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PERMEABILITY AND CHLORIDE PENETRATION OF CONCRETE SUBJECTED TO GAZA SEAWATER EXPOSURES

Zaher Kuhail[*] and **Samir Shihada**[**]
Islamic University, of Gaza,
P.O Box 108, Gaza, Palestine
Email: dr-zaher@consultant.com

النفاذية واختراق الكلور للخرسانة المعرضة للظروف البحرية في مدينة غزة

ملخـص لقد بدأت الدراسات على تأثير مياه البحر على الخرسانة منذ العام 1840 ومن ذلـك الوقـت وحتى وقتنا هذا ازداد عدد هذه الدراسات بشكل كبير مما يدل على أهمية هذا الموضـوع. وعلـى الـرغم من كثرة عدد هذه الدراسات إلا أن نتائجها مثيرة للجدل و غير قاطعـة ولـذا تـم القيام بهذه البحث لدراسة تأثير مياه البحر قبالة شواطئ مدينة غزة على خصـائص الخرسـانة حيث تم إعداد ست خلطات خرسانية باستخدام نسب مختلفة من الماء إلـى الإسـمنت وباسـتخدام محـتويات مخـتلفة من الإسمنت، وتم بعد ذلك اختبار العينات الخرسانية خلال فترة سبعة أشهر من حيث تغلغل الكلور والنفاذية وذلك لثلاث حالات مختلفة من الظروف البحرية، وفي نهاية البحث أدرجت عدة توصيات رئيسية لتوفير الحماية الأفضل للخرسانة.

Abstract **The effect of seawater on concrete was first discussed in 1840. Since these times, the volume of literature has increased considerably, implying the importance of the topic, but the findings are controversial and inconclusive. Therefore, this study was carried out to explore the effect of Gaza seawater on concrete properties. Six concrete mixes were prepared using different water/cement ratios and cement contents. These samples were tested for a period of up to 7 months in terms of chloride iron penetration, and water permeability for three different exposures. The study provides key recommendations in regard to better protection of concrete.**

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[*] Associate Professor of Civil Engineering

[**] Assistant Professor of Civil Engineering

Keywords**:** chloride iron penetration; permeability

1- Introduction

Reinforced concrete is one of the most important structural materials used in construction. It has excellent structural and durability performance. Nevertheless there is evidence of early deterioration when subjected to marine environments. The most common cause of deterioration is corrosion of the reinforcement, with subsequent spalling of the concrete. A careful procedure requires to be followed, in both the design and construction stages, to insure long-term performance of marine concrete structures. Selection of materials, mix design, proper detailing of reinforcement, appropriate construction techniques and a strict control program are the essential parameters to produce a durable marine concrete structure [1-10]. However, corrosion can occur if chlorides manage to penetrate to the surface of the reinforcement, either through cracks in the structure or through concrete of high permeability.

Chloride-induced reinforcement corrosion is one of the most common durability problems associated with reinforced concrete structures exposed to marine environments. The time for corrosion initiation depends on i) how fast chloride ions penetrate the concrete cover to reach the reinforcement and ii) the critical chloride concentration needed to deteriorate the steel reinforcement [11, 7].

Generally, seawater is a solution containing a great number of elements in different proportions. Elements as solutions, combine and precipitate as salts with the evaporation of seawater. Much of the deterioration of concrete can only occur in the presence of water since the aggressive agents which react with the concrete are present in the environment only when they are dissolved in water.

J. Smeaton and L.J. Vicat discussed the problem of concrete deterioration by seawater as early as 1840. A series of papers under the general heading of ‘what is the trouble with concrete in seawater’, prepared by R.J Wig and L.R. Ferguson was published in Engineering News-record in 1917. These papers report on an examination, over a two-year period, of a large number of concrete structures in seawater in the Unite States, Canada, Cuba, and Panama. A summary of the conclusions of these papers appears in Tibbetts [1].

Since these early times, the volume of literature on the durability of concrete and reinforced concrete in marine environment has increased tremendously indicating the ever-growing importance of the topic [2].

The chemical deterioration of concrete in marine environment has been a topic of interest to concrete technologists during the last few decades. The findings have revealed some very important facts, but still it remains to be a dynamic subject for further study and research [6, 12-13].

Long-term performance of concrete depends largely on condition of exposure. Wetting and drying cycles can increase the rate of corrosion in reinforced concrete structures as a result of irons concentration, such as chlorides. The rate of corrosion increases by the evaporation of water during the drying phase. Concrete structures, subjected to cyclic wetting and drying of seawater, are more liable to deterioration compared to those permanently immersed in seawater [4-5, 11, 14-15]. The splash zone is claimed to be the area most vulnerable to corrosion due to these wetting and drying cycles. Surface levels of chloride have been found to be the highest in this area though the depth of penetration is little different from immersed concrete [11, 16]. Underwater, concrete has generally been found to be less permeable than concrete above water, probably as a result of the pores being blocked in the concrete by materials like brucite and aragonite formed from chemical reactions with seawater [14, 17].

The results of an investigation carried out on plain concrete exposed to the North Sea showed that chloride penetration is limited to a depth of 30 mm for concrete of compressive strength 70 N/mm^2 and 60 mm for concrete of compressive strength of 35 N/mm^2. There was no significant increase of either chloride content or depth of penetration after the initial six-month exposure [5, 11].

A report by the Portland Cement Association provides the following conclusions concerning the durability of reinforced concrete piles made with different Portland cements after an exposure to seawater in four different locations in the United States for 20 years:

1- 38-mm of concrete cover over reinforcing steel is adequate for any seawater exposures.
2- Low water-cement ratio concrete mixtures (0.40 to 0.45 by weight) of low slump and high cement contents are necessary for durable concrete. A mix of 400 kg/m^3 represents the minimum cement content that can be used for severe exposure [3].

This study was carried out to explore the effect of Gaza seawater on concrete properties, since there are no relevant studies on the subject. Furthermore, the construction of Gaza Harbour has not yet started and the findings of this study will be made available to the Palestinian Port Authority. The present study is a continuation of a previous study titled

"Effect of Gaza Seawater On Concrete Compressive Strength For Different Exposures", where the same testing programme is used.

Six concrete mixes were prepared using three different water-cement ratios and two cement contents for each of these ratios. The specimens were tested for a period of up to 7 months in terms of chloride iron penetration, and water permeability in three marine exposures; beach, tidal, and permanent immersion.

2- Experimental Program Goals

- Study the effect of seawater exposure on concrete permeability and chloride penetration.
- Determine the optimum concrete mixes to be used in Gaza seawater environment.
- Determine the appropriate concrete cover to be used in Gaza Seawater environment.

Description of Exposure Zones

The specimens will be placed in three different zones of marine environment before they are tested for compressive strength, chloride ion penetration, and water permeability.

Zone A (beach): the specimens are directly laid on the seashore 40m away from the Gaza coastline. This zone combines the adverse effects of chloride attack and carbonation on concrete.

Zone B (tidal): exposure at mean tide level with specimens frequently submerged in tidal waters, thus subject to alternate wetting and drying cycles that cause deterioration of the concrete. The specimens are placed in plastic crates, the crates were tied with ropes and fixed to the sides of the tetra-pods of the Gaza marina at a distance of 30 meters from the coastline. The depth of seawater from seabed to mean sea level was measured at 4 meters.

Zone C (Permanent immersion): exposure at a depth of about 5.3 meters in seawater, 80 meters away from the coastline. The specimens are subjected to forces generated by the weight of the water body and by water-borne sediments.

Materials

The materials used in preparing all of the concrete specimens were as follows:

Cement: ordinary Portland cement, manufactured by the Israeli company, "Nesher" with fly ash of up to 10 % of cement weight, and conforms to

ASTM C150. It is the only cement type available in Gaza market. Table 1 shows the mechanical properties of the cement used.

Coarse Aggregates:

Four fractions of aggregates Types I, II, III, and IV are used with the following proportions: 0.25, 0.15, 0.20, and 0.40, respectively.

- *Coarse Aggregates:* crushed limestone, angular in shape and rough in texture, obtained from the West Bank quarries which is the only aggregate source available in Gaza market. A chemical analysis was carried out showing the chloride content of the aggregate at 240 ppm, and the sulphate content at 100 ppm (see Table 2 for sieve analysis).
- *Sand:* Gaza dune sand (see Table 2 for sieve analysis).

Mixing Water: drinking water from the piped water supply system in IUG was used in preparing all of the concrete mixes. Chemical analyses of this water along with Gaza seawater are shown in Table 3.

Workability Aids: no workability aids or admixtures were used throughout the study.

Table 1: Mechanical properties of cement

Test		Result
Compressive strength kg / cm^2	3-day	200
	7-day	250
Normal consistency (%)		25.6
Initial setting time		135 min
Final setting time		280 min
Fineness		3550 cm^2/gr
Soundness		1.5 mm

Table 2-a: Sieve analysis of coarse aggregates

Sieve mm	25	19	12.5	9.5	4.75
% passing	100	85.6	43.4	16.0	0

Table 2-b: Sieve analysis of fine aggregates

Sieve mm	4.75	2.36	1.18	0.60	0.30	0.15	0.075	0.00	FM
% passing	100	76.6	64.7	62.5	24.7	3.1	2.48	0	**2.68**

Table 3: Chemical analyses of mixing water and seawater

Test	Mixing water	Seawater
Turbidity	< 5 ntu	0.90 ntu
PH	7.0	8.13
E.C*	1053 micro Moh/cm	57.60 micro Moh/cm
T.D.S**	1490 ppm	43300 ppm
Nitrite	- ppm	0.40 ppm
Nitrate	22 ppm	- ppm
Chloride	220 ppm	22500 ppm
Sulfate	110 ppm	1475 ppm
Hardness	246 ppm	- ppm
Calcium	62 ppm	210.6 ppm
Magnesium	28 ppm	1341 ppm
Fluorides	0.90 ppm	- ppm
Potassium	- ppm	477 ppm
Iron	- ppm	0.10 ppm
Bicarbonate	- ppm	168 ppm
Suspended [illegible]	- ppm	164 ppm
Barium	- ppm	< 0.10 ppm
Strontium	- ppm	0.50 ppm
Sodium	- ppm	11720 ppm

* Electrical conductivity **Total dissolved solids

Mix Proportions and Specimen Preparation

In marine environment, relatively richer mixes with low water/cement ratios are usually used. This aspect was kept in mind in planning the experimental program. Six concrete mixes were used (as shown in Table 4) using water/cement ratios of 0.40, 0.45, and 0.50 and two cement contents of 400 kg/m^3 and 500 kg/m^3 for each of the three ratios.

Table 4:Details of concrete mixes(per1m$^{3)}$

Mix	cement content (kg)	W/c ratio	Mixing water (kg)	Aggregate		density Kg/m^3
				Type	Content (kg)	
1	400	0.40	178.41	I II III IV	480 282 381 768	2488
2	400	0.45	197.90	I II III IV	466 274 370 746	2454
3	400	0.50	217.38	I II III IV	453 266 359 724	2420
4	500	0.40	216.56	I II III IV	432 254 342 690	2434
5	500	0.45	240.91	I II III IV	415 244 329 663	2391
6	500	0.50	265.27	I II III IV	398 234 316 636	2348

Curing

For the lab environment, specimens were cured 24 hours after preparation and demoulding by placing them in a curing tank at a temperature of 25° for 28 days. For the beach environment, specimens were placed 24 hours after preparation on the beach sand away from seawater and cured by sprinkling the specimens periodically for a period of 10 days. For tidal and permanent immersion specimens, curing was applied for a period of 7 days in a plastic tank full of seawater before moving them to their designated locations.

3- Methodology of Analysis

To obtain an accurate analysis of the effect of seawater environment, the following factors have been specified:

A. Main factors of seawater (for analytical consideration)

Test parameters	Description
Variable	Exposures : Beach (A) exposure, Tidal (B) exposure, Permanent Immersion (C) exposure, and Humidity
Variable	Duration
Assumed Fixed	Hydrodynamic forces: Currents, waves, and tidal effect
Fixed	Chemical characteristics of seawater

B. Concrete materials factors:

Variable	Water/Cement (W/C) Ratio
Variable	Aggregate /Cement (Agg./C) Ratio
Variable	Cement Contents
Fixed	Chemical composition of cement, aggregate and mixing water
Fixed	Cement type
Fixed	Compaction

4- Characteristics of Exposure Zones

The beach zone is characterised by the following:

- Intermittent curing (by sprinkling seawater) to imitate field conditions
- Intermittent dry and wet action
- Variations in temperature and ambient salty humidity
- No hydrodynamic forces

The tidal zone is characterised by the following:

- Intermittent curing (by tidal effect and splash)
- Continuous dry and wet action
- Variations in temperature and ambient salty environment
- Continuos hydrodynamic forces (waves and currents and intermittent hydrostatic pressure)

The continuous immersion zone is characterised by the following:

- Continuous immersion under seawater
- No thermal variations
- No hydrodynamic forces except hydrostatic pressure

It was impossible to obtain separate full set of results for permanent immersion zone, (the immersion site in Gaza Fishery port was bombed during Isaeli air raids in 2000).

Testing Chloride ion Penetration

This test was carried out to measure the chloride concentration inside the concrete specimens.

For the lab and tidal zones, the test was carried out after 1, 3, 6, and 7 months. For the beach zone, the test was carried out after 1, 3, and 6 months. The test was conducted after 1, and three months for the permanent immersion specimens. Specimens were immediately sealed in airtight bags and brought to the laboratory for immediate processing and analysis. The specimens were cut into slices at 1, 2, 2.5 or 3.0 cm according to the type of exposure, and age of the specimens. Each slice was then ground into powder and tests were carried out according to BS 1881: Part 124.

Water Permeability

Chlorides and sulphates penetrate the concrete through the pores, therefore, it is of great importance to study the permeability of concrete. Cylindrical specimens 15 cm in diameter and 30 cm in height were sawn into two cylinders, each 13 cm high according to DIN: 1048 [19].

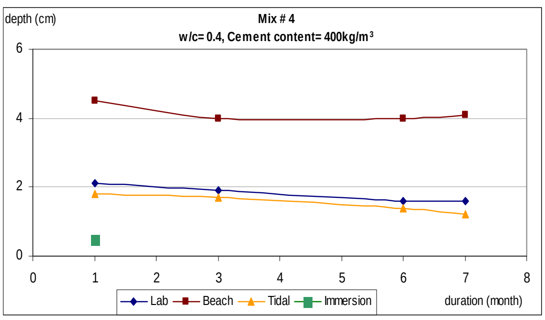
The test was carried out after 1, 3, 6, and 7 months for the lab, beach, and the tidal zones. For the permanent immersion zone, the test was carried out after 1 month.

5- Chloride Penetration Test Results

The chloride penetration test is of critical importance because chloride ions penetrate into concrete pores and chloride salts - such as sodium chloride- may crystallise within the pores inducing internal cracks, which badly affect the compressive strength of concrete. For reinforced concrete, the condition will be much worse as the presence of chloride ions de-passive the concrete around, thus making it possible to initiate reinforcement corrosion.

Table 5 lists the results of chloride concentrations for all the tested mixes subjected to tidal, beach and permanent immersion zones of exposure.

Many trends can be plotted from Table 5. Examples of these trends are plotted in Figures 1-2 .



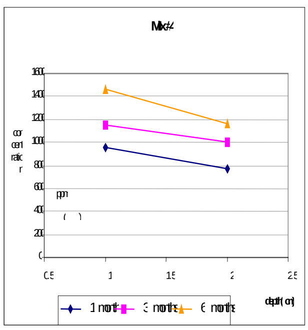


Figure 1 Chloride concentration (ppm) versus depth (cm), Exposure (A), w/c=0.4, CC=400kg/m^3

Figure 2 Chloride concentration (ppm) versus depth (cm), Exposure (A), w/c=0.4, CC=500kg/m^3

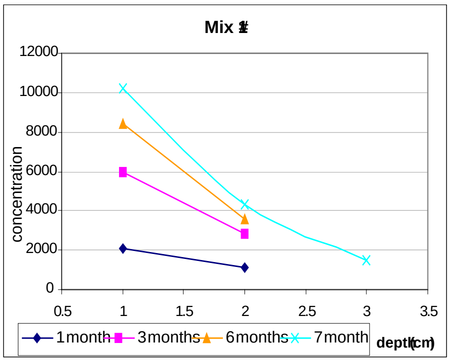


Figure 3 Chloride concentration (ppm) versus depth (cm), Exposure (B), w/c=0.4, CC=400kg/m^3

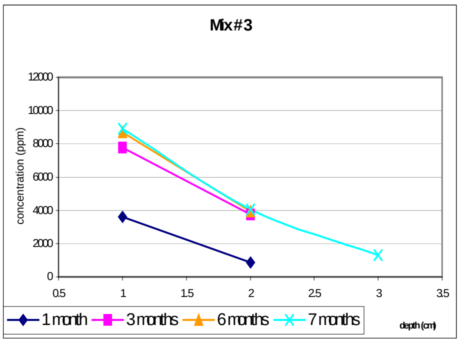


Figure 4 Chloride concentration (ppm) versus depth (cm), Exposure (B), w/c=0.5,

6- Permeability Test Results

Attack by sulphates, acids, and chlorides, induces electrochemical corrosion of steel reinforcement. Since this attack takes place within the concrete mass, the attacking agent must be able to penetrate throughout the concrete, which should be permeable. Permeability who defined it reference the ease with which water can travel through concrete. There is no prescribed test by ASTM and BS for permeability but there is one in DIN 1048.

Permeability test was carried out based on the specification of “DIN1048 teil 1” [19]. The main idea of the test is that water penetrates the concrete specimens under a set pressure for a set period of time. In this study; the used pressure is 5 bars for a period of 72 hours, as selected by the authors.

Table 6, lists the results of the permeability test for each exposure, cement content and W/C combinations at each testing age.

Figures 5 through 10 are sample plots extracted from Table 6.

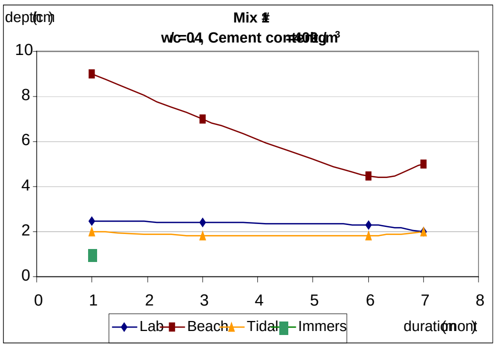


Figure 5 Permeability (As depth of water penetration) versus duration for mix #1 at different exposures

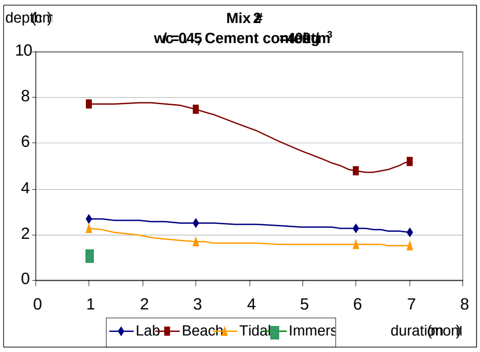


Figure 6 Permeability (As depth of water penetration) versus duration for

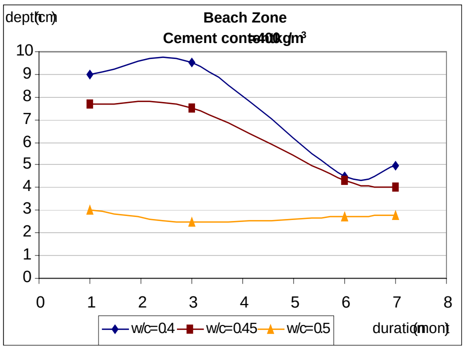


Figure 7 Permeability (As depth of water penetration) versus duration for CC=400kg/m^3, and different water

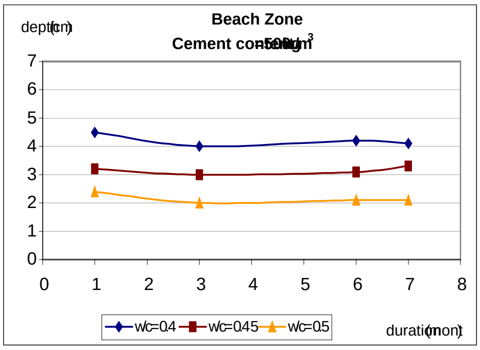
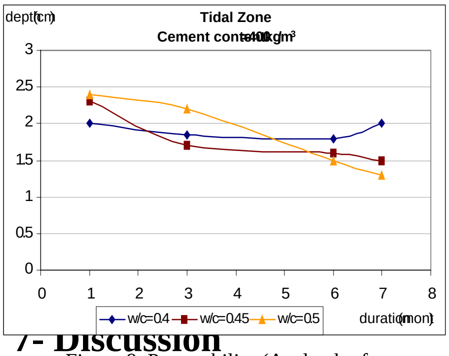


Figure 8 Permeability (As depth of water penetration) versus duration for CC=500kg/m^3, and different water cement



7- Discussion

Figure 9 Permeability (As depth of water penetration) versus duration for CC=400kg/m^3, and different water

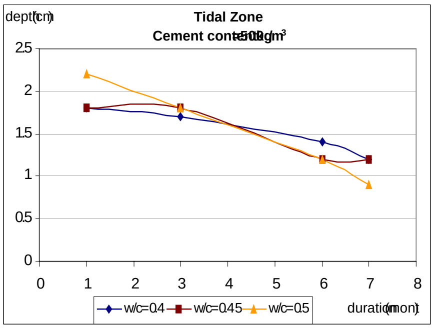


Figure 10 Permeability (As depth of water penetration) versus duration for CC=500kg/m^3, and different water

Chloride Penetration

Values of chloride content of samples placed at beach zone of exposure for six months were around 1500 mg/l which is equivalent to

0.375 % of cement mass. This chloride content is below maximum chloride content specified by the British Standards (0.4% of cement mass) and above the limit stated by ACI committee Report 222 R-85 (0.2% of cement mass). No appreciable difference between mixes of 400 cement content (mixes 1,2, and 3) and mixes of 500 cement content was observed. Hence, concrete in beach zone of exposure is not greatly affected by chloride penetration at such a limited period of time (7 months). It is expected that after many years, greater chloride concentration will result due to saline atmosphere around, and this may explain why steel bars beside the beach corrode over time. No particular distinct relation between chloride content and water cement ratio was observed. Though, concrete of water-cement ratio of 0.5 is the one that recorded the highest chloride content because they contain a higher amount of capillary pores. Also, due to salt leaching permeability increases.

In the tidal zone, where the concrete is vulnerable to wetting and drying cycles and continuous hydrodynamic forces, such as currents and waves, the amount of salt which penetrates through concrete matrix will build up and then it may crystallise inside the concrete. The values of chloride content in this exposure represent the highest values obtained for studied exposures [10350 mg/l (2.5 % of cement mass) for 1 cm depth and 1600 mg/l (0.4% of cement mass) for 3cm depth after 7 months for W/C 0.4 and CC of 500 kg/m^3] which is above the BS limit (0.4% of cement mass). Chloride ingress increases over time, reaching a peak value, after which it slows down or even ceases. So it is important to take care of concrete in this zone. It is expected that at a depth of 5 to 6 cm the chloride penetration level will be acceptable and will not harm reinforcement.

Effect of water-cement ratio

Different water-cement ratio mixes give very close results for chloride concentration, indicating that the chloride concentration is almost the same regardless of the water-cement ratio.

Effect of cement content

The poor and porous surface of samples of CC of 500 kg/m^3 explains the higher concentrations; With time these pores will be filled with chloride, which will prevent ions from travelling deeper into the concrete thus reaching the same situation of the mixes made with a cement content of 400 kg/m^3.

Permeability Test

High permeability values for beach zone of exposure are found while relatively low permeability values for specimens at lab environment and tidal zone of exposure are obtained. Also low permeability values for specimens at continuous immersion zone of exposure are found.

The interpretation of such results highlights two major factors: curing and salt penetration. Considering the first factor in beach zone, where specimens are cured by sprinkling, the depths of water penetration were very low compared with ideal lab conditions or even when compared to other zones of exposure. For tidal zone, the second factor plays an essential role in decreasing the value of DOWP because salts fill the pores of concrete making it tighter. This is only valid to some extent, after that the crystallisation of these salts develop micro cracks inside the concrete matrix. This opens new tracks or paths for water to get in.

An unexpected result, which is responsible for permeability, is hydrated cement paste, as the presence of large capillary pores is controlled by the degree of hydration and water-cement ratio. Permeability is lower for pastes of lower water-cement ratios. There is an amount of cement content and water cement ratio after which the pores become segmented or discontinuous. The large influence of segmenting of capillaries on permeability illustrates the fact that permeability is not a simple function of porosity. So, it is possible for two porous bodies to have similar porosities but different permeability, generally speaking, the more the w/c, the more the permeability. Moreover, the more the cement content, the lesser the permeability [20].

The decline of strength after a certain age corresponds to an increase in DOWP value or permeability rate.

In some tested mixes, DOWP decreases over time, while in some other mixes, DOWP increases after 6 months. This reflects the great effect of crystallisation, which not only damages the microstructure of concrete but also creates paths of water to enter making the DOWP much greater in some cases.

8- Conclusion

The successful performance of a marine concrete structure depends to a great extent on its durability against the aggressive marine environment. An understanding of the aggressive elements of the environment and the mechanism of their attack on concrete structures is essential to develop the right course of action in providing structures to withstand aggression. Most problems of concrete structures deterioration could perhaps be eliminated if appropriate measures are taken into consideration the selection of materials, mix designs, reinforcement detailing, construction techniques and quality control.

A. Beach Zone

- Concrete is subjected to chloride ion penetration when it is exposed to beach environment, but this is not significant since there is no direct contact with seawater. A maximum chloride concentration of 0.375% was obtained; This is less than the 0.4 % of the cement content limit specified by BS.
- Permeability of concrete exposed to beach environment is relatively large, compared to lab environment or even tidal exposure concrete. This is caused by the intermittent salty curing regime. The hydration process is, accordingly, discontinued, which in turn gives no tightness to the concrete, making the pore volume large enough to permit higher permeability values.
- It has been established, from the different tests performed on the beach zone samples, that safe concrete cover in this zone starts from the depth of 3 cm.

B. Tidal Zone

- The values of chloride content in this type of exposure represent part of the highest recorded values of all studied exposures (10350 ppm). In this zone, chloride ingress is initiated by wave action. So, it is recommended to provide enough cover to protect concrete against chloride ingress which increase exponentially with time reaching a limit beyond which it slows down or even ceases, and may be initiated again with time making sequence of attacks due to progressive cracking action.
- It has been established from the different tests performed on the tidal zone samples that safe concrete cover in this zone starts from the depth of 5 cm

C. Permanent Immersion Zone

- In deep immersion zone, the highest value of chloride concentration recorded is 12000 ppm or 12000 mg/liters, which equals to 3 % of the cement mass, i.e. about 8 times the percentage allowed by the BS. This value was obtained at a depth of 1 cm. At this depth reinforcement bars do not exist. For greater depths (2 cm) the highest value was around 3500 that is correspondent to 0.9% of the cement mass, which is about double the percentage allowed by the BS

- Many concrete technologists who conduct research on concrete in seawater believe that the chloride penetration process ceases or continues at very slow rates after 6 months of exposure [5, 11].

A summary of all encountered factors affecting the concrete under different exposure conditions as perceived by the authors, and based on the results of the testing program is shown in Table 7.

Table 7 Summary of Factors Affecting Concrete

Exposure (A): Beach Zone

Curing regime is **intermittent**

	Mix properties				factors affecting the strength			
Mix #	w/c	cc	status	period of exposure (months)	micro-cracking Thermal Expansion	Humidity	permeability	chloride content
1	low	low	very dry	1				
				3				
				6				
				7				
2	medium	low	dry	1				
				3				
				6				
				7				
3	high	low	cohesive	1				
				3				
				6				
				7				
4	low	high	cohesive	1				
				3				
				6				
				7				
5	medium	high	wet	1				
				3				
				6				
				7				
6	high	high	very wet	1				
				3				
				6				
				7				

(pink) refers to negative effect on strength

Exposure (B): Tidal Zone

Curing regime is **cyclic**

	Mix properties				factors affecting the strength			
Mix #	w/c	cc	status	period of exposure (months)	micro cracking (wet-dry effect)	crystallization	permeability	chloride content
1	low	low	very dry	1				
				3				
				6				
				7				
2	medium	low	dry	1				
				3				
				6				
				7				
3	high	low	cohesive	1				
				3				
				6				
				7				
4	low	high	cohesive	1				
				3				
				6				
				7				
5	medium	high	wet	1				
				3				
				6				
				7				
6	high	high	very wet	1				
				3				
				6				
				7				

(pink) refers to negative effect on strength

(black) refers to positive effect on strength

9- Recommendations

Based on the study the following recommendations can be adopted:

- For beach and tidal exposures, mix no. 5 (W/C=0.45, and CC=500 kg/m^3) has low chloride content along with low DOWP values after six months of exposure. So, this mix is recommended in these zones.
- For permanent immersion exposure, mix no. 4 (W/C=0.40, and CC=500 kg/m^3) has the lowest chloride content and DOWP after three months of exposure. So, this mix is recommended in this zone.
- A minimum concrete cover of 3 cm and 5 cm are recommended for seawater exposures (beach and tidal respectively). At this cover, chloride content will not be high enough to deteriorate concrete around the reinforcement.

10- Acknowledgement

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References

- Tibbetts, D. C., Performance of concrete in seawater: some examples from Halifax, N.S., Performance of Concrete, E. G. Swensen, Technical Editor, Canadian Building Series No. 2, University of Toronto Press, 1968, pp. 159-180.
- Escalante, E. and Ito, S., A bibliography on the corrosion and protection of steel in concrete, NBS Special Publication 550, National Bureau of Standards, Washington, DC, 1979.
- Hansen, W. C., Twenty-year report on the long-time study of cement performance in concrete, Research Department Bulletin 175, Portland Cement association, Research and Development Laboratories, Skokie, May 1965.
- Rilem-Aipcn, International Symposium on Behavior of Concrete Exposed to Seawater, Palermo, Italy, May 24-28, 1965.
- K.M. Brook and J.A. Stillwell, Exposure tests on concrete for offshore structures, Corrosion of reinforcement in concrete construction, edited by Alan O. Crane, Published for the Society of Chemical Industry, Ellis Horwood Limited, England, 1983.

- M.A. Aziz, and M.A. Mansur, Deterioration of marine concrete structures with special emphasis on corrosion of steel and its remedies, Corrosion of reinforcement in concrete construction, edited by Alan O. Crane, Published for the Society of Chemical Industry, Ellis Horwood Limited, England, 1983.
- W.R. Holden, C.L. Page, and N.R. Short, The influence of chlorides and sulphates on durability, Corrosion of reinforcement in concrete construction, edited by Alan O. Crane, Published for the Society of Chemical Industry, Ellis Horwood Limited, England, 1983.
- ACI Committee 201.2R-92, Guide to durable concrete, Part 1: Materials and General Properties of Concrete, ACI Manual of Concrete Practice, 1994.
- Building Code Requirements for Structural Concrete (318-99) and Commentary (318 R-99), Farmington Hills, Michigan, USA, American Concrete Institute, 1999.
- A.M. Neville and J.J. Brooks, Concrete Technology, Longman Scientific and Technical, England, 1994.
- P. Sandberg, L. Tang, and A. Andersen, Recurrent studies of chloride ingress in untracked marine concrete at various exposure times and elevations, Cement and Concrete Research, 28 (10), 1998, pp. 1489-1503.
- Sunil Kumar, Influence of water quality on the strength of plain and blended cement concretise in marine environments, Cement and Concrete Research, 30, 2000, pp. 345-350.
- O.S.B. Al-Amoudi, Rasheeduzzafar, M. Maslehuddin, S.N. Abdul-jauwad, Influence of chloride ions on sulphate deterioration in plain and blended cements, Magazine of Concrete Research, 46 (167), 1994, pp. 113-123.
- Regourd, M., Physic-chemical studies on cement paste, mortar, and concretes exposed to seawater, Conference on Performance of Concrete in Marine Environment, New Brunswick; A.C.I. Pub. SP65-4, August 1980.
- K. Hong, and R.D. Hooton, Effects of cyclic chloride exposure on penetration of concrete cover, Cement and Concrete Research, 29, 1999, pp. 1379-1386.
- M.B. Leeming, Corrosion of steel reinforcement in offshore concrete, Corrosion of reinforcement in concrete Construction, edited by Alan O. Crane, Published for the Society of Chemical Industry, Ellis Horwood Limited, England, 1983.

- Conjeaud, M. L., Mechanisms of seawater attack on cement mortar. Conference on Performance of Concrete in Marine Environment, New Brunswick; A.C.I. Pub. SP65-3. August 1980.
- Z. Kuhail, and S. Shihada, Effect of Gaza seawater on compressive strength for different exposures, Under Publication.
- DIN 1048 Teil 5: Prüfverfahren für Beton, Jun 1991, Berlin, Germany.
- A.M. Neville, Properties of Concrete, Longman Scientific and Technical, England, 1994.
- Annual Book of ASTM Standards, Vol. 4.02, Concrete and Aggregates, Section 4, ASTM 100 Barr Harbor Drive, West Conshohocken, PA 19428.
- British Standards Institution, BS 8110, Parts 1 and 2: 1985, Structural Use of Concrete (BSI 1985).