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Methods of Predicting Aggregate Voids

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16 Abstract

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The 0.45 Power Curve Void Prediction Method yields more consistent predictions of percent voids in combined aggregate than the Coarseness Factor Void Prediction Method. The Coarseness Factor Method requires less calibration and physical testing than the 0.45 Power Curve Void Prediction Method. Neither the 0.45 Power Curve nor the Coarseness Factor Void Prediction Method are accurate for combined aggregate that deviates substantially – more than 15% on an individual sieve size – from the 0.45 maximum density line. Well-graded aggregate showed less estimation error than aggregate that was not well-graded using the coarseness factor void prediction method.

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Methods of Predicting Aggregate Voids

Final Report

Prepared by

Danny Smyl

A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Percent voids in combined aggregates vary significantly. Simplified methods of predicting aggregate voids were studied to determine the feasibility of a range of gradations using aggregates available in Kansas. The 0.45 Power Curve Void Prediction Method and the Coarseness Factor Method were tested using thirty-six combined aggregate gradations, most meeting KDOT gradation standards.

The 0.45 Power Curve Void Prediction Method yields more consistent predictions of percent voids in combined aggregate than the Coarseness Factor Void Prediction Method. The Coarseness Factor Method requires less calibration and physical testing than the 0.45 Power Curve Void Prediction Method. Neither the 0.45 Power Curve nor the Coarseness Factor Void Prediction Method are accurate for combined aggregate that deviates substantially – more than 15% on an individual sieve size – from the 0.45 maximum density line. Well-graded aggregate showed less estimation error than aggregate that was not well-graded using the coarseness factor void prediction method.

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Chapter 1: 0.45 Power Curve Void Prediction Method

1.1 Introduction

The 0.45 Power Curve Void Prediction Method was developed at KDOT as an experimental method of predicting combined aggregate voids. The 0.45 Power Curve Void Prediction Method will be covered in this chapter.

1.1.1 Role of Maximum Density Line (MDL)

Maximum density lines are theoretical lines included on the 0.45 power curve that represent the gradation that would produce the maximum bulk density of an aggregate gradation (MoDOT 2005). The maximum density line is determined on the basis of a nominal maximum size aggregate (NMSA). Generally, the NMSA is selected as one aggregate size larger than the first aggregate sieve size that retains more than 5% or 10%. For the void prediction method, 5% was selected to decrease variability in the maximum density line due to small fluctuations in NMSA.

If the composite gradation – tested using the KT-2 test method of sieve analysis, which reflects AASHTO T-27 – passes below the maximum density line, the gradation is designated coarse. If the composite gradation passes above the maximum density line, the gradation is designated fine. Figure 1.1 depicts coarse and fine gradations on the 0.45 Power Curve.

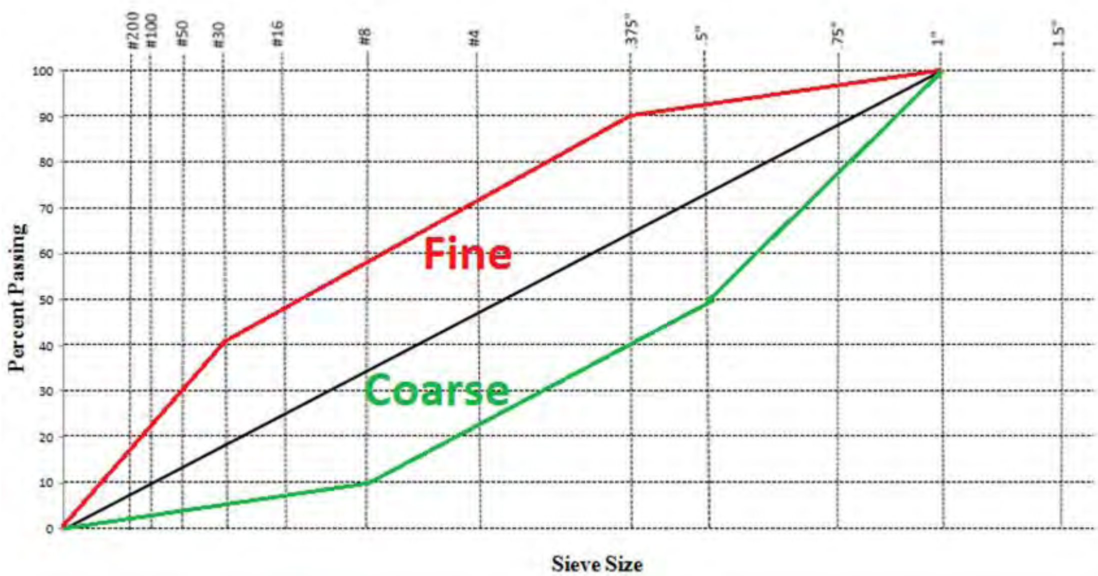

FIGURE 1.1
0.45 Power Curve Combined Aggregate Gradation Depiction

Gap-graded combined aggregate contains missing fractions of aggregate sieve sizes. These gradations may vary significantly from the maximum density line and may produce more or less dense combined aggregate than a gradation that lies exactly on the maximum density line. Variation in combined aggregate density may be caused by aggregate angularity, differences in coarse/fine aggregate specific gravity and aggregate shape factor. Figure 1.2 depicts gap gradation.

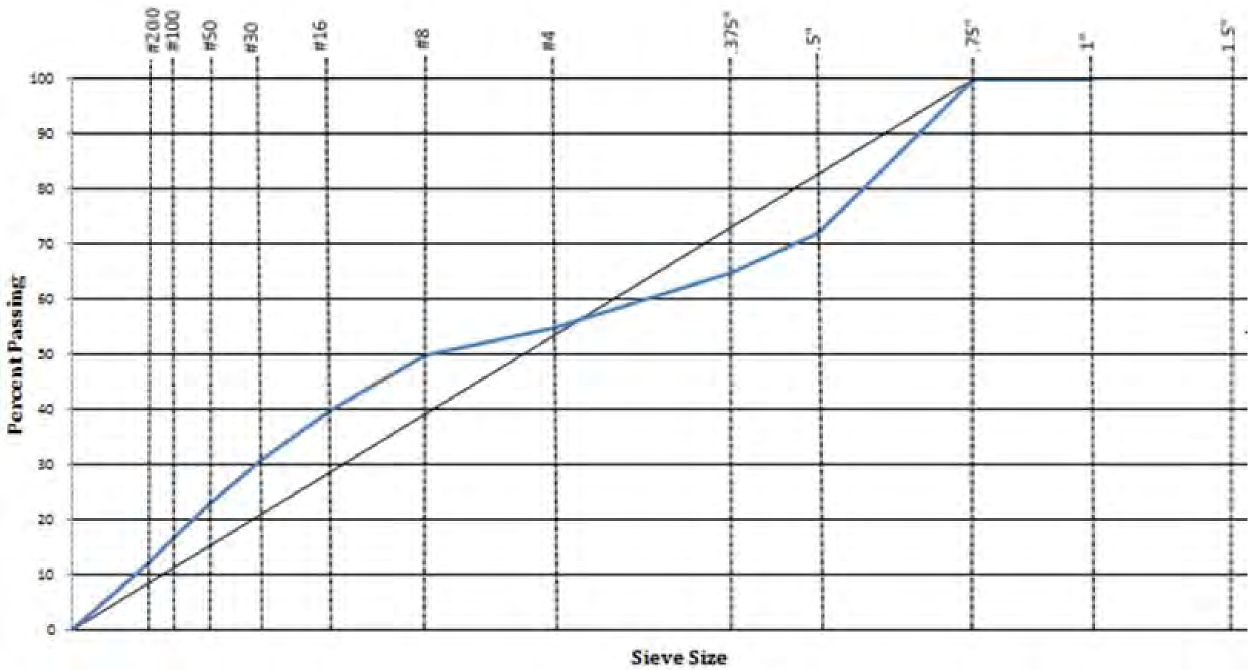

FIGURE 1.2
Gap Gradation Example

1.1.2 Linearization of Aggregate Fractions

Removing a single sieve size from a gradation that lies exactly on the maximum density line changes the dry-rodded bulk density and voids of a combined aggregate mixture – combined aggregate may be tested for percent voids using the KT-5 test method, which reflects AASHTO T-19. An empirical example of the effect of removed aggregate sieve sizes – below the 0. 375 in. sieve – from the maximum density line (NMSA = 1in.) and percent voids are depicted in figures 1.3 and 1.4, the data is from combined aggregate consisting of crushed limestone coarse aggregate and sand tested at KDOT.

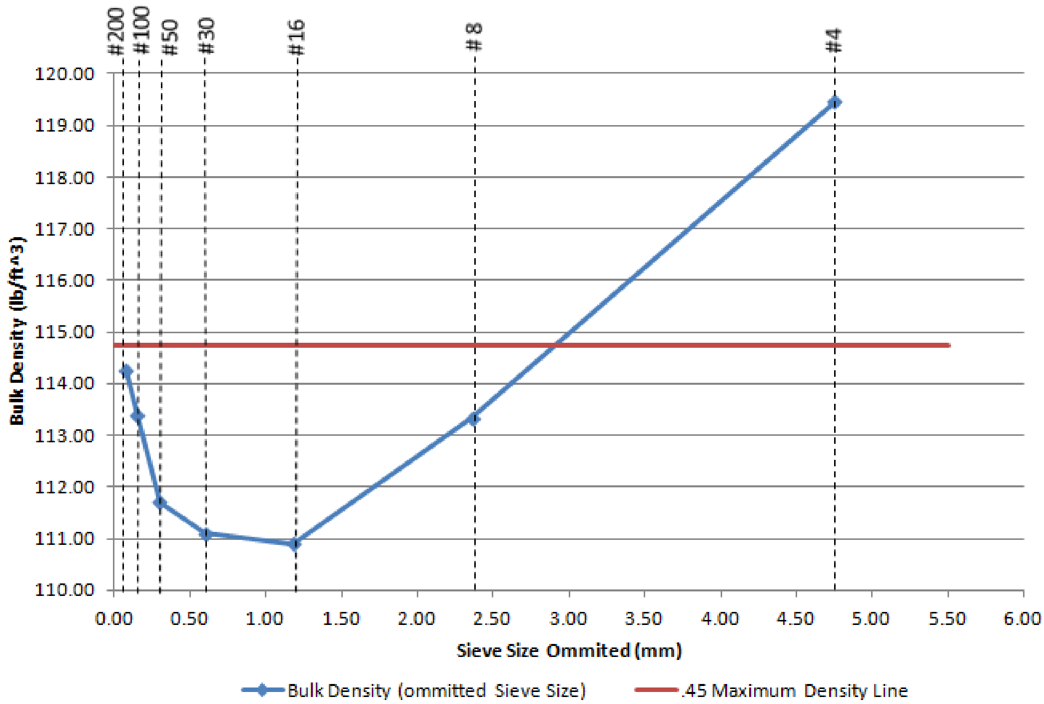

FIGURE 1.3
Effect of Sieve Size Omission on Bulk Density

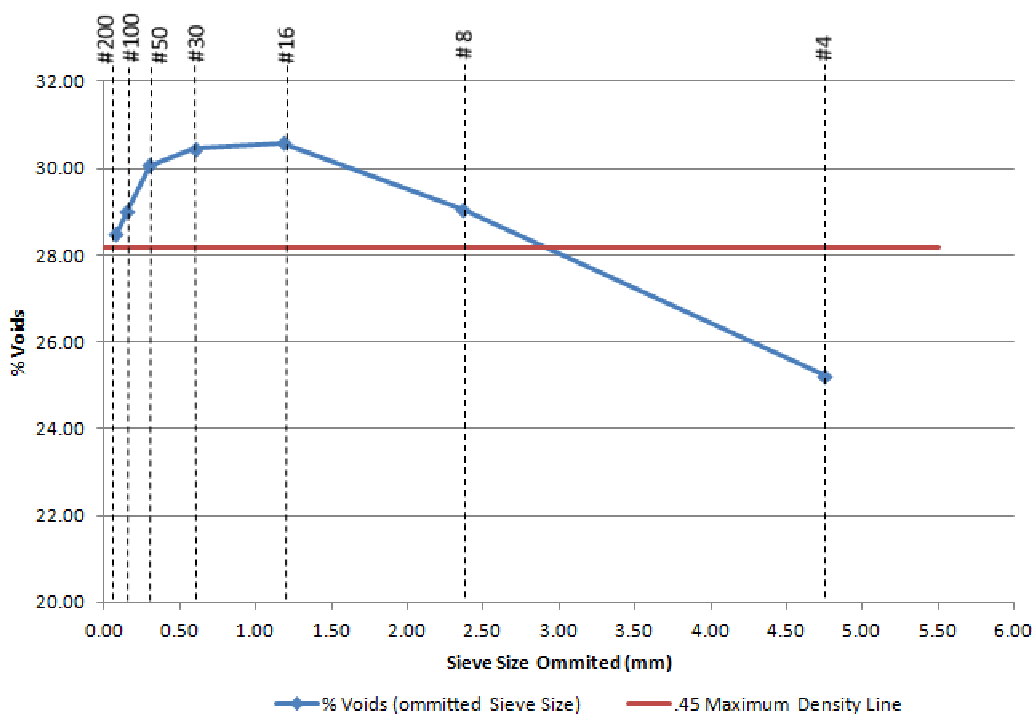

FIGURE 1.4
Effect of Sieve Size Omission on Dry-Rodded % Voids

The above figures demonstrate that when fines (below #4 sieve size) are removed, bulk density decreases and the percent void increases. Removal of the #4 sieve size aggregate had an opposite effect, a bulk density greater than that of the maximum density line was observed. The effect of changing the aggregate retained above the #4 is neglected in this method.

The percent voids in combined aggregate using the 0.45 Power Curve Void Prediction Method can be obtained from the empirical data in figures 1.3 and 1.4. Equation (1) is used to predict aggregate voids, equation (2) depicts the coefficients ($\boldsymbol{C_i}$) that modify the deviation of an individual sieve from the maximum density line (where the percent voids of the maximum density line gradation was measured), and equation (3) depicts the deviation of an individual sieve from the maximum density line ($\boldsymbol{d_i}$).

$$\textbf{Percent Voids} = \mathrm{B} - \sum(\mathrm{C_i} * \mathrm{d_i})_{\textbf{Above MDL}} + \sum(\mathrm{C_i} * \mathrm{d_i})_{\textbf{Below MDL}}$$

Equation 1

$$\mathbf{C_i} = \frac{\%\mathrm{Voids}_{\mathrm{Ommited\ Sieve\ Size}} - \%\mathrm{Voids}_{\mathrm{Max\ Density\ Line}}}{\%\mathrm{Voids}_{\mathrm{Max\ Density\ Line}}}$$

Equation 2

$$\mathbf{d_i} = \left|\mathrm{Percent\ Passing}_{\mathrm{Max\ Density\ Line}} - \mathrm{Percent\ Passing}_{\mathrm{Composite\ Sieve\ Size}}\right|$$

Equation 3

Specifically, $\boldsymbol{B}$ represents the percent voids of combined aggregate that lies on the maximum density line, $\boldsymbol{C_i}$ represents the calculated material coefficients for each sieve size and $\boldsymbol{d_i}$ (depicted in figure 1.5) is the difference –in percent passing – between an individual sieve size that lies on the maximum density line and a corresponding individual sieve size from the composite gradation. If material coefficients ($\boldsymbol{C_i}$) are negative, an individual gradation sieve size is above the maximum density line, the gradation is fine and subtracts from the percent voids. If material coefficients ($\boldsymbol{C_i}$) are positive, an individual gradation is below the maximum density line, the gradation adds to the percent voids.

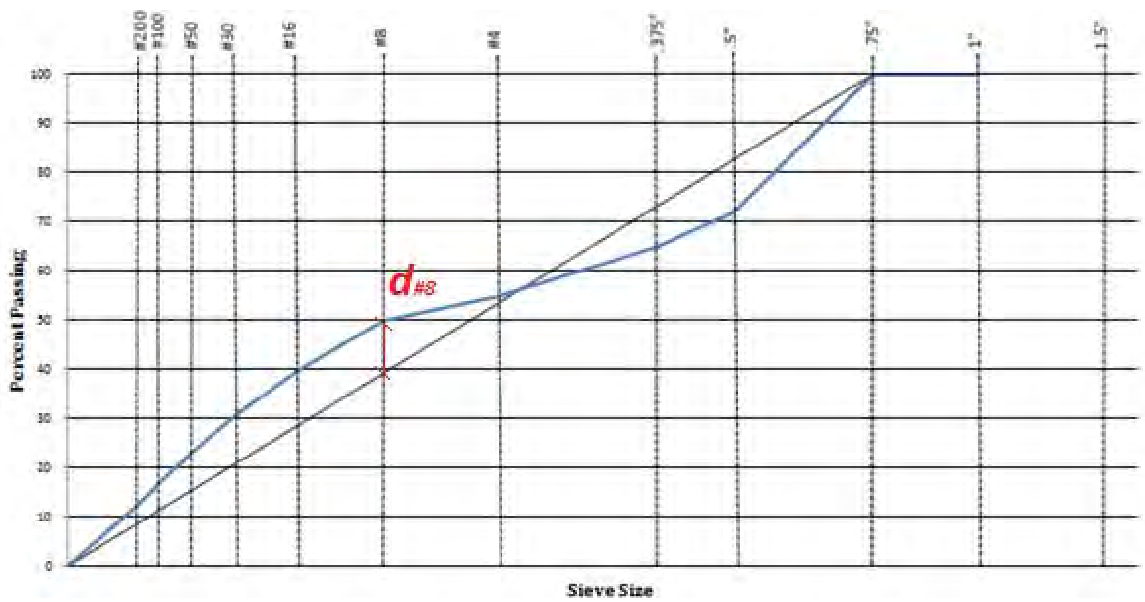

FIGURE 1.5
Example Depiction of "D" Value for the #8 Sieve

1.1.3 Experimental Results Using the 0.45 Power Curve Void Prediction Method

Thirty-six gradations were designed; the percent voids in the combined aggregates were predicted using the 0.45 Power Curve Void Prediction Method. Each combined aggregate was tested for dry-rodded bulk density and percent voids (KT-5). Figure 1.6 depicts predicted percent voids using the 0.45 Void Prediction Method versus measured aggregate voids in the thirty-six tested combined aggregate.

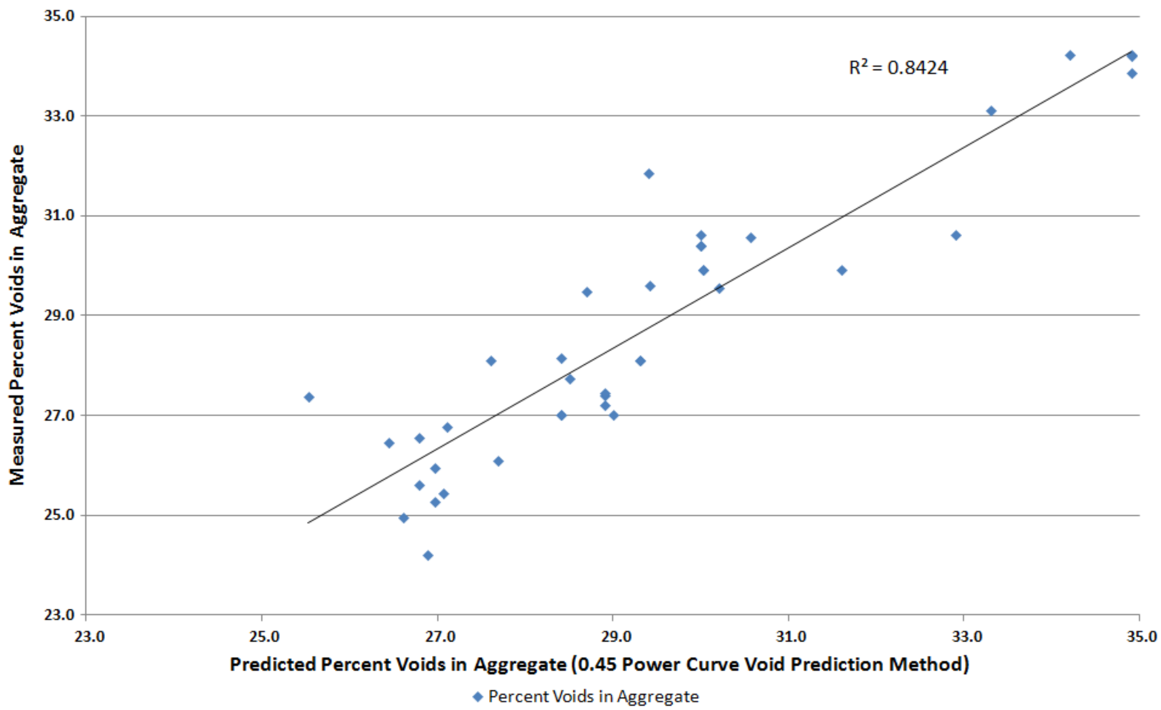

FIGURE 1.6
Predicted Percent Voids Using the 0.45 Void Prediction Method versus Measured Percent Voids in Aggregate

If the 0.45 void prediction method predicted aggregate voids exactly, the slope of the predicted percent voids versus measured percent voids regression line would be one-to-one. The R^2 value for the relationship shown in Figure 1.6 is 0.8424. The maximum deviation from the linear regression line is approximately 2.5 percent.

1.2 Summary of the 0.45 Power Curve Void Prediction Method

- Use of the 5% maximum density line is recommended if minimal deviation in percent voids in aggregate is desired. Commonly, the 10% maximum density line is used in conjunction with the 0.45 power curve; however, the 5% maximum density line allows for less divergence in the bulk density of dry-rodded aggregate with gradation(s) that lie exactly on the maximum density line.
- This Void Prediction Method assumes a linear relationship in addition and subtraction of an individual sieve size from the 5% maximum density line. Removal of aggregate in an individual sieve size is assumed to affect the bulk

density equally with addition of aggregate in an individual sieve size. The 0.45 Power Curve Void Prediction Method is valid within approximately 15 percent deviation ($\boldsymbol{d_i}$) of an individual sieve size retained of the 5% maximum density line.

- At least three bulk densities (KT-5) should be taken of gradations with omitted sizes and the gradation that lies on the maximum density line.
- Aggregate shape factor and angularity affect the bulk density and voids of aggregate gradations; when using different combinations of aggregate types, a new calibration of void coefficients should be calculated with the respective aggregate combinations.
- KDOT will continue to investigate the affect of aggregate shape and angularity in predicting voids in various combinations of aggregates.
- An example of the 0.45 Power Curve Void Prediction Method is provided in the appendix.

Chapter 2: Coarseness Factor Void Prediction Method

2.1 Introduction

The coarseness factor is another option for analyzing aggregate gradation. Rather than analyzing all sieve sizes, the coarseness factor chart looks at aggregate as a whole. The coarseness factor separates aggregates into three categories: coarse, fine and intermediate. Fine particles are included as a component of the mortar. Coarse and Intermediate aggregates are included in the calculation of coarseness factor (Coarse / (Coarse + intermediate)) (2005, Richardson).

The Coarseness Factor Void Prediction Method was created at KDOT as a simplified method of predicting percent voids in combined aggregate. In this method, the coarseness factor is defined in equation 1. The coarseness factor is the dependent variable in the void prediction method; it is easily computed and conveys the overall gradation of combined aggregates with a number.

$$\text{CF} = \frac{\text{percent retained on 0.375 in.sieve}}{\text{percent retained on \#8 sieve}}$$

Equation 4

Workability factor (WF) is a number that acts as a measure of fresh concrete workability. The workability factor is a function of cement content (measured in lb/yd^3) and the percent passing the number eight sieve. Equation 2 is the general definition of workability factor.

$$\text{WF} = \text{\% passing \#8 sieve} + \frac{2.5(\text{Cement Content})}{94}$$

Equation 5

For the purpose of this study, all gradations are assumed to have 521 lb cement/yd$^{3.}$ With this simplification, the workability bounds for a well-graded KDOT combined aggregate is as follows:

$$41.14 - \frac{CF}{6} < WF < 51.14 - \frac{CF}{6}$$

Equation 6

The KDOT workability factor bounds represent diagonal lines on the coarseness factor chart. Vertical lines separate well-graded aggregate on the basis of nominal maximum size aggregates (NMSA). Figure 2.1 depicts the workability factor and NMSA bounds on the coarseness factor chart.

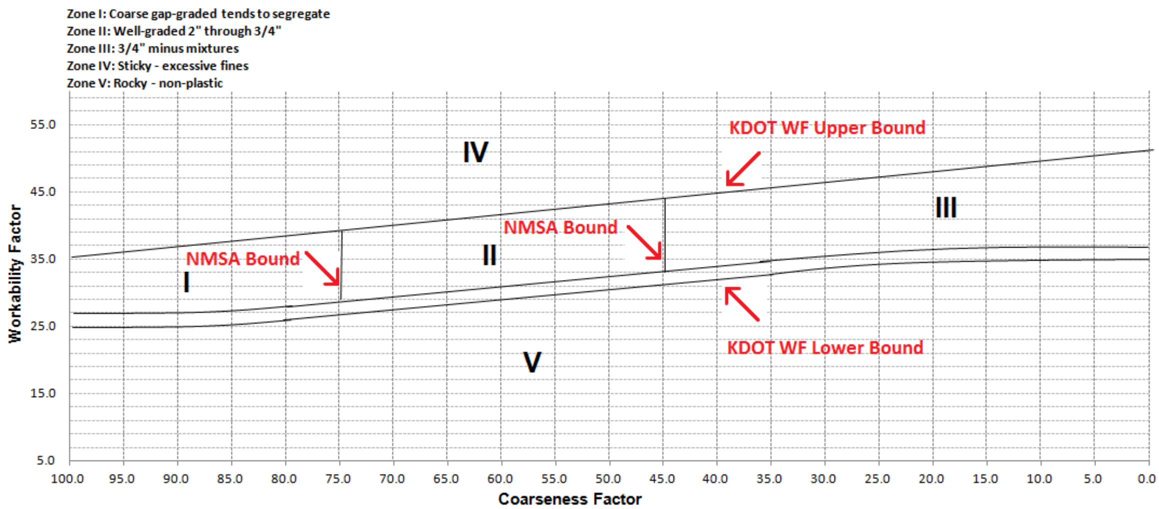

FIGURE 2.1
Workability Factor and NMSA Bounds

2.2 Aggregate Voids and Coarseness Factor

Thirty-six gradations were analyzed for bulk density and percent voids in aggregate using the KDOT KT-5 test method of determining percent voids in aggregate. The gradations were widely distributed; the combined aggregates were designed to contain a suite of coarse, fine, well-graded and not well-graded aggregate. Figure 2.2 depicts the distribution of voids with respect to the coarseness factor.

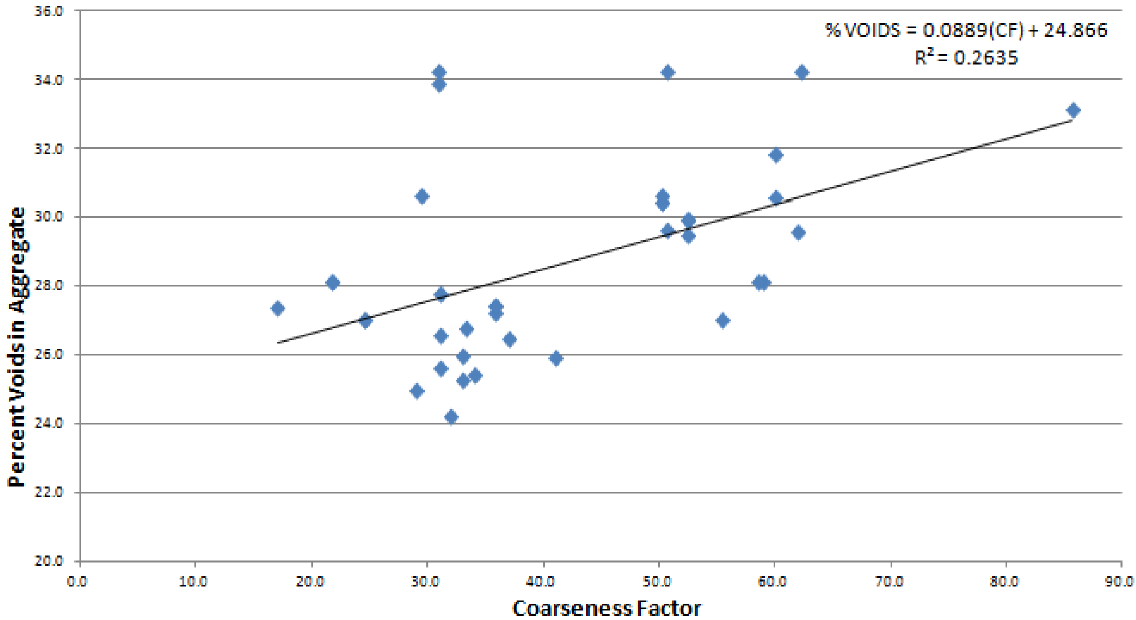

FIGURE 2.2
Coarseness Factor versus Percent Voids in Aggregate

Using a linear trend line, a correlation between coarseness factor and percent voids in aggregate could be obtained. The linear relationship between coarseness factor and percent aggregate voids had an R^2 value of 0.26, which indicates the data did not correlate well.

Combined aggregate with nominal max size aggregate equal to or less than 0.75 inch was considered well-graded if the coarseness factor was within the limits of [45, 75] and within the workability factor limits. Combined aggregate with nominal max sized aggregate equal to or less than 0.375 inch was considered well graded if the coarseness factor was within the limits of [15, 45] and within the workability factor limits. Combined aggregates outside these limits were not well-graded; the distribution of aggregate gradations is depicted in Figure 2.3. Figure 2.4 depicts the relationship between percent aggregate voids and coarseness factor for well-graded aggregate. Figure 2.5 depicts the relationship between percent voids in aggregate and coarseness factor for not well-graded aggregate.

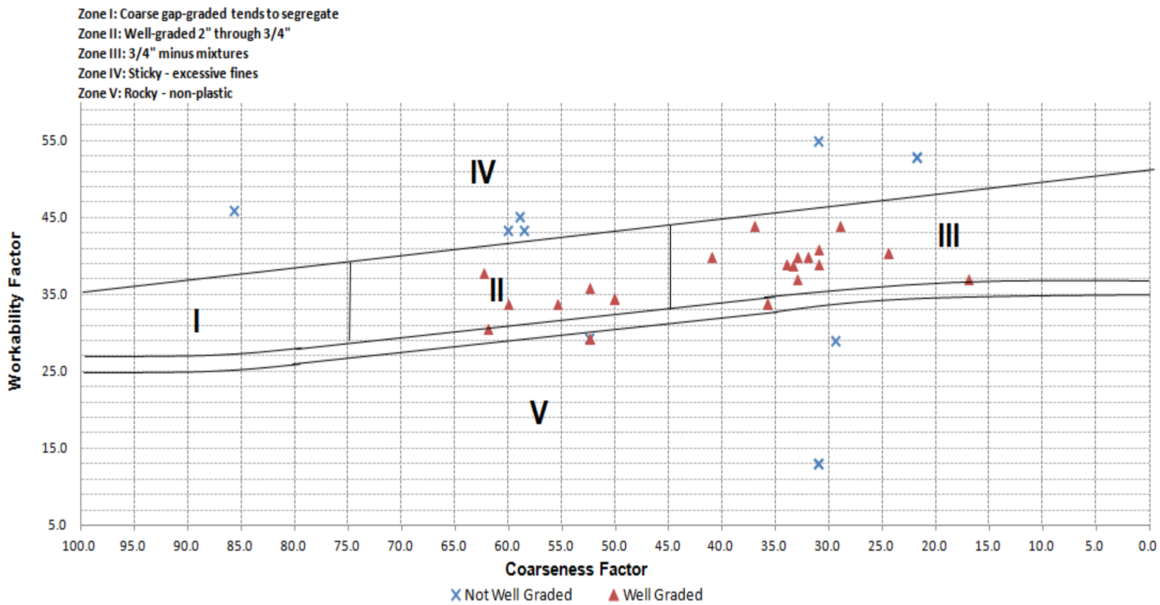

FIGURE 2.3
Combined Aggregate Gradations Studied

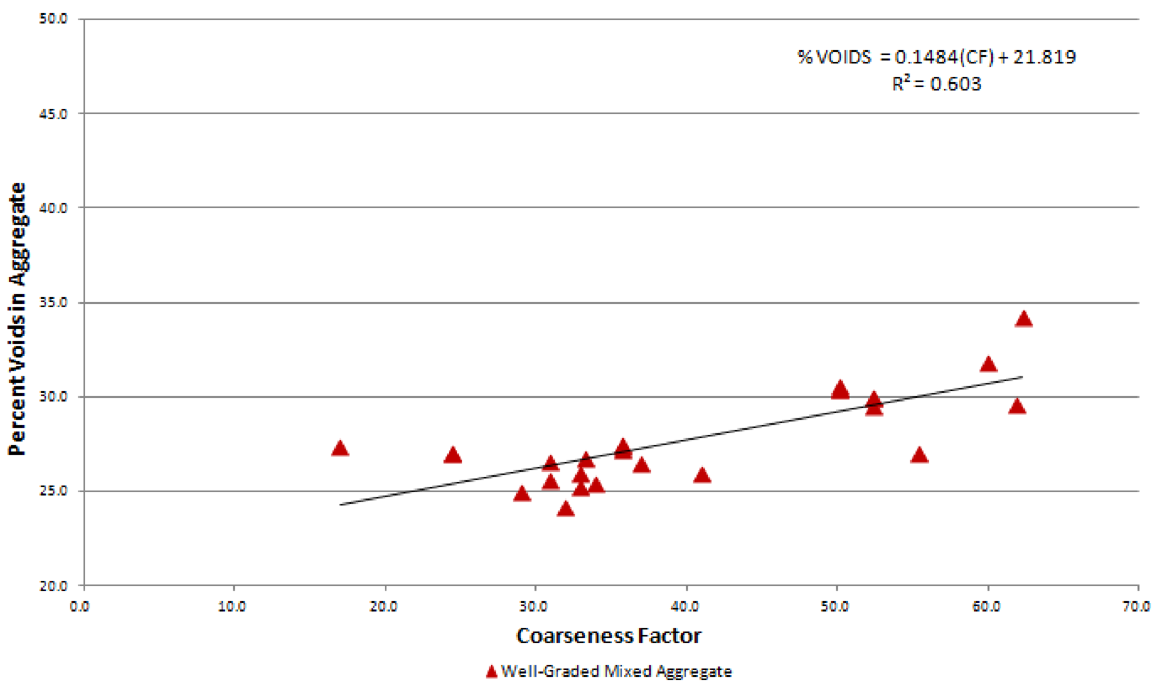

FIGURE 2.4
Coarseness Factor versus Percent Voids in Aggregate, Well-Gradated Combined Aggregate

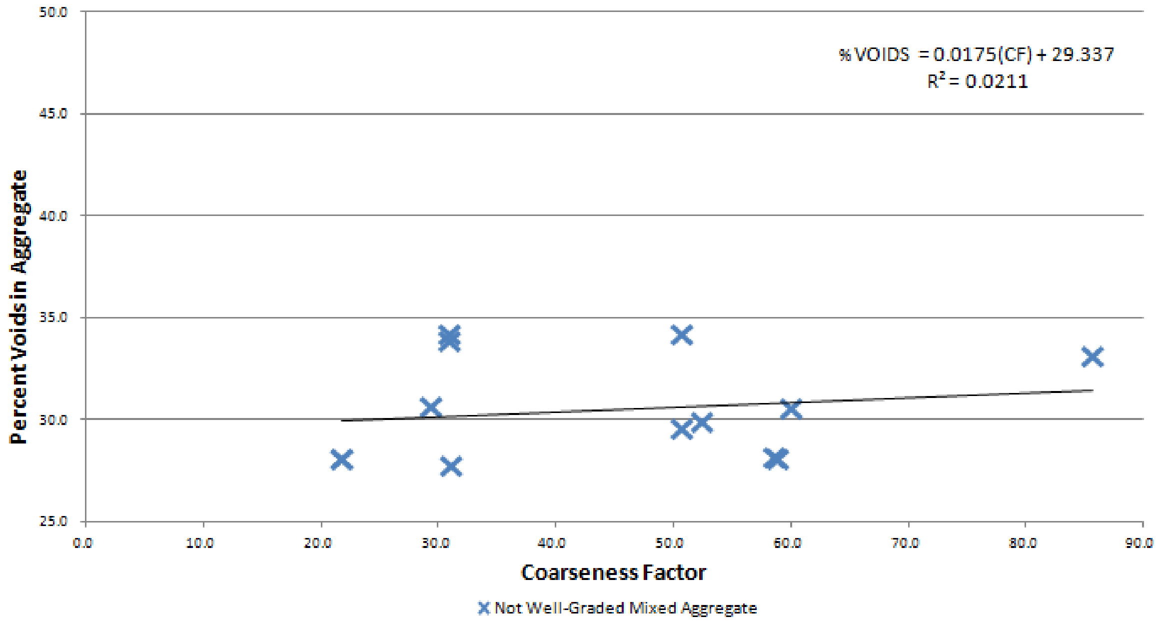

FIGURE 2.5
Coarseness Factor versus Percent Voids in Aggregate, Not Well-Gradated Combined Aggregate

Well-graded combined aggregates in the coarseness factor study had an R^2 value of 0.603, showing a stronger correlation between coarseness factor and percent voids in aggregate. The combinations of aggregates that were not well-graded have an R^2 value of .0211, showing a weak correlation between coarseness factor and percent voids in aggregate. On the average, with increasing coarseness factor, there is little increase in percent voids of combined aggregate that are not well graded; this is may be a result of the coarseness factor not being an accurate representation of poorly-graded aggregate gradation (gap-graded, with large maximum size aggregate) as a whole.

2.3 Summary of Coarseness Factor Void Prediction Method

- Prediction of aggregate voids is inaccurate for poorly-graded or gap-graded combined aggregate
- Prediction of aggregate voids is significantly more accurate for well-graded mixes than poorly graded combined aggregate.
- The correlation of percent voids in combined aggregate and coarseness factor should be calibrated for different combined aggregate. Aggregate shape and

angularity are considerable variables in percent voids in aggregate. As an example, a correlation between percent voids and coarseness factor for a combination of coarse-fine aggregates may not correlate well with total mixed aggregates.

Chapter 3: Conclusions

1. The 0.45 Power Curve Void Prediction Method yields more accurate predictions of aggregate voids than the Coarseness Factor Method of aggregate voids.
2. The 0.45 Power Curve Void Prediction Method must be calibrated for different combined aggregate types (e.g. limestone/sand or granite/sand).
3. The Coarseness Factor Method of Void Prediction requires a suite of previously tested aggregate voids. Higher order regression may be used to increase the R^2 value.
4. The Coarseness Factor Method should be used only for one type of combined aggregate (e.g. limestone/sand or granite/sand).
5. Well-graded aggregate percent voids vary less – and are predicted more accurately – than not well-graded aggregate.

Reference

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Appendix

A.1 0.45 Power Curve Void Prediction Method Example

For the purpose of demonstrating the 0.45 Power Curve Void Prediction Method, approximated values of the measured bulk density – and subsequently, percent voids – will be used. Table A.1 represents the voids in dry-rodded aggregate in omitted sieve sizes and the voids in combined with a gradation lying exactly on the maximum density line. This example assumes that aggregate larger than the #4 sieve has a negligible effect on bulk density for simplicity.

TABLE A.1

Sieve Size Omitted	% Voids in Aggregate
#4	25.5
#8	29.0
#16	30.5
#30	30.3
#50	30.0
#100	29.0
#200	28.5
Max Density Line	28.0

Figure A.1 will be used as the sample gradation to be used for void prediction. The combined aggregate is considered well-graded as it adheres closely to the 5% maximum density line. The gradation varies slightly from the maximum density line at sieve sizes smaller than the #30 sieve.

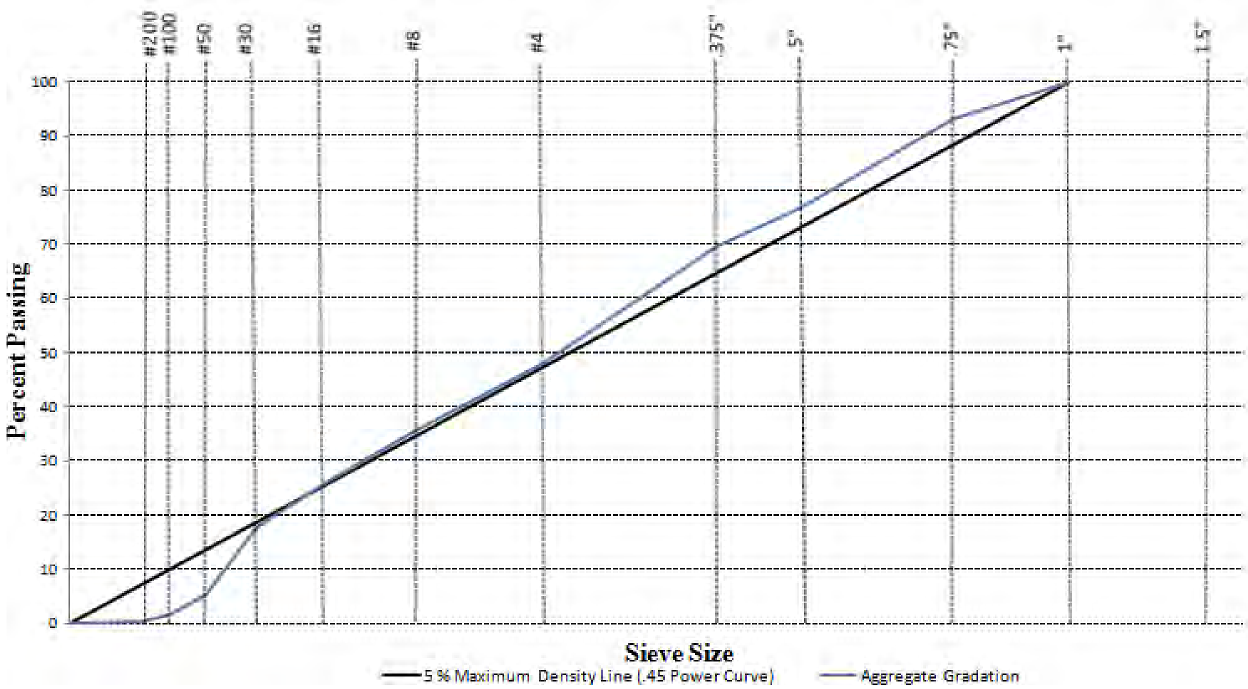

FIGURE A.1

Determining the percent passing on individual sieve sizes and the percent passing on individual sieve sizes for the maximum density line is necessary to calculate the d_i values. These values can be obtained directly from the 0.45 power chart spreadsheet or taken visually from the 0.45 power chart graph. These values are shown in Table A.2.

TABLE A.2

Sieve Size Omitted	% Voids in Aggregate	% Passing	% Passing (MDL)
#4	25.5	48.0	47.0
#8	29.0	35.8	35.0
#16	30.5	25.6	25.0
#30	30.3	17.7	18.0
#50	30.0	5.5	13.0
#100	29.0	1.6	10.0
#200	28.5	0.3	7.0
Max Density Line	28.0	-	-

Values of the difference in percent passing for a designed gradation and the percent passing individual sieve sizes on the maximum density line can now be calculated using the following equation. Absolute values are taken, this allows for direct substitution into subsequent equations. The numerical values of d_i are given in table A.3.

$$\mathbf{d_i} = \left|\text{Percent Passing}_{\text{Max Density Line}} - \text{Percent Passing}_{\text{Composite Sieve Size}}\right|$$

Equation A1

TABLE A.3

Sieve Size Omitted	% Voids in Aggregate	% Passing	% Passing (MDL)	d_i
#4	25.5	48.0	47.0	1.0
#8	29.0	35.8	35.0	0.8
#16	30.5	25.6	25.0	0.6
#30	30.3	17.7	18.0	0.4
#50	30.0	5.5	13.0	7.6
#100	29.0	1.6	10.0	8.4
#200	28.5	0.3	7.0	6.7
Max Density Line	28.0	-	-	-

Coefficients used to compute the effect of individual sieve size omission may now be computed. The following equation is used to calculate the coefficient values (C_i). The percent voids in maximum density line gradations with individual omitted sieve sizes are listed in column two of the previously listed appendix tables. The percent voids of the maximum density line are constant, 28 percent. Table A.4 lists the values for (C_i).

$$\mathbf{C_i} = \frac{\%\text{Voids}_{\text{Ommited Sieve Size}} - \%\text{Voids}_{\text{Max Density Line}}}{\%\text{Voids}_{\text{Max Density Line}}}$$

Equation A2

TABLE A.4

Sieve Size Omitted	% Voids in Aggregate	% Passing	% Passing (MDL)	d_i	C_i
#4	25.5	48.0	47.0	1.0	-0.089
#8	29.0	35.8	35.0	0.8	0.036
#16	30.5	25.6	25.0	0.6	0.089
#30	30.3	17.7	18.0	0.4	0.082
#50	30.0	5.5	13.0	7.6	0.071
#100	29.0	1.6	10.0	8.4	0.036
#200	28.5	0.3	7.0	6.7	0.018
Max Density Line	28.0	-	-	-	-

The final step in the 0.45 Power Curve Void Prediction Method is calculating the individual sieve and cumulative effect of the combined aggregate. Firstly, the coefficients (C_i) and difference in individual sieve percent passing (d_i) are multiplied. If an individual sieve size in the combined aggregate gradation lies below the maximum density line, the product of (C_i) and (d_i) are added to the base percent voids (***B***)**.** If an individual sieve size lies above the maximum density line, the product of (C_i) and (d_i) are subtracted from the maximum density line percent voids (***B***). The following equation shall be used.

$$\text{Percent Voids} = \mathrm{B} - \sum(\mathrm{C_i} * \mathrm{d_i})_{\text{Above MDL}} + \sum(\mathrm{C_i} * \mathrm{d_i})_{\text{Below MDL}}$$

Equation A3

Table A.5 computes the percent voids in the combined aggregate gradation.

TABLE A.5

Sieve Size Omitted	% Voids in Aggregate	% Passing	% Passing (MDL)	d_i	C_i	Voids
#4	25.5	48.0	47.0	1.0	-0.089	-0.09
#8	29.0	35.8	35.0	0.8	0.036	0.03
#16	30.5	25.6	25.0	0.6	0.089	0.05
#30	30.3	17.7	18.0	0.4	0.082	0.03
#50	30.0	5.5	13.0	7.6	0.071	0.54
#100	29.0	1.6	10.0	8.4	0.036	0.30
#200	28.5	0.3	7.0	6.7	0.018	0.12
Max Density Line	28.0	-	-	-	-	28.00
					$\sum$	**28.98**

The summation of the individual void components of sieve sizes and the percent voids of the gradation that lies on the maximum density line is the estimated percent voids in a combined aggregate gradation.

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