Concrete Mix Design and Cylinder Strength Testing with Inconclusive Results

For:
Abear Engineering and Design

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Introduction

In result of Abear Engineering and Design's board of directors' acceptance of CAE Materials Testing Services proposal, a variety of materials tests were performed on behalf of their company. The Statement of Work submitted by Abear Engineering and Design requested a series of tests performed on locally-available aggregates, production of a range of concrete mix designs containing local aggregates, and detailed results of the tests performed. All tests were conducted in accordance with appropriate ASTM standards.

Tests performed on the local aggregates included sieve analysis and gradations. The local aggregates were sourced from Martin Marietta Aggregates & Ready Mix Concrete. These tests showed positive results because the aggregates were found to be the desired sizes specified and the tests showed compliance with the ASTM standards. Other aggregate components tested for were density, absorption, moisture content, and the unit weight of the aggregate to be used in the calculations for the absolute volume method. Concrete batches were designed using the empirical and absolute volume methods. The empirical design mixtures used a range of water-to-cement ratios in order to identify which mixture would be ideal. The absolute volume design mixture was specifically calculated to reach target strengths using the results of the aforementioned testing in order to have a base line to compare the empirically designed batches to. These batches were cast in cylinder molds which were used for the compressive strength tests. Cylinders were tested at 1, 7, 14, and 28-day increments for actual compressive strength. This information was then used for comparison of the volumetrically-designed compressive strength versus the compressive strength of each of the empirically-designed batches. The comparison of the compressive strength for each of the batches is useful for the establishment of a base line for the empirically-designed batches to the volumetric batches to determine an effective water to cement ratio. The compressive strength tests were not conclusive; as a result, the analysis of the volumetrically designed batches versus the empirically designed batches were also inconclusive.

Background

Sieve analysis was performed on locally-available aggregates in order to determine the gradation of the coarse and fine aggregates as well as the fineness modulus to be used in the mix designs. The aggregate was found to be an angular aggregate of ¾ in. nominal maximum size. A ¾ in. nominal maximum size was selected because it is locally available and has a wide range of practicality for varying projects. Tests for density, absorption, moisture content, and the unit weight of the aggregate were performed in order to assist the calculations for the concrete batches designed using the volumetric procedure which allows the specific calculation of concrete constituents to meet the design strength. Trial batches were empirically designed using water-to-cement ratios ranging from 0.4-0.7 with a desired slump for all batches of 3.5 in. ± 0.5in. The targeted water-to-cement range was selected because this range is the most practical for the workability of the product (The Constructor, 2016). Achieving the optimal slump range of 3.5 in. ± 0.5 in. resulted in batch sizes varying due to added water and/or aggregate. Trial batches were also designed using the absolute volume method, as presented in Materials for Civil and Construction Engineers, with target strengths of 3000 psi and 4000 psi for two separate batches. (Mamlouk and Zaniewski 2016, 273-290). The primary difference between the two methods is the absolute volume design method accounts for moisture corrections within the aggregate. The absolute volume method provides specific results for two different strengths. These can be compared to the results of the empirically-designed batches in order to match the correct water-to-cement ratio to the desired design strength. The batches were cast in 4x8 in. cylinder molds to create specimens that were then tested for actual compressive strength at 1, 7, 14, and 28-days and comparisons were analyzed.

Procedures

For the sieve analysis of the concrete aggregate, the sample was acquired in accordance with ASTM C 702 Method B – Quartering, then the standard test method for sieve analysis of fine and coarse aggregates was performed on the sample in accordance with ASTM C 136. ASTM C 33 was utilized to determine if the aggregate met the correct gradation specifications. The information gained through these tests was used to optimize the ratio of coarse to fine aggregate, eliminating the maximum quantity of void space.

ASTM C 127 and ASTM C 128 were used to determine the relative density, moisture content, and absorption of the coarse and fine aggregate, respectively. ASTM C 566 was used to determine the total evaporable moisture content of the aggregate. The bulk density and voids in the aggregate were found using ASTM C 29. The results of these tests were used for the volumetric mix design.

Concrete batching was performed in accordance with ASTM C 192 for making and curing concrete test specimens. The slump and air content of the freshly-mixed concrete were tested in accordance with ASTM C143 and C231. The slump was controlled by adding water if the slump was less than 3.5 inches, and adding aggregate if the slump was greater than 3.5 inches. These standards were used in order to produce both volumetric- and empirically-designed batches. The empirical-design batches used a range of water-to-cement ratios in order to identify which mixture would be ideal. The volumetrically-designed mixture was specifically calculated to reach target strengths. These batches were mixed and tested in accordance with the standards then cast in cylinder molds. These cylinders were tested for strength after a proper curing period of 1, 7, 14, and 28-days as stipulated in ASTM C 192. The concrete cylinders were tested for actual compressive strength in accordance with ASTM C 39. The compressive strength results for the volumetric- and empirically-designed cylinders were then compared to determine which empirically-designed cylinders corresponded to the volumetrically-designed cylinders for required strengths.

Results

Results of sieve analysis performed on the locally-sourced, blended, angular aggregate obtained from Martin Marietta are recorded in Tables 2 and 3. Table 3 shows that the coarse fraction has a nominal maximum size of ¾ in. with 100% passing the 1 in. sieve. The analysis of the raw gradation data showed a low standard of deviation. Figure 1 illustrates Table 3, showing the average percentage passing versus the sieve size as well as showing that the gradation for the coarse fraction meets ASTM C 33 upper and lower bounds for coarse aggregate. After the sieve analysis was performed on the blended aggregate for the coarse fraction, further sieve analysis was performed to determine the fine fraction gradation as shown in Table 2. The fineness modulus is also represented in Table 2 with an average of 3.03; Table 2 also shows low standard of deviation for the raw data. Figure 2 represents Table 2 and shows that the average gradation results are within ASTM C 33 upper and lower bounds for fine aggregate. Table 6 shows the specific gravity, absorption, moisture content, and unit weight for the fine and coarse aggregate fractions. Absorption is determined by subtracting specific gravity (SSD) from the oven-dry mass then dividing by the oven-dry mass, which can be seen in Equation 1(Mamlouk and Zaniewski 2016, 191). For the fine fraction, the apparent specific gravity is 2.7, the absorption is 3.9%, the moisture content is .3%, and the unit weight (M) is 108.6 lb/ft^3. For the coarse aggregate, apparent specific gravity is 2.7, the absorption is .6%, the moisture content is .1%, and the unit weight is 92.4 lb/ft^3. Table 4 shows the blended aggregate gradation data, illustrated in Figure 3, along with the max density. Figure 3 shows the opening^.45 gradation curves plotted with the maximum density line which crosses the blended aggregate fraction at 63% making a 63%-37% blended aggregate. It is important to try to achieve as close to maximum density as possible (60%-40%) in order to minimize void space; this reduces the necessary quantity of cement in the mix and helps improve strength results.

The average strength results of the empirical designs for 1, 7, 14 and 28-day strength tests are shown in Table 7 along with the W/C and COV values for each group. The table shows very high COVs for all tests with the exception of M3 and W5 for day 1 tests; these are the only tests that meet the standard of 3.2% COV set by ASTM C 39. Tables 8 and 9 show the strength test results for the 3000 psi and 4000 psi volumetric mix designs; these results also show very high COV values. The day 7 empirical mix designs strength results showed a downward trend in strength as water content increased. The day 14 empirical mix designs shows a general downward trend in strength as water content increases with the exception of the .4 W/C result, which was lower than the .45 W/C result. Day 28 for the empirical mix designs shows a general downward trend in strength as the water content increases with the exception of the .4 W/C result, which was lower than the .45 W/C result. These results are illustrated in Figure 4. The strength tests for the 7, 14, and 28-day results for the empirical designs show varied strengths, generally increasing from 7 to 28 days, but with many outliers to the trend as shown in Figure 4.

The 3000 psi volumetric mix design shows an increase in strength from day 7 to day 14 and from day 14 to day 28. The 4000 psi volumetric mix design shows a decrease in strength from day 7 to day 14 and an increase in strength from day 14 to day 28. The 3000 psi volumetric mix design shows an average 28-day stress of 3585 psi meeting the 3402 psi required strength (f'cr). However, this batch fails to meet the required COV value of less than 3.2% and is actually 19%. The 4000 psi volumetric mix design fails to meet the required strength of 4537 psi and required COV values, as shown in Table 9. These results are illustrated in Figures 4 and 5.

Tables & Figures

Table 1: Mix Design Constituents for Empirical Designs

Sample No.	Curing	W/C	Cement [lb]	Water [lb]	Actual W/C	Blended Aggregate [lbs.]	Blend Ratio [CA / FA]	Slump [in.]	Air Content	Batch Volume [ft^3]
M1	Fog Room	0.4	28.00	11.20	0.40	46.62	63% / 37%	3.75	Unknown	0.58
M2	Fog Room	0.5	18.01	9.00	0.50	60.94	63% / 37%	3	Unknown	0.52
M3	Fog Room	0.6	18.71	11.02	0.60	94.34	63% / 37%	3.25	Unknown	0.76
M4	Fog Room	0.7	18.00	12.60	0.70	101.56	63% / 37%	3.5	Unknown	0.89
W1	Fog Room	0.4	18.00	7.20	0.40	32.44	63% / 37%	3.75	Unknown	0.40
W2	Fog Room	0.45	18.01	8.10	0.45	49.04	63% / 37%	3.5	Unknown	0.51
W3	Fog Room	0.5	18.00	9.00	0.50	64.04	63% / 37%	3.5	Unknown	0.58
W4	Fog Room	0.55	18.04	9.90	0.55	71.97	63% / 37%	3.5	Unknown	0.68
W5	Fog Room	0.6	21.33	12.84	0.60	97.44	63% / 37%	3.5	Unknown	0.88
W6	Fog Room	0.7	18.00	12.60	0.70	103.24	63% / 37%	4	Unknown	0.89

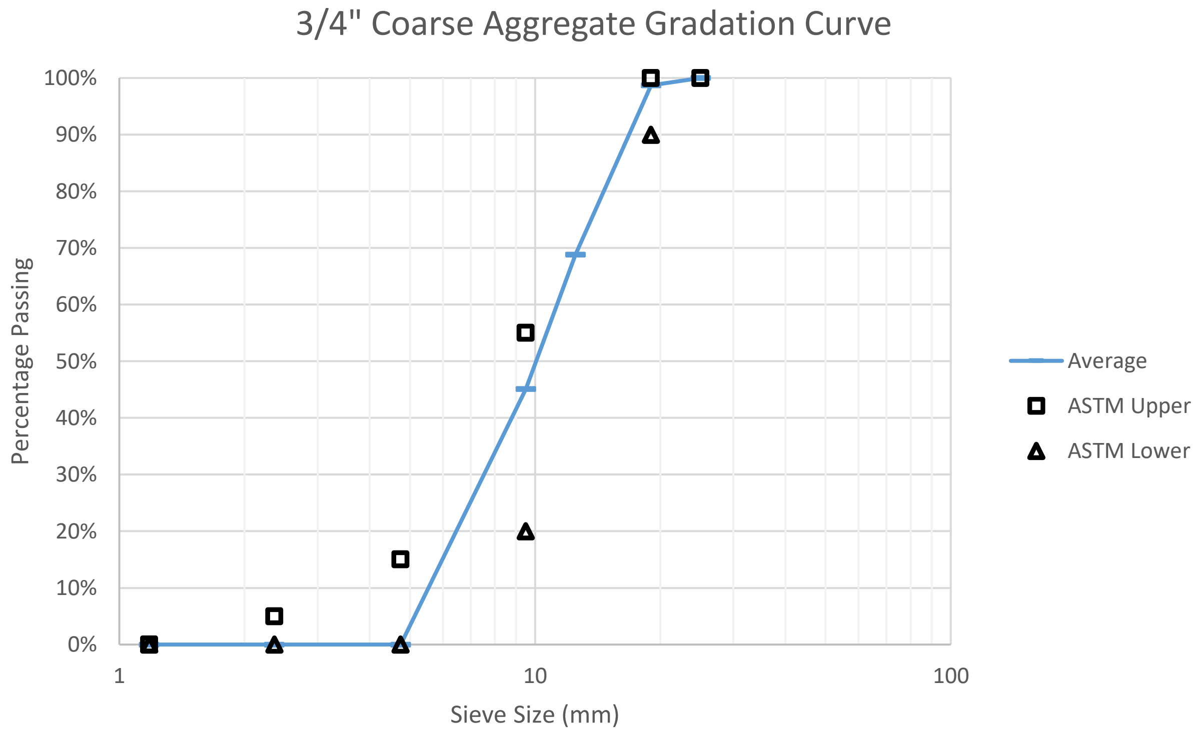

Figure 1: Average Coarse Aggregate Gradation Curve

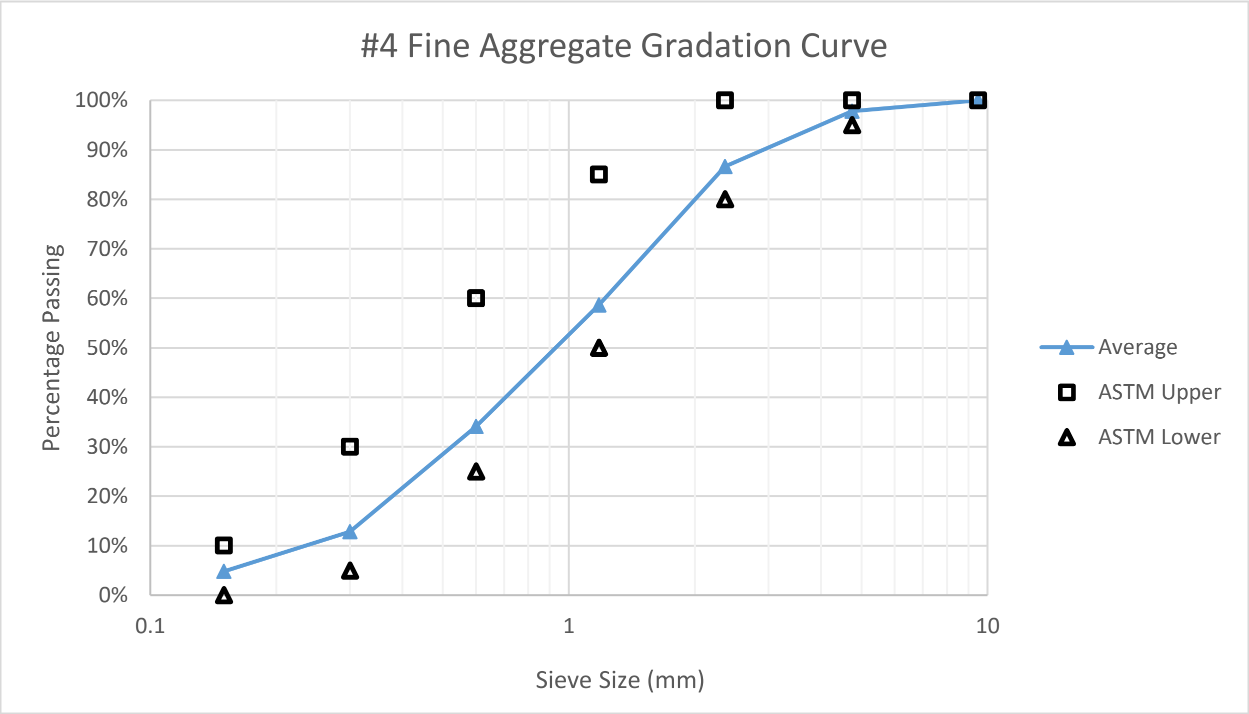

Figure 2: Average Fine Aggregate gradation Curve

Table 2: Average Percentage Passing for Fine Aggregate and Fineness Modulus

Fine Aggregate Fraction **Percentage Passing**

Sieve	Opening (mm)	Opening^.45	M1	M2	M3	M4	W1	W2	W3	W4	W5	W6	Average	Deviation
3/8	9.5	2.75	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
4	4.75	2.02	96%	96%	95%	95%	100%	99%	100%	99%	99%	99%	98%	2%
8	2.36	1.47	88%	89%	84%	80%	91%	85%	92%	87%	84%	85%	87%	4%
16	1.18	1.08					56%	55%	63%	63%	58%	58%	59%	3%
30	0.6	0.79					32%	34%	39%	33%	32%	34%	34%	2%
50	0.3	0.58					12%	14%	15%	10%	12%	13%	13%	2%
100	0.15	0.43					5%	6%	6%	2%	5%	5%	5%	1%
	Fineness Modulus						3.05	3.06	2.87	3.04	3.1	3.05	3.03	8%

Table 3: Average Percentage Passing for Coarse Aggregate

Coarse Aggregate Fraction **Percentage Passing**

Sieve	Opening (mm)	Opening^.45	M1	M2	M3	M4	W1	W2	W3	W4	W5	W6	Average	Deviation
1	25	4.26	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
3/4	19	3.76	98%	98%	97%	100%	99%	98%	100%	99%	99%	99%	99%	1%
1/2	12.5	3.12	66%	68%	69%	68%	71%	69%	72%	73%	71%	62%	69%	3%
3/8	9.5	2.75	43%	46%	46%	44%	47%	45%	50%	47%	43%	40%	45%	3%
4	4.75	2.02	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
8	2.36	1.47	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
16	1.18	1.08	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 4: Blended aggregate Gradation Data and Blend Ratio

Blended Aggregate Gradation Data			Percentage Passing											
Sieve	**Opening (mm)**	**Opening^.45**	**M1**	**M2**	**M3**	**M4**	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**Average**	**Deviation**
1	25	4.26	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
3/4	19	3.76	98%	98%	98%	100%	100%	99%	100%	100%	100%	99%	99%	1%
1/2	12.5	3.12	77%	78%	84%	82%	82%	80%	83%	84%	79%	75%	80%	3%
3/8	9.5	2.75	62%	63%	71%	69%	67%	64%	70%	69%	59%	61%	65%	4%
4	4.75	2.02	32%	31%	47%	45%	37%	35%	40%	42%	28%	35%	37%	6%
8	2.36	1.47	28%	27%	43%	40%	33%	31%	35%	37%	24%	31%	33%	6%
16	1.18	1.08	21%	20%	31%	25%	24%	20%	24%	27%	17%	22%	23%	4%
Blend Ratio		**CA %**	68%	69%	53%	55%	63%	65%	60%	58%	72%	65%	63%	6.2%
		FA %	32%	31%	47%	45%	37%	35%	40%	42%	28%	35%	37%	6.2%
Aggregate Size		**Abs. Max**	1"	1"	1"	1"	1"	1"	1"	1"	1"	1"		
		Nom. Max	3/4"	3/4"	3/4"	3/4"	3/4"	3/4"	3/4"	3/4"	3/4"	3/4"		

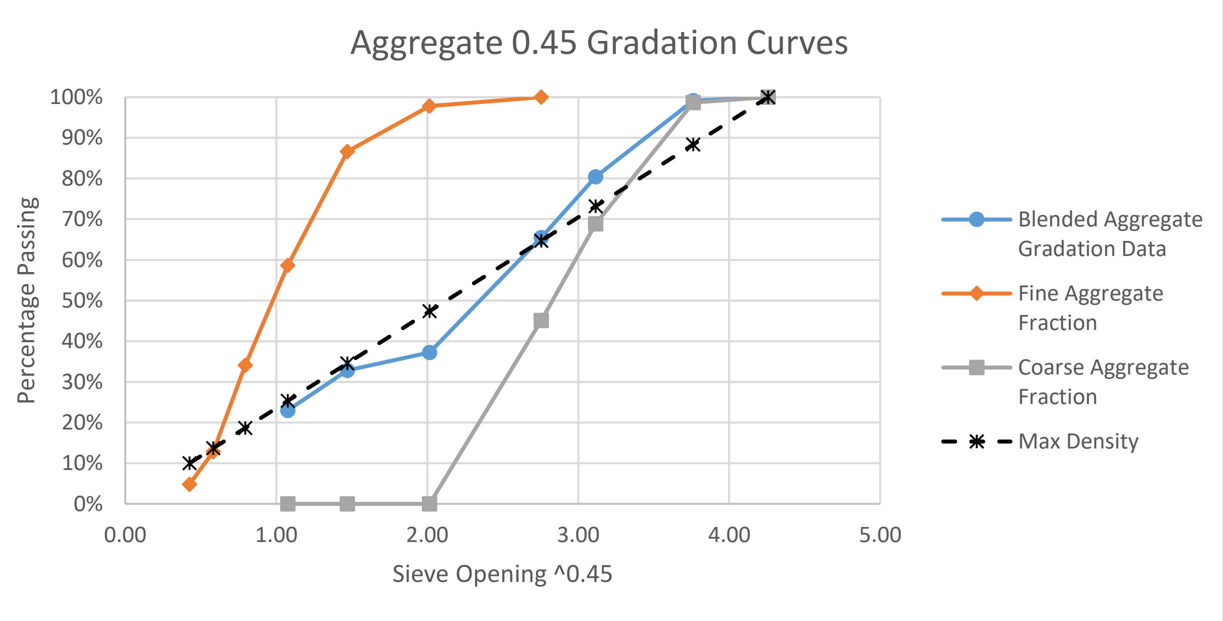

Figure 3: Aggregate 0.45 Gradation Curves and Max Density Plot

Table 5: Max Density

Max Density Opening (mm)	Percentage Passing
4.26	100%
3.76	88%
3.12	73%
2.75	65%
2.02	47%
1.47	35%
1.08	25%
0.79	19%
0.58	14%
0.43	10%

Table 6: Aggregate Specific Gravity, Absorption and Moisture Content

Material Properties	Aggregate Type		Stdev		COV		Number of Specimens	
	Fine	3/4"	Fine	3/4"	Fine	3/4"	Fine	3/4"
S_{dry}	2.4862	2.7171	0.05	0.01	1.8%	0.51%	10	10
S_{SSD}	2.5696	2.7330	0.03	0.01	1.2%	0.53%	10	10
S_A	2.7134	2.7599	0.05	0.02	1.7%	0.60%	10	10
ABS	0.0336	0.0057	1.00%	0.08%	29.6%	14.26%	10	10
MC	0.0031	0.0018	0.07%	0.05%	23.0%	28.80%	10	10
M (lb/ft^3)	108.5610	99.0220	5.19	5.70	4.8%	5.76%	10	10

ABS= (M_ssd - M_od)/M_od*100 **Equation 1**

Where:
ABS = absorption
M_ssd= saturated surface dry mass
M_od = oven-dry mass

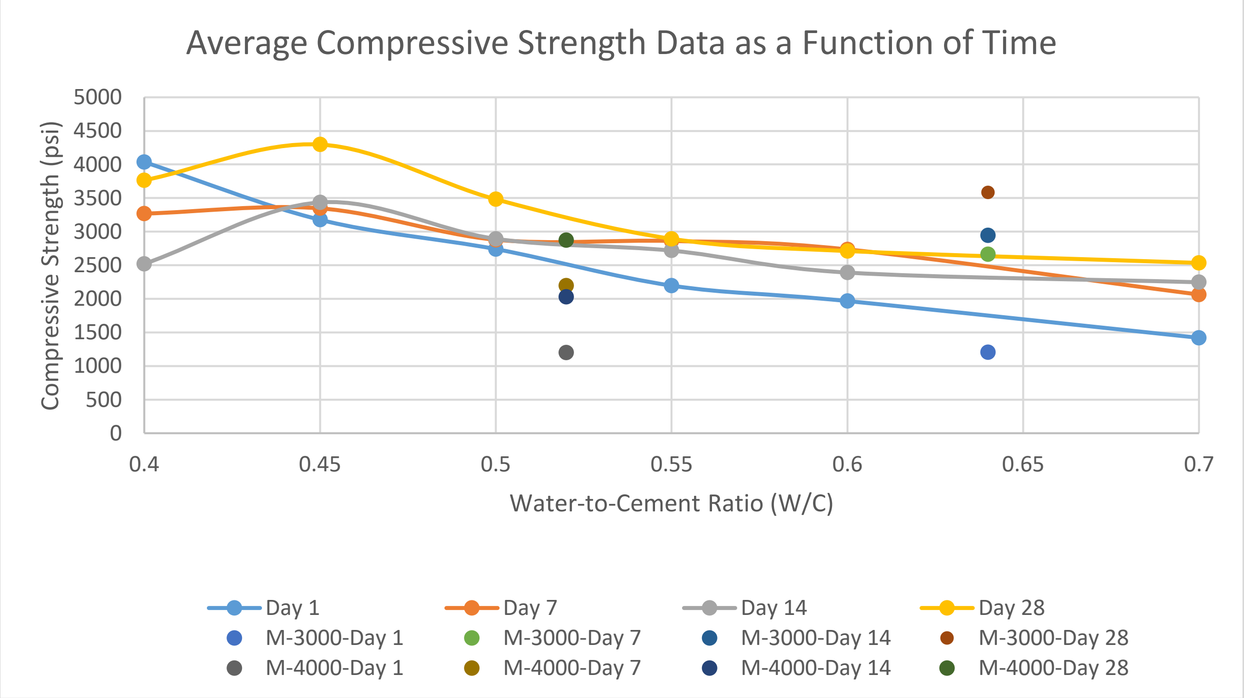

Figure 4: Average Compressive Strength Data as a Function of Time

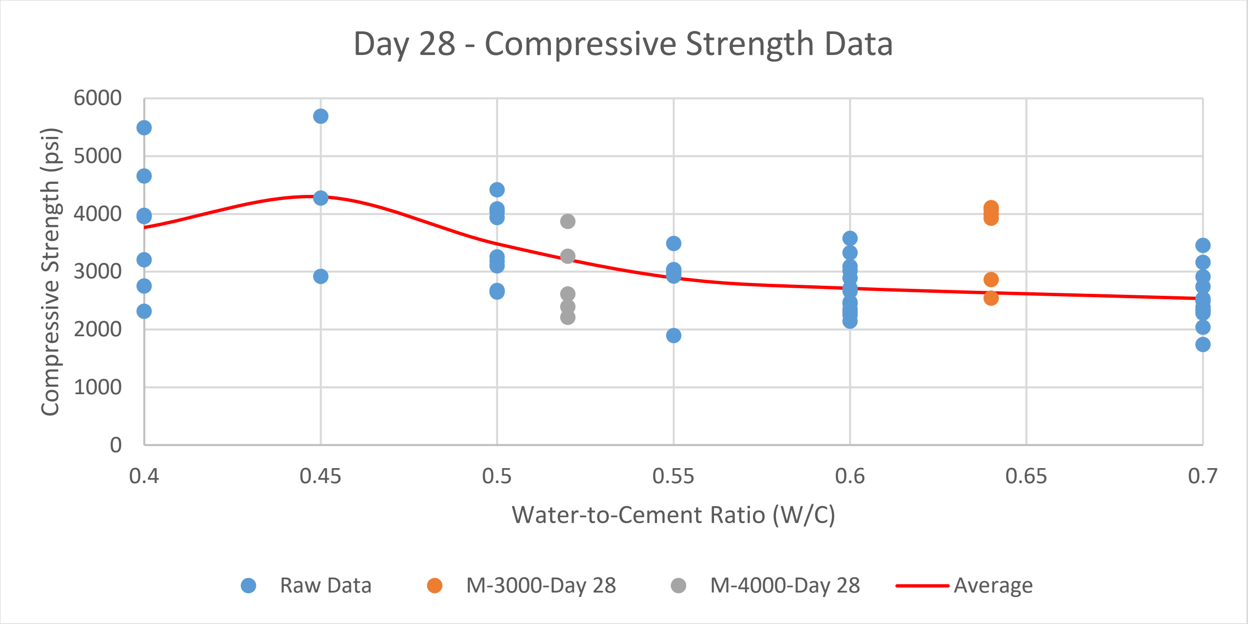

Figure 5: Day 28 – Compressive Strength Data

Table 7: Empirical Designs – Average Strength Results

Empirical Designs - Average Strength Results					
Specimen	**Number Of Samples**	**Cure Time**	**W/C**	**Stress**	**COV**
M1 & W1	2	1	0.4	4036	10%
W2	1	1	0.45	3177	N/A
M2 & W3	2	1	0.5	2741	15%
W4	1	1	0.55	2197	N/A
M3 & W5	2	1	0.6	1967	2%
M4 & W6	2	1	0.7	1420	6%
M1 & W1	3	7	0.4	3269	17%
W2	2	7	0.45	3347	34%
M2 & W3	4	7	0.5	2879	11%
W4	2	7	0.55	2861	32%
M3 & W5	6	7	0.6	2736	23%
M4 & W6	5	7	0.7	2064	16%
M1 & W1	3	14	0.4	2520	12%
W2	2	14	0.45	3436	12%
M2 & W3	4	14	0.5	2893	10%
W4	2	14	0.55	2718	24%
M3 & W5	5	14	0.6	2391	14%
M4 & W6	5	14	0.7	2247	16%
M1 & W1	7	28	0.4	3765	29%
W2	3	28	0.45	4297	32%
M2 & W3	9	28	0.5	3481	19%
W4	6	28	0.55	2893	18%
M3 & W5	13	28	0.6	2712	16%
M4 & W6	12	28	0.7	2535	19%

Table 8: M – 3000 psi– Volumetric Mix Design

M – 3000 psi- Volumetric Mix Design						
Specimen	**Cure Time**	**W/C**	**Load**	**Stress**	**Average**	**COV**
M - 3000	Day 1	0.64	15145	1205	1205	N/A
M - 3000	Day 7	0.64	35415	2818	2662	8%
M - 3000	Day 7	0.64	31500	2507		
M - 3000	Day 14	0.64	42270	3364	2946	12%
M - 3000	Day 14	0.64	35090	2792		
M - 3000	Day 14	0.64	33685	2681		
M - 3000	Day 28	0.64	51185	4073	3585	19%
M - 3000	Day 28	0.64	51630	4109		
M - 3000	Day 28	0.64	50220	3996		
M - 3000	Day 28	0.64	35960	2862		
M - 3000	Day 28	0.64	31940	2542		
M - 3000	Day 28	0.64	49340	3926		

Table 9: W – 4000 psi – Volumetric Mix Design

W - 4000 psi- Volumetric Mix Design						
Specimen	**Cure Time**	**W/C**	**Load**	**Stress**	**Average**	**COV**
W - 4000	Day 1	0.52	15110	1202	1202	N/A
W - 4000	Day 7	0.52	29835	2374	2198	7%
W - 4000	Day 7	0.52	27020	2150		
W - 4000	Day 7	0.52	26010	2070		
W - 4000	Day 14	0.52	19585	1559	2028	21%
W - 4000	Day 14	0.52	26865	2138		
W - 4000	Day 14	0.52	30010	2388		
W - 4000	Day 28	0.52	48660	3872	2872	24%
W - 4000	Day 28	0.52	30070	2393		
W - 4000	Day 28	0.52	27765	2209		
W - 4000	Day 28	0.52	41085	3269		
W - 4000	Day 28	0.52	32850	2614		

Conclusions

The local aggregate used was an ideal aggregate. Both the coarse and fine average gradations were well within the ASTM C 33 upper and lower limits as shown in Figures 1 and 2. The blended aggregate gradation was also a near perfect mixture resulting in a 63%-37% blend as shown in Table 4 and Figure 3.

The mix proportions for the empirical batches were designed to test W/C values ranging from 0.4 to 0.7, with the 0.4 batch having the least water and the 0.7 batch having the most. These batches were designed to reach a target slump of 3.5; the actual slump of each batch was recorded in Table 1. This range of W/C ratios may have been unreasonable because of the workability of the low and the high W/C ratio. In the future, it would be beneficial to limit the range from 0.45 to 0.6. Also, instead of designing to a specific slump, it is recommended to design to a specific volume.

The 0.4 batch should have had the highest strength, and the 0.7 batch should have had the lowest strength. However, the 0.4 batch was an outlier and showed inconsistent results including a day 1 average strength higher than day 28 average strength as shown in Figure 4. The 0.45 W/C showed a general trend of the average strength increasing over time but not nearly the increase in strength expected from day 7 to day 14. In fact, the day 7 and day 14 average strengths are nearly the same. This is also true for the 0.5 W/C results. The 0.55 W/C average strength results show the day 7 strengths to be greater than day 14 and nearly identical to day 28. The 0.6 W/C shows the day 7 strengths to be greater than both the day 14 and day 28 strengths. The 0.7 W/C shows the expected general trend. The overall analysis shows that the results do not meet the expected trends for 80% of strength by day 7 or the expected downward trend as the W/C ratio gets higher based on the day 1-28 results. These results are illustrated in Figure 4.

The volumetric batches were to be used as baselines for comparison to the empirical batches; however, neither the 3000 psi, nor the 4000 psi volumetric batches showed suitable results for comparison. The 3000 psi batch met the average 28 day compressive strength requirement but had a COV of 19%, failing to meet the ASTM C 39 standard and making the concrete unreliable. The 4000 psi batch did not meet the 28 day compressive strength requirement, nor did it meet the COV standard as shown in Table 9.

Despite the fact that all concrete was batched in accordance with ASTM C 192, the results showed high variability and low strength in both the empirically- and volumetrically-designed batches. Possible factors that contributed to these highly varied results could have resulted from the many different technicians mixing the different empirical batches, resulting in slight variance in method and experience and ultimately causing a wide variance in results. The batch sizes were also relatively small which could have possibly made the population of samples for testing too narrow. Due to the high variability of results, it is not recommended to use this concrete and future trials with revised methods should be performed for more credible data.

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