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Analysis of Aggregate Distribution in Self-Consolidating Concrete

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ANALYSIS OF AGGREGATE DISTRIBUTION IN SELF-CONSOLIDATING CONCRETE

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Abstract

Concrete consists of several key ingredients: cement, water, and coarse and fine aggregate. Depending on the proportions of these ingredients, the strength and workability of a concrete mix can be affected adversely. Segregation is the separation of aggregate and cement paste, resulting in a lack of homogeneity. Self-consolidating concrete (SCC) does not require traditional consolidation; however, it can be affected by segregation. This project examines different SCC mixtures and establishes ranges of values for slump flow, T_{20} , Visual Stability Index (VSI), J-ring flow and J-ring flow spread that ensures proper aggregate distribution and therefore reduces the potential of segregation. With this data, the intent is to produce a method of analysis for determining the degree of segregation in SCC. Sixteen concrete wall sections were cast and core samples were taken from nine locations in the walls. Of the nine samples, two cores from each row were tested in compression and a third core was used for aggregation distribution analysis. These cores were cut lengthwise to enable a manual count of the limestone aggregate. Digital images of the cores were captured and processed by a program created in MATLAB. The program generated percentage values of amount of aggregate per core. The results from the program were compared with results from the manual count method and then with the fresh concrete properties to determine if certain properties are indicators of possible segregation.

Keywords: Aggregate distribution, segregation, SCC

1. INTRODUCTION

Aggregate distribution is an important factor in concrete mixes. It can play a significant role in the compressive strength and workability of concrete. Segregation occurs when the coarse aggregate settles and creates an unequal distribution of paste and aggregate in fresh concrete. Segregation is a lack of homogeneity in a mix with regards to aggregate particle size. Segregation is undesirable because it reduces concrete quality and makes it more susceptible to defects, such as shrinkage and formation of cracks. It is also difficult to amend once all the ingredients have been mixed, which increases the importance of reducing the potential for segregation prior to mixing. This project's intent is to develop a method of accurately assessing the degree of segregation in a concrete section and to establish an ideal range of values for fresh concrete tests to reduce the potential for segregation in concrete.

2. BACKGROUND

Self-consolidating concrete (SCC), also known as self-compacting concrete, is a type of concrete used for its flowability and stability.[1] It has no need for mechanical consolidation, allowing for a faster rate of placement, and it requires little or no finishing. Thus, SCC is an appealing option in the concrete industry. SCC is used in applications like drilled shafts. The depth of drilled shafts makes them ideal applications for SCC .[1]

Segregation can often be traced back to a poor mix design. The quantity of water and cement and aggregate gradation are among some of the factors that heavily influence the degree of segregation in concrete.[2] Typically, segregation is combated by reducing the water-cement ratio (w/c), coarse aggregate content and the maximum aggregate size. Additionally, high-range water reducers (HRWRs) admixtures and viscosity modifying admixtures (VMAs) have been effectively used to maintain the stability and flowability of SCC.[1] Determining the optimal concrete mix proportions improves concrete quality.

Standard tests for SCC include slump flow, visual stability index (VSI), J-ring flow, and T_{20}. While these tests are generally reliable for predicting the performance of SCC, their accuracy declines when the SCC is used in sections with heavily congested reinforcement.[2] This demonstrates a need for additional testing to be utilized in conjunction with the already-developed standard tests. Kahn and Kurtis recommend the construction of prototype samples and digital-image-analysis methods to ensure quality in SCC mixtures.[2] Research conducted by Khayat et al. employs a “rapid methodology” to estimate segregation during cement hydration using electrical conductivity and image-processing techniques.[3] The groundwork for evaluating a concrete mixture's aggregate distribution has been laid for continued research into new methods of measuring the degree of segregation in a SCC mixture.

3. EXPERIMENTAL PROCEDURE

This project draws from procedure and follows the data collected from previous research conducted by Smith et al.[4] regarding SCC applications in transportation structures. SCC mixtures with varying fresh concrete properties were used to cast sixteen concrete wall sections. Cores were removed from three locations in each wall and the aggregate distributions were examined for each core using a manual count of aggregate and a MATLAB program. Each aspect of the research program is discussed in greater detail below.

3.1 Wall Sections

Sixteen concrete wall sections were cast using different concrete mix designs, seen in Figure 1. The wall sections measured 4 feet high by 4 feet wide, with a 6 inch thickness, and had a required volume of concrete of 8 cubic feet,[4] as seen below in Figure 2. The SCC mixtures represented a wide range of concrete fluidity. Each wall was cored in nine different locations, shown by Figure 3. For each row, two cores were tested in compression strength, and the third was used for measuring aggregate distribution.

Figure 1: Cast wall sections

Figure 2: A close-up example of a wall section

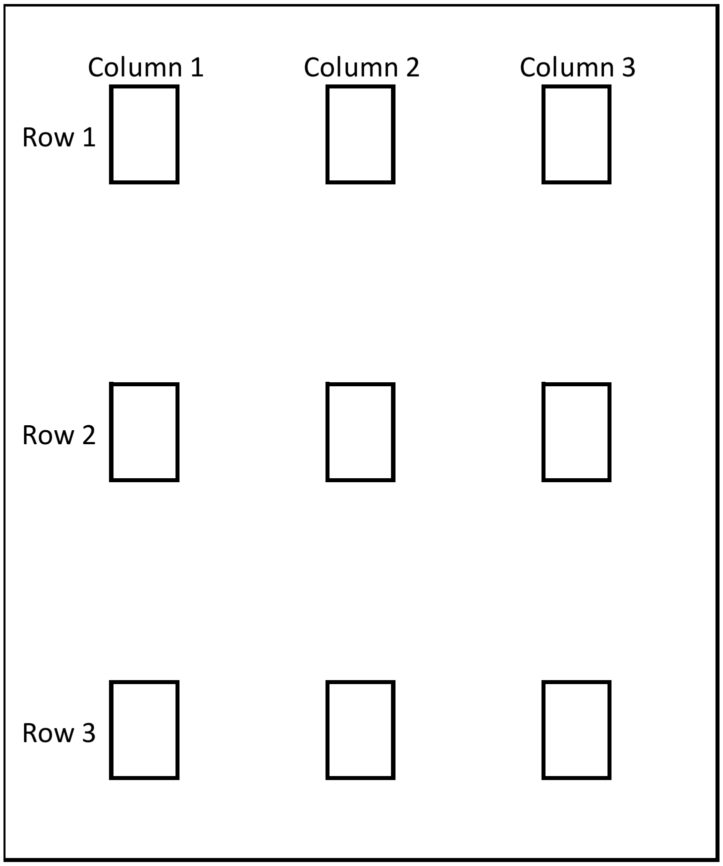

Figure 3: Core locations for a wall section

3.2 Cores

Each core removed from the walls was approximately 4 inches by 6 inches. The cores were cut lengthwise and marked with the batch, row, and column numbers, as seen below in Figure 4. They were then examined to determine the approximate amount of limestone aggregate that was contained in each core. Through a manual count, the number of coarse aggregates was recorded. Each core was also measured in order to calculate its surface area.

Figure 4: Example of a core with batch, row and column numbers

3.3 Image processing

To acquire an image of each core, the specimens were positioned on a flat surface with a blank, neutral-colored background. To enhance the color of the cement paste, each core was wetted thoroughly with a cloth to maximize the contrast between the paste and the aggregate. Digital images were then obtained in black-and-white to narrow the color range to shades of gray, as shown below in Figure 5. This would allow the imaging software to isolate pixels of certain colors within the pictures. The software would highlight the white and similarly colored pixels of the limestone aggregate to determine the percentage of aggregate per core. In order to produce the necessary data, a MATLAB program was developed.

Figure 5: Center of a core

The MATLAB analysis procedure began by loading an image and deciding the degree of rotation, based on the irregularities of the individual cores and how they sat upon the flat surface. The image was then cropped manually to eliminate the background and surface, which would otherwise influence the image processing.

When prompted, a darkness value was entered into the program based on the range of darkness values found in an individual image. Darkness values were chosen from the image's available range of values to isolate the shades of gray of the limestone aggregate. New darkness values could be chosen if the program failed to isolate the colors to a reasonable degree.

Once a darkness value was determined, the images were converted to opaque green and red to provide even greater contrast. The program would then automatically save new image files of the green-red core and the green-red core cut into eight segments, as seen in Figure 6.

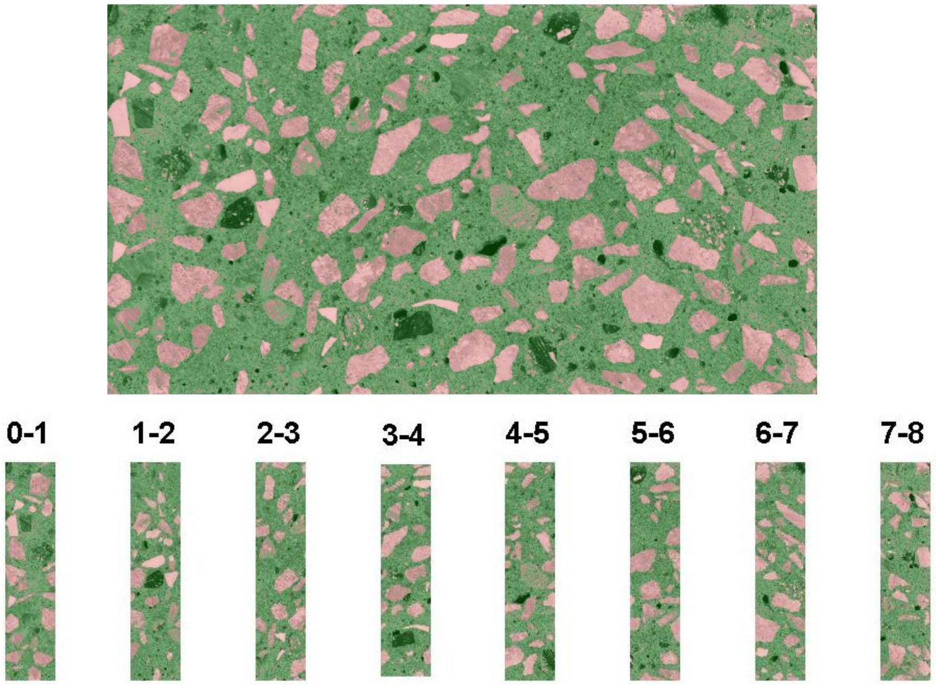

Figure 6: Processed core image and segments

The image data processed by the program was then exported to an Excel spreadsheet. The data consisted of the percentage of rock per segment. This process was repeated in its entirety for all of the forty-seven samples.

4. RESULTS

All data were recorded and exported to a spreadsheet for comparison. Aggregate distribution data and the fresh concrete properties of the individual batches were to determine if there was any correlation between the two. Results from the manual count, seen below in Tables 1 and 2, and the MATLAB program were also compared separately.

Table 1: Manual count results

Specimen	Manual Count
5.1.1	196
5.2.3	205
5.3.1	146
6.1.3	195
6.2.2	165
6.3.2	227
7.1.1	170
7.2.2	199
7.3.3	172
8.1.3	189
8.2.3	185
8.3.3	188
9.1.3	188
9.2.2	204
9.3.1	171
10.1.2	207
10.2.2	208
10.3.3	140
11.1.2	224
11.1.3	223
11.2.3	227
11.3.1	168
12.1.1	173
12.2.3	205

Table 2: Manual count results (cont'd)

Specimen	Manual Count
12.3.1	219
12.3.3	219
13.1.2	196
13.2.2	170
13.3.2	177
14.1.1	154
14.1.2	186
14.1.3	161
14.2.1	157
14.2.2	197
14.2.3	135
14.3.1	149
14.3.2	157
14.3.3	132
16.1.1	160
16.1.2	129
16.1.3	125
16.2.1	135
16.2.2	133
16.2.3	194
16.3.1	144
16.3.2	182
16.3.3	172

4.1 Aggregate Distribution Methods

As previously mentioned, all coarse aggregate particles along the center section of the core were counted. In order to compare the manual count method to the MATLAB method, the number of coarse aggregate particles for area of sample was determined. The resulting values were in terms of number of rocks per square inch. These values are shown below in Tables 3 and 4.

Table 3: Aggregate Distribution Results

Specimen	Rock Per Area (number/in^2)	MATLAB (%)
5.1.1	7.53	29.94
5.2.3	7.88	30.55
5.3.1	5.81	27.04
6.1.3	7.44	34.97
6.2.2	7.01	28.08
6.3.2	8.47	29.12
7.1.1	6.41	28.36
7.2.2	6.82	28.38
7.3.3	6.61	35.67
8.1.3	7.22	28.39
8.2.3	7.04	29.04
8.3.3	7.34	22.51
9.1.3	7.22	25.10
9.2.2	6.77	28.60
9.3.1	6.57	24.15
10.1.2	7.27	29.25
10.2.2	7.00	23.08
10.3.3	6.03	26.92
11.1.2	8.39	33.98
11.1.3	8.54	35.46
11.2.3	8.74	40.08
11.3.1	6.91	30.43
12.1.1	6.42	20.19
12.2.3	7.15	31.98

Table 4: Aggregate Distribution Results (cont’d)

Specimen	Rock Per Area (number/in^2)	MATLAB (%)
12.3.1	8.08	23.01
12.3.3	8.10	31.24
13.1.2	7.17	26.09
13.2.2	6.13	27.15
13.3.2	6.80	21.72
14.1.1	6.88	31.13
14.1.2	7.74	23.51
14.1.3	6.11	20.25
14.2.1	6.95	24.74
14.2.2	6.93	20.92
14.2.3	5.95	18.06
14.3.1	5.92	26.43
14.3.2	7.02	16.02
14.3.3	5.86	28.59
16.1.1	6.43	24.98
16.1.2	5.81	23.03
16.1.3	5.51	19.95
16.2.1	6.27	24.54
16.2.2	6.00	25.08
16.2.3	7.59	19.29
16.3.1	6.37	24.29
16.3.2	7.35	28.39
16.3.3	7.69	27.85

The two methods of measuring aggregate distribution (the manual count and the MATLAB percent aggregate) did not demonstrate any significant correlation. This can be attributed to differing sizes of aggregate in a concrete mix. With no real relationship between the two methods, the manual count is discarded in the following data. The reasons for this discard are as follows.

Different rock sizes in a mixture create difficulty in using an aggregate per area method because there is no standardized size of aggregate particle. If a standardized size was used, the rocks per area could be translated into an area of rock per area measurement, which is comparable to a percent aggregate measurement. Thus, the manual count cannot be considered an effective method of determining aggregate distribution and as an extension a good indicator of segregation.

4.2 MATLAB Data and Fresh Concrete Properties

Fresh concrete properties data of the SCC batches were obtained from previous research by Smith et al.[4] The fresh concrete properties included slump flow, T_{20}, VSI, J-ring flow and J-ring flow spread and are shown below in Tables 5 and 6. The fresh concrete properties were compared with the percent of coarse aggregate per core determined by the MATLAB program. By comparing the two, the researchers could determine if any correlation existed between the two sets of data.

Table 5: MATLAB and Fresh Concrete Properties

Specimen	Slump Flow (in.)	T_{20} (sec)	VSI	J-ring (in)	J-ring ΔH (in.)	Flow difference (in.)	Percent Aggregate (%)
5.1.1	27.0	-	1.0	27.5	0.8	-0.5	29.94
5.2.3	27.0	-	1.0	27.5	0.8	-0.5	30.55
5.3.1	27.0	-	1.0	27.5	0.8	-0.5	27.04
6.1.3	26.5	10.4	1.0	27.5	0.5	-1.0	34.97
6.2.2	26.5	10.4	1.0	27.5	0.5	-1.0	28.08
6.3.2	26.5	10.4	1.0	27.5	0.5	-1.0	29.12
7.1.1	26.5	8.4	1.0	27.0	0.3	-0.5	28.36
7.2.2	26.5	8.4	1.0	27.0	0.3	-0.5	28.38
7.3.3	26.5	8.4	1.0	27.0	0.3	-0.5	35.67
8.1.3	22.5	9.8	0.0	22.0	1.0	0.5	28.39
8.2.3	22.5	9.8	0.0	22.0	1.0	0.5	29.04
8.3.3	22.5	9.8	0.0	22.0	1.0	0.5	22.51
9.1.3	27.5	6.4	0.0	30.0	0.3	-2.5	25.10
9.2.2	27.5	6.4	0.0	30.0	0.3	-2.5	28.60
9.3.1	27.5	6.4	0.0	30.0	0.3	-2.5	24.15
10.1.2	21.0	15.6	0.0	19.0	1.8	2.0	29.25
10.2.2	21.0	15.6	0.0	19.0	1.8	2.0	23.08
10.3.3	21.0	15.6	0.0	19.0	1.8	2.0	26.92
11.1.2	37.5	1.6	2.5	41.0	0.0	-3.5	33.98
11.1.3	37.5	1.6	2.5	41.0	0.0	-3.5	35.46
11.2.3	37.5	1.6	2.5	41.0	0.0	-3.5	40.08
11.3.1	37.5	1.6	2.5	41.0	0.0	-3.5	30.43
12.1.1	31.0	3.8	2.0	29.5	0.8	1.5	20.19
12.2.3	31.0	3.8	2.0	29.5	0.8	1.5	31.98
12.3.1	31.0	3.8	2.0	29.5	0.8	1.5	23.01
12.3.3	31.0	3.8	2.0	29.5	0.8	1.5	31.24
13.1.2	24.0	5.0	0.0	22.5	1.0	1.5	26.09

Table 6: MATLAB and Fresh Concrete Properties (cont'd)

Specimen	Slump Flow (in.)	T_{20} (sec)	VSI	J-ring (in)	J-ring ΔH (in.)	Flow difference (in.)	Percent Aggregate (%)
13.2.2	24.0	5.0	0.0	22.5	1.0	1.5	27.15
13.3.2	24.0	5.0	0.0	22.5	1.0	1.5	21.72
14.1.1	29.5	4.0	1.0	27.0	0.5	2.5	31.13
14.1.2	29.5	4.0	1.0	27.0	0.5	2.5	23.51
14.1.3	29.5	4.0	1.0	27.0	0.5	2.5	20.25
14.2.1	29.5	4.0	1.0	27.0	0.5	2.5	24.74
14.2.2	29.5	4.0	1.0	27.0	0.5	2.5	20.92
14.2.3	29.5	4.0	1.0	27.0	0.5	2.5	18.06
14.3.1	29.5	4.0	1.0	27.0	0.5	2.5	26.43
14.3.2	29.5	4.0	1.0	27.0	0.5	2.5	16.02
14.3.3	16.0	4.0	1.0	27.0	0.5	-11.0	28.59
16.1.1	16.0	NA	NA	NA	NA	NA	24.98
16.1.2	16.0	NA	NA	NA	NA	NA	23.03
16.1.3	16.0	NA	NA	NA	NA	NA	19.95
16.2.1	16.0	NA	NA	NA	NA	NA	24.54
16.2.2	16.0	NA	NA	NA	NA	NA	25.08
16.2.3	16.0	NA	NA	NA	NA	NA	19.29
16.3.1	16.0	NA	NA	NA	NA	NA	24.29
16.3.2	16.0	NA	NA	NA	NA	NA	28.39
16.3.3	16.0	NA	NA	NA	NA	NA	27.85

NA = Not applicable since the concrete mixtures did not flow. Therefore the concrete did not have T_{20}, VSI, etc.

Research conducted by Fang and Labi measured aggregate distribution using image processing software in a similar way. By utilizing subjective VSI ratings and assigning actual criteria to them, they developed a program that could analyze the hardened concrete and output a VSI rating based on the parameters that concrete fell under.[5] For this project, more SCC standard tests were compared with the image processing data from MATLAB, and assigning actual quantifiable parameters for VSI was not attempted.

Several significant patterns emerged from this data. Eight of the eleven batches ranked a 1.0 or lower for VSI, indicating sufficient stability of the slump flow patty, while only four of the eleven batches exhibited slump flows that fell in the desired range of 25 inches and 29 inches.[4] Three of the eleven batches were in the 2 to 5 second range for T_{20}, which is considered acceptable for SCC.[4] Five of the eleven batches had inside-outside J-ring height difference values of less than 0.59 inches, and another five of the eleven batches had slump flow/J-ring flow difference values of less than 4 inches, both of which are considered acceptable for SCC.[4]

None of the eleven batches met all the criteria for ideal SCC. One batch (14) met four of the five criteria, and four batches (6, 7, 9 and 13) met three of the five criteria. The four criteria that Batch 14 met were T_{20}, VSI, slump/J-ring difference, and J-ring height difference.

Batches within the adequate range for T_{20} (2 to 5 seconds) tended to have lower percentages of aggregate, while batches with T_{20} values lower and higher than the adequate range tended to have higher percentages of aggregate. The greater the difference from the 2 to 5 second range, the greater the percentage of aggregate. In addition, batches with T_{20} values outside of the adequate range and with VSI ratings higher than 1.0 showed the highest percentages of aggregate.

Although batch 14 adhered closest to the SCC fresh concrete properties standards, batches 5, 6, 7 and 9 demonstrated the most consistent aggregate percentages through all batch specimens. This suggests that these batches had the most even aggregate distribution and experienced the least amount of segregation. Batch 14 demonstrated aggregate percentage range of 15.11%, while batches 5, 6, 7, and 9 demonstrated ranges of 3.51%, 6.89%, 7.31% and 4.45%, respectively. This analysis of a batch's range of aggregate percentage gives more flexibility to a quantitative definition of segregation, rather than defining segregation as having aggregate percentages within two specific values.

The batches with slump flows outside of the adequate range of 25 to 29 inches tended to fluctuate more in the amount of aggregate present in each core. These cores experienced a greater range of aggregate percentage as a result. Conversely, batches with higher than recommended T_{20} values deviated the least in amount of aggregate present in each core. These cores experienced smaller ranges of aggregate percentage. All of the batches with T_{20} values less than 5 seconds had ranges of percentages of aggregate greater than 8.0%.

Correlation between these sets of data implies that segregation can be properly identified in concrete mixtures based on T_{20} values and the aggregate percentages from the MATLAB program. If a concrete batch possesses a T_{20} of 5 seconds or more, the range of its aggregate percentages are 7.5% or less, while a T_{20} of less than 5 seconds yields a range of aggregate percentages of greater than 7.5%. It can be reasonably assumed then that a batch with range of 7.5% or less has experienced little or no segregation.

However, it is more difficult to attribute sufficient aggregate distribution to specific minimum and maximum values of aggregate percentages due to varying proportions of aggregate in different mixes. It appears to be more reliable to attribute it to the difference of the minimum and maximum percentages, rather than the values themselves. Moreover, this suggests that adequate SCC can be produced with T_{20} values outside the 2 to 5 second range.

5. CONCLUSIONS

- Based on the aggregate distribution data from this project, the manual count method and the MATLAB method have little to no correlation. The manual count only provides the number of coarse aggregate particles per core, not the area of coarse aggregate per core. Therefore, the manual count method cannot be considered a reliable way of determining segregation because of its lack of real units and a standardized size of aggregate particle.

- The MATLAB program can indicate if segregation will occur in a concrete mixture based on its T_{20} and its subsequent aggregate percentage range. According to the data, a T_{20} of 5 seconds or greater implies a concrete mixture will have an aggregate percentage range of 7.5% or less, which suggests sufficient aggregate distribution.

- It is possible to produce adequate SCC outside of the T_{20} range of 2 to 5 seconds. The recommended T_{20} is 5 seconds or more and a VSI rating of 1.0 or less.

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