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Influence of compressive loading on chloride ingress through concrete

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ABSTRACT: Chloride-induced corrosion of steel in concrete is one of the most important durability and safety concerns for reinforced concrete structures. To study chloride ingress into concrete is thus very important. However, most of the researchers focus on the studying chloride ingress through concrete samples without any loading. In reality concrete structures are subjected to different kinds of loads and therefore studying the effect of such loads on chloride transport is critical. In this work, 28 different concrete mixes were subjected to three levels of compressive load (0%, 50% and 75% of compressive failure load – f) for 24 hours. Further to unloading, these samples were subjected to non-steady state chloride diffusion test as per NT Build 443. The results were compared against the diffusion coefficient obtained for concrete samples that had no previous loading. D value for concretes subjected to 75% f showed a significant increase compared to 0% loading condition, but the increase was insignificant for 50% f. The results indicate that the influence of concrete mixes variables on D is more significant than that of loading level. Surface chloride concentration also increased with the loading level, which might be due to the increased concrete surface area caused by micro cracking.

KEY WORDS: Chloride ions; Concrete; Durability; Diffusion; Loading.

1 INTRODUCTION

Chloride-induced corrosion of reinforced concrete structures is one of the most serious problems affecting economy growth and the safety of people’s lives and properties. To study the processes of chloride transport in concrete is very important for engineers to predict the service life of concrete structures. However, most of the studies have just focused on ‘perfect’ concretes which are usually not cracked or withstanding any structural loading. The existing service life prediction models, like Life-365 [1-2], AGEDDCA model [3] and DuraCrete [4], also do not consider any effect of loading or cracking. The predicted service life, based on the performance of concrete without considering the actual loading condition, may not be reliable. As a consequence, premature deterioration of structures in service is common. A field survey of 57 bridges in Kansas indicated that chloride concentration at a depth of 76 mm from the location of a surface crack can exceed the corrosion threshold amount within the first year [5]. Another survey of 15 marine structures in Florida showed that signs of corrosion could be seen at about 10 to 15 years since construction, with the average at about 11.5 years, meaning that corrosion has initiated much earlier than expected [6].

Few studies have been carried out on the influence of loading on chloride diffusion. A consistent decrease of chloride diffusion coefficient up to the loading level at 50% of concrete compressive strength was reported by Wang et al. [7], Li et al. [8] and Lim et al. [9]. The results at higher loading levels were not available. Also, most of the work focused only on pure Portland cement CEMI concrete, and the data on concrete with mineral additives is still limited.

This paper presents data from a test programme conducted to study the influence of loading on the chloride diffusion of concrete subjected to different stress levels. As shown in Table 1, different cement combinations were studied. The result of this study may aid in more accurate predictions of service life and in designing more durable concrete structures.

2 EXPERIMENTAL PROGRAMME

The coarse aggregate used was crushed and well graded basalt of size 5-20mm (size 5-10 mm/ size 10-20mm ratio is 33/67) and the fine aggregate was natural medium graded sand. Both aggregates were oven-dried at 100 ± 5 ℃ for 24 hours to remove the initial moisture and cooled down in air-tight containers before being used. Class 42.5N Portland cement (PC) CEMI conforming to BS EN 197-1:2011 [10] was used. Ground granulated blast-furnace (GGBS) complying with BS EN 6699: 1992 [11], pulverised fuel ash (PFA) complying with BS EN 450 [12] and silica fume (SF) EMSAC 500 S were used to replace part of CEMI in the mixes studied. The mix details and proportions for each mix are given in Table 1. The required quantities of the mix constituents were batched by mass and then mixed using a pan mixer in accordance with BS 1881-125: 1986 [13]. The test samples were casted according to BS EN 12390-2:2000 [14]. Slump of each mix is reported in Table 2. A vibrating table was used to compact the samples. The casting surface of concrete specimen was then smoothed and a thick black polythene sheet was used to cover the concrete. The curing regime was as follows: After demoulding, the specimens were placed in a water bath at 20 ℃ (± 1℃) for the first 3 days and then wrapped in wet hessian and thick black polythene sheets. They were then placed in a constant temperature room at 20 ℃ (± 1℃). A compressive strength test was conducted at an age of 28 and 56 days for each mix, and the results are shown in Table 2.

Table 1. Details of the concrete mixes studied including the mass of ingredients required to produce 1m^3.

Group	Portland Cement	GGBS	PFA	SF	Water	Superplasticiser	10 mm aggregate	20 mm aggregate	Sand
	kg/m^3								
0.45-CEMI,300	300	—	—	—	135	0.39	408	829	825
0.45-CEMI,360	360	—	—	—	162	0.47	384	780	776
0.45-35%GGBS,300	195	105	—	—	135	0.44	407	826	822
0.45-35%GGBS,360	234	126	—	—	162	0.52	382	776	772
0.45-65%GGBS,300	105	195	—	—	135	0.44	405	823	819
0.45-65%GGBS,360	126	234	—	—	162	0.52	371	752	769
0.45-5%SF, 300	270	—	—	15	135	0.44	399	810	821
0.45-5%SF, 360	324	—	—	18	162	0.52	376	762	773
0.45-10%SF, 300	270	—	—	30	135	0.52	406	824	820
0.45-10%SF, 360	324	—	—	36	162	0.63	381	774	770
0.45-17.5%PFA, 300	195	—	52.5	—	135	0.44	403	817	828
0.45-17.5%PFA, 360	234	—	63	—	162	0.52	380	770	781
0.45-35%PFA, 300	195	—	105	—	135	0.87	400	812	808
0.45-35%PFA, 360	234	—	126	—	162	1.04	374	759	755
0.65-CEMI,300	300	—	—	—	195	—	377	765	761
0.65-CEMI,360	360	—	—	—	234	—	346	702	690
0.65-35%GGBS, 300	195	105	—	—	195	—	375	762	758
0.65-35%GGBS, 360	234	126	—	—	234	—	344	699	695
0.65-65%GGBS, 300	105	195	—	—	195	—	374	759	755
0.65-65%GGBS, 360	126	234	—	—	234	—	342	695	692
0.65-5%SF, 300	270	—	—	15	195	0.10	368	747	758
0.65-5%SF, 360	324	—	—	18	234	0.13	339	687	697
0.65-10%SF, 300	270	—	—	30	195	0.22	374	760	756
0.65-10%SF, 360	324	—	—	36	234	0.26	343	696	693
0.65-17.5%PFA, 300	195	—	52.5	—	195	—	381	774	771
0.65-17.5%PFA, 360	234	—	63	—	234	—	352	714	710
0.65-35%PFA, 300	195	—	105	—	195	—	368	748	744
0.65-35%PFA, 360	234	—	126	—	234	—	336	682	679

After 56 days of curing, cores of size 100mm diameter and 80 mm thickness were cut from the blocks and the outermost, approximately 15 mm thick layer, was cut off from the two end surfaces using a water-cooled diamond saw. This was carried out to avoid the effects of the compaction influencing chloride transport and to ensure that results are indicative of mass concrete. The middle part of 50 ± 1 mm was thus used as test specimen. Three cores per mix were used to determine the failure compressive load, f. Based on this failure load, 9 other samples per mix were subjected to a compressive loading level of 0%, 50% or 75% f with three samples per load level. As shown in Figure 1, the load was applied and kept using a steel frame and a torque wrench which can show the load applied. After 24 hours of loading, all faces except the exposure face (one cut face) of the disc specimen were coated with epoxy. Samples were saturated in $Ca(OH)_2$ solution under vacuum conditions as specified in NT Build 443 [15].

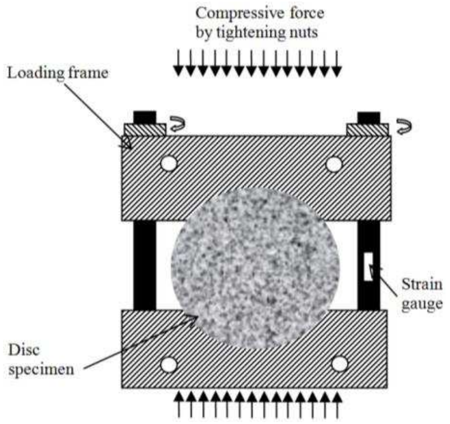

Figure 1. Schematic diagram of the loading set-up used for applying compressive loads on concrete cores.

Table 2. Slump and compressive strength of the different concretes

Mix ID	Slump (mm)	Compressive strength at 28 days			Compressive strength at 56 days		
		Mean (MPa)	SD (MPa)	CV (%)	Mean (MPa)	SD (MPa)	CV (%)
0.45-CEMI, 300	100	58.70	1.78	3.03	60.23	1.06	1.76
0.45-CEMI, 360	120	58.04	0.67	1.16	59.45	0.67	1.13
0.45-35%GGBS, 300	105	49.81	1.79	3.60	62.33	3.62	5.80
0.45-35%GGBS, 360	95	50.71	0.35	0.69	56.73	3.19	5.63
0.45-65%GGBS, 300	95	48.45	2.09	4.30	65.17	2.32	3.57
0.45-65%GGBS, 360	110	48.32	2.36	4.87	65.67	3.06	4.65
0.45-17.5%PFA, 300	110	53.10	1.80	3.40	60.50	0.92	1.51
0.45-17.5%PFA, 360	130	53.70	2.25	4.20	60.67	2.92	4.81
0.45-35%PFA, 300	90	49.22	2.31	4.70	60.40	1.10	1.82
0.45-35%PFA, 360	95	48.83	2.18	4.46	63.03	0.90	1.42
0.45-5%SF, 300	110	58.33	3.12	5.35	63.30	2.43	3.84
0.45-5%SF, 360	115	59.70	2.36	3.96	63.50	2.80	4.41
0.45-10%SF, 300	106	59.63	2.47	4.14	67.50	2.43	3.60
0.45-10%SF, 360	110	58.64	1.47	2.51	68.45	1.31	1.91
0.65-CEMI, 300	95	37.82	1.84	4.86	38.72	2.64	6.82
0.65-CEMI, 360	110	37.59	2.37	6.30	40.89	1.94	4.75
0.65-35%GGBS, 300	100	35.12	1.75	4.99	48.87	1.75	3.59
0.65-35%GGBS, 360	120	36.58	1.96	5.35	47.25	2.03	4.29
0.65-65%GGBS, 300	115	33.51	2.15	6.42	40.62	0.69	1.70
0.65-65%GGBS, 360	125	31.26	2.02	6.48	41.07	2.21	5.38
0.65-17.5%PFA, 300	110	32.04	1.82	5.67	37.05	3.16	8.54
0.65-17.5%PFA, 360	120	33.15	2.22	6.69	37.32	1.90	5.08
0.65-35%PFA, 300	120	29.24	1.23	4.20	38.34	2.40	6.25
0.65-35%PFA, 360	130	30.16	2.25	7.47	39.60	1.15	2.90
0.65-5%SF, 300	120	39.14	2.38	6.07	43.34	2.94	6.79
0.65-5%SF, 360	123	38.86	2.54	6.53	42.51	3.09	7.27
0.65-10%SF, 300	125	39.21	3.53	8.99	49.83	0.47	0.94
0.65-10%SF, 360	100	38.13	2.43	6.37	46.44	1.45	3.12

According to NT BUILD 443 [15], specimens were then immersed in an aqueous NaCl solution (containing NaCl 165 ± 1 g/dm^3) and kept for 35 days. The temperature of the solution was maintained at 23 ± 2 °C. A profile grinder from Germann Instruments was used to grind the powder of concrete from the test specimens after ponding. The Preparation of filtrate containing chloride of each sample powder was conducted in accordance of a recommendation of RILEM TC 178-TMC [16]. The concentration of chloride ions in the filtrate was analysed using a commercial potentiometric titrator. The instrument was calibrated before each set of test by using standard chloride solutions with concentrations of 200ppm, 500ppm and 1000ppm. The principle of the automatic potentiometric titrator was: The solution containing chloride ions showed negative potential. 0.02 mol/L $AgNO_3$ was added to react with chloride ions, and AgCl (white crystalline solid) was formed. The negative potential was balanced. The sudden change of the potential of the solution from negative to positive was identified as the point of that all chloride ions had been reacted. Chloride concentration in the solution was calculated by Equation 1.

$$Cl^- = \frac{M_{Cl} C_{Ag} V_{Ag}}{V_{Cl}}$$

Equation 1

where, Cl^- is the chloride concentration in the tested solution, ppm; M_{Cl} is the molar mass of chloride, M_{Cl} = 35.453 g/mol; C_{Ag} is the molarity of the $AgNO_3$ solution used, mmol/L; V_{Ag} is the volume of the $AgNO_3$ solution used, L; V_{Cl} is the volume of the solution tested, L.

According to NT BUILD 443 [15], chloride diffusion coefficient and surface chloride concentration were determined by fitting Equation 2 to the measured chloride concentration at different depths of concrete. The initial chloride content was measured and can be taken as 0% by mass of concrete.

$$C_x = C_s(1 - \mathrm{erf}(\frac{x}{2\sqrt{D_e t}})$$

Equation 2

where, C_x is the chloride concentration at depth x and time t, % mass of concrete; C_s is the chloride concentration at the surface, % mass of concrete; x is the depth, m; t is the time, s; D_e is the effective diffusion coefficient, m^2/s.

3 RESULTS AND DISCUSSION

As shown in Figure 2, chloride diffusion coefficient of concrete increased with the loading level. Up to 50% f, chloride diffusion coefficient (D) remained constant and did not change much. At 75% f, the D value for normal concretes increased by 50% of the unloaded 0%f value. For concretes with mineral additives this increase was around 30%. The increased micro cracking at 75% f combined with the residual strain that remains in the sample after loading is removed may help to explain the increase in D values observed. As shown in Figure 3, after unloading from 50% f, almost all induced strain is recovered, but a significant unrecoverable residual strain can be found after unloading from 75% f. The net result is that cracks induced by loading can shorten the effective distance of chloride diffusion in concrete, as shown in Figure 4.

D values for concretes with cement content 360 kg/m^3 were slightly higher than those of concretes with cement content 300 kg/m^3. Increased paste content in the former may help to explain the increase in D value. This is based on the assumption that paste volume is contributing to a larger proportion of the chloride transport in concrete.

Chloride diffusion coefficients of concretes with water/binder ratio 0.65 were higher than those of concretes with water/binder ratio 0.45 and this is due to the higher porosity. In summary, chloride diffusion coefficients of normal concretes can be reduced to 25% of the original values if mineral additives were added.

Surface chloride concentration was also derived from the regression analysis Equation 2. As shown in Figure 5, surface chloride concentration generally increased with the increase of loading level. This can be explained by more chloride ingress due to the cracks formed and the expansion of concrete volume caused by cracks, as shown in Figure 6. The decreased surface chloride concentration at 75% f in mix 0.45-5%SF-360 can be caused by the testing errors on chloride concentration.

As shown in Figure 5, concrete with more cement has a slight higher surface chloride concentration, but this trend is not very obvious for many mixes. The effect of loading on change of surface chloride concentration is more significant than the effect of cement content. Surface chloride concentration of concretes with water/binder ratio 0.65 was higher than that of concrete with water/binder ratio 0.45. More chloride ions were allowed to store on the concrete with higher water content because of higher porosity. GGBS and PFA seem to increase the surface chloride concentration as compared with ordinary cement. Slightly increased surface chloride concentration was found in Figure 5 when replacing cement with GGBS and PFA. This might be due to the higher chloride binding capacity [17] and more Friedel's salt formed because of higher alumina content [18]. Figure 5 shows that SF can slightly decrease the chloride surface concentration. SF was found to decrease chloride binding capacity by reduction in PH and dilution effect of C_3A [18].

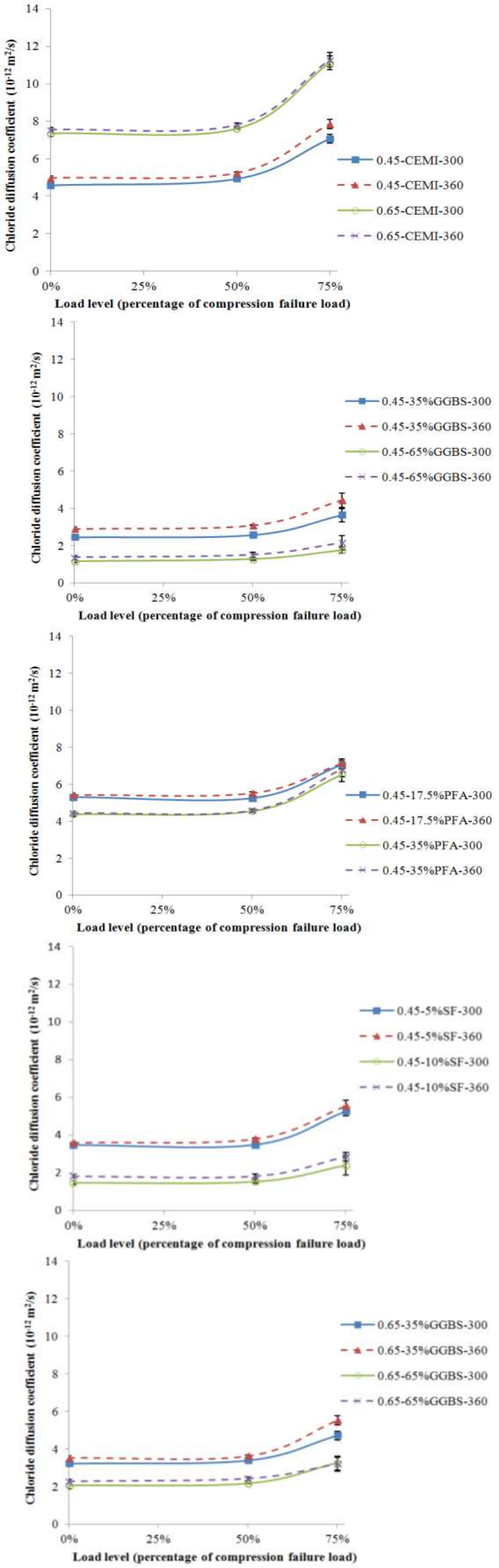

Figure 2. Chloride diffusion coefficient of each mix

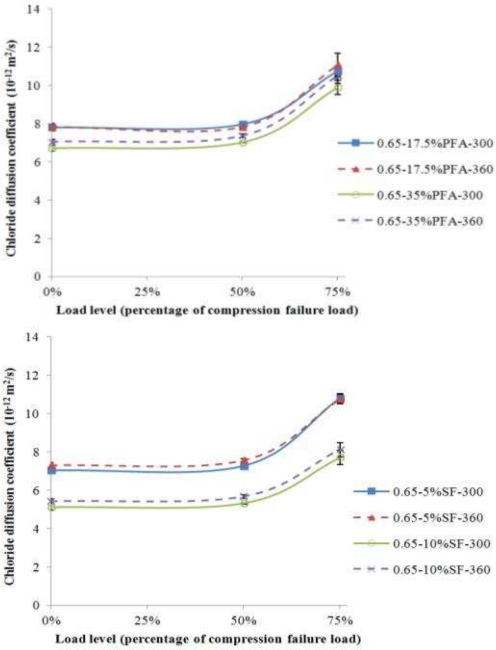

Figure 2. Chloride diffusion coefficient of each mix (continued).

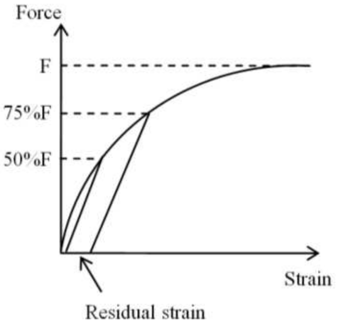

Figure 3. Schematic sketch of the residual strain after unloading.

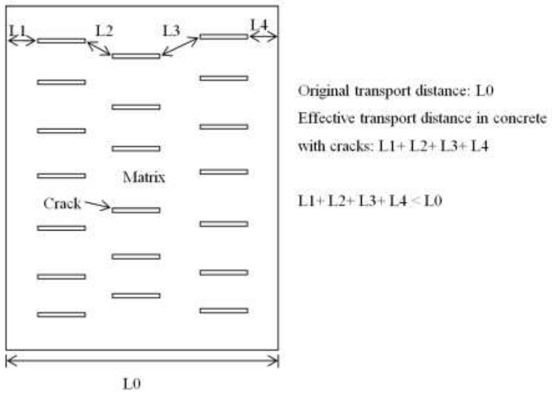

Figure 4. Reduced chloride transport distance by cracks in concrete.

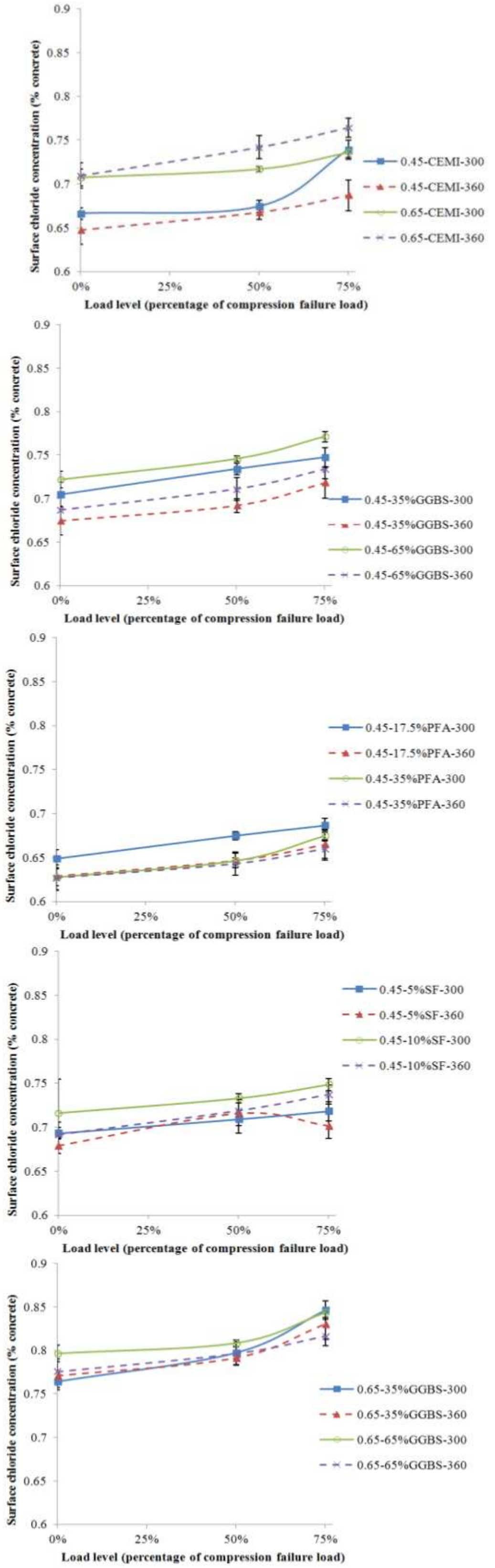

Figure 5. Surface chloride concentration of each mix.

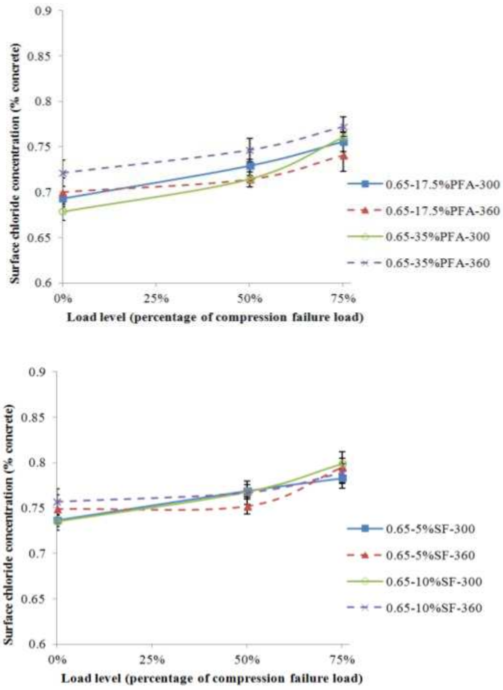

Figure 5. Surface chloride concentration of each mix (continued).

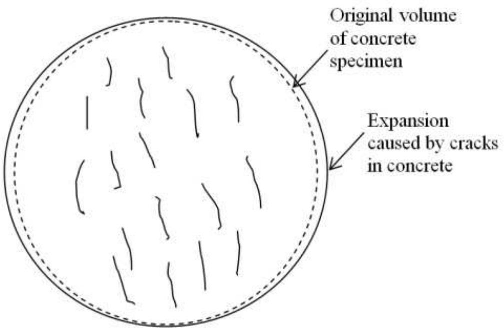

Figure 6. Expansion of volume caused by cracks in concrete.

4 CONCLUSIONS

From the above analysis, the following conclusions can be derived:

1) Loading can increase the chloride diffusion coefficient, the depth to which chloride ions ingress and the surface chloride concentration. There is little change of chloride diffusion coefficient of concrete after unloading from 50% f, but after unloading from 75% f a significant increase is observed. This increase is up to 50% for normal concrete and 30% for concrete with mineral additives.

2) The effect of cement content on chloride ingress is less significant than the effect caused by loading, water/binder ratio or mineral additives.

3) Addition of mineral additives such as GGBS and PFA can slightly increase the surface chloride concentration but SF can slightly decrease chloride surface concentration. These mineral additives can significantly decrease the chloride diffusion coefficient and chloride ingress depth.

4) Lower water binder ratio and addition of mineral additives are the effective means for reducing the chloride ingress into concrete if the expected loading levels can reach up to 75% f.

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