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International Journal of Civil Engineering and Technology (IJCIET)
Volume 9, Issue 9, September 2018, pp. 1573–1581, Article ID: IJCIET_09_09_152
Available online at http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=9
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

CORROSION BEHAVIOR OF REINFORCING STEEL BAR EMBEDDED IN CONCRETE WITH NICKEL SLAG COARSE AGGREGATES

Ridwan Banda
Doctoral Student, Department of Civil Engineering
Hasanuddin University, Gowa, Indonesia

M. W. Tjaronge
Professor, Department of Civil Engineering
Hasanuddin University, Gowa, Indonesia

A. Rachman Djamaluddin
Associate Professor, Department of Civil Engineering
Hasanuddin University, Gowa, Indonesia

A. Bakri Muhiddin
Associate Professor, Department of Civil Engineering
Hasanuddin University, Gowa, Indonesia

ABSTRACT

The present paper aims to investigate the corrosion behavior of reinforcing steel bar embedded in concrete with nickel slag coarse aggregates. Natural coarse aggregates were replaced with 100% nickel slag with cement ratio (w/c) of 0.39 and cured in two conditions, namely, water curing (CA) and air curing (CU). An accelerated corrosion test was carried out on the cylindrical specimen of 100 mm in diameter and 200 mm in height for both curing conditions in 28 days. A constant 10 volt was applied to the specimens immersed in a 5% NaCl solution in order to accelerate the corrosion process of steel bar in concrete. The test results showed that concrete with nickel slag aggregate has good resistances against corrosion and influenced by curing condition. Corrosion resistance of 100 % slag cured in air (CU-100%) is three times higher than normal aggregate cured in air (CU-0%). While no significant differences are found in the specimens cured in water both CA-0% and CA-100%.

Key words: Corrosion, Nickel slag, Concrete and Coarse Aggregate

Cite this Article: Ridwan Banda, M.W. Tjaronge, A. Rachman Djamaluddin and A. Bakri Muhiddin, Corrosion Behavior of Reinforcing Steel Bar Embedded in Concrete with Nickel Slag Coarse Aggregates. *International Journal of Civil Engineering and Technology*, 9(9), 2018, pp. 1573-1581.
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1. INTRODUCTION

Corrosion of steel bar is one of the most deterioration factors in reinforced concrete structures especially in marine environments. Corrosion of steel bar in concrete is influenced by concrete strength, cover depth and humidity. Slag material has improved a good corrosion resistance in concrete [1 - 6]. Slag is by-product from metal processing industry and has impact to the environment after long-term dumped in the stockpile. Nickel production generated about 50 ton slag nickel for each one ton nickel production and disposed in landfill which, adversely affected the environment. Many attempts have been carried out to utilize the slag material in concrete. For instance, Akiyama & Yamamoto [7] studied the concrete containing ferronickel slag as fine aggregate and found that compressive strength slightly lower than normal concrete at the age six months with same w/c ratio. However, after six months the compressive strength is similar to the concrete using river sand as fine aggregate. Sugiri [8] investigated the effect of replacement coarse aggregates with slag in high strength concrete and concluded that strength properties of concrete improved compared to concrete without slag at 3, 7, 14, 28, 56 and 90 days. Similar results have been reported [9, 10].

The corrosion process of steel bar is divided by in two phases, namely phase before cracking and after cracking. Yuan et al. [11] divided phase before cracking in two categories, i.e. descending phase (TP2) and steady phase (TP3). On the other hand, phase after cracking classified into ascending phase (TP4) and steady phase (TP5) as shown Figure 1. Zhao et al. [12] explained the crack mechanism in reinforced concrete in three conditions, namely before crack stage, surface crack stage and after crack stage.

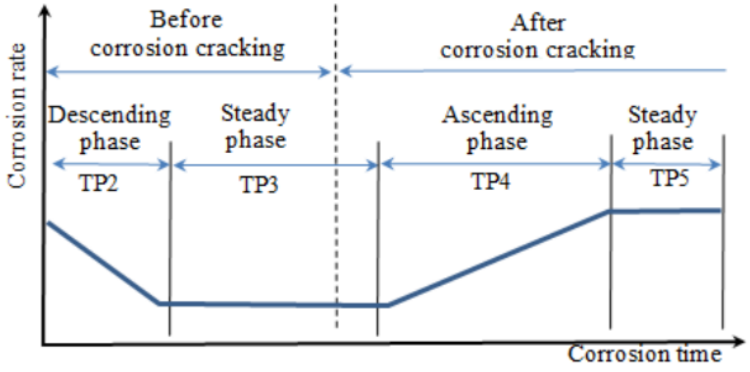


Figure 1 Proposed model of corrosion process of steel bar in concretes [11]

Based on literature review above most researched focus on replacement of slag aggregates on the strength properties of concrete. However, there are no studies relate to the corrosion behavior of steel bar in concrete containing nickel slag aggregate. Therefore, this study aims to investigate the corrosion behavior of reinforcing steel bar embedded in concrete with 100% nickel slag coarse aggregates.

2. EXPERIMENTAL PROCEDURES

2.1. Specimens Preparation

Portland Composite Cement (PCC) with a specific gravity of 3.08 was used. The PCC equivalent with CEM Type II/A-M cement contains 80% clinker and 20% mineral admixture [13,14]. River sand and crushed stone having a specific gravity of 2.47 and 2.63 was used.

Nickel slag aggregates from PT. Vale Indonesia Tbk, Sorowako, East Luwu, South Sulawesi was used. The slag material taken from open air dumping and then processed through mechanical screen method to obtained nickel slag coarse aggregates. The maximum size of nickel coarse aggregate passing through sieve number, 40 mm was used as shown in Figure 2. The physical properties material and chemical compounds of the PCC are presented Table 1 and Table 2, respectively.

Figure 2 Nickel slag coarse aggregates after processing

Tabel 1 Physical and engineering properties

Physical properties	**Cement (PCC)**	**Sand**	**Coarse aggregates**	
			Natural gravel	**Nickel slag**
Specific gravity				
SSD	-	2.52	2.70	3.25
Bulk	3.08	2.47	2.63	3.21
Apparent	-	2.82	2.82	3.34
Bulk density (kg/litre)	1.10	2.52	2.70	3.25
Water content	-	2.45	1.67	0.11
Absorption rate	-	1.83	2.56	1.19
Fineness modulus	-	2.61	8.10	7.83

Table 2 Chemical composition of material (%)

	SiO_2	**Fe_2O_3**	**MgO**	**Al_2O_3**	**CaO**	**SO_3**
Cement (PCC)	18.39	3.41	0.99	5.15	61.79	0.88
Nickel Slag	46.73	21.73	22.84	3.93	0.88	-

All specimens were manufactured with constant w/c of 0.39 and natural coarse aggregate was replaced by 100% of nickel coarse aggregates. Details of mix proportion of concrete are described in Table 3. Specimens were cured in two conditions, namely water curing (CA) and air curing (CU) until 28 days.

Table 3 Mixture proportion of concrete

Mixture	Curing	w/c	Cement (kg)	Water (kg)	Sand (kg)	Crushed stone (kg)	Nickel slag (kg)
CA 0%	Water	0.39	513	205	639	990	0
CU 0%	Air	0.39	513	205	639	990	0
CA 100%	Water	0.39	513	205	639	0	1191
CU 100%	Air	0.39	513	205	639	0	1191

2.2. Testing Methods

Slump and density of fresh concrete were determined according ASTM C143 [15] and ASTM C642 [16], respectively. Compressive strength and modulus elasticity of concrete was carried out based on ASTM C39 [17] and ASTM 469-94 [18], respectively, in cylindrical specimen of ∅100 x 200 mm. An accelerated corrosion test was carried out with constant voltage between the steel bar (anode) and stainless plate (cathode). Concrete cylindrical specimen of ∅100 x 200 mm having 16 mm in diameter and 160 mm in length centrally located on the specimen are used to study the corrosion of steel bar. Concrete specimens were partially immersed in 5% NaCl solution and current pass between anode and cathode were measured regularly once a day until 384 hours. The schematic accelerated corrosion test setup is presented in Figure 3. The sample steel bar is connected to constant a 10 volt DC power supply. The negative terminal of DC power is connected to stainless plate and positive terminal is connected to negative terminal. The corrosion weight loss was calculated according equation (1) [19].

$$M_{th} = \frac{W \; x \; I_{corr} \; x \; T}{F} \qquad (1)$$

Where:

M_{th} : Corrosion loss (%)
W : Atomic steel bar/iron (27.925 g)
I_{corr} : Corrosion current (Ampere/cm^2);
T : Duration of applied current (s)
F : Faraday's constant (96,487)

Figure 3 Corrosion acceleration setup in the laboratory

3. RESULTS AND DISCUSSION

3.1. Slump Value

The slump value of concrete is presented in Table 4. It is observed the slump value of concrete with 100% nickel slag is lower compared to natural aggregate. The slump values were 6.5 cm and 3.5 cm for natural aggregates and nickel slag aggregates, respectively. Decreasing in slump value of nickel slag aggregates due to lower absorption rate compared to natural aggregates. Thus, decrease the bond between phases and the aggregate and caused bleeding.

Table 4 The slump value of fresh concrete

Slag percentage	Slump (cm)	Remarks
0%	6.5	No bleeding
100%	3.5	Bleeding

Table 5 Fresh and hardened density of concretes

Nickel slag	ID	Vol. (m^3)	Weight (kg)		Density (kg/m^3)	
			Fresh concrete	Hardened concrete	Fresh concrete	Hardened concrete
		(a)	(b)	(c)	(d)=(b)/(a)	(e)=(c)/(a)
0%	1	0.00157	3.585	3.560	2282.28	2266.36
	2	0.00157	3.530	3.440	2247.26	2189.97
	3	0.00157	3.505	3.395	2231.35	2161.32
	Averages		3.540	3.465	2253.63	2205.88
100%	1	0.00157	4.030	3.975	2565.57	2530.56
	2	0.00157	3.985	3.935	2536.93	2505.09
	3	0.00157	3.970	3.950	2527.38	2514.64
	Averages		3.995	3.953	2543.29	2516.76

3.2. Density

Table 5 shows the fresh and hardened density of concrete. It is found that both fresh and hardened density of nickel slag concrete is higher than normal concrete. Fresh and hardened density of nickel slag concrete is greater about 12.85% and 14.69%, respectively than normal concrete. This is due to the density of the slag aggregates is higher compared to natural aggregates.

3.3. Compressive Strength

The results of compressive strength of concrete are presented in Table 6. It is observed that the compressive strength of concrete with CA is higher than CU for both with and without nickel slag aggregates. This is can be attributed to the lack of the development of hydration reaction to produce a denser microstructure in CU. Compressive strength of nickel slag concrete were 24.36 and 22.48 MPa, respectively, while normal concrete were 25.82 and 22.02 MPa, respectively. The compressive strength of nickel slag concrete in CU slightly increases compared to normal concrete. While in CA the compressive strength of nickel slag concrete, slightly decreases than normal concrete. It can be concluded that the slag concrete influenced by curing condition.

Table 6 Compressive strength value

Specimen	Curing	Slag (%)	Compressive strength (MPa)
CA-0%	Water	0	25.82
CA-100%	Water	100	24.36
CU-0%	Air	0	22.02
CU-100%	Air	100	23.48

3.4. Accelerated Corrosion Test

3.4.1. Effect of Water Curing

Effect of water curing (CA) on the corrosion of steel bar with and without slag aggregate are shown in Figure 4 and Figure 5. It is observed that the phase before cracking is occurring after 108 h, 168 h for TP2, TP3 respectively in the specimen with natural aggregate (CA-0%). For CA-100%, TP2 and TP3 were achieved after 160 h and 200 h, respectively. It can be said that replacement of slag aggregate instead natural aggregate improves the corrosion resistances of steel bar during initiation corrosion. On the view point of phase after cracking, it is found that corrosion progress of steel bar is same for TP4 and TP5. It is due to the presence of crack could lead chloride penetrate easily into the specimens [20]. In addition, the average corrosion times required to crack the CA-0% and CA-100% were 160 h and 180 h, respectively, indicating the superior corrosion resistances of slag aggregates compare to natural aggregates in water curing.

3.4.2. Effect of Air Curing

Figure 6 and Figure 7 are presented the effect of air curing (CU) on the corrosion of steel bar with and without slag aggregate. It is found that the phase before cracking is reached after 20 h, 40 h for TP2, TP3 respectively in the specimen with natural aggregate (CU-0%). For CU-100%, TP2 and TP3 were achieved after 40 h and 150 h, respectively. It can be said that replacement of slag aggregate instead natural aggregate increase the corrosion resistances of steel bar about two times for TP2 and four times for TP3 during initiation corrosion. Furthermore, increasing in the corrosion current is observed after cracking in the specimen CU-100%, while the CU-0% the corrosion relative stable. It indicates that slag aggregate oxidized due to the presence chloride ion in concrete, thus increases the corrosion current. The slag aggregate contained high ferrous oxide, which easily reacts with chloride ions.

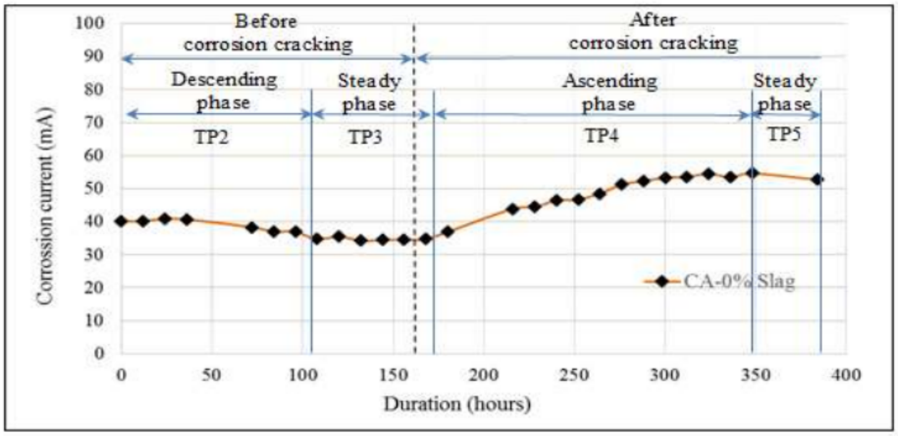


Figure 4 Corrosion current on the specimen CA-0%

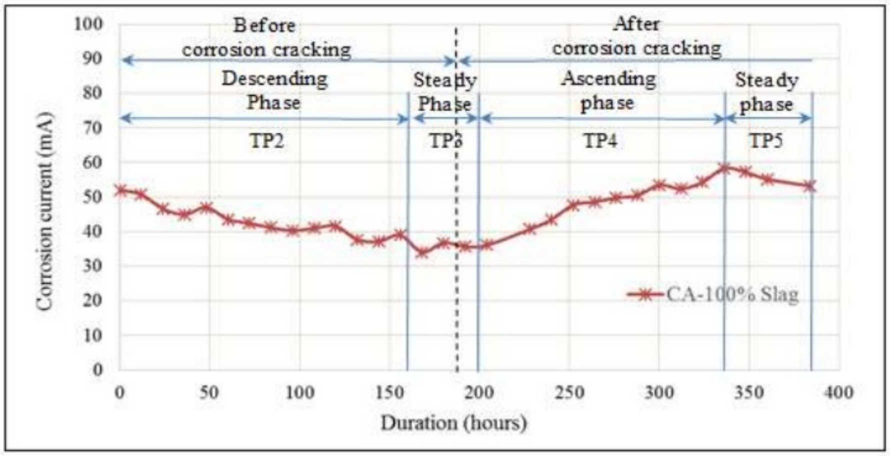


Figure 5 Corrosion current on the specimen CA-100%

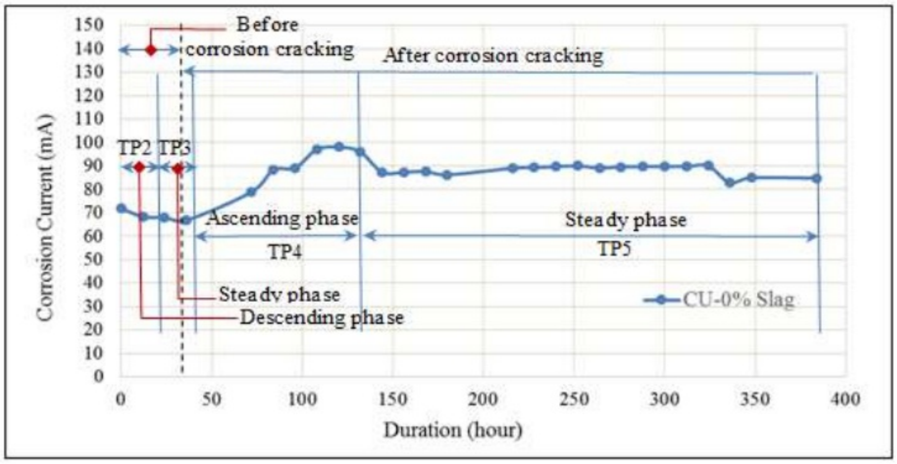


Figure 6 Corrosion current on the specimen CU-0%

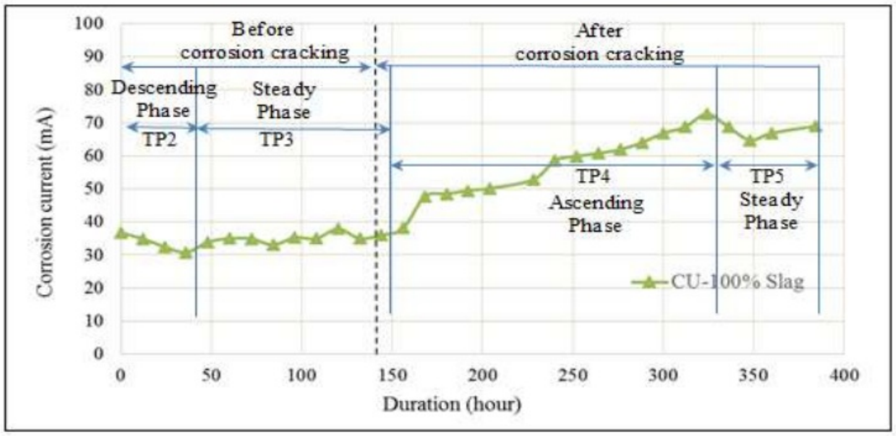
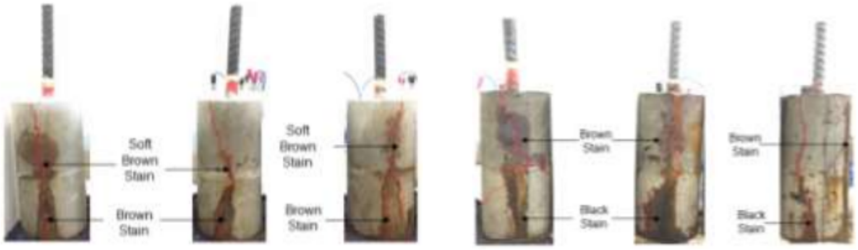


Figure 7 Corrosion current on the specimen CU-100%

3.4.3. Crack Pattern

Figure 8 shows the crack pattern of the specimen with slag aggregate after accelerating corrosion. It is clearly seen that the more severe corrosion condition occurred in the CU compared to CA. The brown stain corrosion product is found in CA, while in CU is black stain. The brown stain indicate that the passivity film of steel bar already damaged and the black stain exhibit the core of steel bar damaged. It can be concluded that corrosion of steel bar in slag concrete significantly affected by the environmental condition.



(a) (b)

Figure 8 Crack pattern after accelerated corrosion (a) CA-100% and (b) CU-100%.

4. CONCLUSIONS

The following conclusion can be drawn from this investigation:

- The use of coarse slag aggregate as in concrete decreased slump and increased density of concrete due to higher density compare to normal aggregate.
- Concrete with slag aggregate achieved similar compressive strength with normal aggregate concrete.
- Concrete with nickel slag aggregate has good resistances against corrosion and influenced by curing condition.
- Corrosion resistance of 100 % slag cured in air (CU-100%) is three times higher than normal aggregate in air curing (CU-0%). While no significant differences is observed found in the specimens cured in water both CA-0% and CA-100%.

ACKNOWLEDGEMENTS

The authors would like to thank PT. Vale Indonesia Tbk who has supplied us slag aggregates in our experiment.

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