Durability of Marine Concrete under Thermal Cycling Loads

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Data on chloride penetration into concrete exposed to a simulated aggressive marine environment are presented. Concrete specimens, large beams and small cubes, are subjected to 90 complete exposure cycles of wetting and drying plus heating and cooling. The applied exposure condition consists of a drying period of 42 hrs followed by a wetting phase of 6 hrs with salt water containing 5% NaCl. The drying phase itself is a thermal regime characterised by a temperature swing from 20 °C to 60 °C within a period of 12 hrs. This simulates, with some accelerations, the aggressive marine environmental condition in hot regions with varying daily temperature including direct solar radiation. Totally 315 temperature cycles and 90 cycles of wetting/drying were applied to specimens in this experiment. It was observed that temperature and humidity variations promote chloride penetration into marine concrete significantly. This particular study shows that thermally-induced microcracks increase, but slightly, the permeability of concrete in "restrained" beams compared to the relatively "stress free" small specimens. Effect of two other significant parameters, i.e. type of curing and type of cement, on chloride ingress rate is also investigated.

Key words: **chloride, cracking, curing, heating/cooling, marine concrete, Portland cement, restraint, slag cement, temperature, thermal stresses, wetting/drying**

1 Introduction

Increasing number of early damages on concrete structures, specially those were built along the coastal areas of the hot countries, have attracted the concern of many researchers to find the main causes of deterioration of concrete in these type of climates leading to corrosion of reinforcement in concrete [1, 2]. While most of laboratory tests are still being performed based only on material properties of concrete, it is well recognised that durability of concrete, particularly marine concrete, in terms of ingress of chloride ions, strongly depends on the prevailing environmental conditions and not only on the concrete material.

Two main characteristics of aggressive marine environments are high temperature fluctuations due to daily and seasonal temperature variations and relatively high saline water. Temperature changes cause thermal stresses in concrete structures, and in case the deformations are restrained, microcracking may occur. It is believed that these microcracks may increase permeability when they make a connected system with the pore structure of concrete providing a good route for the

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aggressive media, sea water in case of marine concrete, and decrease resistance of concrete against penetration of chloride ions [3]. This has been referred as the main reason of low durability of concrete in such environments.

Most laboratory durability investigations fail to provide restrained conditions on concrete specimens as they are sound, uncracked and almost free of stresses. In practice there are always some stresses in concrete elements which may cause cracking. Therefore the laboratory results may not be directly applicable for practical use in such environments. Recent experiences from performance of concrete structures have demonstrated the need for better integration of structural and durability design in concrete structures [4]. The conclusion of Gjørv in his paper reviewing the performance of marine concrete structures along the Norwegian waters also says: " in order to improve the performance and serviceability of concrete structures in the marine environment the integration of both structural and durability design should be the most important" [5].

Investigations on effect of stress level, mostly mechanical, on the rate of chloride penetration show that the severity of chloride attack is, indeed, stress related and increases with the increase in the stress level [6, 7]. By applying heat cycles on concrete specimens, Rasheeduzzafar et al showed that temperature variations cause microcracking in concrete which would increase its permeability significantly [8]. This investigation has been performed on specimens subjected to only heating cycles in a dry environment. The simultaneous action of temperature fluctuations and wetting and drying cycles, however, provides more complicated exposure to concrete. It is why little information can be found in literature on testing concrete specimens exposed to this combined environment.

In a laboratory test, at the Delft University of Technology, the potential durability of concrete specimens under such aggressive marine conditions has been studied. The splash/tidal zone of marine structures has been simulated by alternate cycles of wetting and drying plus heating and cooling applied to concrete specimens. Effect of various parameters are studied in this investigation the results of which are presented in other papers [9–12]. The contribution of temperature variations on promoting chloride penetration into concrete is discussed in this paper. One of the key points in this study is that the temperature effect is examined in both "restrained" concrete elements in which thermally-induced microcrackings may occur and "unrestrained" specimens which are relatively stress free.

More specifically, the objectives of the current research is to investigate the chloride penetration rate into marine concrete for the following evaluations:

1. To evaluate whether the specimens subjected to thermal loading behave differently with those which are subjected to the constant temperature with respect to chloride penetration.

2. To see whether concrete specimens, which are restrained to thermally induced deformations, behave differently from those which are free to deform with respect to chloride penetration.

2 Experimental programme

2.1 *Experimental set-up*

Three 400 × 750 × 6000 mm^3 beams and a large number of 150 mm^3 cubes were made for this experiment. Specimens are subjected to wetting / drying and heating / cooling cycles to simulate the complex splash / tidal zone of marine structures under severe environmental conditions. A general view of the test set-up and a cross section of beam is shown in Fig. 1. Full size beams are selected for this experiment to have the restrained conditions provided in a natural way as in practice. Large deep beams and small cubes represent the "restrained" and "unrestrained " specimens for the imposed strains, respectively.

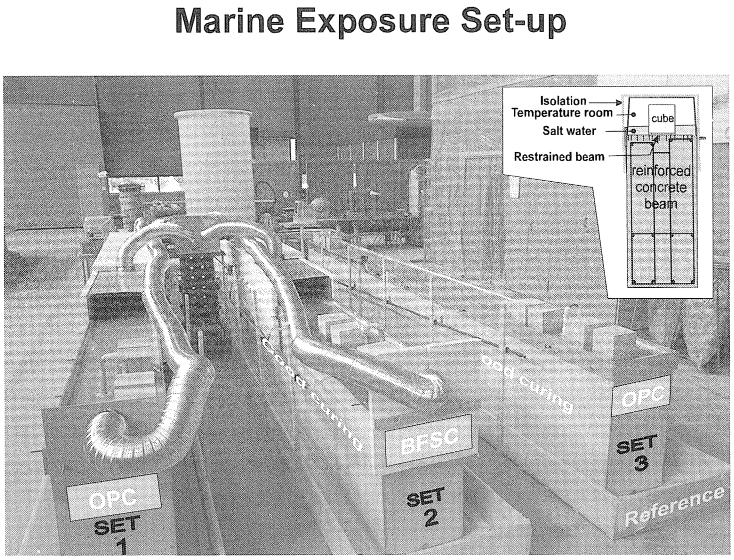
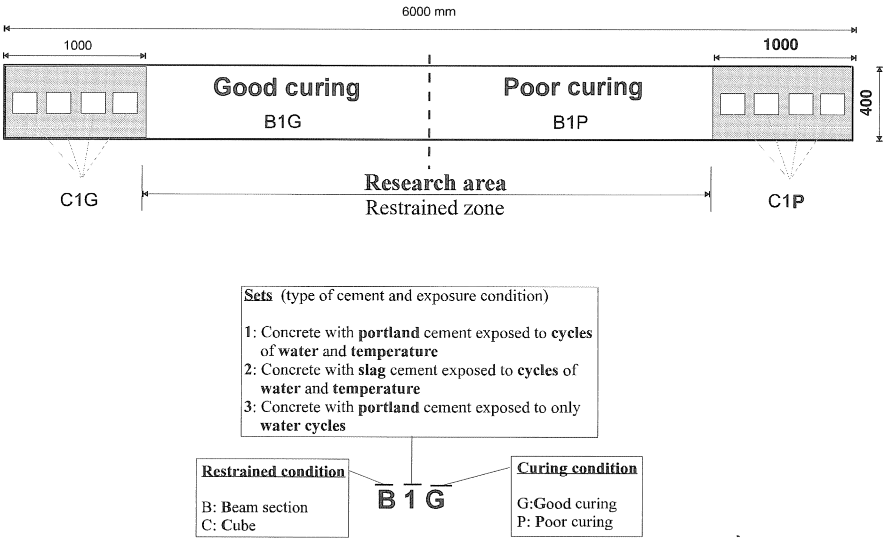


Fig. 1. General view of the marine set-up. The temperature rooms at the top of the sets 1 and 2 are closed and sealed during the test.

Due to varying temperature, the concrete at the top of the beams are loaded in alternate compression and tension and when the tensile stresses exceed the ultimate strength the concrete may crack. The beams are 6 m long and 75 cm deep to assure that bending caused by thermal loading at the top of the beam is prevented in the middle part due to the dead weight. The bottom of the beam is hardly affected by imposed temperature so that the top layers are restrained by the remaining parts.

Three beams and their accompanying cubes in Fig. 1 are identified with "set 1", "set 2" and "set 3". The first and third set are made with ordinary Portland cement and the second set with blast furnace slag cement. All three beams and cubes are subjected to wetting / drying conditions.
The first and second set were also subjected to temperature variation. Salt water can get onto the surface of all three beams and remain during wetting period inside the "dikes" installed on the top of the beams.



Sets (type of cement and exposure condition)

1: Concrete with **portland** cement exposed to **cycles** of **water** and **temperature**
2: Concrete with **slag** cement exposed to **cycles** of **water** and **temperature**
3: Concrete with **portland** cement exposed to only **water cycles**

Fig. 2. Top view of a beam and its components in the experiment and coding system – The research area of the beam is illustrated.

Figure 2 shows a top view of the beam, together with a coding system for the different "specimens". Each specimen, whether beam section or cube, is named by a 3 digit code, explaining the restraint condition, cement type, exposure condition and curing regime. For example C2P refers to the cube (C) made with slag cement and exposed to alternating cycles of wetting and drying plus heating and cooling (2) and cured with temperature (Poor condition). B2P represents the specimen with the same conditions but for the beam section (B) and so on.

2.2 *Materials and specimen preparation*

Two types of concrete were used in this investigation, namely with normal Portland cement and blast furnace slag cement. In the later, about 70% of the Portland cement was replaced by slag. A high W/C ratio was selected for all specimens to get more substantial ingress of chloride in the relatively short duration of the test. The mixture proportion is shown in the following:

Material	Mix 1	Mix 2
Normal Portland cement (kg/m^3)	320	-
Blast furnace slag concrete (kg/m^3)	-	320
Gravel (kg/m^3)	1068	1060
Fines (kg/m^3)	826	820
Water (kg/m^3)	189	187
W/C	0.58	0.58
F28 (MPa)	40	36

The surfaces of all beams and cubes were covered for one day to prevent plastic shrinkage during the hardening process. Two curing regimes were then imposed to the specimens, 1) Good curing and 2) Poor curing. A half of each beam, as well as corresponding cubes, were cured in the normal condition, i.e. room temperature and humidity, for 14 days. The second halves were exposed to the controlled environment with temperature of 38 °C and relative humidity of 50% for also 14 days to simulate elevated temperature curing condition (see Fig. 2) as might occur in tropical regions like Persian Gulf area. All the beams and cubes were kept in open air for about 6 weeks to get hardened enough before exposure.

2.3 *Simulation of marine condition under daily temperature fluctuation*

All specimens of the first and second set including beams and cubes, at the age of 56 days, were subjected to complete exposure condition consisting of a "drying period" of 42 hrs followed by a "wetting period" of 6 hrs with salt water of 5% NaCl content. In the drying period the temperature was changing from 20 to 60 °C with a cyclic period of 12 hrs which simulates, with some accelerations, the varying daily temperature in tropical regions. Consequently a complete cycle of exposure was 48 hrs which is shown in Fig. 3. During the test the control rooms at the top of the first and second beams were closed and fully covered with insulation layers down to 30 cm below the beam surface.

Specimens on the third set, the reference set, were subjected to only wetting and drying cycles without temperature variations, i.e. 42 hrs dry with room temperature and 6 hrs wet with salt water. Temperature developments were continuously monitored and controlled by numerous thermocouples installed along different positions and levels of the beams. A special device was designed for applying water and temperature cycles (see Fig. 4). More information about the features of this experiment is given in [13].

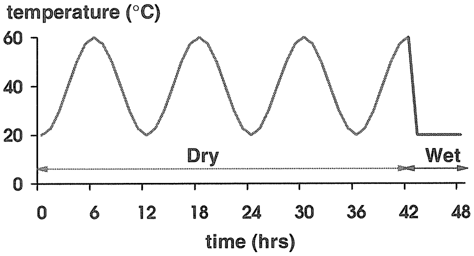


Fig. 3. *Simulated exposure conditions including wetting/drying and heating/cooling cycles applied on concrete surfaces in the experiment.*

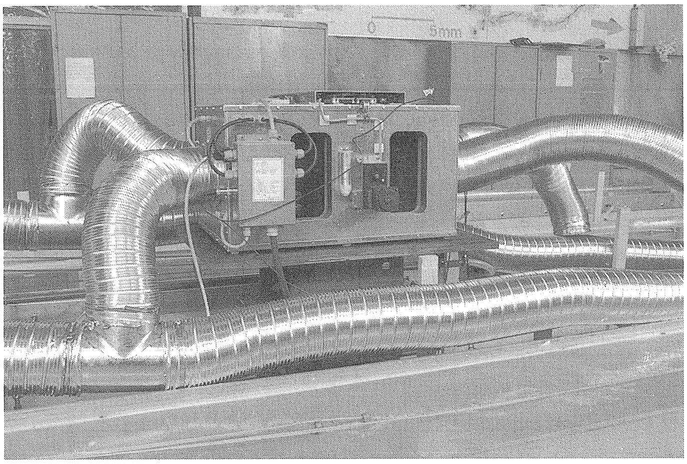


Fig. 4. *A specially developed fully automatic device to apply and control heating/cooling and wetting/drying cycles on concrete surfaces.*

2.4 *Chloride penetration*

The experiment ran for 6 months within which two major measurements of chloride content were carried out. The first one was after about one month, i.e. 18 complete cycles of exposure and the second one after 6 months of exposure with 78 complete cycles. The latter included some 315 temperature cycles and 78 wetting / drying cycles (see Fig. 3). Cores were taken from concrete specimens and slices of 6 mm thick were cut from the cores for chemical analysis of chlorides. A special sawing method was adopted for preparation of the thin slices to have the chloride data at different depths. Alternate slices were cut from two cores of the same sample giving the chloride profiles within 3 and 6 mm intervals. The data are presented here are the total amount of chloride ions, determined after dissolution of powdered samples in hot concentrated nitric acid (HNO_3).

2.5 *Crack investigation*

Apart from the visual inspection of the cracks at the beam surfaces, the distribution of these cracks over the depth were investigated by vacuum impregnation technique. Large cores were taken from the cracked areas and impregnated with a low viscosity fluorescent epoxy in a vacuum tank. Slices were vertically cut from the cores for crack detection.

3 Results and discussions

The structure of data analysis for the whole project is shown in Fig. 5. Effect of different parameters on the rate of chloride penetration have been discussed in previous papers on the basis of available results of the ongoing project [9–12]. In this paper, a part of the latest data, at the end of the project, regarding the effect of restraint condition (comparison of cube and beam sections) and temperature variations (comparison of the first and third set) are presented and evaluated.

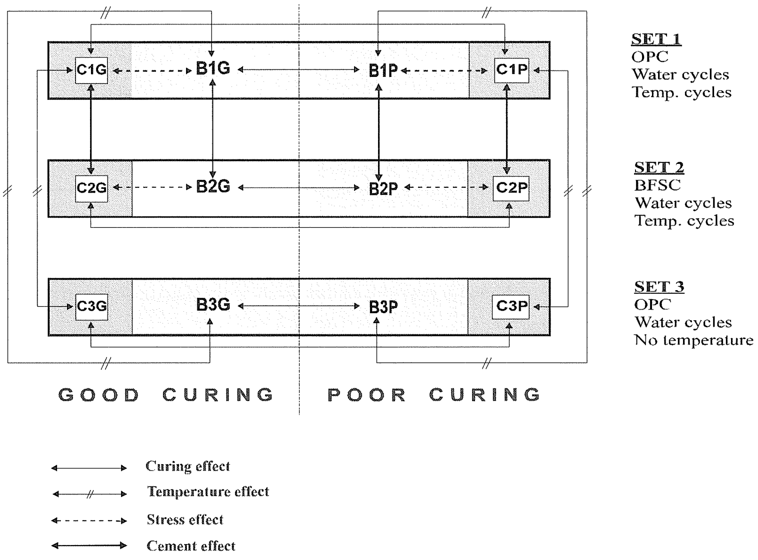


Fig. 5. Analysis structure of the developed data in the experiment.

3.1 *Results*

The chloride data of specimens in the first and third set of the specimens are presented in Tables 1 and 2, respectively. The total chloride content, expressed by weight of cement, over the depth of the specimens are shown in these tables. It is generally seen that in specimens exposed to temperature variations, the chloride ions have penetrated much deeper (down to 66 mm) than the ones without temperature fluctuations, i.e. in specimens in the third set.

Table 1. Chloride contents in the first set of the beam and cubes made with normal Portland cement after 1 month and 6 months of exposure to cycles of water and temperature.

	SET 1 (OPC)							
	Beam				**Cube**			
Depth (mm)	**B1G** Cl %wt cement		**B1P** Cl %wt cement		**C1G** Cl %wt cement		**C1P** Cl %wt cement	
	1st month	**6th month**	**1st month**	**6th month**	**1st month**	**6th month**	**1st month**	**6th month**
6	2.00	3.77	1.52	3.26	1.99	4.05	2.18	4.14
12	1.17	3.12	1.28	3.04	1.01	3.64	1.76	3.46
15	0.70	2.48	1.17	2.36	0.52	3.04	1.61	3.34
21	0.26	2.17	0.60	2.19	0.08	2.35	0.78	2.54
24	0.07	1.58	0.51	1.76	0.04	2.43	0.70	2.72
30		1.25	0.15	1.52		1.27	0.21	2.18
33		0.69	0.03	1.16		1.38	0.04	2.09
39		0.47		0.86		0.36		1.44
48		0.15		0.32		0.08		0.80
57		0.05		0.10		0.05		0.30
66		0.05		0.05		0.04		0.06

Table 2. Chloride contents in the third set of the beam and cubes made with normal Portland cement after 1 month and 6 months of exposure to cycles of water and without temperature cycles.

	SET 3 (OPC)							
	Beam				**Cube**			
Depth (mm)	**B3G** Cl %wt cement		**B3P** Cl %wt cement		**C3G** Cl %wt cement		**C3P** Cl %wt cement	
	1st month	**6th month**	**1st month**	**6th month**	**1st month**	**6th month**	**1st month**	**6th month**
6	2.17	4.53	1.82	3.97	2.25	4.01	1.81	3.07
12	0.83	2.95	1.62	3.17	0.95	2.07	1.42	2.42
15	0.55	1.48	1.43	1.89	0.60	2.1	1.34	1.41
21	0.07	0.48	0.38	0.94	0.44	0.49	0.59	1.14
24	0.05	0.05	0.23	0.47	0.26	0.67	0.47	0.52
30		0.03		0.12		0.06		0.32
33				0.07		0.09		0.14
39				0.05		0.04		0.09

3.2 *Restraint or thermal stress effect*

The chloride profiles of the beam and cubes for the first set after 18 complete cycles of exposure are presented in Fig. 6. It is seen here that slightly more chloride has penetrated into the beam sections compared to the cubes. Observations in this phase of experiment indicated that because of restrained condition, a lot of microcracks occurred at the surface of the beam due to thermal stresses, while the cubes with the same exposure condition remained uncracked. These microcracks have probably increased the permeability of concrete and caused more ingress of chloride into the beam sections.

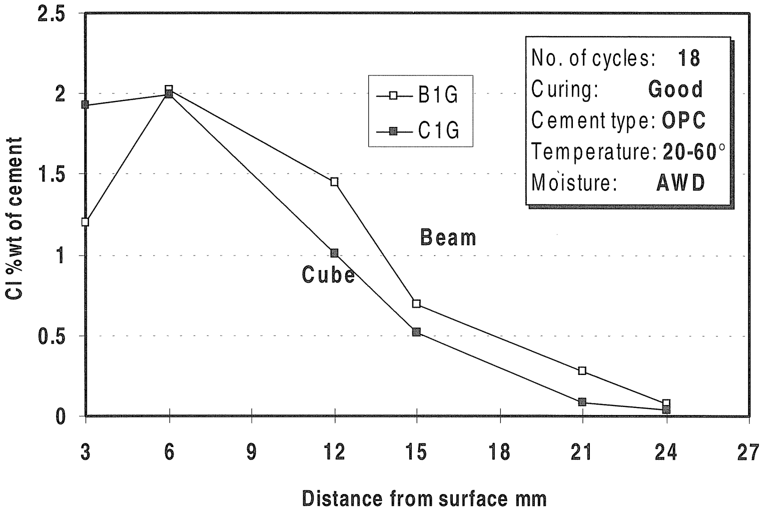


Fig. 6. Effect of thermal stresses on chloride penetration in OPC concrete with good curing exposed to temperature and water cycles, Time = 1 month.

It was thought that further exposure to the simulated environment would cause further propagation of the cracks leading to a more permeable concrete. Crack investigations, using the florescent method, at the end of experiment showed that those cracks have not penetrated deep into concrete, rather distributed more at the surface. The cracks were found to be in a range of 8 mm in depth. So no significant increase of chloride content was found in concrete beams due to microcracks at the beam surfaces. This effect is illustrated in Fig. 7 where chloride measurement at the end of the test are shown. For comparison, the data of the first measurement are also plotted. It is shown that the chloride concentration in the restrained beam is almost similar to the cubes which were relatively free of stress. It could also be possible that the thermally-induced cracks have been sealed off due to self-healing effect.

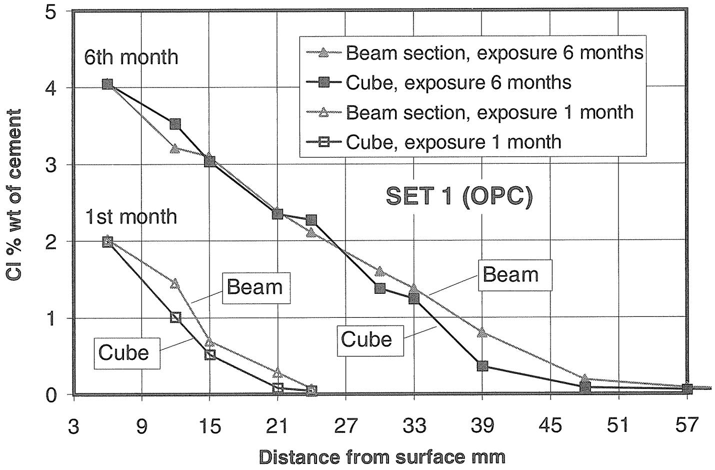


Fig. 7. *Chloride penetration into concrete beams (restrained) and cubes (unrestrained) in the first set of specimens made with Portland cement, after 1 month and 6 months of exposure – Good curing.*

3.3 *Temperature*

The chloride data of the first and third beam, B1G and B3G which are cured with good conditions, are presented in Fig. 8, for both measurements. Data of the first month show a slight increase of chloride concentration over the depth due to temperature fluctuations. This effect is more evident in measurements after six months. The chloride ions have penetrated down to 60 mm in B1G which is exposed to temperature cycles while in the third beam, i.e. B3G, the penetration depth is not more than 24 mm with much less concentration of chloride ions. It means that the resistance of concrete to chloride penetration has considerably decreased due to temperature rise and fall cycles on the first beam. However, the stronger penetration in 20–60 specimens could be the result of more evaporation of water from the specimens than those of constant room temperature. Consequently the drying out is considerably stronger in these specimens, and so the capillary absorption is stronger [15].

Progress of the chloride penetrations over time in Fig. 8 shows that for the specimen without temperature, B3G, the penetration depth has not much increased while the concentration at the upper layers has considerably increased. This might be attributed to the capillary suction due to wetting and drying cycles. But for the specimen which is subjected to both thermal and hygral cycles, B1G, the two profiles are almost parallel to each other. It can be explained that the increase in penetration depth might be due to the diffusion of chloride ions which is promoted by temperature action.
In other word, in the deeper layers of temperature specimens, the diffusion which was promoted by thermal fluctuations, has controlled the transport rather than capillary absorption which is the very nature of wetting / drying exposures.

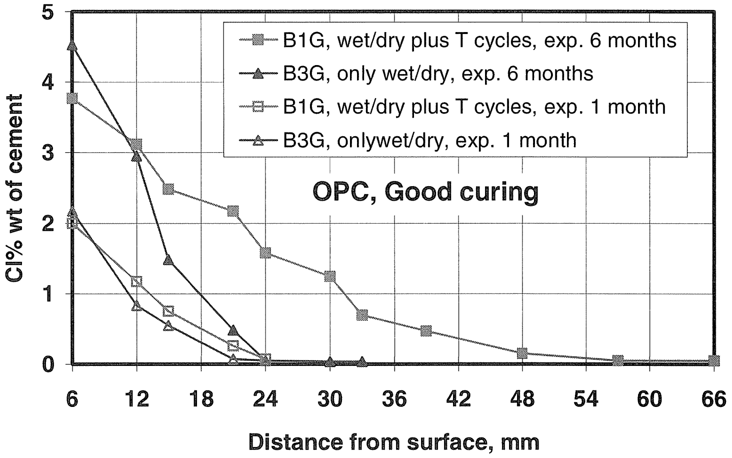


Fig. 8. *Chloride penetration into concrete beams exposed to temperature cycles (set 1) and constant room temperature (set 3), for two measurements – poor curing condition.*

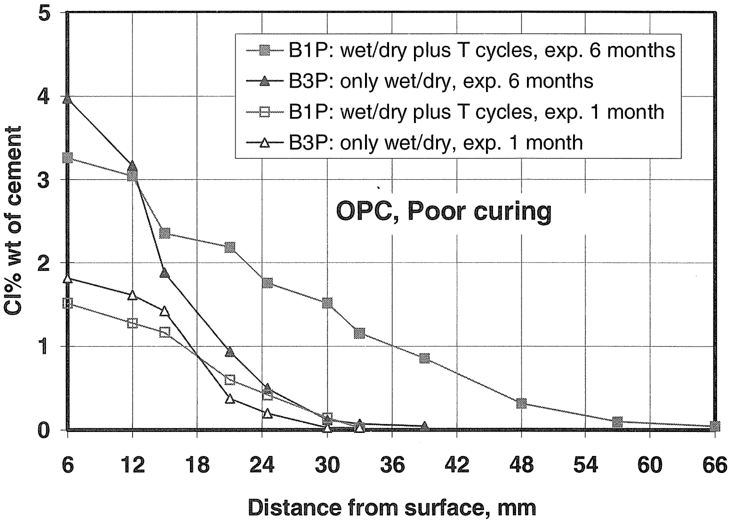


Fig. 9. *Chloride penetration into concrete beams exposed to temperature cycles (set 1) and constant room temperature (set 3), for two measurements – Poor curing condition.*

The same pattern of behaviour was observed for the specimens with poor curing conditions, in the beam sections as well as the cubes. In Fig. 9, the chloride profiles of the beam sections, cured in poor condition, are shown. The dominant influence of temperature here is also very clear. It was found, however, that the chloride contents at the surface of the specimens with temperature cycles were significantly lower than those without temperature cycles. This is in agreement with findings of other investigations. Chloride profiles from sea water exposed concrete structures in hot countries is reported to have shown much lower chloride content at the concrete surface [14]. This point should therefore be considered when the simplified Fick's law is used for prediction of chloride ingress into concrete structures.

3.4 *Slag concrete*

The performance of slag concrete in the simulated marine environment has extensively been discussed in previous paper [12]. It was generally noticed that slag concrete showed much more resistance to chloride penetration in such severe environment compared to concrete made with Portland cement. In Fig. 10, the profiles of the specimens of the first and second beam, B1P and B2P respectively, are presented. Note that both beams are subjected to exactly the same environment. It is clear that Portland concrete is very susceptible to temperature variations by absorbing considerably more chloride ions compared to the slag concrete. Similar observations were made by previous authors, mostly without (such extreme) temperature cycles [16].

The chloride data of the third beam was also plotted in Fig. 10, for comparison purpose. It indicates that in aggressive marine environment with prevailing temperature variations, using slag concrete is highly recommended as much less chloride ions are absorbed compared to the Portland concrete exposed to only wetting and drying and not even temperature variations.

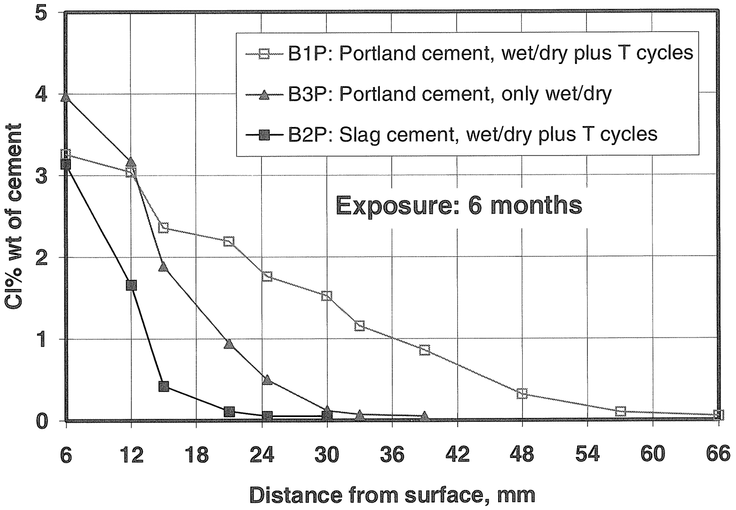


Fig. 10. *Chloride data of concrete specimens with Portland cement and blast furnace slag cement both with poor curing and exposed to temperature and moisture cycles. The chloride data of the third beam (reference beam) is plotted here for comparison.*

Concluding remarks

While, in most cases, chloride attack is evaluated from unloaded specimens, concrete specimens in this investigation are loaded in alternate compression and tension due to varying temperature. In durability analysis of marine concrete structures, the prevailing environmental conditions, mainly temperature variations, should be a major consideration due to the significant adverse effect of temperature on the rate of chloride penetration into concrete. By exposing the concrete specimens in a simulated aggressive marine environment, it was shown that temperature cycles play a dominant role on decreasing the resistance of concrete and promoting chloride ingress in marine condition.

Comparison of large concrete elements and small specimens, both exposed to temperature and hygral variations, showed that microcracks due to restraint of temperature induced deformations promote chloride penetration rate in large specimens slightly. The pronounced effect of temperature cycles, however, found to be the higher penetration of chlorides through the pore structure of the concrete rather than the induced microcracks, at least with the condition of this test.

Temperature and humidity variation which is the main characteristic of marine environment in hot climates, did not significantly affect chloride ingress rate into slag concrete compared with the data available in the literature, this in contrast with the normal Portland concrete. The transport of chlorides was dominant by capillary absorption in the outer layers of the specimens.

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