Durability of Self-compacting Lightweight Aggregate Concretes (LWSCC) as Repair Overlays

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ABSTRACT

For rehabilitation of damaged concrete structures, the durability of repair overlay is a very important issue. Self-compacting concretes (SCC) are known as a suitable repair overlay materials. In this study, the durability of different self-compacting lightweight aggregate concretes (LWSCC) and effect of lightweight aggregate type on them is investigated. 3 mix designs of LWSCC containing three different types of lightweight aggregates and a conventional self-compacting concrete were considered. The Rapid chloride permeability tests (RCPT), Rapid chloride migration tests (RCMT) and Accelerated corrosion tests (ACT) were performed and the Chloride migration coefficients were obtained. The corrosion resistance of the mix designs was investigated and compared. The classification of the concrete resistance against chloride penetration for all lightweight Mixes were acceptable but concrete with Leca and Pumice had the best and the worst performance respectively. As a result of using lightweight aggregates, using Scoria aggregate may cause better protection to steel reinforcement against corrosion than Leca and Pumice aggregate.

1. Introduction

For rehabilitation of damaged concrete structures, the durability of repair overlay is a very important issue. Also the repair overlay should have enough deformability, good segregation resistance to prevent separation of particles in the mix and acceptable self-leveling. Compacting performance of repair overlay can be effective on filling of pores and contact surface characteristics. Self-compacting concrete (SCC) is defined as a concrete which can be placed and
compacted under its self-weight with no vibration effort and which is at the same time cohesive enough to be handled without segregation or bleeding [1]. SCC was originally developed at the University of Tokyo, Japan in 1986 to improve the quality of construction and to overcome the problems of defective workmanship[2]. It is used to facilitate and ensure the proper filling and good structural performance of the restricted areas and heavily reinforced structures[3]. Using of SCC as repair overlay and its bonding to conventional concrete substrate is studied in many cases. The results showed its higher bonding strength to substrate with respect to normal concrete overlays. Bonding between two surfaces generally depends on surface bonding characteristics, friction, involvement of aggregate and specifications that vary over time [4-12].

Using lightweight aggregates (LWA) in concrete has several advantages. The most considerable advantage is reduction in the dead load of buildings which could lead to a considerable decrease in the cross-section of steel-reinforced members and reducing the need for steel reinforcement. The other benefits of Lightweight concretes includes lower thermal connectivity and maximized heat and sound insulation properties due to air voids [13-15].

As durability view, Lightweight concrete is more resistant to elevated temperatures than normal weight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion, and inherent fire stability of an aggregate already heated to over 1100°C during production [13]. In colder climates, it is also important to consider freeze-thaw behavior of concretes as well as their resistance to salt-scaling. LWA with adequate resistance in these conditions has been produced in the past [16]. Resistance to freeze-thaw condition in lightweight concrete depends on various parameters including the pre-wetting of the lightweight aggregate[17], the use of appropriate pozzolans such as silica fume[18, 19], and the use of water-reducing admixtures to increase paste density and improve durability through controlling the micro-cracking behavior of LWA concrete [20].

Self-compacting lightweight aggregate concrete (LWSCC) is a kind of high-performance concrete developed from self-compacting concrete (SCC). LWSCC combines the suitable properties of lightweight aggregate concrete (LWAC) and SCC [21-23]. LWSCC is highly sensitive to changes in mix component properties and their proportions. The typical characteristics of LWSCC mix proportions, which are necessary to ensure adequate fresh properties, can have significant effects on hardened properties like strength, dimensional stability and durability[24]. For instance, the compressive strength of the LWSCC is influenced by the aggregate type and the water to cement and water to total powder[25]. In spite of available studies on the advantages of LWSCC associated with its valuable performance in the fresh state, there are less available studies regarding the hardened properties for mechanical responses and its durability.

In this study, the durability of different self-compacting lightweight aggregate concretes (LWSCC) and effect of lightweight aggregate type on them is investigated. 3 mix designs of LWSCC containing three different types of lightweight aggregates and a conventional self-compacting concrete were considered. The Rapid chloride permeability tests (RCPT), Rapid chloride migration tests (RCMT) and Accelerated corrosion tests (ACT) were performed and the Chloride migration coefficients were obtained. The corrosion resistance of the mix designs was investigated and compared.
2. Materials and Methods

2.1. Materials and Mix Designs

River gravel was used with a maximum grain size of 12.5 mm, density of 2.64 gr/cm³ and water absorption of 1.5 percent. Gradation was done based on the standard ASTM C33[26]. River sand with rounded corners, density of 2.6 gr/cm³ and water absorption of 2.5 percent was used. Type I Portland cement was used. The consumed Silica fume was manufactured by Ferrosilice Co. in Iran which had a density of 2200 Kg/m³. The superplasticizer with the commercial name of FARCO PLAST P103R (based on the modified Polycarboxylates) and had been produced by Shimi Sakhteman Co. in Iran was used. The Lightweight aggregates were used were Leca (Light Expanded Clay Aggregate), Scoria and Pumice. The used leca was provided from Leca Co. in Iran with density of 1250 kg/m³. The Scoria aggregate was provided from Ghorveh mine in Kurdistan province of Iran with density of 1600 kg/m³. Also the Pumice aggregate was from Eskandan of Tabriz city in Iran with density of 1450 kg/m³. The mix designs of this research are shown in Table 1. The amount of water absorption in used lightweight aggregates was 15%, 17% and 10% for Scoria, Pumice and Leca aggregates respectively.

<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>Cement (Kg/m³)</th>
<th>Silica Fume (%)</th>
<th>Lime Stone (0-6) (Kg/m³)</th>
<th>Sand (0-6) (Kg/m³)</th>
<th>Gravel (6-12.5) (Kg/m³)</th>
<th>Pumice (6-12.5) (Kg/m³)</th>
<th>Scoria (6-12.5) (Kg/m³)</th>
<th>Leca (6-12.5) (Kg/m³)</th>
<th>Water (Kg/m³)</th>
<th>W/C</th>
<th>Super Plasticizer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control</td>
<td>450</td>
<td>10</td>
<td>250</td>
<td>750</td>
<td>750</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>175</td>
<td>0.35</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>P</td>
<td>450</td>
<td>10</td>
<td>250</td>
<td>650</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>175</td>
<td>0.35</td>
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<tr>
<td>3</td>
<td>S</td>
<td>450</td>
<td>10</td>
<td>250</td>
<td>650</td>
<td>0</td>
<td>0</td>
<td>510</td>
<td>0</td>
<td>175</td>
<td>0.35</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>450</td>
<td>10</td>
<td>250</td>
<td>650</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>175</td>
<td>0.35</td>
<td>0.9</td>
</tr>
</tbody>
</table>

2.2. Rapid chloride permeability test (RCPT)

The rapid chloride permeability test (RCPT), described in ASTM C1202 [27], is the most common method for assessment of durability against chloride ingress [28]. This test was therefore performed on various mixes in this study at the ages of 28 and 90 days. In the RCPT test the total electrical charge passing through a 50 mm thick concrete disk specimen during a 6 hours period under an electrical potential of 60 V, is determined. The test set up is shown in Fig. 1.

2.3. Rapid chloride migration test (RCMT)

To evaluate the chloride permeability of cement-based materials, a series of testing methods (e.g. the AASHTO T259 test, Bulk diffusion test (NordTestNTBuild 443), AASHTO T277 (ASTM C1202) test, electrical migration techniques, the rapid migration test, resistivity techniques, pressure penetration techniques, etc. [27, 29-35]) have been developed. In this study the non-steady-state chloride migration coefficient has been used to determine the resistance of the concrete against chloride penetration. Chloride migration coefficient can be obtained by using NordTest BUILD 492 [36]. The relationship between the applied initial current and the testing time is shown in Table 2.

The test set up is shown in Fig. 1. The concrete specimen was exposed to a 10% sodium chloride (NaCl) solution on one side of the specimen (cathode) and a 0.3 M sodium hydroxide (NaOH) solution on the other side (anode). During the test, temperature in chamber should be between 20-25 °C. An external electrical potential was applied across the specimen to force the chloride...
ions from the NaCl solution into the specimen. The duration of test depends on the concrete quality.

![Fig. 1 Test setup of RCPT and RCMT](image)

![Fig. 2 Schematic representation of the setup for the accelerated corrosion test [37]](image)

<table>
<thead>
<tr>
<th>Initial current $I_{0V}$ (with 30 V) (mA)</th>
<th>Applied voltage $U$ (after adjustment) (V)</th>
<th>Possible new initial Current $I_0$ (mA)</th>
<th>Test duration $t$ (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0&lt;5$</td>
<td>60</td>
<td>$I_0&lt;10$</td>
<td>96</td>
</tr>
<tr>
<td>$5\leq I_0&lt;10$</td>
<td>60</td>
<td>$10\leq I_0&lt;20$</td>
<td>48</td>
</tr>
<tr>
<td>$10\leq I_0&lt;15$</td>
<td>60</td>
<td>$20\leq I_0&lt;30$</td>
<td>24</td>
</tr>
<tr>
<td>$15\leq I_0&lt;20$</td>
<td>50</td>
<td>$25\leq I_0&lt;35$</td>
<td>24</td>
</tr>
<tr>
<td>$20\leq I_0&lt;30$</td>
<td>40</td>
<td>$25\leq I_0&lt;40$</td>
<td>24</td>
</tr>
<tr>
<td>$30\leq I_0&lt;40$</td>
<td>35</td>
<td>$35\leq I_0&lt;50$</td>
<td>24</td>
</tr>
<tr>
<td>$40\leq I_0&lt;60$</td>
<td>30</td>
<td>$40\leq I_0&lt;60$</td>
<td>24</td>
</tr>
<tr>
<td>$60\leq I_0&lt;90$</td>
<td>25</td>
<td>$50\leq I_0&lt;75$</td>
<td>24</td>
</tr>
<tr>
<td>$90\leq I_0&lt;120$</td>
<td>20</td>
<td>$60\leq I_0&lt;80$</td>
<td>24</td>
</tr>
<tr>
<td>$120\leq I_0&lt;180$</td>
<td>15</td>
<td>$60\leq I_0&lt;90$</td>
<td>24</td>
</tr>
<tr>
<td>$180\leq I_0&lt;360$</td>
<td>10</td>
<td>$60\leq I_0&lt;120$</td>
<td>24</td>
</tr>
<tr>
<td>$I_0\geq360$</td>
<td>10</td>
<td>$I_0\geq120$</td>
<td>6</td>
</tr>
</tbody>
</table>

After test, the specimen was split across its circular cross section. The split surfaces were sprayed with 0.1 M silver nitrate (AgNO3) solution to determine the chloride penetration by measuring the silver chloride precipitates formed. If chloride increases on the surface after spraying the solution, it will create a whitish color, otherwise it will become brown. The color change border indicates the chloride penetration depth. The depth of the chloride penetration was measured. Then the depth was used to determine the diffusion coefficient through the following equation [36]:

$$D_{asm} = \frac{RT}{zFE} \cdot \frac{X_d - \alpha \sqrt{X_d}}{t}$$

Where:

$$E = \frac{U - 2L}{2}$$

$$\alpha = 2 \sqrt{\frac{RT}{zFE}} \cdot erf^{-1} \left(1 - \frac{2c_d}{c_0} \right)$$
where $D_{nssm}$ is non-steady-state migration coefficient ($m^2/s$); $z$ denotes absolute value of ion valence, for chloride $z=1$; $F$ is Faraday constant ($9.648 \times 10^4 J/(V\cdot mol)$); $U$ represents absolute value of applied voltage (V); $R$ is gas constant ($8.314 J/(K\cdot mol)$); $T$ is average value of the initial and final temperatures in the anolyte solution (K); $L$ is thickness of the specimen (m); $X_d$ is average value of the penetration depth (m); $t$ is test duration (s); erf$^{-1}$ represents inverse of error function, the error function encountered in integrating the normal distribution; $c_d$ is chloride concentration at which the colour changes, $c_d=0.07$ N; $c_0$ is chloride concentration in the catholyte solution, $c_0=2$ N.

Since $erf^{-1} \left(1 - \frac{2 \times 0.07}{2} \right) = 1.28$, the following simplified equation can be used:

$$D_{nssm} = 0.0239 \left( \frac{273 + T}{U - 2} \right) \left( x_d - 0.0238 \left( \frac{273 + T}{U - 2} \right) L \cdot X_d \right)$$

where $D_{nssm}$ is non-steady-state migration coefficient ($\times 10^{12} m^2/s$); $U$ is the absolute value of the applied voltage (V); $T$ is the average initial and final temperature in the anolyte solution (°C); $L$ is the thickness of the specimen (mm); $x_d$ is the average value of the penetration depths (mm); $t$ is the test duration (h). The external potential applied to each specimen for different concrete ages were recorded and presented together with the test duration in Table 3.

### 2.4. Accelerated corrosion test (ACT)

Accelerated corrosion test (ACT) is a rapid corrosion testing method which was used to compare the corrosion performance of normal aggregate and lightweight aggregate concretes. This method was performed in many researches [37-42]. In this study, the reinforced concrete specimens were immersed in a 4% sodium chloride solution leveling the top of the concrete cylinder and a steel bar that is working as electrode, is connected to the positive terminal of a DC power source while the negative terminal was connected to steel plates (counter electrode) placed near the specimen in the solution. In this circuit, the steel bar was the anode, the steel plates were the cathode, and the sodium chloride solution was the electrolyte. The corrosion process was initiated by impressing an anodic potential of 30V. A high impressed voltage was used to accelerate the corrosion process. Fig. 2 is a schematic representation of the experimental setup for the accelerated corrosion test [37]. The duration for appearance of corrosion cracks on surface was measured. A data logger was used to record the current variation with time. By appearance of crack, the current increases suddenly. The variation of current with respect to time and also the duration of time for failure of reinforced concrete specimens were determined for all mix designs. Specimens were tested at the age of 28.

### 3. Results and discussion

#### 3.1. Rheological properties and Density

The rheological properties of mixtures at fresh state including Slump flow, T50 flow table, V-funnel time and Blocking ratio are compared together in Fig.3. Also the densities of used mix designs are showed in Fig.4. In figures “P” stands for pumice aggregate, “S” shows scoria aggregate and “L” indicates leca aggregate.
3.2. Compressive strength

The 7, 28, and 90 day compressive strengths for the mixes are shown in Fig.5. It was observed that using lightweight aggregates causes a decrease in compressive strength. Test results indicated that the increase in compressive strength at later ages of SCC concretes made with Scoria was similar to concretes containing Pumice as lightweight aggregate. Because of the same mix design proportion, the most important parameter in
final compressive strength would be the physical and mechanical properties of lightweight aggregates. The Scoria aggregates have higher roughness and compressive resistance in comparison with two other lightweight aggregates. So the SCC which made by using this aggregates showed the highest compressive strength. The concrete mixture containing leca aggregate showed the lowest compressive strength. Generally the compressive strength of mix designs with lightweight aggregate was lower than conventional SCC samples.

![Compressive Strength Graph](image)

**Fig. 5** Variation of compressive strength of mixes at different ages

3.3. Rapid chloride penetration test (RCPT)

In Fig. 6 the passed charge through mixes containing lightweight aggregates are compared with the control mix. The results show an increase in the passed charge at all ages due to incorporation of lightweight aggregates. At the age of 90 days a considerable reduction of the RCPT result occurred in all mixes. The trends observed in the RCPT test are in general similar to the results of the RCMT test which will present in the next section.

![Passed Charge Graph](image)

**Fig. 6** The passed charge through specimens (Coulomb)

3.4. Chloride migration coefficient

As mentioned previously, the non-steady-state chloride migration coefficient of the concrete specimen can be computed based on NT BUILD 492 [36] using the RCMT results. A photo of chloride penetration depths for one of specimens
is shown in Fig. 7. Using the chloride migration coefficient, the concrete can be classified according to the concrete resistance against chloride penetration. In the researches of Zych and other researchers this criteria was classified in a list which is showed in Table 4 [43, 44]. The computed chloride migration coefficients of the specimens from different mixes are presented in Table 5. Generally, the mixes with the lightweight aggregates achieved lower chloride migration coefficient compared to the control mix regardless of the age. The results showed that the coefficient of the chloride migration reduces as the concrete age increases. The classification of the concrete resistance against chloride penetration for all lightweight mixtures were “acceptable” but concretes with Leca and Pumice had the best and the worst performance respectively. The amount of Chloride migration coefficient is extremely depends on amount of porosity. In assessed lightweight aggregates, the minimum porosity was observed in Leca aggregates (due to water absorption tests) and lowest amount of Chloride migration coefficient in this mix design was because of this fact.

**Table 4- Estimation of the concrete resistance to chloride ion penetration [43, 44]**

<table>
<thead>
<tr>
<th>Chloride migration coefficient $$(D_{28} \times 10^{-12} \text{ m}^2/\text{s})$$</th>
<th>Resistance to chloride penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>very good</td>
</tr>
<tr>
<td>2-8</td>
<td>good</td>
</tr>
<tr>
<td>8-16</td>
<td>acceptable</td>
</tr>
<tr>
<td>&gt; 16</td>
<td>unacceptable</td>
</tr>
</tbody>
</table>

**Fig. 7. Illustration of measurement for chloride penetration depths**

**Table 5- Chloride migration coefficient and classification of the concrete for resistance to chloride penetration**

<table>
<thead>
<tr>
<th>mix</th>
<th>Testing age (days)</th>
<th>Chloride migration coefficient $$(D\times10^{12} \text{ m}^2/\text{s})$$</th>
<th>Classification of resistance to chloride penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>28</td>
<td>4.3</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>3.45</td>
<td></td>
</tr>
<tr>
<td>Pumice</td>
<td>28</td>
<td>15.2</td>
<td>acceptable</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>Scoria</td>
<td>28</td>
<td>9.23</td>
<td>acceptable</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>7.52</td>
<td></td>
</tr>
<tr>
<td>Leca</td>
<td>28</td>
<td>8.87</td>
<td>acceptable</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>6.32</td>
<td></td>
</tr>
</tbody>
</table>
3.5. Corrosion resistance

The accelerated corrosion behavior of steel bars embedded in concrete specimens was studied by impressing a constant anodic potential. The current required to maintain the fixed potential was plotted against time and the typical curves of corrosion current versus time for the concrete specimens made with different lightweight aggregates and the electrical resistivity of all mixes are shown in Figs. 8 and 9, respectively. Typical corrosion specimens after the termination of the test are shown in Fig. 10. The Fig.8 indicates that current–time curve initially descended until a specific time and then a steady low rate of increment in current was observed, and after that a rapid increase in current was occurred until failure. The sudden rise of the current coincided with the cracking of the specimen. This curve was utilized to determine the corrosion time of the specimen when the specimen cracked due to corrosion and the current started to increase sharply. The first visual evidence of corrosion was the appearance of brown stains on the surface of the specimens. Cracking was observed in a short time after that and it was associated with a sudden rise in the current. Fig. 11 presents the average corrosion times required to crack the normal SCC concrete and the lightweight SCC concrete specimens. Time to cracking in control specimen was 216 hours (9 days) whereas that in other lightweight concrete specimens was in the range of 84–158 hours (3.5–6.6 days).

As it shows in Fig. 11, the times of corrosion cracking for the normal aggregate concrete specimen was longer than the lightweight concrete specimens. As a result of using lightweight aggregates, figs 8, 9 and 11 show that using scoria may cause better protection to steel reinforcement against corrosion than leca and pumice. Which was because of lower porosity in comparison with Pumice aggregates and higher compressive strength (higher resistance against cracks) in comparison with Leca aggregates.

![Fig. 8. Typical curve of corrosion current versus time at the test of 28 days for the specimens](image-url)
Fig. 9 Typical curve of electrical resistivity of concrete versus time at the test of 28 days for the specimens

Fig. 10 Accelerated corrosion setup and typical corrosion specimens after the accelerated corrosion test

Fig. 11 The average corrosion time required to crack the normal concrete and specimens made with lightweight aggregates
4. Conclusion

As it mentioned before, the SCC overlays are suitable repair materials for damaged concrete structures because of their special features like no need for vibration and high bonding strength to substrate. In this study the durability of Lightweight Self Compacting Concretes (LWSCC) with different types of lightweight aggregates were studied. The results are mentioned below:

- Test results indicated that the increase in compressive strength at later ages of SCC concretes made with Scoria was similar to concretes containing Pumice as lightweight aggregate. The concrete mixture containing leca aggregate showed the lowest compressive strength. The compressive strength of mix designs with lightweight aggregate was lower than conventional SCC samples.

- In RCPT test the results showed an increase in the passed charge at all ages due to incorporation of lightweight aggregates. At the age of 90 days a considerable reduction of the RCPT result occurred in all mixes. The concretes containing Pumice aggregate showed the maximum of passed charge and the worst performance.

- The mixtures containing lightweight aggregates achieved higher chloride migration coefficient than the control mix regardless of the age, which shows that SCC with lightweight aggregates have lower performance against chloride ions compared to conventional aggregate SCC. The results showed that the coefficient of the chloride migration reduces as the concrete age increases. The classification of the concrete resistance against chloride penetration for all lightweight Mixes were “acceptable” but concrete with Leca and Pumice had the best and the worst performance respectively.

- The times of corrosion cracking for the normal aggregate concrete specimens were longer than the lightweight concrete specimens. As a result of using lightweight aggregates, using Scoria aggregate may cause better protection to steel reinforcement against corrosion than Leca and Pumice aggregate.

- By consideration of all investigated parameters, using Scoria aggregates in SCC overlays will cause better durability and protection due to its higher compressive strength and performance in corrosion.

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REFERENCES


