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Effect of Silica Fume and Granulated Blast Furnace Slag on the Durability of Partially-Damaged Concrete

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ABSTRACT. This study investigates the effect of silica fume (SF) and ground granulated blast furnace slag (GGBFS) on the durability properties of concrete subjected to compressive damage. Portland cement was replaced by 10% SF and 60% of GGBFS as a replacement of Portland cement. Thirty-six concrete cylinders (100 x 200 mm) were subjected to three compressive preloading levels (50%, 75%, and 90% of the ultimate strength capacity). After 28 days of curing, the concrete specimens were experimentally tested for electrical resistivity, rapid chloride penetration (RCPT) and the chloride migration. The experimental results showed that the SF increases the compressive strength of concrete by 50% of control concrete. Besides, the GGBFS improves the durability of concrete with the highest electrical resistivity about 4 and 1.85 times the OPC and SF concrete results, respectively. The chloride permeability in GGBFS was found to be about 78% and 65% less than OPC and SF concrete, respectively. The chloride migration coefficient increases in the control samples subjected to 90% compressive damage. However, the replacement of Portland cement with SF and GGBFS improved the concrete durability when subjected to compressive damage up to 90% of the compressive strength.

Keywords: Electrical Resistivity, Durability; Concrete; Chloride Diffusion; Compressive stress.

1. Introduction

The Arabian Gulf region has an aggressive environmental condition where the fluctuation of temperature per day is about 20^o C and reaching about 45^{o}C. The salty environmental condition is enhancing the transport of chlorides and hence extends the deterioration of reinforced concrete structures due to the corrosion of the reinforcement steel. Several experimental studies were conducted in the last three decades to investigate the effect of concrete mix ingredients on the durability of reinforced concrete and several recommendations were suggested to improve the quality of concrete. These efforts were reflected as guidelines and specifications which assure a production of quality concrete. The quality of aggregate in this region is marginal limestone aggregate and has high water absorption up to 2.6% which affect the mechanical and durability properties of concrete as reported by Al-Amoudi *et al.* [1] and Shamsad *et al.* [2].

To improve the durability properties of concrete, mineral admixtures such as silica fume (SF) and Ground Granulated Blast Furnace Slag (GGBFS) were recommended in such aggressive salt environment to increase the maintenance-free service life of concrete structure and to achieve sustainability in concrete industry . Several researchers studied the effect of mineral admixtures on the mechanical and the durability properties of concrete. In the following sections literature review on the effect of SF and GGBFS on the properties of concrete will be presented.

1.1 Effect of SF and GGBFS on Compressive Strength of Concrete

Ground Granulated Blast Furnace Slag (GGBFS) is one of wildly used mineral admixtures which is a waste product of steel industry. GGBFS contains up to 35% of SiO_2 and about 40% of CaO with a marginal higher fineness index compared to Portland cement. Although, several experimental investigations were conducted on the mechanical and the durability properties of the replacement of Portland cement using deferent levels of GGBFS, the results showed different conclusions on the performance of GGBFS in the development of compressive strength after 28 days of curing when compared to ordinary Portland concrete OPC. How-Ji *et al.* [4] conducted comparative experimental study between OPC and GGBFS concrete; they reported that the strength development in GGBFS is at low rate at early age up to 28 days of curing when compared to OPC. Same conclusions were reported by (Qingtao *et al.* [5], Bilim *et al.* [6], Otieno *et al.* [7] and Min-Hong Zhang *et al.* [8]). However, others such as Luc and Frederic [9] reported that the replacement of Portland cement with 35% of GGBFS increases the 28 days compressive strength about 9% more than the OPC concrete. This could be explained due to low pozzolanic reactivity and the fineness index.

In recent study, Teng *et al.* [10] conducted experimental investigation on the durability and mechanical properties of ultra-fine ground granulated blast-furnace slag UFGGBFS – with fineness index approximately twice of that of GGBFS- and reported that the addition of UFGGBS to concrete tends to increase the early compressive strength up to 23% after 3 days of curing compared to normal concrete.

The replacement of Portland cement with 5-10% of silica fume significantly increases the early compressive strength of concrete as reported by (Erhan *et al.* [11], Rafat [12] and Bhanjaa and Sengupta [13]) in which silica fume has more than 50 times fineness index and has a an active pozzolanic activity and cement hydration rate compared to Portland cement.

1.2 Effect of SF and GGBFS on Durability Properties of Concrete

Several experimental research was conducted to evaluate the performance of SF and GGBFS on the durability of concrete. How-Ji *et al.* [4] conducted comparative experimental study between OPC and GGBFS concrete; they reported that a significant reduction in the total porosity was reported for GGBFS concrete compared to OPC which leads to a denser microstructure and improvement in the transport properties in GGBFS concrete. Dellinghausen *et al.* [14] investigated the influence of content of Ground Granulated Blast Furnace Slag and curing time on shrinkage and durability of concrete. Three levels of water to binder ration w/b (0.30, 0.42 and 0.55) and three levels of GGBFS (0%, 50% and 70%) were used in the study. The study reported that the 70% partial replacement of GGBFS reduced the total shrinkage and the chloride penetration by 35% and 47% after 7 days curing, respectively.

Obada *et al.* [15] investigated the contribution of GGBFS and SF on corrosion resistance in concrete. 500 x 500 mm reinforced concrete slabs with several levels of replacement of Portland cement with GGBFS was ponded with 3% NaCl for two years. Obada *et al.* [15] reported that the additional of GGBFS increased the concrete resistance to corrosion. The corrosion current rate was found to be 0.1 $\mu A/cm^2$ in OPC concrete after 2 years compared to 0.04 and 0.032 $\mu A/cm^2$ in SF and GGBFS concrete, respectively.

In recent review, Yong Zhang and Mingzhong Zhang [16] reported that the SF reacts with calcium hydroxide and improves the pore distribution of the interfacial transition zone. Sobhani and Najimi [17] investigated the correlation between the corrosion rate and the compressive strength, rapid chloride permeability test RCPT and water permeability of concrete containing silica fume and reported that the additional of silica fume improves the transport properties of concrete. Xianming *et al.* [18] studied the effect of silica fume and blast furnace slag on the porosity and the chloride binding capacity of the concrete, they reported that the replacement of Portland cement by 50% of GGBFS increases the chloride binding capacity while the addition of 10% SF reduced it. Same results reported by Luo *et al.* [19].

Although the laboratory experimental studies proved the superiority of the replacement of Portland cement by SF or GGBFS on the durability properties of concrete, there is a need to evaluate the performance of such mineral admixtures on concrete subjected to actual loads which represents the actual state of concrete structures. In recent study, Rahman *et al.* [20] conducted an investigation on the chloride migration in normal concrete subjected to different levels of compressive damage. The chloride diffusion coefficients were determined according to chloride migration test (NT-Build 492) [23]. From this study it was noted that the chloride diffusion in concrete samples was significantly increased with the increase of compressive induced damage up to 75% of the compressive strength of concrete.

This paper aims to investigate the effect of Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBFS) on the durability properties of concrete subjected to four levels of compressive loads. Concrete cylinders with SF and GGBFS were subjected to different compressive preloading levels and different durability tests including Electrical Resistivity according to AASHTO TP 95-11 [21], Rapid Chloride Permeability Test (RCPT) according to ASTM C 1202 [22] and the Chloride Migration Test (NT-Build 492) [23] were conducted. The durability of partially damage SF and GGBFS concrete was evaluated.

2. Experimental Program

2.1 Concrete Mix Design

Three concrete mixes were casted and used in this study. Ordinary Portland cement (OPC), 10% Silica Fume concrete (SF) and 60% Ground Granulated Blast furnace Slag concrete (GGBFS). Type I cement and a fixed water to cement ratio of 0.4 were used in the mix design. Sixty percent of coarse aggregate to total aggregate was used in the mix design using Riyadh Road type coarse aggregate. Table 1 shows the details of the mix design and Table 2 shows the physical properties and the chemical analysis of the Type I cement, SF and GGBFS.

Table (1). Concrete mixes ingredients

Concrete Type	Cement + Mineral Admixture Content (kg/m^3)	w/c	Superplasticizer (kg/m^3)	Aggregate (kg/m^3)	Tests (After 28 days of Curing)
OPC	370	0.40	4.7 (DARACEM 255)	1865	1-Compressive Strength 2-Chloride Permeability 3-Chloride Migration 4- Electrical Resistivity
SF	(333 + 37) 10% SF				
GGBFS	(148+222) 60% GGBFS				

Table (2). Physical properties and chemical analysis of materials

Components	OPC	SF	GGBFS
Chemical Analysis			
SiO_2 %	20.78	94.6	32.35
Al_2O_3 %	5.28	0.28	13.5
Fe_2O_3 %	3.27	0.36	0.50
CaO %	64.1	0.45	42.99
MgO %	1.86	0.30	5.08
SO_3 %	2.58	0.05	0.04
Physical Properties			
Specific gravity	3.1	2.22	2.91
Fineness (m^2/kg)	337	19200	419
Moisture %	0.1	0.17	0.13

2.2 Specimens Preparation

To evaluate the effect of applied compressive loads on the durability properties of the SF and GGBFS concrete, thirty six concrete cylinders (100 x 200 mm) were used in this study for the three types of concrete mixes (OPC, SF and GGBFS) and three levels of preloading damage (50%, 75% and 90%). After 28 days of curing, the concrete cylinders where subjected to three levels of damage: 50%, 75% and 90% of compressive strength. Figure 1 shows the concrete cylinders in the curing tanks. The control and the damaged samples were subjected to three durability tests as discussed in the following section.

2.3 Experimental tests

To achieve the objectives of the study, different tests were conducted after 28 days of curing as follows:-

Compressive strength

To create compressive damage, the concrete cylinders were preloaded in three levels of (50%, 75% and 90%) of ultimate compressive strength according to ASTM C39 after 28 days curing period.

Fig. (1). Concrete samples in the curing tanks

Electrical resistivity

The electrical resistivity (in kΩ.cm) was measured as shown in Figure 2. The control and damaged concrete cylinders were tested according to AASHTO TP 95-11.Table 3 was used to correlate the electrical resistivity and the chloride permeability according to AASHTO TP 95-11.

Fig. (2). Electrical resistivity test.

Table (3). Correlation between electrical resistivity and chloride permeability

Chloride Permeability	Resistivity Test kΩ.cm
High	> 12
Moderate	12 – 21
Low	21 – 37
Very low	37 – 254
Negligible	< 254

Rapid Chloride Penetration Test

The rapid chloride permeability test was conducted according to ASTM C1202. In this test, a disk of 50 mm thick and 100 mm diameter was used to evaluate the durability of concrete by measuring the charge passed after 6 hours according to ASTM C 1202. The test cell contains reservoir of 3% NaCl called upstream cathode and 0.3% NaOH called downstream anode and 60 V electrical voltage was applied to accelerate the movement of chloride ions from the upstream cathode to the downstream anode. Figure 3 shows the RCPT cells. Thereafter, the durability of concrete was evaluated using Table 4 in which a correlation between the charge passed after 6 hours in Coulombs and the chloride ion permeability was used as index of the durability of concrete.

Table (4). Chloride ion permeability based on charge passed

Charge in Coulombs	Chloride Ion Permeability
>4000	High
4000 – 2000	Moderate
2000 – 1000	Low
1000 – 100	Very Low
<100	Negligible

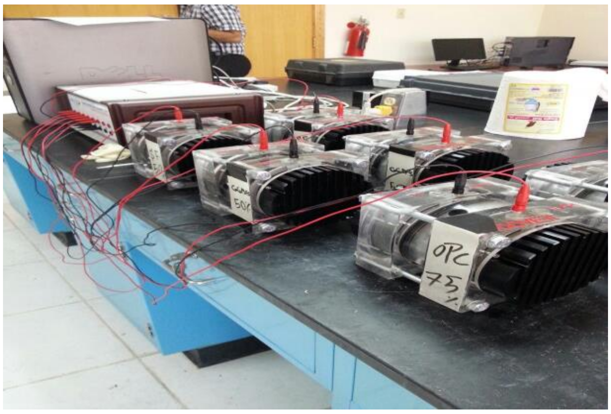

Fig. (3). Rapid chloride permeability test cells

Chloride Migration Coefficient

The chloride migration coefficient of concrete was determined according to NT-BUILD 492 [23]. The test cell contains two containers filled with 10% NaC1 and the 0.3 M NaOH and a 50 mm concrete disk was placed between them. The cell was supplied by power depends on the initial readings of the current as per described in NT-VUILD 492 for 24 h. Thereafter, the disk spill using compression and silver nitrate solution $AgNO_3$ sprayed on the samples and the chloride penetration depth is measured. Figure 4 shows the concrete disks after the spraying the $AgNO_3$ solution. The non-steady-state migration coefficient D_{nssm} (10^{-12} m^2/s) was then calculated based on the following equation and according to NT-BUILD 492 [23]:

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

Where, U is applied voltage in Volt; T temperature in the NaOH solution container in C^o; L is the thickness of the specimen, (50mm); x_d: the penetration depths in mm and t is the test duration in hour.

Fig.(4). Concrete samples treated with silver nitrate

3. Results and Discussions

3.1 Compressive Strength of Concrete

Figure 5 shows the effect of SF and GGBFS on the compressive strength of concrete. The figure shows that the compressive strength of SF is 43 MPa while it is 30 and 26 MPa for OPC and GGBFS, respectively. This indicates that the addition of SF increased the compressive strength of concrete compared to OPC, while the inclusion of GGBFS decreased the compressive strength due to its low rate of pozzolanic reactivity and lower cement hydration rate compared to SF concrete.

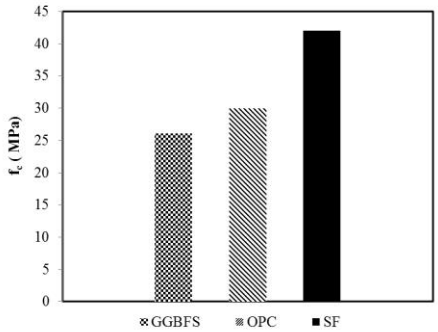

Fig. (5). Compressive strength for OPC, SF, and GGBFS concrete

3.2 Electrical Resistivity of Concrete

Figure 6 presents the effect of SF and GGBFS on the electrical resistivity of concrete. The electrical resistivity of GGBFS was 42.3 kΩ.cm, while it was 18.2 and

9.9 kΩ.cm for SF and OPC respectively. From Table 3 and Figure 6, the OPC concrete was classified with high chloride permeability state while the SF concrete found to be moderate permeability state and the best performance was found for the GGBFS concrete where it has very low chloride permeability due to reduction in the pore connectivity as reported by Hooton [27].

3.3 Rapid Chloride Permeability of Concrete

Figure 7 shows the influence of SF and GGBFS on chloride penetration of concrete. The charge passed in the OPC was 4639 coulomb, while it was 2936 and 1037 coulomb for SF and GGBFS concretes, respectively. The correlation between the charge passed and the chloride permeability was classified for the three types of concrete as shown in Table 4. The OPC concrete was classified as high chloride permeability compared to moderate permeability for SF concrete and low chloride permeability for GGBFS concrete. The GGBFS and SF improved the micro structure of concrete and enhance the pored distribution in concrete and decreased the porosity as reported by Turkmen [24].

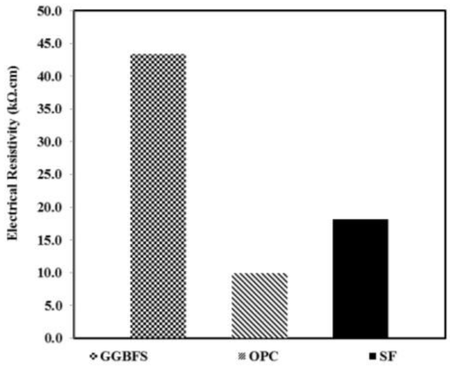

Fig. (6). Electrical resistivity for OPC, SF and GGBFS concrete

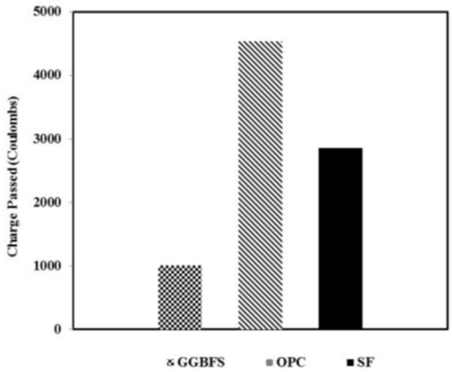

Fig. (7). Rapid chloride permeability of OPC, SF and GGBFS concrete

3.4 Chloride Migration Coefficient of Concrete

Figure 8 shows the effect SF and GGBFS on the chloride migration coefficient of concrete. The migration coefficient of OPC was 17.20x10^{-12} m^2/s, while it was 12.2 and 6.2x10^{-12} m^2/s for SF and GGBFS concrete. This indicates that the D_{nssm} for OPC is about 3 times that of GGBFS concrete, and about 1.5 times that of SF concrete. This indicates the advantages of using GGBFS and SF as replacement of Portland cement to enhance the durability properties of concrete. While the superior performance of SF could be explained by its reaction with $Ca(OH)_2$ that form secondary silicate hydrates production which improves the micro structure of the concrete and reduces the pore structure as its fineness index more than 60 times of the OPC, the GGBFS effect was in raising the chloride binding capacity as results of its large amount of Al_2O_3 content (Obada *et al.* [15] and Ytterdal [25]).

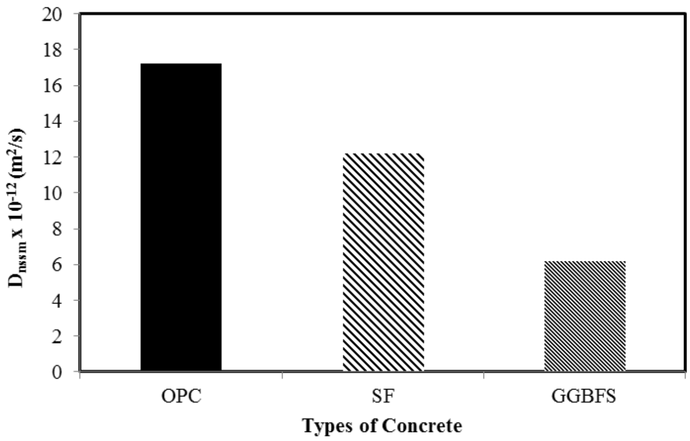

Fig. (8). Chloride migration coefficient in OPC, SF, and GGBFS concrete

3.5 Compressive Damage Level

Figure 9 presents the effect of compressive damage level on the rapid chloride permeability of concrete. For OPC concrete, up to 50% compressive damage level there was no change in the chloride permeability, while the charge passed increased from 4500 Coulombs for control mix to 5330 and 5660 Coulombs for OPC concrete subjected to 75% and 90% compressive damage which is about 1.25 times the undamaged specimens. This indicates a significant effect of compressive damage on the chloride permeability for OPC concrete subjected to compressive load higher than 75% of its ultimate strength. Besides, the additions of SF and GGBFS in concrete reduced the effect of compressive damage by enhancing the chloride permeability in concrete as shown in Fig. 9.

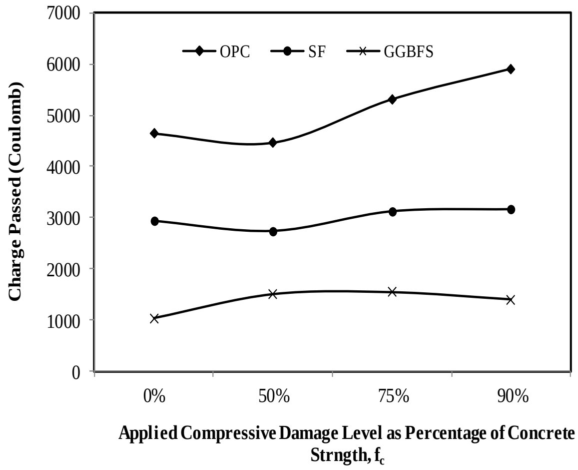

Fig. (9). Effect of compressive damage on RCPT of concrete

Figure 10 shows the influence of compressive damage level on the chloride migration coefficient of concrete (D_{nssm}). It can be observed that for OPC, the chloride migration coefficient increased from 17.2 x 10^{-12} m^2/s for undamaged concrete up to 20.7 x 10^{-12} m^2/s and 24.2 x 10^{-12} m^2/s for 75% and 90% damaged concrete, respectively. This indicates a significant increase (of 40%) in the chloride migration in the 90% damaged OPC concrete compared to undamaged concrete. Besides, the SF concrete improved the resistance of migration of chloride in concrete subjected to compressive induced damage up to 90% damaged concrete. The replacement of Portland cement with GGBFS improved significantly the durability of concrete as shown in Fig. 10 and similar conclusion was reported by Gjørv [26]. Although, the compressive-induced damage up to 90% of the compressive strength increased the chloride migration coefficient up to 2 times of the undamaged concrete, The D_{nssm} in 90% damaged GGBFS concrete was less than the undamaged OPC concrete.

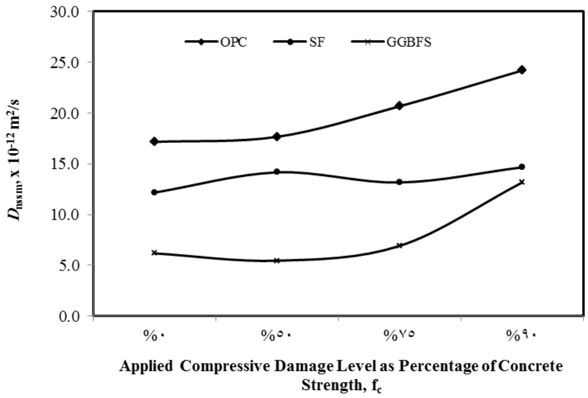

Fig. (10). Effect of compressive damage on chloride migration coefficient

4. Conclusions

The durability of OPC, SF and GGBFS concrete was evaluated using three different concrete durability tests. The following conclusions could be mentioned:

1. The SF increases the compressive strength of concrete by about 50% of OPC concrete after 28 days of curing.

2. The GGBFS concrete has the highest electrical resistivity with about 43 (KΩ.cm) compared to 18.2 KΩ.cm and 9.8 KΩ.cm for SF and OPC concrete which indicates that high, moderate and very low chloride penetration for OPC, SF and GGBFS concrete respectively.

3. The GGBFS concrete has the lowest rapid chloride penetration with about 1037 columns compared with 2936 and 4639 for SF and OPC concrete indicated high, moderate and low chloride penetration for OPC, SF and GGBFS concrete.

4. The chloride migration coefficient in undamaged samples was found to be $17.2x10^{-12}$ m^2/s for OPC concrete compared with $12.2x10^{-12}$ m^2/s and $6.2x10^{-12}$ m^2/s for SF and GGBFS concrete. This indicates that the replacement of Silica Fume and the GGBFS as a percentage of Portland cement leads to decrease in the chloride migration coefficient in SF and GGBFS concrete by 75% and 33 %, respectively.

5. A significant increase in the chloride migration coefficient was found in OPC samples subjected to compressive damage up to 90% of its compressive strength. However, the replacement of Portland cement with SF and GGBFS leads to improvement of the concrete durability even when subjected to compressive damage up to 90% of its compressive strength. Therefore, it is recommended to use GGBFS in concrete structures subjected aggressive environmental conditions such as the Arabian Gulf region.

5. Acknowledgement

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تأثير رماد السيليكا وخبث أفران تصنيع الحديد على قوة تحمل الخرسانة المعرضة للتلف الجزئي

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ملخص البحث. هذا البحث يتناول تأثير خبث الحديد و رماد السيليكا الى الخرسانة العادية والمعرضة لمستويات مختلفة من الضرر الناتج عن اجهادات الضغط. تم اضافة رماد السيليكا وخبث الحديد الى الخرسانة العادية ب (١٠٪ و ٦٠٪) كنسب احلال عن الأسمنت البورتلاندي العادي . تم تعريض ٣٦ عينة اسطوانة خرسانية لثلاثة مستويات (٥٠ %, ٧٥ %, و ٩٠ %) من مقاومتها للضغط . تم اختبار نفاذية الكلوريدات لعينات الخرسانة المتضررة والغير متضررة وذلك باستخدام اختبارات قياس نفاذية الكلوريدات وفقا للمواصفات القياسية NT Build 492 واختبار قياس المقاومة الكهربائية وذلك بعد ٢٨ من المعالجة . أظهرت النتائج المعملية ان اضافة رماد السيليكا يزيد مقاومة الخرسانة للضغط بنسبة ٥٠ % عن العينات القياسية . بالإضافة لذلك , فقد اظهرت النتائج المعملية بالرغم من أن اضافة خبث الحديد يقلل من مقاومة الخرسانة للضغط لكنه يزيد مقاومتها الكهربائية بمقدار اربع مرات عن الخرسانة العادية وبمقدار الضعف عن خرسانة رماد السيليكا. كما ان نفاذية الكلوريدات أظهرت نقصان في خرسانة خبث الحديد بنسبة ٧٨٪ و ٦٥٪ عنها في الخرسانة العادية وخرسانة رماد السيليكا .كان تأثير الضرر الناتج عن الضغط بنسبة تحميل ٩٠٪ واضحا في عينات الخرسانة العادية, بينما لم يظهر للضرر الناتج عن الضغط أي زيادة في نفاذية الكلوريدات وذلك في العينات المحتوية على الاضافات المعدنية.