DEVELOPMENT OF HIGH STRENGTH LIGHTWEIGHT CONCRETE MIX DESIGNS: A PRACTICAL APPROACH

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ABSTRACT

This paper describes a practical approach for developing high strength lightweight concrete (HSLC) mix designs. As part of a research project at Georgia Tech examining the use of HSLC for prestressed highway girders, it was necessary to develop concrete mix designs using slate lightweight aggregate able to achieve design strengths of 8,000 and 10,000 psi (55.2 and 69.0 MPa) with an equilibrium unit weight of approximately 120 pcf (1922 kg/m^3) or less. A methodical approach to proportioning mix components proved effective in determining mix designs. Field testing was conducted to verify the mix designs for use in a production environment. An extensive material testing program produced a database of material properties. Challenges with controlling entrained air, lightweight aggregate moisture content, low water to cementitious materials ratios, and an apparent strength ceiling for slate HSLC are discussed.

Keywords: Mix Design, High Strength Lightweight Concrete, Slate Lightweight Aggregate, Prestressed Concrete, HPC, Lightweight Concrete.

INTRODUCTION

Advances in concrete quality and engineering practices have enabled the design and construction of precast prestressed concrete bridge girders that approach 200 feet in length. Problems occur when trying to move and erect these long and heavy girders. In order to facilitate easier road movement and erection, high-strength lightweight concrete (HSLC) can be used to reduce member self-weight while still allowing a large load carrying capacity[1].

A research project was conducted at the Georgia Institute of Technology that examined the use of HSLC for prestressed highway girders. One goal of the project was the development of HSLC mix designs using slate lightweight aggregate achieving 28-day design compressive strengths (f_c') of 8,000 and 10,000 psi (55.2 and 69.0 MPa) and having equilibrium unit weights less than approximately 120 pcf (1922 kg/m^3). In addition to development of mix designs in the laboratory, field verification at a prestressed concrete plant was performed to ensure that commercial production of the mix designs was feasible.

This paper presents a methodical approach for proportioning HSLC mix designs, a discussion of some of the challenges faced in producing high quality HSLC, and a review of the results of extensive mechanical property testing on both laboratory and field-produced slate HSLC specimens.

EXPERIMENTAL PROGRAM

OVERVIEW

The experimental program was designed to optimize mix variables of the HSLC. The program involved a laboratory phase during which optimum mix designs were developed and a field phase during which batching at a local prestressed concrete manufacturer was accomplished to study the feasibility of producing HSLC in a commercial environment. During the laboratory phase, variables considered were the maximum coarse aggregate size, ratio of coarse to fine aggregate, percent cement paste, percent cement replacement by mineral admixtures, chemical admixtures, and water/cementitious materials (w/cm) ratio. By studying these variables, trends were identified and used in configuring the recommended optimum mix designs. As a constraint during the laboratory phase, no procedures were followed that could not be reproduced during field production. Both ASTM and accelerated curing methods were used to determine the effect on concrete mechanical properties. Accelerated curing modeled curing temperatures found in precast prestressed highway girder production.

MATERIALS

Coarse Aggregate

In order to produce HSLC able to reach compressive strengths in excess of 10,000 psi (69.0 MPa), slate lightweight aggregate (LWA) from North Carolina was selected based on its strength relative to other LWA, moisture absorption characteristics, and ease of availability. The $^{1}/_{2}$-in and $^{3}/_{8}$-in (13-mm and 10-mm) slate LWA used during the study had oven dry specific gravity values of 1.44 and 1.52, respectively. Both aggregate sizes absorbed 6 percent moisture by weight from an oven dry state after soaking for 24 hours and had maximum absorption values of about 10 percent.

Fine Aggregate

After preliminary testing, initial attempts to use lightweight fine aggregate was discontinued due to problems with moisture control and workability in achieving very high strengths.. Natural normal weight fine aggregate (NWA) with a fineness modulus of 2.36 and an average specific gravity of 2.62 was used for the fine aggregate. The sand was approved for structural concrete use by the Georgia Department of Transportation; it met DOT specifications but did not meet ASTM Specification C33.[2]

Portland Cement

The portland cement used during the both the laboratory and field phases was Type III cement. Type III was chosen over the Type I for its superior early strength gain. The higher C_3A and C_3S contents in Type III as compared to Type I allowed the HSLC to achieve higher early strength gain, something beneficial for the production of precast prestressed concrete bridge girders. The Type III portland cement had a specific gravity of 3.08.

Mineral Admixtures

Silica fume and Class F fly ash were used in this research to improve concrete quality, durability, workability, and economy. The silica fume had a specific gravity of 2.20 and was included in mix designs in amounts from 4 to 12 percent of total cementitious materials by weight. The Class F fly ash had a specific gravity of 2.28 and was included in mix designs as 15 percent of cementitious materials by weight. The fly ash satisfied the requirements of ASTM C 618.[3]

Chemical Admixtures

To improve workability and durability, and to meet entrained air requirements, a high-range water reducer (HRWR), low-range water reducer (LRWR), and air entraining admixture (AEA) were incorporated in the mix designs. The LRWR was important in slowing the cement hydration while the HRWR helped to increase workability. Workability was a significant concern considering that the HSLC mixes generally had w/cm ratios less than 0.32. The use of AEA helped achieve a target 4 percent air content.

MOISTURE CONTROL

Control of moisture and accurate determination of moisture content were two of the most important steps involved in making high quality HSLC. Inadequate absorbed moisture in the LWA could result in the absorption of mix water thus reducing workability and changing the w/cm ratio. Excess adsorbed water that was not properly accounted for in the mix design also impacted the mix by affecting the aggregate proportioning and the w/cm ratio.

Figures 1 and 2 show aggregate storage hoppers and misting devices installed at the top of the hoppers, respectively. The misting devices were run continuously until the aggregate had adequate absorbed moisture. Adequate absorbed moisture was 6 percent based on a recommendation from the LWA manufacturer; anything below 6 percent was unacceptable for HSLC production. The misting devices were constructed with nozzles having an output of approximately 3 gallons per hour thus minimizing the water flow through the aggregate and preventing segregation of fine particles from occurring. To reduce the gradient of free moisture inside the hoppers, the water was turned off 24 hours prior to concrete mixing.

Figure 1. Aggregate Hoppers and Cement / Admixture Proportioning Station

Prior to mixing HSLC, a representative sample was taken from the aggregate hopper. Moisture contents in the “as-is” and “saturated surface dry (SSD)” condition were determined by cooking the LWA over hotplates at a medium heat for approximately 1 hour or until all moisture had been removed. Moisture content checks were also performed on the normal weight sand whenever a mix was made.

Figure 2. Misting Device Installed Over Aggregate Hoppers

MIXING

HSLC mixing was accomplished with a 1.75 cubic foot (0.05 cu. M) capacity pan mixer having a shearing type mix action. Some trial mixes were also made in a 4 cubic foot (0.11 cu m) rotary mixer; the resulting mixes were of poor quality. Cylinder strengths from specimens made with the rotary mixer were significantly lower than identical mixes made using the shearing action mixer.

Components were added and mixing was accomplished in the following order:

1. Coarse Aggregate (LWA)
2. Fine Aggregate (NWA)
3. Approximately 2/3 of mix water combined with Low Range Water Reducer (LRWR)
4. Air Entraining Admixture (AEA)
5. High Range Water Reducer (HRWR)
6. 30 seconds of mix effort
7. Type III Portland Cement
8. Class F Fly Ash
9. Remaining mix water and LRWR
10. Silica Fume
11. 2-3 minutes of mix effort
12. Additional HRWR to achieve the desired workability

The same component addition sequence was used for lab and field mixing with good success. The field mixing also used a pan type mixer.

PLASTIC CONCRETE PROPERTIES, SPECIMENS, CURING, AND TESTING

After batching the HSLC, four properties of the concrete were tested. The slump was measured using a standard slump cone per ASTM C 143.[4] The unit weight was measured with a 1/4 cubic foot bucket per ASTM C 138.[5] The temperature of the concrete was measured using ASTM C 1064.[6] The air content was measured with a roll-a-meter per ASTM C 173.[7]

Specimens were made per ASTM C 31.[8] Cylinders size 4 inches x 8 inches (4 x 8) (102 x 204 mm) were cast for determining compressive strength per ASTM C 39.[9] Cylinders size 6 inches x 12 inches (6 x 12) (152 x 305 mm) were cast for determining modulus of elasticity per ASTM C 469.[10] Beams size 4 inches x 4 inches x 14 inches (4 x 4 x 14) (102 x 102 x 356 mm) were cast to perform the modulus of rupture test per ASTM C 78.[11]

Specimens were initially cured either on site or in the lab as per ASTM C 31, or were placed in a curebox to retain the heat of hydration. Accelerated curing using a curebox (Figure 3) was not covered by any ASTM specification, but had been shown to closely replicate girder curing conditions in previous research.[12] After 24 hours, all specimens were removed from molds and placed in a fog room for curing until the time of testing. The fog room maintained 100 percent humidity and a temperature of approximately 73 degrees Fahrenheit. Moduli of rupture specimens were cured in a lime bath in the fog room until the time of testing.

Specimen testing was performed at specified times depending on the type of mix and phase of the research project. Compressive strength testing was performed according to ASTM C 39[9] using hard rubber caps seated in steel end caps according to ASTM 1231.[13] Modulus of elasticity testing was performed according to ASTM C 469[10] using 6 x 12 cylinders and hard rubber end caps. Modulus of rupture was determined in accordance with ASTM C78[11] using 4 x 4 x 14 beams tested using third-point loading.

DEVELOPMENT OF HSLC MIX DESIGNS

The goal of this laboratory development phase was to configure HSLC mix designs that would achieve 8,000 10,000 and 12,000 psi (55.2, 69.0 and 82.8 MPa) design compressive strengths at 28 days; the target mean compressive strengths were 1,400 psi (9.6 MPa) greater than the design strengths. A mix design spreadsheet was created to determine mix design characteristics.

Figure 3. Insulated Curebox

SPECIMEN AND CURING PLAN

The interest initially was to configure mix designs to achieve the objective strengths. Thus, 9 each 4 x 8 cylinders were cast from each mix and cured initially in cureboxes. After 24 hours in the curebox, 3 of the 9 cylinders were tested for compressive strength; the remaining 6 were placed in the fog room to continue curing for strength testing at 3 and 28 days.

INITIAL MIX DESIGNS

The starting points for the three objective HSLC mix design strengths were suggested mix designs received from the lightweight aggregate supplier and shown in Table 1.

Table 1. Initial HSLC Mix Designs from LWA Supplier

Concrete Components to Produce 1 Cubic Yard of HSLC		Concrete Strength (psi)		
		8,000	10,000	12,000
1/2-inch LWA	(lbs)	950	950	950
Normal Weight Fine Aggregate (lbs)		1221	1063	905
Class F Fly Ash	(lbs)	200	200	200
Silica Fume	(lbs)	35	45	56
Cement	(lbs)	500	650	800
Water	(gals)	32	33	34
Air Content	(percent)	4	4	4
Water/Cementitious Materials Ratio	(w/cm)	0.36	0.31	0.27
Theoretical Equilibrium Unit Weight	(pcf)	117.5	117.9	118.3

The coarse aggregate used in all initial mixes was $^1/_2$-inch (13-mm) slate LWA. Dosing on chemical admixtures was not initially specified. Literature from the admixture supplier and guidance from the local sales representative served as starting points.

PLAN FOR MIX DEVELOPMENT

In order to determine optimum HSLC mix designs to meet the objective strengths, it was first necessary to set several parameters. W/CM ratios were set based on the initial mix designs listed in Table 1. The percent Class F fly ash by total weight of cementitious materials was set at 15 percent as a measure to reduce cost, and improve the concrete's characteristics. The percent cement paste that includes all components in the mix except aggregate was set at approximately 39 percent. The following steps were followed:

1. Holding the above parameters steady, vary the ratio of coarse LWA to fine NWA (by volume) over a wide range from approximately 1 to 2. Determine if an optimum coarse to fine aggregate ratio exists in that range.
2. Using the result of Step 1 and holding all other parameters steady, vary the percent cement paste in the mix from approximately 33 percent to 45 percent. Determine if an optimum percent cement paste exists in that range.
3. Using the result of Steps 1 and 2 and holding all other parameters steady, vary the percent of silica fume in the mix from approximately 4 to 12 percent of the total cementitious materials by weight. Determine if an optimum percent silica fume exists in that range.
4. Using the results of Steps 1 – 3 (if possible), test the apparent optimum mix design with different size aggregates to determine the effect.

OVERVIEW OF MIX DEVELOPMENT FOR 12,000 PSI (82.8 MPA) OBJECTIVE STRENGTH

The following sequence describes mix development to meet an objective strength of 12,000 psi (82.8 MPa). Based on that objective strength, a w/cm ratio of 0.23 was selected for mix proportioning, slightly lower than that recommended by the LWA supplier. Similar procedures were used for determining mix designs for the 8,000 and 10,000 psi (55.2 and 69.0 MPa) objective strengths.

Initial Mixes and Air Content

During the execution of Step 1, the manufacturer suggested dose rates for chemical admixtures were followed. The first major problem encountered involved excessive air content. It became apparent that the air-entraining agent was enhanced by the use of the high-range water reducing admixture. In some cases, the resulting air contents approached 10 percent.

A study was conducted to determine specific details about the source of the air, and whether it was entrapped or entrained air. The study involved making three batches of concrete as described in Table 2. The 8,000 psi (55.2 MPa) suggested mix design from Table 1 was used for the test mixes.

Table 2. Air Content Study

Type of Coarse Aggregate	Admixtures Used	Resulting Percent Air Content
Normal Weight (Granite)	HRWR and LRWR	2.0
1/2-inch slate LWA	HRWR and LRWR	2.0
1/2-inch slate LWA	No Admixtures	2.0

The resulting air contents shown in Table 2 indicated that neither the use of LWA nor the use of HRWR and LRWR had an impact on air content. Since the air content was the same for each mix, it was apparent that the mix most likely had 2 percent “entrapped” air. Future mixes were dosed with only 0.75 to 1.0 fluid ounces (6 to 8 ml) of the AEA per 100 weight (45.4 kg) of cementitious materials. Since the HRWR enhanced the effectiveness of the AEA, less AEA was required at higher HRWR dose rates. Based on manufacturer literature, 0.75 fluid ounces per 100 weight (6 ml per 45.4 kg) of cementitious material was the lowest recommended AEA dose rate.

Variation of Coarse to Fine Aggregate Ratio – Step 1

The parameters in Table 3 were held constant throughout all mixes in Step 1:

Table 3. Parameters Held Constant in Step 1

Water / Cementitious Materials Ratio	0.23
Percent Cement Paste	39
Fly Ash as Percent of Total Cementitious Materials by Weight	15
Silica Fume as Percent of Total Cementitious Materials by Weight	8
Type III Cement as Percent of Total Cementitious Materials by Weight	77

The results of Step 1 are shown in Table 4 and graphed in Figure 4.

Table 4. Results of Varying Coarse to Fine Aggregate Ratio – Step 1

Coarse to Fine Aggregate Ratio By Volume	1-Day Compressive Strength (psi)	3-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)
0.94	8,070	8,960	10,100
1.09	8,550	8,860	10,350
1.26	8,980	9,090	10,360
1.46	9,130	10,440	11,020
1.71	7,830	9,370	10,020
2.01	6,820	7,970	10,610

Figure 4 indicates that the optimum coarse to fine aggregate ratio using 1/2-inch (13 mm) slate LWA was approximately 1.46. The resulting strengths did not vary significantly, yet indicated a trend. A similar study using 3/8-inch (10 mm) slate LWA showed the optimum ratio also to be approximately 1.5.

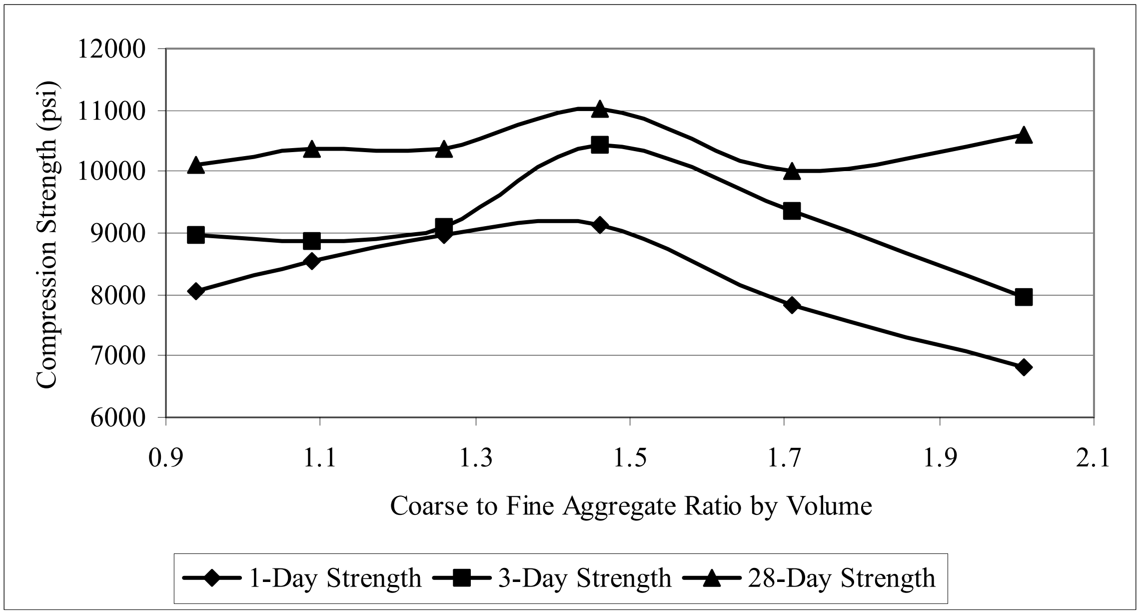

Figure 4. Results of Varying Coarse to Fine Aggregate Ratio

Variation of Percent Cement Paste – Step 2

Using the optimum coarse to fine ratio of 1.46 determined in Step 1, mixes were configured for Step 2 where the percent cement paste was varied between 33 and 39 percent. For a well-graded aggregate profile, 33 percent cement paste was considered optimum. The aggregate grading for this project contained gaps in the #8 and #16 particle sizes. Thus, it was thought that by examining the range from 33 to 39 percent that the additional paste would effectively fill the gaps in the smaller particle sizes. Percent cement paste above 39 percent was not examined based on cost and anticipated workability issues. The parameters in Table 5 were held constant throughout all mixes in Step 2:

Table 5. Parameters Held Constant in Step 2

Water / Cementitious Materials Ratio	0.23
Coarse to Fine Aggregate Ratio by Volume	1.46
Fly Ash as Percent of Total Cementitious Materials	15
Silica Fume as Percent of Total Cementitious Materials	8
Type III Cement as Percent of Total Cementitious Materials	77

The results of Step 2 are shown in Table 6 and graphed in Figure 6.

Table 6. Results of Varying Percent Cement Paste – Step 2

Percent Cement Paste	1-Day Compressive Strength (psi)	3-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)
33	6,760	7,880	9,420
35	8,950	9,350	8,360
37	8,810	9,420	10,280
39	8,920	9,360	10,550

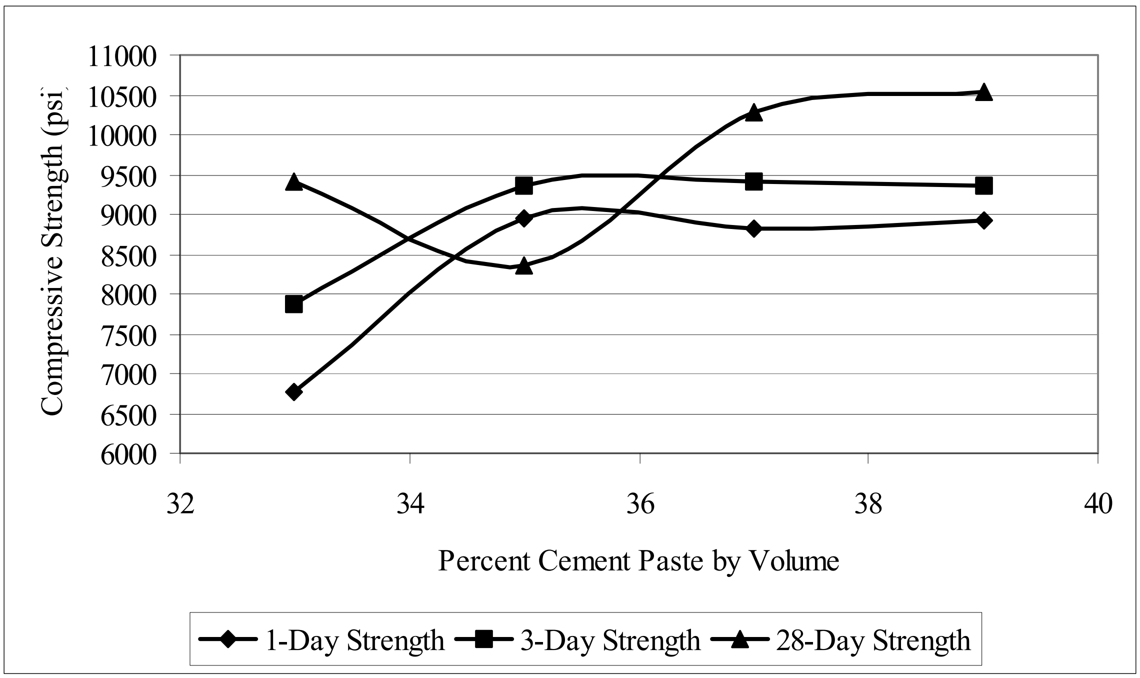

Figure 6. Results of Varying Percent Cement Paste

The results of Step 2 indicated the optimum percent cement paste was not at 33 percent based on the known gap grading in the aggregate profile. The need for additional cement paste appeared necessary. Figure 6 did not indicate an optimum value, but appeared to show a plateau that encompassed 39 percent based on 28-day strength. The drop in strength at 28 days for the 35 percent tests could not be explained. Thirty nine percent was chosen as the optimal percent cement paste value and was implemented in Step 3.

A similar study performed using 3/8-inch (10 mm) slate LWA and varying the percent cement paste from 35 to 45 percent also showed the optimum value to be around 39 percent. Based on gap grading in the overall aggregate profile considering the 3/8-inch (10 mm) slate LWA and normal weight sand proportioned at a coarse to fine aggregate ratio of 1.5, this higher level of cement paste also was justifiable.

Variation of Percent Silica Fume– Step 3

Using the optimum coarse to fine ratio of 1.46 determined in Step 1 and the optimum percent cement paste of 39 percent determined in Step 2, mixes were configured for Step 3 where the percent silica fume was varied from 4 to 12 percent of total cementitious materials by weight. Based on the literature, it was thought that 8 percent silica fume was the upper limit for useful mix designs.[14] The parameters in Table 7 were held constant throughout all mixes in Step 3. Since the percent of silica fume varied during this step, the percent of cement had to vary as well in order to maintain a constant percent cement paste and w/cm ratio.

Table 7. Parameters Held Constant in Step 3

Water / Cementitious Materials Ratio	0.23
Coarse to Fine Aggregate Ratio by Volume	1.46
Percent Cement Paste by Volume	39
Fly Ash as Percent of Total Cementitious Materials by Weight	15

The results of Step 3 are shown in Table 8 and graphed in Figure 7. Figure 7 indicates that silica fume used as 10 percent of the total cementitious materials by weight provided the best strength results at 1, 3 and 28 days. The use of 10 percent silica fume required the use of additional HRWR to provide necessary workability.

Table 8. Results of Varying Percent Silica Fume – Step 3

Percent Silica Fume	1-Day Compressive Strength (psi)	3-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)
4	8,540	8,710	10,660
6	8,920	9,470	10,550
8	8,820	9,400	10,930
10	10,620	11,190	11,330
12	10,200	10,500	11,080

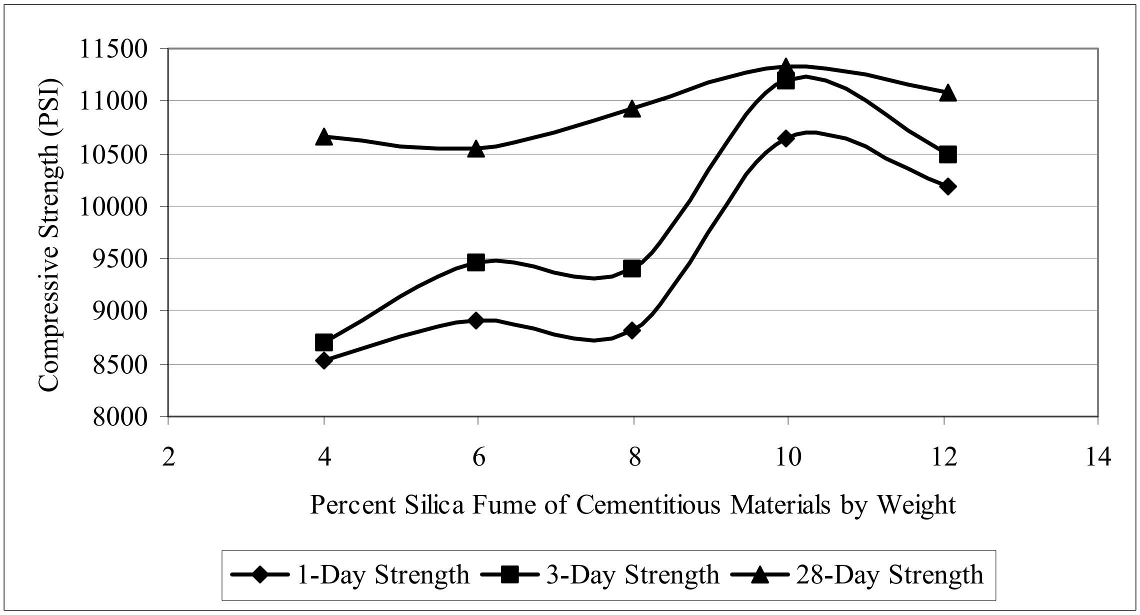

Figure 7. Results of Varying Percent Silica Fume

Strength Ceiling

During mix development, it was noticed that a reduction of the w/cm ratio below 0.23 did not result in higher strengths, indicating a possible strength ceiling. The strength ceiling also appeared to be inversely related to LWA size. The use of smaller aggregate resulted in higher compressive strengths. In order to investigate this phenomenon, a series of mixes was conducted as specified in Table 9. The high-strength normal weight concrete (HSNWC) listed in Table 9 was used for two sets of specimens. The first set incorporated all components in the mix design as listed. The second set of specimens contained only the portion of the mix that would pass through a 3/8-inch (10-mm) screen. The mix was screeded through a 3/8-inch screen in an attempt to remove the larger size coarse aggregate for purposes of determining the strength of the paste. While there may have been some small particles of the granite remaining in the paste, the vast majority was removed during screeding. The volume of coarse aggregate was identical for both mixes; the weight difference between the LWA and NWA is an indication of the weight reduction achieved with HSLC.

The results of the strength ceiling study are listed in Table 10. The HSNWC paste had the highest strength followed by the HSNWC then the HSLC. It would appear from the data that the strength ceiling for HSLC made with 1/2-inch (13-mm) slate LWA is around 11,500 psi (79.3 MPa). This result is in keeping with values estimated by Harmon.[15] Figure 8 shows a graph of the results in Table 10.

Table 9. Mixes for “Strength Ceiling” Study

Concrete Components to Produce 1 Cubic Yard		HSLC	HSNWC
# 67 Crushed Granite	(lbs)	--	1,574
½-inch slate LWA	(lbs)	948	--
Normal Weight Sand	(lbs)	1100	1100
Class F Fly Ash	(lbs)	152	151
Silica Fume	(lbs)	101	101
Type III Cement	(lbs)	760	758
LRWR	(fl oz)	61	61
HRWR	(fl oz)	132	173
AEA	(fl oz)	7.5	7.5
Water	(gal)	28.1	27.8
Slump	(inches)	4	5
Plastic Unit Weight	(pcf)	122.4	147.6
Temperature	(def F)	81	82

Table 10. Results of "Strength Ceiling" Study

Concrete Type	1-Day Strength (psi)	3-Day Strength (psi)	28-Day Strength (psi)
HSNWC Paste	11,780	13,160	13,380
HSNWC	11,740	12,050	13,060
HSLC	10,800	11,190	11,390

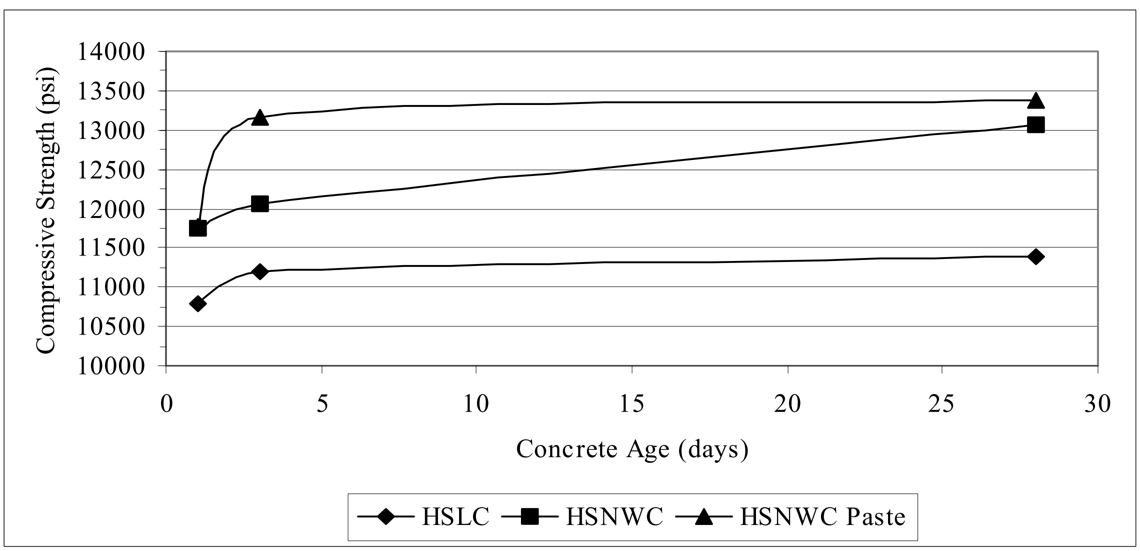

Figure 8. Results of "Strength Ceiling" Study

Final Mix Designs

Using the optimum values determined in Steps 1, 2 and 3 for each objective strength, the mix designs shown in Table 11 were suggested for 8,000, 10,000, and 12,000-psi (55.2, 69.0 and 82.8 MPa) strengths using 1/2-inch (10-mm) slate LWA. It was thought that the use of 1/2-inch (13-mm) aggregate would be more readily accepted in the precast industry than the smaller 3/8-inch (10-mm) aggregate.

Table 11. Objective 8,000, 10,000, and 12,000 psi (55.2, 69.0 and 82.8 MPa) Mix Designs for Field Testing

Concrete Components to Produce 1 Cubic Yard of HSLC Aggregate Assumed to be at SSD		Concrete Mix Designation Objective Strength (psi)		
		8 Mix 8,000	10 Mix 10,000	12 Mix 12,000
1/2-inch Slate LWA	(lbs)	1022	1030	1030
Normal Weight Fine Aggregate	(lbs)	947	955	955
Class F Fly Ash	(lbs)	142	145	150
Silica Fume	(lbs)	19	50	100
Type III Cement	(lbs)	783	765	740
LRWR	(fl oz)	57	58	59
HRWR	(fl oz)	57	65	139
AEA	(fl oz)	9.4	9.6	7.5
Water	(gals)	32.1	29.9	27.3
Water / Cementitious Materials Ratio	(w/cm)	0.28	0.26	0.23
Theoretical Equilibrium Unit Weight	(pcf)	115.6	116.2	116.6

FIELD PRODUCTION

Following the laboratory phase, the three objective mix designs were batched at a commercial prestressed concrete plant. The slate LWA was kept moist after delivery by means of a sprinkler placed above the storage bin. The absorbed moisture content of the LWA was slightly above 6 percent upon delivery and reached almost 9 percent after several days of continuous watering. The sprinkler was shut off 24 hours prior to batching HSLC to equalize the free water gradient throughout the storage bin.

Prior to batching the slate HSLC, moisture testing was performed to determine absorbed and free moisture content of the LWA. Samples of the LWA were taken from the bottom of the bin to ensure the same material was tested as was being transferred into the mixing tower. Absolute control of moisture and water content were found to be vital for batching high quality HSLC and high performance concrete in general.

After batching the HSLC and performing slump, unit weight, and air content measurements, test specimens were cast as they were during laboratory development. By following procedures to control moisture and normal quality control checks, it was possible to mix HSLC in a commercial plant with consistently good results.

MECHANICAL PROPERTY TESTING

This section provides the results of laboratory and field testing of the objective slate HSLC mix designs. It was not possible to achieve a mix design to satisfy a design strength of 12,000 psi (82.8 Mpa). Based on a strength ceiling around 11,500 psi (79.3 MPa), the highest objective design strength achieved was 10,000 psi (69.0 MPa).

Batch designations of "F" refer to specimens batched under field conditions at a local prestressed concrete plant. Batch designations of "L" refer to specimens batched in the laboratory. Curing conditions for the first 24 hours used both insulated cureboxes as describer earlier and ASTM procedures.

Compressive strength, modulus of elasticity, and modulus of rupture results are each an average of three specimens, and those results are presented in Tables 12, 13, and 14, respectively.

Table 12. 4 x 8 Cylinder Compressive Strength Results

Objective Strength Curing	Batch No.	Mean Cylinder Strength (psi) (H=Hours, D=Days, Y=Year)						
		16H	20H	24H	7D	28D	56D	1Y
8,000 Curebox	8F	7,920	8,470	8,870	9,570	9,830	10,600	10,830
	8L	7,320	7,630	7,730	9,300	9,630	10,430	
8,000 ASTM	8F			6,760		10,250	11,090	11,802
	8L			6,300		9,830	10,520	
10,000 Curebox	10F	7,710	9,070	9,750	10,010	10,430	11,170	11,516
	10L				9,260	9,410	9,920	
10,000 ASTM	10F			6,200		11,140	11,300	11,675
	10L			6,950		10,360	11,040	
12,000 Curebox	12F	10,990	10,500	11,490	11,250	11,460	11,550	12,138
	12L	9,840	9,760	11,101	10,230	10,590	10,860	
12,000 ASTM	12F			9,330		11,550	11,620	12,278
	12L			6,890		10,600	11,480	

Table 13. 6 x 12 Cylinder Modulus of Elasticity Results

Objective Strength Curing	Batch No.	Mean Modulus of Elasticity ($x10^6$ psi) (H=Hours, D=Days)			
		16H	24H	28D	56D
8,000 Curebox	8F	3.49	3.67	3.85	3.86
	8L	3.53	3.67		4.02
8,000 ASTM	8F				4.13
	8L				4.39
10,000 Curebox	10F	3.48	3.75	4.22	4.08
	10L				4.08
10,000 ASTM	10F				4.26
	10L				4.33
12,000 Curebox	12F	3.92	4.12	4.30	4.26
	12L	4.08	4.25		4.24
12,000 ASTM	12F				4.40
	12L				4.33

Table 14. Modulus of Rupture Results

Objectiv e Strength Curing	Batch Serie s No.	Mean Modulus of Rupture (H=Hours, D=Days) (psi)		Concrete Compressive Strength (psi)
		24H	56D	56D
8,000 Curebox	8F	788	1,089	10,160
	8L	649	1,077	10,430
8,000 ASTM	8F			
	8L	761	1,030	10,520
10,000 Curebox	10F	641	998	11,170
	10L	670	1,164	9,920
10,000 ASTM	10F			
	10L	678	1,006	11,040
12,000 Curebox	12F	761	1,014	11,550
	12L	645	926	10,860
12,000 ASTM	12F			
	12L	678	918	11,480

Table 12 clearly shows that at 24 hours the accelerated curing produced significantly higher compressive strengths than ASTM curing.

CONCLUSIONS

The methodical development of HSLC mix designs using the procedure outlined in this paper saved time and produced mix designs that were well optimized based on the available materials. The resulting mix designs, when tested under laboratory and field conditions proved to be comparable; the mechanical testing program demonstrated the validity of the procedure. Concrete made with slate lightweight aggregate and natural sand was both laboratory and field produced with 56-day design compressive strengths of 8,000 and 10,000 psi (55.2 and 69.0 MPa).

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