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Influence of Mix Design on Chloride Diffusion in Concrete Structures under Temperature Gradient Conditions

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Abstract – This paper presents the influence of mix design on chloride penetration in concrete exposed to the temperature gradient condition caused by high environmental temperature in arid climate region. Concrete samples with two different w/c ratios of 0.45 and 0.65 were exposed to chloride ion environment under isothermal and temperature gradient conditions. Another set of the concrete samples with 5 % silica fume and a control sample without silica fume were exposed to chloride ion environment under the temperature gradient condition. Results show that the chloride content of the concrete samples was significantly increased with increasing the w/c ratio. The large amount of the reduction in chloride concentration with 5 % silica fume was observed compared with the control sample.

Keywords**:** Chloride penetration, Thermal diffusion, Water-to-cement ratio, Arid climate, High ambient temperature, Silica fume

1. Introduction

Chloride ion penetration into reinforced concrete structures with a rebar is one of the major causes of deterioration of concrete structures [1, 2]. This is because chloride ions corrode a rebar and reduce its cross-sectional area, resulting in reduction of the load carrying capacity of the reinforced concrete structures. Consequently, the service life of the concrete structures is shortened. Environmental factors such as temperature and relative humidity have been reported to affect the rate of chloride ion diffusion in concrete [3, 4]. Furthermore, the concrete microstructural properties such as porosity and permeability play a major role in the diffusion of chloride ions in concrete.

In arid regions, high environmental temperature more than 50 ℃ could be reached especially during the summer period. Concrete structures, such as reactor containment buildings in nuclear power plants built in the UAE, located in such region, are usually maintained at air-conditioned temperatures internally. As a result, a temperature (or thermal) gradient is created at the walls of concrete structures due to the difference in temperature between inside and outside of the structures. Furthermore, reactor containment buildings in nuclear power plants are typically situated at proximity to the seawater for cooling purpose. Because of this, the adsorption of atmospheric chloride ions to the exterior walls of the reactor containment buildings creates a chloride concentration gradient. The objective of this paper is to investigate the influence of w/c ratio and silica fume on chloride ion penetration into concrete structures under the temperature gradient condition caused by high ambient temperature in arid climates.

Thermal diffusion or Soret effect [5], i.e., the movement of moisture or ions as a result of a temperature gradient, could accelerate chloride ion diffusion in concrete. In a previous experimental work by Istieta and Xi [6], concrete samples were exposed to chloride environment under isothermal and temperature gradient conditions. They reported that chloride content for the concrete samples exposed to the temperature gradient condition were much higher than that for the concrete samples exposed to the constant temperature condition. In our previous work [4], we examined the influence of a temperature gradient on chloride ion diffusion in concrete using experimental and numerical methods. It was estimated that the corrosion initiation time of reactor containment buildings at ambient temperature of 50 ℃ could be shortened by 30 ~ 40% due to thermal diffusion caused by a temperature gradient. In the previous studies, the effects of w/c ratio and silica fume on chloride ion diffusion and corrosion initiation time of concrete have not been extensively studied. Therefore, the present study focuses on investigating the influence of varying w/c ratio and including silica fume on chloride ion penetration into concrete structures under the temperature gradient condition.

2. Experimental Methodology

2.1. Mix design of concrete samples

Concrete samples in cylindrical shape with 80 mm in height and 96 mm in diameter were cast and cured for 28 days. To study the effect of the w/c ratio, concrete samples with two different w/c ratios of 0.45 and 0.65 were prepared using the mix proportions in Table 1.

Table 1. Mix proportions for testing of the effect of w/c ratio (unit: kg/m^3)

w/c ratio	Water	Cement	Dune sand	Coarse aggregate	Fine aggregate
0.45	242.70	539.33	404.49	808.99	404.49
0.65	335.48	516.13	387.10	774.19	387.10

To examine the influence of silica fume, two types of the concrete samples were prepared using the mix proportions in Table 2. For the samples with silica fume, 5 % silica fume was added and the control samples without silica fume were fabricated for the purpose of comparison.

Table 2. Mix proportions for testing of the effect of silica fume (unit: kg/m^3)

	Water	Cement	Dune sand	Coarse aggregate	Fine aggregate	Silica fume
Control	255.74	393.44	590.16	590.16	590.16	-
5 % silica fume	266.34	390.24	585.36	585.36	585.36	19.51

Notice that the water-to-binder ratio was fixed in both Tables 1 and 2.

2.2. Experimental setup for chloride diffusion tests under the temperature gradient condition

An experimental setup was accomplished for the chloride diffusion testing of the concrete samples subjected to the thermal (or temperature) gradient condition along with the isothermal condition for comparison at high ambient temperature of 50 ºC. Notice that the concrete samples were placed in acrylic tubes and sealed at their bottom and top edges with silicone paste for a unidirectional flow of chloride ions and moisture. All the tests were performed for 30 days. After curing 28 days, the concrete samples were exposed to two exposure conditions at the ambient temperature of 50 ℃, i.e., isothermal (i.e., constant temperature) and temperature gradient conditions. To achieve the temperature gradient condition, the concrete samples were immersed partially into a digital water bath heated with the saturated NaCl solution at 50 ºC and the other end is exposed to air cooling at room temperature of 22 ℃. The temperature variation throughout the depth of concrete was monitored by measuring via thermocouples inserted at the depths of 10-, 40-, and 70 mm for the duration of the test. In order to set up the isothermal condition, the concrete samples were fully immersed in the heated NaCl solution at 50 ºC. As a result, the concrete maintains constant temperature at 50 ºC during the test duration.

After 30 days of testing, the concrete samples were sliced, cut into five 10 mm slices, and pulverized to measure chloride concentration throughout the depth of concrete. The powder was then used to measure the chloride content by the potentiometric titration according to ASTM C1152/1152 M-04 (2012) standard. More details of the experimental setup for the chloride diffusion tests and the measurement of the chloride content in the concrete samples are referred to as An et al. [4].

3. Results and Discussion

The measured chloride concentrations from the chloride diffusion tests are presented and analysed in this section. We We first begin by studying the influence of the w/c ratio on the chloride penetration into concrete subjected to both isothermal isothermal and thermal gradient conditions at ambient temperature of 50 ℃. In Figure 1, for two different w/c ratios of 0.45 0.45 and 0.65, the chloride concentration profiles of the concrete samples under the temperature gradient condition are compared with those under the isothermal condition. The results show the increasing trend of the chloride concentration along the entire depth of concrete with increasing the w/c ratio from 0.45 to 0.65. Moreover, the concrete samples exposed to the thermal gradient condition had significantly higher chloride content when compared to those exposed to the isothermal condition.

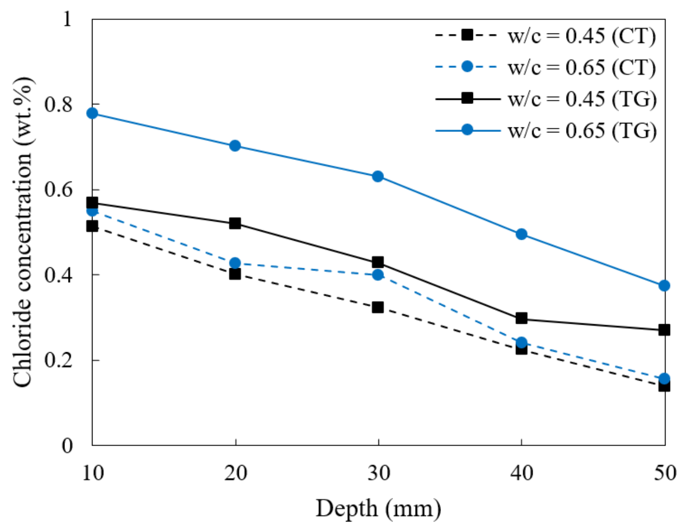

Fig. 1. Chloride concentrations over the depth of concrete for w/c ratios of 0.45 and 0.65 under temperature gradient (TG) and constant temperature (CT) conditions at the ambient temperature of 50 ℃.

At the same temperature of 50 ℃, the significant increase of the chloride concentration under the temperature gradient condition is due to the effect of thermal diffusion. Specifically, there could be up to 40 to 80 % more chloride in the samples exposed to the temperature gradient condition when compared to the isothermal condition. The increase of the chloride content with increasing the w/c ratio is because of the increase of porosity in concrete as the w/c ratio increases. This implies that the concrete samples exposed to the temperature gradient condition will attain the chloride threshold quicker and reach corrosion initiation faster than those exposed to the isothermal condition at high ambient temperature.

In Figure 2, the influence of the inclusion of silica fume under the temperature gradient condition is investigated. The measured chloride profiles from the concrete samples with silica fume and the control samples without silica fume are displayed over the depth of concrete. Based on the findings in Figure 2, it can be observed that the concrete samples containing 5% silica fume exhibited lower chloride content throughout the whole depth in comparison to the control samples without silica fume under the thermal gradient condition at ambient temperature of 50 ℃. Even under the temperature gradient condition, the reduction of chloride concentration with silica fume is significant because it is recognized as a pozzolanic material that effectively can reduce porosity, hinder chloride diffusion, and enhance concrete durability. As previously noted in Figure 1, thermal diffusion significantly influences chloride diffusion. Therefore, the inclusion of silica fume could serve as a crucial method for counteracting the additional chloride content introduced into concrete due to thermal diffusion.

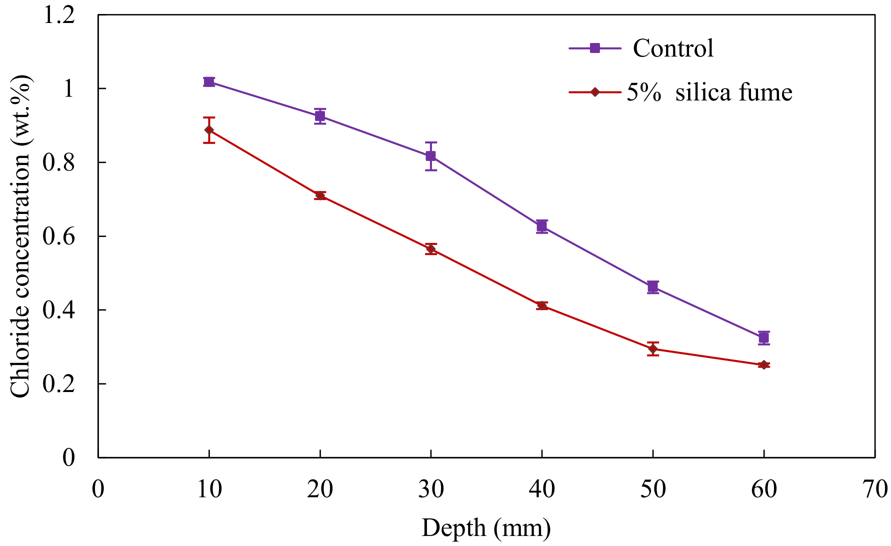

Fig. 2. Total chloride concentrations averaged over two samples with 5 % silica fume and two control samples exposed to the temperature condition at high ambient temperature of 50 ℃.

4. Conclusion

Towards the goal to estimate the service life of the concrete structures in the UAE environmental condition, the effects of the w/c ratio and silica fume on the chloride ion diffusion in the concrete samples exposed to the temperature gradient condition caused by high ambient temperature of 50 ℃ were studied. It was obtained that the chloride ion concentration under the temperature gradient condition is 1.4-1.8 times higher than the constant temperature condition. With 5 % silica fume, the percentage reduction of chloride concentration at each depth compared with the control sample was approximately minimum 12.8 % to maximum 36.2 %. Based on the experimental data, future work will focus on the verification of the accuracy of the results by comparing with numerical analysis based on a theoretical model and the prediction of the service life of the concrete structures, such as reactor contain building, under the TG condition.

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