

# Experimental study on comparison of equivalent concrete compressive strength of cores and rebound hammer tests with in-place and standard cubes

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This study has presented a comprehensive test program that has compared the following, namely, the compressive strength of concrete cores extracted from the plinth beam (PB) of a substation, the compressive strength of both concrete cubes cast for the trial mix and those cast at the time of construction of the plinth beam, and the compressive strength of the plinth beam as assessed with a rebound hammer. Even though various techniques have been available for structural evaluation, there have been significant uncertainties in correlating the actual compressive strength of concrete. The standard procedures have been applied to a case study of a substation at Silapathar, Assam, owned by PowerGrid Corporation of India. To evaluate the quality of construction, different accepted methods suggested by various codes, such as the Indian Standard, the American Society for Testing and Materials Standard, the American Concrete Institute Standard, and the European Standard, have been employed. Experimental results have indicated that the equivalent compressive strength of concrete based on the rebound hammer has been 15.11% higher than the *in-situ* concrete strength. Similarly, the equivalent compressive strength of the concrete cube estimated using European and Indian codes has been 22% and 27% higher than the experimentally measured core compressive strength. The expressions proposed for estimating equivalent cylinder compressive strength have closely predicted the core compressive strength, compared with expressions for estimating cube compressive strength. This information has been useful for practising engineers not to reject concrete solely based on the acceptance criteria of the cube compressive strength of *in-situ* concrete, and to accept concrete based on non-destructive or semi-destructive tests.

**Keywords:** Concrete cores, Equivalent compressive strength, In-place compressive strength, Rebound hammer number, Standard cubes

## 1 Introduction

Concrete is a widely used construction material commonly made by mixing raw materials such as Portland cement with fine aggregate, coarse aggregate, and water. Ensuring the quality and performance of the concrete is mandatory to achieve structural safety and durability<sup>1</sup>. One of the critical parameters that directly influence the structural capacity is the compressive strength of concrete, as it serves as the indicator of overall quality<sup>2</sup>. Testing of compressive strength of concrete is usually done by casting cubes or cylinders alongside structural elements and cured under controlled laboratory conditions. The specimens cast may not necessarily replicate the *in-situ* conditions prevailing in the actual

structure<sup>3</sup>. The disparities between the strength of standard laboratory specimens and concrete in actual structure were varying due to the following factors: difference in type of compaction, curing, and severity conditions of the environment<sup>4</sup>. This discrepancy has led to non-destructive testing and partially destructive methods to assess the *in-situ* strength of concrete<sup>5</sup>. Among the various non-destructive and partially destructive test methods, Schmidt rebound hammer and concrete core test were widely employed to assess the defects or anomalies in concrete structure<sup>6,7</sup>.

The Schmidt rebound hammer test provides advantages such as simplicity, rapid results, and minimal or no damage to the structure that was tested, thereby making it suitable for extensive surveys<sup>8</sup>. However, the accuracy of the rebound hammer test depends on the smoothness of the concrete surface,

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moisture content, depth of carbonation, and the presence of rebar<sup>9</sup>. On the other hand, testing of concrete core offers the direct measurement of strength, but it is time-consuming, partially destructive, and weakens the structure if not executed properly<sup>10</sup>. The size of the specimen plays a crucial role in determining the compressive strength of the concrete<sup>11</sup>. Despite the use of both techniques, a certain amount of uncertainty remains regarding the correlation of test results obtained from these methods and the actual strength of concrete<sup>12</sup>. Past studies demonstrated that the relationship between standard cube strength measured in the laboratory, rebound index, and core strength were influenced by several parameters such as mix design of concrete, age, curing conditions, and the severity of environmental exposure<sup>13,14</sup>. The difference in these relationships has led to the following concern about the reliability of concrete strength based on either method alone.

Moreover, the interpretation of test results obtained and the establishment of correlations between different testing methods remains challenging. The testing procedural guidelines and methods of evaluation have been provided by National and International standards. Even though these standards often incorporate conservative approaches in turn underestimate the actual strength of concrete<sup>15,16</sup>. This conservative approach in ensuring the structural safety often leads to unnecessary interventions and cost enhancement in the assessment and rehabilitation of projects<sup>17</sup>.

Recent improvements in machine learning algorithms and statistical analysis techniques have enabled us to correlate the test results determined from various methods in a sophisticated manner<sup>18</sup>. These approaches have the potential for

improved accuracy in the estimation of concrete strength by considering various influencing parameters simultaneously<sup>19</sup>. However, the practical implementation of the above-said methods requires comprehensive datasets in order to capture the variability encountered in real-time structures.

To comply with the recent advances in seismic criteria for buildings and to make them less probable for failure in strong earthquakes, the evaluation of *in-situ* compressive strength is imperative<sup>20,21</sup>. As the assessment of existing reinforced concrete structures involves structural safety issues, accurate estimation of concrete compressive strength was a major issue<sup>22</sup>. A brief review of procedures recommended by different international standards to establish acceptance of concrete at the laboratory and construction sites was presented in this paper. Special care was taken to consider the factors affecting the estimation of the actual strength and relative correction coefficients of both concrete cores and rebound hammer assessment. This research tries to address the challenges by conducting a structured comparison of compressive strength of concrete as determined by core, rebound hammer, and standard specimens cast at the laboratory. The study investigates the relationships between these methods across various standards to measure the equivalent compressive strength.

Figure 1 shows the normal probability distribution of compressive strength of concrete cores of different grades of concrete varying from M10 to M50, where the standard deviation of concrete cores varied from 1.49 to 7.68, respectively. It was inferred that higher grades of concrete expressed a wider range of distribution, whereas lower grades of concrete showed a shorter range of distribution<sup>23</sup>. The target mean

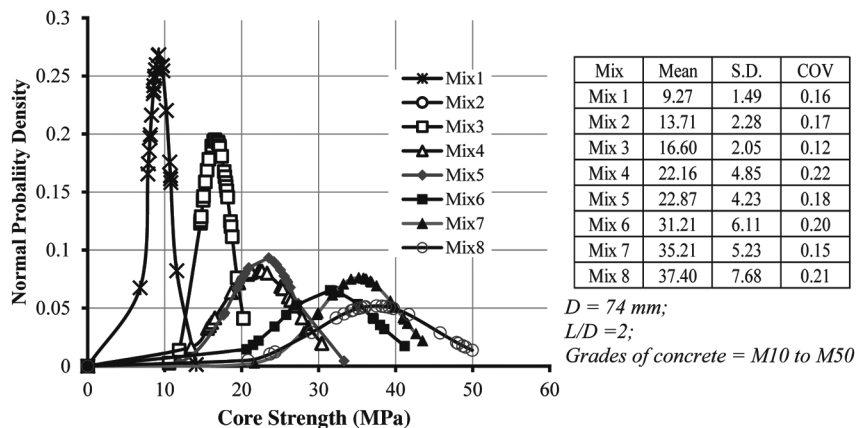


Fig. 1 — Variability of compressive strength of concrete cores.<sup>23</sup>

strength ( $f'_{ck}$ ) of the compressive strength of concrete cores were ranged between 9.24 and 38.18 MPa. This phenomenon raises the question of the correlation between the compressive strength of the concrete of a structure and the compressive strength of a standard-size cube or cylinder strength<sup>24</sup>.

Structural damage was caused due to recent earthquakes resulted from insufficient concrete strength<sup>25</sup>. To determine the compressive strength of concrete, control specimens, i.e., concrete cubes were taken when concrete was placed for construction. Sometimes, the compressive strength observed in control specimens may not be sufficient or reliable<sup>26-28</sup>. Thus, it is essential to get core specimens from hardened concrete. Non-destructive testing and laboratory tests on concrete cores were used to

evaluate the compressive strength of existing concrete structures. These tools are used to assess the quality of concrete, detect defects in the structure, and provide an estimate of in situ concrete compressive strength. The most widely accepted method of determining the *in-situ* concrete compressive strength is testing core specimens obtained by drilling with a diamond core bit<sup>29,30</sup>. Figure 2 represents the flow chart for acceptance of *in-situ* concrete.

The acceptance of concrete for the trial mix, carried out at the laboratory and at the construction site, and for the *in-situ* concrete is described in Fig. 2. The target mean strength serves as the acceptance criterion for the trial mix carried out at both the laboratory and the construction site. When the strength of the samples is less than the target mean

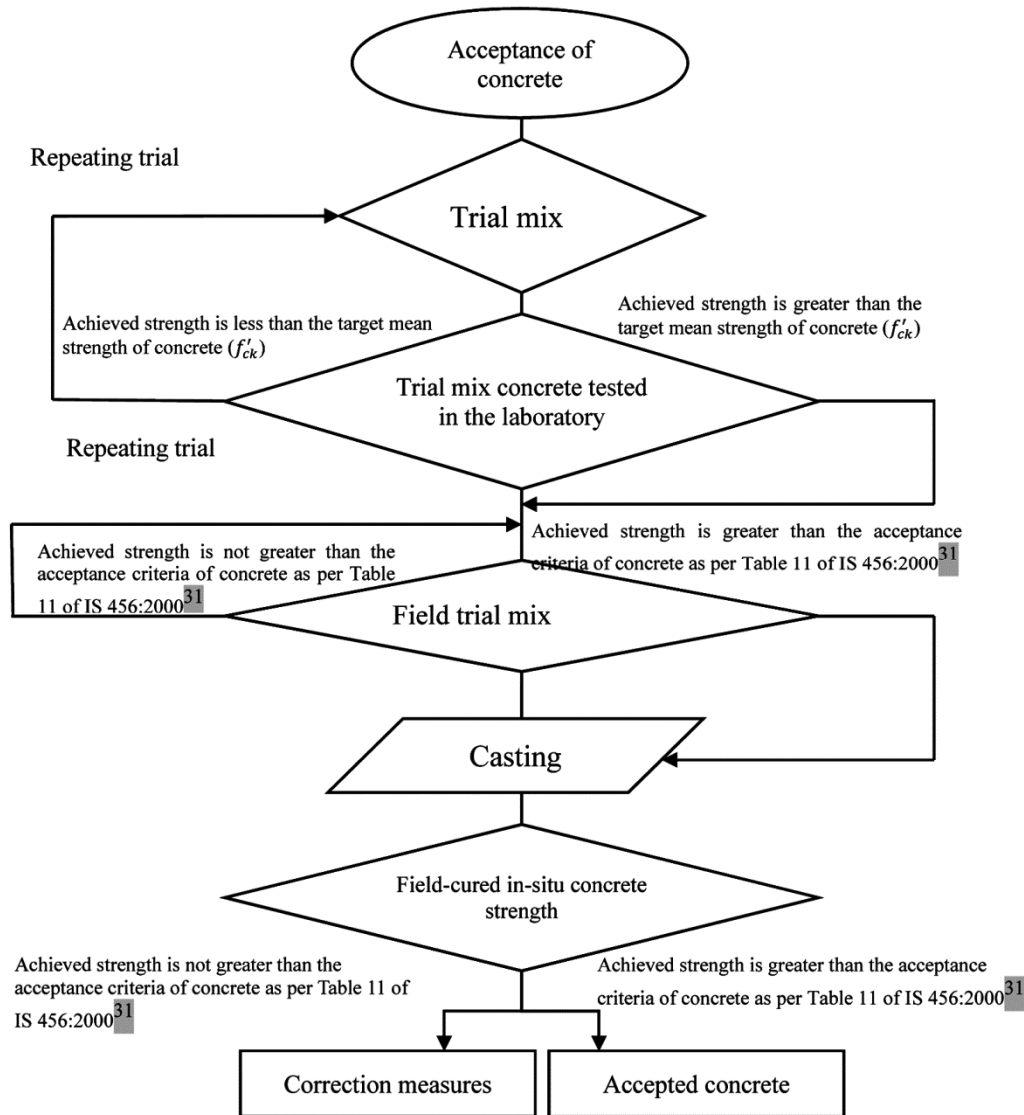


Fig. 2 — Flow chart for acceptance of *in-situ* concrete.

strength, the trial should be repeated with an adjusted mix proportion.

There are penalties for noncompliance with the acceptance criteria of *in-situ* concrete according to the respective codal provision, which is detailed in the following section 2.0. Most researchers have used a normal distribution for deciding target mean strength due to its simplicity and because the central area of the curve is most important in concrete quality control. Findings from this study are relevant to a broad range of concrete professionals, including bridge designers, pavement engineers, building construction personnel, and civil engineering forensic investigators. The factors that influence the relationship between core strength and the corresponding standard size cube or cylinder strength are fully reported by various researchers<sup>32-38</sup>. Recommended procedures for cutting, testing, and interpretation of results are fully established and documented by different standard codes such as ASTM C 42<sup>7,39</sup>.

For general quality control of concrete, the standard cube test specimens are cast during the construction of the structure. The cube specimens that give the potential strength of the concrete are cured and tested according to Indian standard specifications. Conversely, the determination of the actual strength of concrete in a structure shall not be easy because it needs to be conducted through a semi-destructive test while the structure is functioning. The possible reasons for testing concrete cores extracted from the real structure are as follows: when standard cube specimens were missing, while checking the adequacy of the strength of the concrete in a structure, when the structure is supposed to be subjected to higher stresses, when the strength of the member of the structure is suspected and when the quality of concrete is doubted. In such cases, the concrete core test could be the most reliable way to assess the strength characteristics of the concrete in the structure, and it resolves the suspicion of member strength and doubt about the concrete quality. To evaluate the actual concrete strength of a member in the structure, the core test results should be carefully interpreted since there are several factors that govern the core strength.

The non-destructive and semi-destructive techniques, such as the Schmidt rebound hammer and concrete core testing, are the established methods for estimating the compressive strength of concrete. The present study intended to obtain the compressive

strength of the plinth beam of a power substation at Silapathar, Assam, India, using these methods and then compare it with the results of 150 mm cube specimens. In addition, the combination of the methods was used to evaluate correlations between the Schmidt rebound hammer and core testing.

**1.1 Comparison of existing codal provisions**

The acceptance criteria of concrete for laboratory samples and *in-situ* concrete presented in the Bureau of Indian Standards, the American Concrete Institute, the American Society for Testing and Materials and European standards are given below:

**1.1.1 Indian standard**

a. Acceptance of concrete strength at the laboratory

The target mean strength of concrete ( $f'_{ck}$ ) in the laboratory is as follows:

$$f'_{ck} = f_{ck} + 1.65 S \quad \dots(1)$$

where  $f_{ck}$  and S are characteristic compressive strength and standard deviation, respectively. The grades of concrete and their respective assumed standard deviation values are given in Fig. 3.

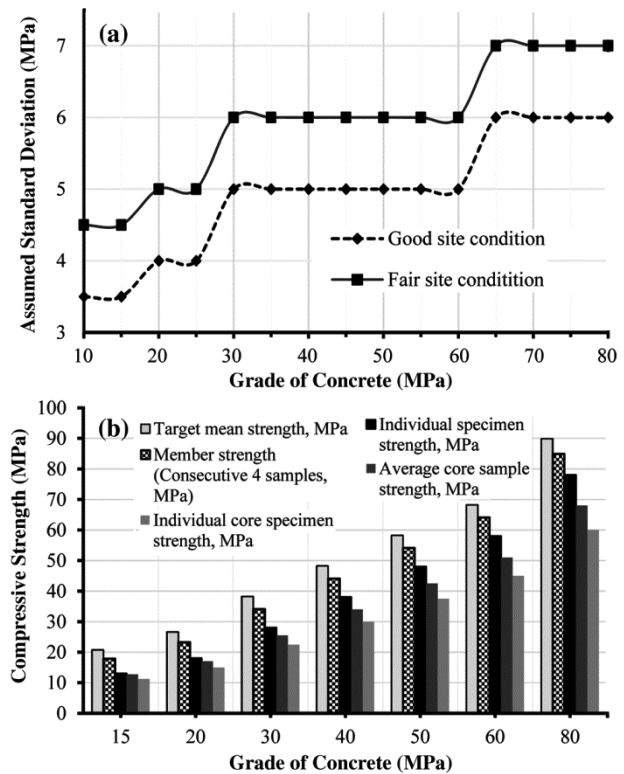


Fig. 3 —Acceptance of concrete (a) Assumed standard deviation for different grades of concrete as per IS 456 2000<sup>39</sup> and (b) Comparison of target mean strength, acceptance of normal and core concrete.

b. Acceptance criteria of in-place concrete

As per IS 456 2000<sup>31</sup>, the strength compliance requirement for in-place concrete of grade M15 and above and its quantity up to 30 m<sup>3</sup> is as follows:

Criteria 1: for 4 non-overlapping consecutive test results

(a) Mean of the group of 4 non-overlapping consecutive test results in MPa,

$$f_{ck,in-situ} \geq \begin{cases} \text{whichever is greater} \\ f_{ck} + 0.825 \times \text{established (or)} \\ \text{assumed standard deviation} \\ \text{(Rounded off to nearest } 0.5 \text{ N/mm}^2 \\ f_{ck} + 3 \text{ N/mm}^2 \end{cases} \quad \dots (2)$$

(b) Individual Test Results in MPa,

$$f_{ck,in-situ} (i) \geq f_{ck} - 3 \text{ N/mm}^2 \quad \dots (3)$$

Criteria 2: for non-overlapping consecutive test results less than 4

(a) Mean of the group of non-overlapping consecutive test results less than 4 numbers in MPa,  $f_{ck,in-situ} \geq f_{ck} + 4 \text{ N/mm}^2$  ... (4)

(b) Individual Test Results in MPa,

$$f_{ck,in-situ} (i) \geq f_{ck} - 2 \text{ N/mm}^2 \quad \dots (5)$$

Criteria 3: For only one non-overlapping consecutive test results

(a) Non-overlapping test result of 1 sample in MPa,  $f_{ck,in-situ} \geq f_{ck} + 4 \text{ N/mm}^2$  ... (6)

The Equations 2, 3, 4, 5 and 6 give the acceptance criteria of concrete for 4, less than 4 and only one non-overlapping consecutive sample, respectively.

As per IS 456-2000<sup>31</sup>, the frequency of sampling to be tested is as follows: 1 sample for 1-5 m<sup>3</sup> of concreting, 2 samples for 6-15 m<sup>3</sup> of concreting, 3 samples for 16-30 m<sup>3</sup> of concreting, 4 samples for 31-50 m<sup>3</sup> of concreting, and 4+1 additional samples for each additional 50 m<sup>3</sup> or part thereof for concreting quantity of 51 m<sup>3</sup> and above.

c. Acceptance criteria of in-place concrete strength assessment with non-destructive testing method- Rebound hammer

As shown in Fig. 4, the rebound hammer comprises a metal body having a plunger that is in contact with the concrete surface, which is struck by a spring-loaded steel hammer (mass) when it is released, and the rebound index is measured on the scale. An impact energy of 2.25 Nm is required for rebound

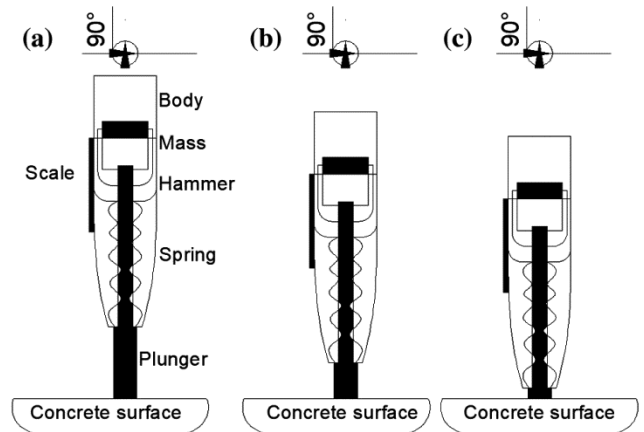


Fig. 2 — Rebound hammer (a) Plunger touching the concrete surface, (b) Hammer hits plunger and transfer the energy to the concrete and (c) Hammer rebounds backward after impact.

hammers for measuring the likely compressive strength of normal concrete.

(a) Plunger touching the concrete surface

(b) Hammer hits plunger and transfer the energy to the concrete

(c) Hammer rebounds backward after impact

(d) Acceptance criteria of concrete core strength of the structural member

The *in-situ* concrete in the structural member represented by a core test shall be considered acceptable as per IS 456:2000<sup>31</sup> through the following criteria:

Average equivalent characteristic cube compressive strength ( $f_{ck,e\_core}$ ) of minimum 3 core specimens (in MPa),

$$f_{ck,e\_core} > 0.85f_{ck} \quad \dots (7)$$

Minimum individual equivalent characteristic cube compressive strength of core specimen (in MPa),

$$f_{ck,e\_core}(i) > 0.75f_{ck} \quad \dots (8)$$

The procedure as per IS 516<sup>40</sup> to assess the equivalent characteristic cube compressive strength of large sets of concrete cores is under:

$$f_{ck,e\_core} > f_{ck} + 1.48 S \quad \dots (9)$$

The acceptance criteria of concrete cores are the same in IS 456<sup>31</sup> and IS 516<sup>40</sup> codes to assess one set of concrete cubes; i.e., 1 set is equal to 4 consecutive samples (4 samples  $\times$  3 cubical specimens = 12 cubical specimens) that are not meeting the acceptance criteria. Herein, 3 concrete specimens are specified as 1 sample, and 1 set is a maximum of 4 samples and a minimum of 1 sample, which is

according to time, the place of concreting and the quantity of batching.

**1.1.2 American Society for Testing and Materials (ASTM)**

For concrete compressive strengths of cylinders between 14 MPa to 42 MPa, including both low and normal density concrete, i.e., density between 1600 to 2400 kg/m<sup>3</sup>, the strength correction factor shown in Fig. 5 is applicable. The larger correction factors shall be adopted for core strengths above 70 MPa concrete.

**1.1.3 American Concrete Institute (ACI)**

a. Acceptance criteria for standard-cured specimens (ACI 318-19)

The acceptance criteria for standard-cured cylindrical specimens were as follows: (1) the average of any three consecutive strength test equals or exceeds the specified cylinder compressive strength of concrete and (2) no strength test falls less than 3.5 MPa from specified cylinder compressive strength if  $f'_c \leq 35$  MPa or  $0.1f'_c$  if  $f'_c > 35$  MPa.

b. Acceptance criteria for field-cured specimens (ACI 318-19)

As per ACI 318-19<sup>41</sup> Field-cured concrete cylinders shall demonstrate the strength of in-place concrete. The compliance requirements are as follows: 1. At test age, the field-cured cylinder's compressive strength is equal to or at least 85% of the standard-cured cylinder's compressive strength. 2. At test age, the average strength of field-cured cylinders exceeds by more than 3.5 MPa from  $f'_c$ .

c. Acceptance criteria for *in-situ* concrete cores strength (ACI PRC-214.4-21)

As given in Eq. (8), the strength of the core partly depends on the length-to-diameter ratio of core specimen, core diameter, moisture condition of core at the time of testing, presence of reinforcement and its orientation, and core drilling direction.

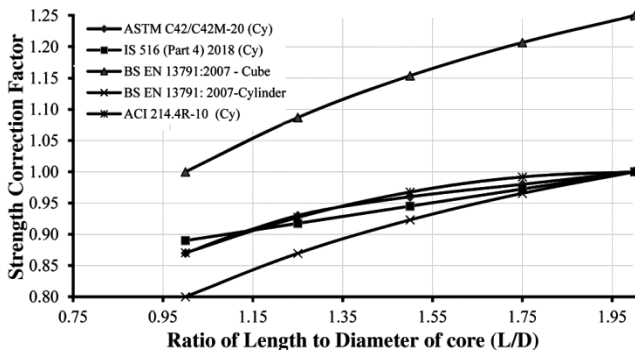


Fig. 5 — Correction factors for strengths from non-standard size concrete cores to standard size concrete cubes or cylinders.

$$f_c = F_{l/d} F_{dia} F_{mc} F_d \dots(10)$$

where  $F_{l/d}$ ,  $F_{dia}$ ,  $F_{mc}$  and  $F_d$  are correction factor for length/diameter ratio, diameter, moisture condition, and drilling damage is calculated from Fig. 6;  $f_{core}$  measures concrete core strength.

As per ACI 318-19<sup>41</sup>, the strength of the concrete core shall be adequate if the average of three cores is equal to at least  $0.85f'_c$  and no single core is less than  $0.75f'_c$ .

**1.1.4 European Standard**

Assessment of *in-situ* compressive strength (EN 13791: 2007)

The concrete core strength shall be converted into equivalent *in-situ* cube and standard-size cylinder strength by multiplying the *in-situ* strength factors  $K_{is,cube}$  and  $K_{is,cyl}$  (Eqs. 11 and 12), respectively, with actual core strength. The strength factors are given below:

$$K_{is,cube} = \frac{2.5}{1.5 + \frac{1}{\lambda}} \dots (11)$$

$$K_{is,cyl} = \frac{2.0}{1.5 + \frac{1}{\lambda}} \dots (12)$$

Reportedly, factors influencing core strength are moisture content, void content, direction relative to the casting, imperfections, length and diameter of the core, flatness of end surfaces, capping of end surfaces, effect of drilling, and presence of reinforcement.

**2 Materials and Methods**

**2.1 Standard moulded and cured concrete for laboratory trial mix**

Ordinary Portland cement (OPC 43 grade of cement), natural aggregates, sand, and superplasticiser were used to produce the trial mix and in-place concrete. Particle size distributions of fine and coarse aggregates are presented in Fig. 7, along with the minimum and maximum gradation curves of zone III fine aggregates (IS 383: 2016)<sup>42</sup>. The physical properties are given in Table 1. To produce concrete mixtures at both the construction site and laboratory, the natural aggregates of two different particle size distributions, namely, maximum nominal size aggregates 20 mm and 10 mm, were blended in the ratio of 60-40%, respectively. A detailed description of the properties of the constituents of concrete and the sources of coarse and fine aggregates is given in

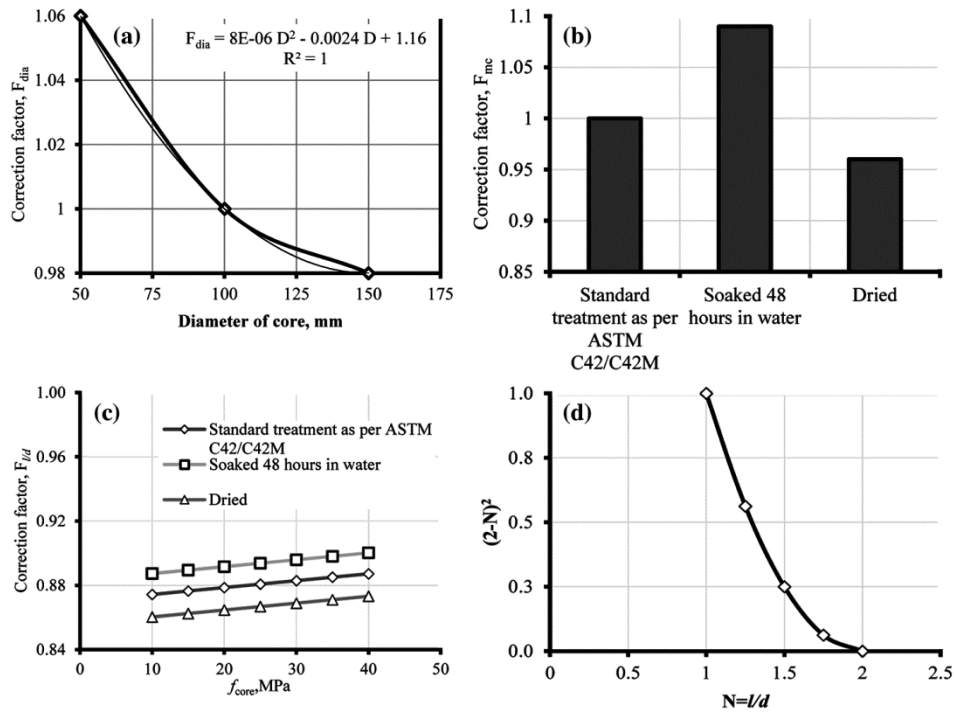


Fig. 6 — Correction factors for estimating core strength as per ACI 214.4R-10<sup>16</sup> (a) Correction factor versus diameter of core, mm, (b) Correction factor for moisture  $F_{mc}$ , (c) Correction factor for  $l/d$  versus  $f_{core}$  and (d) Correction factor for  $l/d$ .

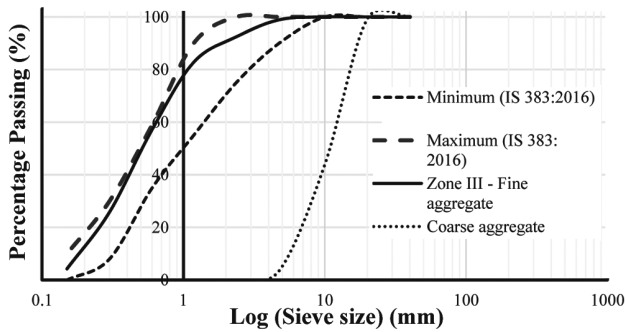


Fig. 7 — Sieve analysis of fine aggregate and coarse aggregate (IS 383 2016)<sup>42</sup>.

Table 1. Both sizes of coarse aggregates were in the range of 2.36–20 mm. A superplasticiser (SP) polycarboxylates aqueous solution type (Forsroc Conplast SP 430-G8) was used to achieve the desired workability.

The required quantity of constituents to produce 1 m<sup>3</sup> of concrete, such as cement, sand, coarse aggregates, chemical admixtures and water, is given in Table 2, along with the mix ratio. The adopted water-cement ratio (W/C), fine aggregate-to-cement ratio and coarse aggregate-to-cement ratio were 0.45, 1.5 and 2.82, respectively. Out of the total aggregates, the fine and coarse aggregate proportions were 34.6% and 65.4 % in saturated surface dry conditions, respectively.

**2.2 In-place standard cured compressive strength test, i.e., trial mix at construction site**

In-place tests on hardened concrete were conducted in the laboratory. Three concrete cube specimens were tested. The concrete was mixed with a batch mixer to ensure no loss of water. Both in-place and in the laboratory, the same mix proportion was used to prepare the concrete. The size of standard specimens used for this study was cubical in shape, with a size of 150×150×150 mm. The test cubes were cast in cast iron moulds to prevent distortion during vibration. The concrete was compacted fully without segregation and excessive laitance by filling and compacting in layers nearly 50 mm deep. The top layer was compacted and followed by finished with a trowel to achieve a smooth surface finish. The concrete test specimens were stored in a place at an average temperature of 28 degrees for 24 hours. The specimens were marked and removed from moulds, then submerged in fresh water. The specimens were dried just before 24 hrs of testing time.

**2.3 In-place concrete cores**

In this investigation, plinth beams were constructed with a concrete mixture proportion as specified in Table 2. A total of four concrete cores were extracted with a rotary cutting tool consisting of 100 mm diameter diamond bit from the plinth beam of the

Table 1 — Material properties of constituents of concrete.

Sl. No.	Material	Properties	Measured value	Permissible limits	Conforming standard
1.	Cement	Specific gravity	3.15	-	IS 8112 1989 <sup>43</sup>
2.		Type and grade	OPC 43	-	
3.	Fine aggregate	Specific gravity	2.60	-	IS 2386 – Part III 1963 <sup>44</sup>
4.		Water absorption	1.22 %	0.1-2 %	
5.		Source	Dhemaji, Assam	-	-
6.		Specific gravity	2.60	-	IS 2386 – Part III 1963 <sup>44</sup>
7.	Water absorption	1.22 %	0.1-2 %		
8.	Coarse Aggregate	Type	Granite	-	-
9.		Source	Liru, Kikabali, Arunachal Pradesh	-	-
10.	Chemical admixture	Type	Forsroc Complast SP 430-G8	-	IS 9103: 1999 <sup>45</sup>
11.		Specific gravity	1.14	-	

Table 2 — Mix proportion of in-place and standard reference concrete.

Cement, kg/m <sup>3</sup>	Water, kg/m <sup>3</sup>	Fine aggregate, kg/m <sup>3</sup>	*Coarse aggregate, kg/m <sup>3</sup>	Admixture, kg/m <sup>3</sup>	W/C ratio	Slump, mm
413.33	186	617.89	1169.58	4.13	0.45	55-60
Mix ratio						
1	0.45	1.50	2.83	0.01	0.45	

\*Coarse aggregate: 60 % of maximum nominal size aggregate 20 mm blended with 40 % of maximum nominal size of aggregate 10 mm

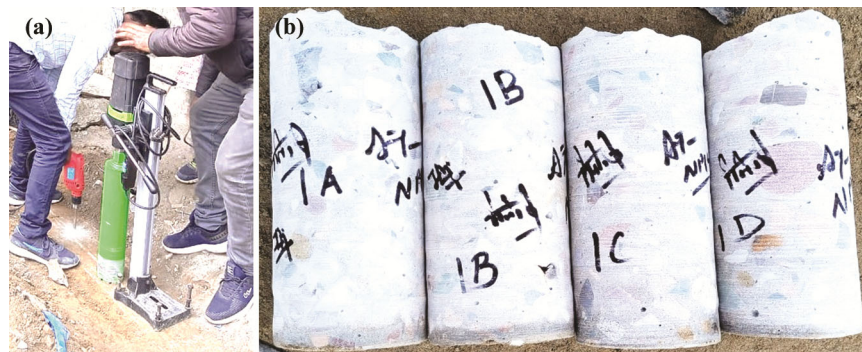


Fig. 8 — (a) Concrete core drilling machine and (b) Core extracted from the plinth beam.

substation at Silapathar, Assam. The cores were drilled perpendicular to the direction of concrete placement. The concrete core specimens were capped with sulphur, and the L/D ratios of capped core specimens were between 1.61 and 2.13. The effects of maximum aggregate size, diameter and l/d ratio of cores, as well as the influence of the shapes of standard test specimens on the strength of concrete, were considered while interpreting core test results.

The drilling equipment was attributed as portable, lightweight, firmly supported and braced over the plinth beam. The expansion bolts prevented relative movement, which could result in a distorted or broken core. Water was poured to lubricate the cutter while drilling. Uniform pressure was applied by a skilled operator. When sufficient depth had been drilled, the core specimens were obtained by inserting a chisel down with a hammer on the side of the core and by breaking off. The cores with rough inner ends are

shown in Fig. 8, where they were removed using the drill or tongs.

After drilling, each core was carefully examined for the existence of sufficient of lengths for compressive strength testing, the existence of excessive reinforcement and voids. It was not required to drill extra cores from adjacent locations as the drilled cores satisfied the abovementioned three criteria, i.e., sufficient length, no excessive reinforcement and voids. Each core was clearly labelled for identification as 1A, 1B, 1C and 1D over the drilled surface as shown, and in the datasheet. The trimming was done with a water-lubricated diamond saw to provide a suitable length for the core, also with parallel ends, which were perpendicular to the axis of the core. The ends of cores were prepared by grinding, followed by capping with a sulphur-sand mixture to provide parallel end surfaces normal to the axis of the core. Caps were kept as thin as possible.

The plinth beam of the substation (member), core designation, height and diameter of concrete cores are given in Table 3.

#### 2.4 Capping of concrete cores

Before capping, the surface of the core specimens was in a dry condition, and the same was clean and free from all loose particles. Care was exercised during sawing, grinding, and capping of concrete cores to avoid damage and to achieve perpendicularity and planeness at the edges as per requirements of IS 516 (Part 4): 2018<sup>46</sup>. The caps were as thin as possible and did not exceed 5 mm thick. The capping material comprised equal mass fractions of sulphur and fine siliceous sand (most of which passes a 250  $\mu\text{m}$  wire cloth sieve conforming to IS 460 (Part 1)<sup>47</sup> and the same was retained on a 125  $\mu\text{m}$  wire cloth sieve. The concrete core capping mould is shown in Fig. 9.

The lower end of the core specimen, which was held vertically and parallel to the 90-degree vertical plates into a pool of molten sulphur mixture on a horizontal plate of the mould. Subsequently, the upper end was placed on the viscous sulphur. The specimen had been allowed to harden at both the top and bottom ends. The capping frame ensured that both capped surfaces were parallel. Oil was used to release the specimens from the capping moulds. The excess surplus capping material on top and bottom of the specimens was trimmed by mild blows with a hammer at the edges of the core specimen. The level of the molten sulphur mixture in the pan was never allowed to fall too low or to overflow to avoid the risk

Table 3 — Core details of member PBCR 3/10.

Member	Cores	Height (L), mm	Diameter (D), mm
PBCR 3/10	1A	200	94
	1B	150	93
	1C	152	93
	1D	200	94

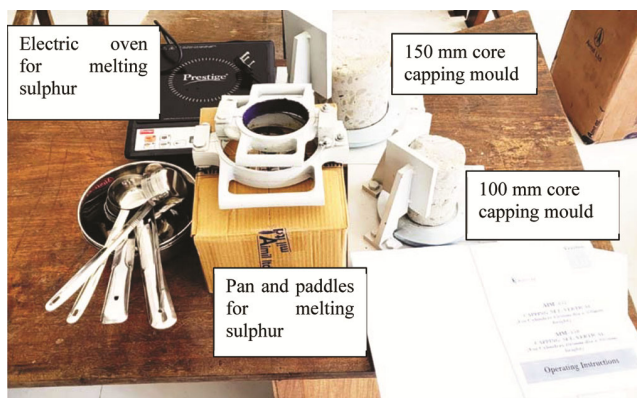


Fig. 9 — Concrete core capping equipment.

of the production of sulphur vapour, which could ignite. For the solid capping layers over a core, the prepared specimens have been checked for adherence of the capping material to both ends of the core specimen. The cap did not fail or fracture before the concrete failed when the core specimen was tested. The compression test on the concrete core specimen was carried out after curing the core capping underwater for 28 days.

#### 2.5 Test Procedure

##### 2.5.1 Laboratory and in-place concrete strength test with the trial mix

The compression testing machine of reliable type with 2000 kN capacity could apply the load at the rate of 13.73 MPa/min (140 kg/sq cm/min). As per the calibration report of the compression testing machine, the error range was within  $\pm 2$  percent of the maximum load. The force was transferred through steel-bearing platens on the top and bottom of the cube specimen. The platens were hardened faces, and the measured deviations were less than 0.02 mm from the plane. Tests were made on three cube specimens on the usual 7 and 28 days. The ages were calculated from the time of the addition of water to the time of testing. Specimens were cured in water and tested immediately after removal from the water, and they were in a surface-dry condition. The dimensions of the specimens have been checked for deviations, and that was within the limit of 0-2 mm. The cube specimen had been placed in between the platens of the compression testing machine for testing in a manner that compressive load shall be applied on the opposite sides of the cube casting direction. The axis of the specimen was carefully aligned with the centre of the testing machine. No packing material, like mortar, was used between the faces of the test specimen and the steel platen of the testing machine. The maximum load applied to the specimen, dimensions, weight, date of testing and type of failure were noted.

##### 2.5.2 Rebound hammer test

The Schmidt rebound hammer shown in Fig. 10 was appropriate to test normal concrete. Before testing the concrete, both readings on the steel reference anvil and the working condition of the rebound hammer were checked. The rebound hammer was used in accordance with the manufacturer's instructions and as per the guidelines specified by IS 516: Part 5 / Sec 4<sup>48</sup>. The test locations and the

purpose of the investigation are determined by the engineer in charge. For comparison, all test locations were tested under similar conditions. As the testing was conducted in one plinth beam with a shortage in compressive strength of cubes, there was no scope for the difference in rigidity and segregation of concrete. The tested concrete surface was smooth and clean. The correlation specified in the instrument was used for relating the rebound number and compressive strength of concrete. A grinding stone was used to remove the extraneous matter present on the surface. For evaluating the compressive strength of concrete using a rebound hammer, only a smooth surface finish was selected rather than the rough surfaces due to improper compaction, lack of workability, spalling and tooled surfaces were not accessed.

The moisture condition of the concrete surface was dry, which was consistent throughout the test. Nine readings were obtained for a reliable estimate of the surface hardness at a point on the concrete surface.



Fig. 10 — Rebound hammer testing of the plinth beams of substation.

The set of nine readings at a point at the concrete surface was measured within 200 mm x 200 mm. The readings obtained were accurate within ± 15% of the mean rebound number. The mean, standard deviation and coefficient of variation of each set of readings were calculated using all the readings (including abnormally high and abnormally low results) unless there was a good reason to doubt the validity of a particular reading.

2.5.3 Concrete core test

The compressive strength of the standard specimens and the concrete cores was determined by a fully automatic compression testing machine, and the rate of application of load for all specimens was 1 kN/s (0.30 MPa/s), i.e., within the standard range of 0.14 to 0.324 MPa/s as per Indian Standard<sup>46</sup>.

3 Results and Discussion

3.1 Trial-mix concrete strength test results

Table 4 shows the details of the compressive strength of concrete made for the trial mix. In the trial mix carried out at the laboratory, the target mean compressive strength of concrete (cube) was 32.4 MPa for M25 grade of concrete, which was 2.53 % higher than the design target mean strength 31.60 MPa (designed as IS 10262:2009<sup>49</sup>). The 7-day compressive strength of the trial mix was 23.7 MPa, which was 73.12 % of the 28-day target mean compressive strength.

3.2 In-place concrete strength test results of the trial mix conducted at the site

Table 5 shows the in-place compressive strength of concrete. The grade of concrete of the member PBCR

Table 4 — Compressive strength of concrete – Trial mix.

Mix ratio	Grade of concrete (IS 456 2000) <sup>31</sup>	7 days compressive strength, MPa	28 days compressive strength, MPa	Target mean compressive strength (Good site condition), MPa
1:1.50:2.83:0.01 (W/C-0.45; CC=413.33 kg/m <sup>3</sup> )	M25	23.7	32.4	31.60
Percentage of compressive strength	-	73.15 % of strength gained in 7 days	26.85 % of strength gained between 7 days and 28 days	2.53 % of strength obtained more than target mean strength

Table 5 — In-place compressive strength of concrete.

Member	Grade of concrete	Consecutive sample Nos.	Date of casting	* Individual specimen strength, MPa	** Sample strength, MPa	Individual specimen strength > f <sub>ck</sub> - 2, MPa	Sample strength > f <sub>ck</sub> + 4, MPa
PBCR 3/10	M25	1	31-Oct-18	29.2	27.8	TRUE	FALSE
				27.1		TRUE	
				27.2		TRUE	

Criteria 1: Minimum sample strength as per IS 456-2000<sup>31</sup> = 29 MPa

Criteria 2: Minimum individual specimen strength as per IS 456-2000<sup>31</sup> = 23 MPa

\*Specimen strength = individual cube compressive strength of size 150 × 150 mm; \*\*Sample strength = average compressive strength of 3 non-overlapping concrete cube specimens of size 150 × 150 mm.

3/10 was M25, and the measured cube compressive strength of the in-place concrete was 29.2, 27.1 and 27.2 MPa with an average of 27.8 MPa. The individual cube strengths were above the acceptance criteria  $f_{ck}-2$  MPa, whereas the mean strength of concrete was just short of 4.13% below the acceptance criteria  $f_{ck}+4$  MPa. Therefore, the core test and rebound hammer test were recommended for checking structural adequacy and eradicating doubt about the strength of concrete.

**3.3 Acceptance/rejection criteria of cube compressive strength measured in the field**

The acceptance criteria of *in-situ* concrete is as follows:

- (a) For the mean of group of samples less than 4 non-overlapping consecutive test results =  $25+4 = 29$  MPa
- (b) For individual test results =  $25 - 2 = 23$  MPa

Though individual specimen strengths were higher than the code-specified minimum individual specimen strength of 23 MPa (i.e.  $f_{ck} - 2$  MPa), the sample strength was 27.8 MPa, which was less than the code-specified minimum sample strength  $f_{ck} + 4$  MPa. Hence, core samples were extracted and tested.

**3.4 In-place concrete strength measure with rebound hammer**

The rebound hammer readings taken in faces of plinth beams of substations were given in Table 6. In each face, readings were taken by drawing grids. The average of 6 hits was rebound number (R) of the point, and the relationships between the rebound number and concrete strength provided in the instrument was used to establish an equivalent compressive strength of concrete. The average compressive strength measured at faces was the concrete strength of a particular beam member. Table

6 provides information about the comparison of cube compressive strength measured at field and equivalent cube compressive strength correlated from rebound hammer number (R).

By comparing field strength and equivalent compressive strength measured with a rebound hammer, the strength of plinth beams was found satisfactory as they are above code-specified acceptance criteria of 29 MPa.

**3.5 In-place concrete strength measured with concrete cores**

The average and individual core strengths were compared with code-specified acceptance criteria of  $0.85 f_{ck}$  for mean strength and  $0.75 f_{ck}$  for individual core strengths. The individual and mean equivalent cube compressive strengths were greater than  $0.75f_{ck}$  and  $0.85f_{ck}$ , respectively. Figure 11 illustrates the comparison of interpreted core test results, such as corrected compressive strength for diameter, equivalent cylinder compressive strength, equivalent cube strength, the check for average strength of concrete cores  $0.85f_{ck}$ , average equivalent cube compressive strength, check for the individual

Table 6 — Rebound hammer number of plinth beams and equivalent compressive strength.

Members	Beam 1	Beam 2	Beam 3	Average Equivalent cube compressive strength, MPa
Hit 1	36	30	32	-
Hit 2	42	39	34	-
Hit 3	30	30	36	-
Hit 4	31	39	32	-
Hit 5	33	32	36	-
Hit 6	36	35	39	-
Average	34.67	34.17	34.83	-
Compressive strength, MPa	32.71	31.56	33.09	32

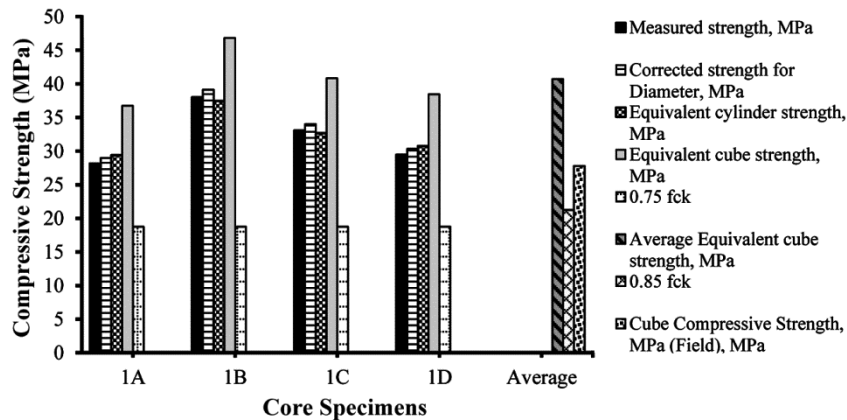


Fig. 11 — Comparison of interpreted core test results with measured cube strength.

Table 7 — Equivalent strength of cores and acceptance criteria as per IS 516 (Part 4): 2018<sup>46</sup>.

Cores	Load, kN	Measured strength, MPa	Correction for diameter, MPa	N=L/D ratio	Correction factor $F = 0.11 N + 0.78$	Equivalent cylinder strength, MPa	Equivalent cube strength, MPa $\geq 18.75$ MPa	Average equivalent cube strength, MPa $\geq 21.25$ MPa
1A	195.2	28.14	28.99	2.13	1.0140	29.39	36.74	40.72
1B	258	38.00	39.14	1.61	0.9574	37.47	46.84	
1C	224.3	33.04	34.03	1.63	0.9598	32.66	40.82	
1D	204.3	29.45	30.34	2.13	1.0140	30.76	38.45	
Average Equivalent cube strength $\geq 0.85f_{ck}$ ( $40.72 > 21.25$ MPa)								
Individual equivalent compressive strength $\geq 0.85f_{ck}$ $\left\{ \begin{array}{l} 36.74 \\ 46.84 \\ 40.82 \\ 38.45 \end{array} \right. > 18.75$ MPa								

strength of the core  $0.75f_{ck}$  with measured concrete cube strength.

The applied load measured strength in MPa, corrected strength by multiplying diameter correction factor and measured strength, slenderness ratio ( $N=L/D$ ), a correction factor for L/D ratio, equivalent cylinder compressive strength, equivalent cube compressive strength and their average values are given in Table 7. As per the given data, the concrete cube strength of size  $150 \times 150$  mm of the critical member was 27.8 MPa, whereas the core compressive strength was 40.72 MPa. Hence, the concrete is accepted.

### 3.6 Failure pattern of concrete cores

By comparing the failure of core specimens with the crack pattern given in IS 516 (Part 4):2018<sup>46</sup>, the mode of failure was found satisfactory. Cone failure was observed when friction at the platens of the testing machine restrained lateral expansion of the concrete when the vertical compressive force was applied. When the friction was eliminated, the cylinder expanded more laterally and exhibited a columnar splitting failure in the longitudinal direction, as shown in Fig. 12 (a – excluding the first specimen). The specimens followed the failure patterns mentioned in ASTM C 39/C 39M – 01<sup>50</sup>. This restraint confined the concrete near the platens and resulted in two relatively undamaged cones, as shown in Fig. 12(b) (First specimen) when the cylinder was tested to fracture.

### 3.7 Comparison of test results

The variation of the ratio of the interpreted strength of concrete cores to the measured compressive strength of concrete cores with compressive strength is shown in Fig. 13(a). The equivalent cylinder strength of concrete cores estimated as per Indian,

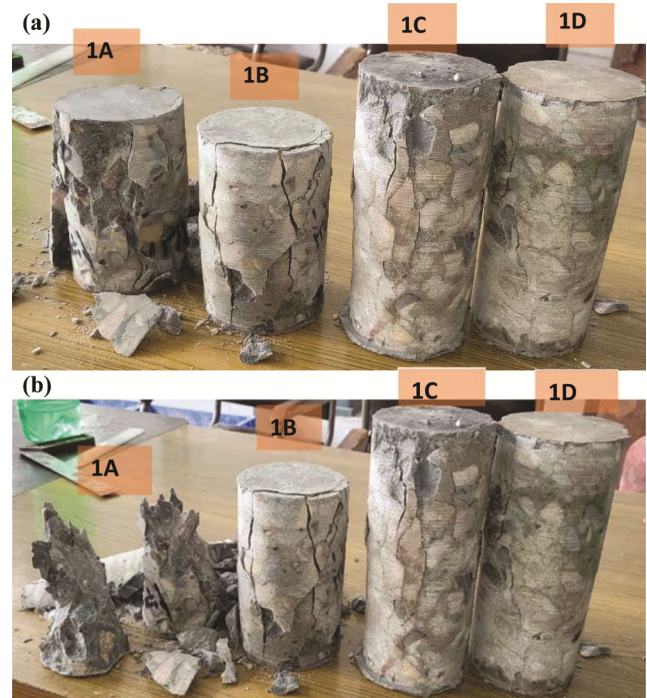


Fig. 12 — Failure pattern of 4 specimens (1A, 1B, 1C and 1D) (a) Crack pattern of concrete cores and (b) Cone and columnar type of fractures in cores (ASTM C 39/C 39M – 01)<sup>50</sup>

ASTM, European and ACI codes was closely matched with the experimentally measured core strength, whereas the equivalent cube compressive strength estimated as per Indian and European codes was underestimated when compared to experimental core compressive strength.

In Fig. 13(b), both equivalent cube and cylinder compressive strengths of extracted cores as per IS 516 (Part 4): 2018<sup>46</sup> were compared with equivalent cylinder strengths estimated as per BS EN 13791:2007 E<sup>15</sup>, ASTM C42/C42M-20<sup>7</sup> and ACI 214.4R-10<sup>16</sup> and with equivalent cube compressive strength of BS EN 13791:2007 E, respectively.

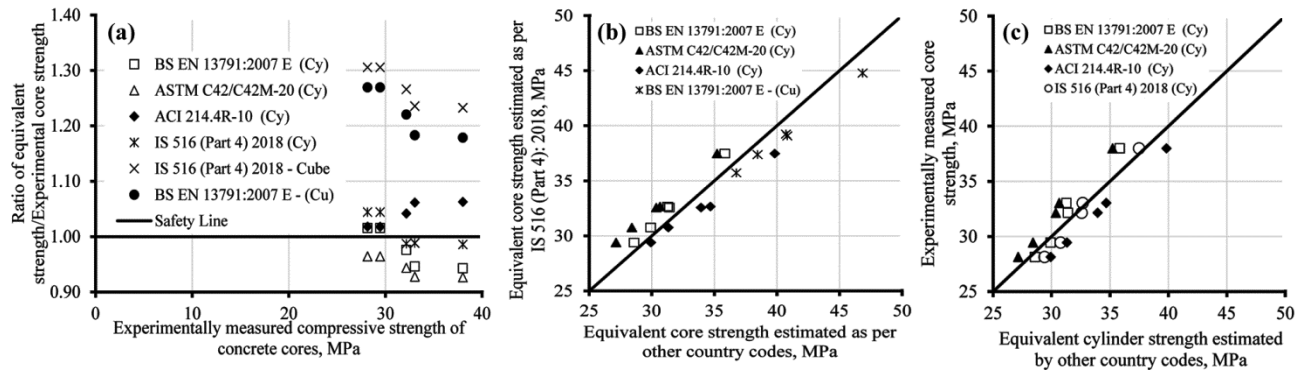


Fig. 13 — Comparison of test results with IS, ACI, ASTM and BSI codes (a) Variation of strength ratio with measured compressive strength of cores, (b) Comparison of estimated core strength by Indian with other countries' codes of practice and (c) Comparison of experimental and estimated cylinder strength by codes of practice.

Figure 13(c) shows the variation of direct compressive strength of concrete cores extracted from the site and estimated equivalent core strengths as per IS 516 (Part 4): 2018, BS EN 13791:2007 E, ASTM C42/C42M-20 and ACI 214.4R-10. Marginal inconsistencies persist while interpreting experimentally measured core strengths.

It is observed from Fig. 13(b), estimating equivalent cube compressive strength of cores as per BS EN 13791:2007 E was conservative than IS 516 (Part 4): 2018, on the other hand, equivalent cylinder compressive strength of cores as per IS 516 (Part 4): 2018 was conservative than BS EN 13791:2007 E. While calculating equivalent cylinder compressive strength of cores, ASTM C42/C42M-20 estimated lowest and ACI 214.4R-10 was the highest. The trend of prediction, as per ACI 214.4R-10 was slightly deviating away from predictions as per IS 516 (Part 4): 2018.

In Fig. 13(c), the experimentally measured compressive strength of cores was underestimated by ASTM C42/C42M-20, and the same was overestimated by ACI 214.4R-10. ACI 214.4R-10 code interpreted core strength of results by 6 % higher than experimentally measured core strength, whereas the ASTM C42/C42M-20 and IS 516 (Part 4): 2018 codes interpreted 5 % and 1 % less than extracted actual core strengths, respectively. The equivalent cube compressive strength of cores was 22 and 27 % higher than the interpretation of core strengths as per codes such as BS EN 13791:2007 E and IS 516 (Part 4): 2018. The strength ratio is the ratio of the equivalent cube or cylinder compressive strength of concrete cores to the experimentally measured compressive strength of the core. The mean of strength ratios of cylinder compressive strengths was

in the range of 0.99 to 1.06 (with standard deviation 0.01-0.04), on the other hand, the mean of strength ratios of cube compressive strengths was in the range of 1.22 to 1.27 (with standard deviation range 0.04-0.05). The coefficient of variation ranges between 0.8 % and 4.20 %.

The equivalent cube strength of cores was obtained in the range 32.2 % to 68.5 % higher than the in-place compressive strength of concrete and 13.4 % to 44.6 % higher than the target mean compressive strength. The equivalent compressive strength of concrete obtained based on rebound hammer number was 15.11 % higher than in-place concrete strength and 1.23 % lesser than target mean compressive strength. The standard deviation and coefficient of variation of in-place concrete strength were 1.18 MPa and 4.36 %.

Table 8 illustrates the strength comparison determined using *in-situ* concrete compressive strength and the rebound hammer test against target compressive strength. It was found out that *in-situ* compressive strength was 14% lower than the target compressive strength. The difference between the target compressive strength and the rebound hammer test was just 1.2%, which was negligible. The equivalent compressive strength determined using various standards was also shown in Table 8. BS EN 13791:2007 E - (Cu) and IS 516 (Part 4) 2018 (Cu) produced significantly higher estimation compared to other standards. Rather than cubical specimens, cylindrical specimens have better estimation (0.95 - 1.06) in determining the compressive strength of concrete. Strength determined using ACI standards resulted in low COV (0.8%), whereas strength determined by cast-*in-situ* showed the highest variability (4.36%).

Table 8 — Comparison of target, in-place and equivalent compressive strengths of concrete.

Sl. No.	Code	Compressive strength, MPa	Equivalent compressive strength, MPa	Mean	Standard Deviation	COV, %
1	Target mean compressive strength, MPa	32.4	-	-	-	-
2	In-place compressive strength, MPa	27.8	-	27.80	1.18	4.36
3	Equivalent compressive strength estimated through rebound hammer, MPa	-	32	32.00	0.80	2.49
Estimation of the equivalent strength of concrete cores				Strength ratio		
4	BS EN 13791:2007 E - (Cu)	-	39.24	1.22	0.05	4.20
5	BS EN 13791:2007 E (Cy)	-	31.39	0.98	0.04	4.18
6	ASTM C42/C42M-20 (Cy)	-	30.35	0.95	0.02	2.27
7	ACI 214.4R-10 (Cy)	-	33.93	1.06	0.01	0.80
8	IS 516 (Part 4) 2018 (Cu)	-	40.71	1.27	0.04	3.26
9	IS 516 (Part 4) 2018 (Cy)	-	32.57	0.99	0.03	3.34

Both the IS and BS EN standards showed a conservative estimation of compressive strength when using cubical specimens compared to cylindrical specimens. This confirms that cubical specimens always yield higher compressive strength of concrete than cylindrical specimens due to confinement and more contact surface area between the cube and upper platen of the compression testing machine, which was absent in the case of cylindrical specimens. The *in-situ* compressive strength was approximately 86% of the target compressive strength, which could indicate issues, particularly with curing and workmanship during project execution. It was also found that the variation in testing methods can significantly influence the evaluation of the structure.

### 3.8 Calculations for Concrete Core Strength Evaluation

The sample calculation of the concrete core strength of sample 1A is given below:

$$\begin{aligned}
 &\text{For sample 1A,} \\
 &\text{Length of core, L (mm)} = 200 \text{ mm} \\
 &\text{Core concrete compressive strength} = \frac{\text{Applied Load (N)}}{\text{Cross sectional area (mm}^2\text{)}} \\
 &= \frac{195.2 \times 1000}{\frac{\pi}{4} D^2} \\
 &= 28.14 \text{ MPa} \\
 &94 \text{ mm } (\geq 3 \times 20 \text{ mm (Maximum nominal size of aggregate)}) = 60 \text{ mm} \\
 &\text{Diameter of core, D (mm)} = \text{nominal size of aggregate} = 60 \text{ mm} \\
 &\text{Corrected compressive strength for diameter} = \text{Core strength} \times \text{correction factor} \\
 &= 28.14 \times 1.03 = 28.99 \text{ MPa} \\
 &\text{Slenderness ratio, N where N = L/D ratio} = \frac{130.05}{64.26} = 2.02 \\
 &\text{Correction factor for slenderness ratio, F where F} = 0.11(2.13) + 0.78 = 1.0140 = 0.11N + 0.78 \\
 &\text{Corrected compressive strength for slenderness ratio in MPa} = \text{Corrected compressive strength for diameter in MPa} \times \text{Correction factor for slenderness ratio}
 \end{aligned}$$

$$\begin{aligned}
 &\text{Equivalent cylinder compressive strength in MPa} = 28.99 \times 1.0140 = 29.39 \text{ MPa} \\
 &\text{Equivalent cube compressive strength in MPa} = \text{Equivalent cylinder compressive strength} \times \frac{5}{4} \\
 &= 29.39 \times \frac{5}{4} = 36.74 \text{ MPa} \\
 &\text{Average cube compressive strength of 1A, 1B, 1C and 1D in MPa} = \frac{36.74 + 46.84 + 40.82 + 38.45}{4} = 40.72 \text{ MPa} \\
 &0.85 \text{ times characteristic compressive strength in MPa} = 0.85 \times 25 = 21.25 \text{ MPa} \\
 &0.75 \text{ times characteristic compressive strength} = 0.75 \times 25 = 18.75 \text{ MPa} \\
 &\text{Check} = \begin{cases} 40.72 > 21.25 \text{ MPa} \\ 36.74 \\ 46.84 \\ 40.82 \\ 38.45 \end{cases} > 18.75 \text{ MPa}
 \end{aligned}$$

The average core concrete compressive strength of PBCR 3/10 is higher than 0.85 times the characteristic compressive strength, and individual core strengths were higher than 0.75 times the characteristic compressive strength. Hence, the structural strength adequacy of concrete is accepted.

### 4 Conclusion

Based on the above study, the following conclusions were arrived:

- The equivalent cylinder compressive strength of concrete cores was estimated by Indian, European, ASTM, and ACI codes in the range of -5.0 to +6.0% of the experimentally measured core compressive strength.
- The equivalent cube compressive strengths of concrete cores were estimated by European and Indian codes to be 22 and 27 % higher than the experimentally measured core compressive strength, respectively. The equivalent cube strength

of cores was 32.2 % to 68.5 % higher than the in-place compressive strength of concrete and 13.4 % to 44.6 % higher than the target mean compressive strength.

- c The equivalent compressive strength of concrete for the rebound hammer number of tested concrete was 15.11 % higher than in-place concrete strength and 1.23 % lower than the target mean compressive strength.
- d Lastly, while comparing the compressive results of cubes of trial mix carried out at the laboratory and construction with equivalent cube compressive strength of concrete cores and rebound hammer index, the concrete cannot be rejected based on the in situ concrete acceptance criteria alone. The doubtful concrete of the member needs to be evaluated with a rebound hammer and core tests to confirm the material strength of the structural member.

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### Conflict of Interest

The authors declare no conflicts of interest. All co-authors have seen and agreed with the contents of the manuscript. The authors certify that the submission is original work and is not under review at any other publication.

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