

- Technical paper -

CORROSION OF REINFORCING STEEL IN GGBS CONCRETE DUE TO CYCLIC EXPOSURE OF CHLORIDE AND CARBONATION

Pakawat SANCHAROEN*¹ and Taketo UOMOTO*²

ABSTRACT: Better chloride resistance; however, worse carbonation resistance of GGBS concrete compared to that of OPC concrete are well known. Also there is a possibility that RC structure is exposed to both chloride and carbonation. So objective of this research is to study corrosion of steel in GGBS concrete under cyclic exposure to carbonation and chloride. GGBS concretes were mixed with different replacement ratios. Specimens, individually or cyclically exposed to chloride and carbon dioxide, were measured corrosion by half-cell potential. Results show that corrosion was accelerated by NaCl-CO₂ cycle but retarded by water-CO₂ cycle.

KEYWORDS: corrosion, reinforcing steel, slag, chloride, carbonation, half-cell potential, cyclic exposure

1. INTRODUCTION

Corrosion of reinforcing steel in concrete structure is one of the most significant factors deteriorating reinforced concrete structure. Normally, the high alkalinity of cement hydration product prevents the reinforcing steel from corrosion by providing passivating ferric oxide film around the steel. This film protects steel from moisture and oxygen that causes corrosion. However, the alkalinity of concrete can be affected by presence of aggressive agents such as carbon dioxide and sulphur dioxide permeating into concrete. Both of them react with alkali hydroxides, forming other compounds such as carbonates or sulphates, and thus reduce the alkalinity. The passivating film is usually destroyed, if the reduction zone of alkalinity spreads through the depth of steel. Nevertheless, if chloride ions exist in the vicinity of the steel, the passivating film can be locally destroyed even though the surrounding concrete is still high in alkalinity and, therefore, corrosion is also possible. Once corrosion occurs, formed rust swell up to 600% of the volume of the steel from which it is formed. Pressure caused by this volume change is then generated inside the concrete structure then results in cracking and spalling of concrete.

There are a number of electrochemical techniques for measuring the severity of rebar corrosion, each with certain advantages and limitations. Half-cell potential measurement is one of the simplest methods to assess state of steel corrosion. ASTM C876 and JSCE-E 601 provide standard test method for half-cell potential measurement of uncoated rebar in concrete structure. Guideline for interpreting measured half-cell potential value provided by ASTM C876 is shown in Table 1. However, there are many factors should be considered before interpreting results such as condition of cover concrete, or type of rebar. Uomoto[1] showed that measured half-cell potential values at concrete surface can be considered as actual value at steel surface, if cover

*1 Department of Civil Engineering, The University of Tokyo, Graduate student, Member of JCI

*2 Institute of Industrial Science, The University of Tokyo, D.Eng., Member of JCI

depth was within 20 mm. Gu and Beaudoin [2] reported that interpretation criteria of ASTM C876 is applicable for corrosion due to chloride and carbonation.

Utilization of ground granulated blast furnace slag (GGBS) as a constituent of concrete had began since 1892 in Germany; while GGBS is widely utilized as a separate cementitious material added at concrete mixer with Portland cement in Japan since 1950. In 2002, Japan used GGBS cement approximately 25% of the total quantity of produced cement. Main advantages of utilizing GGBS, are 1) to reduce the temperature rise due to hydration heat, 2) to suppress alkali-silica reaction, and 3) to improve chemical resistance to actions of sulfate and sea water as well as to improve workability, to reduce bleeding, and to increase strength [3,4]. The chemical resistance of GGBS concrete is mainly focused in this study. There are many researches concluded that chloride binding capacity of GGBS concrete increases with increasing GGBS replacement levels. This is mainly a result of high alumina content in GGBS leading to higher amounts of fixed chloride or Friedel's salt. As a result, amount of free chloride, which destroys passivating film, is reduced. However, lower amount of produced calcium hydroxide in GGBS concrete is suspected to accelerate carbonation process. Although, individual corrosion mechanisms of chloride ion and carbonation are widely conducted and well understood, there is a possibility that reinforced concrete structure will be simultaneously faced with both aggressive chloride and carbon dioxide environment, especially in case of coastal concrete structure. Therefore, the main objective of this study is to investigate corrosion of reinforcing steel in GGBS cement concrete structure due to combined effect of carbonation and chloride permeation

Table 1 Interpretation guideline according to ASTM C876

Half-cell Potential Value (mV)		Corrosion Activity
vs CuSO ₄	vs AgCl	
More than -200	More than -86	90% probability of no corrosion
Between -200 and -350	Between -86 and -236	An increasing probability of corrosion
Less than -350	Less than -236	90% probability of corrosion

2. EXPERIMENTS

2.1 MATERIALS

Ordinary Portland Cement (OPC) Type I was used in this study. GGBS, which is classified as slag4000, was used to replace OPC as replacement ratios of 0%, 45%, and 70%. Washed crushed limestone and natural river sand were used as aggregates. Water reducing and air entraining agent were also added to concrete to ensure its workability. Three concrete mix proportions are shown in Table 2 with slump values, air contents, and compressive strengths. Plain round steel bar with diameter of 10 mm was drilled and tapped at the middle of one end in order to be connected to lead wire. Steel's surface was then polished by sandpaper No.200 and degreased by acetone before being used.

Table 2 Mix proportions and properties of concrete

Mix No.	W/B, %	S/A, %	Replacement Ratio, %	Mixture Proportion, kg/m ³						Slump, cm	Air Content, %	Strength, ksc	
				W	C	GGBS	S	G	Admixtures			28 days	91 days
M00			0	160	291	0	826	1032			304	317	
M45	55	45	45	160	160	131	821	1026	(C+GGBS) * 2%	12±2	5.5±1	269	378
M70			70	160	87	204	818	1023			272	370	

2.2 PREPARATIONS OF SPECIMENS

As stated that concrete resistance has a little effect on measured half-cell potential values at the concrete surface, if the cover depth is less than 20 mm. Therefore, measured potential value at the concrete surface can be considered as potential value at steel surface. In the future, this value

will be used to calculate the corrosion amount by method described by Uomoto [1] can be related to actual corrosion amount after broken the specimens. Therefore, two steel bars with length of 400 mm, were placed at 20 mm and 10 mm from the top and bottom surface as shown in Figure 1, respectively. Size of specimen is 100×100×380 mm. Specimens were de-molded 24 hrs after casting and were cured afterward in 20°C water for 7 days and air-cured for other 7 days under controlled temperature at 20°C and 60% relative humidity. Lead wire was connected to drilled end of steel by connector and bolt. All surfaces, excepting the top and bottom surfaces that were left to be exposed surfaces, were coated with epoxy.

2.3 EXPOSURE CONDITIONS

Exposure conditions were started 3 weeks after casting of specimen. Three concentrations, which were 0%, 3%, and 7% by weight, of sodium chloride (NaCl) solution were used. Temperature of solution was controlled at 20°C. Also two concentrations, which were 0%, and 5%, of CO₂ were used. Conditions were controlled at 40°C and 50%RH. Specimens exposed to only CO₂ are named as AIR and C1, while ones exposed to only solution are named W, CL1, and CL2. Combinations of carbonation and solution, which are C1W, C1CL1, C1CL2, WC1, CL1C1, and CL2C1, represent cyclic exposure condition. Summary of all conditions is shown in Table 3. The details of 2 weeks-long exposure cycle is shown in Table 3.

Table 3 Exposure condition

Name	Duration in 1 cycle			
	Day 1 st -4 th	Day 5 th -7 th	Day 8 th -11 th	Day 12 th -14 th
Air	Air			
C1	CO ₂ 5%	Air		
W	NaCl 0%	Air		
CL1	NaCl 3%	Air		
CL2	NaCl 7%	Air		
C1W	CO ₂ 5%	NaCl 0%		Air
C1CL1	CO ₂ 5%	NaCl 3%		Air
C1CL2	CO ₂ 5%	NaCl 7%		Air
WC1	NaCl 0%	Air	CO ₂ 5%	
CL1C1	NaCl 3%	Air	CO ₂ 5%	
CL2C1	NaCl 7%	Air	CO ₂ 5%	

2.4 MEASUREMENTS

Half-cell potential measurement was conducted by using saturated silver-silver chloride (Ag-AgCl) reference electrode at the same locations on top and bottom surface of specimens. Measurements of half-cell potential were conducted every completed cycle for first 5 cycles, and every 2 completed cycles thereafter. Specimens were air-dried for 3 days before being measured in order to avoid effect of polarization phenomena, which is due to limited oxygen concentration around steel surface after being submerged [5]. Refer to Figure 1; the measurements were made at totally 16 points with 2-cm spacing.

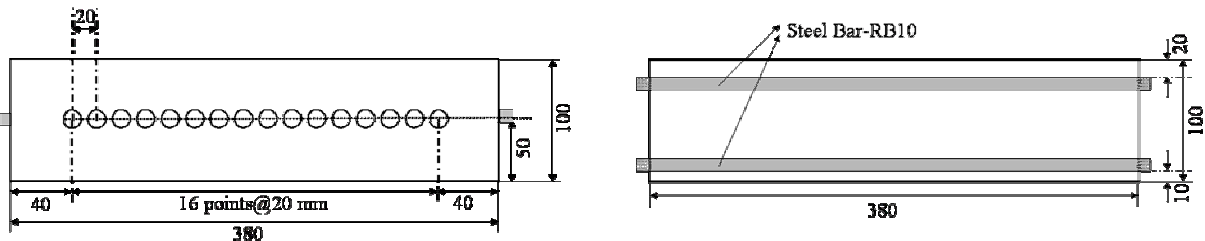


Figure 1 Locations of measurement and cross section of specimen

3. RESULTS AND DISCUSSIONS

3.1 MEASURED HALF-CELL POTENTIAL VALUE

In order to check the reliability between measured half-cell potential value and the actual state of steel corrosion, two of specimens were broken after they were exposed to air or carbonation. It revealed that half-cell potential values showed good correlation with condition of steel corrosion. When experiment was finished, all specimens will be broken and investigated condition of steel corrosion.

Figure 2 shows an example of obtained data from bottom steel cast in OPC concrete specimen cyclically exposed to 5%-CO₂ and 3%-NaCl solution (C1CL1) for 7 cycles. This example shows typical trend of obtained data at 16 different points along the reinforcing steel and different exposure period. As shown in the figure, values measured at the same exposure period were approximately identical among different locations because there is no introduced crack on specimen prior to exposure. This means that condition of steel corrosion at different measured location identically changed due to ingress of CO₂ and NaCl. Moreover, measured value increased as exposed time increased because of more advance ingress of CO₂ and NaCl.

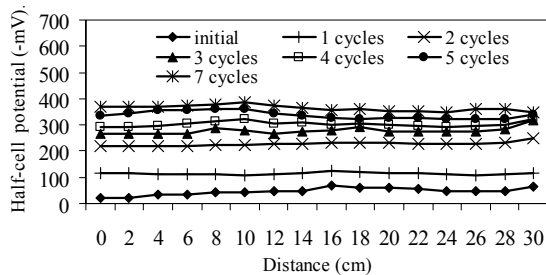


Figure 2 Results at different measured locations

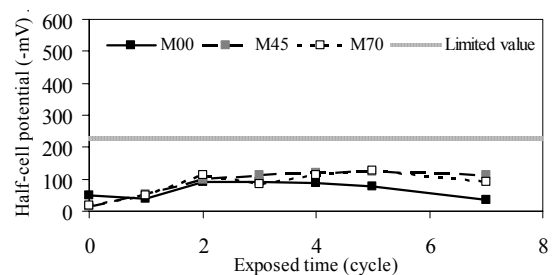


Figure 3 Average results - AIR

3.2 AVERAGE HALF-CELL POTENTIAL VALUE

Since measured values at different points are almost same, their average value is used to specify state of corrosion as shown in Table 1. However, only results of bottom steels, of which cover depth is 1 cm, are shown.

(1) Individual exposure

Firstly, results of specimens just exposed to normal environment (AIR) are shown in Figure 3. As all measured values were less than limited value (-236mV), it shows that all specimens were not corroded; even though, they were left for 7 cycles. On the contrary, figure 4 shows results of specimens individually exposed to 5%-CO₂ (C1). Results show that probability of steel corrosion was less than 90% in case of M00; although, they were exposed for 7 cycles. However, M45 and M70 exposed to the same condition had already shown more than 90% possibility of corrosion since the first cycle. This confirms that resistance of GGBS concrete is actually weak against carbonation. However, stabilizing the measured half-cell potential value of dried concrete, which was continuously placed in carbonation chamber, was quite difficult. Therefore, concrete was wetted before being measured at each cycle. Changing in pore structure of carbonated concrete but used same wetting method may cause decreasing of measured values at later ages.

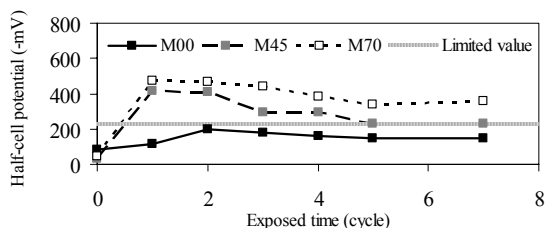


Figure 4 Average results - C1

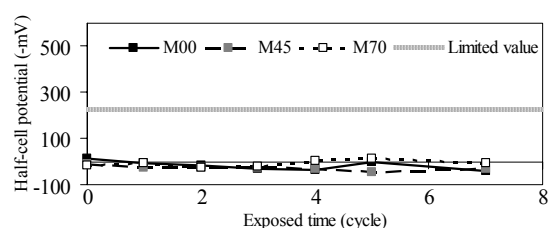


Figure 5 Average results - W

Figure 5, 6 and 7 show results of specimens only exposed to 0%-NaCl (W), 3%-NaCl (CL1) or 7%-NaCl (CL2) solution, respectively. As shown, results of specimens exposed to W did not exceed the limited value. Although results of specimens exposed to CL1 had not exceeded the limited value yet, their values continuously increased. Figure 7 shows that results of M00 and M70 exceeded limited value after exposing for 4 cycles and 5 cycles, respectively. By comparing Figure 5-7, it can be concluded that corrosion was accelerated by higher concentration of NaCl solution. Also better resistance against chloride of GGBS concrete was confirmed in Figure 7.

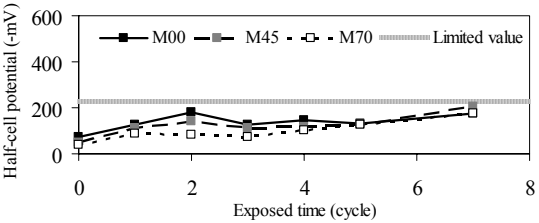


Figure 6 Average results – CL1

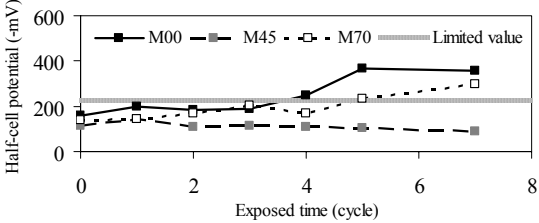


Figure 7 Average results – CL2

(2) Cyclic exposure

In this section, results of specimens cyclically exposed to both of solution and carbonation are shown. Figures on the left side show results of the specimens firstly exposed to solution before being exposed to CO₂, and results of the specimens initially exposed to solution and followed by exposed to CO₂ are shown on the right figure.

Figure 8 and 9 show results of specimens exposed to combination of 5%-CO₂ and 0%-NaCl solution (WC1 and C1W). Results show that only M45 and M70 were corroded after being exposed for a period of time. However, both figures show that cyclic exposure to CO₂ and water retarded corrosion process compared to individually exposing to CO₂ as shown in figure 4.

Figure 10 and 11 show results of specimens exposed to combination of 5%-CO₂ and 3%-NaCl solution (CL1C1 and C1CL1). As shown in the figures, all specimens showed high possibility of corrosion after 2 cycles.

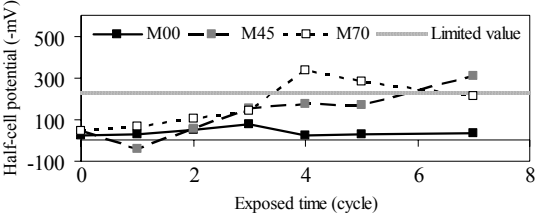


Figure 8 Average results – WC1

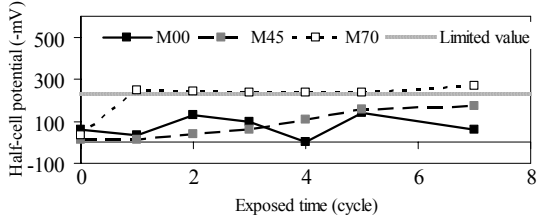


Figure 9 Average results – C1W

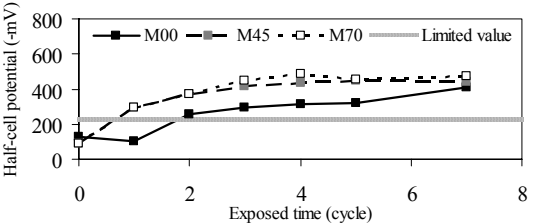


Figure 10 Average results – CL1C1

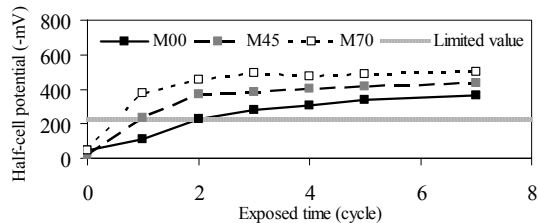


Figure 11 Average results – C1CL1

Figure 12 and 13 show results of specimens exposed to combination of 5%-CO₂ and 7%-NaCl solution (CL2C1 and C1CL2). As shown in the figures, all specimens showed high possibility of corrosion after passed the first cycle.

Effect of cyclic exposure between CO₂ and NaCl solution on steel corrosion can be seen by

comparing results of M00 in Figure 4, 6 and 7 with Figure 10 to 13. In case of Figure 4, 6 and 7, which are individual exposure conditions, results of M00 show low possibility of corrosion at least before the fourth cycle were completed. However, in case of cyclic exposure as shown in Figure 10 to 13, results of M00 exceeded the limited value since completion of the first or second cycle. This indicates that steel corrosion is accelerated by cyclic exposure of CO₂ and chloride. This result is opposite to results of cyclic exposure with water that retarded the corrosion as already discussed. However, effect of cyclic exposure cannot be seen in case of GGBS concrete due to their resistance against carbonation were really weak. As well as, effects of the sequence of exposure condition, that specimens were firstly exposed to, cannot be seen.

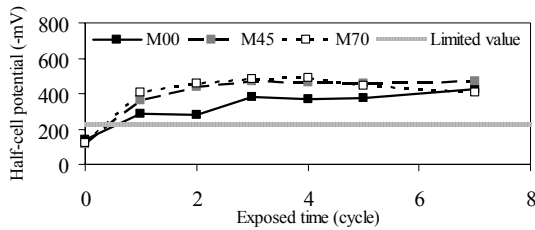


Figure 12 Average results – CL2C1

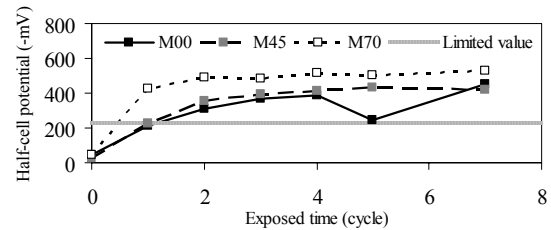


Figure 13 Average results – C1CL2

4. CONCLUSION

As shown in the results, resistance to corrosion of reinforcing steel due to chloride of GGBS concrete were better compared to OPC concrete. However, GGBS concrete showed very low resistance against corrosion of steel due to carbonation. Cyclic exposure between water and CO₂ improved resistance against steel corrosion even though in case of GGBS concrete. In contrast, cyclic exposure between NaCl solution and CO₂ accelerated corrosion of steel. Therefore, GGBS concrete structure simultaneously exposed with both of chloride and carbonation should be carefully considered their durability. However, as stated in the introduction that there are many factors affect measured half-cell potential value. Therefore, correlation between measured value and actual amount of steel corrosion should be further investigated.

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