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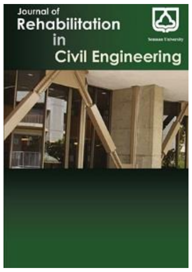

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Durability of Self-Compacting Lightweight Aggregate Concretes (LWSCC) as Repair Overlays

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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 resistance against chloride penetration were acceptable for all mix designs, 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 referred to a concrete which cohesively flows

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under its own weight without the need to vibration and properly fills the space between reinforcement even at congested areas. [1]. In 1986 at University of Tokyo SCC was developed for the first time to improve the quality of construction and to address the difficulties associated with placing concrete in highly reinforcement congested areas [2]. It is used to eliminate the need for vibration are 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. Two surface's bonding depends on friction, characteristics of surface bonding, aggregate involvement and specifications that vary over time [4-12].

Regarding the use of Light Weight Aggregate (LWA) in concrete, several advantages can be listed. 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].

From durability perspective, due to its lower thermal conductivity, lower coefficient of thermal expansion and use of fire stable aggregate (already heated) Lightweight concrete is more resistant to elevated temperatures than normal weight concrete [13]. In colder climates, resistance against freeze thaw cycles and salt-scaling are also of concern. Other researchers have reported the durable behavior of LWA in these conditions [16]. Resistance to freeze-thaw condition in lightweight concrete depends on various parameters such as lightweight aggregate's pre-wetting [17], the use of appropriate pozzolans such as silica fume[18, 19], and the use of superplasticizers to increase paste density and prevent micro-cracking behavior of LWA concrete [20].

Self-compacting lightweight aggregate concrete (LWSCC) is a kind of high-performance concrete in which suitable properties of self-compacting and lightweight aggregate concrete have been combined. [21-23]. Mix components and their proportions highly affect LWSCC properties. The characteristics of LWSCC mix design proportions, which are modified to ensure desired fresh properties, also greatly influence hardened properties such as strength, dimensional stability and durability[24]. For instance, aggregate type and water to cement or water to cementitious materials ratio are the most prominent factors affecting compressive strength of LWSCC [25]. While extensive research have been carried out on LWSCC fresh properties, the number of studies focusing on LWSCC hardened state is surprisingly low.

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. In this study, 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/m^3. The Scoria aggregate was provided from Ghorveh mine in Kurdistan province of Iran with density of 1600 kg/m^3. Also the Pumice aggregate was from Eskandan of Tabriz city in Iran with density of 1450 kg/m^3. 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 1. Concrete mix design details.

No	Name	Cement (Kg/m³)	Silica Fume (%)	Lime Stone (Kg/m³)	Sand (0-6) (Kg/m³)	Gravel (6-12.5) (Kg/m³)	Pumice (6-12.5) (Kg/m³)	Scoria (6-12.5) (Kg/m³)	Leca (6-12.5) (Kg/m³)	Water (Kg/m³)	W/C	Super Plasticizer (%)
1	Control	450	10	250	750	750	0	0	0	175	0.35	0.8
2	P	450	10	250	650	0	490	0	0	175	0.35	1
3	S	450	10	250	650	0	0	510	0	175	0.35	1.1
4	L	450	10	250	650	0	0	0	400	175	0.35	0.9

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 ingression [28]. This test was performed in this study on various mixes at the ages of 28 and 90 days. In the RCPT test, a 50 mm thick concrete disk specimen is subjected to an electrical potential of 60 V for 6 hours, and the total electrical charge passing through the specimen 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 have been developed [27, 29-35]. In this study the resistance of the concrete against chloride penetration has been determined by the non-steady-state chloride migration coefficient. Chloride migration coefficient is obtained according to the equations prescribed in 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 positioned on the plastic support which was immersed in an aqueous catholyte (10% NaCl) on one side and a aqueous anolyte (3% NaOH) on the other. During the test, temperature in chamber should be between 20-25 °C. An external electrical potential, forces the chloride ions from the NaCl solution into the specimen. The duration of test depends on the quality of concrete.

Fig. 1. Test setup of RCPT and RCMT

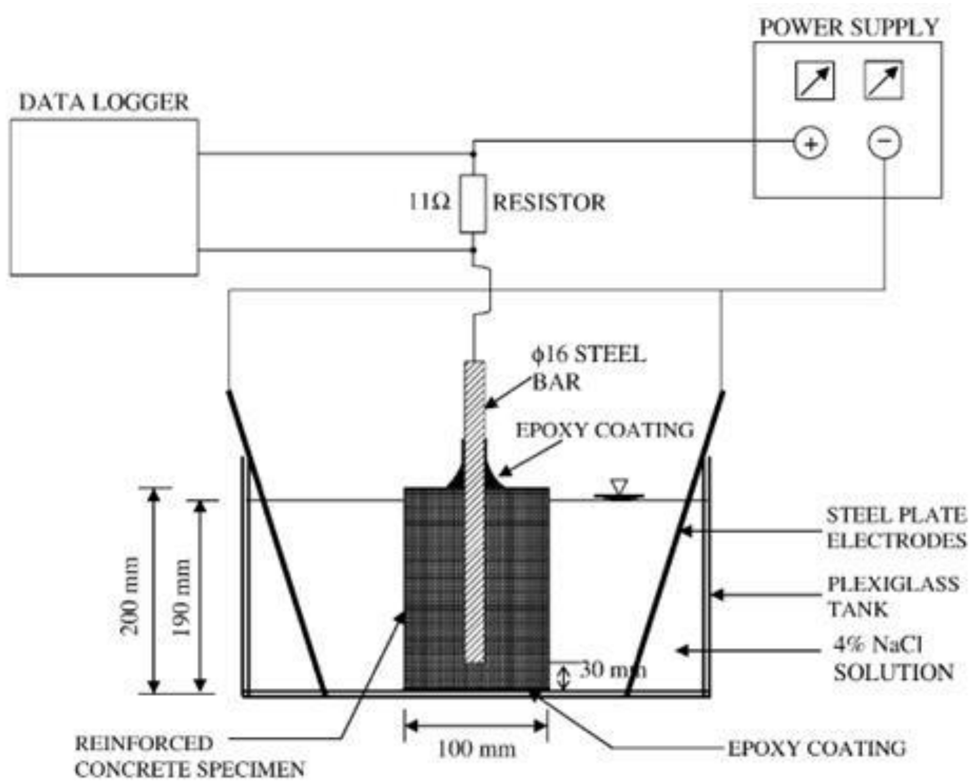

Fig.2. Schematic representation of the setup for the accelerated corrosion test [37]

Table 2. Voltage and test duration for concrete specimen (NT BUILD 492) [36]

Initial current I_{30V} (with 30 V) (mA)	Applied voltage U (after adjustment) (V)	Possible new initial Current I_0 (mA)	Test duration t (hour)
$I_0<5$	60	$I_0<10$	96
$5\leq I_0<10$	60	$10\leq I_0<20$	48
$10\leq I_0<15$	60	$20\leq I_0<30$	24
$15\leq I_0<20$	50	$25\leq I_0<35$	24
$20\leq I_0<30$	40	$25\leq I_0<40$	24
$30\leq I_0<40$	35	$35\leq I_0<50$	24
$40\leq I_0<60$	30	$40\leq I_0<60$	24
$60\leq I_0<90$	25	$50\leq I_0<75$	24
$90\leq I_0<120$	20	$60\leq I_0<80$	24
$120\leq I_0<180$	15	$60\leq I_0<90$	24
$180\leq I_0<360$	10	$60\leq I_0<120$	24
$I_0\geq 360$	10	$I_0\geq 120$	6

After test, the specimen was split across its circular cross section. To determine the chloride penetration, 0.1 M silver nitrate (AgNO3) solution were sprayed on the split surfaces, and the silver chloride precipitates were measured. If chloride increases on the surface after spraying the solution, a whitish color will be appeared, otherwise it will become brown. The chloride penetration depth can be indicated by the color change border. The depth of the chloride penetration measurement is needed so that the non-steady state chloride migration can be calculated using the simplified equation below [36]:

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

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 denotes the specimen's thickness (mm); x_d represents the average value of the penetration depths (mm); t is duration of the test (h). The external potential applied to each specimen for different concrete ages and the test duration is presented in Table 3.

Table 3. Test parameters for RCMT

Mix	Testing age (days)	Voltage (V)	Test duration (hour)
Control	28	30	24
	90	35	24
P	28	25	24
	90	30	24
S	28	30	24
	90	30	24
L	28	25	24
	90	30	24

2.4. Accelerated Corrosion Test (ACT)

To compare and monitor the corrosion behavior of the specimens containing normal weight and light weight aggregates, Accelerated corrosion test (ACT) which is a rapid corrosion testing method was used. This method was performed in many researches [37-42]. In this study, a 4% sodium chloride solution was prepared to simulate harsh marine and tidal environments. The specimens were immersed and partially embedded steel bar was connected to the positive terminal of a DC power supply to work as electrode. The negative terminal was connected to steel plates (counter electrode) placed at the bottom of the tank containing the solution. In this circuit, the steel rebar works as anode, the steel plates were the cathode, and the sodium chloride solution was the electrolyte. The test was initiated by applying 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. Variation of current with time was recorded by a data logger. 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.

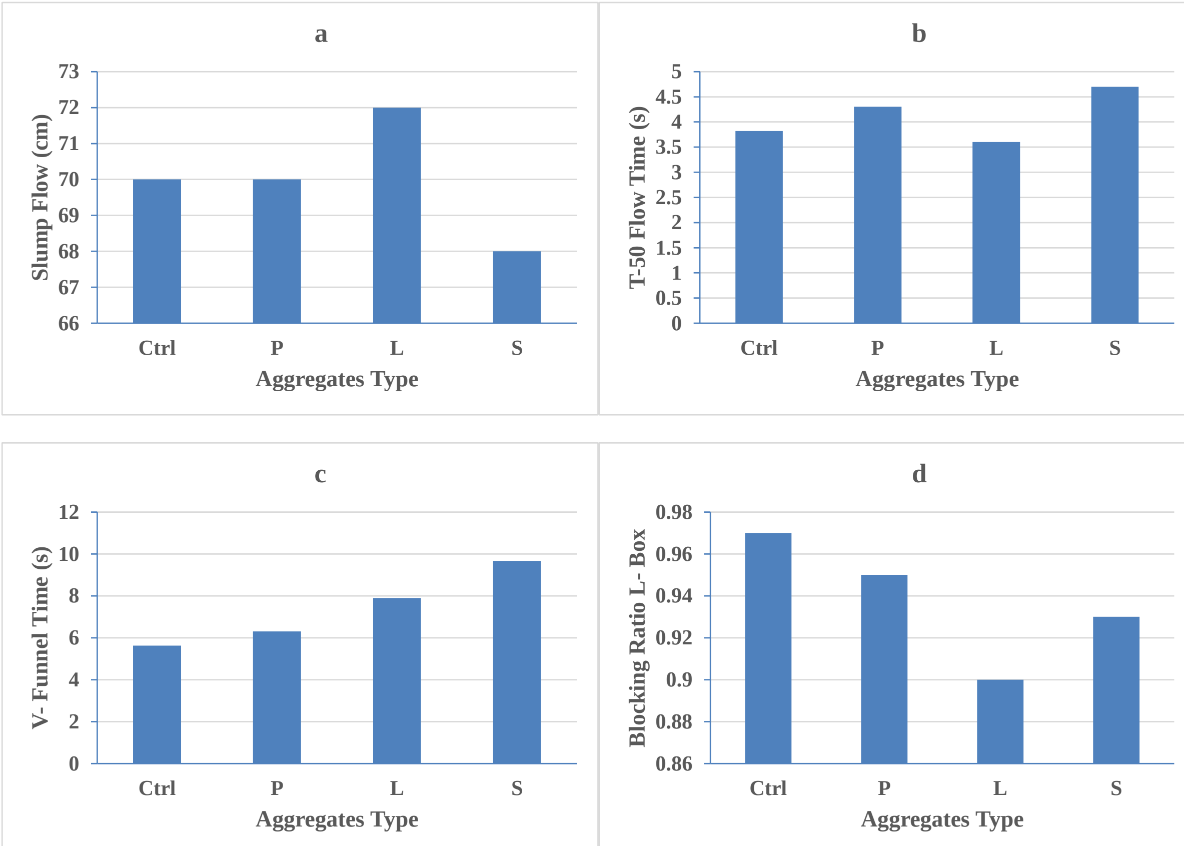

Fig.3. Rheological properties of mixtures; a: Slump flow; b: T50 flow table; c: V-funnel time; d: Blocking ratio

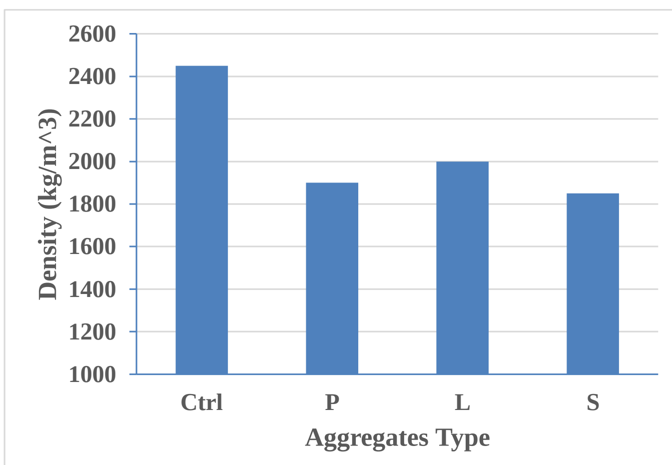

Fig.4. Density of mix designs

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. The results showed 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.

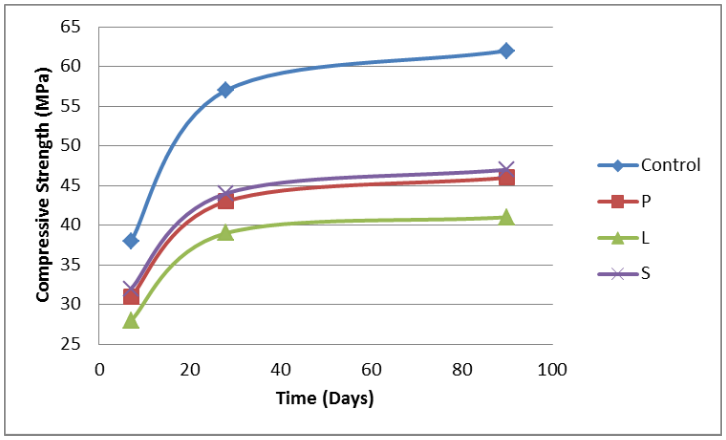

Fig.5. Variation of compressive strength of mixes at different ages

3.3. Rapid Chloride Penetration Test (RCPT)

Fig. 6 shows the results of RCPT test for control and lightweight aggregate containing mixtures. The results show that, at all ages, mixes containing lightweight aggregates have higher passed charge compared with the control mix. At the age of 90 days RCPT results show a considerable reduction in all mixes. The trends observed in the RCPT test and the RCMT test are generally similar to each other. the results of RCMT test will be presented in the next section.

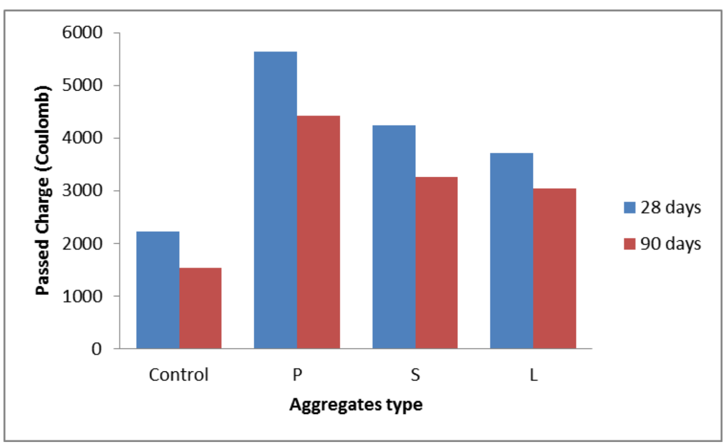

Fig. 6. The passed charge through specimens (Coulomb)

3.4. Chloride Migration Coefficient

As stated before, the non-steady-state chloride migration coefficient of a concrete specimen is computed according to the procedure demonstrated in NT BUILD 492 [36] using the RCMT results. A photo of chloride penetration depths for one of specimens is shown in Fig.7. Mixes can be classified by the chloride migration coefficient, according to thire 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]. Table 5 presents the calculated chloride migration coefficients for all mix designs. Generally, the mixes with the lightweight aggregates achieved higher chloride migration coefficient compared to the control mix, in all ages. The results showed that the coefficient of the chloride migration is reversely proportional to the specimen's age. 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]

Chloride migration coefficient ($D_{28} \times 10^{-12}\ m^2/s$)	Resistance to chloride penetration
< 2	very good
2-8	good
8-16	acceptable
> 16	unacceptable

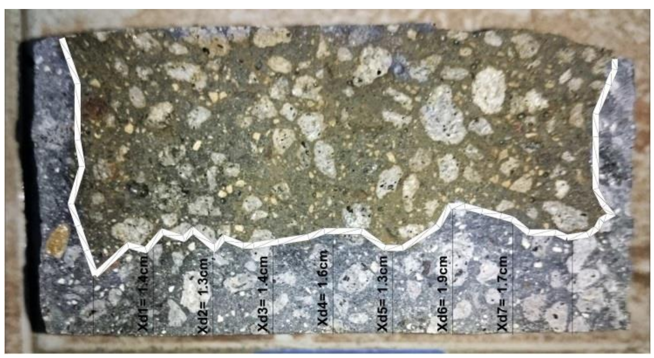

Fig. 7. Illustration of measurement for chloride penetration depths

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

mix	Testing age (days)	Chloride migration coefficient ($D \times 10^{-12}\ m^2/s$)	Classification of resistance to chloride penetration
Control	28	4.3	good
	90	3.45	
Pumice	28	15.2	acceptable
	90	11.6	
Scoria	28	9.23	acceptable
	90	7.52	
Leca	28	8.87	acceptable
	90	6.32	

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. Some of corroded specimens after the finishing 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. This rapid increase shows cracking of the specimen. So the corrosion time was determined in the graph, when the current started to increase sharply because of cracking owing to corrosion. A short time before cracking, brown stains appeared on the surface of the specimens and it was the first visual evidence of corrosion. The sudden rise in the current was simultaneous with the cracking. 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.

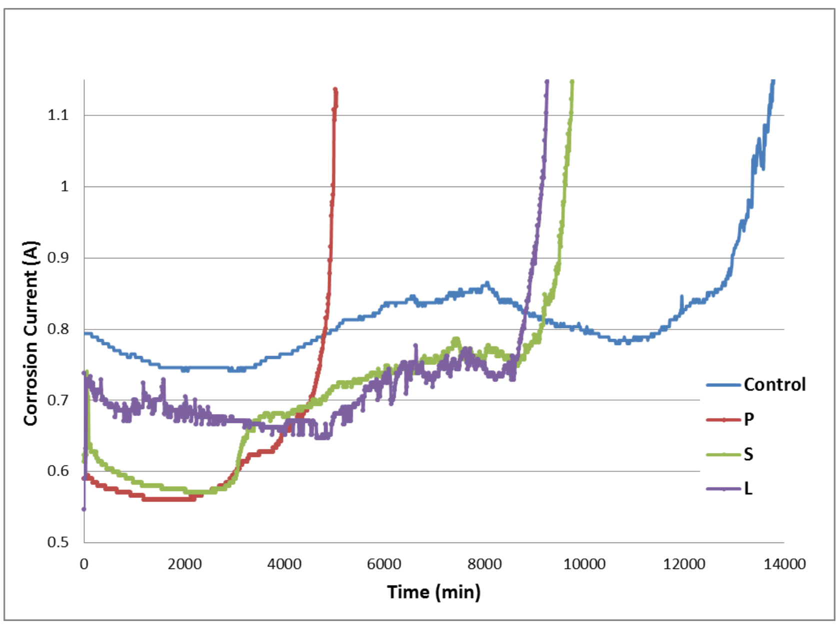

Fig. 8. Typical curve of corrosion current versus time at the test of 28 days for the specimens

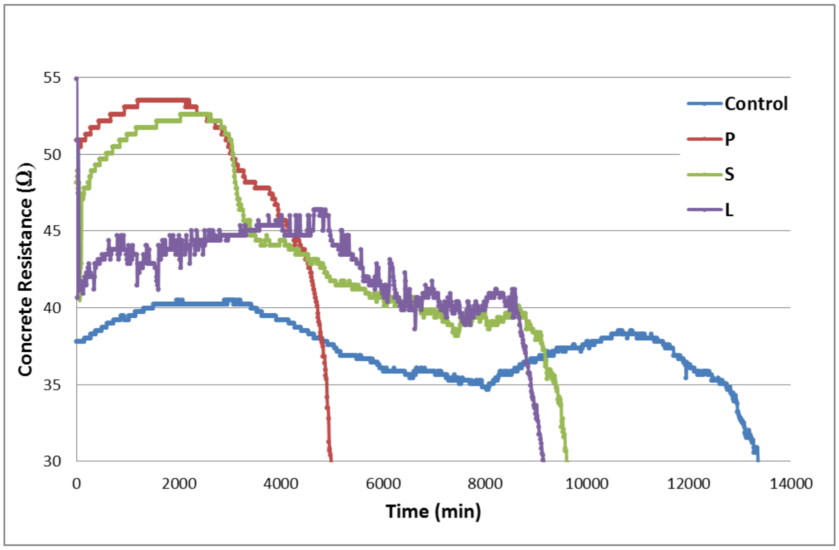

Fig. 9. Typical curve of electrical resistivity of concrete versus time at the test of 28 days for the specimens

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

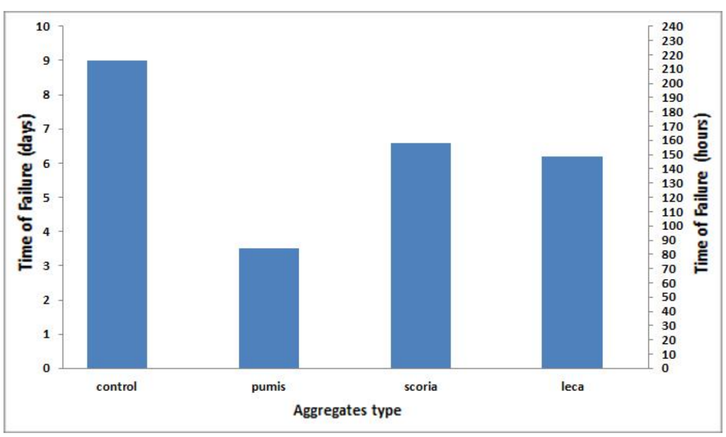

Fig. 11. The average corrosion time required to crack the normal concrete and specimens made with lightweight aggregates

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.

- Regarding RCPT test, the addition of lightweight aggregates led to an increase in the passing charge. 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 indicated that the coefficient of the chloride migration coefficient decreases as the specimen's 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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