NRMCA Research Laboratory

Effect of Continuous (Well-Graded) Combined Aggregate Grading on Concrete Performance

Phase A: Aggregate Voids Content (Packing Density)

Prepared by:
Karthik Obla, PhD, PE
Haejin Kim
Colin Lobo, PhD, PE

Effect of Continuous (Well-Graded) Combined Aggregate Grading on Concrete Performance

Phase A: Aggregate Voids Content (Packing Density)
Project D340
May 2007

Prepared by
Karthik Obla[1], Haejin Kim[2], and Colin Lobo[3]

[1] Managing Director of Research and Materials Engineering, National Ready Mixed Concrete Association
[2] Concrete Research Laboratory Manager of Engineering, National Ready Mixed Concrete Association
[3] Senior Vice President of Engineering, National Ready Mixed Concrete Association

TABLE OF CONTENTS

Introduction

It has been generally accepted that if the aggregate volumes are so chosen that the packing density of the combined aggregates is maximum then the amount of cementitious paste volume required for a given amount of workability (i.e. slump) is reduced to a minimum. The rationale typically provided is as follows: Cementitious paste should completely fill the voids between the aggregate particles and at the same time there must be a certain amount of excess left over to provide the lubrication needed for a given workability. So, if the void content in the aggregate skeleton is reduced (i.e. packing density is increased) then the total cementitious paste required for a given workability is decreased. It is also well accepted that minimizing the volume of cementitious paste in a concrete mixture is desirable to attain lower shrinkage, reduced heat of hydration, improved durability, and lower costs. But how does one go about achieving a maximum aggregate packing density?

There are aggregate packing density models mostly popular in Europe that are known to successfully establish aggregate proportions (for given aggregate properties) to attain a maximum packing density of the combined aggregate. In the United States the approach is more empirical and the aim is to attain a "continuous", also known as "well-graded", combined aggregate grading or particle size distribution. "Combined" here refers to a combination of both coarse and fine aggregate grading in the ratio that they are present in the concrete mixture. The popular approaches for achieving "well graded combined aggregates" (WG) in the US are: 1. Coarseness Factor chart; 2. 8-18 chart; and 3. 0.45 power chart that is commonly used in hot mix asphalt (these are referenced in the optional requirement checklist of ACI 301 and will be discussed in an appendix to a future version of ACI 211.1).

In the Coarseness Factor (CF) chart the x-axis represents the percent of the combined aggregate that is retained on the No. 8 sieve that is also retained on the 3/8 in. sieve and the y-axis represents the percent of the combined aggregate that passes the No. 8 sieve. If a given combined aggregate grading is plotted in Zone II then the combined aggregate grading is termed as optimal. Zone II is the region denoted by a box in Fig. 4. Workability factor should be corrected for different cementitious content - a 94-lb decrease in cementitious weight (from a standard cementitious content of 564 lb/yd^3) requires a 2.5% increase in the workability factor.

The 8-18 Chart sets limits between 8 and 18% for large top size aggregates such as 1-1/2 in. or 8 and 22% for smaller maximum-size aggregates such as 1 or ¾ in. retained on each size below the top size and above the No. 100 sieve. ACI 302.1R-04 Section 5.4.3 adds some more restrictions on certain other sieve sizes (top size, No. 30, No. 50, No. 100) while allowing limited lower individual percent retained on sieves. Figure 4 shows the 8-18 Chart and a combined aggregate plotted in that chart.

In the 0.45 power chart the y-axis represents the combined aggregate percent passing for each sieve size and the x-axis represents the sieve sizes raised to the 0.45 power. A line is plotted from the origin of the chart to the sieve one size larger than the first sieve to have 90% or less passing. Combined aggregate grading plotted should not deviate much from this optimal line.

The CF chart has been correlated with field performance to some extent and all three approaches have their share of promoters and detractors. However, none of these empirical approaches have been scientifically tested in the laboratory to see if it leads to maximum aggregate packing density or lower cementitious paste for a given amount of workability. So, this research project was initiated with the following objectives:

1. To determine if the empirical approaches (CF chart, and the 8-18 chart) which lead to WG actually result in a maximum aggregate packing density.
2. To determine if the empirical approaches lead to improved concrete performance such as lower paste content, lower shrinkage, higher strength, better workability etc.

Due to the scope of the project the first objective was considered as Phase A (Aggregate Voids Content (Packing Density)) and the second objective as Phase B (Concrete Performance). This report will focus on Phase A only and a subsequent report will focus on Phase B. WG in this article is defined as a combined aggregate grading that is plotted in Zone II of the CF chart (shilstone, ACI 302), and meets the requirements of the 8-18 chart as recommended by the ACI 302.1R-04. Combined aggregate gradings that do not meet those two requirements were called as "not well graded combined aggregates" (NWG).

Experimental Study

This research program was conducted at the NRMCA Research Laboratory.

Materials

The following materials were used in this study:
ASTM C 33 Natural sand, Lot #7958
ASTM C 33 No. 467 Crushed Limestone, Lot #7963
ASTM C 33 No. 57 Crushed Limestone, Lot #7998
ASTM C 33 No. 8 Crushed Limestone, Lot#7966

The aggregate characteristics are provided in Table 1. The intermediate coarse aggregate (No. 8) was obtained from the same quarry as the larger coarse aggregates (No. 467, No. 57). This was done in order to keep the particle shape consistent and discount the influence that a different particle shape can have on test results. Further this is more realistic in a concrete plant.

Testing

ASTM or AASHTO standardized testing procedures were followed to the extent possible. Non-standardized tests and deviations from standard methods (if any) are described as applicable. The NRMCA research laboratory participates in proficiency sample testing of the Cement and Concrete Reference Laboratory (CCRL), is inspected biannually for conformance to the requirements of ASTM C 1077 and maintains its accreditation under the AASHTO Laboratory Accreditation Program.

For each aggregate the following aggregate tests were conducted to collect basic information about the aggregates:
- ASTM C127-04 Relative Density and Absorption of Coarse Aggregate
- ASTM C128-04a Relative Density and Absorption of Fine Aggregate
- ASTM C136-05 Sieve Analysis of Fine and Coarse Aggregates
- ASTM C29/C29M-97(2003) Unit Weight and Voids in Aggregate

Combined aggregate density and voids content

Combined aggregate density and calculated voids content was determined according to ASTM C 29. The amount of coarse and fine aggregate was first calculated based on their proportions in the concrete mixture and placed on the pan as shown in Figure 1. The coarse and fine aggregate was then blended together thoroughly using a scoop or shovel as shown in Figure 1. The blended combined aggregate was placed in three layers in the calibrated 0.5 cubic foot container and each layer was rodded 25 times. The weight of the compacted aggregate was measured and from the known relative density of aggregate the voids content was calculated for that combined aggregate grading. This was calculated using the weighted average of the mass fraction of each aggregate. Each test was repeated three or four times with fresh aggregate batches and the average value is reported here.

Experimental Results and Discussions

Effect of Range of Combined Aggregate Grading on Aggregate Voids Content

Two different conditions were tested – 1. No. 57 combined with No. 8 at different percentages by volume; and 2. No. 57 combined with fine aggregate at different percentages by volume. Combined aggregate voids content test for both conditions (total of 14 combined aggregate gradings) was conducted.

Table 2 and Figure 2 show the voids content results of blending different proportions of the No. 57 and No. 8 aggregates. The No. 8 aggregate resulted in an average voids content of 41.3% while the No. 57 aggregate resulted in a voids content of 39.6%. Blending different proportions by volume of No. 57 and No. 8 aggregates resulted in slightly lower void contents. The average voids content for the different proportions of blended aggregate varied between 37.3% and 37.9% which is not a significant difference. Thus when the No. 57 and No. 8 aggregates were combined, which results in a combined aggregate size distribution varying between 1 inch (25 mm) and 3/32 inch (2.36 mm), it resulted in a slight reduction of about 2% in voids content compared to the voids content of No. 57 aggregate.

Table 3 and Figure 3 show the voids content results of blending different proportions of the No. 57 and Fine aggregates. The fine aggregate resulted in a voids content of 35.7% while the No. 57 aggregate resulted in a voids content of 39.6%. Blending different proportions by volume of No. 57 and fine aggregates resulted in significantly lower voids content. When the No. 57 aggregate content varied between 50% and 61% the average void contents for the different proportions varied between 21.6% and 23.3%. Thus when the No. 57 and Fine aggregates were combined, which results in a combined aggregate size distribution varying between 1 inch (25 mm) and 0.075 mm, it resulted in a substantial reduction of about 17% in voids content compared to using the voids content of the No. 57 aggregate.

In summary a broader distribution of aggregate particle sizes (25 mm to 0.075 mm vs 25 mm to 2.36 mm) resulted in a greater reduction in voids content (about 17% vs 2%).

Effect of WG on Aggregate Voids Content

Two different conditions were considered – 1. Blend of 3 aggregates (No. 57, No. 8 and fine) and 2. Blend of 2 aggregates (No. 57, and fine).

Figure 4 shows the CF chart and 8-18 chart results of blending different proportions of the No. 57, No. 8, and fine aggregates (Condition 1) by volume. It is clearly seen that all 5 gradings are WG.

Figure 5 shows the CF and 8-18 chart results of blending different proportions of the No. 57 and fine aggregates (Condition 2) by volume. This is a typical condition at most ready mixed concrete plants that batch 2 aggregates in concrete. It is clearly seen that all the 7 gradings are NWG. The 2 extreme gradings - the one with the 30% fine aggregate and the one with the 30% coarse aggregate can be excluded as these are not practical options and will result in concrete mixtures that are either “too rocky” or “too sandy”, respectively.

Combined aggregate voids content tests for both conditions (total of 12 combined aggregate gradings) are reported in Table 3 and Table 4 and illustrated in Figure 6. The results clearly illustrate that WG actually have slightly higher voids content as compared to the NWG. The WG had an average voids ratio between 23.8% and 26.7% with an overall average of 25.5%. The NWG had an average voids ratio between 21.6% and 23.3% with an overall average of 22.5%. **So, contrary to expectations WG actually increased the voids content by an average of about 3%.**

Round Robin Program

A round robin program was organized by NRMCA to evaluate the findings from the NRMCA research in other regions of the country using aggregates local to that region. Three different NRMCA producer member companies participated in the round robin program. They are:

1. Titan America Technical Services, Jacksonville, FL
2. HTC/Lehigh Research Facility, Atlanta, GA
3. Aggregate Industries, Denver, CO

The participants conducted the basic aggregate tests such as relative density, absorption, sieve analysis and dry rodded unit weight and supplied that information to NRMCA, which is shown in Tables 5-7. Aggregate proportions for combining aggregates were suggested by NRMCA on the basis of typical slab-on-grade concrete mixture proportions. Six aggregate proportions were chosen for each participant so that both WG and NWG gradings could be evaluated. The aggregate mineralogy information is as follows:
Florida – Coarse = Crushed Limestone; Fine = Natural Silica Sand
Georgia - Coarse = Crushed Limestone; Intermediate coarse = Crushed Granite; Fine = Alluvial Concrete Sand
Colorado – Coarse = Gravel; Fine = Natural Sand; all from the same source
At each location the intermediate coarse aggregate was obtained from the same quarry as the larger coarse aggregates. This was done in order to keep the particle shape consistent and discount the influence that a different particle shape can have on test results. Further this is more realistic in a concrete plant.

Experimental Results and Discussions

Florida

Figure 7 illustrates the results from Florida of blending aggregates at different proportions by volume on the CF and 8-18 charts. The blending percentages of No. 57, No. 8, and fine aggregates are reported in Table 8. It is clearly seen that there are 2 WG and 3 NWG gradings.

Combined aggregate voids content results are also reported in Table 8 and illustrated in Figure 8. The two WG had an average voids content of 23.4% and 23.8% with an overall average of 23.6%. The NWG had an average voids content between 22.7% and 23.9% with an overall average of 23.3%. In summary there was no difference in voids content between WG and NWG. The fine aggregate had an average voids content of 36.6%.

Atlanta

Figure 9 illustrates the results from Atlanta of blending aggregates at different proportions on the CF and 8-18 charts. The blending percentages of No. 57, No. 89, and fine aggregates are reported in Table 9. It is clearly seen that there are 2 WG and 3 NWG gradings.

Combined aggregate voids content results are also reported in Table 9 and illustrated in Figure 10. The two WG had an average voids content of 27.4% and 27.9% with an overall average of 27.7%. The NWG had an average voids ratio between 27.7% and 28.3% with an overall average of 28.0%. In summary there was no difference in voids content between WG and NWG.

Denver

Figure 11 illustrates the results from Denver of blending aggregates at different proportionson the CF and 8-18 charts. The blending percentages of the No. 67, No. 8, and fine aggregates are reported in Table 10. It is clearly seen that there are 3 WG and 1 NWG gradings.

Combined aggregate voids content results are also reported in Table 10 and illustrated in Figure 12. The WG had an average voids ratio between 24.5% and 26.7% with an overall average of 25.9%. The NWG had an average voids ratio of 25.5%. In summary there was no difference in voids content between WG and NWG. The fine aggregate had an average voids content of 34.6% and the No. 67 aggregate had an average voids content of 37.0%.

Overall Discussions and conclusions

Figure 13 summarizes the data from the three locations where the round robin tests were conducted. It is clear that there is hardly any difference in voids content between WG and NWG. Table 11 summarizes the voids content data from the four locations, including Maryland. For clarity only the minimum, maximum, and average voids content attained at the different locations for both WG and NWG are presented. The same information is illustrated in Figure 14. These data indicate that combining aggregates to a maximum density as proposed by empirical methods such as the CF or the 8-18 charts does not have any significant impact on the voids content of the combined aggregate. In one case (Maryland) WG actually had a higher voids content than the NWG.

This research does show that the voids content attained varies in different locations. The average voids contents in Florida, Maryland, Georgia, and Colorado were 23.5%, 23.9%, 25.7%, and 27.9% respectively. Since the combined aggregate grading as measured by the CF and 8-18 charts were similar the difference in voids content is most likely due to differences in aggregate shape and texture. In a subsequent Phase II study it was found that for a target slump of 4 inches the Florida, Maryland, and Georgia aggregates required 290 lbs/yd^3, 290 lbs/yd^3, and 320 lbs/yd^3 respectively. So, it appears that the difference in voids content may be leading to differences in water demand but the difference in voids content is not being caused by any difference in combined aggregate gradings.

Past Research

In light of our findings it is useful to evaluate what past researchers have reported on this topic. In 1930 Stanton Walker conducted a series of voids content tests while varying aggregate proportions. His findings were as follows:

1. A broader distribution of particle sizes in a combined aggregate grading led to lower voids content. If the combined aggregate grading spanned a range of ¾ in. to 1 ½ in. a voids content of 35% was attained. Extending the aggregate grading range from No. 8 (2.36 mm) to 1 ½ in. (37.5 mm) reduced the voids content to 29%. Adding fine aggregates and thus extending the range from 1 ½ in. (37.5 mm) to No. 200 sieve (0.075 mm) decreased the voids content down to about 19%.
2. Void content tests of combinations of gravel and sand showed that a more "well graded" combined aggregate grading (with a greater amount of intermediate aggregate sizes) did not reduce the voids content as compared to the "not well graded" combined aggregate grading.

Abrams in Lewis Bulletin No. 1, 1918 makes several comments related to this subject: Page 2: *"Aggregate of equivalent concrete making qualities may be produced from infinite number of different gradings of a given material"* Page 6: *"Any size analysis curve which will give the same combined fineness modulus will require the same quantity of water to produce a mix of same plasticity and strength"* It is known that the combined fineness modulus does not depend on whether the combined aggregate is well graded or not. But he also says Page 20: *"Rich mixes and well graded aggregates are as essential as ever"*

Abrams and Walker in Lewis Bulletin No. 9, 1922 make the following comments: Page 4: *"It is not desirable for fine aggregate and coarse aggregate to have fixed gradings. Rather wide variations in gradings may occur without affecting the quantity of mixing water or quality of resulting concrete"* Page 7: *"The tables illustrate the fact that aggregates of many different sizes and grading may be combined with equally good results in concrete and show that it is not necessary to restrict gradings or sizes to those usually mentioned in specifications"*.

Powers in *Properties of Fresh Concrete*, 1968, discusses various aggregate grading techniques including Fuller gradings in Pages 246-256 and comments: Pages 256, 298: "*The hypothesis that there is an ideal size gradation for concrete aggregate, or for all solid material in concrete has now become almost if not entirely abandoned*"

Dewar who developed a computer program that can predict aggregate packing discusses in his book *Computer Modelling of Concrete Mixtures*, 1999: Section 8.1.1: "*There is a very wide range of acceptable distributions, both continuous and gap-graded, which will result in economic concrete, provided the correct proportioning is achieved in each case*" In personal communications to the principal author of this report he mentioned *"When the coarse aggregate is artificially crushed the finer fractions may be very flaky and their removal and the resultant gap may be beneficial. UK concrete producers often need to reduce the proportion of 10-5 mm material to overcome this problem"*

Summary

Based on aggregate tests from four different sources (MD, FL, GA, and CO) it can be concluded that WG does not necessarily lead to maximum aggregate packing density and thereby a minimum voids content that is considered desirable in concrete mixtures for improved workability, durability and economy. In three of the sources there was no difference in voids content between the WG and NWG gradings. In one source NWG resulted in about a 3% lower voids content. WG in this report are defined as those that were plotted in Zone II of the CF chart, and met the requirements of the 8-18 individual percentage grading as recommended by the ACI 302.1R-04. Aggregate combinations which did not meet those criteria were termed as NWG.

In spite of similar combined aggregate gradings between the 4 locations there was difference in voids content most likely due to aggregate shape and texture. This difference may have contributed to the difference in water demand between those locations.

Past researchers seem to have suggested that an ideal combined aggregate grading does not exist. However, there have been field reports that WG may help improve concrete performance. This has been examined in more detail in Part B of this report.

Acknowledgements

The authors would like to extend their sincere thanks to Mr. Soliman Ben-Barka who conducted the test program at the NRMCA Research Laboratory. The authors would like to thank Dr. Cesar Constantino and Mr. James Cook of Titan America, FL, Mr. Roger Tate of Heidelberger Technology Center, GA and Mr. David Imse of Aggregate Industries, CO for participating in the round robin test program.

References

1. Shilstone, J. M., Sr., 1990, "Concrete Mixture Optimization," Concrete International, V. 12, No. 6, June, pp. 33-39.
2. Harrison, P.J., 2004, "For the Ideal Slab-on-Ground Mixture," Concrete International, V. 26, No. 3, March, pp. 49-55.
3. ACI Committee 302.1R, 2006, "Guide for Concrete Floor and Slab Construction," American Concrete Institute, Farmington Hills, Mich., 77 pp.
4. ACI Committee 211, "Guide for Selecting Proportions for No-Slump Concrete (ACI 211.3R-02), "American Concrete Institute, Farmington Hills, Mich., 26 pp.
5. Phelan, W.S., 2004, "Admixtures and Aggregates: Key Elements in "Athletic Concrete" – Revisited," Concrete International, V. 26, No. 9, September, pp. 40-43.
6. Cramer, S.M., and Bakke, P.M., 1993, "Pilot Study on the Effect of Changes in Total Aggregate Gradation on Portland Cement Concrete Performance," Final Report, WI/EP-07-93, Wisconsin Department of Transportation, Madison, WI.
7. McCall, C., King, M.E., and Whisonant, M., 2005, "Effects of Aggregate Grading on Drying Shrinkage of Florida Concretes," Concrete International, V. 27, No. 3, March, pp. 45-49.
8. Abrams, D.A., 1918, "Design of Concrete Mixtures," Lewis Institute, Structural Materials Research Laboratory, Bulletin No. 1, PCA LS001, 20 pp.
9. Abrams, D.A, and Walker, S., 1921, "Quantities of Materials for Concrete," Lewis Institute, Structural Materials Research Laboratory, Bulletin No. 9, 26 pp.
10. Powers, T.C., 1968, "Properties of Fresh Concrete," John Wiley & Sons, Inc., 654 pp.
11. Dewar, J.D., 1999, "Computer Modeling of Concrete Structures," E & FN Spon, London.
12. Walker, S.W., 1930, "Effect of Grading of Gravel and Sand on Voids and Weights," Circular 8, National Sand and Gravel Association, Inc., November, 18 pp.
13. Stroeven, P., and Stroeven, M., 1999, "Assessment of Packing Characteristics by Computer Simulation," Cement and Concrete Research, V. 29, pp. 1201-1206.
14. Goltermann, P., Johansen, V., and Palbol, L., 1997, "Packing of Aggregates: An Alternative Tool to Determine the Optimal Aggregate Mix," ACI Materials Journal, V. 94, No. 5, September-October, pp. 435- 443.
15. Jones, M.R., Zheng, L., and Newlands, M.D., 2002, "Comparison of Particle Packing Models for Proportioning Concrete Constituents for Minimum Voids Ratio," Materials and Structures, V. 35, June, pp. 301-309.
16. Domone, P.L.J., and Soutsos, M.N., 1994, "An Approach to the Proportioning of High-Strength Concrete Mixes," Concrete International, V. 16, No. 10, October, pp. 26-31.
17. Holland, T., 1998, "Combining Concrete Aggregates into a Single Element," The Concrete Producer, July, pp. 512-517.
18. De Larrard, F., 1999, Concrete Mixture Proportioning: a Scientific Approach," E & FN Spon, London.
19. Quiroga, P.N., 2003, "The Effect of the Aggregates Characteristics on the Perfornance of Portland Cement Concrete," PhD Thesis Dissertation, 368 pp.
20. Glavind, M., and Pedersen, E.J., 1999, "Packing Calculations Applied for Concrete Mix Design," Proceedings Creating with Concrete, May, 10 pp.
21. Quiroga, P.N., and Fowler, D.W., 2003, "The Effects of Aggregates Characteristics on the Performance of Portland Cement Concrete," Report ICAR 104-1F, The University of Texas, Austin, pp. 382.

22. ASTM C 29-03, "Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate,” ASTM International, West Conshohocken, PA, 2006, 4 pp.
23. ASTM C 33-03, "Standard Specification for Concrete Aggregates” ASTM International, West Conshohocken, PA, 2006, 11 pp.
24. ASTM C 127-04, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” ASTM International, West Conshohocken, PA, 2006, 6 pp.
25. ASTMC 128-04a, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate,” ASTM International, West Conshohocken, PA, 2006, 6 pp.
26. ASTM C 136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” ASTM International, West Conshohocken, PA, 2006, 5 pp.
27. ASTM C 1077-05b, "Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation,” ASTM International, West Conshohocken, PA, 2006, 7 pp.

List of Tables

List of Figures

Table 1. Properties of Aggregate from Maryland Used in NRMCA Laboratory Study

Sieve Size	Percent Passing			
	Coarse Aggregate			Fine Aggregate
	No.467	No. 57	No.8	
2 1/2	100.0	100.0	100.0	100.0
2	100.0	100.0	100.0	100.0
1 1/2	97.9	100.0	100.0	100.0
1	73.9	100.0	100.0	100.0
3/4	54.8	74.7	100.0	100.0
1/2	24.7	25.4	100.0	100.0
3/8	12.0	9.3	80.6	100.0
No. 4	3.0	1.3	15.0	100.0
No. 8	0.0	0.0	0.0	87.8
No. 16	0.0	0.0	0.0	66.5
No. 30	0.0	0.0	0.0	39.3
No. 50	0.0	0.0	0.0	13.1
No. 100	0.0	0.0	0.0	4.9
No. 200	0.0	0.0	0.0	0.5
FM	7.32	7.15	6.04	2.88
Bulk Dry Specific Gravity	2.85	2.78	2.83	2.58
Absorption, %	0.22	0.32	0.51	1.06
Dry rodded unit weight, lb/ft^3	109.0	103.0	N/A	N/A

Table 2. Voids content of Different Proportions of No.57 Aggregate and No.8 Aggregate from Maryland

No. 57	No. 8	voids #1, %	voids #2, %	voids #3, %	voids #4, %	Avg. voids, %
0%	100%	41.6	41.1	41.2		41.3
50%	50%	38.0	38.3	37.8	37.6	37.9
60%	40%	38.0	37.8	37.9	37.5	37.8
70%	30%	37.4	37.9	37.7	37.6	37.6
80%	20%	37.8	37.0	37.3	36.9	37.3
100%	0%	39.6	39.6	39.5		39.6

Table 3. Voids content of Different Proportions of No.57 Aggregate and Fine Aggregate from Maryland

No. 57	Fine Agg	voids #1, %	voids #2, %	voids #3, %	voids #4, %	Avg. voids, %
0.0%	100.0%	35.5	35.9	35.6		35.7
30.0%	70.0%	27.5	25.1	25.1	26.3	26.0
50.0%	50.0%	23.1	23.2	21.6	23.0	22.7
53.0%	47.0%	22.1	21.2	22.1	22.4	21.9
55.8%	44.2%	21.4	22.0	21.4	21.6	21.6
57.7%	42.3%	24.4	23.2	23.1	22.3	23.3
61.0%	39.0%	22.8	22.4	23.4	22.5	22.8
70.0%	30.0%	28.2	26.2	27.8	25.1	26.8
100.0%	0.0%	39.6	39.6	39.5		39.6

Table 4. Voids content of Different Proportions of No.57 Aggregate, No.8 Aggregate, and Fine Aggregate from Maryland

No 57	No 8	Fine Agg	voids 1, %	voids 2, %	voids 3, %	voids 4, %	Avg. voids, %
37.5%	20.2%	42.3%	23.3	24.6	24.2	23.3	23.8
46.5%	15.5%	38.0%	26.7	24.2	26.3	24.2	25.4
31.8%	28.2%	40.0%	27.7	26.1	26.4	25.5	26.4
43.1%	12.9%	44.0%	24.5	26.3	26.3	26.3	25.9
29.2%	24.8%	46.0%	25.9	25.3	25.5	25.7	25.6

Table 5. Properties of Aggregate Used in Florida Study

Sieve Size	Percent Passing		
	Coarse Aggregate		Fine Aggregate
	No. 57	No.8	
2 1/2	100.0	100.0	100.0
2	100.0	100.0	100.0
1 1/2	100.0	100.0	100.0
1	97.9	100.0	100.0
3/4	79.7	100.0	100.0
1/2	31.8	100.0	100.0
3/8	9.8	94.5	100.0
No. 4	2.7	18.4	99.9
No. 8	2.6	2.2	98.7
No. 16	0.0	1.5	87.8
No. 30	0.0	0.0	60.2
No. 50	0.0	0.0	27.2
No. 100	0.0	0.0	4.4
No. 200	1.2	0.9	0.1
FM	7.05	5.83	2.22
Bulk Dry Specific Gravity	2.32	2.29	2.63
Absorption, %	3.9	4.9	0.5
Dry rodded unit weight, lb/ft^3	86.48	82.90	N/A

Table 6. Properties of Aggregate Used in Georgia Study

Sieve Size	Percent Passing		
	Coarse Aggregate		Fine Aggregate
	No. 57	No.8	
2 1/2	100.0	100.0	100.0
2	100.0	100.0	100.0
1 1/2	100.0	100.0	100.0
1	100.0	100.0	100.0
3/4	80.3	100.0	100.0
1/2	32.4	100.0	100.0
3/8	3.8	97.7	100.0
No. 4	1.7	29.3	98.4
No. 8	0.7	7.1	91.3
No. 16	0.3	1.3	82.3
No. 30	0.0	1.1	58.2
No. 50	0.0	0.9	10.0
No. 100	0.0	0.7	1.1
No. 200	0.0	0.3	0.5
FM	7.13	5.62	2.59
Bulk Dry Specific Gravity	2.78	2.70	2.53
Absorption, %	0.37	0.49	1.53
Dry rodded unit weight, lb/ft^3	102.0	94.6	N/A

Table 7. Properties of Aggregate Used in Colorado Study

Sieve Size	Percent Passing		
	Coarse Aggregate		Fine Aggregate
	No. 67	No.8	
2 1/2	100.0	100.0	100.0
2	100.0	100.0	100.0
1 1/2	100.0	100.0	100.0
1	100.0	100.0	100.0
3/4	99.0	100.0	100.0
1/2	77.0	100.0	100.0
3/8	41.0	90.0	100.0
No. 4	3.0	18.0	100.0
No. 8	1.0	2.0	92.0
No. 16	0.0	1.0	67.0
No. 30	0.0	0.0	39.0
No. 50	0.0	0.0	11.0
No. 100	0.0	0.0	1.0
No. 200	0.1	0.2	0.4
FM	6.56	5.89	2.90
Bulk Dry Specific Gravity	2.55	2.57	2.58
Absorption, %	1.0	0.4	0.9
Dry rodded unit weight, lb/ft^3	100.0	100.0	N/A

Table 8. Voids content of Different Proportions of No.57 Aggregate, No.8 Aggregate, and Fine Aggregate from Florida

No.57	No.8	Fine Agg	voids 1, %	voids 2, %	voids 3, %	Avg. voids, %
61.0%	0.0%	39.0%	23.8	22.9	24.9	23.9
67.0%	0.0%	33.0%	23.8	22.6	23.8	23.4
40.3%	24.7%	35.0%	23.6	24.4	23.5	23.8
58.5%	6.5%	35.0%	22.2	22.5	23.5	22.7
51.0%	17.0%	32.0%	22.6	24.1	23.5	23.4
0.0%	0.0%	100.0%	36.8	36.8	36.6	36.7

Table 9. Voids content of Different Proportions of No.57 Aggregate, No.8 Aggregate, and Fine Aggregate from Georgia

No.57	No.8	Fine Agg	voids 1, %	voids 2, %	voids 3, %	Avg. voids, %
58.2%	0.0%	41.8%	27.6	27.2	28.4	27.7
62.5%	0.0%	37.5%	28.4	28.4	27.9	28.3
38.1%	23.4%	38.5%	27.6	27.1	27.6	27.4
54.5%	6.1%	39.5%	28.4	27.4	27.9	27.9
48.0%	16.0%	36.0%	27.2	28.6	27.9	27.9

Table 10. Voids content of Different Proportions of No.67 Aggregate, No.8 Aggregate, and Fine Aggregate from Colorado

No.67	No.8	Fine Agg	voids 1, %	voids 2, %	voids 3, %	Avg. voids, %
54.0%	0.0%	46.0%	26.2	25.0	25.3	25.5
60.0%	0.0%	40.0%	26.2	27.0	26.7	26.6
63.0%	0.0%	37.0%	27.0	26.3	26.4	26.6
50.4%	9.6%	40.0%	24.5	23.8	25.2	24.5
100.0%	0.0%	0.0%	37.1	36.9	37.0	37.0
0.0%	0.0%	100.0%	34.7	34.6	34.6	34.6

Table 11. Voids content of WG and NWG Proportions from MD, FL, GA, and CO

Source	Aggregate Grading	Minimum voids, %	Maximum voids, %	Average voids, %
Florida	Well Graded	22.6	24.4	23.6
Florida	Not Well Graded	22.2	24.9	23.3
Georgia	Well Graded	27.1	28.7	27.7
Georgia	Not Well Graded	27.2	28.4	28.0
Colorado	Well Graded	23.8	27.0	25.9
Colorado	Not Well Graded	25.0	26.2	25.5
Maryland	Well Graded	23.3	27.7	25.4
Maryland	Not Well Graded	21.2	24.4	22.5

Figure 1. Combined Aggregate Voids Content Test Sequence

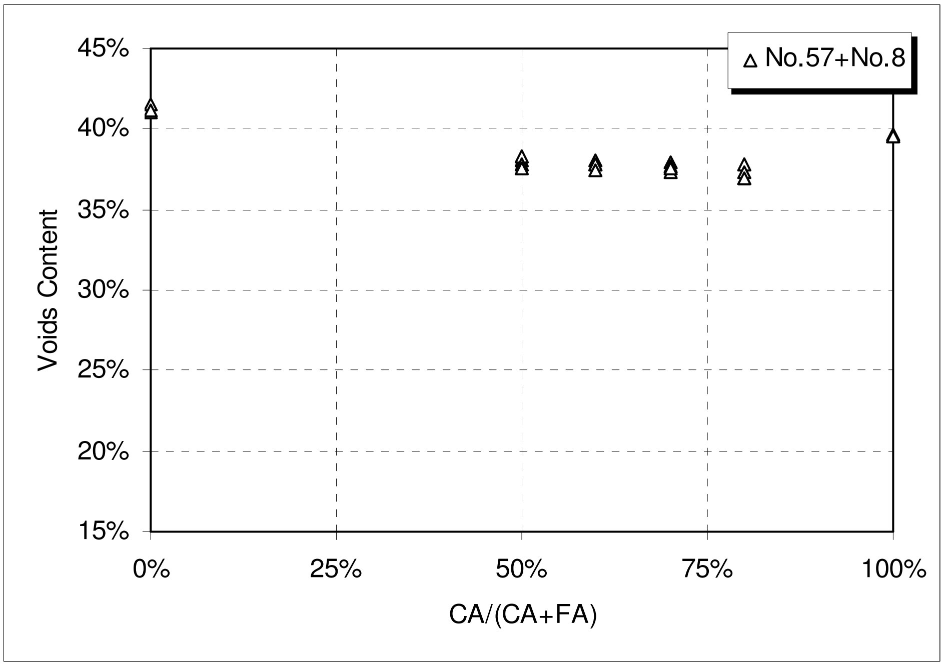


Figure 2. Voids content of Different Proportions of No.57 Aggregate and No.8 Aggregate from Maryland (CA=No. 57 Aggregate, FA= No. 8 Aggregate)

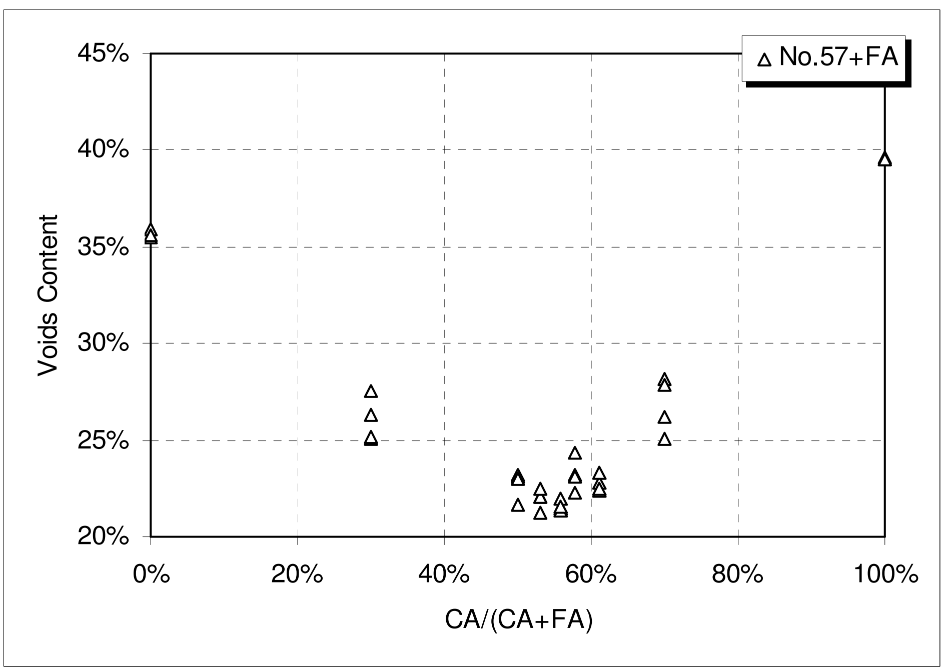
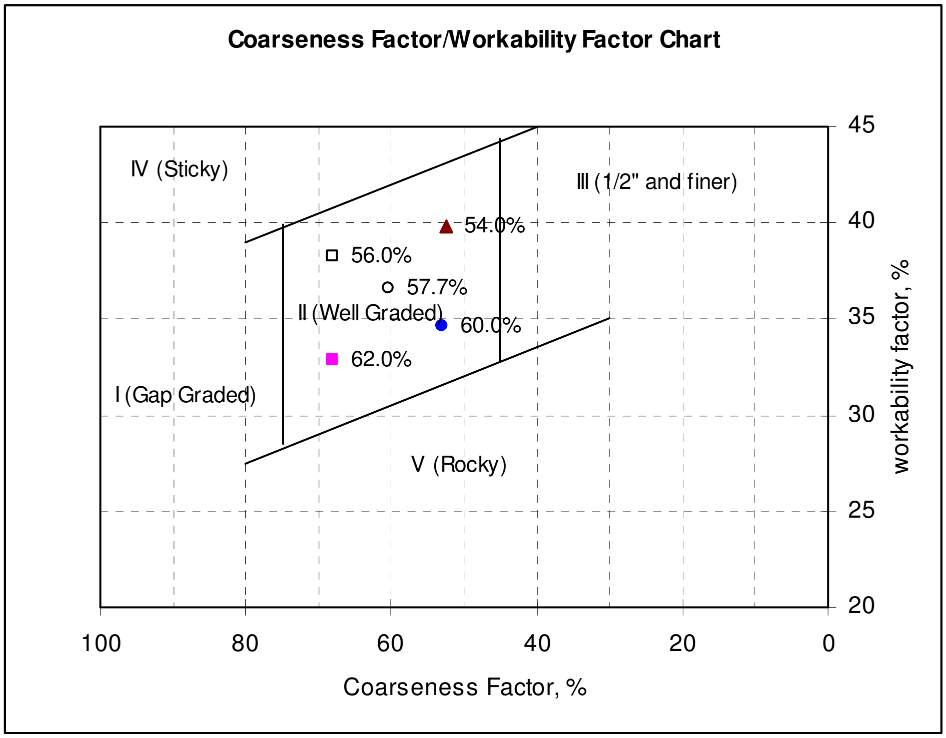


Figure 3. Voids content of Different Proportions of No.57 Aggregate and Fine Aggregate from Maryland (CA=No. 57 Aggregate, FA= Fine Aggregate)



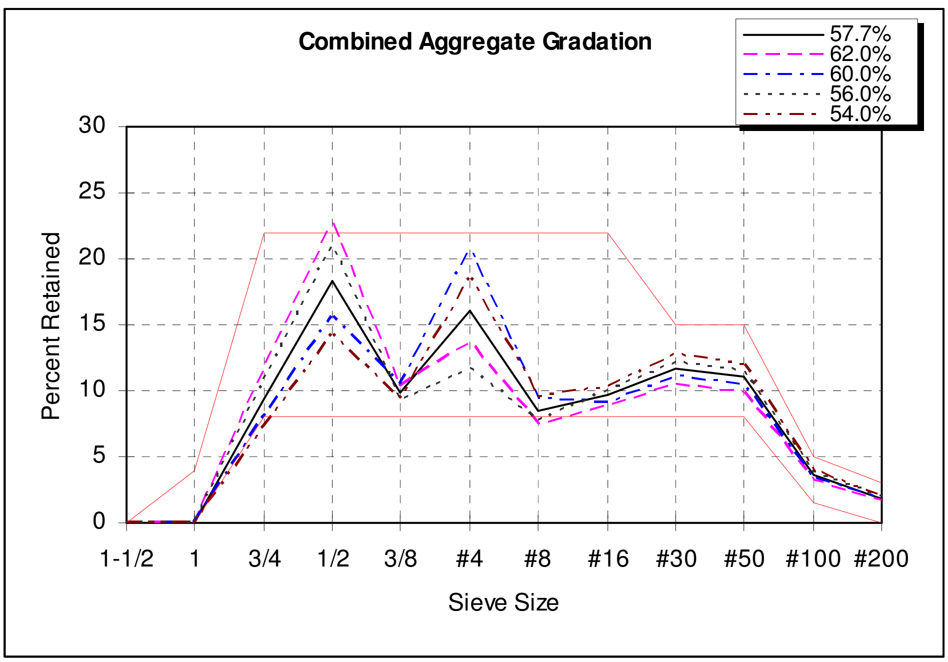
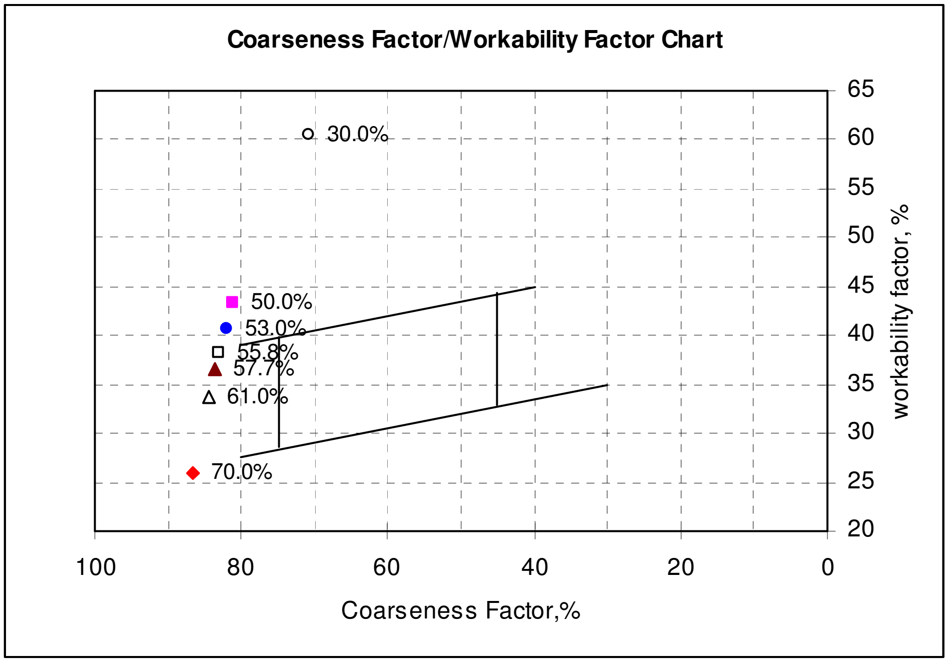


Figure 4. CF Chart and 8-18 Chart showing WG Gradings from Maryland. Values in Charts = Ratio of coarse aggregate (No. 57+No. 8) to total aggregate expressed as percent



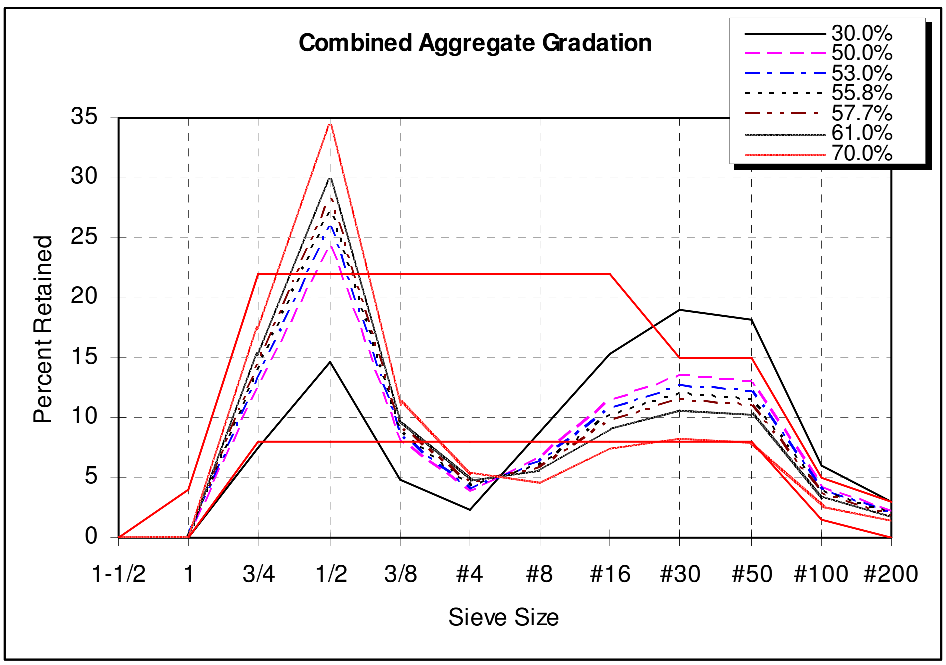


Figure 5. CF Chart and 8-18 Chart showing NWG Gradings from Maryland. Values in Charts = Ratio of coarse aggregate (No. 57+No. 8) to total aggregate expressed as percent

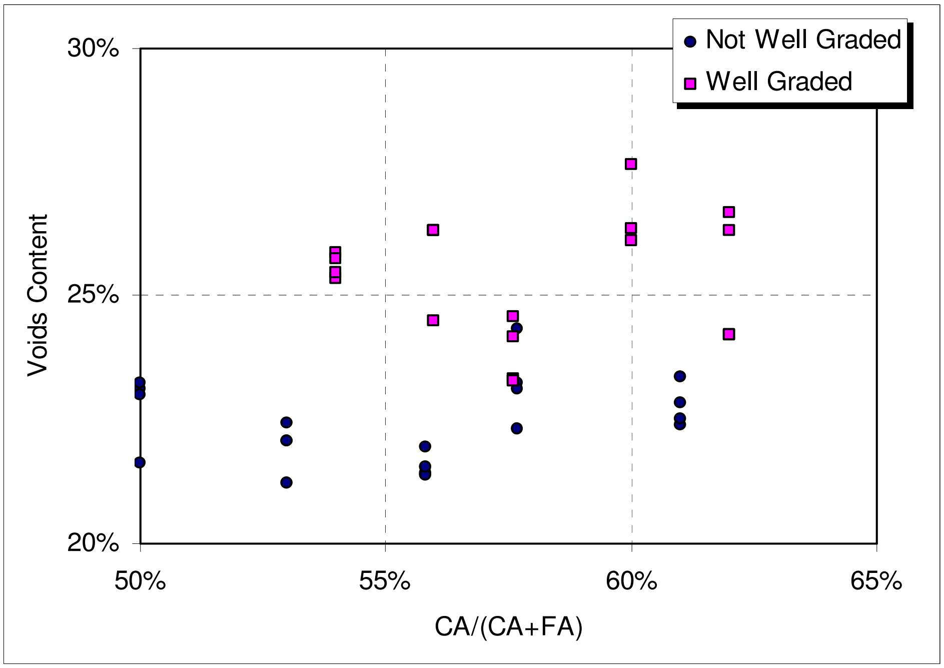


Figure 6. Voids content of WG and NWG Gradings from Maryland (CA=No. 57+No. 8 Aggregate, FA= Fine Aggregate)

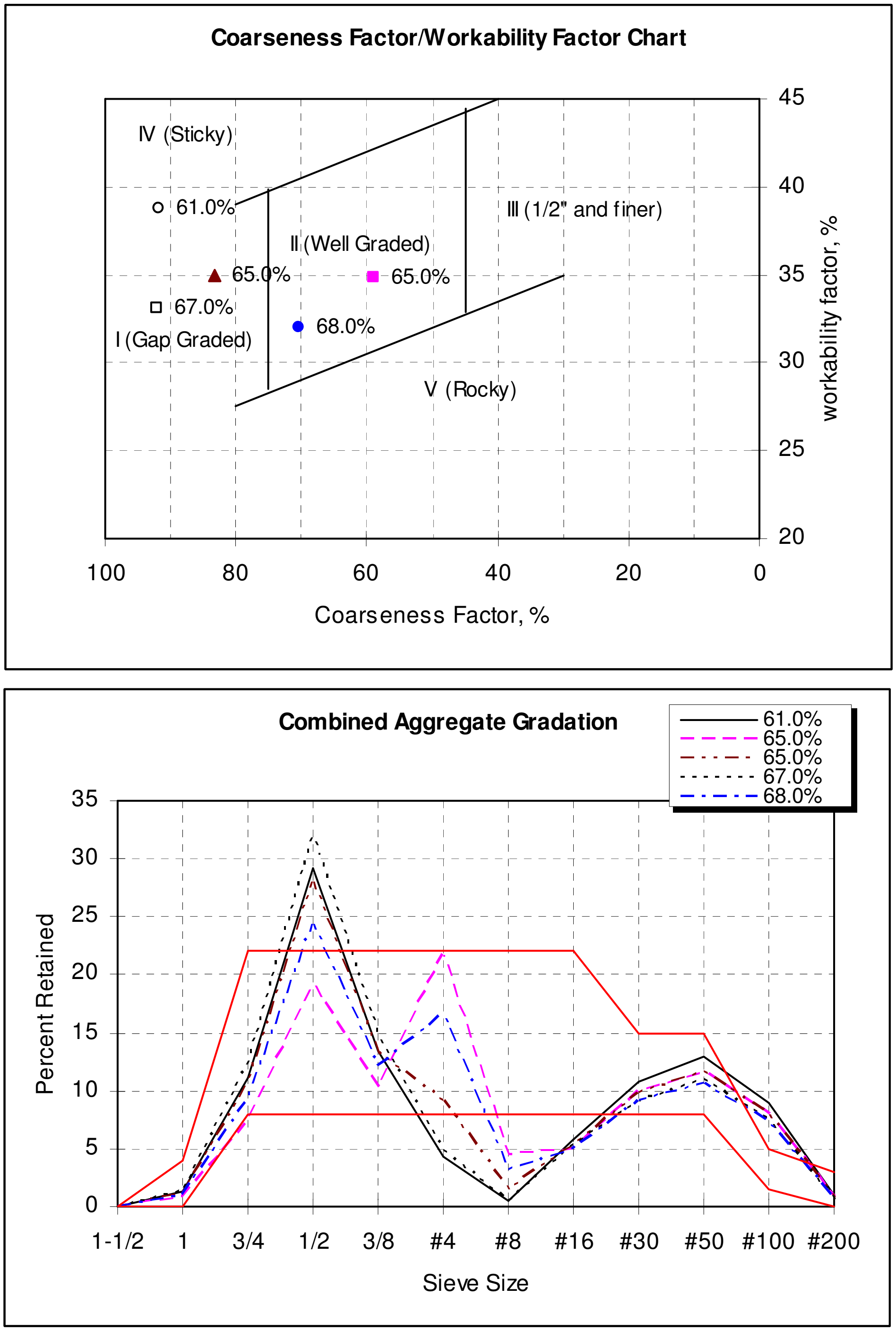


Figure 7. CF Chart and 8-18 Chart Showing WG and NWG Gradings from Florida. Values in Charts = Ratio of coarse aggregate (No. 57+No. 8) to total aggregate expressed as percent

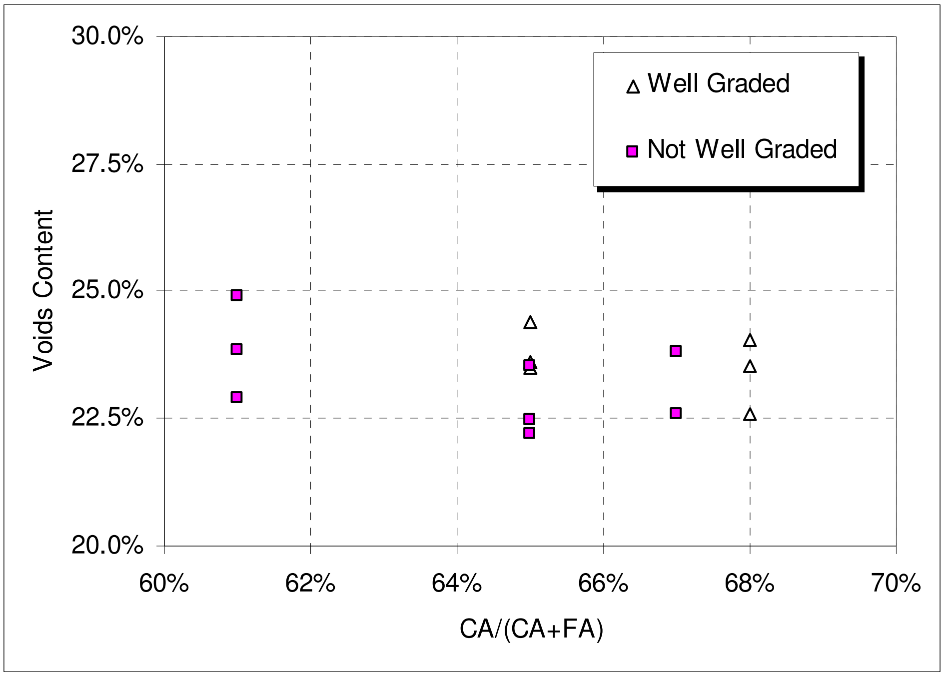
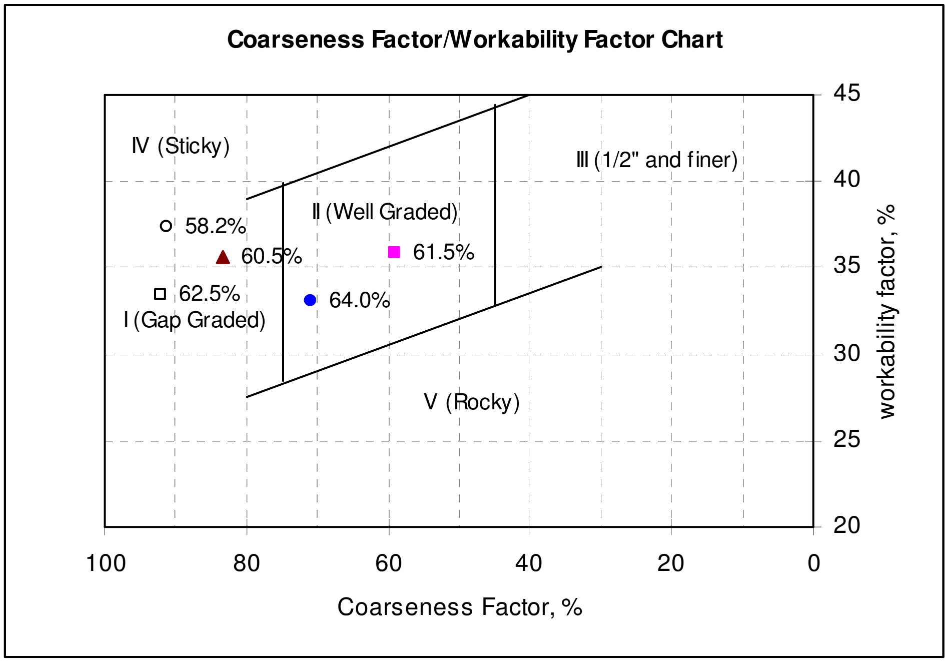


Figure 8. Voids content of WG and NWG Gradings from Florida (CA=No. 57+No. 8 Aggregate, FA= Fine Aggregate Chart



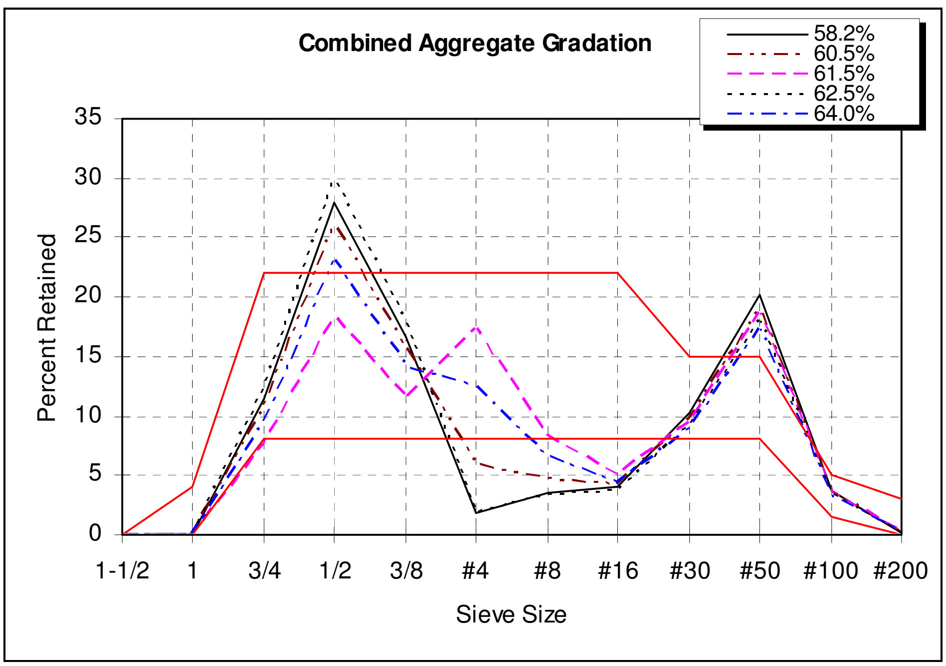


Figure 9. CF Chart and 8-18 Chart Showing WG and NWG Gradings from Georgia. Values in Charts = Ratio of coarse aggregate (No. 57+No. 8) to total aggregate expressed as percent

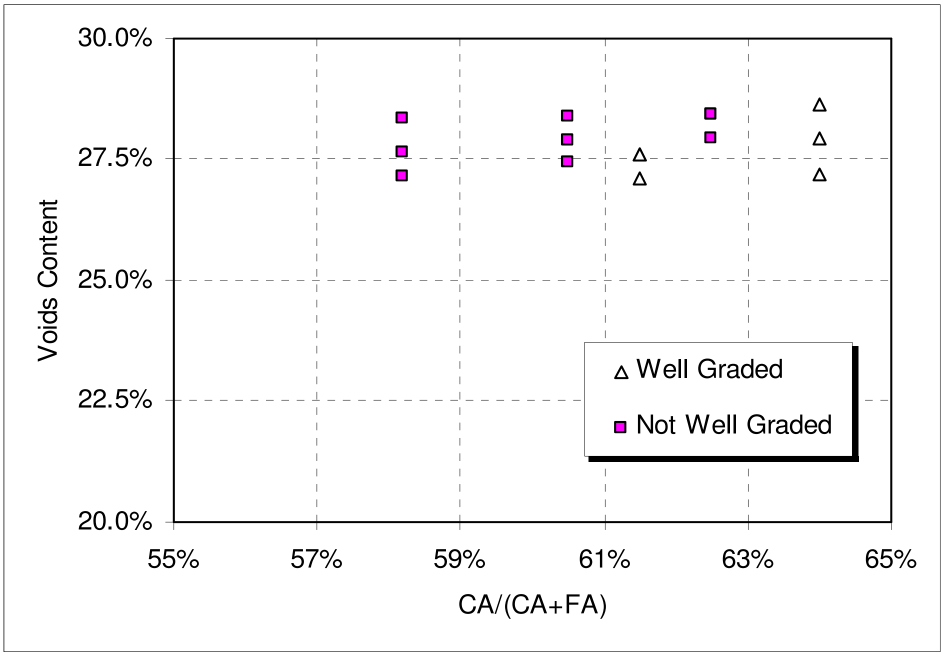
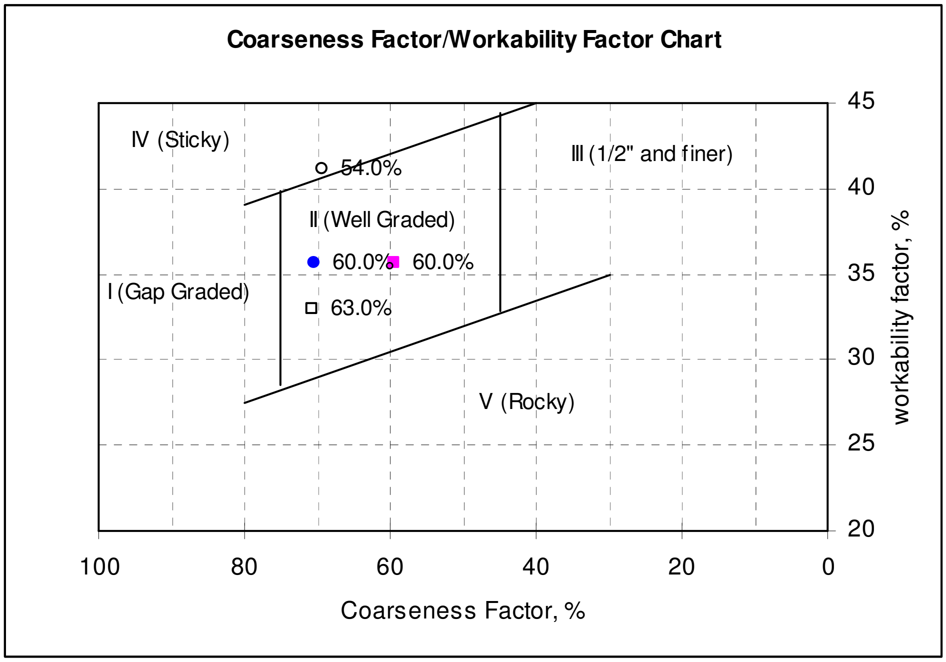


Figure 10. Voids content of WG and NWG Gradings from Georgia (CA=No. 57+No. 8 Aggregate, FA= Fine Aggregate)



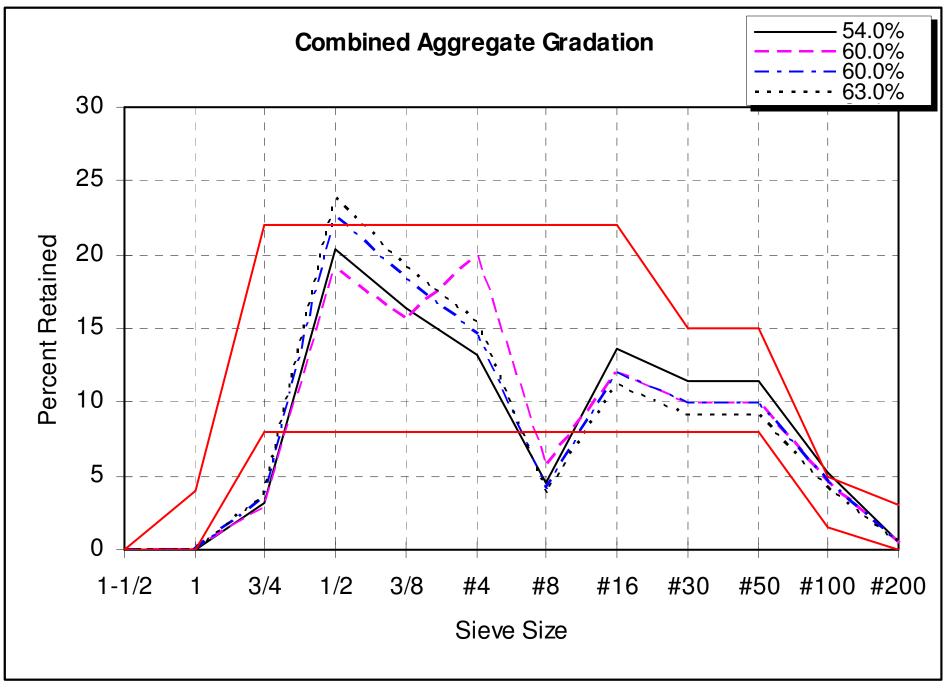


Figure 11. CF Chart and 8-18 Chart Showing WG and NWG Gradings from Colorado. Values in Charts = Ratio of coarse aggregate (No. 67+No. 8) to total aggregate expressed as percent

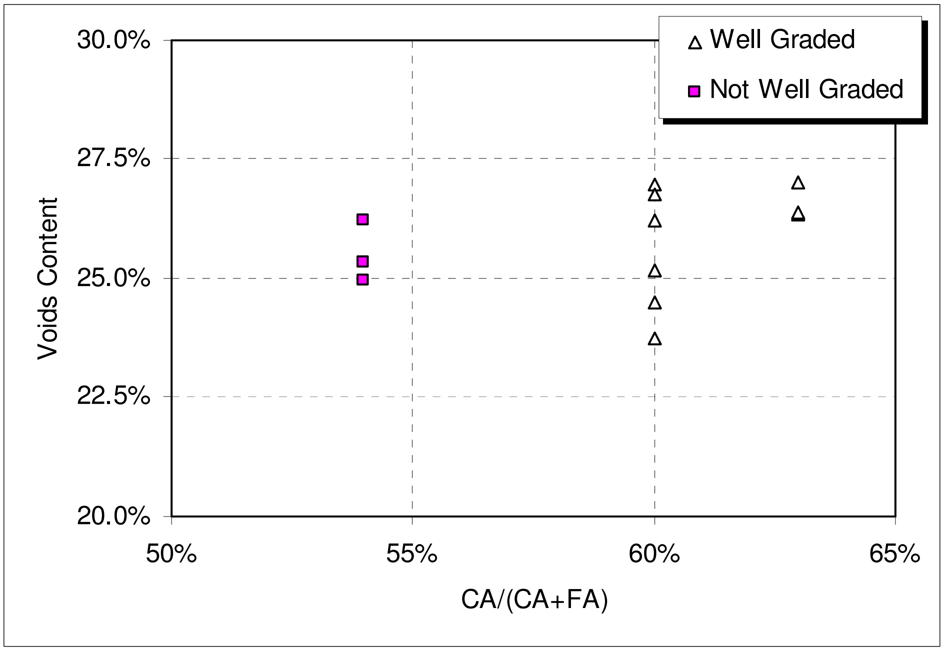


Figure 12. Voids content of WG and NWG Gradings from Colorado (CA=No. 67+No. 8 Aggregate, FA= Fine Aggregate)

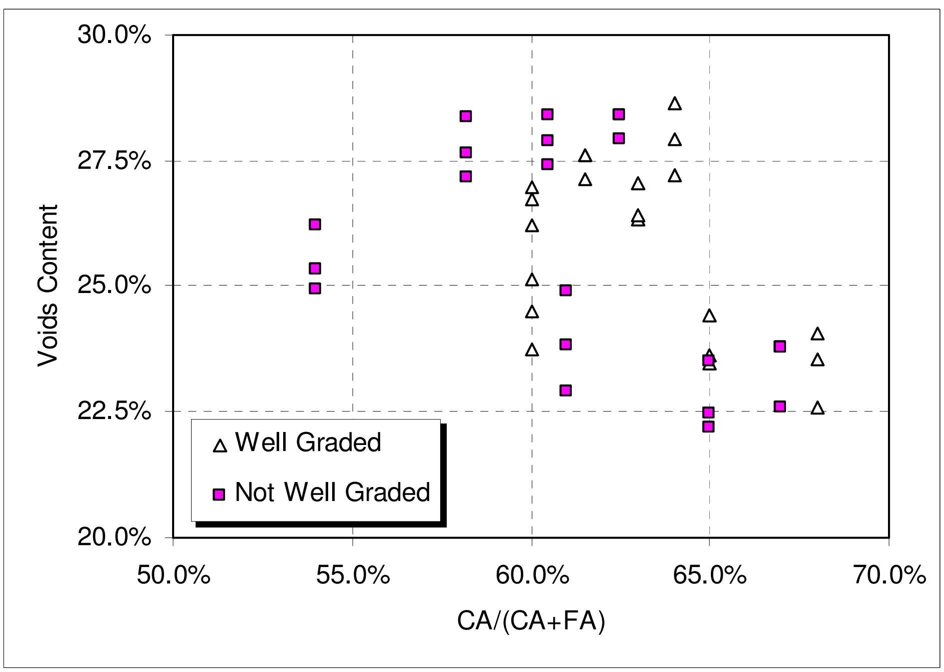


Figure 13. Voids content of WG and NWG Gradings from FL, GA, and CO (CA=No. 57+No. 67+No. 8 Aggregate, FA= Fine Aggregate)

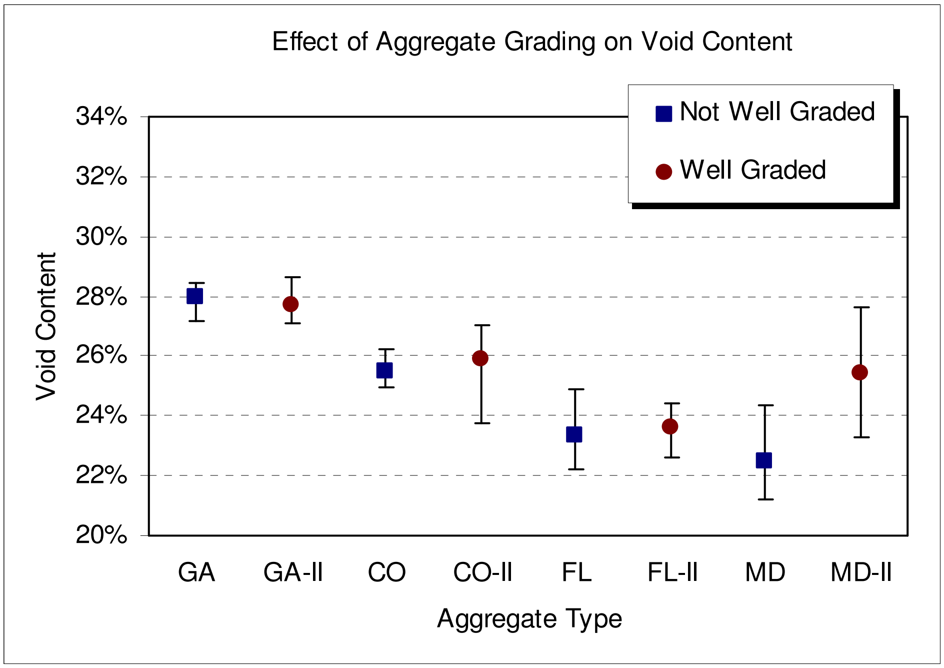


Figure 14. Voids content of WG and NWG Gradings from FL, GA, MD, and CO

Appendix

Aggregates Used for Round Robin Program - FL

Aggregates Used for Round Robin Program - GA