OPTIMIZED 3/4" GRADATION LIGHTWEIGHT AGGREGATE REPORT

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TABLE OF CONTENTS

INTRODUCTION

It has been widely reported that concrete with a well graded aggregate combination reduces water demand, consolidates without segregation, and maintains adequate workability. These properties tend to enhance the concrete strength, long-term performance and placement ability. The results of an investigation examining the effect of optimizing total aggregate gradation on the properties of concrete used for paving in Wisconsin were reported. The investigation used concepts presented by Shilstone[1] to optimize gradations consisting of carefully selected proportions of locally available aggregate. Unit weight, shrinkage, change in the water-to-cement (w/c) ratio at constant slump, change in slump at a constant w/c ratio, compressive strength, and possible segregation under vibration were measured in field test sections and laboratory mixes. This investigation showed that use of optimized total aggregate gradations instead of near-gap-graded gradations in pavement resulted in an increase in compressive strength of 10% to 20%, reduced water demand by up to 15% to achieve comparable slump, air contents achieved with 20 to 30% reductions in air entraining agent, potentially higher spacing factors in the air void system of hardened concrete, and reduced segregation following extended vibration (1 to 3 minutes). Not all efforts at gradation optimization in this study yielded measurable improvements in performance and the availability of local aggregates may still limit, to varying degrees, the ability to optimize. However, a reasonable effort to optimize gradation can lead to significant mix benefits.[2]

MATERIAL GRADATIONS

To achieve a uniform combined aggregate gradation several companies are using a combination of three or more different aggregates. In lightweight concrete production the majority of the mixes are made with lightweight coarse aggregate and normal weight fine aggregate. With many concrete companies unable to mix several different aggregates in the production of lightweight concrete, the need for an optimized lightweight aggregate gradation is necessary. Carolina Stalite Company (Carolina Stalite) initiated this research project to determine the optimum gradation for structural 3/4" lightweight aggregate to be mixed with normal weight fine aggregates to obtain a well-graded aggregate combination. ASTM C330[5] limits the gradations for 3/4" lightweight aggregate to the following:

SIEVE	PASSING
1”	100
3/4"	90-100
1/2"	N/A
3/8”	10-50
#4	0-20
#8	0-10

Historically 3/4" structural lightweight aggregates have been gap graded similar to normal weight aggregates.

STALITE SAMPLES USED IN TESTING

Below are the five different 3/4" structural lightweight aggregate (Stalite) samples used in the testing. The aggregate samples had varying amounts of material passing the 3/8" sieve. This variable is what we will use in the testing to signify the different aggregate combinations.

GRADATION STALITE	
SIEVE	PASSING
1"	100
3/4"	95
1/2"	55
3/8"	30
#4	12
#8	5

GRADATION STALITE	
SIEVE	PASSING
1"	100
3/4"	95
1/2"	55
3/8"	25
#4	10
#8	4

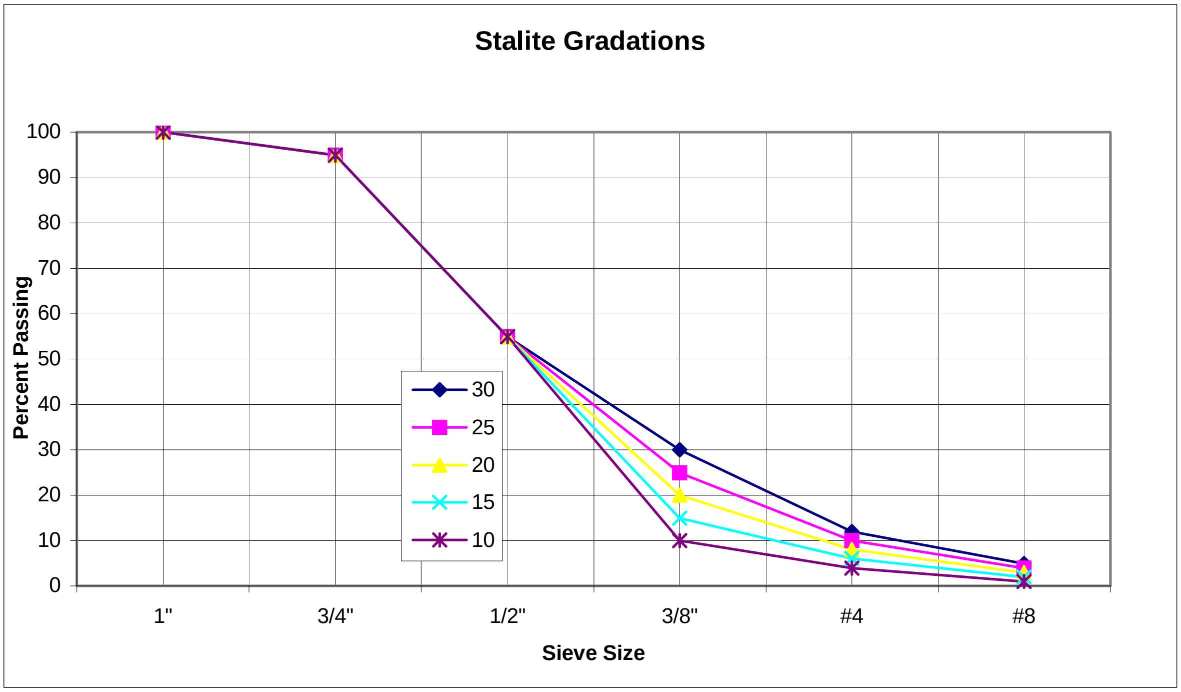
GRADATION STALITE	
SIEVE	PASSING
1"	100
3/4"	95
1/2"	55
3/8"	20
#4	8
#8	3

GRADATION STALITE	
SIEVE	PASSING
1”	100
3/4"	95
1/2"	55
3/8”	15
#4	6
#8	2

GRADATION STALITE	
SIEVE	PASSING
1”	100
3/4"	95
1/2"	55
3/8”	10
#4	4
#8	1

The sand used in the testing had the following gradation:

GRADTION SAND	
SIEVE	PASSING
#4	99.9
#8	93.0
#16	73.4
#30	37.8
#50	7.6
#100	1.2



The above graph depicts five Stalite samples tested. As you can see as the percent of material passing the 3/8" sieve increases, up to 30%, the gradation lines become much less gap-graded.

ANALYZED MIX DESIGNS

Fifteen different concrete mix designs were mathematically analyzed using the Shilstone workability charts, combined gradation graphs, and percent-retained charts. The mix designs analyzed are listed below.

Mix Designs

Mix number	1	6	11
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(30%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix number	2	7	12
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(25%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix Number	3	8	13
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(20%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix Number	4	9	14
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(15%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix Number	5	10	15
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(10%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

The mathematically combined gradation, expressed as percent retained, was calculated for the aggregate mix proposed in the above mix designs. The coarseness factors and workability factors were calculated as follows:

$$\text{Coarseness factor} = \frac{\text{(Combined percent retained above the 3/8”sieve)}}{\text{(Combined percent retained above \# 8 sieve)}} \text{ X100}$$

Workability factor = Combined percent passing the No. 8 sieve *

*The workability factor shall be increased 2.5% for each increase of 94 pounds of cement per cubic yard.[1]

Adjustments for density were made in the analysis because the density of the 3/4” STALITE is approximately half the density of normal weight aggregates generally used in these calculations. The correction was made by multiplying the density correction factor (calculation on page 8) by the weight of the STALITE retained on each sieve.

$$\text{Density Correction Factor} = \frac{\text{(Specific gravity normal weight aggregate)**}}{\text{(Specific gravity 3/4” STALITE)***}}$$

**2.70 was the specific gravity used for the normal weight aggregate

*** 1.50 was the specific gravity used for the 3/4” STALITE

Note: The above correction was for numerical analysis only and was not applied to the batching of test mixes.

In the following table, you will see the corrected coarseness factors and workability factors for each of the mixes studied. The charts on pages 8 and 9 show the density corrected combined gradation logarithmic graphs. Page 10 shows the 8% to 18% retained graphs.

WORKABILITY AND COARSENESS FACTORS

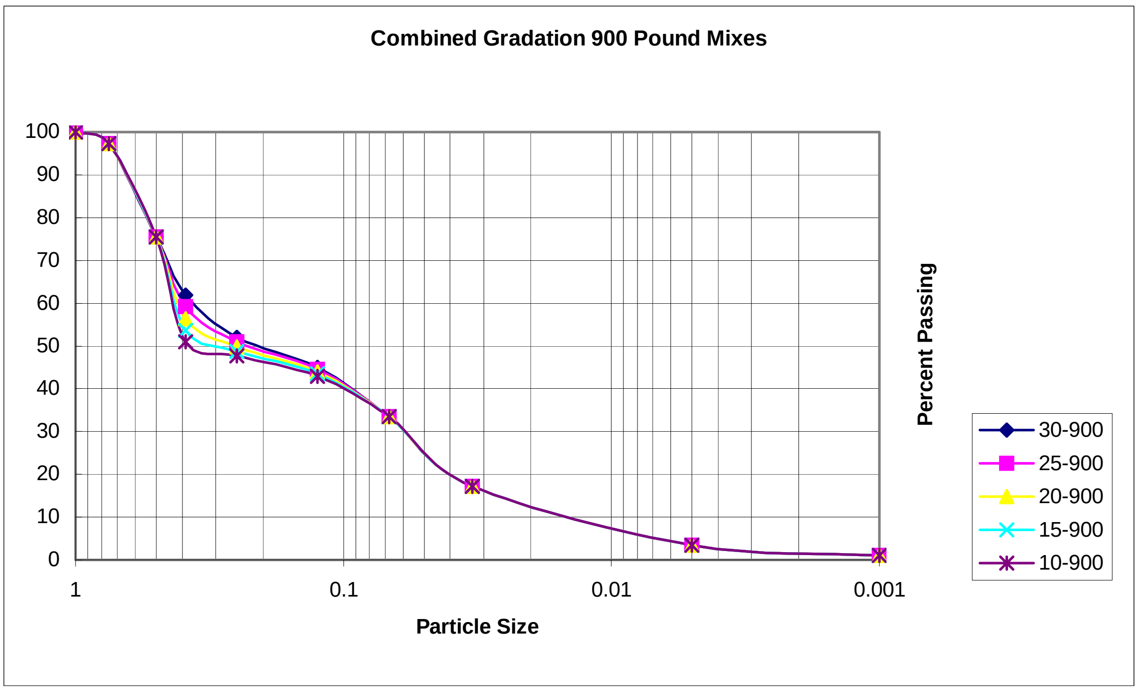
MIX DESIGN NUMBER	POUNDS STALITE	PERCENT STALITE PASSING 3/8“ SIEVE	POUNDS SAND	WORK-ABILITY FACTOR	COARSE-NESS FACTOR
1	900	30	1354	45.1	69.4
2	900	25	1354	44.5	73.6
3	900	20	1354	44.0	77.8
4	900	15	1354	43.4	81.8
5	900	10	1354	42.9	85.8
6	1000	30	1178	39.8	70.2
7	1000	25	1178	39.2	74.5
8	1000	20	1178	38.6	78.8
9	1000	15	1178	38.0	82.8
10	1000	10	1178	37.4	86.9
11	1100	30	1003	34.6	71.0
12	1100	25	1003	33.9	75.3
13	1100	20	1003	33.3	79.8
14	1100	15	1003	32.6	83.7
15	1100	10	1003	31.9	87.8

The workability factor vs. coarseness factor trend lines for the mixes are generally parallel to each other and approach the optimum zone (Zone B) at 30% of the STALITE passing the 3/8” sieve. See the chart from Shilstone[1, 3] in Appendix A.

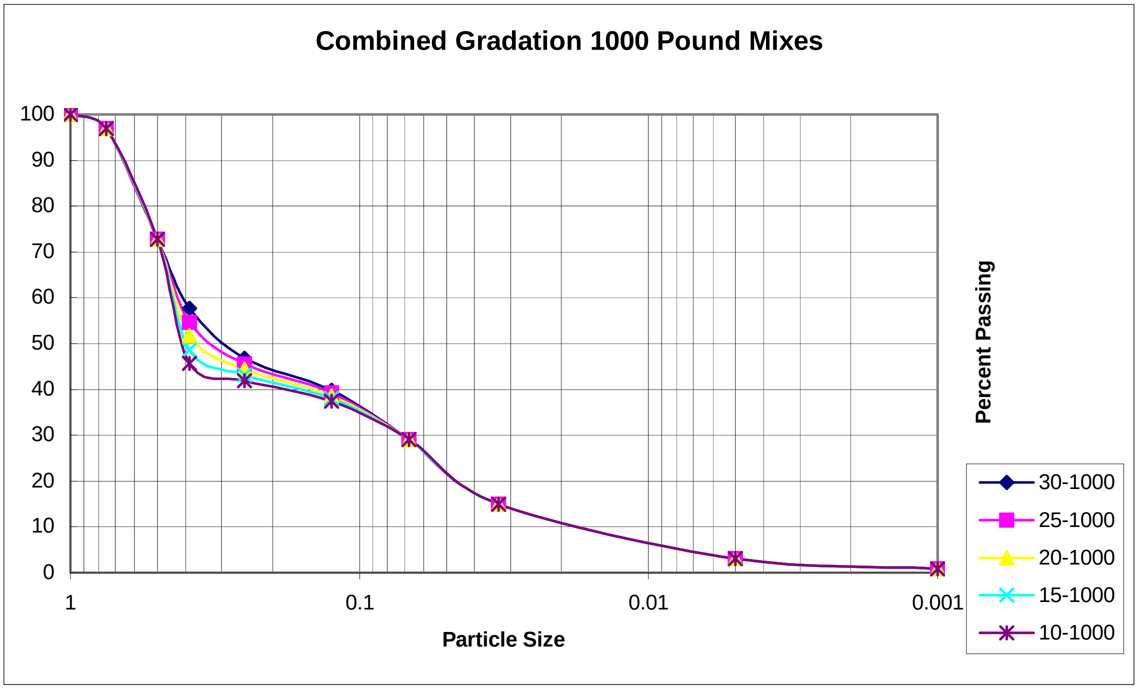
The Shilstone method of analyzing a concrete mix is both a good measure of the concrete workability and compaction characteristics. As with many lightweight concrete mixes the mixes with 900 pounds of STALITE appear to be over sanded landing in area C. Even with the corrected combined aggregate gradation being in area C the trend line shows that as the percent of Stalite passing the 3/8"sieve reaches 30% the coarseness factor corresponds to the optimum zone.

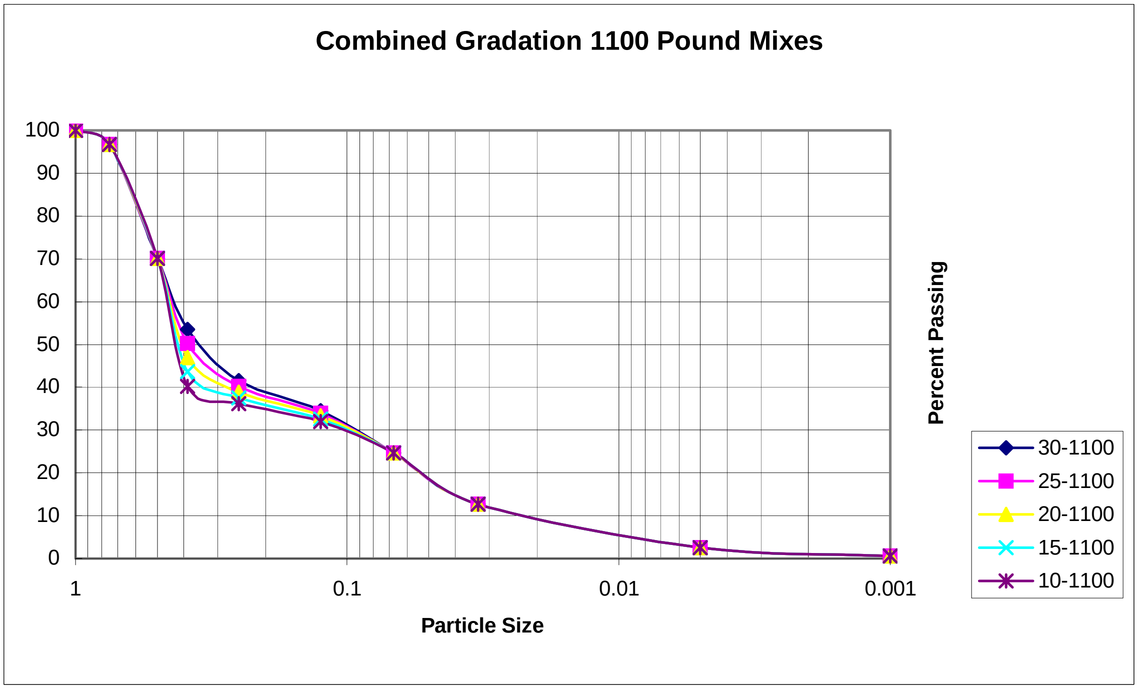
The logarithmic graphs that follow show the combined gradation plots for each of the mixes. These charts are corrected for density.

This graph shows that as the percent of 3/4" STALITE increases to 30% passing the 3/8" sieve the combined gradation curve becomes more uniformly graded.

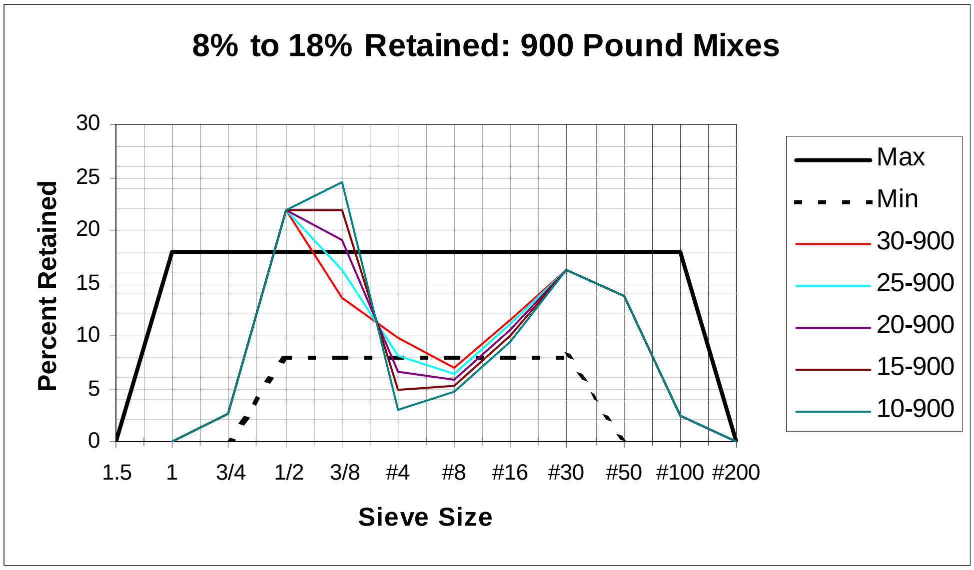


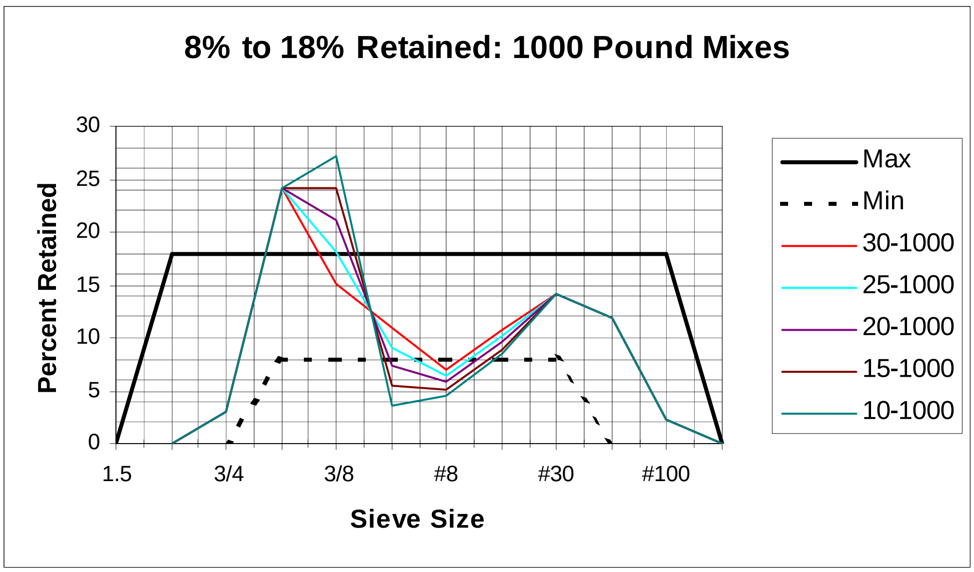
The gradation graphs for the mixes with 1000 pounds of 3/4" STALITE and 1100 pounds of 3/4" STALITE show the same improved uniformity with the addition of the STALITE passing the 3/8" sieve.

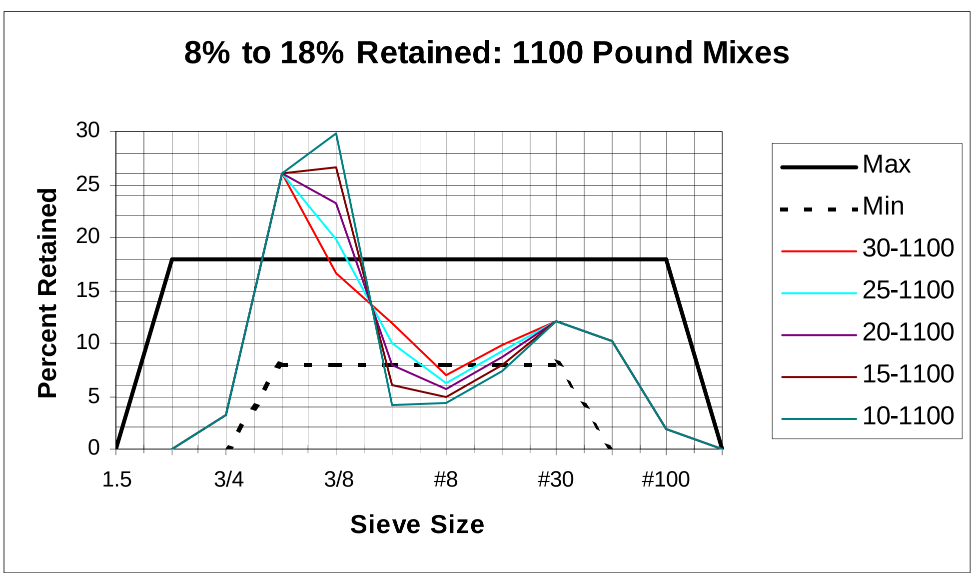




The following percent-retained graphs are designed to limit disproportionate amounts of material retained on any one sieve. The mathematical combined gradations for these graphs are corrected for density. The ideal goal is to have no sieve peak above 18 percent and to have no sieve dip below 8 percent.[3] The graphs show that combined gradation percent retained corresponds most closely with the curve when the percent of STALITE passing the 3/8" sieve is 30%.


8% to 18% Retained: 900 Pound Mixes
Percent Retained
30
25
20
15
10
5
0
1.5
1
3/4
1/2
3/8
#4
#8
#16
#30
#50
#100
#200
Sieve Size
Max
Min
30-900
25-900
20-900
15-900
10-900


8% to 18% Retained: 1000 Pound Mixes
Percent Retained
30
25
20
15
10
5
0
1.5
3/4
3/8
#8
#30
#100
Sieve Size
Max
Min
30-1000
25-1000
20-1000
15-1000
10-1000


8% to 18% Retained: 1100 Pound Mixes
Percent Retained
30
25
20
15
10
5
0
1.5
3/4
3/8
#8
#30
#100
Sieve Size
Max
Min
30-1100
25-1100
20-1100
15-1100
10-1100

TESTED MIX DESIGNS

The numerical analysis determined that the optimum gradation for the 3/4" STALITE was the gradation with 30% passing the 3/8” sieve. In daily production we expect this variable to range between 25% and 35%. After completing the mathematical analyses of all the mixes were completed, 9 mixes were selected for laboratory testing. The mixes are as follows:

Mix Designs

Mix number	1	6	11
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(30%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix number	3	8	13
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(20%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

Mix Designs

Mix number	5	10	15
Cement (lb)	564	564	564
Sand (lb)	1354	1178	1003
Stalite (3/4)(10%)			
Passing (lb)	900	1000	1100
Water (lb)	290	290	290

CONCERETE TESTING RESULTS

Six concrete test cylinders were cast from each mix and the cylinders were wet cured per ASTM C192 specifications. The concrete test cylinders were broken at 7, 28 and 56 days. Air percentage, fresh density and slump measurements were taken for each mix and are listed below.

Fresh Concrete Properties

Mix Number	AIR %	Density (pcf)	Slump (inches)
1	6.00	115.1	4.00
6	5.75	112.5	4.50
11	5.50	110.3	4.00
3	5.75	115.3	4.25
8	6.00	112.0	4.25
13	6.00	110.6	3.75
5	5.50	115.0	4.00
10	6.00	112.6	4.50
15	6.25	109.9	4.25

Average Compressive Strength

Mix Number	7Days (psi)	28 Days (psi)	56 Days (psi)
1	5120	6050	6420
6	5150	6190	6520
11	5130	6000	6490
3	4970	5810	6190
8	4990	5990	6280
13	4950	5790	6200
5	4690	5595	5945
10	4640	5680	5990
15	4510	5350	5890

The results of the tests show an increase in compressive strength for the concrete mixes with the more uniform combined aggregate gradation. The following tables show compressive strength increases ranging from 215 psi to 650 psi with the improved total combined gradation.

900 Pound Mixes	7Days (psi) Increase	28 Days (psi) Increase	56 Days (psi) Increase
30% Passing 3/8" Sieve	430	455	475
20% Passing 3/8" Sieve	280	215	245

1000 Pound Mixes	7Days (psi) Increase	28 Days (psi) Increase	56 Days (psi) Increase
30% Passing 3/8" Sieve	510	510	530
20% Passing 3/8" Sieve	350	310	290

1100 Pound Mixes	7Days (psi) Increase	28 Days (psi) Increase	56 Days (psi) Increase
30% Passing 3/8" Sieve	620	650	600
20% Passing 3/8" Sieve	440	440	310

CONCLUSION

The optimized 3/4" STALITE improves the characteristics of the combined aggregate gradation thus creating a stronger and more durable lightweight concrete. Carolina Stalite Company produces this optimized 3/4" STALITE and it is available to all of our customers. This optimized gradation does meet the ASTM C330[5] specifications.

REFERENCES

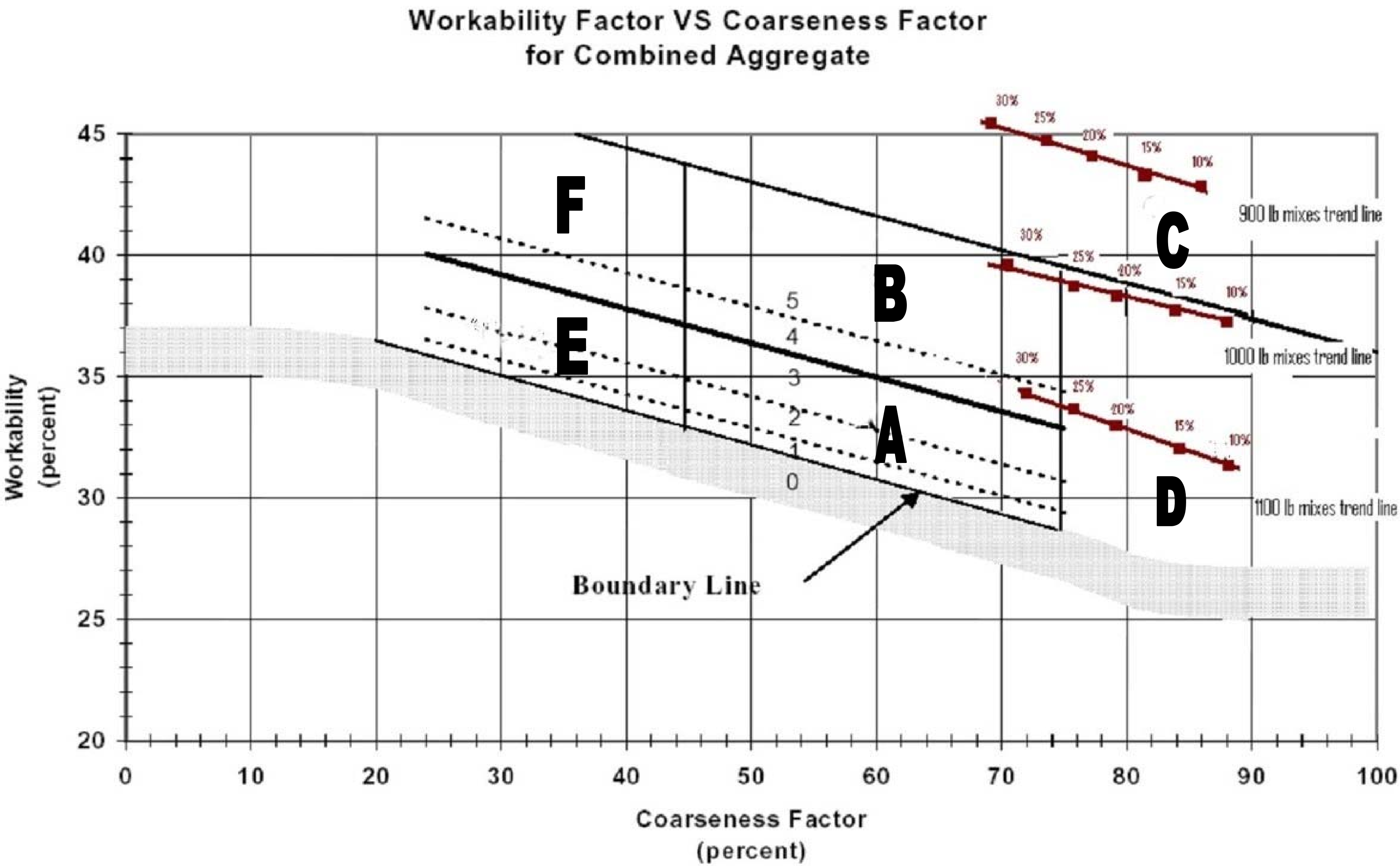
1. Shilstone, J. Sr., “Concrete Mixture Optimization” Concrete International Vol. 2, No. 6, Jun. 1990, pp. 33-39.

2. Cramer, S. M., Hall, M., and Perry J., “Effect of Optimized Gradation on PCC for Wisconsin Pavements” Transportation Research Record 1478, 1999.

3. Iowa Department of Transportation, MATS I.M. 532 “Aggregate Proportioning Guide for Portland Cement Concrete Pavement” October 1999.

4. Anderson, P.J. and Johansen, V., “A Guide for Determining the Optimum Gradation of Concrete Aggregates” 1993,vii, 200pp.

5. American Society of Testing and Materials, 2001 Annual Book of ASTM Standards- Volume 4.02 “Standard Specification for Lightweight Aggregates for Structural Concrete” C330.


Workability Factor VS Coarseness Factor
for Combined Aggregate
Workability (percent)
Coarseness Factor (percent)
45
40
35
30
25
20
0
10
20
30
40
50
60
70
80
90
100
A
B
C
D
E
F
0
1
2
3
4
5
Boundary Line
900 lb mixes trend line
1000 lb mixes trend line
1100 lb mixes trend line
30%
25%
20%
15%
10%