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STUDY ON THE EFFECTS OF MIXTURE PROPORTIONING ON THE STRENGTH AND CRACKING TENDENCY OF S50 STRUCTURAL CONCRETE

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COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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16. Abstract

Based on the study presented in this report, it was determined that S50 structural concrete can be produced to meet the requirements of the CDOT Standard Specification for Road and Bridge Construction, Section 601. S50 mixes using cement as well as cement/fly ash blends can be successfully produced with the aid of proper high-range water-reducing (HRWR) admixtures. The low w/cm ratios used in this study allow the development of a high-strength structural concrete and low drying shrinkage, while retaining air content between 5% and 8% for freeze/thaw durability.

Implementation:

Production of S50 structural concrete as defined by the CDOT specifications is feasible. The five successful mixes presented here should not be considered as the only possible approach to S50 development. Instead, they should be a starting point for professional mix designers to use to develop reliable and economical mixes that meet CDOT requirements.

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Executive Summary

In December 2007, the Colorado Department of Transportation awarded the Colorado School of Mines a research grant to develop feasible mix proportioning of the S50 concrete. The CDOT Standard Specification for Road and Bridge Construction, Section 601, details the requirements of the S50 structural concrete. Among the requirements in this specification is that the S50 concrete "must not exhibit a crack at or before 14 days in the cracking tendency test (AASHTO PP 34)."

Due to the high-strength requirements of the S50 concrete, large amounts of cementitious materials are required (up to 800 lbs per cubic yard). However, replacement of cement with up to 30% of Class F or 20% of Class C fly ash by weight is acceptable. The use of fly ash may reduce the shrinkage and, therefore, the cracking tendency of concrete. Section 601 also requires the use of an approved water-reducing admixture. The use of a water reducer allows for sufficiently low water to cementitious ratio, which in turn leads to greater compressive strength and reduced drying shrinkage, although autogenous shrinkage may be a concern. The specification also requires a minimum of 55% by weight of total aggregate of AASHTO M 43 size No. 67 coarse aggregate and air content between 5 and 8 percent.

This report presents the mixture proportions of a high-strength, low-shrinkage concrete that satisfies the S50 specification. For the purposes of this study, the proportions of fine and coarse aggregate, as well as cementitious materials were kept constant, leaving the water content and high-range water-reducing (HRWR) admixtures the driving variables for the mix designs.

It was found that the use of HRWR admixtures and fly ash created workable concrete mixes that met both the strength requirements and the cracking tendency test. During the experimental program, two batches of each design were mixed, where each batch created a single ring and compressive cylinder samples. In some cases, small adjustments in water content and HRWR were made to the second batch to adjust workability. Results from the experiments performed confirmed that S50 structural concrete as described in the CDOT specifications is practically feasible.

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Introduction

Class S50 concrete is a dense high-strength structural concrete [1]. The S50 concrete must attain 28-day compressive strength of 7250 psi in the field and 8340 psi in a laboratory (115% increase compared to the field value as required by 601-specification [1]). The S50 concrete must also be resistant to cracking as evaluated by the requirement that it must not exhibit a crack at or before 14 days in a constrained shrinkage test (AASHTO PP 34). The high-strength/low-shrinkage requirements are counteracting to some extent, because to achieve high strength, large amounts of cementitious materials are typically required (615 to 800 lbs/yd^3), which unfortunately tend to increase shrinkage. Partial replacement of cement with fly ash as well as a low water to cementitious materials ratio (w/cm <0.38) are known to reduce the drying shrinkage. Unfortunately, their effects on autogenous shrinkage are not favorable.

Up to 20% replacement of Class C fly ash or 30% replacement of Class F fly ash is allowed. The performance-enhancing effects of fly ash on workability, pumpability, strength, shrinkage, and permeability have been discussed in the literature [2]. However, the effects of fly ash on shrinkage are not universally accepted. Both positive effects [3] and negative effects [4] have been reported. Cement replacement for Class S50 concrete is allowed with either Class C or Class F fly ash.

This report presents the findings of a research study on the development of five concrete mix types that satisfy the S50 concrete definition. These five mix types have the following characteristics:

Mix Type 1: 100% Cement
Mix Type 2: 80% Cement, 20% Class F fly ash
Mix Type 3: 70% Cement, 30% Class F fly ash
Mix Type 4: 90% Cement, 10% Class C fly ash
Mix Type 5: 80% Cement, 20% Class C fly ash

Each mix was developed to satisfy reasonable workability (slump test), be within an acceptable range of entrained air content (5 to 8%), develop sufficient compressive strength, and finally not crack under restrained shrinkage (ring test) where the temperature was kept between 18°C - 24°C (65°F - 75°F) and relative humidity not exceeding 40%. More than 20 different mixes were tried in a methodically improving/correcting way, which eventually resulted in the successful mixes presented here.

I. Aggregate Description

Both coarse and fine aggregates were obtained locally from a CDOT approved supplier (Ready Mixed Concrete). Whereas the supplier provided the measured water content of the aggregates, additional tests were performed at the structural laboratory of the Colorado School of Mines to verify their water content (ASTM D4959). In addition, gradation tests were performed for both fine and coarse aggregates to verify compliance with stated CDOT requirement: *When placed in a bridge deck, the concrete mix shall consist of a minimum 55 percent AASHTO M 43 size No. 67 coarse aggregate by weight of total aggregate* [1].

II. Sieve Analysis

The sieve analysis was performed for both sand and coarse aggregate. According to the ASTM standard C 136 (AASHTO M6) the sieves required for the sand are No. 4, 8, 16, 30, 50, 100, and 200. After the sieve analysis was completed, the fineness modulus (FM) was 2.77. The required sieves for the coarse aggregate are 1'', 0.75'', 0.5'', 0.3'', No. 4, and No. 8. The ASTM standard C33-03 (AASHTO M43) required 90% to 100% to pass though 0.75'', 20% to 50% at 0.375'', and 0% to 10% at No. 4 sieve. The coarse aggregate that was used all passed the ASTM standard. The detailed analysis was as followed:

Fine Aggregate, total sample weight, 1002 g. The fineness modulus was calculated as follows:

$$FM = (3.30+29.67+58.35+87.22+98.11)/100 = 2.77$$

Table 1: Sieve Analysis for Fine Aggregate

Sieve No.	Weight (g)	Cumulative Retained weight (g)	Cumulative % Retained	Cumulative Passing Weight (g)	Cumulative % Passing
4	0	0	0	1000.9	100%
8	33	33	3.30	967.9	97%
16	263	297	29.67	704.9	70%
30	287	584	58.35	417.9	42%
50	289	873	87.22	128.9	13%
100	109	982	98.11	19.9	2%
200	15.2	997.3	99.64	4.7	0.4%
Pan	4.7	1002	100		

Coarse Aggregate, total sample weight, 2001.7g.

Table 2: Sieve Analysis for Coarse Aggregate

Sieve No.	Weight (g)	Cumulative Retaining Weight (g)	Cumulative Passing weight (g)	% Passing	AASHTO M43
1"	0	0	2001.7	100%	100%
0.75"	96.9	96.9	1904.8	95%	90-100%
0.5"	817.1	914	1087.7	54%	
0.375"	614	1528	473.7	24%	20-55%
No. 4	467	1995	6.7	0.3%	0-10%
No. 8	4	1999	2.7	0.1%	0-5%
Pan	2.7	2001.7			

III. Mix Design Summary

The following section summarizes the strength and shrinkage tests of the final eight mix designs (not all of which were successful). Mix designs were identified with numerals 1 thought 20 indicating the order in which they were produced. Mixes 1 though 12 were mostly based on ACI recommendations for high strength concrete mix designs [5]. These mixes were only marginally successful in approaching the required performance, and are not listed here. Nevertheless, they were used as a starting point and were gradually adjusted to produce mixes 13 through 20 which are listed here as mixes that succeeded or *almost* succeeded in producing the required quality. With the exception of Mix 14, all mix designs were tested using two batches, in order to have sufficient material for two ring tests and an adequate number of compressive cylinders. Note that the water contribution of the fine aggregate and the HRWR is included within the water given in the proportion tables. For example, in Table 3, the total water in the mix is 216 lbs, where 34.9 lbs of water was contributed by the fine aggregate, 5.5 lbs from the HRWR and 175.6 lbs of free water was added. It is also noted, that when time and space allowed, the rings stayed in their drying environment for more than 14 days to see if failure could be achieved within a reasonable (available) time. We found it necessary to include the water contribution of the HRWR, because there exist HRWR agents that are mostly water, and others that have very little water. It may be misleading to any designer if this is excluded. The HRWR used in this study (Glenium 3030) is 80% water, which contributes between 2% and 5% of the total water.

Mix 13 (Did not satisfy requirements)

Mix 13 was proportioned with 30% replacement of Type F Fly Ash. This was a very workable mix with a high slump. The first batch, 13A, had a slump of almost 8 inches. The second batch, 13B, was slightly adjusted in HRWR and water to reduce the slump without significant change in workability. Both batches of Mix 13 satisfied the 14-day shrinkage test, but neither batch was able to achieve the required 28-day compressive strength. **Thus, mix 13 was rejected.**

Table 3: Mix 13 (30% FA-F) Batch Design (1 yd^3)

Mix 13A – Proportions	Lbs/cy	Water Contribution
Type I/II Cement	560	
Class F Fly Ash	240	
3/4" Aggregate	1789	0.0
Fine Aggregate	1162	34.9
Total Water	216	
Admixtures	**mL/cy**	
Glenium 3030	3086	5.5
Micro Air (AE 90)	49.0	
w/cem =	**0.27**	
Air =	**6.6**	
Slump =	**7.9 in**	

Mix 13B – Proportions	lbs/cy	Water Contribution
Type I/II Cement	560	
Class F Fly Ash	240	
¾" Aggregate	1789	0.0
Fine Aggregate	1162	34.9
Total Water	216	
Admixtures	**mL/cy**	
Glenium 3030	2604	4.7
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**6.4**	
Slump =	**4.3 in**	

Table 4: Mix 13 (30% FA-F) Strength Results

Mix 13 A/B							
Time of Break	Sample #	Strength (psi)	Avg. Strength (psi)	Std. Dev. (psi)	Strength (MPa)	Avg. Strength (MPa)	Std. Dev. (MPa)
7 days	Mix 13A-1	5976.5	**5769.2**	**412.6**	42.1	**40.5**	**3.3**
	Mix 13A-2	5974.8			42.1		
	Mix 13A-3	5975.2			42.1		
	Mix 13A-4	5150.3			35.5		
	Mix 13B-1	6487.7	**5864.7**	**1045.7**	44.7	**40.4**	**7.2**
	Mix 13B-2	4991.8			34.4		
	Mix 13B-3	4965.1			34.2		
	Mix 13B-4	7014			48.4		
28 days	Mix 13A-5	7363	**7023.8**	**347.2**	50.8	**48.4**	**2.4**
	Mix 13A-6	6715			46.3		
	Mix 13A-7	7283			50.2		
	Mix 13A-8	6734			46.4		
	Mix 13B-5	7062	**7147.0**	**120.2**	48.7	**49.3**	**0.8**
	Mix 13B-6	7232			49.9		
Rings did not crack before 14 days							

Mix 14 (Did not satisfy requirements)

Mix 14 was proportioned with 20% replacement of Type F Fly Ash. Only one batch of this mix design was made due to procedural changes attempting to create two rings from a single batch. The mix did not have desirable workability and had a low slump. The mix did pass the 14-day shrinkage test, and was not able to pass the 28-day compressive strength test. **Thus, mix 14 was rejected.**

Table 5: Mix 14 (20% FA-F) Batch Design (1 yd^3)

Mix 14 – Proportions	Lbs/cy	Water Contribution
Type I/II Cement	640	
Class F Fly Ash	160	
¾" Aggregate	1789	0.0
Fine Aggregate	1182	35.5
Total Water	216	
Admixtures	**mL/cy**	
Glenium 3030	3086	5.5
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**4.5**	
Slump =	**2.0 in**	

Table 6: Mix 14 (20% FA-F) Strength Results

Mix 14							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 14-1	5256	**5574**	258.9	36.2	**38.4**	1.8
	Mix 14-R1	5890			40.6		
	Mix 14-R2	5568			38.4		
	Mix 14-R3	5582			38.5		
28 days	Mix 14-11	8132	**8200**	62.6	56.1	**56.6**	0.4
	Mix 14-18	8165			56.3		
	Mix 14-19	8232			56.8		
	Mix 14-20	8270			57.0		
Rings did not crack before 14 days							

Mix 15 (Satisfied requirements)

Mix 15 was proportioned with 20% replacement of Type C Fly Ash. This was the first mix in which we used Type C Fly Ash. Two batches were made for Mix 15. Mix 15A had a low slump and was not very workable. For the second batch, 15B, an adjustment in the amount of HRWR resulted in sufficient workability. Each of the Mix 15 batches satisfied the shrinkage and the 28-day compressive strength test requirements. **Thus, mix 15 is considered successful.**

Table 7: Mix 15 (20% FA-C) Batch Design (1 yd^3)

Mix 15A - Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class C Fly Ash	160	
3/4" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	222	
Admixtures	**mL/cy**	
Glenium 3030	3085	5.5
Micro Air (AE 90)	46.3	
w/cem =	**0.28**	
Air =	**4.9**	
Slump =	**1.25 in**	

Mix 15B - Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class C Fly Ash	160	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	218	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**7.9**	
Slump =	**7.0 in**	

Table 8: Mix 15 (20% FA-C) Strength Results

Mix 15 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 Days	Mix 15A-1	5761	**6551.3**	1053.0	39.7	**45.2**	7.3
	Mix 15A-2	8006			55.2		
	Mix 15A-3	6646			45.8		
	Mix 15A-R1	5792			39.9		
	Mix 15B-1	5021	**6371.5**	1187.0	34.6	**44.0**	8.2
	Mix 15B-2	7002			48.3		
	Mix 15B-3	5797			40.0		
	Mix 15B-4	7666			52.9		
28 days	Mix 15A-4	9916	**9118.5**	1414.2	68.4	**62.9**	9.7
	Mix 15A-5	9692			66.8		
	Mix 15A-6	7002			48.3		
	Mix 15A-R2	9864			68.0		
	Mix 15B-5	9253	**9633.0**	603.9	63.8	**66.4**	4.2
	Mix 15B-6	9058			62.5		
	Mix 15B-7	10396			71.7		
	Mix 15B-8	9825			67.7		
Rings did not crack before 14 days. After 14 days the specimens were removed without achieving crack.							

Mix 16 (Satisfied requirements)

Mix 16 was proportioned with 10% replacement of Type C Fly Ash. Mix 15A, the first batch using Class C fly ash, had a low slump, and was not very workable. A minor adjustment in HRWR was sufficient to improve the workability (expressed by the slump). For Mix 16, the HRWR was increased, compared to Mix 15, to account for the lower replacement of fly ash. Both strength and shrinkage requirements were met for Mix 16. **Thus, mix 16 is considered successful.**

Table 9: Mix 16 (10% FA-C) Batch Design (1 yd^3)

Mix 16A – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	720	
Class C Fly Ash	80	
3/4" Aggregate	1789	0.0
Fine Aggregate	1202	36.1
Total Water	218	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	48.2	
w/cem =	**0.27**	
Air =	**7.0**	
Slump =	**2.5 in**	

Mix 16B –Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	720	
Class C Fly Ash	80	
¾" Aggregate	1789	0.0
Fine Aggregate	1202	36.1
Total Water	220	
Admixtures	**mL/cy**	
Glenium 3030	5014	9.0
Micro Air (AE 90)	44.4	
w/cem =	**0.28**	
Air =	**6.6**	
Slump =	**4.0 in**	

Table 10: Mix 16 (10% FA-C) Strength Results

Mix 16 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 16A-1	8502	**8169.5**	**506.3**	58.6	**56.3**	**3.5**
	Mix 16A-2	7415			51.1		
	Mix 16A-3	8379			57.8		
	Mix 16A-4	8382			57.8		
	Mix 16B-1	6685	**7416.5**	**873.2**	46.1	**51.2**	**6.0**
	Mix 16B-2	6652			45.9		
	Mix 16B-3	8008			55.2		
	Mix 16B-4	8321			57.4		
28 days	Mix 16A-5	10444	**10051.3**	**580.4**	72.0	**69.3**	**4.0**
	Mix 16A-6	10574			72.9		
	Mix 16A-7	9307			64.2		
	Mix 16A-8	9880			68.1		
	Mix 16B-5	9118	**9664.3**	**414.7**	62.9	**66.6**	**2.8**
	Mix 16B-6	9942			68.5		
	Mix 16B-7	9570			66.0		
	Mix 16B-8	10027			69.1		
Rings did not crack before 14 days. After 14 days the specimens were removed without achieving crack.							

Mix 17 (Did not satisfy requirements)

Mix 17 was proportioned with 20% replacement of Class C Fly Ash. Two batches of Mix 17 were made, and no adjustments were made between batches. Mix 17B was less workable than Mix 17A despite identical proportioning of the materials. One of the two rings cracked at 9 days, and thus the test is considered a failure. A technical difficulty forced us to remove these outer ring-molds at 16 hours rather than 24 hours as is required by the AASHTO specification. It is believed that this may have influenced adversely the capacity of the ring to resist cracking. The test is considered a failure, and as a result, the 28 day compressive strength tests were not performed. **Thus, mix 17 was rejected.**

Table 11: Mix 17 (20% FA-C) Batch Design (1 yd^3)

Mix 17A – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class C Fly Ash	160	
3/4" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	208	
Admixtures	**mL/cy**	
Glenium 3030	4435	8.0
Micro Air (AE 90)	44.3	
w/cem =	**0.26**	
Air =	**7.2**	
Slump =	**4.75 in**	

Mix 17B – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class C Fly Ash	160	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	208	
Admixtures	**mL/cy**	
Glenium 3030	4435	8.0
Micro Air (AE 90)	44.4	
w/cem	**0.26**	
Air	**5.5**	
Slump	**2.50 in**	

Table 12: Mix 17 (20% FA-C) Strength Results

Mix 17 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 17A-1	8041	**7756.5**	1107.0	55.4	**53.5**	7.6
	Mix 17A-2	6360			43.9		
	Mix 17A-3	9029			62.3		
	Mix 17A-4	7596			52.4		
	Mix 17B-1	7686	**8106.5**	413.7	53	**55.9**	2.8
	Mix 17B-2	8647			59.6		
	Mix 17B-3	8183			56.4		
	Mix 17B-4	7910			54.5		
28 days	Mix 17A-5	N/A	**N/A**	N/A	N/A	**N/A**	N/A
	Mix 17A-6	N/A			N/A		
	Mix 17A-7	N/A			N/A		
	Mix 17A-8	N/A			N/A		
	Mix 17B-5	N/A	**N/A**	N/A	N/A	**N/A**	N/A
	Mix 17B-6	N/A			N/A		
	Mix 17B-7	N/A			N/A		
	Mix 17B-8	N/A			N/A		
Outer Rings removed after 16 hours of curing							
*** Ring 17B cracked after 9 days** *****Ring 17A did not crack before 14 days, and then was removed for further testing, as we considered failure if any of the two rings cracked before 14 days.							

Mix 18 (Satisfied requirements)

Mix 18 was proportioned without fly ash. As expected, the lack of the lubricating action of the fly-ash spheres resulted in an increased demand of HRWR for the mix to achieve sufficient workability for the formation of the first batch. Small adjustments in water (increase) and HRWR (decrease) were attempted successfully in the second batch. Not surprising, this *all-cement* mix produced a 7-day strength that approached 90% of the required 28-day strength. **Mix 18 is considered successful.**

Table 13: Mix 18 (Only Cement) Batch Design (1 yd^3)

Mix 18A – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	800	
Class F Fly Ash	0	
3/4" Aggregate	1789	0.0
Fine Aggregate	1222	36.7
Total Water	219	
Admixtures	**mL/cy**	
Glenium 3030	5979	10.7
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**5.4**	
Slump =	**2.4 in**	

Mix 18B – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	800	
Class F Fly Ash	0	
¾" Aggregate	1789	0.0
Fine Aggregate	1222	36.7
Total Water	235	
Admixtures	**mL/cy**	
Glenium 3030	4436	8.0
Micro Air (AE 90)	44.4	
w/cem =	**0.29**	
Air =	**4.8**	
Slump =	**1.125 in**	

Table 14: Mix 18 (Only Cement) Design & Strength Results

Mix 18 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 18A-1	8568	**8321.3**	977.6	59.1	**57.4**	6.7
	Mix 18A-2	7956			54.9		
	Mix 18A-3	7226			49.8		
	Mix 18A-4	9535			65.7		
	Mix 18B-1	8196	**7550.0**	723.3	56.5	**52.1**	5.0
	Mix 18B-2	6783			46.8		
	Mix 18B-3	8138			56.1		
	Mix 18B-4	7083			48.8		
28 days	Mix 18A-5	10777	**10492.8**	325.1	74.3	**72.3**	2.2
	Mix 18A-6	10521			72.5		
	Mix 18A-7	10642			73.4		
	Mix 18A-8	10031			69.2		
	Mix 18B-5	8960	**9662.5**	515.4	61.8	**66.6**	3.6
	Mix 18B-6	9775			67.4		
	Mix 18B-7	9716			67.0		
	Mix 18B-8	10199			70.3		
Rings did not crack before 14 days. After 14 days, the specimens were removed without achieving crack.							

Mix 19 (Satisfied requirements)

Mix 19 was proportioned with 30% replacement of Class F Fly Ash. The main difference between Mix 19 and Mix 13 is an increase in HRWR, accompanied by a decrease in water content with the intent of increasing the compressive strength. Note that the increase in compressive strength did not affect the results of the ring tests. **Mix 19 is considered successful.**

Table 15: Mix 19 (30% FA-F) Batch Design (1 yd^3)

Mix 19A – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	559	
Class F Fly Ash	240	
3/4" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	233	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.3	
w/cem =	**0.29**	
Air =	**6.5**	
Slump =	**7.25 in**	

Mix 19B - Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	559	
Class F Fly Ash	240	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Total Water	216	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**6.8**	
Slump =	**7.00 in**	

Table 16: Mix 19 (30% FA-F) Design & Strength Results

Mix 19 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 19A-1	4763	**5752.0**	**995.5**	32.8	**39.7**	**6.9**
	Mix 19A-2	6942			47.9		
	Mix 19A-3	6180			42.6		
	Mix 19A-4	5123			35.3		
	Mix 19B-1	6553	**6456.3**	**802.5**	45.2	**44.5**	**5.5**
	Mix 19B-2	6758			46.6		
	Mix 19B-3	7193			49.6		
	Mix 19B-4	5321			36.7		
28 days	Mix 19A-5	10070	**9874.0**	**401.4**	69.4	**68.1**	**2.8**
	Mix 19A-6	9274			63.9		
	Mix 19A-7	10035			69.2		
	Mix 19A-8	10117			69.8		
	Mix 19B-5	8508	**8939.8**	**481.9**	58.7	**61.6**	**3.3**
	Mix 19B-6	8864			61.1		
	Mix 19B-7	8760			60.4		
	Mix 19B-8	9627			66.4		
Ring 19A did not crack after 21 days.							
Ring 19B cracked after 16 days.							

Mix 20 (Satisfied requirements)

Mix 20 was proportioned with 20% replacement of Class F Fly Ash. The recipe is similar to mix 14, with exception of the water quantity. **Mix 20 is considered successful.**

Table 17: Mix 20 (20% FA-F) Batch Design (1 yd^3)

Mix 20A – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class F Fly Ash	160	
3/4" Aggregate	1789	89.5
Fine Aggregate	1182	35.5
Total Water	202	70.3
Admixtures	**mL/cy**	
Glenium 3030	3857	6.9
Micro Air (AE 90)	48.2	
w/cem =	**0.25**	
Air =	**5.6**	
Slump =	**2.75 in**	

Mix 20B – Proportions	**lbs/cy**	**Water Contribution**
Type I/II Cement	640	
Class F Fly Ash	160	
¾" Aggregate	1789	89.5
Fine Aggregate	1182	35.5
Total Water	202	69.9
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.25**	
Air =	**5.0**	
Slump =	**1.375 in**	

Table 18: Mix 20 (20% FA-F) Design & Strength Results

Mix 20 A/B							
Time of Break	**Sample #**	**Strength (psi)**	**Avg. Strength (psi)**	**Std. Dev. (psi)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Std. Dev. (MPa)**
7 days	Mix 20A-1	5469	**6769.5**	**1074.9**	37.7	**47.5**	**8.1**
	Mix 20A-2	6378			44.0		
	Mix 20A-3	7924			54.6		
	Mix 20A-4	7307			53.8		
	Mix 20B-1	7658	**7651.5**	**574.7**	52.8	**52.8**	**4.0**
	Mix 20B-2	7770			53.6		
	Mix 20B-3	8285			57.1		
	Mix 20B-4	6893			47.5		
28 days	Mix 20A-5	9239	**9749.5**	**375.1**	63.7	**67.2**	**2.6**
	Mix 20A-6	10018			69.1		
	Mix 20A-7	9697			66.9		
	Mix 20A-8	10044			69.3		
	Mix 20B-5	10614	**10337.0**	**346.2**	73.2	**71.3**	**2.4**
	Mix 20B-6	10318			71.1		
	Mix 20B-7	9855			68.0		
	Mix 20B-8	10561			72.8		
Ring 20A did not crack after 20 days.							
Ring 20B cracked after 15 days.							

A GENERNAL NOTE ON THE RING TESTS

Strain versus age for the ring tests was impossible to record, given the time constraints of this project. A pair of rings requires eight simultaneous strain gage recordings. At least 20 mixes were examined during the course of this research study, where typically two different mixes were created per week. This means that at any time, there were eight rings in our temperature and humidity control room. Such testing requires thirty two simultaneous strain gage recordings. Unfortunately, such requirement could not be met by the available hardware in our laboratory, and the cost of expanding our capabilities to this level was prohibitive for the available project budget. As a result, a very detailed visible inspection performed by at least two separate inspectors (in most cases more) was used to detect if a crack was developed.

SUMMARY OF SUCCESSFUL MIXES

Batch Design for S50 concrete with no fly ash (1 yd^3)

Mix A – Proportions	lbs/cy	Water Contribution
Type I/II Cement	800	
Class F Fly Ash	0	
¾" Aggregate	1789	0.0
Fine Aggregate	1222	36.7
Water	219	
Admixtures	**mL/cy**	
Glenium 3030	5979	10.7
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**5.4**	
Slump =	**2.4 in**	

Mix B – Proportions	lbs/cy	Water Contribution
Type I/II Cement	800	
Class F Fly Ash	0	
¾" Aggregate	1789	0.0
Fine Aggregate	1222	36.7
Water	235	
Admixtures	**mL/cy**	
Glenium 3030	4436	8.0
Micro Air (AE 90)	44.4	
w/cem =	**0.29**	
Air =	**4.8**	
Slump =	**1.125 in**	

Batch Design for S50 concrete with 10% Fly Ash type C replacement (1 yd^3)

Mix A – Proportions	lbs/cy	Water Contribution
Type I/II Cement	720	
Class C Fly Ash	80	
¾" Aggregate	1789	0.0
Fine Aggregate	1202	36.1
Water	218	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	48.2	
w/cem =	**0.27**	
Air =	**7.0**	
Slump =	**2.5 in**	

Mix B –Proportions	lbs/cy	Water Contribution
Type I/II Cement	720	
Class C Fly Ash	80	
¾" Aggregate	1789	0.0
Fine Aggregate	1202	36.1
Water	220	
Admixtures	**mL/cy**	
Glenium 3030	5014	9.0
Micro Air (AE 90)	44.4	
w/cem =	**0.28**	
Air =	**6.6**	
Slump =	**4.0 in**	

Batch Design for S50 concrete with 20% Fly Ash type C replacement (1 yd^3)

Mix A - Proportions	lbs/cy	Water Contribution
Type I/II Cement	640	
Class C Fly Ash	160	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Water	222	
Admixtures	**mL/cy**	
Glenium 3030	3085	5.5
Micro Air (AE 90)	46.3	
w/cem =	**0.28**	
Air =	**4.9**	
Slump =	**1.25 in**	

Mix B - Proportions	lbs/cy	Water Contribution
Type I/II Cement	640	
Class C Fly Ash	160	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Water	218	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**7.9**	
Slump =	**7.0 in**	

Batch Design for S50 Concrete with 20% Fly Ash type F replacement (1 yd^3)

Mix A - Proportions	lbs/cy	Water Contribution
Type I/II Cement	640	
Class F Fly Ash	160	
¾" Aggregate	1789	89.5
Fine Aggregate	1182	35.5
Water	202	70.3
Admixtures	**mL/cy**	
Glenium 3030	3857	6.9
Micro Air (AE 90)	48.2	
w/cem =	**0.25**	
Air =	**5.6**	
Slump =	**2.75 in**	

Mix B – Proportions	lbs/cy	Water Contribution
Type I/II Cement	640	
Class F Fly Ash	160	
¾" Aggregate	1789	89.5
Fine Aggregate	1182	35.5
Water	202	69.9
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.25**	
Air =	**5.0**	
Slump =	**1.375 in**	

Batch Design for S50 Concrete with 30% Fly Ash type F replacement (1 yd^3)

Mix A - Proportions	lbs/cy	Water Contribution
Type I/II Cement	559	
Class F Fly Ash	240	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Water	233	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.3	
w/cem =	**0.29**	
Air =	**6.5**	
Slump =	**7.25 in**	

Mix B – Proportions	lbs/cy	Water Contribution
Type I/II Cement	559	
Class F Fly Ash	240	
¾" Aggregate	1790	0.0
Fine Aggregate	1182	35.5
Water	216	
Admixtures	**mL/cy**	
Glenium 3030	4050	7.3
Micro Air (AE 90)	44.4	
w/cem =	**0.27**	
Air =	**6.8**	
Slump =	**7.00 in**	

IV. Conclusions and Recommendations

Based on the study presented in this report, it was determined that S50 structural concrete can be produced to meet the requirements of the CDOT Standard Specification for Road and Bridge Construction, Section 601. S50 mixes using cement as well as cement/fly ash blends can be successfully produced with the aid of proper HRWR admixtures. The low w/cm ratios used in this study allow the development of a high-strength structural concrete and low drying shrinkage, while retaining air content between 5% and 8% for freeze/thaw durability.

It was also found here that mixes with higher quantities of fly ash (cement replacement) can produce workable mixes with lower amounts of HRWR admixtures. This is attributed to the lubricating nature of fly ash. It should be pointed out however, that the increased amounts of fly ash as a concrete replacement also result in lower early strength. These are significant points to consider when economy of mix design and needs for early strength is considered.

References

[1] Colorado Department of Transportation (2006), *Revision of Sections 601 And 701 Structural Concrete*, October 19, 2006.

[2] A. M. Neville (1996), *Properties of Concrete,* Fourth Edition, John Wiley and Sons Inc., p. 844.

[3] P. J. Tikalsky, P. M. Carrasquillo, and R. L. Carrasquillo, (1988), "Strength and Ductility Considerations Affecting Mix Proportioning of Concrete Containing Fly Ash," ACI Materials Journal, Vol. 49, No. 6, pp. 505-511.

[4]. J. J. Brooks, and A. Neville, (1992), "Creep and Shrinkage of Concrete as affected by Admixtures and Cement Replacement Materials," *Creep and Shrinkage of Concrete: Effect of Materials and Environment,* ACI SP-135, pp. 19-36.

[5] ACI 211.4R-93 Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash.