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A Critical Review on Relation Between Non-Destructive Tests and Pull-out Load of Imbedded Anchor Bolts in Concrete

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Abstract

Anchor bolts are widely utilized in numerous industries, including mechanical, construction, and mining. Anchor bolt uses range from installing permanent objects, including hybrid constructions, illumination poles, and directional signs, to installing temporary structures, such as formwork and safety netting. Several destructive testing instruments exist in the construction industry for determining the load-bearing capacity of concrete anchors. However, there has been a lack of attention to developing non-destructive testing (NDT) techniques for estimating pull-out loads. This study highlights the limited research on evaluating the pull-out strength of embedded steel bolts in concrete using non-destructive tests and illustrates their relationship. This critical review has demonstrated that embedded concrete anchor pull-out strength depends on alignment, embedment length, anchor bolt diameter, micro flaws, and bolt geometry. The embedment length of anchor bolts contributes much more to the improvement in pull-out strength than the bolt diameter. The ultrasonic pulse velocity (UPV) assessment and the Schmidt hammer (SH) assessment can successfully monitor the quality of embedded anchor bolts in normal-strength concrete structures by identifying defective anchor bolts with porous bonds. Anchor bolts with insufficient bonding were found to have a lower rebound value and a prolonged ultrasonic pulse time of transit.

Keywords: Anchor bolt, Pull-out strength, Non-Destructive test (NDT), Schmidt hammer (SH), Ultrasonic pulse velocity (UPV).

1. Introduction

In civil engineering, it is imperative to establish structural continuity among concrete members and other components to ensure reliable stress transmission during the construction of a structure. One commonly employed method for achieving this is using anchor bolts, widely utilised in new and existing structures [1, 2]. Anchor bolts of steel are extensively employed in the building sector for many applications. Anchor fasteners are produced in various sizes and forms to cater to diverse applications [3, 4]. The selection of an anchor for a particular application is influenced by several aspects, including the kind of installation material, the necessary load-carrying capability, the characteristics of the project, the prevailing environmental conditions, and the availability of competent labor [4]. Precast installation is favored for big anchor bolts because it facilitates rigorous quality assurance measures. Nevertheless, post-installed anchors are widely employed in the construction sector primarily because of their ease of installation and the absence of a requirement for highly specialized labor [4, 5].

Traditionally, the categorization of embedded steel bolts in concrete is commonly based on whether they are installed during post-construction or pre-construction stages. The anchor bolts added after the completion of construction can be further categorized into two distinct classifications.

I. Concrete anchor bolts are often inserted in predrilled holes filled with epoxy to achieve chemical adherence. Using skilled workers is imperative for appropriately handling, positioning, and installing these anchor bolts due to their exceptional load-bearing capacity.

II. The process involves drilling or inserting friction-installed concrete anchor bolts into pre-drilled holes. The anchor bolts enhance resistance against withdrawal forces by utilizing a mechanical interlocking mechanism. These particular bolts are favored in settings that do not necessitate highly specialized labor and where the installation and placement procedures are uncomplicated, owing to their reduced load-bearing capacity compared to the previous type.

Pre-construction inserted anchor bolts are the second classification of anchor bolts commonly employed within the construction industry. These tools are commonly employed in building, mining, and geo-stabilization. The installation of these anchors necessitates thorough planning, design, and commitment to specific standards. Seismic retrofitting and structural rehabilitation commonly use these materials within the building sector [2, 4-7]. Anchor bolts are used in many applications, such as railway foundations, modular wall structures, tunnel roofing, and nuclear-related facilities. Their utilisation is expected to persist [8-13]. However, a comprehensive assessment of the anchor bolt's maximum strength when subjected to a pull-out load has just been done. The reduction in pull-out resilience of bolts is a concern due to inadequate installation circumstances and the natural degradation of concrete materials over time [1].

Recent studies have been conducted to determine the ultimate strength of anchor bolts embedded in concrete. In a broad sense, the fracture mechanisms of anchor bolts under the influence of a pull-out load can be classified into three categories: bolt fracture, concrete body (cone) fracture, and bond fracture. If the steel strength is sufficient, concrete cone failure is the most frequently observed failure mode for static pull-out evaluations of headed anchoring with shallow embedding lengths [1, 2]. Figure 1 depicts the customary fracture modes considered during the design of anchor bolts and the corresponding equations used to compute the pull-out strength associated with each fracture type. The system's design is mostly determined by the pull-out capability of the fracture mode, specifically the fracture mode depicted as the weakest among the predicted fracture modes illustrated in Figure 1 [1]. Where T: maximum pull-out load, σ_y: steel yield strength, α0: nominal cross-section area of bolt, σ_B: concrete compressive strength, τ: maximum bond stress, d_a: anchor bolt nominal diameter, and l_e: embedded depth.

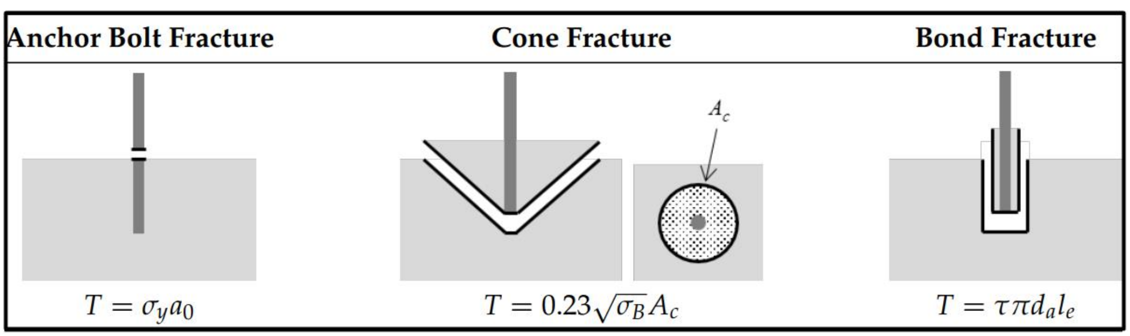

Figure 1. Anchor bolts fracture modes [1].

2. Literature Review

2.1 General Review

Several studies on the pul-lout load of anchor bolts have already been conducted [12, 14, 15]. Thus, there are experimental research focusing on base concrete damage [16, 17], bond failure of concrete and anchor bolt [18, 19], and long-term strength against aging efficiency [20]. Following studies by Nilforoush et al. [21] on the impact of member thickness and anchor head size, it was shown that the concrete cone resistance improves with increasing member thickness and/or anchoring head size. Mallee [22] and Eligehausen et al. [23] developed a thorough design guideline for post-installed anchoring systems in concrete construction, considering limit-state design, durability, fire resistance, fatigue, and seismic effects. Zamora [24] and Fuchs et al. [25] investigated the design and performance of tensile-loaded-headed, unheaded, and grouted anchors. Cook [26] and Eligehausen et al. [27] tested the effectiveness of an anchor under monotonic pull-out loads. Takiguchi et al. [28] investigated the response of bolts in cracked concrete and compared the results to non-cracked specimens. Wang et al. [29] studied the behavior of large-diameter anchors in concrete foundations subjected to static pull-out loads. Tadayoshi et al. [30] used the acquired knowledge and offered numerous new and old approaches to retrofit Japanese railway infrastructure using the concrete anchor successfully. In contrast, a multitude of analytical inquiries has been conducted utilizing numerical techniques, such as the Finite Element Method (FEM) [31, 32], the Galerkin method [33], the Smooth Particles Hydrodynamic (SPH) method [1], and peridynamic theory [34]. Furthermore, there exist research papers that employ neural networks to predict the strength of anchor bolts, taking into account various installation situations [35].

However, it is important to note that all of the investigations, as mentioned earlier, are either analytical or depend on the anchors' destructive analysis. Some non-destructive assessments can be employed for evaluating the load-bearing capacity of concrete anchors, both pre-installed and post-installed anchors.

Nowadays, construction has been revolutionized by non-destructive testing technology [3-5, 35, 36]. Non-destructive testing is extensively employed within the building sector to estimate the state of preexisting structures. This technique allows engineers to estimate the strength of components and materials without causing harm or altering them [3-5, 35, 36]. One of the key benefits of non-destructive examination compared to destructive testing is preserving the structural integrity throughout and following the testing process [5, 35, 36]. Non-destructive testing can be categorized into several distinct groups, including techniques that rely on mechanical waves, techniques that utilize electromagnetic fields, techniques that employ radiography, techniques that utilize radar and radio frequency, and techniques that rely on fiber optics. These techniques utilize optics and techniques that involve actuators and receivers [37, 38]. Various techniques that rely on mechanical waves are employed in the field. These techniques encompass the Tap Test, the Schmidt hammer test, Acoustic Emission Monitoring, Ultrasonic testing, the Impact-Echo Method, and Noncontact Wave Sensing [37, 38]. The Schmidt hammer (SH) and ultrasonic pulse velocity (UPV) tests are widely employed NDT techniques on a global scale.

The Schmidt hammer, developed in 1948 by Swiss scientist Ernest Schmidt, is a portable and cost-effective tool for approximating the elasticity of cemented concrete. The technique above is a widely employed and viable approach that is non-invasive. It serves as a benchmark test on a global scale for approximating the compressive strength of concrete [39]. The prospective applications of the SH have been acknowledged by researchers, who have utilized it to establish a correlation between the rebound value and the compressive strength of rocks [40-43]. Additionally, the SH has been employed to do qualitative examinations of various materials. Previous studies have investigated the impact of many factors, such as the angle of rebound, concrete construction parameters, and surface preparation techniques, on the SH recoil number [44-46]. The link between SH recoil numbers, slake endurance index, and p-wave velocity was found by Sharma et al. [47]. In their study, Multib et al. [48] employed non-destructive testing methods, specifically stress wave propagation (SH) and ultrasonic pulse velocity, to assess the long-term condition of enormous constructions, such as bridges. The researchers determined that these instruments proved valuable in tracking the structural integrity of various components over time through regular monitoring and inspection. In addition, the researchers investigated the impact of rapid-hardening cement, the kind and size of aggregate, the influence of concrete age, and its workability. Their findings indicate that the ultrasonic pulse velocity (UPV) test is a valuable non-destructive technique for assessing the characteristics of concrete [35, 36, 48]. The bond-corrosion model established by Li et al. [49], Yalciner et al. [50], and Desnerck et al. [51] was utilized to investigate the impact of bond loss on crack propagation. Researchers established equations for the estimation of anchor bolt bond strength. Specific presumptions were employed to simplify the modeling procedure due to the intricate nonlinearity observed at the interface between concrete and steel [35, 49-51].

Furthermore, Inadsu et al. [52] and Ongpeng et al. [53] effectively utilized an ANN (artificial neural network) to forecast the width of cracks and the compressive strength of concrete by leveraging a UPV assessment. Table 1 summarizes the equations for predicting the pull-out load of embedded anchor bolts in concrete using non-destructive tests from articles reviewed in this study. Table 2 summarizes the relationships between non-destructive tests and the pull-out load of embedded anchor bolts in concrete from the limited available articles reviewed in this study.

Table 1. The reviewed summary of pull-out load equations with non-destructive tests.

References	Bolt Properties (Diameter - Embedment length)	Value of Pull-out Load
Saleem et al. [4]	8 mm – 50 mm	$-0.0038R^2+0.7608R$
	10 mm – 50 mm	$0.0144R^2-0.3823R$
	12 mm – 50 mm	$0.0036R^2+0.3654R$

R: Rebound Number of Schmidt hammer test

Table 2. The reviewed summary of pull-out load relations with non-destructive tests.

References	Type of non-destructive tests and analysis (if any)	Factors of interest
Saleem and Nasir [3]	Schmidt Hammer	Bolt diameter (8, 10, and 12 mm)
Saleem et al. [4]	Schmidt Hammer	Bolt diameter (8, 10, and 12 mm) and length of embedded depth (1/3 and 1/2 of bolt diameter)
Saleem and Hosoda [5]	Schmidt Hammer and Latin Hypercube Sensitivity Analysis	Bolt diameter (8, 10, 12, 16, and 20 mm) and embedded depth (50 and 70 mm)
Saleem [36]	Schmidt Hammer and UPV	Bolt diameter (12 mm) and embedded depth (50 and 70 mm)
Saleem [35]	Schmidt Hammer, UPV and ANN analysis	Bolt diameter (16 and 20 mm) and embedded depth (50 and 70 mm)

2.2 Bolt pull-out relation with Schmidt Hammer

A thorough literature review determined that most past research has focused on the mechanical behavior of anchor bolts when exposed to monotonic or cyclic loading conditions. In contrast, the effects of impact loading have received little attention. Therefore, Saleem and Nasir [3] investigated the impact loading impacts on the deformational reaction of anchor bolts. Additionally, they assessed the bond performance of anchor bolts that were put before construction and afterwards exposed to impact loading. The impact loading exhibited similarities to the force the Schmidt hammer rebound applied. The experimental program considered many elements that can affect the pull-out load of anchor bolts. These factors encompass inherent faults present in the surrounding concrete, the length of embedment, the diameter of the bolt, the alignment of the bolt, and the potential ingress of water. Fifty-four cylindrical concrete specimens with 150 x 300 mm dimensions were prepared using ordinary Portland cement (type I). The concrete mixture contained 160 kg/m^3 of water, 288 kg/m^3 of cement, 828 kg/m^3 of sand, and 1043 kg/m^3 of gravel, and the water-cement ratio was 0.40. The slump was around 100 mm, and the average compressive strength after seven days of curing was 28.5 MPa. Three bolts with 8, 10, and 12 mm diameters were utilized for the investigation. These bolts had a length of 153 mm, and approximately one-third of their whole length was implanted within the concrete specimens. The specimens underwent testing utilizing a Schmidt hammer, wherein the rebound value number (R) of the anchor bolts implanted within the concrete samples was measured. The test apparatus depicted in Figure 2 was utilized to quantify the R and impact load of the SH. The hammer's base was securely affixed, and the plunger gradually descended before the digital data-collecting system captured the impact load. In summary, the first application of compressive impact force on the bolts, as illustrated in Figure 3, led to flaws in the concrete surrounding the bolts.

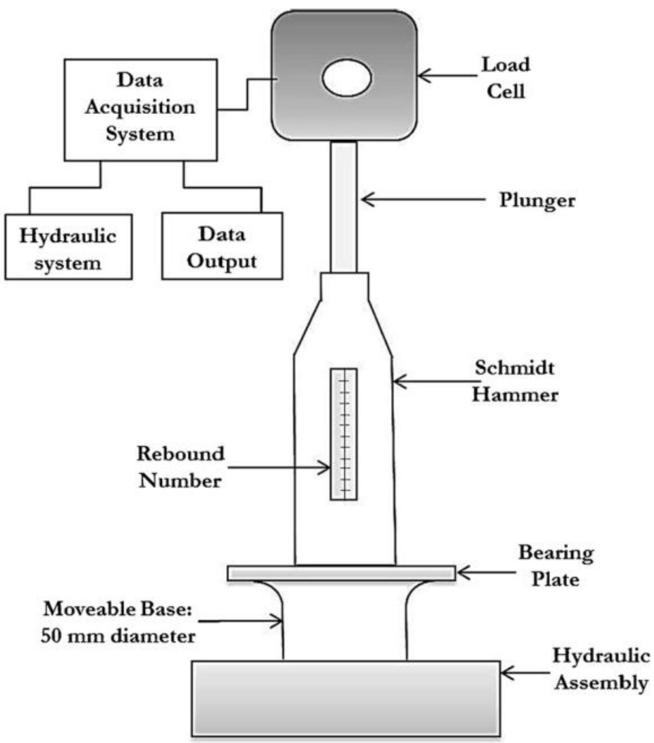

Figure 2. The experimental set up for measuring the Schmidt hammer impact force [3].

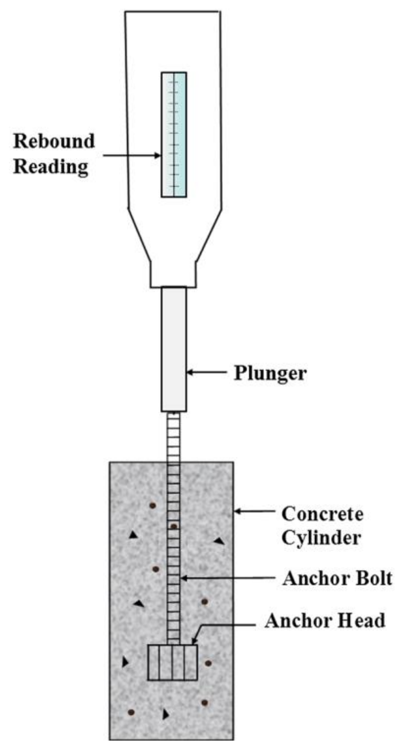

Figure 3. Configuration of the experimental for recording the rebound value on the anchor bolt [3].

The test results showed the SH rebound number, and installed bolts can be inspected for defects. It was observed that bolts with misalignment, micro-cracking, and poor surrounding concrete quality have a lower rebound value because they cannot impart impact loading to the surrounding concrete. Also, the ability to transfer impact loading to the surrounding concrete results in higher rebound numbers for bolts with high-quality surrounding concrete and appropriate installation. As for the bolt's diameter effect, due to greater bond strength, the pull-out force of a bolt increases as its diameter grows. Furthermore, a comprehensive analytical model has been developed to incorporate many factors such as bolt diameter, form effect, installation length, alignment, micro flaws, and interfacial bond. This model accurately forecasts the maximum load-carrying capacity of bolts based on experimental data.

A study by Saleem et al. [4] investigated non-destructive testing procedures to evaluate the pull-out strength of concrete anchor bolts and to establish a new relationship between the pull-out load (P) of concrete anchors and the SH recoil value (R). Fifty-four standard concrete cylinders were prepared using type I Portland cement and cured at room temperature for 28 days before testing. The maximum size of the gravel was 20 mm, while dune sand was used as the fine aggregate. The concrete mix proportion was 1:2.87:3.62 (cement: sand: gravel), with a water-cement ratio 0.4 and 4.1% air-entrained agents. The study utilized steel anchor bolts of 8, 10, and 12 mm, as depicted in Figure 4. The combined length of the 12-mm and 10-mm anchor bolts amounted to 150 mm, whilst the 8-mm anchor bolt had a total length of 125 mm. Figures 4 and 5 depict that one-third of the embedment length (L_d) was embedded into the concrete cylinder before casting, and two-thirds of the total length (L_e) was exposed. Every anchor bolt's placement occurred in the cylindrical mould's precise centre, and its stability was ensured through wires. The authors adjusted the embedment depth using the guide wires to prevent displacement during the concrete casting. The measurements obtained from the rebound hammer were documented on the surface of the anchor bolt once the curing process had concluded. The average value from five measurements was used for data analysis. By employing the anchor cage that has been designed, as illustrated in Figures 6 and 7, the researchers successfully performed pull-out load testing utilizing the universal testing machine (UTM), thereby obviating the necessity of procuring additional expensive apparatus.

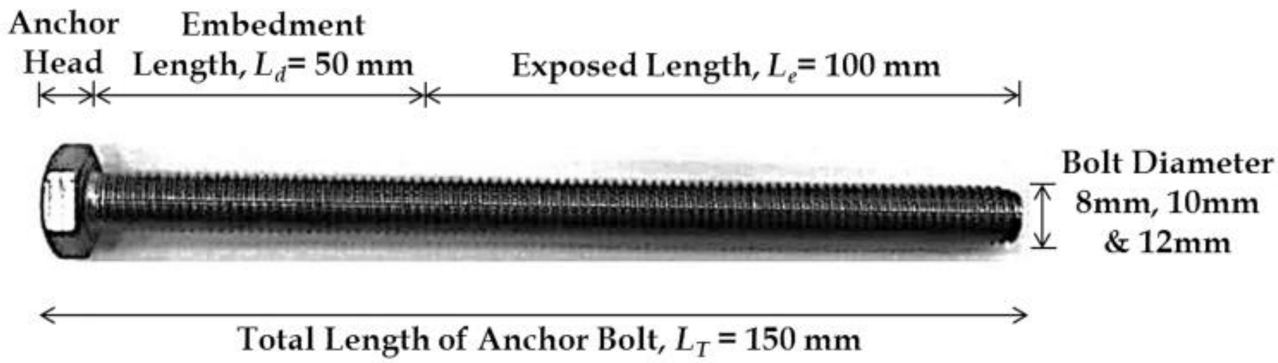

Figure 4. A view of the anchor bolt [4].

Figure 5. A view of a concrete cylinder with an embedded anchor bolt [4].

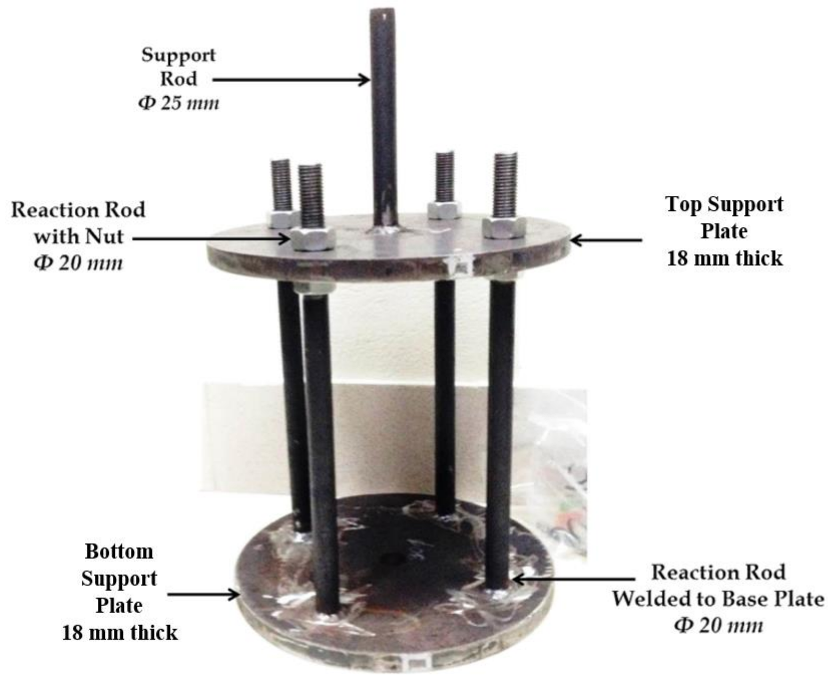

Figure 6. A view of the anchoring device [4].

Figure 7. A view of the testing setup [4].

They provided a correlation between the SH R value and pull-out load (P) of anchor bolts embedded in normal-strength concrete based on the test results with a coefficient of determination (R^2) of more than 0.90, shown in Figure 8. Furthermore, it has been observed that several experimental variables, including installation length, bolt diameter, bolt alignment, and surrounding concrete strength, significantly influence the correlation. The study's findings indicate that anchor bolts not positioned vertically and those set in low-quality concrete exhibit limited ability to withstand significant pull-out loads. Additionally, it has been announced that an SH value, denoted as R, of 45 for an anchor bolt with a diameter of 8 mm and an R-value of 60 for anchor bolts with diameters of 10 mm and 12 mm are indicative of suitable installation, vertical alignment, and ability to sustain loads. A number denoted as R, which falls below the criteria above, can point to inadequate installation, lack of vertical alignment, or substandard quality of the surrounding concrete.

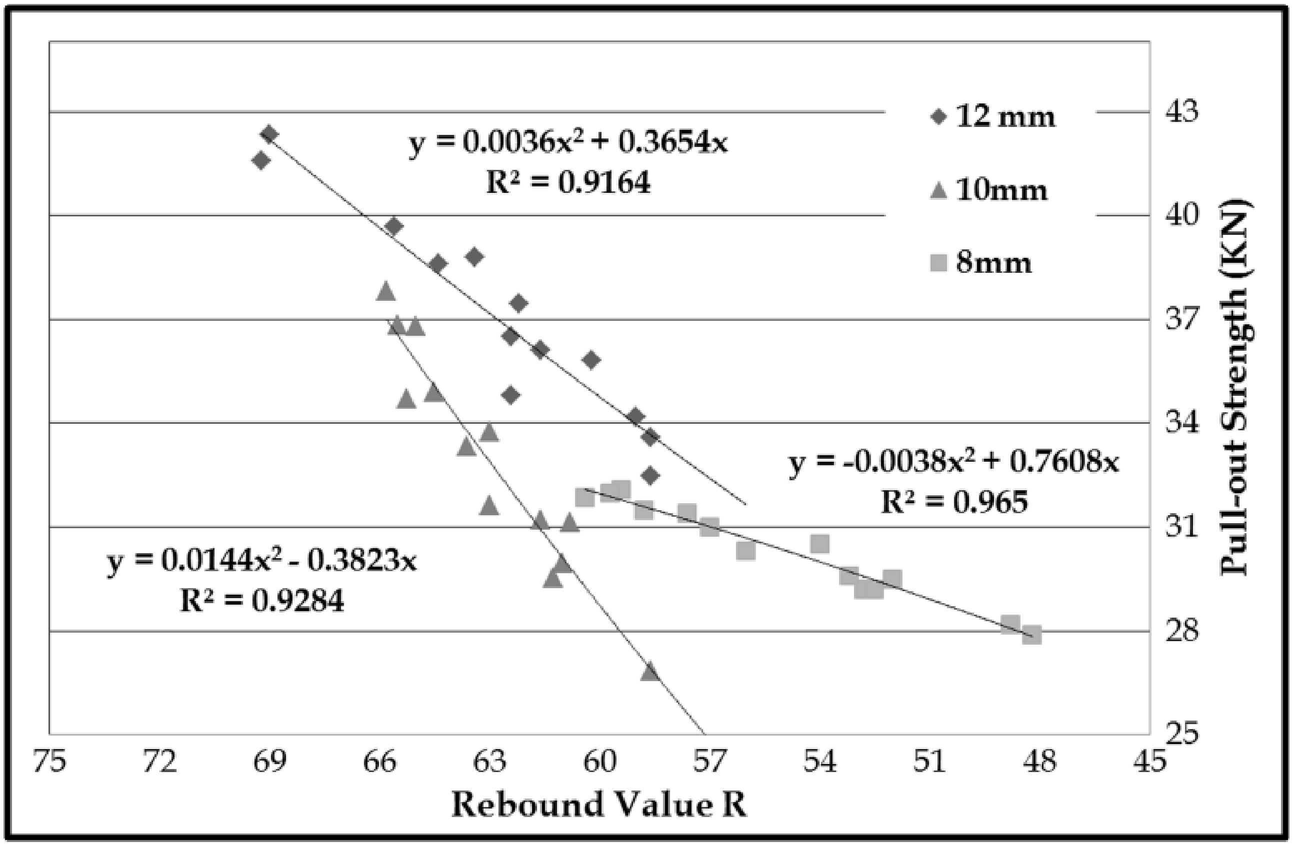

Figure 8. Relationship between combined pull-out load and rebound value [4].

Saleem and Hosoda [5] conducted a study on Latin Hypercube sensitivity analysis and non-destructive testing for evaluating the pull-out strength of embedded steel anchor bolts in concrete. A total of 144 anchor bolt samples were cast, and a total of 24 cylindrical samples were produced to measure compressive strength. All experiments were conducted using conventional OPC type-1 cement. All experimental procedures following ASTM C150/C150M and C192/C192M standards utilized concrete specimens of standard strength. The mixture's water content was 157 kg/m^3, while the cement content was 281 kg/m^3. The sand and aggregate content were determined to be 873 kg/m^3 and 1039 kg/m^3, respectively.

The mixture's water to cement ratio was also calculated to be 0.36. Dune sand, chosen as a fine aggregate, possesses a bulk specific gravity of 2.43 and an absorption rate of 0.59%. Limestone was employed as a coarse aggregate, possessing a specific gravity of 2.57 and an absorption rate of 1.12%. The study investigated a set of five bolts, each with varying sizes of 8 mm, 10 mm, 12 mm, 16 mm, and 20 mm. Additionally, the bolts were subjected to two different embedment depths, specifically 50 mm and 70 mm. The study team endeavored to devise a novel non-destructive testing technique by employing a conventional Schmidt hammer. In this context, the decision was made to employ readily accessible 150-mm anchor bolts. The researchers determined that the minimum installation length for the bolts should be one-third of their overall length.

Consequently, a length of 50 mm was chosen as the minimum installation length. As depicted in Figure 9, the bolt's overall length (L_C) measured 150 mm, with an embedment length (L_E) of 50 mm and outer lengths (L_O) of 100 mm and 80 mm, respectively. The anchor bolt's embedment length was denoted using a marker, and guide wires were employed to fasten the anchor bolt within the mold depicted in Figure 10. The primary function of the guide wires' placement was twofold: firstly, to signify the installation length, and secondly, to ensure the stability of the anchor during the casting process. Special precautions were implemented to prevent any disruption to the guide wires during the concreting process and to avoid tampering, as these actions could lead to misalignment and alter the installation length of the anchor bolt. The specimens underwent a curing process within a designated container for 28 days, maintaining a consistent room temperature. The measurement of SH rebound values was conducted on the tip of the anchor bolt after the curing process, as depicted in Figure 11. A collection of five distinct readings was documented as a cohesive unit. To mitigate the slippage of the Schmidt hammer plunger upon impact, precautionary measures were implemented to ensure proper alignment of the plunger with the anchor bolt point. The pull-out evaluation apparatus employed in the experiment is seen in Figure 12. Various expensive, specialized pull-out evaluation rigs are available in the market. The authors have created a novel anchor cage suitable for performing pull-out evaluation using a universal testing machine (UTM), as described in prior literature [4].

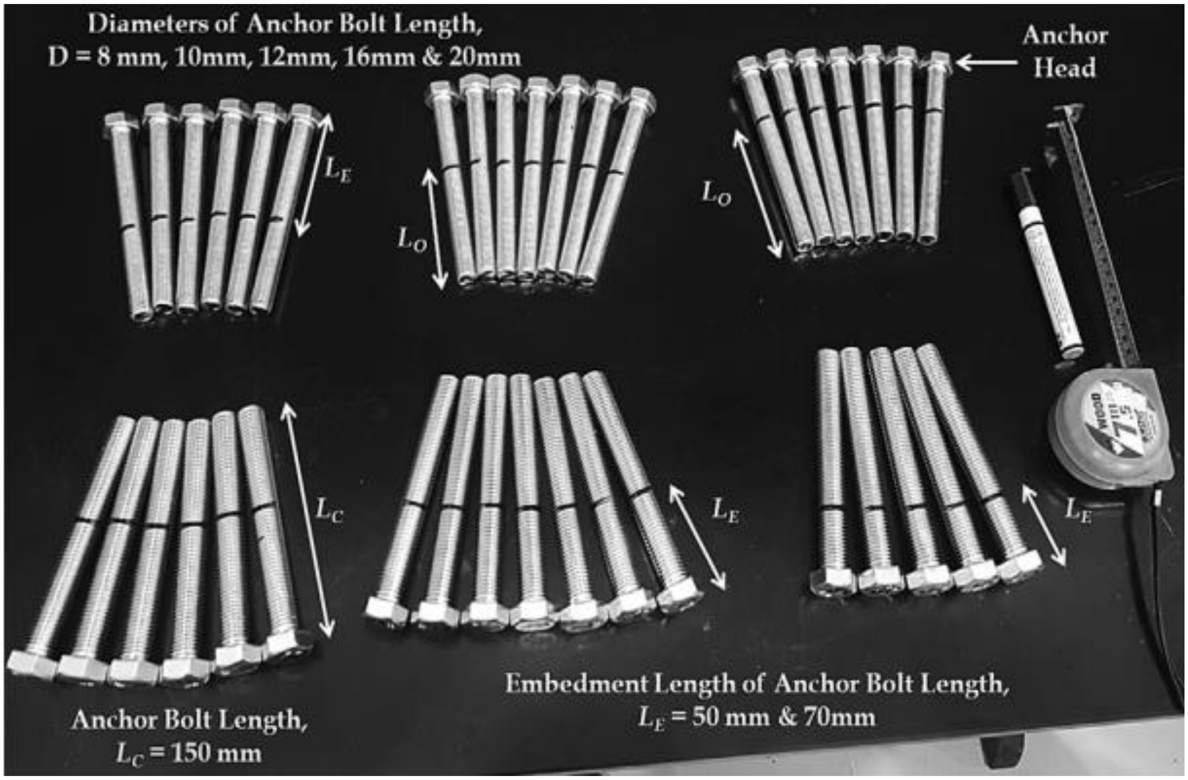

Figure 9. A view of used concrete anchor bolts in the study [5].

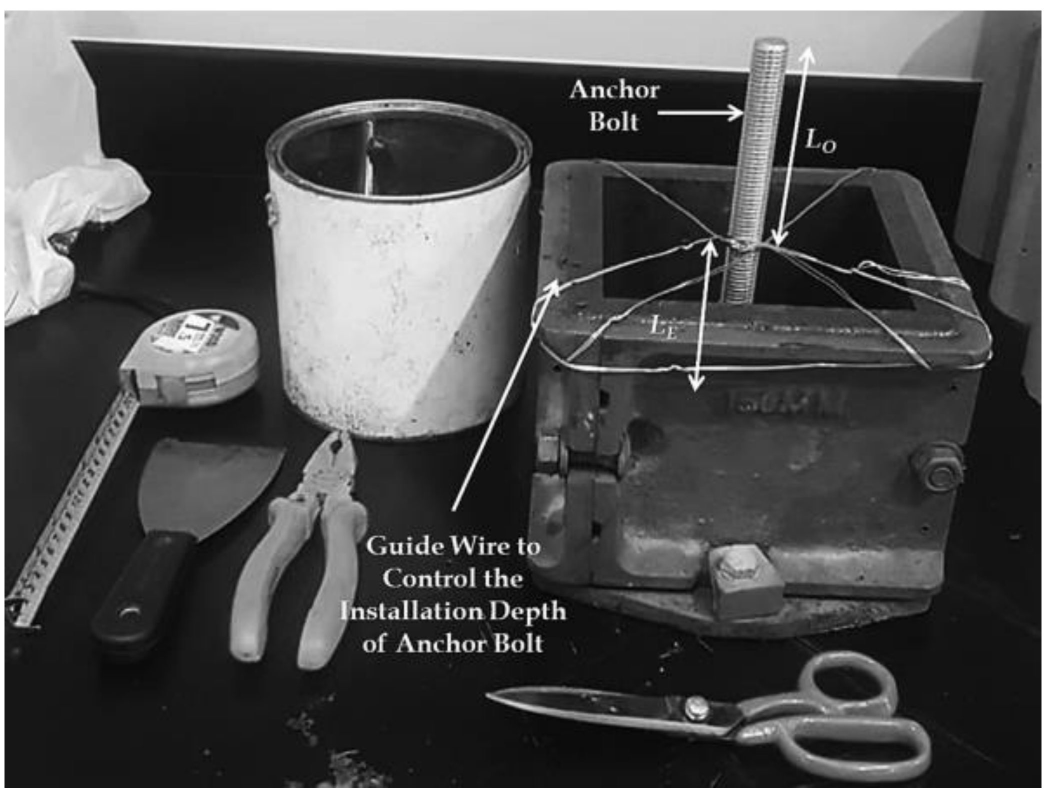

Figure 10. A view of the guide wire mechanism for steel Anchor bolt installation [5].

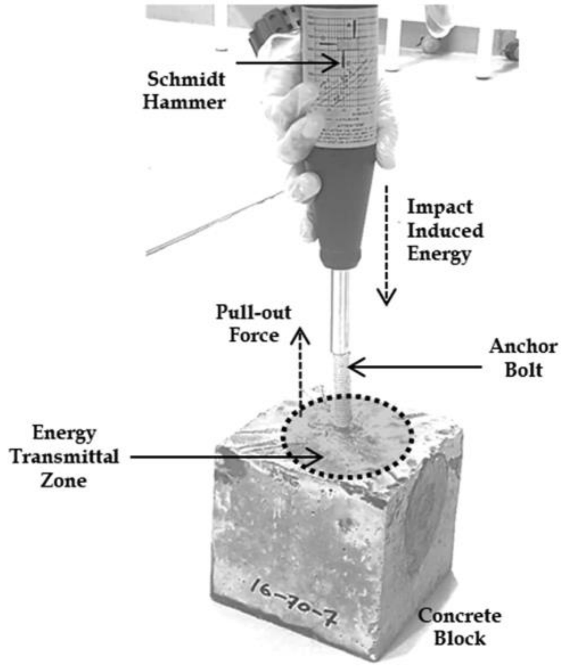

Figure 11. A View of the mechanism used for testing the cube specimens [5].

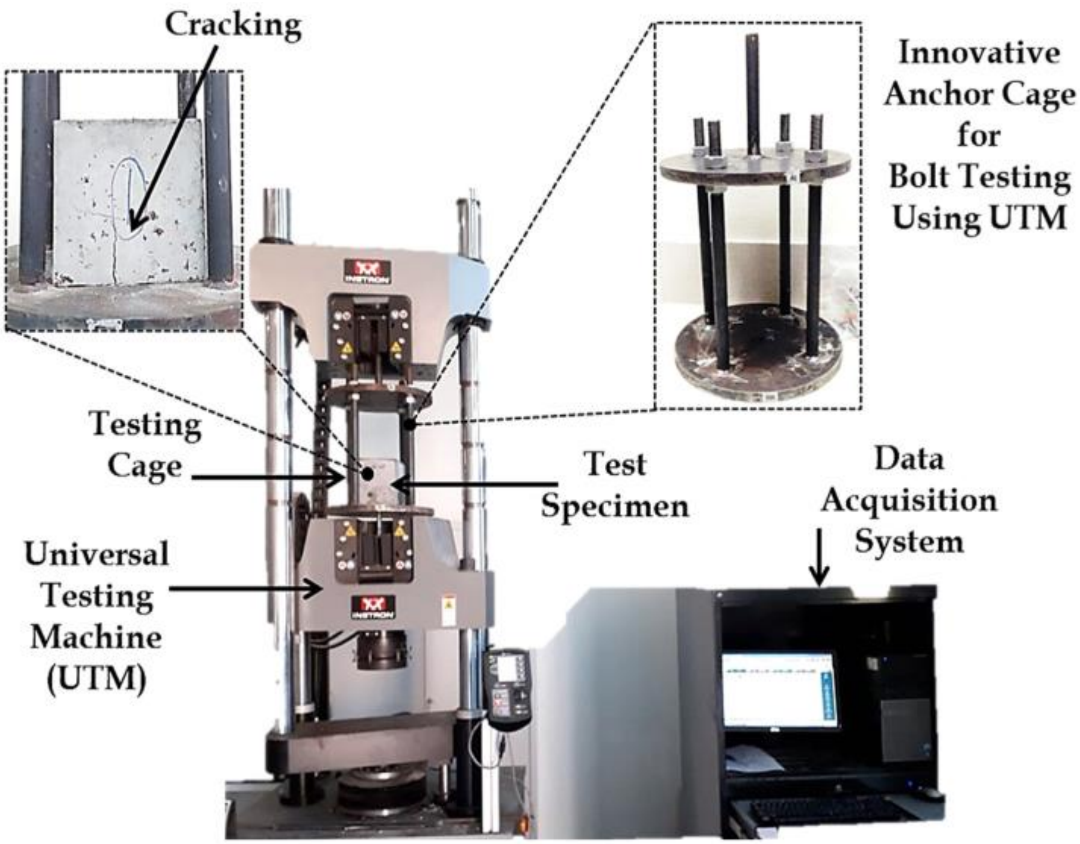

Figure 12. The test setup and anchor cage employed for the execution of pull-out testing with the Universal Testing Machine [5].

The experimental findings suggest that the rebounding values (R) of 56 and 61 can be considered threshold values for anchor bolts with 8 mm and 10 mm diameters and installation lengths of 50 mm. Furthermore, it could be claimed that the rebounding values (R) of 55, 53, and 51 can serve as threshold values for anchor bolts with diameters of 12 mm, 16 mm, and 20 mm and installation lengths of 50 mm and 70 mm, respectively. Bolts exhibiting higher R are considered to have been placed successfully. Bolts exhibiting a diminished R are indicative of potential deficiencies in the installation process and the condition of the surrounding concrete. The examination of Latin Hypercube sensitivities (LHS) showed that the ability to bear pull-out load is more responsive to changes in installation length than an augmentation in bolt diameter. Additionally, it was found that anchor bolts positioned at non-vertical angles had the most substantial impact on diminishing the pull-out strength.

2.3 Bolt pull-out Relation with Ultrasonic Plus Velocity

A study by Saleem [36] employed ultrasonic pulse velocity (UPV) tests to assess the integrity of concrete anchor bolts. The objective was to establish a correlation between the pulse velocity measurements and internal cracks inside the concrete. The researcher employed a methodology involving ultrasonic pulse velocity and Schmidt hammer testing in this study. This approach aimed to identify anchor bolts installed with a high proficiency level while estimating their pull-out strength. This estimation was achieved by establishing a correlation between the pull-out strength and the rebound value (R) obtained from the Schmidt hammer test. Following ASTM C150, forty 150 x 150 x 150 mm cube specimens and six 150 x 300 mm cylindrical specimens for compressive strength testing were cast using conventional Portland cement (Type-I) with a specific gravity of 3.15. The utilization of desert sand as a fine aggregate was seen, wherein its bulk specific gravity was determined to be 2.66, and its water absorption was measured at 0.60%. The water-cement ratio utilized in the experiment was 0.41, accompanied by a water content measurement of 120 kg/m^3. The cement had a mass of 290 kg/m^3, while the air entrainment level was determined to be 4.2%. The sand and gravel components had 828 and 1043 kg/m3 masses, respectively. Limestone coarse aggregate with a maximum particle size of 19 mm was used, and it was graded according to ASTM C33 with a bulk specific gravity of 2.45 and a water absorption of 2.05%, respectively. The specimens were curing within a water container that was maintained at a controlled temperature. Subsequently, the mean compressive strength of the samples was determined to be 34.1 MPa after 28 days. During the preparatory work, a steel anchor bolt with a diameter of 12 mm and a total length (L_t) of 150 mm was installed. The anchor bolt had installation lengths (L_d) of 50 mm and 70 mm and visible lengths (L_E) of 100 mm and 80 mm, respectively.

Five measurements using the SH rebound method were conducted on the lower surface of the anchor bolt. The average value obtained from these measurements was utilized for further investigation. Using the previously established anchor cage, as exemplified in other studies [4, 5], the researcher successfully performed pull-out load testing using a UTM, thus obviating the necessity of acquiring costly new equipment. The UPV measurements were conducted following the guidelines specified in ASTM C597. The study considered many factors, including sample dimensions, aggregate size, anchor bolt size, frequency, concrete hydration condition, temperature, and an anchor bolt positioned perpendicular to the path of pulse propagation.

Furthermore, as illustrated in Figure 13, the transducer and receiver were securely positioned at opposing extremities of the cube specimen, and petroleum jelly was employed to ensure adequate coupling between the transducer and the cube specimen. The velocity of the wave was calculated by dividing the 150 mm width of the specimen by the shortest time, measured in microseconds (s), taken by the ultrasonic wave to traverse. Three measurement locations were selected along the anchor bolt's embedment depth. Additionally, three measurements were taken at each point. The quickest wave travel time, corresponding to the shortest transit time, was recorded.

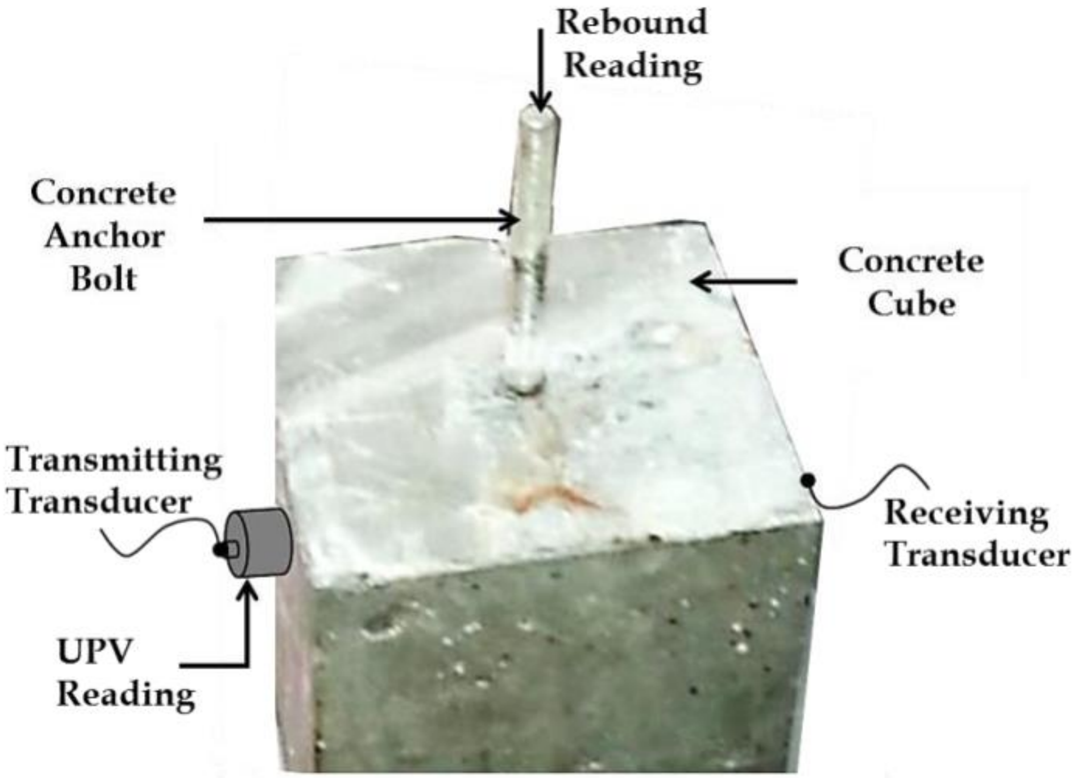

Figure 13. Cube-shaped specimen illustrating Schmidt hammer and UPV testing [36].

It was concluded that combining UPV and SH assessments can effectively identify defective anchor bolts with porous bonds. Anchor bolts with inadequate bonding exhibit a reduced R and an extended UP transit time. The findings of this study indicate that anchor bolts with misalignment and porosity cannot be considered dependable means for enhancing the load carrying capability during pull-out. Furthermore, non-destructive testing techniques make it feasible to accurately identify anchor bolts with diminished capacity to withstand pull-out loads. According to the research, a cut-off value (R) of 52 for a 32 kN pull-out strength and 55 for a 47 kN pull-out strength can be applied to anchor bolts with a diameter of 12 mm and embedment lengths of 50 mm and 70 mm, respectively. Anchor bolts with an R lower than the prescribed value cannot be deemed dependable for supporting heavy load-carrying capacities.

Another study by Saleem [35] assessed the load-carrying capacity of concrete anchor bolts using non-destructive tests and an artificial multilayer neural network. Using artificial neural networks (ANN) to model the complex nonlinear interactions of parameters is a modern method used by Saleem [35] in this study. There is no need to minimize the complexity of the factors in such techniques, as no assumptions are required. This method applies to the original experimental data. Artificial neural networks are employed to develop intelligent systems capable of predicting rational answers, drawing inspiration from the logical principles governing biological brain networks while avoiding oversimplifications. Concerning this matter, 48 cube samples, each measuring 150 x 150 x 150 mm, were produced to evaluate the pull-out force capacity of anchor bolts by utilising non-destructive assessment techniques, specifically the SH and UPV tests. To mitigate potential discrepancies in the quality of concrete, it was ensured that all samples were cast using a uniform quantity of concrete. This factor was taken into account to eliminate bond variation. In addition to the cube specimens, six standard cylindrical specimens were also cast to evaluate the compressive strength of concrete.

The casting process involved using OPC-Type I cement, which had a specific gravity of 3.17, in compliance with the criteria outlined in ASTM C150. The fine aggregate used in concrete production was desert sand, with a bulk specific gravity of 2.55 and water absorption of 0.77%. The concrete mixture had a 5.9% air content and initial and final setting times of 163 and 237 minutes, respectively. Limestone with a maximum diameter of 20 mm was used as coarse aggregate according to ASTM C33. The water-to-cement ratio was consistently maintained at 0.35, while the mass ratio of fine-to-coarse aggregate was 0.57. A slump measurement of 100 millimeters was recorded when a superplasticizer dosage of 0.63 percent by weight of cement was applied. All samples were aged in the curing container for 28 days. A recorded average compressive strength of 45.96 MPa was obtained following the guidelines outlined in ASTM C39.

Figure 14 depicts the pre-construction installation of the anchor bolts utilized in this investigation by the researcher [35]. Two 16 mm and 20 mm bolts were used, and each bolt was examined with two different installation lengths of 50 mm and 70 mm. The length of the bolt (L_C) was 150 mm. L_E indicated the installation lengths of 50 mm and 70 mm, while L_O represented the outside lengths of 100 mm and 80 mm. The same procedure was followed for recording SH values (R) and UPV measurements, as well as the pull-out load of the specimens, as demonstrated in previous research [36]. Following the documentation of the SH readings, the UPV evaluation was conducted again, capturing three readings at three distinct positions along the entirety of the anchor bolt's embedment. This experimental study assessed the variation in UPV measurements before and after subjecting the material to SH impact loading.

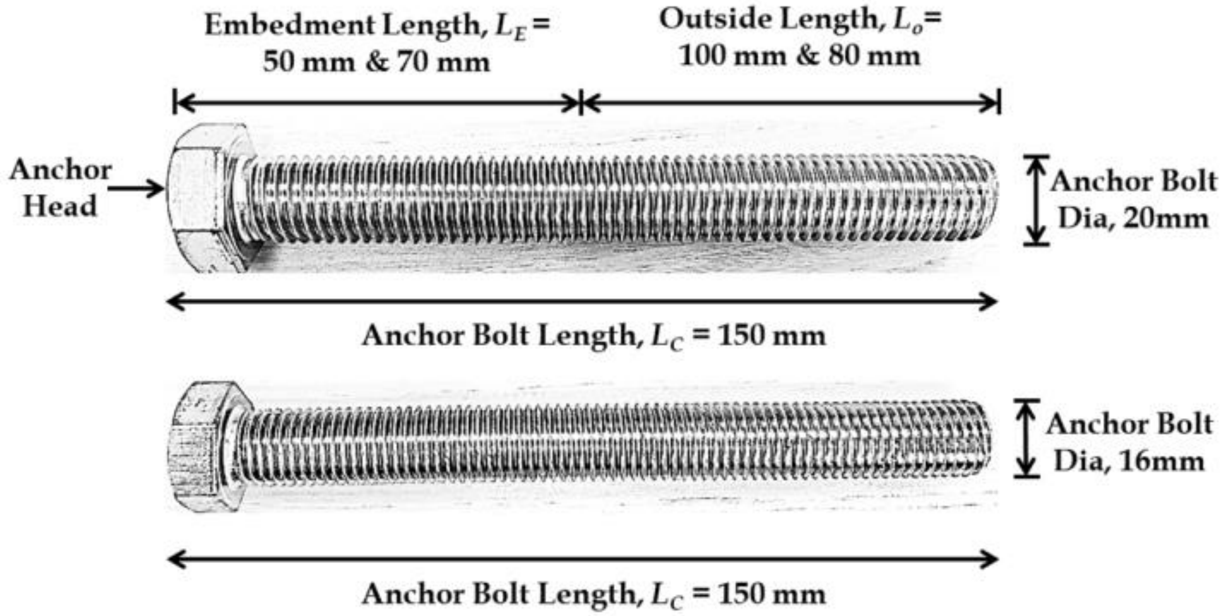

Figure 14. A view of concrete anchor bolt [35].

It was concluded that the SH rebound number (R) increases as pull-out strength increases. Nevertheless, the increase in pull-out force is more significantly influenced by the installation length rather than the bolt diameter. The SH rebound numbers 47, 49, 51, and 53, denoted as R, correspond to pull-out strengths of 32 kN, 43 kN, 44 kN, and 50 kN for anchor bolts with diameters of 16 mm and 20 mm and installation lengths of 50 mm and 70 mm, can be considered as the lower limits below which the load carrying capability cannot be reliably reached. The factors significantly influencing anchor bolt pull-out strength prediction were UPV (Ultrasonic Pulse Velocity), Schmidt hammer, installation length, and anchor bolt diameter. The MLP-5-4-1 artificial neural network (ANN) was assessed alongside other architectures and showed superior performance. This is illustrated in Figure 15, where the MLP-5-4-1 ANN had the most favorable outcomes. Figure 16 displays the normalized relevance of the factors included in this ANN model (MLP-5-4-1). The data show that the UPV and R value have the biggest impact on anchor bolt pull-out load estimation. Using the model presents an opportunity to enhance the evaluation of NDT anchor bolts by introducing a new dimension. Figure 17 shows the parametric individual analysis of the relationship between the pull-out force of embedded anchors in concrete and UPV for the model.

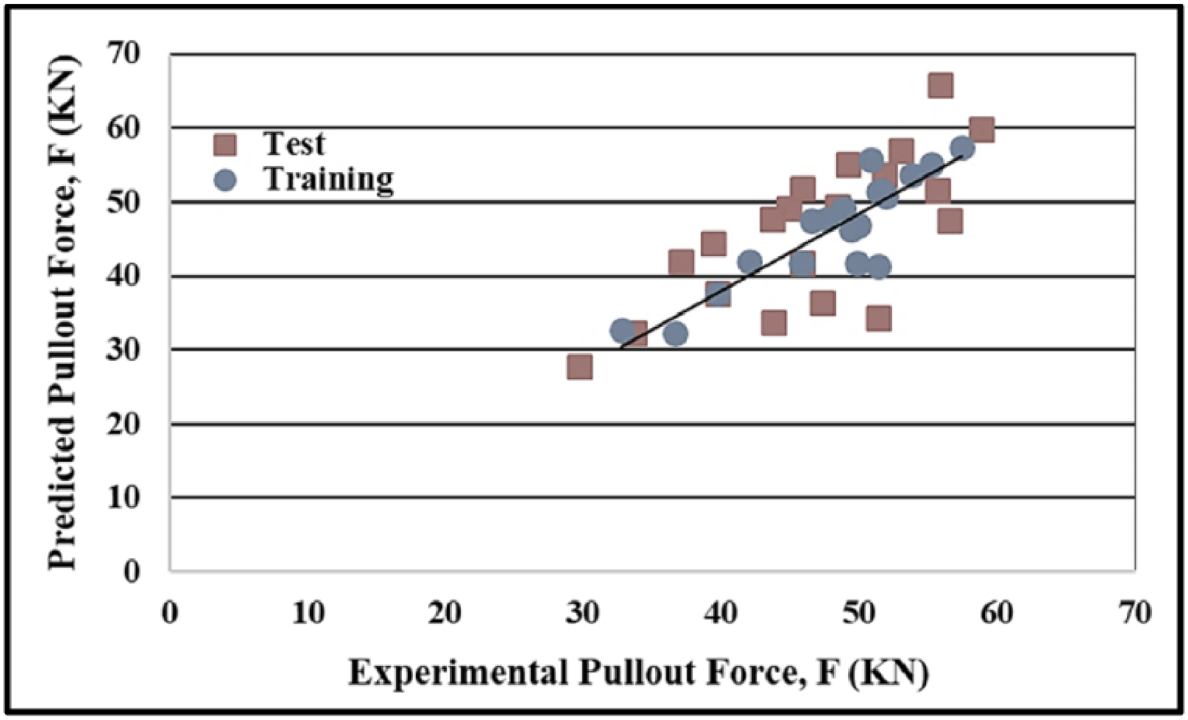

Figure 15. Comparison between the experimental pull-out force and the projected pull-out force using an MLP-5-4-1 neural network [35].

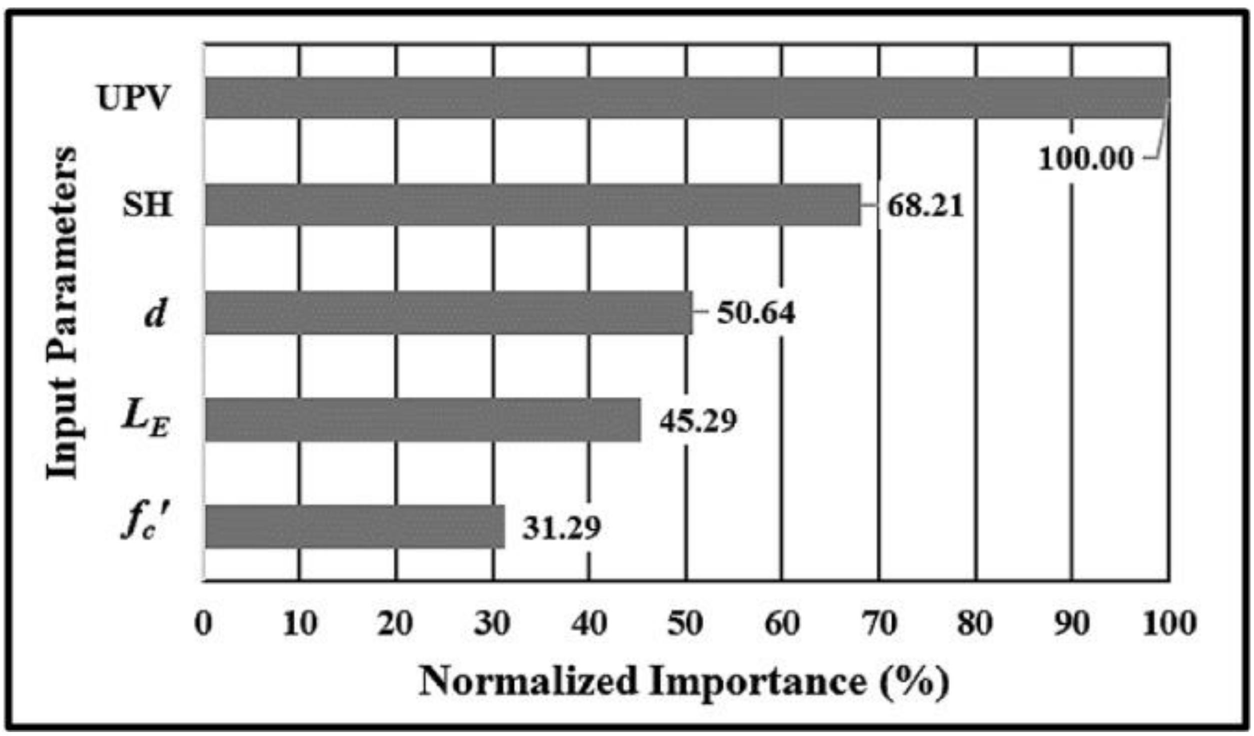

Figure 16. Normalized input parameter importance for MLP-5-4-1 [35].

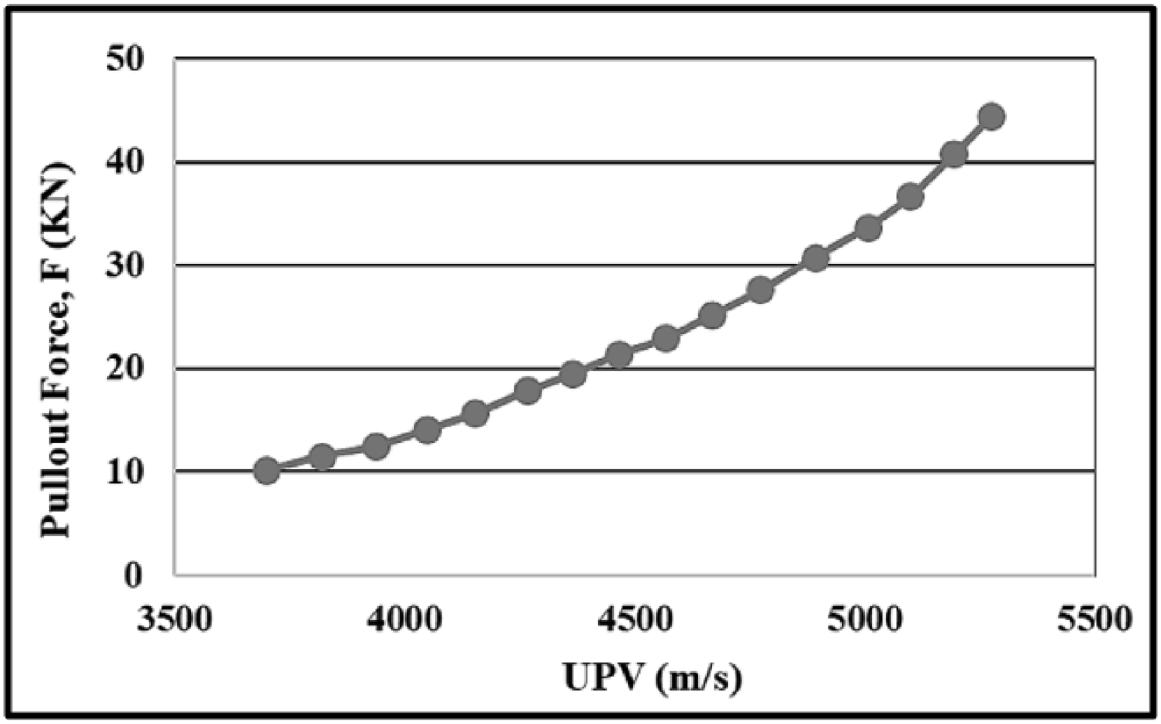

Figure 17. The pull-out force of an embedded anchor bolt in concrete is examined concerning the UPV [35].

3. Conclusion

The focus of this study was to review the limited research on the pull-out strength of embedded anchor bolts in concrete using non-destructive tests. Based on the previous studies in the literature on the use of non-destructive tests in evaluating embedded anchor bolt pull-out strength in normal concrete, the following conclusions are drawn:

1. Anchor bolt diameter, alignment, embedment length, interfacial bond, micro defects, and bolt shape affect the pull-out resistance of embedded anchors in concrete.
2. Anchor bolts with misalignment, microcracking, and poor surrounding concrete quality have a lower rebound value since they cannot impart impact loading to the surrounding concrete. In addition, the ability to transmit impact loads to the surrounding concrete results in increased rebound numbers for anchor bolts with high-quality surrounding concrete and proper installation.
3. Schmidt's hammer rebound number and pull-out strength have a strong correlation. A Schmidt hammer can be used to check the quality and health monitoring of the embedded anchor bolts in normal-strength concrete. The higher R number means higher pull-out strength. However, embedment length significantly improves pull-out strength more than bolt diameter.

4. The UPV and SH evaluations can detect defective anchor bolts with poor bonds. Anchor bolts with insufficient bonding have a lower rebound value and a prolonged ultrasonic pulse time of transit.
5. Engineers and researchers can use the UPV and Schmidt hammer tests to identify anchor bolts with inadequate installation, alignment, porous bond, or embedment. If anchor bolts have low rebound numbers, UPV assessment is a confirmation tool to reveal improper installation.
6. The pull-out load can be successfully predicted from the SH rebound value using the provided equations in the literature while considering the cut-off value of the anchor bolts. The rebound values of 56 and 61 for anchor bolts with 8- and 10-mm sizes and 50-mm installation lengths can be regarded as cut-off values. Any rebound measurement beneath these points indicates defective installation, non-verticality, or substandard concrete in the surrounding area.
7. The minimum value (R) for the anchor bolts of a 12 mm diameter size with installation lengths of 50 and 70 mm is 52 for 32 kN pull-out strength and 55 for 47 kN pull-out strength, respectively. Anchor fasteners with a lesser rebound value than specified are unreliable.
8. SH rebound values 47, 49, 51, and 53 for pull-out force of 32 kN, 43 kN, 44 kN, and 50 kN for 16 and 20-mm diameter anchors with installation lengths of 50 and 70 mm are the lowest values beneath which strength cannot be attained safely.

References:

[1] Lu, C., & Sonoda, Y. (2021). An analytical study on the pull-out strength of anchor bolts embedded in concrete members by SPH method. *Applied Sciences*, *11*(18), 8526.

[2] Shafei, E., & Tariverdilo, S. (2021, December). Seismic pullout behavior of cast-in-place anchor bolts embedded in plain concrete: Damage plasticity based analysis. In *Structures* (Vol. 34, pp. 479-486). Elsevier.

[3] Saleem, M., & Nasir, M. (2016). Bond evaluation of steel bolts for concrete subjected to impact loading. *Materials and Structures*, *49*, 3635-3646.

[4] Saleem, M., Al-Kutti, W. A., Al-Akhras, N. M., & Haider, H. (2016). Nondestructive testing procedure to evaluate the load-carrying capacity of concrete anchors. *Journal of Construction Engineering and Management*, *142*(5), 04015104.

[5] Saleem, M., & Hosoda, A. (2021). Latin hypercube sensitivity analysis and non-destructive test to evaluate the pull-out strength of steel anchor bolts embedded in concrete. *Construction and Building Materials*, *290*, 123256.

[6] Saleem, M., & Tsubaki, T. (2010). Multi-layer model for pull-out behavior of post-installed anchor. *Proc. FRAMCOS-7, Fracture Mechanics of Concrete Structures, AEDIFICATIO publishers, Germany*, *2*, 823-830.

[7] Tsubaki, T., Ihara, T., & Yoshida, M. (1992). Statistical variation and modeling of drying shrinkage of concrete. *Trans. of the Japan Concrete Institute*, *14*, 123-130.

[8] Xiang, N., & Alam, M. S. (2019). Comparative seismic fragility assessment of an existing isolated continuous bridge retrofitted with different energy dissipation devices. *Journal of bridge engineering*, *24*(8), 04019070.

[9] Yu, P., Manalo, A., Ferdous, W., Salih, C., Abousnina, R., Heyer, T., & Schubel, P. (2021). Failure analysis and the effect of material properties on the screw pull-out behaviour of polymer composite sleeper materials. *Engineering Failure Analysis*, *128*, 105577.

[10] Sharda, A., Manalo, A., Ferdous, W., Bai, Y., Nicol, L., Mohammed, A., & Benmokrane, B. (2021). Axial compression behaviour of all-composite modular wall system. *Composite Structures*, *268*, 113986.

[11] Yuan, C., Fan, L., Cui, J. F., & Wang, W. J. (2020). Numerical simulation of the supporting effect of anchor rods on layered and nonlayered roof rocks. *Advances in Civil Engineering*, *2020*, 1-14.

[12] Hashimoto, J., & Takiguchi, K. (2004). Experimental study on pullout strength of anchor bolt with an embedment depth of 30 mm in concrete under high temperature. *Nuclear engineering and design*, *229*(2-3), 151-163.

[13] Munemoto, S., & Sonoda, Y. (2017). Experimental analysis of anchor bolt in concrete under the pull-out loading. *Procedia Engineering*, *171*, 926-933.

[14] Richardson, A. E., Dawson, S., Campbell, L., Moore, G., & Mc Kenzie, C. (2019). Temperature related pull-out performance of chemical anchor bolts in fibre concrete. *Construction and Building Materials*, *196*, 478-484.

[15] Yilmaz, S., Özen, M. A., & Yardim, Y. (2013). Tensile behavior of post-installed chemical anchors embedded to low strength concrete. *Construction and Building Materials*, *47*, 861-866.

[16] Nilforoush, R., Nilsson, M., & Elfgren, L. (2017). Experimental evaluation of tensile behaviour of single cast-in-place anchor bolts in plain and steel fibre-reinforced normal-and high-strength concrete. *Engineering Structures*, *147*, 195-206.

[17] Eligehausen, R., Bouska, P., Cervenka, V., & Pukl, R. (1992). Size Effect of the Concrete Cone failure Load of Anchor Bolts, FramCoS I.

[18] Bajer, M., & Barnat, J. (2012). The glue–concrete interface of bonded anchors. *Construction and building materials*, *34*, 267-274.

[19] Liu, Q., Chai, J., Chen, S., Zhang, D., Yuan, Q., & Wang, S. (2020). Monitoring and correction of the stress in an anchor bolt based on Pulse Pre-Pumped Brillouin Optical Time Domain Analysis. *Energy Science & Engineering*, *8*(6), 2011-2023.

[20] Delhomme, F., Debicki, G., & Chaib, Z. (2010). Experimental behaviour of anchor bolts under pullout and relaxation tests. *Construction and Building Materials*, *24*(3), 266-274.

[21] Nilforoush, R., Nilsson, M., Elfgren, L., Ožbolt, J., Hofmann, J., & Eligehausen, R. (2017). Tensile capacity of anchor bolts in uncracked concrete: Influence of member thickness and anchor's head size. *ACI Structural Journal*, *114*(6), 1519-1530.

[22] Mallée, R., & Eligehausen, R. (2013). *Design of fastenings for use in concrete: the CEN/TS 1992-4 provisions*. John Wiley & Sons.

[23] Eligehausen, R., Mallée, R., & Silva, J. F. (2006). *Anchorage in concrete construction* (Vol. 10). John Wiley & Sons.

[24] Zamora, N. A., Cook, R. A., Konz, R. C., & Consolazio, G. R. (2003). Behavior and design of single, headed and unheaded, grouted anchors under tensile load. *Structural Journal*, *100*(2), 222-230.

[25] Fuchs, W., Eligehausen, R., & Breen, J. E. (1995). Concrete capacity design (CCD) approach for fastening to concrete. *Structural Journal*, *92*(1), 73-94.

[26] Cook, R. A., Kunz, J., Fuchs, W., & Konz, R. C. (1998). Behavior and design of single adhesive anchors under tensile load in uncracked concrete. *Structural Journal*, *95*(1), 9-26.

[27] Eligehausen, R., & Balogh, T. (1995). Behavior of fasteners loaded in tension in cracked reinforced concrete. *Structural Journal*, *92*(3), 365-379.

[28] Takiguchi, K., Harada, R., & Ishizeki, K. (1999). Pull out strength of an anchor bolt embedded in cracked concrete.

[29] Wang, D., Wu, D., He, S., Zhou, J., & Ouyang, C. (2015). Behavior of post-installed large-diameter anchors in concrete foundations. *Construction and Building Materials*, *95*, 124-132.

[30] Ishibashi, T., & Tsukishima, D. (2009). Seismic damage of and seismic rehabilitation techniques for railway reinforced concrete structures. *Journal of Advanced Concrete Technology*, *7*(3), 287-296.

[31] Satoh, A., Takeda, K., & Murakami, K. (2019). FEM analysis on combined bond-cone fracture of a post-installed adhesive anchor filled with UHPFRC. *Theoretical and Applied Fracture Mechanics*, *100*, 46-54.

[32] Obata, M., Inoue, M., & Goto, Y. (1998). The failure mechanism and the pull-out strength of a bond-type anchor near a free edge. *Mechanics of materials*, *28*(1-4), 113-122.

[33] Soparat, P., & Nanakorn, P. (2008). Analysis of anchor bolt pullout in concrete by the element-free Galerkin method. *Engineering structures*, *30*(12), 3574-3586.

[34] Lu, J., Zhang, Y., Muhammad, H., Chen, Z., Xiao, Y., & Ye, B. (2019). 3D analysis of anchor bolt pullout in concrete materials using the non-ordinary state-based peridynamics. *Engineering Fracture Mechanics*, *207*, 68-85.

[35] Saleem, M. (2020). Assessing the load carrying capacity of concrete anchor bolts using non-destructive tests and artificial multilayer neural network. *Journal of Building Engineering*, *30*, 101260.

[36] Saleem, M. (2018). Evaluating the pull-out load capacity of steel bolt using Schmidt hammer and ultrasonic pulse velocity test. *Struct. Eng Mech*, *65*(5), 601-609.

[37] Shull, P. J. (2002). Nondestructive evaluation: theory, techniques, and applications. CRC press.

[38] Chang, P. C., & Liu, S. C. (2003). Recent research in nondestructive evaluation of civil infrastructures. Journal of materials in civil engineering, 15(3), 298-304.

[39] Schmidt, E. (1951). A non-destructive concrete tester. *Concrete*, *59*, 34-35.

[40] Miller, R. P. (1965). *Engineering classification and index properties for intact rock*. University of Illinois at Urbana-Champaign.

[41] Cargill, J. S., & Shakoor, A. (1990, December). Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* (Vol. 27, No. 6, pp. 495-503). Pergamon.

[42] Yurdakul, M., Ceylan, H., & Akdas, H. (2011, June). A predictive model for uniaxial compressive strength of carbonate rocks from Schmidt hardness. In *45th US Rock Mechanics/Geomechanics Symposium*. OnePetro.

[43] Torabi, S. R., Ataei, M., & Javanshir, M. (2011). Application of Schmidt rebound number for estimating rock strength under specific geological conditions. *Journal of Mining and Environment*, *1*(2).

[44] Brozovsky, J., & Zach, J. (2011, October). Influence of surface preparation method on the concrete rebound number obtained from impact hammer test. In *Pan American Conference for NDT* (Vol. 6, No. 10).

[45] Liu, J. C., Sue, M. L., & Kou, C. H. (2009). Estimating the strength of concrete using surface rebound value and design parameters of concrete material. *Journal of Applied Science and Engineering*, *12*(1), 1-7.

[46] Katalin, S. (2013). *Rebound surface hardness and related properties of concrete* (Doctoral dissertation, Doctoral dissertation, Ph. D. thesis, Budapest Univ. of Technology and Economics, Dept. of Construction Materials and Engineering, Budapest, Hungary).

[47] Sharma, P. K., Khandelwal, M., & Singh, T. N. (2011). A correlation between Schmidt hammer rebound numbers with impact strength index, slake durability index and P-wave velocity. *International Journal of Earth Sciences*, *100*, 189-195.

[48] Mutlib, N. K., Baharom, S. B., El-Shafie, A., & Nuawi, M. Z. (2016). Ultrasonic health monitoring in structural engineering: buildings and bridges. *Structural Control and Health Monitoring*, *23*(3), 409-422.

[49] Li, J., Gao, X., & Zhang, P. (2007). Experimental investigation on the bond of reinforcing bars in high performance concrete under cyclic loading. *Materials and structures*, *40*, 1027-1044.

[50] Yalciner, H., Eren, O., & Sensoy, S. (2012). An experimental study on the bond strength between reinforcement bars and concrete as a function of concrete cover, strength and corrosion level. *Cement and Concrete Research*, *42*(5), 643-655.

[51] Desnerck, P., Lees, J. M., & Morley, C. T. (2015). Bond behaviour of reinforcing bars in cracked concrete. *Construction and Building Materials*, *94*, 126-136.

[52] Inadsu, K., Tamura, T., & Nakamura, H. (2010). Study on the Cracking Occurrence Prediction of Civil Engineering Structures Using a Neural Network (In Japanese). 65th Annu. *Meet. Japan Soc. Civ. Eng*, *403*, 1-3.

[53] Ongpeng, J., Soberano, M., Oreta, A., & Hirose, S. (2017). Artificial neural network model using ultrasonic test results to predict compressive stress in concrete. *Computers and Concrete*, *19*(1), 59-68.

مراجعة مكثفة للعلاقة بين الاختبارات غير المدمرة وقوة السحب لبراغي التثبيت المدمجة في الخرسانة

الخلاصة : *تستخدم مسامير التثبيت على نطاق واسع في العديد من الصناعات ، بما في ذلك قطاعات البناء والميكانيكية والتعدين. تتراوح استخداماتهم من تركيب أشياء دائمة مثل الهياكل الهجينة وأكوام الإضاءة وعلامات الاتجاه إلى تركيب الهياكل المؤقتة. توجد عدة أنواع من معدات الاختبار المدمرة في الصناعة لتحديد قدرة تحمل المراسي الخرسانية. ومع ذلك ، فإن تطوير التقنيات غير المدمرة لم يتلق سوى القليل من الاهتمام. تسلط هذه الدراسة الضوء على البحث المحدود حول تقييم قوة سحب البراغي الفولاذية المضمنة في الخرسانة باستخدام اختبارات غير مدمرة في جميع أنحاء العالم وتوضح علاقتها مع بعضها البعض. أظهرت هذه المراجعة النقدية أن قطر مسمار التثبيت وطول التضمين والمحاذاة والعيوب الدقيقة والرابطة البينية وهندسة البراغي تؤثر على قوة سحب المراسي الخرسانية المضمنة. يساهم طول ترسيخ مسامير التثبيت في زيادة قوة السحب أكثر بكثير من قطر البرغي. يمكن استخدام اختبار سرعة النبض بالموجات فوق الصوتية واختبار مطرقة شميدت بنجاح لمراقبة جودة وصحة مسامير التثبيت المضمنة في الهياكل الخرسانية ذات القوة العادية عن طريق تحديد مسامير التثبيت المعيبة ذات الروابط المسامية. مسامير التثبيت ذات الترابط غير الكافي لها رقم ارتداد أقل ووقت عبور نبضي طويل بالموجات فوق الصوتية.*

الكلمات الدالة: *مرساة الترباس ، قوة الانسحاب ، اختبار غير مدمر ، مطرقة شميدت ، سرعة النبض بالموجات فوق الصوتية.*