Correlation of Tensile Strength between Mechanical and Chemical Anchors with Concrete's Compressive Strength

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Abstract

This study evaluated the preliminary relationship between anchor tensile strength and concrete compressive strength through semi-destructive pull-out tests. Anchors were tested in concrete with compressive strengths of 18, 24, and 32 MPa, using mechanical (drop-in and wedge) and chemical anchors sized 8 and 10 mm, embedded at 40 mm depth. Results indicated that higher concrete compressive strength correlates with increased anchor tensile strength. On average, a 30–60% rise in concrete strength led to a 15–70% increase in anchor tensile strength, varying with anchor type and size. Chemical anchors demonstrated the highest tensile strength, followed by drop-in and wedge anchors, respectively. Additionally, 8 mm anchors generally exhibited higher tensile strength than 10 mm anchors. Two primary failure modes were observed: concrete failure and threaded rod failure. Concrete failure predominated in the tests. Despite yielding valuable insights, the study has limitations such as fixed drilling depth and limited anchor and concrete strength variations. Nevertheless, these findings lay a foundation for further research and development aimed at optimizing anchor performance in construction applications. In summary, this study underscores the initial link between anchor tensile strength and concrete compressive strength, emphasizing the influence of anchor type and size. Future studies could benefit from expanding these parameters to enhance the accuracy and applicability of anchor performance assessments in diverse construction scenarios.

Keywords: Tensile Strength, Compressive Strength, Anchors, Semi-Destructive Testing

1. Introduction

Currently, there is a growing utilization of anchors in engineering, particularly in construction. This involves enhancing existing structures to make them more robust for their intended purposes, whether through modifications or additions. Additionally, new structures may require the connection of structural components, such as welding steel and concrete composite structures together or installing a steel structure on a large reinforced concrete base. Wang et al. [1] discuss how the variety of available anchors meets the specific needs of different structures. The increasing prevalence of anchors is attributed to their straightforward, convenient, and swift installation processes. Anchors are categorized into two main groups based on their installation: 1) Anchors installed during construction (cast-in-place anchors), like bolts and rail anchors, and 2) Anchors installed after construction (post-installed anchors), including mechanical and chemical anchors. Once installed and components are welded together, anchors play a crucial role in resisting external forces on composite structures, such as tension, shear, or a combination of both [2–3]. Researchers have recently delved into studying anchor behavior under various loads, such as Lee et al. [4] investigated the shear resistance of rail anchors, Karmokar et al. [5] investigated the failure patterns of concrete cone shapes under anchor tension, Delhomme et al. [6] explored the impact of nut loosening on the withdrawal force of post-installed mechanical anchors, and examining the behavior of post-installed chemical anchors under tension [7–10]. The study aims to use different types of anchors appropriately for the application. [2], [8], [11], [12], etc. This study examines the relationship between the tensile strength of anchors and the compressive strength of concrete used for anchoring various types of anchors.

In the construction industry in Thailand, various anchor types are commonly employed to interconnect different structural components, especially in the construction of building extensions where a steel structure needs to be securely combined with concrete or reinforced concrete. Consequently, selecting anchors suitable for these extensions becomes essential. The appropriate choice of each anchor type is contingent on several factors, including the anchor's type, size, and distance [13–15], the building's nature (whether it's an existing or new structure), Eligehausen et al. [3] discussed the intended application of anchors to withstand specific forces, such as tensile or shear forces as well as factors like concrete strength by Jutakanon and Sathitisangworn [15] and the presence of cracks in building structures [16], [17]. All these factors collectively influence anchor utilization, as mentioned earlier. Therefore, the primary focus of this study is to explore the relationship between the tensile force or tensile strength associated with anchors (both mechanical and chemical) and the compressive strength of concrete. At the preliminary stage, this exploration aims to provide an initial guideline for assessing the performance of anchors. The study draws insights from existing literature [18–20] on the behavior and failure characteristics of anchors subjected to tension, serving as a reference for the ongoing investigation.

Considering the aforementioned reasons and guidelines, the research team anticipates the primary value of this study lies in its analysis of the correlation between the tensile force or tensile strength of different anchor types (specifically mechanical and chemical anchors) embedded in concrete with varying compressive strength values (three different values were considered in this study). To align with the study's objectives of using anchors effectively for tensile force, understanding the concrete's compressive strength post-installation is crucial. This evaluation ensures optimal utilization of concrete's compressive strength to determine the anchors' subsequent tensile capacity, following specific installation methods for each anchor type. Assessing concrete strength beforehand facilitates selecting anchors—type, size, and quantity—that best suit the structural installation or connection. Therefore, various methods must be employed to verify concrete's compressive strength before using these values to gauge anchor tensile strength. Concrete samples are collected following the ASTM C172-08 [21] standards through drilling at the test site. Non-destructive concrete quality testing is carried out using the hammer impact method and ultrasonic pulse velocity method, offering a cost-effective means to inspect extensive areas. This serves as an initial assessment of concrete compressive strength, crucial for establishing the correlation with the tensile strength of anchors embedded in the aforementioned concrete. Subsequent to installation, the anchors undergo testing in accordance with ACI 318M -19 [22]. This study is envisioned by the research team to be particularly valuable to small to medium-sized construction contractors involved in anchor usage during construction operations, as well as other interested parties.

2. Research theory and methods

2.1 Research methods

This investigation involved the creation of a concrete test yard, abbreviated as CTY, with dimensions of 1.10 m in width, 1.50 m in length, and a thickness of 15.00 cm. Three test yards were constructed in total. Each of these test yards featured a distinct compressive strength value for the concrete used in their construction, specifically 18.00, 24.00, and 32.00 MPa, as indicated in **Table 1**.

The data presented in **Table 1** is utilized for assessing the compressive strength and quality of concrete through three distinct methods: 1) Destructive Testing: This involves assessing the compressive strength of concrete through the collection of standard cylindrical concrete blocks. These blocks have diameters of 15.00 cm and heights of 30.00 cm, as well as standard cube sizes measuring 15.00 cm. This testing method adheres to ASTM C39/C39M-1 4 [2 3] . Additionally, drilling, known as Concrete Coring Testing, is performed with a diameter of 5.00 cm and a height of 10.00 cm, following ASTM C42-C42M [24]. 2) Non-Destructive Testing (NDT): The Rebound Hammer Test is employed, referencing ASTM C805-97 [25] and DPT 1502-51 [26]. Additionally, testing is conducted using ultrasonic pulse velocity (UPV) in accordance with ASTM C597-97 [27]. And 3) Semi-Destructive Testing (SDT): A tensile test, specifically the Pull-Out Test, is carried out on anchors embedded in the concrete test field. This includes two types of anchors: mechanical anchors and chemical anchors. The tests are conducted based on ACI 318M-19 [22]. All results obtained from these tests will be thoroughly analyzed and subsequently presented. In terms of failure patterns of anchoring devices in concrete, there are 6 types of failure patterns that can occur: 1) Steel Failure: It is a failure caused by the anchoring material tearing from the tensile force because the strength of the base material is higher than the strength of the anchor. 2) Pull Out: It is a failure caused by the threaded rod and the sleeve or the sleeve and the concrete sliding apart due to insufficient friction to resist the pulling force acting on the dowel. 3) Concrete Breakout: It is a failure caused by cracking in concrete from the end of the anchor to the upper surface. The design assumes a failure in the shape of a pyramid. The angle of failure plane is equal to 35º around the axis of the anchoring material. 4) Concrete Splitting: It is a failure of concrete samples in the form of cracking to the side surface. It usually occurs with anchors installed in concrete with limited size and close to the edges of the samples or in the case of anchor groups with anchor spacing closer than the specified standard. 5) Side - face Blowout: It is a failure where the concrete cracks laterally due to the anchor being installed too close to the edge of the concrete. 6) Bond Failure: It is a failure caused by the shallow embedment distance of the anchor or the chemical adhesive with low bonding strength, causing the bond between the chemical and the concrete or the chemical and the embedded material to be less than the strength that the concrete can withstand.

Table 1 Concrete test yard ingredients (per 1 m^3)

CTY	Cement (kg)	Sand (kg)	Rock (kg)	Water (kg)
CTY1	263.52	857.28	1093.44	136.06
CTY2	304.69	820.70	1093.44	137.89
CTY3	375.00	758.24	1093.44	141.01

2.2 Material properties Testing tools and equipment

The primary materials employed in the experiment can be categorized into two main components: 1) Concrete: As detailed in Section 2.1 and outlined in **Table 1**, the concrete used in the test yard comprises standard hydraulic cement of general use type TIS 2594-2013, coarse sand, clean water, and ¾-inch construction stones. And 2) Anchors for the Pull-Out Test: The anchors utilized in the pull-out test encompass two types of mechanical anchors, namely the Drop-In Anchor (DA) and Wedge Anchor (WA), each with diameters of 8 mm and 10 mm, and drilled to a depth of 40 mm. Additionally, chemical anchors (CA) are employed, consisting of a threaded rod and an epoxy solution for connection points. High-strength anchors, specifically the HILTI HIT-RE 500 V3 [28], are also part of the materials used. The necessary equipment for handling these chemical components, along with visual representations of anchors and associated equipment, are depicted in **Figure 1**.

Several tools and instruments utilized in the research encompass: Rebound Hammer: Employed to gauge the Rebound Index resulting from the hammer's impact on the test concrete surface. At each pressing location, a grid is created using a future board with dimensions of 25.00 cm in width, 25.00 cm in length, and 16 holes, each approximately 2.50 cm apart. This grid configuration is designed to accommodate 16 pressure points, forming a pattern resembling a hammer, as illustrated in **Figure 2(a)**. Ultrasonic Pulse Velocity (UPV): Depicted in **Figure 2(b)**, this testing machine necessitates calibration with a reference bar before conducting tests. A designated point for testing is set, specifying that the initial distance from the transmitter head to the receiver head is denoted as "b." For the subsequent measurement, the receiver head is moved to a distance of “2b,” with a separation of 15 cm between the points. The obtained value from the test is expressed in microunits per second, representing the time, and indicates the speed of travel between the two points during the test.

The subsequent apparatus is a concrete testing machine that employs the Pull-Out Test method, depicted in **Figure 2(c)**. This machine is utilized after the installation of anchors in their designated positions. A reference height is established to monitor the withdrawal distance of the anchor, recorded through dial-gauge readings. Additionally, the pull-out force is determined via load cell readings facilitated by the hydraulic system. For concrete compressive strength testing, a universal testing machine (UTM) with a capacity of 2,000 kN is employed, as illustrated in **Figure 2(d)**. Tools designed for drilling samples from each test yard are also part of the equipment, and subsequent testing with the UTM machine will be conducted utilizing various tools presented in **Figure 1** and **Figure 2**. The testing and analysis of results adhere to the standards initially outlined in Section 2.1.

2.3 Samples and testing methods

In the initial phase of casting three concrete test yards (CTY), cylindrical samples will be gathered, comprising standard cube shapes, with three samples for each test area. Subsequently, upon demolding, all samples will undergo a 28-day water curing process before being subjected to compressive and tensile strength testing using a UTM machine, illustrated in **Figure 2 (d)**, applying a force rate of 6.80 kN per second until failure occurs (destructive testing). The generated force during the test will be recorded. This timeframe aligns with the CTY concrete's minimum 28-day lifespan, employing water curing. Following this period, testing will commence using various methods, starting with non-destructive testing utilizing a hammer, as outlined in sections 2.1 and 2.2. Each CTY will undergo testing at five positions (including the middle and four corners) with 16 points pressed using tools from **Figure 2 (a)**.

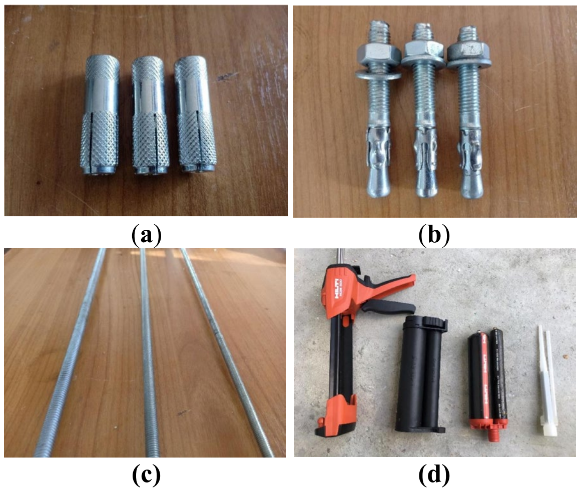

Figure 1 Materials and equipment used in the study **(a)** Drop-in anchor **(b)** Wedge anchor **(c)** threaded steel studs **(d)** equipment for using chemical solutions

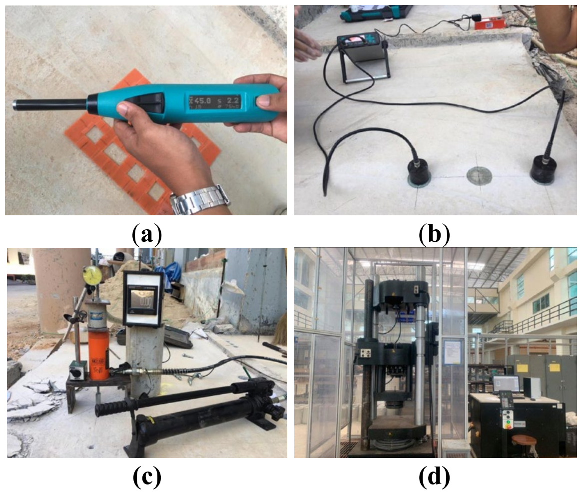

Figure 2 Tools and equipment used in the study **(a)** Impact hammer **(b)** UPV **(c)** tensile testing machine **(d)** compression testing

The Rebound Index value average will be calculated for each position, and if more than three values exceed the average by more than 6, further testing in different locations will ensue. Alternatively, if the average Rebound Index values do not differ by more than 6 and there are no fewer than 10 values, the test is considered complete. Subsequently, the obtained values will be analyzed in relation to the concrete's compressive strength, referencing the Rebound Index [25]. Upon completing the impact hammer test, the CTY will undergo UPV Testing, depicted in **Figure 2 (b)**. Testing will occur at five positions per CTY, mirroring the locations used in the impact hammer test. After calibrating the tester with the Reference Bar and setting the ultrasonic wave travel time through the bar at 25.4 μs, testing will initiate. Each position will undergo testing at three points, with a distance of b (15.00 cm) between each point. The instrument will display the ultrasonic pulse velocity, utilizing these values to assess the concrete quality of each CTY test yard. Simultaneously with non-destructive testing, concrete coring (drilling) will be conducted on each CTY using a 5.00 cm diameter drill head. This process will yield three concrete samples, each 10.00 cm high, from one edge of the CTY. These samples will be used for compressive strength testing using a UTM machine (**Figure 2 (d)**) at a force application rate of 6.80 kN per second until failure, mirroring the procedures for cylindrical and cube samples mentioned earlier (destructive testing).

The final stage involves assessing the tensile strength of diverse anchor types. As detailed in Sections 2.1 and 2.2 and illustrated in **Figure 1**, the Pull-out method is employed. Drill holes with a depth of 40.00 mm into the CTY, and install mechanical anchors of 8.00 and 10.00 mm in diameter. These anchors can be either mechanically affixed by hammering and tightening nuts or chemical anchors that necessitate the addition of an epoxy solution, along with the installation of threaded steel studs in a vertical orientation (aligned with a long bubble water level). Allow the chemical cementing reaction to occur and harden over a period of 5-8 hours or more. Subsequently, tensile testing begins using a machine depicted in **Figure 2 (c)**. For each CTY yard, anchor locations and extents are determined to gauge the concrete cracking distance, approximately 20.00 × 20.00 cm. Testing involves 18 anchor positions per CTY, with tensile force applied manually through hydraulic pumping. The load cell displays the tensile force value, and simultaneous recording of test values is conducted. Additionally, the vertical pull of the anchor is recorded using a dial gauge for each hydraulic press or pump. The relationship between pulling force and distance is obtained from the test and subsequently analyzed. The tensile strength acquired from this test, in accordance with ACI 318M-19 [22], is utilized to calculate the compressive strength of concrete through equation (1) [22], signifying the concrete's detachment from pulling anchors to Concrete Breakout type, as illustrated.

$$f_c' = \left[\frac{N_b}{k_c \lambda_a h_{ef}^{1.5}}\right]^2 \tag{1}$$

In the provided equation, N_b represents the fundamental tensile strength or breaking force (measured in newtons), f_c' denotes the compressive strength of concrete (expressed in megapascals), h_{ef} stands for the effective embedding distance (measured in millimeters), λ_a is the correction factor for lightweight concrete (which, in this concrete-focused study, is assigned a value of 1), and k_c is a variable dependent on the anchor installation method. Specifically, it takes on a value of 7 for post-installed anchors and 10 for Cast-in anchors. The overall test procedure is succinctly outlined in **Figure 3**, and the subsequent section presents the analysis results derived from the conducted tests.

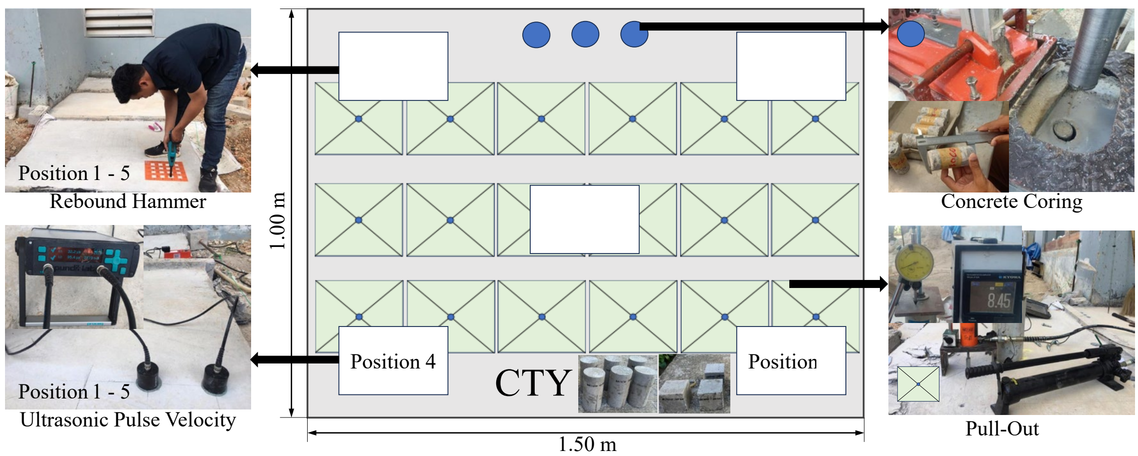

Figure 3 Dimensions of the testing area (CTY) and diverse testing locations (Rebound Hammer and Ultrasonic Pulse Velocity positions 1-5, Concrete Coring, and Pull-Out Test).

3. Research results and discussion

In Section 2.3, the tests can be categorized into three primary groups. Group 1 involves Destructive Testing, encompassing the examination of cylindrical samples measuring dia.15.00 × 30.00 cm, cuboidal samples with dimensions of 15.00 × 15.00 × 15.00 cm, and cylindrical samples obtained through drilling dia. 5.00 × 10.00 cm. Group 2 pertains to Non-destructive testing (NDT) and includes Rebound Hammer testing and Ultrasonic Pulse Velocity (UPV) testing. Lastly, Group 3 involves Semi-Destructive Testing, specifically assessing the tensile strength of various anchor types through the Pull-Out Testing method. The presentation and discussion of the test results follow the outlined order.

3.1 Destructive test results

Destructive test results are shown in **Table 2.**

Table 2 Results from destructive testing on both a cylinder (Cylinder) and a cube (Cube) specimen.

CTY	Sample	Strength (MPa)			
		Cylinder dia.15 × 30		Cube 15 × 15 × 15	Cylinder dia.5 × 10
		Comp	Tens	Comp	Comp
CTY1	1	19.31	2.29	21.17	14.69
	2	20.31	2.39	20.64	14.67
	3	20.85	1.17	21.32	14.57
CTY2	1	25.02	2.41	26.89	20.49
	2	22.45	2.45	25.03	17.42
	3	21.08	2.26	27.15	24.91
CTY3	1	27.66	2.96	28.57	23.68
	2	25.85	2.42	27.83	19.65
	3	28.10	2.59	33.46	24.11

According to **Table 2**, the average compressive strength of concrete, obtained from samples collected in each CTY test yard, follows an increasing trend from the lowest to highest values, namely CTY1, CTY2, and CTY3. This consistent trend is observed across three sets of identical samples – cylindrical samples sized dia.15.00 × 30.00 cm exhibit average compressive strengths of 20.16 MPa, 22.85 MPa, and 27.20 MPa, respectively. Cuboidal samples with dimensions of 15.00 × 15.00 × 15.00 cm have average compressive strengths of 21.04 MPa, 26.36 MPa, and 29.95 MPa for CTY1, CTY2, and CTY3, respectively. Similarly, cylindrical samples acquired through drilling, with dimensions dia. 5.00 × 10.00 cm, have average compressive strengths of 14.51 MPa, 20.94 MPa, and 22.48 MPa for CTY1, CTY2, and CTY3, respectively. This observed trend in compressive strength values, despite an overall increase in the destructive testing of samples, suggests an uneven rate of growth in compressive strength. Such variations may be attributed to factors such as material quality (cement, stone, sand, water, and other admixtures), mixing ratios, water-to-cement ratios, pouring methods, and curing conditions. Some of them have compressive strength values lower than the design compressive strength, i.e. CTY3 has a compressive strength value lower than the design strength by an average of about 6–15%. This may be because the materials used this time are the first batch of materials, which have different basic properties, resulting in some of the strengths not being as designed. Initial analysis of the results from the destructive tests revealed a correlation between the compressive strength and the type of sample. Specifically, the compressive strength of dia.15.00 × 30.00 cm cylindrical samples averaged approximately 85% to 95% of the compressive strength of 15.00 × 15.00 × 15.00 cm cubic samples, both cured for about 28 days. Additionally, the compressive strength of dia. 5.00 × 10.00 cm cylindrical samples averaged approximately 70% to 80% of the compressive strength of the corresponding cubic samples at the same curing period. Furthermore, the tensile strength derived from testing dia.15.00 × 30.00 cm cylindrical samples showed an average value ranging from approximately 8% to 15% of the compressive strength obtained from testing the same-sized cylindrical samples. Furthermore, the compressive strength test results indicate an opportunity to illustrate the correlation between stress and strain for a cylindrical sample with dimensions of 15.00 × 30.00 cm as depicted in **Figure 4.**

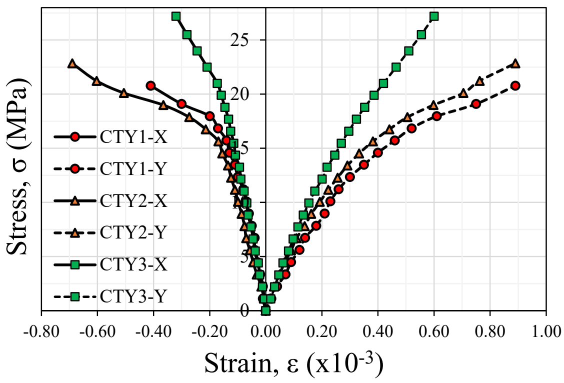

Figure 4 Relationship between stress and strain of a cylindrical sample sized dia.15 × 30 cm.

According to **Figure 4**, it was observed that the Modulus of Elasticity of Concrete for the three CTY test yards stood at 21.43 GPa, 22.47 GPa, and 25.72 GPa for CTY1, CTY2, and CTY3, respectively. This analysis considers the Secant Modulus, typically ranging from 25% to 50% of the effective compressive strength (f_c'), and for this specific analysis, it is used at 50%. The Poisson's Ratio was determined to have an average value of 0.292. (The positive and negative strain values are calculated from the lateral expansion and vertical contraction of the test sample.)

3.2 Non-destructive test results (NDT)

The average velocities recorded from the UPV test were 2.03 km/s, 2.64 km/s, and 3.35 km/s for CTY1, CTY2, and CTY3, respectively. Additionally, the average reflection index values from the hammer test were found to be 30.30, 35.70, and 40.60 for CTY1, CTY2, and CTY3, respectively.

The observed average values indicate variations in concrete densities within the test yard, leading to differences in the time taken for wave movement in the UPV test and distinct Rebound Index values. The concrete density follows a gradient from low to high, corresponding to CTY1, CTY2, and CTY3, respectively. This aligns with the earlier presented destructive test results in Section 3.1, where CTY1, CTY2, and CTY3 exhibit ascending concrete strength values. Initial UPV testing revealed that the concrete slated for semi-destructive testing displayed an absence of surface and textural cracks, crucial since cracks could impact the subsequent Pull-Out test. Furthermore, utilizing the reflection index value from the test, an analysis based on DPT 1502-51 [26] indicates that the compressive strength of the concrete can be determined. By examining the relationship between reflection value and compressive strength, derived from laboratory tests, the strength values of CTY fall within the range of approximately 250 ksc to 330 ksc (roughly 25 MPa to 33 MPa), consistent with the obtained test results. However, it's important to note that these outcomes are contingent on material quality (cement, stone, sand, water, and other admixtures), mixing ratios, and water-to-cement ratios, along with factors like pouring techniques into the mold yard and curing, as previously discussed.

3.3 Semi-destructive test results

In this segment, the outcomes of the tensile tests on various anchor types, encompassing Drop-In Anchors, Wedge Anchors, and Chemical Anchors, are presented. These anchors were installed in the CTY1, CTY2, and CTY3 test yards, following the details outlined in Section 2.3 and illustrated in **Figure 3** above. All anchor types were embedded in the test field at a standardized distance of 40.00 mm, subjected to withdrawal force, and the test results are illustrated in the form of the correlation between pull force and withdrawal distance. Refer to **Figure 5–7** for a visual representation of these results.

Examining the correlation between tensile force and withdrawal distance for various anchor types in **Figure 5–7** reveals that the anchor diameter plays a significant role in determining tensile force. As illustrated in **Figure 5**, a set of 8.00 mm diameter drop-in anchors (depicted by the dashed line) shows a trend of greater withdrawal distance than the set of 10.00 mm diameter drop-in anchors (depicted by the solid line) at identical tension positions. This suggests that drilling holes for larger anchors results in a more considerable loss of concrete volume at that location, impacting anchor attachment more significantly than drilling holes for smaller anchors. Consequently, there needs to be a material to facilitate adhesion between the anchor and the concrete within the drill hole. Furthermore, from **Figure 5–7**, it is evident that chemical anchors exhibit a higher ability to withstand tensile force, surpassing drop-in anchors and wedge anchors.

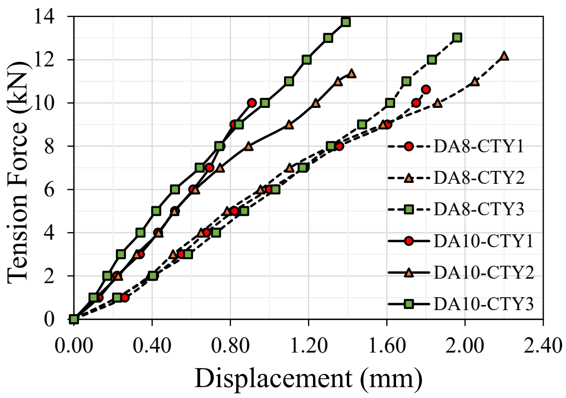

Figure 5 Relationship between tensile force and withdrawal distance. Drop-In Anchor (DA)

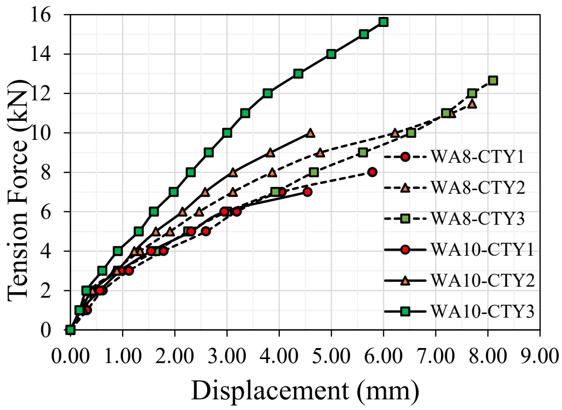

Figure 6 Relationship between tensile force and withdrawal distance. Wedge Anchor (WA)

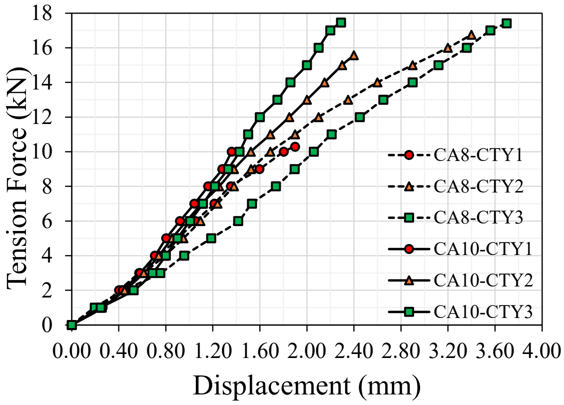

Figure 7 Relationship between tensile force and withdrawal distance. Chemical Anchor (CA)

This may be attributed to the introduction of chemicals into the drill holes, promoting enhanced adhesion and, consequently, a greater capacity to withstand tensile forces. Additionally, the results pertaining to the maximum tensile force leading to anchor failure are documented in **Table 3** and visualized in **Figure 8**.

Table 3 Results of tensile test of various types of anchors. It is anchored on three concrete testing yards.

CTY	Diameter (mm)	Average Tensile Strength (MPa)		
		Drop-In Anchor (DA)	Wedge Anchor (WA)	Chemical Anchor (CA)
CTY1	8	10.64	7.36	10.24
	10	8.59	5.32	7.87
CTY2	8	12.21	11.42	16.66
	10	9.49	7.78	12.39
CTY3	8	13.05	12.59	17.32
	10	11.47	12.43	13.88

Examining **Table 3** and **Figure 8** reveals a notable trend: the average maximum tensile strength required to extract the anchor increases proportionally with the rise in concrete compressive strength. Specifically, CTY3, with the highest concrete compressive strength, demands a greater average maximum tensile strength to pull the embedded anchor compared to CTY2 and CTY1, which have lower compressive strength values. Within the same anchor type in CTY1, it is evident that an 8.00 mm diameter anchor exhibits a higher average maximum tensile strength than its 10.00 mm counterpart. This pattern holds true for CTY2 and CTY3 as well. Additionally, drop-in anchors exhibit a higher average tensile strength than wedge anchors, while chemical anchors surpass both drop-in and wedge anchors, especially when considering the collective results for CTY1, CTY2, and CTY3.

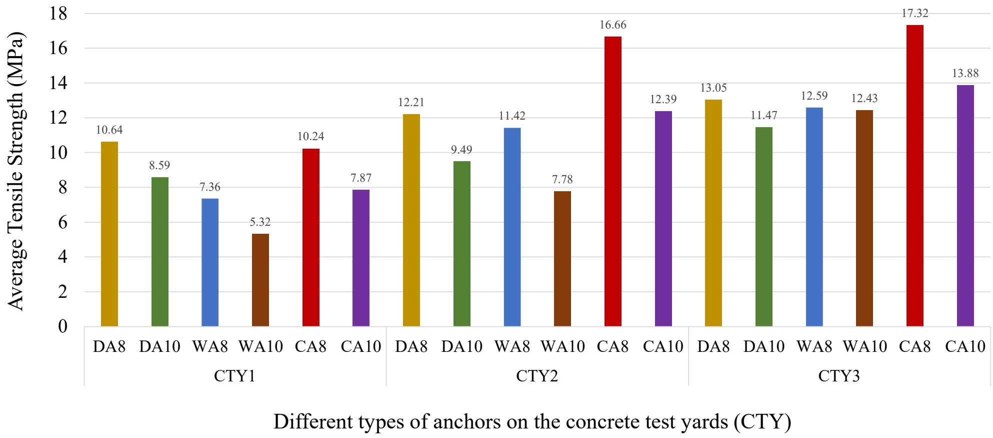

Figure 8 Test results of the maximum average tensile strength of each type of anchor on the three concrete test yards (CTY).

This aligns with the observations in **Figure 5–7**, illustrating the relationship between tensile force and withdrawal distance. The factors influencing the capacity of anchors to withstand tensile forces include anchor size or diameter, anchor type, concrete compressive strength, and the embedding distance (with a fixed distance in this study). The tests, detailed in **Table 3** and **Figure 8**, were conducted until the anchor could no longer bear the tensile force and failed, separating from the concrete plaza under examination. Failures primarily manifested in two ways: 1) Concrete Breakout, where the entire set of anchors dislodges and adheres to the concrete in a conical shape with a broad base (as depicted in **Figure 9** and **Figure 10**), and 2) Anchor failure (Steel Failure), where the anchor breaks apart. Notably, only two instances of chemical anchors on the CTY3 test site exhibited this type of failure, suggesting that higher concrete strength and superior adhesion properties of chemical anchors may contribute to such occurrences. Therefore, it is essential to exercise caution when using anchors with exceptionally strong concrete, ensuring both the material quality and anchor integrity to mitigate such failures.

Figure 9 Picture of the disaster in pulling anchors from the test yard in the Concrete Break Out format.

Figure 10 Failure pattern in Pull-Out test

It was found that from the pull-out test results of the anchor until the failure occurred from the test, a total of 18 samples, all of the failures (approximately 16 samples) were concrete breakout failures as shown in **Figure 9** and **Figure 10**. It is a failure caused by cracking in concrete from the end of the anchor to the upper surface. The design assumes a failure in the shape of a pyramid. The angle of failure plane is equal to 35º around the axis of the anchoring material. This shows that the anchoring by the adhesive has sufficient bond strength between the anchor and concrete. However, when considering the strength of the concrete and the depth of the drilling hole at only 40.00 mm, which is a greater value, it may affect the maximum tensile force and the failure pattern changes. For the other two examples, it was a steel failure, which is a failure caused by the embedded material tearing from the tensile force because the strength of the base material is higher than the strength of the anchor, which usually occurs with anchors with a long embedment distance. This steel failure occurred with the 8.00 mm chemical anchor drilled at CTY3, which was also the location that gave the highest average pull-out force in this study.

Moreover, when considering the average maximum tensile force values from **Table 4** for each anchor type embedded in the three test sites, these values are utilized in the calculation using Eq. (1). This calculation aims to determine the compressive strength derived from the tensile force involved in extracting the anchor from the concrete. The outcomes of this analysis are presented in **Table 4**.

Table 4 Results of analysis of compressive strength from various types of anchor tensile strength.

CTY	Diameter (mm)	Compressive Strength from Eq. (1) (MPa)		
		Drop-In Anchor	Wedge Anchor	Chemical Anchor
CTY1	8	35.96	17.46	33.79
	10	31.17	14.24	31.19
CTY2	8	47.33	42.00	89.47
	10	41.20	30.50	77.34
CTY3	8	54.08	51.05	96.62
	10	60.20	47.20	97.06

Table 4 reveals notable disparities between the analyzed values and the compressive strength obtained from sample tests, as detailed in Section 3.1 (**Table 2**). Specifically, when analyzing the average tensile force from the wedge anchor, there is a discernible difference in compressive strength between the test results and the values derived from Eq. (1). This difference ranges widely, averaging from 20–120%, and varies across CTY1, CTY2, and CTY3, as well as anchor sizes. The variance is more pronounced for anchors with an 8.00 mm diameter and even greater for those with a 10.00 mm diameter. The dissimilarity in analytical results becomes more apparent when considering differences in anchor types. Chemical anchors exhibit the most significant difference between the values analyzed from Eq. (1) and those obtained from the test, with an average difference ranging from 130–300%. Drop-in anchors follow with an average difference ranging between 90% and 160%, and finally, wedge anchors, as mentioned earlier. Despite these differences, combining the values calculated from Eq. (1) using the maximum average tensile force still reveals a trend. The trend indicates that the concrete strength increases from CTY1 to CTY2 and CTY3, respectively. This suggests that the equation analysis may be suitable for specific applications, with Eq. (1) providing a closely aligned calculation for the wedge anchor embedded in the CTY1 yard, where the average compressive strength difference does not exceed 20%.

3.4 Relationship between the tensile strength of anchors and the compressive strength of concrete.

In this segment, the outcomes of both the test results and analytical assessments are employed to establish a correlation between the tensile force or tensile strength of the anchor and the compressive strength of the concrete derived from diverse testing methods. The aim is to offer a comprehensive guideline for more precise utilization of anchors according to their intended applications. This relationship is visually presented in **Figure 11–14**.

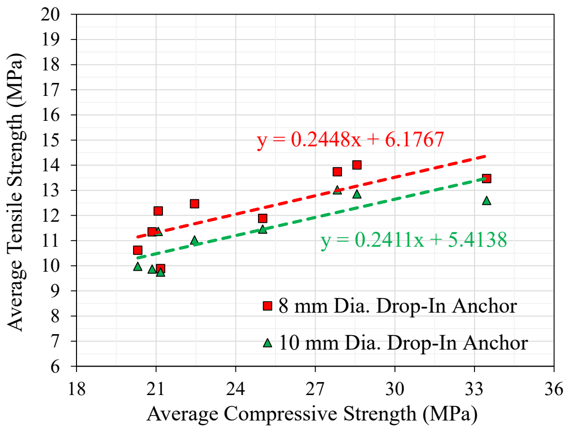

Figure 11 Relationship between average tensile strength of DA and average compressive strength from destructive testing.

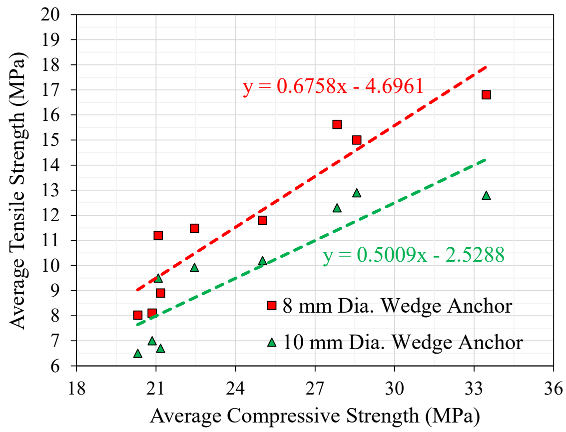

Figure 12 Relationship between average tensile strength of WA and average compressive strength from the destructive test.

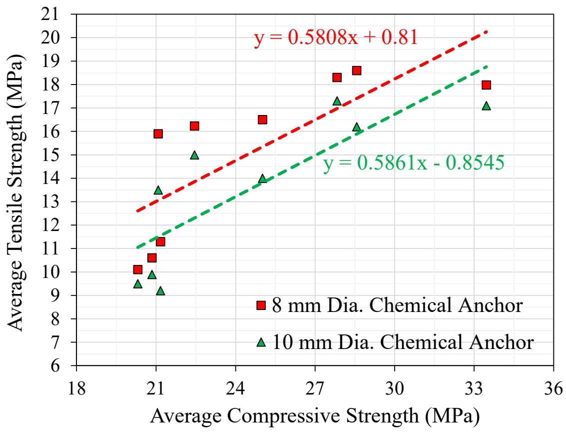

Figure 13 Relationship between average tensile strength of CA and average compressive strength from destructive testing.

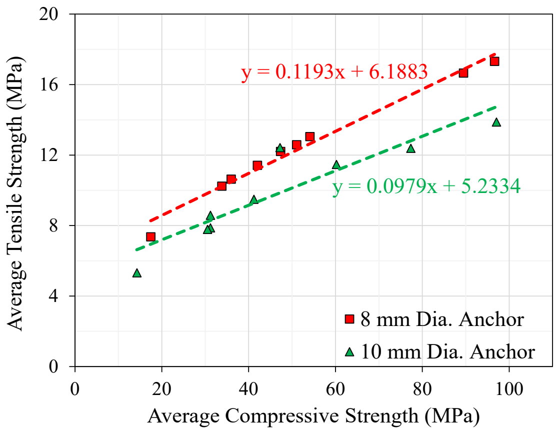

Figure 14 Relationship between average tensile strength of anchors and average compressive strength from Eq. (1).

Figure 11–14 depict the correlation between average compressive strength (on the horizontal axis or x-axis) and the average tensile force or average tensile strength from each anchor type (on the vertical axis or y-axis).

The groups are segregated based on anchor diameter (8.00 mm and 10.00 mm), and the equation representing the trend of this relationship is illustrated in the figures. It is observed that the tendency for increased tensile force aligns with higher concrete compressive strength. Notably, chemical anchors exhibit the highest tensile force, followed by wedge anchors and drop-in anchors. Additionally, anchors with an 8.00 mm diameter demonstrate a greater capacity to withstand tensile force compared to their 10.00 mm counterparts, as previously mentioned. The relationships portrayed in these figures stem from destructive tests involving the collection of concrete samples, as well as the relationship derived from Eq. (1), offering an evaluative tool for initial anchor usage.

In **Figure 11–14**, the relationship between the average tensile strength of the anchor and the average compressive strength of the concrete is shown, classified by the types of anchors (drop-in anchors, wedge anchors, chemical anchors, and the relationship from Eq. (1), respectively). In each figure, the relationship lines are classified into 8.00 mm and 10.00 mm anchors, which are applied according to the type and size of the dowel. The top dotted line shows the relationship trend of the 8.00 mm anchors as mentioned above, and the bottom dotted line shows the relationship trend of the 10.00 mm anchors as mentioned above. All these relationships (**Figure 11–14**) can be used as an alternative to evaluate the average tensile strength of the anchor initially based on the compressive strength data of concrete, which can be obtained from various methods, both destructive and non-destructive testing.

From the presented results, there are several limitations, such as the tensile strength of each type of anchor with different installation and usage (both size, embedment distance, etc.), which affects the efficiency of use. In addition, the tools or equipment used to collect samples to find the compressive strength of concrete, which are diverse, will affect the compressive strength differently, resulting in different evaluations of the anchor's tensile strength. This limitation should be considered and studied further.

4. Summary of study results

The article investigates the correlation between the tensile strength of different types of anchors (drop-in, wedge, and chemical) and the compressive strength of concrete across three test sites (CTY1, CTY2, CTY3), employing a blend of semi-destructive and non-destructive testing techniques. It reveals that drilled and cylindrical samples exhibit compressive strength values ranging from 70–95% compared to cube samples. The tensile strength of cylindrical samples is approximately 8–15% of their compressive strength. Among the test sites, CTY3 demonstrates the highest compressive strength, followed by CTY2 and CTY1, a trend consistent with non-destructive testing outcomes. Impact hammer tests establish a direct link between concrete compressive strength and reflection index, with average indices of 30.3, 35.7 (good), and 40.6 (very good) for CTY1, CTY2, and CTY3, respectively. Ultrasonic pulse velocity tests indicate increasing wave speed with higher compressive strength, averaging 2.03 km/s (fair), 2.64 km/s, and 3.35 km/s (moderate) for CTY1, CTY2, and CTY3. Pull-out tests demonstrate that chemical anchors surpass drop-in and wedge anchors in tensile strength performance, particularly with 8.00 mm diameter anchors outperforming 10.00 mm due to reduced drilled volume. This underscores that anchor tensile strength improves with higher concrete compressive strength. On average, a 30–60% increase in concrete compressive strength correlates with a 15–70% increase in anchor tensile strength, depending on anchor type and size. The study identifies two primary failure modes in anchor tests: concrete breakout and steel failure.

This study has limitations that impact the anchor tensile strength and failure patterns. It employed three types of anchors, each with two sizes and a single drilling depth, excluding high-strength concrete variables. This omission affects the maximum tensile strength of anchors. Additionally, the study did not account for reinforced concrete's unseen internal or external cracks, which can influence anchor strength. Preliminary non-destructive testing might be necessary to assess these factors comprehensively. Furthermore, a more precise correlation between anchor tensile strength and concrete compressive strength could be established if future research incorporates these considerations. Thus, addressing these limitations could enhance the accuracy and applicability of the findings regarding anchor performance in varied concrete conditions.

These findings serve as valuable information for tailoring the use of anchors to align with the performance of the concrete in various applications. The emphasis is particularly on reinforced concrete structures or smaller buildings undergoing renovations, where the connection of structures is facilitated by anchors. Furthermore, the study serves as a foundational reference for potential extensions, contributing preliminary guidelines for future investigations aimed at broader applications of anchors.

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