NRMCA Research Laboratory

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

## Phase B: Concrete Performance


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



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## Phase B: Concrete Performance
## Project D340
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## 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

Based on aggregate packing tests conducted at four locations Phase A report concluded that the use of "well graded combined aggregates" (WG) does not necessarily lead to a reduction in the voids content of the aggregate as compared to the "not well graded combined aggregates" (NWG). The aim of this report is to evaluate whether the use of WG improves the fresh and hardened properties of concrete.

## Experimental Study

A major portion of the experimental program was conducted at the NRMCA Research Laboratory in Maryland. Additionally, a planned testing program was conducted at two other locations (Florida, and Georgia) with their local materials.
The study at NRMCA was divided into 4 stages and the main differences between the stages are provided in Table 1. The NRMCA study is discussed first followed by the round robin study.

### Materials

The following materials were used in the experimental study conducted at Maryland. Local materials were used at the other two locations.
ASTM C 150 Type I Portland Cement Lot #7999 (Stage I, II), Lot #7970 (Stage II high slump, III, IV)
ASTM C 618 Class F fly ash, Lot #7948
ASTM C 989 Ground granulated blast furnace slag, Lot #7945
ASTM C 260 Tall oil air entraining admixture, Lot#7941
ASTM C 494 Type A Lignin-based water reducing admixture, Lot#7974
ASTM C 494 Type F Naphthalene sulfonate high range water reducing admixture, Lot#7975
ASTM C 33 Natural sand, Lot #7958
ASTM C 33 No. 57 Crushed Limestone, Lot#7998
ASTM C 33 No. 467 Crushed Limestone, Lot#7963
ASTM C 33 No. 8 Crushed Limestone, Lot#7966
The aggregate characteristics are provided in the Phase A report. 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.

### Mixing

A revolving drum mixer with a mixing capacity of 2.5 $ft^3$ was used to mix the concrete. Concrete batch size for all stages was 1.0 $ft^3$ except Stage I which was 1.6 $ft^3$. Concrete mixtures were mixed in accordance with ASTM C 192. When a HRWR admixture was used (Stage IV) concrete was mixed for an additional 2 minutes (during the first mixing cycle) over the standard mixing time that is recommended in ASTM C 192.

### Testing

Table 2 gives a quick overview of the various tests conducted as part of this research study. ASTM standardized testing procedures were followed to the extent possible. Non-standardized tests and deviations from ASTM standards (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.

**Fresh Concrete Tests**

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138, and temperature, C 1064.

Bleeding was measured for all stages except Stage I, in accordance with ASTM C 232 (Method A: sample consolidated by tamping) with the following change: Concrete was placed in a 6 in. diameter plastic container to a depth of 6 in. instead of the standard ½-$ft^3$ container. The total accumulated bleed water is represented as a percent of the mix water.

A segregation test was developed to evaluate the segregation potential of the various mixtures under internal vibration. This test, called the column segregation test, is based on the newly standardized static segregation test for self consolidating concrete (ASTM C 1610). The test setup is shown in Figure 1. Fresh concrete is filled up to the top in one layer and then vibrated for 15 seconds using a 5/8" rod tied to an internal vibrator. Using a sawing motion concrete from the top third and the bottom third of column are collected on a pan, weighed and washed over a 4.75 mm (No.4) sieve. The washed aggregate retained on the No. 4 sieve for both the the top and the bottom portion of the column is weighed and expressed as the coarse aggregate mass percent of the total concrete mass of that portion. Concrete mixtures that had significant segregation would result in a lower coarse aggregate percentage in the top third of the column compared to the bottom third.

The placement segregation was developed to evaluate the segregation potential of the various mixtures as the concrete is discharged from the truck chute. In this test immediately after mixing, concrete from the revolving drum mixer is discharged into a wheelbarrow without subjecting the mixer or wheel barrow to any agitation. Two scoops of concrete are removed from the far end of the concrete pile and from the center of the concrete pile where concrete is discharged. The collected concrete is weighed and washed over of a No.4 sieve and the coarse aggregate is expressed as a percent of the total concrete sample weight. If the concrete is susceptible to segregation, the coarse aggregate content of samples obtained from the two locations would differ significantly. However experiments did not reveal significant differences and moreover the test was not repeatable. As a result the placement segregation test was not conducted for all stages.

A finishability test was devised to evaluate the finishability of the different mixtures used in flatwork applications. In this test immediately after mixing, concrete from the revolving drum mixer is discharged into a flat steel pan to form a pad approximately 2 ft. x 2 ft. x 3 in . The concrete is roughly leveled using a shovel and finished using a 12 x 4 in. magnesium float. The test set up is shown in Figure **2**. A total of three passes starting from a specific side and repeated perpendicularly was referred to as "1" pass. A finishability rating (FR) for the concrete mixture was assigned based on the number of passes and a visual evaluation of the quality of the surface finish. The quality of the finish was quantified as follows:

1 – Excellent finishability; minor surface defects, smooth surface.
2 – Adequate finishability; few surface defects, not a smooth surface but acceptable.
3 – Not acceptable; substantial surface defects regardless of the number of passes.

A rating of 2T-1 would indicate that it needed a total of two passes and that the final surface quality was excellent with minor defects. The same technician conducted the finishability evaluation for each mixture.

**Hardened Concrete Tests**

Compressive strength tests for concrete mixtures were conducted in accordance with ASTM C 39. Specimen size used was 4 x 8 in. cylindrical specimens. Test specimens were transferred to the 100% humidity room as soon as they were made and cured until the test age. Neoprene caps of 70 durometer hardness were used to cap the test specimens in accordance with ASTM C 1231. Strength test results reported are the average of 2 test cylinders tested at the same age.

Length change of concrete due to drying shrinkage was tested by ASTM C 157. Prismatic specimens 3 x 3 x 11 in. with embedded studs were used to measure the length change, using a gage length of 10 in. between the insides of the studs. The shrinkage test specimens were moist cured for 7 days and after that they were stored in at 70 ºF and a relative humidity of 50%. Length change measurements were obtained at various periods of air drying as indicated in the reported results. The length change reported is the average of 2 specimens.

**Common Aspects in Mixture Proportioning for Each Stage**

Within each stage the absolute volumes of cementitious materials, mixing water, and total aggregate were held constant. Different volume ratios of coarse (No. 57 or No. 467), intermediate (No. 8) and fine aggregates were selected to attain multiple WG and NWG mixtures.

WG mixtures were designed to meet both the Zone II requirement in the Coarseness Factor (CF) chart and the 8-18 chart requirement as recommended in ACI 302.1R-04. NWG met neither the Zone II requirement in the CF chart nor the 8-18 chart requirements. NWG mixtures typically were located in Zone I or Zone IV of the CF chart. A short description of the CF and 8-18 charts can be found in the Phase A report.

For each stage the first mixture denoted by the suffix ACI is the **control mixture** in which the aggregate contents were proportioned according to the ACI 211 $b/b_o$ procedure. The control ACI mixture had NWG in each stage. The other NWG mixtures were developed by increasing or decreasing the coarse aggregate content. The WG mixtures were developed by adding an intermediate aggregate. It was not possible to create a WG mixture without an intermediate aggregate suggesting that local aggregates in all three locations were deficient in intermediate aggregates.

Since the mixing water content was held constant within each stage it is assumed that a higher measured slump for a specific mixture would be indicative of a lower water demand.

**Stage I**

All concrete mixtures were non air-entrained with a cementitous materials content of 517 lb/yd$^3$ and did not contain any chemical admixtures or supplementary cementitious materials. The mixing water content was maintained at 290 lb/yd$^3$ and the slump was allowed to vary. ASTM C 33 Size No. 467, No. 8 and fine aggregates were used. The following concrete mixtures were prepared:

| Mixture ID | Coarse aggregate % by volume | Combined FM | Zone, CF, WF | Modified Specific Surface |
|---|---|---|---|---|
| I-NWG-ACI | 60.4 | 5.56 | I, 81.8, 34.0 | 20.0 |
| I-WG-1 | 60.5 | 5.39 | II, 67.9, 34.1 | 20.7 |
| I-WG-2 | 60.6 | 5.27 | II, 57.4, 34.2 | 21.2 |
| I-NWG-1 | 60.4 | 5.53 | I, 83.4, 33.9 | 20.0 |
| I-NWG-2 | 50.2 | 5.11 | IV, 78.8, 42.9 | 24.3 |
| I-NWG-3 | 66.4 | 5.83 | I, 83.2, 28.8 | 17.5 |
| I-NWG-4 | 55.3 | 5.34 | I, 80.4, 38.4 | 22.2 |

WF=Workability Factor; FM=Fineness modulus.
Modified specific surface is a non-dimensional value calculated as the summation of the product of percent retained and a factor for each of the sieves for the combined aggregate grading. More details can be found in the literature (Day, 2006). A higher specific surface and lower combined FM is generally indicative of finer material.

## Mixture Proportions

Detailed mixture proportions and test results are provided in Table 3 and CF and 8-18 charts for the combined aggregates are shown in Figure 3.

1. Mixture I-NWG-ACI was the **Control ACI mixture** and it had NWG
2. Mixture I-WG-1 had WG.
3. Mixture I-WG-2 had WG with 19% less No. 57 aggregate than Mixture I-WG-1.
4. Mixture I-NWG-1 had NWG with a combined aggregate grading identical to that of the control mixture except that 15% of the No. 467 aggregate was replaced with aggregate size between the 3/4 and ½ in. sieves in an attempt to make the combined aggregate more NWG.
5. Mixture I-NWG-2 had NWG with 17% less coarse aggregate than the Control.
6. Mixture I-NWG-3 had NWG with 10% more coarse aggregate than the Control.
7. Mixture I-NWG-4 had NWG with 8% less coarse aggregate than the Control.

## Discussion of Test Results

WG mixtures had about the same slump (water demand) as compared to the control ACI mixture. Among NWG mixtures if coarse aggregate content was increased relative to control, as in Mixture I-NWG-3, then the slump increased sharply (water demand decreased). If fine aggregate content was increased relative to control, as in Mixture I-NWG-2 and Mixture I-NWG-4, then the slump decreased by 1 to 2 in. (water demand increased).
Air contents (entrapped) were generally between 1.5 to 2%. For mixtures with a higher fine aggregate content relative to the ACI mixture the entrapped air content increased to about 3.5%.
There was not much difference in finishability between the different mixtures.
Compressive strengths ranged between 4,860 and 5,250 psi. WG mixtures generally had about 150-200 psi higher strength as compared to the NWG mixtures. This is not considered a statistically significant difference in strength.

Shrinkage of the different mixtures did not vary significantly and after 28 days of drying the average length change values of all mixtures were about 0.018%.

### Stage II

All concrete mixtures were non air-entrained and had a cementitous materials content of 500 lb/yd$^3$, with 15% Class F fly ash by weight of cementitious materials. A Type A water reducer was used at a dosage of 5 to 6 oz/cwt. of cementitious materials. The mixtures were proportioned and mixed to a constant mixing water content of 270 lb/yd$^3$ and the slump was allowed to vary. ASTM C 33 Sizes No. 57, No. 8 and fine aggregates were used. The following concrete mixtures were prepared:

| Mix ID | Coarse agg, % | Combined FM | Zone, CF, WF | Specific Surface |
|---|---|---|---|---|
| II-NWG-ACI | 55.2 | 5.24 | I, 82.5, 38.3 | 22.3 |
| II-WG-1 | 57.5 | 5.11 | II, 60.3, 36.2 | 22.3 |
| II-WG-2 | 61.0 | 5.32 | II, 67.6, 33.2 | 20.6 |
| II-NWG-1 | 58.5 | 5.38 | I, 83.5, 35.4 | 20.9 |
| II-WG-3 | 54.1 | 4.91 | II, 52.5, 39.2 | 24.0 |
| II-NWG-2 | 51.7 | 5.09 | IV, 81.4, 41.3 | 23.8 |

### Mixture Proportions

Detailed mixture proportions and test results are provided in Table 4 and CF and 8-18 charts for the combined aggregates are shown in Figure 4.

1. Mixture II-NWG-ACI was the **Control ACI mixture** and had NWG.
2. Mixture II-WG-1 had WG.
3. Mixture II-WG-2 had WG with 22% more No. 57 aggregate than Mixture II-WG-1.
4. Mixture II-NWG-1 had NWG with 6% more coarse aggregate than the Control.
5. Mixture II-WG-3 had WG with 22% less No. 57 aggregate than Mixture II-WG-1.
6. Mixture II-NWG-2 had NWG with 6% less coarse aggregate than the Control.

### Discussion of Test Results

The average slump of the three WG mixtures was 3.75 in. as compared to 4.00 in. for the NWG mixtures suggesting that WG did not help reduce water demand.
No difference was noticeable in entrapped air content between the different mixtures.
Bleeding was measured only for two of the mixtures and both the WG and NWG mixture showed the same amount of bleed water at about 2.9%.
There was not a significant difference in finishability between the different mixtures. The average FR of all mixtures was 2T-1.
Column segregation tests were conducted only on two of the mixtures and the results indicate that the segregation of the WG mixture was higher (6%) than that of the NWG mixture (3.8%).
All mixtures gave similar compressive strength test results. The WG mixtures varied between 5060 psi and 5330 psi with an average of 5230 psi. The NWG mixtures varied between 5040 psi and 5310 psi

with an average of 5210 psi. The difference in strength between the WG and NWG mixtures is not statistically significant.
All mixtures gave similar 180-day drying shrinkage test results. The WG mixtures had a length change between 0.053% and 0.056% with an average of 0.054%. The NWG mixtures varied between 0.045% and 0.057% with an average of 0.052%.

The first four mixtures were repeated on a different day at a higher water content of 290 lb/yd$^3$ and the same admixture dosage of 5 oz/cwt. The aggregate ratios were slightly changed so that the same CF, and WF were attained as for the corresponding lower slump mixtures. These tests were conducted to evaluate if the fresh concrete performance of the different mixtures would change at a higher slump. The slump of the different mixtures was about 7 in. for all four mixtures thus suggesting again that WG did not help reduce water demand.
All mixtures gave similar bleed test results. The average bleed water of the two WG mixtures was 7.1% and the average bleed water for the NWG mixtures was 6.7%.
Column segregation test results showed that the segregation of the WG mixtures (1.6%, 4.9%) were lower than those of the NWG mixtures (5.8%, 8.9%).

## Stage III

All concrete mixtures were non air-entrained and had a cementitous materials content of 400 lb/yd$^3$, with 50% slag as a percent by weight of the cementitious materials. A Type A water reducing admixture was used at a dosage of 5 oz/cwt. of cementitious materials. The mixing water content was maintained at 270 lb/yd$^3$ and the slump was allowed to vary. ASTM C 33 Size No. 57, No. 8 and fine aggregates were used. The following concrete mixtures were prepared:

| Mix ID | Coarse agg, % | Combined FM | Zone, CF, WF | Specific Surface |
|---|---|---|---|---|
| III-NWG-ACI | 52.9 | 5.14 | I, 81.8, 37.5 | 23.3 |
| III-WG-1 | 54.0 | 4.98 | II, 59.6, 36.5 | 23.7 |
| III-WG-2 | 57.5 | 5.18 | II, 66.8, 33.4 | 22.0 |
| III-NWG-1 | 55.9 | 5.27 | I, 82.7, 34.8 | 22.0 |

## Mixture Proportions

Detailed mixture proportions and test results are provided in Table 5 and CF and 8-18 charts for the combined aggregates are shown in Figure 5.

1. Mixture III-NWG-ACI was the **Control ACI mixture** and had NWG.
2. Mixture III-WG-1 had WG.
3. Mixture III-WG-2 had WG with 23% more No. 57 aggregate than Mixture III-WG-1.
4. Mixture III-NWG-1 had NWG mixture with 5.8% more coarse aggregate than the control.

### Discussion of Test Results

The average slump of the two WG mixtures was 2.5 in. as compared to 3.25 in. for the NWG mixtures. This suggests that WG does not help reduce water demand.
No difference was evident in entrapped air content between the different mixtures.
The average bleed water of the two WG mixtures was 5.8% and the average bleed water for the NWG mixtures was 5.2%.
There was no difference in finishability between the different mixtures (FR of all mixtures was 2T-1).
Column segregation test results showed that the segregation of the WG mixtures (-1.5%, 5.9%) was not better than that of the NWG mixtures (3.4%, 3.7%).
All mixtures had similar compressive strength test results.
All mixtures had similar 180 day drying shrinkage test results. The WG mixtures had a length change between 0.033% and 0.046% with an average of 0.040%. The NWG mixtures varied between 0.035% and 0.046% with an average of 0.041%.
More water was added to the low slump mixtures to increase the slump to about 7 in. and evaluate the concrete fresh properties.
The average bleed water of the two WG mixtures was 6.4% and the average bleed water for the NWG mixtures was 6.9%. The bleed water for these high slump mixtures was slightly higher than that of the low slump mixtures.
Column segregation test results showed that the segregation of the WG mixtures (5.9%, 5.3%) was not better than that of the NWG mixtures (3.3%, 8.4%).

### Stage IV

All concrete mixtures contained a cementitious materials content of 550 lb/yd$^3$ with 27% Class F fly ash by weight of cementitious materials. The mixtures were air-entrained to attain an air content of 4 to 5%. A Type A water reducing admixture was used at a dosage of 5 oz/cwt. and a Type F High Range Water Reducer was used at a dosage of about 23 oz/cwt. of cementitious content. The mixing water content was maintained at 220 lb/yd$^3$ and the slump was allowed to vary. ASTM C 33 Size No. 57, No. 8 and fine aggregates were used. The following concrete mixtures were prepared:

| Mix ID | Coarse agg, % | Combined FM | Zone, CF, WF | Specific Surface |
|---|---|---|---|---|
| IV-NWG-ACI | 55.4 | 5.25 | IV, 82.6, 40.0 | 22.2 |
| IV-WG-1 | 58.7 | 5.16 | II, 60.5, 37.1 | 21.8 |
| IV-WG-2 | 62.0 | 5.36 | II, 67.8, 34.2 | 20.2 |
| IV-NWG-1 | 60.2 | 5.45 | I, 83.9, 35.8 | 20.2 |

### Mixture Proportions

Detailed mixture proportions and test results are provided in Table 6 and CF and 8-18 charts are shown in Figure 6.

1. Mixture IV-NWG-ACI was the **Control ACI mixture** and had NWG.
2. Mixture IV-WG-1 had WG.
3. Mixture IV-WG-2 had WG with 22% more No. 57 aggregate than Mixture IV-WG-1.

4. Mixture IV-NWG-1 had NWG with 5.8% more coarse aggregate than the Control.

**Discussion of Test Results**

The average slump of the two WG mixtures was 7.0 in. as compared to 6.5 in. for the NWG mixtures. This suggests that WG does not help reduce water demand. The HRWR dosage of Mix IV-NWG-1 was at 21 oz/cwt., which was slightly lower than the other three mixtures.
There was no major difference in the air entraining admixture dosage and the air content of the mixture varied between 4.5% and 4.9%.
Both the WG and NWG mixtures showed extremely low amount of bleeding (0.0% to 0.3%) which was expected because of the low mixing water content.
There was no difference in finishability between the WG and the NWG mixtures. However, the two mixtures with a higher amount of coarse aggregate content had a better finishibility rating of 2T-2 compared to the other two mixtures at 3T-2.
Column segregation test results showed that the segregation of the WG mixtures (0.4%, 1.6%) were lower than that of the NWG mixtures (2.0%, 4.7%).
All mixtures gave similar compressive strength test results.
All mixtures gave similar 180-day drying shrinkage test results. The WG mixtures had a length change between 0.032% and 0.034% with an average of 0.033%. The NWG mixtures varied between 0.033% and 0.036% with an average of 0.035%.

**Round Robin Program Introduction**

The results presented above used one set of aggregate from sources in Maryland. It was decided to extend this study to other locations to broaden this evaluation to other types of local aggregates. Two of the three producers who participated in the aggregate voids content round robin program (Phase A) took part in the concrete testing as well.

1. Titan America Technical Services, Jacksonville, FL
2. Heidelberger/Lehigh Research Facility, Atlanta, GA

The participants conducted the basic concrete tests such as Slump (ASTM C 143), density (ASTM C 138), air content (ASTM C 231), 28 day compressive strength (ASTM C 39), shrinkage (ASTM C 157), and bleeding (ASTM 232 but using a 6 x 12 in cylinder). NRMCA Engineering staff suggested the aggregate proportions. Five aggregate proportions were chosen for each participant so that both WG and NWG combinations could be evaluated.

**Materials**

The participants used local concrete making materials. Information on the aggregate characteristics was provided in the Phase A report. The participants were instructed to isolate and use the same aggregates with the same grading for both Phases of the study.

## Florida

All concrete mixtures were non air-entrained had a cementitous materials content of 517 lb/yd$^3$ and did not contain any chemical admixtures or supplementary cementitious materials. The mixing water content was allowed to vary to attain a target slump of 2.5 in. to 4.5 in. ASTM C 33 Size No. 57, No. 8 and fine aggregates were used. The following concrete mixtures were prepared:

| Mix ID | Coarse agg, % | Combined FM | Zone, CF, WF | Specific Surface |
|---|---|---|---|---|
| FL-NWG-ACI | 60.7 | 5.15 | IV, 91.8, 39.1 | 23.8 |
| FL-WG-1 | 64.0 | 5.02 | II, 59.0, 35.9 | 23.5 |
| FL-WG-2 | 67.0 | 5.23 | II, 67.7, 33.0 | 21.5 |
| FL-NWG-1 | 66.0 | 5.41 | I, 92.0, 34.0 | 21.0 |
| FL-NWG-2 | 64.0 | 5.23 | I, 83.3, 35.9 | 22.4 |

## Mixture Proportions

Detailed mixture proportions and test results are provided in Table 7 and CF and 8-18 charts for the combined aggregates are shown in Figure 7.

1. Mixture FL-NWG-ACI was the **Control ACI mixture** and had NWG.
2. Mixture FL-WG-1 had WG.
3. Mixture FL-WG-2 had WG with 22% more No. 57 aggregate than Mixture FL-WG-1.
4. Mixture FL-NWG-1 had NWG with 8.7% more coarse aggregate than the Control.
5. Mixture FL-NWG-2 had NWG with 5.5% more coarse aggregate than the Control out of which 10% by weight was No. 8 aggregate.

## Discussion of Test Results

The average slump of the two WG mixtures was 3.25 in. at an average mix water of 297 lb/yd$^3$ as compared to 3.75 in. for the NWG mixtures at an average mix water of 291 lb/yd$^3$. This suggests that WG do not help reduce water demand. On the contrary Mix FL-NWG-2 had much lower water content and higher slump as compared to all other mixtures suggesting that mixture optimization based on aggregate grading but not necessarily resorting to WG is possible.
No difference was noticeable in entrapped air content between the different mixtures.
The average bleed water of the two WG mixtures and the three WG mixtures was 0.8%. Only Mix FL-NWG-2 had much lower bleed water of 0.3%.
The average 28 day compressive strength of the two WG mixtures was 6490 psi as compared to 6240 psi for the NWG mixtures, i.e. about 250 psi higher. However, this is still within the range acceptable range of strength of two batches and is not considered a statistically significant difference.
All mixtures gave similar 60 day drying shrinkage test results. The WG mixtures had a length change between 0.041% and 0.044% with an average of 0.043%. The NWG mixtures varied between 0.043% and 0.050% with an average of 0.047%.
The participant reported that all mixtures appeared to have similar workability and finishability with the exception of Mixture FL-NWG-2 which demonstrated better performance.

## Georgia

All concrete mixtures were non air-entrained had a cementitous materials content of 517 lb/yd$^3$ and did not contain any chemical admixtures or supplementary cementitious materials. The mixing water content was kept constant at 320 lb/yd$^3$ and the slump was allowed to vary. ASTM C 33 sizes No. 57, No. 89 and fine aggregates were used. The following concrete mixtures were prepared:

| Mix ID | Coarse agg, % | Combined FM | Zone, CF, WF | Specific Surface |
|---|---|---|---|---|
| GA-NWG-ACI | 58.2 | 5.23 | IV, 91.1, 37.3 | 22.6 |
| GA-WG-1 | 61.5 | 5.03 | II, 59.1, 35.8 | 22.9 |
| GA-WG-2 | 64.3 | 5.23 | II, 67.4, 33.0 | 21.3 |
| GA-NWG-1 | 62.5 | 5.43 | I, 92.0, 33.4 | 20.6 |
| GA-NWG-2 | 60.8 | 5.26 | I, 83.3, 35.4 | 21.9 |

## Mixture Proportions

Detailed mixture proportions and test results are provided in Table 8 and CF and 8-18 charts for the combined aggregates are shown in Figure 8.

1. Mixture GA-NWG-ACI was the **Control ACI mixture** and had NWG.
2. Mixture GA-WG-1 had WG.
3. Mixture GA-WG-2 had WG with 20% more No. 57 aggregate than Mixture GA-WG-1.
4. Mixture GA-NWG-1 had NWG with 7.6% more coarse aggregate than the control.
5. Mixture GA-NWG-2 had NWG with 4.6% more coarse aggregate than the control out of which 10% by weight was No. 89 aggregate.

## Discussion of Test Results

The average slump of the two WG mixtures was 4.0 in. as compared to 4.25 in. for the NWG mixtures. This suggests that WG did not have an impact in reducing the water demand. The slump of Mixture GA-NWG-1 tended to shear during testing suggesting that the mixture was not very placeable and is explained by the fact that this mixture had the highest coarse aggregate content.
No difference was noticeable in entrapped air content between the different mixtures.
Bleeding varied between 1.6%, and 3.1%. The average bleed water of the two WG mixtures was 2.4% and the average bleed water for the NWG mixtures was 2.5%. This is not a significant difference.
There was no statistically significant difference in compressive strengths of the WG and NWG mixtures. The average 28 day compressive strength of the two WG mixtures was 4340 psi as compared to 4290 psi for the NWG mixtures.
All mixtures gave similar 90 day drying shrinkage test results. The WG mixtures had a length change between 0.045% and 0.048% with an average of 0.047%. The NWG mixtures varied between 0.041% and 0.047% with an average of 0.045%. The differences are not significant.

## Overall Discussions

In this section the experimental results from NRMCA/MD (4 stages), FL, and GA that were discussed individually above are summarized together to draw conclusions regarding the concrete performance of WG and NWG mixtures. The results are presented in Figures 9-13, and Table 9 and the discussions are provided here. In the figures I, II, III, IV represent the different experimental stages conducted at NRMCA; the suffix HS attached to a stage indicates a higher slump mixture; FL, and GA represent the experiments conducted at those locations. All of this will be collectively termed as scenarios in the discussions below. Each scenario contained several WG and NWG mixtures that are compared to the control ACI mixture for that scenario which had NWG. Not every scenario included all the tests (e.g. FL, GA did not include finishability or segregation tests) and therefore comparisons are made only where applicable.

### Water demand

Figure 9a illustrates the slumps of the various mixtures in each scenario and Figure 9b illustrates the difference between slumps of the various mixtures and that of the control ACI mixture for that scenario. It should be pointed out that in each case the control ACI mixture had NWG. If a particular mixture had a different mixing water content than the control the potential slump was estimated for equivalent water content by assuming that an increase in 1 in. slump would need 8 lbs of water..

Out of the 15 WG mixtures designed for the seven scenarios, 10 had a slump that was ± 3/4 in. of the control. The remaining 5 mixtures had a slump that was in excess of 1 in. less than that of the control mixture. Out of the 13 NWG mixtures, 4 had a slump that was ± 3/4 in. of that of the control mixture. Five mixtures had a slump that was in excess of 1-in. higher while the remaining 4 mixtures had a slump that was in excess of 1 in. less than that of the control mixture.

In summary as compared to the control the use of WG resulted in similar slumps in 67% of the cases and lower slumps in 33% of the cases. NWG mixtures resulted in higher slumps than the control when the coarse aggregate content was higher and thereby had a reduced fine aggregate content. Two of the three NWG mixtures that had lower slumps had lower coarse aggregate content.

### Entrapped air content and Density

A slight increase in entrapped air content was observed when a higher amount of fine aggregate was used. Other than that no noticeable change was observed in the entrapped air content and density between the different mixtures.

### Bleeding

Figure 10a illustrates results of the bleed water amount of the various mixtures in each scenario and Figure 10b shows the difference in bleed water amount of the various mixtures as compared to that of the control ACI mixture for that scenario. Out of the 12 WG mixtures designed for the six scenarios, 9 mixtures had a bleed water amount that was ± 1% of the control. The remaining 3 mixtures had a bleed water amount that was greater than 1% higher. Out of the 8 NWG mixtures, 3 mixtures had a bleed water amount that was ± 1% of the control. Five mixtures had a bleed water amount that was greater than 1% higher.

In summary as compared to the control the use of WG resulted in similar bleeding characteristics in concrete mixtures in 75% of the cases and increased bleeding in 25% of the cases. NWG mixtures showed higher bleeding characteristics than the control when a higher coarse aggregate content was used. At low w/cm (0.40), the mixtures had less bleeding despite having a high slump (Stage IV).

**Finishability**

Table 9a illustrates results of the finishibility rating (FR) of the various mixtures in each scenario and Table 9b summarizes the distribution of the FR for the various mixtures after considering all the scenarios. Table 9b illustrates that improved finishability was not evident for the WG mixtures compared to the NWG mixtures. For both the WG and NWG mixtures FR was either 2T-1, or 2T-2 in 80% of the batches evaluated.

Out of the 9 WG mixtures in the four scenarios, 5 mixtures had the same FR as the control ACI mixture. Three mixtures had a better FR while 1 mixture had demonstrated some reduction in finishability characteristics. Out of the 8 NWG mixtures, 6 mixtures had the same FR as the control ACI mixture. Two mixtures had a better FR.

All the WG mixtures with a higher assigned value for FR than the control had combined aggregate grading resulting in higher coarseness factor and lower workability factor (about 68/33). Most of the WG mixtures that had similar FR had an intermediate coarseness factor and workability factor (about 60/35). A low w/cm (Stage IV) led to a deterioration in finishability despite having an adequate slump and this was observed regardless of the aggregate grading. Finishability was marginally improved in such cases when the coarse aggregate content was increased in the mixture.

**Compressive Strength**

Figure 11a illustrates results of the compressive strength of the various mixtures in each scenario and Figure 11b shows the difference in compressive strength of the various mixtures as compared to that of the control ACI mixture for that scenario. Out of the 9 WG mixtures designed for the four scenarios, 6 mixtures had a strength that was $\pm 300$ psi of the control. One mixture had a strength that was greater than 300 psi higher while the remaining 2 mixtures had a strength that was more than 300 psi lower than the control mixture. Out of the 10 NWG mixtures, 8 mixtures had a strength that was $\pm 300$ psi of the control mixture. The remaining 2 mixtures had a strength that was more than 300 psi lower than the control mixture.

In summary as compared to the control the use of a WG resulted in similar strengths in 67% of the cases, lower in 22% of the cases and higher in 11% of the cases. The differences in strength overall are not very significant.

**Drying Shrinkage**

Figure 12a illustrates results of the length change (drying shrinkage) of the various mixtures in each scenario and Figure 12b shows the difference in drying shrinkage of the various mixtures as compared to that of the control ACI mixture for that scenario. Out of the 13 WG mixtures designed for the six scenarios, 12 mixtures had an average length change that was within $\pm 0.005\%$ of that of the control. The remaining mixture had an average length change exceeding that of the control by more than 0.005%. Out of the 11 NWG mixtures, 7 mixtures had an average length change that was within $\pm 0.005\%$ of the control mixture. Two mixtures had an average length change amount that exceed edthat of the control mixture by greater than 0.005% while the other two mixtures had an average length change amount more than 0.005% lower.

In summary as compared to the control the use of WG resulted in similar shrinkage in 92% of the cases and marginally higher shrinkage in 8% of the cases. Considering the precision of ASTM C 157, a difference in length change of about 0.01% is not considered to be a statistically significant difference.

**Segregation**

Figure 13a illustrates results of the segregation of the various mixtures in each scenario and Figure 13b shows the difference in segregation of the various mixtures as compared to that of the control ACI mixture for that scenario. Out of the 8 WG mixtures designed for the four scenarios, two mixtures had a segregation that was within ± 1% of that of the control. Three mixtures had segregation values more than 1% lower while the segregation value of the remaining 3 mixtures was greater than 1% higher. Out of the 4 NWG mixtures the segregation of one mixture was within ± 1% of that of the control and the remaining 3 mixtures had a segregation that was greater than 1% higher.

All the WG mixtures that demonstrated a lower segregation potential than the control had a combined aggregate grading with an intermediate coarseness factor and workability factor (about 60/35). WG mixtures with a higher coarseness factor and lower workability factor (about 68/33) had similar or higher segregation. A very low w/cm led to lower segregation (Stage IV) in spite of the high slump. NWG mixtures showed higher segregation than the control when the mixtures contained a higher coarse aggregate content.

For each scenario, with the exception of Florida, the quantity of cementitious materials and mixing water were kept constant for all of the mixtures and the resulting slump was measured as a relative indicator of the water demand of the mixture. A higher measured slump would suggest that water reductions are feasible for that mixture. If the WG mixtures had been designed at lower paste content (lower cementitious and lower water content) as compared to the control NWG-ACI mixture for that scenario it is possible that they could have had lower shrinkage. *However, in such a situation the slump of the WG mixture would have been lower as compared to the NWG-ACI mixture.* The reader can easily come to this conclusion by looking at any one of the scenarios and considering a 6 to 10% reduction in cementitious and water content (i.e. 6 to 10% lower paste content) of the WG mixture (Mixture III-WG-1). Lower paste content means that lower excess paste is available after filling all the voids in the combined aggregate grading. Lower the excess paste content lower will be the workability and finishability for a given concrete mixture. Since at equal paste contents the WG mixtures had similar or lesser slump values as compared to the control NWG-ACI mixture, reduced paste content can only lead to lower slumps.

Since concrete slump has to meet specifications the only way to compensate for a lower slump is to increase water or water reducing admixture dosage. Increasing the water content increases the paste content and may lead to higher shrinkage and lower strength. Reducing paste contents through the use of a water reducing admixture is feasible with NWG mixtures as well.

It should be pointed out that the paste contents of the Stage I, II, III, IV, FL, and GA mixtures were about 27%, 26%, 24%, 25%, 27%, and 29% respectively.

**Conclusions and Recommendations**

As compared to the control NWG mixture in which the aggregate contents were proportioned according to the ACI 211 $b/b_o$ procedure the use of WG in this study resulted in:

1. Water demand: Similar (67%) and higher (33%) of the cases
2. Bleeding water amount: Similar (75%) and higher (25%) of the cases
3. Strength: Similar (67%) and lower (22%) of the cases
4. Shrinkage: Similar (92%) and higher (8%) of the cases
5. Finishability: Better FR with higher coarseness factor and lower workability factor (about 68/33) and similar FR with intermediate coarseness factor and workability factor (about 60/35)
6. Segregation: Lower segregation with intermediate coarseness factor and workability factor (about 60/35) and similar or higher segregation with higher coarseness factor and lower workability factor (about 68/33)

Based on the test results from three different locations in the country (MD, FL, GA) it is evident that a concrete mixture designed to meet a WG specification would not have had a lower water demand, lower bleeding, lower shrinkage or higher strength as compared to a NWG mixture designed according to the ACI 211 $b/b_o$ procedure. When NWG mixtures with a higher coarse aggregate content (5 to 10%) than that required by the ACI 211 $b/b_o$ procedure were used the concrete mixtures tended to have a lower water demand but higher bleeding, and higher segregation.

**Based on the results of this study, it can be concluded that there is no assurance that a concrete specification that includes a requirement for WG through compliance with CF and/or 8-18 charts will lead to reduced mixing water content or lower shrinkage as is typically the goal with these controls on aggregate grading.** Another point is that there is no means of verifying the grading of a concrete mixture other than that documented in a pre-construction submittal. If low shrinkage is important for the application, it is recommended that the specification include a mixture pre-qualification requirement for length change in accordance with ASTM C 157. Typical specification limits range from 0.04% to 0.06% following a 7-day moist cure prior to a 28-day drying period. Note that none of the mixtures in the portion of this study conducted at the NRMCA laboratory had a length change that exceed 0.05% after 180 days of drying. Characteristics of local materials, such as aggregates and cementitious materials, as well as production constraints for a concrete producer, will control whether these specification limits can be achieved. When these targets cannot be achieved, alternative design concepts should be evaluated.

**The above conclusion does not mean that aggregate grading is unimportant for concrete performance.** For example if adequate fine material is not present then the concrete can become prone to segregation, and high bleeding. On the other hand too much of fine material may make it sticky and difficult to finish. ACI 211 $b/b_o$ procedure takes this into account through Table 6.3.6 which recommends that if fine aggregates have a high proportion of fine material (resulting in lower fineness modulus) then the amount of coarse aggregate be increased resulting in lower amounts of that fine aggregate. WG through the use of CF and 8-18 charts are proposed as an improvement over the ACI 211 $b/b_o$ procedure. While the use of the CF and 8-18 charts did not help achieve reductions in water demand or shrinkage they did help attain better finishability, and lower segregation depending on where the WG mixture was located inside Zone II of the CF chart. At CF=60, WF=35 it was possible to attain lower segregation but similar finishability where as at CF=68, WF=33 it was possible to attain better finishability but similar or higher segregation. This indicates that the concrete producer could make use of tools such as the CF and 8-18 charts to evaluate whether such concepts benefit the performance of his concrete mixtures with local materials and within production constraints. **In**

**summary CF and 8-18 charts are potential concrete mixture optimization tools. These should not be invoked as requirements in project specifications.**

## Final Thoughts

The reader may be interested to conduct a similar research program with local materials. A detailed approach is provided in the Appendix.

In particular comparisons between WG and NWG mixtures must be made with the same general variables. The following points must be noted:

1. For all mixtures the cementitious materials type/content, and admixture type/content should be identical.
2. The intermediate aggregate should ideally have the same shape and texture as the larger coarse aggregate. Practically the closest one can come to achieve this would be to procure the intermediate aggregate from the same quarry as the larger coarse aggregate. Using a natural rounded shape gravel as the intermediate aggregate where the coarse aggregate is crushed would introduce an aggregate particle shape variable into what should strictly be a study on the effect of aggregate grading. A rounded shape aggregate is known to reduce water demand.
3. For both the WG and NWG mixtures the nominal maximum size of the aggregate should be the same. Using a larger size aggregate will reduce paste and water demand.
4. The coarse aggregate content of the control mixture should be in line with that determined by the ACI 211 $b/b_0$ approach. The control mixture must not be over sanded or under sanded.
5. It is important that the research program be conducted in a laboratory setting under controlled conditions so that clear conclusions can be drawn. It is harder to establish controlled conditions in the field. Field experiences which state that cracking and curling are reduced with WG mixtures must be backed up by test results which employ identical curing procedures, construction and design practices, such as joint spacing, and quality control procedures.

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## List of Tables



## List of Figures

**Table 1. Brief Outline of Mixtures from Different Stages**

| Stage | Coarse Aggregate | Total Cementitious Content, lb/yd$^3$ | Supplementary Cementitious Material | w/cm | Chemical Admixtures |
|---|---|---|---|---|---|
| I | No. 467 | 517 | None | 0.56 | None |
| II | No. 57 | 500 | 15% Class F fly ash | 0.54 | Type A = 5 oz/cwt. |
| III | No. 57 | 400 | 50% Slag | 0.68 | Type A = 5 oz/cwt. |
| IV | No. 57 | 550 | 27% Class F fly ash | 0.40 | Type A = 5 oz/cwt., Type F = 20 oz/cwt., Air entrained |

Fine aggregate was natural sand for all stages
Where required an intermediate size crushed coarse aggregate No. 8 (same quarry as the larger coarse aggregate) was used

**Table 2. Brief Outline of Concrete Tests Performed on Mixtures from Different Stages**

| Tests | Stage I | Stage II | Stage III | Stage IV |
|---|---|---|---|---|
| Air (C 231), Slump (C 143), Density (C 138), Temperature (C 1064) | √ | √ | √ | √ |
| Compressive Strength (C 39) | √ | √ | √ | √ |
| Drying Shrinkage (C 157) | √ | √ | √ | √ |
| Finishability | √ | √ | √ | √ |
| Placement Segregation | | √ | | |
| Column Segregation | | √ | √ | √ |
| Bleeding (C 232) | | √ | √ | √ |

Placement segregation test was discontinued after Phase II due to lack of consistent results
Stage II, and III mixtures were repeated with a higher slump (6 in. to 7 in.) achieved through adding more water. For those cases only the bleeding, and column segregation tests were conducted.

**Table 3. Details of Stage I Mixtures**

| | I-NWG-ACI | I-WG-1 | I-WG-2 | I-NWG-1 | I-NWG-2 | I-NWG-3 | I-NWG-4 |
|---|---|---|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, $lb/yd^3$ | | | | | | | |
| Cement | 515 | 512 | 514 | 520 | 501 | 511 | 499 |
| Coarse Aggregate No.467 | 2080 | 1656 | 1352 | 2102 | 1682 | 2270 | 1847 |
| Coarse Aggregate No.8 | 0 | 414 | 728 | 0 | 0 | 0 | 0 |
| Fine Aggregate | 1237 | 1231 | 1236 | 1249 | 1514 | 1043 | 1354 |
| Water | 289 | 287 | 289 | 292 | 281 | 287 | 280 |
| w/cm | 0.56 | 0.56 | 0.56 | 0.56 | 0.56 | 0.56 | 0.56 |
| Fresh Concrete Properties | | | | | | | |
| ASTM C 143, Slump, in. | 4 | 4.5 | 3 | 3.5 | 2 | 8 | 2 |
| ASTM C 231, Air, % | 1.9 | 2.2 | 1.8 | 1.5 | 3.5 | 1.5 | 3.5 |
| ASTM C 138, Density, $lb/ft^3$ | 153.3 | 152.5 | 153.2 | 154.9 | 148.1 | 152.9 | 148.1 |
| ASTM C 1064, Temp., ºF | 70 | 65 | 68 | 71 | 68 | 68 | 68 |
| Finishability Rating | 2T-2 | 2T-1 | 2T-2 | 2T-2 | 2T-2 | 1T-1 | 2T-2 |
| Hardened Concrete Properties | | | | | | | |
| ASTM C 39, Compressive Strength, psi | | | | | | | |
| 28 days | 4960 | 5180 | 5250 | 4950 | 4860 | 5010 | 5040 |
| ASTM C 157, Length Change, % | | | | | | | |
| 28 days | -0.017% | -0.015% | -0.018% | -0.018% | -0.018% | -0.020% | -0.020% |

**Table 4. Details of Stage II Mixtures**

| | II-NWG-ACI | II-WG-1 | II-WG-2 | II-NWG-1 | II-WG-3 | II-NWG-2 |
|---|---|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, $lb/yd^3$ | | | | | | |
| Cement | 426 | 425 | 428 | 430 | 422 | 425 |
| Fly Ash | 75 | 75 | 76 | 76 | 74 | 75 |
| Total Cementitious Content | 501 | 500 | 504 | 506 | 496 | 500 |
| Coarse Aggregate No.57 | 1869 | 1272 | 1564 | 1998 | 982 | 1748 |
| Coarse Aggregate No.8 | 0 | 685 | 521 | 0 | 837 | 0 |
| Fine Aggregate | 1412 | 1335 | 1234 | 1319 | 1439 | 1517 |
| Water | 271 | 270 | 272 | 273 | 275 | 270 |
| w/cm | 0.54 | 0.54 | 0.54 | 0.54 | 0.55 | 0.54 |
| Type A WR (oz/cwt.) | 6 | 5 | 5.5 | 5 | 6.7 | 5.5 |
| Fresh Concrete Properties | | | | | | |
| ASTM C 143, Slump, in. | 4.5 | 3.5 | 5 | 3.75 | 2.5 | 3.5 |
| ASTM C 231, Air, % | 2.7 | 2.7 | 2.5 | 2.4 | 3 | 3 |
| ASTM C 138, Density, $lb/ft^3$ | 150.9 | 151.3 | 152.5 | 152.5 | 150.1 | 150.3 |
| ASTM C 1064, Temp., ºF | 70 | 68 | 65 | 70 | 70 | 70 |
| ASTM C 232, accumulated bleeding water, % | - | - | - | - | 2.8 | 2.91 |
| Finishability Rating | 2T - 1 | 2T - 1 | 1T - 1 | 2T - 1 | 2T-2 | 2T-1 |
| Plus No.4 (top), % | - | - | - | - | 40.7 | 41.1 |
| Plus No.4 (bottom), % | - | - | - | - | 46.7 | 44.9 |
| Segregation, % | - | - | - | - | 6.0 | 3.8 |
| Hardened Concrete Properties | | | | | | |
| ASTM C 39, Compressive Strength, psi | | | | | | |
| 28 days | 5040 | 5060 | 5310 | 5310 | 5330 | 5270 |
| ASTM C 157, Length Change, % | | | | | | |
| 28 days | -0.043 | -0.039 | -0.049 | -0.041 | -0.046 | -0.045 |
| 180 days | -0.053 | -0.056 | -0.054 | -0.045 | -0.053 | -0.057 |

**Details of Stage II Mixtures (with higher slump)**

| | II-NWG-ACI | II-WG-1 | II-WG-2 | II-NWG-1 |
|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, lb/yd$^3$ | | | | |
| Cement | 426 | 425 | 430 | 431 |
| Fly Ash | 75 | 75 | 76 | 76 |
| Total Cementitious Content | 501 | 500 | 506 | 507 |
| Coarse Aggregate No.57 | 1840 | 1248 | 1532 | 2006 |
| Coarse Aggregate No.8 | 0 | 672 | 511 | 0 |
| Fine Aggregate | 1385 | 1311 | 1233 | 1268 |
| Water | 293 | 290 | 293 | 294 |
| w/cm | 0.59 | 0.58 | 0.58 | 0.58 |
| Type A WR (oz/cwt.) | 5 | 5 | 5 | 5 |
| Fresh Concrete Properties | | | | |
| ASTM C 143, Slump, in. | 6.5 | 6.75 | 6.75 | 7.75 |
| ASTM C 138, Density, lb/ft$^3$ | 149.7 | 149.7 | 151.7 | 151.7 |
| ASTM C 1064, Temp., ºF | 68 | 67 | 68 | 67 |
| ASTM C 232, accumulated bleeding water, % | 6.1 | 6.72 | 7.44 | 7.36 |
| Plus No.4 (top), % | 43.7 | 45.3 | 47.6 | 45.6 |
| Plus No.4 (bottom), % | 49.5 | 46.9 | 52.5 | 54.5 |
| Segregation, % | 5.8 | 1.6 | 4.9 | 8.9 |

**Table 5. Details of Stage III Mixtures**

| | III-NWG-ACI | III-WG-1 | III-WG-2 | III-NWG-1 |
|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, lb/yd$^3$ | | | | |
| Cement | 199 | 197 | 200 | 200 |
| Newcem, slag | 199 | 197 | 200 | 200 |
| Total Cementitious Content | 398 | 394 | 400 | 400 |
| Coarse Aggregate No.57 | 1827 | 1207 | 1506 | 1940 |
| Coarse Aggregate No.8 | 0 | 650 | 502 | 0 |
| Fine Aggregate | 1514 | 1462 | 1373 | 1421 |
| Water | 269 | 273 | 270 | 270 |
| w/cm | 0.68 | 0.69 | 0.68 | 0.68 |
| Type A WR (oz/cwt.) | 5 | 5 | 5 | 5 |
| Fresh Concrete Properties | | | | |
| ASTM C 143, Slump, in. | 3 | 2.5 | 2.5 | 3.5 |
| ASTM C 231, Air, % | 3.2 | 3.3 | 2.7 | 3 |
| ASTM C 138, Density, lb/ft$^3$ | 149.3 | 148.5 | 150.9 | 150.1 |
| ASTM C 1064, Temp., ºF | 67 | 66 | 68 | 68 |
| ASTM C 232, accumulated bleeding water, % | 4.06 | 6.36 | 5.20 | 6.34 |
| Finishability Rating | 2T-1 | 2T-1 | 2T-1 | 2T-1 |
| Plus No.4 (top), % | 44.3 | 45.0 | 44.3 | 45.1 |
| Plus No.4 (bottom), % | 47.7 | 43.5 | 50.2 | 48.8 |
| Segregation, % | 3.4 | -1.5 | 5.9 | 3.7 |
| Hardened Concrete Properties | | | | |
| ASTM C 39, Compressive Strength, psi | | | | |
| 28 days | 4330 | 4130 | - | - |
| 90 days | - | - | 6580 | 6320 |
| ASTM C 157, Length Change, % | | | | |
| 28 days | -0.024 | -0.035 | -0.017 | -0.029 |
| 180 days | -0.035 | -0.046 | -0.033 | -0.046 |
| | | | | |
| Concrete Properties after adding extra water | | | | |
| ASTM C 143, Slump, in. | 6.25 | 6.25 | 7.5 | 6.75 |
| ASTM C 232, accumulated bleeding water, % | 3.89 | 4.67 | 8.13 | 9.98 |
| Plus No.4 (top), % | 47.4 | 40.0 | 43.9 | 46.9 |
| Plus No.4 (bottom), % | 50.7 | 45.9 | 49.2 | 55.3 |
| Segregation, % | 3.3 | 5.9 | 5.3 | 8.4 |

**Table 6. Details of Stage IV Mixtures**

| | IV-NWG-ACI | IV-WG-1 | IV-WG-2 | IV-NWG-1 |
|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, lb/yd$^3$ | | | | |
| Cement | 404 | 404 | 405 | 405 |
| Fly ash | 152 | 152 | 152 | 152 |
| Total Cementitious Content | 556 | 556 | 557 | 557 |
| Coarse Agg #1 (#57) | 1855 | 1285 | 1567 | 2021 |
| Coarse Agg #2 (#8) | 0 | 692 | 522 | 0 |
| Fine Aggregate | 1386 | 1286 | 1183 | 1241 |
| Water | 223 | 222 | 223 | 223 |
| w/cm | 0.40 | 0.40 | 0.40 | 0.40 |
| AEA (oz/cwt.) | 0.23 | 0.23 | 0.3 | 0.3 |
| Type A WR (oz/cwt.) | 5 | 5 | 5 | 5 |
| Type F HRWR (oz/cwt.) | 23 | 23 | 23 | 21 |
| Fresh Concrete Properties | | | | |
| ASTM C 143, Slump, in. | 7 | 6.5 | 7.5 | 6 |
| ASTM C 231, Air, % | 4.5 | 4.5 | 4.5 | 4.9 |
| ASTM C 138, Density, lb/ft$^3$ | 149.7 | 150.5 | 150.9 | 150.5 |
| ASTM C 1064, Temp., ºF | 70 | 70 | 68 | 68 |
| ASTM C 232, accumulated bleeding water, % | No bleeding | No bleeding | 0.3 | 0.09 |
| Finishability Rating | 3T-2 | 3T-2 | 2T-2 | 2T-2 |
| Plus No.4 (top), % | 44.7 | 45.4 | 50.4 | 47.3 |
| Plus No.4 (bottom), % | 46.7 | 45.0 | 52.0 | 52.0 |
| Segregation, % | 2.0 | -0.4 | 1.6 | 4.7 |
| Hardened Concrete Properties | | | | |
| ASTM C 39, Compressive Strength, psi | | | | |
| 28 days | 7160 | 7600 | - | - |
| 56 days | - | - | 8350 | 7920 |
| ASTM C 157, Length Change, % | | | | |
| 28 days | -0.027 | -0.027 | -0.029 | -0.030 |
| 180 days | -0.033 | -0.034 | -0.032 | -0.036 |

**Table 7. Details of Florida Mixtures**

| | FL-NWG-ACI | FL-WG-1 | FL-WG-2 | FL-NWG-1 | FL-NWG-2 |
|---|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, lb/yd$^3$ (SSD) | | | | | |
| Cement | 526 | 525 | 527 | 527 | 527 |
| Coarse Aggregate No.57 | 1799 | 1169 | 1429 | 1961 | 1711 |
| Coarse Aggregate No.8 | - | 725 | 562 | - | 193 |
| Fine Aggregate | 1265 | 1157 | 1065 | 1095 | 1162 |
| Water | 290 | 298 | 295 | 299 | 283 |
| w/cm | 0.55 | 0.57 | 0.56 | 0.57 | 0.54 |
| Fresh Concrete Properties | | | | | |
| ASTM C 143, Slump, in. | 4.00 | 3.75 | 2.75 | 3.00 | 4.25 |
| ASTM C 231, Air, % | 0.6 | 1.0 | 1.0 | 0.8 | 0.8 |
| ASTM C 138, Density, lb/ft$^3$ | 143.7 | 143.6 | 143.6 | 143.8 | 143.1 |
| ASTM C 232, Bleeding, % | 1.03 | 0.97 | 0.63 | 1.06 | 0.3 |
| Hardened Concrete Properties | | | | | |
| ASTM C 39, Compressive Strength, psi | | | | | |
| 28 days | 6150 | 6570 | 6410 | 6180 | 6390 |
| ASTM C 157, Length Change, % | | | | | |
| 60 days | -0.043 | -0.041 | -0.044 | - | -0.050 |

**Table 8. Details of Georgia Mixtures**

| | GA-NWG-ACI | GA-WG-1 | GA-WG-2 | GA-NWG-1 | GA-NWG-2 |
|---|---|---|---|---|---|
| Yield Adjusted Mixture Proportions, lb/yd$^3$ (SSD) | | | | | |
| Cement | 518 | 520 | 518 | 520 | 517 |
| Coarse Aggregate No.57 | 1905 | 1241 | 1484 | 2056 | 1783 |
| Coarse Aggregate No.8 | - | 761 | 607 | - | 198 |
| Fine Aggregate | 1247 | 1151 | 1063 | 1121 | 1167 |
| Water | 321 | 322 | 321 | 322 | 320 |
| w/cem | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 |
| Fresh Concrete Properties | | | | | |
| ASTM C 143, Slump, in. | 3.50 | 3.50 | 4.25 | 4.75* | 4.50 |
| ASTM C 231, Air, % | 0.9 | 1.0 | 0.9 | 0.9 | 1.2 |
| ASTM C 138, Density, lb/ft$^3$ | 147.8 | 148.0 | 147.9 | 148.9 | 147.6 |
| ASTM C 232, Bleeding @ 6hrs, % | 1.6 | 2.3 | 2.4 | 3.1 | 2.9 |
| Hardened Concrete Properties | | | | | |
| ASTM C 39, Compressive Strength, psi | | | | | |
| 28 days | 4710 | 4320 | 4350 | 3930 | 4220 |
| ASTM C 157, Length Change, % | | | | | |
| 90 days | -0.047 | -0.048 | -0.045 | -0.047 | -0.041 |

* Tendency to shear during testing.

**Table 9. (a) Finishability Test Results (b) Distribution of Finishability Ratings**

(a) Finishability Test Results

| Stage | Control ACI Mixture | WG Mixtures | NWG Mixtures |
|---|---|---|---|
| I | 2T-2 | 2T-1, 2T-2 | 2T-2, 2T-2, 1T-1, 2T-2 |
| II | 2T-1 | 2T-1, 1T-1, 2T-2 | 2T-1, 2T-1 |
| III | 2T-1 | 2T-1, 2T-1 | 2T-1 |
| IV | 3T-2 | 3T-2, 2T-2 | 2T-2 |

(b) Distribution of Finishability Ratings

| WG Mixtures | NWG Mixtures |
|---|---|
| 3T-2 = 1 | 3T-2 = 1 |
| 2T-2 = 3 | 2T-2 = 5 |
| 2T-1 = 4 | 2T-1 = 5 |
| 1T-1= 1 | 1T-1 = 1 |

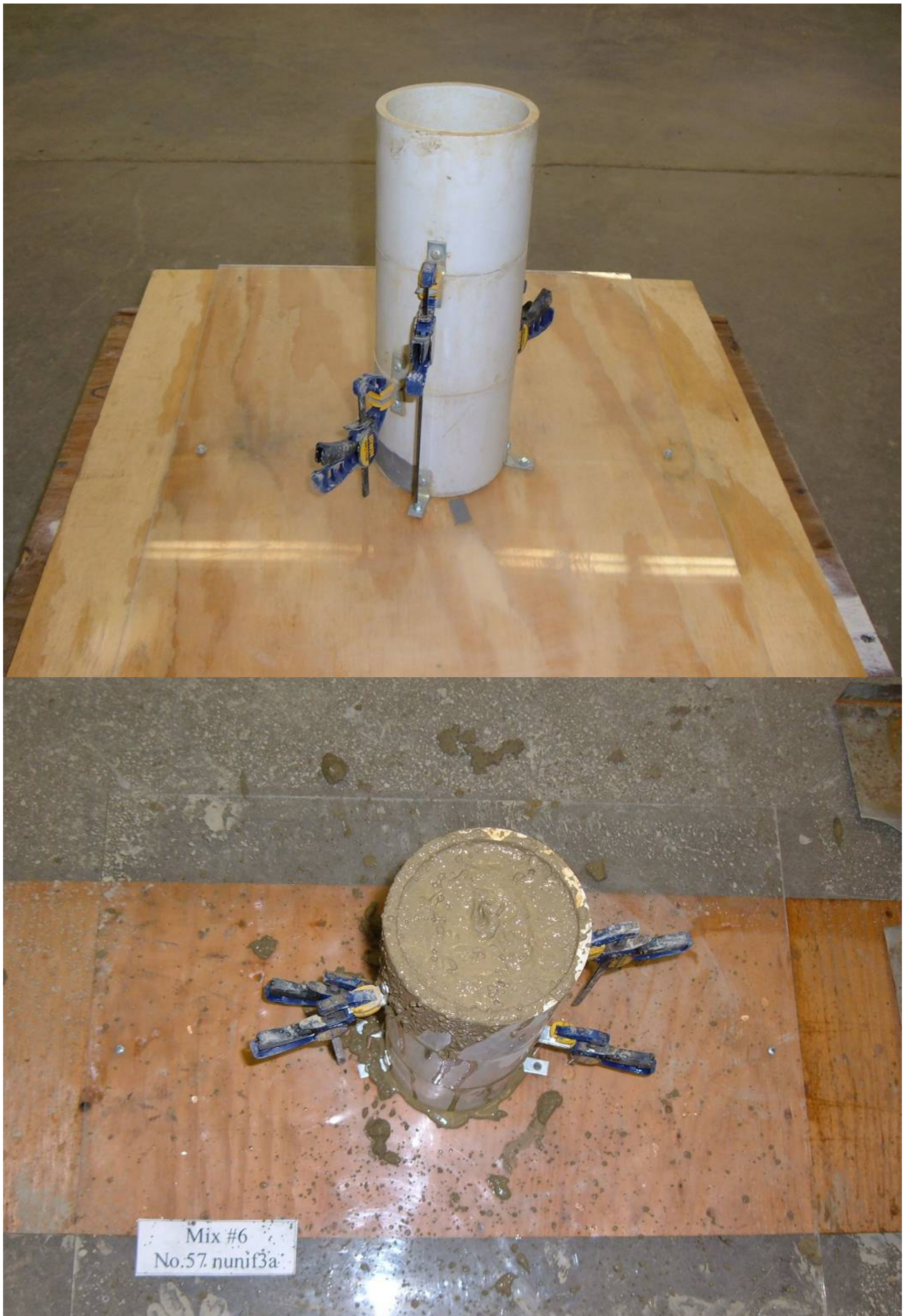
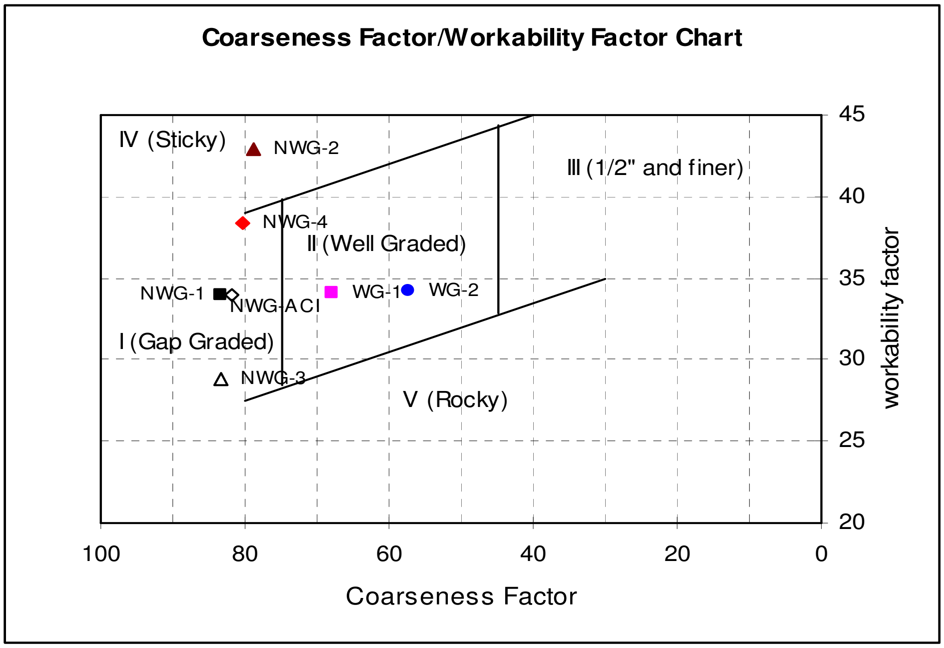



**Figure 1. Column Segregation Test Set up**


**Figure 2. Finishability Test Set up**



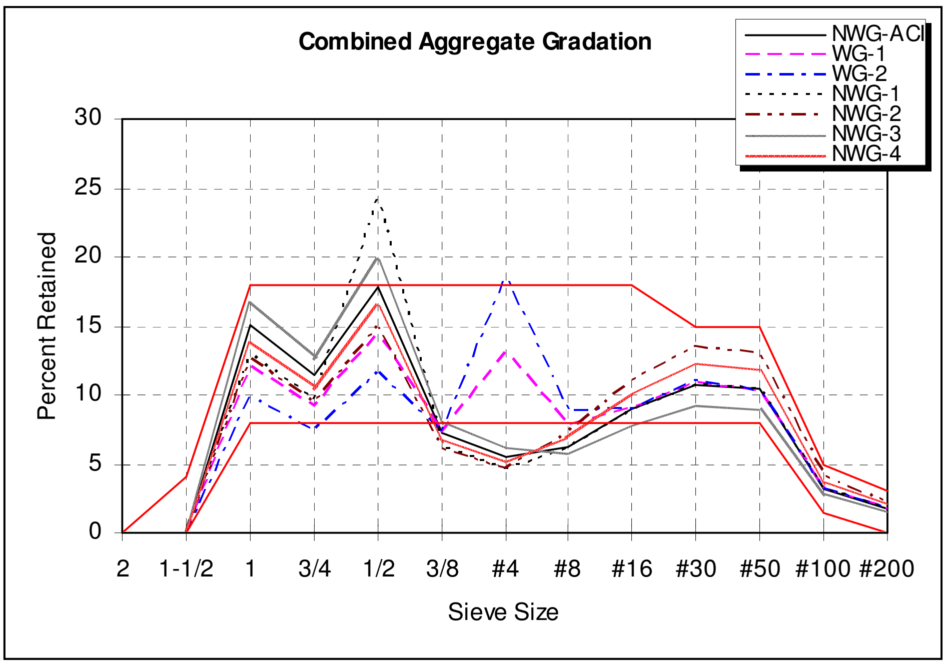
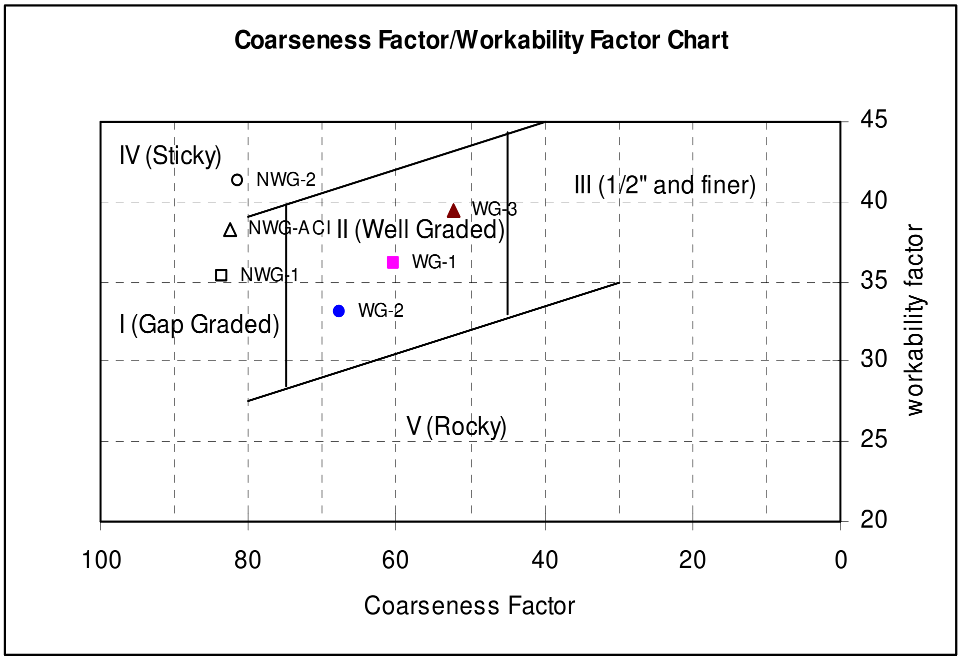




**Figure 3. Coarseness Factor Chart and 8-18 Chart for Stage I Mixtures**



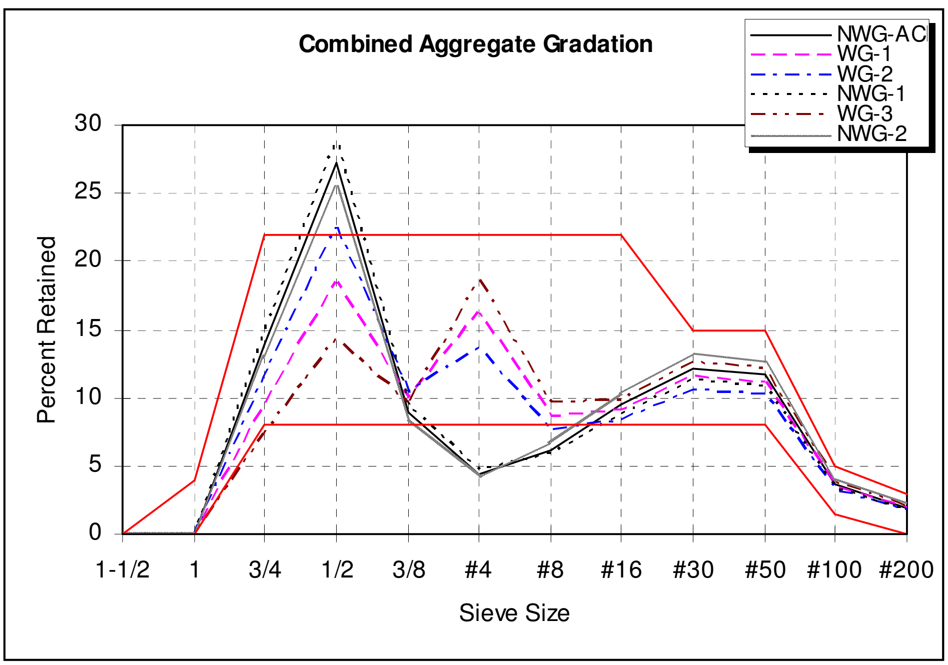
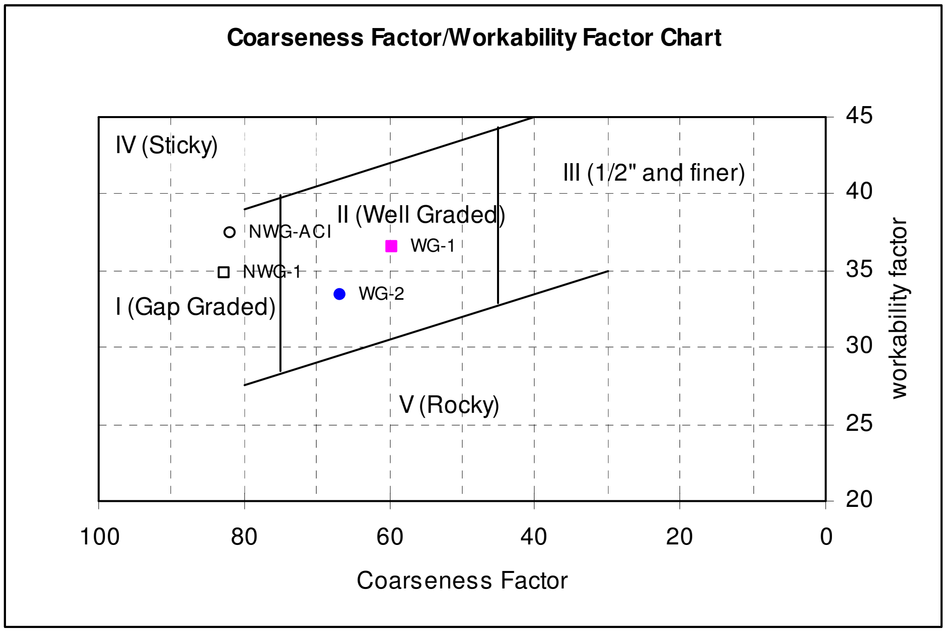




**Figure 4. Coarseness Factor Chart and 8-18 Chart for Stage II Mixtures**



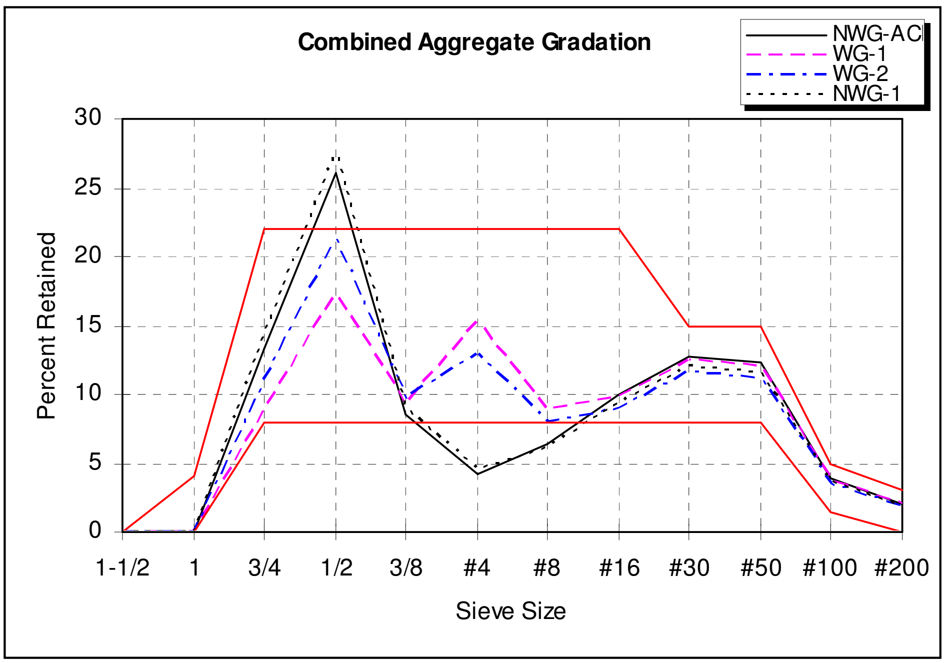




**Figure 5. Coarseness Factor Chart and 8-18 Chart for Stage III Mixtures**

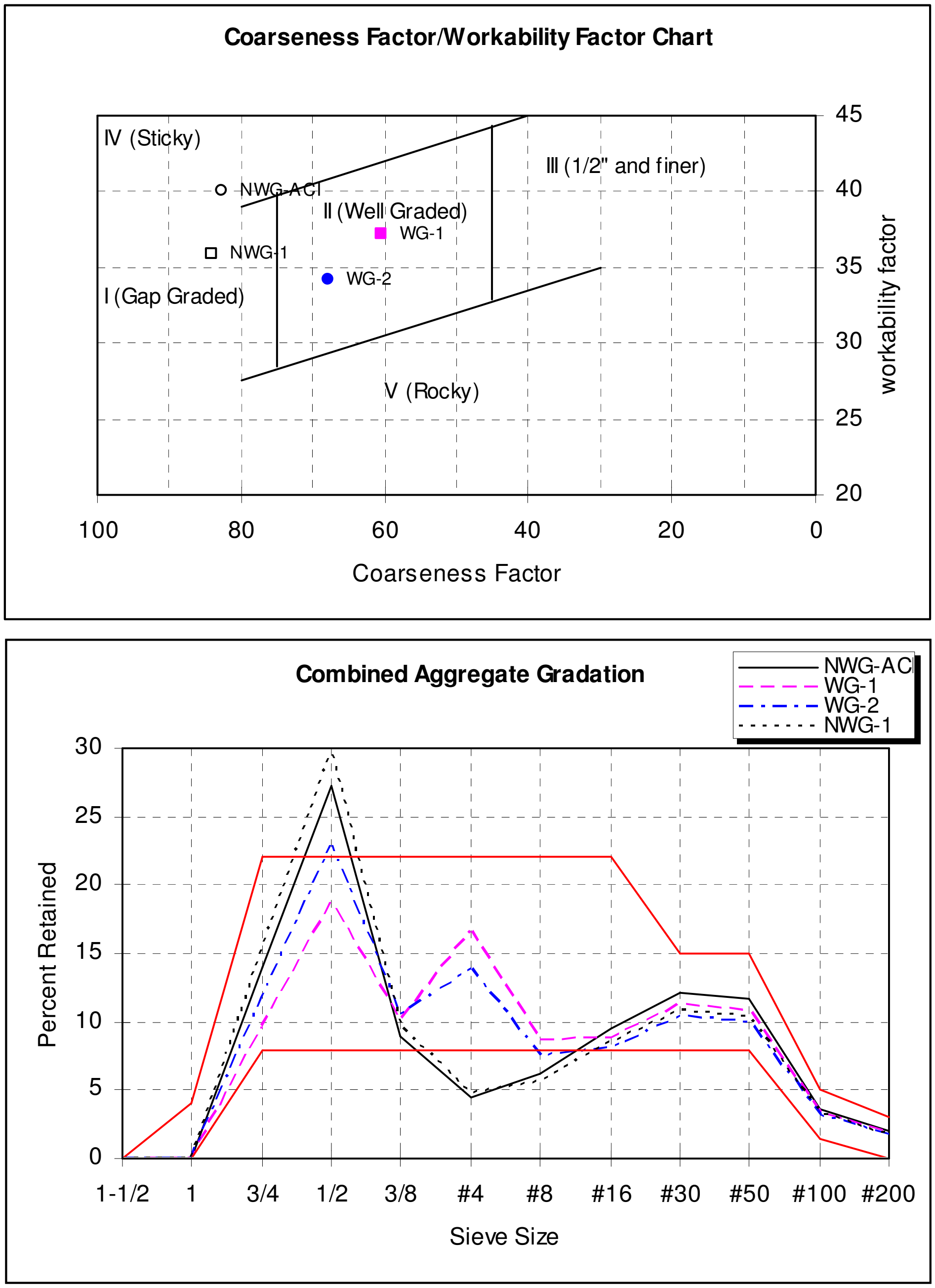
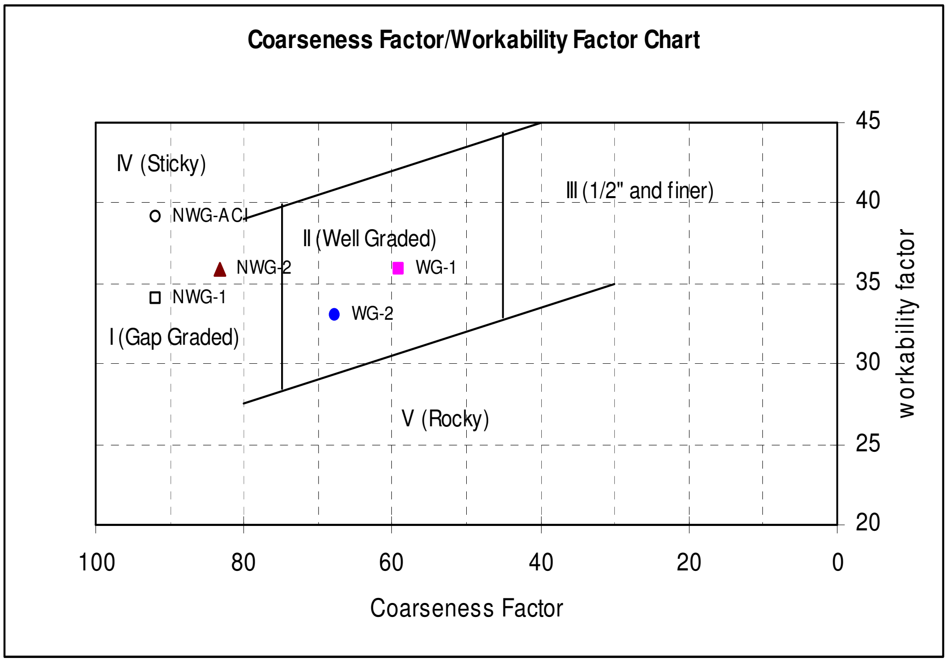



**Figure 6. Coarseness Factor Chart and 8-18 Chart for Stage IV Mixtures**



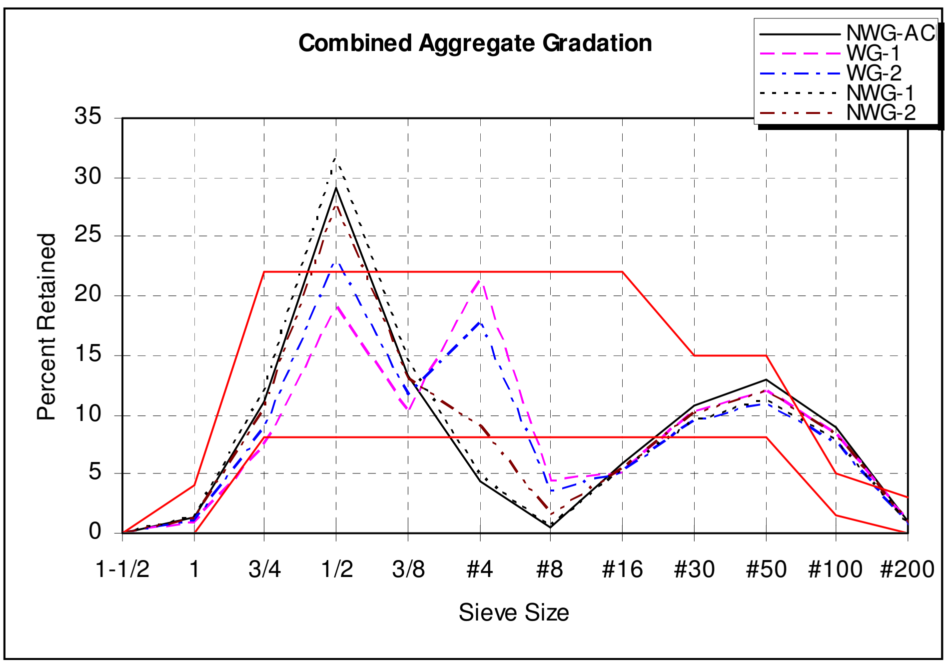
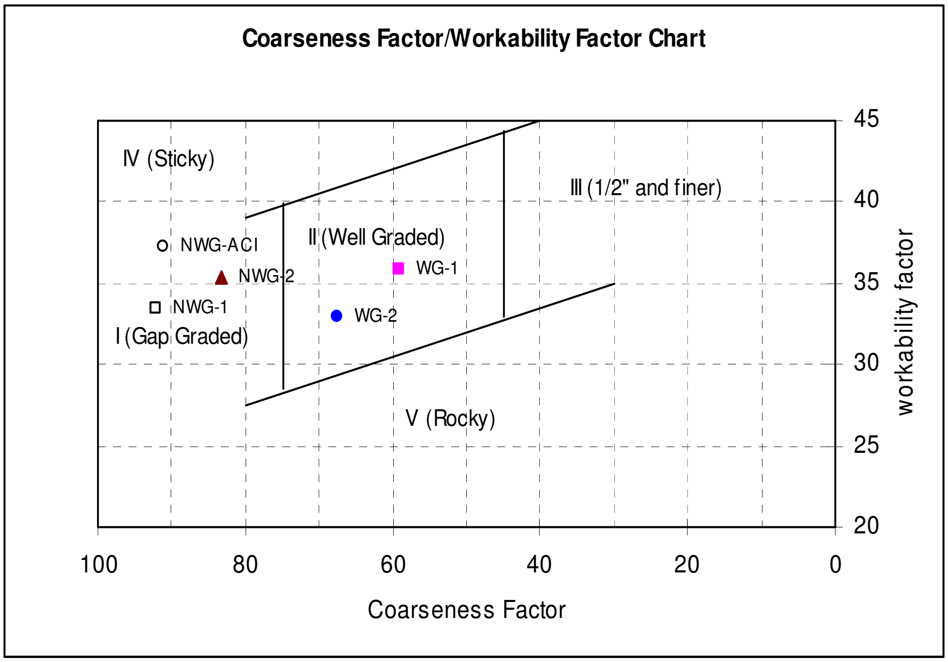




**Figure 7. Coarseness Factor Chart and 8-18 Chart for Florida Mixtures**



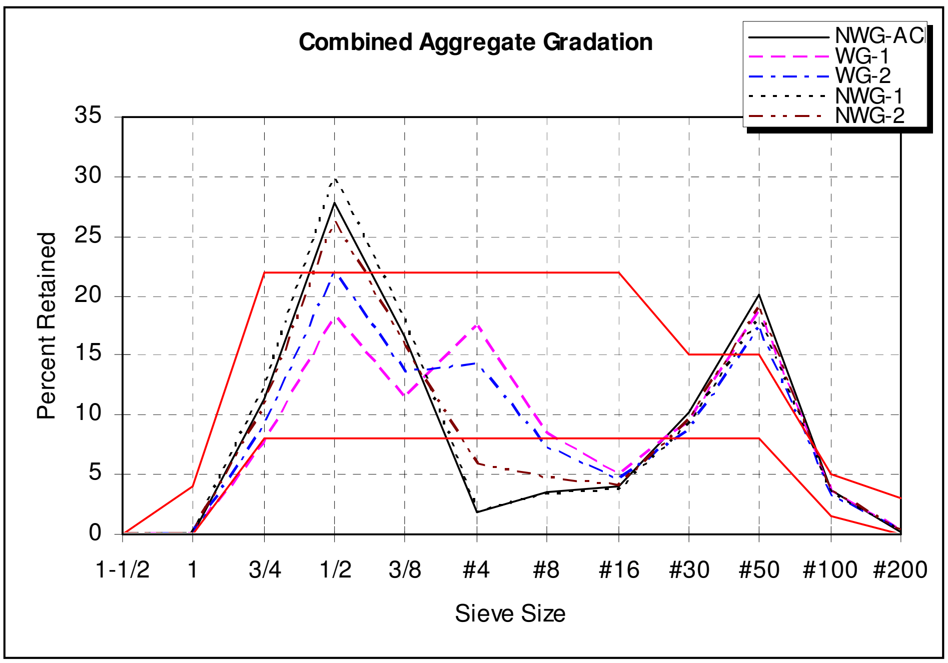
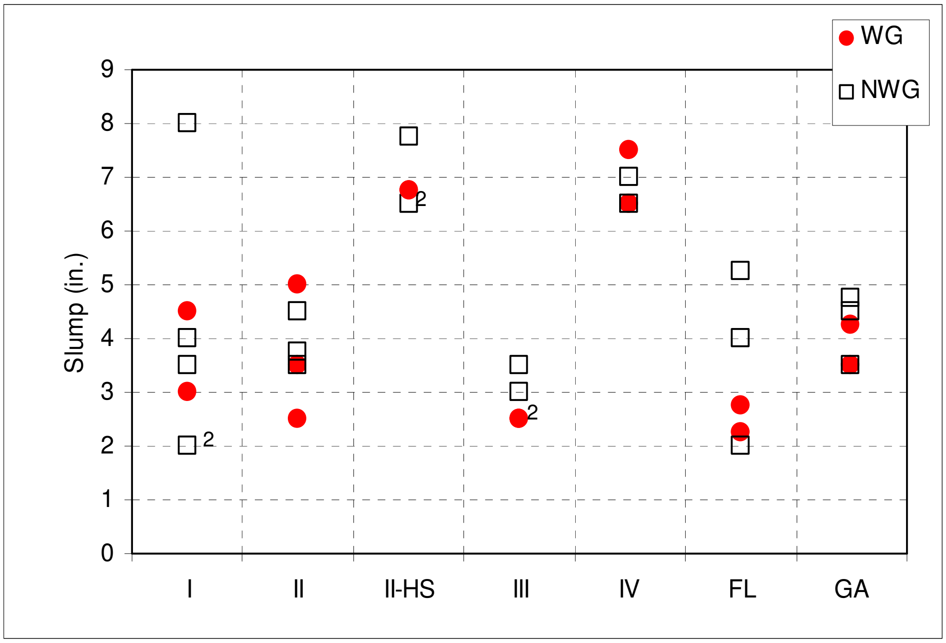
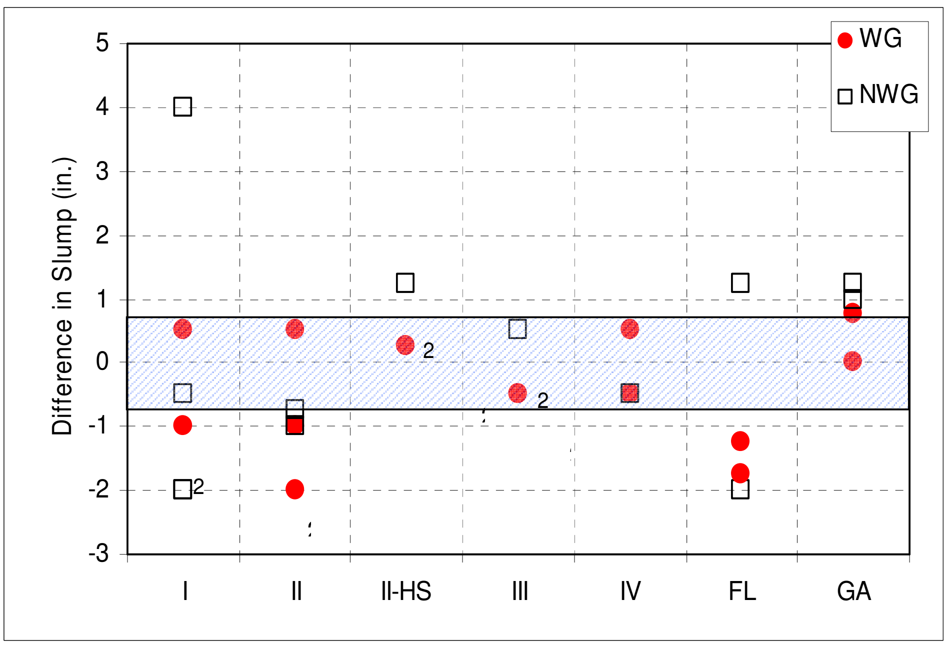




**Figure 8. Coarseness Factor Chart and 8-18 Chart for Georgia Mixtures**

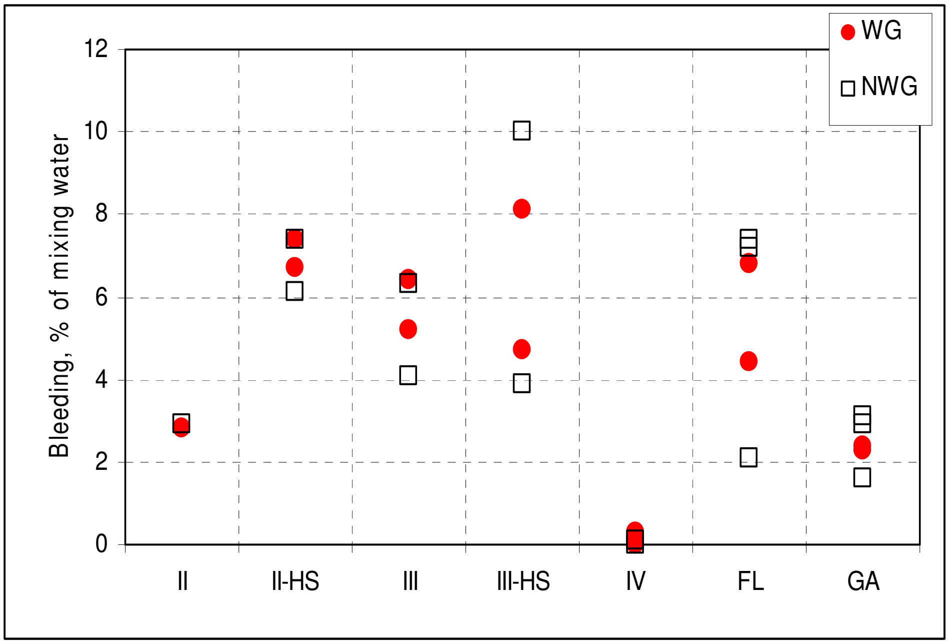



**(a)**




**(b)**

**Figure 9. (a) Slump of WG and NWG Mixtures (b) Difference in Slump of WG and NWG Mixtures as Compared to ACI 211 b/b$_o$**

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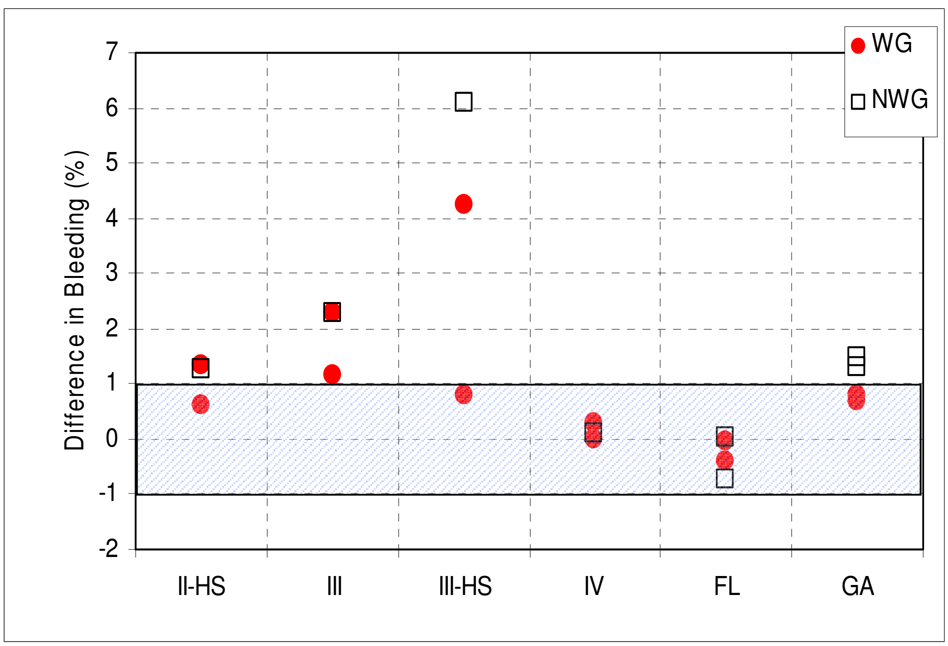
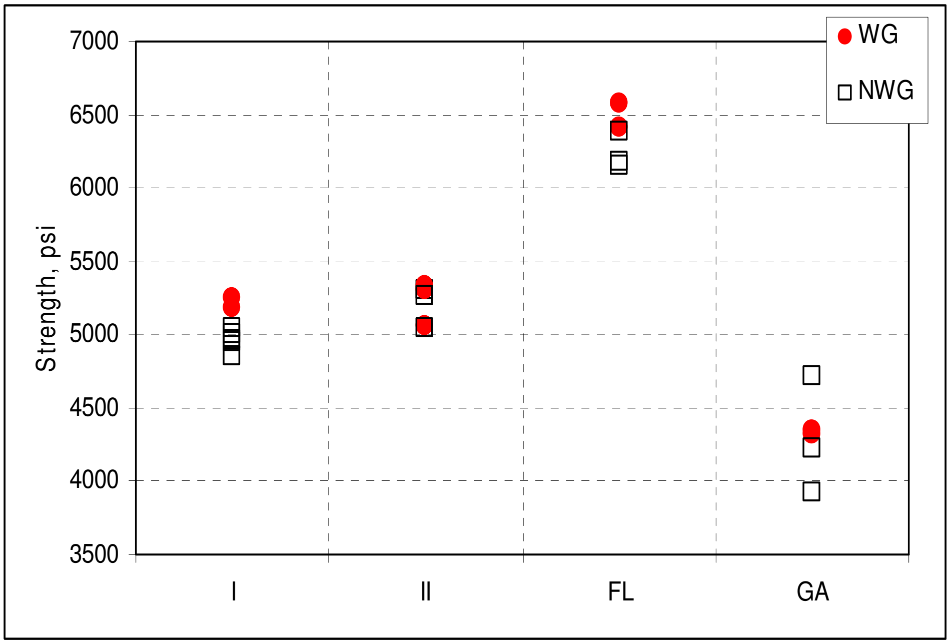
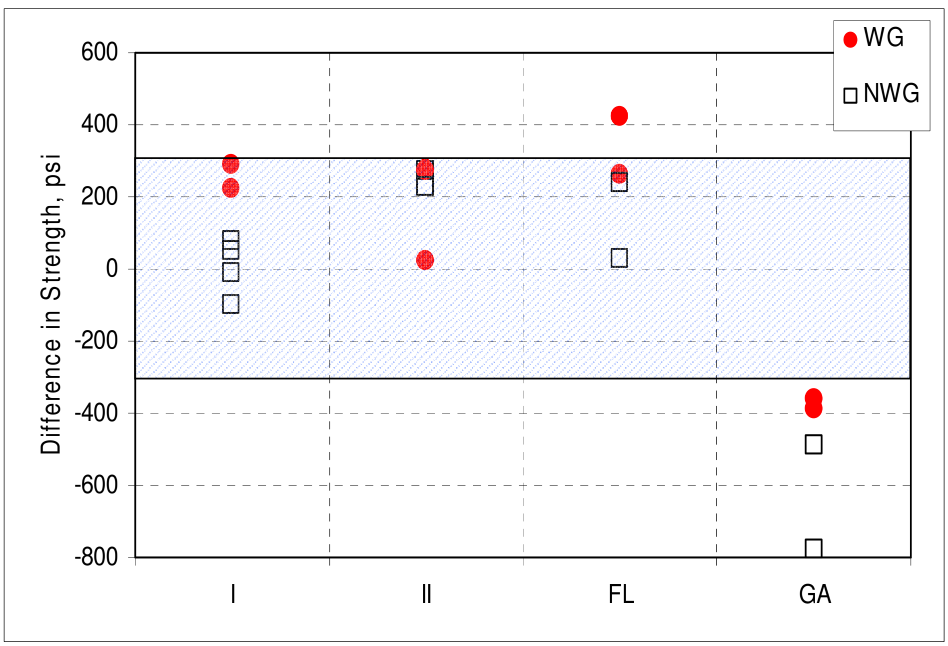



**(b)**

**Figure 10. (a) Bleeding of WG and NWG Mixtures (b) Difference in Bleeding of WG and NWG Mixtures as Compared to ACI 211 $b/b_o$**

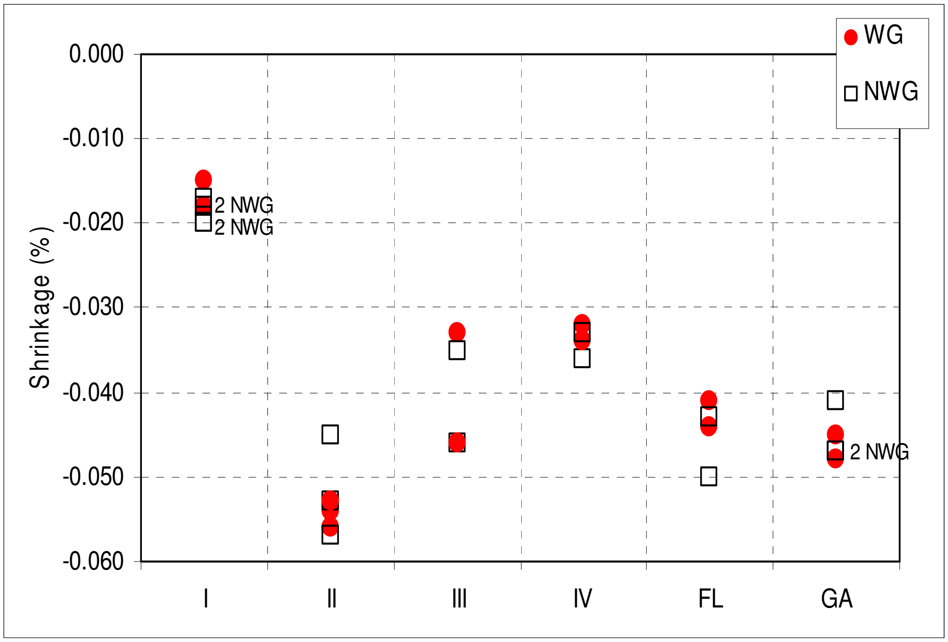



**(a)**

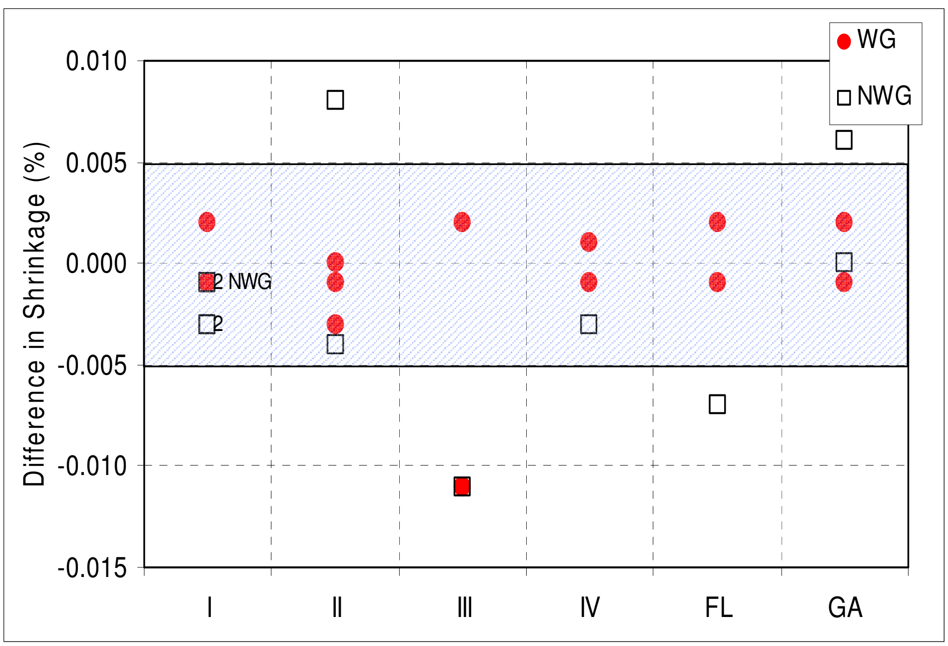



**(b)**

**Figure 11. (a) Strength of WG and NWG Mixtures (b) Difference in Strength of WG and NWG Mixtures as Compared to ACI 211 b/b$_o$**

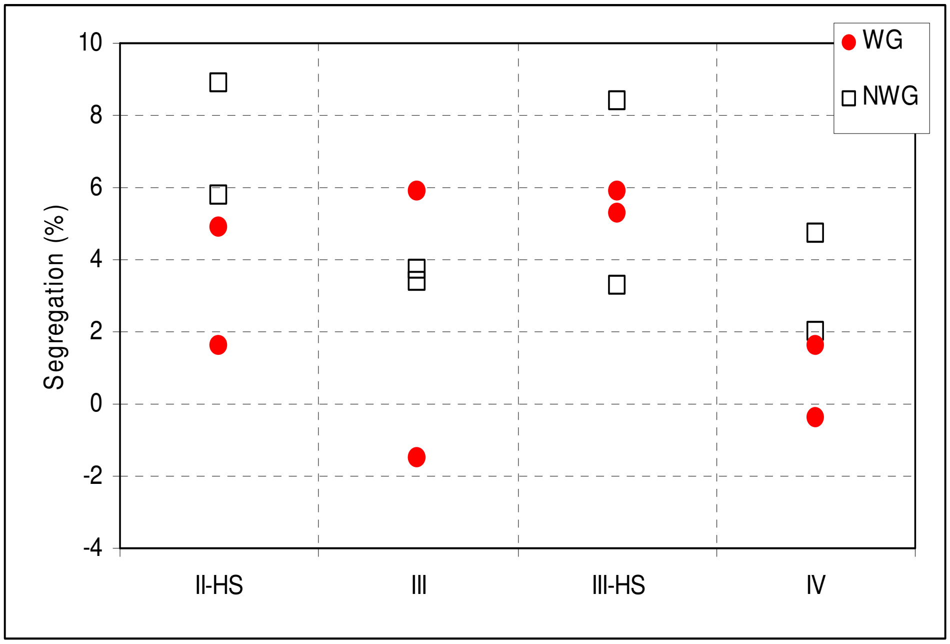



**(a)**

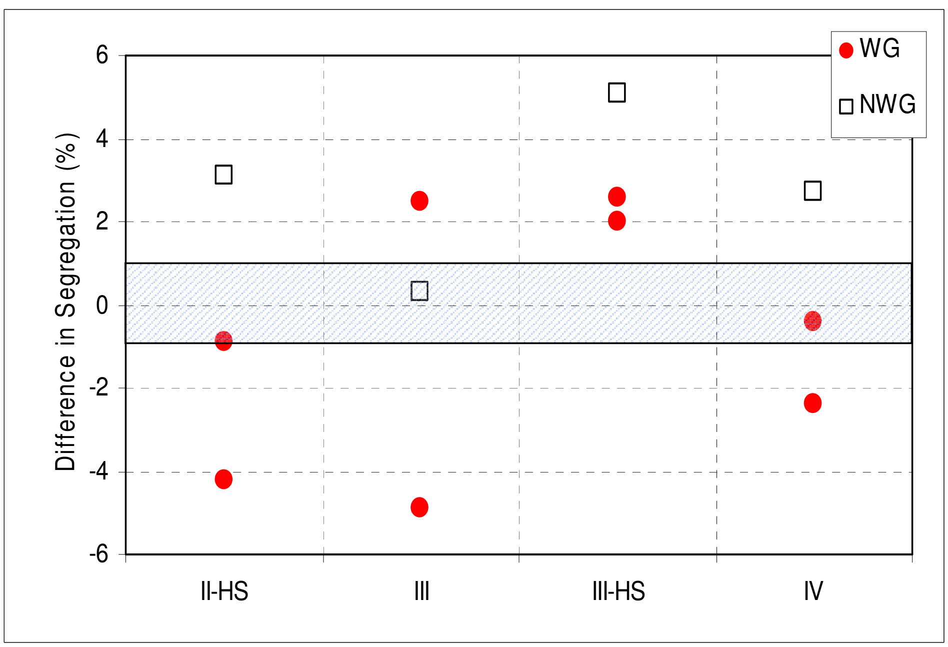



**(b)**

**Figure 12. (a) Shrinkage of WG and NWG Mixtures (b) Difference in Shrinkage of WG and NWG Mixtures as Compared to ACI 211 b/b$_o$**




**(a)**




**(b)**

**Figure 13. (a) Column Segregation of WG and NWG Mixtures (b) Difference in Column Segregation of WG and NWG Mixtures as Compared to ACI 211 b/b$_o$**

## Appendix - Recommended Procedure for Evaluating Aggregate Grading

The following is a general outline of the procedure used in this study to select mixture proportions for comparing the effects of aggregate grading. Readers interested to undertake a similar study with their materials can use this approach for developing their experimental program. One aspect in this study is to maintain the same quantities of cementitious materials (and type), mixing water and admixture dosage (and type) for all mixtures evaluated. This is the preferred procedure. A different procedure would be to adjust the water demand for a target slump for all the mixtures. However, that approach is a little trickier and it is possible for minor differences in water demand between mixtures to get blown up into bigger differences. A non air entrained mixture is preferable as variations in air content can cause varying yield between mixtures and make comparisons more difficult. Mixing and testing procedures should be in accordance with ASTM C 192.

### Control – ACI mixture

- Establish a control non air-entrained concrete mixture based on the ACI 211 procedure of proportioning concrete mixtures.
- Select a typical cement (or cementitious material) content used for floor mixtures in the range of 475 to 550 lb/yd$^3$
- Select the nominal maximum size of the coarse aggregate – ¾-in., 1-in. or larger as appropriate
- Select the mixing water content and admixture dosage, if any, to target a slump of 3 to 4 in.
- Establish the weight of coarse aggregate using the ACI 211 b/b$_o$ procedure Table 6.3.6.
- Calculate the weight of fine aggregate using the absolute volume calculation. Aggregate weights calculated by the ACI procedure are dry weights and to calculate SSD aggregate weight multiply the dry weights by their absorptions.
- Using a spreadsheet or commercially available software determine the grading of the combined aggregate for both individual percent retained on each sieve. **Note that the combined aggregate grading calculations are based on volume and not weight.**
  For example if total coarse and fine aggregate weights are 1800 lbs/yd$^3$ and 1200 lbs/yd$^3$ respectively and their relative densities (specific gravities) are 2.0 and 2.5 then the coarse aggregate to total aggregate ratio is 0.652 (by volume) and 0.6 (by weight). If 5% of coarse aggregate and 40% of fine aggregate are the individual percent retained on a sieve the combined aggregate individual percent retained on that sieve will be 5%x0.652+40%x0.348 = 17%. If calculations are done on a weight basis the combined aggregate individual percent retained on that sieve will be 5%x0.6+40%x0.4 = 19% which is incorrect.
- Plot the combined aggregate grading on the CF and 8-18 charts as in Figures 3 to 8
- This mixture can be designated as the NWG-ACI mixture.

### Mixture 2 – Not well graded

- In this mixture the weight of coarse aggregate is increased by 5 to 10%. The authors have found that beyond about 10% more than the ACI 211 b/b$_o$ recommendation for coarse aggregate the tendency for segregation increases.
- Calculate the resulting weight of fine aggregate using the absolute volume procedure. This will be reduced by approximately the increased weight of coarse aggregate as all other ingredients are kept the same.
- Plot the combined aggregate grading on the CF and 8-18 charts as in Figures 3 to 8

- This mixture can be designated as NWG-1 mixture

**Well Graded Mixtures**

- Select an intermediate size aggregate (typically No. 8 or No. 89) to modify the NWG mixtures. The intermediate aggregate should be natural rounded shape gravel if the coarse aggregate is natural rounded shape gravel. If the coarse aggregate is crushed then the intermediate aggregate must also be crushed possibly from the same quarry.
- Using the spreadsheet, vary the quantity of the three aggregates to target Zone II on the CF chart.
- Target 2 locations within Zone II of the CF chart (See Figure 5) for this purpose: At the center and towards the lower left. Ensure that the total absolute volume of the aggregates is the same as the previous mixtures.
- Designate these two mixtures as WG-1, and WG-2.
- Plot the combined aggregate grading on the CF and 8-18 charts and make sure it meets the 8-18 chart requirements as laid out in the ACI 302.1R-04 report.

**Testing**

It is important that the four mixtures are conducted on the same day and under identical conditions to avoid batching and other variabilities. Also the same concrete making materials should be used. Aggregate moisture contents must be measured and the added water adjusted before batching.

Conduct fresh concrete tests: slump, ASTM C 143, air content, C 231, density, C 138, temperature, C 1064, and prepare strength specimens to test the compressive strength in accordance with C 31 and C 39 tests for all four mixtures.

Additional tests that could be conducted are bleeding, ASTM C 232, length change, C 157, segregation, based on C1610 and a visual evaluation of the mixture finishability. These tests have been described in this report.

The slump test by itself should indicate whether the WG mixtures are capable of providing water reductions. If the slumps of the WG mixtures are 2 to 4 in. higher than the NWG mixtures it is indicative that a water reduction is feasible along with a reduction in cementitious content. Slump that does not vary by more than 1 in. suggests an insignificant difference and is indicative that it may not be appropriate to reduce the water and cementitious content of the WG mixture. Note that a 2 to 4 in. higher slump may not lead to a 6-10% reduction in paste volume (as typically expected by the rule of thumb 1 gallon/yd$^3$ for 1 in. slump) as not all the water and cement amounts can be reduced without compromising properties such as finishability, and workability.

This program should first be conducted in the laboratory where it is easier to do testing under controlled conditions. As a next step if there is interest to do batches in the truck similar controlled conditions should be followed and the mixtures repeated several times to average out possible extraneous variabilities and clearly identify the difference between the WG and NWG mixtures.