Developing Lightweight Self-Consolidating Concrete Mixtures

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ABSTRACT

Results from a research project that developed sand lightweight self-consolidating concrete mixtures are presented. The mixtures were developed specifically for precast/prestressed bridge girders. The targeted release strength of the mixtures was 4000 psi and 28 day strength was 7,000 psi. Two types of lightweight aggregate, expanded clay and expanded shale, were included in the study. The targeted unit weight of the mixtures was 120 lb/ft^3. Slump flow, T_{20}, J-ring, and the visual stability index (VSI) were measured for all mixtures. The variables examined in the study included water to binder ratio (w:b), binder content, and coarse aggregate type and content. Several mixtures were cast containing normal weight coarse aggregate and lightweight coarse aggregate. The preliminary results show that the total water content and aggregate strength are the major factors that need to be addressed in producing lightweight self-consolidating concrete (LWSCC). The paper also discusses the necessary balancing act between cement content and lightweight aggregate quantity needed to produce high compressive strengths but maintain unit weights of approximately 120 lb/ft^3. Finally, quality control procedures necessary for batching LWSCC are also discussed.

Keywords: Lightweight, Self-Consolidating Concrete

INTRODUCTION

Structural lightweight concrete has numerous benefits when used in certain applications and especially in precast/prestressed concrete members due to its lower self-weight and increased durability. Lightweight structural concrete is defined as "concrete having a minimum 28-day compressive strength in excess of 2500 psi (17 MPa), an equilibrium density between 70 and 120 lb/ft^3 (1120 to 1920 kg/m^3), and consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate."[1] Structural lightweight concrete unit weights typically range between 105 lb/ft^3 and 120 lb/ft^3 (1680 kg/m^3 to 1920 kg/m^3). Self-consolidating concrete (SCC) has also become increasingly common in prestressed applications due to the possibility for reduced time, labor, and noise during construction as well as providing an improved surface finish. Exact definitions may vary, but SCC should flow and fill forms under its own weight without vibration, remain homogeneous through long flow distances and vertical drops, and flow through congested areas without blockage or segregation.[2] Self-consolidating concrete can be used for intricately shaped and highly congested sections where conventional concrete would be extremely difficult to consolidate. Combining these two materials produces numerous benefits in certain applications. LWSCC has garnered more study in recent years in regards to bridge girders due to a desire for weight reduction in long span girders and to fit with the increasingly common production methods used in precast plants.[3] However, SCC is a complex material and can exhibit variability in conjunction with minor changes in components or procedures.[4] Developing concrete mixtures that are both lightweight and self-consolidating can be especially challenging due to the very high absorption capacity of most lightweight aggregates. Tight quality control is necessary to ensure that the concrete meets the required workability without segregation. The weak nature of lightweight aggregate can also make it difficult to attain the high strengths necessary for prestressed concrete applications.

The results presented herein are part of a larger research project concerning the bond of 0.6 in. prestressing strands cast in sand lightweight self-consolidating concrete (LWSCC) intended for precast/prestressed bridge girders. Concrete mixtures were developed using expanded clay and expanded shale aggregates and a control SCC mixture was developed using conventional limestone coarse aggregate. Targeted mixture properties included compressive strengths of 4000 psi and 7000 psi at one (f'_{ci}) and 28 days (f'_c), respectively, slump flow of 24-30 in., T_{20} between 2 and 5 seconds, J-Ring Δh less than 1.5 in., and VSI of 1.0 or less. Effects of water to binder ratio (w:b), binder content, and coarse aggregate type and content on both compressive strength and fresh concrete properties were examined.

BACKGROUND

Self-consolidating concrete combines the properties of a low yield stress allowing for high deformability of the fresh concrete with a high viscosity and resistance to segregation. It can therefore fill formwork and achieve adequate compaction without the need of vibratory consolidation. The high viscosity of the paste reduces blockage effects as the concrete moves around obstructions by reducing localized internal stresses at the individual aggregate particles .[5,6] Use of a superplasticizer is necessary to achieve the required deformability.

Unlike an increase in water content that decreases the initial yield stress and viscosity, the use of superplasticizer decreases the yield value with little impact on the viscosity of the mixture.[7] This allows for a low water-cementitious materials ratio (*w/cm*), which combined with a relatively high cementitious material content is one method of providing a high paste viscosity.[2,5,7,8] Other powder materials, such as supplementary cementitious materials and fillers, can also be added in enhance cohesiveness and stability. These materials also slow the rate of strength gain and limit the heat of hydration at high cementitious material contents.[6] Fly ash, slag cement, glass filler, limestone powder, silica fume, and quartzite filler are commonly used in SCC mixtures.[6,7,9] A viscosity modifying admixture (VMA) can also be used to increase the paste viscosity when a more moderate *w/cm* is used.[2,6,7] These two methods, typically referred to as "powder-type" and "VMA-type" SCC, are the basic methods of proportioning SCC. Characteristics of powder-type SCC mixtures tend to be very similar to high-performance concrete due to the low *w/cm* and incorporation of mineral admixtures. These properties provide the durability characteristics desired by the first SCC designers in Japan.[2] SCC mixtures typically contain much less coarse aggregate than conventional mixtures, which reduces the energy absorption caused by interaction between the aggregate particles, and in turn reduces the tendency for blockage.[2,5] A high internal absorption of energy can contribute to blockage of concrete flow in narrow or congested sections even when the mixture is highly deformable under a free flow condition such as a slump flow test. Adequate viscosity is required to keep the aggregate particles in suspension and reduce friction between aggregate particles. The maximum aggregate size is usually limited as well.[7,8,10] Lack of stability and bleeding can result in a weak interfacial transition zone between the paste and aggregate later leading to microcracking that increases permeability and can adversely affect mechanical properties.[11] This problem may be mitigated by the absorptive nature of lightweight coarse aggregate and the improved interfacial transition zone produced by internal curing effects and a pozzolanic reaction at the surface of the aggregate particles.[12]

Most previous research outlines many of the same important factors to consider in the development of an SCC mix proportion. These include aggregate volume, particle size distribution, ratio of sand to total aggregate volume (*s/agg*), *w/cm*, total powder content, total water content, and admixture dosages.[2,5,6,7,13,14] It is possible to develop LWSCC mixtures using normal weight SCC mixtures with replacement of the normal weight aggregate with equal volumes of lightweight aggregate. These mixtures meet the required properties for self-consolidating behavior, density, and compressive strength. Some modifications are necessary due to the high absorption capacity of lightweight aggregates.[15] Success has been documented using the absolute volume method with specific gravity factors to proportion LWSCC as well.[14]

Mixtures required for LWSCC bridge girders typically consist of a sand-lightweight concrete with a density slightly greater than typical LWC due to the increased cement content, lower *w/cm*, and reduced coarse aggregate content required for SCC. Due to the variation of density with particle size in most lightweight aggregates, special consideration must be made for maximum aggregate size and aggregate content. Incorporation of a portion of lightweight fine aggregate in addition to lightweight coarse aggregate or using lightweight fine aggregate and normal weight coarse aggregate can increase the segregation resistance of LWSCC.[3] Proper moisture control in the lightweight aggregate is very important for LWSCC due to the sensitive nature of the mixture composition and the high susceptibility of LWSCC to segregation with a large dosage of superplasticizer.[3,14] It is also important to only target the slump flow required for a given application since mixtures with larger slump flows are more likely to segregate.[3]

Okamura and Ouchi outlined a method of proportioning SCC that provided set limits for aggregate contents and required only adjustments of *w/cm* and superplasticizer dosage.[5] Khayat described methodologies for meeting the contradicting demands of high deformability and adequate segregation resistance for SCC. Reducing the coarse aggregate volume requires an increased volume of cement or other supplementary cementitious materials and fillers. These materials not only aid in the fluidity and cohesiveness of the mixture, but also help offset heat generation caused by a high cement content. Use of both a low *w/cm* and VMA also increases stability. The use of a low dosage of VMA can also decrease variability of fresh concrete properties.[7] El-Chabib and Nehdi observed decreased segregation resistance with higher values of *w/cm* and dosage of superplasticizer. They also confirmed VMA as an effective tool for reducing segregation and determined that the *s/agg* only had a minor impact on segregation resistance. Increasing the cementitious materials content increased segregation for mixtures with a high *w/cm* and improved segregation resistance for mixtures with a low *w/cm*.[16] The study used to produce NCHRP Report 628 recommended that SCC used for precast bridge girders should have a slump flow between 23.5 and 29 in., J-ring flow between 21.5 and 26.0 in., and difference between slump flow and J-Ring flow of less than 4 in. A *w/cm* of between 0.34 and 0.40 was recommended along with a low *s/agg* of between 0.46 and 0.50 and a small maximum aggregate size of less than ½ in. Increasing the binder content and *w/cm* were found to decrease the viscosity of the concrete mixture and increasing *s/agg* led to a small increase in viscosity.[8] Wall provided general guidelines for sand-lightweight LWSCC for bridge girders of a slump flow between 22 and 26 in., maximum *w/c* of 0.40, cement content between 700 and 850 lb/yd^3, 32% absolute volume of coarse aggregate, air content between 4.5 and 7.5%, a nominal maximum coarse aggregate size of 0.5 in., and a compressive strength of 8000 psi.[3] Abdelaziz determined that dosage of superplasticizer has a major influence of workability of LWSCC with a point of diminishing returns, increasing the *s/agg* ratio increases slump flow for LWSCC, and *w/c* had only a minor effect on slump flow in the range of 0.25 to 0.35 that was tested.[14] Variations of these different ideas and recommendations were used to define the important variables and to produce the LWSCC mix designs examined in this project.

MATERIALS AND METHODS

Concrete mixtures were designed and tested using two different lightweight aggregates as well as a locally available crushed limestone. The lightweight aggregates included expanded clay manufactured from clay obtained from natural deposits in the Mississippi River in Louisiana and expanded shale manufactured in Missouri. Specific gravity factors (SG) and absorption capacities (AC) were determined for each of the lightweight aggregates using the requirements put forth in the appendix of the Standard Practice for Selecting Proportions for

Structural Lightweight Concrete.[17] Specific gravity was determined using both the pycnometer method and the procedures of ASTM C 127 on samples that were submerged in water for 24 hours. The results of these tests are shown in Table 1. Aggregate absorption was also determined using the procedures of ASTM C 127 and the centrifuge method described in ACI 211.2.[17] Both values are shown in Table 1. The absorption capacity obtained using the centrifuge method was used for moisture content adjustments. Locally available river sand with a specific gravity of 2.6 and absorption capacity of 0.48% was used for each concrete mixture along with Type I cement and superplasticizer.

Table 1. Coarse Aggregate Properties

Aggregate Type	Limestone	Expanded Clay	Expanded Shale
Nom. Max. Size (in.)	3/8	1/2	3/4
SG (ASTM C 127)	2.68	1.24	1.41
SG (ACI 211.2)	NA	1.25	1.41
AC (ASTM C127) (%)	0.38	16.3	9.9
AC (ACI 211.2) (%)	NA	15.0	9.3

Due to the high absorption capacity of the lightweight coarse aggregate, the moisture content could not be determined overnight prior to concrete batching like that for the conventional limestone and fine aggregates. A relationship between the aggregate density and moisture content was instead developed. Lightweight aggregates were immersed in water for a period of time between 12 and 24 hours prior to concrete batching to ensure that the aggregate absorbed a minimum amount of the mixing water. The aggregate was then drained in a manner to remove as much free water as possible ensuring a repeatable moisture content. Several methods were examined for this process including a large barrel with a perforated pipe drain covered in geosynthetic material, soaking in buckets then draining in the barrel, and soaking in buckets then draining on a tarp. Preparation of the aggregate using buckets and a tarp can be seen in Figure 1. Each method was found to produce consistent results. Once the aggregate was drained, a unit weight test was performed using a 0.25 ft^3 measure filled in three layers rodded 25 times each. It was difficult to obtain a uniform surface due to the irregular shape of the aggregate, but results were consistent for a single operator. Performance of the unit weight test can be seen in Figure 1. A moisture content sample was then taken from the material in the measure. These unit weights and moisture contents were plotted and a second order polynomial was used to fit the data. This plot was updated with each batch so that as the project went on, more data were included in the prediction. The moisture density plots used for the final test batches are shown in Figures 2 and 3. As experience with the aggregates increased, it was possible to make a reasonable estimate of the aggregate moisture content using this prediction method.

Each trial batch was 1.5 ft^3 and was mixed in a 12.5 ft^3 rotating drum concrete mixer at the University of Arkansas Engineering Research Center. The mixing procedure was to add all of the coarse aggregate and all the water to the mixer with the mixer at rest, then the sand and lastly the cement were added with the mixer turning. A reasonable dosage of superplasticizer was added to the mixing water before it was added to the mixer and then additional increments were added until the concrete reached the desired consistency. Mixing times

Figure 1. Aggregate Preparation and Unit Weight

varied slightly since different amounts of superplasticizer were required based on the mix design and the ambient temperature. The average mixing time was approximately 15 minutes.

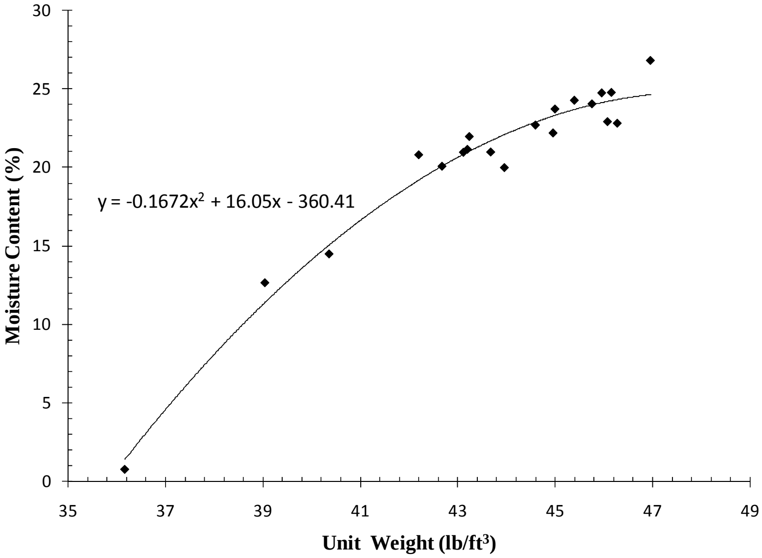

Figure 2. Expanded Clay Moisture Density Relationship

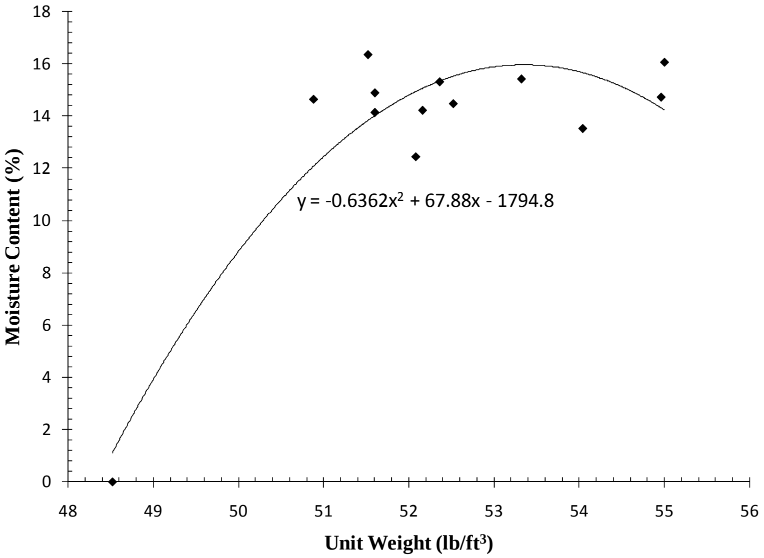

Figure 3. Expanded Shale Moisture Density Relationship

Fresh concrete tests including slump flow, J-Ring flow, T_{20}, VSI, and unit weight were performed for each batch. The combination of slump flow and J-Ring flow give a full indication of filling ability, passing ability, and filling capacity without the need for more complicated testing.[8] The difference in height between the inside and outside of the J-Ring was also measured as an indicator of blockage similarly to previous research at the University of Arkansas. These tests were performed in accordance with the specific ASTM standards for each test, ASTM C 1611 for slump flow, T_{20}, and VSI, ASTM C 1621 for J-Ring, and ASTM C 138 for unit weight. No rodding was used for the unit weight test, only taps with a rubber mallet. Six, 4 in. by 8 in. cylinders were cast for each test batch for compressive strength testing at one (f'_{ci}) and 28 days (f'_c) of age.

MIXTURE DESIGN

Mix designs meeting the required concrete property specifications were developed using each of the three aggregates mentioned previously. The baseline LWSCC mix design was based on work done previously at the University of Arkansas.[18] Two variations of previous mixes were examined and then adjusted to account for differences in the lightweight aggregate from that particular expanded clay to the one used in this research along with the expanded shale aggregate. The specific gravity factors and absorption capacities of these aggregates varied from those used in Ward's research.

Several different variables were manipulated to produce LWSCC with the desired properties. These included, cement content, water-cement ratio (*w/c*), total water content, ratio of sand to total aggregate by volume (*s/agg*), and dosage of superplasticizer. Since the strength requirements at one day were relatively high and the lightweight aggregate is weaker than conventional aggregate, only the powder-type method of developing SCC was examined. No supplementary cementitious materials or other mineral admixtures were incorporated due to their detrimental effects on either early age strength or workability, as in the case of fly ash and silica fume, respectively.

Mixtures using expanded clay aggregate were examined first. The different mix designs that were tested using expanded clay can be seen in Table 2 and the concrete properties in Table 3. After the first two batches it was obvious that the *w/c* and total water content were too high, due to significant segregation of the mixture with a typical dosage of superplasticizer. The water content was then reduced to provide a *w/c* of 0.38. Batches 3 through 9 and 11 used this *w/c* with a constant cement content of 795 lb/yd^3. Superplasticizer dosage or *s/agg* was varied for these mixtures to examine the effects on flowability and stability. Mixtures with *s/agg* ratios between 0.48 and 0.52 produced acceptable slump flow, T_{20}, and VSI values, but significant blockage was indicated by the J-Ring. Increasing *s/*agg produced an increase in slump flow with a *s/*agg of 0.51 producing the best combination of deformability and viscosity. The compressive strength of all these first mixtures did not meet the required 4000 psi minimum at 24 hours. Since compressive strength of lightweight concrete is considered to be more closely related to cement content than to water content,[1] the cement content was increased to 850 lb/yd^3 without changing the water content, which reduced the *w/c* to 0.36. This increase in the volume of fine material with no more available water

Table 2. Trial Batches Using Expanded Clay

Batch	Cement (lb/yd^3)	Coarse Agg. (lb/yd^3)	Fine Agg. (lb/yd^3)	Water (lb/yd^3)	HRWR (oz/cwt)	w/c	s/agg
1	795	715	1218	390	5.0	0.49	0.46
2	795	668	1218	390	4.6	0.49	0.48
3	795	743	1365	302	4.0	0.38	0.48
4	795	743	1365	302	3.0	0.38	0.48
5	795	743	1365	302	4.0	0.38	0.48
6	795	700	1451	302	4.0	0.38	0.51
7	795	684	1483	302	3.0	0.38	0.52
8	795	684	1483	302	4.0	0.38	0.52
9	795	700	1451	302	2.5	0.38	0.51
10	850	675	1402	302	4.0	0.36	0.5
11	795	700	1451	302	4.0	0.38	0.51
12	795	648	1462	318	4.5	0.40	0.52
13	850	675	1402	302	7.0	0.36	0.50
14	825	649	1407	329	6.5	0.40	0.51
15	825	642	1450	318	8.5	0.39	0.52
16	825	636	1434	329	6.0	0.40	0.52
17	795	659	1491	298	13.0	0.37	0.52
18	825	636	1434	329	8.0	0.40	0.52
19	825	649	1407	329	8.0	0.40	0.51
20	825	662	1380	329	7.5	0.40	0.50
21	825	676	1350	329	7.5	0.40	0.49
22	825	662	1380	329	7.0	0.40	0.50

greatly increased the viscosity of the mixture, so the cement content was reduced to 825 lb/yd^3 and the water content was increased to produce a *w/c* of 0.40. Using these parameters, the *s/agg* and superplasticizer dosage were adjusted until a mixture was obtained that was acceptable for each fresh concrete property and met the minimum one-day strength. This process can be seen in batches 14-16 and 18-22. Batch 17 was produced simply to fill in data missing from the 795 lb/yd^3 series. It was very important to have a high cement content and low *w/c* to fulfill the flow and strength requirements, but an aggregate content of at least approximately 650 lb/yd^3 was required to keep the unit weight under the 120 lb/ft^3 requirement. The final mix design that was chosen for use for the expanded clay aggregate is shown in Table 9. The ranges of fresh concrete properties and compressive strength measured during beam construction for each of the final mix designs are also shown in Table 9. The variation in each of these properties is due to differences in ambient temperature of up to 30° F between days that beams were cast. The slump flow of the final expanded clay mixture is shown in Figure 4. Bleed water is noticeable around edges of the slump flow patty but the mixture exhibited adequate cohesiveness along with adequate slump flow.

Table 3. Concrete Properties of Expanded Clay Batches

Batch	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring Δ (in.)	J-Ring ΔH (in.)	Unit Weight (lb/ft^3)	f'_{ci} (psi)	f'_c (psi)
1	--	--	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--	--	--
3	27.0	7.4	3.0	19.5	7.5	4.00	109.7	2860	4450
4	15.0	--	--	12.0	3.0	--	113.5	3330	5280
5	24.5	6.2	1.5	16.0	8.5	3.50	111.1	3380	5720
6	29.5	3.2	1.5	26.0	3.5	2.00	113.4	2590	4970
7	16.5	--	--	12.0	4.5	--	115.0	3020	5170
8	28.5	2.6	1.5	22.0	6.5	3.00	114.1	2750	4850
9	22.5	3.4	0.5	16.5	6.0	2.25	116.0	2930	5370
10	26.0	6.2	0.5	21.0	5.0	2.25	113.7	3640	5680
11	24.0	6.4	0.0	21.5	2.5	2.00	114.2	3760	5970
12	23.5	6.2	0.0	20.0	3.5	2.00	115.2	3650	5730
13	26.0	8.4	0.5	22.5	3.5	2.25	117.3	4780	6320
14	28.0	5.2	1.5	25.0	3.0	2.25	113.7	3520	5540
15	21.5	12.2	0.0	16.5	5.0	2.75	118.1	4510	6000
16	20.5	5.4	0.0	15.5	5.0	2.50	118.9	3740	6810
17	27.5	8.6	1.5	24.0	3.5	2.75	119.2	3770	5580
18	22.5	6.8	0.0	16.0	6.5	3.25	119.1	4400	7000
19	26.0	5.4	0.0	20.5	5.5	2.25	116.3	3630	6020
20	27.0	6.0	0.5	23.5	3.5	2.00	118.1	4250	6630
21	28.5	5.0	1.0	24.0	4.5	2.50	118.4	3640	5580
22	28.5	4.4	1.0	24.5	4.0	2.50	117.3	3990	5120

Note: -- indicates no measurements due to lack of SCC behavior

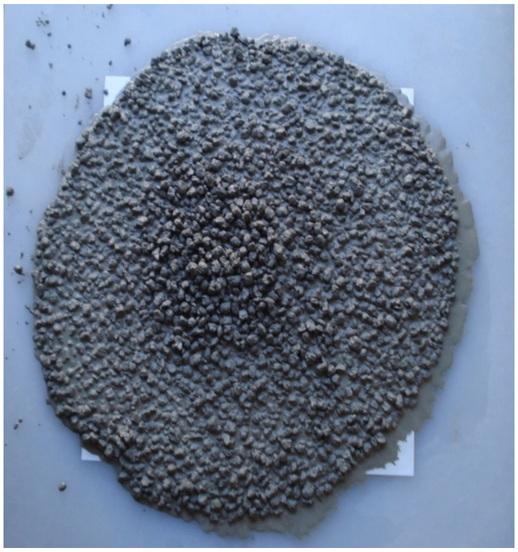

Figure 4. Slump Flow of Final Expanded Clay Mixture

The mixture proportions tested using expanded shale can be seen in Table 4 and the fresh concrete properties in Table 5. The first mixture, batch 23, using expanded shale was again based on the mixtures used by Ward,[18] but had an increased aggregate content to keep the unit weight at a reasonable value. After this batch the *s/agg* and cement content were increased to provide more fine particles since the first mix was very rocky and showed significant blockage. The same 0.40 *w/c* was used for batches 23-25, but low strengths prompted a decrease in *w/c* and a further increase in cement content to 850 lb/yd^3. These values were then used for batches 26-29, 32, and 34. The slump flow and stability of all but batches 23 and 31 were adequate, but problems with T_{20} and in turn blockage persisted throughout testing. Several different *s/agg* values were examined as seen in Table 3. It was

Table 4. Trial Batches Using Expanded Shale

Batch	Cement (lb/yd^3)	Coarse Agg. (lb/yd^3)	Fine Agg. (lb/yd^3)	Water (lb/yd^3)	HRWR (oz/cwt)	w/c	s/agg
23	800	790	1344	320	4.0	0.40	0.48
24	825	747	1376	330	6.0	0.40	0.51
25	825	717	1432	330	6.0	0.40	0.52
26	850	733	1465	298	7.5	0.35	0.52
27	850	748	1437	298	8.0	0.35	0.51
28	850	748	1437	298	11.0	0.35	0.51
29	850	764	1408	298	8.0	0.35	0.50
30	850	748	1383	319	7.0	0.38	0.50
31	900	726	1392	315	4.0	0.35	0.50
32	850	748	1437	298	6.0	0.35	0.51
33	900	726	1392	315	6.0	0.35	0.51
34	850	748	1437	298	6.0	0.35	0.51
35	900	726	1392	315	5.0	0.35	0.51

Table 5. Concrete Properties of Expanded Shale Batches

Batch	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring Δ (in.)	J-Ring ΔH (in.)	Unit Weight (lb/ft^3)	f'_{ci} (psi)	f'_c (psi)
23	22.0	4.0	0.0	16.0	6.0	3.00	122.0	3090	5740
24	24.0	4.2	0.0	24.0	0.0	2.00	114.1	3000	5140
25	26.5	3.2	1.0	24.5	2.0	2.00	118.4	2940	5280
26	27.0	8.2	1.0	21.5	5.5	2.50	116.2	3430	5450
27	25.0	12.8	0.5	21.5	3.5	1.50	120.2	3920	6270
28	25.5	11.0	1.0	20.0	5.5	2.00	121.3	4010	5270
29	26.0	7.4	0.5	23.5	2.5	1.25	118.4	3520	5080
30	28.5	4.2	1.5	22.0	6.5	3.00	115.4	2720	4580
31	17.5	--	0.0	17.5	0.0	2.75	117.0	2880	5500
32	25.0	4.8	0.5	21.0	4.0	2.75	122.1	3690	5280
64/33	27.5	4.0	1.0	26.5	1.0	2.00	113.4	3900	5550
34	26.0	6.6	1.0	25.5	0.5	1.50	118.8	4080	6070
35	25.0	5.4	0.5	23.0	2.0	1.50	119.5	3860	6450

Note: -- indicates no measurements due to lack of SCC behavior

again determined that using a *s/agg* of 0.51 was the best balance of flow and viscosity to allow for minimal blockage. It was also decided that a higher difference in J-Ring heights was acceptable for the lightweight aggregate than for normal weight mixtures. The final mixture used for the expanded shale aggregate and its concrete properties are shown in Table 9. Figure 5 shows the result of the slump flow test for this mixture. As with the final expanded clay mixture, some bleed water is visible but the stability of this mixture was also adequate.

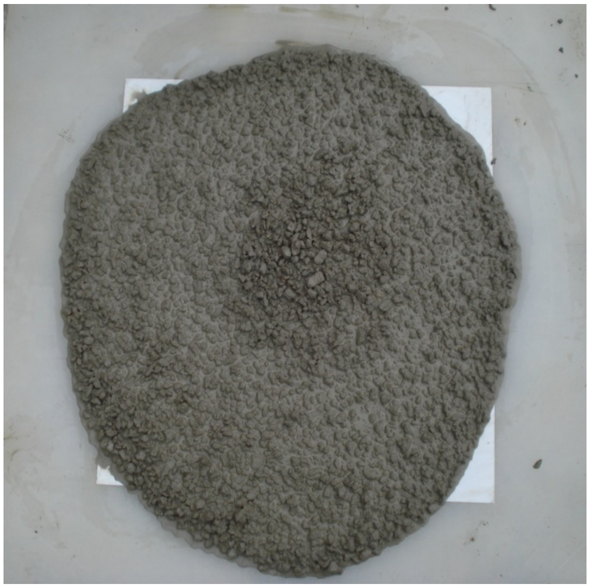

Figure 5. Slump Flow of Final Expanded Shale Mixture

The major issues in proportioning LWSCC were worked out through the expanded clay mixtures and the major problems for the expanded shale mixtures were blockage measured with the J-Ring and low compressive strength. The continually lower strength for the expanded shale mixtures in spite of a higher cement content and lower *w/c* were attributed to a combination of several factors. The aggregate surface appeared to be somewhat smoother than the expanded clay, which combined with the lower absorption capacity of the aggregate produced a weaker paste to aggregate bond. It is also possible that the effects of internal curing water at the interfacial transition zone were also less pronounced due to the reduced available moisture in the aggregate particles. Therefore a stronger paste was required to achieve the same one day strength. It was also observed that a small number of larger irregularly shaped aggregate particles were contributing to the blockage problems in the J-Ring test. The aggregate used for batches 34 and 35 was sieved over a ½ in. sieve prior to soaking in water. This significantly reduced the observed blockage from a Δh of over 2 in. to 1.5 in. and a slight increase in compressive strength was also realized. It is possible that the larger aggregate particles were not only causing blockage problems, but that the reduced density of these particles caused irregularities in the concrete and thus a slightly lower compressive strength.

Throughout the testing of both the expanded clay and expanded shale mixtures, the importance of consistency in material preparation and procedures was constantly evident. Lightweight aggregate continues to absorb water for a long period of time and it was noted that the absorption rates of the expanded clay and shale were somewhat different. The expanded clay seemed to absorb water at a much faster rate, with that rate slowing over time. This allowed for more variation in the time that the aggregate was presoaked without a significant variation in moisture content. This was not true for the expanded shale. The rate of absorption seemed to remain high over the typical presoaking period of 24 hours or less. This produced greater variation in the moisture content of the aggregate if the presoaking time was not held constant. Due the sensitive nature of SCC mixtures and the tendency for segregation, it was important to maintain consistent practice of soaking the aggregate for as close to the same period of time for every batch. This produced a fairly consistent moisture content that allowed for an accurate adjustment of the mixing water for each mixture. It was also clearly evident that expanded shale aggregate that had been presoaked previously and not returned to the original moisture condition would behave much differently the next time it was used for the same presoaking time. This was again not as evident for the expanded clay. The variation of compressive strength at one day (f'_{ci}) with respect to the error between the estimated and actual moisture content of the lightweight aggregate for the clay and shale test batches at the final *w/*c is shown in Figures 6 and 7, respectively. A negative error indicates that the actual moisture content was lower than that used to determine the batch weights resulting in less water in the mix than expected. A positive error indicates more water in the mix than expected. These plots indicate that the minor errors between estimated and actual moisture content had little effect on f'_{ci} at the *w/c* used for these mixtures. This is a result of the low *w/c* for these mixtures and the limiting effect of the lightweight aggregate on the strength of these mixtures.

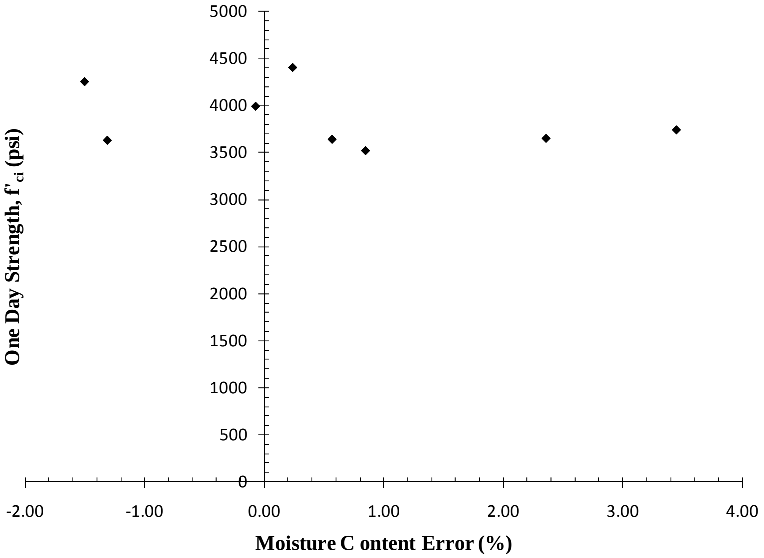

Figure 6. Effect of Moisture Content Error on Expanded Clay f'_{ci}

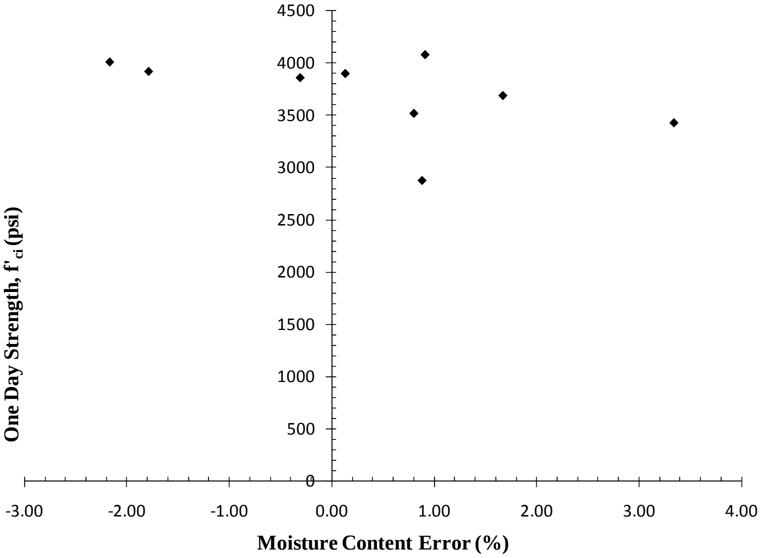

Figure 7. Effect of Moisture Content Error on Expanded Shale f'_{ci}

The conventional SCC mixture was developed by modifying a mix design produced as part of other research at the University of Arkansas. The trial mixtures are shown in Table 7 and the concrete properties in Table 8. The Arkansas State Highway and Transportation Department specified maximum *w/c* was used for batches 36-38. Slight variations were then made in cement content and *s/agg* and batch 39, with a higher cement content and a lower *w/c* producing the best fresh properties. The compressive strength of this mixture was somewhat higher that desired for an adequate comparison the other mixtures so for the final mix design, the *w/c* and *s/agg* were kept the same as batch 39, but the cement content was lowered back to 775 lb/yd^3. The final mix design used as the conventional SCC control mixture and its concrete properties are shown in Table 9.

Table 7. Trial Batches Using Limestone

Batch	Cement (lb/yd^3)	Coarse Agg. (lb/yd^3)	Fine Agg. (lb/yd^3)	Water (lb/yd^3)	HRWR (oz/cwt)	w/c	s/agg
36	761	1380	1454	335	7.0	0.44	0.52
37	775	1367	1439	341	7.0	0.44	0.52
38	775	1425	1384	341	6.0	0.44	0.50
39	825	1362	1433	330	6.0	0.40	0.52

Table 8. Concrete Properties of Limestone Batches

Batch	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring Δ (in.)	J-Ring ΔH (in.)	Unit Weight (lb/ft^3)	f'_{ci} (psi)	f'_c (psi)
36	19.5	7.0	0.0	15.5	4.0	3.00	147.8	4970	11150
37	26.0	4.0	1.0	21.0	5.0	2.00	148.0	4480	9770
38	23.0	4.8	0.0	20.0	3.0	1.75	147.2	4110	9860
39	27.0	3.6	0.5	23.5	3.5	1.50	149.2	5890	12200

Table 9. Final Mix Designs

Material	Expanded Clay	Expanded Shale	Limestone
Cement (lb/yd^3)	825	850	775
Coarse Agg. (lb/yd^3)	649	748	1408
Fine Agg. (lb/yd^3)	1407	1437	1481
Water (lb/yd^3)	329	298	310
w/c	0.40	0.35	0.40
s/agg	0.51	0.51	0.52
Slump Flow (in.)	25.0 – 28.0	26.0 – 29.5	19.0 – 27.0
T_{20} (sec)	3.4 – 5.4	2.0 – 6.4	2.0 – 3.2
J-Ring Δh (in.)	1.25 – 2.25	1.25 – 2.25	1.0 – 2.25
f'_{ci} (psi)	3800 – 5600	3700 – 4500	4000 – 5600
f'_c (psi)	4900 – 7200	5800 – 7100	6700 – 8000

CONCLUSIONS

This research indicates that, while it is somewhat more difficult to produce LWSCC than a normal weight mixture, it is possible to develop mix designs to meet specifications for use in precast bridge girder production. The mix designs presented herein were used successfully to cast prestressed concrete beam specimens for use in transfer and development length testing. With a better understanding of the effects of different variables on the fresh and hardened concrete properties one can more easily produce a workable LWSCC mixture. Based on these preliminary results, the most important variables affecting fresh properties of LWSCC are cementitious material content, total water content, and aggregate content. A relatively high cement content and in turn substantial total water are necessary to attain adequate flow. A small maximum aggregate size is critical to prevent excessive blockage. The cementitious material content and *s/agg* must be high to produce adequate viscosity and still achieve the required strengths with relatively weak lightweight aggregate. Coarse aggregate content must be kept at a level high enough to attain the desired unit weight while still providing a *s/agg* between 0.5 and 0.52. Cement content, aggregate strength and quality, and to a lesser extent maximum aggregate size are the most important variables affecting the early age compressive strength that is vital in the prestressed concrete industry. Procedures ensuring consistency of practice and superior quality control are vitally important to produce good quality LWSCC with minimal variation. Aggregates should be presoaked for a consistent period of time for each batch and based on the beginning moisture condition, or should be kept continually moist. More research is necessary to produce standardized mixing procedures for LWSCC that also account for addition of extra superplasticizer required for variations in ambient temperature.

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