Mechanical Behavior of Industrial Waste Product Based Ultra-high Performance Seawater and Sea-sand Concrete

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Abstract: Scarcity of fresh water and river sand has motivated the development of seawater and sea-sand concrete (SWSSC) as a promising construction material, especially in coastal infrastructures. To achieve improved durability and reduction in sectional size of members, it is desirable to produce ultra-high performance concrete from abundant marine resources. Additionally, replacing conventional ordinary Portland cement (OPC) in concrete with industrial waste products can lead to sustainable development by decreasing the carbon footprint. This paper presents an experimental investigation on the mechanical behavior of ultra-high performance seawater and sea-sand concrete (UHP-SWSSC) with partial replacement of OPC by supplementary cementitious materials such as ground granulated blast-furnace slag and silica fume. A number of UHP-SWSSC mixes were prepared with different replacement ratio of cement. Both early age and long-term strength of cube UHP-SWSSC specimens with varying percentages of cement substitution were analyzed through axial compression tests. Effects of different aggregate types, cement replacement ratio and curing conditions on the axial compressive strength and workability of UHP-SWSSC were studied. Potential alkali reactivity of sea-sand was examined by the mortar-bar method. Performance of slag to curtail the alkali silica reaction (ASR) expansion of concrete containing seawater and sea-sand was also evaluated. Incorporation of industrial waste as supplementary cementitious materials, sea-sand as fine aggregate and seawater as mixing water are found to be effective in producing ultra-high performance concrete based on their performance.

Keywords: Ultra-high performance seawater and sea-sand concrete (UHP-SWSSC), OPC replacement, alkali silica reaction (ASR), strength.

1. Introduction and Background

Increased demand for conventional ordinary Portland cement (OPC) concrete in numerous infrastructures has aggravated the scarcity of natural resources i.e., river sand and fresh water. At the same time, production of OPC is responsible for substantial CO₂ emission, which poses a threat to the environment (Xiao et al. (1)). Being manufactured from abundant marine resources (seawater, sea-sand) and industrial waste products (i.e., ground granulated blast furnace slag, fly ash by fully or partially replacing OPC) which may otherwise compromise the environmental sustainability, seawater and sea-sand concrete (SWSSC) has an immense potential of replacing conventional concrete in the days to come (Li et al. (2), Li et al. (3)), especially in the infrastructure development in coastal regions. It has been established by existing research that direct utilization of sea water and sea-sand in mixing and curing of concrete negatively affects the workability (Limeira et al. (4)), which is mainly attributed to the presence of excessive salt and sea-shell contents. Seawater (Kaushik and Islam (5), Mohammed et al. (6)) and sea-sand (Xiao et al. (1), Ramaswamy et al. (7)) can enhance the early age compressive strength of concrete as a result of their high chloride content. However, the development of strength slows down due to leaching of hydration products and crystallization of salt, which leads to a lower long-term compressive strength. Use of seawater in curing of SWSSC has been found to yield lower compressive strengths compared to ordinary concrete with fresh water curing (Cui et al. (8)). A study (Kupwade-Patil and Allouche (9)) has exhibited that the expansion of concrete due to alkali silica reaction (ASR) which eventually leads to cracking of concrete can be significantly reduced through the application of geopolymers such as fly ash, blast furnace slag and silica fume. Therefore, exploitation of such industrial byproducts in SWSSC has a potential to not only resolve the reactivity issues in concrete, but also promote sustainable construction practice.

Nowadays, ultra-high performance concrete (UHPC) is becoming an attractive substitute to normal strength concrete due to its outstanding mechanical as well as durability performance; thereby presenting a possibility of using substantially smaller sized sections. UHPC is often characterized by its higher binder content and extremely low water to binder ratio. Utilization of very fine powders (i.e., quartz powder, silica
fume etc.) can achieve a dense microstructure, which induces ultra-high compressive strength and significantly lower porosity (Wang et al. (10)). Application of supplementary cementitious materials such as ground granulated blast furnace slag, fly ash, metakaolin and nano particles are attributed to the enhanced performance of UHPC in terms of strength (compressive, flexural), workability, ductility, toughness and durability (Shi et al. (11)). According to the review of Shi et al. (11), replacing cement with these supplementary cementitious materials has proved to yield cost effective UHPC without any substantial strength loss. Teng et al. (12) were among the first to develop UHPC utilizing seawater and sea-sand. They performed experiments to evaluate the mechanical properties of this novel material. Application of such innovative construction material can be proved worthy in the development of marine infrastructures.

In this research, a proper mix of ultra-high performance seawater and sea-sand concrete (UHP-SWSSC) was developed which achieved desired strength and workability. In order to produce an environmentally viable concrete mix, OPC has been partially replaced by ground slag and silica fume; and fresh water as well as river sand were substituted by seawater and sea-sand respectively. Several mixes were prepared by altering the cement substitution ratio and the influence of OPC replacement on compressive strength and workability was analyzed. UHPC using tap water and river sand (UHP-TWRSC) as well as washed Sydney beach sand (UHP-TWWBSC) were also produced and tested for comparison purposes, keeping the same mixing ratio. Alkali silica reaction (ASR) tests have been carried out to compare the reactivity of sea, river and washed beach sand. The ability of supplementary cementitious materials to curtail the concrete expansion due to alkali silica reaction was assessed.

2. Materials and Methods

2.1 Materials

General purpose cement from Cement Australia which conforms to the requirements of AS 3972-2010 (13) was used as OPC. Ground granulated blast-furnace slag (GGBFS) was procured from Australian Builders, while undensified silica fume was acquired from Simcoa, plant Kemerton, Western Australia. The aggregate and mixing as well as curing water (e.g., sea-sand and seawater) to produce UHP-SWSSC have been collected from Malabar beach, Sydney, New South Wales, Australia. The aggregates were dried and sieved to separate organic materials, sea-shells, stones and other impurities. For comparison analysis, natural river sand was acquired from Bagged Product Supplies, Taren Point, New South Wales. Washed Sydney beach sand was obtained from the Infrastructure Laboratory of University of New South Wales, Australia.

The sea-sand was prepared and modified by sieving prior to using as aggregate. Sea-sand particles larger than 1.18 mm was found to be mainly comprised of sea-shells, stone chips, plant remains etc., which weighed up to be an insignificant 2.85% of the sand sample. Therefore, as recommended by Willie and Boisvert-Cotullo (14), particles over 1.18 mm were excluded from the sea-sand before using it as fine aggregate. Particle size distribution of three types of fine aggregates according to AS 1141.11.1-2009 (15) is shown in Figure 1. Unlike well graded river sand, sea-sand was found to be gap graded with almost 90% of its particles retaining at 0.6 mm and 0.3 mm sieves. Overall, the fineness of sea-sand was in between that of washed Sydney beach sand and river sand.

![Figure 1. Particle size distribution curves of different sand aggregates.](image-url)

As ultra-high performance concrete possesses extremely low water-to-binder ratio (less than 0.2), polycarboxylate based high range water reducer (HRWR) has been utilized to achieve the required
workability. BASF MasterGlenium SKY 8700 has been chosen for the UHP-SWSSC for desired workability and has exhibited excellent performance. The proposed UHPC has been developed without steel fibers to make it more cost efficient and exclude the possibility of steel corrosion.

### 2.2 Mix Designs

For comparison analysis, eight UHPC mixes were prepared (4 UHP-SWSSC, 2 UHP-TWRSC and 2 UHP-TWWBSC). Four mix ratios with different percentage of OPC replacement were selected for UHP-SWSSC. UHP-SWSSC with 100% OPC (control mix) along with 25%, 37.5% and 50% OPC replacements by GGBFS and silica fume were prepared to determine the influence of cement replacement on the performance of resulting concrete. In this study, a maximum of 50% OPC has been successfully replaced by 37.5% slag and 12.5% silica fume without sacrificing their strength and workability. The proposed mix ratio has been utilized to produce UHPC with river sand and washed Sydney beach sand as well. Both natural river sand and processed river sand (same particle size distribution as the sea-sand) were used. Seawater was used as mixing water for UHP-SWSSC and tap water from the laboratory was utilized for UHP-TWRSC and UHP-TWWBSC. The fine aggregate content, water-to-binder and HRWR-to-binder ratio were kept same for all the mixes (1000 kg/m³, 0.2 and 0.02 respectively). The different mixing ratios are listed in Table 1.

**Table 1. Mixing ratios of materials for UHPC.**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Type of Aggregate and mixing water</th>
<th>OPC (kg/m³)</th>
<th>Ground Slag (kg/m³)</th>
<th>Silica fume (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>HRWR (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Sea-sand and sea water (100% OPC)</td>
<td>1200</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M2</td>
<td>Sea-sand and sea water (25% OPC replacement)</td>
<td>900</td>
<td>300</td>
<td>0</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M3</td>
<td>Sea-sand and sea water (37.5% OPC replacement)</td>
<td>750</td>
<td>300</td>
<td>150</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M4</td>
<td>Sea-sand and sea water (50% OPC replacement)</td>
<td>600</td>
<td>450</td>
<td>150</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M5</td>
<td>Washed Sydney beach sand and tap water (100% OPC)</td>
<td>1200</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M6</td>
<td>Washed Sydney beach sand and tap water (50% OPC replacement)</td>
<td>600</td>
<td>450</td>
<td>150</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M7</td>
<td>Natural river sand and tap water (50% OPC replacement)</td>
<td>600</td>
<td>450</td>
<td>150</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
<tr>
<td>M8</td>
<td>Processed river sand and tap water (50% OPC replacement)</td>
<td>600</td>
<td>450</td>
<td>150</td>
<td>1000</td>
<td>240</td>
<td>24</td>
</tr>
</tbody>
</table>

First, the cement, supplementary cementitious materials and aggregate were mixed for ten minutes. Water and superplasticizer were mixed separately and added to the dry materials over a period of 30 seconds. After the addition of water to HRWR, mixing is continued for another 10 minutes until a workable mix is achieved. The concrete is cast in a single layer without any tamping or vibration. The concrete filled molds are stored in a moist chamber at a temperature of 23°C and 50% relative humidity for a period of 24 ± 2 hours. After demolding, the specimens were cured in both tap water and seawater to examine the effect of curing condition.

### 2.3 Testing Procedures

Axial compressive strength and workability of the resulting concrete were determined in accordance with ASTM C1856-2017 (16). Cube specimens (50 mm × 50 mm) were prepared to evaluate compressive strength of different UHPC mix. The loading rate was kept at 1 MPa/ second so that the specimens reach failure at around 2 minutes and 30 seconds. Both early age (1 day, 3 day and 7 day) and long-term (28 day and 90 day) compression tests are determined to investigate the strength development of UHP-SWSSC with varying cement replacement ratio under different curing conditions. Flow table test was carried out to assess the workability of fresh UHPC mix. The flow table was not dropped throughout the test and the workability was determined by measuring the diameter of the spread.

Alkali silica reactivity (ASR) tests were performed on mortar bars prepared from three types of aggregates based on AS 1141.60.1-2014 (17). The influence of supplementary cementitious materials (e.g., slag, silica fume) to reduce the reactivity of seawater and sea-sand concrete exposed to alkaline medium (1 N sodium
hydroxide solution) was also evaluated. The ASR tests were carried out for 56 days to compare the long-term reactivity behavior of UHPC, which is beyond the scope of the currently available standard.

3. Results and Discussion

3.1 Compressive Strength

3.1.1 Effect of seawater and sea-sand

Cube compressive strength tests were performed on ultra-high performance seawater sea-sand, tap water river sand and tap-water washed Sydney beach sand specimens under both tap water and seawater curing conditions. The river sand was processed to have the same particle size distribution as the sea-sand to exclude the influence of particle size. The test results exhibit that utilization of sea-sand as fine aggregate and seawater as mixing water yields slightly higher compressive strength up to 28 days. UHP-SWSSC with 100% OPC (control mix) showed significantly high early age strength (85 MPa and 106 MPa after 1 day and 3 days respectively). The control mix with seawater and sea-sand achieves 153% and 35.4% more strength than the similar mix with tap water and river sand at 1 day and 3 days respectively. This behavior has been attributed to the high chloride content present in seawater and sea-sand which initially accelerates the hydration reaction, which blocks the concrete pores and thereby expedites the initial strength gain (Xiao et al. (1), Limeira et al. (4)). The proposed mix with 50% OPC replacement by 37.5% slag and 12.5% silica fume reaches the highest strength of 137 MPa after 28 days under tap water curing (Figure 2), which is respectively 6% and 2.1% higher than the tap water washed Sydney beach sand and tap water river sand variants with the same mix ratios. The proposed UHP-SWSSC mix produces 11.3% and 3.4% more 28-day compressive strength compared to washed beach sand UHPC and river sand UHPC when cured under seawater condition. However, the variation of long-term compressive strength (after 90 days of curing) was found to be insignificant (within 4.3%).

![Figure 2. Effect of seawater and sea-sand as mixing water and aggregate (tap water curing).](image)

3.1.2 Effect of OPC replacement by ground slag and silica fume

It is apparent from Figure 3 that percentage of OPC replacement moderately affects the compressive strength of concrete. A 50% of OPC replacement (37.5% slag and 12.5% silica fume) produces the highest compressive strength compared to other UHP-SWSSC mixes when cured in seawater. The proposed mix was found to generate 10.8% and 7.5% more strength than the mix with no cement replacement (control mix) after 28 day and 90 days, respectively. Mixes with silica fume tend to generate more strength as silica fume with much smaller particle size densifies the cementitious matrix and thereby improves the microstructure. The 50% OPC replaced seawater and sea-sand UHPC (M4) yields maximum 7-day, 28-day
and 90-day strength among all 8 mixes, except the 90-day strength of tap water and river sand UHPC (M8) which was 4.2% larger (Figure 4).

3.1.3 Effect of seawater curing

Seawater as curing water was observed to have a negative effect on the compressive strength of UHPC specimens. From Figure 5, it is evident that UHP-SWSSC gains higher strength when cured in tap water in comparison with seawater curing, with a strength increase of 18.4%, 9.6%, 10.1% and 9.7% after 3, 7, 28 and 90 days, respectively. Similar strength improvements were observed for tap water river sand and washed beach sand UHPC mixes as well. The river sand and washed beach sand concrete experiences 10.3% and 13.8% strength loss respectively at 28 days under seawater curing compared to tap water curing conditions. This
phenomenon is believed to have occurred due to the formation of expansive (e.g., ettringite and Friedel's salt) as well as leachable components in the concrete microstructure under exposure to seawater environment (Islam et al. (18)). The formation of micro cracks due to chloride and sulfate attack along with leaching of soft hydration products are the principal reasons behind the degradation of concrete strength development under seawater curing conditions.

3.2 Workability

All mixes of UHPC were found to possess excellent workability (Figure 6). Use of seawater and sea-sand slightly reduced the workability of concrete, with 360 mm flow spread diameter compared to 390 mm for washed beach sand concrete with same mix ratio. This may have happened as a result of the size fraction and uniformity of sea-sand particles as well as the presence of angular shaped sea-shells and other impurities (Xiao et al. (1)). Chloride in seawater has very little influence on the fluidity of the fresh mix. Replacing OPC with slag and silica fume also exhibited a marginally lower workability. The flow spread of 50% OPC replaced UHP-SWSSC was measured to be 340 mm, compared to 360 mm spread of the control mix (100% OPC). Angular shape of sand particles and accelerated calcium reaction together with the irregular carbon content in silica fume decrease the workability of fresh UHPC (Shi et al. (11)). However, all the mixes were more workable compared to the results of 180–240 mm achieved by Willie and Boisvert-Cotulio (14).

![Figure 6. Comparison of workability among UHPC mixes (by flow table test).](image)

3.3 Alkali Silica Reactivity of Different Aggregate Types

Assessment of potential alkali silica reactivity (ASR) was carried out for different concrete made up of three fine aggregate types. Seawater was used as mixing water for seawater and sea-sand concrete, whereas tap water was utilized in river sand and washed beach sand concrete. The comparative expansion percentage of the mortar bars submerged under 1M sodium hydroxide solution at 80 °C is exhibited in Figure 7. The percentage of expansion of 100% OPC based SWSSC, TWRSC and TWWBSC after 21 days was found to be 0.29%, 0.23% and 0.24% respectively. It is apparent that sea-sand is slightly more reactive than river sand and washed Sydney beach sand, however, all aggregates fall under slowly reactive category according to aggregate reactivity classification in 1141.60.1-2014 (17). In order to evaluate the performance of slag and silica fume to reduce the ASR reaction, seawater and sea-sand concrete based on replacing a portion of OPC by 50% slag as well as 37.5% slag and 12.5% silica fume were also analyzed. Addition of slag and silica fume was found to significantly curtail the ASR expansion. After 21 days of NaOH exposure, the percentage of mortar bar expansion was 0.1% and 0.02% respectively for mixes with 50% slag only and combined slag-silica fume. Inclusion of silica fume has proved to further reduce the reactivity of aggregates. Geopolymer concrete is known to be less susceptible to ASR induced expansion because of the lack of available calcium in the matrix, which produces non-expansive alkali silica gel (Kupwade-Patil and Allouche (9)). Silica fume can be effective in curbing the ASR expansion due to its negligible calcium content together with the ability to produce dense microstructure compared to OPC based concrete. From X-ray fluorescence (XRF) analysis, the calcium content (percentage as oxides) in the OPC, ground slag and silica fume used in this study were found to be 63.45%, 42.56% and 0.10% respectively. Therefore, there is a strong reason to believe that the ASR reactivity is substantially reduced when high calcium OPC is replaced by low calcium slag or silica fume.
The specimens were under observation beyond the testing timeframe suggested by the relevant standard to evaluate their long-term reactivity. After 56 days of submersion in alkaline solution, the comparative trends for long-term aggregate reactivity were found to be similar to their short-term reactivity.

4. Conclusions

Based on the experiments and discussion on the mechanical properties of ultra-high performance concrete utilizing seawater and sea-sand as well as the alkali silica reactions of different aggregate types, the following conclusions can be drawn:

- Utilizing sea-sand and seawater as fine aggregate and mixing water leads to noticeably higher early age compressive strength and slightly higher 28-day strength, whereas the difference in long-term strength was negligible.
- Inclusion of industrial waste (ground slag and silica fume) by replacing conventional OPC moderately affects the compressive strength. The proposed mix in this study (50% OPC replacement by 37.5% slag and 12.5% silica fume) yielded highest strength among all 8 mixes examined.
- Seawater curing was found to moderately decrease the compressive strength of UHPC, regardless of the aggregate types.
- Use of sea-sand, seawater and industrial wastes caused a marginal reduction in fresh concrete’s workability. However, all the UHPC mixes were found to be sufficiently workable.
- All three types of sands fall in the category of slowly reactive aggregates in alkaline medium. Slag and silica fume were proved to significantly inhibit both the short and long-term alkali silica reaction induced expansions of seawater and sea-sand based concrete.

Overall, incorporation of industrial wastes as supplementary cementitious materials as well as sea-sand and seawater in producing ultra-high performance concrete can be effective, especially in the coastal infrastructure development. However, the importance of understanding the durability characteristics of ultra-high performance seawater and sea-sand concrete is paramount before they can be trialed in the field. Studies are currently being conducted by this researcher to address the durability aspect of such concrete in adverse environment.

5. References


