International Journal of GEOMATE, Oct. 2023, Vol. 25, Issue 110, pp.1-8
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.110.3963
Geotechnique, Construction Materials and Environment

PULL-OUT CAPACITY OF EXPANSION ANCHOR BOLT AS INFLUENCED BY CORROSION

*Kim U. Mosquera[1] and Gilford B. Estores[2]

[1,2]School of Civil, Environmental and Geological Engineering, Mapua University, Philippines

*Corresponding Author, Received: 2 June 2023, Revised: 20 June 2023, Accepted: 21 July 2023

ABSTRACT: The expansion stud anchor bolt is one of the most used construction materials due to its flexibility in installation and connecting structural members. However, due to the geographic condition of the Philippines, consisting of 7,107 islands with 36,289 kilometers of coastline, water particulates from seawater increased the corrosion process of any steel material, including expansion stud anchor bolts. The objective of the study is to use neural network modeling to determine the effect of corrosion on the pull-out capacity of an expansion stud anchor bolt as influenced by corrosion considering different parameters such as Half-cell Potential, Gravimetric Test Result, compressive strength of concrete, and presence of waterproofing. The Impressed Voltage Technique (IVT) accelerated the corrosion process on 35 pieces of 250 mm x 250 mm x 150 mm concrete samples with and without waterproofing admixture, installed with uncorroded expansion stud anchor bolts. The behavior of the pull-out capacity, including the order of importance of the input parameters, was analyzed using neural network modeling. Among the parameters considered, the number of days subjected to IVT, which accelerated the corrosion process, is the primary and most significant variable in influencing the pull-out capacity of an anchor bolt.

Keywords: Pull-out capacity, Expansion stud anchor bolt, Half-cell potential, Artificial Neural Network, Percentage of corrosion

1. INTRODUCTION

Corrosion is one of the world's leading problems due to its alarming capability to weaken any structure made up or composed of steel [1]. In addition, corrosion on any steel is difficult to identify or measure when embedded in concrete, thus making other researchers and professionals design a safety factor depending on the type of structure or create preventive measures to avoid corrosion. However, due to the passage of time and continuous exposure to various weather conditions, corrosion will still seek its way and could result in the loss of integrity of the structure. Moreover, the scenario worsens when the static forces acting on any structural member are coupled with the dynamic forces from disasters such as earthquakes and typhoons. Furthermore, with the geographic condition of the Philippines, wherein its coastline is 36,289 kilometers and composed of 7,107 islands, the possibility that corrosion could occur is being expedited by water particulates from seawater depending on the wind profile and topography. Aside from the geographic condition of the Philippines, one of the significant concerns, also in connection with corrosion, are the old structures in Metro Manila, such as hi-rise buildings, bridges, telecommunication towers, etc. The existence of corrosion lessens the ability of old structures to withstand disasters like an earthquake. According to the study of Metro Manila Earthquake Impact Reduction Study (MMEIRS), Metropolitan Development Authority (MMDA), and Japan International Cooperation Agency (JICA) in 2010, approximately 33,500 casualties and 113,600 wounded could result from a 7.2 magnitude earthquake in Metro Manila. In this regard, parameters such as cost, strength, lifespan, and installation process must be considered in finding construction materials. One of the most used construction materials is the anchor bolt. Anchor bolts are classified into two: (1) post-installed anchor bolts (installed after the concrete has hardened) and (2) pre-installed anchor bolts (installed before concrete pouring). A post-installed anchor bolt is much easier to use due to its flexibility in placement when it comes to installation and connecting members of any structure [2]. In the construction of new structures, post-installed anchor bolts are primarily seen in short columns commonly known as pedestals or in adding cantilever steel roof rafters typical to entrances of buildings. Another case aside from that is the renovation of structures to strengthen their current integrity and comply with the current National Structural Code of the Philippines (NSCP) 2015 and other existing standards. Additional steel bracing and steel jacketing are two of the most common retrofitting methods considered in renovation wherein anchor bolts are used, and the number of bolts is determined depending on the design and construction methodology. Anchor bolts can be compared to reinforced steel bars because both are embedded in the concrete, resist shear and tension, and are mostly located near the edge of the concrete. In relation to corrosion, the capacity of the anchor bolt can be reduced depending on the percentage of corrosion, which could result in catastrophic events. To avoid these scenarios, several researchers focused on the study of corrosion and techniques on how to measure the possibility of it occurring to any steel member. The half-cell potential test is the most advanced in determining the possibility of corrosion in reinforcement bars embedded in concrete [3]. The pull-out capacity of the post-installed anchor bolt can be solved using neural networks [4]. The determination of the corrosion through mass loss in the anchor bolt embedded in concrete was incorporated and considered as one of the factors in the modeling of the Neural Network affecting the pull-out capacity of the anchor bolt in this study. Artificial Intelligence, such as Neural Network modeling, is a powerful tool for solving various problems given survey data, experimental results, theoretical data, or a combination. The tool uses that data to produce a reliable answer by training the network model. This study focused on the pull-out capacity of an expansion stud anchor bolt, which is denoted as the most standard and generic type of anchor bolt, using neural network-given data such as a result of half-cell potential, gravimetric test, concrete compressive strength, and waterproofing to address the uncertainty in the actual capacity of the anchor bolt in tensile loading as affected by corrosion.

2. RESEARCH SIGNIFICANCE

Structural engineering involves the design and analysis to ensure the safety and reliability of different structures every time. Currently, one of the significant challenges that structural engineers encounter is that no available equation exists in any codes and standards to determine the pull-out capacity of post-installed anchors, considering the effect of corrosion. For this reason, an Artificial Neural Network (ANN), a machine learning tool, was used in this study to predict the pull-out capacity of post-installed anchors subjected to corrosion. The primary purpose of this study is to prove that the pull-out strength of an expansion stud anchor bolt is affected by corrosion, considering other parameters such as half-cell potential, gravimetric test result, compressive strength of concrete, and the presence of waterproofing. Moreover, this study considered these parameters to address the safety and design concerns encountered by structural engineers since no specific guidelines or studies were available, particularly for post-installed anchor bolts being affected by corrosion.

3. METHODS

3.1 Materials

The materials that were used in this experiment were expansion stud anchor bolts, type 1P Portland cement, aggregates, Sahara waterproofing admixture, and the half-cell potential apparatus, which was made through the guidelines provided by ASTM C876-15 (Reapproved 1999) [5]. All materials were locally made and sourced in Luzon. Testing machines such as Universal Testing Machine (UTM) were provided and coordinated with the Bureau of Research and Standards by the Department of Public Works and Highways of the Philippines. The technical data for an expansion stud anchor is shown in Table 1.

Table 1 Technical data for expansion stud anchor

Anchor Bolt Diameter	8	mm
Nom. Anchorage Depth	49	mm
Depth of Drill Hole	54	mm
Torque Moment	15	Nm
Nom. Tensile Strength	580	N/mm^2

The fine aggregates were sourced from Porac, Pampanga, with a Specific Gravity (SG) of 2.652, while the absorption capacity was 2.4%. The coarse aggregates were sourced from Montalban, Rizal, and have an SG of 2.823 while the absorption capacity is 0.730%. The concrete design mix was based on the ACI 211 Mix Design Method [6].

3.2 Specimen and Testing

The specimens for anchor bolt concrete bases and compressive cylinders are shown in Fig. 1. The design strength of the concrete base is 21 Mpa, consisting of a 0.50 water-cement ratio and 2% entrapped air. Two concrete sample groups were prepared; the first group consisted of ordinary concrete, while the other group had a Sahara waterproofing admixture. Other components of the mix, such as coarse aggregate size, water, cement, and fine aggregate, remained the same for both groups. 35 pieces of 250 mm x 250 mm x 150 mm concrete bases and fourteen (14) cylinders were made per sample group. The expansion stud anchor bolt was installed after the curing period and was referred to as "Day 0". This was established as a benchmark to determine the variation in the pull-out strength as corrosion progresses. The tests conducted during "Day 0" were pull-out, compressive, half-cell potential, and gravimetric tests. These tests were repeated after every seven (7) days, and all data were recorded accordingly. The pull-out test was done per ASTM E 488-96 [7], while the compressive test was performed according to ASTM C39-05 [8].

Fig.1 Concrete bases (left) and test cylinders (right)

Table 2 Specimen Matrix for Ordinary Type 1P Cement

Sample Data, Day 0 is referred to as 28th Day Concrete Strength or fc’	Pull-out Test	Compressive Test	Gravimetric Test
Day 0	3	2	2
Day 7	3	2	2
Day 14	3	2	2
Day 21	3	2	2
Day 28	3	2	2
Day 35	3	2	2
Day 42	3	2	2
Total	21	14	14

Table 3 Specimen Matrix for Ordinary Type 1P Cement with Sahara Waterproofing Compound Admixture

Sample Data, Day 0 is referred to as 28th Day Concrete Strength or fc’	Pull-out Test	Compressive Test	Gravimetric Test
Day 0	3	2	2
Day 7	3	2	2
Day 14	3	2	2
Day 21	3	2	2
Day 28	3	2	2
Day 35	3	2	2
Day 42	3	2	2
Total	21	14	14

As indicated in Tables 2 and 3, the IVT process began on "Day 0" by submerging all the concrete base samples and cylindrical specimens in 5% Sodium Chloride (NaCl) Solution with DC 3 volts, facilitating the rapid corrosion on the anchor bolt. Due to the high tensile strength of the anchor bolt compared to the concrete, it is assumed that the failure will most likely be the concrete breakout. The pull-out capacity was tested in a setup shown in Fig. 2. The pull-out capacity of the anchor bolt can be described in theory by the concrete breakout equation as per NSCP 2015 [9].

$$\boldsymbol{N = 9.8 \ x \sqrt{fc'} \ x \ h_{ef}^{\ 1.5}} \qquad (1)$$

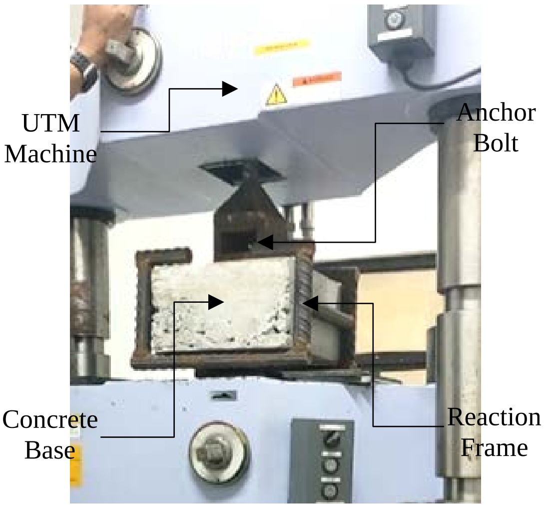

Fig. 2. Pull-out test setup

The possibility of occurrence of corrosion was determined through the Half-cell Potential and Gravimetric Method. The damage due to corrosion was obtained by deducting the mass after the IVT process from the original mass of the expansion stud anchor bolt.

$$\textit{mass loss} = (\textit{initial mass}) - (\textit{mass after IVT}) \qquad (2)$$

The pull-out test was conducted through UTM using built-up brackets made up of 28mm diameter Grade 60 reinforcing steel bars to eliminate any deformation or failure aside from the anchor bolt or concrete. The presence of corrosion was visually observed after 14 days, as shown in Fig. 3. In the absence of cleaning material, a rust converter can be used according to ASTM G1-90 (1999)e1 [10]. Light steel brushing is also acceptable according to this standard. The concrete specimen where the expansion stud anchor bolt was embedded was split into parts to recover the corroded anchor bolt. The procedure was done using a diamond disk cutter to minimize the disturbance to the steel material. The anchor bolt weighed with an accuracy of 0.01 grams.

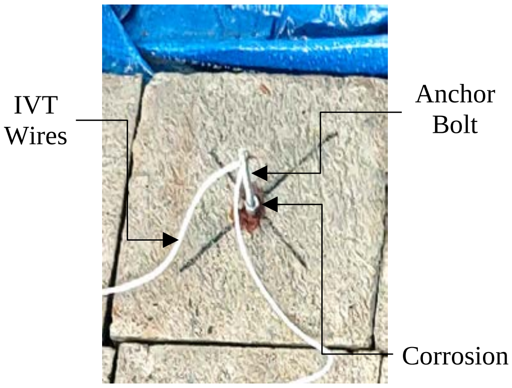

Fig. 3. Concrete base specimens under IVT showing the presence of corrosion on the anchor bolt after 14 days

3.3 ANN Modeling

The Artificial Neural Network model's accuracy in predicting the anchor bolt's pull-out capacity depends on the training and the layers of nodes. This phase determined the capability of the Neural Network to determine the pull-out strength of the expansion stud anchor bolt considering the effect of corrosion. Seventy (70%) percent of the data was used for training, fifteen (15%) percent of the data for validation, and fifteen (15%) percent of the data for the test. The development of the Neural Network for predicting the pull-out capacity of the expansion stud anchor bolt was implemented using the Neural Network Toolbox of MATLAB 2021a. Using the Levenberg-Marquardt (trainlm) as the training algorithm and the hyperbolic tangent sigmoid (tansig) function as the transfer function, a varying number of hidden neurons ranging from 1-10 were simulated.

4. RESULTS AND DISCUSSIONS

4.1 Compressive strength of concrete

Two cylindrical specimens were tested per group sample. Their average value was used in computing the theoretical pull-out capacity as per the NSCP 2015 formula for concrete breakout strength since it relied on the effective embedment depth of the expansion anchor and fc'. The "Day 0" (fc') and "Day 42" concrete strength for ordinary concrete was 21.41 MPa and 24.61 MPa, respectively. The increase in strength of the concrete cylinders was attributed to the continuous hydration provided by the NaCl solution.

4.2 Pull-out capacity of expansion anchor

Three specimens per group sample were tested. The experimental benchmark pull-out capacity for ordinary concrete and concrete with Sahara was 11.09 kN and 10.69 kN, respectively. The pull-out test was conducted until the 42nd day, wherein the failure changed from concrete breakout failure to material failure for the group samples of ordinary concrete, considering that the tensile strength of the expansion anchor was less than the concrete breakout strength. The expansion anchor failed at 12.52 kN, considering that based on the NSCP 2015 equation, the theoretical pull-out capacity is 12.70 kN.

4.3 Half-cell potential of the expansion anchor

The half-cell potential test, as shown in Fig. 4 was performed in accordance with ASTM C876 to determine the possibility of corrosion. A measure of -350mV from a half-cell potential test, which signifies a 90% probability of corrosion was achieved. Initially, the control specimen's readings ranged between -110mV to -164mV. As the number of days progressed, the readings increased, reaching up to -843mV for ordinary concrete.

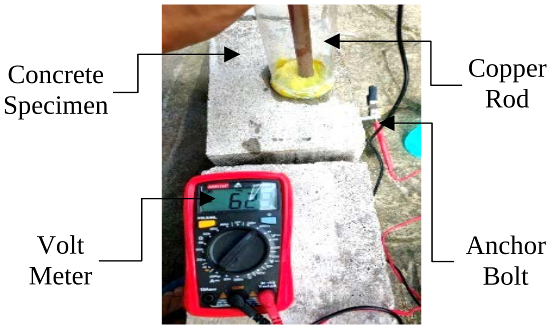

Fig. 4. Half-cell potential reading on one of the specimens on the 21st Day after the start of the IVT process

4.4 Gravimetric result

The weight of the expansion stud anchor bolt was measured using the weighing scale to determine the mass loss during the progress of corrosion. As the corrosion progresses, the mass increases, expanding or widening the diameter until the particles are loose enough to separate from the anchor bolt itself.

4.5 ANN Model of pull-out capacity

4.5.1 Performance of Neural Network Model

Figures 5 and 6 show the performance of ANN models in terms of regression value (R-value) and mean square error (MSE) against the number of hidden neurons, respectively. The highest value obtained in validation was 0.9983 for R-value and 0.0137 for MSE. The results show that the best model obtained has a topology of 5-4-1 (input-hidden-output). It has the highest R-value and least

MSE among the topologies simulated in the study.

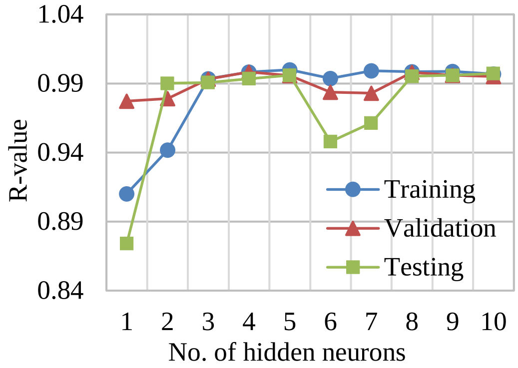

Fig. 5 Regression Value (R-Value) vs. Number of Hidden Neurons

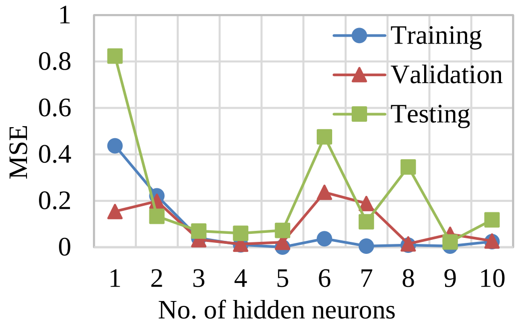

Fig. 6 Mean Square Error (MSE) vs. Number of Hidden Neurons

The best validation performance is 0.013695 MSE, which occurred faster at 13 epochs, as presented in Fig. 7. Moreover, the regression plots of the different phases of development of the pull-out capacity model were also obtained as shown in Fig. 8 to 11.

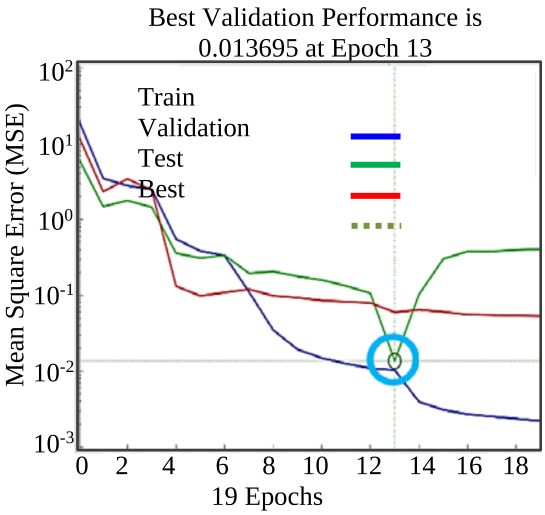

Fig.7 Mean Square Error vs. Epochs of 5-4-1 model

The R-value for training data is 0.99818, 0.99831 for validation data, 0.99335 for testing data, and 0.99652 for all data. Since these R values are close to 1, as shown in Fig. 8 to 11, these simply indicate a close relationship between the considered input variables and the target variable concrete breakout strength of an expansion anchor bolt.

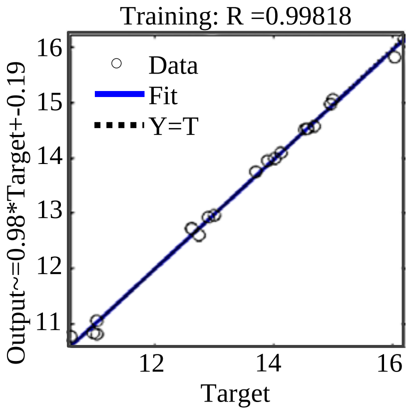

Fig.8 R-value for training data (Output vs. Target)

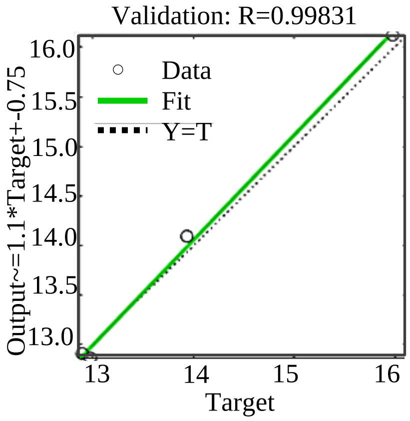

Fig.9 R-value for validation data (Output vs. Target)

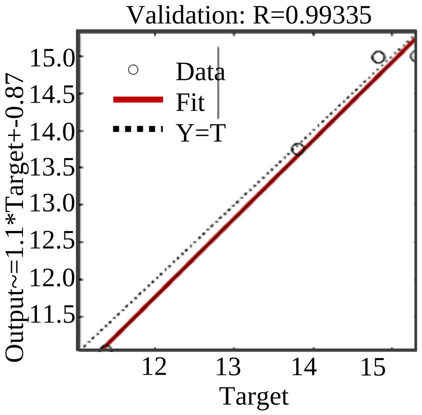

Fig.10 R-value for testing data (Output vs. Target)

All data: R =0.99652

16

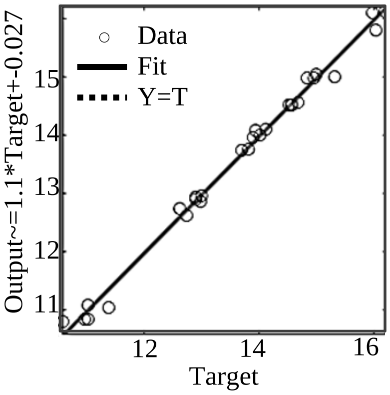

Fig.11 R-value for all data (Output vs. Target)

4.5.2 Relative importance of each variable

Each input variable influenced the results from the Neural Network model at a certain level of importance, as indicated in Table 4. It shows that among input parameters, the most important factor to influence the pull-out capacity of the expansion stud anchor bolt, which mainly comprised of concrete breakout failure, was due to the number of days it was subjected to IVT for the corrosion process followed by the gravimetric test, waterproofing, half-cell potential reading, and compressive strength.

Table 4 Weights of 5-4-1 ANN Model

Hidden	Input Layer					Output Layer
Node	DSC	HCP	GT	f'c	WP	EP
1	-0.85	1.21	6.22	-0.39	-1.61	1.68
2	4.08	0.69	-0.96	-0.06	-0.02	0.55
3	-1.26	-0.75	-0.17	0.84	0.48	-0.93
4	5.49	-0.23	-0.66	1.19	1.84	-0.09
RI(%)	42.39	11.71	22.35	10.66	12.88	
Rank	1	4	2	5	3	

Note: RI is "Relative Importance", DSC is "Days Subjected to Corrosion", HCP is "Half-Cell Potential", GT is "Gravimetric Test", WP is Waterproofing, and EP is "Experimental Pull-out."

4.5.3 Parametric Analysis

Parametric analysis was performed based on the 5-4-1 ANN model to determine the behavior of the expansion stud anchor bolt's pull-out capacity upon having varying independent parameter values, as shown in Fig. 12 to 16. The pull-out strength increased as the number of days increased due to the upper body of the expansion stud anchor bolt (above the expansion sleeve) expanding, which contributed to the tensile resistance, indicating that expansive force was being induced to the concrete as a result of the expansion of the cross-sectional area of steel material as a result of corrosion [11].

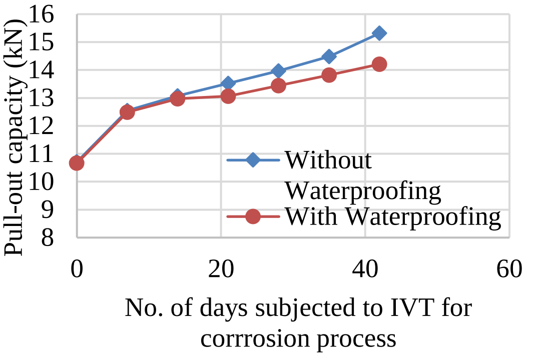

Fig.12 Parametric Analysis: Pull-out capacity (kN) vs. Number of days subjected to IVT for corrosion process

The Half-cell potential reading increased as the pull-out strength increased, indicating that the steel material within the concrete was more susceptible to corrosion if a higher reading of Half-cell potential was obtained.

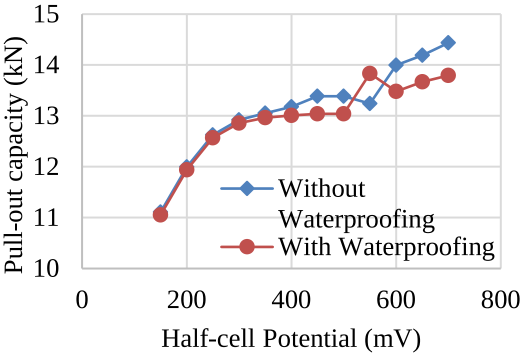

Fig.13 Parametric Analysis: Pull-out capacity (kN) vs. Half-Cell Potential (mV)

An increase in the gravimetric test would also increase the pull-out capacity of the expansion stud anchor bolt. This was also attributed to the increase in the cross-sectional area at the early stage of corrosion, causing an increase in volume.

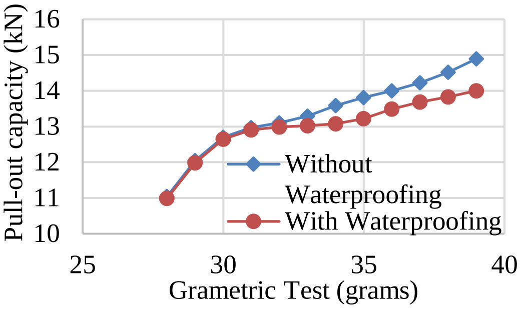

Fig.14 Parametric Analysis: Pull-out capacity (kN) vs. Gravimetric Test (grams)

4.5.4 Comparison with NSCP 2015 Concrete Breakout Capacity

Fig. 15 and Fig. 16 show the pull-out capacity graph of normal concrete and concrete with waterproofing, respectively, against the number of days submerged in NaCl solution for both theoretical values and actual test results. The theoretical values were obtained from the NSCP 2015 equation. The graph under Fig. 13 shows that the pull-out capacity for the actual test result was significantly increasing, considering that the diameter of the expansion anchor was expanding as a result of initial corrosion, adding frictional resistance, which increased the pull-out capacity until the corrosion was severe enough, breaking down the steel material, causing the pull-out test to change from concrete breakout to steel tensile failure at 42nd day. The theoretical values obtained from the pull-out capacity equation of NSCP 2015 did not differ significantly since corrosion was not considered, and the equation only depends on the effective embedment depth and the fc’. Moreover, the actual test result of the compressive strength relative to the number of days has no significant difference. Therefore, comparing the two, it was observed that corrosion significantly contributes to the actual test results of the pull-out capacity of the anchor bolt.

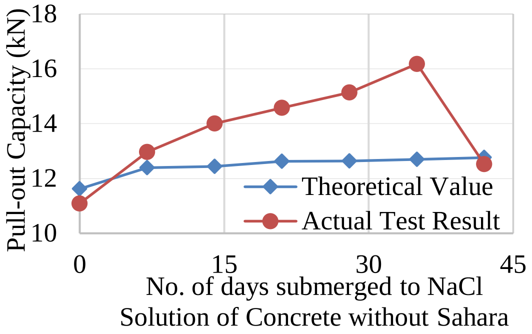

Fig. 15 Pull-out test of concrete without Sahara admixture as affected by corrosion: Theoretical (NSCP 2015 Equation) vs. Actual test result

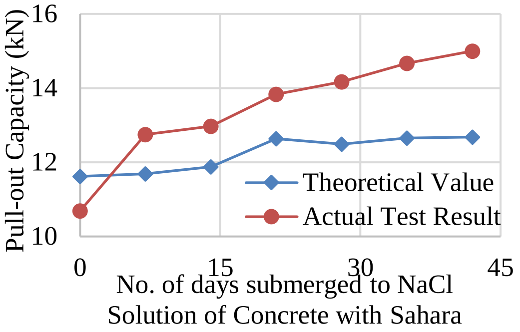

Fig. 16 Pull-out test of concrete with Sahara admixture as affected by Corrosion: Theoretical (NSCP 2015 Equation) vs. Actual test result

The Sahara admixture slowed the progress of corrosion, limiting the NaCl solution penetration through concrete voids, and considering that the steel material expanded, it also decreased the gap between the expansion stud anchor bolt and the concrete, making it more watertight.

5. CONCLUSION

Previous study supported the results and showed that the pull-out capacity of the expansion stud anchor bolt was affected by other varied factors like concrete aggregate sizes aside from the effective depth of the expansion anchor and the fc’ [12]. This study showed that it is also affected by corrosion and that the Neural Network is a powerful tool to predict its pull-out capacity considering the number of days subjected to corrosion, half-cell potential readings, gravimetric test, concrete strength, and waterproofing. It was also observed that the failure mode changed from the concrete cone to steel material on the 42nd day after reaching its peak value, considering that the corrosion mostly consumed the portion of the expansion stud anchor bolt located immediately above the drill hole on the concrete surface as shown in Fig. 17. Furthermore, the increase in pull-out capacity for the normal concrete faster than the concrete with admixture as compared can be attributed to the seepage of NaCl solution in the concrete, affecting the cross-sectional area by increasing it because of expansion due to corrosion.

Fig.17 Concrete Cone failure of Corroded Expansion Stud Anchor bolt

Considering that expansion was happening on the cross-sectional area above the expansion sleeve of the expansion stud anchor bolt due to corrosion, it was unable to exert enough force to crack the concrete because of the edge distance compared to reinforcing steel bars. Rather, the corrosion product was pushed out between the gap on the drill hole and the expansion stud anchor bolt, which made the NaCl solution more concentrated above the expansion sleeve. The waterproofing had the least effect on the pull-out capacity because the NaCl solution immediately reached the expansion stud anchor bolt depicting its actual application wherein part of it was exposed, unlike reinforcing steel bars that are completely embedded.

6. ACKNOWLEDGMENTS

The material used in this study was M8x105 from Hilti, Philippines. The author would like to thank Mapua University, Bureau of Research and Standards - Department of Public Works and Highways and LLZEK Hardware for their significant assistance in this study. Utmost gratitude to Engr. Charity Hope A. Gayatin, Engr. Rolando J. Quitalig, and Engr. Wyndell A. Almenor for their valuable support in this study.

7. REFERENCES

[1] Benito E, Madlangbayan M, Tabucal N, Sundo M and Velasco P, “Corrosion damage Measurement on Reinforced Concrete by Impressed Voltage Technique and Gravimetric Method”, International Journal of GEOMATE, Vol. 13 (39), 2017, pp. 198-205.

[2] No H and Sonoda Y, “Potential Effects of Corrosion Damage on the Performance of Reinforced Concrete Member”, Journal of MATEC Web of Conferences, Vol. 47 (02007), 2016.

[3] Ha-Won S and Saraswathy V, “Corrosion Monitoring of Reinforced Concrete Structures - A Review”, International Journal of Electrochemical Science, Vol. 2, 2007, pp. 1-28.

[4] Ashour A and Alqedra M, “Concrete Breakout Strength of Single Anchors in Tension using Neural Networks”, Journal of Advances in Engineering Software, Vol. 36(2), 2004, pp. 87-97.

[5] ASTM C876-15, “Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete”, ASTM Manual of Aggregate and Concrete Testing, Vol. 4 (02), 2015.

[6] ACI Committee 211, “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete”, 2002.

[7] ASTM E 488-96, “Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements”, ASTM Standards in Building Codes, Vol. 4 (43), 2006.

[8] ASTM C 39-05, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM Standards in Building Codes, Vol. 1 (43), 2006.

[9] NSCP 2015, “National Structural Code of the Philippines 7th Ed.”, Anchoring to Concrete, Vol. 1, 2015, pp. 97-109.

[10] ASTM G1-90(1999)e1, “Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens”, ASTM Standards for Corrosion of Metals: Wear and Erosion, Vol. 3(2), 1999.

[11] Noh H and Sonoda Y, “Potential Effects of Corrosion Damage on the Performance of Reinforced Concrete Member”, MATEC Web of Conferences, Vol. 47 (02007), 2016.

[12] Estores G, Almenor W and Gayatin C, “Regression Modeling of Breakout Strength of an Expansion Anchor Bolt as Influenced by Concrete Aggregates”, International Journal of GEOMATE, Vol. 16 (57), 2019, pp. 163-169.