A sustainable solution for ceramic and steel wastes in self-consolidating, high-performance concrete

S M Soleimani¹, A Alaqqad¹*, T Afrasiab¹, A Jumaah¹, A Behbehani¹, A Majeed¹, M H AlSawwaf⁶ and S AlMuhanna¹

¹Department of Civil Engineering, Australian College of Kuwait - West Mishref, Kuwait

* a.alaqquad@ack.edu.kw

Abstract. This study aims to investigate the applicability of using waste materials produced in Kuwait as partial replacements of conventional concrete materials in self-consolidating, high-performance concrete. Processed ceramic products, along with steel slag obtained from electric-arc furnaces, were used as partial replacements of coarse and fine aggregate at various dosages. The fresh and hardened properties of the concrete were then measured and compared. Results have shown that using crushed ceramic products (in the form of sand-like and 3/16” aggregates) increases the rate of strength gain as the concrete cures, while using electric-arc furnace slag to replace 3/8” aggregates increases the compressive strength when compared to a benchmark mix.

1. Introduction

Some of the most prominent industries in Kuwait are the sanitary ware production and the structural steel production industries. The sanitary ware industry generates plenty of waste ceramics due to strict internal quality control standards and given the brittle nature of finished ceramic products which can be damaged during the manufacturing and transportation processes and are therefore rendered useless.¹ The local structural steel industry uses electric-arc furnaces as opposed to conventional blast furnaces, and therefore produces electric-arc furnace slag (EAFS) as a by-product. Although steel slag has no use in the industry, it is known to have cementitious properties when pulverized. Studies have shown that EAFS is characteristically harder and has a density that is approximately 20-25% higher than blast furnace slag.² As these waste materials have no use, they end up in various landfills across the country; this raises concerns over the state of the environment in Kuwait, and begs the question of whether materials are produced and consumed in a sustainable way or not. Studies have shown that concrete containing crushed ceramics as a partial replacement for aggregates in a normal concrete mix show similar, if not better, fresh properties when compared to a concrete made with conventional materials.³ Additionally, the introduction of ceramic wastes in coarse and fine aggregate forms has been shown to improve the fresh and hardened properties when introduced in a standard concrete mix.⁴ Self-compacting concrete is a relatively new category of high-performance concrete that is characterized by its high workability that allows it to flow evenly through restricted sections,⁵ enables it to resist segregation, and allows for quicker casting compared to conventional concrete.⁶ This study aims to investigate the effects of introducing various waste materials (such as ceramic sand, ceramic
aggregates, and EAFS) into a self-compacting, high-performance concrete mix by evaluating its fresh and hardened properties.

2. Methodology

2.1. Selection of Quality Control Tests
In order to verify that a sample of concrete can be considered an SCC sample, the following ASTM and British Standards quality control tests were selected to be conducted:

**L-Box Test:** used to measure the SCC’s flow-ability, particularly through tight reinforcement configurations. After the SCC flows through the L-Box, the ratio of the height of the SCC at each end (labelled H1 and H2, respectively) is taken.\(^7\)

**J-Ring Test:** a test used to demonstrate the ability of SCC to flow around reinforcements. This test is done to ensure workability and correct placement, and shows the SCC’s susceptibility to segregation. The results from this test are compared with a traditional slump flow test to check for any variation, which would indicate the SCC’s susceptibility to blocking action.\(^8\)

**V-Funnel Test:** a test used to measure the SCC’s workability. It is the time required for a batch of SCC to flow through a constricted V-shaped container. The test is performed twice: once when the SCC when is freshly mixed and once after it has been allowed to sit in the V-Funnel for 5 minutes. This test should show the SCC’s susceptibility to segregation.\(^9\)

Afterwards, the SCC was cast in 100x200 mm cylinders and left to cure in submerged conditions for periods in the range of 3-56 days. To test the SCC’s compressive strength, sulphur capping was used to prepare the samples for compressive strength testing, unless the compressive strength was expected to be less than 80 MPa. In the latter case, steel caps with neoprene pads were used to cap the samples.

2.2. Selecting a Benchmark Mix
The study began with the determination of a suitable SCC mix to be used as a baseline upon which the additives’ effects can be compared to (henceforth referred to as the benchmark). It is worth noting that the effects of each additive have been investigated separately.

Figure 1 shows the benchmark mix had identical average diameters when tested for both J-Ring and slump flow. This implies that the benchmark mix is not susceptible to segregation or blocking action. Additionally, the benchmark mix meets the criteria for SCC, which is to have an average diameter of two diameters measured in perpendicular directions to be at least 50cm for both slump and J-Ring flow, as well as to not have more than a 2cm difference in the diameter.

Seeing as the ratio of the benchmark mix’s heights at each end of the L-Box were identical (as shown in Figure 2) the L-Box test results showed that the benchmark mix had perfect workability. The H2/H1 ratio of the benchmark mix easily met the minimum requirements for a concrete mix to be considered an SCC, which is to have a ratio of at least 0.8.

The V-Funnel test results in Figure 3 show that the benchmark mix had undesirable viscosity at both tests, as it exceeded the maximum time limit of 10 seconds to clear the V-Funnel. It should be noted that the difference between the two tests should also not exceed 10 seconds. Since SCC does not have a set viscosity to be used as a benchmark, the results of the V-Funnel test can be split into ‘Desirable’ and ‘Undesirable’ ranges, therefore the undesirable viscosity of the concrete was accepted.

Multiple samples of the benchmark mix were tested at different curing ages in submerged conditions, with tests occurring at 3, 7, 14, 21, 28, and 56 days. The results of the compressive strength tests are shown in Figure 4 with a trend-line. The benchmark mix had an average 56-day compressive strength of 91.2 MPa. The mix design proportions used in the benchmark mix are shown in Table 1.
Figure 1. Comparison between Slump Flow and J-Ring Flow results of benchmark mix with minimum diameter cut-off.

Figure 2. L-Box Test results for benchmark mix with minimum H2/H1 cut-off.

Figure 3. V-Funnel Test results for benchmark mix with maximum time cut-off for desirable workability.

Figure 4. Variation of the benchmark mix’s compressive strength with curing age.

Table 1. Mix Design Proportions of Benchmark Mix.

| Material                        | Quantity |
|---------------------------------|----------|
| Cement (kg/m³)                  | 550      |
| Silica Fume (kg/m³)             | 40       |
| Fly Ash (kg/m³)                 | 60       |
| Sand (kg/m³)                    | 600      |
| 3/8” Coarse Aggregate (kg/m³)   | 360      |
| 3/16” Coarse Aggregate (kg/m³)  | 720      |
| Water (kg/m³)                   | 169      |
| Water/Binder Ratio              | 0.26     |
| Water/Cement Ratio              | 0.32     |
| SIKA® ViscoCrete®-5070 (L)      | 2.2      |
2.3. Using Ceramic Waste
Waste ceramic products were repurposed and used in two forms: ceramic waste fine aggregate (CWFA) was used to partially replace sand, whereas ceramic waste coarse aggregate (CWCA) was used to partially replace 3/16” aggregates. The waste ceramics were placed in a Los Angeles Abrasion machine and were subjected to iterations of 1000 revolutions using 12 steel charges, which were then sieved through US Standard Sieves No. 200 and No. 4 to obtain the CWFA and CWCA, respectively.

Each ceramic additive was investigated separately: CWCA was used to replace up to 20% of the aggregate and CWFA was used to replace up to 20% of the sand used in the mix. Both additives were introduced to the benchmark mix in increments of 5%. The physical parameters of the CWCA and CWFA used in the mix are shown in Table 2.

2.4. Using EAFS
The 3/8” aggregates used in the benchmark mix was partially replaced by appropriately sized EAFS. The EAFS was sieved through US Standard Sieve No. 3/8” to obtain suitably sized aggregates. The effects of using EAFS were studied with dosages of up to 20% in increments of 5%. The physical parameters of the EAFS used are shown in Table 3.

| Table 2. Physical Parameters of Ceramic Additives. | Table 3. Physical Parameters of EAFS. |
|-------------------------------------------------|-------------------------------------|
| Parameter                                      | Value                              | Parameter                         | Value                          |
| 3/16” Ceramic waste coarse aggregate (CWCA):    |                                     | Loose Bulk Density (g/cm³)         | 1.750                          |
| Loose Bulk Density (g/cm³)                      | 1.295                               | Compacted Bulk Density (g/cm³)     | 1.902                          |
| Compacted Bulk Density (g/cm³)                  | 1.434                               | Bulk Specific Gravity              | 3.502                          |
| SSD Specific Gravity                            | 2.401                               | SSD Specific Gravity               | 3.550                          |
| Apparent Specific Gravity                       | 2.421                               | Apparent Specific Gravity          | 3.629                          |
| Absorption (%)                                  | 0.84                                | Absorption (%)                     | 0.853                          |
| Ceramic waste fine aggregate (CWFA):            |                                     |                                    |                                |
| Absorption (%)                                  | 0.08                                |                                    |                                |
| Fineness                                        | 100                                 |                                    |                                |

3. Results & Discussion

3.1. Effects of CWFA and CWCA Use on Fresh Properties
The introduction of CWCA and CWFA into the benchmark mix, as shown in Figure 5, neither affects the passing ability of the SCC nor do these additives subject it to any significant segregation. All mixes containing CWCA or CWFA met the criteria for SCC.

The introduction of CWCA and CWFA into the benchmark mix, as shown in Figure 6, does not affect the flow-ability as shown by satisfactory results in the L-Box Test for all samples. Figure 7 shows that the introduction of CWCA and CWFA into the benchmark mix had mixed results. It is worth noting that all mixes showed undesirable viscosity as they exceeded the maximum time limit of 10s, therefore these results are inconsequential.

The initial introduction of CWCA to the benchmark mix at a low dosage (5%) initially increased the time required to clear the V-Funnel, but then as the dosage of CWCA increased beyond 5% the time required to clear the V-Funnel decreases. This was the case up to 20% CWCA, which saw a complete reversal. This trend was observed in the results of t=0 minutes, t=5 minutes, as well as in the difference between them. As for CWFA, its introduction at a dosage of 5% improved the time required to clear the V-Funnel, made it worse at 10%, then improved it again at 15% and 20% replacement. Much like the results of CWCA, this trend was observed at t=0 minutes, t=5 minutes, as well as the difference between the two.
Figure 5. Comparison between Slump Flow and J-Ring Flow results for mixes containing ceramic additives with minimum diameter cut-off.

Figure 6. L-Box Test results for mixes containing ceramic additives with minimum H2/H1 cut-off.

Figure 7. V-Funnel Test results for mixes containing ceramic additives with maximum time cut-off for desirable workability.

3.2. Effects of CWFA and CWCA Use on Hardened Properties

As shown in Figure 8, it is evident that introducing CWCA at any dosage improves the rate of strength gain in the concrete mix, which is shown in slope of the trend-line for each mix. Introducing 5% CWCA into the benchmark mix unified the rate of strength gain for the first 21 days. All dosages but 15% CWCA showed an improvement in the 28-day compressive strength of the mix. Although using 20% CWCA had a slight improvement in the 56-day compressive strength over the benchmark mix, it can be safely concluded that none of the CWCA dosages show any significant improvement at the 56-day mark.

As shown in Figure 9, it is clear that introducing 20% CWFA into the benchmark mix showed an initial improvement in the rate of strength gain over the benchmark mix, but then showed a drop in compressive strength at the 28-day mark, followed by a significant decrease in compressive strength at the 56-day mark. The results of 20% CWFA at 56 days can be considered anomalous. Additionally, it is shown that the introduction of CWFA at dosages up to and including 15% slightly improves the 56-day compressive strength of the benchmark mix.
Figure 8. Variation of compressive strength for mixes containing various CWCA dosages.

Figure 9. Variation of compressive strength for mixes containing various CWFA dosages.

3.3. Effects of EAFS use on Fresh Properties

Figure 10 shows the results of the slump flow and J-Ring flow test results of concrete mixes containing various EAFS dosages. It is shown that the introduction of EAFS into the benchmark mix neither affects the passing ability of the SCC nor does it subject it to any significant segregation.

Figure 11 shows the L-box test results of mixes containing various EAFS dosages. Introducing EAFS into the benchmark mix has no effect on the flow-ability of the SCC, since all mixes had identical results to the benchmark mix and met the minimum requirement of 0.8. The introduction of EAFS into the benchmark mix has mixed results, which are shown in Figure 12. While introducing 5% EAFS into the benchmark mix initially improved the viscosity of the mix, all other dosages showed results that are not significantly different to the benchmark mix. Generally speaking, the results from Figure 12 indicate that the introduction of EAFS to the benchmark mix makes the SCC more susceptible to segregation. All mixes showed undesirable viscosity as they exceeded the maximum time limit of 10s.

3.4. Effects of EAFS Use on Hardened Properties

The variation of compressive strength of mixes containing various dosages of EAFS compared to the benchmark mix is shown in Figure 13. By examining the average compressive strength of the mixes at 56 days, it is evident that the introduction of EAFS at any dosage improves the compressive strength of the benchmark mix. However, the 56-day compressive strength of the concrete tends to decrease with increasing EAFS dosage; introducing 5% EAFS had the highest compressive strength at 104.7 MPa whereas introducing 20% EAFS yielded an identical compressive strength to the benchmark mix. The rate of strength gain remains largely unaffected by the introduction of the EAFS.
4. Conclusions

It is feasible to utilize waste materials sourced from Kuwaiti factories to produce sustainable replacements of conventional materials in the production of SCC. The fresh and hardened properties of multiple SCC mixes containing various dosages of additives (such as CWCA, CWFA, and EAFS) have been measured, compared, and analyzed.

It has been shown that using CWFA at lower dosages and CWCA at higher dosages improved the flow-ability and reduced segregation in the benchmark mix. While the introduction of both ceramic additives improved the rate of strength gain in the SCC, their introduction only had a marginal effect on the overall compressive strength of the SCC.

Additionally, the introduction of EAFS reduces the probability of segregation in the SCC, and its introduction at any dosage at or below 15% increases the compressive strength of the SCC, with the optimum dosage being 5%.

The results of this study can be used to perform further research on the applicability of Kuwaiti waste materials in SCC production, particularly in the optimization of a hybrid mix that uses CWCA, CWFA, and EAFS to obtain ideal fresh and hardened properties.
Acknowledgements
The authors would like to thank United Steel Industrial Company and Gulf Shores Company for Sanitary Wares and Construction Building Materials for generously providing their waste materials for their use in this study. Additionally, the authors wish to thank SIKA and Combined Group Contracting Co. for providing the admixture and concrete raw materials used in this study, respectively. This project was funded “partially” by the Kuwait Foundation for the Advancement of Science under project code: PN18-15EV-01.

References
[1] Halicka A, Ogrodnik P, and Zegardlo B 2013 Using ceramic sanitary ware waste as concrete aggregate Construction and Building Materials 48 295-305
Medina C, Sánchez de Rojas M, and Frias M 2012 Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes Cement and Concrete Composites 34-1 48-54
[2] Australasian (Iron & Steel) Slag Association 2019 Electric Arc Furnace Slag http://www.asa-inc.org.au/products/electric-arc-furnace-slag
[3] Juan A, Medina C, Guerra MI, Llamas B, Morán JM, and Tascón A 2010 Re-use of construction and demolition residues and industrial wastes for the elaboration or recycled eco-efficient concretes Span J Agric Res 8-1 25–34
Senthumarai RM, and Manoharan P D 2005 Concrete with ceramic waste aggregate Cement & Concrete Composites 27 910-913
Gomes M and de Brito J 1999 Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. Mater Struct 42-5 663–675
[4] Anderson D J, Smith S T, and Au F T K 2016 Mechanical properties of concrete utilizing waste ceramic as coarse aggregate Construction and Building Materials 117 20-28
Awoyera P O, Ndambuki J M, Akinmusuru J O, and Omole D O 2016 Characterization of ceramic waste aggregate concrete HBRC Journal 14 282-287
[5] Arulsivanantham P and Gokulan R 2017 A Review on Self Compacting Concrete International Journal of ChemTech Research 10-11 62-68
[6] Khayat K H 1999 Workability, Testing and Performance of Self Consolidating Concrete ACI Materials Journal 96-3 346-354
[7] British Standards Institution 1998 BS EN 12350-10:2010: Testing fresh concrete. Self-compacting concrete. L box test
[8] ASTM International 2017 ASTM C1621/C1621M-17 Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring
[9] British Standards Institution 1998 BS EN 12350-9:2010: Testing fresh concrete. Self-compacting concrete. V funnel test