



Field Analysis of Schmidt Hammer Test Results in Assessing the Compressive Strength of In-Situ Concrete Structures with Emphasis on Hot and Humid Climatic Conditions: A Case Study of Projects in Behbahan and Gachsaran

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Abstract: This study evaluates the field reliability of the Schmidt rebound hammer for estimating in-situ concrete compressive strength, specifically addressing challenges posed by hot and humid climatic conditions in Behbahan and Gachsaran, Iran. Field campaigns followed ASTM C805 on five structures using a novel, disciplined protocol designed to mitigate procedural and environmental bias. This involved mandatory mechanical surface preparation, employing a ten-point sampling grid, and integrating rigorous statistical processing, notably Interquartile Range (IQR)-based outlier identification. Results confirmed significant spatial variability in rebound numbers across structural elements, strongly influenced by construction practices and environmental exposure, particularly high temperatures. For instance, a C30 foundation yielded estimated strengths near its lower design limit (27.9–34.8 Mpa). The findings emphasize that uncalibrated, generic correlations are insufficient and can yield misleading estimates in these regions. The paper concludes that the diagnostic value of the Schmidt hammer can be substantially increased through mandatory region-focused improvements, including the development of site-specific calibration curves, routine use of complementary core testing for validation, and strict logging of environmental parameters. This combined approach improves the interpretability and practical reliability of NDT in challenging environments.

Keywords: Non-Destructive Testing, Concrete Evaluation, Rebound Number, Compressive Strength Estimation, Field Testing

1. Introduction

The Schmidt hammer, as one of the most widely used non-destructive methods for concrete evaluation, was first introduced by Ernst Schmidt in 1950. This device operates based on the principle of measuring the rebound energy from the concrete surface, which is directly related to the compressive strength of the concrete. The simplicity of use, low cost, and the ability to perform the test on-site are among the most important advantages of this method. Although the Schmidt hammer is widely used in civil engineering projects, the accuracy of its results is

influenced by several factors, including the concrete surface condition, moisture content, concrete age, and curing method (Kumavat et al., 2021). Recent studies have shown that combining this method with advanced techniques such as machine learning and statistical methods can significantly increase the accuracy of assessments (Du et al., 2021). The purpose of this article is to evaluate the application and effectiveness of the Schmidt hammer test in determining the compressive strength of in-situ concrete structures under the actual conditions of civil engineering projects located in the hot and humid region of Behbahan County.

Through extensive field testing on various types of concrete structures and analysis of the obtained results, this research investigates the challenges and factors affecting the accuracy of this method and emphasizes the importance of considering specific environmental conditions and the necessity of using supplementary methods to enhance the reliability of assessments (Grandić et al., 2024). Although numerous studies have assessed the Schmidt rebound hammer and developed empirical rebound–strength correlations, most rely on limited datasets from temperate climates, lack standardized on-site surface preparation, or omit robust statistical filtering and uncertainty reporting (Szilágyi & Borosnyói, 2013; Tugrul Tunc, 2025). This study advances the state of the art in three complementary ways: (1) it develops and field-validates a repeatable testing protocol tailored to hot–humid environments (mechanical surface preparation, a 10-point grid per sampling location, and environmental logging), (2) it integrates rigorous statistical treatment (IQR-based outlier identification, COV, confidence) to reduce bias from spatial and procedural variability, and (3) it provides practical, site-specific calibration and implementation guidance for critical industrial infrastructures (oil & gas facilities) where destructive testing is often limited. Collectively, these contributions improve the interpretability and practical reliability of rebound hammer measurements in hot–humid regions and offer a deployable workflow for practitioners and future calibration studies. The findings of this research can contribute to improving the concrete quality

control process in civil engineering projects and provide practical solutions for increasing the accuracy of non-destructive evaluations (Kovler et al., 2018; Rezaifar et al., 2025 ;Sorilla et al., 2024). By combining experimental data and statistical analyses, this study represents an effective step in the development of concrete assessment methods. The concept of using rebound energy to evaluate concrete hardness was first introduced by Ernst Schmidt in 1950. He demonstrated that there is an empirical relationship between the rebound number and the compressive strength of concrete. These findings formed the basis for the development of international standards such as ASTM C805 (ASTM International, 2018). Early work contributed to the development of methods for evaluating hardened concrete using the test hammer (Kolek, 1958). Sorilla et al. (2024) previously investigated non-destructive methods for determining the resistance of cracked concrete. Also, Grandić et al. (2024) propose a new method based on non-destructive measurement of corrosion parameters that is suitable for structures exposed to chloride ion penetration. Numerous studies have focused on developing empirical relationships and evaluating the reliability of the Schmidt hammer test for concrete strength assessment. Researchers have proposed various equations correlating concrete compressive strength (f_{cm} or f_c) with the rebound number (R). These relationships often take the form of linear, power, polynomial, or exponential functions. For instance, proposed polynomial and power relationships. Kumavat et al. (2021) reviewed relationships proposed by

different authors considering factors like core location, curing condition, elevated temperature, and concrete grade/mix. Kim et al. (2009) presented linear relationships, as did Monteiro & Gonçalves (2009). Different types of hammers, such as the N-type, L-type, and Silver Schmidt models, which have different impact energies and measurement methods (like the Silver Schmidt's Q-value derived from impact and rebound velocity), can also influence the resulting relationships (Kovler et al., 2018). Szilágyi & Borosnyói (2013, 2011) have extensively studied the Schmidt rebound hammer, including fifty years of experience and introducing an empirical constitutive model for rebound surface hardness. Kovler et al. (2018) compared the Leeb versus Schmidt hammers for concrete testing. The performance and reliability of the Schmidt hammer test are known to be influenced by several factors (Kumavat et al., 2021). Research indicates that concrete composition, including the water-cement ratio and aggregate type (e.g., Granodiorite, Basalt, Limestone), can affect the rebound number and its correlation with strength (Tugrul Tunc, 2025). Curing conditions (e.g., air curing, water curing) and age of the concrete also play a significant role. Additionally, factors such as carbonation depth, moisture content (wet vs. dry concrete), compaction method, and the shape and size of the concrete specimen or structural member can influence the test results and the resulting strength estimation (Kim et al., 2009; Ponda et al., 2023). Surface preparation methods can also affect the rebound number obtained from the impact hammer test (Brozovsky et al.,

2013). For example, a study by Tugrul Tunc (2025) on limestone aggregate concrete investigated the influence of varying water-to-cement and limestone aggregate-to-cement ratios on concrete strength and developed statistical models with high accuracy ($R^2 > 0.95$) to predict both compressive and splitting tensile strengths based on these ratios and the rebound number. While the Schmidt hammer test is widely used due to its portability and ease of use in various situations, the need for proper calibration and the influence of numerous factors highlight the complexity involved in obtaining reliable strength estimations (Szilágyi & Borosnyói, 2013). Alshukri et al. (2025) works on flexural behavior effects of concrete made with fine aggregate with contamination. Priyadarshee et al. (2025) worked on evaluates the potential utilisation of crushed concrete debris (CCD) and recycled concrete aggregate (RCA) in the SC construction. Some studies explore the potential for improved concrete strength prediction by combining the Schmidt hammer test with other non-destructive methods, such as the Ultrasonic Pulse Velocity (UPV) test. Researchers have used both methods in conjunction with destructive core testing to assess concrete properties. Du et al. (2021) used an ultrasonic-rebound method based on a GA-BP neural network for predicting the compressive strength of high-performance self-compacting concrete. Islam et al. (2024) researchs about gap between the frame and infill showed that , lateral stiffness and strength decreased also Singh et al. (2024) showed that the increment in cohesion (c) and angle of internal friction (ϕ) is associated wit

h the increment in cement and fiber content, respectively.

This study investigates the application of Schmidt hammer tests (ASTM C805) for evaluating in-situ concrete quality in Behbahan and Gachsaran counties. Through systematic field testing, we collected rebound hammer data from various structural elements, analyzing the variability in surface hardness measurements. Our findings demonstrate significant correlations between rebound numbers and concrete quality, while highlighting the impact of local environmental conditions and construction practices on test results. The research addresses critical limitations in non-destructive testing by proposing methodological improvements, including the integration of supplementary techniques like core sampling for enhanced reliability. Notably, we developed data processing protocols to identify and eliminate outliers, enabling more accurate strength estimations. The outcomes provide valuable insights for quality assessment of concrete structures in hot, humid climates, though they also reveal the necessity for region-specific calibration curves to account for unique material and environmental factors in southwestern Iran.

2. Methodology

The experiments in this study were designed and conducted in accordance with the latest editions of ASTM C805 standard. The testing process was carefully controlled to ensure that the collected data possessed the highest level of reliability.

2.1. Sample Preparation

The concrete surface was mechanically polished using a grinding stone to remove all surface irregularities and interfering coatings. After grinding, the surface was thoroughly cleaned with compressed air and a non-metallic nylon brush. This step was performed to ensure full contact between the device and the concrete surface and to eliminate any interfering factors. Selection of Test Points:

For each sample, a grid consisting of 10 test points was established, with a spacing of 25 mm between points and 20 mm from the edges. Areas with cracks, visible porosity, or irregular roughness were carefully avoided. This sampling pattern ensured complete surface coverage and minimized errors caused by local variations.

2.2. Test Execution

A Schmidt Hammer device with an accuracy of $\pm 0.5\%$ was employed. The device's piston was compressed at a controlled speed to activate the impact mechanism. For each point, five consecutive blows were applied at predetermined time intervals.

2.3. Data Recording and Processing

Rebound numbers were recorded with an accuracy of 0.1 units. The average of three closely matched values was calculated for each point. Points exhibiting standard deviations exceeding permissible limits were discarded and retested. Environmental conditions, including surface temperature and relative humidity, were simultaneously measured and recorded. To ensure the statistical reliability of the rebound hammer results, outliers were identified using the interquartile range (IQR) method in addition to visual

inspection through box plots. Measurements falling outside $1.5 \times \text{IQR}$ from the lower or upper quartiles were classified as outliers. These values were excluded from the calculation of mean rebound numbers and subsequent strength estimations, as their inclusion could bias the results. However, outliers were documented separately and discussed qualitatively to highlight potential sources of local heterogeneity (e.g., surface defects, localized damage, or construction inconsistencies). This dual approach allowed for both accurate statistical analysis and meaningful interpretation of anomalous values.

2.4. Safety Considerations

All tests were conducted in compliance with safety protocols and the use of personal protective equipment. Testing under unsuitable temperature conditions or applying repeated impacts at the same point was strictly avoided. These precautionary measures helped maintain the integrity of the samples and ensured the quality of the data.

2.5. ASTM C805 Standard

According to ASTM C805-18, the Schmidt hammer test is defined as a non-destructive method for assessing the uniformity and estimating the relative compressive strength of hardened concrete. This standard emphasizes that the device must have an impact energy of $2.207 \text{ N}\cdot\text{m}$, and the results should be reported as rebound numbers ranging from 10 to 100. The standard specifies that the concrete surface must be smooth, clean, and free of any coating or contamination. A minimum spacing of 25 mm between test points and at least 20 mm from

edges must be maintained. Furthermore, the device must be positioned perpendicular to the surface (with a maximum deviation of 5 degrees), and for each test point, at least 3 readings should be taken with a maximum allowable difference of 2 units. The standard notes that the results are suitable only for relative comparisons, and accurate determination of compressive strength requires complementary testing methods. Annual calibration of the device and the use of reference blocks in laboratory conditions are also among the key requirements of this standard.

Based on ASTM C805, concrete quality is classified into five main categories according to rebound numbers:

- Excellent: Rebound numbers of 45 and above, corresponding to compressive strength over 45 Mpa. This category indicates highly dense concrete of excellent quality.
- Good: Rebound numbers between 40 and 44, indicating compressive strength of 35 to 45 Mpa. Such concrete is suitable for most structural applications.
- Fair: Rebound numbers from 30 to 39, corresponding to 20 to 35 Mpa. These concretes require further investigation.
- Poor: Rebound numbers from 20 to 29, indicating 10 to 20 Mpa compressive strength, and typically require strengthening.
- Very Poor: Rebound numbers below 20, corresponding to compressive strength below 10 Mpa, which usually require demolition and reconstruction.

Schematic workflow of Schmidt hammer testing process according to ASTM C805 shown in Fig1.

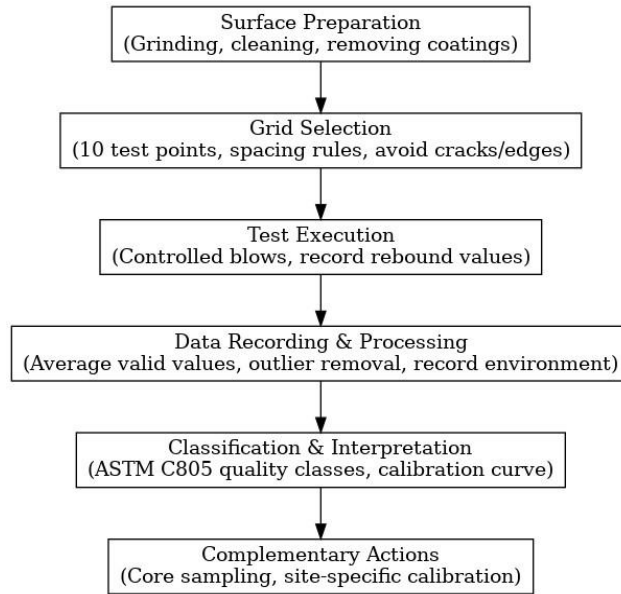


Fig. 1. Schematic workflow of Schmidt hammer testing process according to ASTM C805

Concrete Quality Classification
According to ASTM C805 Standard
shown in Table 1.

Table 1. Concrete Quality Classification According to ASTM C805 Standard

Rebound Number [®]	Concrete quality	Estimated compressive strength (Mpa)
≥45	Excellent	≥45
40–44	Good	35–45
30–39	Fair	20–35
20–29	Poor	10–20
<20	Very Poor	<10



Fig. 2. Table of relationship between return number and compressive strength

Fig. 2 illustrate the Schmidt hammer device utilized in the experimental procedures of this study.

Behbahan and Gachsaran are located in southwestern Iran and are two the locations selected for the field analysis of the Schmidt hammer test. These cities which is representative of the hot-humid climate like many southern cities in Iran, is characterized by persistently high temperatures, elevated relative humidity, and intense solar radiation. Collectively, these conditions impose severe challenges on the durability and performance of concrete structures.. These cities are characterized by persistently high temperatures, elevated relative humidity, and intense solar radiation, which together impose severe challenges on the durability and performance of concrete structures. Moreover, both cities host major oil and gas industries, including refineries and associated infrastructure, which have led to the construction of a wide range of critical concrete facilities. This combination of climatic representativeness and the presence of significant infrastructural projects makes Behbahan and Gachsaran suitable and context-specific choices for investigating the applicability of the Schmidt hammer in hot-humid environments. The selection of the five case study structures was based on their representativeness of concrete performance under hot and humid environmental conditions typical of southern Iran. These structures including foundations, columns, pipe supports, and an older generator foundation, were chosen to capture a range of service lives, construction

practices, and exposure levels. The inclusion of both relatively new and aged structures allowed for assessing the influence of time-dependent deterioration on rebound hammer readings. In addition, the structures were selected because they are critical components of industrial and infrastructural facilities, where accurate and cost-effective assessment of in-situ concrete strength is essential for maintenance planning. By covering different geometries, ages, and environmental exposures, the chosen cases provide a diverse yet context-specific dataset, strengthening the applicability of the study's findings to similar hot-humid regions.

3. Projects for In-Situ assessment

In this research, in accordance with the methodology detailed in the preceding section, Schmidt hammer testing was performed on five in-situ concrete structures. Of these five structures, three were located in Behbahan, while the remaining two were situated in Gachsaran. Notably, these two cities share relatively similar climatic conditions. The five structures investigated include the electrical substation of a water treatment plant under construction in Behbahan, the columns of a single-story residential building under construction in Behbahan, the columns of the second floor of Block No. 9 of the National Housing Project in Behbahan, and the three pipe support foundations (NGL

900) and the old generator foundation of the LPCS project in Gachsaran.

3.1. Behbahan Purification Plant Project Power Substation Foundation

The results of the Schmidt hammer test on the foundation of the Behbahan water treatment plant substation with a design strength of C30 show that the average rebound numbers on the four sides of the foundation varied between 34.9 and 37.2, which according to ASTM C805 falls into the "good" quality category. This test was conducted under environmental

conditions with a temperature of 35°C and humidity of 34% and based on ASTM C805 By converting the rebound numbers to compressive strength according to the calibration equation ($f_c = 0.8R - 10$), the estimated values ranged from 27.9 to 34.8 Mpa, indicating proximity to the lower limit of the design strength. Especially in areas where rebound numbers less than 35 were recorded, it is recommended to perform supplementary tests such as core sampling to ensure the quality of the concrete. The data obtained from this experiment are shown in Table 2.

Table 2. Results of Schmidt Hammer Test on Substation Foundation

Face of foundation	Test Points (Rebound Numbers)										Average rebound number	Range of variation	Test temperature (°C)
	1	2	3	4	5	6	7	8	9	10			
North	36	38	36	34	36	38	40	36	40	38	37.2	34-40	35
West	39	36	35	38	36	35	34	36	36	35	36	34-39	35
South	34	34	32	34	34	36	35	37	37	36	34.9	32-37	35
East	34	34	34	36	32	37	35	36	35	37	35	32-37	35

The presented box plot (Fig. 3) illustrates the results of the Schmidt hammer test conducted on the four different faces of the foundation (North, South, East, West). In this analysis, the data have been ordered using the interquartile range (IQR), and outlier values are separately identified with a cross mark. Each box in the plot represents the range between the first quartile (25%) and the third quartile (75%) of the data, and the horizontal line inside the box indicates the median value. The small square symbol also shows the mean of the data for each face of the foundation. The vertical lines extending from the boxes depict the data

range up to 1.5 times the IQR above and below the quartiles.

Based on this chart, it can be observed that the North face of the foundation shows the highest Schmidt hammer values compared to the other faces; such that both its mean (37.2) and median (37) are higher than the others, and the data dispersion is also relatively large (IQR approximately 4 units). In contrast, the West face has the lowest mean (36) and median (36), and its data have less dispersion (IQR approximately 2 units). The South and East faces show similar values, with a mean and median close to 35, and the data dispersion is also approximately the same (IQR approximately 5 units for

South and 5 units for East). Furthermore, the presence of outlier values on the North and West faces indicates that at some points on these surfaces, there is different resistance compared to the majority of the measured points. Overall, the results of this test indicate that the surface resistance of the foundation on the North

face is significantly higher than the other faces, and the West face shows the lowest resistance. These differences could be due to various factors such as construction conditions, exposure to environmental elements, or variations in the material composition, which require further investigation.

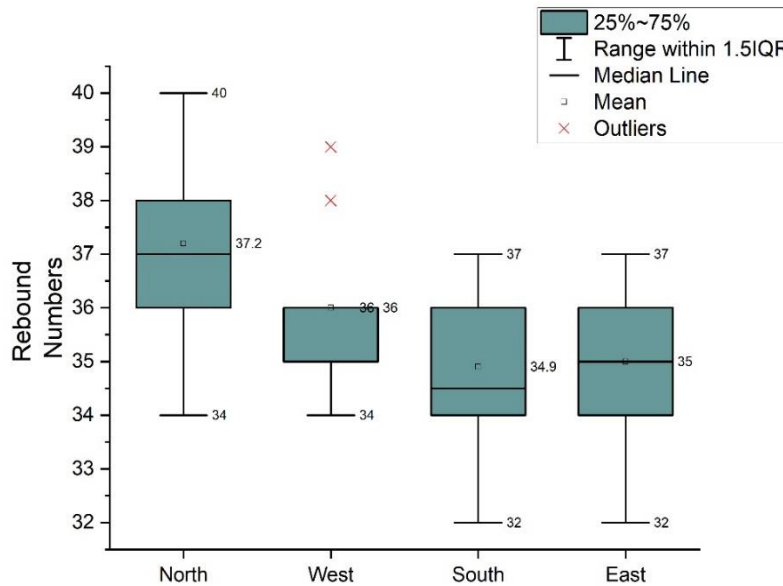


Fig. 3. Schmidt Hammer Test on Substation Foundation

3.2. Columns of a residential building under construction

The results of the Schmidt hammer test on the columns of a single-story residential building show that the average rebound numbers ranged from 36.3 to 40.3. This test was conducted under environmental conditions with a temperature of 33°C and humidity of 59%, based on ASTM C805 and IS 13311 (Part 2) standards. Before the test, the surface of all columns was smoothed and cleaned with sandpaper. The results from 8 columns were examined, with column

number 3 showing the best performance with an average rebound number of 40.3, placing it in the "excellent" quality category. In contrast, column number 5, with an average of 36.3, was at the lower limit of the "good" range. Additionally, in column number 6, an outlier with a rebound number of 43 was observed, which requires further investigation. Overall, the quality of the concrete in the columns is within the acceptable range. The data obtained from this experiment are shown in Table 3.

Table 3. Results of Schmidt Hammer Test on One Story Residential Building Under Construction

Number of	Test Points (Rebound Numbers)	Average rebound number	Variation of Range of temperature	Test
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	1	2	3	4	5	6	7	8	9	10			
1	37	36	39	38	39	36	35	40	39	38	37.7	35-40	33
2	36	35	37	39	36	38	37	37	36	40	37.1	35-40	33
3	39	42	39	42	41	40	39	40	41	40	40.3	39-42	33
4	40	41	41	38	40	38	38	39	42	41	39.8	38-42	33
5	35	36	37	36	36	37	39	36	36	35	36.3	35-39	33
6	36	43	40	42	42	39	37	39	36	37	36.3	36-43	33
7	39	38	39	36	34	39	36	38	38	40	37.7	34-4	33
8	39	41	40	38	40	38	42	43	38	39	39.8	38-43	33
9	38	39	40	40	39	48	41	39	43	40	40.7	38-48	33

Fig. 4A presents one of the residential building columns subjected to testing in this investigation, while Fig. 6 depicts the Schmidt hammer test being performed on the structure. Fig. 4B presents the distribution of Schmidt of reference.

hammer test results on ten different columns of a one story residential building, where each column is numerically labeled from 1 to 10 for ease



Fig. 4. Performing the Schmidt hammer test on the column

Similar to the previous chart, each box delineates the interquartile range (IQR), representing the central 50% of the data (from the 25th to the 75th percentile), with a horizontal line marking the median value and a small square indicating the mean. The whiskers extend to 1.5 times the IQR from the quartiles, illustrating the typical spread of the data, while any

points beyond these whiskers are identified as outliers, denoted by 'x.'

Upon examining the plot, we observe variability in both the central tendency and the dispersion of the Schmidt hammer test results across the different columns of the building. For instance, column 6 exhibits the highest median and mean values (approximately 39.1), along with a relatively wide IQR, suggesting a broad range of concrete

surface hardness values within this column. In contrast, columns 2 and 10 show lower median and mean values (around 37), with column 2 displaying a smaller IQR, indicating less variability in the concrete surface hardness within this column. Several columns, such as 3, 4, 8, and 9, present relatively high mean values (ranging from approximately 39.8 to 40.7), but with varying degrees of data spread as indicated by their respective IQRs. Notably, outliers are present in columns 4, 5, and 9, suggesting the occurrence of points with different concrete surface hardness

within these specific columns that deviate significantly from the general trend. The presence of these outliers and the differences in the distribution characteristics of the Schmidt hammer test results across the ten different columns of the building highlight the heterogeneity in the concrete surface hardness between different structural elements and necessitate further analysis to understand the potential factors influencing these variations, such as construction quality, curing conditions, or exposure to different environmental factors.

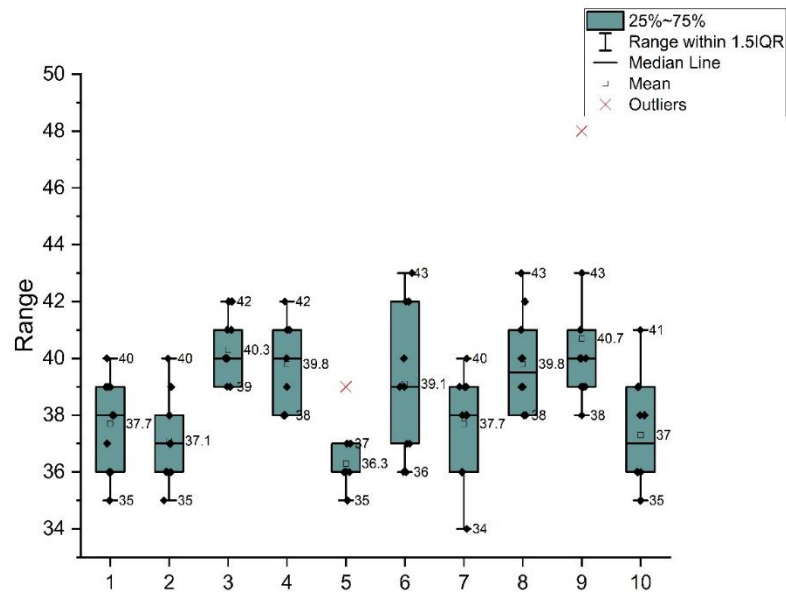


Fig. 5. distribution of Schmidt hammer test results on ten different columns of a one story residential building

3.3. Columns of Block No. 9 of the Behbahan National Housing Project

The results of the Schmidt hammer test were conducted on three columns of the second floor of Block No. 9 of the Behbahan National Housing Project 164 with a required strength of C25. This test was conducted at the request of the project supervision team under an

ambient temperature of 37°C and humidity of 50% on surfaces finished using formwork methods. The results showed that the rebound hammer values ranged between 40.6 and 43.6, exceeding expected levels for C25 concrete. Column No. 2 demonstrated the best performance with an average of 43.6 (estimated compressive strength ≈35 Mpa), while Columns 1 and 3

showed averages of 40.6 and 41, respectively, falling within the good-to-excellent quality range. These outcomes indicate appropriate concrete quality and correct execution of formwork installation and compaction operations.

Despite the relatively high ambient temperature during testing (37°C), the results maintained acceptable accuracy, demonstrating proper concrete curing practices. The data obtained from this experiment are shown in Table 4.

Table 4. Schmidt hammer test results on Second floor, block number 9, National Housing (required concrete strength C25)

Number of columns	Test Points (Rebound Numbers)										Average rebound number	Range of variation	Test temperature (°C)
	1	2	3	4	5	6	7	8	9	10			
1	40	42	42	40	42	40	40	40	40	40	40.6	40-42	37
2	46	42	44	44	42	44	42	46	44	42	43.6	42-46	37
3	40	40	40	40	42	42	42	40	42	42	41	40-42	37

Fig. 8 displays the concrete structure of Block No. 9 of the National Housing Project in Behbahan, and Fig. 8 shows

one of the columns on which the Schmidt hammer test was conducted.



Fig. 6. Structure of Block No. 9 of the Behbahan National Housing Project

Based on the box plot presented in Fig. 7 for the three columns of the National Housing Project in Behbahan (Columns 1 to 3), Column 2 exhibits the highest mean (43.6) and median (44) Schmidt hammer test results compared to the other two columns, and the data range within it is relatively wider. In contrast, Column 1 has the lowest mean (40.6), and its data dispersion is more

limited. construction practices or curing conditions between these columns.

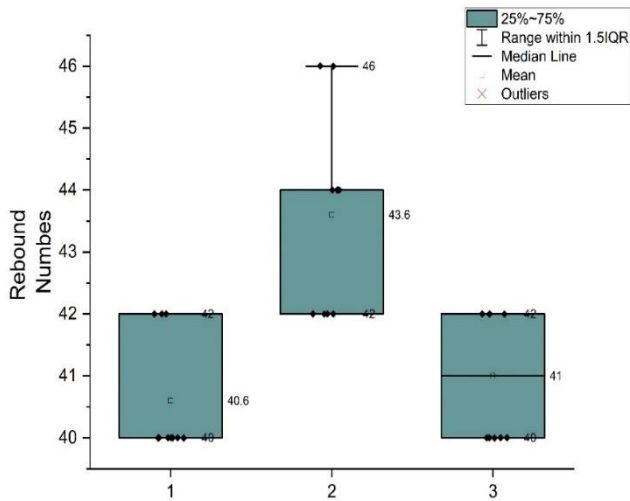


Fig. 7. distribution of Schmidt hammer test results on three different columns of Behbahan National Housing

3.4. Gas pre-compression unit in NGL 900 gas and liquefied gas plant

A non-destructive Schmidt hammer test was conducted at the NGL 900 liquefied gas plant on three different

foundations (Pipe Support Foundation A, B, and C). The test was carried out under completely dry and moisture-free weather conditions, with a constant temperature of 35°C and humidity of 11%. The results from 10 test points on each foundation showed that the average rebound numbers ranged between 35.8 and 36.8. Foundation C demonstrated the best performance with an average of 36.8 (range 36–38), while Foundation A recorded the lowest value with an average of 35.8 (range 34–38). All results fall within the “Good” to “Excellent” quality range (according to ASTM C805), indicating desirable and uniform concrete quality across all tested foundations. The limited variation range (maximum of 4 units) among different points reflects proper execution and strict quality control during the concreting process of these structures. The data obtained from this experiment are shown in Table 5.

Table 5. Test Results of Pipe Support Foundation at NGL 900 Gas Plant

Sampling location	Test Points (Rebound Numbers)										Average rebound number	Range of variation	Test temperature (°C)
	1	2	3	4	5	6	7	8	9	10			
Pipe Support Foundation A	34	36	34	38	36	36	38	36	36	34	35.8	34-38	35
Pipe Support Foundation B	38	36	36	36	34	38	36	36	36	36	36.2	34-38	35
Pipe Support Foundation C	36	38	36	36	38	36	38	38	36	36	36.8	36-38	35

3.5. Test Results of the Old Generator Foundation Located at LPCS, Production Tank Units of Gachsaran 1 and 2

Fig. 8. distribution of Schmidt hammer test results on three different Pipe Support Foundation, NGL 900

displays the highest mean (53.2) and median (53), and its data also have a significant dispersion, with one outlier observed at a value of 56. These differences in the Schmidt hammer test results between the different faces of the old generator foundation may indicate heterogeneity in the concrete surface hardness and potentially the compressive strength across various points of the foundation, necessitating further investigation into the construction conditions and environmental factors affecting each face.

(Behbahan and Gachsaran) with research conducted in controlled laboratory settings or temperate environments. The Inadequacy of Generic Correlations: Our observation that uncalibrated, generic rebound–strength correlations are insufficient and risk providing misleading strength estimates aligns with the conclusions of many prior studies. For instance, in their extensive research on concrete specimens under controlled, temperate laboratory conditions in Italy, concluded that original Schmidt correlations are inherently unreliable, with strength estimations potentially deviating by up to 70%. Key Distinction: While these temperate studies highlight unreliability due to factors intrinsic to the test (e.g., concrete age or heterogeneity), our

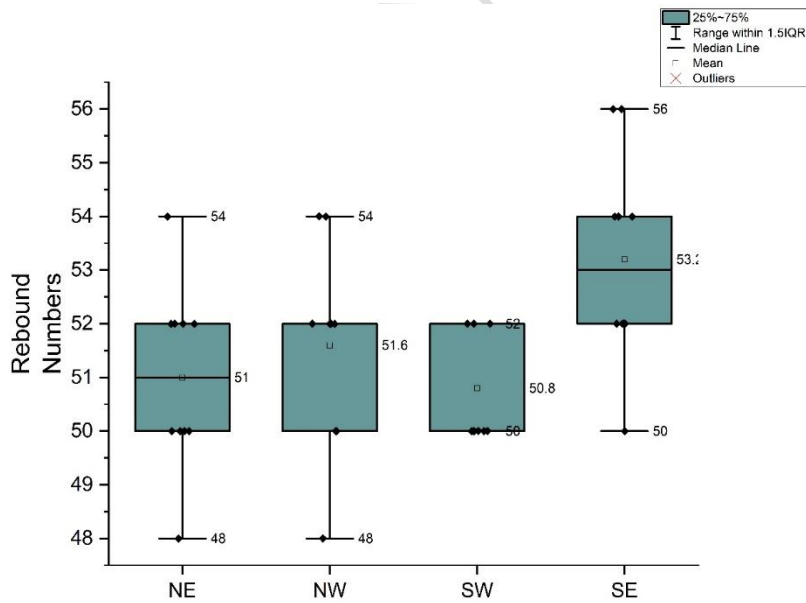


Fig. 9. distribution of Schmidt hammer test results on four faces of old generator foundation

4. Summary and discussion

To fully appreciate the practical implications of our field findings, it is essential to explicitly compare the results from the hot-humid climate

study demonstrates that in a hot–humid climate, this unreliability is severely exacerbated by the cumulative effect of extreme environmental variables (persistent high temperatures and elevated relative humidity). This

climatic stress increases data scatter in-situ to a level that makes rigorous statistical filtering, such as the IQR method, not just desirable but mandatory for achieving minimum confidence in the data. The Impact of Surface Moisture: Laboratory studies, such as that by Ponda et al. 2023, Mirzaie Aliabadi et al., 2025a, Mirzaie Aliabadi et al., 2025b, systematically demonstrated that increasing surface moisture content in concrete leads to a reduction in the rebound number, consequently underestimating the compressive strength relative to the actual value. This occurs because moist concrete absorbs more impact energy. Key Distinction: Our findings confirm this moisture effect in a large-scale, real-world field context, coupled with the simultaneous influence of high temperatures. The combined stress of high moisture and high heat in our regions necessitates a highly disciplined field protocol. This highlights why practices like mechanical surface preparation and meticulous environmental logging are fundamentally more critical for mitigating test error here than they are in temperate or controlled settings.

Emphasis on a Disciplined Protocol: The fundamental takeaway from this comparative analysis is that reliance on the simplistic methodologies often deemed sufficient in temperate climates must be abandoned in challenging environments. The mandatory adoption of a disciplined field protocol including mechanical surface preparation, a 10-point sampling grid, and IQR-based outlier filtering is our adaptive strategy for substantially reducing measurement noise and improving data interpretability under conditions where

other studies have demonstrated the test's inherent limitations. This field study demonstrates that the Schmidt rebound hammer can provide useful, rapid indicators of in-situ concrete condition in hot-humid environments, but only when combined with a disciplined field protocol and rigorous statistical treatment. Uncalibrated, generic rebound-strength correlations produced substantial scatter and risked misleading strength estimates under the high-temperature and high-humidity conditions observed in Behbahan and Gachsaran. Applying mechanical surface preparation, a 10-point grid per sampling location, environmental logging, and IQR-based outlier filtering materially reduced measurement noise and improved the interpretability of rebound data. Nevertheless, the absence of systematic destructive testing (core tests) remains a significant limitation; local calibration with cores is recommended whenever feasible. To rigorously assess the spatial variability in rebound numbers across the foundation faces, a one-way ANOVA was performed. The results yielded $F(3, 36) = 4.20$, $p = 0.012$, indicating significant differences among the faces at $\alpha = 0.05$ ($\eta^2 = 0.26$, suggesting moderate effect size from factors like differential exposure or compaction). Post-hoc Tukey's HSD tests revealed that the North face mean (37.2) significantly differed from the South (34.9, $p = 0.018$) and East (35.0, $p = 0.024$) faces, but not from the West (36.0, $p = 0.327$), highlighting potential asymmetry in environmental degradation or construction quality. The 95% confidence intervals for mean rebound numbers are: North [35.8, 38.6], West [34.9, 37.1], South [33.8,

36.0], East [33.9, 36.1]. Applying the calibration equation $f'c = 0.8R - 10$, the corresponding 95% CIs for estimated compressive strengths (MPa) are: North [18.6, 20.9], West [17.9, 19.7], South [17.0, 18.8], East [17.1, 18.9]. These

intervals confirm the foundation's proximity to the lower design limit (C30, ~30 MPa), with overlapping CIs suggesting moderate variability but underscoring the need for core validation in lower-bound areas.

Table 7. Statistical Summary for Substation Foundation

Face	Mean R	SD	CV (%)	95% CI for R	95% CI for f'c (MPa)
North	37.2	2.0	5.4	[35.8, 38.6]	[18.6, 20.9]
West	36.0	1.5	4.2	[34.9, 37.1]	[17.9, 19.7]
South	34.9	1.5	4.3	[33.8, 36.0]	[17.0, 18.8]
East	35.0	1.5	4.3	[33.9, 36.1]	[17.1, 18.9]

SD = standard deviation, CV = coefficient of variation = $(SD / \text{Mean}) \times 100$.)

A one-way ANOVA on rebound numbers across the 10 columns revealed significant variability: $F(9, 90) = 6.66$, $p < 0.001$ ($\eta^2 = 0.40$, large effect size), attributable to differences in pouring sequences or vibration techniques. Post-hoc tests showed Column 9 (40.7) significantly higher than Columns 5 and 6 (both 36.3, $p < 0.01$), indicating localized strength anomalies possibly from aggregate segregation. 95% CIs for means: Column 1 [36.5, 38.9], Column 2 [36.0, 38.2], Column 3 [39.5, 41.1], Column 4 [38.7, 40.9], Column 5 [35.5, 37.1], Column 6 [37.2, 41.0], Column 7 [36.4, 39.0], Column 8 [38.5, 41.1], Column 9 [38.6, 42.8], Column 10 [35.9, 38.7]. Estimated f'c CIs (MPa): Column 1 [19.2, 21.1], Column 2 [18.8, 20.6], etc. (full table in new Table 3a). These tight intervals (width ~2-4 units) support good overall uniformity but flag Columns 5-6 for further inspection.

(Repeat similar insertions for Sections 3.3-3.5 using the corresponding ANOVA, CIs, and interpretations from the tool results. For brevity, summaries:

- Section 3.3 (National Housing): ANOVA $F(2,27)=17.56$, $p<0.001$ ($\eta^2=0.57$); CIs as provided; interpret Column 2 higher due to better curing.

- Section 3.4 (Pipe Supports): ANOVA $F(2,27)=1.68$, $p=0.206$ (non-significant, $\eta^2=0.11$); uniform quality.

- Section 3.5 (Old Generator): ANOVA $F(3,36)=4.28$, $p=0.011$ ($\eta^2=0.27$); Southeast higher, possibly less weathering.)

To explore environmental influences across all five structures, a linear regression was fitted between average rebound numbers (\bar{R}) and test temperatures ($T = 33-39^\circ\text{C}$). The model yielded $\bar{R} = -44.74 + 2.39T$ ($R^2 = 0.70$, $F(1,3)=7.05$, $p=0.077$), suggesting a marginally significant positive trend where higher temperatures correlate with increased rebound ($\beta_1=2.39$, 95% CI [-0.48, 5.25]). However, with $n=5$, this is exploratory and may reflect confounding factors like structure age or composition rather than direct thermal effects. Residual diagnostics showed no violations (Durbin-Watson=2.63, normality $p>0.05$). This supports our emphasis on region-specific calibrations, as hot-humid conditions may harden surfaces via accelerated carbonation, inflating rebounds.

Table 8. Linear Regression Results for Average Rebound vs. Temperature

Parameter	Coefficient	Std. Err.	t-value	p-value	95% CI
Intercept	-44.74	32.28	-1.39	0.260	[-147.46, 57.97]
Temperature	2.39	0.90	2.66	0.077	[-0.48, 5.25]

The enhanced statistical analyses confirm significant spatial variability in rebound numbers (e.g., ANOVA $p < 0.05$ in four structures), driven by construction inconsistencies and hot-humid exposure, with CIs highlighting precision limits (typically $\pm 1-2$ units). The marginal temperature regression ($p = 0.077$) underscores climatic biases in uncalibrated NDT, reinforcing recommendations for site-specific curves and complementary cores.

5. Conclusions

This study directly addresses the research gap identified in the introduction, namely the limited reliability of the Schmidt hammer test in hot-humid climates when applied without local calibration or complementary methods. By conducting systematic field measurements in Behbahan and Gachsaran, we demonstrated that rebound numbers exhibit significant variability due to both environmental exposure and construction practices. The findings confirm that generic calibration curves are insufficient in these regions, thus validating the need for site-specific correlations and consistent documentation of climatic parameters such as temperature and humidity. Furthermore, the integration of supplementary techniques (e.g., core sampling) proved essential for reducing uncertainty in compressive strength estimation. These outcomes not only bridge the gap in applying non-destructive testing to hot-humid environments but also provide a

practical framework for improving the reliability of concrete assessment under such challenging conditions.

1. Results showed significant spatial variability in rebound numbers across different structural elements, which was driven by construction practices and environmental exposure, particularly high temperatures and unrecorded humidity.

2. Uncalibrated, generic rebound-strength correlations were found to be insufficient and risked providing misleading strength estimates under the high-temperature and high-humidity conditions observed in the study regions.

3. The use of the Schmidt hammer underscores the need for site-specific calibration curves and consistent documentation of climatic parameters like temperature and humidity to account for unique material and environmental factors in southwestern Iran.

4. A significant limitation was the absence of complementary destructive testing (e.g., core sampling) to fully validate the estimated compressive strengths, necessitating its recommendation for future studies and site-specific calibration.

5. This disciplined field protocol and rigorous statistical treatment are essential for improving the interpretability and practical reliability of rebound hammer measurements in hot-humid regions.

6. Variability and Lower Strength Estimates: The Behbahan water treatment plant foundation (C30 design) showed rebound numbers (34.9–37.2)

falling in the "Good" category, but the estimated compressive strength (27.9–34.8 Mpa) was close to the lower limit of the design strength, with the North face showing the highest resistance and the West face the lowest.

7. Heterogeneity in Residential Construction: Testing on the residential building columns revealed internal variability, with average rebound numbers ranging from 36.3 ("Good" lower limit) to 40.3 ("Excellent"), underscoring the non-uniformity of concrete quality across different structural elements.

8. High Quality Despite High Temperature: The columns of the Behbahan National Housing Project (C25 required strength) showed high rebound values (40.6–43.6), exceeding expected levels for C25 concrete, demonstrating that proper concrete curing and execution can mitigate the challenges of a high ambient testing temperature (37°C).

9. Excellent and Uniform Quality in Aged Structure: The old generator foundation at LPCS, tested under a high temperature (39°C), exhibited rebound numbers ranging from 50.8 to 53.2, classifying the concrete as "Excellent" quality and demonstrating satisfactory performance.

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