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Edge distance effects on the tensile behaviour of screw anchors installed in early age concrete: Experimental research and predictive model

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Abstract: Screw anchors are increasingly used for temporary applications and are therefore implemented in both structural and non-structural capacities, such as: fixing of temporary safety handrails or barriers to concrete slabs in multistorey constructions, connection of scaffolding to the slab edge running up the face of a building during construction or connection of prop system to the concrete slab for formwork assembly. Current design codes, based on the Concrete Capacity Method (CCM), assume a mature concrete cone failure mode, which is highly sensitive to edge distance. This study investigates this assumption through an experimental program of 24 pull-out tests on M10 anchors in concrete at 24h, 48h, 7 days, and 28 days, at edge distances of 40mm, 60mm, and 90mm. The findings reveal a fundamental shift in the failure mechanism: all early-age samples failed via pull-out failure, irrespective of edge distance. This is attributed to low concrete strength being insufficient to activate cone failure. Consequently, the pull-out mode, which is independent of edge proximity, becomes the governing limit state, rendering edge distance insignificant in early-age applications and contradicting CCM-based models. This study further demonstrates that existing pull-out models significantly overestimate capacity in early-age concrete. Therefore, a new predictive model for pull-out failure is proposed, recalibrating the existing model's calibration factor (k=15.6) based on the early-age experimental data to improve prediction accuracy. The conclusions drawn in this study are therefore restricted to this anchor configuration, installed in normal-strength N40 concrete at ages of 24 h, 48 h, 7 days and 28 days and at edge distances of 40–90 mm, and should be interpreted within this specific range of test conditions.

Keywords: screw anchor, early-age concrete, pull-out failure, edge distance, predictive capacity model, Concrete Capacity Method (CCM).

1. Introduction

The use of post-installed screw anchors has seen significant proliferation in temporary construction works, such as the fixing of safety handrails, scaffolding ties, and formwork prop systems [1]. The rapid, non-percussive installation and immediate load-bearing capacity of these anchors are highly advantageous for accelerating construction schedules [2,3]. However, these temporary applications often necessitate anchor installation in concrete at a very early age, potentially within 24 to 48 hours of casting, to avoid delays. Compounding this, applications like perimeter safety barriers and scaffolding systems frequently require installation near the slab edge. This scenario combining early-age (low-strength) concrete with reduced edge distances presents a critical safety challenge, as existing design standards and manufacturer recommendations are typically predicated on the behaviour of anchors in mature concrete [4–6].

Current design provisions, such as those codified in AS5216 [5], are largely based on the Concrete Cone Capacity (CCM) method, originally developed by Fuchs et al [7]. This model assumes a cone failure mechanism, where the anchor's tensile capacity is governed by the projected area of a concrete cone. Consequently, the CCM is highly sensitive to edge distance; as the anchor is placed closer to an edge, this projected area is truncated, and significant reduction factors are applied [8–10]. Manufacturer technical data mirrors this logic, providing reduction factors for near-edge installations. The critical limitation, however, is that this entire design framework and its associated reduction factors was developed and validated using data solely from mature-age concrete. Its applicability to early-age concrete, where mechanical properties are vastly different, remains unverified. In fact, experiments on anchors in high-strength and ultra-high-performance concretes show that standard design assumptions may not directly apply in those cases, further highlighting the need to reassess anchor design models for non-conventional concrete conditions [11].

An important hypothesis emerges: the low tensile strength of early-age concrete may be insufficient to facilitate the development of a full concrete cone [12,13]. This low strength may inhibit the standard cone mechanism, causing the dominant failure mode to shift to pull-out failure [1]. Unlike cone failure, pull-out resistance is generated locally by the mechanical interlock of the anchor threads with the concrete substrate [1,14]. Theoretically, this mechanism's capacity is governed by the concrete volume confined between the threads and is thus independent of the anchor's proximity to an edge. If this mechanistic shift occurs, the foundational assumption of the CCM and its associated edge distance sensitivity becomes invalid, rendering current design guidance potentially inappropriate [15].

This uncertainty defines an important research gap. While pull-out models exist, such as the widely cited one of Mohyeddin et al [13], they are rarely validated against early-age data. Recent comparisons have revealed that both CCM-based manufacturer specifications and the pull-out model of Mohyeddin et al significantly over-predict the tensile capacity of anchors in early-age concrete [16]. In parallel, numerical studies have underscored the difficulties in accurately simulating anchor behavior under such novel conditions [17], which further emphasizes the lack of a reliable predictive tool for practitioners. As these formulae were not calibrated using low-strength concrete data, their applicability in this domain is highly questionable, leaving practitioners without a reliable predictive tool. Additionally, recent testing of screw anchors in thin concrete elements has demonstrated that member geometry (such as limited concrete thickness) can markedly influence anchor tensile capacity [18], further complicating direct extrapolation of standard models to all field conditions.

This paper addresses this gap by investigating three primary questions: (Q1) Does edge distance influence the tensile behaviour of screw anchors installed in early-age concrete when pull-out failure is the dominant mode? (Q2) Why does the dominant failure mechanism shift under early-age conditions? (Q3) Can a reliable predictive model for early-age pull-out resistance be calibrated? To answer these, this study provides three key contributions: (i) controlled experimental evidence clarifying that edge distance is not a governing parameter when pull-out failure occurs at early ages; (ii) a mechanistic interpretation linking the failure mode shift directly to the concrete's tensile strength development; and (iii) a newly calibrated pull-out model that demonstrates high predictive accuracy (R^2 = 0.985) for anchors in early-age concrete.

2. Methodology

2.1. Test matrix and specimens

2.1.1. Anchor selection

Galvanised carbon steel screw anchors of size M10x100mm were selected for of this research (Fig. 1). This particular choice was governed by its representation of typical scaffolding anchor ties used in the Australian construction industry, which typically fall within the M10 or M12 range.

Fig. 1. M10x100 galvanised ankascrew [19]

Table 1. Anchor installation data [13]

Anchor Parameter	M10 Anchor
Drill Hole Diameter	10 mm
Drill Depth	85 mm
Nominal Embedment Depth	65 mm
Effective Embedment Depth	59 mm
Anchor Length	100 mm
Minimum Concrete Thickness	89 mm

To isolate the research variables, all anchor installation parameters were kept constant throughout the experimental programme. These parameters, obtained from the manufacturer [19], are summarised in Table 1 and Fig. 2. Key controlled parameters included a drill hole diameter (d_0) of 10 mm, a drill depth (h_1) of 85 mm, a nominal embedment depth (h_{nom}) of 65 mm, and an effective embedment depth (h_{ef}) of 59 mm.

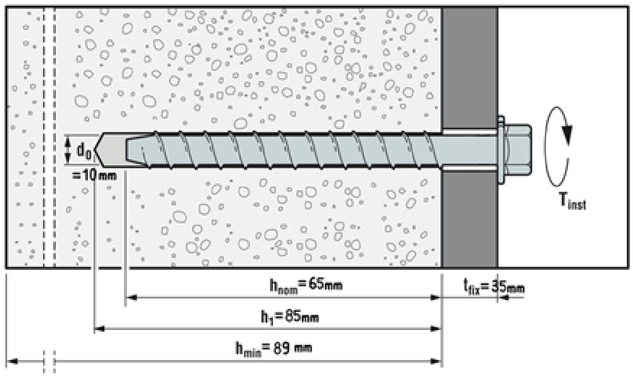

Fig. 2. Anchor installation parameters.

The following parameters in Table 2 are determined by the adapted CCM as per AS5216 [5]. This data governs the selection of research parameters; namely the critical spacing of anchors so as to avoid the influence of interaction between anchors and critical edge distance to dictate test edge distances which will impose an influence on cone formation.

Table 2. Anchor parameter data

Anchor Parameter	M10 Anchor
Critical Edge Distance (Cone)	88.5 mm
Critical Spacing (Cone)	177 mm
Critical Edge Distance (Splitting)	88.5 mm
Critical Spacing (Splitting)	177 mm

2.1.2. Concrete substrate specimens

The concrete substrate was cast into 10 separate beams, each with dimensions of 200 mm (Width) x 750 mm (Length) x 125 mm (Depth). This size was selected to allow three anchors to be tested per beam while meeting spacing requirements.

A normal class N40 concrete mix design, in accordance with AS1379 [20], was used consistently for all specimens. The mix comprised 10mm maximum aggregate size and Ordinary Purpose Cement (OPC) conforming to AS3972 [21]. The selection of N40 concrete reflects standard industry conditions and facilitates direct data comparison with previous studies [2,22]. Concrete beam specimens were ambient cured. After being stripped of formwork the day after casting, the specimens were covered with a plastic sheet to ensure consistent elemental exposure across all test beams.

A key methodological decision was the selection of the 125 mm beam depth. This depth is significantly greater than the minimum concrete thickness (h_{min}) of 89 mm specified by the manufacturer (presented in Table 1). By ensuring the substrate thickness was not a limiting factor, this experimental design effectively isolated edge distance as the primary geometric variable influencing failure, removing slab thickness as a confounding variable.

2.1.3. Concrete cylinder samples

To measure the evolving mechanical properties of the concrete at each test interval, control cylinder samples were cast concurrently from the same batch as the beam specimens. Six cylinder samples, 100mm (Diameter) x 200mm (Height), were required for each associated test beam. These samples were designated for determining the compressive and tensile strength at the time of the pull-out test. Compressive strength tests were conducted in accordance with AS1012.9 [23], while indirect tensile strength tests were conducted per AS1012.10 [24].

2.1.4. Experimental variable matrix

The programme investigated two primary independent variables: edge distance and concrete age at testing. Three edge installation distances were tested in this research. One installation distance is the critical edge distance as per Table 2, which has been rounded to 90mm. This is a control distance as it theoretically does not provide any edge effect to the pull-out data. This is comparable to the previous study conducted by Mohyeddin et al [2] with a data set of 70 screw anchor pull-out tests, where edge influence was not introduced. The remaining two edge installation distances are incremental decreases from the critical edge distance, being 60mm and 40mm. Minimum edge installation distance was limited to 40mm in order to mitigate the potential for unsuccessful installation due to concrete splitting.

Each edge distance at each test age has a sample size of 2, meaning the test is repeated twice to increase validity and reliability. Given this limited sample size of two specimens per age–edge-distance combination, the statistical indicators reported later in this paper (mean values and coefficients of variation) should be regarded as indicative measures of variability rather than precise estimates of population parameters, and the interpretation of scatter focuses on relative trends rather than formal statistical inference.

Each edge distance was tested at a total of four concrete ages, meaning data is gathered for four separate compressive strengths. Test ages of 24hr, 48hr and 7 days are classified as the early age period for concrete in this research with respect to compressive and tensile strength gain. A 28-day test age was included as a control test age to provide validity to data as comparison is facilitated against a standard N40 concrete mix design performance. Screw anchors were installed and tested at each specified test age. Compressive crush test and indirect tensile tests were simultaneously conducted at each test age to accompany pull-out data.

Table 3. Test specimen code

Batch Number	Age	Edge distance	Example Test Code
1, 2, 3, 4 & 5	24hr, 48hr, 7day & 28day	90mm, 60mm, 40mm	B1-24-90

Each pull-out test is defined by a specimen code which allows the identification of its installation variables. The code is comprised of batch number to indicate different concrete pours, followed by concrete age at which test was conducted and ending with edge installation distance. This is summarised below in Table 3 for clarity.

2.2. Pull-out Behaviour Testing

2.2.1. Installation

Installation holes are drilled using a rotary hammer drill on a stand, which allows for accuracy of installation and aims to reduce error by increasing uniformity. The positions of the holes are shown in Fig. 3. The guide hole was drilled to the recommended depth as per Table 1 and prepared as per the specification by Ramset [19]. Screw anchors were installed using a manual torque wrench where the maximum torque does not exceed 110kNm to prevent damage to the screw anchor during installation [12]. An impact torque wrench whilst used in previous literature was decided against due to findings of Mohyeddin et al [8] that edge installation with this method induces cracking of the concrete which has the potential to detrimentally influence the pull-out capacity of the anchor. As this study focuses on the effect of edge distance, introducing premature installation-induced cracks would have compromised the results, confounding installation damage with load-induced failure. Therefore, the manual method was chosen to protect the integrity of the concrete substrate at reduced edge locations.

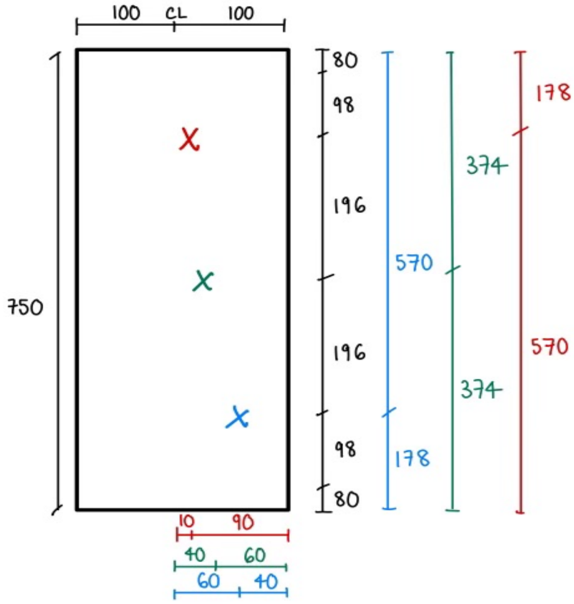

Fig. 3. Sample installation layout (mm)

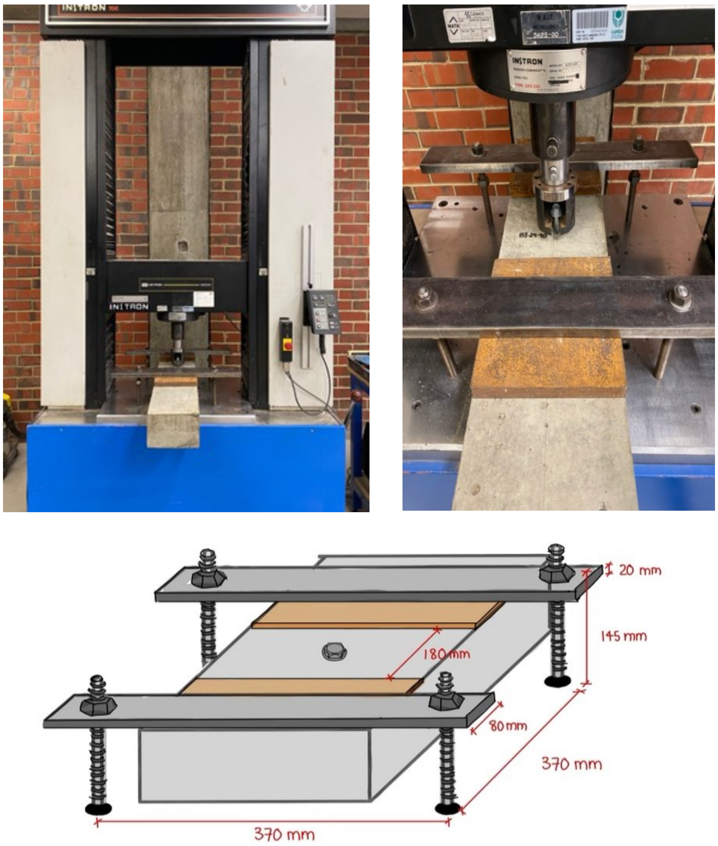

Fig. 4. Experimental Pull-out test set up

2.2.2. Pull-out Behaviour Testing

The ultimate tensile capacity of the screw anchors was measured using the Instron 5500R Universal Testing Machine. This machine was selected as it allows for pull-out testing using a universal test grip, without the restrictions of a circular reacting frame support. This method used in previous literature was identified as having potential influence on the cone formation behaviour of the pull-out test as the clear span of the reacting frame was not sufficient, as cone formation extended beyond this perimeter [1]. The Instron was set up with two steel restraint plates which were designed to be outside the area of influence, the test set up is demonstrated in Fig. 4. The loading rate, 3kN/min, applies a load at a controlled slow rate to reflect onsite conditions where deformation due to load will occur gradually.

3. Results and Discussion

3.1. Experimental Research Results

The experimental results on 24 experimental samples are summarized in Table 4. This table includes the specimen identification code, the observed failure mode, the ultimate tensile strength (N_{ult}), the concrete compressive (F_c) and splitting tensile ($F_{t,sp}$) strengths at the time of testing, and the corresponding peak displacement. An initial analysis of the data reveals an expected and clear proportional trend between concrete strength and the ultimate tensile capacity of the anchor. As the concrete age increased from 24 hours (with F_c ranging from 7.4–11.2 MPa) to 28 days (with F_c ranging from 40.0–47.6 MPa), the average tensile capacity of the anchors increased significantly.

Table 4. Summary of Experimental Data

CODE		Failure Mode	Nult (kN)	Avg N_{ult} (kN)		CV of Nult (%)		F_c (MPa)	$F_{t,sp}$ (MPa)	Peak Disp. (mm)
	90	Pull-out	12.77							0.955
B1-24-	60	Pull-out	11.20	11.97		6.53		11.24	1.57	0.780
	40	Pull-out	11.94							0.813
	90	Pull-out	10.39							0.777
B3-24-	60	Pull-out	10.46	9.62		14.42		7.39	1.11	0.802
	40	Pull-out	8.02							0.716
	90	Pull-out	14.89							0.874
B1-48-	60	Pull-out	12.35	14.80		16.28		20.17	2.05	2.088
	40	Pull-out	17.17							3.141
	90	Pull-out	15.10							1.562
B4-48-	60	Pull-out	15.21	14.64		6.07		21.95	2.42	0.931
	40	Pull-out	13.62							0.928
	90	Pull-out	17.38							1.067
B2-7-	60	Pull-out	15.86	16.58		4.60		32.46	2.92	1.284
	40	Pull-out	16.49							2.273
	90	Pull-out	18.42							1.450
B4-7-	60	Pull-out	17.21	17.68		3.70		34.73	2.82	1.327
	40	Pull-out	17.40							1.819
	90	Combined	21.65							1.956
B2-28-	60	Pull-out	16.07	18.07	16.28*	17.23	1.77*	47.57	3.36	1.225
	40	Pull-out	16.48							1.481
	90	Combined	21.62							1.872
B5-28-	60	Pull-out	17.96	18.93	17.59*	12.46	3.02*	39.95	3.25	1.560
	40	Pull-out	17.21							1.438

**Combined failure results omitted. Only the pull-out failure results are considered.*

Note: CV = Coefficient of Variation

A critical observation is the Coefficient of Variation (CV) for N_{ult}, it was significantly higher in early-age samples, such as 14.42% for batch B3-24, compared to more mature samples like B4-7, which had a CV of only 3.70%. This high variability at 24 hours is not merely statistical noise; it is indicative of a fundamental material property of early-age concrete. This period is characterised by rapid development of the hydration microstructure, resulting in a material that is more mechanically heterogeneous and less predictable than stabilised 28-day concrete. The high CV is therefore a symptom of this inherent inhomogeneity, leading to inconsistent anchor performance and implying that larger factors of safety are required to address this uncertainty in practical applications.

Comparing the experimental results to manufacturer specifications, as presented in Fig. 5, reveals a critical contradiction. The manufacturer's predictions, which adhere to AS 5216 [5] and are based on the Concrete Cone Capacity (CCM) method, overpredicted the actual capacity for anchors at the 90mm edge distance. Conversely, for the reduced 60mm and 40mm edge distances, the manufacturer's models (which are reduced for edge influence) significantly underpredicted the experimentally observed capacity.

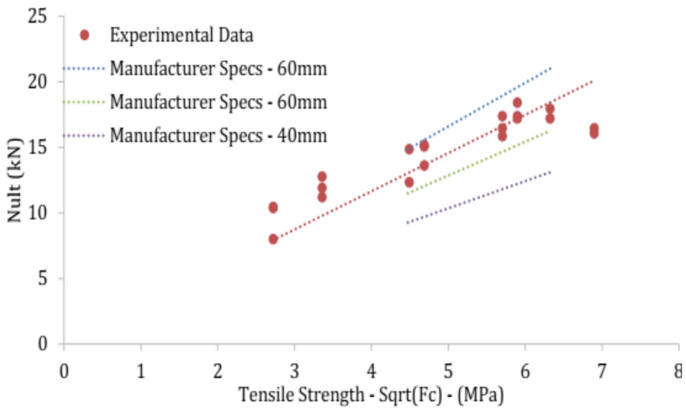

Fig. 5. Manufacturer Specifications for Screw Anchor Capacity and Experimental results

This inconsistency stems from a difference in underlying assumptions. The manufacturer's CCM models assume a concrete cone failure mode, where reducing the edge distance truncates the projected cone area and thus drastically reduces the predicted capacity. However, as discussed in the following section, the experimental results predominantly showed a different failure mode (pull-out) that is not sensitive to edge influence. This discrepancy in Fig. 5 is the initial evidence that the fundamental assumptions of standard design models may be invalid for screw anchors in early-age concrete.

3.2. Failure modes of test specimens

The classification of the failure mode is critical to understanding the anchor's behaviour. Findings from this study show the overwhelming prevalence of pull-out failure, which accounted for 92% (22 out of 24) of all test specimens. This mode, defined as the anchor pulling out of the hole with only negligible concrete debris at the surface (cone depth < 20% of the embedment depth h_{nom}), is represented in Fig. 6.

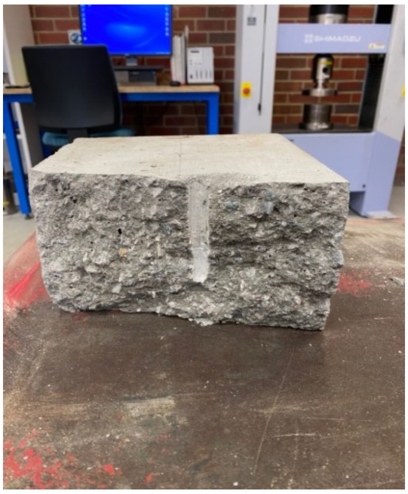

Fig. 6. Representative Pull-out Failure (B4-48-90)

In contrast, combined failure was only observed in 8% (2 out of 24) specimens. Critically, both of these instances occurred only in 28-day concrete samples and at the largest 90mm edge distance. This outcome differs markedly from tests on fully matured anchors with standard embedments, where combined concrete breakout/pull-out modes have been reported as a predominant failure mode [25]. A representative combined failure specimen is shown in Fig. 7. This specimen exhibits a distinct concrete cone with measured depths of 25mm and 28mm (38% and 43% of h_{nom}, respectively), fitting perfectly within the definition of combined failure (cone depth between 20% and 85% h_{nom}). No specimens exhibited pure concrete cone failure. In this test series, no specimens exhibited cone depths in the immediate vicinity of the 20%h_{nom} threshold; specimens classified as pull-out displayed only negligible surface spalling, whereas the two combined-failure specimens developed clearly visible cones with depths of 38% and 43% of h_{nom}, respectively. This variability in cone size and angle is consistent with earlier observations that shallow anchor embedments produce flatter (wider) failure cones while deeper embedments produce steeper cones [26].

The prevalence of pull-out failure in early-age samples is not coincidental; it is identified as a direct consequence of low concrete strength. Notably, a similar shift toward pull-out-governed behavior is observed in other scenarios where concrete tensile strength is relatively high but cone formation is suppressed – for example, torque-controlled expansion anchors in ultra-high performance fiber-reinforced concrete tend to pull out (or pull-through) rather than produce full concrete cones [27]. Cone failure requires the concrete to possess sufficient tensile strength to distribute the load from the anchor out to a large cone of material. In early-age concrete (e.g., 24 and 48 hours), the inherent compressive and tensile strengths are very low. As the study indicates, this low strength significantly reduced the ability of the concrete to form a cone as resistance. Instead of the concrete fracturing in a large cone, the high local stresses at the screw anchor threads exceed the shear strength of the weak concrete paste. This causes the anchor to strip the concrete grooves it created, resulting in a pull-out failure, a mechanism depicted. Low concrete strength is therefore the controlling variable dictating the failure mode, an effect that appears more dominant than that of edge distance in these specimens.

Fig. 7. Representative Combined Failure (B2-28-90)

A complicating observation noted is that all specimens, regardless of their primary pull-out or combined failure mode, ultimately experienced splitting failure. This was characterised by a crack running from the anchor location to the edges of the specimen, as clearly illustrated in Fig. 8. The study investigated whether this splitting was a primary or secondary failure mechanism. Three-point bending tests ruled out flexural failure of the specimen beams, as the beams were found to have a flexural capacity more than double the maximum applied pull-out load. The explanation provided is that this splitting is a secondary or concurrent phenomenon, instigated by the outward pushing force exerted by the screw anchor into the concrete substrate as it is pulled upwards. This wedging action of the threads generates significant hoop stress in the surrounding concrete. As concrete early-age concrete is very weak in tension, this hoop stress readily exceeds the material's tensile strength, forming a longitudinal crack. High-speed camera evidence used on the 28-day samples confirmed this sequence. For the small edge distance samples (40mm and 60mm), splitting occurred first, followed by the pull-out failure. This is logical, as there was less concrete material available to resist the hoop stress. For the 90mm sample, cone formation and splitting occurred almost simultaneously, inferring that the cone failure precipitated the split. This implies that even when pull-out is the ultimate failure, the anchor's performance is still influenced by the concrete's tensile strength, which governs the onset of secondary splitting.

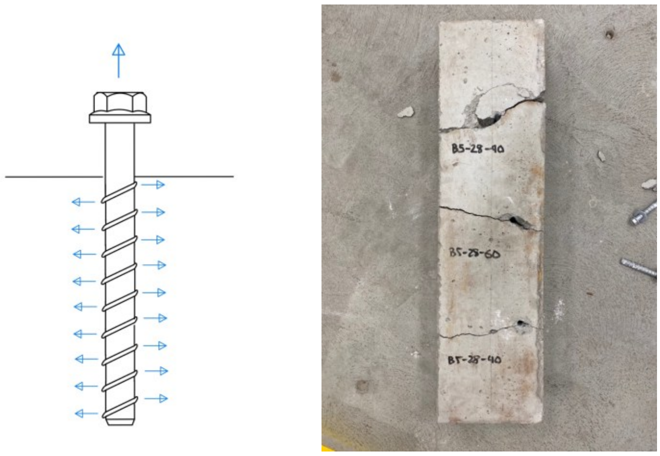

Fig. 8. Specimen Demonstrating Splitting Failure

3.3. Load-Displacement relationship

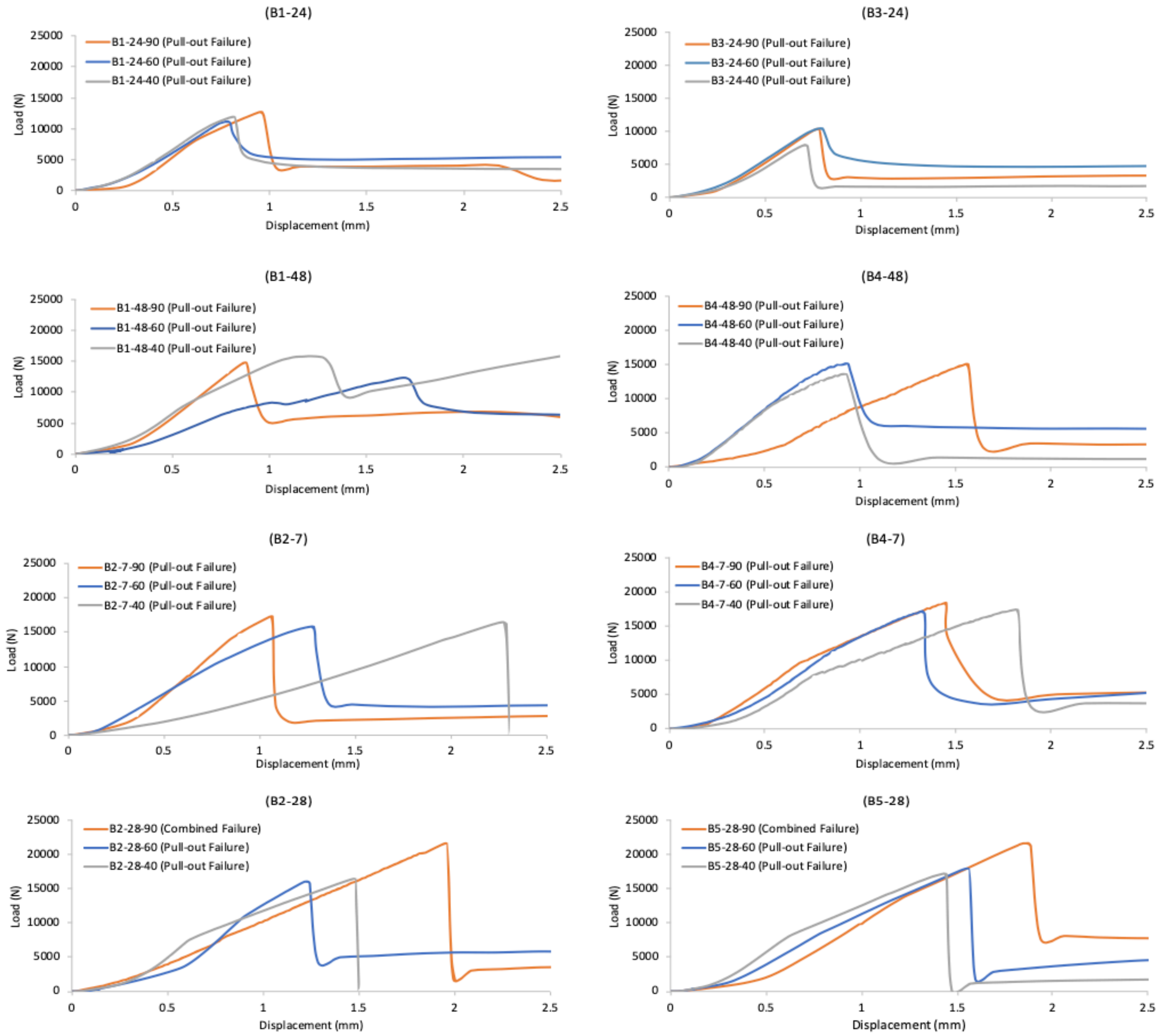

Fig. 9. Load-Displacement Curves

Two distinct curve profiles were observed, corresponding directly to the two failure modes (Fig. 9):

Pull-out Failure: These curves are characterised by a varying gradient as load increases, described as mini failures or slipping of the anchor. More importantly, after reaching the peak load, these curves exhibit a moderate decline. This behaviour represents a progressive failure. The mini failures are likely the local crushing of concrete at individual threads. The gradual post-peak decline is attributed to residual friction between the anchor shaft and the failed concrete, providing a ductile-like form of behaviour.

Combined Failure: These curves are entirely different. They show a nearly constant (linear-elastic) gradient leading to the peak load, followed by an abrupt, near-vertical drop in load-carrying capacity, which is consistent with the study of Stuart et al [28]. The concrete in the cone withstands the load elastically until it suddenly reaches its tensile strength and fractures as a single mass, causing an immediate loss of resistance.

The average peak displacement for the more ductile pull-out failure was 1.203 mm, whereas the average for the more brittle combined failure was significantly larger at 1.914 mm. While the study suggests the residual friction in the combined failure's pull-out component allows for greater displacement, a more likely explanation may relate to the concrete strength. The combined failures only occurred in high-strength 28-day concrete, while the pull-out failures occurred at all strengths, including low-strength early-age. The stronger, stiffer concrete could sustain much higher loads before failing, allowing for more total elastic and inelastic deformation to accumulate, resulting in a larger overall peak displacement. Therefore, the difference in displacement may be more correlated with the underlying material strength than the failure mode itself. Recent tests of anchors in >100 MPa high-strength concrete support this explanation – such anchors achieved substantially higher breakout loads (versus normal-strength predictions) and showed greater pre-failure energy absorption [29].

3.4. Effect of edge distance on tensile strength

The central question of this research was to investigate the effect of edge distance on tensile strength, particularly in early-age concrete. To analyse this, the tensile strength data was normalised by dividing by the square root of the compressive strength $\frac{N_{ult}}{\sqrt{F_c}}$ to remove the influence of varying concrete strength (Fig. 10).

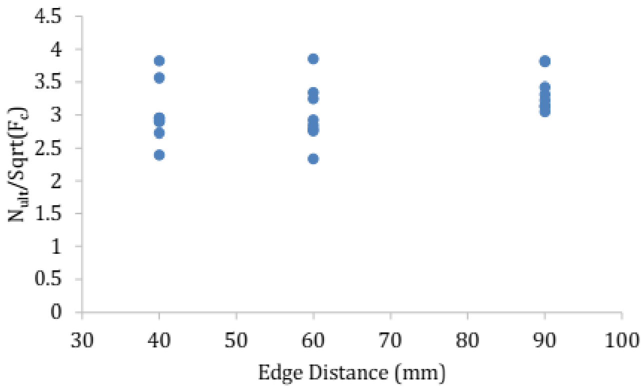

Fig. 10. Normalised Tensile Capacity of Anchors due to Edge Distance

The plot in Fig. 10 shows a large scatter of data and, notably, no clear systematic trend or correlation between edge distance and the normalised tensile capacity. This observation is based on qualitative visual inspection of the data, supported by the fact that the differences between the average capacities at 40 mm, 60 mm and 90 mm remain comparable to the inherent scatter reported in Table 4, rather than on a formal statistical hypothesis test. The smallest edge distance (40mm) did not necessarily correspond to the lowest tensile capacity. The main finding of this study, therefore, is that the effect of edge distance on the tensile capacity of screw anchors in early-age concrete appears, at first sight, counter-intuitive, as it shows no clear influence once the capacities are normalised by concrete strength; however, this behaviour is consistent with the dominance of pull-out failure in weak concrete.

This finding, while seemingly counter-intuitive, is logically explained by the previous observations on failure mode. The theory of pull-out failure posits that capacity is derived from the volume of concrete between the threads. This volume is a constant dependent only on the anchor geometry (diameter, pitch, embedment depth) and is not dependent on the anchor's proximity to an edge. Therefore, if the failure mode is pull-out, the edge distance does not theoretically affect the tensile strength. The scattered experimental data in Fig. 10 is seen as confirmation of this theory. The lack of correlation is not a failure of the experiment; it is evidence that the failure mechanism has shifted from an edge-sensitive one to an edge-insensitive one due to the low concrete strength.

However, this creates a significant prediction problem. Standard design models CCM are based on the assumption of cone failure and apply heavy reduction factors for edge influence. As seen in Fig. 11, these theoretical models (based on CCM) overpredict the actual performance at 40mm and 60mm distances (ratio of $N_{predicted}/N_{experimental} > 1.0$), which is dangerous. The assuming cone failure (and using reduction factors) may be overly conservative if pull-out occurs, but assuming pull-out (and ignoring edge distance) may be unsafe if the concrete is just strong enough to initiate a partial cone. This inability to know which failure mode will govern makes accurately predicting the tensile capacity extremely challenging.

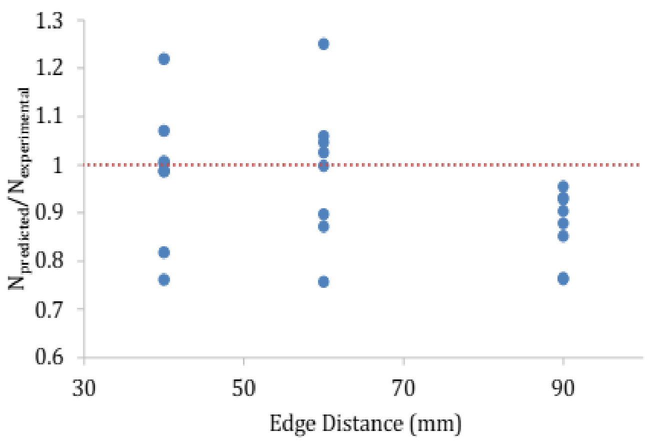

Fig. 11. Ratio of predicted to experimental tensile capacity of anchors against edge distance

3.5. Development of a predictive model for tensile behaviour

Given the prevalence of pull-out failure in this dataset, evaluating pull-out predictive models is necessary. The study examined the existing model by Mohyeddin et al [14], presented as Equation 1. When this model (Fig. 12) was plotted against the experimental data, it was clear that the existing model overestimates the capacity.

$$N_{pullout} = 23.5 \times d^{0.5} \times h_{ef} \times \sqrt{F_c} \quad \text{(Equation 1)}$$

This inaccuracy is attributed to the fact that the original dataset used to develop (Equation 1) did not include early-age concrete. This suggests that the relationship between $\sqrt{F_c}$ and pull-out strength may not be a universal constant, and that early-age concrete performs more poorly in this pull-out mechanism than mature concrete of the same F_c. To address this, the study proposed a new predictive model, calibrated against the experimental dataset that includes early-age concrete. By keeping the variables the same and recalculating the calibration factor, Equation 2 was developed:

$$N_{pullout} = 15.6 \times d^{0.5} \times h_{ef} \times \sqrt{F_c} \quad \text{(Equation 2)}$$

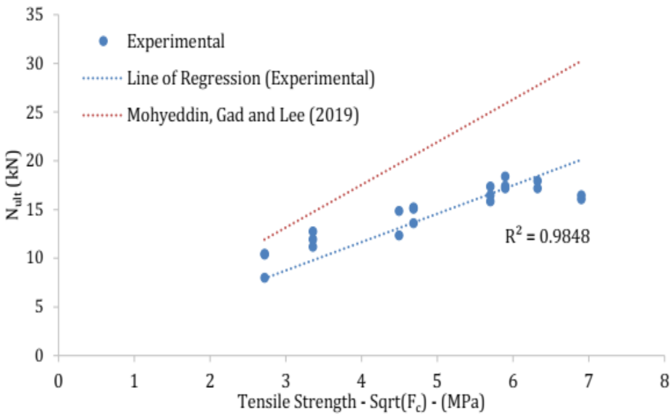

Fig. 12. Tensile capacity of anchors due to pull-out failure

This new model (Fig. 12) shows a high statistical fit to this dataset, with an $R^2 = 0.9848$. The k factor is reduced from 23.5 to 15.6, reflecting the lower performance observed in these tests. However, even this new model has limitations. A closer analysis of Fig. 12 reveals that while the new trendline fits the data overall, it most accurately predicts middle age concrete, whereas early age and mature age data lies largely outside of the trendline. Specifically, the new model appears to still overpredict performance at the very lowest strengths and underpredict performance at high strengths. This suggests the relationship may not be perfectly linear with $\sqrt{F_c}$ across the entire maturation process.

The practical implication of all these findings is clear: given the high variability (CV) of early-age concrete, the uncertainty in predicting the failure mode, and the imperfections of even calibrated predictive models, the application of a large factor of safety (or reduction factor) is critical. Fig. 13 demonstrates this point by applying the manufacturer's 0.6 reduction factor to the CCM prediction lines. With this safety factor included, the prediction lines finally fall safely below all experimental data points, even at the 40mm and 60mm edge distances. This confirms that, despite the mechanical complexities, the only safe approach in practice is to use proven reduction factors to account for the inherent risks and uncertainties of anchoring in concrete, especially during its early age.

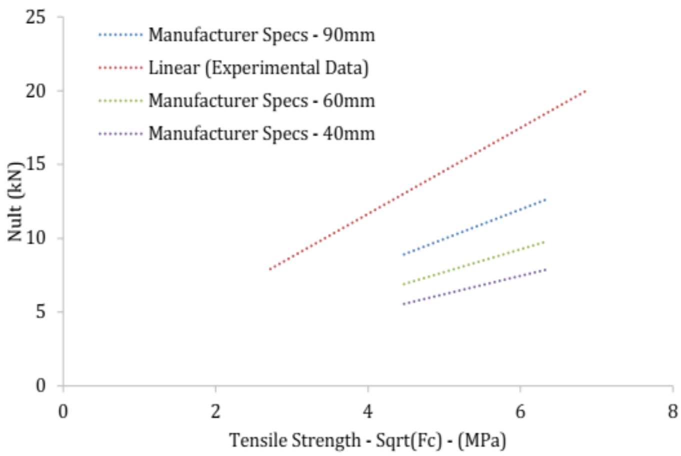

Fig. 13. Manufacturer specifications for screw anchor capacity with safety reduction factor and experimental results from this study

4. Conclusions

This study systematically investigated the relationship between installation edge distance and the tensile pull-out strength of screw anchors in early-age concrete. Detailed analysis of the tests showed that every anchor installed in early-age concrete failed by pull-out, regardless of edge distance. By contrast, combined (cone) failures occurred only in specimens with fully mature concrete and large edge distances. In other words, reducing the edge distance suppressed cone formation and made combined failure less likely. The fact that combined failures were seen only at older concrete ages implies that concrete strength had a much greater influence on the failure mode than proximity to the edge.

This finding indicates that existing design models, which assume a conventional concrete-cone failure, greatly overestimate anchor capacity under these conditions. Indeed, the standard pull-out capacity model was found to severely overpredict the measured strengths in this early-age dataset. To address this discrepancy, an adjusted prediction model was developed for pull-out failure, calibrated to the early-age data to account for the reduced strength of the young concrete. This calibrated model shows a very high R^2 value (0.9848), meaning it very accurately predicts the mean trend of the data. However, the Coefficient of Variation (CV) at early ages is high, meaning individual data points can scatter far from that mean trendline. So while the model is accurate on average, it is unreliable for a single-point prediction without an appropriate safety factor. Therefore, the external validity of this model mandates its use in conjunction with a sufficiently large factor to cover this inherent variability.

When comparing the experimental data to manufacturer predictions, the study found that the 0.6 reduction factor was sufficient to ensure the manufacturer's predictions fell safely below the experimental data. This means that, while the manufacturer's predictive model CCM is mechanistically incorrect (assuming cone failure instead of pull-out), the safety factor they apply (0.6 or 0.55 for working loads) inadvertently compensates for the model's inaccuracy and the high data variability, resulting in a design that is safe in practice. These conclusions apply to pull-out-dominated behaviour of the tested M10×100 concrete screw anchor with a constant effective embedment depth (h_{ef} = 59 mm) in normal-strength N40 concrete within the investigated ranges of age (24 h–28 days) and edge distance (40–90 mm); extrapolation to other anchor types, embedment depths or concrete classes should therefore be made with caution.

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