.4	143.6	737	15
50 Blow Mechanical Hammer	2.306	95.3	4.7	74.3	143.9	754	12
75 Blow Manual Hammer	2.303	95.2	4.8	73.8	143.7	963	16
75 Blow Mechanical Hammer	2.308	95.4	4.6	74.7	144.0	864	11
100 PSI 30 Gyrations	2.320	95.9	4.1	76.8	144.8	1159	13

TABLE 3

PHYSICAL PROPERTIES OF MIX NO. 2 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids - %	V.F.A. -%	Density lbs./cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.5% Theoretical Gravity - 2.456							
200 PSI 30 Gyrations	2.295	93.4	6.6	60.5	143.2	1417	9
200 PSI 45 Gyrations							
200 PSI 60 Gyrations	2.319	94.4	5.6	64.6	144.7	2415	8
250 PSI 30 Gyrations	2.293	93.4	6.6	60.5	143.1	1875	8
250 PSI 45 Gyrations	2.297	93.5	6.5	60.9	143.3	2212	8
250 PSI 60 Gyrations	2.338	96.5	3.5	74.7	145.9	2502	8
Asphalt Content - 5.0% Theoretical Gravity - 2.439							
50 Blow Manual Hammer	2.233	91.5	8.5	56.4	139.3	1158	6
50 Blow Mechanical Hammer	2.223	91.1	8.9	55.1	138.7	1033	7
75 Blow Manual Hammer	2.277	93.3	6.7	62.6	142.1	1654	5
75 Blow Mechanical Hammer	2.206	90.4	9.6	53.0	137.7	936	5
100 PSI 30 Gyrations							
100 PSI 45 Gyrations	2.283	93.6	6.4	63.6	142.5	1535	8
100 PSI 60 Gyrations	2.310	94.7	5.3	68.1	144.1	1870	8
200 PSI 30 Gyrations	2.322	95.9	4.1	73.5	144.9	2044	9
200 PSI 45 Gyrations	2.293	94.0	6.0	65.2	143.1	2086	9
200 PSI 60 Gyrations	2.337	96.5	3.5	76.6	145.8	2312	11
250 PSI 30 Gyrations	2.322	95.2	4.8	69.7	144.9	2021	10
250 PSI 45 Gyrations	2.304	94.5	5.5	67.2	143.8	2276	11
250 PSI 60 Gyrations	2.346	96.9	3.1	78.8	146.4	2409	8
Asphalt Content - 5.5 % Theoretical Gravity - 2.422							
50 Blow Manual Hammer	2.261	93.3	6.7	64.7	141.0	1564	7
50 Blow Mechanical Hammer	2.231	92.1	7.9	60.4	139.2	1104	8
75 Blow Manual Hammer	2.297	94.9	5.1	70.8	143.3	1680	7
75 Blow Mechanical Hammer	2.234	92.2	7.8	60.7	139.4	1104	9
100 PSI 30 Gyrations	2.305	95.2	4.8	72.1	143.8	1554	12
100 PSI 45 Gyrations	2.296	94.8	5.2	70.4	143.3	1690	11
100 PSI 60 Gyrations	2.334	96.4	3.6	77.8	145.6	1975	9
200 PSI 30 Gyrations	2.327	96.8	3.2	79.7	145.2	1870	12
200 PSI 45 Gyrations	2.304	95.1	4.9	71.7	143.8	2105	11
200 PSI 60 Gyrations	2.341	97.4	2.6	82.9	146.1	1904	16
250 PSI 30 Gyrations	2.336	97.2	2.8	81.8	145.8	1880	8
250 PSI 45 Gyrations	2.319	95.7	4.3	70.4	144.7	2064	11
250 PSI 60 Gyrations	2.342	97.5	2.5	83.5	146.1	1827	10
Asphalt Content - 6.0% Theoretical Gravity - 2.403							
50 Blow Manual Hammer	2.271	94.5	5.5	70.7	141.7	1575	8
50 Blow Mechanical Hammer	2.245	93.4	6.6	66.7	140.1	1160	9
75 Blow Manual Hammer	2.298	95.6	4.4	75.4	143.4	1498	11
75 Blow Mechanical Hammer	2.254	93.8	6.2	68.1	140.6	1296	9
100 PSI 30 Gyrations	2.317	96.4	3.6	79.1	144.6	1644	13
100 PSI 45 Gyrations	2.304	95.9	4.1	76.8	143.8	1538	12
100 PSI 60 Gyrations	2.322	96.6	3.4	80.2	144.9	1383	14
200 PSI 30 Gyrations	2.326	97.4	2.6	84.0	145.1	1627	14
200 PSI 45 Gyrations	2.310	96.1	3.9	77.7	144.1	1843	12
200 PSI 60 Gyrations	2.332	97.7	2.3	85.6	145.5	1494	12
250 PSI 30 Gyrations	2.333	97.7	2.3	85.7	145.6	1543	13
250 PSI 45 Gyrations							
250 PSI 60 Gyrations	2.332	97.7	2.3	85.6	145.5	1452	15
Asphalt Content - 6.5% Theoretical Gravity - 2.386							
100 PSI 30 Gyrations	2.312	96.8	3.2	82.2	144.3	1454	12
100 PSI 60 Gyrations	2.304	96.5	3.5	80.8	143.8	1080	21

TABLE 4

PHYSICAL PROPERTIES OF MIX NO. 3 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V. F. A. -%	Density lbs. / cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.0% Theoretical Gravity - 2.485							
250 PSI 30 Gyrations	2.281	91.8	8.2	52.3	142.3	1908	6
250 PSI 45 Gyrations	2.306	92.8	7.2	55.6	143.9	2366	7
250 PSI 60 Gyrations	2.312	93.0	7.0	62.1	144.3	2439	7
Asphalt Content - 4.5% Theoretical Gravity - 2.464							
200 PSI 45 Gyrations	2.312	93.8	6.2	62.2	144.3	2323	9
200 PSI 60 Gyrations	2.311	93.9	6.1	62.6	144.2	2392	6
250 PSI 30 Gyrations	2.300	93.3	6.7	59.2	143.5	2022	6
250 PSI 45 Gyrations	2.320	94.2	5.8	63.3	144.8	2570	7
250 PSI 60 Gyrations	2.323	94.3	5.7	64.1	145.0	2528	7
Asphalt Content - 5.0% Theoretical Gravity - 2.448							
50 Blow Manual Hammer	2.291	93.6	6.4	63.6	143.0	1654	10
50 Blow Mechanical Hammer	2.244	91.7	8.3	57.0	140.0	1251	8
75 Blow Manual Hammer	2.298	93.9	6.1	64.9	143.4	1817	7
75 Blow Mechanical Hammer	2.297	93.9	6.1	64.9	143.3	1875	14
100 PSI 30 Gyrations	2.273	92.8	7.2	60.7	141.8	1317	5
100 PSI 45 Gyrations	2.295	93.7	6.3	64.5	143.2	1695	8
100 PSI 60 Gyrations	2.298	93.9	6.1	64.9	143.4	1712	7
200 PSI 30 Gyrations	2.304	94.1	5.9	65.7	143.8	1860	5
200 PSI 45 Gyrations	2.320	94.8	5.2	68.6	144.8	2086	8
200 PSI 60 Gyrations	2.329	95.1	4.9	70.0	145.3	2262	8
250 PSI 30 Gyrations	2.321	94.8	5.2	68.7	144.8	2139	8
250 PSI 45 Gyrations	2.331	95.2	4.8	70.4	145.5	2339	9
250 PSI 60 Gyrations	2.341	95.6	4.4	72.3	146.1	2551	7
Asphalt Content - 5.5% Theoretical Gravity - 2.428							
50 Blow Manual Hammer	2.300	94.7	5.3	70.1	143.5	1564	8
50 Blow Mechanical Hammer	2.268	93.4	6.6	64.9	141.5	1251	7
75 Blow Manual Hammer	2.305	94.9	5.1	70.9	143.8	1627	12
75 Blow Mechanical Hammer	2.311	95.2	4.8	72.2	144.2	1877✓	12
100 PSI 30 Gyrations	2.299	94.7	5.3	70.1	143.5	1553	8
100 PSI 45 Gyrations	2.313	95.3	4.7	72.6	144.3	1832	8
100 PSI 60 Gyrations	2.323	95.7	4.3	74.4	145.0	1844✓	10
200 PSI 30 Gyrations	2.322	95.6	4.4	74.0	144.9	1996	7
200 PSI 45 Gyrations	2.329	95.9	4.1	75.4	145.3	1870	11
200 PSI 60 Gyrations	2.338	96.3	3.7	77.3	145.9	1991	9
250 PSI 30 Gyrations	2.330	96.0	4.0	75.9	145.4	2041	8
250 PSI 45 Gyrations	2.337	96.3	3.7	77.3	145.8	1827	12
250 PSI 60 Gyrations	2.339	96.3	3.7	77.3	146.0	1695	11
Asphalt Content - 6.0% Theoretical Gravity - 2.413							
50 Blow Manual Hammer	2.259	93.6	6.4	67.5	141.0	1283	12
50 Blow Mechanical Hammer	2.278	94.4	5.6	70.5	142.1	1180	9
75 Blow Manual Hammer	2.305	95.5	4.5	75.1	143.8	1322	14
75 Blow Mechanical Hammer	2.298	95.2	4.8	74.2	143.4	1421✓	15
100 PSI 30 Gyrations	2.314	95.9	4.1	76.9	144.4	1470	8
100 PSI 45 Gyrations	2.317	96.0	4.0	77.3	144.6	1712	9
100 PSI 60 Gyrations	2.321	96.2	3.8	78.2	144.8	1559✓	10
200 PSI 30 Gyrations	2.319	96.1	3.9	77.8	144.7	1643	9
200 PSI 45 Gyrations	2.324	96.3	3.7	78.7	145.0	1580	10
200 PSI 60 Gyrations	2.329	96.5	3.5	79.7	145.3	1560	13

TABLE 5

PHYSICAL PROPERTIES OF MIX NO. 4 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu. ft.	Marshall Stability	Flow
Asphalt Content - 3.0% Theoretical Gravity - 2.559							
100 PSI 60 Gyrations	2.415	94.4	5.6	55.7	150.7	2201	11
200 PSI 30 Gyrations	2.417	94.5	5.5	56.1	150.8	2250	9
200 PSI 45 Gyrations	2.425	94.8	5.2	57.6	151.3	2668	10
200 PSI 60 Gyrations	2.443	95.5	4.5	61.3	152.4	3276	9
250 PSI 30 Gyrations	2.414	94.3	5.7	55.2	150.6	2014	9
250 PSI 45 Gyrations	2.432	95.0	5.0	58.6	151.8	2874	8
250 PSI 60 Gyrations	2.437	95.2	4.8	59.7	152.1	2953	9
Asphalt Content - 3.5% Theoretical Gravity - 2.538							
50 Blow Manual Hammer	2.414	95.1	4.9	62.6	150.6	2049	12
50 Blow Mechanical Hammer	2.376	93.6	6.4	55.8	148.3	1379	10
75 Blow Manual Hammer	2.424	95.5	4.5	64.7	151.3	2385	9
75 Blow Mechanical Hammer	2.417	95.2	4.8	63.1	150.8	2189	10
100 PSI 30 Gyrations	2.406	94.8	5.2	61.1	150.1	1895	10
100 PSI 45 Gyrations	2.425	95.5	4.5	64.7	151.3	2025	10
100 PSI 60 Gyrations	2.447	96.4	3.6	69.8	152.7	2712	10
200 PSI 30 Gyrations	2.434	95.9	4.1	66.9	151.9	2277	8
200 PSI 45 Gyrations	2.449	96.5	3.5	67.1	152.8	2934	11
200 PSI 60 Gyrations	2.455	96.7	3.3	71.6	153.2	3173	10
250 PSI 30 Gyrations	2.430	95.7	4.3	65.8	151.6	2590	11
250 PSI 45 Gyrations	2.441	96.2	3.8	68.6	152.3	3007	10
250 PSI 60 Gyrations	2.461	97.0	3.0	73.6	153.6	2961	13
Asphalt Content - 4.0% Theoretical Gravity - 2.519							
50 Blow Manual Hammer	2.417	96.0	4.0	70.1	150.8	2296	11
50 Blow Mechanical Hammer	2.401	95.3	4.7	66.5	149.8	1584	10
75 Blow Manual Hammer	2.426	96.3	3.7	71.8	151.4	2349	11
75 Blow Mechanical Hammer	2.426	96.3	3.7	71.8	151.4	2119	11
100 PSI 30 Gyrations	2.428	96.4	3.6	72.4	151.5	2070	10
100 PSI 45 Gyrations	2.439	96.8	3.2	74.8	152.2	1830	10
100 PSI 60 Gyrations	2.453	97.4	2.6	78.5	153.1	2484	10
200 PSI 30 Gyrations	2.449	97.2	2.8	77.3	152.8	2325	12
200 PSI 45 Gyrations	2.454	97.4	2.6	73.3	153.1	2349	11
200 PSI 60 Gyrations	2.469	98.0	2.0	82.7	154.1	2939	11
250 PSI 30 Gyrations	2.446	97.1	2.9	76.6	152.6	2357	11
250 PSI 45 Gyrations	2.454	97.4	2.6	78.6	153.1	2537	11
250 PSI 60 Gyrations	2.465	97.9	2.1	82.0	153.8	3030	11
Asphalt Content - 4.5% Theoretical Gravity - 2.501							
50 Blow Manual Hammer	2.425	97.0	3.0	77.9	151.3	1783	12
50 Blow Mechanical Hammer	2.415	96.6	3.4	75.6	150.7	1512	12
75 Blow Manual Hammer	2.430	97.1	2.9	78.6	151.6	1757	12
75 Blow Mechanical Hammer	2.425	97.0	3.0	77.9	151.3	1792	10
100 PSI 30 Gyrations	2.436	97.4	2.6	80.4	152.0	1851	13
100 PSI 45 Gyrations	2.451	98.0	2.0	84.3	152.9	1848	15
Asphalt Content - 5.0% Theoretical Gravity - 2.482							
50 Blow Manual Hammer	2.412	97.2	2.8	80.7	150.5	1366	16
50 Blow Mechanical Hammer	2.416	97.3	2.7	81.3	150.8	1532	14
75 Blow Manual Hammer	2.417	97.4	2.6	81.9	150.8	1285	16
75 Blow Mechanical Hammer	2.409	97.1	2.9	80.1	150.3	1178	18
100 PSI 30 Gyrations	2.433	98.0	2.0	85.5	151.8	1559	16
100 PSI 45 Gyrations	2.437	98.2	1.8	86.8	152.1	1434	18

TABLE 6

PHYSICAL PROPERTIES OF MIX NO. 5 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stability	Flow
Asphalt Content - 3.0% Theoretical Gravity - 2.470							
200 PSI 45 Gyrations	2.269	91.8	8.1	44.9	141.6	3722	12
250 PSI 60 Gyrations	2.304	93.3	6.7	50.0	143.8	4817	9
Asphalt Content - 3.5% Theoretical Gravity - 2.449							
100 PSI 45 Gyrations	2.251	91.9	8.1	48.6	140.5	2858	11
200 PSI 45 Gyrations	2.281	93.1	6.9	52.9	142.3	4026	7
200 PSI 60 Gyrations	2.285	93.3	6.7	53.7	142.6	3674	9
250 PSI 30 Gyrations	2.304	94.1	5.9	57.0	143.8	3372	7
250 PSI 45 Gyrations	2.335	95.3	4.7	62.8	145.7	3770	8
250 PSI 60 Gyrations	2.351	96.0	4.0	66.6	146.7	4328	9
Asphalt Content - 4.0% Theoretical Gravity - 2.432							
50 Blow Manual Hammer	2.242	92.1	7.9	47.6	139.9	2205	11
75 Blow Mechanical Hammer	2.230	91.6	8.4	49.2	139.2	2137	10
75 Blow Manual Hammer	2.285	93.9	6.1	59.3	142.6	2936	10
100 PSI 30 Gyrations	2.254	92.7	7.3	54.5	140.6	2192	13
100 PSI 45 Gyrations	2.294	94.3	5.7	61.0	143.1	2591	11
100 PSI 60 Gyrations	2.309	94.9	5.1	63.8	144.1	2808 ✓	12
200 PSI 30 Gyrations	2.278	93.7	6.3	58.4	142.1	3019	10
200 PSI 45 Gyrations	2.290	94.2	5.8	60.5	142.9	3310	9
200 PSI 60 Gyrations	2.303	94.7	5.3	62.8	144.1	3659	11
250 PSI 30 Gyrations	2.324	95.5	4.5	66.7	145.0	3563	9
250 PSI 45 Gyrations	2.342	96.2	3.8	70.5	146.1	3633	10
250 PSI 60 Gyrations	2.355	96.8	3.2	74.1	147.0	3241	10
Asphalt Content - 4.5% Theoretical Gravity - 2.414							
50 Blow Mechanical Hammer	2.265	93.8	6.2	61.5	141.3	2182	14
50 Blow Manual Hammer	2.303	95.4	4.6	68.6	143.7	3122	16
75 Blow Mechanical Hammer	2.312	95.8	4.2	70.6	144.3	3206	16
75 Blow Manual Hammer	2.327	96.4	3.6	73.9	145.2	2882	18
100 PSI 30 Gyrations	2.283	94.6	5.4	64.9	142.5	2119	12
100 PSI 45 Gyrations	2.310	95.7	4.3	70.1	144.1	2518	10
100 PSI 60 Gyrations	2.315	95.9	4.1	71.1	144.5	2745	12
200 PSI 30 Gyrations	2.287	94.7	5.3	65.3	142.7	3120	9
200 PSI 45 Gyrations	2.318	96.0	4.0	71.7	144.6	3084	11
200 PSI 60 Gyrations	2.323	96.2	3.8	72.8	145.0	3495	10
250 PSI 30 Gyrations	2.298	95.2	4.8	67.7	143.4	3150	7
250 PSI 45 Gyrations	2.329	96.5	3.5	74.4	145.3	3828	13
250 PSI 60 Gyrations	2.348	97.3	2.7	79.2	146.5	2776	10
Asphalt Content - 5.0% Theoretical Gravity - 2.398							
50 Blow Mechanical Hammer	2.295	95.7	4.3	72.2	143.2	2344	16
50 Blow Manual Hammer	2.303	96.0	4.0	73.6	143.7	2361	21
75 Blow Mechanical Hammer	2.307	96.2	3.8	74.7	144.0	2353 ✓	17
75 Blow Manual Hammer	2.317	96.6	3.4	76.8	144.6	2279	18
100 PSI 30 Gyrations	2.303	96.0	4.0	73.6	143.7	2461	11
100 PSI 45 Gyrations	2.311	96.4	3.6	75.7	144.2	2212	11
100 PSI 60 Gyrations	2.321	96.8	3.2	77.9	144.8	2260 ✓	11
200 PSI 30 Gyrations	2.297	95.8	4.2	72.6	143.3	2665	8
200 PSI 45 Gyrations	2.334	97.3	2.7	80.8	145.6	2137	14
200 PSI 60 Gyrations	2.326	97.0	3.0	79.0	145.1	2915	13
250 PSI 45 Gyrations	2.333	97.3	2.7	80.8	145.6	2322	15
Asphalt Content - 5.5% Theoretical Gravity - 2.381							
50 Blow Mechanical Hammer	2.295	96.4	3.6	77.3	143.2	1914	17
100 PSI 30 Gyrations	2.296	96.4	3.6	77.3	143.3	1988	13

TABLE 7

PHYSICAL PROPERTIES OF MIX NO. 6 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stability	Flow
Asphalt Content - 4.5% Theoretical Gravity - 1.857							
50 Blow Manual Hammer	1.537	82.8	17.2	28.1	95.9	1606	9
50 Blow Mechanical Hammer	1.501	80.8	19.2	13.9	93.7	1033	8
75 Blow Manual Hammer	1.563	84.2	15.8	30.2	97.5	1663	9
100 PSI 45 Gyrations	1.523	82.0	18.0	27.0	95.0	1407	9
100 PSI 60 Gyrations	1.548	83.4	16.4	29.2	96.6	1563	9
200 PSI 30 Gyrations	1.528	82.3	17.7	27.4	95.3	1786	13
200 PSI 45 Gyrations	1.578	85.0	15.0	31.5	98.5	1750	9
250 PSI 45 Gyrations	1.602	86.3	13.7	33.8	100.0	2351	9
250 PSI 60 Gyrations	1.586	85.4	14.6	28.5	99.0	2661	10
Asphalt Content - 5.0% Theoretical Gravity - 1.848							
50 Blow Manual Hammer	1.564	84.6	15.4	33.0	97.6	1820	10
50 Blow Mechanical Hammer	1.524	82.5	17.5	29.7	95.1	1200	8
75 Blow Manual Hammer	1.574	85.2	14.8	34.0	98.2	1991	9
100 PSI 30 Gyrations	1.550	83.9	16.1	31.8	96.7	1249	9
100 PSI 45 Gyrations	1.536	83.1	16.9	30.6	95.8	1623	8
100 PSI 60 Gyrations	1.570	85.0	15.0	33.7	98.0	1785	10
200 PSI 30 Gyrations	1.561	84.5	15.5	32.8	97.4	1818	12
200 PSI 45 Gyrations	1.578	85.4	14.6	34.4	98.5	1979	10
200 PSI 60 Gyrations	1.621	87.7	12.3	39.0	101.2	2325	11
250 PSI 30 Gyrations	1.603	86.7	13.3	36.9	100.0	1854	10
250 PSI 45 Gyrations	1.607	87.0	13.0	37.5	100.3	2616	10
250 PSI 60 Gyrations	1.603	86.7	13.3	36.9	100.0	2807	9
Asphalt Content - 5.5% Theoretical Gravity - 1.839							
50 Blow Manual Hammer	1.557	84.7	15.3	35.2	97.2	1669	10
50 Blow Mechanical Hammer	1.561	84.9	15.1	35.6	97.4	1137	8
75 Blow Manual Hammer	1.589	86.4	13.6	38.4	99.2	2237	9
100 PSI 30 Gyrations	1.554	84.5	15.5	34.9	97.0	1350	9
100 PSI 45 Gyrations	1.575	85.6	14.4	36.9	98.3	1670	8
100 PSI 60 Gyrations	1.566	85.2	14.8	36.1	97.7	1874	12
200 PSI 30 Gyrations	1.574	85.6	14.4	36.9	98.2	1865	12
200 PSI 45 Gyrations	1.606	87.3	12.7	40.3	100.2	1950	10
200 PSI 60 Gyrations	1.632	88.7	11.3	43.6	101.8	2561	11
250 PSI 30 Gyrations	1.597	86.8	13.2	39.2	99.7	2140	10
250 PSI 45 Gyrations	1.606	87.3	12.7	40.3	100.2	2359	10
250 PSI 60 Gyrations	1.590	86.5	13.5	38.6	99.2	2879	12
Asphalt Content - 6.0% Theoretical Gravity - 1.832							
50 Blow Mechanical Hammer	1.564	85.4	14.6	38.4	97.6	1181	7
75 Blow Manual Hammer	1.595	87.1	12.9	41.9	99.5	2018	10
100 PSI 30 Gyrations	1.559	85.1	14.9	37.9	97.3	1424	9
100 PSI 45 Gyrations	1.566	85.5	14.5	38.6	97.7	1810	11
100 PSI 60 Gyrations	1.570	85.7	14.3	39.0	98.0	1723	12
200 PSI 30 Gyrations	1.584	86.5	13.5	40.6	98.8	2037	10
200 PSI 45 Gyrations	1.608	87.8	12.2	43.4	100.3	2242	11
200 PSI 60 Gyrations	1.610	87.9	12.1	43.7	100.5	2669	12
250 PSI 30 Gyrations	1.631	89.0	11.0	46.3	101.8	2095	10
250 PSI 45 Gyrations	1.622	88.5	11.5	45.1	101.2	2542	11
250 PSI 60 Gyrations	1.611	87.9	12.1	43.7	100.5	2870	13

TABLE 7

PHYSICAL PROPERTIES OF MIX NO. 6 USING VARIOUS COMPACTIVE EFFORTS (CONTINUED)

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stabitliy	Flow
Asphalt Content - 6.5% Theoretical Gravity - 1.824							
75 Blow Mechanical Hammer	1.591	87.2	12.8	44.2	99.3	1561	9
100 PSI 30 Gyrations	1.654	90.7	9.3	52.9	103.2	1480	9
100 PSI 45 Gyrations	1.665	91.3	8.7	54.7	103.9	1703	10
200 PSI 45 Gyrations	1.698	93.1	6.9	60.8	106.0	2147	11
200 PSI 60 Gyrations	1.646	90.2	9.8	51.5	102.7	2398	9
250 PSI 45 Gyrations	1.651	90.5	9.5	52.3	103.0	2150	9
250 PSI 60 Gyrations	1.630	89.4	10.6	49.3	101.7	2383	10
Asphalt Content - 7.0% Theoretical Gravity - 1.816							
75 Blow Mechanical Hammer	1.594	87.8	12.2	47.0	99.5	1730	9
100 PSI 30 Gyrations	1.603	88.3	11.7	48.2	100.0	1543	10
100 PSI 45 Gyrations	1.670	92.0	8.0	58.7	104.5	1665	9
200 PSI 45 Gyrations	1.697	93.4	6.6	63.6	105.9	2061	8
Asphalt Content - 7.5% Theoretical Gravity - 1.810							
75 Blow Mechanical Hammer	1.649	91.1	8.9	57.4	102.9	1576	9
100 PSI 30 Gyrations	1.666	92.0	8.0	60.3	104.0	1602	10
100 PSI 45 Gyrations	1.666	92.0	8.0	60.3	104.0	1863	9
Asphalt Content - 8.0% Theoretical Gravity - 1.800							
100 PSI 30 Gyrations	1.574	87.4	12.6	49.3	98.2	1813	13

TABLE 8

AVERAGE RESULTS OF LABORATORY MIXES AT 100 PSI VERTICAL PRESSURE

Number of Gyrations	Specific Gravity	% Theoretical Gravity	Voids %	V. F. A %	Density lbs/cu ft	Marshall Stability	Flow
Mix 1 Optimum Asphalt Content - 4.8% Theoretical Gravity - 2.443							
10	2.280	93.3	6.7	61.6	142.3	895	11
20	2.314	94.7	5.3	67.3	144.4	1288	10
30	2.325	95.2	4.8	69.5	145.1	1455	11
40	2.333	95.5	4.5	70.9	145.6	1559	9
50	2.345	96.0	4.0	73.4	146.3	1774	9
60	2.351	96.2	3.8	74.5	146.7	1851	9
Mix 2 Optimum Asphalt Content - 5.2% Theoretical Gravity - 2.411							
10	2.238	92.8	7.2	61.3	134.7	628	10
20	2.272	94.2	5.8	66.6	141.8	931	10
30	2.291	95.0	5.0	70.0	143.0	1171	10
40	2.301	95.4	4.6	71.8	143.6	1293	8
50	2.306	95.6	4.4	72.8	143.9	1467	8
60	2.315	96.0	4.0	74.7	144.5	1580	8
Mix 3 Optimum Asphalt Content - 5.2% Theoretical Gravity - 2.450							
10	2.198	87.7	12.3	47.4	137.2	611	8
20	2.226	90.9	9.1	55.3	138.9	914	8
30	2.256	92.1	7.9	59.0	140.8	1219	7
40	2.262	92.3	7.7	59.7	141.1	1234	8
50	2.271	92.7	7.3	61.1	141.7	1327	8
60	2.285	93.3	6.7	63.3	142.6	1550	8
Mix 4 Optimum Asphalt Content - 4.6% Theoretical Gravity - 2.492							
10	2.354	94.5	5.5	65.9	146.9	736	8
20	2.378	95.4	4.6	70.0	148.4	966	9
30	2.398	96.2	3.8	74.0	149.6	1193	11
40	2.410	96.7	3.3	76.7	150.4	1338	8
50	2.418	97.0	3.0	78.4	150.9	1613	9
60	2.428	97.4	2.6	80.8	151.5	1697	9
Mix 5 Optimum Asphalt Content - 4.5% Theoretical Gravity - 2.414							
10	2.216	91.8	8.2	54.1	138.3	1543	10
20	2.268	94.0	6.0	62.3	141.5	2099	10
30	2.296	95.1	4.9	67.2	143.3	2444	10
40	2.295	95.1	4.9	67.2	143.2	2772	11
50	2.308	95.6	4.4	69.6	144.0	2828	12
60	2.321	96.1	3.9	72.2	144.8	2772	12
Mix 6 Optimum Asphalt Content - 7.0% Theoretical Gravity - 1.816							
10	1.589	87.5	12.5	46.6	99.2	840	10
20	1.622	89.3	10.7	51.0	101.2	1273	10
30	1.629	89.7	10.3	52.0	101.6	1426	11
40	1.645	90.6	9.4	54.6	102.6	1678	10
50	1.637	90.1	9.9	53.1	102.1	1575	11
60	1.621	89.2	10.8	50.7	101.2	1933	11

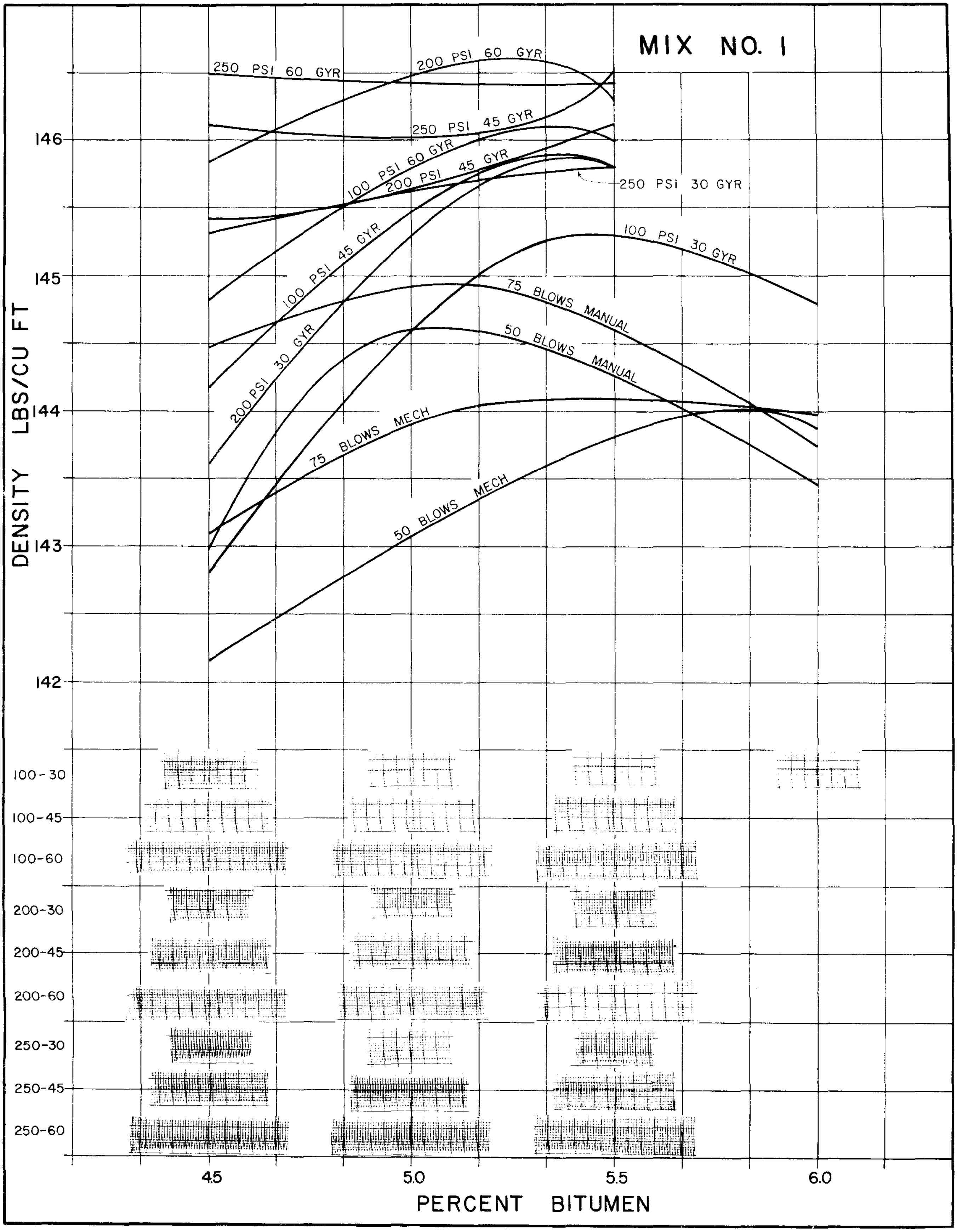


Figure 4 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 1.

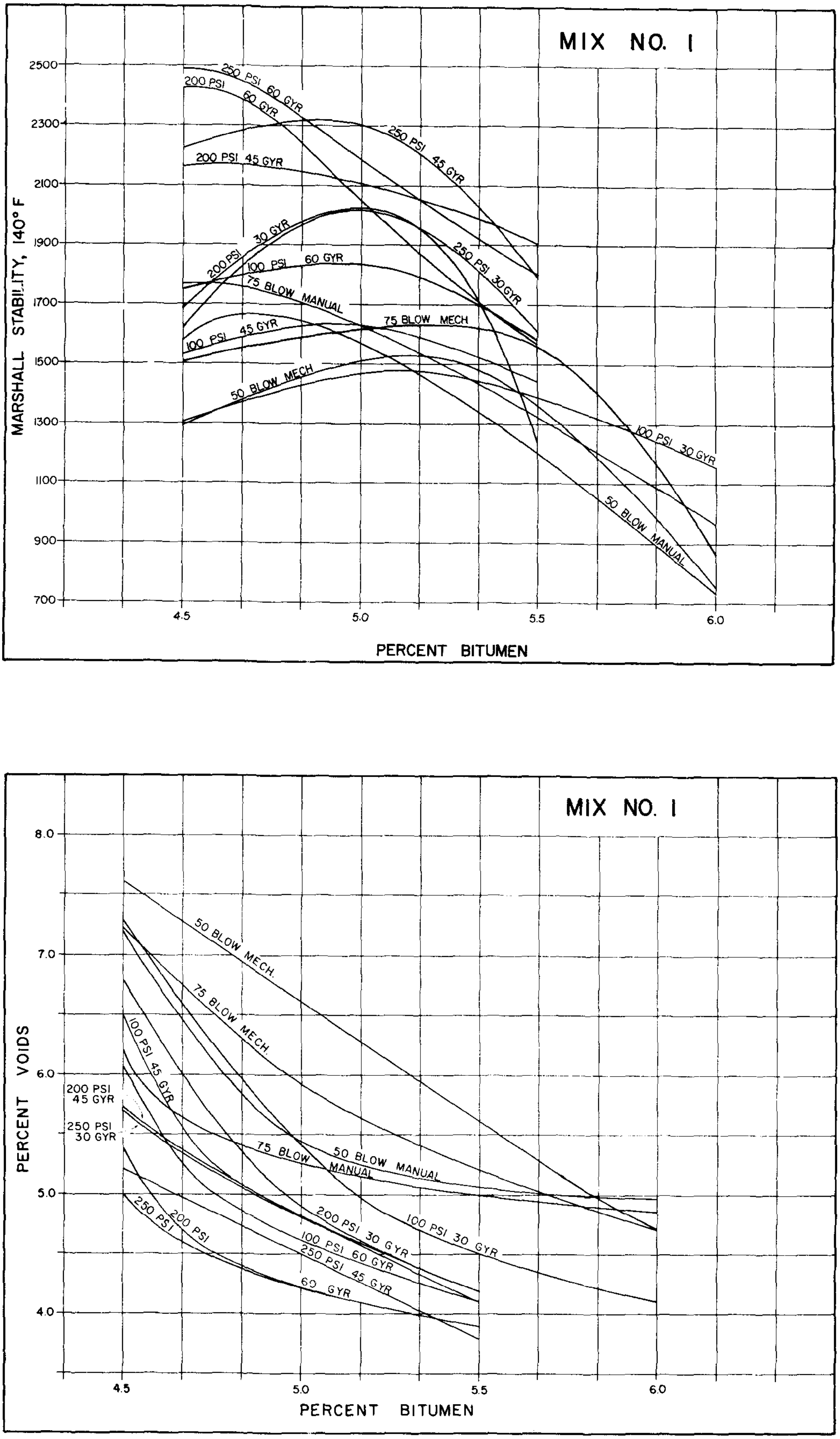


Figure 5 - Relationship of Marshall Stability and void content versus Percent Bitumen of various Efforts for gravel Mix 1.

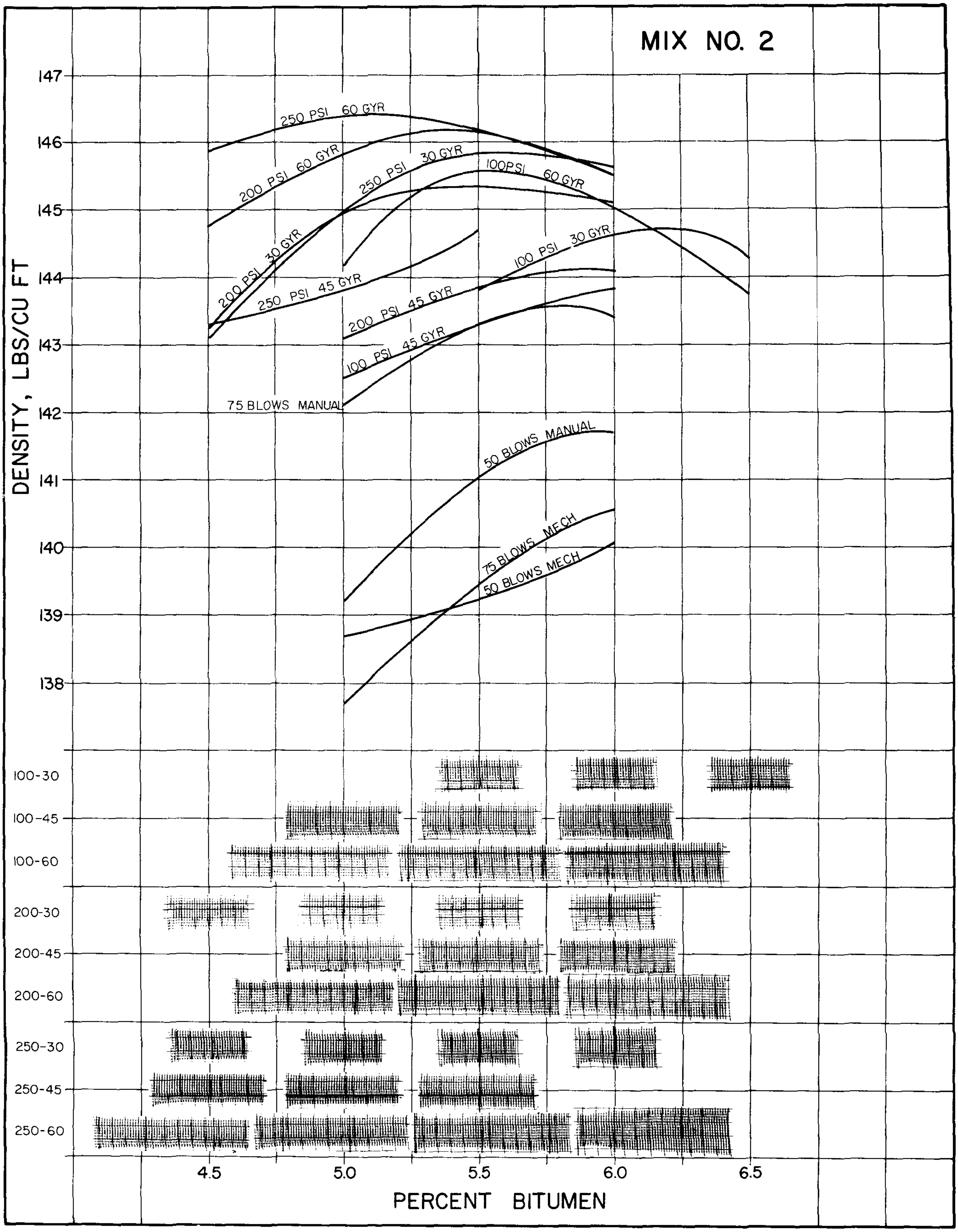
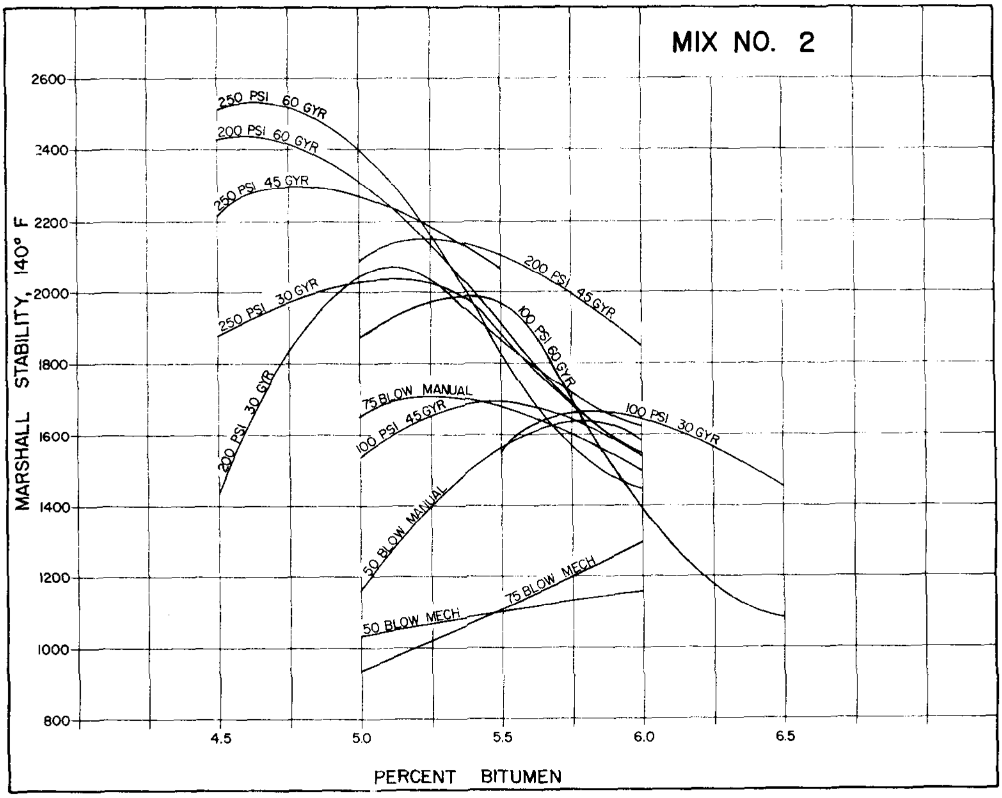


Figure 6 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 2.



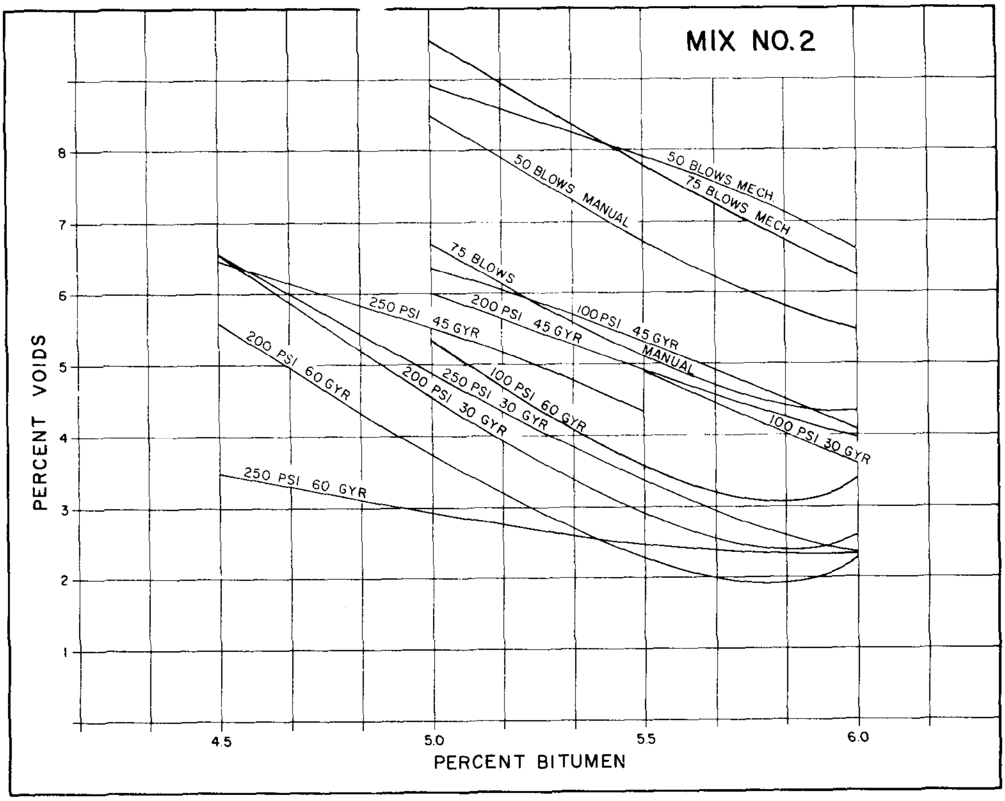


Figure 7 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for Gravel Mix 2.

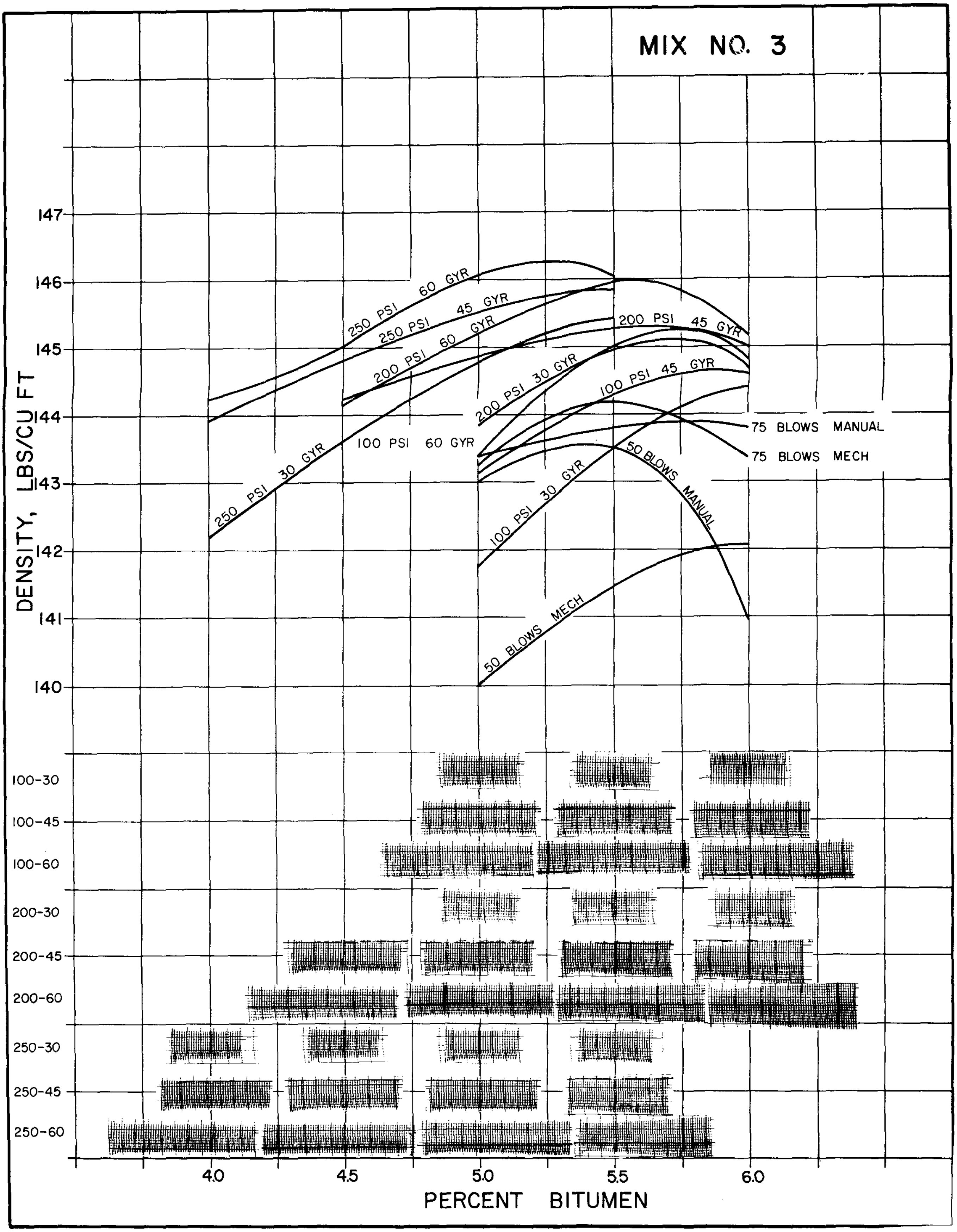


Figure 8 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 3.

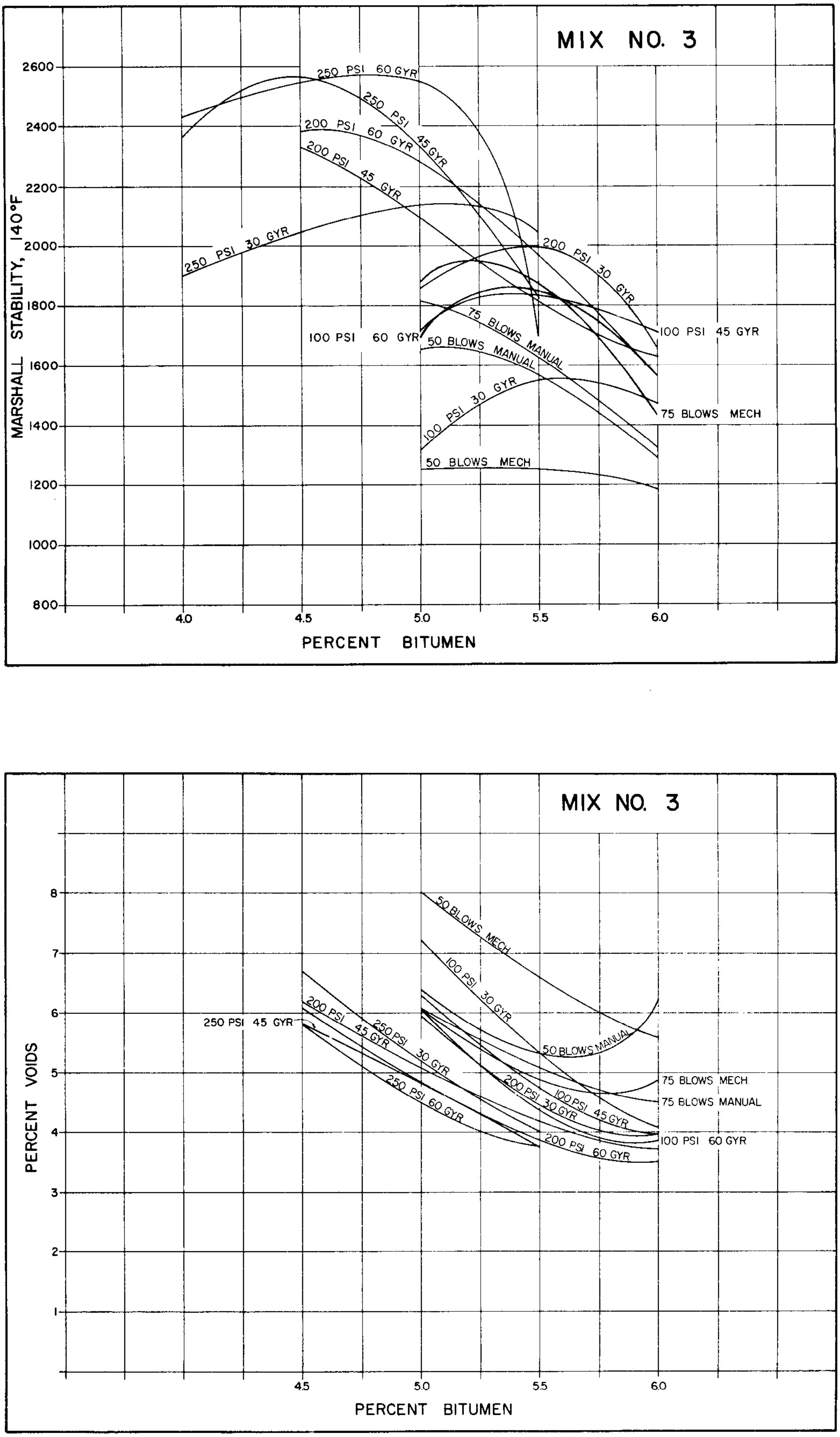


Figure 9 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for gravel Mix 3.

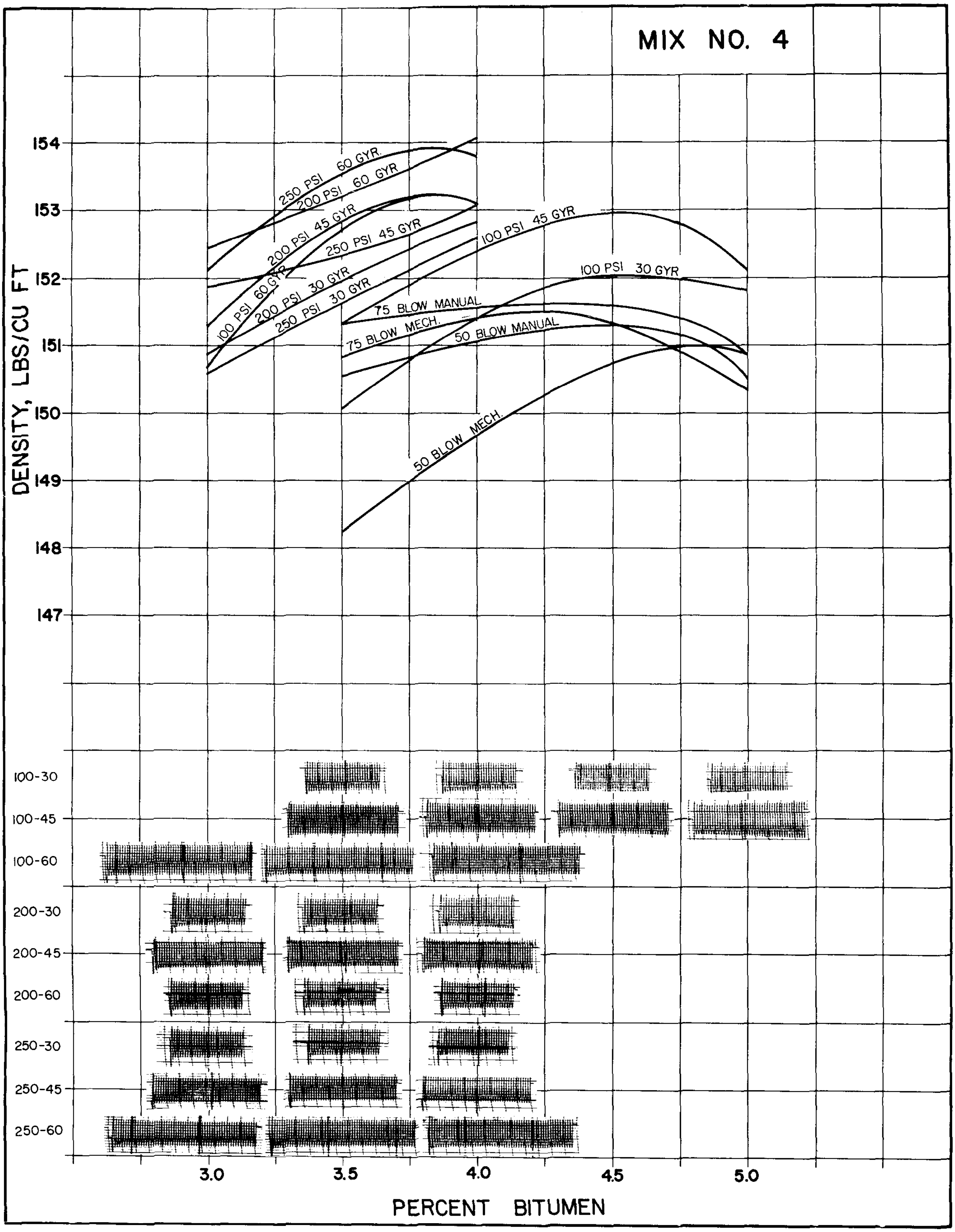


Figure 10 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for limestone Mix 4.

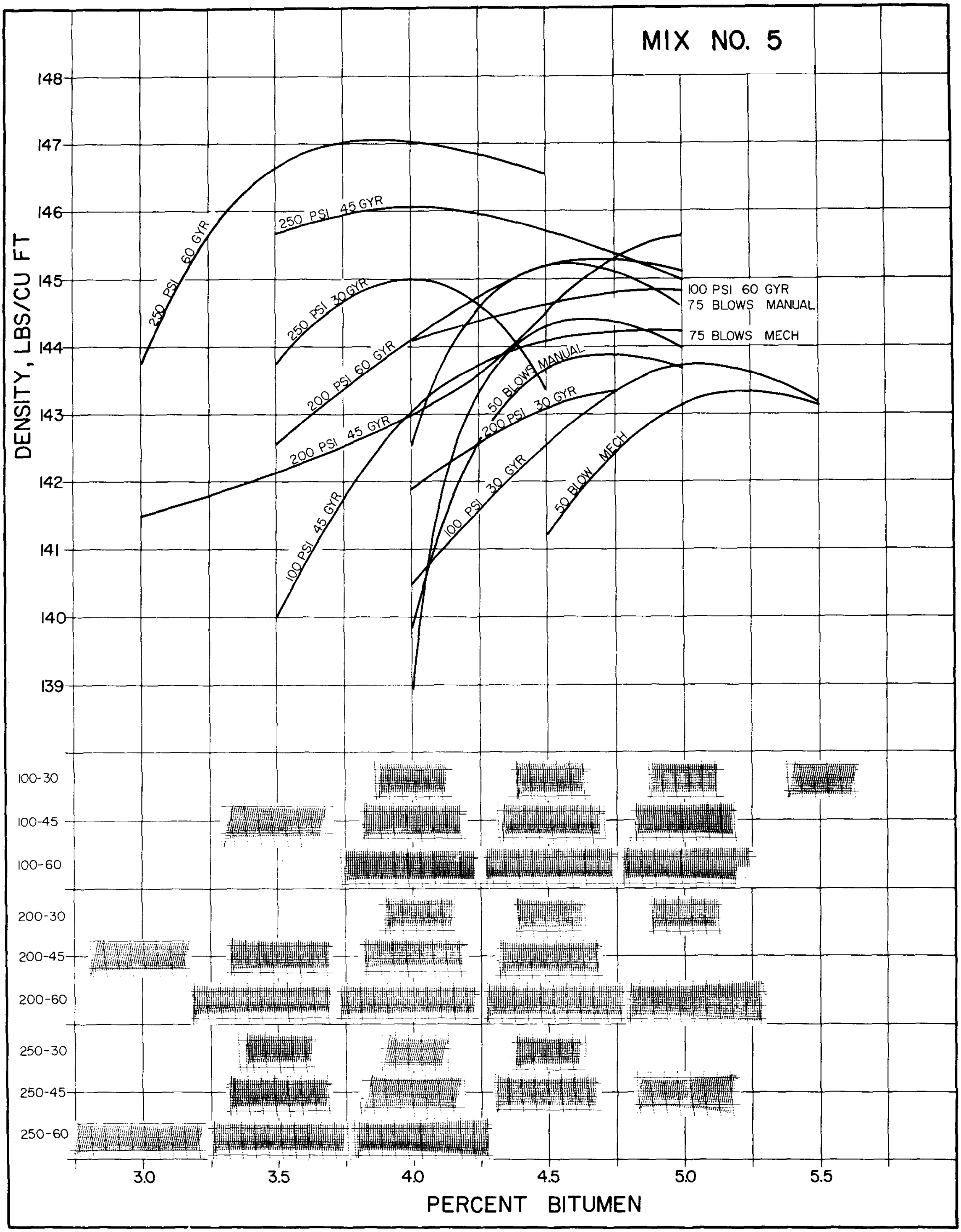
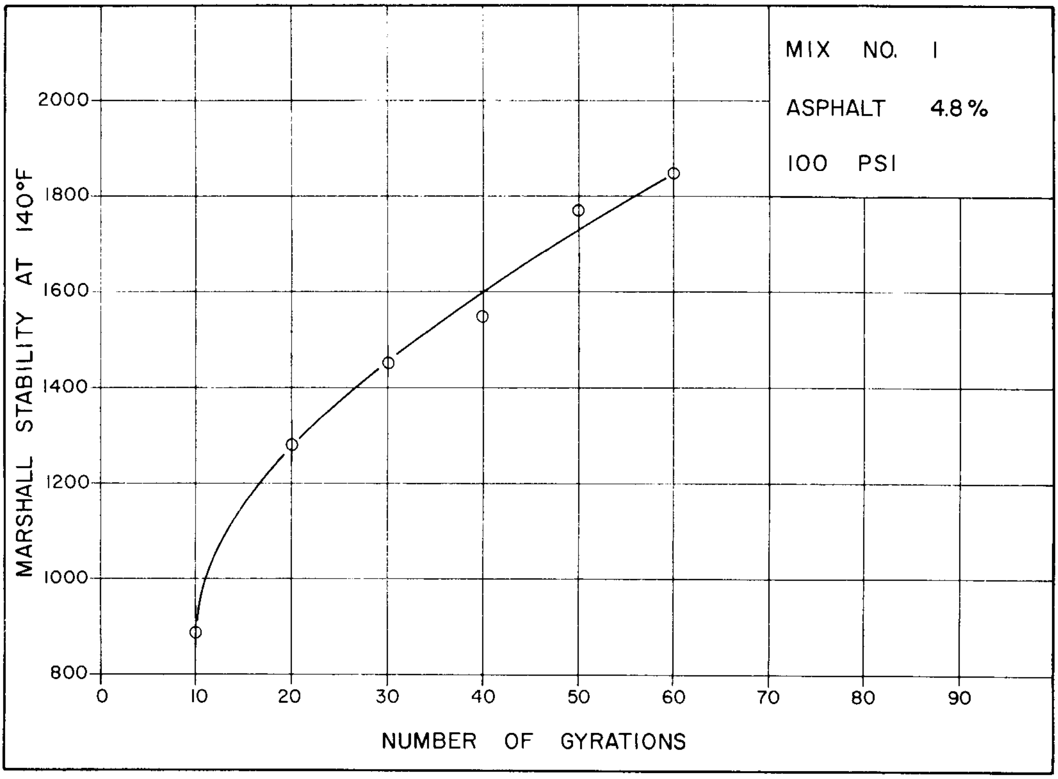


Figure 12 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for limestone Rock Asphalt Mix 5.



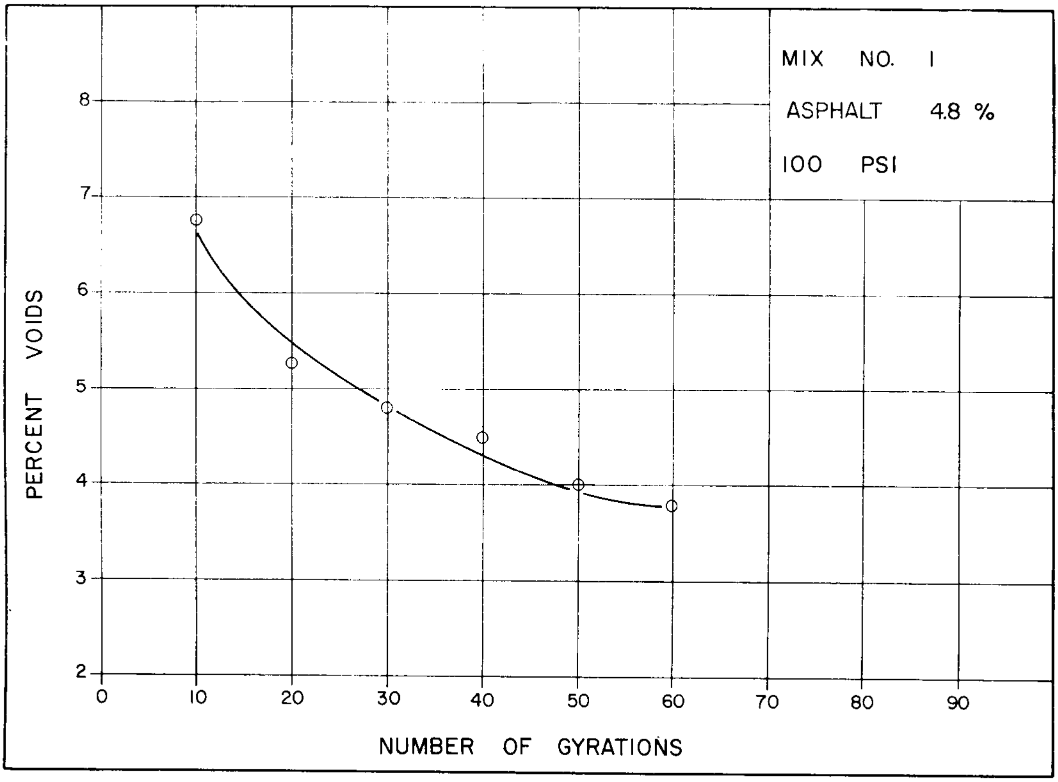
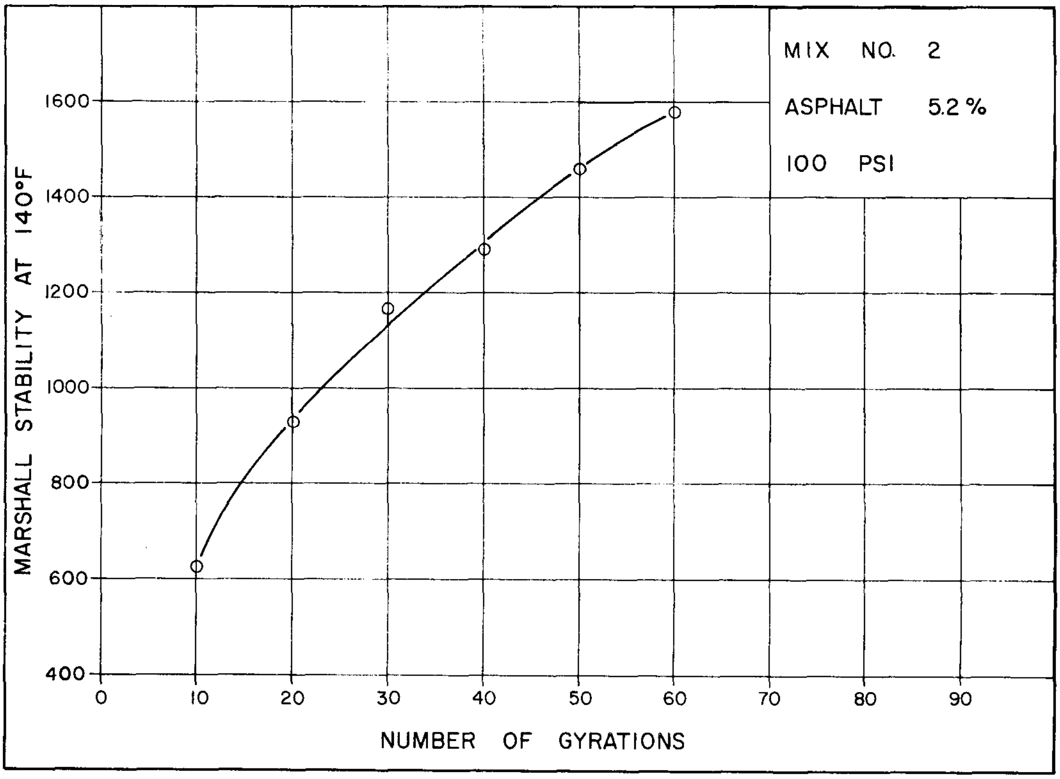


Figure 16 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 1.



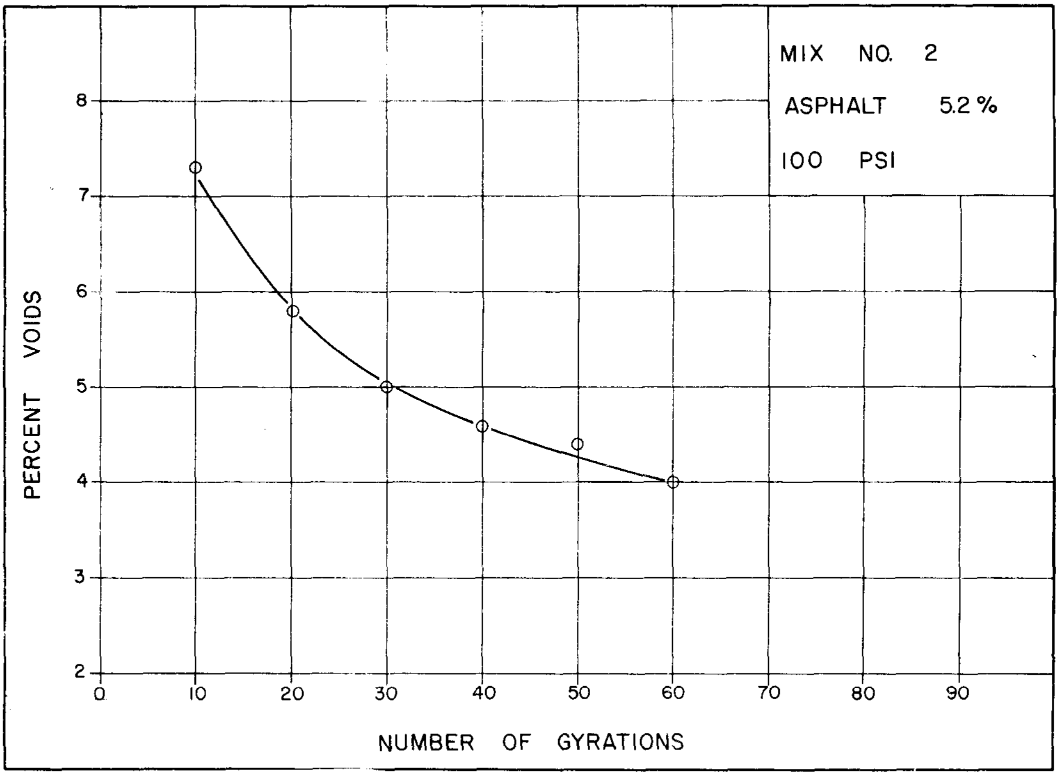
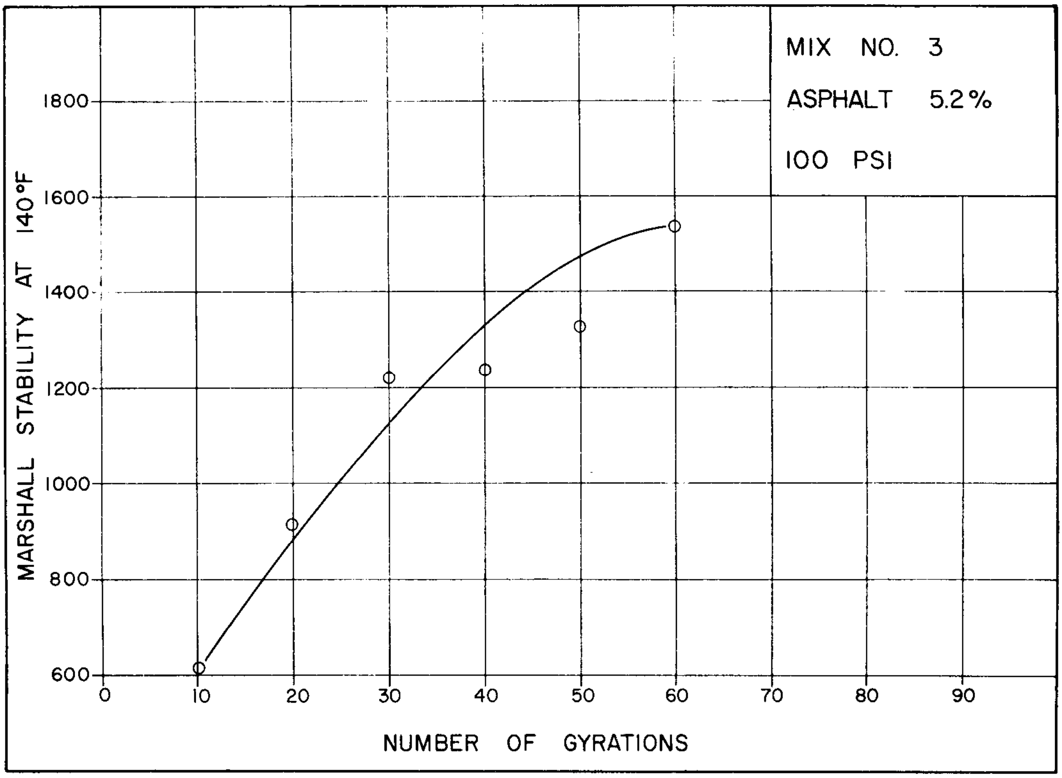


Figure 17 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 2.



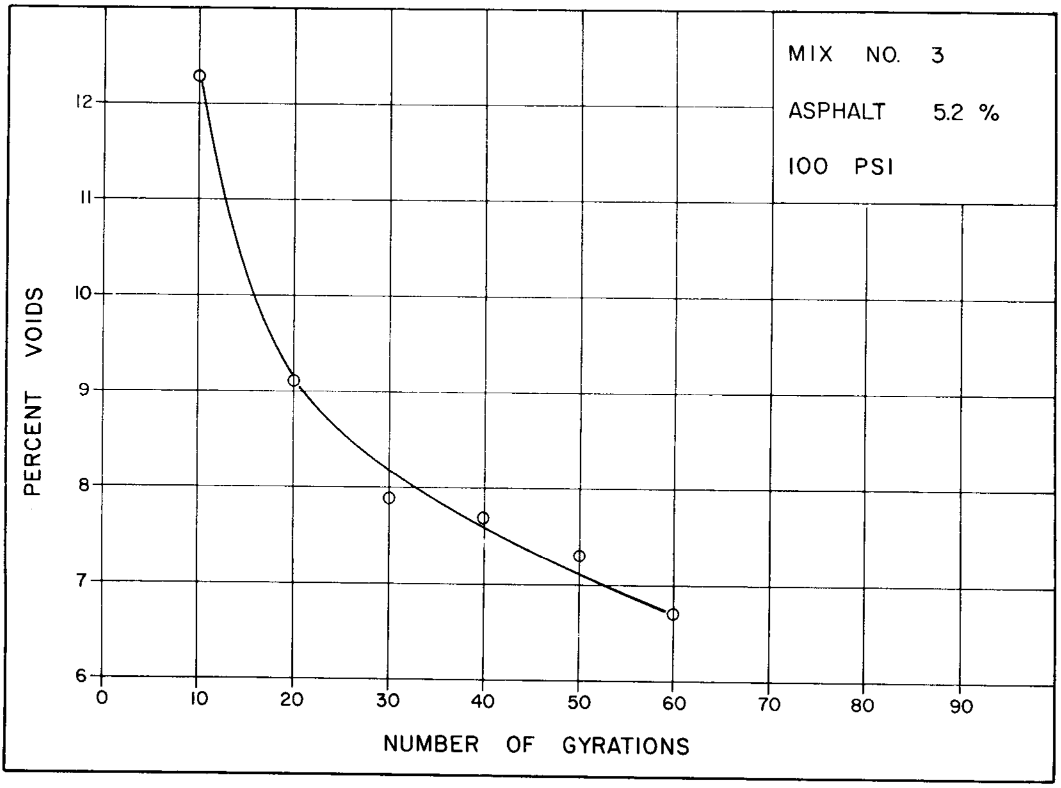
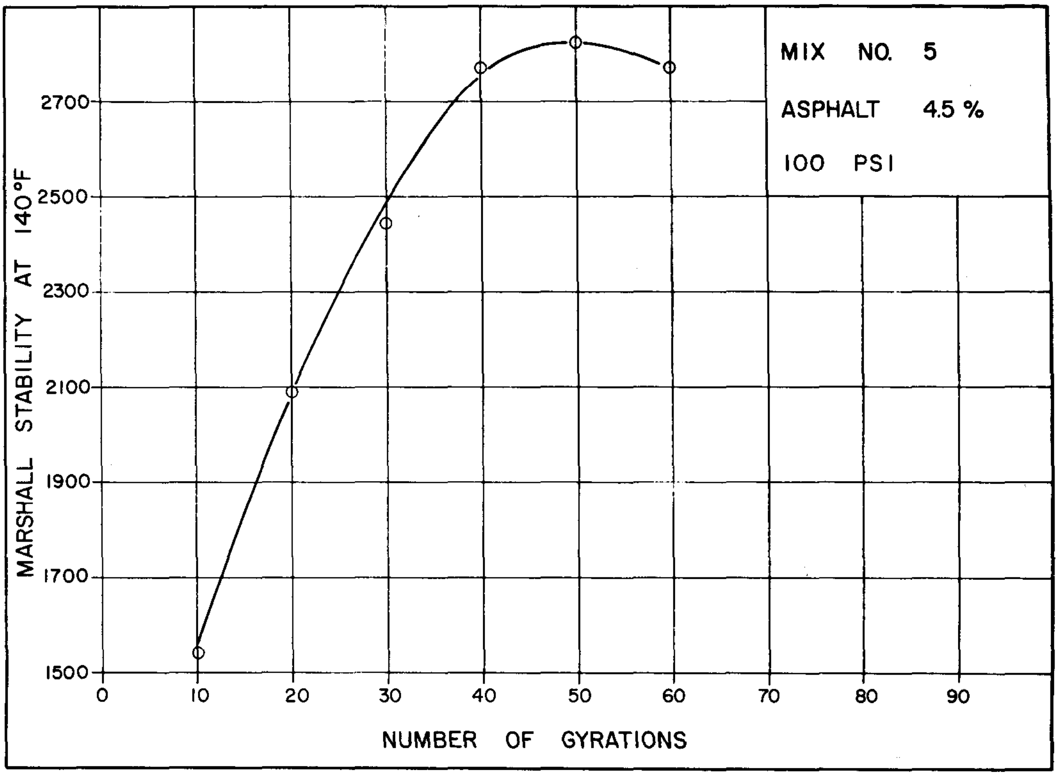


Figure 18 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 3.



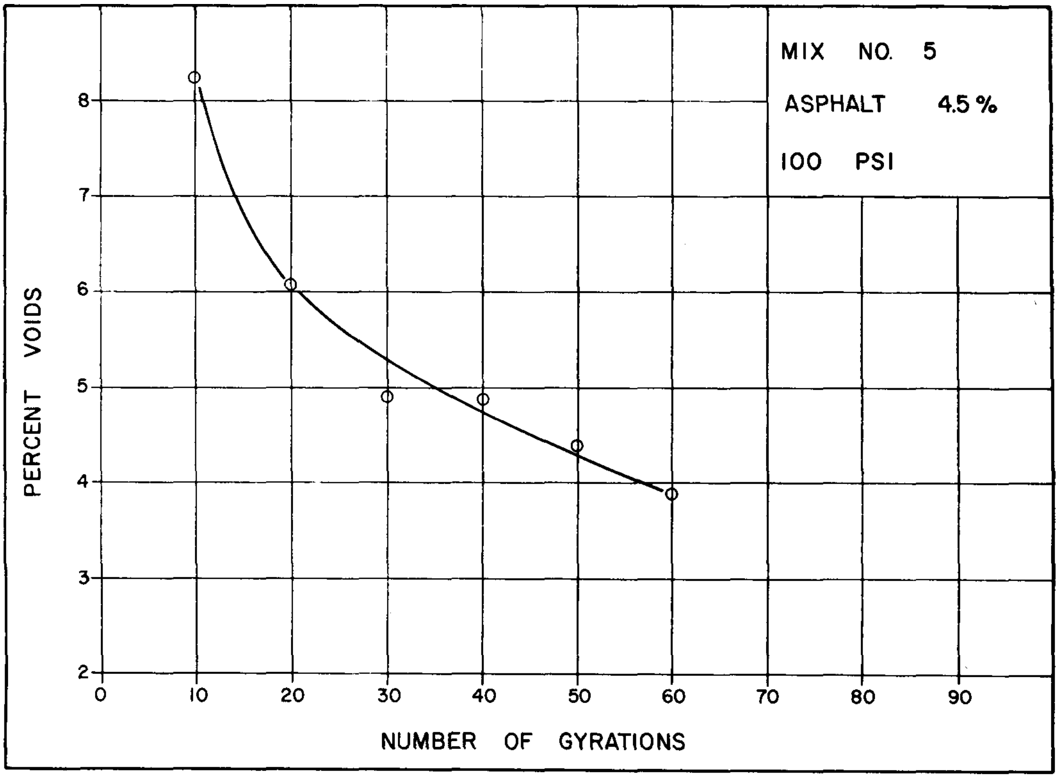


Figure 20 - Percent voids and Marshall stability versus Number of Gyrations for limestone rock asphalt Mix 5.

Louisiana Highway Research

EVALUATION OF THE GYRATORY COMPACTOR FOR USE IN DESIGNING ASPHALTIC CONCRETE MIXTURES

Louisiana Department of Highways – Research & Development Section

EVALUATION OF THE GYRATORY COMPACTOR FOR USE IN DESIGNING ASPHALTIC CONCRETE MIXTURES

by

PHILIP J. ARENA
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Research Report No. 26

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Conducted by
LOUISIANA DEPARTMENT OF HIGHWAYS
Research and Development Section
In Cooperation with

Department of Transportation
Federal Highway Administration
Bureau of Public Roads

Final Report

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TABLE OF CONTENTS

SYNOPSIS

The primary objective of this study was to evaluate the gyratory kneading compactor and to investigate the possibilities and capabilities of this type of equipment.

Curves were developed for six different asphaltic concrete mixes with varying compactive efforts and asphalt contents. These curves indicated that a wide range of compactive efforts can be applied by the gyratory compactor which would be a definite advantage over the presently used Marshall impact hammer.

Results showed that the optimum asphalt content can be obtained by means of the gyrographs which indicate whether or not the asphalt content for a mix at a given compactive effort is excessive.

Results of cores taken after 6 months of service showed that the void contents had decreased below the 75 blow laboratory design, indicating the need for a higher compactive effort in the laboratory, which may be beneficial in extending the service life of pavements.

The test results discussed herein deal with the gyratory machine as a compaction machine only. However, it is anticipated to supplement this study to evaluate the shear and bearing resistance of asphaltic concrete mixes in the laboratory using the gyratory machine, and attempt to correlate these results with similar mixes in the field.

INTRODUCTION

During the past several years the Louisiana Department of Highways, through necessity, had to increase the intensity of the pneumatic rollers for compacting asphaltic concrete pavements. This, consequently, made it necessary to increase the compactive effort of the laboratory design of asphaltic concrete mixtures. The need for this increase had become critical due to the excessive rutting and shoving observed on asphaltic concrete pavements after being subjected to traffic.

In an attempt to remedy this problem, high intensity pneumatic rollers capable of exerting contact pressures of up to 90 psi were incorporated into the specifications. To supplement this, the laboratory design compactive efforts were increased from 50 blows to 75 blows on both sides of a 4 inch diameter specimen using a standard Marshall impact hammer.

Although these modifications have shown a vast improvement in asphaltic concrete pavements in Louisiana, it again appears that an additional increase in design compactive effort is essential in obtaining maximum design life, due to the rapid increase of traffic volume encountered on the highways.

One of the objectives of this study then, is to establish an adequate laboratory compactive effort for design of asphaltic concrete by use of the gyratory compactor.

The gyratory compactor has several advantages that cannot be matched by the Marshall method as follows:

(1) It produces test specimens by a kneading compaction process which has stress-strain properties that are more representative of pavement compaction.

(2) It has the capability of indicating high plasticity by the aid of a gyrograph which shows whether or not a mix has an excess of voids filled with asphalt due to densification or due to an excessive asphalt content for a given mix at a given compactive effort.

(3) It is capable of producing a very large range of compactive efforts by the use of repetitive loading, or increase in gyrations, at a given vertical pressure from 0 to 300 psi.

(4) Optimum asphalt contents for a given compactive effort can be obtained using the gyrographs during the molding procedure and before actual testing of the specimens.

With these advantages, the gyratory compactor could very well be an essential piece of equipment for designing bituminous mixtures at higher compactive efforts.

Although the gyratory machine will be referred to in this report as a compaction apparatus, it is also an excellent testing machine. It is capable of determining the allowable shear stress for a given mix subjected to various contact pressures due to traffic at any desired temperature. It can also be used in evaluating mix designs that may vary in asphalt content, type of aggregate, proportioning of aggregate and mineral fillers. This report, however, will be confined to using the gyratory as a compaction machine only.

FUNDAMENTALS OF THE GYRATORY COMPACTOR

The compactive effort, is controlled mainly by three components.

(1) The gyratory angle used in compacting the specimen. This was limited to only 1° for this study, as suggested by the manufacturer, because the strain is believed to be closely related to the field strain.

(2) The vertical pressure applied to the specimen during compaction.

(3) The number of gyrations or revolutions used to compact the specimen.

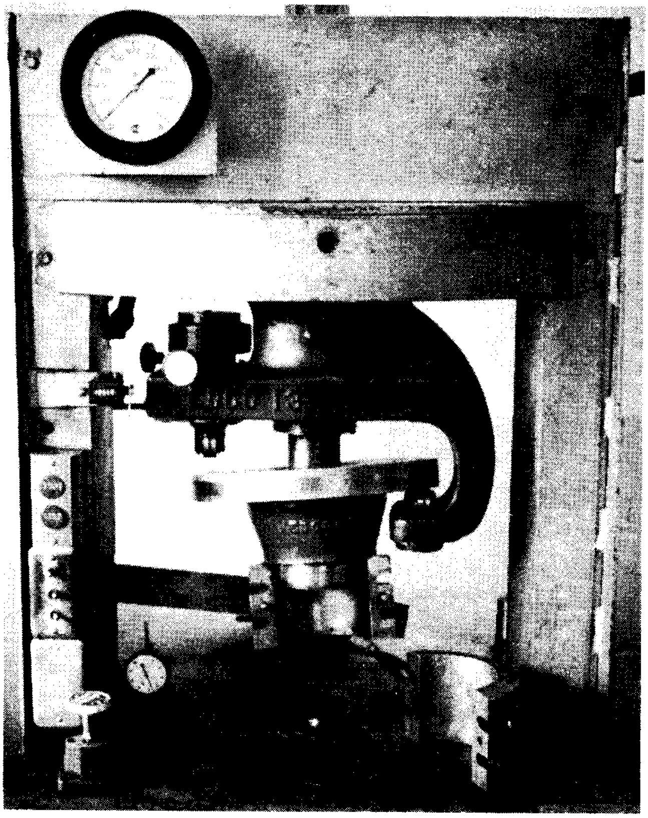
The gyratory angle represents the percent strain applied to the specimen. The higher the angle the higher is the percent strain. The 1° angle seems to be the most satisfactory for design purpose at this time.

The vertical pressure ranges from 0 to 300 psi which is a large enough range to design mixes for any anticipated contact pressures that might be encountered on highways. The number of gyrations can be varied without limitations to the compactive effort desired on a particular design.

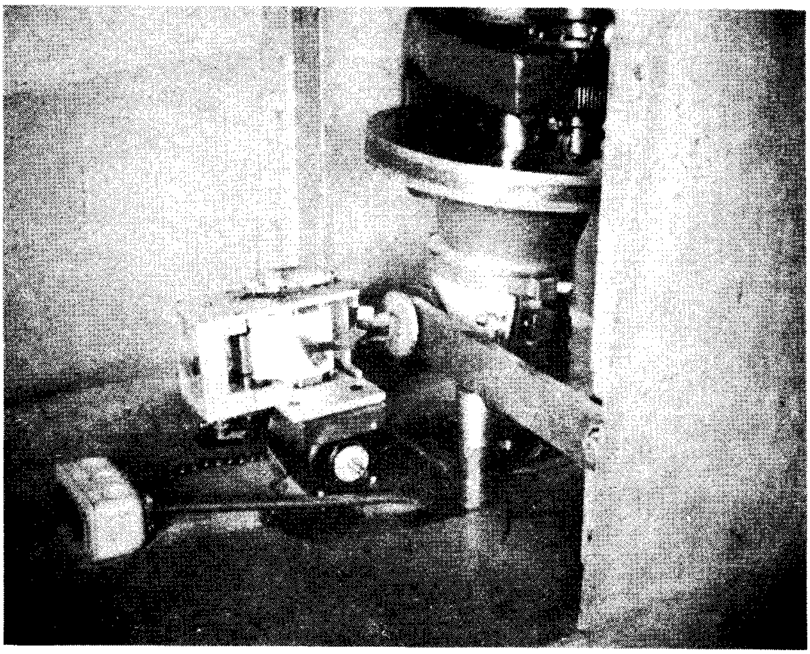
Figure 1, photograph A, shows the front view of the compaction assembly for the gyratory compactor used in this study. Photograph B shows the rear view of the assembly and also a close up of the gyrograph mechanism.

To better understand the operation of the gyratory compactor, a schematic of the gyratory assembly is shown in Figure 2.

In this figure, mold A, containing a test specimen, is clamped in position in the flanged mold chuck B. Vertical pressure on the test specimen is maintained by



A



B

Figure 1 - Photographs of the working mechanisms of the Gyratory Compactor.
A. Front View of the Compaction Assembly.
B. Rear View of the Compaction Assembly and close up of the gyrograph mechanism.

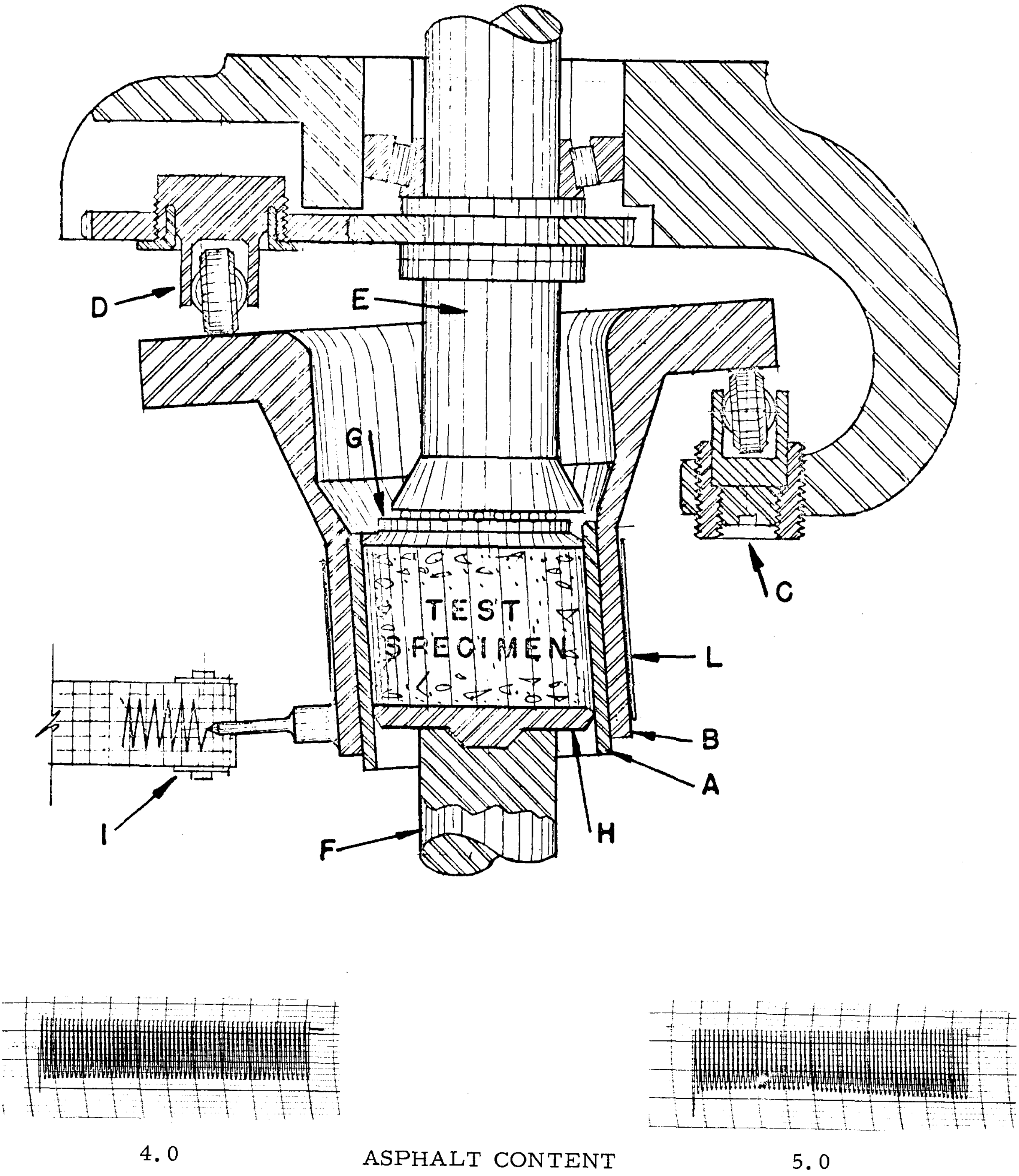


Figure 2 - Schematic Section through Gyrating Mechanism.

the upper and lower ram E and F acting against heads G and H respectively. A gyratory motion is imparted to mold chuck B by rollers C and D as they travel around the flange portion of the chuck, with the flanged portion of the chuck at an angle between rollers C and D.

The gyrograph is identified by the letter I in the figure. When the chuck gyrates, the pen on the side of the chuck records the angle maintained by the chuck in compacting the specimen. When the specimen has been compacted to a maximum density at a given asphalt content, any additional compaction applied will result in a reduction of density which increases the angle made by the chuck causing widening of the recordings on the gyrograph. Each division on the gyrograph is equal to approximately 7.5 minutes. If the asphalt content it too high for a given compactive effort, widening of the gyrograph will also occur. This is illustrated by the two gyrographs at the bottom of Figure 2. An asphalt content of 4.0 percent gives a uniform angle indicating that the specimen is not flushing and that higher density is being obtained with each revolution. The gyrograph representing 5.0 percent asphalt content shows a widening of the chart indicating that a maximum density has been reached and the additional revolutions of the machine are causing a decrease in density due to flushing of the asphalt or excessive asphalt for that compactive effort.

It is evident then that an optimum asphalt content can be obtained at a given compactive effort if specimens are molded at asphalt contents of 0.5 percent increments. When flushing or widening of the gyrograph first appears it will indicate that the optimum asphalt content for that compactive effort is less than the asphalt content that showed flushing.

SCOPE

This study was initiated in April, 1961 as a research project in cooperation with the Bureau of Public Roads, and consists of two phases.

Phase I consists of molding six different mixes at various compactive efforts and asphalt contents using the gyratory compactor and the Marshall impact hammer and analyzing the physical properties of the specimens.

Phase II consists of establishing an adequate compactive effort for the gyratory compactor, which could be used for design of the asphaltic concrete mixes and which would possibly aid in increasing the life of bituminous concrete pavements.

METHODOLOGY

A. Mixes Used

Six different mixes were used in this study to determine the effects the gyratory compactor has on each in varying the composition of the asphalt aggregate and the compactive effort.

The mixes are designated as Mix 1 through Mix 6 inclusive, and are composed of the following materials.

Mixes 1, 2 and 3 - Crushed siliceous gravel and a combination of sand and mineral filler.

Mix 4 - Crushed limestone, coarse sand, fine sand and mineral filler.

Mix 5 - Limestone rock asphalt and coarse sand.

Mix 6 - Expanded clay aggregate, coarse sand, fine sand, and mineral filler.

The majority of asphaltic concrete mixes used in Louisiana are crushed siliceous gravel, sand, and mineral filler. Mixes 1, 2 and 3 are composed of gravel obtained from three different hot mix plants in the state having similar characteristics. The composition and proportion of the various mix designs are shown in Table 1 of the Appendix.

B. Test Procedure

Specimens were molded on each of the above mentioned mixes, varying the compactive effort from a minimum of 50 blows with the Marshall hammer to a maximum of to 250 psi, 60 gyrations with the gyratory compactor. The physical properties of these mixes are given in the Appendix in Tables 2 through 7. In order to evaluate the different mixes along with effects of the compactive effort, curves were developed for each mix plotting percent bitumen versus percent voids, Marshall stability and density. The curves are shown in the Appendix. The tests performed were in accordance with the followings test procedures

(1) Specific gravity of compressed bituminous mixture LDH TR 304

(2) Marshall stability and flow LDH TR 305

The design laboratory compactive effort selected from this study was 100 psi, 60 gyrations which appears to be practical, especially on gravel mixes, from a construction standpoint. This compactive effort will probably vary for other areas depending on the aggregate type, asphalt cement, location, traffic volume and method of obtaining void contents. The theoretical specific gravity, as used in computing void contents in this study, was obtained by the apparent specific gravity method which is presently being used in Louisiana.

The formula for calculating the theoretical gravity along with the Louisiana Department of Highways mix design criteria for determining optimum asphalt content by the Marshall procedure are found in Table 9 of the Appendix.

TEST RESULTS

Phase I

The gravel mixes, represented by Figures 4 through 9 of the Appendix, indicate that as the compactive effort is increased, density and Marshall stability is increased and the void content is reduced. Also it appears that the higher the compactive effort the lower the optimum asphalt content.

At the bottom of each of the density curves are the gyrographs for each respective compactive effort and asphalt content. Using Mix No. 1 as an example, the gyrograph at 100 psi, 30 gyrations, from Figure 4 showed flushing of the asphalt (widening of the gyrograph) at 6.0 percent bitumen, whereas, at an effort of 250 psi, 60 gyrations flushing started at 5.0 percent bitumen. In addition to the void content, Marshall stability, and density results shown on the curves in Figures 4 and 5 the gyrographs also indicate that an increase of compactive effort decreases the optimum asphalt content.

It is also interesting to note that, in most cases, the gyrograph that did not show flushing preceding the gyrograph that did flush is usually very near the optimum asphalt content. An example of this is shown in Figure 4 Mix No. 1 at 100 psi, 60 gyrations. As shown by the gyrograph, flushing began at an asphalt content of 5.5 percent. The Marshall stability at that asphalt content was 1580 lbs., void content 4.1 percent, and density 146 lbs/ cu.ft. The gyrograph that did not show flushing at 5.0 percent bitumen had a Marshall stability of 1839 lbs, void content 4.6 percent, and density of 145.8 lbs/cu.ft. This indicates that 5.0 percent bitumen would be the optimum asphalt content. Results for gravel Mixes 2 and 3 are represented by Figures 6 through 9 and show very similar characteristics as Mix 1.

Figures 10 and 11 show curves for Mix No. 4 which was composed of crushed limestone aggregate. The characteristics mentioned for the gravel mixes were also very similar for the limestone mixes with the exception that these mixes gave much higher densities and Marshall stabilities and lower void contents.

Figures 12 and 13 represent curves for Mix No. 5 composed of limestone rock asphalt. The limestone rock asphalt contained approximately 4 percent natural asphalt and had an apparent specific gravity of 2.54. Again, the trend of the curves were similar to the gravel and limestone mixes. The stabilities, as seen by the curve in Figure 13, were extremely higher than any of the other mixes, going as high as 4817 lbs. at 3.0 percent additional asphalt and 250 psi, 60 gyrations compactive effort.

Figures 14 and 15 represent curves for Mix No. 6 composed of expanded clay aggregate, sand, and mineral filler. The apparent specific gravity of the expanded clay aggregate is approximately 1.30 depending on the size of the aggregate. This is a very light material and, consequently, results in low density as seen on the curve. The expanded clay mixes are somewhat different from others in that they can absorb a large quantity of asphalt without signs of flushing. As shown by the gyrographs, flushing has not occurred on any of the expanded clay mixes.

Due to the fact that the expanded clay does absorb a large quantity of asphalt without showing signs of flushing, it becomes more difficult to obtain an optimum asphalt content. It has been indicated by the curves that the Marshall stability results are probably the most appropriate to use to obtain the optimum asphalt content, because as the asphalt is increased the density will increase and voids will decrease to a point where the Marshall stability will have a very low value indicating that the density percent void curves alone would be misleading in obtaining optimum asphalt content. The optimum asphalt content cannot be obtained by the gyrograph due to the fact the gyrograph will not show flushing until the asphalt content is exceptionally high. For example, in Figure 14 at 250 psi, 60 gyrations the density appears to be rising at 6.5 percent bitumen just as the percent voids in Figure 15 are decreasing at that same bitumen content. The Marshall stability shows a peak at approximately 6.0 percent bitumen and has a definite drop at 6.5 percent bitumen, indicating that an additional increase in bitumen content would be a decrease in Marshall stability which would, therefore, be detrimental to the mix. For this reason, it appears that for expanded clay mixes, the optimum asphalt content should be based primarily on the Marshall stability curve, but in conjunction with density and percent voids.

The first phase of this study, as discusssed, is to determine what affect the gyratory compactor would have on the various mixes when varying the compactive effort and the asphalt content, and to compare the results with that obtained by the Marshall compaction hammer. This has been accomplished as discussed and as shown by the tabulated results in Tables 2 through 7 in the Appendix.

Phase II

This phase consists of establishing an adequate compactive effort for use with the gyratory compactor, through the aid of the results obtained in Phase I, for increasing the design life of asphaltic concrete pavements.

This study was initiated to supplement a previous study by the Louisiana Department of Highways (1)*. In that study it was concluded that the asphaltic concrete pavements constructed in the 1950's were showing excessive rutting, flushing,

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* Number in parenthesis refer to list of references at the end of report.

and lack of densification at the end of five years or equivalent to an estimated total traffic volume of 10 million vehicles. The anticipated design life of these pavements was 15 years or a traffic volume of approximately 30 million vehicles. From the findings (1) the actual life of the pavement was only one-third the design life anticipated.

It was also established in that study that after five years the void content was reduced to two percent in which the pavement showed shoving, rutting and cracking. It is known that hot mix pavement containing low density and high void contents immediately after compaction are much more susceptible to hardening or oxidation of the asphalt in addition to the rutting that will occur due to traffic densification.

It is believed that the reason for the deterioration after five years of service was not due to the void content approaching two percent voids, but due to the low compactive effort applied in the laboratory and in the field, giving a high initial void content and causing rapid oxidation of the asphalt due to weathering. This was also the reason for the excessive rutting after five years of service.

At the time these projects were being constructed the laboratory design method for asphaltic concrete mixes required 50 blow Marshall compaction. In the field the hot mix pavement was being compacted using a pneumatic roller with a 55 psi contact pressure. It has been proven since that time, that higher contact pressures are essential in obtaining higher densities and lower initial void contents, thereby minimizing rutting and cracking of the mix.(2) (3) In that report, results indicated that the test sections rolled at 85 psi contact pressure with the pneumatic roller showed less rutting after 3 years than did the test sections rolled at 55 psi contact pressure. It was also necessary to increase the compactive effort in the laboratory to the presently used 75 blow of the Marshall compaction effort.

In order to increase the design life of hot mix pavements, it was first thought that by using the gyratory compactor and varying the number of gyrations or repetitive loads at a certain vertical pressure, the mix could be densified to give two percent air voids or equivalent to 10 million vehicles as obtained in the Pavement Survey Study(1). After this was accomplished the number of gyrations equivalent to 30 million vehicles could be computed. Specimens would then be compacted using this computed value for the number of gyrations and vertical pressure and the data evaluated for percent voids using a different design compactive effort. However, this approach to the problem proved to be futile, due to the fact that in the laboratory the asphalt and the mixing and compaction temperatures remains fairly constant, whereas, the repetitive load in the field occures over a period of five years or more during which time the asphalt changes due to oxidation and weathering and the temperatures at the time of these loads change with the season and also the time of day.

To increase the design life of asphaltic concrete pavements, it is necessary first of all to start with the laboratory design which should result in the void content in a hot mix pavement after final rolling being adequate to minimize oxidation of the asphalt and eliminate excessive rutting due to traffic. In attempting to do this, a compactive effort of 100 psi, 60 gyrations with the gyratory compactor was chosen as a laboratory design. A vertical pressure of 100 psi was chosen mainly because it is very close to the contact pressures used by the pneumatic rollers and also the contact pressures applied to the finished pavements by the heavy truck traffic encountered.

In establishing a reasonable number of gyrations for design purposes, specimens were molded on the gyratory compactor using Mix No. 2 which had the same aggregate and mix design as that used in the compaction study. (2) (3) A vertical pressure of 100 psi was used on these specimens and the gyrations were varied from 10 to 70. The asphalt content was 5.8 percent, the same used on the roadway.

Figure 3 illustrates the curve obtained from these specimens plotting percent voids versus number of gyrations. The void content goes from a maximum of 7.8 percent for 10 gyrations to 3.5 percent for 70 gyrations at a constant pressure of 100 psi. Note that the design void content for this project was at 5.9 percent voids shown as 75 blow plant (mechanical) on the curve. Roadway results were obtained immediately after completion (designated original) then at 6, 15, and 36 months. It is interesting to note that only 6 months after completion of the project the void content had already decreased below the laboratory design indicating a need for higher compactive efforts in the mix design.

The curve also shows that cores taken after 36 months gave a void content of 4.0 percent. Had the mix been designed by the gyratory compactor at 100 psi, 60 gyrations, a design void content of 3.7 percent would have been obtained at 5.8 percent asphalt.

As also shown by the curve, as the number of gyrations approach 50 the void content begins to level off and shows very little change from 50 gyrations to 70 gyrations. It is believed that similar results are obtained on the roadway. That is, if a mix is designed for lower initial voids, and if a certain percentage of this design is required in the field, then the void content will change at a slower rate with time and traffic thus eliminating excessive rutting, oxidation of the asphalt, and providing a longer design life.

It should be mentioned that although the void content at 60 gyrations was 3.7 for Mix 2, (at 5.8 percent asphalt) had this mix been designed originally with the gyratory compactor at 100 psi, 60 gyrations the optimum asphalt content would have been lower because of the increase of laboratory compactive effort over the 75 blow design. This can be seen in Figures 6 and 7 on Phase I of this study.

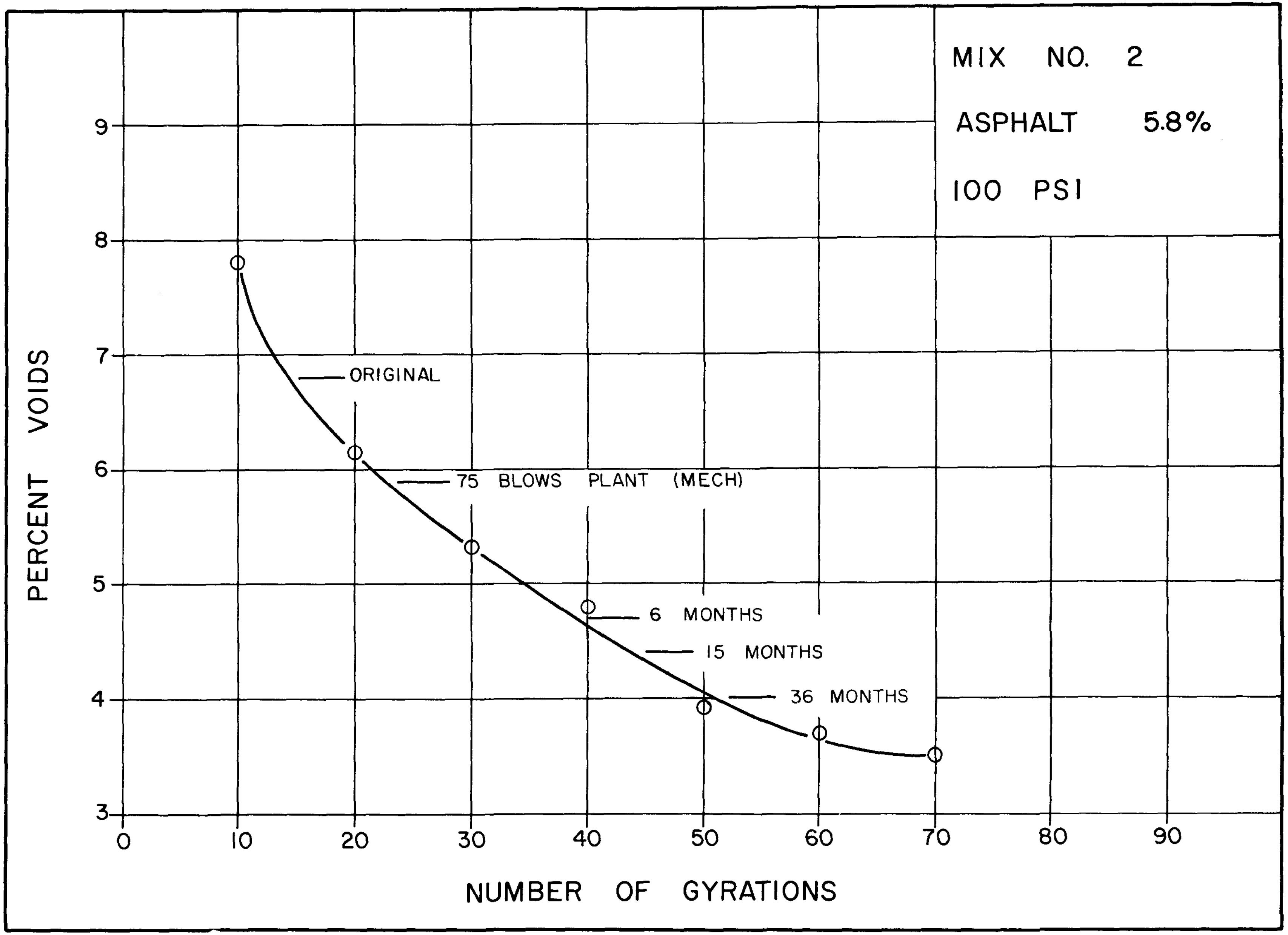

Figure 3 - Comparison of the Percent Voids, number of Gyrations Curve to the void content of roadway specimens from the original to 36 months.

At 100 psi, 60 gyrations for Mix No. 2, the optimum asphalt content appears to be approximately 5.2 to 5.5 percent. This shows a design void content of 4.0 percent.

In choosing a design compactive effort at 100 psi, specimens were molded on each of the six mix designs varying the number of gyrations from 10 to 60. The asphalt content used on these mixes was that which appeared to be optimum from the curves in Phase I at 100 psi, 60 gyrations. All test results are compiled in Table 8 of the Appendix.

Figure 16 through 21 represent the curves for Marshall stability and void content versus number of gyrations on each of the six mixes. As indicated by the curves, as the number of gyrations increases the void contents decreases and at 60 gyrations begins to level off with the exception of Figure 21 Mix No. 6. It was mentioned previously that due to the absorptive characteristics and the high void content of the expanded clay it became very difficult to base optimum conditions on void content or density alone.

This again is seen in Figure 21 which shows an irregular percent voids versus number of gyration curve, however, the Marshall stability shows a high value at 60 gyrations indicating an optimum condition.

Based on the results discussed in Phases I and II, it is believed that a compactive effort of 100 psi, 60 gyrations would be a superior design than the 75 blow Marshall hammer and would require a maximum effort in the field thus providing a longer design life of asphaltic concrete pavements.

CONCLUSIONS

The results from this study warrant the following conclusions and are confined to the materials and equipment studied herein:

(1) For the 75 blow Marshall method of design, the void content on the roadway after 6 months of traffic had already decreased below that obtained in the laboratory. This indicates a need for higher compactive efforts in the laboratory.

(2) As the void content approached 4 percent for a gravel mix at optimum asphalt content, any additional compactive effort applied would decrease the voids very little thus indicating that a mix compacted in the field near 4 percent voids may remain fairly constant over a period of years which would definitely increase the life of the pavement.

(3) Higher compactive efforts in the laboratory would naturally result in higher standards to be met in the field which would give higher densities, lower void contents and would minimize rutting and hardening of the asphalt obtained with time.

(4) It was confirmed that optimum asphalt contents can be predicted from the gyrographs at a given compactive effort and excessive asphalt can be detected by widening of the gyrograph which indicates flushing of the asphalt.

(5) For highly absorptive aggregate such as expanded clay the gyrograph will not show flushing even though the asphalt content is in excess of the amount needed to obtain suitable stability values. Therefore, the Marshall stability is probably the best means of obtaining optimum asphalt contents on expanded clay mixes at this time.

(6) The gyratory compactor is capable of producing a large range of compactive effort and when correlated with field results, this method of design would be a more meaningful and possibly a necessary means in extending the design life of asphalt concrete pavements. The time required to compact the specimens is approximately the same as the Marshall method.

RECOMMENDATIONS

Because of the advanced technical data now available through the manufacturer*, it is recommended that future studies be undertaken to further evaluate the gyratory machine as a testing apparatus. Field trials should be made in conjunction with additional laboratory studies to develope the most suitable design criteria.

The gyratory apparatus is capable of obtaining shear strengths, bearing resistance and strain data on asphaltic concrete mixtures. This data correlated with field conditions could be very important in predicting the performance of asphaltic concrete pavements.

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* Edco Engineering Developments Company Inc. Vicksburg, Mississippi

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(2) V. Adam, S. C Shah, P. J. Arena, Jr., "Compaction of Asphaltic Concrete Pavement with High Intensity Pneumatic Roller" Part I, Louisiana Department of Highways Research Report No. 10, July 1963

(3) S. C. Shah, "Compaction of Asphaltic Concrete Pavement with High Intensity Pneumatic Roller", Part II, Densification Due to Traffic. Louisiana Department of Highways Research Report No. 19, October 1965

(4) Operators manual for the Gyratory Testing Machine, Engineering Development Company, Inc. Vicksburg, Mississippi

APPENDIX

TABLE 1

COMPOSITION AND PROPORTIONS OF THE VARIOUS MIX DESIGNS

MIX 1

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.650	45
2	2.650	35
3	2.640	15
Mineral Filler (Silica)	2.670	5
60-70 Pen (Shell Oil Co.)	1.030	Varied

MIX 2

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.629	48
2	2.634	27
3	2.627	20
Mineral Filler (Silica)	2.656	5
80-100 Pen (Shell Oil Co.)	1.020	Varied

GRADATION

U.S. Sieve	Per Cent Passing				
	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"					100
1/2"		100	100		100
3/8"		99	57		93
No. 4	100	36	1		63
No. 10	85	6			45
No. 40	52	1		100	29
No. 80	29			99	18
No. 200	11			98	10

U.S. Sieve	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"			100		100
1/2"			99		99
3/8"		100	49		90
No. 4	100	43	14		68
No. 10	86	22	4		52
No. 40	49	9	2	100	31
No. 80	24	3	2	99	17
No. 200	13	1	1	81	10

TABLE 1 (Cont.)

MIX 3

Composed of Gravel and a Combination of Sand and mineral filler

Bin No.	Specific Gravity	Proportions-%
1	2.646	50
2	2.633	36
3	2.628	10
Mineral Filler (Limestone)	2.734	4
60-70 Pen (Shell Oil Co.)	1.030	Varied

MIX 4

Composed of Crushed Limestone, Coarse Sand, fine Sand and mineral filler

Aggregate Size	Specific Gravity	Proportions-%
1"-3/4" Limestone	2.718	15
3/4"-1/2" Limestone	2.718	17
1/2"-No. 4 Limestone	2.735	20
Pass No. 4 Limestone	2.700	4
Coarse Sand	2.620	30
Fine Sand	2.635	11
Mineral filler (Limestone Dust)	2.699	3
60-70 Pen (Esso)	1.030	Varied

GRADATION

U.S. Sieve	Per Cent Passing				
	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"					
1/2"		100	100		100
3/8"		99	57		95
No. 4	100	12	2		59
No. 10	85	1			48
No. 40	59			100	35
No. 80	40			96	24
No. 200	17			81	12

U.S. Sieve	Per Cent Passing				
	Limestone	Coarse Sand	Fine Sand	Mineral filler	Composite
1"					100
3/4"	Graded in individual				85
1/2"	sizes as shown above				68
No. 4		100			48
No. 10		90			39
No. 40		20	100		19
No. 80		1	98	100	14
No. 200		0	28	88	6

TABLE 1 (Cont.)

MIX 5

Composed of Limestone Rock Asphalt, Coarse Sand

Aggregate	Specific Gravity	Proportions-%
(Limestone Rock Asphalt)	2.542	65
(Coarse Sand)	2.656	35
60-70 Pen (Texaco)	1.030	Varied

MIX 6

Composed of Expanded Clay, Coarse Sand, Fine Sand and mineral filler

Aggregate Size	Specific Gravity	Proportions-%
3/4"-1/2"	1.243	15
1/2"-No. 4	1.312	20
Coarse Sand	2.644	50
Fine Sand	2.635	10
Mineral filler (Limestone Dust)	2.699	5
60-70 Pen (Esso)	1.030	Varied

GRADATION

U.S. Sieve	Limestone Rock Asphalt	Coarse Sand	Composite
3/4"			
1/2"			
3/8"	100	100	100
No. 4	93	99	95
No. 10	73	88	78
No. 40	40	54	45
No. 80	25	14	21
No. 200	14	3	10

U.S. Sieve	Expanded Clay	Coarse Sand	Fine Sand	Mineral filler	Composite
3/4"					100
1/2"	Graded in individual	100			85
No. 4	sizes as shown above	98			64
No. 10		89	100		60
No. 40		47	99		39
No. 80		10	97	100	20
No. 200		0	29	87	7

TABLE 2

PHYSICAL PROPERTIES OF MIX NO. 1 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs/ cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.0% Theoretical Gravity - 2.49							
250 PSI 60 Gyrations	2.328	93.5	6.5	58.4	145.3	2423	9
Asphalt Content - 4.5% Theoretical Gravity - 2.47							
50 Blow Manual Hammer	2.292	92.8	7.2	59.1	143.0	1572	8
50 Blow Mechanical Hammer	2.282	92.4	7.6	55.7	142.4	1295	8
75 Blow Manual Hammer	2.316	93.8	6.2	63.0	144.5	1775	10
75 Blow Mechanical Hammer	2.293	92.8	7.2	59.1	143.1	1501	6
100 PSI 30 Gyrations	2.289	92.7	7.3	58.0	142.8	1306	10
100 PSI 45 Gyrations	2.309	93.5	6.5	61.1	144.1	1527	7
100 PSI 60 Gyrations	2.320	93.9	6.1	62.7	144.8	1749	9
200 PSI 30 Gyrations	2.302	93.2	6.8	59.9	143.6	1696	9
200 PSI 45 Gyrations	2.330	94.3	5.7	64.3	145.4	2166	7
200 PSI 60 Gyrations	2.336	94.6	5.4	65.6	145.8	2433	8
250 PSI 30 Gyrations	2.329	94.3	5.7	64.3	145.3	1622	10
250 PSI 45 Gyrations	2.341	94.8	5.2	66.5	146.1	2230	9
250 PSI 60 Gyrations	2.347	95.0	5.0	67.4	146.5	2493	8
Asphalt Content - 5.0% Theoretical Gravity - 2.45							
50 Blow Manual Hammer	2.317	94.6	5.4	67.9	144.6	1574	10
50 Blow Mechanical Hammer	2.289	93.6	6.6	61.6	142.8	1504	8
75 Blow Manual Hammer	2.322	94.8	5.2	68.6	144.9	1638	10
75 Blow Mechanical Hammer	2.306	94.1	5.9	65.7	143.9	1617	7
100 PSI 30 Gyrations	2.317	94.6	5.4	67.9	144.6	1459	9
100 PSI 45 Gyrations	2.332	95.2	4.8	70.4	145.5	1633	7
100 PSI 60 Gyrations	2.336	95.4	4.6	70.9	145.8	1839	9
200 PSI 30 Gyrations	2.329	95.1	4.9	70.0	145.3	2028	9
200 PSI 45 Gyrations	2.333	95.2	4.8	70.4	145.6	2107	8
200 PSI 60 Gyrations	2.347	95.8	4.2	73.2	146.5	2051	9
250 PSI 30 Gyrations	2.333	95.2	4.8	70.4	145.6	2017	7
250 PSI 45 Gyrations	2.339	95.5	4.5	7.18	146.0	2301	7
250 PSI 60 Gyrations	2.346	95.8	4.2	73.2	146.4	2191	9
Asphalt Content - 5.5% Theoretical Gravity - 2.44							
50 Blow Manual Hammer	2.310	94.7	5.3	70.2	144.1	1206	13
50 Blow Mechanical Hammer	2.304	94.4	5.6	68.9	143.8	1362	11
75 Blow Manual Hammer	2.318	95.0	5.0	71.4	144.6	1290	12
75 Blow Mechanical Hammer	2.309	94.6	5.4	69.7	144.1	1559	12
100 PSI 30 Gyrations	2.331	95.5	4.5	73.6	145.3	1385	11
100 PSI 45 Gyrations	2.337	95.8	4.2	78.8	145.8	1443	10
100 PSI 60 Gyrations	2.340	95.9	4.1	79.3	146.0	1580	11
200 PSI 30 Gyrations	2.337	95.8	4.2	78.8	145.8	1227	11
200 PSI 45 Gyrations	2.341	95.9	4.1	79.3	146.1	1911	11
200 PSI 60 Gyrations	2.345	96.1	3.9	76.4	146.3	1565	12
250 PSI 30 Gyrations	2.337	95.8	4.2	75.0	145.8	1612	9
250 PSI 45 Gyrations	2.347	96.2	3.8	76.9	146.5	1791	11
250 PSI 60 Gyrations	2.346	96.1	3.9	68.2	146.4	1800	11
Asphalt Content - 6.0% Theoretical Gravity - 2.42							
50 Blow Manual Hammer	2.301	95.1	4.9	73.4	143.6	737	15
50 Blow Mechanical Hammer	2.306	95.3	4.7	74.3	143.9	754	12
75 Blow Manual Hammer	2.303	95.2	4.8	73.8	143.7	963	16
75 Blow Mechanical Hammer	2.308	95.4	4.6	74.7	144.0	864	11
100 PSI 30 Gyrations	2.320	95.9	4.1	76.8	144.8	1159	13

TABLE 3

PHYSICAL PROPERTIES OF MIX NO. 2 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids - %	V.F.A. -%	Density lbs./ cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.5% Theoretical Gravity - 2.456							
200 PSI 30 Gyrations	2.295	93.4	6.6	60.5	143.2	1417	9
200 PSI 45 Gyrations							
200 PSI 60 Gyrations	2.319	94.4	5.6	64.6	144.7	2415	8
250 PSI 30 Gyrations	2.293	93.4	6.6	60.5	143.1	1875	8
250 PSI 45 Gyrations	2.297	93.5	6.5	60.9	143.3	2212	8
250 PSI 60 Gyrations	2.338	96.5	3.5	74.7	145.9	2502	8
Asphalt Content - 5.0% Theoretical Gravity - 2.439							
50 Blow Manual Hammer	2.233	91.5	8.5	56.4	139.3	1158	6
50 Blow Mechanical Hammer	2.223	91.1	8.9	55.1	138.7	1033	7
75 Blow Manual Hammer	2.277	93.3	6.7	62.6	142.1	1654	5
75 Blow Mechanical Hammer	2.206	90.4	9.6	53.0	137.7	936	5
100 PSI 30 Gyrations							
100 PSI 45 Gyrations	2.283	93.6	6.4	63.6	142.5	1535	8
100 PSI 60 Gyrations	2.310	94.7	5.3	68.1	144.1	1870	8
200 PSI 30 Gyrations	2.322	95.9	4.1	73.5	144.9	2044	9
200 PSI 45 Gyrations	2.293	94.0	6.0	65.2	143.1	2086	9
200 PSI 60 Gyrations	2.337	96.5	3.5	76.6	145.8	2312	11
250 PSI 30 Gyrations	2.322	95.2	4.8	69.7	144.9	2021	10
250 PSI 45 Gyrations	2.304	94.5	5.5	67.2	143.8	2276	11
250 PSI 60 Gyrations	2.346	96.9	3.1	78.8	146.4	2409	8
Asphalt Content - 5.5 % Theoretical Gravity - 2.422							
50 Blow Manual Hammer	2.261	93.3	6.7	64.7	141.0	1564	7
50 Blow Mechanical Hammer	2.231	92.1	7.9	60.4	139.2	1104	8
75 Blow Manual Hammer	2.297	94.9	5.1	70.8	143.3	1680	7
75 Blow Mechanical Hammer	2.234	92.2	7.8	60.7	139.4	1104	9
100 PSI 30 Gyrations	2.305	95.2	4.8	72.1	143.8	1554	12
100 PSI 45 Gyrations	2.296	94.8	5.2	70.4	143.3	1690	11
100 PSI 60 Gyrations	2.334	96.4	3.6	77.8	145.6	1975	9
200 PSI 30 Gyrations	2.327	96.8	3.2	79.7	145.2	1870	12
200 PSI 45 Gyrations	2.304	95.1	4.9	71.7	143.8	2105	11
200 PSI 60 Gyrations	2.341	97.4	2.6	82.9	146.1	1904	16
250 PSI 30 Gyrations	2.336	97.2	2.8	81.8	145.8	1880	8
250 PSI 45 Gyrations	2.319	95.7	4.3	70.4	144.7	2064	11
250 PSI 60 Gyrations	2.342	97.5	2.5	83.5	146.1	1827	10
Asphalt Content - 6.0% Theoretical Gravity - 2.403							
50 Blow Manual Hammer	2.271	94.5	5.5	70.7	141.7	1575	8
50 Blow Mechanical Hammer	2.245	93.4	6.6	66.7	140.1	1160	9
75 Blow Manual Hammer	2.298	95.6	4.4	75.4	143.4	1498	11
75 Blow Mechanical Hammer	2.254	93.8	6.2	68.1	140.6	1296	9
100 PSI 30 Gyrations	2.317	96.4	3.6	79.1	144.6	1644	13
100 PSI 45 Gyrations	2.304	95.9	4.1	76.8	143.8	1538	12
100 PSI 60 Gyrations	2.322	96.6	3.4	80.2	144.9	1383	14
200 PSI 30 Gyrations	2.326	97.4	2.6	84.0	145.1	1627	14
200 PSI 45 Gyrations	2.310	96.1	3.9	77.7	144.1	1843	12
200 PSI 60 Gyrations	2.332	97.7	2.3	85.6	145.5	1494	12
250 PSI 30 Gyrations	2.333	97.7	2.3	85.7	145.6	1543	13
250 PSI 45 Gyrations							
250 PSI 60 Gyrations	2.332	97.7	2.3	85.6	145.5	1452	15
Asphalt Content - 6.5% Theoretical Gravity - 2.386							
100 PSI 30 Gyrations	2.312	96.8	3.2	82.2	144.3	1454	12
100 PSI 60 Gyrations	2.304	96.5	3.5	80.8	143.8	1080	21

TABLE 4

PHYSICAL PROPERTIES OF MIX NO. 3 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu. ft.	Marshall Stability	Flow
Asphalt Content - 4.0% Theoretical Gravity - 2.485							
250 PSI 30 Gyrations	2.281	91.8	8.2	52.3	142.3	1908	6
250 PSI 45 Gyrations	2.306	92.8	7.2	55.6	143.9	2366	7
250 PSI 60 Gyrations	2.312	93.0	7.0	62.1	144.3	2439	7
Asphalt Content - 4.5% Theoretical Gravity - 2.464							
200 PSI 45 Gyrations	2.312	93.8	6.2	62.2	144.3	2323	9
200 PSI 60 Gyrations	2.311	93.9	6.1	62.6	144.2	2392	6
250 PSI 30 Gyrations	2.300	93.3	6.7	59.2	143.5	2022	6
250 PSI 45 Gyrations	2.320	94.2	5.8	63.3	144.8	2570	7
250 PSI 60 Gyrations	2.323	94.3	5.7	64.1	145.0	2528	7
Asphalt Content - 5.0% Theoretical Gravity - 2.448							
50 Blow Manual Hammer	2.291	93.6	6.4	63.6	143.0	1654	10
50 Blow Mechanical Hammer	2.244	91.7	8.3	57.0	140.0	1251	8
75 Blow Manual Hammer	2.298	93.9	6.1	64.9	143.4	1817	7
75 Blow Mechanical Hammer	2.297	93.9	6.1	64.9	143.3	1875	14
100 PSI 30 Gyrations	2.273	92.8	7.2	60.7	141.8	1317	5
100 PSI 45 Gyrations	2.295	93.7	6.3	64.5	143.2	1695	8
100 PSI 60 Gyrations	2.298	93.9	6.1	64.9	143.4	1712	7
200 PSI 30 Gyrations	2.304	94.1	5.9	65.7	143.8	1860	5
200 PSI 45 Gyrations	2.320	94.8	5.2	68.6	144.8	2086	8
200 PSI 60 Gyrations	2.329	95.1	4.9	70.0	145.3	2262	8
250 PSI 30 Gyrations	2.321	94.8	5.2	68.7	144.8	2139	8
250 PSI 45 Gyrations	2.331	95.2	4.8	70.4	145.5	2339	9
250 PSI 60 Gyrations	2.341	95.6	4.4	72.3	146.1	2551	7
Asphalt Content - 5.5% Theoretical Gravity - 2.428							
50 Blow Manual Hammer	2.300	94.7	5.3	70.1	143.5	1564	8
50 Blow Mechanical Hammer	2.268	93.4	6.6	64.9	141.5	1251	7
75 Blow Manual Hammer	2.305	94.9	5.1	70.9	143.8	1627	12
75 Blow Mechanical Hammer	2.311	95.2	4.8	72.2	144.2	1877 ✓	12
100 PSI 30 Gyrations	2.299	94.7	5.3	70.1	143.5	1553	8
100 PSI 45 Gyrations	2.313	95.3	4.7	72.6	144.3	1832	8
100 PSI 60 Gyrations	2.323	95.7	4.3	74.4	145.0	1844 ✓	10
200 PSI 30 Gyrations	2.322	95.6	4.4	74.0	144.9	1996	7
200 PSI 45 Gyrations	2.329	95.9	4.1	75.4	145.3	1870	11
200 PSI 60 Gyrations	2.338	96.3	3.7	77.3	145.9	1991	9
250 PSI 30 Gyrations	2.330	96.0	4.0	75.9	145.4	2041	8
250 PSI 45 Gyrations	2.337	96.3	3.7	77.3	145.8	1827	12
250 PSI 60 Gyrations	2.339	96.3	3.7	77.3	146.0	1695	11
Asphalt Content - 6.0% Theoretical Gravity - 2.413							
50 Blow Manual Hammer	2.259	93.6	6.4	67.5	141.0	1283	12
50 Blow Mechanical Hammer	2.278	94.4	5.6	70.5	142.1	1180	9
75 Blow Manual Hammer	2.305	95.5	4.5	75.1	143.8	1322	14
75 Blow Mechanical Hammer	2.298	95.2	4.8	74.2	143.4	1421 ✓	15
100 PSI 30 Gyrations	2.314	95.9	4.1	76.9	144.4	1470	8
100 PSI 45 Gyrations	2.317	96.0	4.0	77.3	144.6	1712	9
100 PSI 60 Gyrations	2.321	96.2	3.8	78.2	144.8	1559 ✓	10
200 PSI 30 Gyrations	2.319	96.1	3.9	77.8	144.7	1643	9
200 PSI 45 Gyrations	2.324	96.3	3.7	78.7	145.0	1580	10
200 PSI 60 Gyrations	2.329	96.5	3.5	79.7	145.3	1560	13

TABLE 5

PHYSICAL PROPERTIES OF MIX NO. 4 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu. ft.	Marshall Stability	Flow
Asphalt Content - 3.0% Theoretical Gravity - 2.559							
100 PSI 60 Gyrations	2.415	94.4	5.6	55.7	150.7	2201	11
200 PSI 30 Gyrations	2.417	94.5	5.5	56.1	150.8	2250	9
200 PSI 45 Gyrations	2.425	94.8	5.2	57.6	151.3	2668	10
200 PSI 60 Gyrations	2.443	95.5	4.5	61.3	152.4	3276	9
250 PSI 30 Gyrations	2.414	94.3	5.7	55.2	150.6	2014	9
250 PSI 45 Gyrations	2.432	95.0	5.0	58.6	151.8	2874	8
250 PSI 60 Gyrations	2.437	95.2	4.8	59.7	152.1	2953	9
Asphalt Content - 3.5% Theoretical Gravity - 2.538							
50 Blow Manual Hammer	2.414	95.1	4.9	62.6	150.6	2049	12
50 Blow Mechanical Hammer	2.376	93.6	6.4	55.8	148.3	1379	10
75 Blow Manual Hammer	2.424	95.5	4.5	64.7	151.3	2385	9
75 Blow Mechanical Hammer	2.417	95.2	4.8	63.1	150.8	2189	10
100 PSI 30 Gyrations	2.406	94.8	5.2	61.1	150.1	1895	10
100 PSI 45 Gyrations	2.425	95.5	4.5	64.7	151.3	2025	10
100 PSI 60 Gyrations	2.447	96.4	3.6	69.8	152.7	2712	10
200 PSI 30 Gyrations	2.434	95.9	4.1	66.9	151.9	2277	8
200 PSI 45 Gyrations	2.449	96.5	3.5	67.1	152.8	2934	11
200 PSI 60 Gyrations	2.455	96.7	3.3	71.6	153.2	3173	10
250 PSI 30 Gyrations	2.430	95.7	4.3	65.8	151.6	2590	11
250 PSI 45 Gyrations	2.441	96.2	3.8	68.6	152.3	3007	10
250 PSI 60 Gyrations	2.461	97.0	3.0	73.6	153.6	2961	13
Asphalt Content - 4.0% Theoretical Gravity - 2.519							
50 Blow Manual Hammer	2.417	96.0	4.0	70.1	150.8	2296	11
50 Blow Mechanical Hammer	2.401	95.3	4.7	66.5	149.8	1584	10
75 Blow Manual Hammer	2.426	96.3	3.7	71.8	151.4	2349	11
75 Blow Mechanical Hammer	2.426	96.3	3.7	71.8	151.4	2119	11
100 PSI 30 Gyrations	2.428	96.4	3.6	72.4	151.5	2070	10
100 PSI 45 Gyrations	2.439	96.8	3.2	74.8	152.2	1830	10
100 PSI 60 Gyrations	2.453	97.4	2.6	78.5	153.1	2484	10
200 PSI 30 Gyrations	2.449	97.2	2.8	77.3	152.8	2325	12
200 PSI 45 Gyrations	2.454	97.4	2.6	73.3	153.1	2349	11
200 PSI 60 Gyrations	2.469	98.0	2.0	82.7	154.1	2939	11
250 PSI 30 Gyrations	2.446	97.1	2.9	76.6	152.6	2357	11
250 PSI 45 Gyrations	2.454	97.4	2.6	78.6	153.1	2537	11
250 PSI 60 Gyrations	2.465	97.9	2.1	82.0	153.8	3030	11
Asphalt Content - 4.5% Theoretical Gravity - 2.501							
50 Blow Manual Hammer	2.425	97.0	3.0	77.9	151.3	1783	12
50 Blow Mechanical Hammer	2.415	96.6	3.4	75.6	150.7	1512	12
75 Blow Manual Hammer	2.430	97.1	2.9	78.6	151.6	1757	12
75 Blow Mechanical Hammer	2.425	97.0	3.0	77.9	151.3	1792	10
100 PSI 30 Gyrations	2.436	97.4	2.6	80.4	152.0	1851	13
100 PSI 45 Gyrations	2.451	98.0	2.0	84.3	152.9	1848	15
Asphalt Content - 5.0% Theoretical Gravity - 2.482							
50 Blow Manual Hammer	2.412	97.2	2.8	80.7	150.5	1366	16
50 Blow Mechanical Hammer	2.416	97.3	2.7	81.3	150.8	1532	14
75 Blow Manual Hammer	2.417	97.4	2.6	81.9	150.8	1285	16
75 Blow Mechanical Hammer	2.409	97.1	2.9	80.1	150.3	1178	18
100 PSI 30 Gyrations	2.433	98.0	2.0	85.5	151.8	1559	16
100 PSI 45 Gyrations	2.437	98.2	1.8	86.8	152.1	1434	18

TABLE 6

PHYSICAL PROPERTIES OF MIX NO. 5 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	% Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stability	Flow
Asphalt Content - 3.0% Theoretical Gravity - 2.470							
200 PSI 45 Gyrations	2.269	91.8	8.1	44.9	141.6	3722	12
250 PSI 60 Gyrations	2.304	93.3	6.7	50.0	143.8	4817	9
Asphalt Content - 3.5% Theoretical Gravity - 2.449							
100 PSI 45 Gyrations	2.251	91.9	8.1	48.6	140.5	2858	11
200 PSI 45 Gyrations	2.281	93.1	6.9	52.9	142.3	4026	7
200 PSI 60 Gyrations	2.285	93.3	6.7	53.7	142.6	3674	9
250 PSI 30 Gyrations	2.304	94.1	5.9	57.0	143.8	3372	7
250 PSI 45 Gyrations	2.335	95.3	4.7	62.8	145.7	3770	8
250 PSI 60 Gyrations	2.351	96.0	4.0	66.6	146.7	4328	9
Asphalt Content - 4.0% Theoretical Gravity - 2.432							
50 Blow Manual Hammer	2.242	92.1	7.9	47.6	139.9	2205	11
75 Blow Mechanical Hammer	2.230	91.6	8.4	49.2	139.2	2137	10
75 Blow Manual Hammer	2.285	93.9	6.1	59.3	142.6	2936	10
100 PSI 30 Gyrations	2.254	92.7	7.3	54.5	140.6	2192	13
100 PSI 45 Gyrations	2.294	94.3	5.7	61.0	143.1	2591	11
100 PSI 60 Gyrations	2.309	94.9	5.1	63.8	144.1	2808 ✓	12
200 PSI 30 Gyrations	2.278	93.7	6.3	58.4	142.1	3019	10
200 PSI 45 Gyrations	2.290	94.2	5.8	60.5	142.9	3310	9
200 PSI 60 Gyrations	2.303	94.7	5.3	62.8	144.1	3659	11
250 PSI 30 Gyrations	2.324	95.5	4.5	66.7	145.0	3563	9
250 PSI 45 Gyrations	2.342	96.2	3.8	70.5	146.1	3633	10
250 PSI 60 Gyrations	2.355	96.8	3.2	74.1	147.0	3241	10
Asphalt Content - 4.5% Theoretical Gravity - 2.414							
50 Blow Mechanical Hammer	2.265	93.8	6.2	61.5	141.3	2182	14
50 Blow Manual Hammer	2.303	95.4	4.6	68.6	143.7	3122	16
75 Blow Mechanical Hammer	2.312	95.8	4.2	70.6	144.3	3206	16
75 Blow Manual Hammer	2.327	96.4	3.6	73.9	145.2	2882	18
100 PSI 30 Gyrations	2.283	94.6	5.4	64.9	142.5	2119	12
100 PSI 45 Gyrations	2.310	95.7	4.3	70.1	144.1	2518	10
100 PSI 60 Gyrations	2.315	95.9	4.1	71.1	144.5	2745	12
200 PSI 30 Gyrations	2.287	94.7	5.3	65.3	142.7	3120	9
200 PSI 45 Gyrations	2.318	96.0	4.0	71.7	144.6	3084	11
200 PSI 60 Gyrations	2.323	96.2	3.8	72.8	145.0	3495	10
250 PSI 30 Gyrations	2.298	95.2	4.8	67.7	143.4	3150	7
250 PSI 45 Gyrations	2.329	96.5	3.5	74.4	145.3	3828	13
250 PSI 60 Gyrations	2.348	97.3	2.7	79.2	146.5	2776	10
Asphalt Content - 5.0% Theoretical Gravity - 2.398							
50 Blow Mechanical Hammer	2.295	95.7	4.3	72.2	143.2	2344	16
50 Blow Manual Hammer	2.303	96.0	4.0	73.6	143.7	2361	21
75 Blow Mechanical Hammer	2.307	96.2	3.8	74.7	144.0	2353 ✓	17
75 Blow Manual Hammer	2.317	96.6	3.4	76.8	144.6	2279	18
100 PSI 30 Gyrations	2.303	96.0	4.0	73.6	143.7	2461	11
100 PSI 45 Gyrations	2.311	96.4	3.6	75.7	144.2	2212	11
100 PSI 60 Gyrations	2.321	96.8	3.2	77.9	144.8	2260 ✓	11
200 PSI 30 Gyrations	2.297	95.8	4.2	72.6	143.3	2665	8
200 PSI 45 Gyrations	2.334	97.3	2.7	80.8	145.6	2137	14
200 PSI 60 Gyrations	2.326	97.0	3.0	79.0	145.1	2915	13
250 PSI 45 Gyrations	2.333	97.3	2.7	80.8	145.6	2322	15
Asphalt Content - 5.5% Theoretical Gravity - 2.381							
50 Blow Mechanical Hammer	2.295	96.4	3.6	77.3	143.2	1914	17
100 PSI 30 Gyrations	2.296	96.4	3.6	77.3	143.3	1988	13

TABLE 7

PHYSICAL PROPERTIES OF MIX NO. 6 USING VARIOUS COMPACTIVE EFFORTS

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stability	Flow
Asphalt Content - 4.5% Theoretical Gravity - 1.857							
50 Blow Manual Hammer	1.537	82.8	17.2	28.1	95.9	1606	9
50 Blow Mechanical Hammer	1.501	80.8	19.2	13.9	93.7	1033	8
75 Blow Manual Hammer	1.563	84.2	15.8	30.2	97.5	1663	9
100 PSI 45 Gyrations	1.523	82.0	18.0	27.0	95.0	1407	9
100 PSI 60 Gyrations	1.548	83.4	16.4	29.2	96.6	1563	9
200 PSI 30 Gyrations	1.528	82.3	17.7	27.4	95.3	1786	13
200 PSI 45 Gyrations	1.578	85.0	15.0	31.5	98.5	1750	9
250 PSI 45 Gyrations	1.602	86.3	13.7	33.8	100.0	2351	9
250 PSI 60 Gyrations	1.586	85.4	14.6	28.5	99.0	2661	10
Asphalt Content - 5.0% Theoretical Gravity - 1.848							
50 Blow Manual Hammer	1.564	84.6	15.4	33.0	97.6	1820	10
50 Blow Mechanical Hammer	1.524	82.5	17.5	29.7	95.1	1200	8
75 Blow Manual Hammer	1.574	85.2	14.8	34.0	98.2	1991	9
100 PSI 30 Gyrations	1.550	83.9	16.1	31.8	96.7	1249	9
100 PSI 45 Gyrations	1.536	83.1	16.9	30.6	95.8	1623	8
100 PSI 60 Gyrations	1.570	85.0	15.0	33.7	98.0	1785	10
200 PSI 30 Gyrations	1.561	84.5	15.5	32.8	97.4	1818	12
200 PSI 45 Gyrations	1.578	85.4	14.6	34.4	98.5	1979	10
200 PSI 60 Gyrations	1.621	87.7	12.3	39.0	101.2	2325	11
250 PSI 30 Gyrations	1.603	86.7	13.3	36.9	100.0	1854	10
250 PSI 45 Gyrations	1.607	87.0	13.0	37.5	100.3	2616	10
250 PSI 60 Gyrations	1.603	86.7	13.3	36.9	100.0	2807	9
Asphalt Content - 5.5% Theoretical Gravity - 1.839							
50 Blow Manual Hammer	1.557	84.7	15.3	35.2	97.2	1669	10
50 Blow Mechanical Hammer	1.561	84.9	15.1	35.6	97.4	1137	8
75 Blow Manual Hammer	1.589	86.4	13.6	38.4	99.2	2237	9
100 PSI 30 Gyrations	1.554	84.5	15.5	34.9	97.0	1350	9
100 PSI 45 Gyrations	1.575	85.6	14.4	36.9	98.3	1670	8
100 PSI 60 Gyrations	1.566	85.2	14.8	36.1	97.7	1874	12
200 PSI 30 Gyrations	1.574	85.6	14.4	36.9	98.2	1865	12
200 PSI 45 Gyrations	1.606	87.3	12.7	40.3	100.2	1950	10
200 PSI 60 Gyrations	1.632	88.7	11.3	43.6	101.8	2561	11
250 PSI 30 Gyrations	1.597	86.8	13.2	39.2	99.7	2140	10
250 PSI 45 Gyrations	1.606	87.3	12.7	40.3	100.2	2359	10
250 PSI 60 Gyrations	1.590	86.5	13.5	38.6	99.2	2879	12
Asphalt Content - 6.0% Theoretical Gravity - 1.832							
50 Blow Mechanical Hammer	1.564	85.4	14.6	38.4	97.6	1181	7
75 Blow Manual Hammer	1.595	87.1	12.9	41.9	99.5	2018	10
100 PSI 30 Gyrations	1.559	85.1	14.9	37.9	97.3	1424	9
100 PSI 45 Gyrations	1.566	85.5	14.5	38.6	97.7	1810	11
100 PSI 60 Gyrations	1.570	85.7	14.3	39.0	98.0	1723	12
200 PSI 30 Gyrations	1.584	86.5	13.5	40.6	98.8	2037	10
200 PSI 45 Gyrations	1.608	87.8	12.2	43.4	100.3	2242	11
200 PSI 60 Gyrations	1.610	87.9	12.1	43.7	100.5	2669	12
250 PSI 30 Gyrations	1.631	89.0	11.0	46.3	101.8	2095	10
250 PSI 45 Gyrations	1.622	88.5	11.5	45.1	101.2	2542	11
250 PSI 60 Gyrations	1.611	87.9	12.1	43.7	100.5	2870	13

TABLE 7

PHYSICAL PROPERTIES OF MIX NO. 6 USING VARIOUS COMPACTIVE EFFORTS (CONTINUED)

Compactive Effort	Specific Gravity	%Theoretical Gravity	Voids-%	V.F.A.-%	Density lbs./cu.ft.	Marshall Stabitliy	Flow
Asphalt Content - 6.5% Theoretical Gravity - 1.824							
75 Blow Mechanical Hammer	1.591	87.2	12.8	44.2	99.3	1561	9
100 PSI 30 Gyrations	1.654	90.7	9.3	52.9	103.2	1480	9
100 PSI 45 Gyrations	1.665	91.3	8.7	54.7	103.9	1703	10
200 PSI 45 Gyrations	1.698	93.1	6.9	60.8	106.0	2147	11
200 PSI 60 Gyrations	1.646	90.2	9.8	51.5	102.7	2398	9
250 PSI 45 Gyrations	1.651	90.5	9.5	52.3	103.0	2150	9
250 PSI 60 Gyrations	1.630	89.4	10.6	49.3	101.7	2383	10
Asphalt Content - 7.0% Theoretical Gravity - 1.816							
75 Blow Mechanical Hammer	1.594	87.8	12.2	47.0	99.5	1730	9
100 PSI 30 Gyrations	1.603	88.3	11.7	48.2	100.0	1543	10
100 PSI 45 Gyrations	1.670	92.0	8.0	58.7	104.5	1665	9
200 PSI 45 Gyrations	1.697	93.4	6.6	63.6	105.9	2061	8
Asphalt Content - 7.5% Theoretical Gravity - 1.810							
75 Blow Mechanical Hammer	1.649	91.1	8.9	57.4	102.9	1576	9
100 PSI 30 Gyrations	1.666	92.0	8.0	60.3	104.0	1602	10
100 PSI 45 Gyrations	1.666	92.0	8.0	60.3	104.0	1863	9
Asphalt Content - 8.0% Theoretical Gravity - 1.800							
100 PSI 30 Gyrations	1.574	87.4	12.6	49.3	98.2	1813	13

TABLE 8

AVERAGE RESULTS OF LABORATORY MIXES AT 100 PSI VERTICAL PRESSURE

Number of Gyrations	Specific Gravity	% Theoretical Gravity	Voids %	V. F. A %	Density lbs/cu ft	Marshall Stability	Flow
Mix 1 Optimum Asphalt Content - 4.8% Theoretical Gravity - 2.443							
10	2.280	93.3	6.7	61.6	142.3	895	11
20	2.314	94.7	5.3	67.3	144.4	1288	10
30	2.325	95.2	4.8	69.5	145.1	1455	11
40	2.333	95.5	4.5	70.9	145.6	1559	9
50	2.345	96.0	4.0	73.4	146.3	1774	9
60	2.351	96.2	3.8	74.5	146.7	1851	9
Mix 2 Optimum Asphalt Content - 5.2% Theoretical Gravity - 2.411							
10	2.238	92.8	7.2	61.3	134.7	628	10
20	2.272	94.2	5.8	66.6	141.8	931	10
30	2.291	95.0	5.0	70.0	143.0	1171	10
40	2.301	95.4	4.6	71.8	143.6	1293	8
50	2.306	95.6	4.4	72.8	143.9	1467	8
60	2.315	96.0	4.0	74.7	144.5	1580	8
Mix 3 Optimum Asphalt Content - 5.2% Theoretical Gravity - 2.450							
10	2.198	87.7	12.3	47.4	137.2	611	8
20	2.226	90.9	9.1	55.3	138.9	914	8
30	2.256	92.1	7.9	59.0	140.8	1219	7
40	2.262	92.3	7.7	59.7	141.1	1234	8
50	2.271	92.7	7.3	61.1	141.7	1327	8
60	2.285	93.3	6.7	63.3	142.6	1550	8
Mix 4 Optimum Asphalt Content - 4.6% Theoretical Gravity - 2.492							
10	2.354	94.5	5.5	65.9	146.9	736	8
20	2.378	95.4	4.6	70.0	148.4	966	9
30	2.398	96.2	3.8	74.0	149.6	1193	11
40	2.410	96.7	3.3	76.7	150.4	1338	8
50	2.418	97.0	3.0	78.4	150.9	1613	9
60	2.428	97.4	2.6	80.8	151.5	1697	9
Mix 5 Optimum Asphalt Content - 4.5% Theoretical Gravity - 2.414							
10	2.216	91.8	8.2	54.1	138.3	1543	10
20	2.268	94.0	6.0	62.3	141.5	2099	10
30	2.296	95.1	4.9	67.2	143.3	2444	10
40	2.295	95.1	4.9	67.2	143.2	2772	11
50	2.308	95.6	4.4	69.6	144.0	2828	12
60	2.321	96.1	3.9	72.2	144.8	2772	12
Mix 6 Optimum Asphalt Content - 7.0% Theoretical Gravity - 1.816							
10	1.589	87.5	12.5	46.6	99.2	840	10
20	1.622	89.3	10.7	51.0	101.2	1273	10
30	1.629	89.7	10.3	52.0	101.6	1426	11
40	1.645	90.6	9.4	54.6	102.6	1678	10
50	1.637	90.1	9.9	53.1	102.1	1575	11
60	1.621	89.2	10.8	50.7	101.2	1933	11

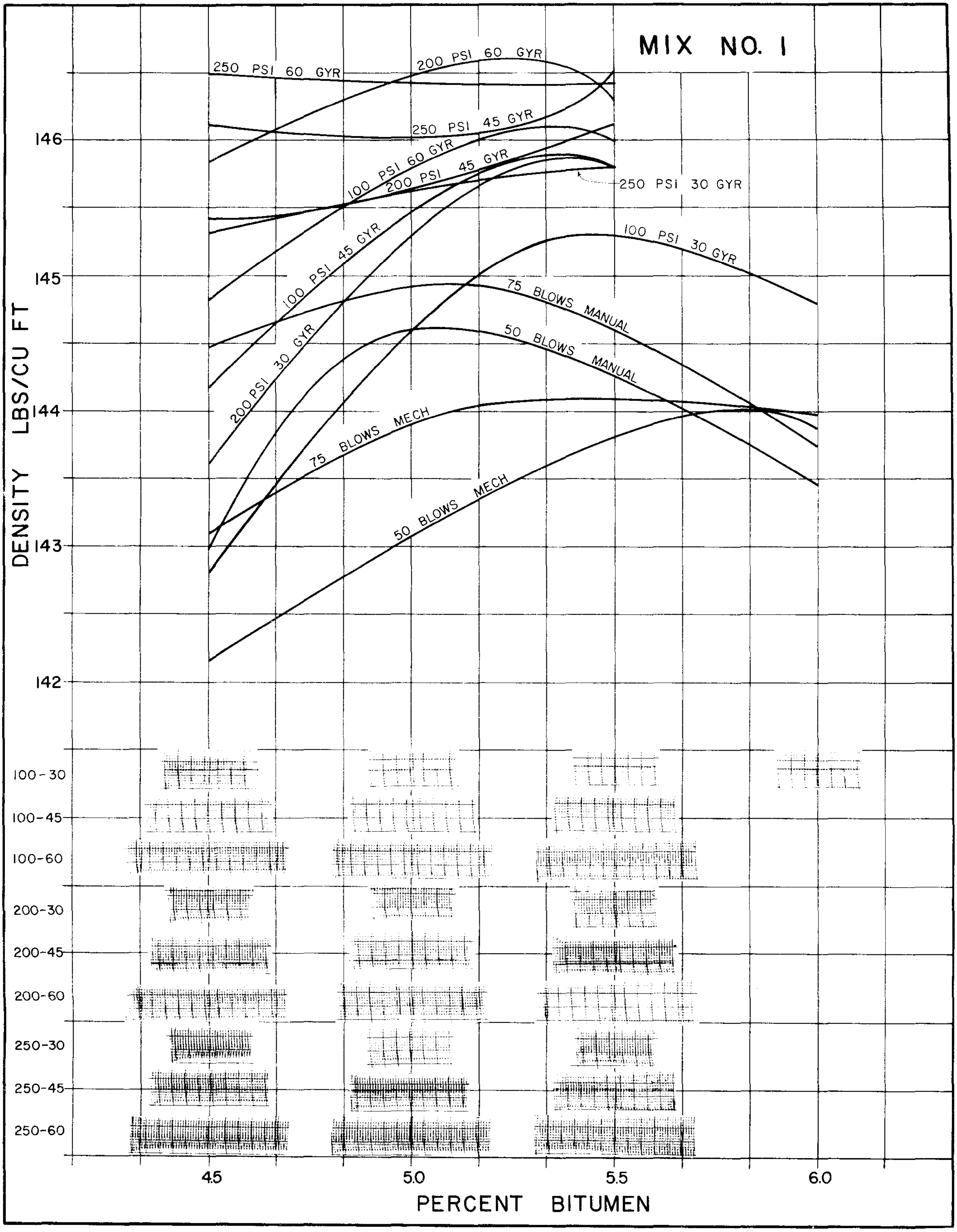


Figure 4 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 1.

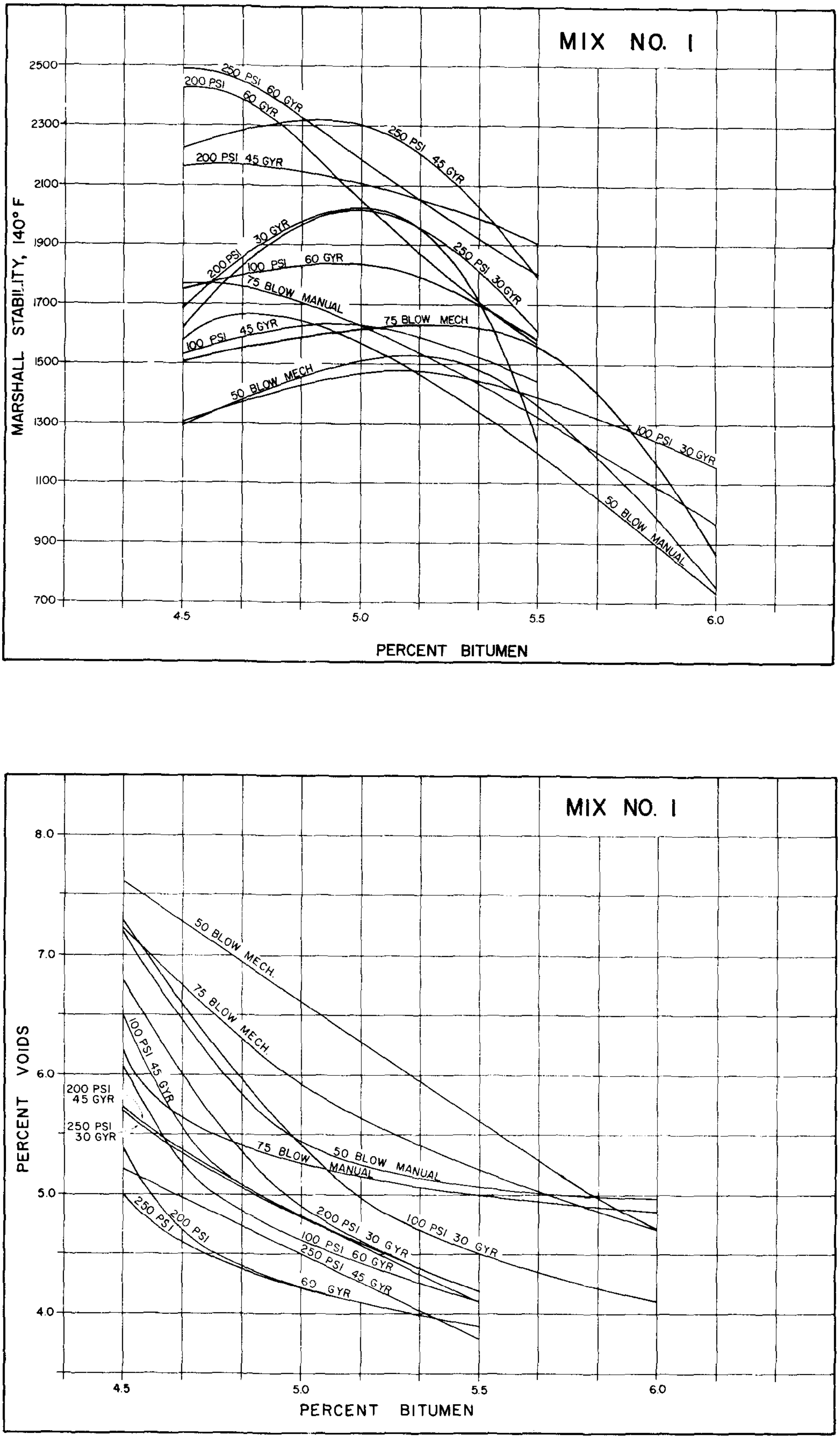


Figure 5 - Relationship of Marshall Stability and void content versus Percent Bitumen of various Efforts for gravel Mix 1.

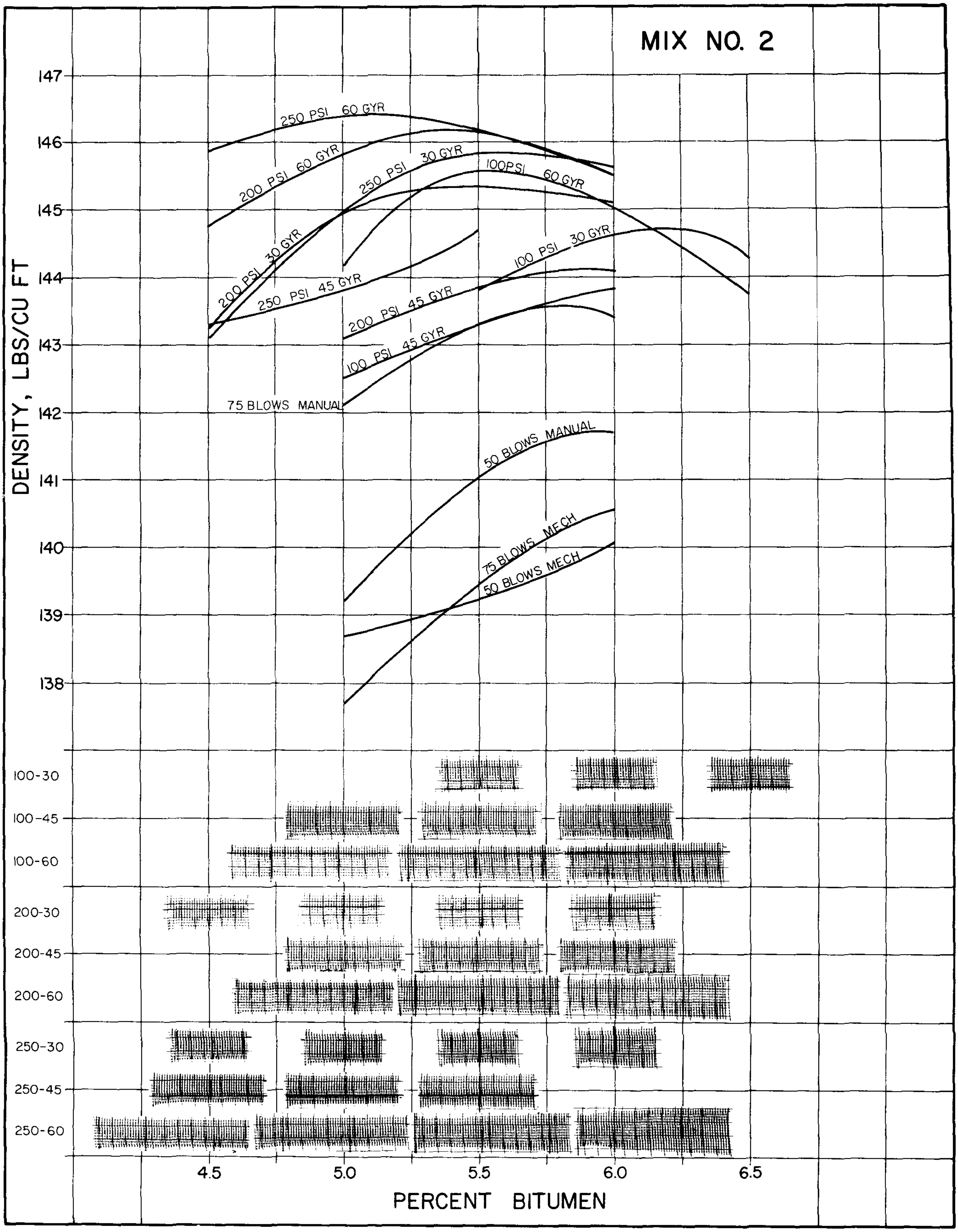


Figure 6 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 2.

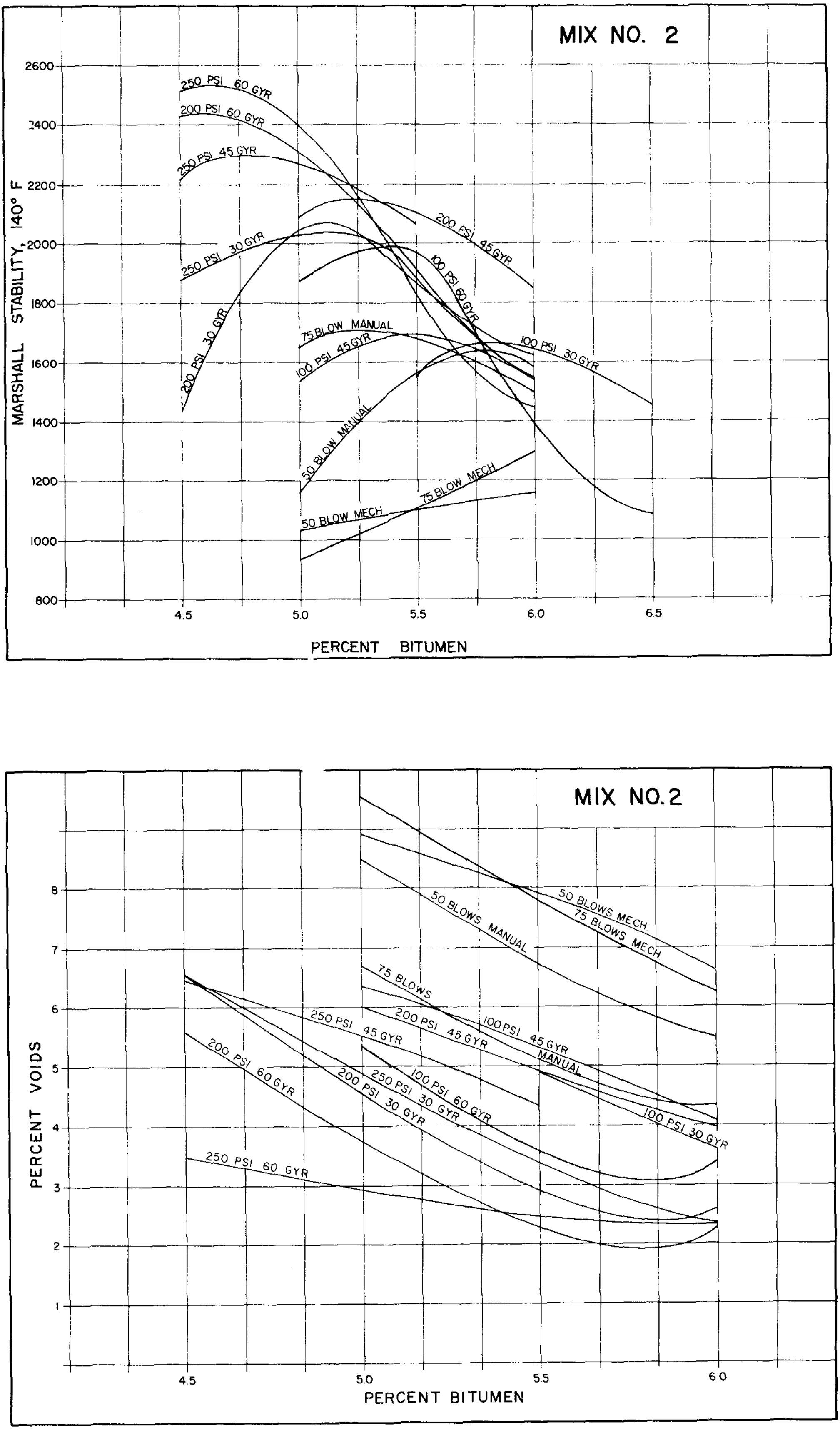


Figure 7 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for Gravel Mix 2.

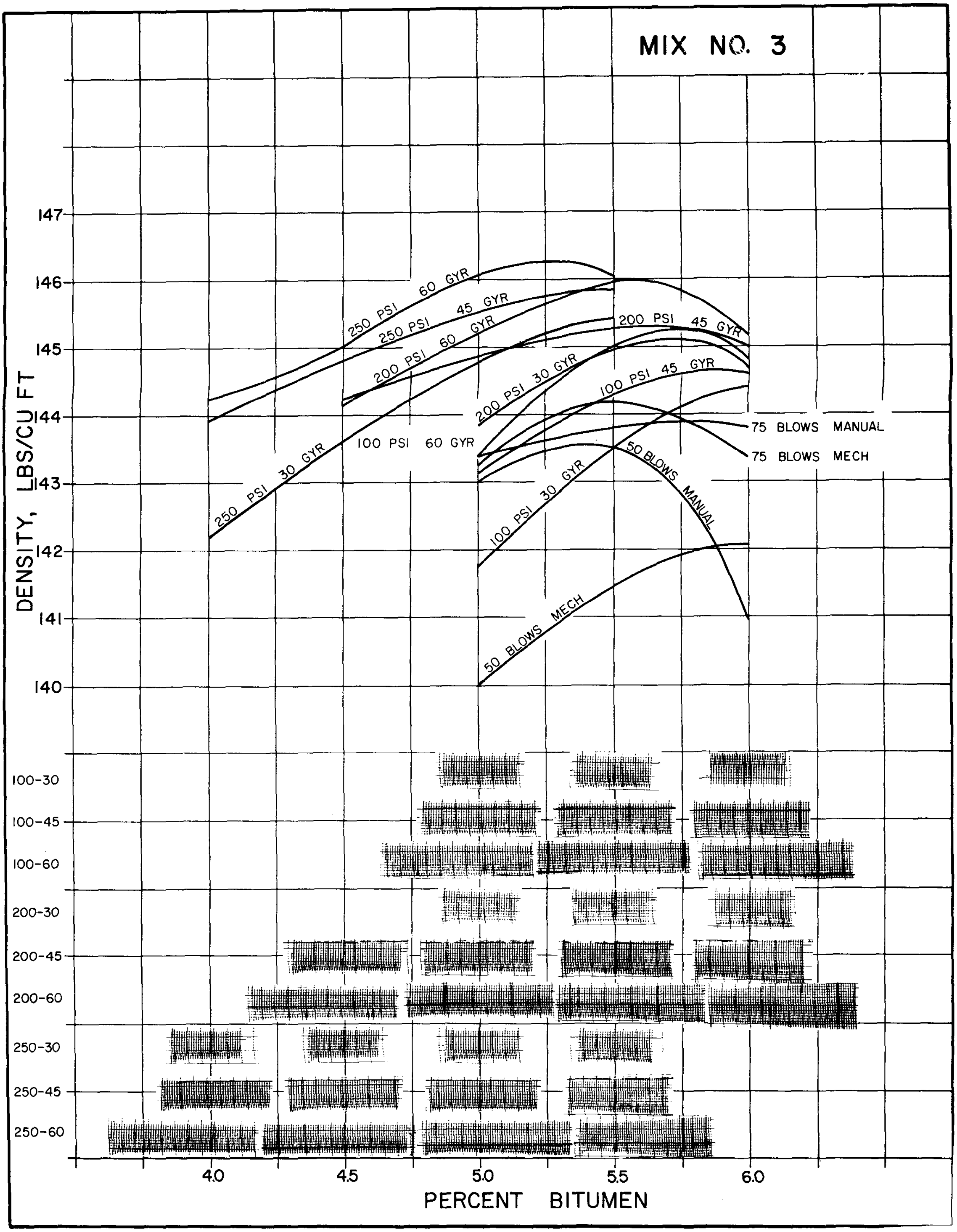


Figure 8 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for gravel Mix 3.

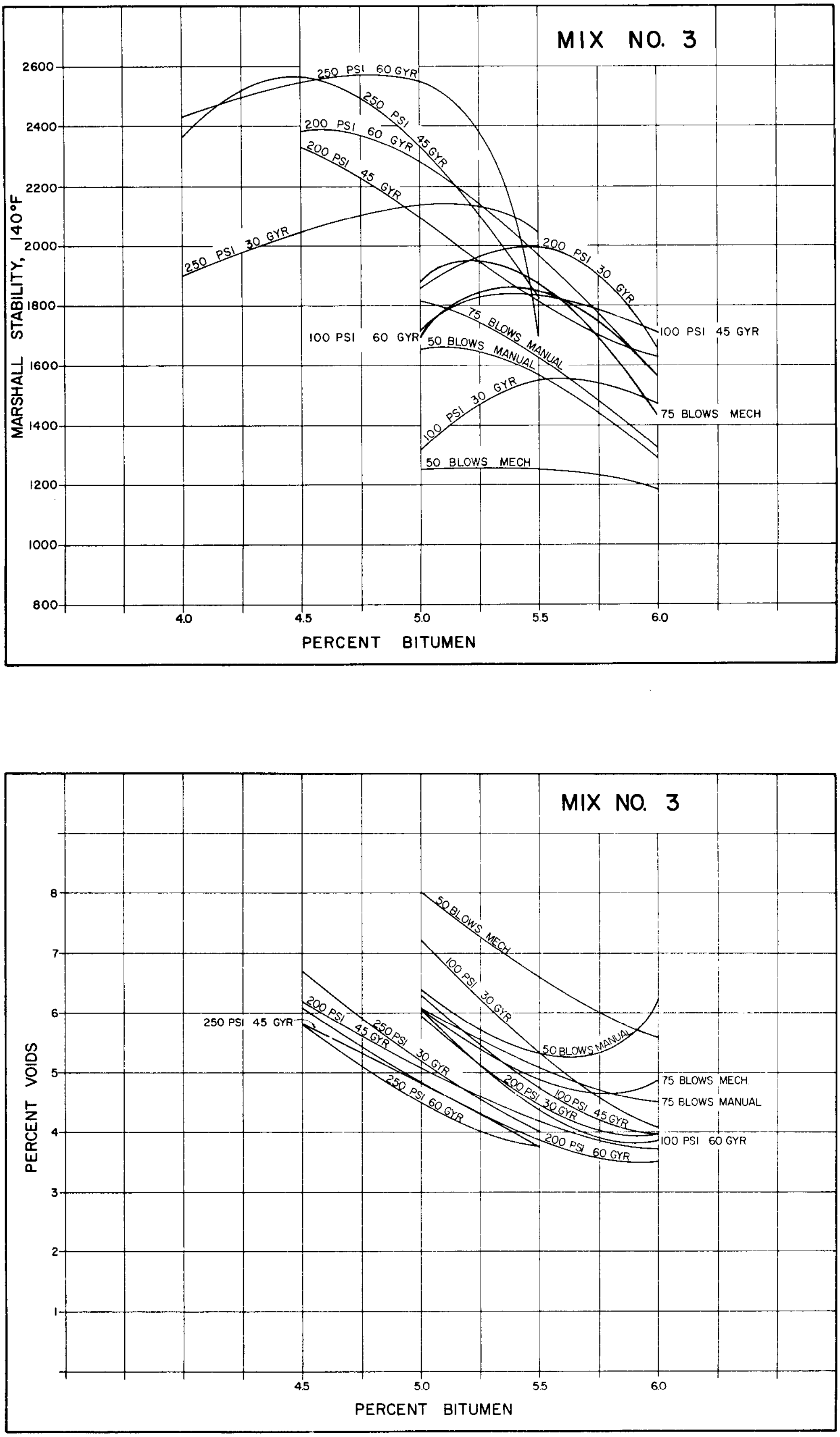


Figure 9 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for gravel Mix 3.

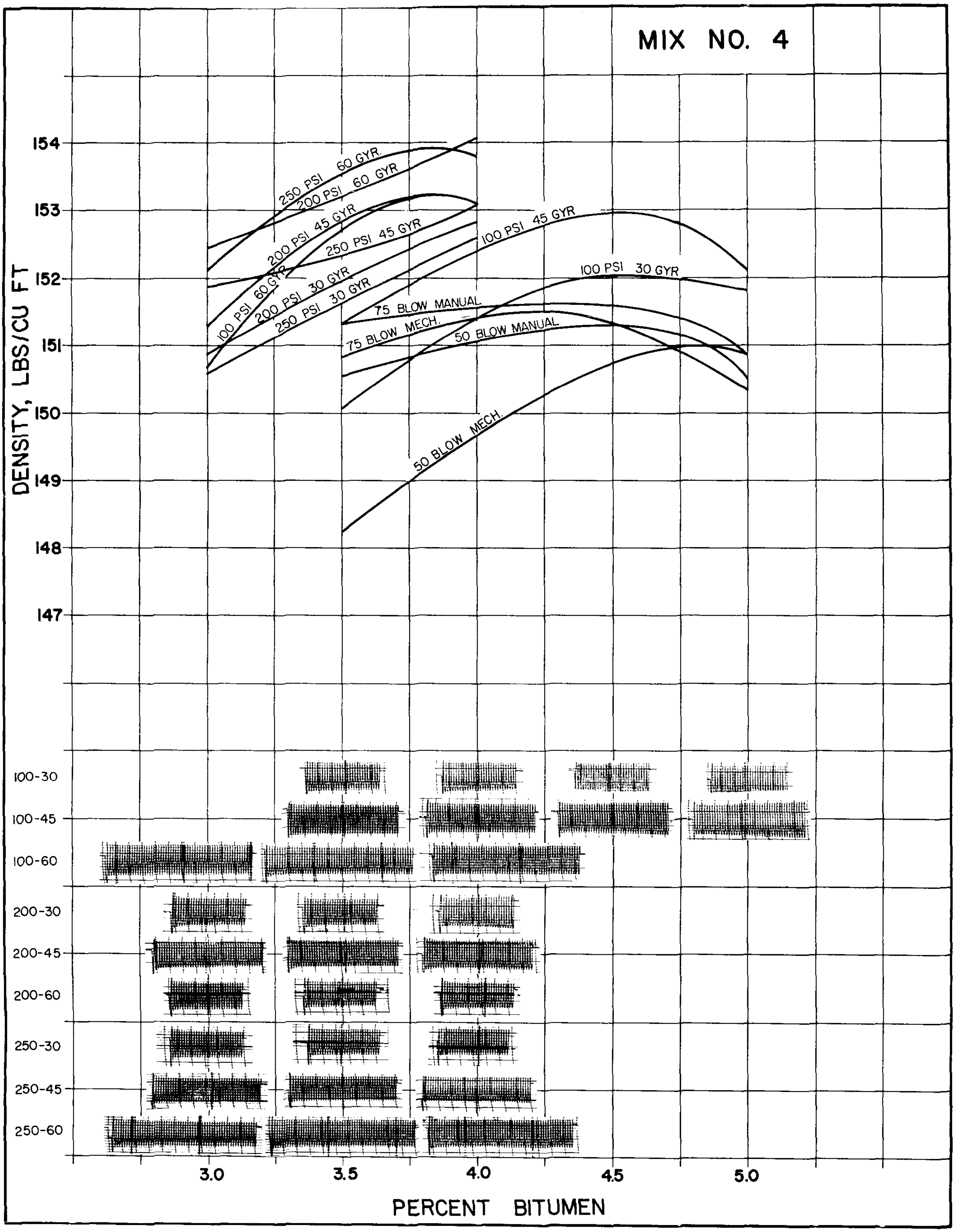


Figure 10 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for limestone Mix 4.

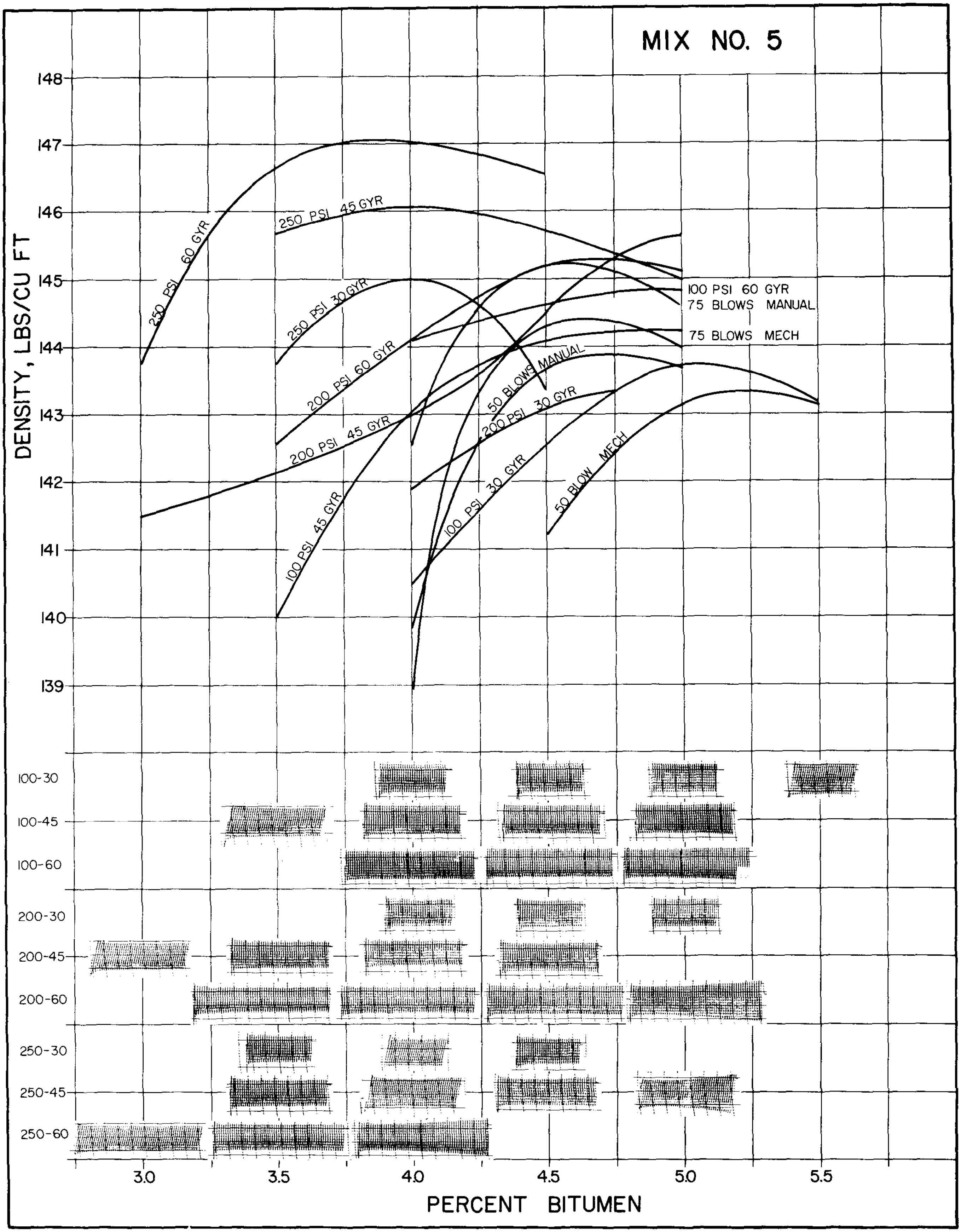
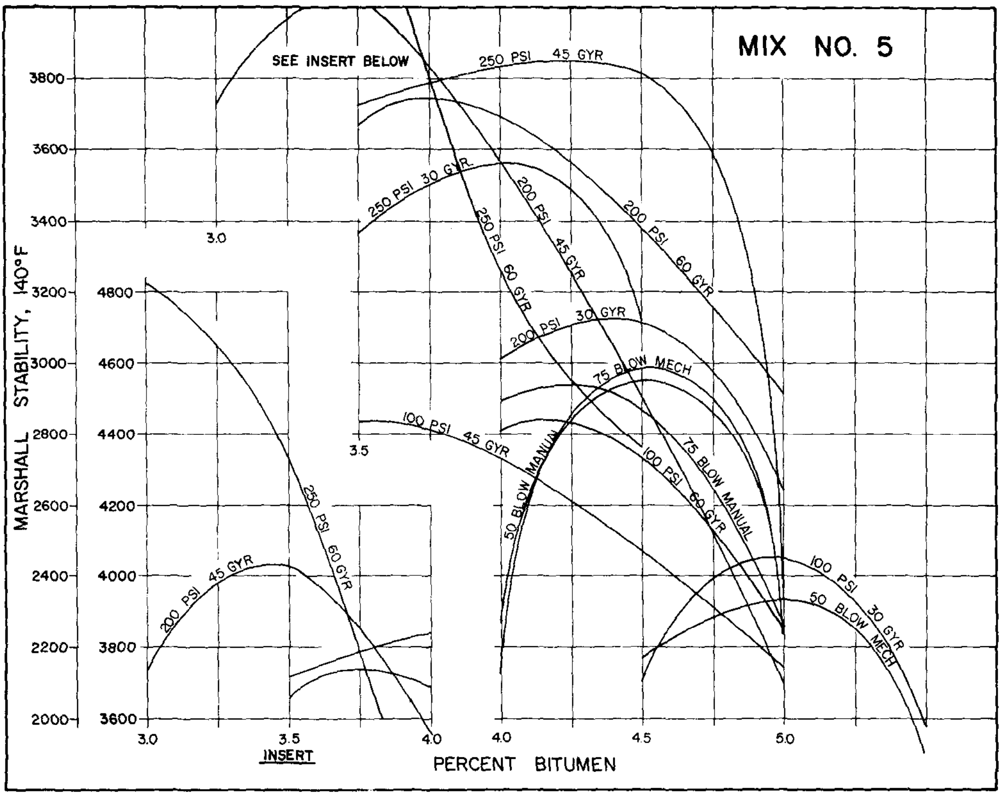


Figure 12 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for limestone Rock Asphalt Mix 5.



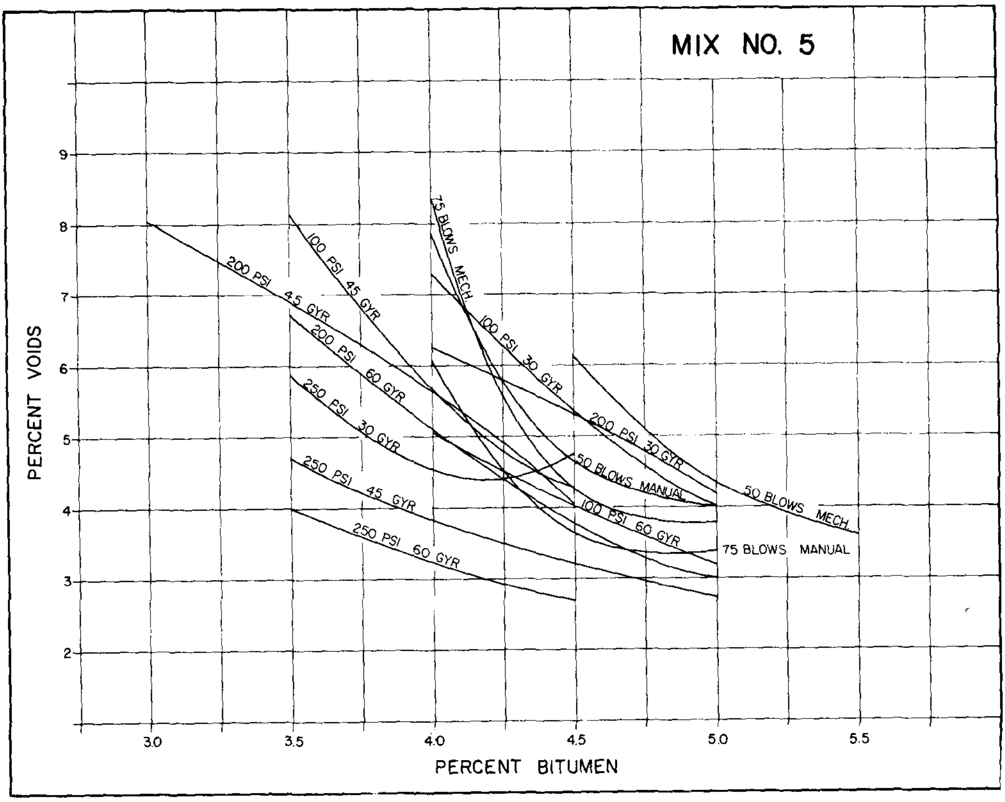


Figure 13 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for limestone Rock Asphalt Mix 5.

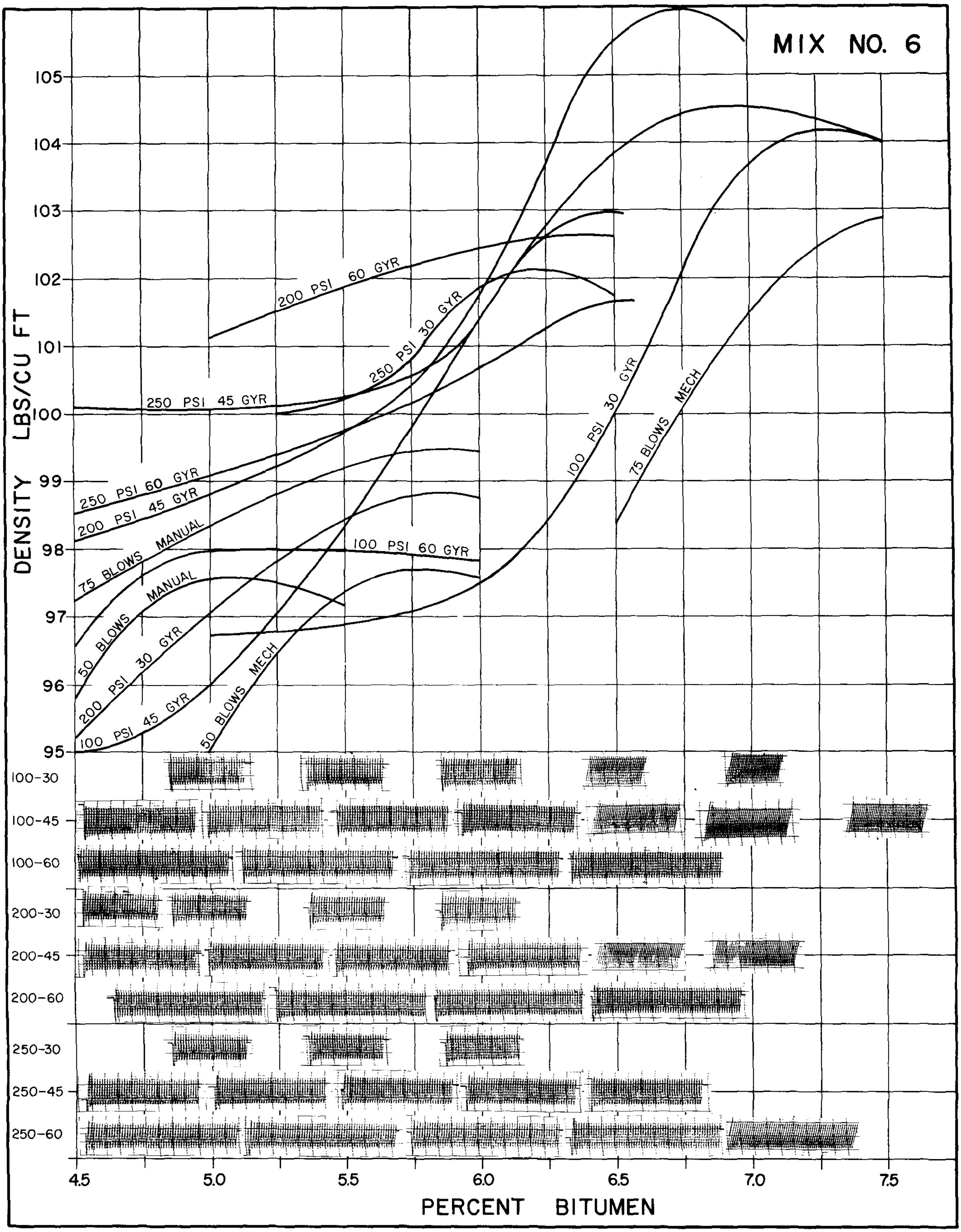
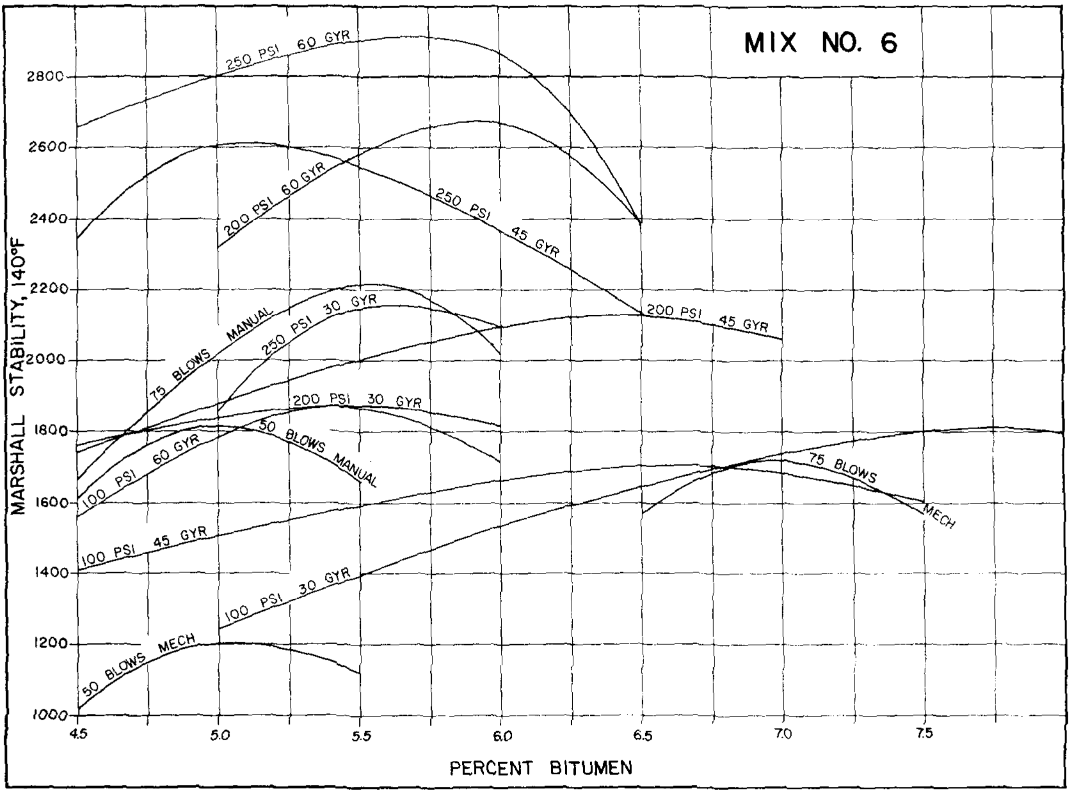


Figure 14 - Relationship of Density versus Percent Bitumen at various Compactive Efforts for expanded clay Mix 6.



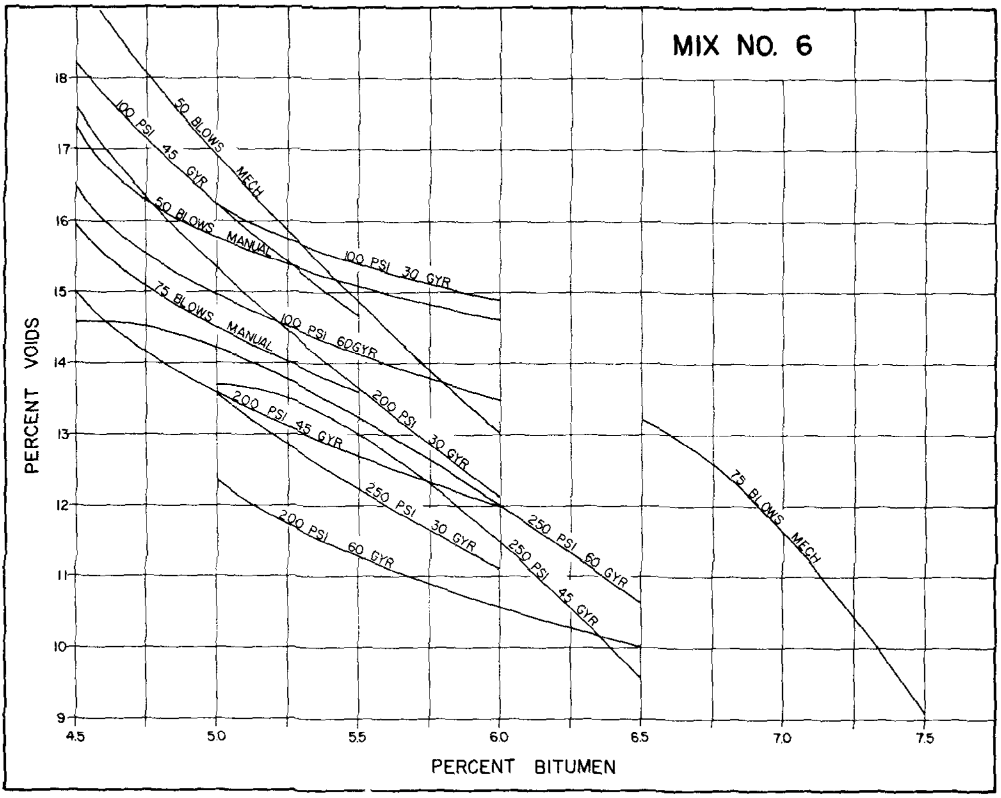


Figure 15 - Relationship of Marshall Stability and void content versus Percent Bitumen at various Compative Efforts for expanded clay Mix 6.

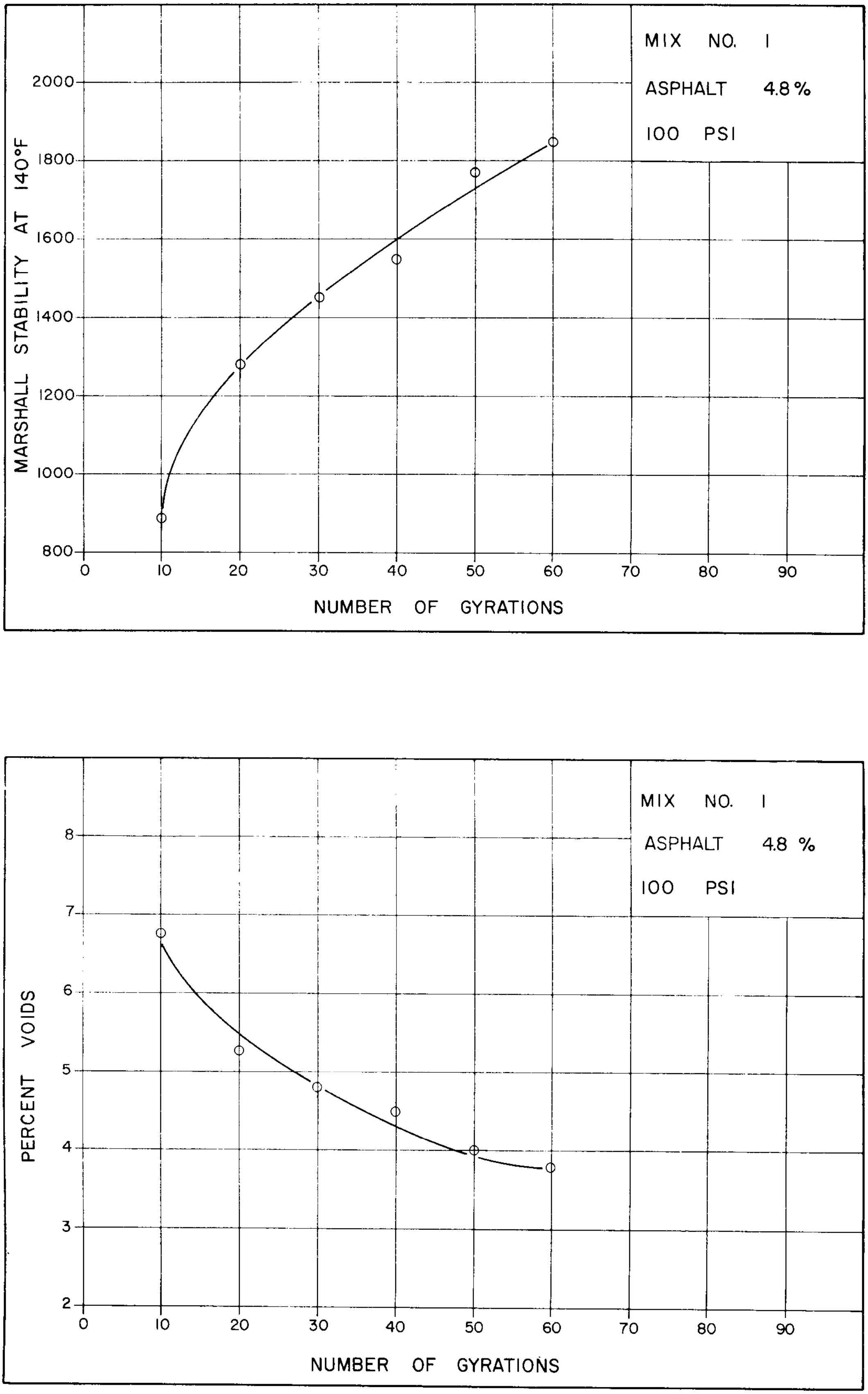
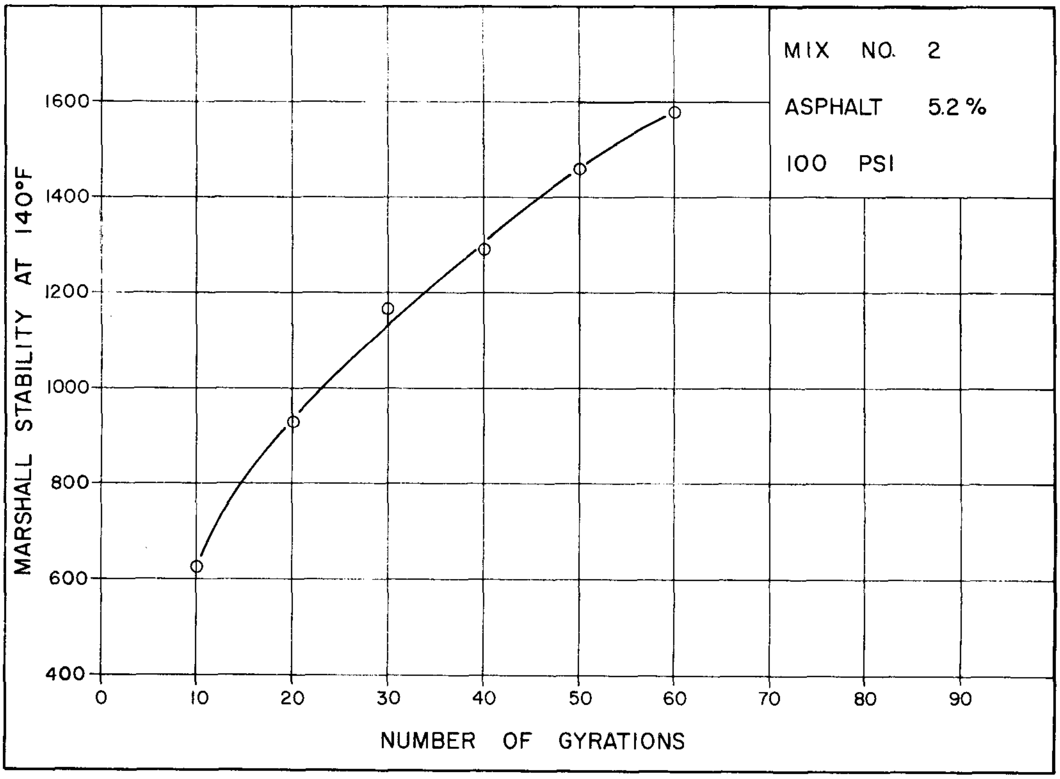


Figure 16 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 1.



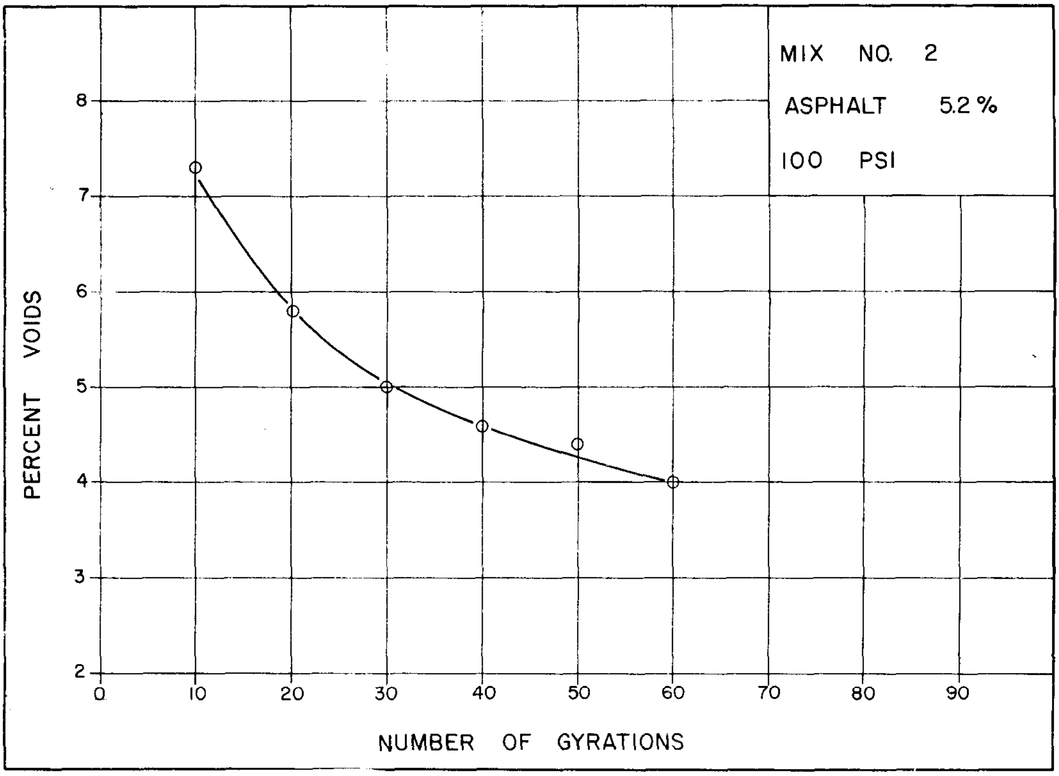
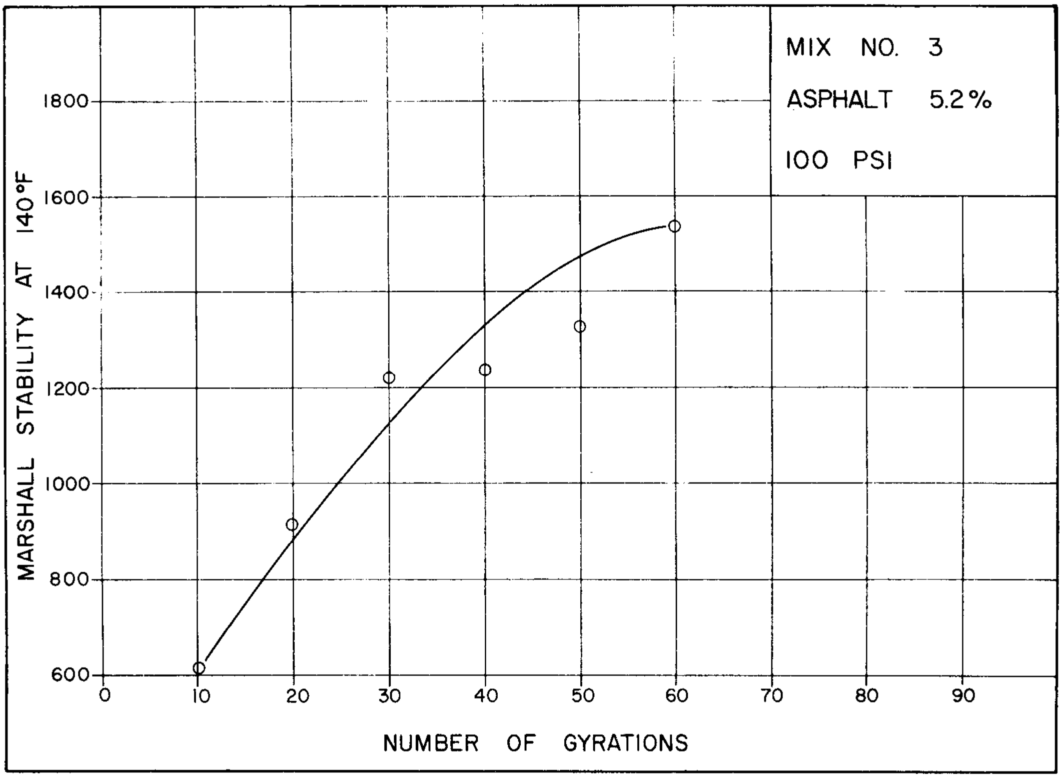


Figure 17 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 2.



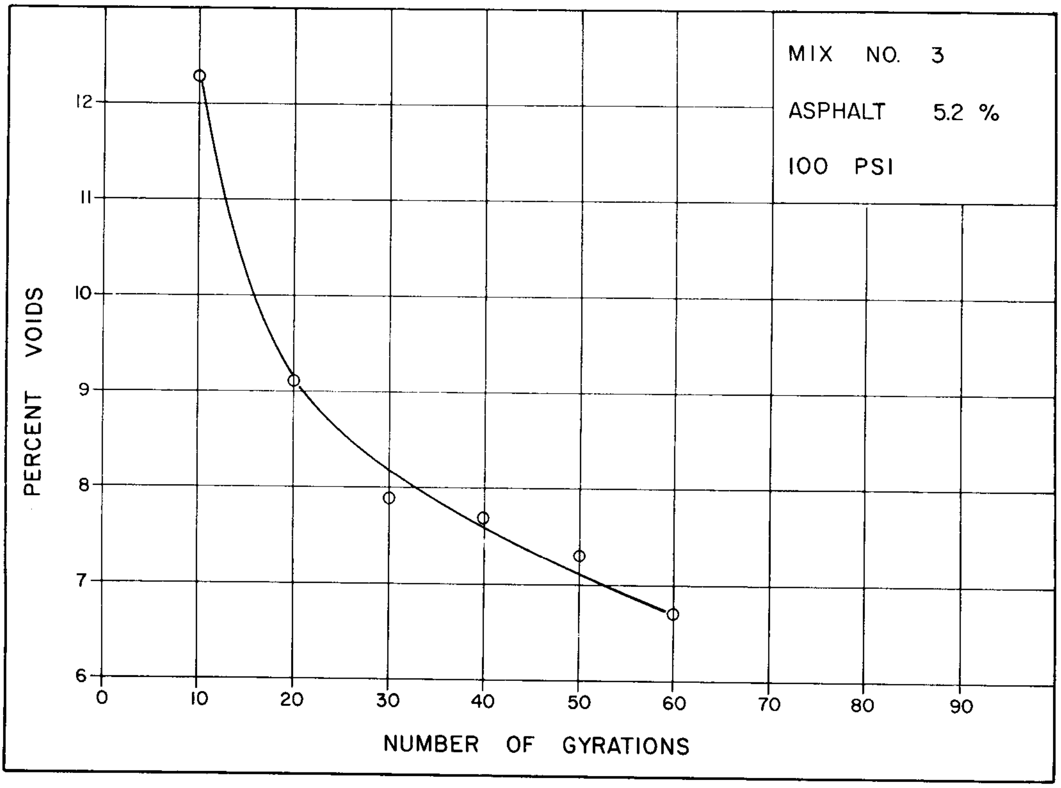
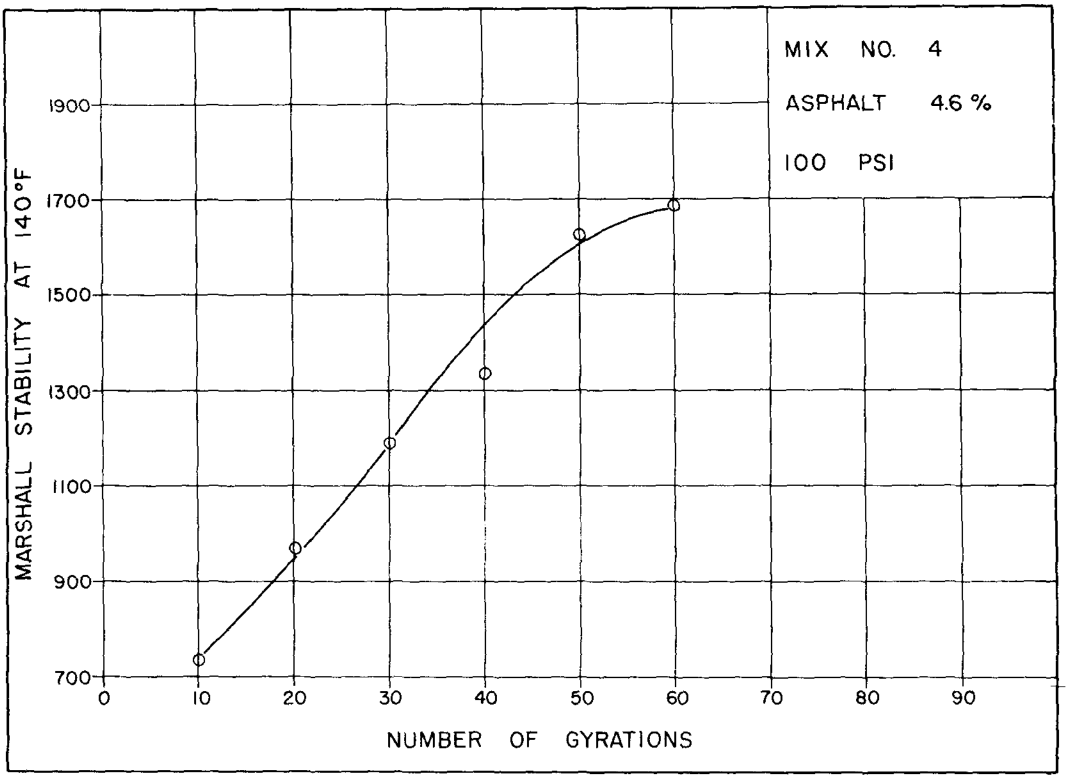


Figure 18 - Percent voids and Marshall stability versus Number of Gyrations for gravel Mix 3.



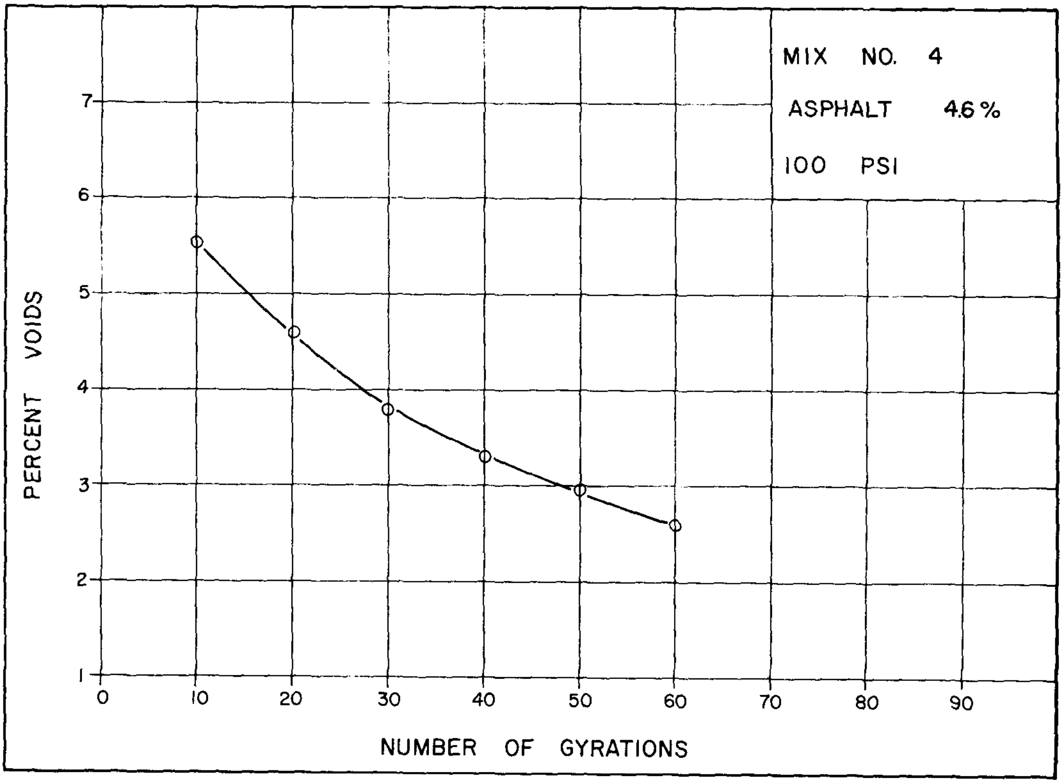
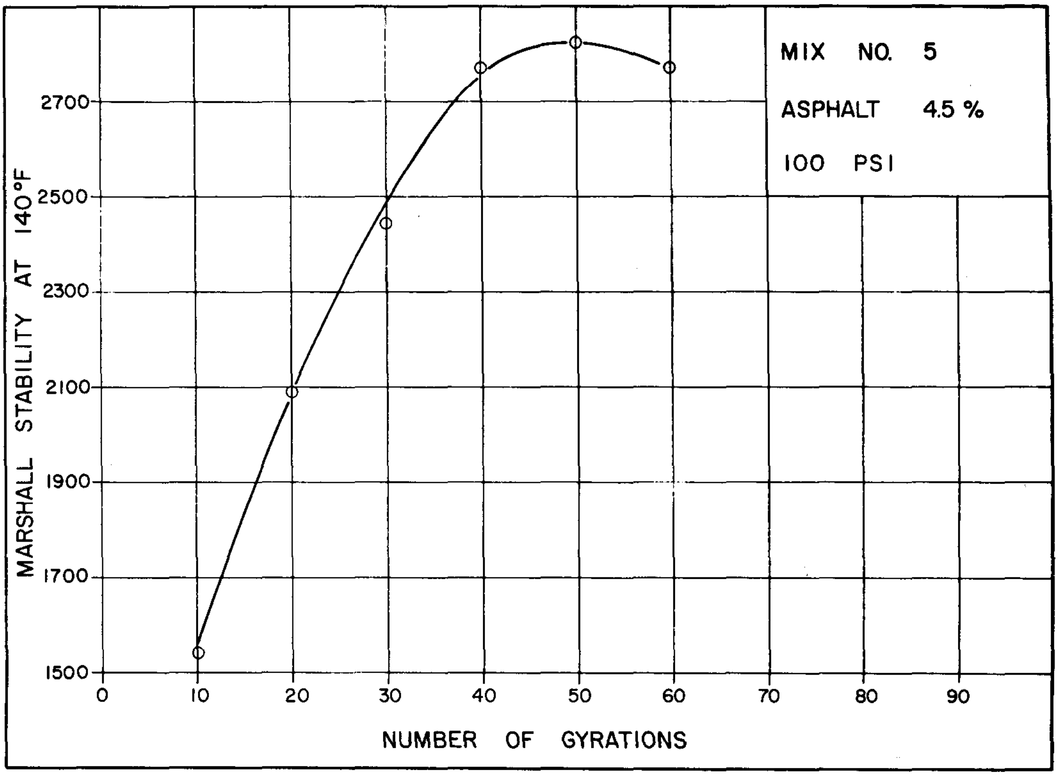


Figure 19 - Percent voids and Marshall stability versus Number of Gyrations for limestone Mix 4.



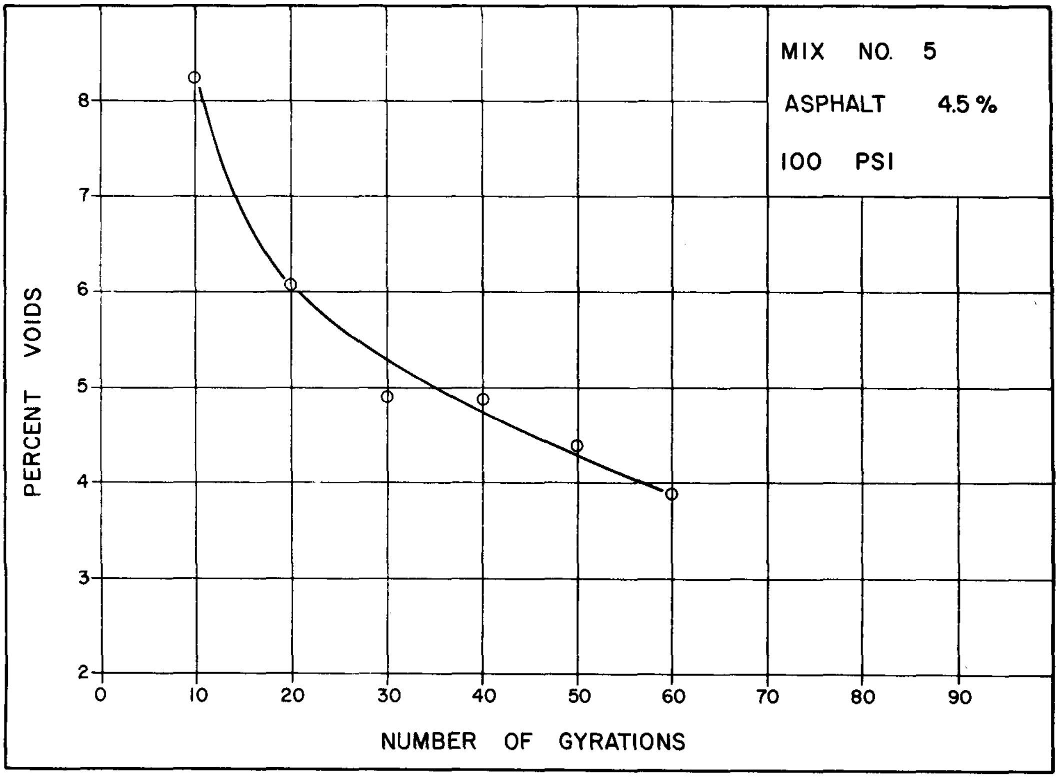
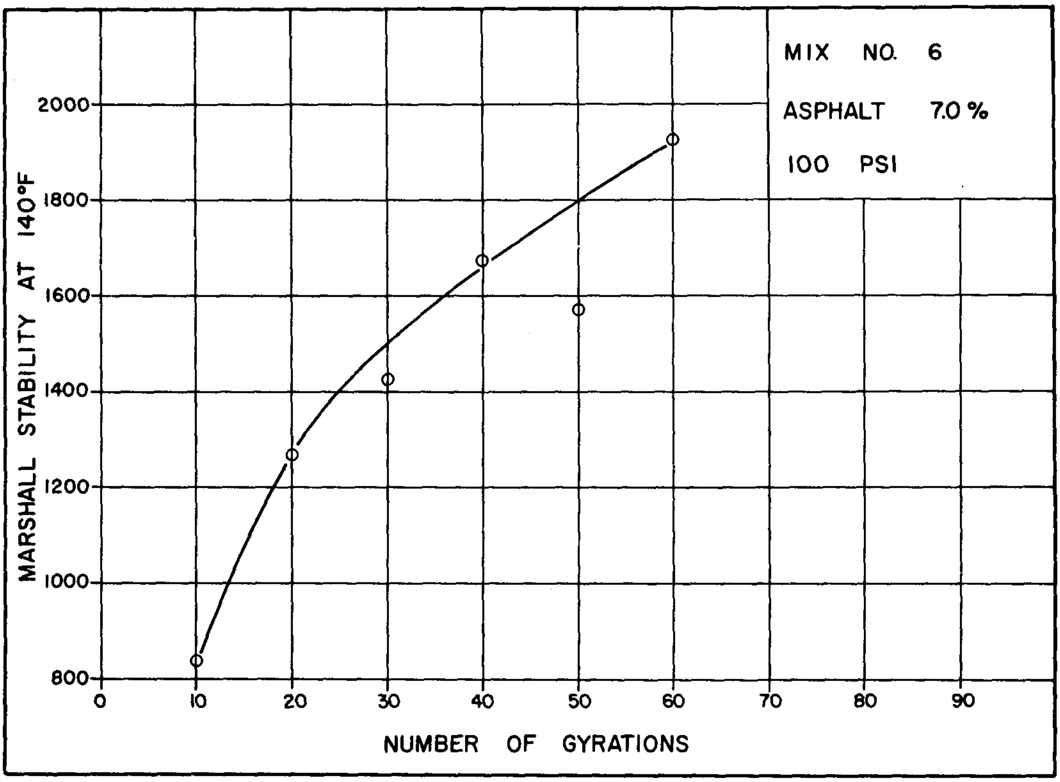


Figure 20 - Percent voids and Marshall stability versus Number of Gyrations for limestone rock asphalt Mix 5.



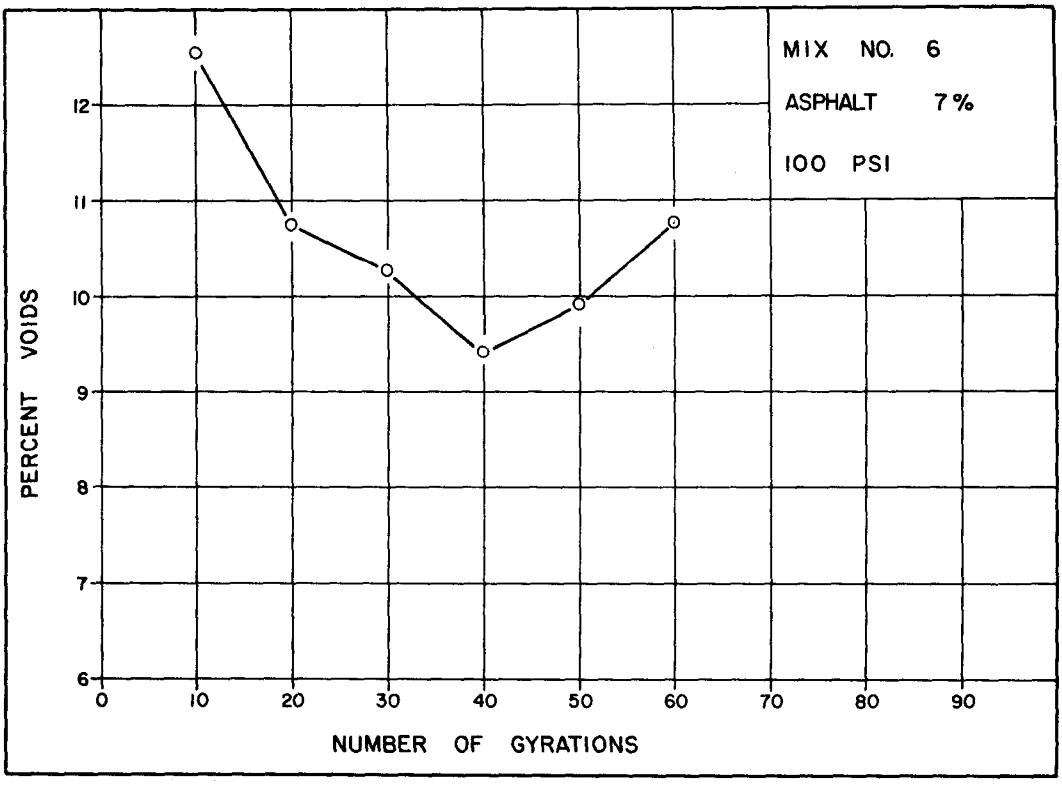


Figure 21 - Percent voids and Marshall stability versus Number of Gyrations for expanded clay Mix 6.

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3. Use of Expanded Clay Aggregate in Bituminous Construction. H.L. Lehmann and Verdi Adam, 1959.
4. Application of Marshall Method in Hot Mix Design. Verdi Adam, 1959.
5. Effect of Viscosity in Bituminous Construction. Verdi Adam, 1961.
6. Slab Breaking and Seating on Wet Subgrades with Pneumatic Roller. J.W.Lyon, Jr.,January, 1963.
7. Lightweight Aggregate Abrasion Study. Hollis B. Rushing, Research Project No. 61-7C, February, 1963.
8. Texas Triaxial R-Value Correlation. Harry L. Roland, Jr., Research Project No.61-1S, March, 1963.
9. Asphaltic Concrete Pavement Survey. S.C.Shah,Research Project No. 61-1B, April, 1963.
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12. Correlation of the Manual Compaction Hammer with Mechanical Hammers for the Marshall Method of Design for Asphaltic Concrete. P.J.Arena, Jr., Research Project No. 63-1B, September, 1964.
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