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Durability of Blast- Furnace Slag Cement Concrete with Different Curing Methods

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Cement type; Concrete; Water/cement ratio; Curing techniques; Pore structure; Chloride; Sulfate; Carbonation.

Abstract

The concrete industry in Egypt has incorporated Blast Furnace Slag Cement Concrete, BFSCC, as a replacement to Ordinary Portland Cement Concrete, OPCC, in favor to resist harsh conditions related to water hydraulic structures. The practice cannot follow the strict requirements of curing according to the Egyptian code of practice (ECP), where in such cases it was necessary to evaluate the mechanical behavior of such concretes experimentally with practical curing methodologies. Two different methods were used to cure concrete specimens; IC samples were immersed in water until testing time, and secondly, FC samples were kept at a certain relative humidity and temperature and sprinkled with water every twelve hours for one week, simulating practical field curing conditions. The slump, flow, air content, and unit weight of fresh concrete were measured. Compressive strength, dynamic elastic modulus, and pulse velocity are investigated for hardened concrete. The main characteristics of the concrete pore structure were determined. The chloride content of the concrete was evaluated via titration analysis after 1-, 3-, and 5-months' immersion in sodium chloride solution. Moreover, the concrete specimens were immersed in a 10% sodium sulfate solution for 360 days to test their sulfate resistance. The carbonation depths of the concrete sample were measured at 1, 2, 4, 8, and 12 weeks. The results indicated good agreement between the destructive and non-destructive tests. In addition, as the curing methods and cement type were changed, the pore structure characteristics, sulfate resistance, carbonations, chloride penetration, and diffusion coefficients were significantly influenced.

1. Introduction

Supplementary cementing materials (SCMs) are divided into two types: natural and artificial. Natural SCMs include volcanic tuffs and real pozzolans, while by-products including blast-furnace slag, silica fume, and fly ash are considered artificial [1-4]. Slag has been identified and is being used to directly replace cement on a large scale [1]. In most applications, around half of the cement component in concrete can be substituted with slag

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[5]. Incorporating as little as 30% slag after the first 48 hours can reduce the accumulated heat by 25% [6].

Concrete pore structure has been extensively studied by concrete engineers during the last few decades. Concrete is a porous, nonhomogeneous construction material with a network of pores of varied sizes and shapes [7]. This pore structure has a large influence on the physical and chemical properties of the material. For example, in cement-based materials, pore structure features are intricately linked to compressive strength, corrosion resistance, durability, and permeability [8]. Total porosity is the fundamental determinant of permeability, which is regulated by the presence of pores and defects. Because of the sample size, the influence of poor curing on concrete strength is less than that of surface permeability [9].

Many adverse weather conditions have been proven to have a significant impact on the structural durability of reinforced concrete structures [10–12]. Chloride-induced reinforcing steel corrosion in concrete structures has become a durability problem in the concrete industry. It has been explored by several researchers [13]. There is no direct relationship between concrete strength and permeability, and when exposed to chloride, concrete should have an impermeable cover layer. When there is enough moisture and temperature, strength gains continue beyond 28 days [14].

Sulfate attack occurs when sulfate ions in the pore solution of concrete react with concrete components, resulting in the formation of novel reaction products with a large molar volume [15,16]. Several studies have been undertaken to reduce the attack and increase the service life of concrete structures exposed to sulfate conditions [15, 17]. After immersion in a salt solution for 28 days, the effect of chloride and sulfate attacks on ground granulated blast furnace slag (GGBFS) concrete strength was investigated [18]. The study found that when the percentage of cement that is replaced by GGBFS goes up by 20%, the durability of the concrete improves.

Carbonation occurs when carbon dioxide (CO_2) in the air combines with hydration products dissolved in pore water, lowering the pH of the concrete solution, and speeding up uniform steel corrosion [19]. Furthermore, it appears to raise the density of the concrete's surface layer, lowering chloride ion permeability and, as a result, sorptivity [20,21]. Moreover, carbonation has both positive and negative impacts on the durability of concrete [13]. The use of GGBFS as SCMs can improve the durability of concrete made entirely of OPC [22]. The latent hydraulic reaction that occurs during the hydration phase of the cement improves the GGBFS concrete's durability [23]. Therefore, when GGBFS is added to concrete, it strengthens and plugs pores, increasing durability and preventing water and other pollutants from infiltrating the concrete [24].

Previous studies [25-27] demonstrated that concrete made from GGBFS has improved rheological properties due to reduced fluidity and hydration heat, increased durability in the pozzolanic reaction, and enhanced long-term strength through self-hydration. Furthermore, researchers [28,29] showed that GGBFS has outstanding workability and is resistant to chemical penetration by acids and seawater. Another study [30] provides a method for forecasting concrete durability using GGBFS. Moreover, previous studies [31,32] reported that using GGBFS as a cement replacement has a significant environmental impact because the CO_2 emissions associated with cement production can be reduced and the cost of concrete production can be saved. But because GGBFS has a latent hydraulic property that causes hydration with cement hydrate as a catalyst, replacement ratio limitation and appropriate curing measures are required for effective expression of the initial strength [33].

Austin et al. [34] compared the permeability and strength of OPC and GGBFS-modified concretes cured in a simulated arid climate. The results of their research indicated that the strength of the OPC control concrete was lower than that of GGBFS concretes at 7, 14, and 28 days. Thus, partial cement replacement with GGBFS has the potential to generate more durable and stronger concrete in hot areas. Furthermore, GGBFS concretes are more sensitive to poor curing than OPC concretes, necessitating extra caution when utilizing this type of concrete on-site.
Krishna et al. [35] replaced cement with GGBFS up to 50% and investigates the mechanical properties of GGBFS concrete under immersed curing and membrane curing methods. They concluded that concrete workability is decreased as the percentage of GGBFS increases. The compressive strength of concrete is increased up to 30% by the replacement of cement with GGBS under both immersed curing conditions and membrane curing conditions.

Recently, many companies in the concrete industry in Egypt used Blast Furnace Slag cement to construct regulators, aqueducts, barrages, culverts, and other types of water structures. Most elements of concrete water structures expose to sulfate, chlorides, and carbonation. The practice cannot follow the strict requirements of curing according to the Egyptian code of practice (ECP) where in such cases it was necessary to evaluate the mechanical behavior of such concretes experimentally with practical curing methodologies. Therefore, the present research was made to study the effects of changes in the concrete curing method used in some structures in Egypt in the field (FC) and compared results with samples cured immersed in water (IC).

2. Experimental program

The materials used in this research were supplied by Japan's construction materials. All the concrete specimens were made with Type B blast-furnace slag cement (BFSC) and Portland cement (OPC). The physical and chemical properties of OPC and BFSC comply with Japanese industrial standards (JIS) specifications numbers JIS R5210 [36] and JIS R5211 [37], respectively. The chemical compositions of the two mentioned types of cement are listed in **Table 1**. Sand with a specific gravity of 2.55, a fineness modulus of 2.49, and a water effective absorption of 1.63 percent was used. The coarse aggregate is crushed basalt with a nominal maximum size of 15 mm, a specific gravity of 2.61, and a fineness modulus of 6.18. With a dose of 1.4 percent by cement weight, the used chemical additive is a superplasticizer with a highly water-reducing agent. The properties of used materials are listed in **Table 2**. For six different concrete mixes, the water/cement (w/c) ratios were 0.4, 0.5, and 0.6. The cement content was 400 kg/m^3 and the sand/aggregate ratio was 0.5. **Table 3** includes the mix proportions of the studied concrete mixtures.
The concrete mixing begins by batching the coarse aggregate, followed by the sand, and finally the cement and the mixer continuous for three minutes (1.5 minutes for dry mixing and 1.5 minutes after adding water with admixture). After mixing, slump (JIS A1101) [38], flow, air content (JIS A1128) [39], and unit weight were measured. Two types of specimens were prepared: 10 x 20 cm cylinders for determination of compressive strength, and prisms of dimensions 40 x 10 x 10 cm were used to measure durability aspects. The numbers of specimens used for each test were 3 and the results are the average. All the specimens were compacted by a vibrator, finished, and stripped from their molds the day following casting. There were two different curing methods used, the first method (IC) immersed samples in water until testing time. To simulate field curing, the second method (FC) kept samples at

22°C and 80 percent relative humidity for one week and sprinkled them with water every twelve hours.

Compressive strength, dynamic elastic modulus (DEM) - JIS A1127 [40], and pulse velocity, are all investigated properties of hardened concrete. Destructive tests are used to determine compressive strength (JIS A1108) [41], whereas non-destructive tests are used to determine the DEM and pulse velocity. The non-destructive parameters were measured on cylinder specimens (depth = 10 cm, height = 20 cm) before the compression test. The DEM, pulse velocity, and compressive strength were measured for specimens of 0.4 w/c ratio at various ages up to 180-day. After the compression test, the pore structure samples were taken from the mortar of the crushed concrete samples. During the preparation of such types of samples, the following precautions should be taken:

- The sample should be selected from different parts of all the crushed mortar to represent completely the mixes.
- Samples should be chosen from positions faraway from both the sample surfaces and the rupture surfaces.
- The size of the samples should be less than 5 mm to facilitate their insertion into the mercury Porosimetry cell and should not take a long time to be completely dry.
- A vacuum was used to dry the sample. Under vacuum conditions, it takes at least two days.
- About 2 - 4 gm of the sample is used to measure the pore structure of mortar.

Table 1: Chemical composition of used cements

Constituents	Percentage by weight (%)		Constituents	Percentage by weight (%)	
	BFSC (Type B)	**OPC**		**BFSC (Type B)**	**OPC**
Ignition loss	0.80	0.70	SO_3	2.00	1.90
Insoluble residue	0.20	0.20	Na_2O	0.28	0.36
SiO_2	26.10	22.00	K_2O	0.47	0.58
$Al2O_3$	8.50	5.10	TiO_2	0.60	0.29
Fe_2O_3	1.90	3.00	P_2O_5	0.07	0.11
CaO	54.60	63.80	MnO	0.31	0.12
MgO	3.50	1.50	-----	-----	-----

Table 2: Main characteristics of used materials

Material	Physical properties			
	Specific gravity	**Specific surface area cm^2/gm**	**Fineness modulus**	**Water absorption**
OPC	3.16	3310	-------	-------
BFSC	3.04	3860	-------	-------
Fine aggregate (sand)	2.55	-------	2.49	1.63 %
Coarse aggregate (Crushed basalt) with 15 mm Nominal Maximum Size	2.61	-------	6.18	-------
Chemical admixture (superplasticizer)	High range water reducing agent, with a dose of 1.4 percent by weight of cement			

Table 3: Mixtures details

Mix No.	Cement type	W/C ratio	kg/m³					
			Cement	Water	Sand	Crushed basalt	Admixture
1	OPC	0.4	400	160	877	898	5.6
2		0.5		200	826	845	
3		0.6		240	775	793	
4	BFSC	0.4		160	871	892	
5		0.5		200	820	840	
6		0.6		240	769	787	


Fig. 1: Mercury Intrusion Porosimetry (PoreSizer 9320 apparatus)

The Mercury Intrusion Porosimetry (**Fig. 1**) was used to investigate the pore structure characteristic of concrete. The used apparatus was PoreSizer 9320 is a 30,000 psia mercury porosimeter covering the pore diameter range from approximately 360 to 0.006 µm. The unit has two built-in low-pressure ports and one high-pressure chamber. Data collection, data reduction, and data display are processed by the optional control module. All aspects of the high-pressure analysis are also managed by the control module.

After 28 days of curing, some prisms 10x10x40 cms were immersed in a 5% sodium chloride solution for 5 months. This solution was changed every day to keep the concentration constant. The specimens were taken out of the solution after the desirable period of exposure and left to dry in laboratory air for 7 days. Three samples, each measuring 7 x 4 x 1 cm, were cut from the surface of the concrete specimen by a dry cutting machine. All the samples were crushed by using a certain crusher tool till passing from 0.15 mm sieve diameter and dried for 3 days in laboratory air. A grinding machine was used to grind the sample for 5 hours (the weight of the sample ranged from 20 gm to 40 gm according to JIS). To avoid changing the actual chloride content, the crusher, and container of the grinding machine are cleaned with ethanol or acetone after crushing or grinding every sample. The grounded concrete was used for the determination of the total and soluble chloride content. After 1, 3, and 5 months of exposure to sodium chloride solution, the chloride contents of the concrete samples were evaluated using automatic potentiometric titration (JIS K0113) [42].

The flowchart represented in **Fig. 2** explains the chloride contain measurements starting from concrete mixing until titration analysis. To determine total chloride content, the samples were titrated, and chloride was removed. The content of water-soluble chloride, on the other hand, is determined by immersing the specimen in hot water. The soluble and total chloride contents of powdered samples were determined using the titration method at depths of 0~10, 10~20, and 20~30 mm. The procedure for measuring chloride content and the equipment utilized are described in Ref. [43].

The concrete specimens (D = 10 cm and H = 20 cm, as well as prisms 10 by 10 by 40 cm) were cured for 28 days before being immersed in a 10% sodium sulfate solution for one year. After 7, 28, 90, 180, and 360 days, the submerged samples were tested to determine pulse velocity, dynamic elastic modulus, flexural strength, and compressive strength. Concrete samples were exposed to CO_2 (5%), relative humidity (60%), and 30° C after curing. After 1, 2, 4, 8, and 12 weeks of exposure, the carbonation depths were measured. Fresh concrete was exposed, and a phenolphthalein indicator was sprayed on to determine carbonation. This research work is part of a big research project that investigates the effects of curing methods on concrete made from various types of cementitious materials. The experimental work of this research has been done in the structural engineering materials laboratory at Kyoto University, Civil Engineering Department, Japan. The test samples were prepared according to JIS A1138 [44] used to determine the above-mentioned properties. More details about different testing and measurements are available in Ref. [43].

Fig. 2: Flowchart explains the chloride contain measurements starting from concrete mixing until titration analysis using potentiometric titration

3. Fresh concrete properties

The measured parameters of fresh concrete reveal that BFSCC mixes have higher workability, and air content values than OPCC mixes (**Table 4**). The admixture dose was fixed for all investigated mixes that yielded varying levels of fresh concrete workability i.e., the slump (workability) values rose as the w/c ratio increased. As a result, only the slump could be measured for mixes with a w/c ratio of 0.4, whereas concrete with a w/c ratio of 0.5 and 0.6 changed to be flowable and the flow could be measured. Furthermore, for the same cement type, raising the w/c ratio causes the measured air content to decrease. Because the specific gravity of cement varies, the concrete unit weight changes according to the type of cement used. As a result, BFSC concrete has a higher unit weight than OPC concrete. For the same type of cement, the unit weight of concrete decreases with an increase in the w/c ratio.

Table 4: Fresh concrete mixtures properties

Cement type	**W/C ratio**	**Unit weight (t/m^3)**	**Air content %**	**Flow (cm)**	**Slump (cm)**
OPC	0.4	2.384	1.8	------	19.2
	0.5	2.361	1.2	69.4	------
	0.6	2.342	0.9	71.9	------
BFSC	0.4	2.353	2.5	------	21.6
	0.5	2.344	1.7	70.5	------
	0.6	2.321	1.5	72.4	------

4. Hardened concrete properties

For the studied mixes, compression, dynamic modulus of elasticity, and pulse velocity tests were performed on concrete. **Figure 3** shows the measured compressive strengths of mixtures with a w/c ratio of 0.4 for curing IC and FC at ages up to 180 days. The compressive strength of concrete cured in method IC is greater than that of concrete cured in method FC for all ages tested. Moreover, when BFSC concretes were compared to OPC concretes with curing FC, the compressive strength of the BFSC concretes was lower. With IC curing, BFSC concretes show less strength than that of OPC concretes at 3 and 7 days. This is attributed to the fact that BFSC made little contribution to the strength during the first seven days and had a significant impact beyond that. The BFSC mixture has approximately equivalent strength to the mix of OPC at ages 28, 90, and 180 days under, and it). The results show that the strength gain is affected by the change in cement type and curing method. Depending on the obtained results, it is possible to make workable concrete with good mechanical properties with OPC and BFSC using a w/c ratio of 0.4 and a suitable dose of superplasticizer.

Figure 4 shows the pulse velocity values of tested concrete with time. The pulse values are influenced by changes in the type of cement and curing method, where the results of the IC method are greater than those of the FC method. **Figure 5** shows the dynamic elastic modulus values measured throughout time. The results demonstrate a slight difference in DEM values between the two curing methods, where DEM values for concrete of IC curing are greater than those for concrete of FC curing. Both pulse velocity and DEM findings for different mixes show a similar trend to compressive strength, and both tests can be used to compare or assess concrete quality, as illustrated in **Figs. 4** and **5**. Moreover, there is a good agreement between the result obtained from the destructive and non-distractive tests. More information about the effect of changing water to cement ratio and curing method in hardened concrete properties of OPC and BFSC such as compress, tensile, flexural strengths as well as pulse velocity and DEM have been published in Ref. [45].

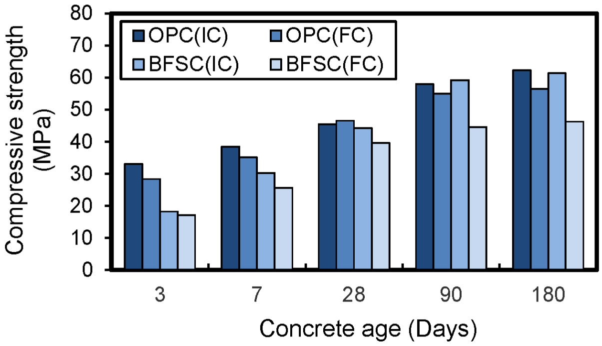

Fig. 3: Results of Compression Test with Time

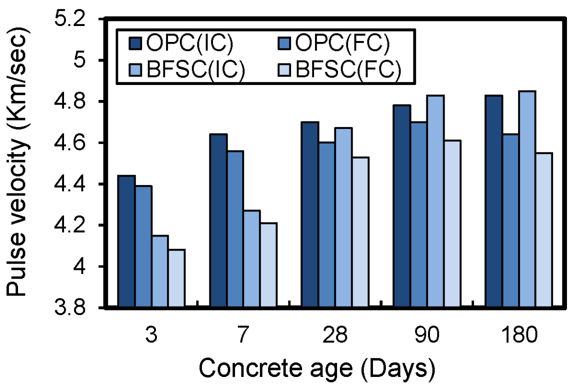

Fig. 4: Pulse velocity with time

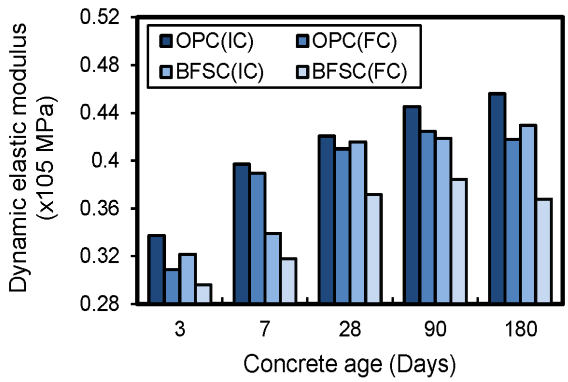

Fig. 5: Dynamic elastic modulus with time

5. Pore structure characteristics

As mentioned above, Ref. [45] includes some published results from this research project, which involves information about the effect of changing water to cement ratio and curing method on the most important characteristics of concrete pore structure. These results include pore volume, porosity, average pore diameter, and pore surface area of OPC concrete and BFSC concrete.

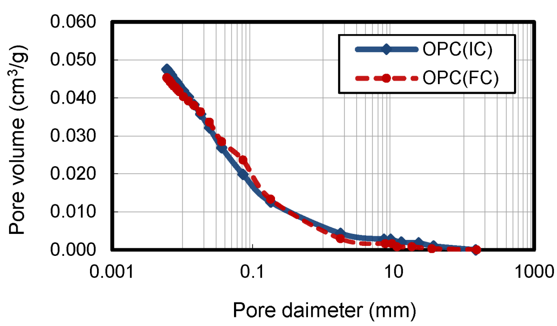

Fig. 6: Results of pore size for OPC mix

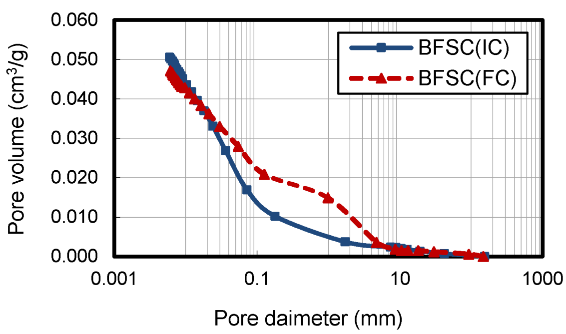

Fig. 7: Results of pore size for BFSC mix

Therefore, in this research, the relationship between pore volume and pore diameter has been demonstrated through the distribution profiles. **Figures 6** and **7** illustrate the pore volume distribution profiles for the tested concrete. The profile shape varies slightly depending on the curing method and cement type, and there are additional available results reported by Anwar [47].

6. Chloride ion permeability

The chloride contents of the tested concrete are listed in **Table 5**. The results demonstrate that when the depth of the tested samples was increased, the observed chloride level decreased dramatically. Furthermore, the results indicate that the first ten mm of concrete samples have minimal resistance to chloride penetration. In comparison to OPC concrete with curing IC and FC, the zones 10~20 mm and 20~30 mm of the BFSC mixture show lower chloride contents. As the curing method changed, the measured chloride contents were influenced due to changes in cement type, see **Figs. 8** and **9**.

Table 5: Chloride contents of the tested concrete

Cement Type	**Curing Type**	**Depth (mm)**	**One month**		**Three months**		**Five months**	
			Total %	**Soluble %**	**Total %**	**Soluble %**	**Total %**	**Soluble %**
OPC	IC	0~10	0.26700	0.06933	0.29315	0.18574	0.32375	0.19236
		10~20	0.01791	0.00893	0.01937	0.01096	0.02225	0.01224
		20~30	0.00965	0.00801	0.00988	0.00964	0.01173	0.01013
	FC	0~10	0.34524	0.08563	0.41305	0.19468	0.36321	0.22395
		10~20	0.02217	0.01197	0.02328	0.01234	0.02851	0.01557
		20~30	0.01310	0.00912	0.01471	0.00981	0.01589	0.01093
BFSC	IC	0~10	0.18295	0.04327	0.41881	0.19840	0.33852	0.11235
		10~20	0.01517	0.00717	0.01685	0.00775	0.01719	0.00839
		20~30	0.00907	0.00708	0.00933	0.00734	0.00959	0.00747
	FC	0~10	0.32812	0.06033	0.34239	0.20652	0.49541	0.25746
		10~20	0.01714	0.00736	0.01988	0.00821	0.02199	0.00851
		20~30	0.00934	0.00724	0.00968	0.00785	0.00998	0.00825

Marusin [48] reported that about 0.03 percent of soluble chloride (by concrete weight) is the limit of the corrosion threshold. The measured soluble chloride concentrations for zone 20~30 mm at 5 months were lower than the limit given by Marusin in this study.

In general, the total and soluble chloride content of concrete cured with curing IC was lower than that of concrete cured with curing FC. BFSC mixtures have a positive impact on the performance of concrete, particularly in terms of improving its resistance to chloride attack, with the measured soluble chloride of BFSC being lower than that of OPC. Where, after 5 months at a depth of 20~30mm, the BFSC concrete shows a soluble chloride content of about 73% and 75% of that of OPC concrete for IC and FC curing, respectively. Furthermore, BFSC-containing concrete may require less concrete cover to protect the reinforcement. Gaynor [49] found that the soluble/total chloride ratio ranged from 0.5 to 0.75 percent and that this amount of soluble chloride is therefore responsible for reinforcement corrosion. The results of this study show a lower percentage of soluble/total chloride than Gaynor's range. The BFSC soluble/total chloride ratios are lower than the OPC mix ratios. Furthermore, the data shows that there are no significant changes in soluble and total chloride for zone 20~30 mm.

As shown in **Fig. 10**, the diffusion coefficient values fluctuate according to changes in the curing method and cement type, and there are minor variations between the results of all mixtures. Furthermore, the BFSC mix diffusion coefficients are lower than those of the OPC. According to Nagaro [50], the arbitrary limits of the diffusion coefficient are 10^{-7} and 10^{-8} cm^2/sec. The obtained values of all mixes are within the ranges mentioned by Nagaro.

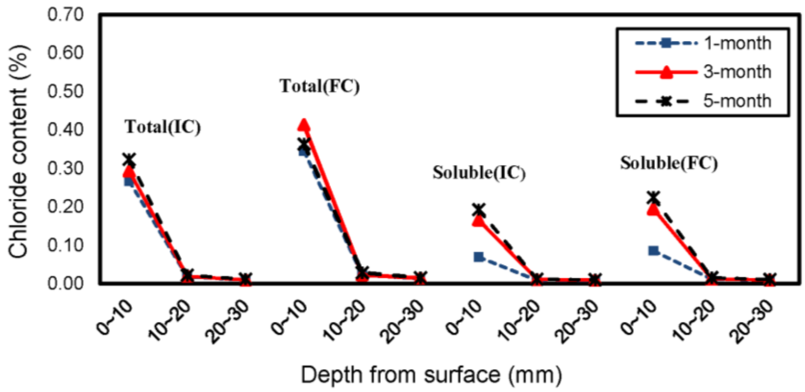

Fig.8: Chloride contents of OPC mix

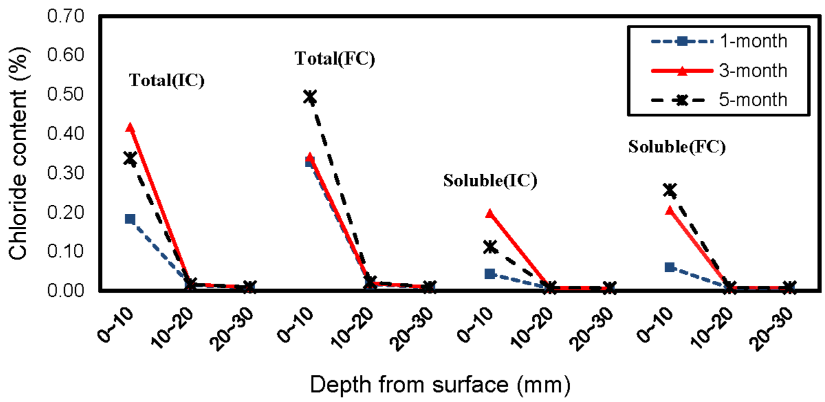

Fig.9: Chloride contents of BFSC mix

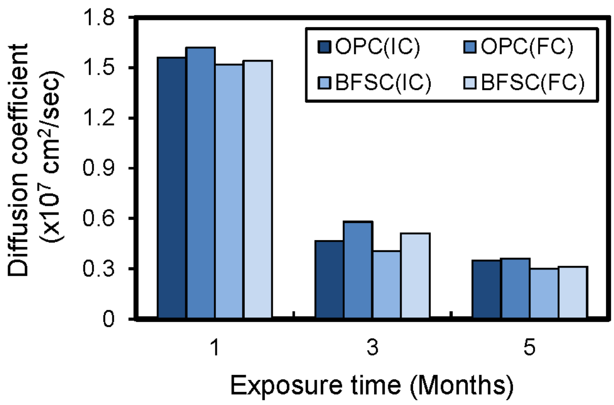

Fig. 10: Diffusion coefficient of studied concretes

7. Sulphate resistance

Figures 11 and **12** represent the influence of exposing concrete to sodium sulfate on the measured properties. The results of compression and flexural testing increase as the immersion time increases until 180 days, after which they show lower values at 360 days than at 180 days. The increase in strength induced by cement hydration is larger than the decrease in strength caused by immersion in a 10% sodium sulfate solution till 180 days of immersion.

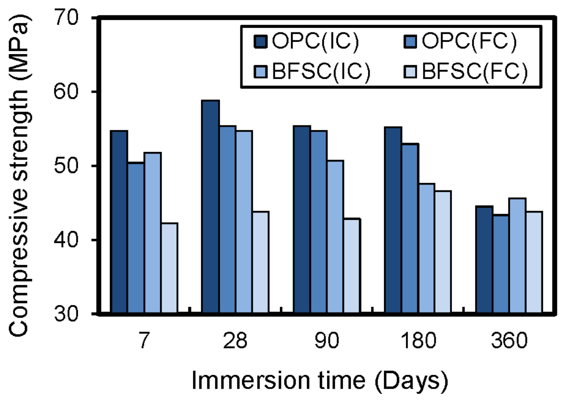

Fig. 11: Compressive strength after immersion

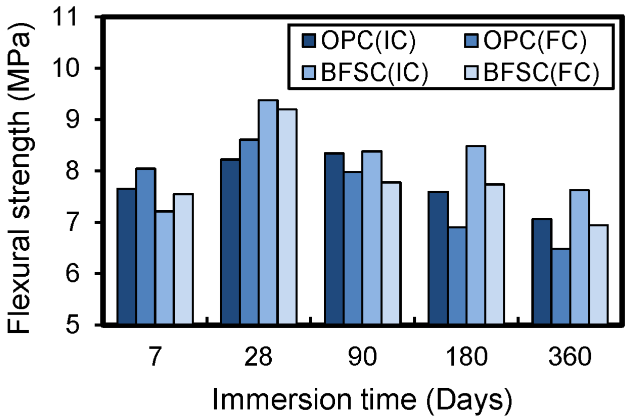

Fig. 12: Flexural strength after immersion

Figure 11 indicates that BFSC concrete has compressive strengths that are approximately 10% and 20% lower than OPC concrete after IC and FC curing, respectively. When immersed in a sulfate solution, the curing methods IC and FC of BFSC and OPC concrete show approximately equivalent values of flexural strength (**Fig. 12**). The flexural strengths of curing IC concrete are greater than those of curing FC concrete at all times tested.

Figures 13 and **14** illustrate the measured dynamic elastic modulus and pulse velocity, both of which follow the same general pattern as compressive strength. Both tests should be used to compare and evaluate concrete quality. Furthermore, most values of pulse velocity and dynamic elastic modulus rise with time until 180 days of immersion with cures IC and FC. Following that, the values show a slight decrease with time.

The pulse velocity and dynamic elastic modulus of cured IC concrete are higher than those of cured FC concrete. Furthermore, the obtained compressive strength data, as well as pulse velocity and dynamic elastic modulus, are highly consistent. The results of all mixes are affected by changes in cement type and curing method. The findings of research [51] include further information about the effect of sulfate on the concrete made with a ternary system of cementing materials, including combinations of by-products materials such as fly ash and silica fume.

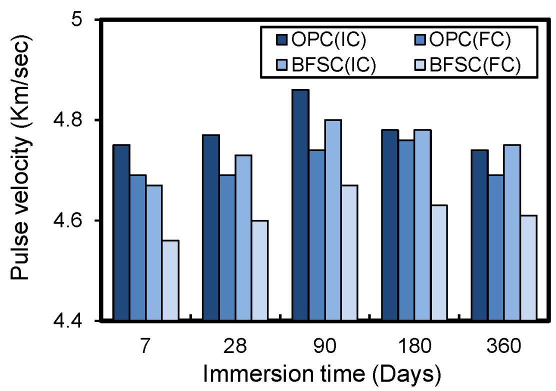

Fig. 13: Pulse Velocity after Immersion

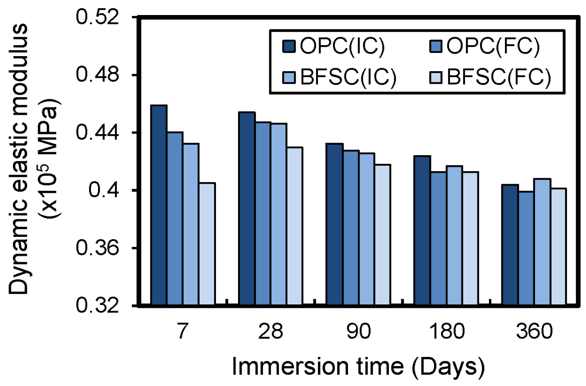

Fig. 14: Dynamic Elastic Modulus after Immersion

8. Carbonation depth of concrete

Figures 15 and **16** illustrate the measured carbonation depths (an average of 10 measurements) in this study. The results reveal that as the exposure time increases, the absorbed carbonation depths increase as well. The measured carbonation depth is influenced by the curing methods, cement type, and w/c ratio. It noted that BSFC concretes with 0.4 and 0.5 w/c ratios have greater carbonation depths than OPC concretes under both IC and FC curing methods. Furthermore, carbonation depths in OPC concrete with a 0.6 w/c ratio after IC curing are larger than in BFSC concrete. Moreover, compared to BFSC-cured FC concrete, OPC concrete has lower carbonation depths.
For the studied w/c ratios, the obtained results show that the curing method has an influence on the measured carbonation depths, with OPC concrete curing IC indicating greater carbonation depths than curing FC concrete. BFSC concrete that is curing IC has less carbonation depths than concrete that is curing FC, as shown in **Figs. 15** and **16**. Additionally, the obtained carbonation depth results are consistent with previous investigations [52,53], which reported that long-term carbonation depths were larger in slag concrete. This was because the carbonation of the slag-cement paste made the pore size distribution coarse.

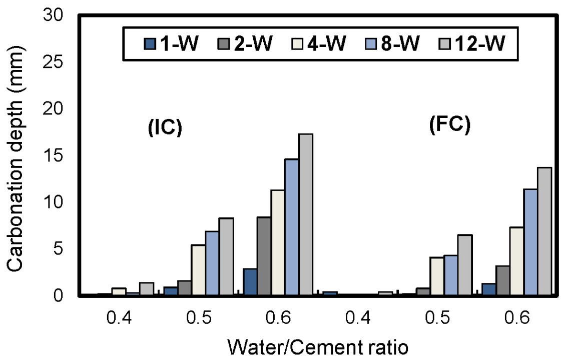

Fig. 15: Carbonation depths of the tested OPC mix

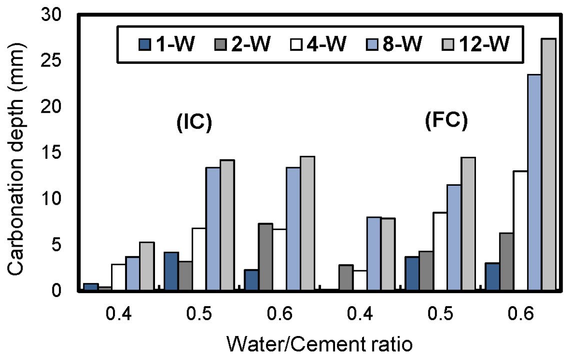

Fig. 16: Carbonation depths of the tested BFSC mix

9. Conclusions

1. Using a w/c ratio of 0.4 and a suitable dose of superplasticizer, it is possible to make workable concrete with good mechanical properties with OPC and BFSC.
2. By incorporating BFSC into concrete, the resistance of concrete to chloride attack is significantly improved. Where, after 5 months at a depth of 20~30mm, the BFSC concrete shows a soluble chloride content of about 73% and 75% of that of OPC concrete for IC and FC curing, respectively.
3. The concrete's resistance to chloride attack depends on the curing method as well as the cement type. Furthermore, soluble, and total chloride concentrations, as well as diffusion coefficients, are lower in curing IC concrete than in curing FC concrete.
4. During a year of exposure to a 10% sodium sulfate solution, concrete with a binder content of 400 kg/m^3 and a w/c ratio of 0.4 showed good resistance to sulfate. There was no observable deterioration caused by the sulfate attack on the concrete.
5. The influence of curing methods on concrete sulfate resistance was significant. In addition, mixtures of curing IC showed better performance against sulfate attack than those of curing FC.

6. Both curing methods and cement type influence the measured carbonation depths, where OPC shows lower carbonation depths than those of BFSC. Moreover, the curing methods showed slightly different values of carbonation with the used cement types.
7. When BFSC is used, the concrete's durability improves. Furthermore, the strength of BFSC is less affected by chemicals than ordinary concrete when it is exposed to an aggressive environment.

References

[1] Amran, Mugahed, Murali, G., A. Khalid, N. Hafizah, Fediuk, Roman, Ozbakkaloglu, Togay, Lee, Y. Huei, Haruna, Sani, Lee, Y. Yong, “Slag uses in making an ecofriendly and sustainable concrete: A review,” Construction and Building Materials, vol. 272, no. 121942, 2021, Doi: 10.1016/j.conbuildmat.2020.121942

[2] A. Al-Yousuf, T. Pokharel, J. Lee, E. Gad, K. Abdouka, J. Sanjayan, “Effect of fly ash and slag on properties of normal and high strength concrete including fracture energy by wedge splitting test: Experimental and numerical investigations,” Construction and Building Materials, vol. 271, no. 1215532021, Doi: 10.1016/j.conbuildmat.2020.121553

[3] V. B. R. Suda, P. S. Rao, “Experimental investigation on optimum usage of Micro silica and GGBS for the strength characteristics of concrete,” Materials Today: Proceedings, vol. 27, pp. 805-811, 2020, doi:10.1016/j.matpr.2019.12.354

[4] F. Hussain, I. Kaur, A. Hussain, “Reviewing the influence of GGBFS on concrete properties,” Materials Today: Proceedings, vol. 32, pp. 997–1004, 2020.

[5] S. Samad, A. Shah, “Role of binary cement including supplementary cementitious material (SCM), in production of environmentally sustainable concrete: A critical review,” International Journal of Sustainable Built Environment; vol. 6, pp. 663–674, 2017.

[6] D. Gao, Y. Meng, L. Yang, J. Tang, M, “Lv Effect of ground granulated blast furnace slag on the properties of calcium sulfoaluminate cement,” Construction and Building Materials, vol. 227, no. 116665, 2019.

[7] M. Anwar, D. A. Emarah, “Pore structure of concrete containing ternary cementitious blends,” Results in Materials, vol: 1, no. 100019, 2019.

[8] W. J. Cho, M. J. Kim, J. S. Kim, “Study on the pore structure characteristics of ferronickel-slag-mixed ternary-blended cement,” Materials (Basel), vol.13, no. 4863, 2020.

[9] C. V. Nielsen, “Service life modeling of chloride ingress,” ACI Materials Journal, vol. 116, no. 5, 2019.

[10] N. Sathyakumar, M. Arun, N. Arunachalam, “Development of ultra-high strength concrete using silica fume and its mechanical & durability properties - experimental Investigation,” Research Square 2021.

[11] P. Kanaujia, R. Banerjee, S. A. Husain, S. Ahmad, “A review paper on the effect of sulfate attack on concrete durability. International Journal for Research in Applied Science and Engineering Technology, vol. 9, pp. 246–250, 2021.

[12] Czarnecki L, Woyciechowski P. Evaluation of concrete structures durability under risk of carbonation and chloride corrosion,” Concrete Repair Book, Rehabilitation and Retrofitting IV, CRC Press, 2015.

[13] M. Anwar, D. A. Emarah, “Resistance of concrete containing ternary cementitious blends to chloride attack and carbonation,” Journal of Materials Research and Technology, vol. 9, pp. 3198-3207,2020.

[14]. B. Ozer, M. H. Ozkul, “Effect of initial water curing on sorptivity properties of ordinary Portland and pozzolanic cement concretes,” Journal of Materials in Civil Engineering, vol. 29, no. 04017073, 2017.

[15] Q. Wu, Q. Ma, X. Huang, “Mechanical properties and damage evolution of concrete materials considering sulfate attack,” Materials (Basel), vol. 14, no. 2343, 2021.

[16] J. Wang, B. Huang, Z. Mao, Y. Wang, “Study on adsorption properties of calcined mg-al hydrotalcite for sulfate ion and chloride ion in cement paste,” Materials (Basel), vol. 14, no. 994, 2021.

[17] P. Kanaujia, R. Banerjee, S. A. Husain, S, “Ahmad Review paper on the effect of sulfate attack on

concrete durability," International Journal for Research in Applied Science & Engineering Technology (IJRASET), vol. 9, no. 5, 2021.

[18] D. K. Ashish, B. Singh, S. K. Verma, "The effect of attack of chloride and sulfate on ground granulated blast furnace slag concrete," Advances in Concrete Construction, vol. 4, pp. 107-121, 2016.

[19] W. J. Long, Y.-c. Gu, F. Xing, K.H. Khayat, "Microstructure development and mechanism of hardened cement paste incorporating graphene oxide during carbonation," Cement and Concrete Composites, vol. 94, pp. 72-84, 2018.

[20] R. Malheiro, A. Camões, G. Meira, M. T. Amorim, J. Castro-Gomes, "Effect of coupled deterioration by chloride and carbonation on chloride ions transport in concrete," RILEM Technical Letters, vol. 5, pp. 56-62, 2020.

[21] P. Chindaprasirt, W. Kroehong, N. Damrongwiriyanupap, W. Suriyo, C. Jaturapitakkul, "Mechanical properties, chloride resistance and microstructure of Portland fly ash cement concrete containing high volume bagasse ash," Journal of Building Engineering, vol. 31, no. 101415, 2020.

[22] M. Uysal, M. Sumer, "Performance of self-compacting concrete containing different mineral admixtures," Construction and Building Materials, vol. 25, pp. 4112-4120, 2011.

[23] J. Lee, T. Lee, "Influences of chemical composition and fineness on the development of concrete strength by curing conditions," Materials (Basel), vol. 12, no. 4061, 2019.

[24] A. Mohan, K.M. Mini, "Strength and durability studies of SCC incorporating silica fume and ultra-fine GGBS," Construction and Building Materials, vol.171, pp. 919-928, 2018.

[25] R. K. Majhi, A. N. Nayak, B. B. Mukharjee, "Characterization of lime activated recycled aggregate concrete with high-volume ground granulated blast furnace slag," Construction and Building Materials, vol. 259, no. 119882, 2020.

[26] A. M. Rashad, "An overview on rheology, mechanical properties and durability of high-volume slag used as a cement replacement in paste, mortar and concrete," Construction and Building Materials, vol. 187, pp. 89-117, 2018.

[27] Y. Jiang, T. C. Ling, C. Shi, Pan, SY, "Characteristics of steel slags and their use in cement and concrete-A review," Resour. Conserv. Recycl, vol. 136, pp. 187-197, 2018.

[28] D. Shi, J. Ye, Zhang W, "Effects of activator content on properties, mineralogy, hydration and microstructure of alkali-activated materials synthesized from calcium silicate slag and ground granulated blast furnace slag," J. Build. Eng., vol. 32, no. 101791, 2020.

[29] P. Du˙zy, M. Sitarz, M. Adamczyk, M. Choi nska, I. Hager, "Chloride ions' penetration of fly ash and ground granulated blast furnace slags-based alkali-activated mortars," Materials, vol. 14, no. 6583, 2021.

[30] Y. Yue, J. J. Wang, P. A. M. Basheer, Y. Bai, "Establishing the carbonation profile with Raman spectroscopy: Effects of fly ash and ground granulated blast furnace slag," Materials, vol. 14, no. 1798, 2021.

[31] E. Özbay, M. Erdemir, H. I. Durmus, "Utilization and efficiency of ground granulated blast furnace slag on concrete properties-A review," Construction and Building Materials 2016;105:423-434.

[32] S. W. Kim, Y. J. Lee, J. Y. Lee, K. H Kim, "Application of electric arc furnace oxidizing slag for environmental load reduction," Asian J. Chem., vol. 26, pp. 5867-5870, 2014.

[33] Y. J. Lee, B. S. Lee, J. S. Lee, S. W. Kim, K. H. Kim, "Bond performance of precast RC beams according to replacement ratio of ground granulated blast furnace slag," J. Arch. Inst. Korea, vol. 29, pp. 61-68, 2013.

[34] S. A. Austin, P. J. Robins, and A. Issaad, "Influence of curing methods on the strength and permeability of GGBFS concrete in a simulated arid climate," Cement and Concrete Composites, vol. 14, no. 3, pp. 157-167, 1992.

[35] B. R. Krishna, K. H. Kumar, T. M. Kumar, I. Likitha, "Properties of GGBS concrete under various curing conditions," International Journal of Emerging Trends in Engineering Research, vol. 8, no. 4, pp. 1384-1387, 2020.

[36] JIS R5210. AMD 1 Portland Cement. JIS: Tokyo, Japan 2019.

[37] JIS R5211. AMD 1 Portland Blast-Furnace Slag Cement. JIS: Tokyo, Japan 2019.

[38] JIS A1101. Method of Test for Slump of Concrete. JIS: Tokyo, Japan 2020.

[39] JIS A1128. Method of test for air content of fresh concrete by pressure method. JIS: Tokyo, Japan 2020.

[40] JIS A1127. Method of Test for dynamic modulus of elasticity, rigidity, and dynamic Poisson’s ratio of concrete specimens by resonance vibration. JIS: Tokyo, Japan 2020.
[41] JIS A1108. Method of test for compressive strength of concrete. JIS: Tokyo, Japan 2018.
[42] JIS K0113. General rules for methods of potentiometric, amperometric, coulometric, and Karl Fischer titrations. JIS: Tokyo, Japan 2015.
[43] M. Anwar, “Use of rice husk ash as part of cement content in concrete,” PhD Thesis, Cairo university, Faculty of Engineering 1996.
[44] JIS A1138. Method of making test sample of concrete in the laboratory. JIS: Tokyo, Japan 2018.
[45] M. Anwar, K. Yamada, “Effect of curing method on the properties of blast–furnace slag concrete, HBRC Journal, Housing & Building National Research Center, vol. 3, pp. 1-12, 2007.
[46] A. C. Raymond, C. H. Kenneth, “Mercury Porosimetry of cement-based materials and associated correction factors,” ACI Materials Journal, vol. 90, pp. 152-161, 1993.
[47] M. Anwar, “The effects of type of cement and curing methods on the pore structure of concrete,” First International Conference. Computational Methods in Materials Characterization New Mexico, USA, pp. 287-296, 2003.
[48] S. L. Marusin, “Influence of length of moist curing time on weight change behaviour and chloride ion permeability of concrete containing silica fume,” 3rd Int. Conf. on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Trondheim, Norway, pp. 929-944, 1989.
[49] R. Gaynor, “Understanding chloride percentages. Steel Corrosion in Concrete causes and restraints, ACI,” pp. 161-165, 1987.
[50] N. HaN, T. H. E., “Application of diffusion theory to chloride penetration into concrete located in splashing zones,” Transactions of the Japan Concrete Institute, vol. 7, pp. 157-164, 1985.
[51] M. Anwar, “Effect of cementitious materials on concrete against sulfate attack,” Engineering Research Journal, Helwan University, Faculty of Engineering, Mataria, Cairo 2005.
[52] M. Á. Sanjuán, E. Estévez, C. Argiz, D. d. Barrio, “Effect of curing time on granulated blast-furnace slag cement mortars carbonation,” Cement and Concrete Composites, vol. 90, pp. 257-265, 2018.
[53] G. G. Litvan, and A. Meyer, “Carbonation of granulated blast-furnace slag cement concrete during twenty years of field exposure,” ACI SP-91, pp. 1446-1462, 1986.

قوة التحمل مع الزمن لخرسانة أسمنت خبث الأفران العالية مع طرق معالجة مختلفة

الملخص العربي

تتعرض المنشآت المائية لظروف قاسية اثناء تشغيلها مثل تعرضها لأملاح الكبريتات والكلوريدات وغيرها من العوامل الضارة بالخرسانة ولذا تم التوجه الى استخدام الخرسانة المحتوية على أسمنت خبث الأفران كبديل لخرسانة الأسمنت البورتلاندي العادي في إنشاء بعض المنشآت الخرسانية بمصر لزيادة مقاومتها لتلك الظروف. وقد نصّت الكودات والمواصفات المتعلقة بصناعة الخرسانة على طرق معالجة تتناسب مع نوعها ومكان استخدامها، إلا أنه في بعض الحالات لا يتم الالتزام بكل متطلبات تلك الأكواد والمواصفات وخاصة طريقة معالجة الخرسانة بالموقع. ولذا كان من الضروري تقييم خواص الخرسانة المختلفة معملياً نتيجة لتغيير طريقة معالجتها. ولذا يهدف هذا البحث إلى دراسة تأثير استخدام الأسمنت المحتوي على خبث الأفران العالية على قوة التحمل مع الزمن للخرسانة. وقد اشتمل هذا البحث على اختبار عدد ست خلطات خرسانية مصنعة بنسب مياه إلى أسمنت ٤٠٪، ٥٠٪، ٦٠٪، واستخدم الأسمنت البورتلاندى العادي كمرجع للمقارنة. ولدراسة تأثير تغيير أسلوب المعالجة، تم معالجة العينات الخرسانية بطريقتين مختلفتين، ففي الطريقة الأولى تمت المعالجة بالطريقة القياسية وهي غمر العينات بالمياه حتى موعد الاختبار، وفي الطريقة الثانية تم حفظ العينات الخرسانية عند درجة حرارة ٢٢°م ونسبة رطوبة ٨٠٪ مع الرش بالمياه كل ١٢ ساعة لمدة الأسبوع الأول من عمر الخرسانة مما يحاكي ظروف معالجة الخرسانة التي يتم استخدامها أحياناً بالموقع دون التقيد بمتطلبات الأكواد والمواصفات. وقيست خواص الخرسانة في حالتيها الطازجة والمتصلدة، كما تم تحديد خواص التركيب الهيكلي للفراغات، وكذا تعيين المحتوى الكلي والذائب ومعامل الانتشار لأملاح الكلوريدات للعينات ذات نسبة مياه إلى الأسمنت ٤٠٪، علاوة على ذلك، فقد تم غمر العينات الخرسانية ذات نسبة مياه إلى الأسمنت ٤٠٪ في محلول ١٠٪ كبريتات الصوديوم لمدة ٣٦٠ يومًا لاختبار مقاومة الكبريتات. كما تم تحديد عمق التحول الكربوني لمجموعة أخرى من العينات ذات نسب مياه إلى الأسمنت ٤٠٪، ٥٠٪، ٦٠٪، وقد خلص البحث إلى أن جميع خواص الخرسانة الطازجة والمتصلدة تأثرت نتيجته للتغيير في طريقة المعالجة أو لاستخدام الأسمنت المحتوي على خبث الأفران العالية. وأن استخدام الأسمنت المحتوي على خبث الأفران العالية يؤدي إلى الحصول على خرسانة ذات نفاذية قليلة جداً مما يزيد من مقاومتها لاختراق العناصر الضارة لها (أملاح الكلوريدات والكبريتات) وبالتالي تزداد قوة تحملها مع الزمن. كما أظهرت النتائج أن عمق التحول الكربوني يزداد بزيادة نسبة المياه إلى الأسمنت وأن أعماق التحول الكربوني للعينات المعالجة بغمرها بالمياه أقل من مثيلتها التي تمت معالجتها بالطريقة الأخرى.

<u>الكلمات الدالة</u>: أسمنت بورتلاندى عادي، أسمنت خبث الأفران العالية، خرسانة طازجة ومتصلدة، طرق معالجة، التركيب الهيكلي للفراغات، املاح الكلوريدات، معامل الانتشار، املاح الكبريتات، عمق التحول الكربوني.