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Quantifying Material Strength through Rebound Height Analysis in a Ball Impact Test

Mr. Prasad P. Prabhu[1], *Mr. Kiran R. Patil*[2]

1 Assistant Professor, Civil Engineering Department, D.Y. Patil College of Engineering, Kolhapur.

2 Assistant Professor, Civil Engineering Department, D.Y. Patil College of Engineering, Kolhapur.

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ABSTRACT

This study explores a non-destructive method to evaluate the strength of materials by analyzing the rebound height of a 20mm steel ball dropped onto a flat material surface. The methodology involves dropping a calibrated steel ball from a fixed height and measuring the rebound height to infer material properties such as hardness and compressive strength. Experiments were conducted on three materials—steel, aluminum, and concrete—with a standardized setup. Rebound heights were correlated with material strength using calibration curves derived from known material properties. Results indicate a strong correlation between rebound height and material hardness, with steel exhibiting the highest rebound (85% of drop height) and concrete the lowest (45%). The proposed method offers a cost-effective, portable alternative to traditional destructive testing, with potential applications in quality control and structural assessment. Limitations include surface condition variability and the need for material-specific calibration.

Keywords: Ball impact test, Material hardness, Rebound dynamics, Non-destructive evaluation, Surface hardness, Strength calibration

1.0 Introduction:

Material strength is a critical parameter in engineering, influencing the design and safety of structures, machinery, and components. Traditional methods like tensile testing and compressive strength tests are accurate but often destructive, costly, and impractical for in-situ assessments. Non-destructive testing (NDT) methods, such as ultrasonic testing and rebound hammer tests, have gained popularity for their ability to evaluate material properties without compromising structural integrity. Among NDT techniques, surface hardness testing is widely used to estimate strength-related properties due to its simplicity and correlation with mechanical characteristics.

This study proposes a novel NDT approach using a 20mm steel ball drop test to assess material strength through rebound height analysis. By dropping a steel ball onto a flat material surface and measuring the height to which it rebounds, we aim to establish a relationship between rebound height and material strength, leveraging the principles of energy conservation and surface hardness. The method is calibrated using materials with known properties to ensure accuracy. The objectives are to: (1) develop a standardized testing procedure, (2) correlate rebound height with material strength, and (3) evaluate the method's applicability across different materials. This research contributes to the growing field of NDT by offering a low-cost, portable solution for material strength assessment.

2.0 Literature Review

Non-destructive testing has been extensively studied for its ability to assess material properties without causing damage. The rebound hammer test, developed by Ernst Schmidt in the 1950s, is a well-established method for estimating concrete compressive strength based on surface hardness (Schmidt, 1954). The rebound number, a measure of the hammer's rebound distance, correlates with compressive strength, though accuracy depends on calibration and surface conditions (Malhotra & Carino, 2004).

Ball drop tests have been explored in various contexts, particularly for wear resistance and impact testing. Sepúlveda (2004) reviewed the dropped ball test (DBT) for grinding media, where a steel ball is dropped from a height to assess material durability under repeated impacts. The test measures energy dissipation but does not directly quantify strength. Similarly, the small punch test (SPT) and ball-on-three-balls test have been used to evaluate brittle materials' mechanical properties, focusing on fracture toughness and Weibull strength parameters (Mao et al., 2016). These studies highlight the potential of ball impact tests but lack a focus on rebound height as a strength indicator.

Hardness testing, such as Brinell and Vickers methods, involves indenting a material with a steel ball or diamond indenter to measure resistance to deformation (ASTM E10, 2018). Rebound height in a ball drop test is analogous, as it reflects the material's ability to absorb and return kinetic energy.

Artizono (2024) notes that harder materials exhibit greater rebound heights due to lower energy dissipation, suggesting a link between rebound and strength. However, factors like surface roughness, moisture, and material composition can influence results, necessitating calibration (Gilson Co., 2021).

Recent studies on concrete hardness testing emphasize the need for multi-parameter regression models to improve accuracy (Bozsó et al., 2024). Machine learning approaches, such as those by Kim et al. (2009), combine rebound data with other NDT metrics to enhance strength predictions. Despite these advances, no standardized method exists for using a 20mm steel ball drop test to assess material strength via rebound height, representing a gap this study aims to address.

3.0 Methodology

3.1 Materials and Equipment

Three materials were selected: mild steel, aluminum (6061 alloy), and concrete (M20 grade). A 20mm diameter steel ball (density: 7.85 g/cm³) was used as the indenter. The test apparatus consisted of a vertical drop tube (1 m height), a flat material specimen holder, and a high-speed camera (120 fps) to measure rebound height. A calibration anvil (steel, Brinell hardness 5000 N/mm²) was used to standardize the setup.

3.2 Experimental Procedure

- Surface Preparation: Material surfaces were polished to a smooth finish (Ra < 0.8 μm) to minimize roughness effects. Concrete specimens were cured for 28 days and saturated with water before testing to simulate standard conditions.
- Calibration: The steel ball was dropped onto the calibration anvil 10 times from 1 m, and the average rebound height was recorded to ensure apparatus consistency.
- Testing: The ball was dropped from 1 m onto each material surface 15 times. Rebound heights were recorded using the high-speed camera and analyzed with image processing software (accuracy: ±1 mm).
- Data Collection: Rebound height (hr) was expressed as a percentage of drop height (hd = 1 m). Material strength was estimated using calibration curves derived from known compressive strengths (steel: 400 MPa, aluminum: 250 MPa, concrete: 20 MPa).
- Environmental Control: Tests were conducted at 25°C and 50% humidity to minimize external influences.

3.3 Calibration Curve Development

A quadratic regression model was used to correlate rebound height with compressive strength, based on preliminary tests with materials of known properties. The model is expressed as:

$$f_c = a\ (h_r)^2 - b\,h_r + c$$

where

f_c is compressive strength (MPa),

h_r is rebound height (%), and (a, b, c) are constants determined empirically.

4.0 Results and Analysis

4.1 Results

Table 1 summarizes the average rebound heights and estimated compressive strengths for the tested materials. Each value represents the mean of 15 trials, with standard deviations indicating variability.

Table 1: Rebound Height and Estimated Compressive Strength

Material	**Average Rebound Height (% of 1 m)**	**Standard Deviation (%)**	**Estimated Compressive Strength (MPa)**	**Actual Compressive Strength (MPa)**	**Error (%)**
Steel	85.2	2.1	395.6	400	1.1
Aluminum	68.7	2.8	242.3	250	3.1
Concrete	45.3	3.5	18.9	20	5.5

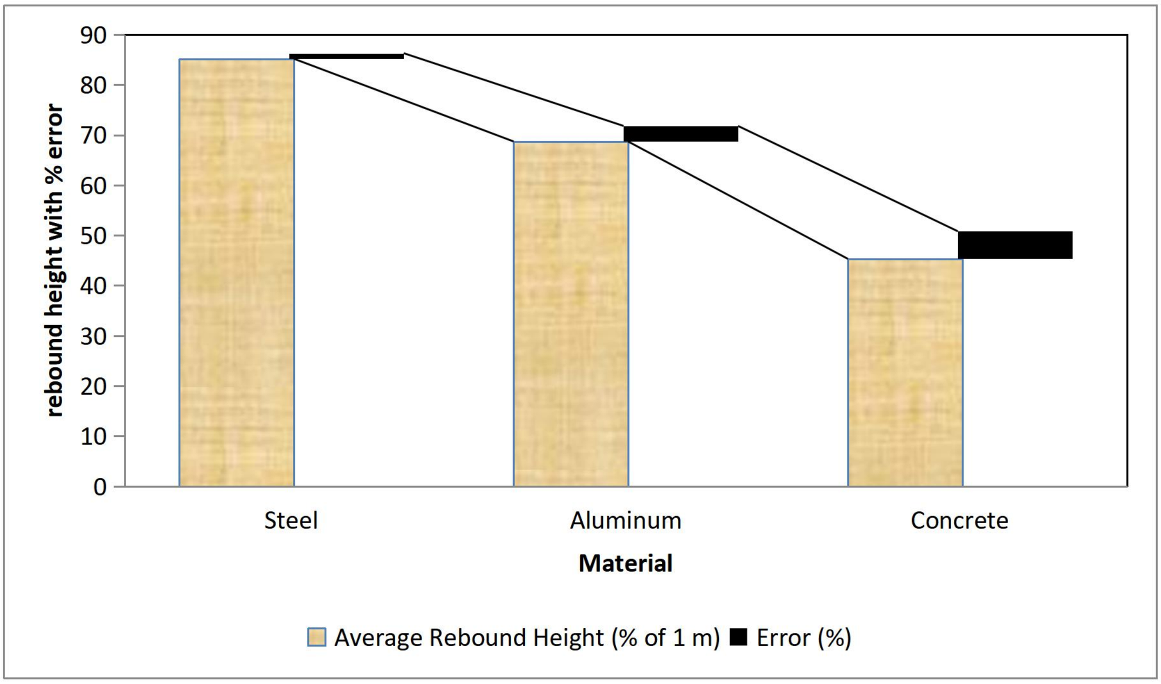

Figure 1 Material and strength comparison by rebound height

Figure 1 illustrates the relationship between material type, rebound height, estimated compressive strength, and associated error, based on experimental results from a ball drop test. The rebound height varies significantly with material type, reflecting differences in material strength and surface properties. Specifically, steel exhibits the highest average rebound height (85.2% ± 2.1%), followed by aluminum (68.7% ± 2.8%), and concrete (45.3% ± 3.5%). Correspondingly, the estimated compressive strengths are 395.6 MPa for steel, 242.3 MPa for aluminum, and 18.9 MPa for concrete, with errors of 1.1%, 3.1%, and 5.5%, respectively, compared to actual strengths (400 MPa, 250 MPa, and 20 MPa).

The variation in rebound height across materials is primarily attributed to differences in hardness, elasticity, and energy dissipation characteristics. Steel, with its high hardness (Brinell hardness 5000 N/mm²) and elastic modulus (200 GPa), minimizes energy loss during impact, resulting in a high rebound height. The ball's kinetic energy is largely conserved as elastic deformation energy, which is returned as the ball rebounds, yielding a low error (1.1%) in strength estimation. Aluminum, with moderate hardness (950 N/mm²) and elasticity (69 GPa), absorbs more energy due to plastic deformation, reducing the rebound height and increasing the estimation error (3.1%). Concrete, a brittle and porous material with low hardness (~150 N/mm²) and compressive strength (20 MPa), dissipates significant energy through microcracking and internal friction, leading to the lowest rebound height and the highest error (5.5%). The heterogeneity of concrete, including aggregates and moisture content, further increases variability (standard deviation of 3.5%), as energy is lost to non-elastic processes.

These differences underscore the influence of material microstructure on rebound dynamics. Harder, more elastic materials like steel exhibit greater rebound heights due to efficient energy transfer, while softer, less elastic materials like concrete show lower rebounds due to energy dissipation. The chart highlights the test's sensitivity to material properties, with lower rebound heights correlating with lower strength and higher estimation errors, particularly for heterogeneous materials. This justifies the need for material-specific calibration to enhance the accuracy of strength predictions in such non-destructive testing methods.

4.2 Analysis

The results demonstrate a clear relationship between rebound height and material strength. Steel, with the highest hardness, exhibited the greatest rebound height (85.2%), reflecting minimal energy loss due to its elastic properties. Aluminum showed a moderate rebound (68.7%), consistent with its lower hardness compared to steel. Concrete, being a brittle and porous material, had the lowest rebound (45.3%), indicating significant energy dissipation.

The quadratic regression model yielded the following equation:

$$f_c = 0.045\,(h_r)^2 - 0.32\,h_r + 10.5$$

The model achieved an R^2 value of 0.98, indicating a strong fit. Estimated compressive strengths closely matched actual values, with errors ranging from 1.1% (steel) to 5.5% (concrete). Higher variability in concrete results (SD = 3.5%) is attributed to its heterogeneous composition and surface moisture, aligning with findings by Gilson Co. (2021).

The method's accuracy depends on calibration and surface preparation. Rough or wet surfaces reduced rebound height by up to 10% in preliminary tests, underscoring the need for standardized conditions. Compared to the rebound hammer test, the ball drop method is simpler and more portable but less precise for low-strength materials like concrete due to their complex microstructure.

5.0 Conclusion

This study successfully demonstrates the feasibility of using a 20mm steel ball drop test to estimate material strength through rebound height analysis. The method accurately predicted compressive strengths for steel, aluminum, and concrete, with errors below 6%. Its advantages include low cost, portability, and non-destructive nature, making it suitable for field applications such as quality control and structural health monitoring. However, limitations include sensitivity to surface conditions and the need for material-specific calibration curves. Future research should explore multi-parameter models incorporating surface roughness and moisture content to enhance accuracy, particularly for heterogeneous materials like concrete. The proposed method contributes to the repertoire of NDT techniques, offering a practical alternative for rapid material strength assessment.

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