Scientific paper

Semi-quantitative Prediction of the Corrosion Risk of Steel in Concrete Using XRD Analysis

Do Gyeum Kim¹, Ho Jae Lee¹ and Ki Yong Ann²

Received 22 January 2011, accepted 15 September 2011

Abstract

The present study concerns a technique for determining the chloride binding capacity, using the XRD curve containing the peaks for Friedel's salt. The influence of chloride binding on the corrosion behaviour was also evaluated. The binding capacity of chloride ions in cement paste was determined by the water extraction method. As a result, it was found that the chloride binding capacity is strongly dependent on the W/C, binder type, curing age and total chloride concentration in the paste. It is notable that chloride binding has a crucial influence on corrosion propagation: an increase in the binding capacity resulted in a decrease in the corrosion rate at a given chloride concentration in mortar specimens. However, the impact of chloride binding on the onset of corrosion was marginal, presumably due to a release of bound chlorides into free chlorides at the stage of corrosion, accompanying a pH fall in the vicinity of the steel. A strong relation between the peak intensity for Friedel's salt and the concentration of bound chloride was observed, which can be used to determine the bound chlorides and thus the risk of chloride-induced corrosion of steel in concrete.

1. Introduction

Chloride binding has been thought a key factor for preventing the corrosion of steel in concrete, which is exposed to a corrosive environment containing chloride ions such as a marine environment or where deicer is used, as chlorides bound in the cement matrix do not have an impact on the corrosion process (Song *et al.* 2008). Binding of chloride ions can be defined as a chemical reaction between chlorides and hydration products to remove chloride ions from the pore solution (Ann 2005). Thus, bound chlorides can exist in the crystallised form in the cement matrix. In fact, it has been held that only free chloride ions can participate in the corrosion activity in the majority of previous studies (Hope 1985). Chloride binding simultaneously has an impact on chloride transport (Glass and Buenfeld 2000). The removal of free chloride ions in the cement matrix may allow further buildup of chloride ions, implying an increase in chloride ingress, when expressed in terms of total chloride concentration.

Likewise, chloride binding is a crucial factor in assessing the durability of concrete structures under chloride-induced corrosion. Notwithstanding this, there has been no quantitative method for determining the chloride binding capacity, in particular the binding ratio to total chloride concentration at depths of concrete. The pore press method and water extraction have been widely used to measure the concentration of chloride ions in concrete. However, these methods have limita-

tions in determining a chloride profile with binding capacity (Arya *et al.* 1990). For example, the pore press method is only applicable to bulk concrete and thus does not allow profiling of chloride ion concentrations as a function of depth. As the water extraction method provides only information on the free chloride concentration, a double measurement for total chlorides is required to complete the profile with binding capacity, which requires much time and effort.

To date, there has rarely been information on the chloride binding capacity, measured in a consistent way considering W/C, binder type and chloride concentration present in the cement paste. Thus, binding capacity has been usually rendered using the fitted curves (e.g. Langmuir and Freundlich isotherms), derived from experimental results on binding ratio to total chlorides, which are randomly obtained by different research projects. This may be attributed to the limitation of measuring chloride concentration in terms of free and bound chlorides in the cement matrix, as mentioned above.

In the present study, binding isotherms were determined with different mix proportion and chloride concentration, using the experimental results obtained by the double water extraction method to simultaneously measure the free and bound chloride concentration in the cement paste. Also, a semi-quantitative method was proposed to detect the concentration of bound chlorides using the XRD curve containing the peaks for Friedel's salt (i.e. bound chlorides). The relation between the peak intensity and the concentration of bound chloride was determined to evaluate the risk of chloride-induced corrosion of steel in concrete.

2. Experiments

In the present study, cement paste and mortar specimens

¹Department of Infrastructure Research, Korea Institute of Construction Technology, Republic of Korea.

²School of Civil and Environmental Engineering, Yonsei University, Republic of Korea.

E-mail: k.ann@yonsei.ac.kr

were used to assess the chloride binding capacity, XRD characteristics and corrosion behaviour. For chloride binding and the XRD analysis, cement paste was cast, assuming that aggregate does not affect the chemistry of chloride binding in the cement matrix, whilst mortar specimens were used to detect the corrosion rate to further assess the corrosion risk depending on the chloride binding. **Table 1** gives the mix proportion for each test.

2.1 Chloride binding

Cement paste was cast in a prism mould (100×100×50 mm) to test the chloride binding capacity at the W/C of 0.3, 0.4, 0.5 and 0.6. To evaluate the effect of binder type, 30% pulverised fuel ash (PFA) and 65% ground granulated blasted furnace slag (GGBS) were tested together with ordinary Portland cement (OPC). The oxide composition of binders is given in **Table 2**. Immediately after casting the cement paste with five levels of chloride ions (0.0, 0.5, 1.0, 2.0 and 3.0% by weight of binder) in the form of NaCl, the specimens were rotated at 6 rpm for 24 hours to minimise segregation of chloride ions. After demoulding, the specimens were cured by wrapping them in polythene film at 20±1°C, to avoid leaching out of chloride and hydroxyl ions from the cement paste, which may take place during open-wet curing. The duration of curing was 7, 28 and 150 days. Prior to sampling by crushing and grinding, the specimens were dried in an oven at 104°C for 24 h. Then, ground dust sample was sieved through a 300 µm mesh, and 1.0-3.0 g of the dust sample was placed in a beaker with 50 ml of still water at 50°C. The suspension sample was stirred for 5 min and stood for 30 min to extract water-soluble chloride, as being mostly equivalent to free chloride (Arya *et al.* 1987). Then, the sample was filtered to measure the concentration of free chloride ions, using potentiometric titration with silver nitrate.

The replications always consisted in four samples and the average was taken.

2.2 XRD analysis

Simultaneously, all paste samples containing chloride ions were tested using XRD. After drying and grinding the paste specimens, the powder samples were investigated with the XRD technique. The experimental background of the XRD analysis consisted of measurement range (2θ): 5-60°, scan rate: 0.1°/sec, voltage: 20 kV, current density: 10.0 mA, maximum background noise: 2 count/sec, and tube: W, Mo, Cu, Fe, Cr, Ag. All samples were analysed at using XRD immediately after grinding of the specimen to avoid further chemical reaction between the paste powder and atmosphere (e.g. carbonation and hydration).

2.3 Corrosion of steel

To investigate the corrosion behaviour, mortar specimens were cast in a cylindrical mould (ø60.0×90.0 mm) with a centrally located steel rebar 10.0 mm in diameter to produce cover depth of 25.0 mm. The proportion of cement to sand was kept at 2.45 with variations in the W/C, corresponding to the binding test. At the variation in the binders (i.e. OPC, 30% PFA and 65% GGBS), the mix proportion of mortar was binder:water:sand = 1.00:0.40:2.45. The ends of the steel bars were clad using rich cement paste and a rubber coating for double protection, and one end of the steel rebars was protruded to allow connection of a electrical wire. The specimens were then wrapped in polythene film for curing at 20±1°C for 28 days. To speed up the corrosion process, the specimens were then exposed to wet/dry cycling consisting of 3 wet days and 4 dry days, up to 20 cycles. The anodic polarisation technique was used to measure the corrosion rate of the steel rebar. The experimental

Table 1 Mix proportion for specimens.

Type	Water	OPC	PFA	GGBS	Sand	Remark
Paste	0.30	1.00	-	-	-	Binding & XRD
	0.40	1.00	-	-	-	
	0.50	1.00	-	-	-	
	0.60	1.00	-	-	-	
Mortar	0.40	1.00	-	-	2.45	Corrosion
	0.40	0.70	0.30	-	2.45	
	0.40	0.40	-	0.60	2.45	

Table 2 Oxide composition of binders.

	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	Mn ₂ O ₃	TiO ₃	SO ₃
OPC	64.7	20.7	4.6	3.0	1.0	0.13	0.65	-	-	3.0
PFA	17.0	48.7	18.8	7.7	1.0	0.4	1.9	-	0.9	0.64
GGBS	41.2	34.2	11.7	1.43	8.81	0.29	0.31	0.3	0.58	-

Fig. 1 Experimental set-up for measuring the corrosion rate of steel in mortar.

setup for measuring the corrosion rate is given in **Fig. 1**. To maintain equal conditions for the cathodic reaction on the steel surface, the top of each specimen was exposed to the same atmospheric condition for the supply of oxygen, while the rest of the specimen was immersed in 0.5M NaCl electrolyte solution to form an electro-chemical circuit. The potential was set +25 mV above the corrosion potential and then applied at 0.1 mV/s. The IR drop was automatically compensated by using the interruption technique. Once the polarisation resistance was obtained, the corrosion rate was calculated by Ohm's law, as given in Eq. (1).

$$I_{corr} = \frac{B}{R_p} \quad (1)$$

where I_{corr} is the corrosion rate calculated by the polarization technique, R_p the polarization resistance and B the corrosion potential as a constant of 26 mV for the active state. To avoid biased information, four replications were tested and the average value was used in determining the corrosion behaviour.

3. Results

3.1 Chloride binding capacity

The concentration of chloride ions measured in ppm from the extraction water was converted into a percentage relative to the weight of binder. The subtraction of the concentration of water-soluble (free) chloride ion from the total was taken as the concentration of bound chloride. **Figure 2** gives the chloride binding capacity as a function of curing age, W/C and binder type. It is evident that an increase in the curing age resulted in an

(a)

(b)

(c)

Fig. 2 Chloride binding capacity with (a) curing age, (b) W/C and (c) binder type.

Fig. 3 Isotherms between free and bound chlorides with fitted equations depending on (a) curing age, (b) W/C and (c) binder type.

increase in the binding capacity, at 0.4 W/C, except at 0.5% total chlorides, at which level most chlorides seemed to be bound irrespective of curing. At 1.0% total chlorides and beyond, the effect of the curing age became clear. The chloride binding capacity was much influenced by the W/C after 150 days of curing: an increase in the W/C resulted in a decrease in the binding capacity, presumably due to the different level of hydration products related with chloride binding. At 0.4 W/C, the influence of binder type on chloride binding is evident. At 0.5 W/C and 1.0% total chloride, there was only a marginal difference in chloride binding with binder type. However, at 2.0 and 3.0% of chlorides, 65% GGBS paste showed the highest level of chloride binding, followed by 30% PFA and OPC paste. It seems that a higher binding of 65% GGBS and 30% PFA may arise from the high level of Al_2O_3 in binder, which subsequently is formed in C_3A and C_4AF to bind chloride ions. To render the chloride binding, the Langmuir isotherm was used in the form of the relation between free and bound chlorides, as shown in Eq. (2).

$$C_{bound} = \frac{\alpha C_{free}}{1 + \beta C_{free}} \quad (2)$$

where C_{bound} is the concentration of bound chloride, C_{free} is the concentration of free chloride, and α and β are constants, respectively. Figure 3 gives the binding isotherms as a function of curing age, W/C and binder type. As the binding capacity is dependent on those factors at a given total chloride concentration, the range of free and bound chloride concentrations is different. It is evident that free chlorides at lower total chloride are mostly bound, irrespective of binder type and W/C. The characteristic of binding isotherm was clearly seen at free chlorides beyond 0.5-1.0%: a low W/C, longer curing age and pozzolanic materials have benefits in terms of raising the chloride binding capacity.

3.2 Bound chlorides in XRD analysis

The XRD curve for paste samples containing 3.0% chlorides by weight of binder is given in Fig. 4. The peak intensity and location can be seen to be strongly

Fig. 4 XRD curves for cement pastes with (a) W/C and (b) binder type.

dependent on binder type and W/C, implying that the formation of hydration products occurred differently. For example, an increase in the W/C resulted in a decrease in the peak intensity at all degrees although the locations of the peaks were mostly identical due to the use of the same binder in the paste samples (i.e. OPC). This may suggest that the XRD analysis would provide semi-quantitative information on hydration, as long as an identical setup of the XRD analysis is applied. A different binder in the paste sample produced different XRD curves. For the OPC paste in the XRD curve, portlandite and calcite were mainly observed, while quartz and gypsum were often seen in 30% PFA and 65% GGBS pastes, respectively. Notwithstanding, the peak for Friedel's salt was commonly observed in all the XRD curves, due to chloride binding in the cement matrix.

3.3 Corrosion behaviour

The corrosion rate measured by the anodic polarisation technique after 20 cycles was depicted in Fig. 5. It is evident that the corrosion rate of steel rebar is dependent on the binder type, W/C and chloride concentration admixed in mortar. Regarding the variation in W/C, the corrosion rate was not much influenced at 0.5% chlorides, but at 1.0% chlorides and beyond, an increase in the W/C resulted in a sharp increase in the corrosion rate at a given chloride concentration. However, the corrosion rate at 0.6 W/C was always higher than for

other W/Cs, and thus the corrosion rate at 3.0% of chlorides was out of range of the measurement. The higher corrosion rate at 0.6 W/C could be attributed to the higher oxygen supply to the steel, which may accelerate corrosion. However, as all specimens in this study were exposed to the same atmospheric condition to supply an identical concentration of oxygen, variations in oxygen level should not be a factor influencing the corrosion behaviour. The high corrosion rate at 0.6 W/C may be more attributable to the cement content. The lower cement content results in lower binding capacity, meaning a higher concentration of free chloride (i.e. higher risk of corrosion). Moreover, the amount of hydration products is strongly dependent on cement content. Consequently, higher W/C would lose the higher risk of corrosion, leading to the higher corrosion rate, as long as the same corrosion conditions, including chloride, water and oxygen, are maintained.

Binder type is crucial to the corrosion behaviour as well. At lower chloride levels such as 0.5 and 1.0% chlorides, 30% PFA and 65% GGBS mortars produced a higher corrosion rate than OPC. However, when the chloride concentration in mortar exceeds 2.0%, OPC showed the highest corrosion rate. This may be attributed to the inhibitive nature and pore structure of binder. As 30% PFA and 65% GGBS mortars did not produce as much precipitated $\text{Ca}(\text{OH})_2$, which inhibits the fall in pH that accompanies pit nucleation, the resistance of pozzolanic materials to the onset of corrosion may be

Fig. 5 Corrosion rate for steel in mortar measured by the polarisation technique after 20 wet/dry cycles depending on (a) W/C and (b) binder type.

lower than Portland cement. Although their greater binding capacity cripples free chlorides in the cement matrix, most bound chlorides are released at the stage of corrosion initiation, due to a fall in pH in the vicinity of the steel (Song *et al.* 2010). However, after corrosion initiation, the dense pore structure of 30% PFA and 65% GGBS mortars may restrict water and oxygen supply to the steel. Moreover, the higher binding capacity would mitigate further progress of the corrosion reaction on the steel surface.

4. Discussion

4.1 Evaluation of chloride binding

As bound and free chlorides are simultaneously present in the pore solution or in the cement matrix, it is very difficult to separately measure the concentration of chloride ions. Thus, the total chloride concentration has been the preferred measurement parameter for assessing the risk of chloride-induced corrosion. Apart from the bound chlorides, there have been two ways to measure the free chloride concentration: water extraction and the pore press method. The pore press method, which involves extracting the pore solution from the cement paste under high pressure, is more accurate than the water extraction method (Tritthart 1989). However, with this method, bound chlorides may be freed so that the free chloride concentration can be overestimated (Glass *et al.* 1996; Byfors *et al.* 1986). Moreover, the pore press method is only applicable to bulk concrete, which largely precludes profiling of chloride ingress as a function of depth. Thus, it may be said that the free chloride concentration can be measured from a solution obtained by boiling the extracted dust concrete/mortar sample in water (ASTM C 1218). The concentration of chloride can be determined using potentiometry or a chloride ion sensitive electrode. Free chloride measured by water extraction is dependent on the fineness of the pulverised

sample, amount of added water, temperature, agitation method and time allowed for extraction (Arya and Newman 1990). To obtain a profile for bound chlorides in cover concrete, the total chloride (i.e. acid soluble chloride) must be simultaneously measured, when the water extraction method is used to determine free chloride: thus, double measurement of chloride concentration is called for.

In the present study, peaks for the bound chlorides at every level of total chloride were observed in the XRD analysis as expected. Simultaneously, binding isotherms to an equivalent total chloride concentration were derived from the water extraction method. Consequently, it was found that an increase in the bound chloride in the cement matrix resulted in an increase in the peak intensity for Friedel's salt in the XRD analysis, as shown in Fig. 6, where the peak intensity can be seen to sharply increase at about 11.18°, which is attributed to Friedel's salt, depending on the concentration of bound chloride. Thus, all information on the bound chloride concentration vs. the peak intensity for Friedel's salt in the XRD curve was used to determine their relation, as shown in Fig. 7. The binding capacity of chloride ions is strongly dependent on the W/C, binder and total chloride concentration, as already shown in Figs. 2 and 3. Thus, variation in the bound chloride concentration could be produced in this study, and powder samples of the specimens were again used for XRD analysis to quantify the peak intensity for Friedel's salt. It is evident that an increase in the concentration of bound chlorides in the cement matrix resulted in an increase in the peak intensity for Friedel's salt in the XRD curve, irrespective of the W/C, binder and total chlorides.

The above may suggest that XRD analysis of cement paste could be used to quantify the concentration of bound chloride, giving the inhibition effect of the cement matrix (Goni and Guerrero 2003). If a binding isotherm for the cement paste is, moreover, additionally

Fig. 6 High peak intensity for the Friedel's salt with different bound chloride concentration

Fig. 7 Relation between the concentration of bound chloride ions in cement matrix and the peak intensity for the Friedel's salt

provided or obtained, the free, bound and total chloride concentrations can be calculated in a depth of the cover concrete. For example, the concentration of bound chlorides in a cement paste can be calculated by the relation between the peak for Friedel's salt and bound chloride concentration, once XRD analysis of the cement paste is completed. Then, the free chloride concentration can again be calculated by the binding isotherm, and subsequently the free, bound and total chloride concentrations in a concrete cover are calculated. Information on the concentration of bound chloride may be used to evaluate the inhibition effect of hydration products in the cement matrix and to predict the onset of corrosion or/and rate of corrosion propagation, if corrosion has already begun,

as the chloride binding capacity is strongly associated with the corrosion process. Another benefit of XRD analysis for bound chloride concentration is its in-situ feasibility. As mentioned above, the procedure for measuring the bound chloride concentration is extremely complex, consisting of water/acid extraction from the paste sample to measure the free chloride concentration, and measurement of the total chloride. However, if the relation between the bound chloride concentration and peak intensity for the Friedel's salt is clearly determined, XRD analysis provides an easier and more time efficient way to measure the bound chloride concentration after obtanment of the concrete dust sample,. Notwithstanding, the XRD technique shows limitations in quantifying the bound chloride concentration. As the peak intensity in an XRD curve is dependent on the sample weight, diffraction angle and range of angle, identical setup for the analysis must be maintained to avoid the influence of these variables in the measurement procedure. Otherwise, the XRD analysis would give only information on whether or not bound chlorides exist.

4.2 Role of bound chlorides at corrosion

Chloride binding may be a key factor in assessing the risk of chloride-induced corrosion of steel in concrete, owing to its impact on the corrosion process and chloride transport. Chloride binding can be defined as the removal of chloride ions from the pore solution by a chemical reaction of hydration products with free chloride ions and by the physical adsorption of precipitated $\text{Ca}(\text{OH})_2$. Thus, bound chloride has been thought to be of marginal influence on the corrosion process, whereas free chlorides are strongly associated with corrosion activity. In fact, the role of bound chloride in the corrosion process is dependent on the stage of corrosion (corrosion initiation and propagation) (Glass *et al.* 2000). At the stage of corrosion initiation, a fall in pH of the pore solution in the vicinity of the steel accompanies pit nucleation, due to an electrochemical reaction on the steel surface that releases hydrogen ions. Thus, bound chlorides are usually released into free chlorides, which implies that both free and bound chlorides will participate in the corrosion process. However, further propagation of corrosion is dependent on the residue of free chlorides, as chloride ions are not consumed in the corrosion initiation, being the catalyst (Page *et al.* 1986). This suggests that the higher binding capacity, the greater the inhibitive effect against corrosion propagation once corrosion starts.

The present study confirmed that the corrosion propagation is much influenced by the binding capacity, as given in Fig. 8. The influence of binding capacity on the corrosion rate was found to be dependent on whether or not corrosion has started. The corrosion rate often exceeds $1.0\text{--}2.0\text{ mA/m}^2$ (Alonso *et al.* 2002), at which the chloride concentration at the depth of the steel accounts for 0.5-1.0% by weight of binder. When it

Fig. 8 Corrosion with the binding capacity depending on (a) W/C and (b) binder type.

comes to the corrosion rate in the passive state or at corrosion initiation (i.e. the chlorides admixed are below 1.0%), the binding capacity has a marginal impact on the corrosion rate. In fact, there was no relation between the binding capacity and corrosion rate. However, after corrosion initiation, it is clear that an increase in the binding capacity resulted in a decrease in the corrosion rate. This suggests that higher binding may lower the propagation of corrosion, owing to a reduction of further participation of free chloride ions in the corrosion process.

Binding capacity is crucial to the buildup of chloride ions on the surface of cover concrete. The concentration of free chlorides on the surface of concrete, when the concrete is exposed to a chloride environment (e.g. marine environment or where deicer is used), is mostly equated (Ann *et al.* 2007). Thus, an increase in the bind-

ing capacity would result in an increase in the total chlorides. A recent study showed that the binding capacity in terms of the C_3A content influences the surface chloride concentration: the higher the level of C_3A content, the higher the concentration of surface chlorides. Substantially, an increase in the surface chloride may allow the progressive buildup of higher total chloride content, leading to a higher gradient of chloride concentration (Glass and Buenfeld 1997). Thus, the ingress of chlorides in inner concrete can be significantly increased at the higher binding capacity. However, chloride binding reduces the concentration of free chlorides within concrete and the concentration gradient at depth, as binding removes chloride from the transport process. Binding of chloride ions may not directly convert the pore structure and chemical composition of the pore solution. As variation in the binding capacity arises from different oxide compositions of cement and hydration products, the pore solution/structure can be varied with the binding capacity. Thus, chloride transport presents a high degree of complexity in relation to chloride binding.

5. Conclusions

In the present study, the factors for chloride binding, its influence on the corrosion behaviour and a semi-quantitative method of measuring the bound chloride concentration were investigated. The conclusions from the experimental study are as follows:

- (1) The chloride binding capacity was dependent on the W/C, curing age and binder type. An increase in the curing age and a decrease in the W/C resulted in an increase in the binding capacity. Also, pozzolanic materials (i.e. 30% PFA and 65% GGBS) were of benefit in raising chloride binding.
- (2) Chloride binding had no impact on the corrosion rate in the passive state of steel and at the stage of corrosion initiation, presumably because bound chlorides are mostly released into free chlorides in the process of electrochemical reaction on the steel surface, accompanying a fall in the pH of the pore solution. However, after the onset of corrosion, an increase in the binding capacity resulted in a decrease in the corrosion rate, arising from a reduction of free chlorides in the vicinity of the steel.
- (3) There was a strong relation between the peak intensity for Friedel's salt (i.e. bound chloride) and the concentration of bound chloride in the cement paste: an increase in the concentration of bound chloride resulted in an increase in the peak intensity, irrespective of binder type, W/C and curing age. Thus, this information can be used to determine the concentration of bound chloride using XRD analysis of Friedel's salt.

Acknowledgement

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technol-

ogy Evaluation and Planning (KETEP) grant funded by the Ministry of Knowledge Economy of Korea (Grant No. 2010161010007C).

References

- Alonso, C., Castellote, M. and Andrade, C., (2002). "Chloride threshold dependence of pitting potential of reinforcements." *Electrochimica Acta*, 47(21), 3469-3481.
- Ann, K. Y., (2005). "Enhancing the chloride threshold level for steel corrosion in concrete." Thesis (PhD). Imperial College, London.
- Ann, K. Y., Song, H. W., Lee, C. H. and Jung, M. S., (2007). "Chloride binding capacity of cementitious materials and its influence on concrete structures." Concrete under Severe Conditions: Environments and Loading (CONSEC'07), In: Proceedings of the 5th International Conference on Concrete under Severe Conditions: Environment and Loading, 4-6 June 2007, Tours, France, 351-360.
- Arya, C., Buenfeld, N. R. and Newman, J. B., (1990). "Factors influencing chloride binding in concrete." *Cement and Concrete Research*, 20(2), 291-300.
- Arya, C., Buenfeld, N. R. and Newman, J. B., (1987). "Assessment of simple methods of determining the free chloride ion content of cement paste." *Cement and Concrete Research*, 17(6), 907-918.
- Arya, C. and Newman, J. B., (1990). "An assessment of four methods of determining the free chloride content of concrete." *Materials and Structures*, 23(5), 319-330.
- ASTM C 1218, (1999). "Standard test method for water-soluble chloride in mortar and concrete."
- Byfors, K., Hansson, C. M. and Tritthart, J., (1986). "Pore solution expression as a method to determine the influence of mineral additives on chloride binding." *Cement and Concrete Research*, 16(5), 760-770.
- Glass, G. K. and Buenfeld, N. R., (2000). "The influence of chloride binding on the chloride induced corrosion risk in reinforced concrete." *Corrosion Science*, 42(2), 329-344.
- Glass, G. K., Wang, Y. and Buenfeld, N. R., (1996). "An investigation of experimental methods used to determine free and total chloride contents." *Cement Concrete Research*, 26(9), 1443-1449.
- Glass, G. K., Reddy, B. and Buenfeld, N. R., (2000). "The participation of bound chloride in passive film breakdown on steel in concrete." *Corrosion Science*, 42(11), 2013-2021.
- Glass, G. K. and Buenfeld, N. R., (1997). "The presentation of the chloride threshold level for corrosion of steel in concrete." *Corrosion Science*, 39(5), 1001-1013.
- Goñi, S. and Guerrero, A., (2003). "Accelerated carbonation of Friedel's salt in calcium aluminate cement paste." *Cement and Concrete Research*, 33(1), 21-26.
- Hope, B. B., Page, J. A., and Poland, J. S., (1985). "The determination of chloride content of concrete." *Cement and Concrete Research*, 15(5), 863-870.
- Page, C. L., Short, N. R. and Holden, W. R., (1986). "The influence of different cements on chloride induced corrosion of reinforcing steel." *Cement and Concrete Research*, 16(1), 79-86.
- Song, H. W., Jung, M. S., Lee, C. H., Kim, S.-H. and Ann, K. Y., (2008). "Influence of chemistry of chloride ions in cement matrix on corrosion of steel." *ACI Materials Journal*, 107(4), 332-339.
- Song, H. W., Lee, C. H., Jung, M. S. and Ann, K. Y., (2008). "Development of chloride binding capacity in cement pastes and influence of the pH of hydration products." *Canadian Journal of Civil Engineering*, 35(12), 1427-1434.
- Tritthart, J., (1989). "Chloride binding in cement, I. Investigation to determine the composition of porewater in hardened cement." *Cement Concrete Research*, 19(4), 586-594.