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FACTORS THAT AFFECT THE VOIDS IN THE MINERAL AGGREGATE IN HOT MIX ASPHALT

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The contents of this report reflect the views of authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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16. Abstract
The Colorado Department of Transportation (CDOT) will be specifying a minimum Voids in the Mineral Aggregate (VMA) for the 1993 construction season. The purpose of this report was to provide guidance and information for obtaining VMA.

101 of the mix designs performed by the CDOT during 1992 were analyzed to determine the most appropriate method for drawing the maximum density line. The Texas reference gradation line and the line drawn from the origin to the actual percent passing on the nominal maximum aggregate size provided the best correlation with measured VMA. Staying away from the maximum density line at the No. 30 sieve and the fourth largest sieve to retain material is advised.

In addition, 24 laboratory mix designs were prepared to examine the effect of varying four variables considered important in obtaining VMA: gradation, quantity of P200, size of P200, and fine aggregate angularity. The gradation provided the largest changes in VMA. The quantity of P200 and angularity also caused significant changes to VMA. The quantity of P200 made more substantial changes to the VMA of fine gradations than coarse gradations. The angularity of the fine aggregates affected the VMA of the coarse gradations more than the fine gradations. The size of the P200 had little effect on the VMA; however, although the sizes of P200 of the two materials used in the experiment were significantly different, the sizes were both fine.

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I. INTRODUCTION

Voids in the mineral aggregate (VMA) is a specification that controls the minimum asphalt content of a mixture to ensure good durability of hot mix asphalt (HMA) pavements. The VMA specification was developed by McLeod (1,2) and Lefebvre (3) in the late 1950s using the bulk specific gravity of the aggregate, the 75-blow Marshall design, and empirical observation of pavement performance.

The use of VMA has gained wide acceptance as a specification for HMA. Since the 1960s, the Asphalt Institute has recommended a VMA specification (4); and the specification is reported by Huber (5). The Federal Highway Administration also set forth guidance that VMA should be a mix design specification (6). Still in draft form, the Strategic Highway Research Program has recommended the use of VMA as a specified mix design property (7) when performance-related testing is not performed. All three entities recommended using the bulk specific gravity of the aggregate to calculate VMA.

The Colorado Department of Transportation (CDOT) has proposed a VMA mix design specification for the 1993 construction season. For the 1992 construction season, the VMA was calculated using the bulk specific gravity of the aggregates and reported for information. This allowed one year for contractors and CDOT personnel to learn which mixes had low VMA and to analyze factors that would increase VMA. Approximately two-thirds of all mixes tested for 1992 failed the proposed VMA specification.

The purpose of this report is to provide guidance in adjusting HMA to meet the VMA specification. The gradations of mixes used in 1992 are reported to provide guidance in using the maximum density line to develop mixes with VMA. Secondly, a laboratory study was performed to identify important properties which affect the VMA of mixes used in Colorado. The findings of this research are summarized in the conclusions.

II. ANALYSIS OF 1992 MIX DESIGNS

The 101 mix designs analyzed for this study were performed by the CDOT during the 1992 construction season. Each gradation was analyzed to determine its relationship to the maximum density line versus the measured VMA. It was hypothesized that the further the gradation was away from the maximum density line, the higher the VMA would be.

A plot of the gradation of aggregates in an HMA consists of the percent passing each sieve size plotted on an arithmetic Y axis and the sieve sizes, in microns, raised to the 0.45 power plotted on the X axis. The standard sieve sizes as defined in ASTM D 3515 were used to compare the maximum density line to the actual gradation. The standard sieve sizes used were: 2 in. (50 mm), 1.5 in. (37.5 mm), 1 in.(25.0 mm), 3/4 in. (19.0 mm), 1/2 in. (12.5 mm), 3/8 in. (9.5 mm), No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 um), No. 50 (300 um), No. 100 (150 um), and No. 200 (75 um).

<u>Maximum Density Lines.</u> Eight maximum density lines were used to analyze the data (Fig. 1). A maximum density line is defined by two points. Seven of the maximum density lines went through the origin; the second point was defined using the (X,Y) coordinates shown on Fig. 1. The definitions of the variables are listed below:

X = P100 = smallest sieve passing 100% of the aggregate,
X = P<90 = largest sieve retaining more than 10% of the aggregate,
X = P<90 + 1 = one sieve size larger than the first sieve to retain more than 10% of the aggregate **(Nominal Maximum Aggregate Size)**,
X = P<90 + 2 = Two sieve sizes larger than the first sieve to retain more than 10% of the aggregate **(Maximum Aggregate Size)**,
X = P100 - 1 = one sieve size smaller than the P100,

Y = 100% = 100% passing, and
Y = Actual = actual percent passing the sieve for the selected X coordinate.

When the maximum density line passed through the origin, the equation for the maximum density line was:

$$P = (Y / X^n) \times d^n \qquad \text{[Eqn. 1]}$$

where:
P = Maximum density line Y coordinate, percent passing the d sieve size,
X = Defined above, microns,
Y = Defined above, percent,
d = Sieve size opening, microns, and
n = exponent of 0.45 (8,9).

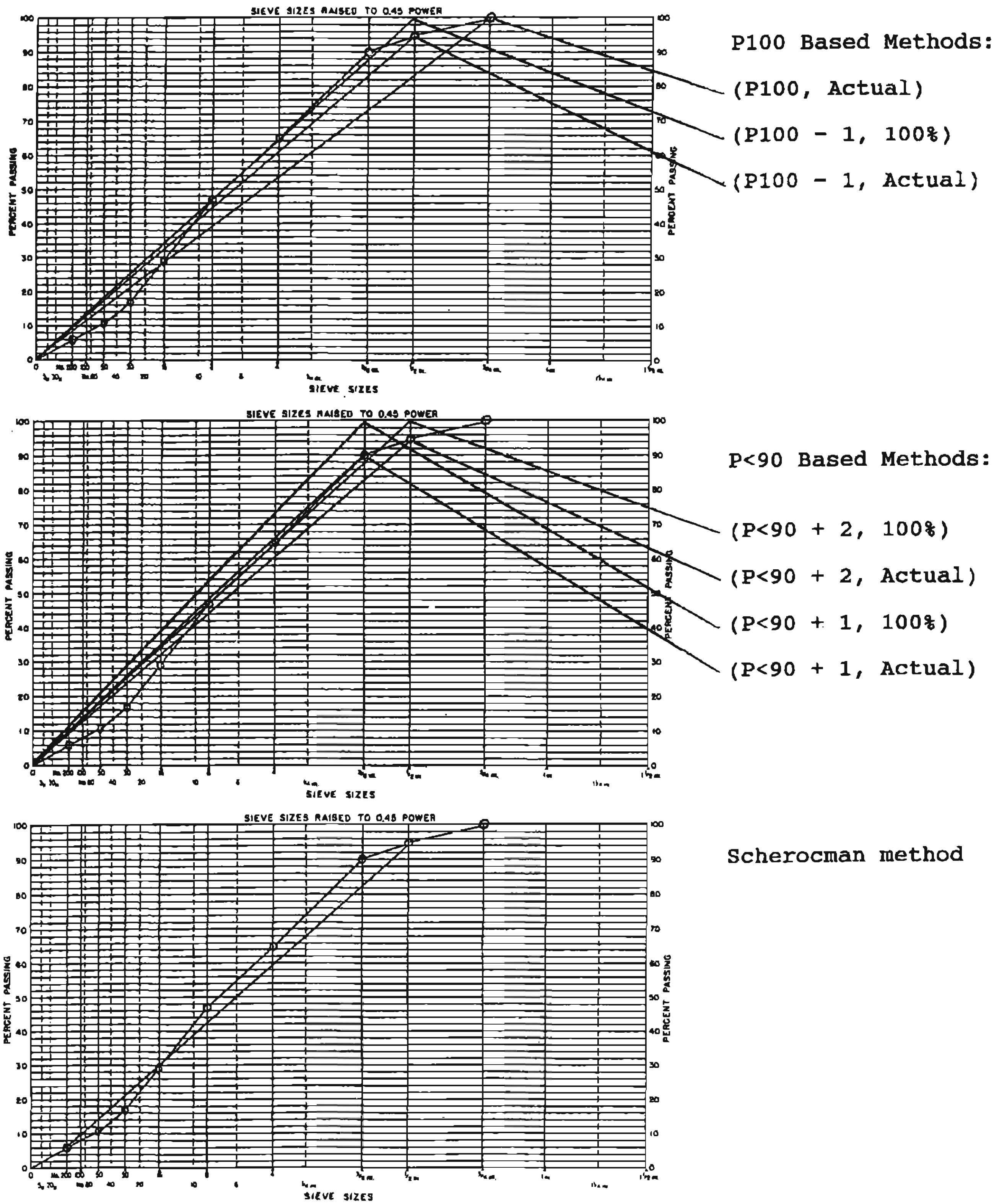
The eighth method analyzed was developed by Mr. Jim Scherocman, Consultant, and Dr. Thomas Kennedy, University of Texas at Austin, and commonly is referred to as the Texas reference gradation line. The Texas reference gradation line was drawn from the actual P200 to the actual percent passing the first sieve to retain any material. The equation used for the Texas reference gradation line was:

Figure 1

Gradation Study - Maximum Density Line Examples

P100 - The smallest screen size passing 100%
P<90 - The largest screen size passing less than 90%

(X, Y Coordinates)



$$P = \frac{(100 - P200)}{(Dn - 75n)} \times (dn - 75n) + P200 \qquad \text{[Eqn. 2]}$$

where:

D = Sieve size opening of the first sieve to retain any material, microns, and

P200 = percent passing the #200 sieve.

Both the distance and area between the maximum density line and the actual gradation were calculated as shown on Fig. 2. Measured VMA had a similar correlation to both the area and the distance methods of calculating the difference between the maximum density lines and the actual gradations. The distance method was used because it was simpler.

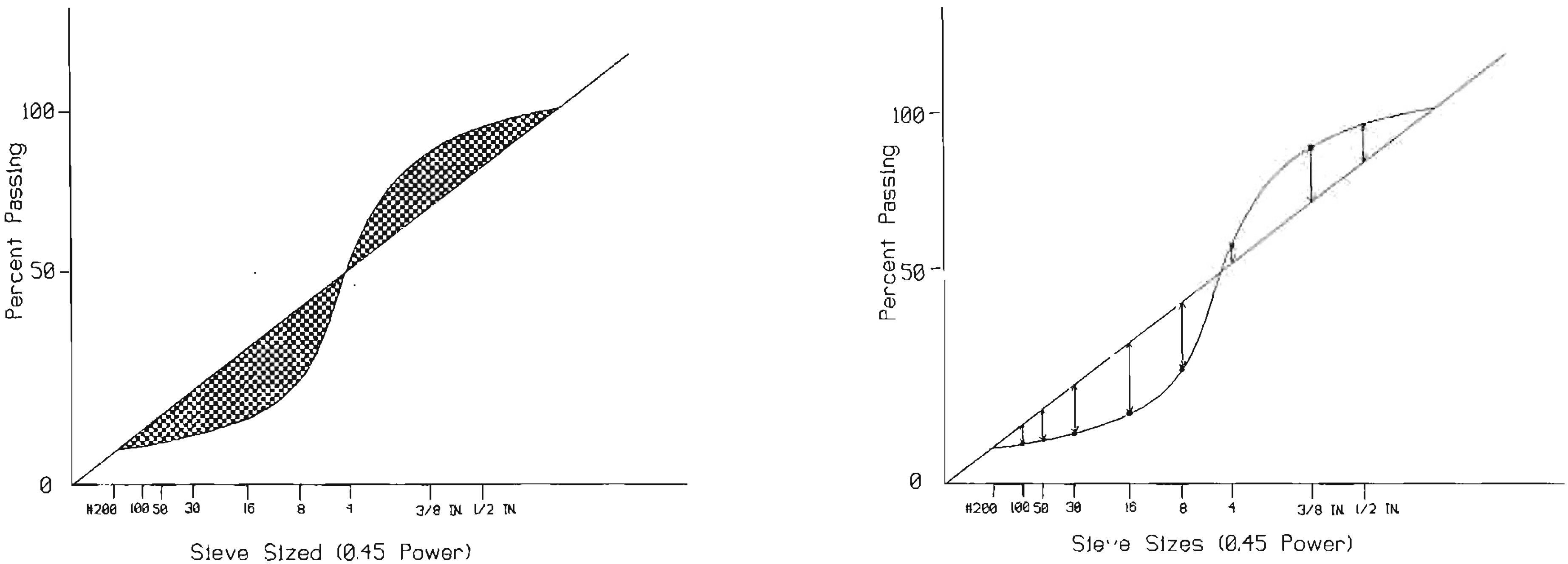
Adjustment for Nominal Size. Specifications recommended for VMA are a function of the nominal maximum aggregate size (2,5,6,7), so the effect of the nominal maximum aggregate size was investigated (Table 1). For the 1992 mix designs, the differences in the VMA values as related to the nominal maximum aggregate size were remarkably similar to the differences in VMA recommended by others (2,5,6,7). When the data was analyzed as one large data set, the VMA values were normalized to account for the differences in VMA apparently caused by the nominal maximum aggregate size.

Table 1. Difference Between Average VMA Values as a Function of Nominal Maximum Aggregate Size.

Difference in Nominal Maximum Aggregate Size	Average Difference in Measured VMA
3/8" to 1/2"	0.89
1/2" to 3/4"	1.16
3/4" to 1"	0.64
1" to 1-1/2"	0.83

Figure 2

Methods Used For Comparing Gradation and Maximum Density Lines



Area Method

Distance Method

0.45 Power Gradation Curve. The analyses were performed using sieve sizes raised to several different powers. Since the best correlations occurred when the sieve sizes were raised to the 0.45 power, the 0.45 power gradation chart was used.

Results

Simple Analysis. A total of 390 regression analyses were performed using 6 different maximum density lines, 5 different nominal maximum aggregate sizes, and 13 different ranges of bracketed sieve sizes. The maximum density lines used were the Texas reference gradation line and five maximum density lines which extended from the origin to the (X,Y) coordinates of (P100, 100%), (P<90+1, 100%), (P<90+1, Actual), (P<90+2, 100%), and (P<90+2, Actual). The nominal maximum aggregate sizes used were 1 in. (25.0 mm), 3/4 in. (19.0 mm), 1/2 in. (12.5 mm), 3/8 in. (9.5 mm), and all sizes combined. The distance between the maximum density line and the actual gradation was calculated and summed for ranges of sieve sizes, for example, bracketing from the No. 8 to the No. 30 sieve size.

The most promising coefficients of correlation, r, are shown on Table 2. The best correlation with VMA was to the distance between the actual gradation and the maximum density line drawn using the Texas reference gradation line summed between the No. 4 and No. 50 sieve sizes. The differences from the maximum density line drawn to the nominal maximum aggregate size correlated well with VMA for all of the aggregate sizes combined. The strongest apparent contributions to the correlation between VMA and the distance between the actual gradation and the maximum density line were from the No. 16 sieve size and smaller.

Table 2. Correlation Coefficients, r, for VMA versus the Distance from the Actual Gradation to the Maximum Density Line.

		Bracketed Ranges of Sieve Sizes			
Maximum Density Line (X,Y)	Nominal Maximum Agg. Size	All Sieves	No. 4 to No. 50 Sieves	No. 16 to No. 200 Sieves	No. 30 to No. 200 Sieves
Maximum, Actual	19.0 mm 12.5	0.32 0.46	0.36 0.31	0.48 0.32	0.55 0.24
Maximum, P100	19.0 12.5	0.32 0.45	0.36 0.31	0.48 0.32	0.55 0.24
Nominal, Actual	19.0 12.5	0.38 0.11	0.44 0.14	0.43 0.21	0.39 0.21
Nominal, P100	19.0 12.5	0.38 0.21	0.43 0.11	0.43 0.02	0.39 0.06
P100, Actual	19.0 12.5	0.38 0.03	0.44 0.18	0.43 0.35	0.39 0.40
Texas	19.0 12.5	0.46 0.13	0.44 0.36	0.42 0.26	0.47 0.14

Complex Analyses. To determine if the method of adding the differences at many sieve sizes together was masking significant contributions to VMA by individual sieve sizes, more complex methods were attempted. All gradations were treated as one large data set and the VMA values were normalized to account for the nominal maximum aggregate size. The regression analyses were performed to correlate the VMA to the absolute differences between the actual gradation and the eight different maximum density lines (Fig. 1). The six smallest sieve sizes and the 6 largest sieve sizes below the first sieve to retain material (P100-1) were examined.

Using the Texas reference gradation line, a combination of two sieve sizes provided a high correlation to VMA: the No. 100 sieve and the fourth sieve smaller than the largest sieve passing 100% of the material (P100-4). The fourth sieve smaller than the P100 sieve size typically was the No. 4 sieve or the 3/8 in. (9.5 mm) sieve. Using the nominal maximum aggregate size to draw the maximum density line, the two sieve sizes where the differences correlated most highly with VMA were the No. 30 sieve and the fourth sieve smaller than the P100.

The further the gradation was away from the maximum density line, the higher the VMA tended to be. The best correlation was obtained using the Texas reference gradation line and combining the effects of the No. 100 sieve and the fourth sieve smaller than P100. The second best correlation was obtained using the maximum density line drawn from the origin to the actual percent passing the nominal maximum aggregate sieve size: an (X,Y) coordinate of (P<90+1, Actual). Using this method, either the No. 30 sieve or the fourth sieve passing the P100 gave equivalent correlations. The correlation coefficients for the two best methods were:

Maximum Density Line	Correlation Coefficient, r
Texas reference gradation line:	0.65
Actual percent passing the nominal maximum aggregate size:	0.60

Numerous other methods were attempted to improve the method of predicting the VMA using the gradation. The most promising method evaluated consisted of dividing the difference at a sieve by the distance from the center of the gradation. This would indicate that a difference at the extreme ends of a gradation has more effect on an HMA with a smaller maximum size and less effect on an HMA with a larger maximum size aggregate. The results still indicate, however, that the effect of increasing the distance from the gradation to the maximum density line increases the VMA.

Qualifying Statements. In comparing the CDOT data relative to other data bases, three qualifying statements need to be made about the data being analyzed: 1) the overall distance of the actual gradation from the maximum density line, 2) the age of the data contained in the data bases, and 3) the differences between the nominal maximum aggregate sizes and aggregates used to compile the data in the various data bases.

The coefficients of correlation, r, reported for the analyses in this study were very low. It should be noted that the gradations analyzed in this study had to be produced within the 1992 CDOT specified Master Range. The 1992 CDOT Master Range was very narrow but was widened significantly for 1993.

The ranges of the distances (sum of the absolute values of the percent passing) from the maximum density line to the actual gradation from data bases analyzed by Huber and Shuler (4) are shown on Table 3. Correlations were poor when the range of distances in the various data bases were small and were excellent correlations when the ranges of distances were larger.

Table 3. Relationship of the Correlation Between the Distance from the Maximum Density Line to the Actual Gradation for Various Ranges of Distances.

	Distance of Actual Gradation From the Maximum Density Line Drawn to:			
	Maximum Size		Nominal Maximum Size	
Data Base	Range	r2	Range	r2
1992 CDOT	15- 80	0.122	15- 70	0.144
D'Angelo (13)	30- 70	0.208	10- 35	0.001
Goode (9)	40-120	0.915	20- 50	0.004
Lefebvre (3)	50-150	0.815	30-100	0.232

It is possible to conclude that when gradations follow the maximum density line closely (for example, when the distance from the maximum density line drawn to the maximum aggregate size was less than 70 or 80), factors other than the gradation are critical in controlling VMA. When gradations are allowed to move away from the maximum density line (for example, when the distance from the maximum density line drawn to the maximum aggregate size was greater than 100), the gradation has a significant influence on VMA.

It should also be noted that data gathered from the 1990s (1992 CDOT and Ref. 13) indicated that gradations commonly were closer to the maximum density line. Data gathered from the 1950s (3,9) indicated gradations commonly were further from the maximum density line. Apparently, changes have occurred during the past 35 years to promote the production of aggregate gradations closer to the maximum density line.

The excellent correlations in the Goode and Lufsey data (9) were from mixes produced using only one aggregate source. The Lefebvre data (3) was generated in the laboratory using only two aggregate sources. As aggregate sources and particle shapes change, the correlation would be expected to deteriorate. The CDOT and D'Angelo (13) data bases contain mixes produced from a wide variety of aggregate sources and a correspondingly lower correlations.

Finally, the maximum density line drawn to the maximum aggregate size provided the best correlations for the smaller sized aggregates; all data in Ref. 3 and 9 were predominately 1/2 in. (12.5 mm) nominal maximum aggregate size. The 3/8 in. (9.5 mm) nominal maximum aggregate size in the 1992 CDOT data base consistently had significantly higher correlations than the larger 1/2 in. (12.5 mm) and 3/4 in. (19.0 mm) nominal maximum aggregate sizes. Before a definitive conclusion can be made to promote the best method for drawing the maximum density line, a data base with several different nominal maximum aggregate sizes should be investigated.

<u>Summary.</u> The gradation is important in obtaining VMA. By increasing the distance between the gradation and the maximum density line, a mix gradation can be developed which has a better chance of possessing VMA than if the maximum density line was not used. The smaller sieve sizes consistently had the most effect on VMA by all methods used. Based solely on distances from the maximum density line to gradations from the No. 30 to the No. 200 sieve sizes, the maximum density line drawn to the nominal maximum aggregate size gave the best correlation for this data. The gradations of the mixes used for this analysis with the maximum density line drawn to the actual percent

passing of the nominal maximum sieve size are shown in Appendix A. The gradations are in order of lowest to highest VMA corrected for the nominal maximum aggregate size.

Based on the relatively low regression coefficients, other factors besides the gradation are important to obtain VMA. An attempt to quantify these other factors was made in phase 2 of this study. This analysis has shown that the only way to be certain of the VMA of an HMA is to produce a sample and perform the appropriate tests and calculations.

III. LABORATORY EXPERIMENT

An experiment was performed to determine the effect on VMA by changing several properties which were considered likely to affect VMA. The variables examined in the study included the gradation, the size of material passing the No. 200 sieve (P200), the quantity of P200, and the angularity of the material passing the No. 4 sieve.

Materials Used

Aggregate Selection. Two angularities of aggregate were used. Crushed aggregate was obtained from the Specification Aggregate Quarry, a granite source in Golden, Colorado. 100% of the crushed coarse aggregate had two or more fractured faces. Natural material was from the Monk Pit adjacent to the Big Sandy Creek near Limon, Colorado. It contained no fractured faces. The properties of the aggregates are shown on Table 4.

Asphalt Cement Selection. One asphalt cement was used for the entire study. The asphalt cement was an AC-10 grade obtained from the Conoco refinery in Commerce City, Colorado. The properties of the asphalt cement are shown on Table 5. The mixing and compacting temperatures were selected using equiviscous temperatures.

Table 4. Aggregate Properties.

Aggregate / Size	Bulk S.G.	Water Absorp.
Specification Agg.		
1/2"	2.66	0.9%
#4	2.67	0.5
P4	2.68	1.4
P200	2.83	-
Monk Pit		
P4	2.56	0.9
P200	2.72	-
Hydrated Lime	2.38	-

Table 5. Asphalt Cement Properties.

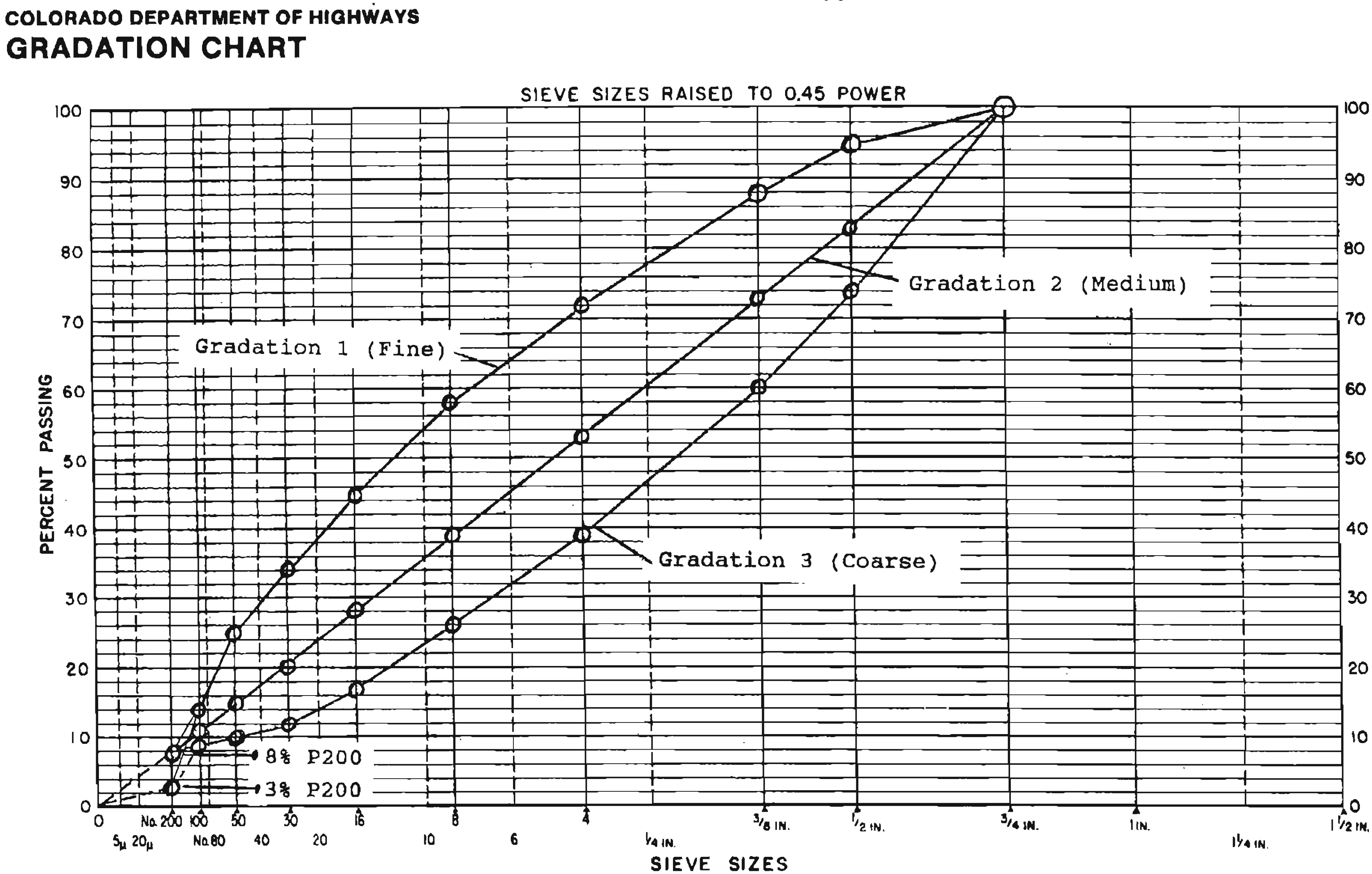
Test	Result
Viscosity (60oC)	1020 poises
Viscosity (135oC)	384 cSt
Penetration (25oC)	109 dmm
Softening Point	51 oC
Specific Gravity	1.029

Variables Investigated

Gradation. The mix examined was a 3/4 in. (19.0 mm) top-size gradation. Three gradations (fine, coarse, and straight) were used, as shown on the gradation chart, with sieve sizes raised to the 0.45 power (Fig. 3). The fine gradation is the finest gradation allowed by the CDOT master range. The coarse gradation is 4% to 6% coarser than allowed by the CDOT master range.

Figure 3

Laboratory Experiment - Aggregate Gradations



Three Gradations and Two Levels of -200 Material
Evaluated in the VMA Study

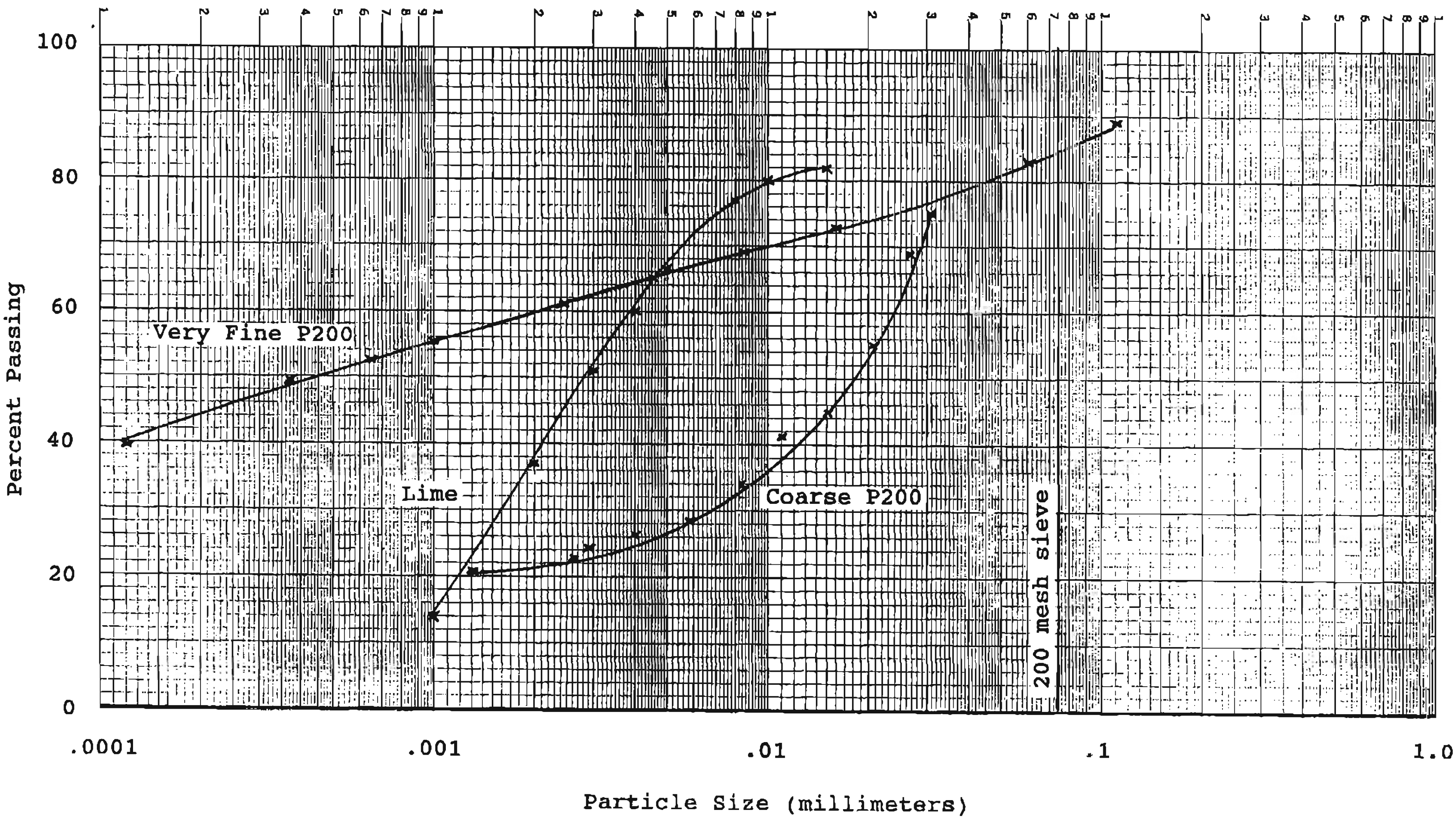
P200 Size and Quantity. Two sizes of P200 material were used in the study. One was selected from the quarried granite source and the other was selected from the Monk natural sands. Hydrated lime was used at 1% by weight of the aggregate for all mixes. The hydrometer analysis (ASTM D 422) results for each P200 material are shown on Fig. 4. Sodium hexametaphosphate was used as a dispersing agent. The coarse P200 had 55% passing the 20 micron size; the fine P200 had 75% passing the 20 micron size. It should be noted that both types of P200 were fine, but one was finer than the other.

Two quantities of P200 were selected: 3% and 8%. These values were typical of those observed through the 1992 construction season and represented the maximum range allowed by the CDOT specifications for project produced material.

Fine Aggregate Angularity. The National Aggregate Association's (NAA) test, Method A, was used to determine the particle shape and texture of the fine aggregates or sands. The results were reported as the uncompacted air void content. Based on comparative studies with natural and manufactured sands by Kandhal (10), and Mogawer and Stuart (11), an uncompacted air void content of 44.5% or 43.5%, respectively, could be used to distinguish between crushed and natural sands. Typical angularities of material in Pennsylvania are shown on Fig. 5 (10). The uncompacted air void content of the quarried material was 49.4%, and the natural sands were 41.6%. The difference between 41.6% and 49.4% represents a tremendous difference in the particle shape and texture of the two fine aggregates.

Figure 4

Laboratory Experiment - P200 Particle Size Distributions

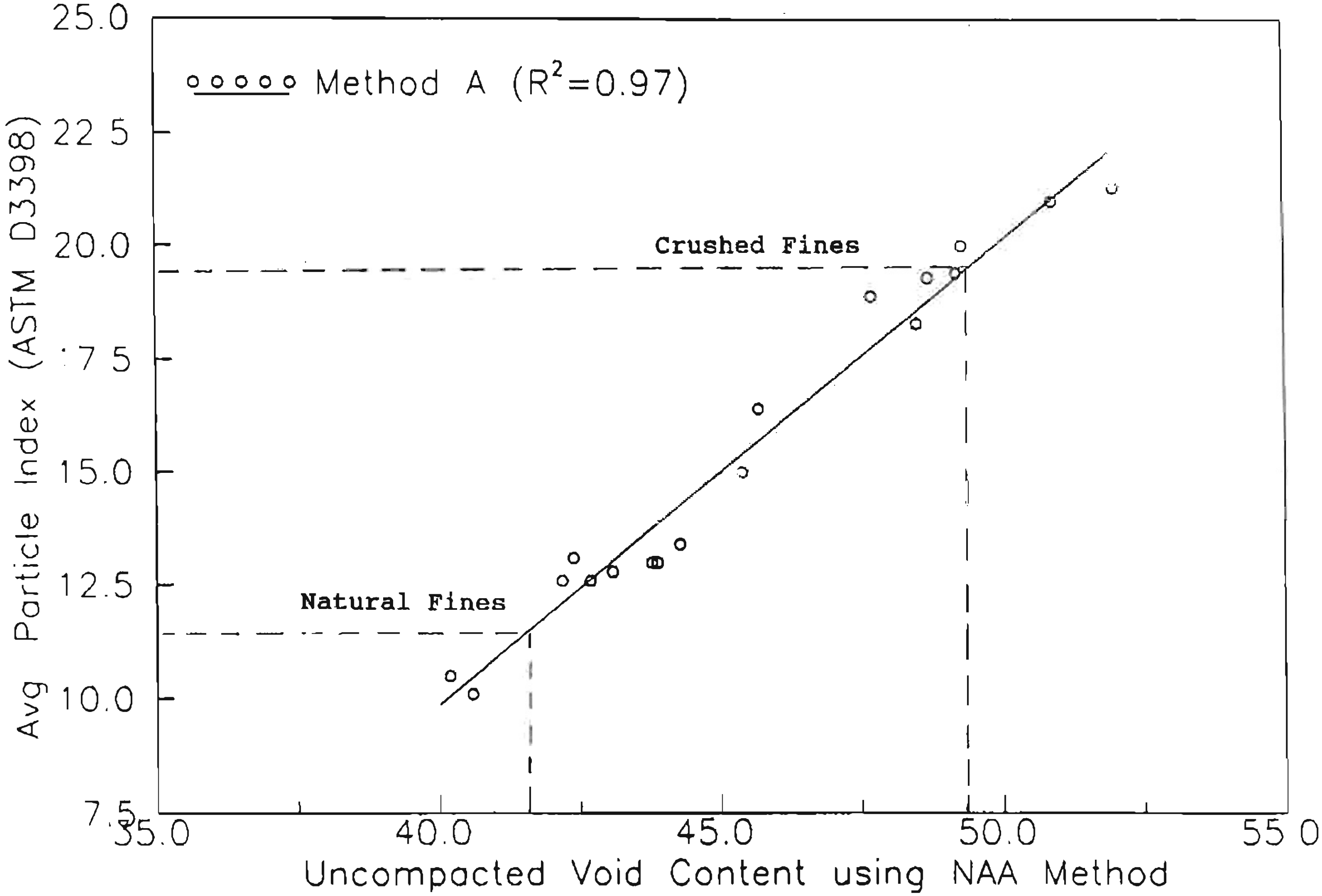


Hydrometer Results: Very Fine P200, Coarse P200 and Lime

Figure 5

Laboratory Experiment - Angularity of Fine Aggregates

Kandhal, et. al.



Average Particle Index using ASTM D3398 versus Uncompacted Void Contents using NAA's Method A

Mix Design Methodology

A total of 24 mix designs were performed which included all possible combinations of 3 gradations, 2 types of P200, 2 quantities of P200, and 2 levels of aggregate angularity. A full parametric study was performed.

Each aggregate was split into its individual standard sieve sizes as defined by ASTM D 3515 and stockpiled. Each size of aggregate was then washed and oven-dried prior to use. To account for the slight amount of over-sized and under-sized material in each stockpile, the gradation of each stockpile was measured and the results were used to set up the mixes.

The mix designs were performed using the Texas gyratory compactor (ASTM D 4013). A study performed by Brown (12) indicated that the laboratory compactive effort of the Texas gyratory compactor is slightly greater than a 75-blow Marshall. Four asphalt contents were used for each mix design and 3 samples were compacted at each asphalt content. A total of 288 samples were compacted for this study and 24 maximum specific gravities (AASHTO T 209) were performed. Hveem stabilometer testing (AASHTO T 246) was performed on each of the compacted samples.

Results

Data Extremes. The VMA obtained from the 24 mix designs made for the laboratory experiment provided a very wide range of values. Selected at 4.0% air voids, optimum asphalt contents (AC) ranged from 4.2% to 7.0%, and the corresponding VMA ranged from 12.5 to 18.1 percent. The data is summarized on Table 6.

The variables hypothesized to produce the highest and lowest VMA were correctly projected with the exception of the P200 size material for the lowest VMA values. It should be noted that both types of P200 were fine, and the changes in VMA values from the two P200 sizes were negligible. It is still speculated that a coarser P200 than the coarse P200 used in this study would have a greater effect on the range of the results.

Table 6. Extreme Ranges of VMA and Asphalt Content at 4.0% Air Voids.

Property	Highest Values	Lowest Values
VMA (%) AC (%)	18.1 7.0	12.5 4.2
Variables:	Fine Gradation 3% P200 100% Crushed Coarse P200	Coarse Gradation 8% P200 20% Natural Coarse P200

<u>**Effect of Component Variables on VMA.**</u> Results from all 24 mix designs at 4% air voids are shown on Table 7. The average effect on VMA of each component variable for all mixes is shown on Table 8.

When the P200 size was changed from coarse to fine, the resulting VMA increased very slightly. Although this was the opposite effect from that expected, it was hypothesized that the small change occurred because both P200 sizes were fine.

When the gradation was changed from the straight line to the coarse gradation, the resulting VMA decreased. This was not thought to be caused by testing variability since all straight gradations had higher VMA than the

Table 7
Test Results from Laboratory Experiment

			100% Crushed Aggregate				80% Crushed and 20% Natural Aggregate			
Gradation	Percent P200	Size of P200	Design Number	VMA @ 4% Voids	A.C. Conte @ 4% Void	Stability @ 4% Voids	Design Number	VMA @ 4% Voids	A.C. Conte @ 4% Void	Stability @ 4% Voids
Fine	3	Fine	1	17.9	6.8	50	13	17.7	6.6	35
Fine	3	Coarse	3	18.1	7.0	46	15	17.5	6.5	33
Fine	8	Fine	2	16.9	6.0	44	14	16.7	6	39
Fine	8	Coarse	4	15.7	5.7	48	16	15.7	5.6	38
Straight	3	Fine	5	14	4.9	53	17	13.5	4.7	43
Straight	3	Coarse	7	15.1	5.3	49	19	13.1	4.5	42
Straight	8	Fine	6	14	4.7	43	18	13.1	4.3	42
Straight	8	Coarse	8	13.8	4.6	51	20	13	4.4	40
Coarse	3	Fine	9	13.9	4.8	42	21	12.6	4.3	42
Coarse	3	Coarse	11	13.8	4.6	49	23	12.6	4.2	41
Coarse	8	Fine	10	13.3	4.3	44	22	12.7	4.2	42
Coarse	8	Coarse	12	13.2	4.1	46	24	12.5	4.2	38

corresponding coarse gradations. However, it should be emphasized that only one coarse gradation was examined in this experiment. In Colorado's experience, it has been very difficult to obtain VMA on the coarse side of the maximum density line. It was hypothesized that coarser mixes can result in higher VMA, but the single gradation studied in this laboratory experiment did not affirm this hypothesis.

Table 8. Average Effect of Each Variable on VMA Using All Mixes.

Variable	Change in VMA
Gradation - Straight to Fine	+ 3.3
P200 - 8% to 3%	+ 0.8
Angularity - 80% to 100% Crushed	+ 0.8
Gradation - Coarse to Straight	+ 0.6
P200 - Fine to Coarse	- 0.2

When analyzing the effects of the individual component variables, several localized changes in VMA were identified, as shown on Table 9. The angularity changed the VMA by 1.0 for the straight and coarse gradations, but angularity had only a slight effect on the VMA of the fine gradation.

Table 9. Changes in VMA for Individual Variables at Optimum Asphalt Content.

Changes in VMA			
Variable	Fine	Straight	Coarse
P200 - 8% to 3%	+ 1.6	+ 0.5	+ 0.3
P200 - Fine to Coarse	- 0.5	+ 0.1	- 0.1
Angularity - 80% to 100% Crushed	+ 0.3	+ 1.1	+ 1.0

The VMA of the fine gradation was more sensitive to the amount of P200 than the coarse or straight gradation. While the VMA of the fine gradation changed 1.6 by varying the amount of P200, the straight and coarse gradations were affected significantly less. The size of P200 had no significant effect on the straight or coarse gradations but did cause a change in VMA of 0.5 for the fine gradation.

Effect of Component Variables on Hveem Stability. The effect of the variables on Hveem stability at optimum asphalt content is shown on Table 10. The Hveem stability value was greatly affected by the angularity of the fine aggregates but not by the other variables studied. For all mixes, the stability value increased by 8 when the 20% natural fine aggregates were replaced by crushed fine aggregates.

Table 10. Changes in Stability for Individual Variables at Optimum Asphalt Content.

Changes in Stability			
Variable	Fine	Straight	Coarse
P200 - 8% to 3%	- 1	+ 3	+ 1
P200 - Fine to Coarse	- 1	0	+ 1
Angularity - 80% to 100% Crushed	+ 11	+ 7	+ 5

Sensitivity of Mixes to Changes in Air Voids

It has been shown that HMA designed in the laboratory does not always represent the material produced in the field (13). Air voids of field produced material can drop 1% or 2% from the HMA mix design. It was considered desirable to identify properties of HMA that would cause a mix to be sensitive: that is, to have a large change in strength corresponding to a small change in air voids. For this analysis, the Hveem stability and air voids versus asphalt content were examined. The purpose of this analysis was to identify properties of a mix that ensured a high VMA for durability concerns while simultaneously maintaining a flat curve of Hveem stability versus air voids to address permanent deformation concerns. Stable (Mix 12) and sensitive (Mix 14) HMA are shown on Fig. 6.

Effect of Component Variables on Sensitivity. The sensitivity of the HMA was defined by the drop in Hveem stability when the air voids were lowered from 4.0% to 2.0%. There was a wide range of sensitivity for the 24 mix designs performed for the laboratory experiment. Stability drops corresponding to a 2% change in air voids were as low as 2 and as high as 24. The data is summarized on Table 11. The VMA is reported for the sample at 4.0% air voids.

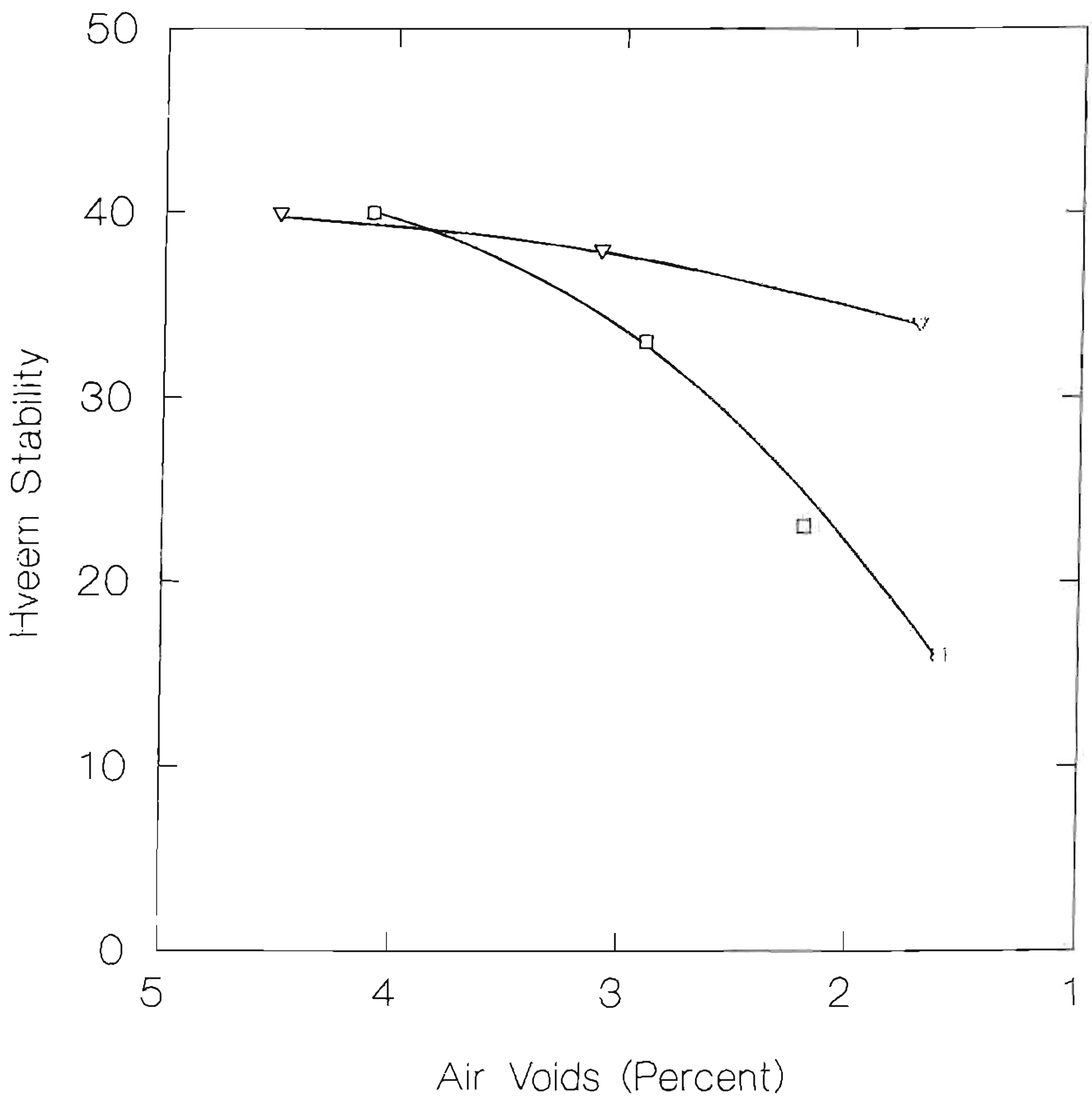
Table 11. Extreme Ranges of HMA Mixture Sensitivity, (Drop in Stability from 4.0% to 2.0% Air Voids).

Property	Highest Sensitivity	Lowest Sensitivity
VMA (%) Stab. Drop	18.1 24	12.6 2
Variables:	Fine Gradation 3% P200 100% Crush Coarse P200	Coarse Gradation 3% P200 20% Natural Coarse P200

Of the variables investigated, gradation was the variable which showed the best correlation to sensitivity of the HMA. Coarse-graded HMA were the least sensitive and fine-graded HMA were the most sensitive as shown on Table 12. Although the stability values dropped less for the HMA samples with 20% natural sands, the stability values at 4% air voids were consistently lower.

Figure 6

Laboratory Experiment - Sensitive and Stable Mixes



▽ - Stable (Coarse Gradation, 3% Fine P200, 100% Crushed Aggregate)

□ - Sensitive (Fine Gradation, 8% Coarse P200, 80% Crushed Aggregate)

Stability vs. Air Voids for a Stable and a Sensitive Mix

Table 12. **Average Stability Drop When Air Voids Change from 4.0% to 2.0%.**

Average Stability Drop			
Variable	Fine	Straight	Coarse
100% Crushed	-15	-15	-6
80% Crushed	-11	-10	-6

<u>**Influence of Voids Filled With Asphalt.**</u> The voids filled with asphalt (VFA) were calculated for all mix designs. The VFA has been correlated with the rutting performance of HMA (14,15) and is considered an important mix design property (5). The VFA related significantly to the sensitivity of the HMA as shown on Fig. 7. A maximum VFA of 75% to 80% appeared to be necessary to avoid large stability drops. Coarse-graded HMA were the least sensitive and fine-graded HMA were the most sensitive.

<u>**Analysis of 1992 CDOT Mix Designs.**</u> The dominant variable controlling the sensitivity of the 1992 mix designs performed by the CDOT was the P200. The 57 Grading C, 3/4 in. (19.0 mm) top size, mix designs were analyzed. The higher the P200, the more sensitive the mix. The second most influential parameter was the VMA relative to the specified value. The more sensitive mixes had high P200 and a lower VMA than the specified value. The best fit equation of the drop in stability had a correlation coefficient, r, of 0.64 and is described below:

$$\text{Stab.} = 4.0(\text{P200}) - 1.8(\text{VMAr}) - 12.2 \qquad \text{[Eqn. 3]}$$

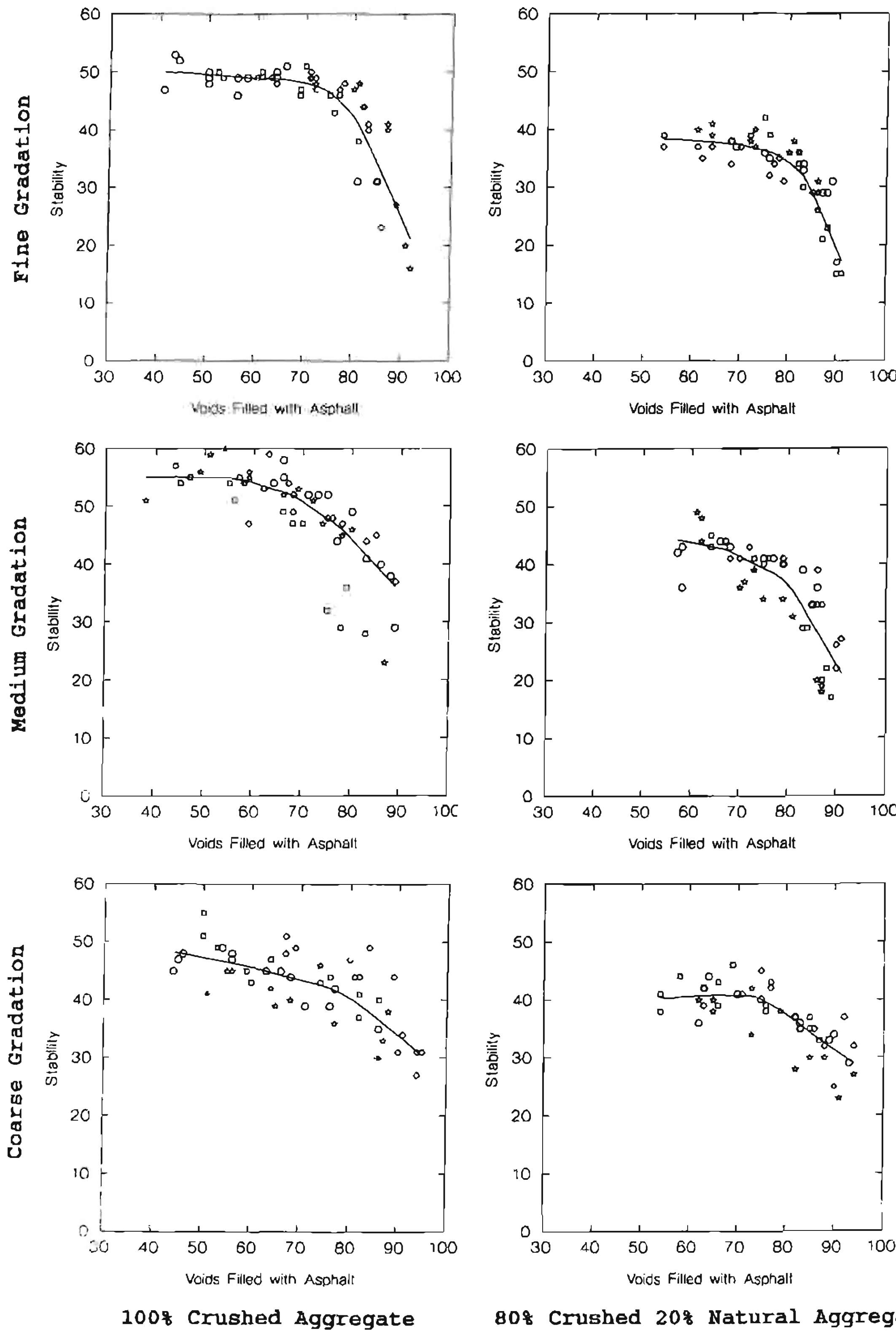
where:

Stab. = Drop in Hveem stability from 4.0% to 2.0% air voids,
P200 = percent passing the No. 200 sieve, and
VMAr = VMA of the mix at 4.0% air voids minus the specified VMA (per the Asphalt Institute).

It should be noted that no samples in the data base had VMA more than 1.5 higher than the specification.

Figure 7

Laboratory Experiment - Stability vs. Voids Filled with Asphalt



○ - 3% Fine P200 □ - 8% Fine P200 ◇ - 3% Coarse P200 ☆ - 8% Coarse P200

IV. CONCLUSIONS

Based upon the analysis of 1992 CDOT mixes and on the laboratory experiment to determine the factors which influence VMA, the following conclusions were determined.

1992 CDOT Mix Designs

1) The maximum density line is useful as a rule-of-thumb for providing guidance to develop gradations that meet the VMA specification.

2) Based on analysis of 101 gradations from 1992 mix designs in Colorado, the maximum density line could be drawn a number of ways. It is recommended to draw the maximum density line from the origin to the actual percent passing the nominal maximum aggregate size.

3) Emphasis should be placed on keeping the gradation away from the maximum density line throughout the fine sieve sizes, in particular, on and near two sieve sizes: 1) material passing the No. 30 sieve size, and 2) the fourth sieve size smaller than the first sieve size passing 100% of the material.

4) The tight Master Range used by the CDOT in 1992 prevented the development of gradations that had enough room in the mineral aggregate for asphalt cement (sufficient VMA). The tight Master Range may have contributed to the poor correlation found between VMA and the distance between the actual gradation and the maximum density line.

   The Master Range proposed for use in 1993 in conjunction with the VMA specification has opened significantly from the very tight Master Range used in 1992.

Laboratory Experiment

1) Gradation was the single largest factor that affected the VMA of the mixes studied. The gradation on the fine side of the maximum density line increased the VMA tremendously above the VMA of the gradation which followed the maximum density line.

   Producing coarse gradations which meet the VMA specifications has been historically very difficult. The coarse gradation used in this experiment had lower VMA than the VMA of the gradation which followed the maximum density line. Only one coarse gradation was examined. Although the coarse gradation in this study had low VMA, it is still believed that VMA can be achieved on the coarse side of the maximum density line; it is just very difficult.

2) The quantity of P200 in a HMA mixture significantly affected the VMA. The lower quantities of P200 produced the higher VMAs. The higher quantities of P200 produced the lower VMAs.

   When a gradation was on the fine side of the maximum density line, the quantity and size of the P200 affected the VMA more than for a coarse-graded HMA.

3) The angularity of the aggregate was a substantial factor that affected the VMA. Higher quantities of crushed aggregates and more angular crushed aggregates used in an HMA mixture produced higher VMAs. Higher quantities of rounded, natural sands and more rounded sands produced lower VMAs.

When a gradation was on the coarse side of the maximum density line or followed the maximum density line, the angularity of the fine aggregate influenced the VMA more than for a fine-graded HMA.

4) The size of the P200 was not conclusively shown to influence the VMA. The sizes of P200 used in this study were both fine; however, one was significantly finer than the other. Despite the results of the laboratory experiment, it is still recommended that coarse-sized P200 be used to increase VMA.

5) The sensitivity of an HMA mixture to changes in air voids is an important property that must be considered. Gradation contributed greatly to sensitive mixes based on the 24 mix designs performed for the laboratory experiment: the coarser the gradation, the less sensitive the mix. A VMA which meets the Asphalt Institute specifications does not ensure a mix which is not sensitive; HMA with high VMA can be very sensitive. The more sensitive mixes from those performed by the CDOT for 1992 had high P200 contents and a lower VMA than the specified value.

   A maximum limit of 75% or 80% should be placed on the VFA to reduce the chance of obtaining a sensitive mix. This limit is more important for fine-graded HMA than coarse-graded HMA.

V. RECOMMENDATIONS FOR FUTURE RESEARCH

Based on information presented in this study, it is hypothesized that both fine and coarse mixes that meet the VMA requirements have the potential for long term performance. Each grading of HMA has its relative advantages and disadvantages as shown on Table 13. Additional work should be done to validate this hypothesis. Since coarse-graded HMAs are not used extensively in Colorado, additional information should be obtained before using coarse mixtures statewide.

Table 13. Summary of Advantages and Disadvantages of Coarse and Fine-Graded HMA.

	Coarse Grading	Fine Grading
Constructability	Difficult	Easy
Producability	Easy	Difficult
Durability	Difficult	Easy

Constructability is defined as the ease of construction of an HMA pavement in terms of segregation, compaction, etc.

Producability is defined as the lack of sensitivity of an HMA mix to the minor variations between the laboratory mix design and field production. Losses of air voids or stability during the production process affects the long-term performance of a pavement.

Durability is defined as the ability of an HMA sample to resist moisture damage as measured by specifications, such as the modified Lottman testing (AASHTO T 283) and VMA.

Fine mixes have the ability to perform well on interstate highways in the hottest parts of Colorado (16) and have survived very tough torture testing related to rutting (17). Fine-graded HMA are easier to construct than coarse mixtures since they have a tendency to segregate less. Fine-graded HMA has better durability characteristics, based upon modified Lottman testing and VMA. Unfortunately, fine-graded HMA is very sensitive to changes which can occur during production. Air voids change greatly with changes in the amount and size of P200, and stability changes greatly with changes in the angularity of the fine aggregates.

A coarse-graded HMA is not as sensitive as a fine-graded HMA to changes that may occur in production. However, it is typically more difficult to obtain the durability characteristics of VMA and modified Lottman values with a coarse-graded HMA than with a fine-graded HMA. Additionally, in Colorado, segregation of coarse-graded HMA is a major concern which needs to be addressed.

Secondly, HMA pavements with acceptable and unacceptable levels of VMA should be tested in performance related equipment. This testing would be useful to draw a correlation between acceptable levels of VMA and predicted performance.

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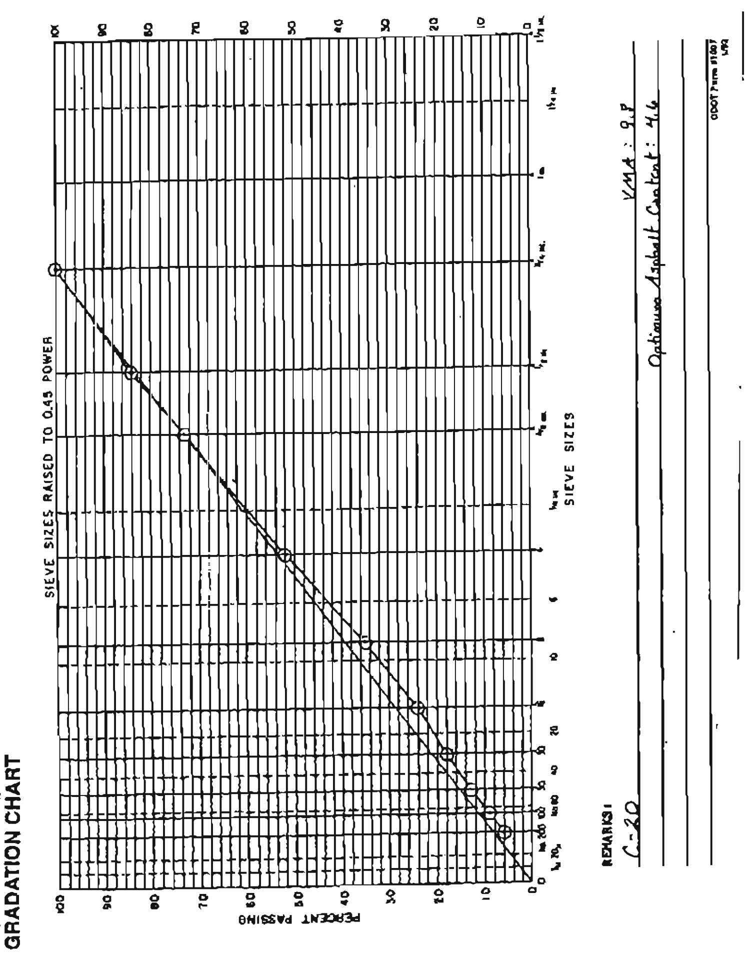
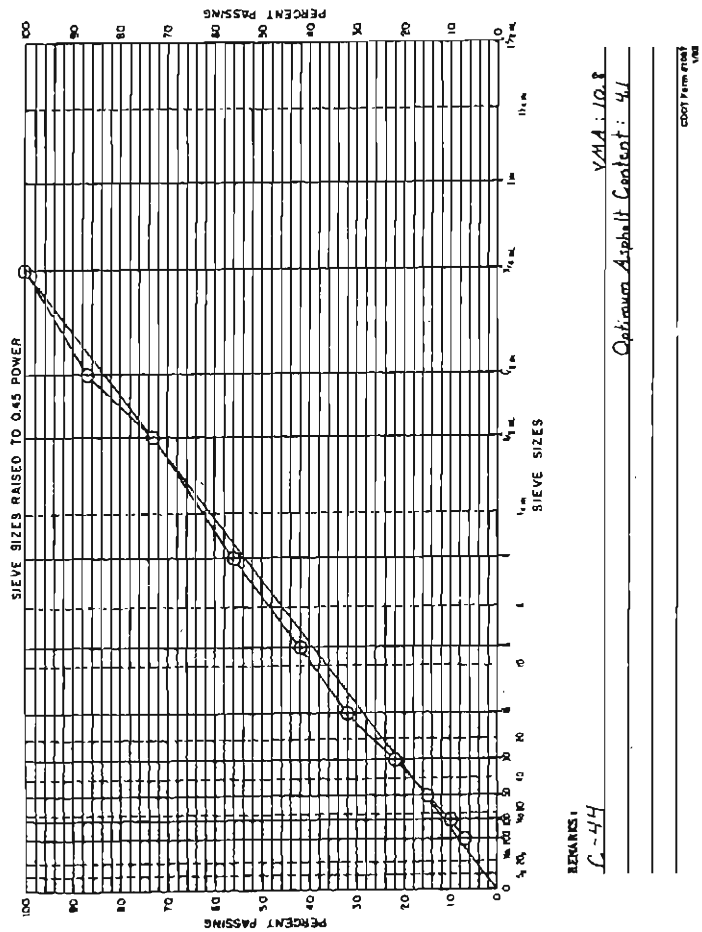
APPENDIX A

Gradation Plots of 1992 CDOT HMA Designs Used in this Analysis


GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
SIEVE SIZES
PERCENT PASSING
REMARKS:
C-20
VMA : 9.8
Optimum Asphalt Content : 4.6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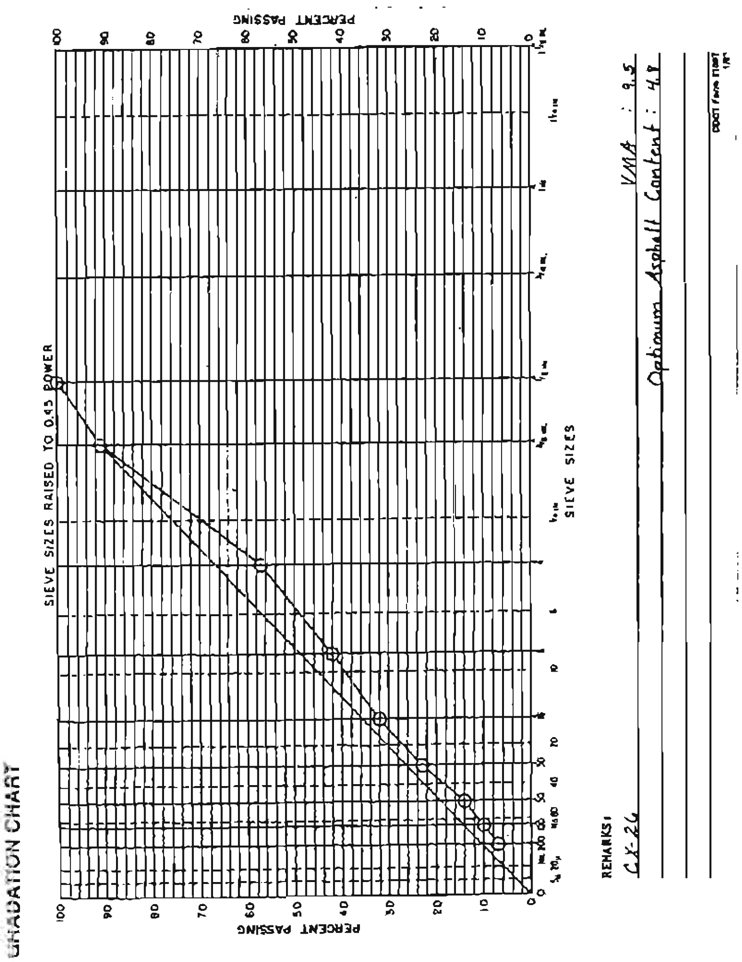
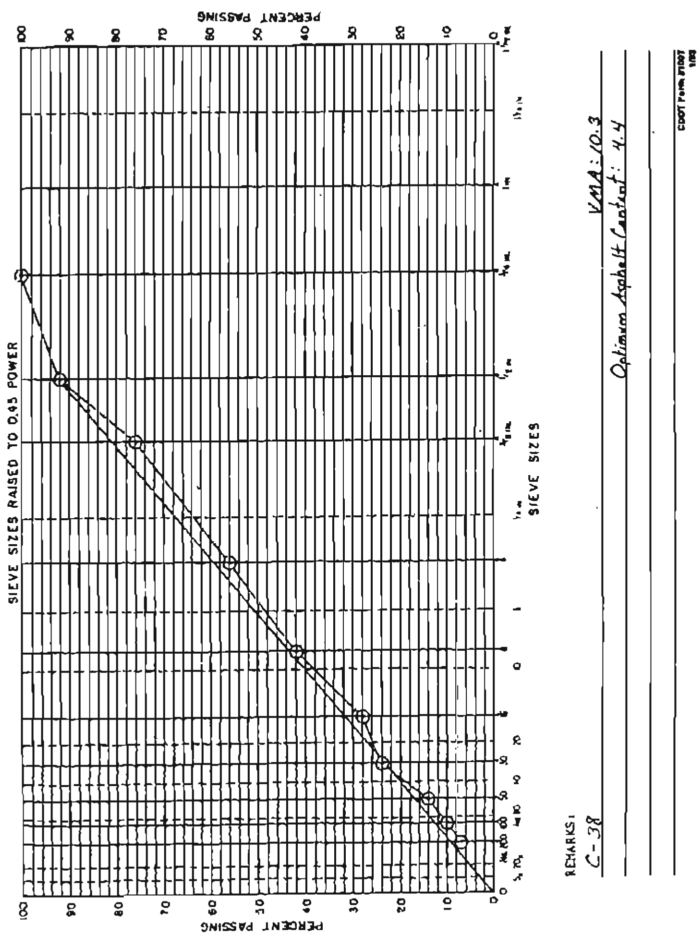
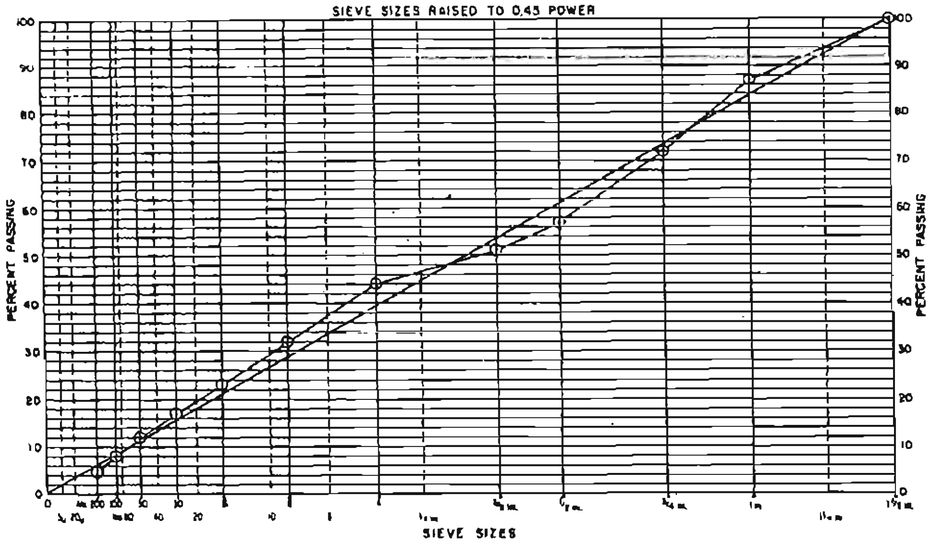
SIEVE SIZES
PERCENT PASSING
REMARKS:
C-44
VMA : 10.8
Optimum Asphalt Content : 4.1


GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
SIEVE SIZES
PERCENT PASSING
REMARKS:
CX-26
VMA : 9.5
Optimum Asphalt Content : 4.8


SIEVE SIZES RAISED TO 0.45 POWER
SIEVE SIZES
PERCENT PASSING
REMARKS:
C-38
VMA: 10.3
Optimum Asphalt Content : 4.4

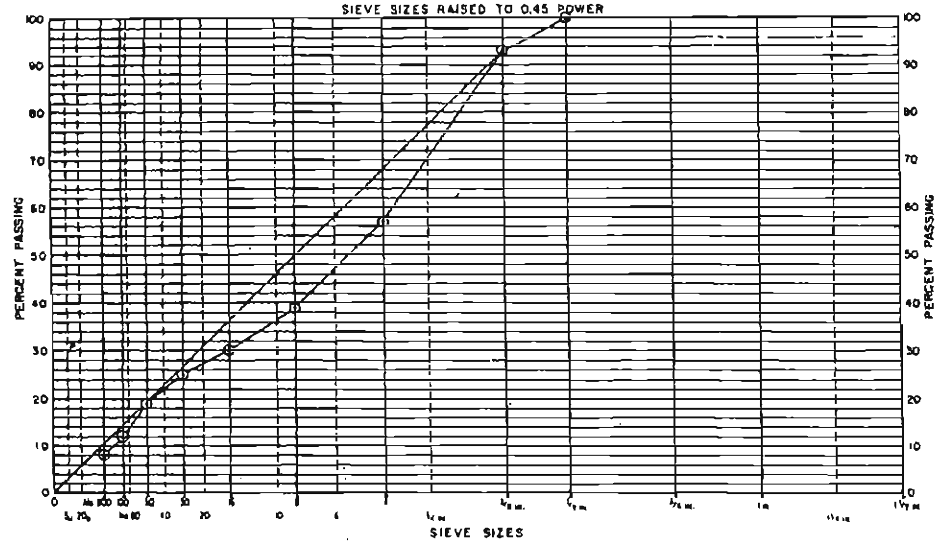
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
G-7
VMA = 9.0
Optimum Asphalt Content = 3.5

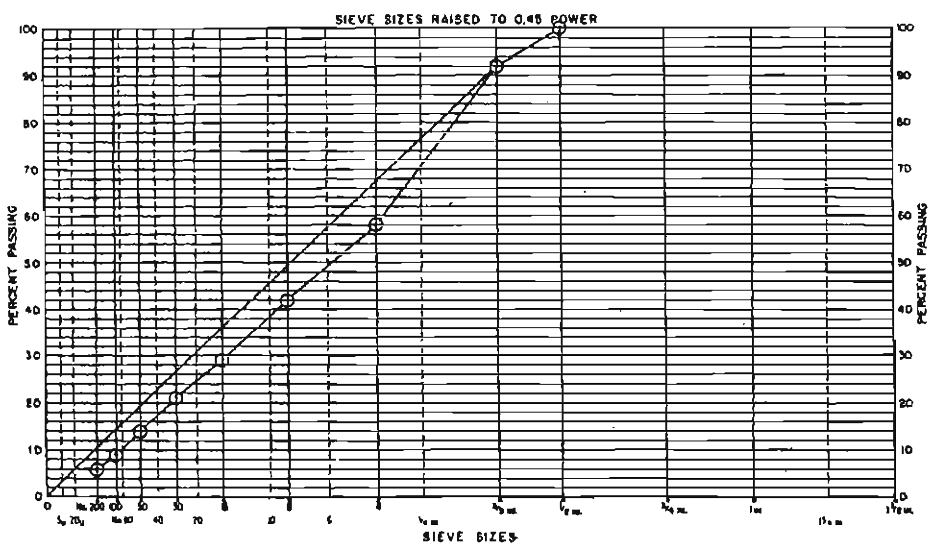
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



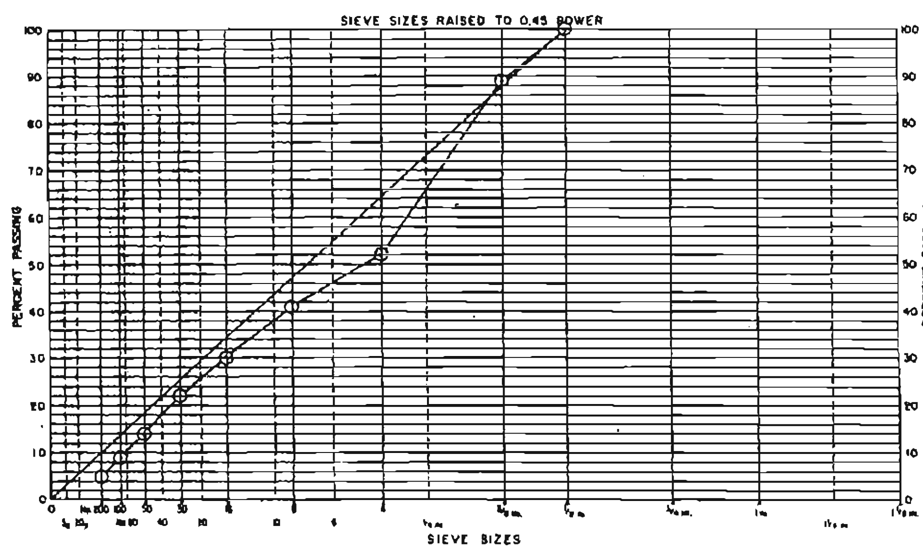
REMARKS:
CX-36
VMA : 11.9
Optimum Asphalt Content : 5.1

CDOT Form #1007 1/92



REMARKS:
CX-20
VMA : 14.3
Optimum Asphalt Content : 6.9

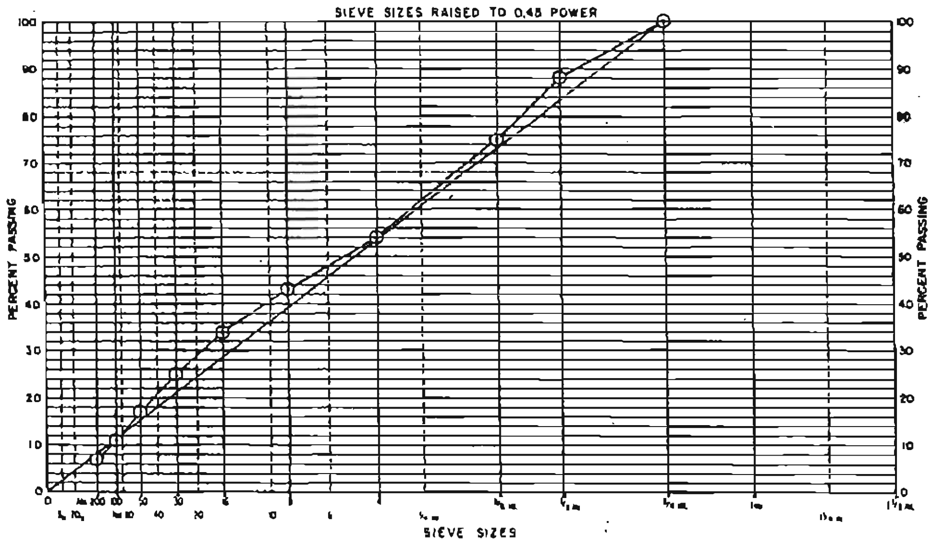
CDOT Form #1007 1/92



REMARKS:
CX-2
VMA : 12.0
Optimum Asphalt Content : 4.7

CDOT Form #1007 1/92

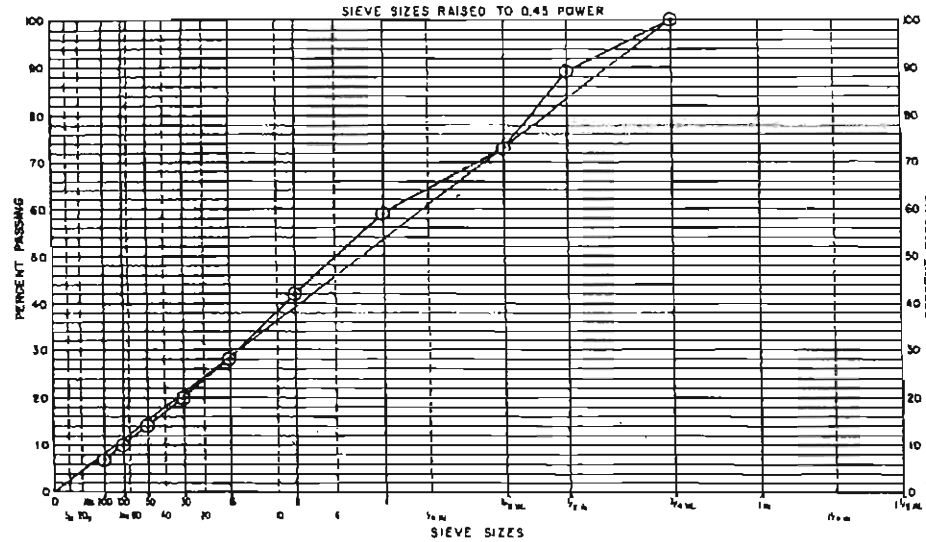
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-8
VMA : 11.3
Optimum Asphalt Content: 4.3

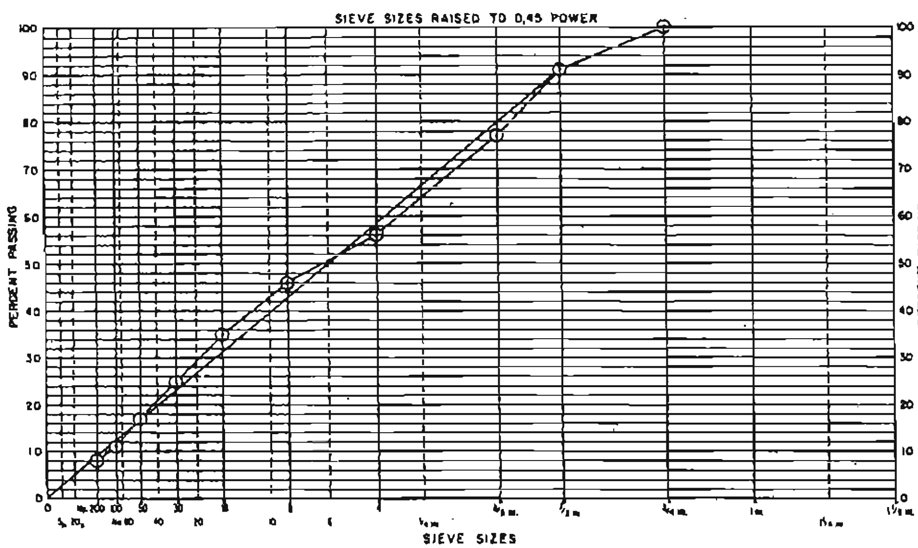
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



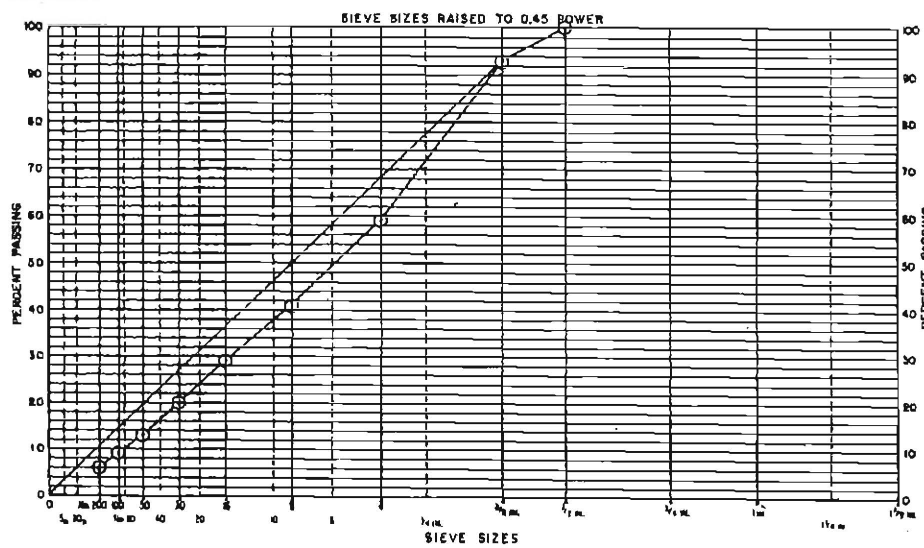
REMARKS:
C-16
VMA : 11.4
Optimum Asphalt Content: 4.8

CDOT Form #1007 1/92



REMARKS:
C-26
VMA : 11.5
Optimum Asphalt Content: 4.5

CDOT Form #1007 1/92



REMARKS:
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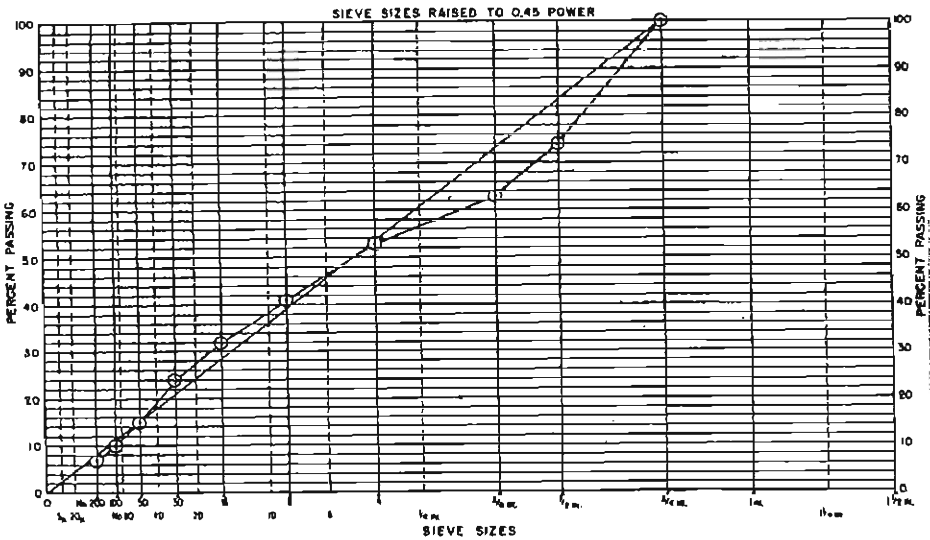
VMA : 12.4
Optimum Asphalt Content: 4.7

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION

GRADATION CHART



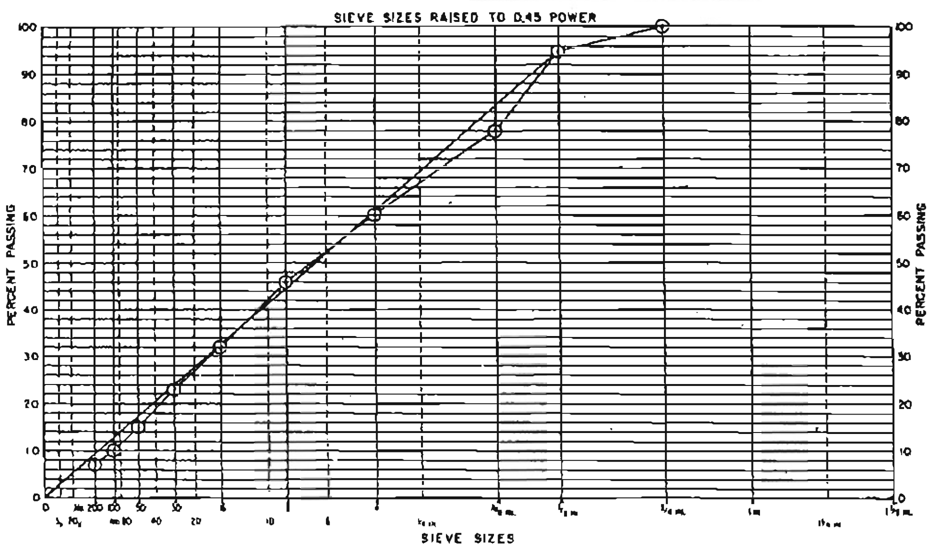
REMARKS:

C-2

VMA: 11.6

Optimum Asphalt Content: 4.5

CDOT Form #1087 1/92



REMARKS:

C-30

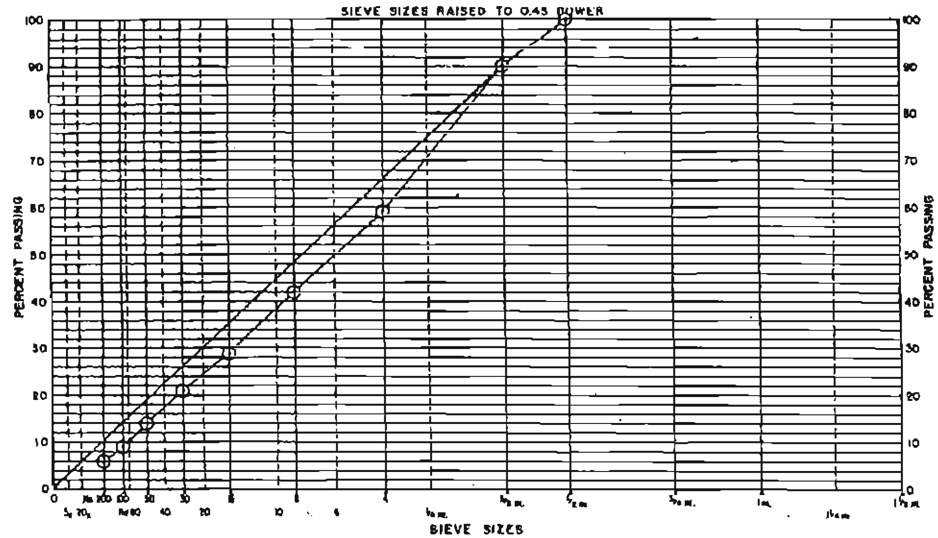
VMA: 11.7

Optimum Asphalt Content: 4.8

CDOT Form #1087 1/92

COLORADO DEPARTMENT OF TRANSPORTATION

GRADATION CHART



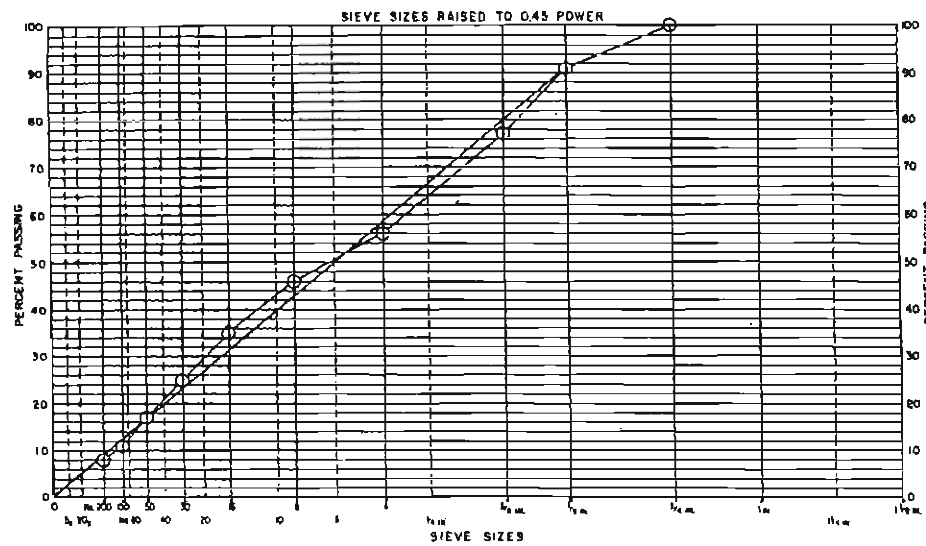
REMARKS:

CX-21

VMA: 12.5

Optimum Asphalt Content: 5.0

CDOT Form #1087 1/92



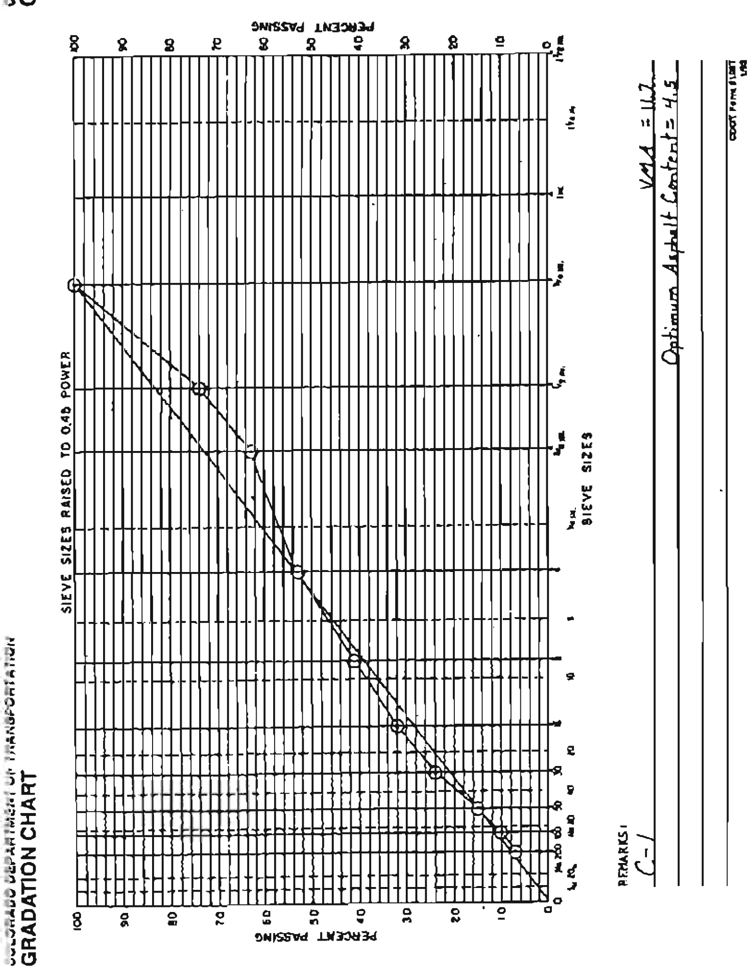
REMARKS:

C-31

VMA: 11.3

Optimum Asphalt Content: 4.8

CDOT Form #1087 1/92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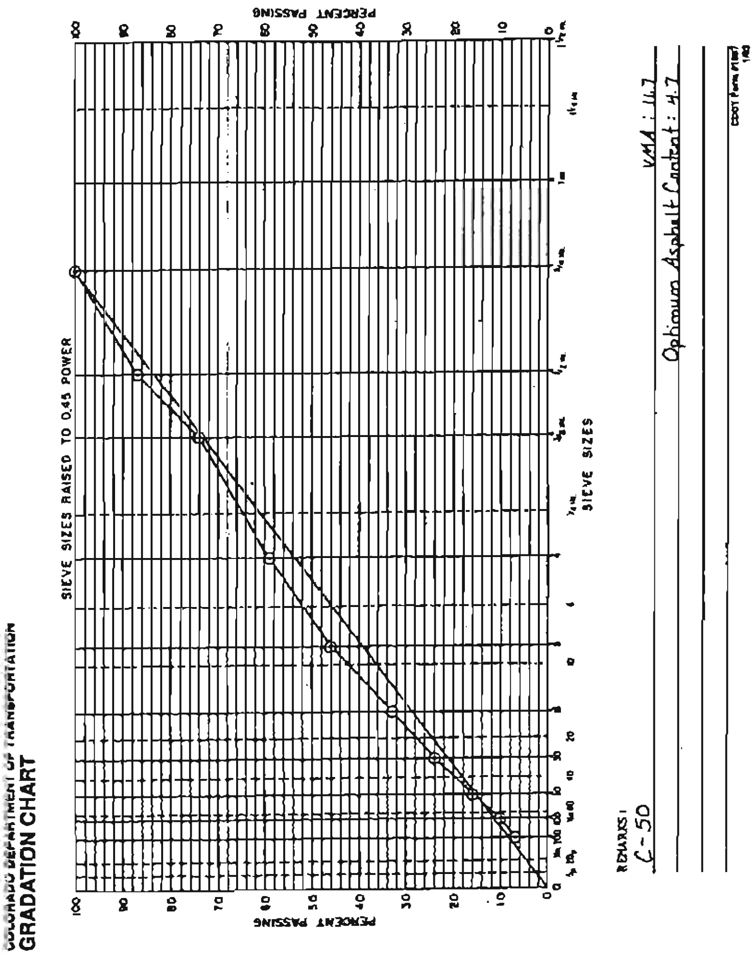
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-1
VMA = 11.7
Optimum Asphalt Content = 4.5


COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
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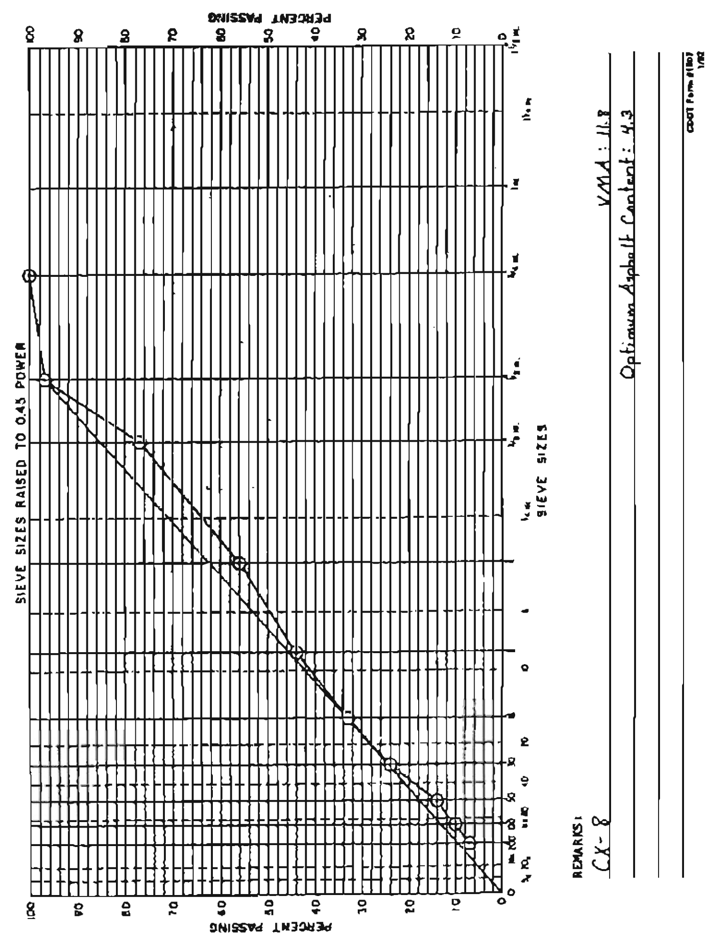
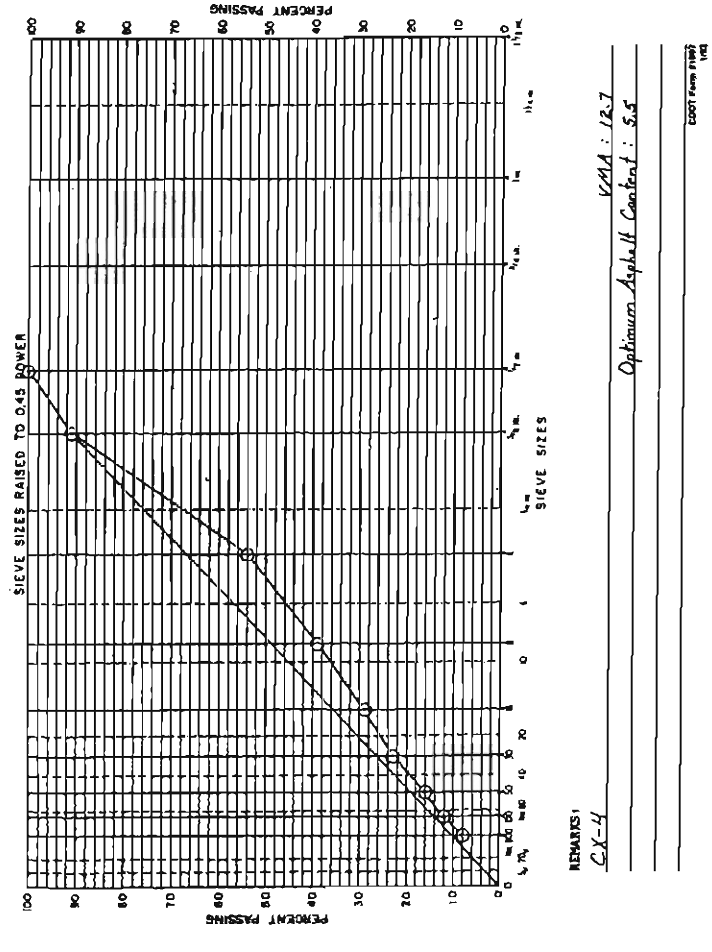
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-50
VMA: 11.7
Optimum Asphalt Content: 4.7


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-8
VMA: 11.8
Optimum Asphalt Content: 4.3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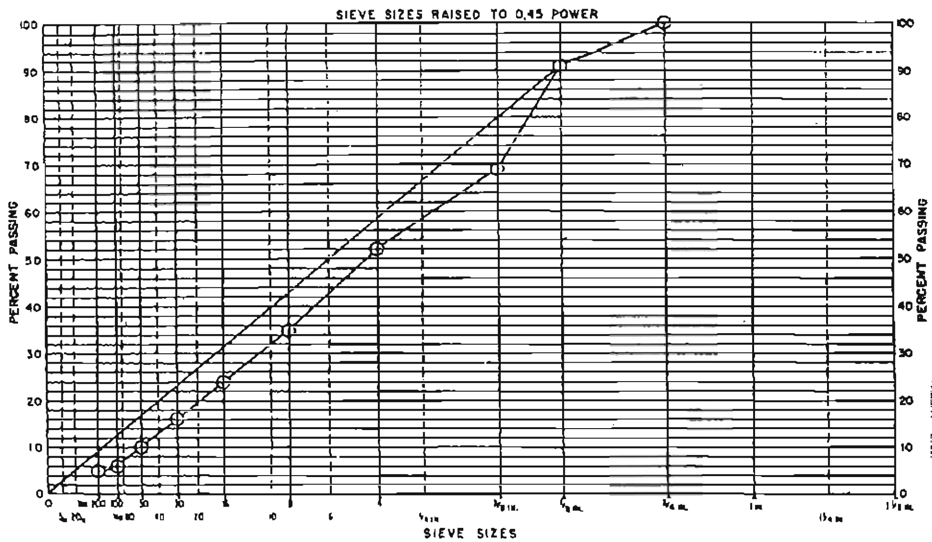
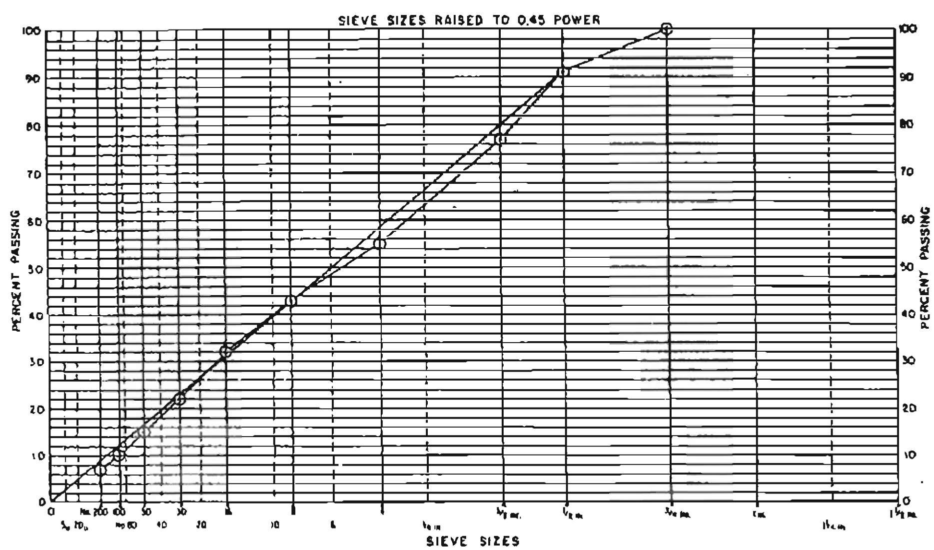
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-4
VMA: 12.7
Optimum Asphalt Content: 5.5

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-42 VMA : 11.9
Optimum Asphalt Content : 5.5

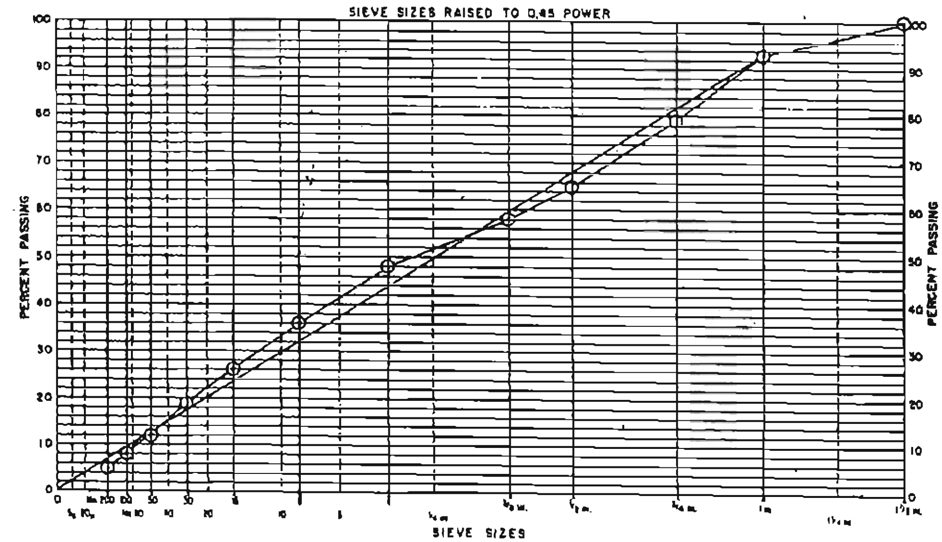
CDOT Form #1007 1/92



REMARKS:
C-53 VMA : 11.98
Optimum Asphalt Content : 4.6

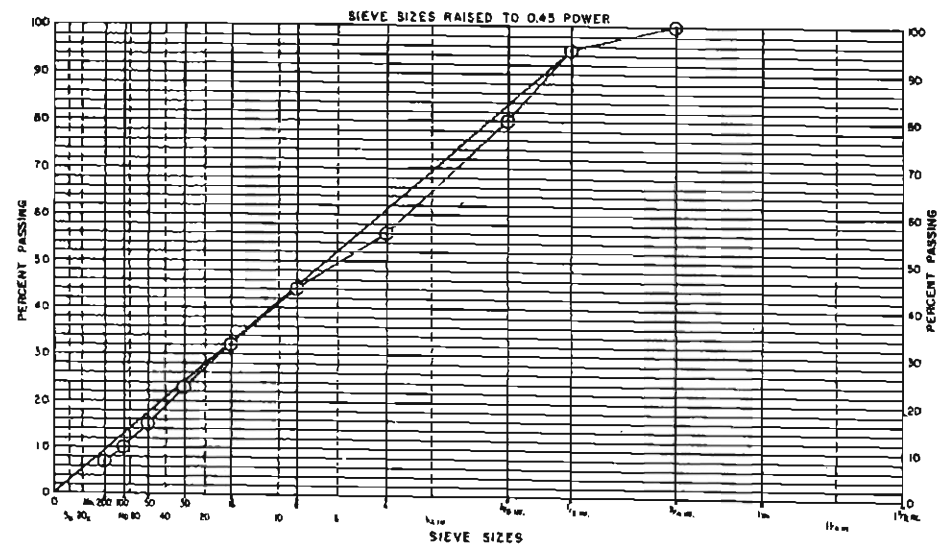
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
G-6 VMA : 10.1
Optimum Asphalt Content : 3.7

CDOT Form #1007 1/92



REMARKS:
CX-10 VMA : 11.9
Optimum Asphalt Content : 4.6

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
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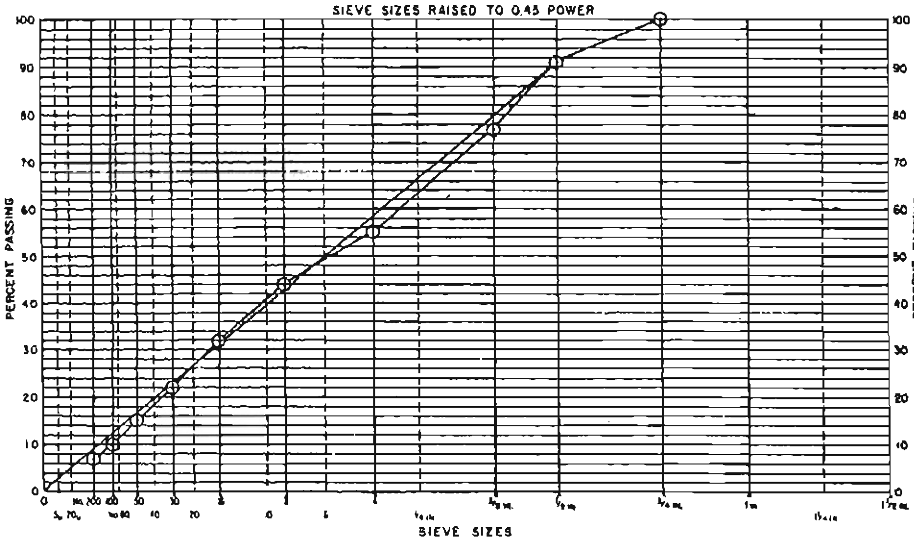
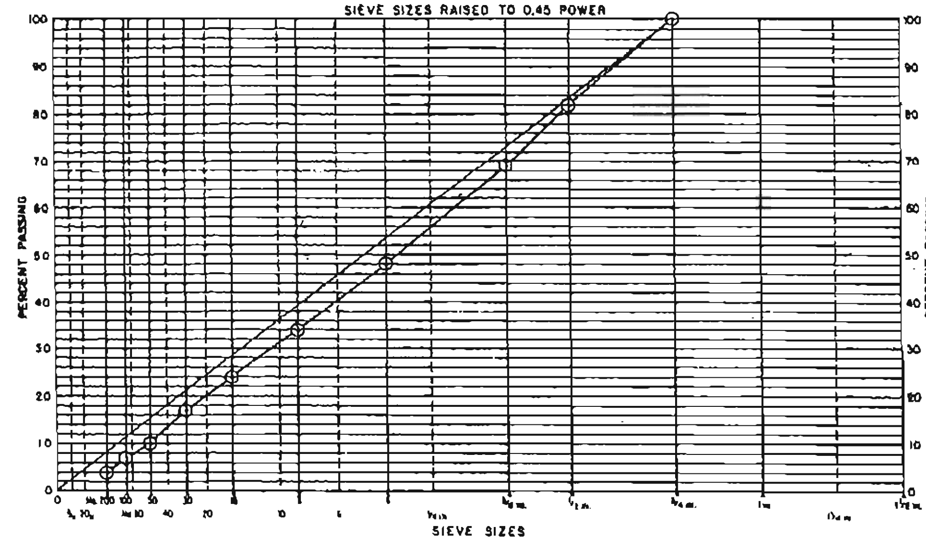


REMARKS:
C-25 VMA: 12.0
Optimum Asphalt Content: 4.6

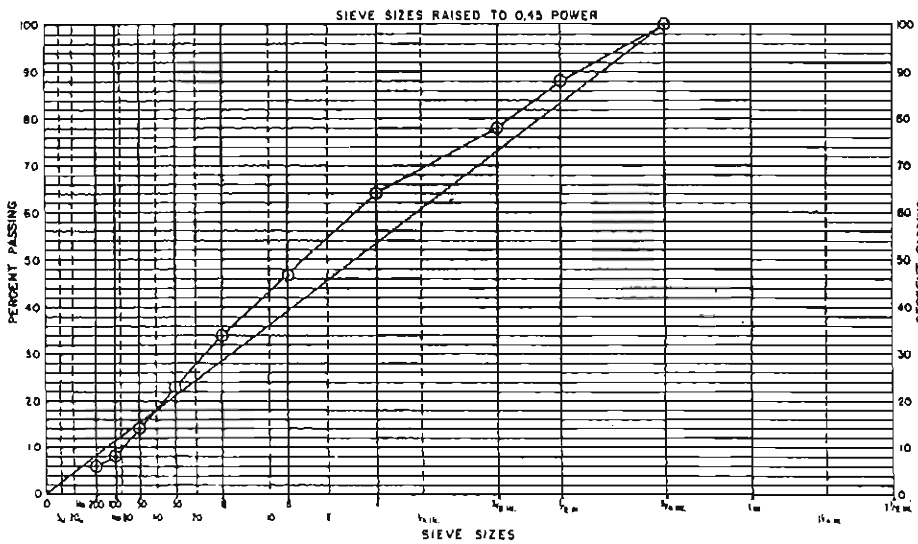
CDOT Form #1087 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



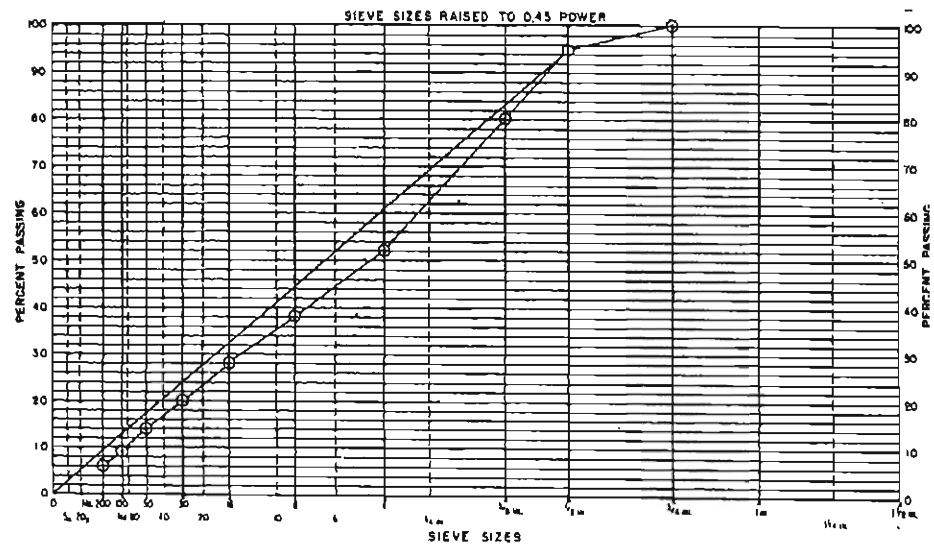
REMARKS:
C-17 VMA: 10.9
Optimum Asphalt Content: 4.0

CDOT Form #1087 1/92



REMARKS:
C-51 VMA: 12.08
Optimum Asphalt Content: 4.6

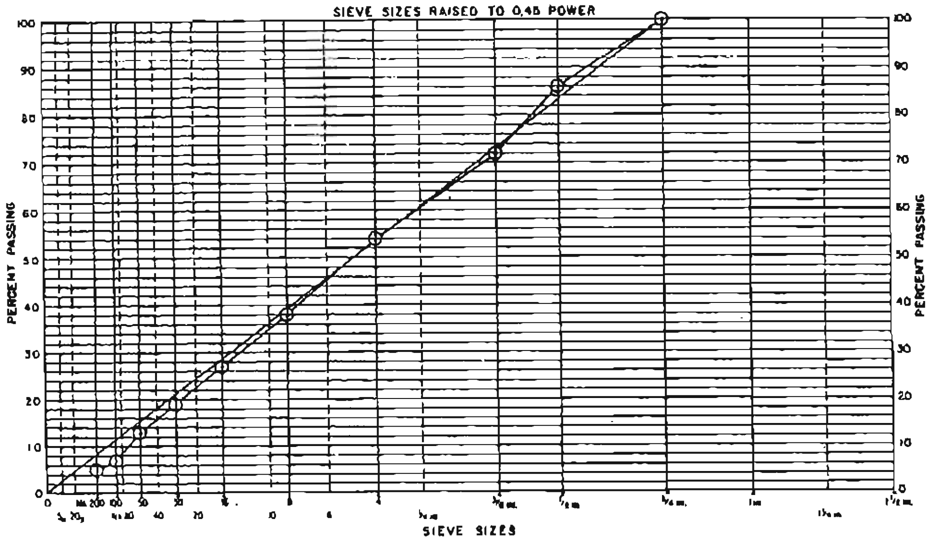
CDOT Form #1087 1/92



REMARKS:
C-55 VMA: 12.09
Optimum Asphalt Content: 4.7

CDOT Form #1087 1/92

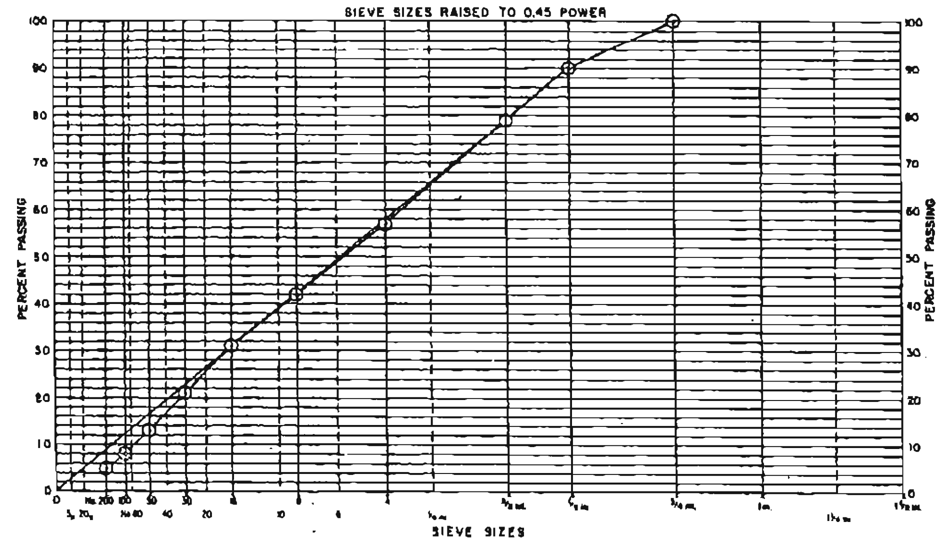
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-27 VMA: 12.1
Optimum Asphalt Content: 5.5

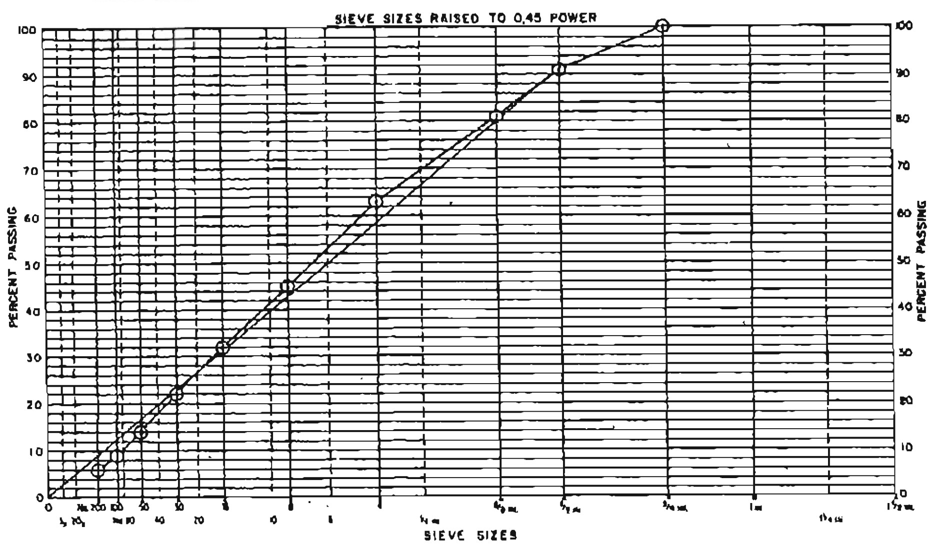
CDOT Form #1007

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



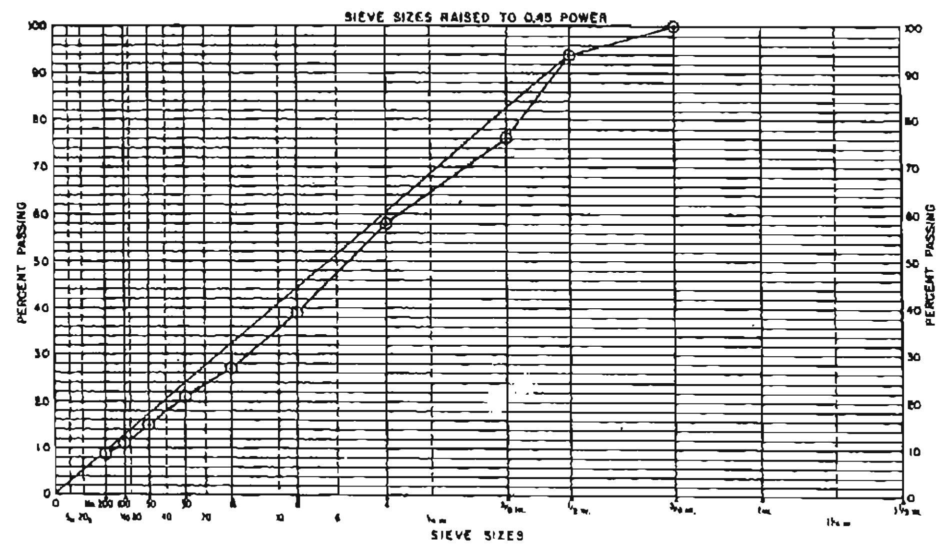
REMARKS:
C-29 VMA: 12.2
Optimum Asphalt Content: 4.5

CDOT Form #1007



REMARKS:
C-36 VMA: 12.2
Optimum Asphalt Content: 4.5

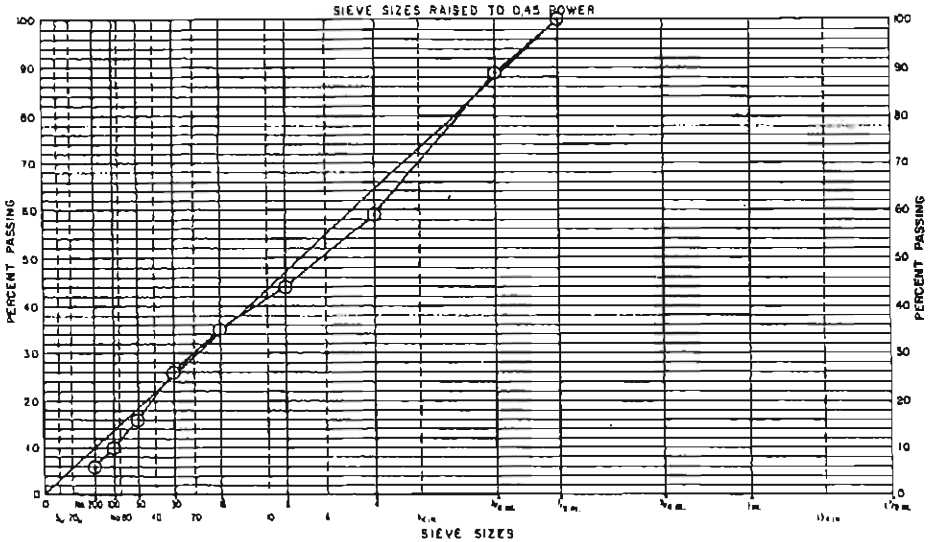
CDOT Form #1007



REMARKS:
C-56 VMA: 12.2
Optimum Asphalt Content: 4.5

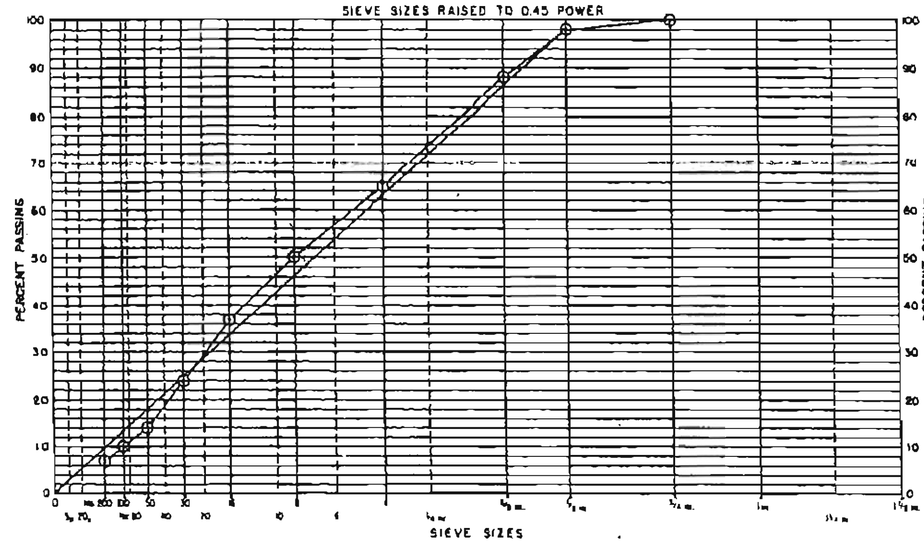
CDOT Form #1007

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

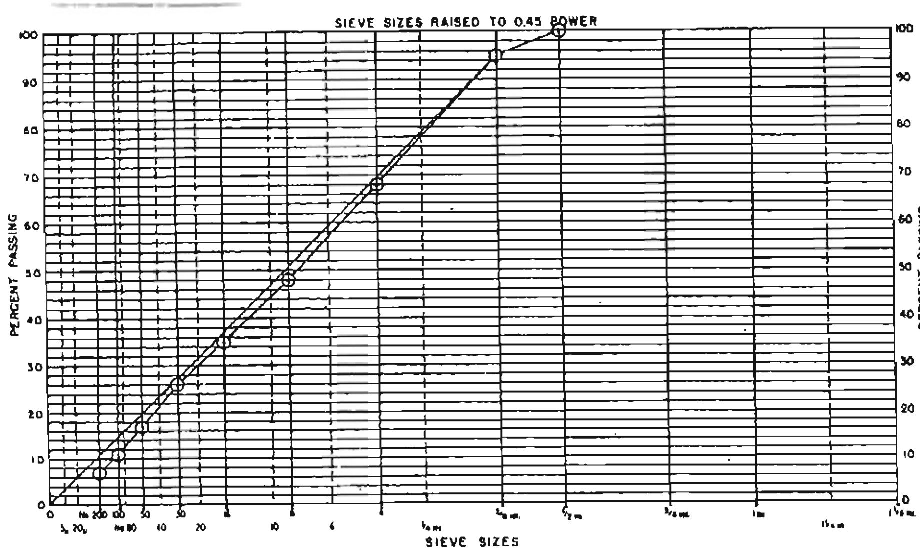


REMARKS:
CX-32
VMA: 13.2
Optimum Asphalt Content: 4.7

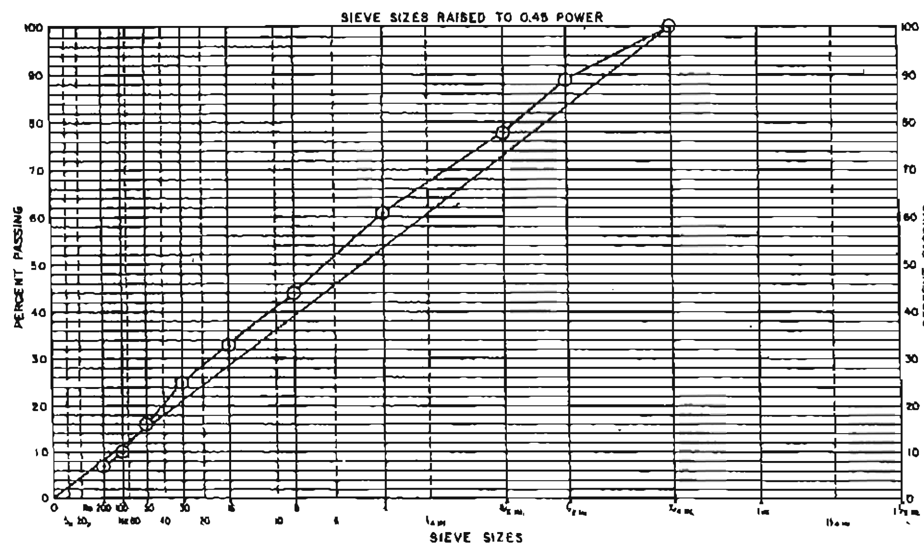
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-57
VMA: 12.38
Optimum Asphalt Content: 4.9



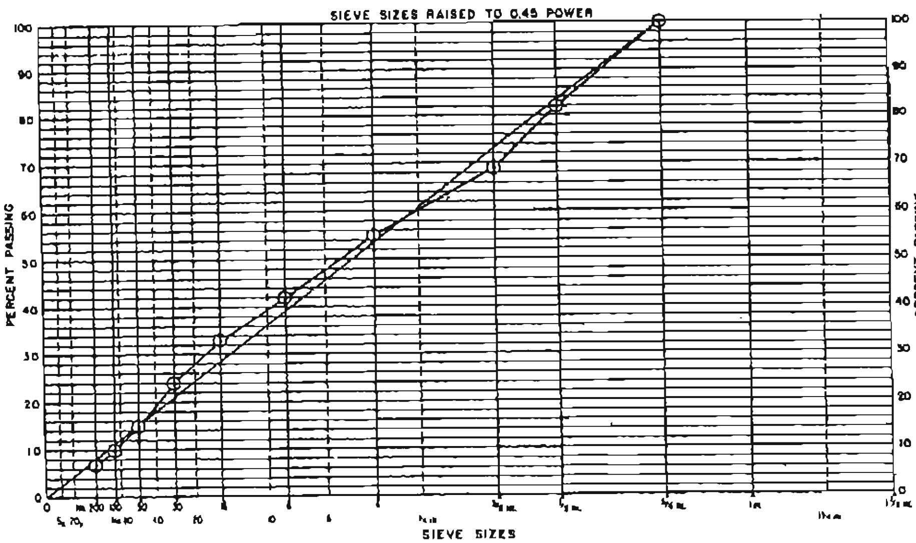
REMARKS:
CX-1
VMA: 13.2
Optimum Asphalt Content: 5.0



REMARKS:
C-37
VMA: 12.3
Optimum Asphalt Content: 4.4

A-10

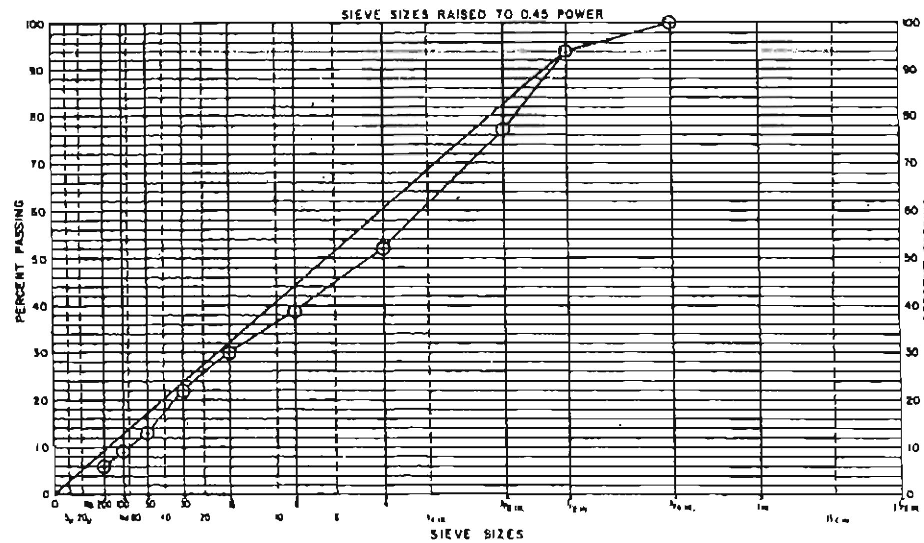
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-3 VMA : 12.5
Optimum Asphalt Content: 4.7

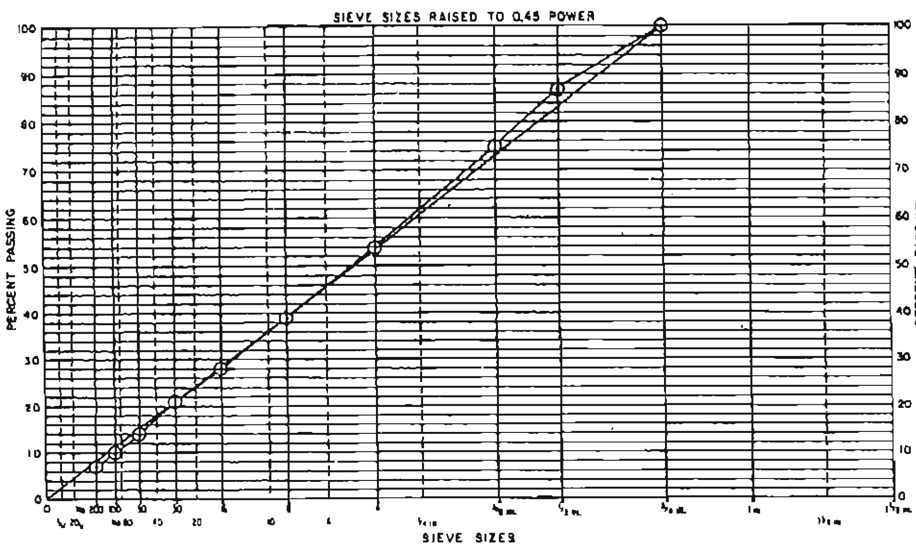
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



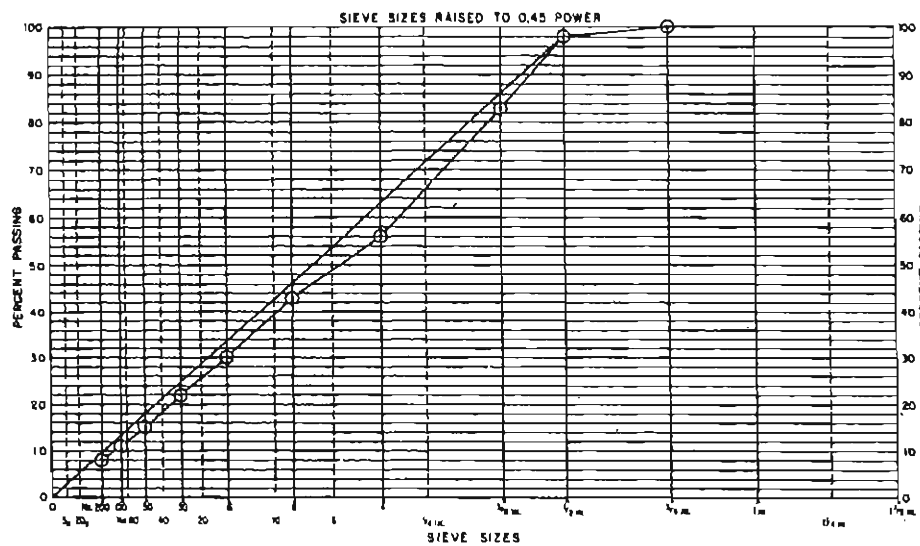
REMARKS:
C-39 VMA : 12.5
Optimum Asphalt Content: 4.5

CDOT Form #1007 1/92



REMARKS:
C-40 VMA : 12.5
Optimum Asphalt Content: 4.3

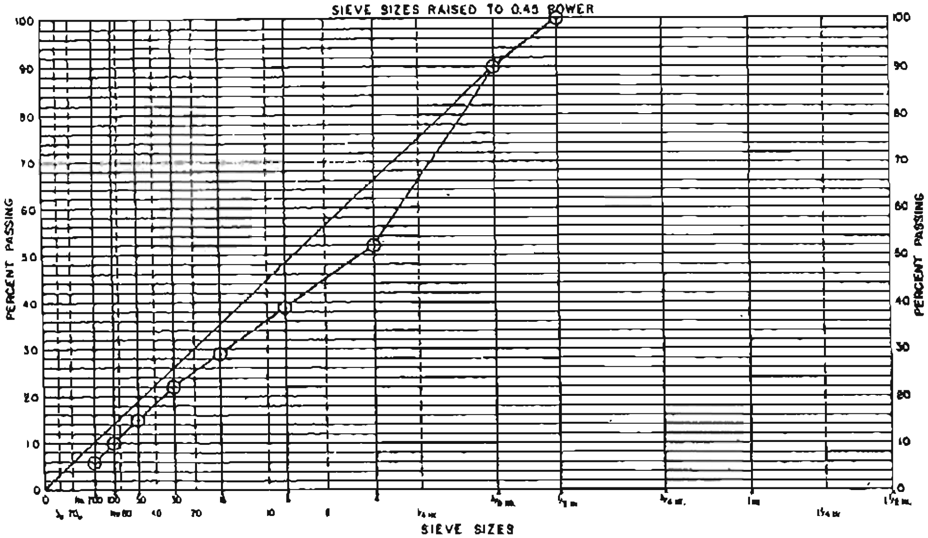
CDOT Form #1007 1/92



REMARKS:
CX-5 VMA : 12.7
Optimum Asphalt Content: 5.2

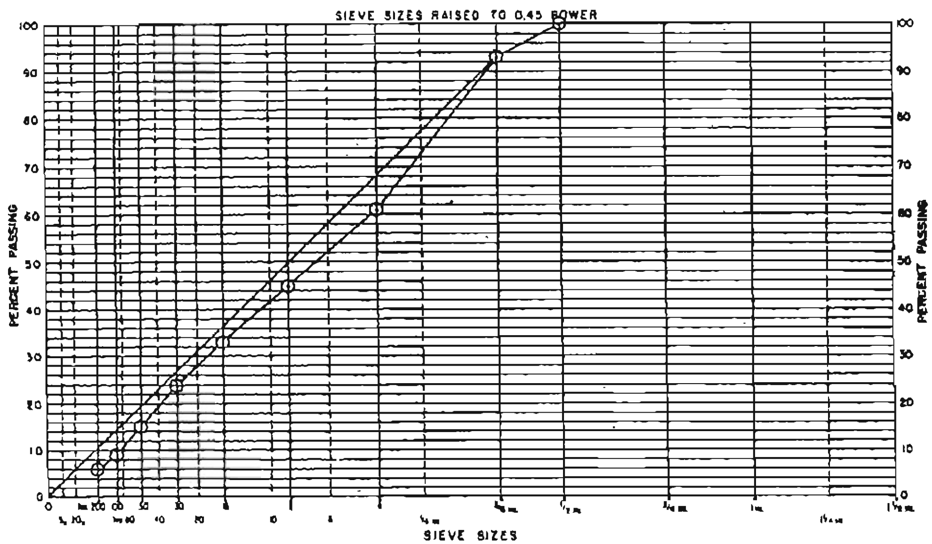
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
CX-14 VMA: 13.6
Optimum Asphalt Content: 4.7

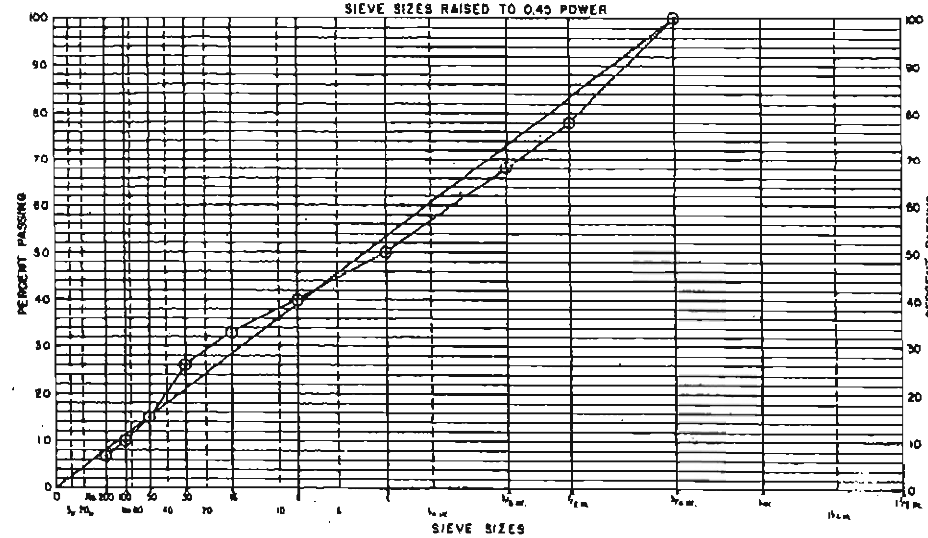
CDOT Form #1007 1/92



REMARKS:
CX-15 VMA: 13.7
Optimum Asphalt Content: 5.1

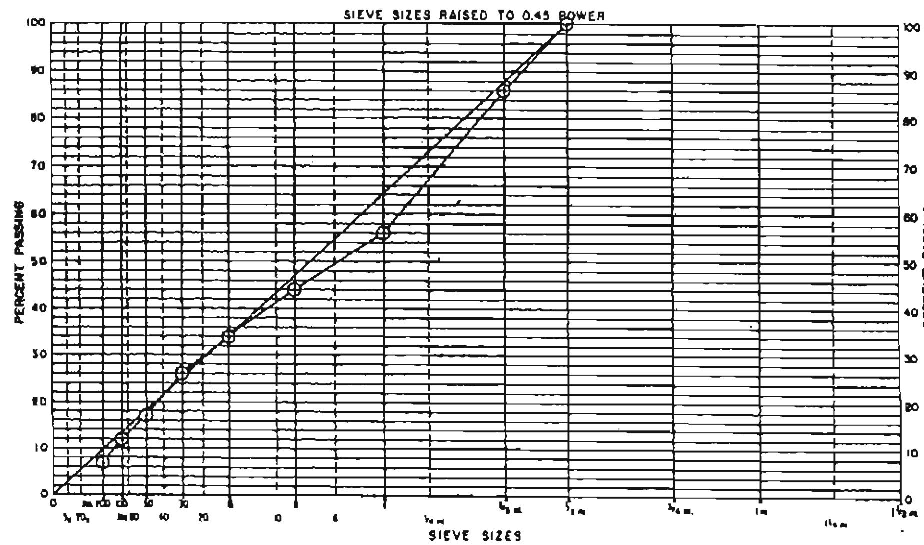
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-47 VMA: 12.68
Optimum Asphalt Content: 4.4

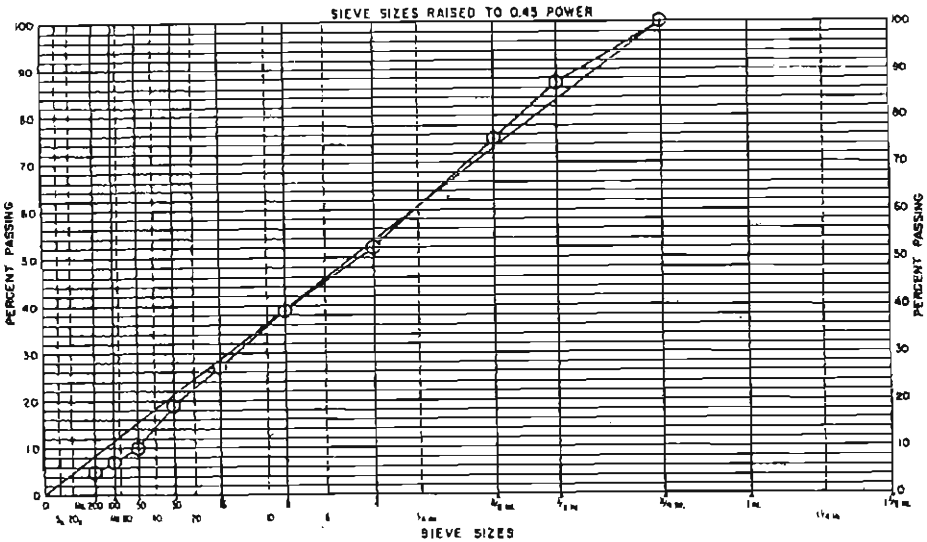
CDOT Form #1007 1/92



REMARKS:
CX-3 VMA: 13.2
Optimum Asphalt Content: 5.1

CDOT Form #1007 1/92

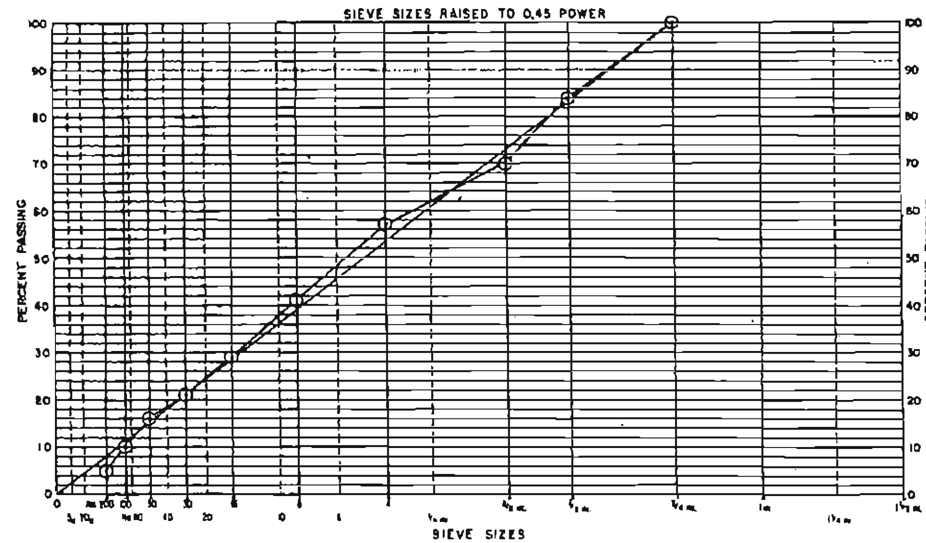
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-28 VMA: 12.9
Optimum Asphalt Content: 5.6

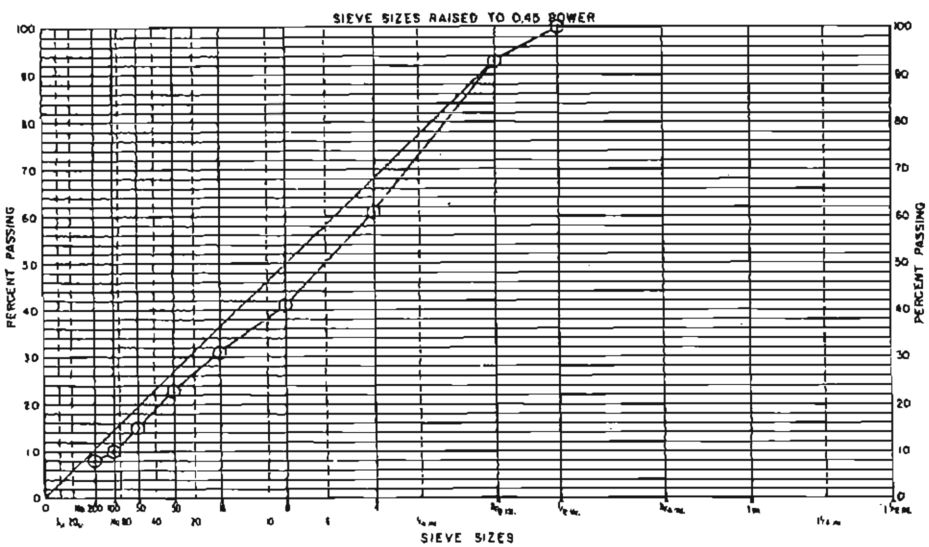
CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



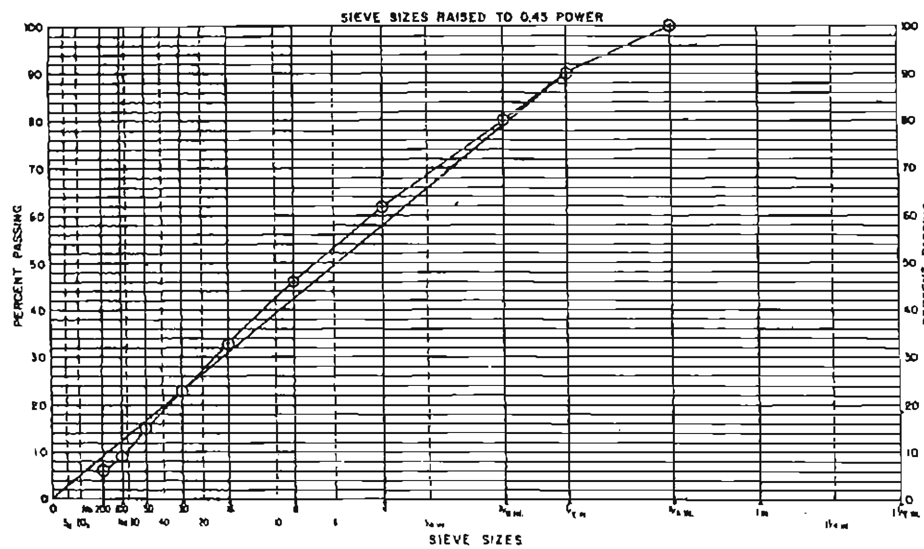
REMARKS:
C-12 VMA: 12.8
Optimum Asphalt Content: 4.7

CDOT Form #1007 1/92



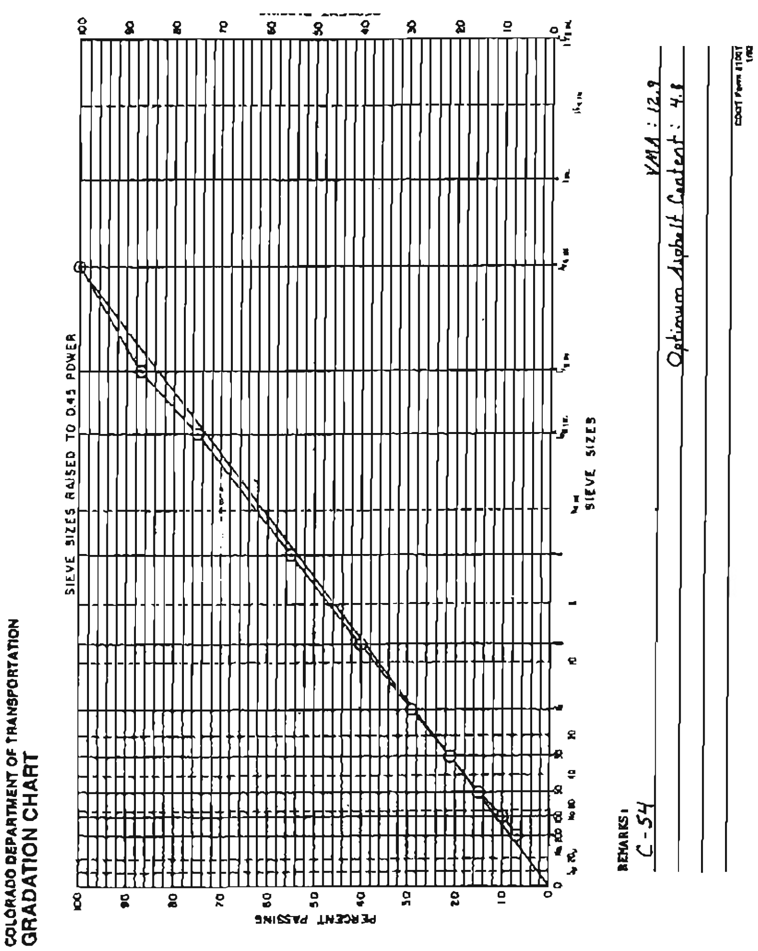
REMARKS:
CX-29 VMA: 13.7
Optimum Asphalt Content: 5.0

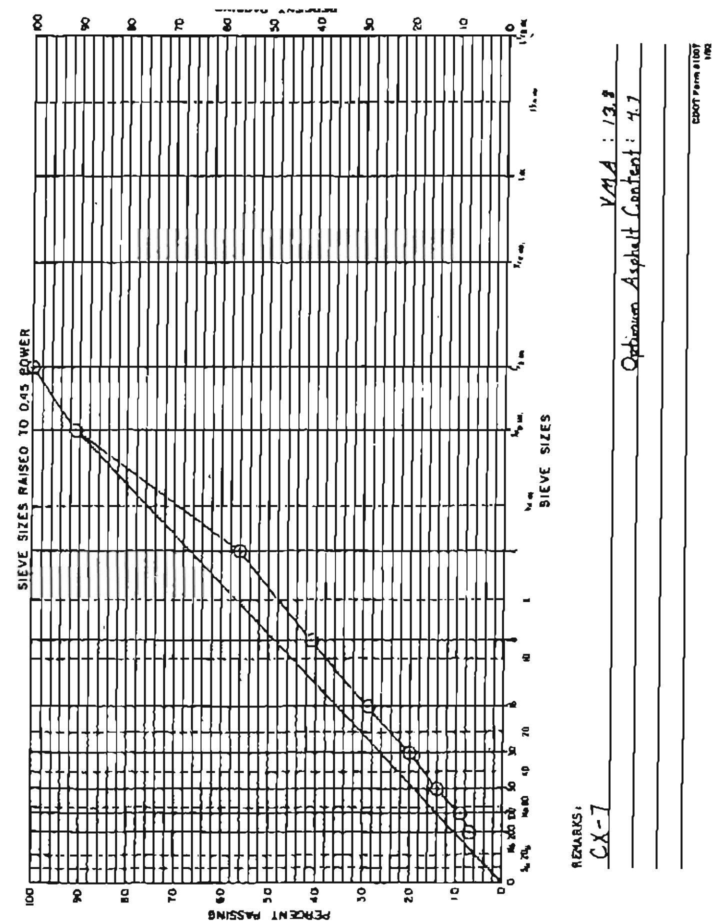
CDOT Form #1007 1/92

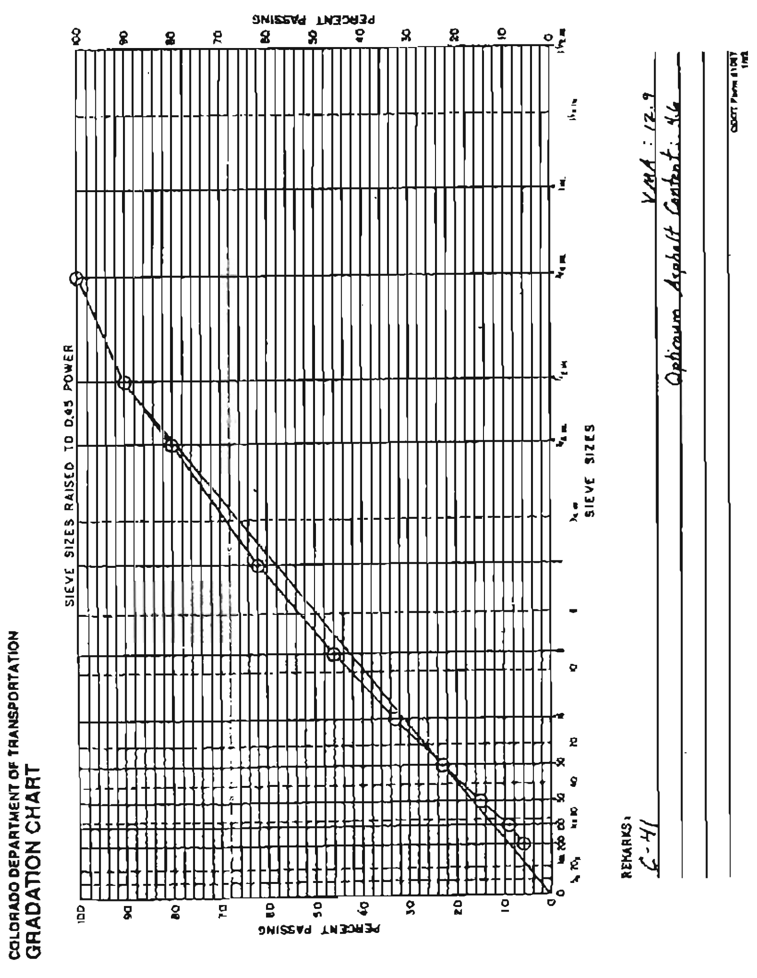


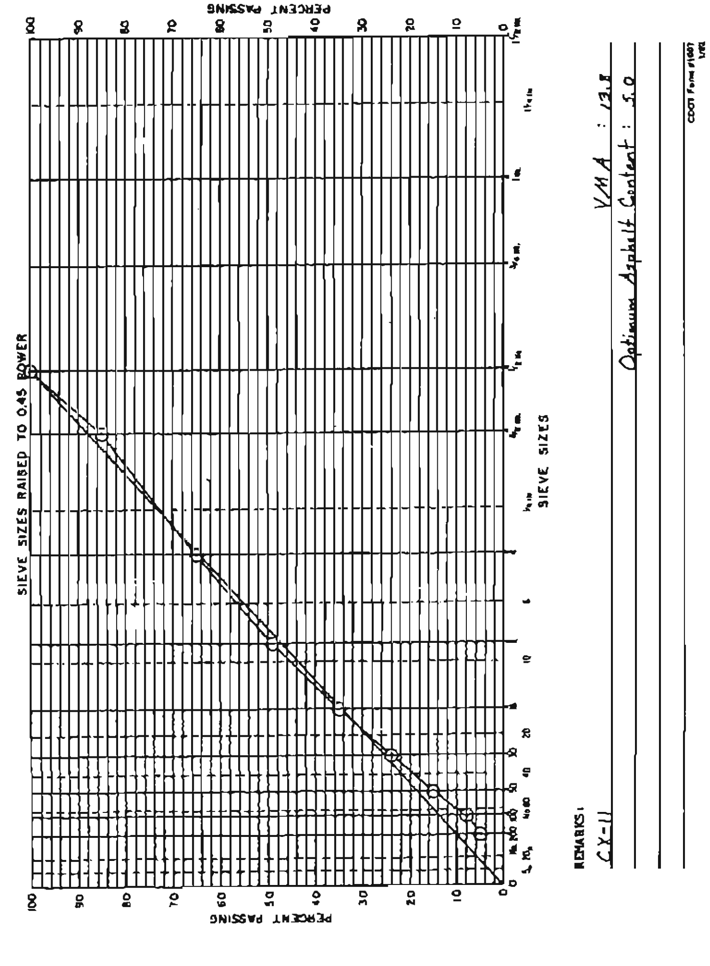
REMARKS:
C-52 VMA: 12.9
Optimum Asphalt Content: 5.0

CDOT Form #1007 1/92

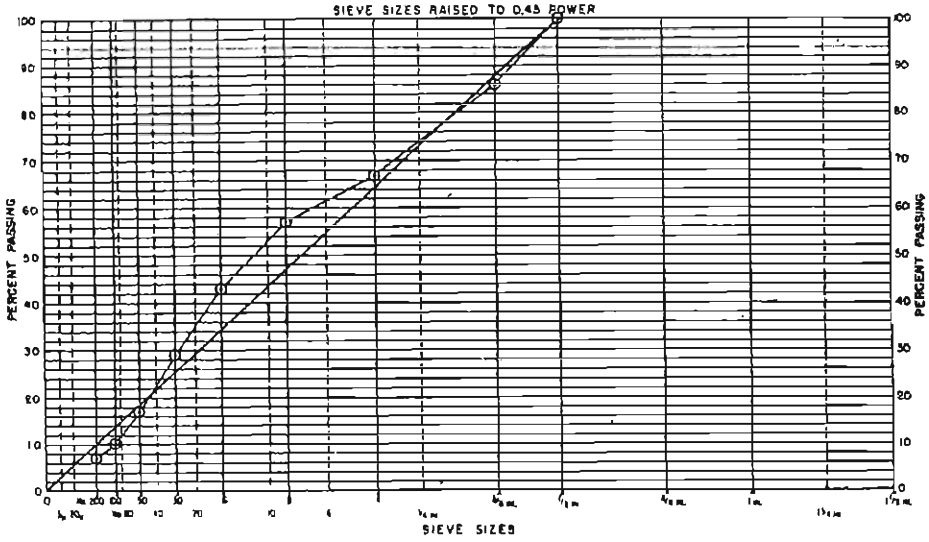

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-54
VMA : 12.9
Optimum Asphalt Content : 4.8
CDOT Form #1067


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-7
VMA : 13.8
Optimum Asphalt Content : 4.7
CDOT Form #1067


COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-41
VMA : 12.9
Optimum Asphalt Content : 4.6
CDOT Form #1067


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-11
VMA : 13.8
Optimum Asphalt Content : 5.0
CDOT Form #1067

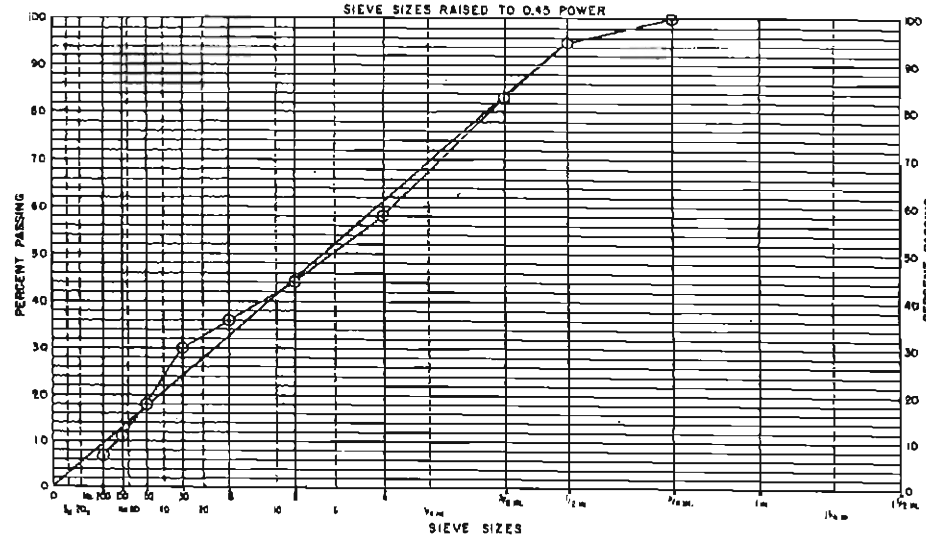
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
CX-35
VMA : 13.82
Optimum Asphalt Content: 4.7

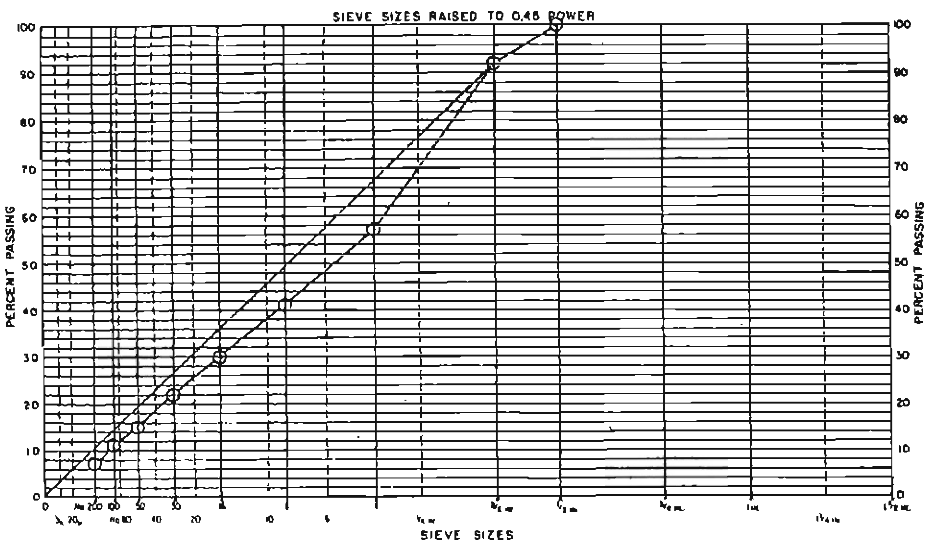
CDOT Form #1007 1/93

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



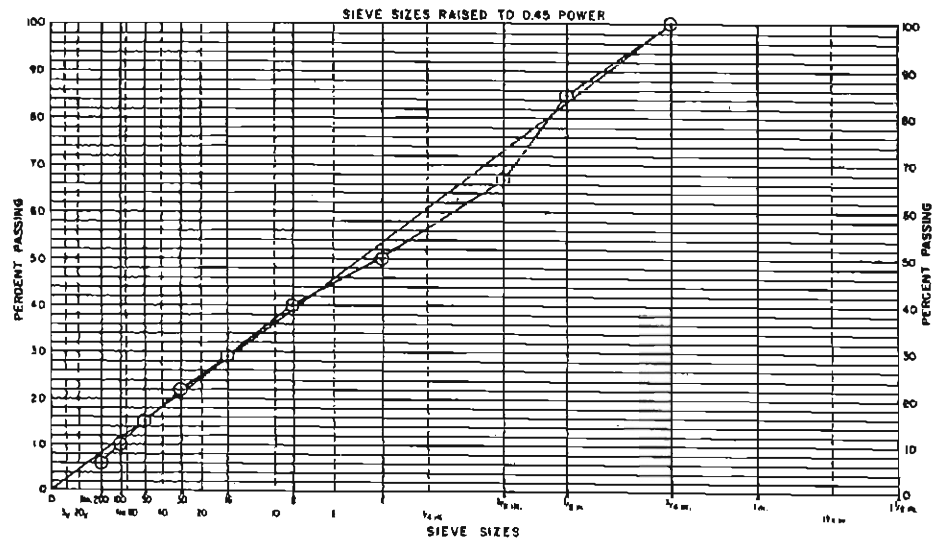
REMARKS:
C-46
VMA : 12.95
Optimum Asphalt Content : 5.0

CDOT Form #1007 1/92



REMARKS:
CX-25
VMA : 13.9
Optimum Asphalt Content: 4.8

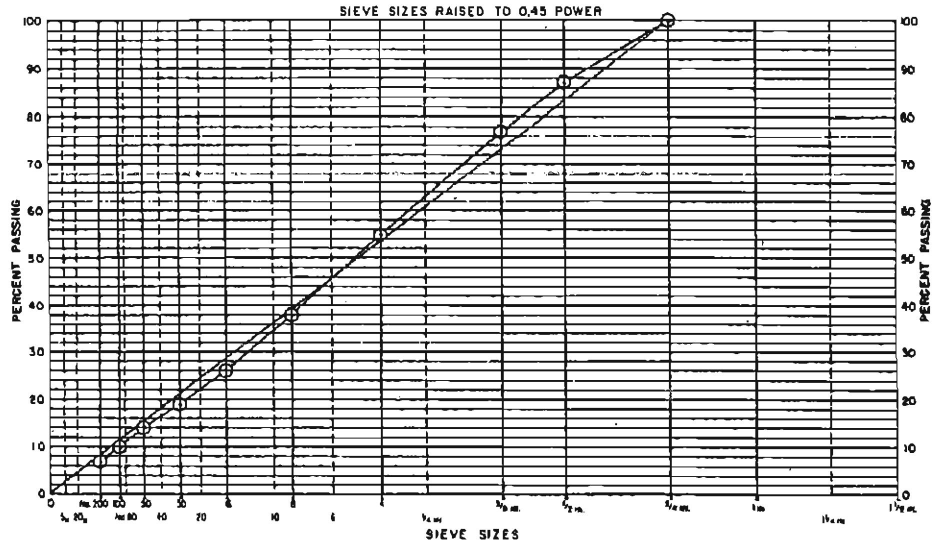
CDOT Form #1007



REMARKS:
C-15
VMA : 13.1
Optimum Asphalt Content: 4.5

CDOT Form #1007

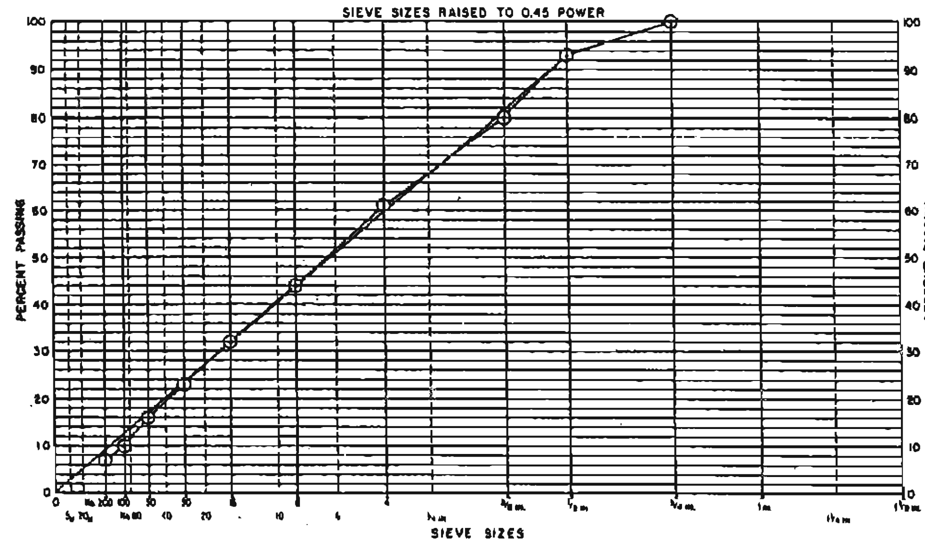
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-23 VMA: 13.1
Optimum Asphalt Content: 4.8

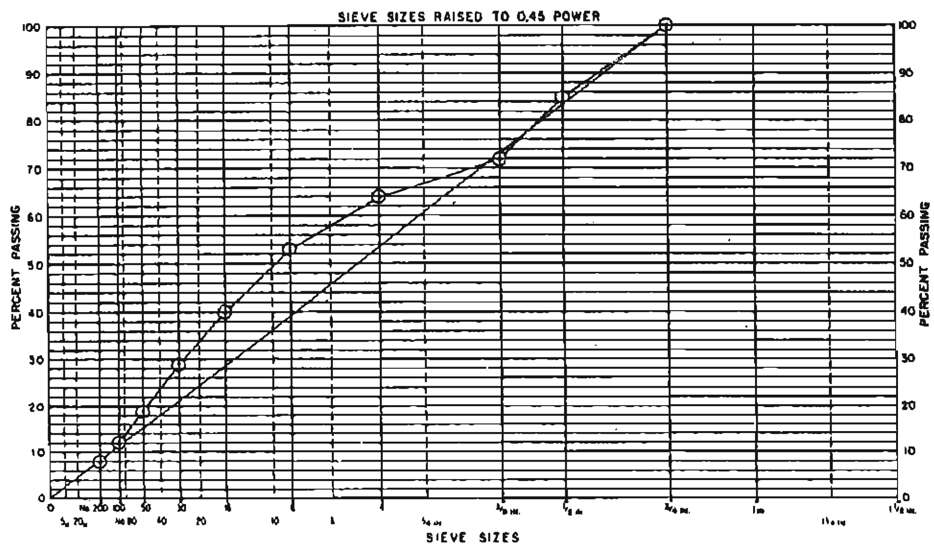
CDOT Form #1097 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



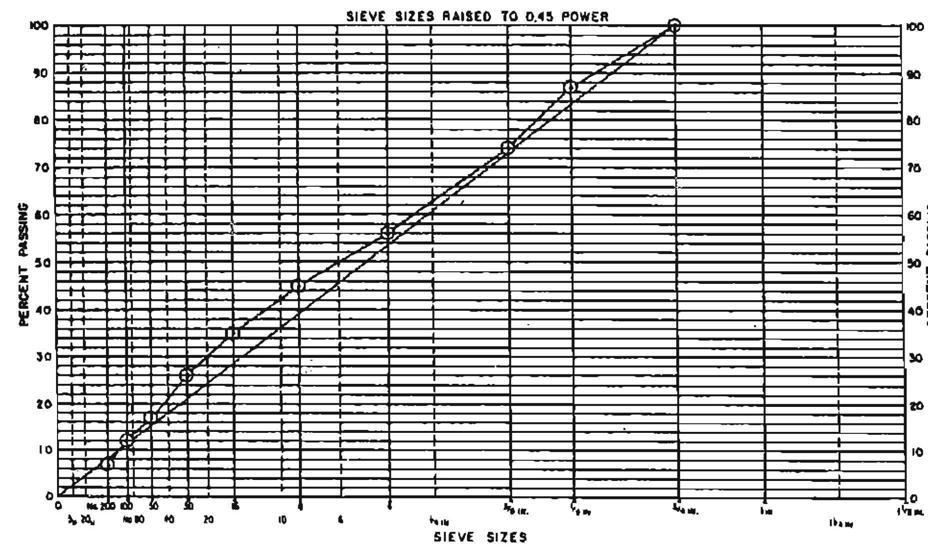
REMARKS:
C-43 VMA: 13.1
Optimum Asphalt Content: 5.2

CDOT Form #1097 1/92



REMARKS:
C-18 VMA: 13.0
Optimum Asphalt Content: 4.7

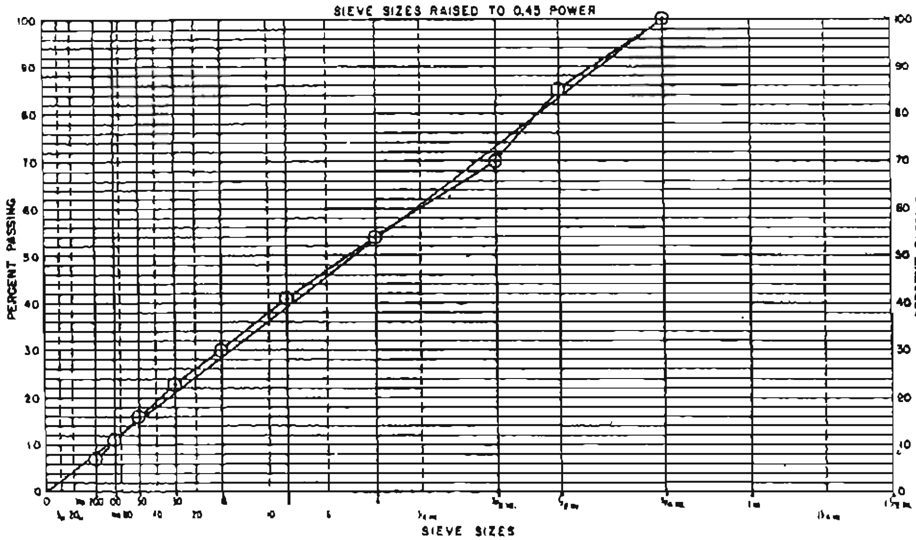
CDOT Form #1097 1/92



REMARKS:
C-10 VMA: 12.4
Optimum Asphalt Content: 4.7

CDOT Form #1097 1/92

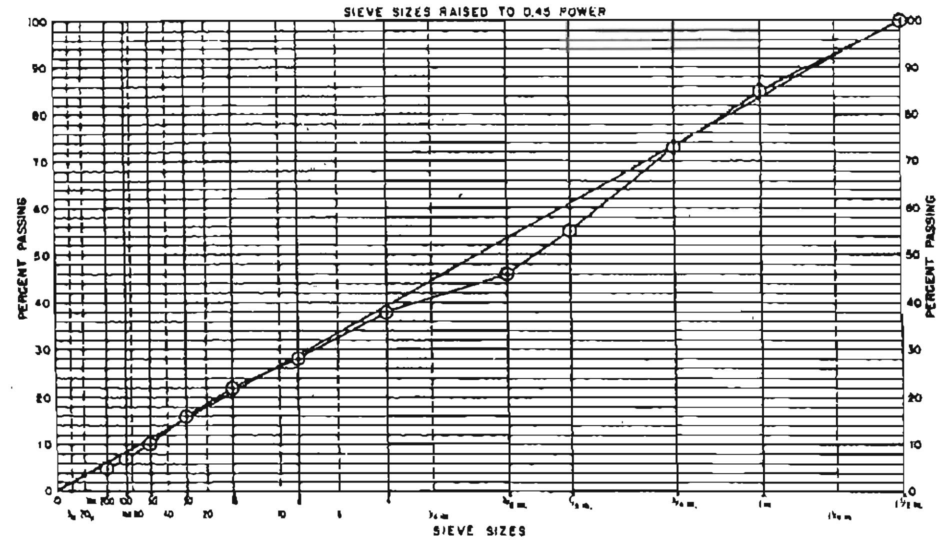
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-7 VMA: 12.8
Optimum Asphalt Content: 4.7

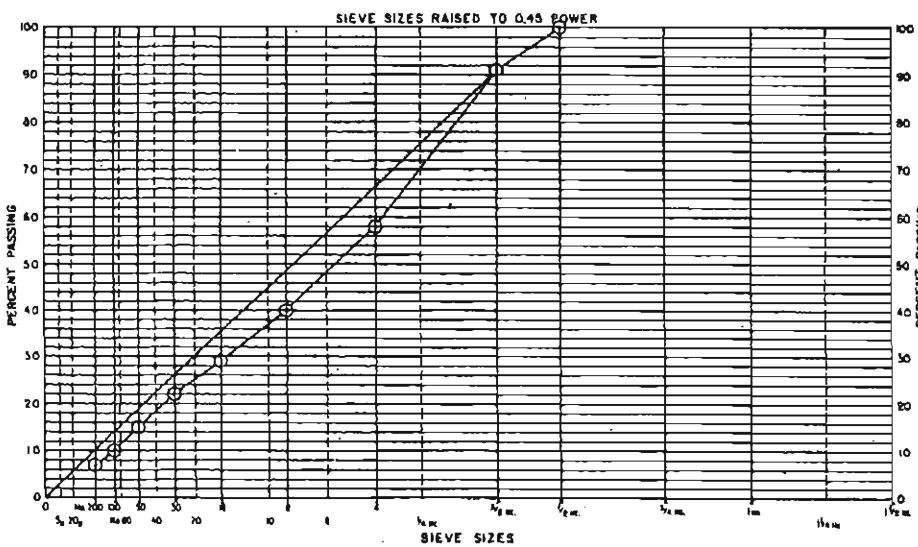
CDOT Form #1087

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



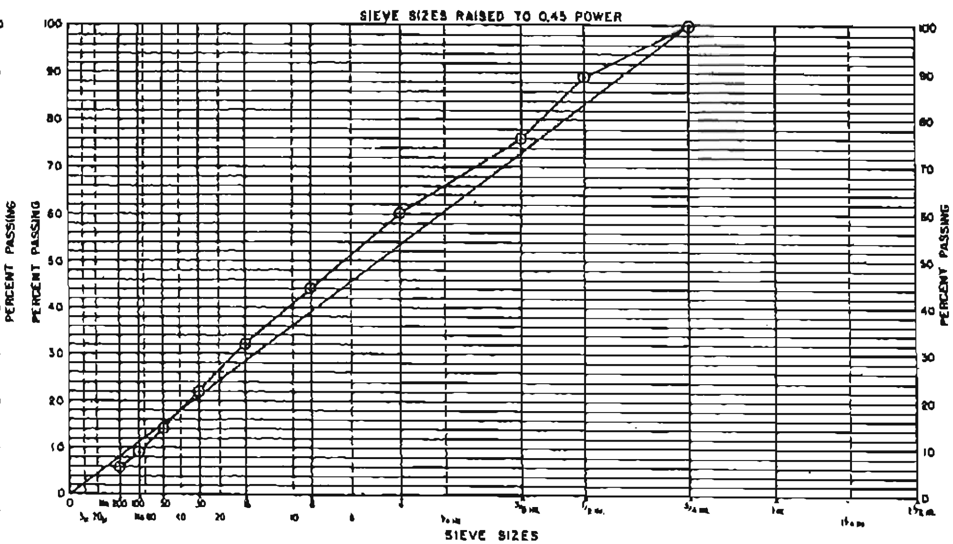
REMARKS:
G-1 VMA: 11.4
Optimum Asphalt Content: 4.0

CDOT Form #1087



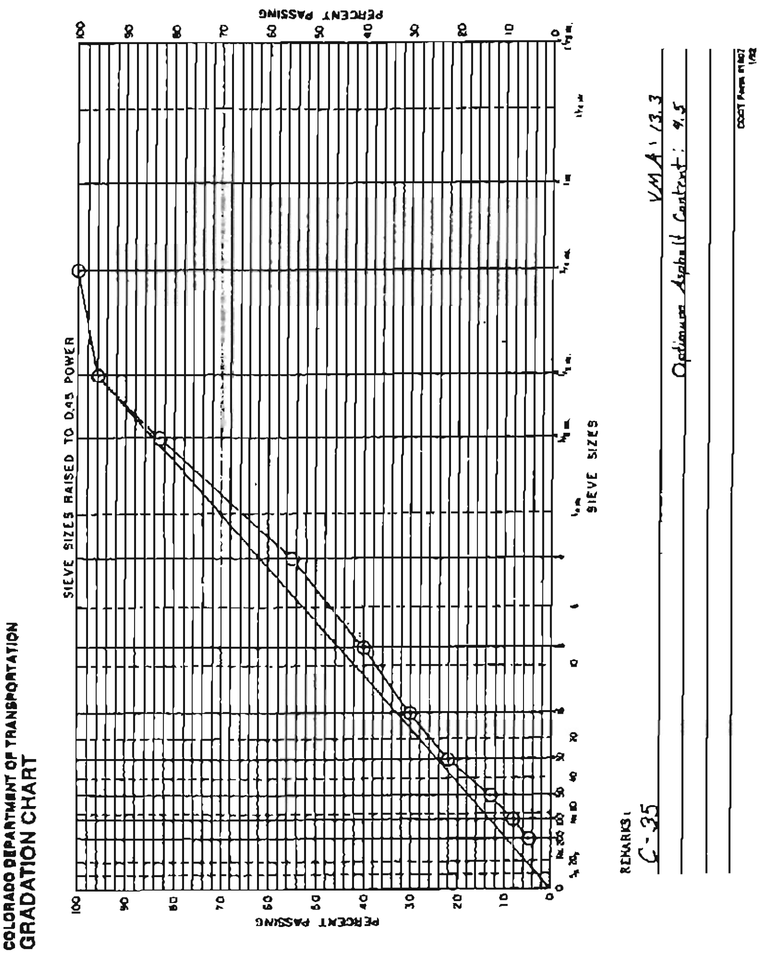
REMARKS:
CX-6 VMA: 14.0
Optimum Asphalt Content: 5.0

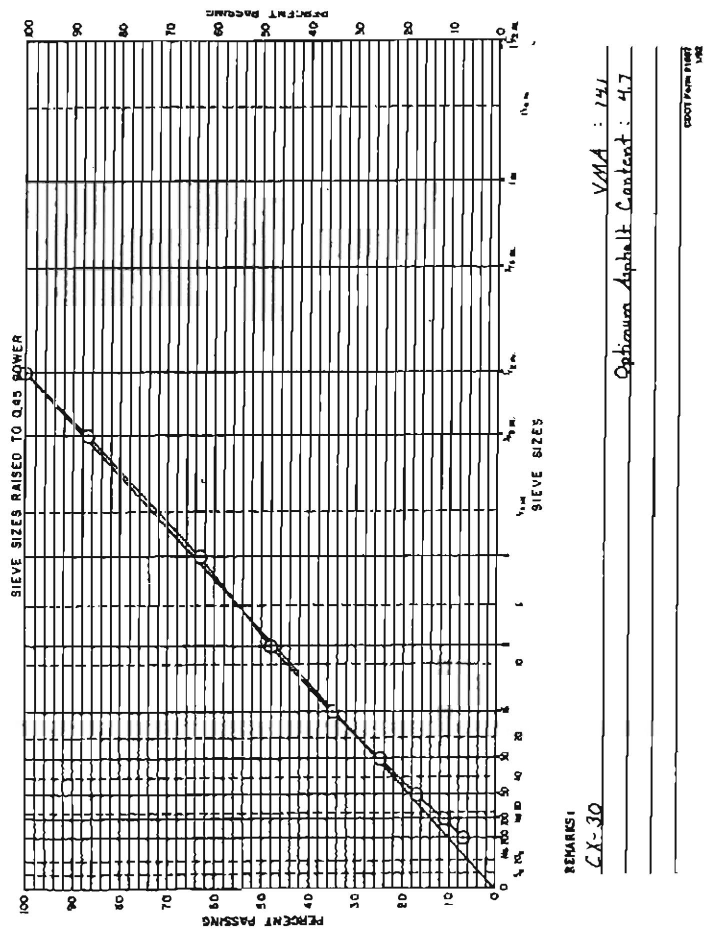
CDOT Form #1087

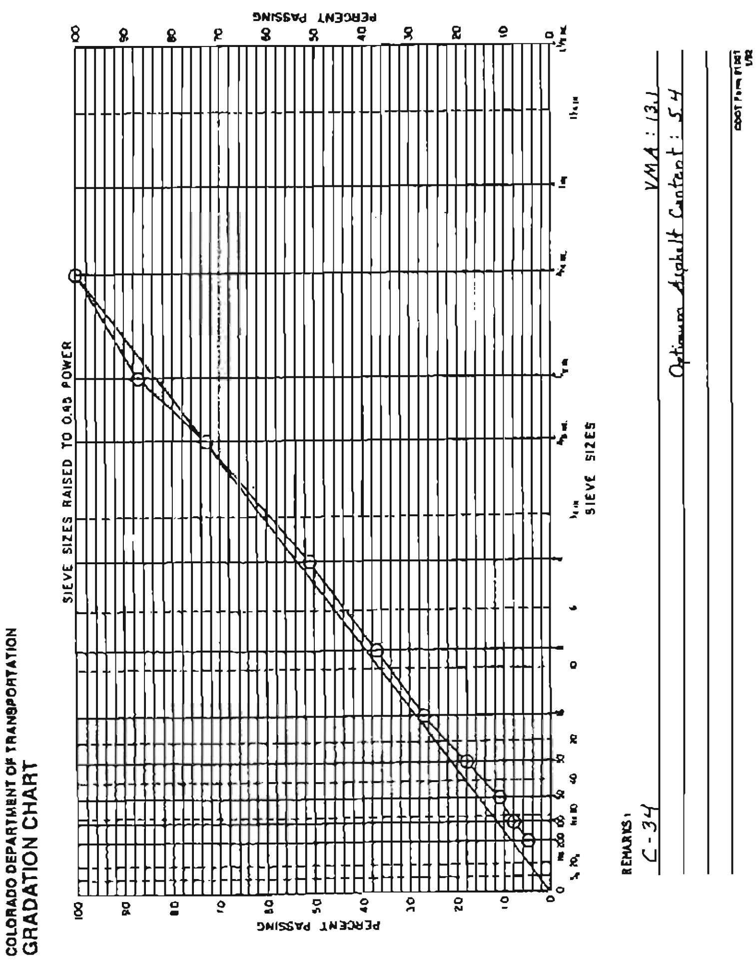


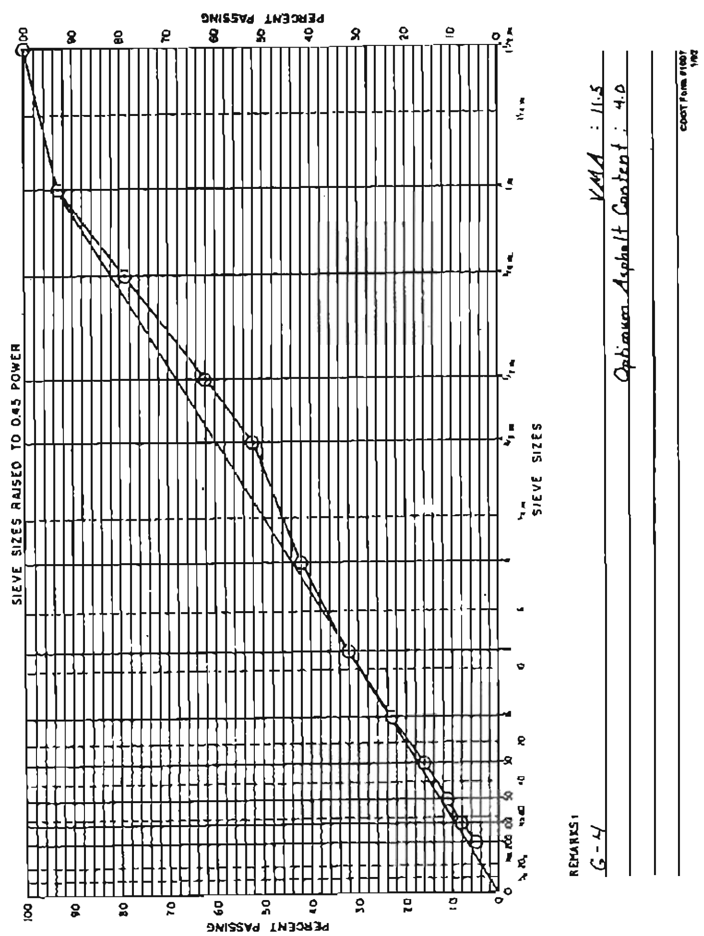
REMARKS:
C-45 VMA: 13.3
Optimum Asphalt Content: 4.5

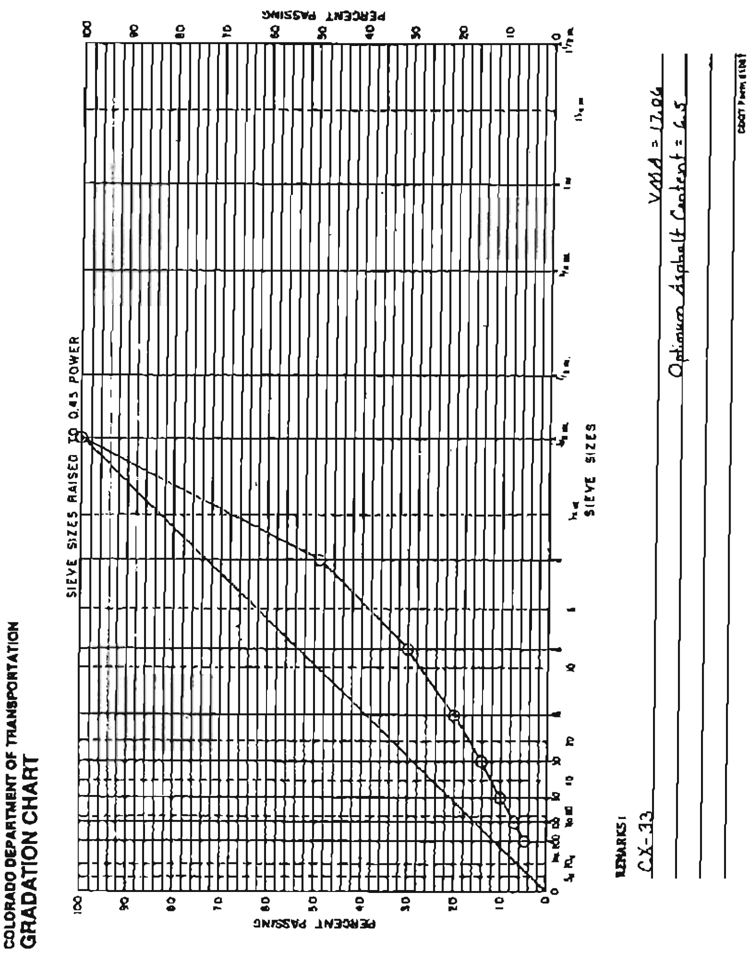
CDOT Form #1087

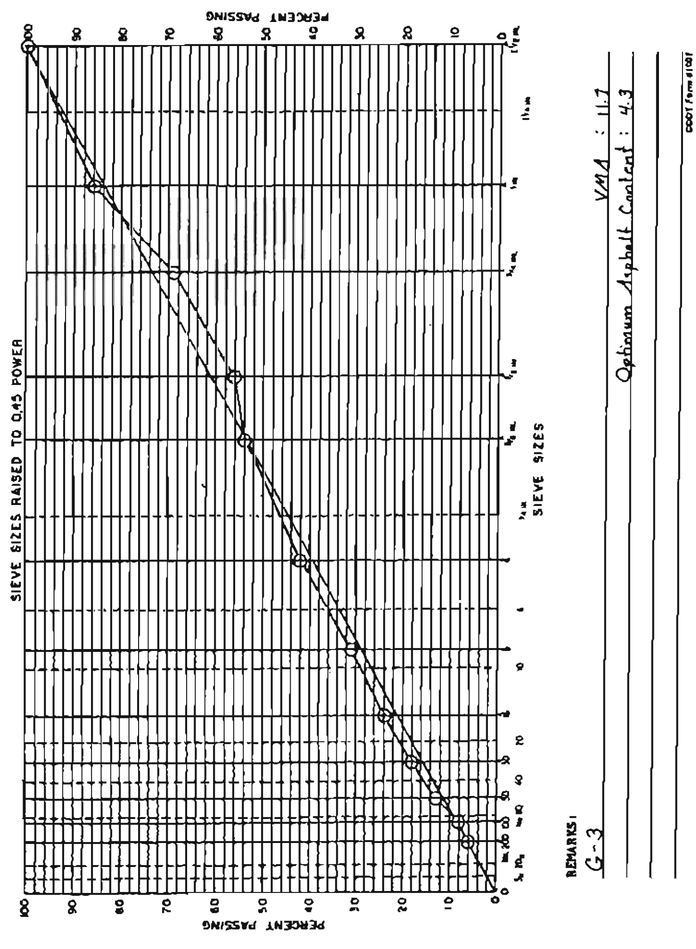

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-35
VMA: 13.3
Optimum Asphalt Content: 4.5

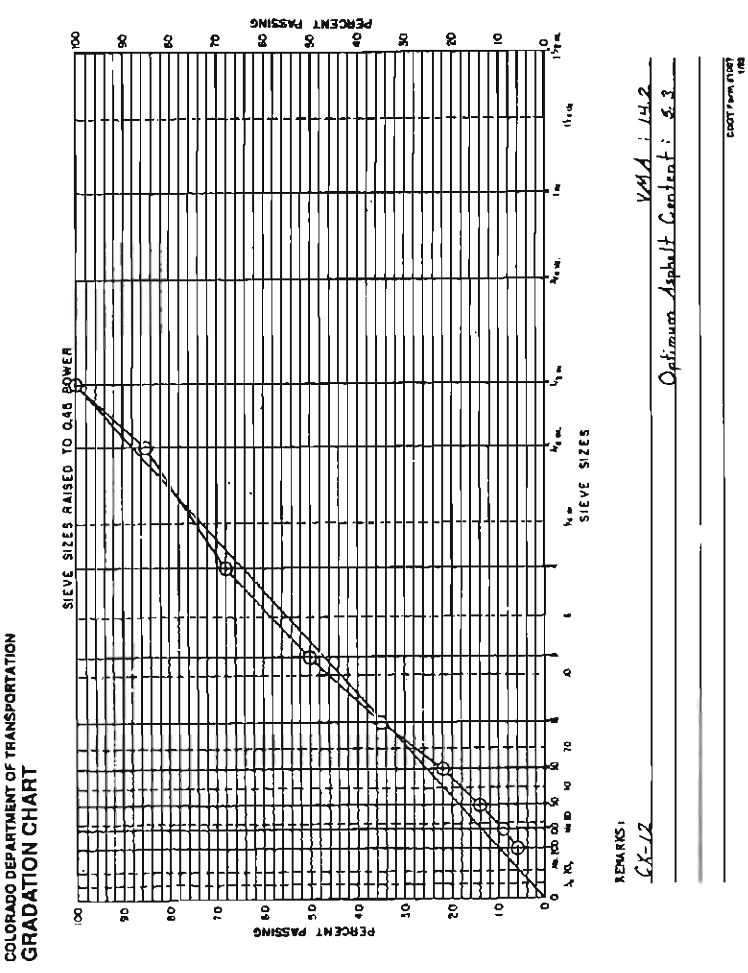

SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-30
VMA: 14.1
Optimum Asphalt Content: 4.7

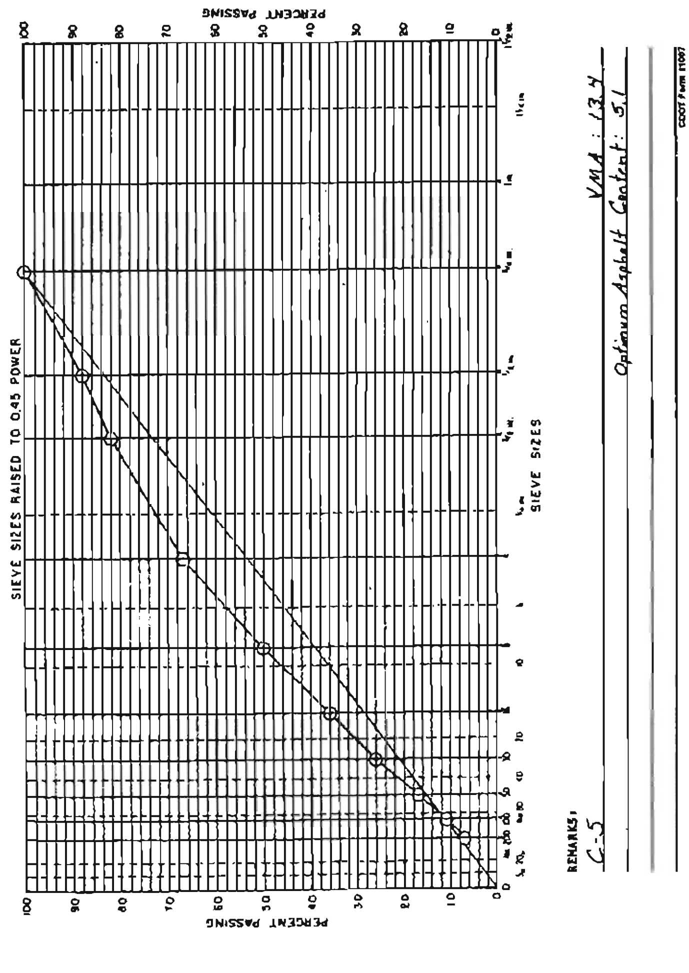

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-34
VMA: 13.1
Optimum Asphalt Content: 5.4

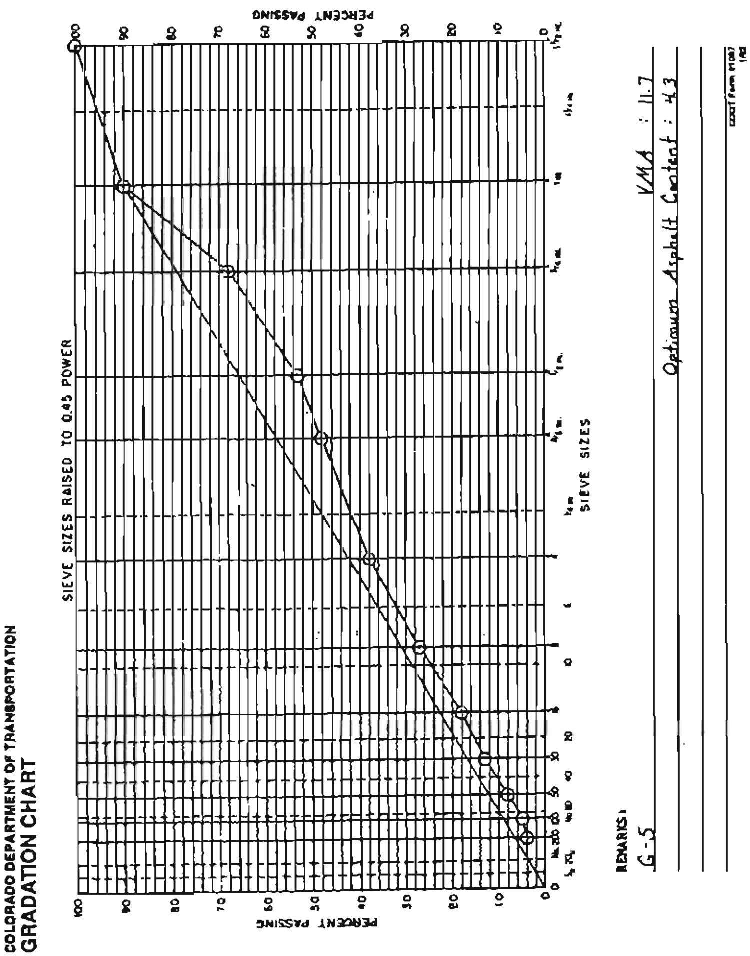

SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
G-4
VMA: 11.5
Optimum Asphalt Content: 4.0

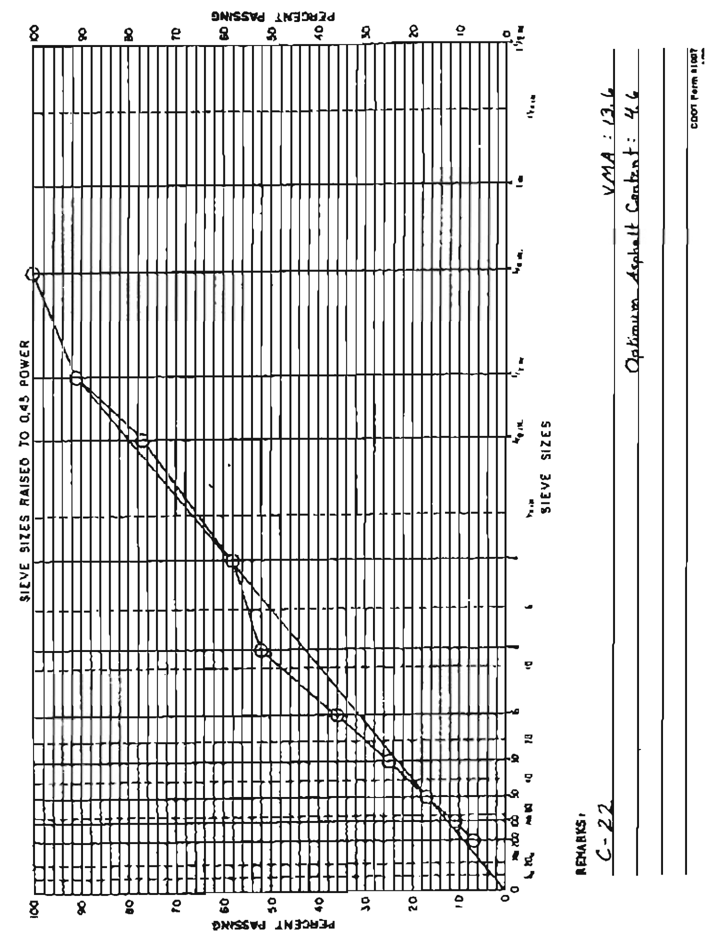

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-33
VMA = 17.06
Optimum Asphalt Content = 6.5

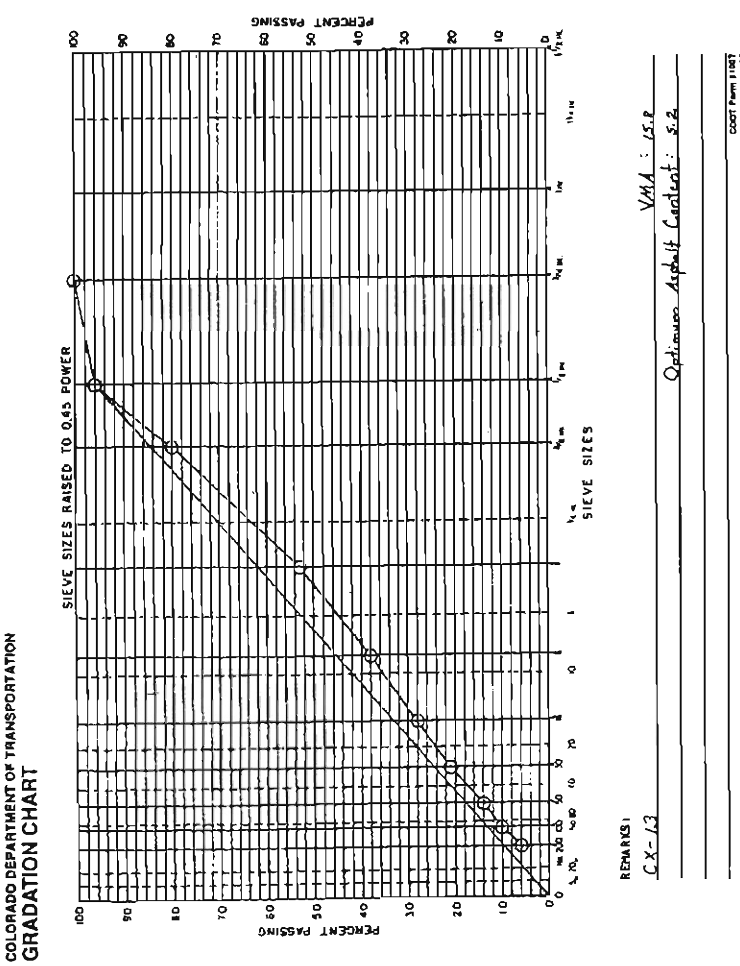

SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
G-3
VMA : 11.1
Optimum Asphalt Content : 4.3

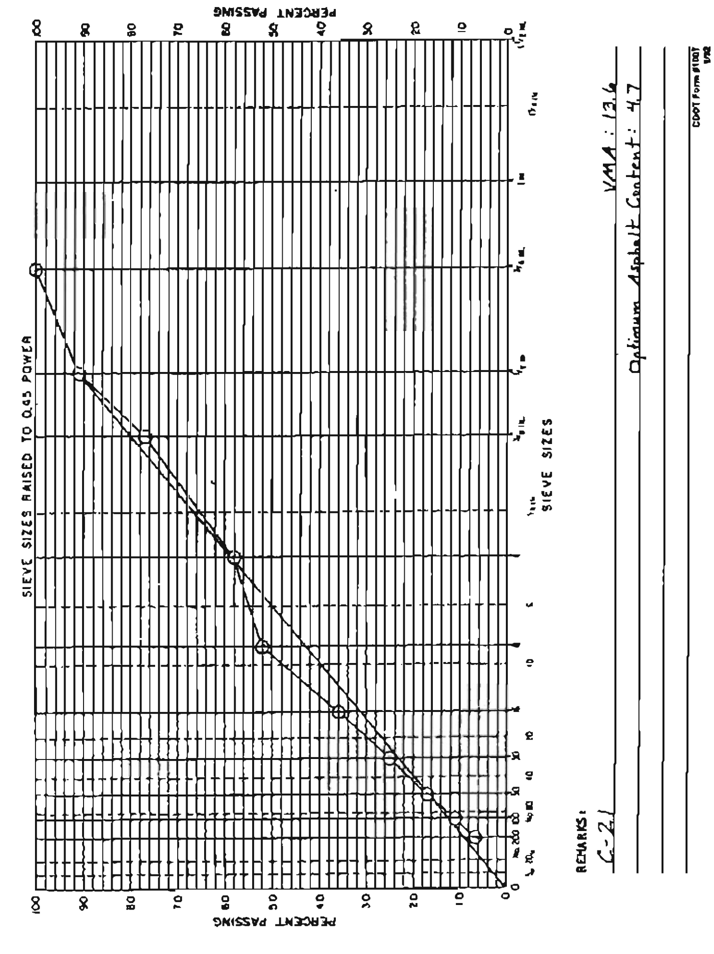

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-12
VMA : 14.2
Optimum Asphalt Content : 5.3


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
G-5
VMA : 13.4
Optimum Asphalt Content : 5.1

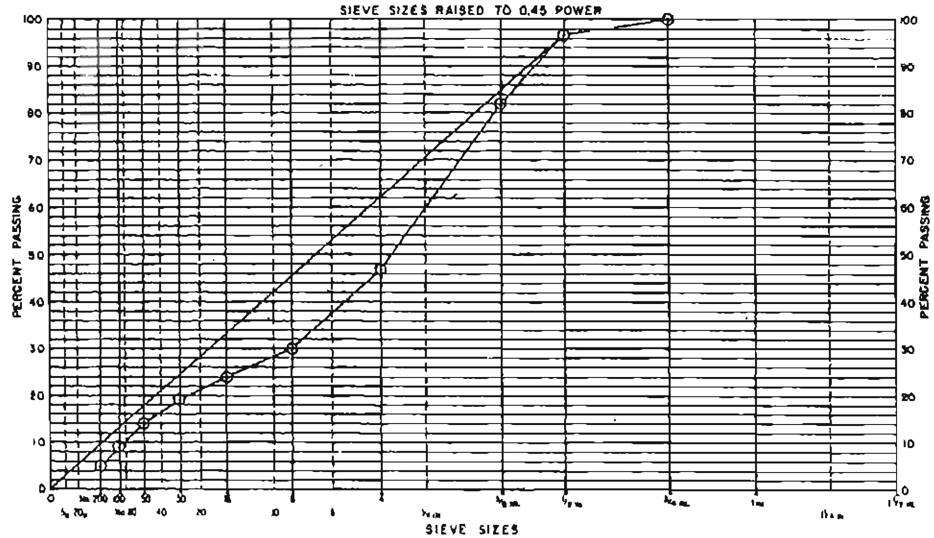

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
G-5
VMA : 11.7
Optimum Asphalt Content : 4.3


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-22
VMA : 13.6
Optimum Asphalt Content : 4.6


COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART
SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
CX-13
VMA : 15.8
Optimum Asphalt Content : 5.2


SIEVE SIZES RAISED TO 0.45 POWER
PERCENT PASSING
SIEVE SIZES
REMARKS:
C-21
VMA : 13.6
Optimum Asphalt Content : 4.7

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



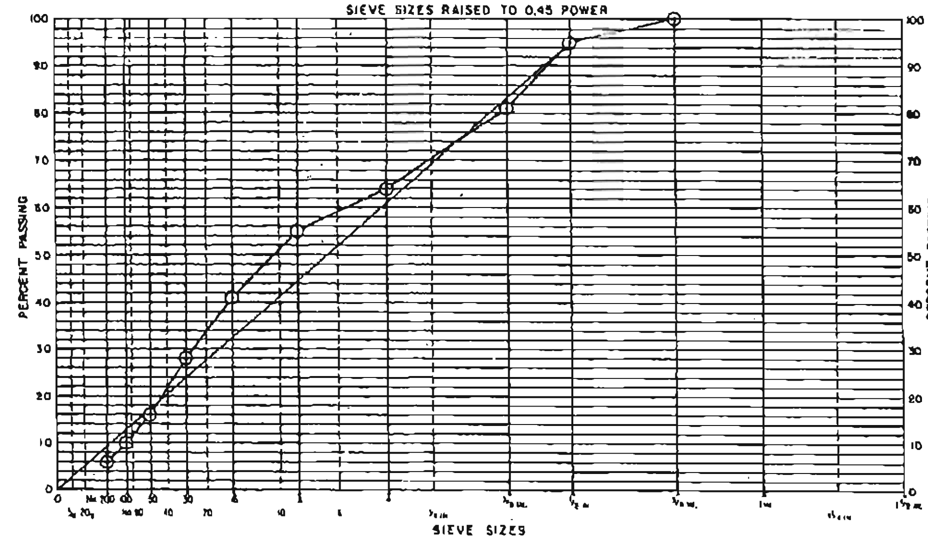
REMARKS:

CX-34 VMA: 12.5

Optimum Asphalt Content: 4.7

CDOT Form #1087

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

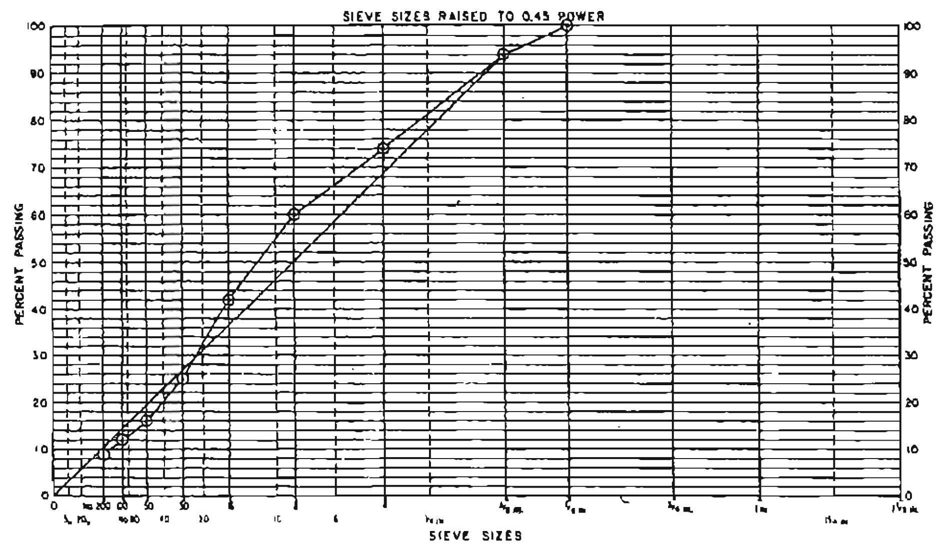


REMARKS:

C-9 VMA: 13.7

Optimum Asphalt Content: 5.5

CDOT Form #1087

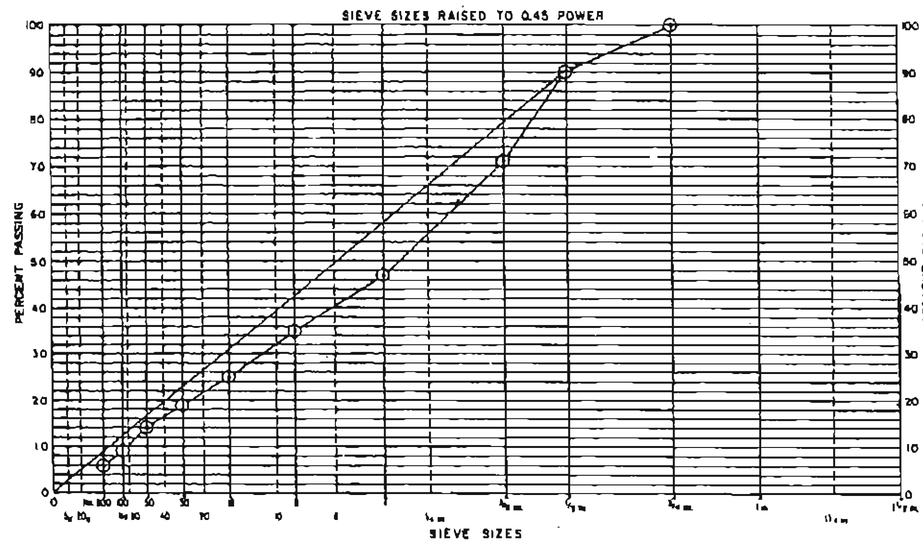


REMARKS:

CX-37 VMA: 14.7

Optimum Asphalt Content: 6.5

CDOT Form #1087



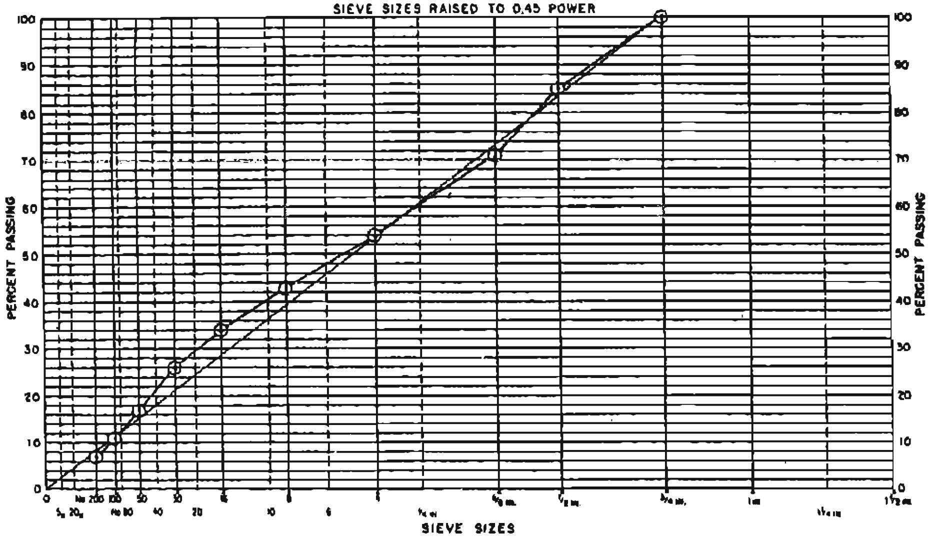
REMARKS:

C-19 VMA: 13.9

Optimum Asphalt Content: 4.7

CDOT Form #1087

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

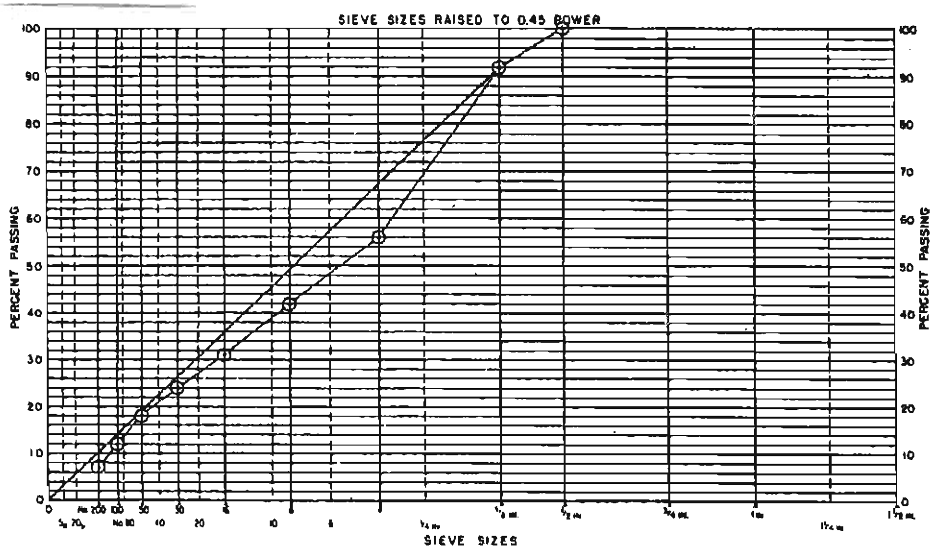


REMARKS:

C-11 VMA: 13.9

Optimum Asphalt Content: 4.7

CDOT Form #1007 1/92



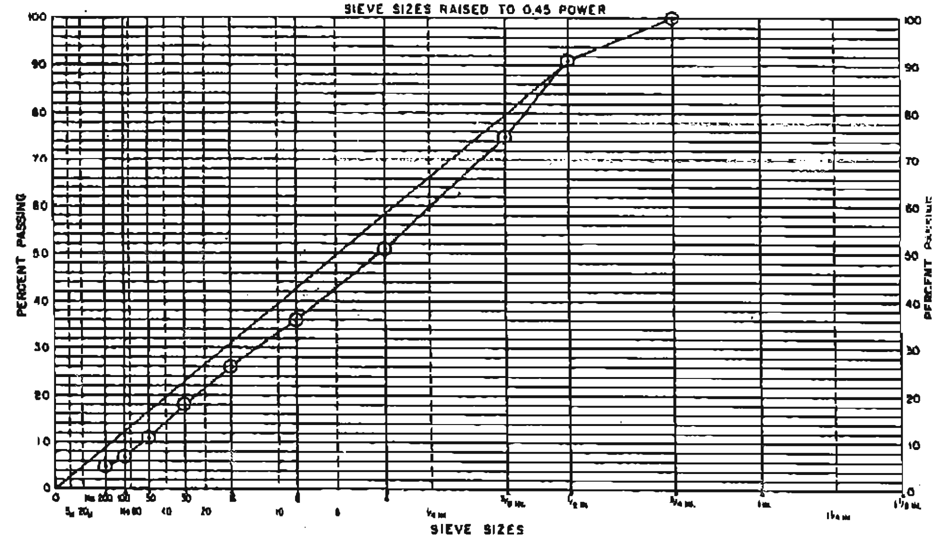
REMARKS:

CX-9 VMA: 14.5

Optimum Asphalt Content: 5.0

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

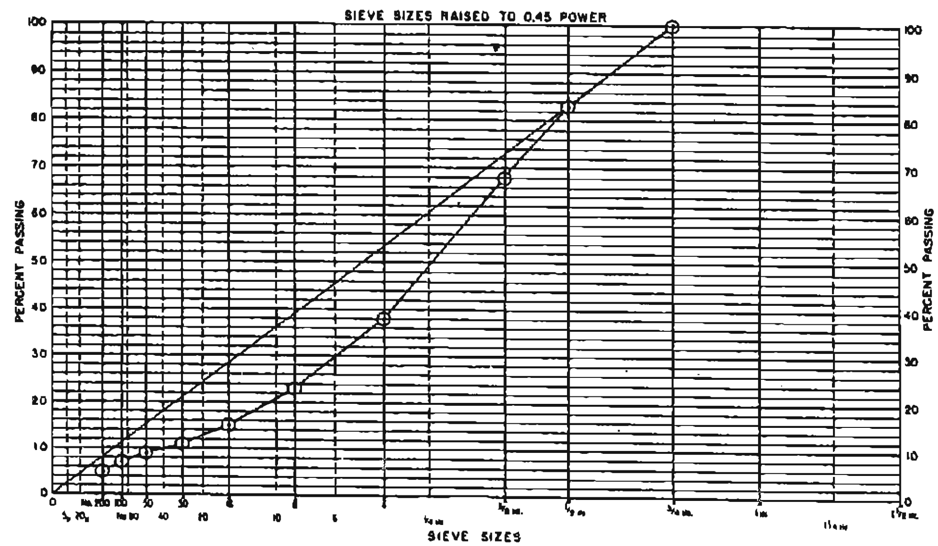


REMARKS:

C-6 VMA: 14.9

Optimum Asphalt Content: 5.9

CDOT Form #1007 1/92



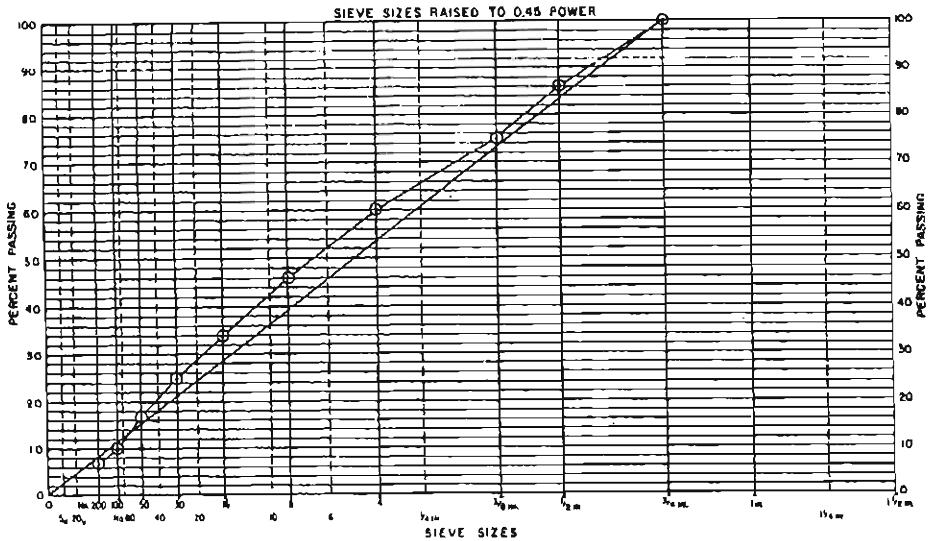
REMARKS:

C-14 VMA: 14.1

Optimum Asphalt Content: 4.6

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



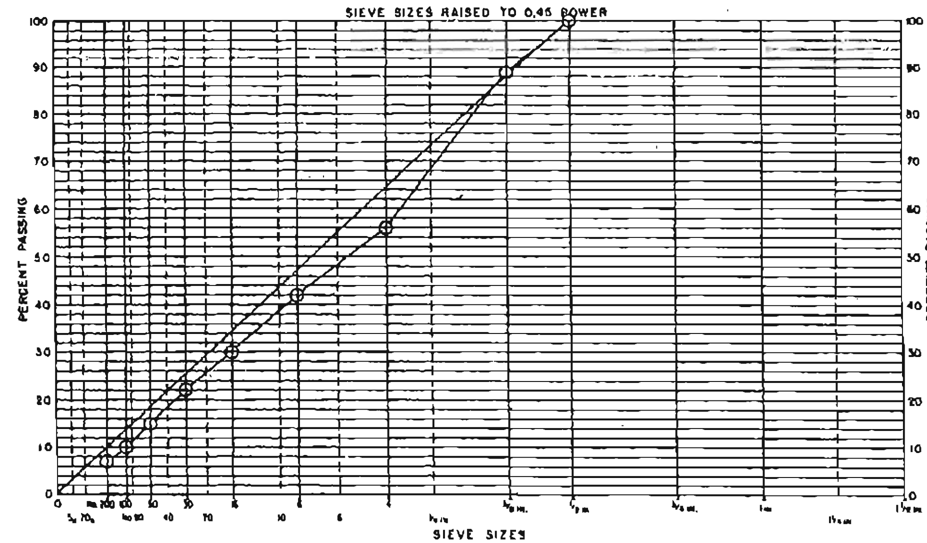
REMARKS:

C-49 VMA: 12.36

Optimum Asphalt Content: 4.3

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

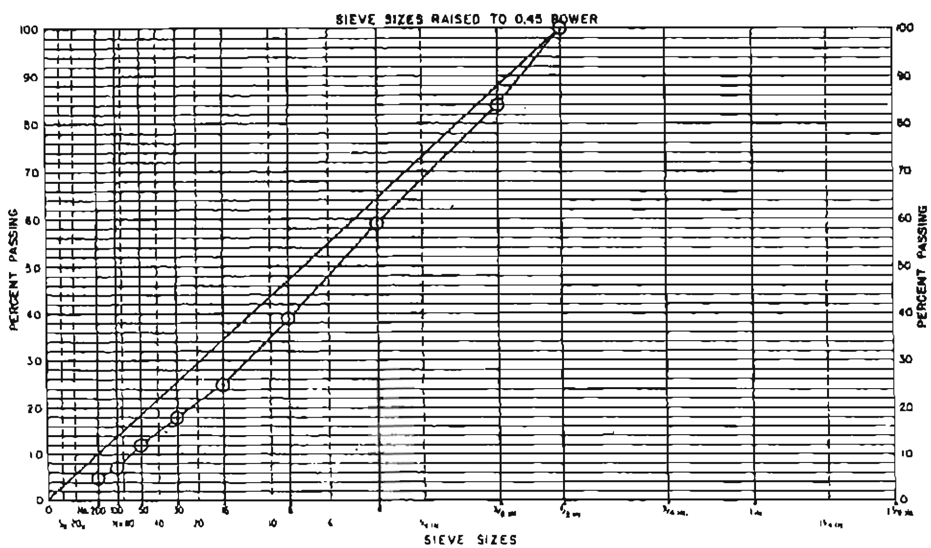


REMARKS:

CX-19 VMA: 15.9

Optimum Asphalt Content: 5.0

CDOT Form #1007 1/92

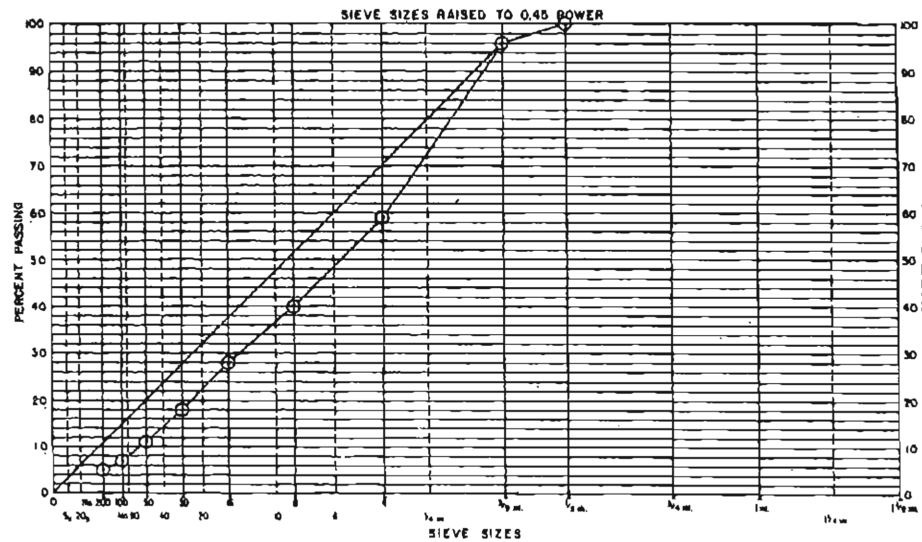


REMARKS:

CX-18 VMA: 14.1

Optimum Asphalt Content: 4.8

CDOT Form #1007



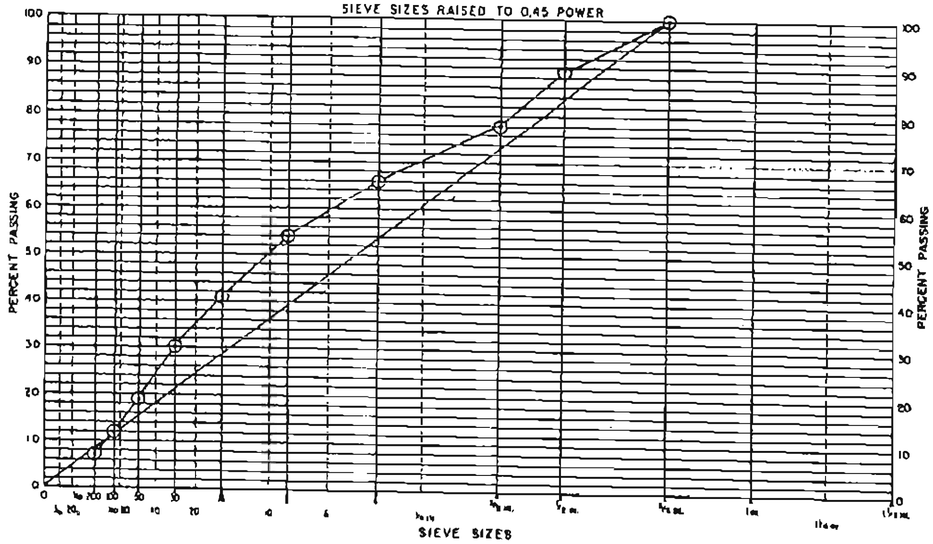
REMARKS:

CX-31 VMA: 18.0

Optimum Asphalt Content: 6.5

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

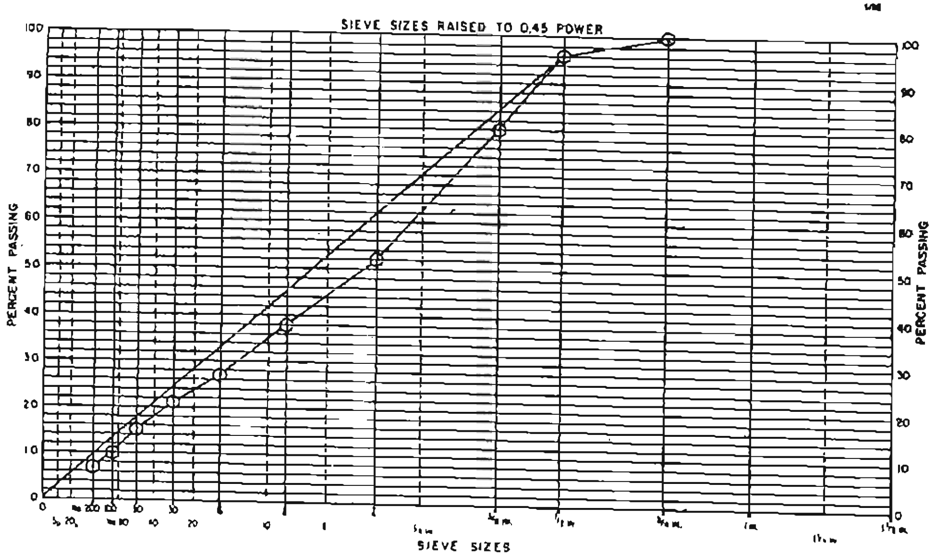


REMARKS: C-33

VMA: 14.3

Optimum Asphalt Content: 5.5

CDOT Form #1007



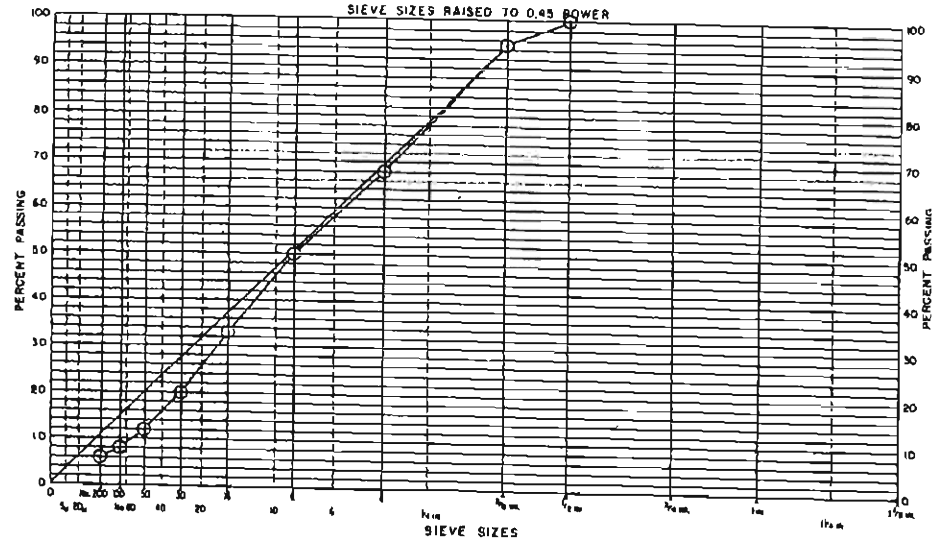
REMARKS: CX-16

VMA: 14.2

Optimum Asphalt Content: 4.7

CDOT Form #1007

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART

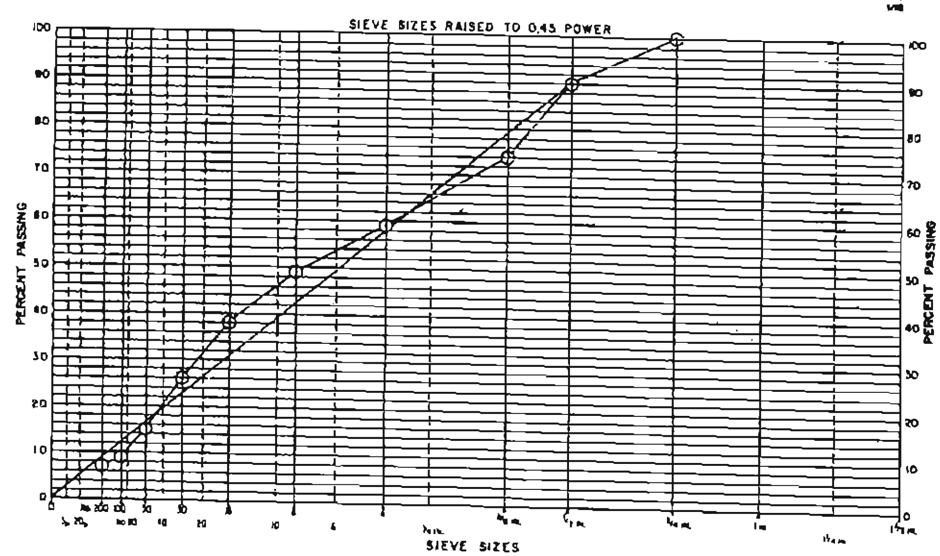


REMARKS: CX-24

VMA: 15.2

Optimum Asphalt Content: 7.0

CDOT Form #1007



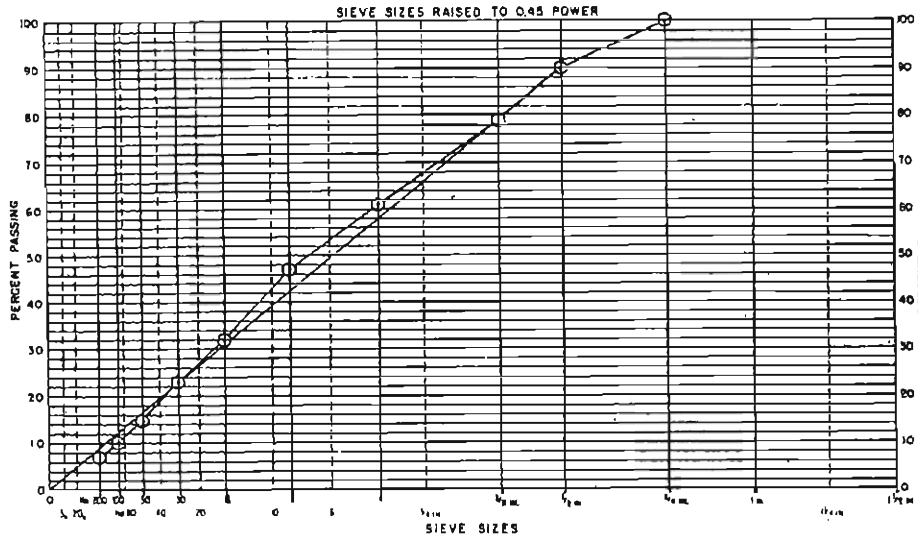
REMARKS: C-32

VMA: 14.3

Optimum Asphalt Content: 5.3

CDOT Form #1007

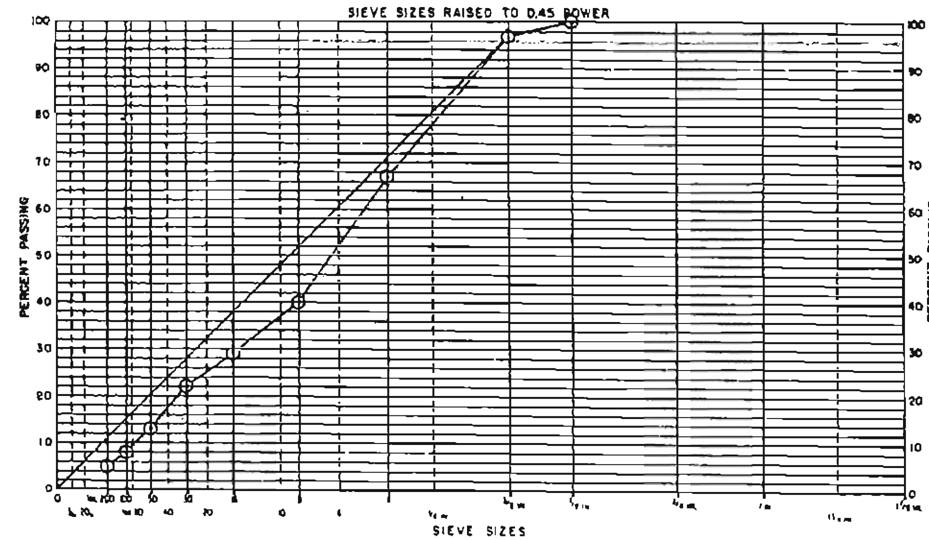
COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



REMARKS:
C-24 VMA : 14.5
Optimum Asphalt Content: 5.0

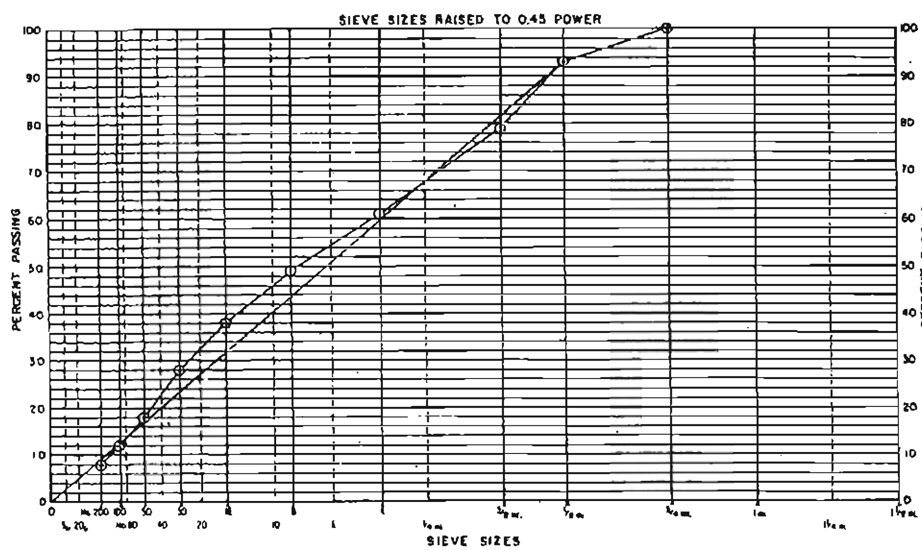
CDOT Form #1007

COLORADO DEPARTMENT OF TRANSPORTATION
GRADATION CHART



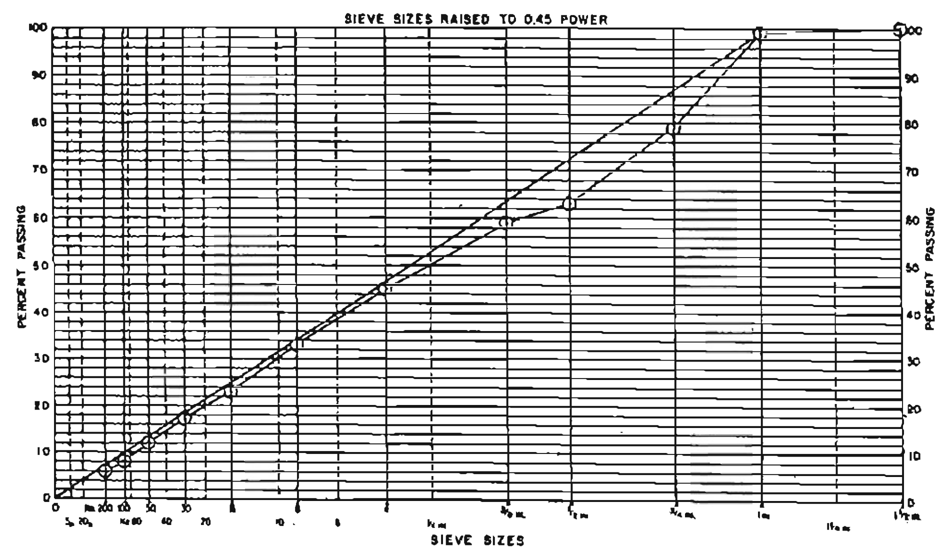
REMARKS:
CX-27 VMA : 15.5
Optimum Asphalt Content: 5.7

CDOT Form #1007



REMARKS:
C-4 VMA : 14.6
Optimum Asphalt Content: 4.9

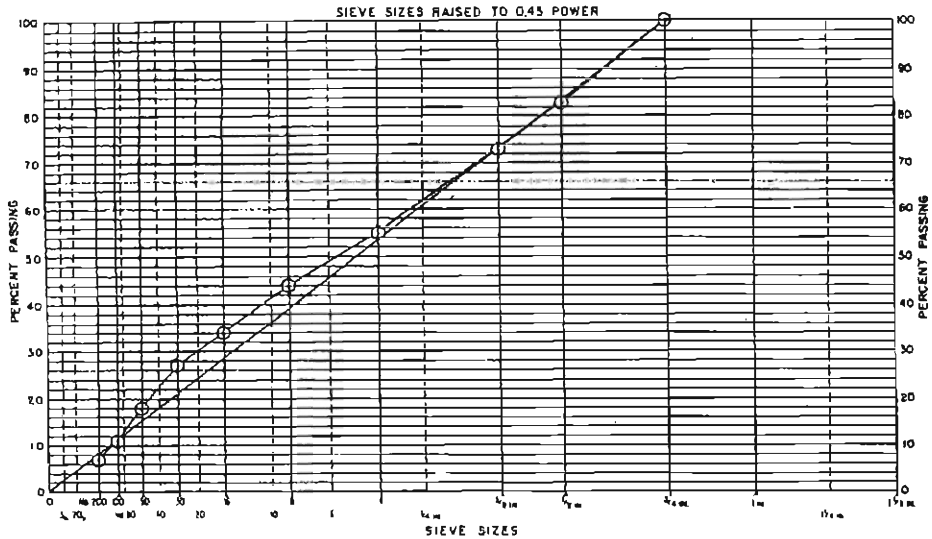
CDOT Form #1007



REMARKS:
G-2 VMA : 12.9
Optimum Asphalt Content: 4.2

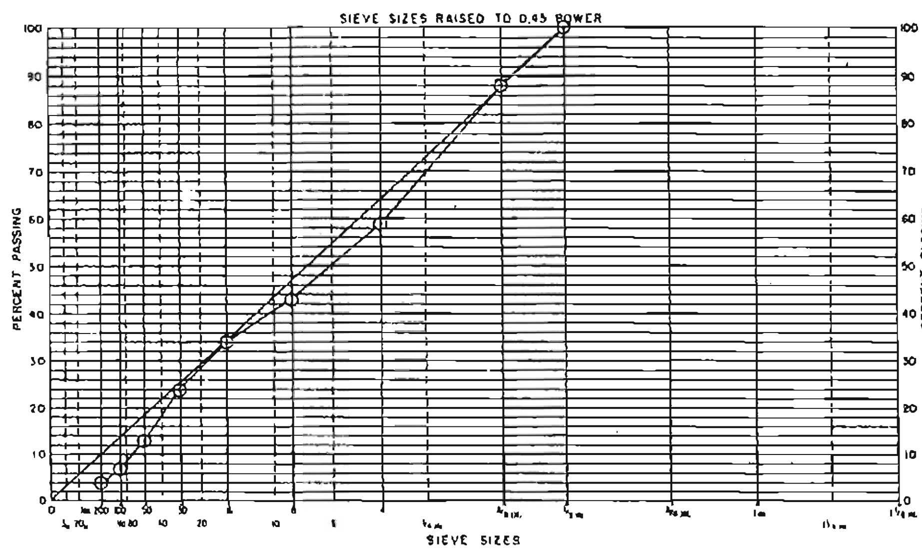
CDOT Form #1007

GRADATION CHART



REMARKS:
C-24A
VMA : 13.1
Optimum Asphalt Content : 4.7

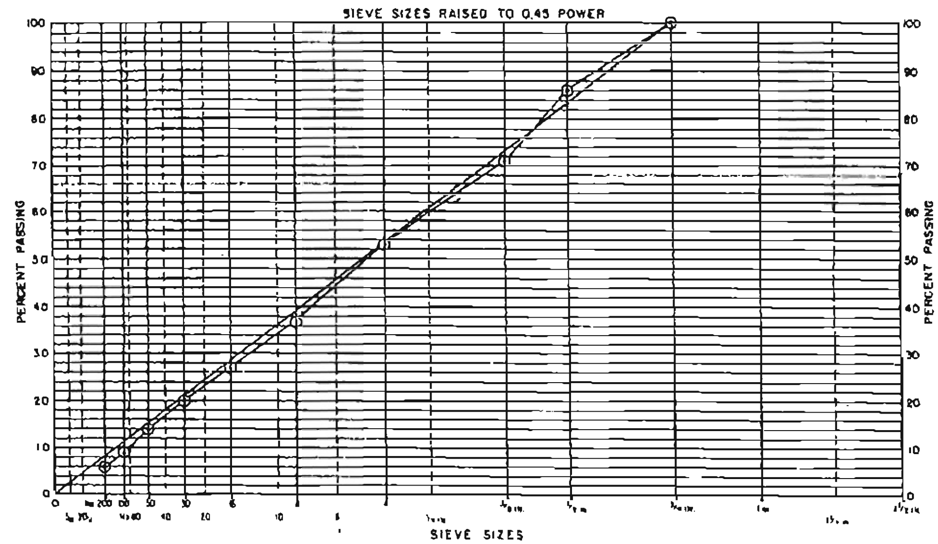
CDOT Form #1007 1/92



REMARKS:
CX-28
VMA : 16.4
Optimum Asphalt Content : 5.4

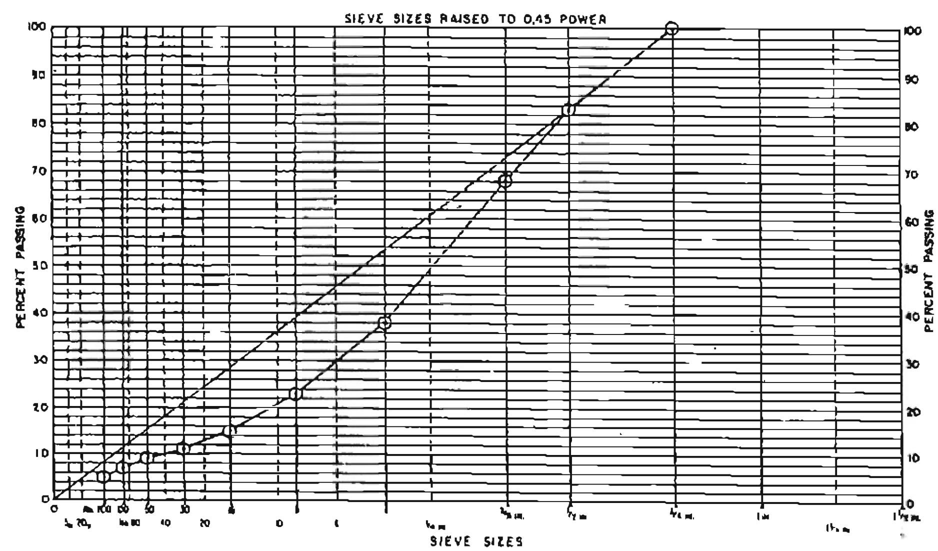
CDOT Form #1007 1/92

GRADATION CHART



REMARKS:
C-48
VMA : 13.52
Optimum Asphalt Content : 4.9

CDOT Form #1007 1/92

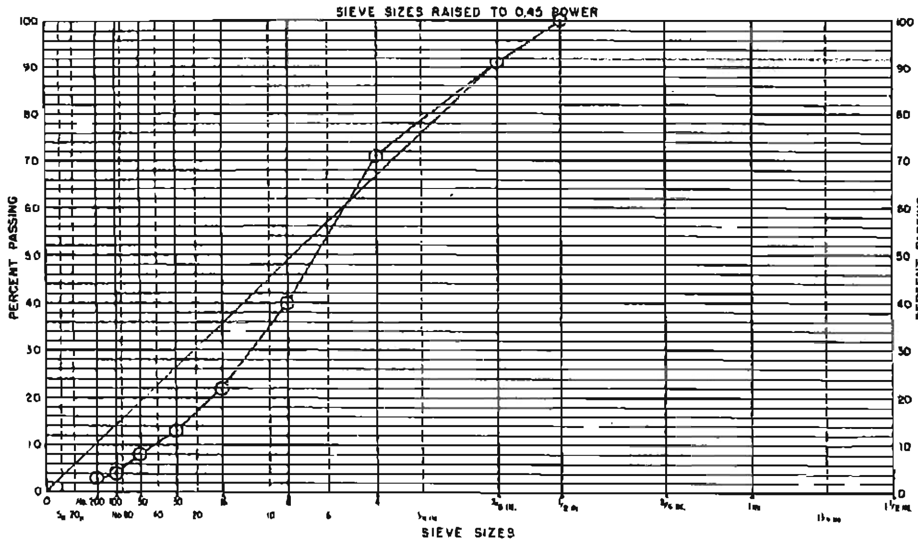


REMARKS:
C-13
VMA : 16.2
Optimum Asphalt Content : 5.0

CDOT Form #1007 1/92

COLORADO DEPARTMENT OF TRANSPORTATION

GRADATION CHART



REMARKS:

CX-23

VMA : 18.0

Optimum Asphalt Content : 6.8

CDOT Form #1097 1/93