SENSITIVITY OF LIGHTWEIGHT SCC TO VARIATIONS IN AGGREGATE MOISTURE

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ABSTRACT

Consistently mixing and producing lightweight concrete and lightweight self-consolidating concrete (LWSCC) can be challenging due to variations in aggregate absorption and specific gravity within a sample of lightweight aggregate. Typically, producers continuously soak their lightweight aggregate to ensure the moisture content is consistent. However, LWSCC can be more sensitive to changes in aggregate moisture than typical lightweight concrete. This paper reports the findings of a study that examined the effects of inaccurately estimating aggregate moisture content has on LWSCC and documents the development of a LWSCC mixture with specific properties. The LWSCC had a targeted one day compressive strength of 4000 psi, 28 day strength of 6000 psi, and a unit weight of 120 lb/ft^3. The LWSCC were batched based on an assumed aggregate moisture content using the loose unit weight of the aggregate. After mixing and testing, an aggregate sample was placed in the oven to determine the true moisture content. Generally, the difference between assumed and measured moisture content was approximately ±5 percent. The results showed that there was almost no difference in compressive strength when the error was within ±3 percent. As for workability, the differences in aggregate moisture were compensated with adjustments in the high range water reducer dosage rate.

Keywords: Lightweight, Self-Consolidating Concrete

INTRODUCTION

Lightweight self-consolidating concrete (LWSCC) combines the properties and benefits of both lightweight concrete (LWC) and self-consolidating concrete (SCC). The potential is available for savings in both the loads on the structure as well as for concrete placement. It is possible to obtain self-consolidating behavior using the same materials as LWC and methods similar to those used for normal weight SCC. Concrete density tends to be slightly higher for LWSCC when compared to LWC due to the increased paste content required for SCC as well as the need to limit the coarse aggregate content for stability.[1] Developing LWSCC can be difficult because of the high absorption capacity of the lightweight aggregates. This high absorption capacity makes determining aggregate moisture content prior to batching difficult. This paper reports the findings of a study that examined the effects of inaccurately estimating aggregate moisture content has on LWSCC.

BACKGROUND

It is possible to obtain good quality SCC using lightweight aggregates, as has been demonstrated by several researchers.[1,2,3,4] As is the case for normal weight SCC, it is necessary to pay careful attention to the constituents of LWSCC. Aggregate size and gradation is an important factor to consider for SCC. The combination of lightweight and normal weight aggregates can also have a substantial impact on the properties of LWSCC.[2] The density differences between large and small lightweight aggregate particles can cause increased segregation potential in LWSCC. Therefore, maximum size and percentage of large particles should be limited. Combinations of both lightweight coarse and fine aggregates along with normal weight aggregates can be used to achieve the specified density, segregation resistance, and finish. Lightweight fine aggregates have been shown to be detrimental to some hardened concrete properties, such as creep and shrinkage, but can greatly improve finishing characteristics and segregation resistance.[1]

It is important to be aware of other aspects of LWSCC just as is the case for normal weight SCC. Proper moisture conditioning of the lightweight aggregates is necessary along with proper determination of free water content in order to have control over the water content of the concrete mixtures. Adequate viscosity very similar to normal weight SCC is necessary to control flow and stability. Flow characteristics should be suited to the application to limit the possibility of segregation. Air entrainment improves the workability and durability of the mixture while also helping reduce the density of the paste to something more similar to the aggregate which helps with stability.[1]

As is the case with normal LWC and NWC, mix proportioning of LWSCC is different than that for normal SCC. The volume of paste necessary to produce the desired flow characteristics is based on many of the aggregate characteristics including gradation, particle shape, surface texture and ratio of fine to coarse aggregate. Supplementary cementitious materials and other fillers have been used successfully in LWSCC to obtain the extra paste required for flowability. These include fly ash, slag cement, and waste glass powders. Shi and Wu documented successful use of waste glass powder without deleterious expansion of the concrete due to alkali-aggregate reaction. This may be a result of the porous nature of the aggregates accommodating the reaction products.[4] In addition to high paste, relatively high amounts of VMA have been required to increase stability.[5] As a lightweight aggregate producer, Wall suggested a *w/c* for LWSCC of 0.3 to 0.4 with total binder between 700 and 850 lb/yd^3 (415 and 504 kg/m^3). He recommended a slump flow between 22 and 26 in. (560 and 660 mm), air content between 4.5 and 7.5%, a maximum lightweight coarse aggregate volume of 32% with a maximum size of 0.5 in. (12.7mm).[1]

EXPERIMENTAL PROGRAM

The research program examined the effects of inaccurately estimating coarse aggregate moisture content has on the fresh and hardened properties of LWSCC. Twenty-two LWSCC mixtures were developed using expanded clay, lightweight aggregate. The mixtures were batched using a moisture content based on the loose unit weight of the aggregate. The moisture content was then measured by oven drying a sample of the aggregate.

MATERIALS

Type I cement from a single source and washed river sand (normal weight) with a fineness modulus of 2.50 were used for all mixtures. The high range water reducer (HRWR) was classified as both an ASTM C494 Type and ASTM C1017 Type I plasticizer. A regionally available, expanded clay lightweight aggregate was used in the study. The aggregate properties are shown below in Table 1.

As seen in Table 1, the specific gravity (SG) and absorption capacity (AC) was measured using two methods. Specific gravity factors and absorption capacities were determined using the guidelines provided in the appendix of the Standard Practice for Selecting Proportions for Structural Lightweight Concrete and ASTM C127.[6,7] When correcting for aggregate moisture content when mixing, the absorption capacity obtained using the centrifuge method was used.[6]

Table 1. Coarse Aggregate Properties

Material Property	Expanded Clay
Nom. Max. Size (in.)	1/2
SG (ASTM C127)	1.24
SG (ACI 211.2)	1.25
AC (ASTM C127) (%)	16.3
AC (ACI 211.2) (%)	15.0

MIXING

For normal weight concrete, the moisture content of the coarse and fine aggregate is determined prior to mixing by drying an aggregate sample overnight in an oven. However, the high absorption content of the lightweight aggregate prevents this from occurring. For lightweight coarse aggregate, a relationship between the aggregate density and moisture content was developed. The lightweight aggregate was immersed in water for 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. Each method was found to produce consistent results.

Once the coarse aggregate was drained, unit weight test was measured using a 0.25 ft^3 container 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. A moisture content sample was then taken from the material in the measure. These unit weights and moisture contents were then plotted and a second order polynomial was used to fit the data. This plot was updated with each batch so that as the project progressed, more data were included in the prediction. 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 consisted of adding all of the coarse aggregate and all the water to the mixer with the mixer at rest, then the sand and cement with the mixer turning. A reasonable dosage of HRWR was added to the mixing water before it was added to the mixer and then additional amounts were added until the concrete reached the desired consistency. Mixing times varied slightly since different amounts of HRWR were required based on the mix design and the ambient temperature. The average mixing time was approximately 15 minutes.

TESTING

Fresh concrete tests including slump flow, J-Ring flow, T_{20}, VSI, and unit weight. 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.[8,9,10] No rodding was used for the unit weight test, only taps with the rubber mallet. Six 4 in. by 8 in. cylinders were cast for each test batch for compressive strength testing at one and 28 days of age.

The mixtures had a targeted compressive strength of 4000 psi (28 MPa) at one day of age (f'_{ci}) and 6000 psi (48 MPa) at 28 days (f'_c). A slump flow between 25 in. and 30 in. (635 mm and 760 mm), T_{20} between 2 and 5 seconds, VSI of 1.0 or less, and a J-Ring Δh less than 1.5 in. (38 mm) were targeted for each of these concrete mixtures.

MIXTURES

The baseline LWSCC mixture used for development of those used in this research project was based on previous work at the University of Arkansas by Ward.[3] His research focused on LWSCC containing expanded clay aggregate. Two variations of mixtures used in Ward's research were examined and then adjusted to account for differences in the lightweight aggregate between the expanded clay aggregate used in Ward's research and the expanded clay used in this research. The specific gravity factors and absorption capacities of these aggregates varied from those used in Ward's research.

A series of trial batches with adjustments between batches was used to determine the optimum mix design for each combination of material property specifications. The variables that were adjusted between batches included: cement content, total water content, water-cementitious materials ratio (*w*/*cm*), coarse aggregate content and ratio of sand volume to total aggregate volume (*s*/*agg*). HRWR dosage was adjusted between batches to account for differences in cementitious materials, ambient temperature and aggregate moisture content error.

MIXTURE PROPORTION DEVELOPMENT

The different mix proportions that were tested are shown in Table 1 and the properties of these concrete mixtures are shown in Table 2. The properties of the expanded clay aggregate were not adequately known when trial batching commenced, so the specific gravity factor from Ward's research was used along with an assumption of an SSD condition after soaking of the aggregate for the first nine trial batches. Since the absorption capacity was not known at the time these batches were made, the moisture density relationship was not usable until batch 10 when an approximate absorption capacity was determined using the methods of ASTM C127.[7] This absorption capacity of 17% was used for batches 10 through 13 until the absorption capacity was determined using the centrifuge method. This absorption capacity of 15% was utilized for the remaining trial batches.

The *w*/*c* and total water content were too high for the first two batches, as indicated by the significant segregation of these mixtures with the recommended HRWR dosage. The lack of knowledge of the aggregate properties most likely contributed to these difficulties. The water content was then reduced in order to change the *w*/*c* from 0.49 to 0.38 for batch 3. Trial batches 3 through 9 and 11 used this 0.38 *w*/*c* with a constant cement content of 795 lb/yd^3 (276 kg/m^3). HRWR dosage or *s*/*agg* was varied for these mixtures to examine effects on flowability and stability. Mixtures with *s*/*agg* between 0.48 and 0.52 produced acceptable slump flow, T_{20}, and VSI values, but the J-Ring test showed the potential for significant blockage. Increasing *s*/*agg* from 0.48 resulted in an increase in slump flow, and a *s*/*agg* of

0.51 produced the best combination of deformability and viscosity. None of these first mixtures reached the required minimum compressive strength of 4000 psi (28 MPa) at 24 hours of age.

Table 1. Concrete Mixture Proportions

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	0.50
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

Note: 1 lb = 0.454 kg, 1 oz = 29.57 mL, 1 yd^3 = 0.765 m^3

Since compressive strength of lightweight concrete is considered to be more closely related to cement content than to water content when the exact moisture adjustment parameters are unknown, the cement content for batches 10 and 13 was increased to 850 lb/yd^3 (295 kg/m^3) without changing the water content, which reduced the *w/c* to 0.36.[6] This increase in the volume of fine particles with no more available water increased the viscosity of the mixture and required a larger dose of HRWR. The cement content of the remaining trial batches, 14-22 was then reduced to 825 lb/yd^3 (490 kg/m^3); except for batch 17, which was produced to simply fill in data missing from the 795 lb/yd^3 (472 kg/m^3) mixtures. The water content was increased to produce a *w/c* of 0.40 for batches 14, 16, and 18-22 and 0.39 for batch 15. The proportions resulting from these mix design modifications are shown in Table 1. The reduction in cement content and increase in water content allowed for a better slump flow for these mixtures as can be seen in Table 2. The *s/agg* was varied from 0.49 to 0.52 and the

HRWR dosage was adjusted between these mixtures until a mixture was developed that exhibited acceptable values for each fresh concrete property.

As only three of the trial batches met the required minimum for one-day compressive strength, a mixture with an acceptable combination of flow properties and unit weight, and a compressive strength greater than 3500 psi (24 MPa) was chosen for casting the first set of beam specimens. This mix design corresponded to that used for batches 14 and 19 presented in Table 1 with a HRWR dosage that varied with ambient temperature. A slump flow of the final mixture design is shown in Fig. 1. In determining the final expanded clay mix design it was very important to keep a high cement content and relatively low *w/c* in order to fulfill both the workability and compressive strength requirements. It was also necessary to have a coarse aggregate content of at least 650 lb/yd^3 (385 kg/m^3) to keep the unit weight under the 120 lb/ft^3 (1922 kg/m^3) requirement.

Table 2 Concrete Properties

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: 1 in. = 25.4 mm, 1 psi = 0.006895 MPa, 1 lb = 0.454 kg, 1 ft^3 = 0.0283 m^3, -- indicates no measurements were taken

Errors were observed between the predicted moisture content used for adjusting the mixing water for each batch and the actual moisture content measured from the unit weight of the aggregate sample. These errors were due to the fact that the moisture content could not be measured in the traditional manner before each batch was mixed. For normal weight concrete, the moisture content of the coarse and fine aggregate is determined prior to mixing by drying an aggregate sample overnight in an oven.

In lightweight concrete, the lightweight aggregates are continually soaked or saturated until mixing. Therefore, if a sample of lightweight aggregate was removed from the stockpile and placed in the oven to dry overnight, this sample would have a lower moisture content than the aggregate in the stockpile that was allowed to soak until batching. The stockpiled aggregate would have an additional 24 hours to absorb water when compared to the sample placed in the oven. The stockpiled aggregate would have a higher moisture content than the sample placed in the oven. As previously mentioned, the lightweight aggregate moisture content in this research program was determined by measuring the loose unit weight of the aggregate. The moisture content error was determined by placing a sample of the lightweight aggregate in the oven the day the concrete batched and allowed to dry overnight. The difference between the true moisture content and that obtained from the aggregate loose unit weight is the moisture content error.

The relationship between this moisture content error and f'_{ci} for each w/c is plotted in Fig. 2. The values are the difference in the predicted percent of moisture by weight and the actual measurement. A positive error indicates that there was more water in the mix than anticipated, whereas a negative error implies less water in the mix than anticipated. No statistical analyses were performed due to the small sample size, but the plot indicates that small errors (less than 3 percent) in moisture content did not appear to have a large effect on f'_{ci} for a given w/c. There is also some scatter in the results for the closely spaced data points from mixtures with a 0.40 w/c. This scatter is even more evident in the plot of moisture content error with f'_c for each w/c shown in Fig. 3. Small errors (less than 3 percent) in moisture content do not appear to have a large effect on f'_c for these mixtures either.

Fig. 1 Slump Flow for Mixture 19

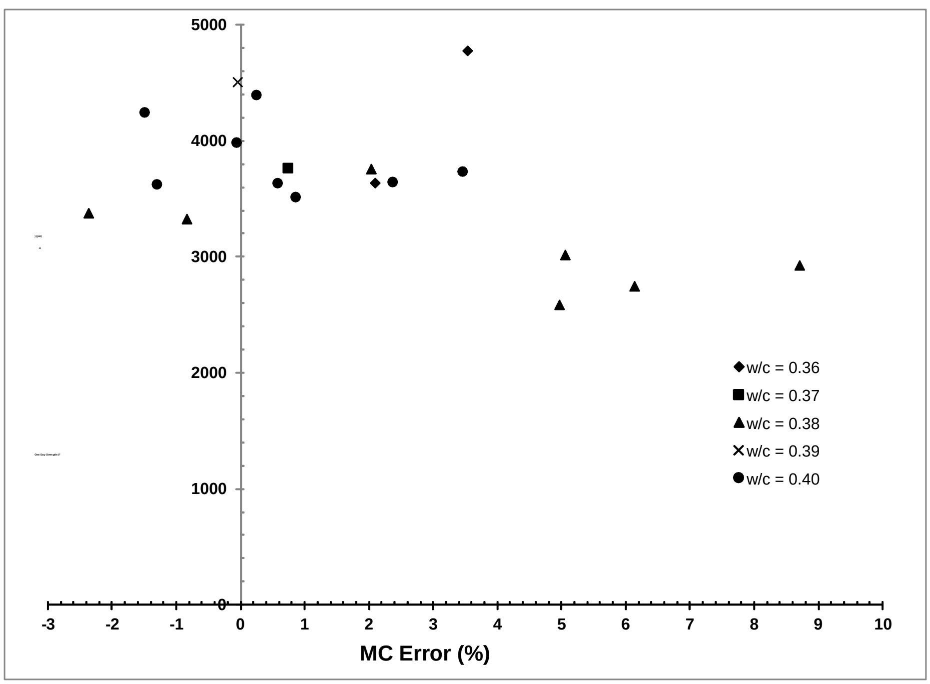

Fig. 2 Effect of Aggregate Moisture Content Error on One Day Compressive Strength

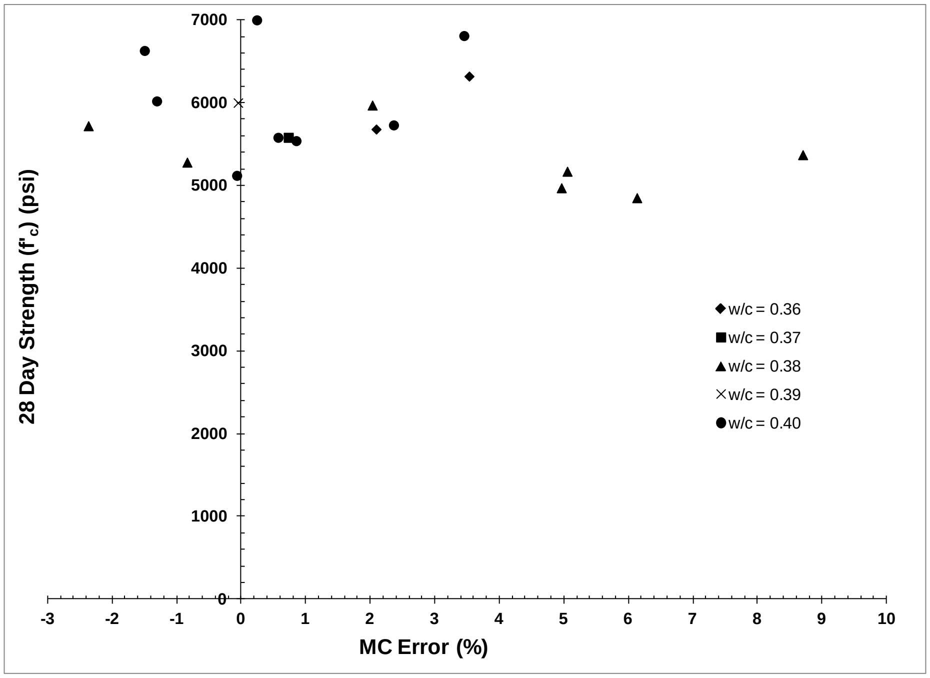

Fig. 3 Effect of Aggregate Moisture Content Error on 28 Day Compressive Strength

CONCLUSIONS

A total of 22 trial batches were required to develop LWSCC mixtures meeting both the fresh property and compressive strength requirements. The variables adjusted to meet these requirements included cement content, water content, *w/c*, *s/agg*, and HRWR dosage. HRWR dosages within the range recommended by the manufacturer were adequate for these mixtures. The most difficult aspect of the mixture development was finding the proper balance between fresh properties and compressive strength.

The effect of error in estimating the moisture content of the lightweight aggregate on f'_{ci} is shown in Fig. 2 and the effect on f'_c is shown in Fig. 3. As was indicated by the results of the trial batches, these plots provide no indication moisture content estimation errors less than 3 percent in magnitude had any significant effect on the compressive strength of the beam batches at one or 28 days. This was most likely due to the high cement content for all of the mixtures and the limiting effect of the coarse aggregate on the compressive strength of the lightweight concrete.

Researchers also determined that presoaking the lightweight aggregate for a consistent time period is necessary to obtain a consistent moisture content. A relationship between unit weight of the presoaked aggregate and the aggregate moisture content is effective for consistently estimating aggregate moisture content. An error typically exists between the estimated moisture content of the aggregate used for mix design adjustments and that measured from the sample used to determine aggregate unit weight. The effects of these errors on workability of the concrete can be accounted for by adjusting the HRWR dosage during mixing of each batch.

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