Celebrating 75 years of innovation: A Review of Schmidt Rebound Hammer Applications and Developments

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Abstract- *The Schmidt rebound hammer is still a common method to access the surface hardness of concrete without disturbing it. This measures the rebound index, which in itself is an intuitive way of estimating compressive strength. For the past 75 years, giant strides and even more research have enabled us to find out much more about how one can use the tool and just what its limits are. This method is easy to use, but it leads to estimation errors because of variance in rebound readings and because the system is sensitive to surface conditions, which could perhaps make the method accessible to people who aren't very good at it. Under normal operating conditions, errors in estimating strength are generally around 30%. This explains how careful calibration and interpretation should be. Real-world relationships exist between rebound values and compression strengths, but only under specific conditions. Therefore, the values cannot be used in other circumstances. This paper approaches a fresh look at changes in time that have taken place with the Schmidt rebound hammer in focus as far as its use in real life, how science has advanced, and what we have learned in the last decades. It is intended to provide engineers and specialists with new ideas on how to make it remain useful in the future for testing concrete.*

Key Words- Schmidt rebound hammer, Non-destructive concrete testing, compressive strength estimation, Rebound index variability, Calibration of rebound hammer.

1. Introduction to Schmidt Rebound Hammer

The Schmidt rebound hammer, one of the vital tools in the NDT field, has undergone tremendous development in the last many decades with the design of a go-to tool measuring the surface hardness of concrete and consequently the compressive strength of it. Since its invention at the mid-20th century, scientists have been striving to make the use of this device more accurate and precise. This introduction attempts to synthesize findings drawn from several studies wherein better understanding of full capabilities and limitations of the rebound hammer is done, with regard to its potential applications and research gaps.

Brinell introduced the method of testing steel hardness by using the technique of ball indentation. In-situ testing of concrete structures was first undertaken in the 1930s. There were several testing methods in use at the time, including as the chisel blow, gun firing, split, Brinell hardness, and pullout tests. This later method, because of the fact that it is relatively simple and fast to operate, has been the approach that has been used the most in Europe for centuries.(Hertz n.d.1881)(A. Szymanski, J.M. Szymanski 1989)(J.A. Brinell n.d.1901)(R.B. Crepps, R.E. Mills 1923)(B.G. Skramtajew 1938). The first NDT equipment for in-place concrete hardness testing came to Germany in 1934 and took the ball indentation hardness testing technique from it(K.A. Gaede 1934)(E. Schmidt 1950). In 1951, Shore employed the hardness test method developed by Schmidt and the measuring of the hardness value is well known to be a rebound index rather than the ball penetration(G.W. Greene 1954)(A.R. Anderson, D.L. Bloem, E.L. Howard, P. Klieger, H. Schlintz 1955). The recent development was finished as the Silver Schmidt hammers were available from November 2007(S.A. Proceq n.d.).(Kumavat, Chandak, and Patil 2021)

The pioneer work on the Schmidt rebound hammer, for which Eng (1958) is noted, dealt with its use in non-destructive testing of concrete. As an immediate outcome of that pioneer study, the importance of self-derived calibration curves, according to concretes' mix, was underlined; it was indeed mentioned that the compaction method used, whether hydraulic pressing or concrete vibration, influences directly the calibration curve thus the strength calculated afterwards. This initial study suggested that rebound readings were fundamentally variable, particularly at low strengths; thus, adaptive calibration could potentially increase reliability.(Eng 1958). More recently, Szil reviewed over fifty years of empirical data on issues with the Schmidt rebound hammer when tested at various conditions. Empirical correlations between rebound index and compressive strength have a potential error of up to 30% and may become accentuated further when applied by less experienced operators. The study proposed the method of using Quantile functions as an avenue for bridging the disparities and, at the same time, states it is still in need of further validation. Szil's findings revealed a gigantic space in the knowledge regarding the relation between carbonation and surface hardness about the correlation between them, especially in terms of types of HSC and FRC.(Szil 2009).

Study enhanced the debate on the non-destructive testing by comparing ultrasonic pulse velocity and rebound tests. The SonReb method he put forth was to utilize the two NDT methods together with a double power law model in order to ensure that greater accuracy was involved in the estimations of strength. In his work, Breysse discovered that the model error was less sensitive than that of the error of the measurement and that any core number for calibration could be lessened without reducing quality. It found that there was a research gap on the understanding of how NDT values relate to concrete strength and encouraged further studies in material variability as well as the reduction of error in large structures (Breysse 2012).

In 2014 one of researcher conducted an extensive analysis of rebound hammer readings over six decades, including more than 80,000 readings from various sources. Their research emphasized the need for updated standards regarding the repeatability and precision of rebound hammer tests. Szilágyi et al. identified that factors like cement type, water-cement ratio, and concrete age greatly influence rebound index variability. The study highlighted the role of carbonation, noting that while rebound index variability decreases between 28 and 56 days, it increases again as carbonation effects set in. The authors called for further research to address the limitations in the calibration process and to refine testing methods for better accuracy(Szilágyi, Borosnyói, and Zsigovics 2014).

As the concrete testing science matures, integrating artificial intelligence and machine learning into non-destructive methods can make the processes more precise and reliable. With integration such as advanced technologies, the process can be real time with dynamic calibrations of curves in accordance to instantaneous environmental condition feedback or properties of the material. It is also established that the use of a combination of various NDT techniques, such as rebound hammer in combination with ultrasonic pulse velocity, provides a more holistic understanding of the integrity of concrete.(Kovler, Wang, and Muravin 2018)

The latest study by Kumavat, Chandak, and Patil (2021) enlightens one on the limitations associated with the application of regression equations obtained from laboratory tests to site concretes. According to them, factors such as cement type, curing conditions, and various levels of temperature result in a considerable overestimation of compressive strength with the aid of a Schmidt rebound hammer. The nature of rebound hammer technique as half-destructive has not been appropriately reflected by the current integrity of concrete structures. In other words, that relatively good integrity of concrete structures shown by NDT evaluation is not correctly reflected. There is a need to enhance the standards of NDT based on the shortcomings presently existing in the regression models applied. This also includes further investigation of the impact of carbonation, moisture, etc. on the rebound readings.(Kumavat, Chandak, and Patil 2021).

Together, they describe how the development of the Schmidt rebound hammer and practice of its use in concrete testing have evolved from the 1950s to the present. A greater demand for more accurate calibration techniques and specially developed methods to align NDT practices with differing field conditions, therefore, calls for consideration. Although the tool has been useful, overall accuracy will largely depend on appropriate consideration regarding characteristics of concrete, testing conditions, and the practitioner. Future research in this direction should involve attempts toward calibrating better methods, understanding carbonation influence, and providing better models to enforce reliability in the Schmidt rebound hammer with respect to concrete strength under various conditions and types of concretes.

2. Principles of Operation, Mechanism, and its Applications

The research paper describes the procedure for finding the rebound number with a spring-driven steel hammer on hardened concrete, while such a rebound number is an important factor in characterizing concrete quality and uniformity. This rebound number is used to predict the concrete strength development, but the attained results depend on a number of factors including moisture content, surface preparation, and depth of carbonation. The methodology involves a steel hammer hitting a plunger in contact with the concrete surface, and the rebound distance is recorded on a linear scale. Although an extremely invaluable source of information on the quality of the concrete, the rebound hammer test is not appropriate for concrete acceptance or rejection due to uncertainties in the estimated strength. It drove in that point further that to correctly evaluate the rebound number, a definite relationship between the rebound number and the strength of the concrete should be established. Apart from this, safety guidelines should be observed, and honeycombing, scaling, or high porosity of the area under test would not be appropriate since these can affect the reliability of the hammer.(Standard Test Methods for Rebound Number of Hardened Concrete, ASTM Standards, 1997). The paper discusses the rebound hammer method in the evaluation of compressive strength of concrete while noting its applicability and limitations. Besides that point, it states that open texture concrete like masonry blocks is not appropriate for this test since the tested correlations between rebound index and compressive strength in partially compacted concrete are not reliable. Several factors affect the rebound numbers such as cement type, aggregate, surface condition, moisture content, and concrete age, among others. The paper also outlines that indirect rebound hammer testing methods would complement other methods such as ultrasonic pulse velocity for higher precision. Core testing is mentioned as another reliable but invasive method of measurement of compressive strength through direct measurement. Gaps in the accuracy of rebound hammer test methods were identified with an estimate of reliability at 25%. It indicates further research work in order to improve the reliability of the method and to study the concurrent use of UPV and rebound hammer tests to minimize errors caused by material and environmental factors. The relationships established by laboratory samples are further not applicable to in-situ concrete, hence a further investigation on the subject is required. Such limitations of the rebound hammer method are sensitivity towards surface texture and moisture, leading to incorrect predictions of strength, mainly for open texture concrete and trowelled surfaces. Strength predictions are only good to about 25%, and correlations are mix proportion-dependent as well as material-dependent.(IS 13311 (Part 2) 1992)

Rebound surface hardness is a good in-situ concrete testing measurement; it has proven to be useful to-date. Compressive strength, on the other hand, portrays a more or less complicated phenomenon, such that the variance cannot be adequately modeled by simple two-parameter regressions; this holds especially for such factors as water-cement ratio and hydration. High-strength concrete, for instance, presents a much stronger correlation between rebound hardness and Young's modulus than between rebound hardness and compressive strength. A phenomenological model has been developed to describe rebound hardness behavior. It is evident that the empirical constants of the model would need further refinement in addition to adjustment of impact energy to achieve improved strength prediction. Other studies are also suggested to work on the influence of the water-cement ratio on hardness and the influences of carbonation on low-strength concretes. Inherent problems with the use of regression models with limited applicability and an inability to establish a direct relationship between rebound hardness and strength, at least at very high strengths, are identified.(Szilágyi, Borosnyói, and Zsigovics 2015) Here, comparing two regression analysis alternatives, the paper presents methodologies for estimating in-situ concrete compressive strength according to EN 13791 using the rebound hammer test. One major difference is established here: Alternative 2 shows much more erroneous results, especially for low rebound values, and an estimated loss of about 4 MPa from regression uncertainties. The compressive strength was evaluated by 210 rebound hammer readings combined with the core strength tests at 21 test locations, or columns. The methods consist of the following: core testing and indirect methods of rebound hammer, ultrasonic pulse velocity (USPV), and pull-out tests. The paper highlights confidence levels and precision levels in analysis but states that the document EN 13791 does not define any specific confidence level or tolerance interval for the application of potential ambiguity. There is an open research gap wherein tolerance limit expressions in literature are not established while applying methodologies in EN 13791. It also questions the sensitivity of the rebound hammer test regarding variations in compressive strength and the assumption of homoscedasticity, which demands further study on the reliability of the rebound hammer test versus core tests. Future research should be targeted in many ways, namely, in the improvement of all non-destructive testing, in the study of the rebound reading relationship with the environmental conditions, and in the refinement of all existing statistical models used in regression analysis. Moreover, further determinations of more robust tolerance limits for any unlimited variety of concrete conditions would be essential. The authors also point out errors in rebound hammer readings, sometimes underestimating the standard deviations, and even suggest an increase in the number of readings per test location to overcome this problem. Finally, the paper underlines the problems in expressing tolerance intervals that appear to be taxing, especially when errors in the rebound index are considered.(Monteiro and Gonçalves 2009). The report introduces the "Summary" window feature of Hammerlink, which supports uniformity testing and is most helpful in gauging areas of inferior quality within datasets. In creating summaries, data series with consistent units should be used, otherwise stable and reliable data analysis will not be guaranteed. Both the inclusion and exclusion of a series from the summary could be indicated in the impact counter column. Facilities of the interface also offer flexibility in the ability to switch between different alternative views of data, thus presenting data in different ways. However, despite these strengths, it shows weaknesses in the sense that its database appears to have a very limited range of data it can accept in the form of 5-30 MPa. This may limit the applicability of the results. Performance check and management of batteries may be extremely crucial for data accuracy. The definition of custom curves is highly complex and may require more information than can be given by words alone, thereby making it very complex for new users. In addition, there is no export option to third-party software for further analysis, as a con for anyone in search of an all-in-one package. As far as the conclusion of the paper is concerned, the features related to Hammerlink make it a very effective tool for data analysis and quality assessment in respect of some aspects that require more improvement. *(SilverSchmidt_Operating Instructions_English_high.pdf*. (n.d.).

Comparatively, this study compares the concrete hardness measuring method widely used today, the Schmidt rebound hammer, with the less frequently used Leeb rebound hammer in concrete testing. The study concluded that the compressive strength is on average reduced by 10.5 MPa with the use of the Schmidt hammer which, therefore, classifies it as semi-destructive. In contrast, Leeb rebound hammer correlated consistently with compressive strength at varied w/c ratios and relative predicted strength with an error margin of 10%. The potential of this method is yet to be explored much in the concrete engineering society, but the method is highly standardized in geology and metallurgy. The methods, in this case, had a direct testing of concrete samples with w/c ratios of 0.33, 0.4, and 0.5 with both the Schmidt and Leeb hammers. Nonetheless, some cube specimens were clamped for the Schmidt test, while flat surfaces were used for the Leeb test. In fact, it is evident that there is a wide gap in the research highlighting the lack of literature in the awareness among practitioners that the Leeb rebound hammer can be helpful for concrete testing. It also calls for further investigation regarding the influence of carbonation and moisture contents in surface conditions to Leeb rebound tests as well as nearness of aggregate towards the surface which could introduce variability. In addition, limitations of the Schmidt hammer were also observed to include semi-destructive characteristics and unsuitability for the determination of low-strength concrete. For future research, the paper recommends standardising Leeb rebound testing for concrete, explore the effect of surface moisture and carbonation on test results, and develop guidelines of its use on different categories of concrete strength. Tests should focus on uncertainty minimisation by testing concrete with dry surfaces and understanding the behavior of a test on older, carbonated concrete. Restriction is that Schmidt hammer is not applicable to early-age concrete (less than 3 days) or for a compressive strength less than 7 MPa, as it possesses a high impact energy and can easily reduce the strength. The Leeb hammer is not damaging, and thus sensitive to moisture and carbonation of the surface; and it lacks standardization for testing in concrete, so it is not as commonly used among practitioners..(Kovler, Wang, and Muravin 2018)

NDT methods, particularly pulse velocity and rebound hammer techniques, are appropriate for evaluating HSC, which has strengths in the range of 30-150 MPa. Sensitivity of NDT parameters was found to reduce with the increase in compressive strength, especially for high-strength concretes. Regression analysis showed correlations of NDT parameters with estimated cube strength, and combinations like the SonReb method produced more reliable estimates. However, methods like pull-out and probe penetration tests were very inefficient at very high strength levels and a disaster waiting to happen if that was the case in practice. The study included several NDT techniques, which were: pulse velocity, rebound hammer, pull-out, probe penetration, microcoring, and combined SonReb approaches, in an effort to demonstrate the wide range of applicability of these techniques across the strength spectrum. The research established a lacuna in the utilization of existing NDT techniques for HSC, specifically referring to the pull-out and probe penetration tests that are inadequate at very high strengths. It also underscored a need for additional work to establish more robust strength relationships at higher strengths and to develop appropriate test rigging for brittle HSC. The generally declining insensitivity of NDT parameters to strength change with increasing compressive strength reveals the demands of better adapted testing techniques for HSC. Future research work should be directed toward the validation of the applicability of the NDT methods, particularly the pulse velocity, rebound hammer, and SonReb, to HSC. Probably most important are further extension of the probe penetration method operating range, improving pull-out method efficiency, and calibration of empirical relationships for different mixtures of concretes in order to make more accurate strength estimations. A reduced sensitivity with NDT methods at increased compressive strength could likely impact reliability at higher strength levels. In addition, the bond at the matrix-aggregate interface in HSC may influence the behavior of NDT parameters as well, which makes the testing procedure more complicated. At present, NDT relationships are mostly validated for normal-strength concrete up to 50 MPa; therefore, there is a need for further refinement to extend into applications involving HSC.(Pascale, Leo, and Bonora 2003)

3. Comparative Analysis with Other Concrete Testing Methods

A mathematical model for indirect estimating of concrete compressive strength with the help of ultrasonic pulse velocity and rebound hammer index measurements is proposed in the research paper. Such a model confirms a direct relationship between indirect measurements and real compressive strength through the results of linear regression, thus indicating that both direct and indirect methods provide comparable quality assessments of concrete, although indirect estimates are more dispersed. The study covers non-destructive methods, such as rebound hammer and ultrasonic pulse velocity, while also including destructive methods, like core testing-this again indicates that greater the number of non-destructive measurements taken increases the reliability of results. Laboratory tests confirm the model by emphasizing the sample size for both methods when measuring the quality of concrete in situ. 'n' is the sample size in direct and indirect measurements, but the paper emphasized the increase in the samples of non-destructive measurement, thereby improving the strength estimations. Based on this research, there is a requirement for further investigations in terms of the applicability of the model over diverse types of concretes and environmental conditions besides integrating further testing methods. Future research could encompass efforts to enhance precision under changing conditions regarding non-destructive techniques and may consider even advanced statistical models, like machine learning, for further strengthening estimation. For instance, the verifications of long-term performance tests of the structures can be made through these methods with the reliability of the given methods. Certain limitations arise from the fact that the concrete cores removed from the structures typically have lower strength values by 10-30% compared with standard samples, and hence accurate checks become difficult. This deviation is duly compensated with a coefficient 'k' in many international standards. Furthermore, more dispersion in indirect measurement calls for larger sample sizes to have the same accuracy as that of the direct measurements.(Mikuli, Pause, and Ik 1992).

Correlation was proven through the Schmidt rebound hammer test and destructive compression tests; as such, rebound numbers could estimate concrete strength. Calibration was done on cube specimens aged 28 to 90 days and core samples of various structures, henceforth producing correction factors for different classifications of concrete. The study found the compressive strength values for the 28- and 90-day specimens to be significantly greater than those for the core samples with comparable rebound numbers, indicating a requirement to adjust the measurement of the older concrete. The results of the study point to the fact that among others, surface conditions govern the interpretation of the Schmidt hammer results. The procedure used consisted of a Schmidt rebound hammer, an NDT technique that relates surface hardness to compressive strength as well as destructive compression tests, which actually measure compressive strength. Calibration was obviously important, with an emphasis both on lab-prepared samples and in-situ core material so that correction factors could be obtained reliably. There was a hole in previous work: earlier studies focused either more or less solely on laboratory specimens and lacked data on in-situ samples. It also emphasized the necessity for superior calibration techniques, especially for old concrete, and additional studies on the role of surface conditions, moisture content, and kind of aggregate on test precision. For future research, efforts should be made towards improving calibration techniques of the Schmidt hammer on older structures also, with a more precise correction factor for it. Improvements in in situ strength assessment can be realized by looking into the effects of moisture and temperature on the rebound value as well as into other non-destructive methods. The limitations of the study are that it is sensitive to anisotropy and heterogeneity of materials, has small test areas, surface roughness and the effect of hammer inclination on the outcomes. Hence, there is a need to have selective correction factors that account for the difference in surface conditions like carbonation and moisture variation in the empirical relationships between hardness and strength.(Aydin and Saribiyik 2010).

The study proposes the SBZ-model which is a phenomenological constitutive model of rebound surface hardness of concrete and underlines its time-dependent character based on the capillary pore system developing in the hardened cement paste, especially sensitive to the water-cement ratio. Experimental verification in broad ranges was undertaken for 864 concrete specimens at various states of age and for a variety of different water-cement ratios, confirming the model's potential to be used for the estimation of compressive strength from rebound indices. It identifies other key influencing parameters in the study, such as water-cement ratio, cement type, and concrete age. This is with regard to the limitations in conventional empirical relationships and least-squares regression analysis. The research identified an enormous gap in understanding the rebound surface hardness as a time-dependent property while pinpointing the lack of general theories explaining the surface hardness with compressive strength. Future researches should be based upon improving the SBZ-model for practical applications on different types of concrete, by looking for simplifications to make it usable and clarify the generating functions that compose the base of this model. Further, the limits of practical application of the model should be understood as well. The limitations of the SBZ-model include difficulties in parameter fitting due to many empirical constants and restriction of empirical relationships to certain testing conditions, which, therefore cannot be generalized towards all concrete types. Model predictions are limited by data, and conventional regression methods may underestimate uncertainties in strength estimates.(Szilágyi, Borosnyói, and Zsigovics 2011).

The study demonstrates that coupling rebound hammer and UPV tests in the SonReb method is a very effective predictor of concrete compressive strength, especially when the strength values are larger than 40 MPa. The appropriate use of the upvaried sensitivities of UPV and RI to various factors through proposed SonReb formulations provides reliable predictions as demonstrated by the study. In addition, it stresses the application of destructive and non-destructive testing together for increased accuracy in the prediction of strength. It assesses several methods of prediction, including computational modeling, artificial intelligence, and the parametric multi-variable regression models, and finds that the latter is the most feasible for use in application. However, there are some gaps including exploring the impact of various concrete mixtures and environmental conditions on the SonReb prediction accuracy; there is no study comparing various methods used for prediction. Future work should be on more sophisticated computational models which can be easily integrated with AI techniques like the artificial neural network to make better predictions besides improvements in regression models towards extended use. This, furthermore, increases the need for more research to be carried out in correlating core testing results to in-situ strength values towards enhancing the accuracy of NDT.(Nobile 2014)

4. Influence of Environmental Factors on Schmidt Rebound Hammer Readings

The influence of carbonation on the rebound number and strength development is large, and the influence depends on the level of strength. The described inaccuracies in the evaluation of the strength reduction are caused by the fact that this kind of dependence with respect to the level of involved strength is not taken into account in the well-known existing equations for the strength reduction coefficient. The newly developed equation continues to display better predictability capability and intuitively captures the relationship between strength level and normalized strength reductions. The two methods of concrete strength evaluation were: Method I without compensation by carbonation, and Method II compensated by carbonation through the strength reduction coefficient. Carbonation should be considered especially for applied conditions. Such results demand further experimental information to determine and update more accurately the strength reduction coefficient equation, which remains mostly still based on national data from South Korea and does not fully exploit the range of strength levels. Further experimental data are needed for reducing the age-dependent errors and the strength assessment of rebound numbers. Further experiments would be targeted at delivering further experimental data with more refinements on the accuracy of this new equation. The explorations are undertaken in other environments rather than under standard conditions and over a wider range of concrete mixtures. Long-term tests have to be performed in order to establish the influence of carbonation on mechanical properties after periods of more than 3 months. An effort should be made to put into effect the derived equation at widely dispersed locations. Limitations of the proposed equation are that the existing equation does not account for strength-level effects that would reduce the accuracy if stronger concrete were being considered. More importantly, the generality of the proposed equation is limited by its dependence on domestic data, and thus it would have to undergo further revisions before its application to distant locations could be considered.(Kim et al. 2009)(Yonggan, Yunsheng, and Wei n.d.). It has been found that the compressive strength of the concrete is directly proportional to the moisture content in it. According to the latest studies, there was a decrease in the rebound index by 20–25% as the moisture content of the concrete increased from an air dry to a water saturated condition. It may also have a reducing effect on the compressive strength of the concrete because of the pressure developed within the inner pores. As discussed earlier, the strength gain of an oven-dried specimen is reversible. Further resaturation of the specimen can restore the original strength of the concrete(Monteiro and Gonçalves 2009)(A.M. Neville 2001). Szilágyi has shown that the measurement uncertainty of the tests performed on-air dry surface is lesser compared to that of the tests performed on the wet surface(Szilágyi, Borosnyói, and Zsigovics 2014). Although the testing criteria of the rebound hammer do not enable to perform the test on damp surfaces. It makes sense to check the moist surfaces of different content to set the upper limit, which does not affect the rebound index. Yang et al. discussed that a decrease in the specimen size from 200 to 100 mm increases the rebound index but the rate of increase was very high(Yonggan, Yunsheng, and Wei n.d.). Most of the experiments focused on the effect of exposed heat load on rebound index. It was obtained that increase in the rebound number at the temperatures of 200°C–400°C heat applied is compared with the rebound number of the concrete testing under normal temperature - 27°C. The main determinants of the results of tests are: dehydration of concrete, the synergic effect of dehydration of the concrete, and defects (micro-cracks) in its internal structure. This is because when concrete is subjected to a heat load, micro crack defects develop on its surface due to the release of free, capillary and chemically bound water.(O. Olomo, O. Aderinlewo, M. Tanimola, S. Croope 2012)(L. Bodnarova, J. Valek, L. Sitek, J. Foldyna 2013)(V. Kodur 2014)(J. Brozovsky 2016). Rebound variation due to pre-and post-exposed heat load concrete structural members at 800 °C in relation to core strength. They reported that the rebound ratio was much higher than compressive strength. It has also been reported that the rebound index up to 420 °C does not change. Concrete has demonstrated the trend of decreasing portlandite composition, with increased calcium carbonate, with pore sizes appear to be smaller than before from the microstructural studies(P. Pattamad, T. Danupon 2018). Unlike the core test, rebound hammer overestimates strength values because it measures strength by surface hardness. Meanwhile, concrete exposed to heat makes the structural element porous in nature. Rebound hammer only gives the strength estimation on the outer surface of the structure and does not predict its integrity in the members(A. Aseem, W.L. Baloch, R.A. Khushnood, A. Mushtaq 2019)(Kumavat, Chandak, and Patil 2021).

The research reports on the validity of concrete strength assessment by a combination of NDT and destructive tests in several key factors influencing the accuracy: the number of cores (NC), the within-test variability of rebound measurements, and the inherent variability of concrete strength. Observably, reliability with strength assessment enhances with the increase in cores and lowers with decreasing variability within the test as well. In addition, conditional selection of the core location, as the study has suggested, improves the reliability without bringing about the increase in extra cost. This study made extensive use of 17 datasets and analyzed the effects through 1700 test results. The methodology included three steps: evaluating mean strength, strength standard deviation, plotting of cumulative distribution function curves, and building risk curves to assess the quality of strength estimates. The study looked into the effects of selection of core test location, using both random and conditional methods. The size of the sample used was 17 datasets containing 100 pairs of test results. The median value from every ranked group of rebound numbers was selected to ensure adequate representation and minimize sampling bias. The research found that there is a gap in the knowledge of how reliable it is to combine NDT and destructive tests under varying conditions and concrete types and the influence of external factors such as environment conditions and age of structure. At the same time, it brings into the discussion further research on differences of approach in identification of the model: is regression versus bi-objective models? Also, in connection with the proposed location along the reinforcement and external dimensions, a more extended dataset is needed to check conditional selection rules for the core locations. Further study shall be oriented to improve the reliability in concrete strength estimation through alternative NDT methods, among others which can be combined - rebound hammer and ultrasonic pulse velocity, respectively, and studies could be oriented toward the understanding of factors of environmental impacts upon the strength variability, which is still under study and still relevant especially for aged structures. Determination of accuracy by different core selection strategies and development of sophisticated statistical models to account for uncertainty in strength predictions will further be improved in assessment accuracy. Limitations were recognized in the reliability of NDT-based strength assessments to account for uncertainties of strength predictions, especially those influenced by variability in rebound measurement and variability of true concrete strength. The number of test locations, whether it is a random or conditional method of selection for core locations, also determines the outcome, such as having to use an increasingly higher NC to determine results accurately. To check for variability is slower than that for mean strength assessment and thus requires larger NC values for accuracy(Alwash et al. 2017).

The investigation was focused on the high temperatures effects on concrete properties: for the first time, large changes in both physical and mechanical characteristics occurred. Large increases in rebound numbers measured by the Schmidt rebound hammer were observed at temperatures between 200 and 400°C compared to those under standard conditions for wet concrete. Conversely, there was a decrease in rebound numbers at temperatures ranging from 600 to 800°C and therein, in parallel, a compressive strength decrease. Rebound numbers had a good correlation with compressive strength, as evidenced by the relation of 0.98, which enabled simple estimation of compressive strength with the aid of corrective coefficients. The article presented determination of compressive strength of concrete after exposure to high temperatures using the rebound hammer. Surface preparation of concrete and averaging several readings were the basic steps in determining compressive strength with the rebound hammer. Calibration curves and standard relations, such as CSN EN 13791, were used in estimating compressive strength including corrective coefficients for greater precision. It acknowledges the absence of accuracy in the non-destructive testing results of cores taken from actual building structures, subjected to high temperatures. It therefore means methods already put in place are not detailed enough. It also draws attention to the fact that very little research has been conducted to date on the application of rebound hammers when testing fire-affected concrete, and much future study is still needed in the effects of dehydration and micro-cracking on testing data. Its future studies would be on high-strength concrete (HSC) and high-performance concrete (HPC) under extreme conditions, especially related to behaviour under fire attack and rebound hammer readings. Research studies related to additive effects, in terms of nanoparticles and carbon nanotubes, on the durability and mechanical properties of heat-exposed concrete may help better clarify this. The calibration relationships for the Schmidt rebound hammer may be further developed to better estimate the strength for heat-exposed concrete. Some limitations in research include effects of moisture in concrete and carbonation depth on rebound hammer methods, which would provide inaccurate results. Calibration relationships are generally formulated under standard curing conditions; therefore, the measurement in heat-exposed concretes would not be so reliable. Though core sampling is accurate, it takes some time and is not always feasible for compressive strength assessment.(Brozovsky and Bodnarova 2016).

5. Case Studies and Field Applications

A two-stage procedure has been developed to estimate concrete strength in situ by non-destructive testing methods, namely ultrasonic pulse velocity and Schmidt hammer tests. The investigation covered 103 different mixes of concretes tested at various ages ranging from 7 days to 90 days. The data used were from the results to derive mathematical relationships through multiple linear regression analyses for initial estimates of strength. In the second stage, correlations of the estimates were done with the actual strengths from the cores cut from the structure; thus, much-improved accuracy was achieved. From the case studies, standard errors of estimate are 2.95 MPa and 0.91 MPa and thus resulting effectively from this procedure. It utilized variables including water-to-cement ratio, aggregate-to-cement ratio, and concrete density in its methodology. In the second phase of correlation which takes 5 to 10 cores cut from different points in the structure for a comprehensive range of concrete strengths, it identifies deficiencies in current non-destructive methods that require correlative approaches since mix proportions and in situ conditions are often omitted in traditional methods. It pointed out that, although the two-stage procedure improved the prediction, there still were deficiencies in the inclusion of these factors in the models. Further validation across different concretes is also needed. Recommendations for future studies: There should be further development in the non-destructive testing with the consideration of the in situ factors such as steel reinforcements and surface carbonation which are at present not considered in regression models. The effectiveness of machine learning techniques in handling a wider scope of concrete mixes and environmental conditions may be a better approach with increased datasets. The long-term durability of concrete evaluated with these should also be considered within the scope of the study. Limitations: Limitations associated with the methods include the fact that non-destructive testing techniques like ultrasonic pulse velocity or Schmidt hammer tests are unreliable as they are conducted in isolation. Moreover, sourcing the detailed construction documentation and curing conditions proves to be a challenge. Wet against dry conditions and proportions of mix were often not taken into account, which substantially impacted the validity of strength appraisal.(Kheder 1999).

The paper, therefore presents an early age, direct non-destructive test to assess the quality of concrete by ultrasonic pulse velocity and rebound hardness measurements at 24 hours and 3 days after mixing. The method ensures reasonably accurate prediction of 28-day compressive strength, thereby overcoming inadequacies of conventional indirect methods that fall short of what is required for early durability assessments. The results have demonstrated that UPV and rebound hardness combined offer sound predictions not only in compressive strength but also in tensile strength, dynamic modulus of elasticity, density, and water absorption. Test Program The test program consisted of 50 measurements per test method on companion specimens, and averages were determined over multiple points within the concrete walls. The study finds a need for early-stage nondestructive evaluation methods and calls for an integrated, inexpensive system that is readily accessible. It also emphasizes critical need for preliminary trial mixes to enhance the accuracy of strength predictions, particularly in the higher strength ranges. Such research should be in the area of strengthening prediction that is above 50 to 60 MPa, long-term durability using nondestructive testing, and aggregate and matrix behavior under different conditions. The implementation of a unified and simple evaluation system will go a long way in enhancing the practical use of the methods in the field. Limitations of the paper include the fact that it needs further experimental verification and more trial mixes to further refine the prediction equations for the strength of higher strength concrete.(Nozaki 2006).

The investigation could conclude that the Schmidt Hammer Test is valid in terms of determining the compressive strength of the concrete, especially in studying the impact of environmental exposure, such as brackish water. Generally, the comparison between the concrete exposed to normal conditions and those exposed to brackish water revealed that the rebound numbers (RN) are significantly lower in the latter, meaning it has lower strength. But again, it has been found that rebound curves offered by the manufacturer alone cannot but underestimate the compressive strength. This is because the Schmidt Hammer Test needs supplementing with the results of direct compression tests for the achievement of more accurate results. Again, a high level of moisture content, very smooth surface, and environmental conditions proved influential in significantly affecting rebound readings. Comparing direct compression tests with rebound hammer results on concrete samples under different environmental conditions, such as drying and wetting cycles in brackish water and continuous immersion, was the objective of this investigation. Therefore, a total of 108 concrete cubes were tested under three different exposure conditions. According to the study, it can be emphasized that no study was found exploring the interactions between the surface hardness factors, such as: moisture content and surface roughness, and no specific rebound correlation curves for the local construction practices. Further research is still required in this respect, mainly not only reducing the highly high dispersion of rebound readings but also improving the predictive models. Future studies should use development of local rebound correlation curves, study other environment factors like temperature and humidity, and monitor the influence of the differences in concrete and aggregate composition on rebound. The limitations of this study come from its sensitivity to a few factors influencing surface hardness in the Schmidt Hammer Test, the high dispersion of data connected with samples exposed to brackish water, and the tendency of curves supplied by manufacturers to underestimate the compressive strength in every case.(Sanchez and Tarranza 2014).

Experimental investigation deals with the reliability of the rebound hammer test in determining the residual strength of RC beams subjected to fire exposure, and it indicates that rebound values remain less degraded compared to those of the compressive strength of concrete cores, so the test is a conservative strength estimator. Further, it was indicated that up to 420 °C, the rebound values were stable. An X-ray diffraction analysis showed an increased amount of calcium carbonate, indicating greater surface hardness, and a scanning electron microscopy revealed decreased porosity in fire-exposed concrete. Yet with these observations made, the overall conclusion is still that a rebound hammer test is insufficient to predict the strength of post-fire concrete due to the lack of sensitivity to temperatures. The methods used in the experiment were: rebound hammer surface hardness tests carried out without causing damage to the surface; compressive strength tests carried out on concrete cores for accurate measurements; analyses by XRD and SEM for potential chemical and microstructural changes, and finite element simulations to estimate temperature variations when exposed to fire. Thus, it consists of fourteen reinforced concrete beams, made from standard Thai mix design and so prepared with deformed bars and stirrups, heated using a furnace to have conditions of fire. The study raises an issue with some research in terms of limitations on the rebound hammer test of post-fire concrete, thereby calling for further research on specific reduction coefficients of rebound values in heat-treated concrete. As such, the present practices fail to provide adequate representation of compressive strength in these situations and require further empirical work in developing predictive models. In the years ahead, reduction factors would be established that would allow evaluating compressive strength through rebound hammer testing on heated concrete, with particular attention to temperatures exceeding 500 °C. Other recommendations include studying different types of aggregates on rebound values and compressive strength after fire exposure. Limitations of the study. The value of rebound cannot be relied upon to predict compressive strength in heat-treated concrete as standard conversion equations used for unheated concrete overestimate compressive strength. Rebound values may make possible the comparison of both damage levels and temperatures in heated concrete, but they become insensitive below 420 °C, and the degradation pattern is less serious than for compressive strength, so difficult to evaluate. The rebound hammer test is not regarded as appropriate for direct strength estimation after fire exposure.(Panedpojaman and Tonnayopas 2018).

6. Limitations and Challenges in Using Schmidt Rebound Hammer

The paper discloses an indirect mathematical model to evaluate concrete compressive strength using a test measurement, like ultrasonic pulse velocity and rebound hammer index. The model represents the linear relationship between indirect measurements and corresponding actual compressive strength values, which proves that both direct and indirect methods estimate about the same values for concrete quality appraisal although indirect methods generate more dispersed estimates. The study is a combination of non-destructive methods, rebound hammer and ultrasonic pulse velocity, and destructive methods: core testing. It highlighted that increasing the number of non-destructive measurements enhances the reliability of results. Laboratory tests are used to validate the model and underline the importance of combining both methods in the in situ quality assessment of concrete. Whereas 'n' may stand for the sample size for both direct and indirect measurements, the paper points out that the number of non-destructive measurement samples needs to increase as well in order to improve the precision of strength estimations. The study suggests that the model needs to be further investigated with different types of concrete and different environmental conditions and other forms of testing to be included. Future research into this matter can target the improvement of the precision of non-destructive methods and different environmental states and progress towards advanced statistical models apart from machine learning for strength prediction. Besides, long-term durability and performance tests of concrete structures measured by these methods may determine the validity of reliability. However, considering concrete cores of structures have 10-30% reduced strength compared to standard samples, it becomes hard to make precise estimations. This is typically compensated by using an adjustment coefficient 'k' in most international standards. Greater variability also associated with indirect measurement requires higher sample sizes to maintain the precision of direct measurement methods.(Mikuli, Pause, and Ik 1992).

Over 80 000 readings collected from thousands of test locations during 60 years have shown very significant variability in the concrete rebound hardness, in general, highlighting a problem for reassessment of presently accepted standards on repeatability and precision of rebound hammer tests and concomitant identification of gaps in the literature in relation, especially to the influence of cement types, water-cement ratios, and the effect of age of concrete on variability in the rebound index. Rebound index variability has been shown to decrease until 28-56 days but is increased by the carbonation effect. Using extensive statistical analysis and the Shapiro-Wilk test, this research included in its considerations water-cement ratio, concrete age, and testing conditions. The database included 8,955 pairs of data from 48 sources including both in-situ and laboratory tests with the collection of over 8,800 individual rebound readings. The work suggested areas for future work in order to take care of the within-test coefficient of variation and to clarify the influences on rebound hammer test results. It also highlighted the necessity of improving the calibration and the designing of the devices to minimize the observational errors to a minimum. Key Limitations The calibration of rebound tests to the core strength negates the non-destructive testing benefits, and there are issues with the EN 13791 curve used for calibration. Included also are observational errors arising from device design and variability with cement type, water-cement ratio, and concrete age. The study concludes that test methods and statistical analyses need refinement in order to make proper strength estimations.(Szilágyi, Borosnyói, and Zsigovics 2014).

The study explores the relevance of the rebound hammer (RN) and ultrasonic pulse velocity (UPV) test results to the strength variability of concrete, and it develops expressions to predict in situ strength variability of concrete from the result of NDT. The study concludes that although there are many methods to estimate the mean concrete strength, only the bi-objective approach gave reliable estimates of variability, and power and exponential models showed higher correlations for UPV as well as its variability with concrete strength as compared with linear models. To improve the correlation analysis, the ROUT procedure of robust regression and outlier removal is applied in a three-step process to detect and remove outlying observations in the data that may otherwise degrade the goodness-of-fit of the regression models. Overall, the study used 78 data sets: 68 had strength on core and rebound hammer data, 50 had strength on core and UPV data, and 40 contained both RN and UPV test results. The authors point out that there is a limitation in the relatively low number of data triplets taken for regression analysis, namely, 40, and state that this may be inadequate to characterise the investigation properly as a whole. There is no reliable correlation for the estimation of the standard deviation of concrete strength based on RN test results. Areas of research gaps in the sensitivity of SonReb-like models about the RN/UPV data correlation are identified, and additional research is proposed to improve these models. Future studies should be concentrated on developing general empirical expressions for estimating in situ concrete strength variability using NDT results, sensitivity assessment of the SonReb model and exploration of the possibility of applying these models to older reinforced concrete structures with limited prior information. This study has few limitations: small number of data triplets, inasmuch as the analyses regarding the three-variable models are too complex, not fully analyzing the M2-SonReb model because of not having sufficient correlation data, errors in distributional assumptions, as the normality assumption for gCoVfc ratios was rejected.(Pereira and Romão 2018).

Limitation and challenges while using rebound hammer Moreover, the integration of advanced statistical methods and machine learning techniques into the analysis of rebound hammer data could significantly enhance the predictive accuracy of concrete compressive strength assessments. By employing algorithms that can account for multiple variables simultaneously—such as moisture content, carbonation depth, and age of the concrete—a more nuanced understanding of material properties may emerge, potentially addressing some limitations inherent in traditional regression models(Kumavat, Chandak, and Patil 2021). For instance, utilizing a multivariate approach could allow practitioners to develop dynamic calibration curves tailored to specific environmental conditions and concrete formulations, thus improving reliability across diverse applications(Sanchez and Tarranza 2014)

7. Future Directions and Innovations in Concrete Testing

The concrete was tested for compressive strength using some of the non-destructive techniques, namely: ultrasonic pulse velocity and rebound hammer tests and the strengths are in the range of 20 to 50 MPa. Relationships involving UPV and compressive strength as well as rebound number (RN) and compressive strength were developed giving rise to a prediction formula validated with experimental results. The study produced ISO-strength curves which could correctly predict the compressive strength of concrete within the set range with a close correlation between predicted and experimental values scattered within 15% of the line of equality. Different methods used were UPV tests that measured the travel time of ultrasonic pulses through the concrete, correlated with its elastic properties and rebound hammer tests assessing surface hardness in relation to compressive strength. Therefore, regression analysis is carried out for such NDT results to further refine the relationships between the given NDT results and concrete strength. Very large variability in NDT results was noticed, and the number of cores taken and sensitivity of the technique is a main reason; hence, standardized protocols are required to achieve better reliability. A gap that was noted is there was no single study that is holistic along with integration of various NDTs for accurate strength prediction. Indeed, the existing models of regression were proved to overestimate and, in some cases, underestimate strength, thereby establishing a need for more accurate predictive models that take into account different concrete mixtures. More importantly, the long-term effectiveness of these NDTs under different environmental conditions is yet to be explored and developed. Hence, future studies in this direction should be guided towards enhancing the precision of NDTs by exploring the sensitivity of concrete mix and environmental conditions. Studies can investigate further on the relationship of the number of cores with the accuracy in strength prediction and refine advanced regression models for more precise predictions. Some of the limitations of the study is that rebound hammers are prone to some problems related to force and stress-wave transmission, and this influences the accuracy. Equipment calibration was observed to be necessary in some cases for safety since it overestimates compressive strength. Also, the RN values may not really represent the internal concrete hydration process at early ages, which will even make things harder with respect to assessments.(Rashid and Waqas 2017).

Self-compacting concrete is a type of concrete showing different characters, especially higher cement paste content and lower volume proportion coarse aggregate content, in comparison with normal vibrated concrete. In the present study, an attempt has been made to analyze the feasibility of using non-destructive tests for compressive strength estimation of SCC. Compressive strengths were comparatively correlated with ultrasonic pulse velocity, surface hardness, pullout, and concrete maturity tests. The following variability analysis showed that there were significant differences between SCC and NVC especially in surface hardness and pull-out force. The methods of NDT that were used were: the PUNDIT apparatus using ultrasonic pulse velocity test, the Schmidt rebound hammer type N for surface hardness test, Lok-test for pull-out test, and COMA-meter for concrete maturity test. These are chosen because they are simple to apply and present immediate and non-damaging results. Some of the important research findings identified relate to the application of NDT methods to SCC, wherein special correlations are of paramount importance due to the uniqueness of SCC mix proportions and the absence of vibration that may compromise the reliability of NDT methods. In addition, many areas pertaining to increased research will relate to the effects of curing conditions on compressive strength of SCC. Future studies should include adaptations to SCC of NDT variations, influence of mix proportions and environmental conditions on accuracy of NDT, and more specific correlations for the different types of SCC. In addition, the study identifies a few limitations: the specific characteristics of SCC may impose a variation in correlation with compressive strength, and the pulse velocity tests based on the ultrasonic method lose sensitivity at higher velocities for both SCC and NVC. This is also further complemented by stating that SCC-specific correlations of NDT are required because SCC would have different surface hardness and other concrete properties compared to NVC.(Bernardo 2019).

The study indicates that the type of parent rock from which coarse aggregate is derived significantly affects rebound numbers in Schmidt hammer tests on HSC. The basis for such a belief might be that stronger aggregates will necessarily yield higher rebound numbers. The aim of this paper is to bring to light the necessity of having particular calibration relationships for HSC as standard relationships for normal-weight concrete are inappropriate. This also recognizes that the granulometric curve of the aggregate impacts measurements, but in a lesser way compared to the strength of the parent material. For testing with the Schmidt hammers, types N and L, several measurements were taken at a time and averaged to eliminate outliers so as to ensure results were accurate. Aspects that have been recognized as needing further development in the subject matter of concrete include the composition, types of aggregate that can be used, influences such as humidity, among other aspects related to age, especially when it comes to HSC. Further work in the future will focus on the calibration relations of HSC, including strength and aggregate composition while accounting for the environmental effects on the properties of the concrete. However, for example, applying calibration curves of normal-weight concrete to HSC resulted in it being undervalued in compressive strength, and a very high influence of the aggregate type on rebound numbers.(Taylor and Brozovsky 2014).

8. Conclusion and Recommendations for Practitioners

One of the most frequent limitations that is cited is high variability in rebound hammer readings, especially when different environmental exposures, such as brackish water exposure or after fire damage, prevail. Standard manufacturer-supplied curves for conversions tend to underpredict compressive strength, thus requiring local calibration and correlation curves. Advanced statistical models and machine learning are thought to be feasible alternatives for multiple-variable refinement of predictions including the age of concrete, mix proportions, and environmental exposure.

Recommendations for Practitioners:

1. **Localized calibration:** Curves need to be applied for specific concrete mixes as well as conditions for improving the accuracy of rebound hammer tests. This is more essential in cases such as HSC or concrete with some environmental exposure, for example, brackish water or high temperatures.
2. **Machine Learning for Improved Predictions**: By using machine learning techniques for data analysis, compressive strength predictions can be improved. Models can include a combination of variables that are moisture content, carbonation depth, and properties of aggregate, hence better representing calibration curves to be more specific and accurate.
3. **Focus on Early-Stage Assessments**: Where early durability matters, practitioners could consider methods combining UPV with rebound hardness at 24 hours to 3 days, as they have been shown to be of value in predicting compressive strength at 28 days reasonably accurately.

4. **Environmental Consideration:** Several environmental parameters like surface smoothness, moisture, and temperature affect the rebound values. A rebound hammer should be used considering all such parameters, and changes should be accommodated in the analysis.
5. **Validation and Field Trials**: NDT techniques should be calibrated periodically through field tests to validate existing models and redefine them for new concrete types and construction conditions.

With these recommendations, practitioners can augment the reliability and accuracy of concrete strength to meet the quality and safety standards of modern construction projects.

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