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Breakout Capacity of Headed Anchors in Steel Fibre Normal and High Strength Concrete

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ABSTRACT

This research studied the breakout capacity of cast-in-place single short-headed anchor bolts embedded in both normal and high strength steel fibrous reinforced concrete. Concrete strength ranged from 27.4 to 58 MPa, four volume fractions of steel fibres (0.4, 0.8, 1.2 and 1.6%), two aspect ratios (19.63, 36.36), three anchor diameters (8, 10 and 12 mm) and four embedment depths (25, 37.5, 50 and 62.5 mm) were used. The majority of the specimens were failed by concrete cone failure and the cone breaks into pieces in some cases (concrete failure), while the other specimens were failed by yielding or fracture of the bolts (steel failure). The tests results showed that the concrete angle cone is increasing with the embedment depth, the fibre reinforcing index and decreasing with the concrete strength. The breakout capacity of the anchors were increased by the addition of steel fibres to concrete and the size of the cones failure in fibrous concrete were smaller than the cones in plain concrete specimens. Based on the experimental results, an expression is proposed to estimate a variable concrete cone angle which is then used to predict the breakout capacity of single headed anchors embedded in normal and high strength fibrous concrete and showed good agreement with the test results. A regression equation based on the observed breakout capacities is also proposed to predict the breakout capacity and both methods showed the same degree of accuracy.

Key words: Anchor, breakout, high strength concrete, normal strength concrete, concrete cone angle, fiber

INTRODUCTION

Anchor bolts are often used as connections in reinforced concrete members for attachments of instruments and other non-structural members, as well as many other uses. A short anchor bolt is the one whose embedment depth is insufficient to develop tensile yield and usually fail by pullout or concrete cone failure (Klingner and Mendoca, 1982). Anchors transfer loads to the concrete by one or more of the following mechanisms, friction, chemical adhesion, mechanical interlock and bearing against the head (Fuchs *et al*., 1995).

Klingner and Mendoca (1982) presented a literature survey on the tensile capacity of short anchor bolts. They compared the results of available tensile tests with predictions of six design procedures and showed that these methods are not conservative and showed considerable scatter and procedures that are more accurate are necessary to predict safely the breakout capacity of anchor bolts. When failure occurs by a concrete cone failure, they recommended the use of (ACI, 1976) method.

The ACI Committee 349 (ACI, 1976) developed the circular cone model to predict the concrete breakout capacity of headed anchors. The failure surface is assumed in the form of a frustum circular cone making an angle of 45 with the concrete surface, Fig. 1a. The average tensile stress at failure assumed equal to ($\sqrt{f'_c}/3$), f 'c cylinder strength of concrete, the concrete breakout capacity, thus, equal to:

$$P = \frac{\sqrt{f'_c}}{3}\pi.h_{ef}^2\left(1+\frac{d_h}{h_{ef}}\right) \quad (1)$$

where, h_{ef} embedment depth measured from the upper edge of the anchor head to the concrete surface, d_h = head diameter. Correction factors were proposed for edge effect, i.e., anchors with edge distance ($c<h_{ef}$) and/or anchors affected by other concrete breakout cones.

However (Cannon *et al.*, 1975) suggested that the cone angle varies from about 25° for short embedment to about 45° for longer ones.

Fuchs *et al.* (1995) presented what they called the Concrete Capacity Design (CCD) approach to predict the concrete failure load of fastenings in uncracked concrete under monotonic tensile and shear loading. In tension, the inclination between the failure surface and the surface of the concrete member assumed = 35°. The failure surface was assumed as a right square pyramid, with its apex at the top of the anchor head and its base on the concrete surface with a side length of $3.h_{ef}$, Fig. 1b. The following equation was proposed:

$$P = k_{nc}.\sqrt{f'_c}.h_{ef}^{1.5} \quad (2)$$

where, k_{nc} =16.7 and is the product of three calibration factors k_1, k_2 and k_3. $k_1.\sqrt{f'_c}$ = nominal concrete tensile stress at failure over the failure area which is given by $k_2.h^2_{ef} = 9h^2_{ef}$ and $k_3/\sqrt{h_{ef}}$ is the size effect. The method showed accurate prediction of the concrete failure load of headed anchors. On the other hand, the predictions of ACI (1976) method are sometimes unconservative and sometimes conservative.

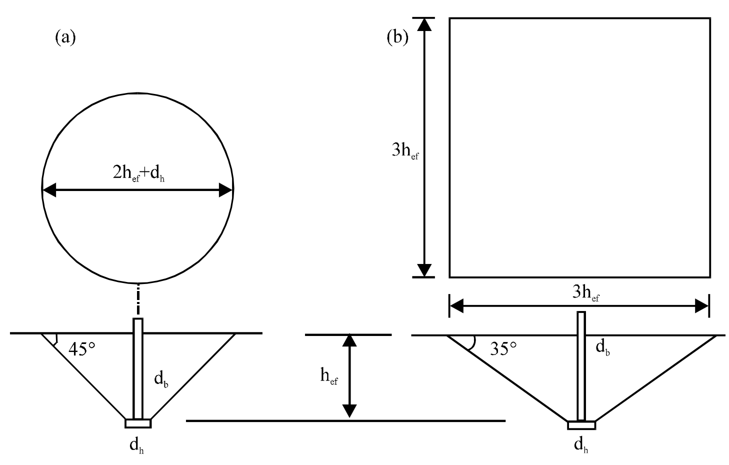

Fig. 1(a-b): Concrete cone failure geometry, (a) ACI 349-85 Method [76, 85] and (b) CCD-Method (Fuchs *et al.*, 1995)

The validity of Eq. 1 and 2 was tested by Farrow *et al.* (1996) and what they called the variable angle cone method VAC by comparing the test results of tensile capacity of 801 single anchors placed in uncracked, un-reinforced concrete and governed by concrete cone failure with the prediction of these three methods. The variable angle cone method has the following form:

$$P = 0.96\sqrt{f_{cc}}\,h_{ef}(h_{ef}/\tan(\theta) + d_h) \tag{3}$$

where, f_{cc} = cube strength and θ = angle of inclination of the failure cone with the concrete surface and is assumed equal to:

$$\theta = 28+0.134h_{ef} \text{ for } h_{ef} \leq 127 \text{ mm} \tag{4a}$$

$$\theta = 45° \text{ for } h_{ef} > 127 \text{ mm} \tag{4b}$$

It was found that for single tension anchors with embedment depths less than 200 mm, all the three capacity prediction methods fit most of the data relatively well. However, the CCD method is more accurate and has a distinctly lower probability of failure when the embedment depth is greater than 200 mm.

Concrete cone failure was generally observed for anchors embedded in normal and high strength steel fibrous concrete with shallow depths by Gesoglu *et al.* (2005). The measured cone angles ranged from 20 to 25° for 40 to 80 mm embedment depths. The concrete cones for the concrete fibres specimens were of two or more pieces rather than a complete cone, so that, the angle of failure could not be easily measured.

Qian and Li (2009) investigated the influence of the material ductility on the anchor bolt performance, by replacing the conventional concrete with a relatively new ductile concrete material (engineered cementitious composite ECC), this type of material have a strain hardening to several percent tensile strain capacity (Anwar *et al.*, 2009). Both 2D and 3D specimens were used together with five concrete materials with tensile strain capacities ranging between 1.5-2.5%. The experimental results showed that the anchor/ECC connections exhibit a more ductile failure mode, a higher ultimate strength, a higher displacement capacity and higher energy absorption compared with connections with conventional concrete. A tentative equation was proposed to predict the pullout load capacity of an anchor embedded in ECC, in the following form:

$$P = 3.8h_{em}^2 . f_{tu} \tag{5}$$

where, h_{em} = embedment length including the anchor head thickness and f_{tu} = tensile strength of the composite.

The objective of this investigation was to propose a method for the prediction of the breakout capacity of single short-headed anchor bolts embedded in normal and high strength steel fibrous concrete.

MATERIALS AND METHODS

Ordinary Portland cement and gravel with maximum aggregate size of (10 mm) are used for both the normal strength concrete (Mohammed, 2006) and high strength concrete (Al-Jaffal, 2007). Medium size sand with a fineness modulus of 2.91 and 2.77 were used for the normal strength and high strength concretes, respectively. Harex steel fibres of shelled deformed cross section were used with two lengths L_f = 16 and 32 mm and four volume fractions V_f = 0.4, 0.8, 1.2 and 1.6%. The details of the mixes were shown in Table 1. For high strength concrete, three mix proportions were used (Mix M1, Mix M2 and Mix M3) and super plasticizer was used to increase the workability of concrete (Dawood and Ramli, 2011).

Table 1: Details of the Mix proportions

		High strength concrete		
Concrete type	Normal concrete	Mix M1	Mix M2	Mix M3
Mix proportions by weight				
Cement	1	1	1	1
Sand	1.7	1.5	1.35	1.35
Gravel	3.5	2	1.6	1.6
W/C	0.45	0.38	0.35	0.32
Admixture type	-	Pozzolith LD10	Pozzolith LD12	Rheobuild SP1
Admixture dose (mL kg^{-1}) of cement	-	4	4	10
Concrete cylinder strength (MPa)	27.4-34.5	45	53	58
Anchor diameter (mm)	8, 10,12	10, 12	10, 12	10, 12
Fibres volume percentage (V_f)	0, 0.4, 0.8,1.2, 1.6	0, 0.4,0.8, 1.2	0, 0.4,0.8, 1.2	0, 0.4,0.8, 1.2
Fibres aspect ratio (L_f/D_f)	19.63, 36.36	36.36	36.36	36.36
Embedment depth h_{ef} (mm)	25, 37.5, 50, 62.5	25, 37.5, 50	25, 37.5, 50	25, 37.5, 50
No. of specimens	90	22	24	23

The mixing procedure, detail of the control specimens, curing regime, concrete properties, dimensions of the specimens and the testing procedure were mentioned by Al-Taan and Mohammed (2010a, b) and Al-Taan and Al-Jaffal (2011).

The test results were presented by Mohammed (2006), Al-Taan and Mohammed (2010a, b) Al-Jaffal (2007) and Al-Taan and Al-Jaffal (2011) and a brief description of the studied variables are shown in Table 1. The total number of the tested specimens was 180; twenty-one specimens were failed by steel fracture and excluded from the analysis performed in this study. The detail of the other 159 specimens that were failed by concrete cone were shown in Table 1.

RESULTS AND DISCUSSION

Proposed methods: Two methods were proposed for the prediction of the breakout capacity of single headed anchors embedded in steel fibre normal and high strength concrete.

First method: Concrete cone failure was generally observed for anchors embedded both in normal and high strength concrete, as shown in Fig. 2a, d and f. The concrete cones for some of the concrete fibrous specimens were of many pieces rather than a complete cone, as shown in Fig. 2c and e, as shown also by Gesoglu *et al.* (2005) and for this reason, the angle of the concrete cone could not be easily measured.

In this method, failure of the specimens is assumed as that in (ACI-Committee 349) but with variable angle cone (Farrow *et al.*, 1996); i.e., a circular frustum cone with its apex at the anchor head but with a varying angle with the anchor head. The breakout capacity (P_o) of headed anchors embedded in plain concrete in this case equal to:

$$P_o = f_t' \pi . h_{ef} [h_{ef} / \tan(\theta) + d_h] \qquad (6)$$

Fig. 2(a-f): Failure patterns of some specimens (a) $f'_c = 30$ MPa, $h_{ef} = 25$ mm, $d_b = 8$ mm, $V_f = 0$, (b) $f'_c = 27.4$ MPa, $h_{ef} = 37.5$ mm, $d_b = 10$ mm, $V_f = 12\%$, $L_f = 32$ mm, (c) $f'_c = 34.5$ MPa, $h_{ef} = 62.5$ mm, $d_b = 10$ mm, $V_f = 0.8\%$, $L_f = 16$ mm, (d) $f'_c = 45$ MPa, $h_{ef} = 37.5$ mm, $d_b = 12$ mm, $V_f = 0.8\%$, $L_f = 32$ mm, (e) $f'_c = 53$ MPa, $h_{ef} = 50$ mm, $d_b = 10$ mm, $V_f = 1.2\%$, $L_f = 32$ mm and (f) $f'_c = 58$ MPa, $h_{ef} = 25$ mm, $d_b = 10$ mm, $V_f = 0$

where, f'_t = tensile strength of plain concrete assumed equal to $\sqrt{f'_c}/3$. Steel fibres enhance many mechanical engineering properties of concrete among which is the tensile strength, (Ramli and Dawood, 2011a, b; Wegian *et al.*, 2011). For anchors embedded in steel fibres concrete, the contribution of the steel fibres to the breakout capacity is estimated as proposed by Mohammed (2006) by multiplying the lateral surface area of the failure cone by the post cracking tensile strength (σ_{ct}) of the steel fibres concrete:

$$P_f = \sigma_{ct}.\pi.h_{ef}[h_{ef}/\tan(\theta)+d_h] \quad (7)$$

$$\sigma_{ct} = (\tau_u/2).V_f(L_f/D_f) \quad (8)$$

and τ_u interfacial bond strength of the steel fibres to concrete, and assumed equal to 4.15 MPa as proposed by Swamy *et al.* (1974). By adding both sides of Eq. 6 and 7, the total breakout capacity (P_t) of headed anchors embedded in steel fibres concrete, thus equal to:

$$P_t = (f'_t+\sigma_{ct}).\pi.h_{ef}[h_{ef}/\tan(\theta)+d_h] \quad (9)$$

The angle of inclination (θ) is calculated from the above equation, by using the observed breakout capacity. The calculated values of the angle of inclination seemed to increase with the embedment depth, fibre reinforcement index ($V_f.L_f/D_f$) and decrease with the concrete strength. A regression analysis is performed for (θ) as the dependent variable, h_{ef}, $V_f.L_f/D_f$ and the concrete strength f'c as the independent variables. The regression analysis resulted in the following equation for the angle of inclination:

$$\theta = 7.56\sqrt{\frac{h_{ef}}{(1-V_f.L_f/D_f)\sqrt{f'_c}}}+6.3 \quad (10)$$

With a correlation coefficient = 0.8.

Equation 4a,b of the variable angle method (Farrow *et al.*, 1996) was compared with Eq. 10 and Fig. 3 shows the two equations. The difference between the two equations decreased from 37% for an embedment depth of 25 mm to 3% for an embedment depth of 127 mm.

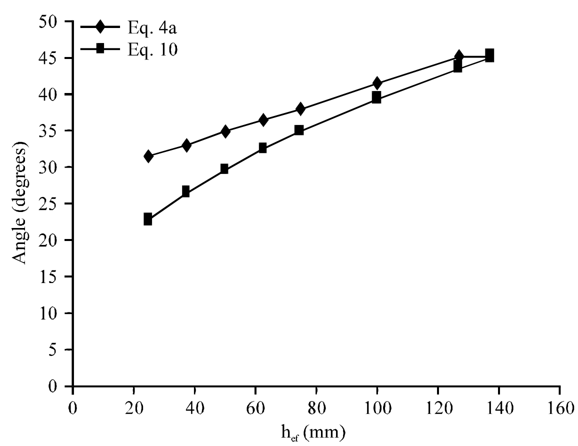

Fig. 3: Variation of the angle of inclination with the embedment depth, V_f = 0, f'_c = 27.4 MPa

Figure 4 shows that both the calculated values of the angle of inclination from Eq. 9 with those computed from Eq. 10 increased with the embedment depth, for a concrete strength of 45 MPa. The same trend were also noticed for other concrete strengths.

Figure 5 shows that both the calculated values of the angle of inclination from Eq. 9 with those computed from Eq. 10 decreased with the concrete strength. Similar trend was noticed for other embedment depths and fibre reinforcement index.

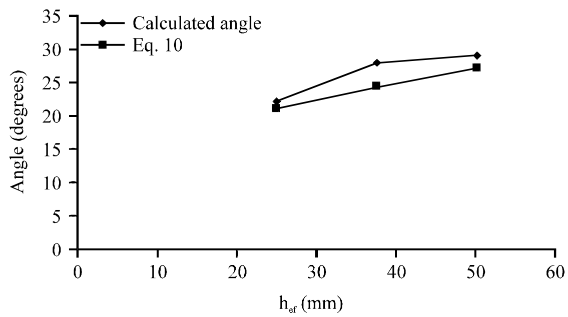

Fig. 4: Variation of the angle of inclination with the embedment depth, $f'_c = 45$ MPa, $V_f = 0$, $d_b = 12$ mm

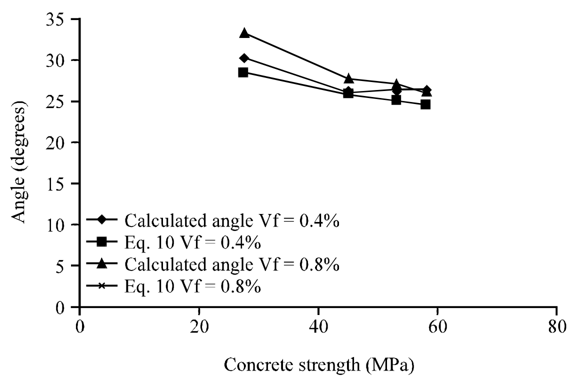

Fig. 5: Variation of the angle of inclination with the concrete strength, $h_{ef} = 37.5$ mm, $D_b = 10$ mm

Figure 6 shows that both the calculated values of the angle of inclination from Eq. 9 with those computed from Eq. 10 increased with the fibre reinforcement index $V_f.L_f/D_f$. This is in agreement with Gesoglu *et al.* (2005) finding that the failure cone is becoming smaller with the addition of steel fibres.

Equation 10 was used to estimate the failure angle and to predict the breakout capacity as shown in Eq. 9 of the headed anchors tested by Mohammed (2006) and Al-Jaffal (2007). In some of the specimens, the small angles led to a cone with a diameter higher than that of the specimen, like the one shown in Fig. 2b, in these cases the calculated breakout capacity should be reduced by multiplying it by a Modification Factor (MF) as follow:

$$MF = (1.2 - 0.6V_f L_f / D_f)\frac{\pi D^2/4}{\pi(2h_{ef}/\tan(\theta) + d_h)^2/4} \leq 1.0 \quad (11)$$

where, D = diameter of the specimen.

The average value of the tested/calculated breakout capacity of the 159 specimens is 1.007, standard deviation = 0.089, coefficient of variation = 0.088 and a skewness α = 0.184 (very small), which means that the right tail of the curve is slightly longer than the left tail, 80 values out of the 159 is concentrated to the right of the equality line 1.0. Figure 7 shows the histogram and the normal distribution curve of the P_{test}/P_{pred} values. The histogram show that 73% of the results lies within ±10% of the equality line 1.0.

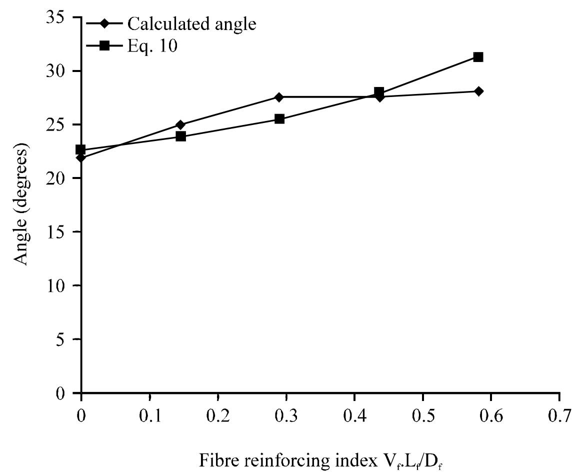

Fig. 6: Variation of the angle of inclination with the fiber reinforcement index, D_b = 8 mm, h_{ef} = 25 mm, f'_c = 30 MPa

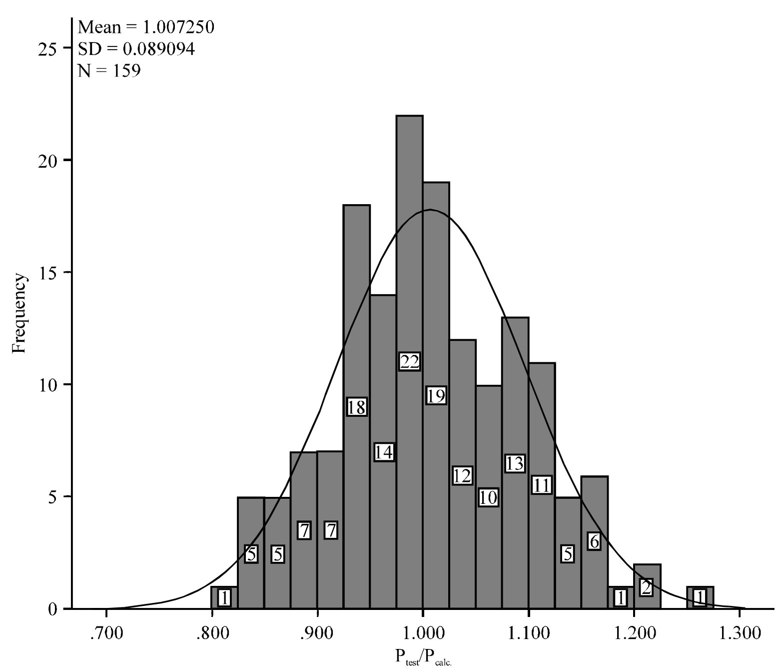

Fig. 7: Histogram and normal distribution curve for the proposed method

Second method: The following equation was derived from a regression analysis by Mohammed (2006) to predict the breakout capacity of headed anchors embedded in steel fibres normal concrete with cylinder strength ranging from 27.4 to 34.5 MPa:

$$P = [16.2\sqrt{f_c^{'}} + 49.V_f.L_f / D_f]h_{ef}^{1.5} \tag{12}$$

In this study, a similar equation was also derived for the (69) high strength concrete specimens with cylinder strength ranging from 45 to 58 MPa and the following equation was obtained:

$$P = [16.7\sqrt{f_c^{'}} + 89.V_f.L_f / D_f]h_{ef}^{1.5} \tag{13}$$

By comparing, Eq. 12 and 13 it can be seen that the first term is almost the same as that of Eq. 2 of the CCD method (Fuchs *et al*., 1995). The increase in the second term of Eq. 13 over that of Eq. 12, could be interpreted as follow; higher concrete strength will result in higher interfacial bond strength of the steel fibres which will increase the post cracking strength of steel fibres concrete as shown in Eq. 7. To use a unified equation for both normal and high strength concrete, the second term of Eq. 12 was modified as follow, to compensate for the increase in the concrete strength:

$$P = [16.2\sqrt{f_c^{'}} + (2.f_c^{'} - 11)V_f.L_f / D_f]h_{ef}^{1.5} \tag{14}$$

The average value of the tested/calculated breakout capacity is 1.007, standard deviation = 0.103, a coefficient of variation = 0.102 and a skewness α = -0.65 which means that the mass of the distribution (100 values out of the 159) is concentrated on the right of the figure. Figure 8 shows

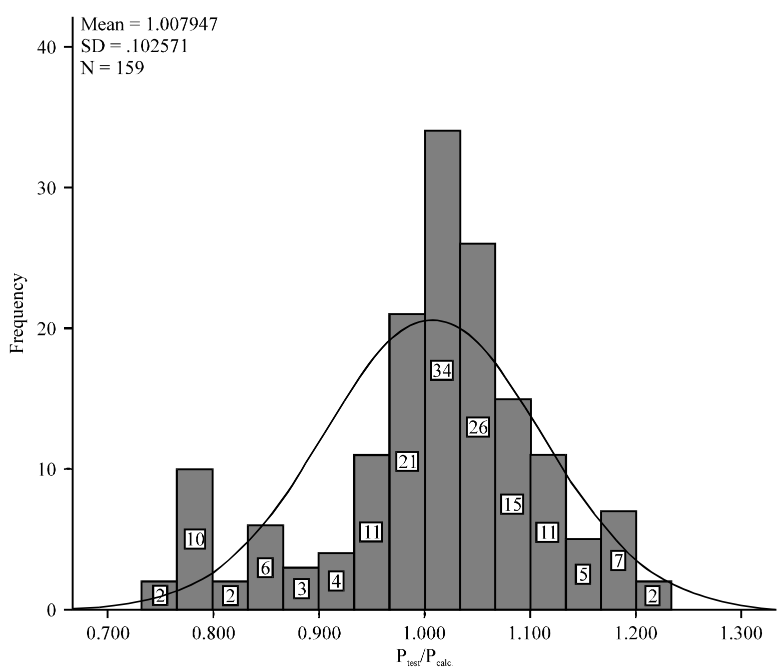

Fig. 8: Histogram and normal distribution curve for the proposed method regression Eq. 13

the histogram and the normal distribution curve of the P_{test}/P_{pred} values. The histogram show that 70% of the results lies within ±10% of the equality line 1.0. The prediction for this method is more conservative than the first one.

The failure angle proposed by Farrow *et al.* (1996) in Eq. 4a for embedment depth = 127 mm was used in Eq. 9 to estimate the breakout capacity of the tested specimens. The average value of the tested/calculated breakout capacity is 1.137, standard deviation = 0.155, coefficient of variation = 0.136 and a coefficient of skewness of $\alpha = 0.18$, (very small) which means that the right tail of the curve is longer than the left tail (90 values out of the 159). Figure 9 shows the histogram and the normal distribution curve of the P_{test}/P_{pred} values. The histogram show that 33% of the results lies within ±10% of the equality line 1.0. The prediction for this method is more conservative than the first two methods.

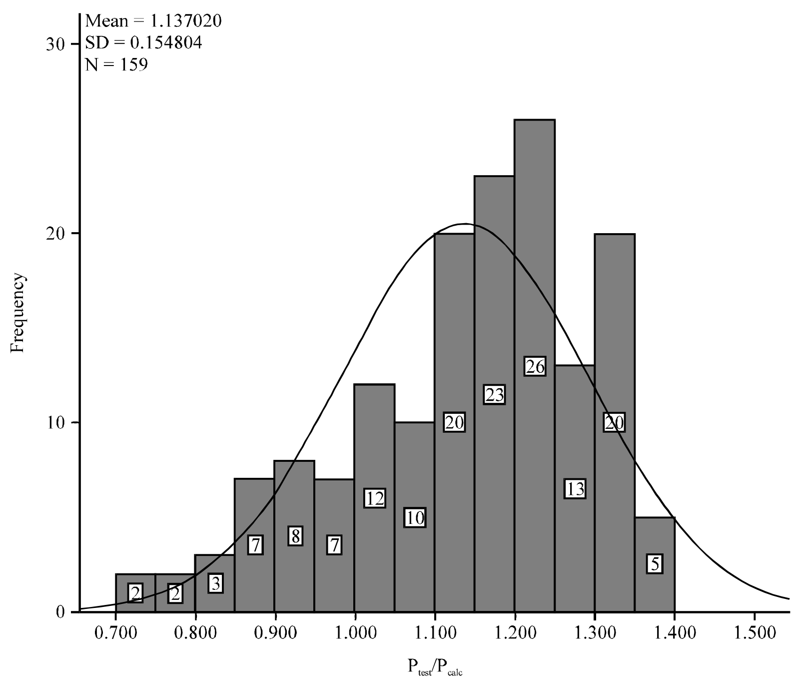

Fig. 9: Histogram and normal distribution curve for Eq. 4a and 9

Table 2, shows that methods 1 and 2 have the same equal average ratio of P_{test}/P_{pred} but method 1 has smaller standard deviation, coefficient of variation, skewness value and the highest number of the ratios P_{test}/P_{pred} within ±10% of the equality value, therefore, it can be considered superior to method 2.

Table 2: Comparison of the three methods of predicting the breakout capacities

Method	Average p_{test}/p_{calc}	Standard deviation	Coefficient of variation	Skewness	Percentage within ±10% of the equality line
Proposed method using Eq. 9, 10	1.007	0.089	0.088	0.184	73
Regression Eq. 13	1.007	0.103	0.102	-0.65	70
Proposed method using Eq. 4a	1.137	0.126	0.109	0.18	33

Table 2 show also, that methods 1 and 2 are preferable to method 3, because of the higher average ratio P_{test}/P_{pred}, standard deviation, coefficient of variation and the least number of the ratios P_{test}/P_{pred} within ±10% of the equality value.

CONCLUSIONS

The failure angle which was calculated from the experimental results showed that it was increased with the embedment depth, the fibre reinforcing index and decreased with the concrete strength. The two proposed methods predicted the breakout capacity of short headed anchors embedded in normal and high strength fibrous concrete with acceptable degree of accuracy.

More experimental data may result in a better understanding of the role of steel fibres in enhancing the breakout capacity and changing the failure mode and a more accurate and reliable prediction method.

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