VARIABILITY OF LIGHTWEIGHT AGGREGATE SOURCE: EFFECT ON THE DEVELOPMENT OF HIGH STRENGTH LIGHTWEIGHT SCC MATRIX BLENDED WITH NORMAL WEIGHT AGGREGATE


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Dedicated to Prof. György L. Balázs
for his 65th birthday

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Structural lightweight concrete is a valuable alternative to normal weight concrete. Concrete prepared with coarse lightweight aggregate provides reduction of a structure self-weight and better structural performance in regions prone to seismic activities. However, variability of the coarse lightweight aggregate affects production and properties of the concrete. In addition, availability of the aggregate influences the long-term use and stability in the construction industry. Lightweight aggregate is imported from Iran, Turkey, Saudi Arabia, UK, and Greece to the United Arab Emirates (UAE) and has been used in structural and non-structural applications.

This paper presents the development of a self-consolidating high strength lightweight concrete (SCHSLWC) matrix with available materials in UAE. Specific gravity, unit weight, gradation, particles' shape and absorption were used during the development and selection of aggregates source. In addition, percentage of normal weight aggregate that could be used to improve the matrix was optimized. Results of the experimental investigation showed that self-consolidating concrete mixes with more than 50 MPa cube compressive strength could be produced with aggregates having specific gravity factors in the range of 1.15 to 1.4. Additionally, up to 12% per volume of the coarse lightweight aggregate could be replaced by normal weight coarse aggregate while maintaining a unit weight less than 2000 kg/m^3.

Keywords: self-consolidating concrete, SCC, Lightweight aggregate, Aggregate source

1. INTRODUCTION

Durability and strength requirements are equally important for normal and lightweight concrete mix development/proportioning. Exposure conditions influence the short and long-term structural performance; on the other hand, strength is essential for the structural design. Durability requirements are achieved by controlling the water-to-cementitious ratio (*w/cm*); reduction of cement content and addition of other cementitious materials (slag, silica fume, fly ash and natural pozzolans) based on exposure conditions. Generally, aggregate strength and cementitious materials paste affect concrete strength; however, in the case of lightweight concrete, interfacial transition zone (ITZ) contribute to the overall strength. Therefore, aggregate strength, specific gravity, unit weight, and absorption capacity are the most important parameters which should be considered during any lightweight concrete mixture development. These parameters are related to aggregate type and production method.

Several sources of lightweight aggregates are available in the United Arab Emirates (UAE); however, the variability of the aggregate source; often times the variability within the same source, affects the fresh and hardened concrete properties. Therefore, the objective of this research is to develop a self-consolidating high strength lightweight concrete (SCHSLWC) mixture utilizing lightweight aggregate from a single source that is available in UAE. In addition, lightweight aggregate from four other sources available in UAE, were used to evaluate the variability of the aggregate source on the developed mixture. The evaluation criteria during this stage of the project were fresh properties, unit weight, and compressive strength.

2. BACKGROUND

Many research efforts were devoted lately to the development and evaluation of lightweight aggregate concrete. These efforts could be classified under three categories; aggregate production/properties, mix proportioning, and durability/strength evaluation. These efforts are briefly discussed in the following subsections. In addition, several guidelines for the development of Self-Consolidated Concrete (SCC), High-Strength Concrete (HSC), High-Strength Lightweight Concrete (HSLWC), and Self-Consolidated High Strength Lightweight Concrete (SCHSLWC) found in the literature were summarized and presented.

2.1 Lightweight Aggregate Production/Properties

Utilizing lightweight aggregate in concrete mixtures help reduce structures' dead load, in addition, it provides other desired qualities for concrete such as, thermal and acoustic insulation, and fire resistance (Banawair et. al. 2019, Nadesan and Dinakar 2017, Cerny 2016, Barbosa et al., 2012; Jo et al., 2007). However, performance of lightweight aggregate concrete is controlled by the physical and mechanical properties of the lightweight aggregate used in the mixture. These properties include specific gravity factor, water absorption, aggregate size and shape, porosity, gradation and aggregate strength (Chi et al., 2003; Lo & Cui, 2004; Lo et al., 2007; Lo et al., 2008; Bentz, 2009; Silva et al., 2010; Kockal & Ozturan, 2010, Yang et. al 2014, Nadesan and Dinakar 2017). Absorption and aggregate's strength greatly influence concrete production and mechanical properties of lightweight concrete. Total pore volume accessible to water determines the absorption of the lightweight aggregate. Generally, absorption is in the range of 5 to 20 % by mass of the dry lightweight aggregate and may reach up to 30% in certain types of lightweight aggregate (LWA) (Chi et al., 2003). This high absorption imposes difficulty in determining the *w/cm* needed for the mix (ACI 318-19). Moreover, the ACI213R-14 emphasizes on the importance of pre-wetting because of the absorptive nature of lightweight aggregates. In addition, slump or self-consolidation levels will be difficult to achieve without a pre-wetting process (ACI 213R-14; Kabay & Aköz, 2012). It is also, expected that a longer mixing duration will be required when mixing lightweight concrete to achieve homogeneity (Barbosa et al., 2012).

The cellular structure of the LWA affects aggregate strength and consequently affects the concrete strength. LWA has a high crushing value which is an indication of low strength, typically, is in the range of 22- 40% (Haque et al., 2004). Several research efforts were devoted to improve both properties by using different binders, special heat treatment or by adding polymers to enhance the durability and strength of the lightweight concrete (Wasserman & Bentur, 1996; Kockal & Ozturan, 2011, Nadesan and Dinakar 2017, Yang et. al. 2014). However, the commonly used lightweight aggregates for structural applications are Pumice, Foamed Slag, Expanded Clays and Shales, and Sintered Pulverized–fuel ash aggregate (ASTM 2014; Chandra, Berntsson, & Knovel (Firm), 2002; Neville, 1995). The specific gravity factors of the lightweight aggregate for structural applications is typically in the range of 1.2 to 1.5 for coarse aggregate and the bulk density of the aggregate is in the range of 300 – 900 kg/m^3 based on the production process (Chandra et al., 2002; Neville, 1995). Furthermore, the ASTM C330 specifies (880 kg/m^3) as the maximum dry loose bulk density of lightweight aggregates for structural concrete coarse aggregate. This means in some cases, the aggregate will have a lower density than that of the mortar paste (typically 2100-2200 kg/m^3), compromising stability of the mix and segregation becomes a concern especially in the case of self-consolidation or if vibration is required et al., 2005). Moreover, whether the aggregate will float or not depends not only on the density difference, but also viscosity of the mix will play a role in determining the resultant driving force.

2.2 Mix Development

Mix proportioning to achieve self-consolidating, high strength lightweight concrete should consider guidelines/recommendations specified for each characteristic. The following subsections summarize different approaches for mix proportioning, sample of mixes found in the literature and general guidelines for producing SCC, HSC, HSLWC, and SCHSLWC.

2.2.1 Mix proportioning - Available approaches from literature

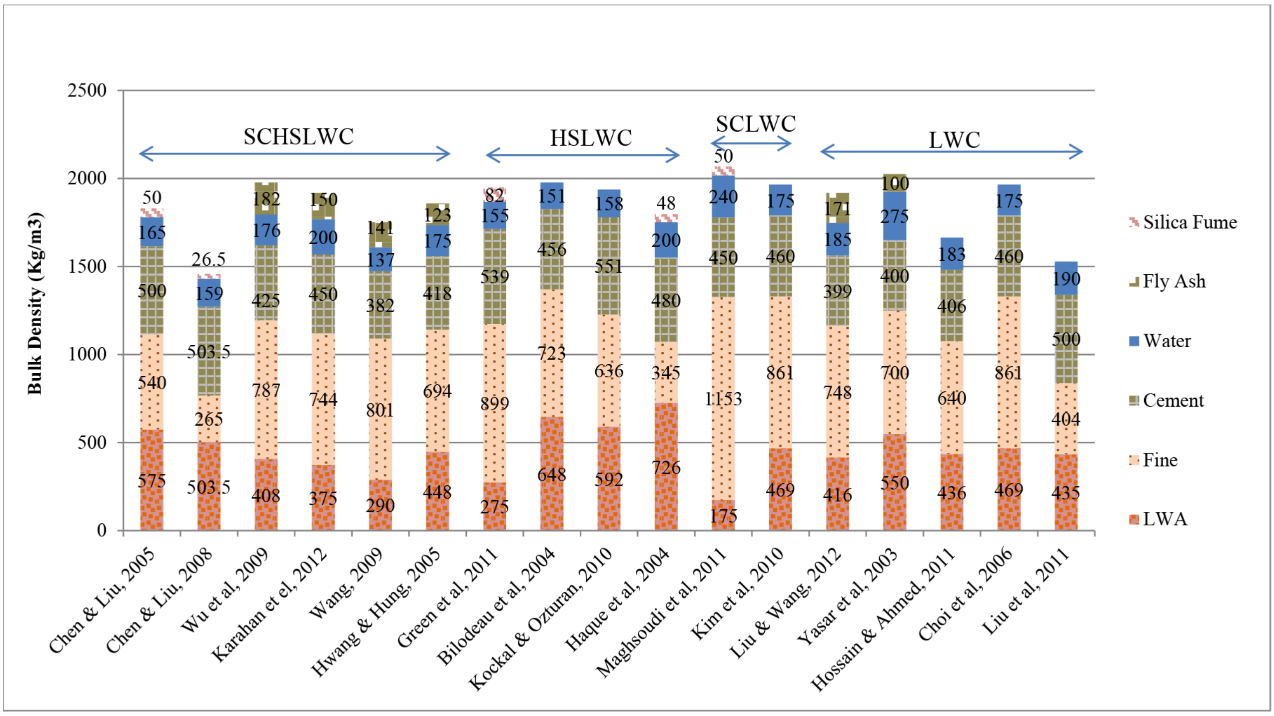
The microstructure of the lightweight aggregate usually leads to high absorption, which imposes difficulties in determining the mixing water and the amount that will be absorbed by the aggregate. Therefore, different approaches could be followed to proportion and determine the weight of each ingredient. ACI PRC-211.1-22 methods (weight method and volumetric method) and Densified Mixture Design Algorithm (DMDA) (Hwang & Hung, 2005) are examples of these approaches. However, these methods require adjustment; therefore, trial batches should be prepared to adjust mixing water, target slump, and unit weight of fresh concrete.

2.2.2 Lightweight Concrete Mixtures from literature

Several lightweight, self-consolidating, high strength and self-consolidating high strength lightweight concrete mixtures found in literature were summarized as shown in Figure 1. These mixtures were classified based on the ACI 213R-14 strength requirement (40 MPa) and on concrete workability. Taking into consideration, variability of the lightweight aggregate (properties, particle size, gradation, etc.), variability of the local materials (including admixtures) and variability of the volumetric ratios for each ingredient, these mixtures were compared with respect to unit weight, structure efficiency (strength/unit weight), strength, and percentage of coarse aggregate, as shown in Figure 1. The comparison showed that the volumetric ratio of the coarse lightweight aggregate should be in the range of 30 to 45% of the total mix. In addition, high strength could be achieved by w/cm in the range of 0.32 to 0.42 and by utilizing supplementary cementitious materials, which will help in producing a dense Interfacial Transition Zone (ITZ), hence, improving concrete strength (Kockal & Ozturan, 2010). General guidelines collected from the literature to produce SCC and HSC with normal weight aggregate and lightweight are summarized in Table 1. These guidelines provide a volumetric range of each ingredient and recommendations about materials' specifications.

The minimum durability and strength requirements in ACI 318 building code are based on the exposure categories and classes. Development of sustainable, dense, and impermeable concrete could be achieved by the use of supplementary cementitious material and by controlling w/cm ratio (Chen & Liu, 2008). In addition, dense mixes will help achieve high strength; however, strength of lightweight concrete (LWC) depends also on the interfacial zone (ITZ). The ITZ is affected by aggregate absorption, porosity of the interface which in turn is affected by the use of supplementary materials and fine sand (Liu et al., 2011). However, higher percentage of fines influences the time-dependent properties (shrinkage and creep) and impact concrete durability. Therefore, careful mix proportioning is necessary to control factors that affect shrinkage and creep (ACI 213R-14).

In this paper, an experimental investigation to develop a SCHSLWC utilizing local material available in the UAE is presented. Lightweight coarse aggregate and normal weight fine aggregate were used during the investigation.



Strength	42.5	50	50.1	39.7	48	53	42.5	62.8	42.3	49.5	28.5	28	29	32	23	34	38
Unit Weight	1830*	1477	1920	1958	1634*	2052	1960	1977	1860	1800*	1870	1970	1876	1860	1861	1965	1610
Eff.	23.2	33.9	26.1	20.3	29.4	25.8	21.7	31.8	22.7	27.5	15.2	14.2	15.5	17.2	12.4	17.3	23.6
Coarse %	40	45	29	26	31	31	23	45	38	56	17	30	52	38	46	31	39

Fig. 1: Sample of SCHSLWC, HS LWC, SCLWC and LWC mixtures found in the literature

Table 1: Guidelines for materials' proportioning SCC, HSC, HSLWT and SCHSLWC (ACI, 2003, 2004, 2007, 2010, 2011b; 2014, 2022, Bilodeau et al., 2004; Chen & Liu, 2005, 2008; Choi et al., 2006; Green et al., 2011; Haque et al., 2004; Hossain & Ahmed, 2011; Hwang & Hung, 2005; Karahan et al., 2012; Kim et al. , 2012; Kimet al., 2010; Kockal & Ozturan, 2010; Liu et al., 2011; Liu & Wang, 2012; Maghsoudi et al., 2011; Wang, 2009; Wet al., 2009; Yasar et al., 2003)

	SCC	HSC	HSLWT	SCHSLWC
Water Cement Ratio	Based on strength requirements, refer to w/cm ratio and strength relation	Typically w/c >0.4	Based on strength requirements, refer to w/c ratio and strength relation	To achieve high strength with self-consolidation, typically w/c falls within 0.32-0.42.
Water Content	Refer to ACI 318-11, Table 4.4.1	100- 140 kg/m³, depends on the use of Super plasticizers and mineral admixtures	Not specific content because of the higher absorption capacity and difficulty in determining the free water in the mix.	Not specific content because of the higher absorption capacity and difficulty in determining the free water in the mix. Typically 140-200 kg/m³ (15-25% of total volume).
Cementitious Material Content	18% per volume or maximum 200 kg/m³ (12.48 lb. /ft³). Typically silica fume can replace up to 5% of cement to enhance strength gain and viscosity, and fly ash up to 10% to enhance strength and flowability	350 – 400 kg/m³, typically silica fume can replace up to 5% of cement to enhance strength gain and viscosity, and fly ash up to 10% to enhance strength and flowablity	420-500 kg/m³ (25.9 – 31.11 lb./ft³) for 40 MPa concrete strength – 630 kg/m³ (38.89 lb./ft³) for 70 MPa concrete strength	380-520 kg/m³ (10-20% of total volume). Typically silica fume can replace up to 5% of cement to enhance strength gain and viscosity when avoiding for avoiding viscosity modifying admixtures, and fly ash up to 10% to enhance strength and flowablity
Fine normal weight aggregate	350-450 kg/m³ (21.9 – 28.09 lb./ft³) – Max fly ash 25% by weight	Fine aggregate with fineness modulus (F.M.) > 2.9 due to high cement content	Can replace light weight fine aggregate to improve placing and compaction – increase in concrete density is expected	Can replace light weight fine aggregate to improve placing and compaction to improve placing and compaction – increase in concrete density is expected. Typically 270-860 kg/m³ (10-40% of total volume)

Fine lightweight Aggregate	N/A	N/A	Fines passing #4 sieves (4.75 mm) are expected to greatly affect strength, for they lower crushing strength. Thus inclusion will unlikely provide more than 40 MPa f'c.	Fines passing #4 sieve (4.75 mm) are expected to greatly affect viscosity and stability of flowable concrete, for finer particles will not blend properly in the matrix, causing segregation
Coarse Aggregate	Should be in the range of 0.48-0.54 – 1/2 in. nominal aggregate size	Smaller maximum size of aggregate to improve strength; typically maximum size of 10 mm.	Smaller maximum size of aggregate to improve strength, typically 10 or 5 mm.	Smaller maximum size of aggregate to improve strength, mainly maximum size of 4.75 mm (#4 sieves). Typically 300-580 kg/m^3. (20-50% of total volume)
Chemical Admixtures	Should follow the manufacturer recommended dose	Should follow the manufacturer recommended dose	Should follow the manufacturer recommended dose	Should follow the manufacturer recommended dose. Super plasticizer dose is 1-2% of total volume.

3. EXPERIMENTAL PROGRAM

The main objective of the experimental program was to develop a self-consolidating high strength lightweight concrete (SCHSLWC) for structural applications meeting the target strength [40 MPa (6000 psi)] and unit weight less than 2000 kg/m^3 (120 lb/ft^3) as defined by ACI 213R-14. This objective could be achieved by using 100% coarse lightweight aggregate or by partial replacement of normal weight coarse aggregate in addition to normal weight fine. Therefore, optimization of the percentage of normal weight coarse aggregate that could be used while maintaining the unit weight requirement was investigated. In addition, effect of aggregate source variability on the properties of developed mixes was evaluated by monitoring the variation in concrete properties. Therefore, the experimental program consisted of two phases: Phase I focuses on the development of the mix and phase II concentrates on the evaluation of aggregate source variability on the developed mix at the fresh and hardened stages.

3.1 Methodology

The following highlights the main steps of the mix development:

1- SCHSLWC mix is developed to achieve higher compressive strength with one source of LWA in the UAE, utilizing 100% coarse LWA and normal weight sand in all mixes. Then, adjust the mixture to meet characteristics of SCC.
2- Partial replacement of normal weight coarse aggregate is introduced to achieve dense mix, hence, improve concrete strength.
3- Mixes are evaluated and adjusted for workability and compressive strength.
4- In the optimized mix, lightweight aggregates (specific gravity, particle size and shape, gradation) from another source is used to evaluate the effect on workability, unit weight and strength.

3.2 Phase I – Development of SCHSLWC mix

Material properties

Lightweight Aggregate – Source #1

Lightweight aggregate from one source in UAE was used during this phase of the investigation. Figure 2 shows a sample of the aggregate (Pumice) which is labeled "Source #1" in the discussion.

The aggregate gradation is shown in Table 2. The sieve analysis of the samples as received indicated that about 55% of source #1 had size less than 4.75mm (Sieve No. 4); however, 45 % of this source had sizes between 9.5 and 4.75mm.

Other Materials

Concrete mixes in this study, in addition to the lightweight coarse aggregate, utilized an ordinary Portland cement Type-I (SG 3.14), fly ash class F (SG 2.1), silica fume (SG 2.22), normal weight coarse aggregate (SG 2.58) with 10 mm nominal maximum aggregate size (for partial replacement), normal weight dune sand (particle size 100% passing 0.6 mm, SG 2.60), and coarse sand (maximum particle size 4.75 mm, SG 2.60).

Mix Proportioning

The mix proportion of the SCHSLWC mix was similar to that of a self-consolidating high strength normal weight (SCHSNW) mix developed by (Yehia et. al. 2009). The

Figure 2. Pumice – Sample of Source 1

Table 2: *Gradation of aggregate used in the investigation*

	Sieve Size (mm)								
	19	12.5	9.5	4.75	2.36	1.18	0.3	0.15	0.075
	ASTM C 330M-2009 Limits (Coarse 9.5-2.36 mm)								
	As Received (%Passing)								
Grading requirement / Aggregate source	-	100	100-80	40-5	20-0	10-0	-	-	10-0
Source #1	0	100 (Y)	100 (Y)	55 (N)	30 (N)				
Source #2	0	100 (Y)	99.3 (N)	70.5 (N)	42 (N)	25.1 (N)	8.8	3.3	0.3 (Y)
Source #3	0	100 (Y)	71.1(N)	39.8 (Y)	19.1 (Y)	5.3 (Y)	0.34	0.13	0.13 (Y)
Source #4	0	100 (Y)	66.1 (N)	8.9 (Y)	3.5 (Y)	2.9 (Y)	0.3	0	0 (Y)
Source #5	0	100 (Y)	19.9 (N)	6.5 (Y)	4.6 (Y)	4.1 (Y)	3.3	1.5	0 (Y)
	ASTM C 330M-2009 Limits (Combined fine and aggregate, 9.5-0 mm)								
	Combined with fine 100% (%Passing)								
Grading requirement / Aggregate source	-	100	100-90	90-65	65-35	-	25-10	15-5	10-0
Source #2	100	100 (Y)	99.2 (Y)	60.6 (N)	57.1 (Y)	49.2	34.5 (N)	16.1 (N)	2.3 (Y)
Source #3	100	100 (Y)	100 (Y)	60.1 (N)	55.2 (Y)	45.6	29.7 (N)	10.1 (Y)	1.2 (Y)
Source #4	100	100 (Y)	100 (Y)	80.9 (Y)	55.8 (Y)	47.4	28.9 (N)	8.4 (Y)	2.1 (Y)
Source #5	100	100 (Y)	100 (Y)	59.7 (N)	56.1 (N)	47.9	33.1 (N)	12.5 (Y)	1.4 (Y)
	ASTM C 330M-2009 Limits (Combined fine and aggregate,12.5-0 mm)								
	Combined with fine 88-12% (%Passing)								
Grading requirement / Aggregate source	100	100-95	-	80-50	-	-	20-5	15-2	10-0
Source #2	100(Y)	100(Y)	97.5	55.6 (Y)	51.5	43.4	28.9 (N)	8.6 (Y)	0.9 (Y)
Source #3	100(Y)	100(Y)	97.5	57.9 (Y)	53.4	46.7	33.5 (N)	16.8 (N)	2.5 (Y)
Source #4	100(Y)	100(Y)	98.4	73.8 (Y)	66.6	44.4	31.1 (N)	11.6 (Y)	1.2 (Y)
Source #5	100(Y)	100(Y)	98.3	55.5 (Y)	51.4	42.6	30.0(N)	7.42 (Y)	0.5 (Y)

Source #2
Light expanded clay

Source #3
Pumice

Source #4
Pumice

Source# 5
Sintered pulverized–
fuel ash aggregate

*Shaded cells do not meet ASTM gradation requirement

volumetric ratios of the SCHSNW mix based on the absolute volume method were 19.5 % cement and mineral admixtures (fly ash and silica fume) and 63% aggregate (31% coarse and 32% fine aggregate). These volumetric ratios are comparable and are within the ranges of that reported in the literature, Table 1. Therefore, the same volumetric ratio of the normal weight aggregate (NWA) was replaced by source #1 LWA; however, minor adjustments were required to determine weight of the lightweight aggregate and w/cm needed for the mix. In addition, normal weight coarse and dune sand were used in all mixes.

Mixing

Several mixes were prepared with the full gradation of source #1; however, difficulties were encountered due to the high percentage of fine lightweight blended with the coarse aggregate (about 60% of the particle had size less than 4.75 mm). Therefore, particle size of the LWA smaller than 4.75 mm was excluded from all mixes after the initial trials. In addition, optimization was conducted to determine percentage of NWA that could be used maintaining the target unit weight and compressive strength. Workability, unit weight, and compressive strength were the evaluating criteria at this stage.

3.2.1 Results and discussion - Phase I - Development

The experimental investigation included several mixes with 100 % normal weight aggregate (control mix), 100% lightweight aggregate and partial replacement of lightweight aggregate with normal weight aggregate. Two ratios 25% (75LWA-25NW) and 50% (50LWA-50NW) of the volumetric ratio of the LWA were substituted with NWA. Results of the evaluation criteria during this stage is discussed in the next subsections.

Workability and surface finish

Slump flow test was used to evaluate flowability and visual stability of the mixes. All mixes [control (100% SCHSLWC) and LWA with partial replacement of NWA] had acceptable flow with a diameter in the range of 550 to 600 mm in less than a minute with no sign of segregation. In addition, there was no aggregate floating at the surface and there was no difficulties finishing the surface, as shown in Figure 3 (source #1).

Optimization to introduce coarse NWA – partial replacement of coarse LWA

Average cube compressive strength of the control mix and 100% LWC source #1 was 65 MPa and 48 MPa, respectively. Results of the 50LWA-50NW showed that the dry unit weight is higher than 2000 kg/m^3; therefore, higher percentages of NWA were not included in the optimization. Figure 4 shows the results of the optimization with respect to the unit weight. A target unit weight (1850 kg/m^3) was selected from the optimization chart and corresponding percentage of NWA which could be used, was determined to be 12%. The 88LW-12NW mix was prepared and evaluated. The average cube compressive strength was 63 MPa and the dry unit weight was 1843 kg/m^3. These results showed that the mix 88LWA-12 NWA met the unit weight and compressive strength requirements for structural applications. Figure 5 provides a comparison between average compressive strength and unit weight of all mixes in phase I. The results showed that the 12% NWA replacement would help improve the compressive strength while maintaining the unit weight less than 2000 kg/m^3. However, this percentage depends on gradation, particle shape and specific gravity factor of the LWA used in the investigation.

3.3 Phase II – Evaluation of Different Sources of LWA

The main objective of this phase is to investigate impact of aggregate source variability on the concrete properties. Four physical properties (specific gravity factor, bulk density, gradation, and absorption) are believed to have influence on the lightweight concrete production ((Banawair et. al. 2017, Nadesan and Dinakar 2017, Cerny 2016, Kockal & Ozturan, 2010; Lo et al., 2008; Lo et al., 2007). Therefore, these properties were considered in the evaluation. The mix developed in phase I, 88LWA-12NWA, was taken as a control mix in this phase.

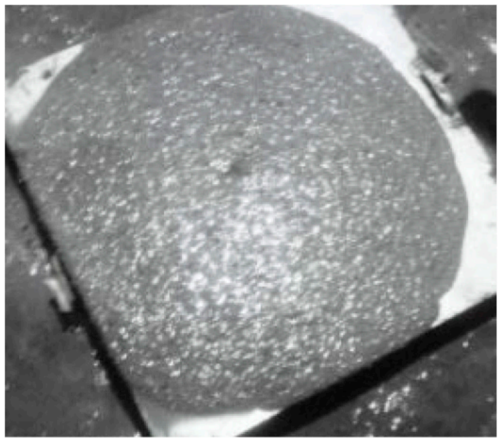


Fig. 3: Slump flow test – Source 1

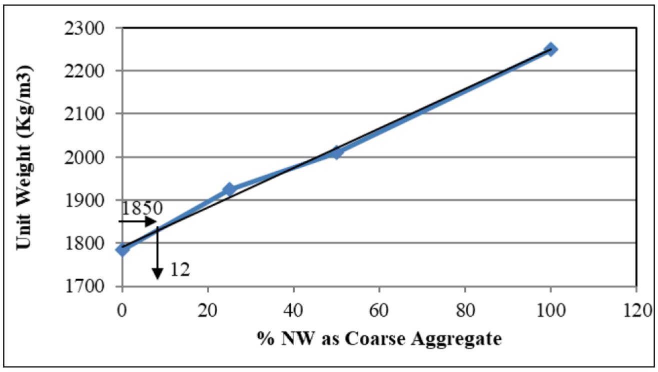


Fig. 4: Unit Weight vs. percentage of NWA used in the optimization

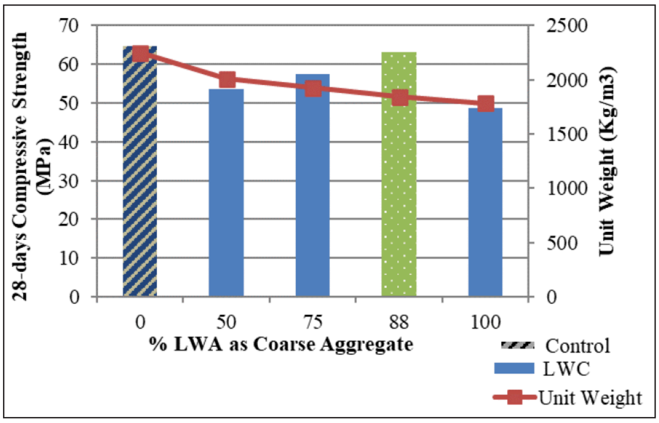


Fig. 5: Summary of the optimization results

Material properties - Lightweight Aggregate

Light expanded clay (source #2), pumice lightweight aggregate from different sources (source #3, source #4) and sintered pulverized–fuel ash aggregate (source # 5) were used in this investigation, samples are shown in Table 2. Sources #2 and #5 particles had spherical shape, while sources # 3 and # 4 particles had angular shape (crushed with rough surface). Sieve analysis was conducted for all samples as received and compared to the grading requirements by ASTM C330/C330M, as shown in Table 2. The Sieve analysis indicated that source #2, source #3, and source # 4 had about 50%, 70%, and 50% passing from 4.75mm (Sieve No. 4), respectively. On the other hand, about 1% of source #2 had sizes between 12.5

Table 3: *Properties of the lightweight aggregate and concrete produced with respective sources*

Source / Property	Source #1	Source #2	Source #3	Source #4	Source #5
Specific gravity	1.3	0.7	0.7	1.35-1.40	1.15-1.25
Bulk density (kg/m^3)	560-660	380 - 480	490 - 575	750 - 800	700-800
Particle shape	Angular	Spherical	Angular	Angular	Spherical
Microstructure (Absorption as indicator)	11	20	36	18	28
Cube concrete strength produced with the source (MPa)	63.1	26	10	57.7	52.2
Dry unit weight at 28-days (kg/m^3)	1843	1946	1776	2060	1954

and 9.5mm, whereas sources #3 and #4 have no aggregate size greater than 9.5 mm. Therefore, lightweight coarse aggregate (aggregate retained on Sieve No. 4 and above) was only considered in this study, as the case of source #1. In addition, sieve analysis was conducted for the following samples (i) coarse LWA (particles more than 4.75mm) and fine normal weight and (ii) coarse LWA, fine normal weight and coarse normal weight. Results showed that inclusion of normal weight aggregate (12%) with a size larger than 9.5 mm (12.5 mm) enhanced the aggregate gradation, although particle sizes (4.75 mm, 0.30 mm and 0.15 mm) for one or more sources did not meet the ASTM C330/C330M due to the replacement of the lightweight fine aggregate by normal weight dune and coarse sand. However, the authors decided to include these sources to evaluate the effect of particle size and specific gravity factor on the strength and unit weight of the developed mix. Bulk dry density and specific gravity factors (SGF) of all sources are summarized in Table 3. Specific gravity factors less than "1" was determined by trial and error in separate batches by evaluating the yield and unit weight of wet concrete.

3.3.1 Results – Phase II

Fresh stage evaluation

The 88LWA–12NWA developed in phase I was used as a control mix for comparison and to investigate impact of variation of aggregate properties (source variability) on the fresh and hardened properties. Variation of the specific gravity factors and absorption among the four sources and their impact were taken into consideration during the mix proportioning. However, cementitious materials and w/cm were kept the same for all mixes. Table 4 provides a comparison of the fresh stage (workability and surface finish) properties evaluated in the study.

Mixing

Specific gravity factor of sources #2 and #3 were less than 1; consequently, the aggregate was floating to the surface during mixing, as shown in the pictures, Table 4.

Workability

The slump flow test showed that all mixtures met the ACI 237-07 SCC characteristics (500 mm spread) without segregation for sources #4 and #5; however, sources #2 and #3 a small percentage of the lightweight aggregate was piled in the center of the spread as indicated by circle in the pictures correspond to these sources in Table 4. This could be explained by the low specific gravity of sources #2 and #3 that caused floating of the particles and segregation to occur.

Surface Finish

Lightweight aggregate sources #2 and #3 were floating due to their low specific gravity; as a result, volume instability was exhibited and difficulties were encountered during the surface finish of the samples, as shown in Table 4.

Hardened stage evaluation

Cube compressive strength and dry unit weight were the evalaution ceriteria at this stage of the investigation. Compressive strength and dry unit weight of source #1 were the base of comparison while using the same volumetric ratio of light to normal weight coarse aggregte. Table 3 summarizes the results of the 28-day testing. In addition, monitoring of the strength development was also conducted for all concrete mixtures.

Compressive strength

Cube compressive strength for sources #4 and #5 achieved more than 50 MPa which is less than that for source #1. This could be attributed to the difference in particle size and distribution. In addition, source# 4 achieved higher compressive strength than that for source #5, this was believed to be due to the particles' shape since all other parameters (specific gravity and bulk density) are within the same range. The above findings are acceptable for the specific gravity factor in the range of 1.15 to 1.4 and bulk density between 500 to 800 kg/m^3 (Chen & Liu, 2008).

On the other hand, sources #2 and #3 had compressive strength less than 40 MPa which is the value defined by ACI 213R-14 as high strength lightweight concrete for structural applications. Low specific gravity factor (less than 1), higher percentage of smaller size aggregate (4.75 mm) and high absorption are the reasons for not achieving dense mixes and high compressive strength (Lo et al., 2007). Particle shape in both sources was not the determining factor of the performance; however, performance of source #2 was better than that of source #3, this might be contributed to the spherical shape particles (Cui et al., 2012). Close inspection for several cross-sections of the mixtures revealed that sources #2 and #3 had high percentage of internal voids and voids between aggregate particles, as shown in the pictures, Table 5. The presence of these voids is expected to lead to high shrinkage and creep strains in addition to low compressive strength (Neville, 1995).

Failure patterns

Pictures in Table 5 show typical failure patterns of cylindrical specimens during the compressive strength testing. Specimens from sources #1, #4, and #5 showed vertical splitting which is commonly observed in high-

Table 4: Fresh stage properties phase II

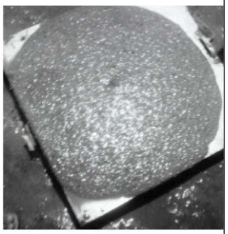
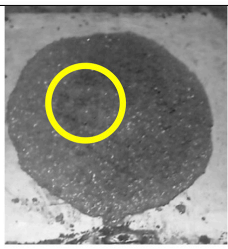
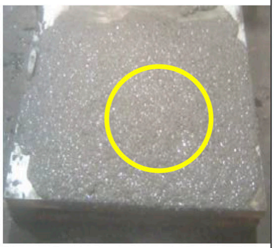
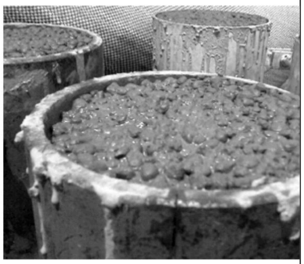
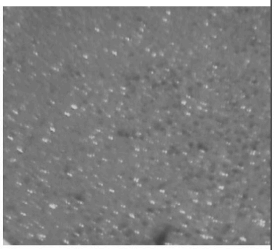
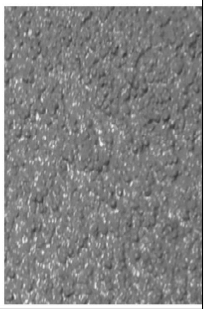
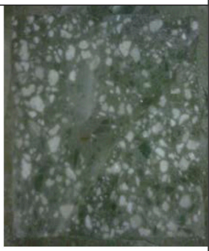
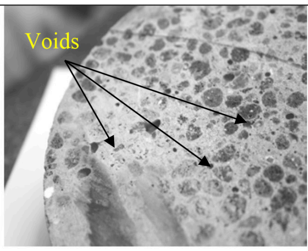
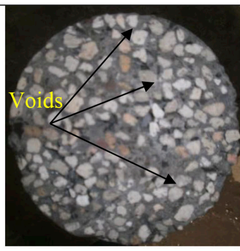
Source / Property	Source #1	Source #2	Source #3	Source #4	Source #5
Workability					
Surface finish					

Table 5: Hardened stage properties

Source	Source #1	Source #2	Source #3	Source #4	Source #5
Typical Failure Mode					
Cross section					

strength concrete specimens. However, failure patterns from sources #2 and #3 specimens' indicated weak bond between the lightweight aggregate and the cementitious materials, in addition to weakness due to high porosity of the aggregate. This also could be explained by the weak interfacial transition zone (ITZ) as discussed by (Lo & Cui, 2004; Bentz, 2009).

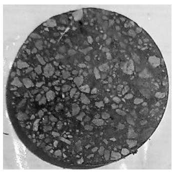
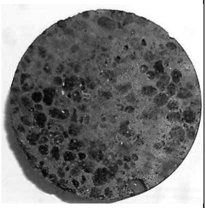
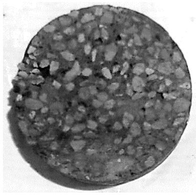
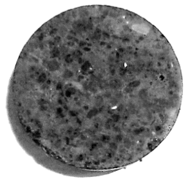
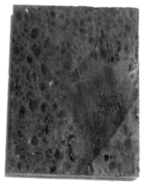
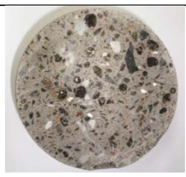
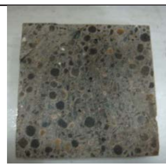
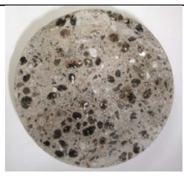
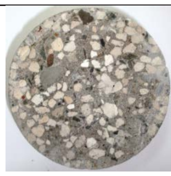
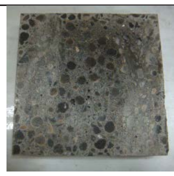
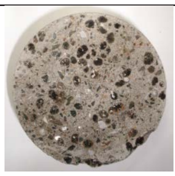
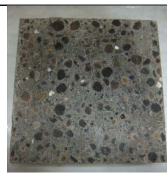
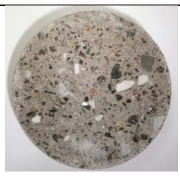
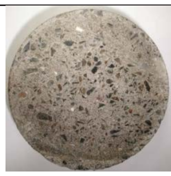
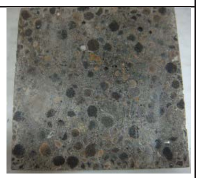
Unit weight

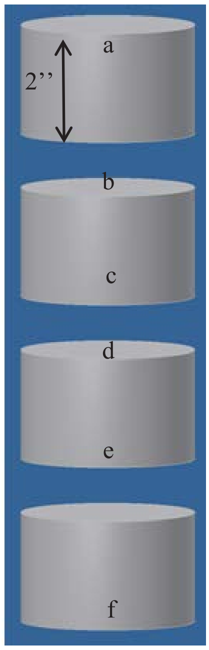
Dry unit weight was determined for samples from all sources and summarized in Table 3. Sources #1 and 4 #5 had slightly higher unit weight than that recommended by ACI 213R-14; however, higher compressive strength was achieved by these sources. The other two sources met the recommended unit weight; however, both had low compressive strength for the reasons discussed before in previous section.

Static stability

Specimens from all sources were examined to ensure that the proposed SCHSLWC mixes maintain adequate resistance to segregation and settlement. Specimens (100mm x 200mm cylinders) were cut to four sections each 50mm and labeled as top (a), middle1 (top (b) and bottom(c)), middle 2 (top (d) and bottom (e)), and bottom (f), as shown in Table 6. The cross sections of source #1, source # 4 and source # 5 specimens showed good distribution of the lightweight aggregate and no sign of segregation was found. However, sources # 2 and # 3 showed a clear segregation, which was identified by the low concentration of the lightweight aggregate within the bottom 100 mm of the cylinders, as shown in "e and f" source #2 and #3, Table 6. This could be explained by the low specific gravity factors of these two sources, which led to floating of the aggregate in the flowable SCC mix.

Table 6: Cross section evaluation for static stability

	Source #1	Source #2	Source #3	Source #4	Source # 5
Top (a)					
Middle 1-top (b)					
Middle 1 - bottom (c)					
Middle 2-top (d)					
Middle 2-bottom (e)					
Bottom (f)					



3.3.2 Discussion

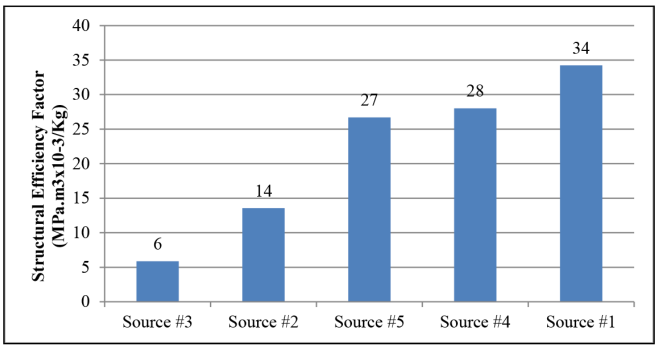
Effect of aggregate properties on concrete properties

Specific gravity factor and aggregate bulk density are the most important properties that should be considered when selecting lightweight aggregate for structural applications. Higher specific gravity factor and bulk density will help achieve durable and high strength concrete. This also influences the microstructure of the coarse aggregate (porosity), which in turn, affects the absorption. On the other hand, aggregate gradation (particle size and distribution) affects the compacted density and the ability to achieve high strength. In addition, smaller size in the range of 4.75 mm to 12.5 mm of coarse aggregate will help minimize the effect of aggregate weak strength and will not affect the self-consolidation. It is also important to note that in case of different aggregate with comparable properties (specific gravity factor, bulk density, particle size and gradation); particle shape plays a role in achieving better bond with the paste and overall higher strength.

Structural efficiency factor (SEF)

The structural efficiency factor (strength/unit weight) for the concrete produced with the lightweight aggregate from the five sources was compared as shown in Figure 6. Concrete produced with aggregates from sources #1, #4 and #5 has SEF 34, 28 and 27; respectively. The high compressive

Fig. 6: Structure efficiency factor for mix 88LW-12NW- all aggregates source



strength and low unit weight helped achieving high SEF values. On the other hand, concrete produced by aggregates from sources #2 and #3 has lower unit weight, however, compressive strength was low and consequently, SEF values were small. This is another reflection of aggregate properties on the concrete quality.

4. CONCLUSIONS

The current study focused on the development of a SCHSLWC mix utilizing local available materials in the UAE. SCHSLWC concrete was produced utilizing coarse lightweight aggregate from 5 different sources. The main objective of the experimental program is to evaluate the impact on the fresh and hardened properties of concrete due to variability of the aggregate source. Mixes with 100% LWT coarse aggregate and normal weight coarse and fine sand were evaluated. In addition, volume fraction of normal weight coarse aggregate was introduced to the mixture while maintaining the target unit weight (2000 kg/m^3) and achieving high compressive strength (40 MPa or higher). Results from both phases showed the following:

- Specific gravity and unit weight are important properties of the lightweight coarse aggregate for structural applications. For comparable properties from different sources, particle shape will considerably impact concrete quality
- Self-consolidating, high strength lightweight concrete with cube compressive strength up to 60 MPa could be produced with aggregates having specific gravity factors in the range of 1.15 to 1.4 and aggregate unit weight in the range of 500-800 kg/m^3
- Up to 12% of the coarse lightweight aggregate could be replaced by normal weight coarse aggregate while maintaining a unit weight less than 2000 kg/m^3
- Structural efficiency factor in the range of 27- 34 could be achieved by lightweight coarse aggregate available in UAE

Other mechanical properties of the 88LW-12NW mix needs to be evaluated to ensure adequacy for structural applications. In addition, durability of concrete produced by the lightweight aggregate from available sources should be investigated.

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