International Journal of GEOMATE, Jan., 2023, Vol.24, Issue 101, pp.76-83
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.101.s8575
Geotechnique, Construction Materials and Environment

CORROSION BEHAVIOR ANALYSIS OF SELF-COMPACTING CONCRETE USING IMPRESSED CURRENT AND RAPID CHLORIDE PENETRATION TEST

Stephen John C. Clemente[1*], Bernardo A. Lejano[2] and Jason Maximino C. Ongpeng[2]

[1]Asst. Professor, FEU Institute of Technology, Philippines; [2] De La Salle University, Philippines

*Corresponding Author, Received: 07 July 2022, Revised: 27 Dec. 2022, Accepted: 8 Jan. 2023

ABSTRACT: Corrosion is the leading reason for reinforced concrete structures reduced service life. Structures such as ports and harbors and bridges and other offshore and near shore are prone to chloride-induced corrosion. This research evaluates the use of self-compacting concrete (SCC) as an alternative concrete for such structures. In theory, SCC reduced water content, and high cement and powder content will help protect the reinforcement from chloride intrusion because of its lower porosity and the alkalinity that the cement provided. Sixteen different mixtures of SCCs were mixed and tested for rheology, compressive strength, rapid chloride ion penetration test (RCPT), and impressed current (IC). Water content is the significant factor that affects both RCPT and IC. The segregation of SCC when too much water-cement ratio is combined with a high amount of superplasticizer resulted in a high level of corrosion in the reinforcement. The formation of cracks accelerates the corrosion due to the increased flow of current in the IC set-up. The impressed current technique is the suggested method for determining the corrosion resistance of concrete since it simulates the similar effect of corrosion to concrete which is cracking. It also stimulates the effect of rust on the flow of current. A rapid chloride penetration test is a good indicator of the durability of concrete but may be insignificant for predicting the corrosion level of reinforcement for SCC. Segregation negatively affects the total charge passed in the impressed current and the corrosion level of the rebar.

Keywords: Self-Compacting Concrete, Corrosion, Impressed Current, Rapid Chloride Penetration, Segregation

1. INTRODUCTION

Self-compacting concrete is one of the new types of concrete that has high workability as compared to conventional concrete. SCC constituents are similar to normal concrete except for the addition of chemical admixtures such as superplasticizer (SP) for improving the flowability and viscosity agent for controlling the segregation. SCC can be utilized for most concrete structures that have formworks. It is best used for structures with high-density reinforcement such as ports, buildings, and bridges since it can easily penetrate and flow freely through the tight spacing of reinforcement. The demand for this type of concrete has constantly increased and the need there is a growing need for a better understanding of its behavior, especially for its performance in a corrosive environment. According to several research papers [1,2], it has the potential to perform better in terms of corrosion resistance than other types of concrete.

Corrosion is one of the problems for reinforced concrete structures, especially those exposed to high chloride environments such as near shore and offshore structures. The service life of such structures are shortened drastically due to the formation of cracks, decreasing of rebar cross-sectional area, and spalling of concrete cover. These occurrences can affect the serviceability and safety of reinforced concrete structures.

The rate of corrosion in reinforced concrete structures is influenced by several factors related to material constituents of the mixture such as porosity which is usually affected by water and particle size distribution, the amount of cement that helps the formation of a passive protective layer in rebars [3], amount of fine materials and water that affects the segregation of the concrete. When the steel is converted to rust which is commonly 3-6 times the original volume of steel [4], this will induce stress on the concrete. Stress will cause cracking and eventually spalling of the concrete cover. Cracks and spalling will eventually cause acceleration of corrosion since the reinforcement will not have any protection [5][6].

Different mixtures of SCC particularly different amounts of cement, water, and SP will yield different rheological properties, compressive strength, and pore structure of the hardened concrete. Similar to normal concrete, SCC is prone to segregation because of the presence of a superplasticizer [7]. SP should be checked for compatibility with the cement and other constituents of the concrete. Most SPs brand indicates the limit for the dosage of SP to ensure that bleeding and segregation are prevented.

This research explored the use of self-compacting concrete for marine structures using rapid chloride ion penetration and impressed current technique for accelerated corrosion. Different mixtures of SCC with varying amounts of cement, water, and superplasticizer were tested for rheology, 28^{th}-day rapid chloride ion penetration, and corrosion test. Linear regression analysis was performed to determine the effect of materials constituents on the RCPT and corrosion level of rebar. Segregation resistance of the SCC was also tested and correlated to the total charge passed in the impressed current and the corrosion level of the rebar.

2. RESEARCH SIGNIFICANCE

Several established standards for SCC like EFNARC and ACI do not cater to the corrosion resistance of SCC. There is a very limited number of research that pertains to the corrosion behavior of SCC. This research helps in establishing our understanding of the corrosion performance of SCC, the effect of the three most significant influential factors (cement, water, and superplasticizer) [5,6], segregation resistance [7] of SCC and chloride permeability to the corrosion resistance [8]. The derived models and parametric analysis can be a guide for designing SCC in the future [9,10].

3. METHODOLOGY

3.1 Design Mix of Self-Compacting Concrete

According to literatures, the three most influential factors that affect the strength and rheology of self-compacting concrete are cement, water, and superplasticizer. Sixteen different mixtures of SCC are used for the experiments conducted as shown in Table 1. Cement was varied between 430 to 500 kg/m^3. Water was varied between 210 to 250 liters/ m^3 and superplasticizer content was between 1% to 1.8% by weight of cement. The gravel and sand were fixed at 780kg/m^3 and 830 kg/m^3 respectively. The researchers used a central composite design for the design mix of SCC. Plus sign (+) or capital (A) indicates the highest amount or dosage of the constituents, while the negative sign (-) or small (a) indicates the lowest amount or dosage. Zero (0) indicated the middle amount or dosage. The researcher used 3/8 inches as the maximum size for coarse aggregates and river sand. For the cement, this research used Type 1 cement and a polycarboxylate ether type for SP conforming to ASTM C494 Type G.

3.2 Rheological Test

Rheological tests were performed to check the workability of the concrete. The researchers follow the standard of EFNARC [14] with regard to the performance of these tests. Four criteria were considered: flowability, viscosity, passing ability, and segregation resistance. Table 2 shows the rheological tests needed for each criterion including the equipment used and the passing level for each test.

Table 1 Design Mix of SCC

Mix No.	Cement (kg)	Water (kg)	SP (%)
SCC1	500	250	1.0
SCC2	500	210	1.8
SCC3	430	210	1.0
SCC4	430	210	1.8
SCC5	500	230	1.4
SCC6	430	230	1.4
SCC7	500	210	1.0
SCC8	465	250	1.4
SCC9	465	230	1.4
SCC10	430	250	1.0
SCC11	465	230	1.8
SCC12	465	230	1.4
SCC13	465	230	1.0
SCC14	500	250	1.8
SCC15	430	250	1.8
SCC16	465	210	1.4

Table 2 Rheological Tests [14]

Criteria	Rheological Test	Equipment	Passing
Slump Flow	Slump Flow	Slump Cone	550mm
Viscosity	T500	Slump Cone	-
Passing Ability	L-Box	L-Box	0.8
Segregation	Segregation	GTM Screen	20%

3.3 Rapid Chloride Ion Penetration Test

A rapid chloride ion penetration test was used to check the durability as well as the porosity of the different design mixes of SCC. The researchers follow the standard of ASTM C1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. Using a 100mm diameter by 50mm sample cast from the different design mix of SCC. The samples were coated at the side using marine epoxy to ensure that there is no leakage (See Figure 1). The samples were put in a dry vacuum for 3 hours and then 1 hour for saturated vacuum and allowed to be soaked for 18 hours ± 2 hours. After soaking, the samples were inserted into the cells, the right-side cell is positively charged and filled with 0.3N of NaOH solution, meanwhile, the left side has a negative charge with a 3% NaCl solution (See Figure). The cells were connected in a 60Volts potential for 6 hours while the reading was taken every half hour. The total charge passed was computed in Coulombs (C).

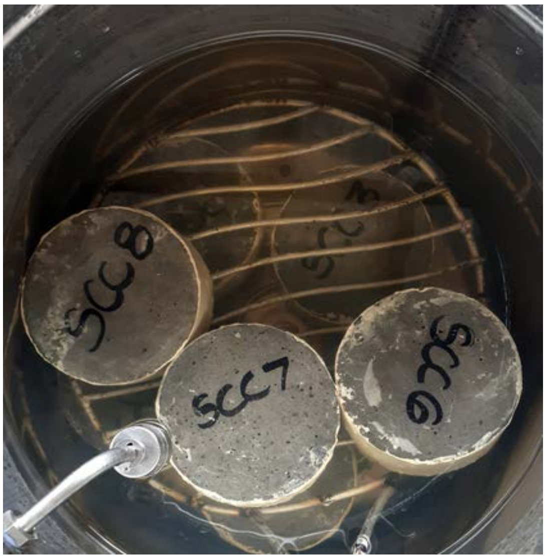
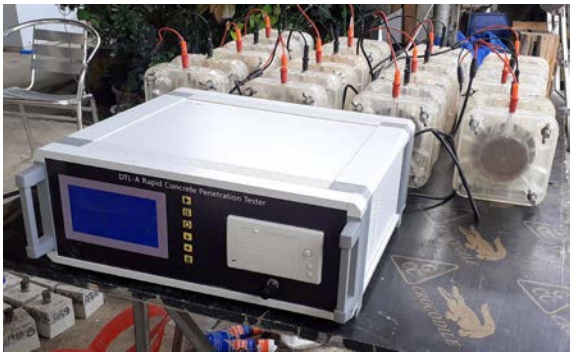


Fig. 1 Preparation of Samples for RCPT



(b)

Fig. 2 RCPT Set-Up

3.4 Impressed Current Technique

To accelerate the corrosion of the reinforcement, the impressed current technique was used [11]. This technique accelerates corrosion by increasing the rate of chloride ions flowing with the help of a power source.

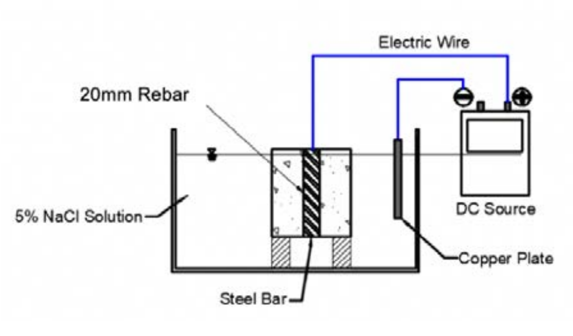


Fig. 3 Impressed Current Set-up

This research used a 100mm cube sample with a 20mm diameter rebar at the center. The concrete cover is 40mm on all sides. The rebar is attached negative charge of a 12V adaptor and a copper plate as the cathode. The samples were soaked in a 5% NaCl solution as shown in Figure 3. Reinforcements were weighted first before casting the samples. Sixteen samples were exposed to impressed current for 5 and 10 days [12]. After the desired duration, the reinforcement was cleaned soaked in hydrochloric acid for 15 minutes and washed using clean water. A steel brush was used to remove the remaining rust.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength Rheological Properties

As shown in Table 3 are the results of the rheological tests results and the compressive strength test result. Since the researchers used a high amount of cement and sand (830kg/m^3), many of the design mixes yield low flowability and passing ability. SCC with a higher amount of fine materials (sand and cement) will have higher viscosity [13,14]. Only mixtures 1, 5, 8, 10, 12, and 14 passes all requirements for rheology.

Table 3. Rheological and Compressive Strength

Mix No.	SF (mm)	T50 (sec)	L-Box	GTM (%)	fc' (Mpa)
SCC1	610	1	0.95	0.3	42.35
SCC2	470	8	0.12	0.21	41.83
SCC3	460	5	0.33	0.29	35.75
SCC4	540	6	0.29	0.75	34.17
SCC5	650	2	0.85	1.7	27.98
SCC6	540	2	0.63	5.72	17.77
SCC7	300	DNR	0	0.2	47.71
SCC8	630	2	0.8	3.09	26.76
SCC9	560	3	0.75	0.62	33.81
SCC10	630	2	0.8	0.77	31.18
SCC11	575	3	0.57	1.69	41.54
SCC12	565	3	0.84	0.74	36.5
SCC13	540	2.5	0.72	0.47	31.84
SCC14	720	1	1	10.02	41.57
SCC15	665	1	0.67	9.78	22.33
SCC16	470	7	0.41	0.23	32.45

Note: DNR- did not reach (since the slump flow is less than 500mm, t50 test cannot be performed).

4.2 Rapid Chloride Ion Penetration Results

All 16 mixes of SCC were tested in RCPT, mixtures 1, 8, 9, 10, 11, 13, 15, and 16 yield a high chloride permeability which is >4000. This is due to the high water-cement ratio of these samples which is >0.50. Other mixtures yield moderate chloride permeability (between 2000-4000) which is typical for concrete with a water-cement ratio between 0.40 to 0.50 [15].

Table 4. RCPT Result

No.	Design	Total Charge (Actual)	Total Charge (Estimate)
SCC1	++-	4400	4394.17
SCC2	+−+	3378	3372.15
SCC3	−−−	3902	3895.14
SCC4	−−+	3648	3643.05
SCC5	A00	3803	3797.34
SCC6	a00	3983	3975.05
SCC7	+−−	3770	3762.56
SCC8	0A0	4788	4778.18
SCC9	000	4925	4924.39
SCC10	−+−	5628	5622.69
SCC11	00A	4163	4159.25
SCC12	000	3557	3555.35
SCC13	00a	4323	4317.58
SCC14	+++	3922	3919.35
SCC15	−++	4238	4237.28
SCC16	0a0	4046	4040.92

Shown in Figure 4 SCC mix number 10 yields the highest current flowing for the whole duration of the test. This mixture has high water content with the lowest cement and SP.

Although other mixtures with high water content yield lower flow of current, it can be observed that these mixtures yield high segregation of about 10.02% for SCC14 and 9.78% for SCC15 have the two lowest currents flowing among all mixtures with (+ or A) levels of water content. The segregation or bleeding is due to the high amount of water and superplasticizer.

During the experimentation, the researchers noticed a little bleeding of water on these mixes due to the high SP content of 1.8% by weight of cement. This bleeding may contribute to the loss of water in the mixture during casting and may contribute to denser concrete. The height of the specimen used for RCPT which is 50mm may play a big role in diffusing the negative effect of bleeding and segregation in the specimen used for RCPT. Several researchers explored this but there are still no established guidelines about this phenomenon.

4.2.1 Correlation of RCPT and Material Constituents

Simple regression analysis is performed to analyze the effect of each constituent on the total charge passed in Coulombs. As shown in Table 5A, the linear model derived has an R-squared value of 0.6026. Although water is the only significant factor with a P-value of less than 0.05, cement and SP may still be considered substantial factors with P-values of 0.12 and 0.06 respectively.

Only water yields a positive coefficient, meaning increasing its amount will result in increased charge passed (Coulombs) [16].

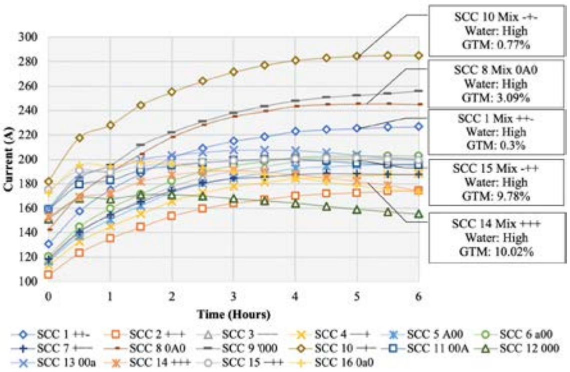


Fig. 4 RCPT Graph

Table 5A. Regression Analysis for RCPT (Regression Statistics)

Regression Statistics	Value
Multiple R	0.7763
R Square	0.6026
Adjusted R Square	0.5032
Standard Error	403.1950
Observations	16

For the SP, a higher amount of SP will result in a lower charge passed. This result may provide evidence that a certain range of bleeding in concrete may result in a denser concrete which results in high compressive strength and lower charge passed referring to SCC14.

Table 5B. Regression Analysis (Coeff and P-Values)

	Coeff	S. Error	t Stat	P-value
Intercept	3048.27	2286.64	1.33	0.21
Cement	-6.07	3.64	-1.67	0.12
Water	21.16	6.38	3.32	0.01
SP	-668.50	318.75	-2.10	0.06

The researchers considered a linear correlation between the water-cement ratio and the total charge passed in RCPT. Although considered as a moderate correlation having an R^2 value of 0.432 as shown in Figure 5, the model suggests that a higher water-cement ratio of SCC will yield to higher charge passed which is an indication of higher porosity in the concrete [17].

4.3 Impressed Current

4.3.1 Comparison of Corrosion Level

Shown in Figure 5 is the corrosion level of each sample exposed in impressed current for 5 days and 10 days. Some samples more than doubled after their corrosion level considering 5 days to 10 days of exposure due to the presence of cracks and eradication of the passive layer that protects the reinforcement.

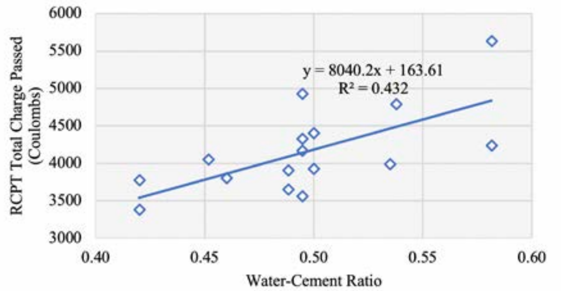


Fig. 5 Correlation Between W/C and RCPT

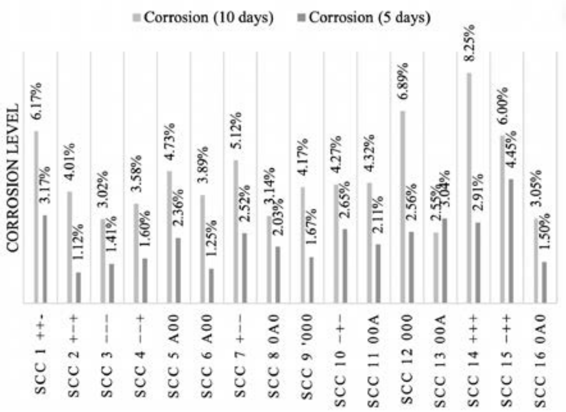


Fig. 6 Corrosion Level

4.3.2 Influence of Material Constituents and Cracks on Impressed Current

SCC 7 shows a hairline crack before reaching the 5th day on impressed current. This is due to the very high current density of around 1.59mA/cm^2 for SCC7. SCC14 which yields the 4th most corrosion level among 16 mixes exposed to 5 days of impressed current is due to the uneven surface due to high segregation (See Figure 7). Bleeding and segregation also cause diluted cement paste and decrease the transport resistance of the concrete [18].

SCC 7 which ranks 5th for the highest corrosion level out of 16 samples shows a crack parallel to the length of the rebar. The crack started at around 90 hours as shown in Figure 7, the current started to pick up due to the direct path of the current. SCC14 shows a severe crack at the edge and the bottom part which resulted in a big chunk of reinforcement corroded at the bottom part. This crack is directly towards the reinforcement that resulted in a high flow of current. Due to the presence of rust on the surface of reinforcement and sometimes filling in the voids and cracks, it can alter the flow of current since rust is a poor conductor of electricity [19][20].

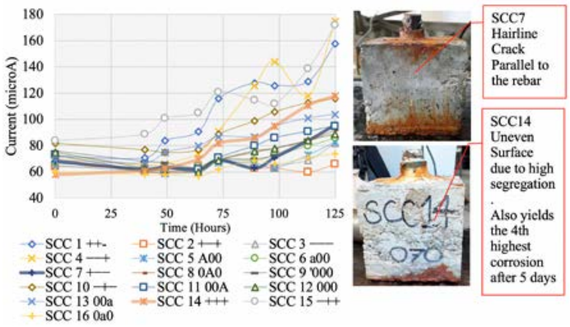


Fig. 7 Impressed Current (5 days)

Also shown on the graph, the current goes up and down over time. This is due to the change in the resistance of concrete, and the presence of cracks and rust.

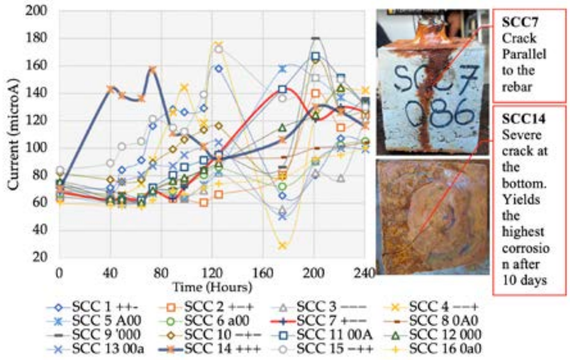


Fig. 8 Impressed Current (10 days)

A simple regression analysis was conducted to analyze the relationship between the cement, water, and SP content of SCC to the corrosion level of the rebar. As shown in table 6, an R2 value of 0.44 was derived from the regression model that indicated a moderated correlation.

4.3.3 Regression Analysis Corrosion Level

Table 6. Regression Analysis for Corrosion Level (Regression Statistics)

Regression Statistics	Value
Multiple R	0.6674
R Square	0.4454
Adjusted R Square	0.3068
Standard Error	0.0130
Observations	16

Table 7 shows the derived linear regression model. Water content is the only significant factor with P-values of 0.05. All coefficients were positive as shown in the table. A higher dosage of SP will be induced bleeding, but in this experiment, the dosage of SP is limited to 1.8% by weight of cement which is below the recommended 2% by the manufacturer. The segregation was also within the allowed range of below 20%. SP-induced bleeding for samples with a high amount of cement as observed from SCC14 may result in high compressive strength but the segregation of coarse aggregates at the bottom contributed to the pore structure of the concrete, thus increasing the corrosion on the reinforcement [21].

Table 7. Regression Analysis for Impressed Current (Coefficients and P-Values)

	Coeff	S.Error	t Stat	P-value
Intercept	-0.1759	0.0739	-2.38	0.03
Cement	0.0002	0.0001	1.82	0.09
Water	0.0005	0.0002	2.20	0.05
SP	0.0126	0.0103	1.22	0.25

4.4 Correlation Analysis Between Corrosion Level and Total Charge Passed (RCPT and Impressed Current)

The total charge passed is calculated using the area generated by the current flowing (y-axis) and time in seconds (x-axis). As shown in Figure 9, a moderate correlation with an R2 value of 0.48 was observed between the total charge passed and corrosion level. In this experiment, the voltage of the power source is set as a constant. The rate of electron flowing in the circuit (power source→copper →NaCl solution→porous structure of concrete→steel reinforcement→power source) serves as the resistance of concrete.

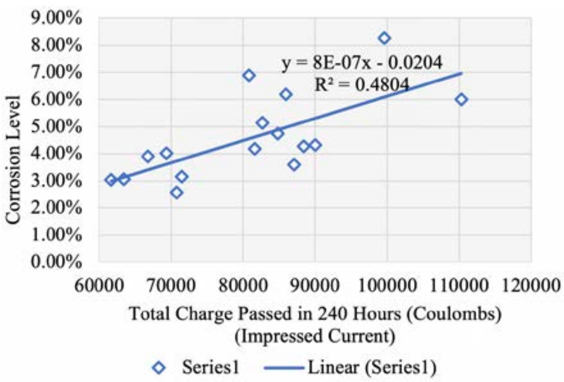


Fig. 9 Impressed Current (10 days)

The result of the RCPT has no significant correlation to the total charge passed in the impressed current with an R^2 value of 0.0206. The poor performance of the model suggests that other factors influence the corrosion severity of the samples. The RCPT test results only characterized the concrete's pore structure. The corrosion of reinforcement inside the concrete is affected by other factors such as the passive layer of protection, cracks, temperature, etc. Future studies should consider the cracking behavior of the concrete in the models such as (crack severity (width, depth etc), and time to crack.

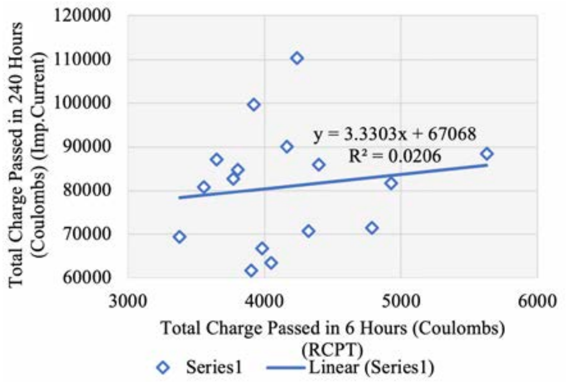


Fig. 10 Impressed Current (10 days)

4.5 Effect of Segregation on Corrosion and Total Charge Passed

As shown in Figure 11, the model suggests that higher segregation in SCC resulted in to increase in the total charge passed in the impressed current set-up and also yields higher corrosion levels in the reinforcement with R squared of 0.5539 and 0.2877 respectively.

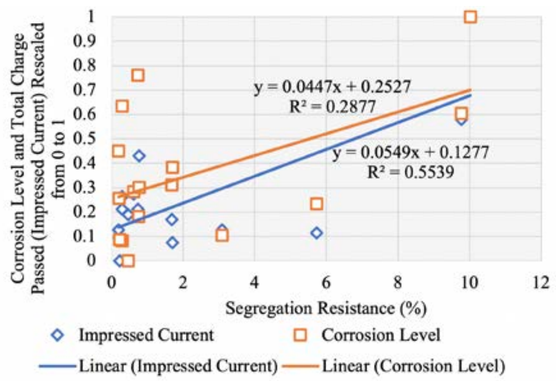


Fig. 11 Effect of Segregation on Corrosion

5. CONCLUSION

Water is the only significant factor with P-value less than 0.05 for both the RCPT test and impressed current (corrosion level). The water-cement ratio is the leading factor in the porosity of the SCC and increases the total charge passing in the specimen for the RCPT test.

The crack in SCC7 increases the flow of current in the circuit. This is the reason for the high corrosion level of the reinforcement in that specimen. SCC14 has the highest segregation of 10.02% and the concrete shows inconsistencies on the surface due to bleeding. Segregation at the bottom of the specimen increases the potential for chloride intrusion due to the pore structure created by the capillary action at the coarse aggregates.

RCPT is not a good indicator for SCC in predicting its corrosion resistance. This is due to the other factors present that affect the rate of corrosion such as cracks and the formation of rust. The impressed current technique performed in this experiment can be a standard for testing the corrosion resistance of concrete as protection for the reinforcement. It will capture most of the factors such as the materials constituents, cracks, porosity, and temperature.

6. ACKNOWLEDGMENTS

The researchers want to give thanks to the whole project team for doing the experiments, Engr. Jaysoon Macmac, Engr. John Bryan Tiu, Engr. Angelou Faye Nuñez, Engr. Rafael Reymundo, Engr. Hannah Lou Argota and Engr. Angel Rose Macapanas. Special thanks to the Department of Science and Technology Philippine Council for Industry, Energy, and Emerging Technology Research and Development for the funding of the project.

7. REFERENCES

[1] Al-Akhras N, Aleghnimat R., Evaluating Corrosion Deterioration in Self-compacted Reinforced Concrete Beams and Prisms Using Different Tests. Construction and Building Materials, 2020, Sep 30;256:119347.

[2] Jain S, Pradhan B., Fresh, Mechanical, And Corrosion Performance Of Self-Compacting Concrete in The Presence Of Chloride Ions. Construction and Building Materials, 2020, Jun 30;247:118517.

[3] Roxas CL, Lejano BA., An artificial neural network model for the corrosion current density of steel in mortar mixed with seawater. GEOMATE Journal. 2019 Apr 29;16(56):79-84.

[4] Liu X, Yan Z, Wang D, Zhao R, Niu D, Wang Y., Corrosion Cracking Behavior of Reinforced Concrete Under Freeze-Thaw Cycles. Journal of Building Engineering, 2022 Nov 26:105610.

[5] Medeiros MH, Rocha FC, Medeiros-Junior RA., Helene P., Corrosion Potential: Influence of Moisture, Water-Cement Ratio, Chloride Content and Concrete Cover. Revista IBRACON De Estruturas E Materiais, 2017;10:864-85.

[6] Tammam RH, Mogoda AS, Gharbawy MH., Influence of Cement Superplasticizer on Steel Corrosion in 3.5% NaCl Solution. Int. J. Electrochem. Sci, 2020 Sep 1;15:8408-21.

[7] Concha NC, Baccay MA, Effects of Mineral and Chemical Admixtures on the Rheological Properties of Self Compacting Concrete. GEOMATE Journal, 2020 Feb 26;18(66):24-9.

[8] AL-Ameeri AS, Rafiq MI, Tsioulou O., Combined impact of carbonation and crack width on the Chloride Penetration and Corrosion Resistance of Concrete Structures. Cement and Concrete Composites, 2021 Jan 1;115:103819.

[9] Salami BA, Rahman SM, Oyehan TA, Maslehuddin M, Al Dulaijan SU., Ensemble machine learning model for corrosion initiation time estimation of embedded steel reinforced self-compacting concrete. Measurement, 2020 Dec 1;165:108141.

[10] Nosratzehi N, Miri M., Experimental Investigation on Chloride Diffusion Coefficient of Self-compacting Concrete in the Oman Sea. Periodica Polytechnica Civil Engineering, 2020 May 6;64(3):647-57.

[11] Concha N, Oreta AW., A Model for Time-To-Cracking Of Concrete Due to Chloride Induced Corrosion Using Artificial Neural Network. In IOP Conference Series: Materials Science and Engineering, 2018, Oct 1 (Vol. 431, No. 7, p. 072009). IOP Publishing.

[12] Oreta AW., Bond Strength Prediction Model of Corroded Reinforcement in Concrete Using Neural Network. GEOMATE Journal, 2019, 16(54):55-61.

[13] Clemente SJ., Artificial Neural Network Modeling of Rheological Parameters and Compressive Strength of Self-Compacting Concrete with Zeolite Mineral as Partial Replacement for Cement, 2015.

[14] EFNARC S., Guidelines for Self-Compacting Concrete, European Federation for Specialist Construction Chemicals and Concrete Systems, Norfolk, UK. English ed., February, 2002.

[15] Çelik Z, Bingöl AF, Ağsu AS. Fresh, Mechanical, Sorptivity and Rapid Chloride Permeability Properties of Self-Compacting Concrete with Silica Fume and Fly Ash. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2022 Apr;46(2):789-99.

[16] Yang CC, Chiang CT., On The Relationship Between Pore Structure and Charge Passed From RCPT in Mineral-Free Cement-Based Materials, Materials Chemistry And Physics. 2005, Sep 15;93(1):202-7.

[17] Prakash MR, Nirmala MR. An Experimental Study on Rapid Chloride Penetration Test of Self Compacting Concrete. 2019.

[18] Safiuddin M, West JS, Soudki KA., Durability performance of self-consolidating concrete. Journal of Applied Sciences Research., 2008;4(12):1834-40.

[19] Concha NC, Oreta AW., Investigation of the effects of corrosion on bond strength of steel in concrete using neural network. Comput. Concr., 2021 Jul 1;28:77-91.

[20] Yoo DY, Gim JY, Chun B., Effects of Rust Layer and Corrosion Degree on The Pullout Behavior of Steel Fibers From Ultra-High-Performance Concrete. Journal of Materials Research And Technology., 2020 May 1;9(3):3632-48.
[21] Gao X, Zhang J, Su Y., Influence of Vibration-Induced Segregation on Mechanical Property and Chloride Ion Permeability of Concrete With Variable Rheological Performance. Construction and Building Materials., 2019, Jan 10;194:32-41.