International Journal of GEOMATE, May 2019, Vol.16, Issue 57, pp.163 - 169
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2019.57.8196
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

REGRESSION MODELING OF BREAKOUT STRENGTH OF AN EXPANSION ANCHOR BOLT AS INFLUENCED BY CONCRETE AGGREGATES

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*Corresponding Author, Received: 12 June. 2018, Revised: 30 Dec. 2018, Accepted: 14 Jan. 2019

ABSTRACT: The frictional resistance of an expansion anchor bolt depends directly on the normal forces generated by the anchor expansion mechanism around the anchorage zone of the concrete base material. However, only the concrete aggregates around the anchorage zone have the direct shear contact with the anchor. This study aims to develop a regression model that predicts the breakout strength of an expansion anchor in plain concrete as influenced by the coarse aggregate size, coarse aggregate content, and fine aggregate content. Crushed coarse aggregates of sizes 10mm, 12.5mm, 19mm, and 25mm were used. The coarse aggregate content for each coarse aggregate size was 0.3452, 0.4046, 0.4462, and 0.4750, respectively. The fine aggregate content for each coarse aggregate size was 0.4243, 0.3771, 0.3514, and 0.3341, respectively. A heavy duty type of an expansion anchor bolt was used. There were five samples of base material specimens considered for each size of coarse aggregate. Each specimen was tested first for its compressive strength to ensure that it will meet the designed compressive strength and it will vary only at an acceptable deviation before the installation of the expansion anchors. The installed anchor bolts were then tested for pull-out. Tests results showed that among the parameters considered, coarse aggregate size is the most significant factor that could influence the breakout strength of an expansion anchor and it is optimum at 19mm size. A polynomial regression model is recommended to predict the concrete breakout strength of an expansion anchor bolt as influenced by the coarse aggregate size.

Keywords: Concrete Breakout Strength, Coarse Aggregate Size, Expansion Anchor Bolt, Regression Modeling, Coarse Aggregate Content

1. INTRODUCTION

Anchor bolts are widely used in composite construction such as for steel-to-concrete connections. The selection of anchor bolt is based on structural considerations typically designed and detailed by a structural engineer because they are relevant to life safety and failure could pose a threat to life or could bring about significant economic loss. Due to his involvement in the design criteria, the structural engineer should be able to consider not only the properties of anchor bolts but also the properties of the concrete base material, which could influence its pull-out resistance. This is essential, for when anchors are subjected to an extreme tensile load, they become prone to breakout failure - concrete block breaking out from the bulk concrete. Thus, such failure evidently impend the safety and reliability of structures built with overloaded anchor connections. A number of researches have attempted to investigate the influence of base material on anchor properties. One research about possible effects of masonry aggregate in the highly stressed anchorage area of an anchor was investigated. Masonry aggregate concrete was introduced because in theory, with mixed recycled aggregates, it is most probable that only concrete aggregates will be located around the anchorage zone [1]. Other researchers did an extensive study on pull-out strength of fasteners under static load. As stated in their research, concrete breakout failure load is influenced by the concrete mechanical properties E_c (Modulus of Elasticity) and G_f (Fracture Energy). Moreover, given that these properties are related to the compressive strength of concrete, it is assumed that the compressive strength of concrete and the effective embedment length of the anchor bolt, that the failure load is proportional to the square root of compressive strength [2]. However, it should be noted that for the same compressive strength, E_c and G_f may also be influenced by the concrete mix, in particular, the type and the maximum size of aggregate. On the other hand, another study concluded that a nominal maximum aggregate size has an influence on the concrete compressive strength [3]. From these researches, it is thought that the size of coarse aggregates will have an effect on the anchor bolt pull-out performance.

In this study, the pull-out load capacity of an expansion anchor bolt at concrete breakout failure or simply breakout strength of an expansion anchor bolt was investigated as influenced by the concrete aggregates. Expansion anchors are post-installed anchors that transfer tension load to the concrete principally by friction. The frictional resistance of the anchor depends directly on the normal forces generated by the anchor expansion mechanism during installation and throughout the life of the anchorage. It is assumed that concrete aggregates located around the anchorage zone have sole direct shear contact with the anchor. These are fine aggregates and coarse aggregates. The influence of these aggregates in concrete breakout strength relative to its size and content was done by the demonstration of the pull-out test which measures the pull-out load capacity of the anchor bolts embedded in the concrete. Specifically, the factors considered in the investigation to influence the breakout strength of an expansion anchor bolt were coarse aggregate size, coarse aggregate content and fine aggregate content. The size of the coarse aggregate was selected since it covers more direct shear contact around the anchorage zone as compared to fine aggregates. This research was conducted to give significant information needed by a structural engineer on the design of expansion anchor bolts connection to structural concrete members relative to its concrete aggregate size and content. Specifically, this research will lead the construction industry to take a new approach involving the safe design of expansion anchor bolts connection for new construction or in some cases where there is a need for connecting a new structural member to an existing structural concrete member.

This research attempted also to identify factors of concrete aggregates that will optimize the breakout strength of an expansion anchor bolt in concrete. Lastly, this study aims to develop a regression model that could predict the breakout strength of an expansion anchor bolt as influenced by the concrete aggregates used relative to its size and content.

2. METHODOLOGY

2.1 Materials

The components of the pull-out specimens used in this research were the expansion anchor bolt and the concrete base material. In this research, a heavy-duty torque controlled mechanical expansion anchor bolt was used, with a diameter of 8mm, with a total length of 98mm and with a nominal tensile strength of 800MPa. The technical data of the anchor bolt is presented in Table 1 (i.e. required torque (T), effective embedment depth (h_{ef}), drilling depth (h_d), drilled hole diameter (D), and base thickness (H).

Table 1 Technical data of expansion anchor bolt

Type	T (Nm)	h_{ef} (mm)	h_d (mm)	D (mm)	H (mm)
	25	70	80	12	125

The concrete base material was composed of cement (C), water (W), fine aggregates (FA), and coarse aggregates (CA). Portland cement from Norzagaray, Bulacan Cement Plant that meets the American Society for Testing and Materials (ASTM) standard specification C150 was used in the design mix [4]. The water used was clean and of good quality. Crushed coarse aggregates with four sizes were considered - 10mm, 12.5mm, 19mm, and 25mm having a mass density of 1651kg/m^3 and 1.00% absorption were used as shown in Fig. 1. These coarse aggregates came from a single crusher located in Montalban, Rizal. For fine aggregates, sand with 2.6 fineness modulus and 0.80% water absorption was used.

Fig. 1 Crushed coarse aggregates sizes (25mm, 19mm, 12.5mm, and 10mm)

2.2 Specimens

Different concrete mixture proportions were used for different concrete specimens. This is presented in Table 2. The specimens varied according to their coarse aggregate size (S), coarse aggregate content (CAC), and fine aggregate content (FAC). The coarse aggregate content for each coarse aggregate size was 0.3452, 0.4046, 0.4462, and 0.4750, respectively. The fine aggregate content for each coarse aggregate size was 0.4243, 0.3771, 0.3514, and 0.3341, respectively. It is noticeable here that as the coarse aggregate size increases, the concrete aggregates content also increases, and on the other hand, the fine aggregates content decreases.

Although the mixture proportions varied, a uniform compressive strength of 21MPa at 28days curing period had been considered in the design mixture. This is to ensure that the compressive strength of the concrete specimens would not interfere with the pull-out performance of the expansion anchor bolts.

Table 2 Mix proportions of the specimens

S mm	W kg/m^3	C kg/m^3	CA (CAC) kg/m^3	FA (FAC) kg/m^3
10	222.84	304.66	790.13 (0.3452)	970.98 (0.4243)
12.5	214.67	291.61	938.28 (0.4046)	874.36 (0.3771)
19	203.62	274.20	1053.51 (0.4462)	829.82 (0.3514)
25	195.33	261.14	1135.82 (0.4750)	799.04 (0.3341)

Five samples were used for each type of coarse aggregate size, this is in accordance with ASTM E 488-96 [5]. The rectangular solid base material specimens measuring 350mm x 350mm x 125mm were made and cured for 28days. Then, the expansion anchors were installed in these base materials following the setting instructions recommended by the manufacturer as shown in Fig. 2. Simultaneously, 150mm concrete cube specimens for compressive strength test were prepared for each type of concrete base specimen. Two samples were used for each type of coarse aggregate size in accordance with ASTM C 39-05 [6]. After pouring, all the specimens were cured for 28days to attain the design compressive strength of 21MPa. During curing, the specimens were placed in an area where the rays of the sun could not reach; this is to ensure that the air temperature within the area was controlled.

Fig. 2 Installed expansion anchor bolts in concrete bases

2.3 Testing

The compressive strength of each specimen was tested according to ASTM C39-05 after 28days of curing period. Before the pull-out test of the expansion anchor bolts in concrete base material specimens takes place, actual compressive strength (fc) test result should meet the designed compressive strength (f'c) and should vary only within the acceptable deviation as per ASTM C39-05 [6]. The results from the compressive tests were first analyzed to check if all the concrete specimens have met the consistency requirement for compressive strength as specified by ASTM C 39-05 [6]. The consistency was also tested statistically using a one sample mean t-test at a level of significance of $\alpha = 0.01$. Specifically, the null hypothesis (H_o) was tested, i.e., if there is a significant difference between the actual compressive strength of the concrete specimens and the design compressive strength. The one sample mean t-test equation given by Scheaffer et al., is

$$t\text{-}stat = (\bar{x}-\mu)\left(\sqrt{n}/s\right) \quad (1);$$

where $\bar{x}$ = sample mean, μ = population means, n = sample size, and s = standard deviation of the samples [7]. The setup for the pull-out test and the concrete base specimen's failure mode are illustrated in Fig. 3.

Fig. 3 Pull-out test setup and concrete breakout failure mode

The loading device is positioned in such a way that it is centered over the anchor bolt that is to be tested. A reaction frame with four legs and with a side dimension greater than the diameter of cone failure was placed on the concrete base specimen to provide uniform contact between the surface of the structural member and the support frame. This is done in such a way that a concrete breakout failure was free for pull-out. Then, a pulling fixture was inserted at the anchor's head to pull it up vertically from the structural specimen as the load was applied slowly by Universal Testing Machine (UTM) to the pulling fixture. The pulling fixture is shown in Fig. 3 was of sufficient size to ensure that it would not fail when pulling the expansion anchor bolt from the concrete specimen. The concrete breakout failure, as also shown in Fig. 3, occurred after the point of maximum pull-out load.

2.4 Regression Modeling

The next step was to model the pull-out test results by linear and polynomial regression. These regression models display the effect on one variable when the response of the other variable is either a linear or curvilinear. General principles of multiple regressions also apply here. In this study, the influence of coarse aggregate size, coarse aggregate content and fine aggregate content to influence the concrete breakout strength of an expansion anchor bolt were checked. The linear and polynomial regression models as given by Montgomery and Runger are generally defined as

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i \quad (2)$$

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i<j}\sum \hat{\beta}_{ij} x_i x_j \quad (3);$$

where $\hat{y}$ is the concrete breakout strength, x_i, x_j are the factors of concrete aggregates, and $\hat{\beta}$ is the least squares estimate of model coefficients [8]. The significance and adequacy of these models were checked using F-test at α = 0.01. This is to ensure that the recommended model will give a satisfactory estimate of the true system. Then, the adjusted coefficient of multiple determination, R^2_{adj} and error metric were defined for each regression model and were compared. The adjusted coefficient of multiple determination or R^2_{adj} is a good measure for multiple predictor variables that estimate Pearson's correlation ratio with a value from 0 to 1 and is defined as:

$$R^2_{adj} = 1 - [SS_E/(n-p)]/[SS_T/(n-1)] \quad (4);$$

where SS_E is the sum of squares of the residuals, SS_T is the total sum of squares, n is the total samples used and p = k+1 degrees of freedom at their corresponding regressor (k). While the metric of error used was the mean square of error or MSE. The MSE as defined by Montgomery and Runger is [8],

$$MSE = SS_E / (n-p) \quad (5).$$

Finally, the regression model with highest R_{adj} and with least MSE was selected and its optimum result was compared to ETAG 001 (Guideline for European Technical Approval of Metal Anchors for Use in Concrete), and NSCP 2015 (National Structural Code of the Philippines 2015) equations for verification.

ETAG 001equation for the concrete breakout of a single anchor in non-cracked plain concrete is given by [9],

$$N = 10.1\sqrt{fc_{cube}}\, h_{ef}^{\,1.5} \quad (6)$$

The compressive strength using cylinder specimen was computed using the equation of Kumavat, HR and Patel, VJ [10],

$$fc = 0.95\, fc_{cube} \quad (7)$$

While the NSCP 2015 equation for the concrete breakout of a single post-installed anchor in non-cracked plain concrete is given by [11],

$$N = 9.8\sqrt{f'_c}\, h_{ef}^{\,1.5} \quad (8)$$

3. RESULTS AND DISCUSSIONS

3.1 Compressive Strength

The concrete cube specimens with dimension 150mm x 150mm x 150mm were tested for compressive strength, followed by the pull-out test of the expansion anchor bolt. The actual compressive strength (fc) of the concrete cube specimens as compared to the design compressive strength (f'c) was statistically tested to check their significant difference. The result of compressive strength test and test of significant difference is presented in Table 3 and Table 4, respectively.

Table 3 Compressive strength at 28 days result

CAS (mm)	Load, P (KN)	Stress, fc (MPa)	Mean fc (MPa)
10	410.3	18.24	
10	468.7	20.83	19.53
12.5	455.4	20.24	
12.5	426.3	18.95	19.59
19	449.7	19.99	
19	463.6	20.60	20.30
25	446.6	19.85	
25	454.9	20.22	20.03

Note: Mean fc Average = 19.86 MPa
Coefficient of Variance (CV) = 1.83%
Acceptable CV = 3.20%

It can be observed in Table 3 that all the compressive stress values show no difference with the required compressive stress. The actual coefficient of variance, the CV of the mean fc for all cases is 1.83%, which is less than the acceptable CV of 3.20% as set by ASTM C 39-05. This only shows that the test result for compressive strength as a whole is consistent. The consistency of the fc result was tested further for their significance difference using t-test as indicated in Table 4.

Table 4 t-test result

Parameters	Remarks
H_0	fc = f'c
H_1	fc ≠ f'c
n	8
t-statistics	-2.6306
t-critical	3.5
α, df	0.01, 7

Table 4 indicates that the t-statistics are numerically less than the t-critical. This results in the acceptance of the null hypothesis (H_o) and the rejection of the alternative hypothesis (H_1) at 0.01 level of significance (α) and at degrees of freedom (df) equals 7. This leads to a decision that there is no significant difference between fc and f'c of the concrete specimens. This means that fc of all concrete specimens are the same with those of f'c. This result allowed the pull-out test to proceed.

3.2 Concrete Breakout Strength

After passing the consistency requirements for fc, all the expansion anchor bolts were installed in their respective concrete base materials and then tested for pull-out where the results are tabulated in Table 5.

Table 5 Pull-out test result

CAS (mm)	Concrete Breakout Strength, N (KN)	Mean N (KN)
10	18.10	
10	20	
10	21	
10	21.6	
10	20	20.14
12.5	23.5	
12.5	21.8	
12.5	24.9	
12.5	23.1	
12.5	22.2	23.10

Table 5 Pull-out test result (cont.)

CAS (mm)	Concrete Breakout Strength, N (KN)	Mean N (KN)
10	18.10	
19	25.5	
19	26.4	
19	24.2	26.32
25	26.9	
25	26.4	
25	24.8	
25	25.8	
25	24.9	25.76

Generally, the mean concrete breakout strength increases as the size of the coarse aggregate increases. Specifically, the increased in concrete breakout strength occurred only from 10mm up to 19mm size and then decreased at 25mm. This result implies the possibility of a curvilinear relationship between the coarse aggregates size and the pull-out load capacity of an expansion anchor bolt.

The results of the pull-out test at concrete breakout failure are shown in Fig. 4, Fig. 5 and Fig. 6 relative to the coarse aggregate size, coarse aggregate content, and fine aggregate content, respectively. From these scatter plots, the response of breakout strength to each concrete aggregate regressor is obviously curvilinear rather than linear.

Among the concrete aggregate factors, the coarse aggregate size gives the best polynomial fit to the response as shown in Fig. 4. The breakout strength measures 20.14KN initially at 10mm and increased to 23.10KN by 14.70% and increased again to 26.32KN at 19mm by 14.00% and then decreased to 25.76KN at 25mm by 2.20%. It only implies that the breakout strength is optimum at 19mm coarse aggregates size.

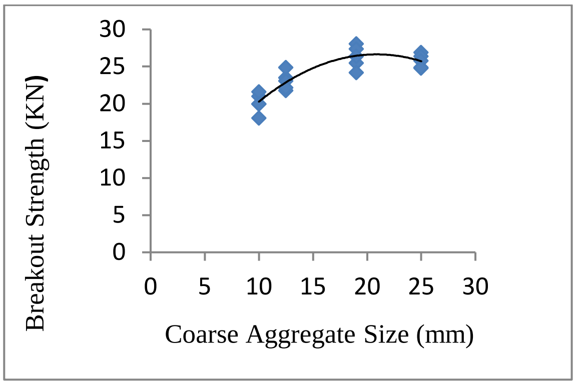

Fig. 4 Scatter plot of breakout strength against the coarse aggregate size

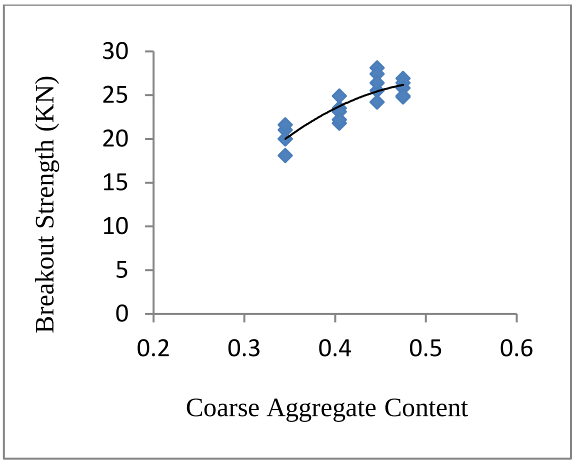

Fig. 5 Scatter plot of breakout strength against coarse aggregate content

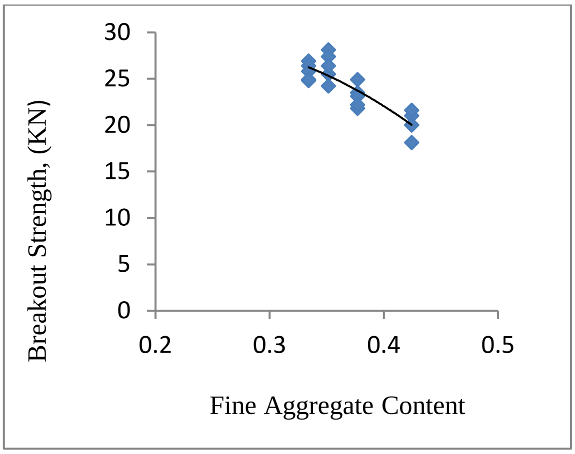

Fig. 6 Scatter plot of breakout strength against fine aggregate content

Table 6 shows the best performance of linear and polynomial regression model to predict the breakout strength of an expansion anchor bolt in concrete. Each regression was tested for the adequacy using the R_{adj}, MSE, and F-test at $\alpha = 0.01$. It is noticeable that breakout strength is best predicted using the polynomial regression model with coarse aggregate size as the sole predictor with R_{adj} of 0.894 and MSE of 1.55.

The optimum result of this model at 19mm coarse aggregate size and using cube compressive strength of 19.86MPa and h_{ef} = 70mm was verified to Eq. (6) and Eq. (8) as shown in Table 7. Note that the cylinder compressive strength was computed using Eq. (7).

Table 6 Comparison of regression models

Model	R_{adj}	MSE	F	$F_{\alpha,k,n-p}$
Poly(S,S^2)	0.894	1.55	38.74	6.11
Lin (S, CAC, FAC)	0.889	1.62	24.83	5.29

Note: S = Coarse Aggregate Size
CAC = Coarse Aggregate Content
FAC = Fine Aggregate Content

Table 7 Verification of polynomial regression model with other models

Model	Breakout Strength (KN)
Polynomial	26.455
NSCP 2015	24.930
ETAG 001	26.361

It can be observed that breakout strength result using the polynomial regression model is equally comparable to the results calculated from NSCP 2015 and ETAG 001 equations. This only implies that a polynomial regression model can be used to estimate the breakout strength of an expansion anchor bolt in concrete with coarse aggregate size as its predictor. The polynomial regression model is given by

$$N = -0.0539S^2 + 2.2493S + 3.1762 \quad (9);$$

where N is the breakout strength of an expansion anchor bolt at h_{ef} = 70mm, and S is the coarse aggregate size. This model applies only to the crushed coarse aggregate size ranging from 10mm to 25mm and to the concrete base material with compressive strength ranging from 19MPa to 21MPa.

4. CONCLUSION

Among the concrete aggregate predictors considered, coarse aggregate size turned out as the most significant variable to influence the breakout strength of an expansion anchor bolt embedded in concrete using a polynomial regression model.

Test results also show that breakout strength is optimum at 19mm coarse aggregate size.

5. ACKNOWLEDGMENTS

The following are acknowledged for their contribution in the completion of this research. Hilti for the HSL-3 M8/20 expansion anchor bolt used and Mapua University for its unceasing and vital support.

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