Core and hammer tests for in-place compressive strength of hardened concrete

Alemayehu Gessesse (MSc, BSc in Civil Engineering)
Manager, ADERA Engineering Pvt. Ltd. Co.
P.O.Box 24630, 1000 Addis Ababa, Ethiopia
klm.alemayehu@gmail.com

Abstract

The use of core and hammer tests for determining the in-place compressive strength of hardened concrete is studied. The study consulted pertinent literature on both test methods and supported the discussion with actual field data. Although the two methods are applicable for in-place compressive strength determination, they have their own deficiencies. Hammer tests are indirect methods of measuring strength and are very sensitive requiring proper calibration. On the other hand, core tests are direct in-place strength measuring methods where core samples taken from the actual structure are tested in a similar way to test specimens. However, analysis and interpretation of both tests is a tricky business that has to be handled professionally. Before testing is carried out, both hammer and core tests require adequate planning including the methods and criteria for analysis, interpretation, acceptance and rejection.

Key words: core test, hammer test, in-place strength, hardened concrete, interpretation

1. Introduction

Certainty of knowledge on the in-place compressive strength of hardened concrete of a structure may be needed for a number of reasons. The need for this strength may be required in both a structure under construction and that of a functioning one. The reasons may include: shore and form removal, post-tensioning, or early load application; investigation of damage due to freezing, fire, or adverse curing exposure; evaluation of older structures; and when a lower strength concrete is placed in a member by mistake [1]. Nevertheless, accurate determination of the intrinsic strength of concrete in the actual structure is more often intractable for understandable but complex rationales.

It is well acknowledged by experts on concrete that the strength of standard specimens at the age of 28 days indicates only the potential strength of concrete. It is also accepted that the potential strength can in no way be exactly identical to that in the actual structure. This means that having results from standard test specimens at various ages cannot directly equate to the strength in a member of a structure. As far back as 1938, D.G. Skramtajev commented differences between standard test specimens and that in the actual structure are observed due to: differing curing conditions, inadequacy of number of specimens in representing members in a structure and the insufficiency of information from the 28 days strength in indicating later-age strength [2].

Concrete is a heterogeneous material exhibiting a versatile moldable property while fresh and obstinately inflexible when hardened. The latter property of concrete makes measuring in-place strength at later age difficult. But, this property has not prevented the invention and development of in-place strength test methods. Over the years, a number of test methods have been developed that serve for quality assurance and existing condition evaluation purposes.

Both destructive and nondestructive testing (NDT) methods are available. Surface hardness tests, penetration resistance, pull out, break-off and maturity tests are some included under NDT. It should however be noted that, these methods are not completely nondestructive in a true sense since they cause some kind of damage that must be repaired [3].

The Schmidt Rebound Hammer Test is the most commonly used surface hardness test. Another direct, but destructive, test method for checking in-place strength of concrete is core test. A brief description of core and hammer tests are given hereunder.

2. The basics of Core and Rebound Hammer Tests

2.1 Core tests

Core testing is a method of obtaining drilled core cylinders from an existing concrete with the help of core drilling machine. The machines are electrically

driven with a base and column to aid the proper performance of the core barrel. The core barrel houses diamond impregnated bits that are capable of resisting high friction. The core barrel further allows the drilling of different diameter cores. Depending upon the manufacturer's recommendations, drilling may be performed either in wet or dry conditions.



Figure 1: Portable core cutter machine

(CONTROLS Inc.)

Unlike the standard test specimens that are cast and tested by taking samples from fresh concrete, core tests are directly taken from the structure under evaluation. Due to these basic differences, the purpose served by cores and standard test specimens differs appreciably. The compressive strength of standard test specimens of concrete represents the quality of concrete batching, mixing and transportation as well as the sampling, preparation, handling, curing and testing of the specimens. On the other hand, core compressive strength, in addition to concrete batching, mixing and transportation; it represents the quality of placement, consolidation, and curing including the techniques for obtaining and testing cores [4].

Generally, core sampling requires prior adequate planning and preparation on why, where, how, what size and what moisture condition of cores to have. Minimizing the risk of cutting of reinforcement bars and other undesirable damages to the structure is one of the fundamental purposes of the planning. In this regard, a close examination of reinforcement bar schedules from the structural drawings, understanding the influence diagram of a member of the structure where cores are to be drilled and/or using metal sensors may be of help.

2.2 Rebound hammer tests

The rebound hammer (alternatively named as Schmidt hammer or Swiss hammer) is basically a surface hardness testing machine having no direct compressive strength measuring mechanism. It simply gives an indication of the compressive strength based on surface properties. A spring loaded mass at defined energy impacting against a concrete surface is measured in terms of rebound numbers. The rebound is dependent on the hardness of the concrete and is measured by the test equipment itself.

The rebound numbers can be prepared in the form of correlation curves whereby the compressive strength is indicated as ordinate and the rebound as abscissa. Manufacturers provide correlation curves by testing standard test specimens using both the hammer test and the compressive strength testing machine.

While using the hammer, it should be held at right angles to the surface. The test is also sensitive to surface characteristics of the concrete (such as laitance, trowelling, or honeycombing), orientation of the hammer, moisture content of concrete, presence and closeness of reinforcing steel to the test surface, depth of carbonation, etc. [5], [6].

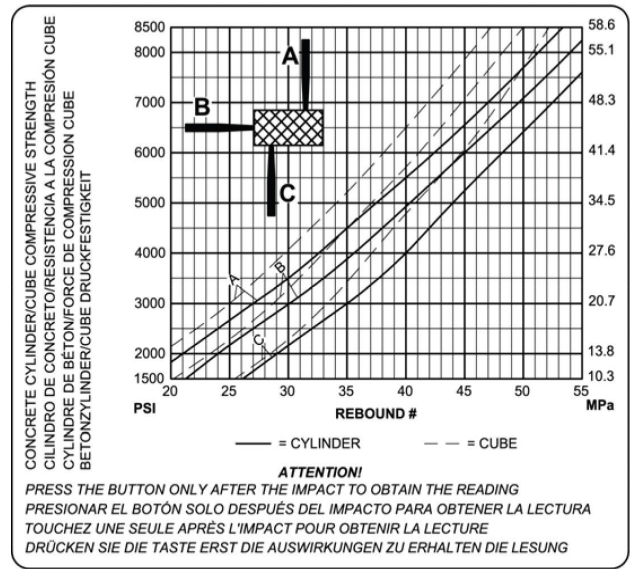


Figure 2: Typical correlation curves *(Humboldt Inc.)*

Orientation of the hammer is critical in correlating the strength. For obvious reasons of the force of gravity, testing with a hammer on the soffit side of a beam or slab will yield less number of rebounds than that is directed downwards and so do the correlation curves. Figure 2 above shows hammer impinging directions and associated curves.

3. Actual data from a Project…

A health center construction project[1] undergoing in one of the rural localities of Ethiopia missed sampling intervals for casting cubes. This 'error' from the side of the Contractor made the Employer doubtful of the strength of two blocks of the health center; namely, Blocks G & I. Concrete to be tested Foundation beam of Block G and Grade Beam of Block I.

In its concrete quality assurance section, the contract specification allows the use of 'drilled cores or non-destructive methods (such as gamma radiography, ultrasonic test, rebound hammer test, or electromagnetic cover measuring devices)'. Also, the characteristic cube compressive strength of concrete for structural concrete is specified as 25MPa.

To ascertain the in-place compressive strength of concrete, the Contractor ordered two laboratories[2]. For easy reference, the laboratories are named as Lab I and Lab II. Lab I was tasked with rebound hammer test at Blocks F, G & I. All blocks used the same mix design as well as same source of ingredients. The type of cement used was Portland Pozzolana Cement. At the time of ordering hammer test, cube test results were available for Block F. But, Block F was intentionally included in the hammer test to serve as an indicator of the departure of this test from the cube tests.

The Hammer test was conducted on the grade beam of Block F (Delivery), foundation beam of Block G (Pit Latrine) and Grade beam of Block I (Laundry). All tests were carried out setting the hammer vertically downward. Rebound Hammer test results for three blocks from the first laboratory are indicated in Table 1.

Table I: Summary of rebound hammer test results from Lab I

Block	Lab I Report on Rebound Hammer Test		Cube Test data	Remarks
	Average Rebound Number	Compressive Strength (MPa)	Compressive Strength (MPa)	
F	40.30	40.30	31.81	Cubes were tested at 28 days and hammer test thereafter.
G	38.56	38.56	None	Hammer test was done after 28 days.
I	38.83	38.83	None	

The rebound hammer testing laboratory forwarded his findings to the Contractor and quality assurance engineers have examined them critically. The report is very simplistic and lacks professionalism. First and foremost, rebound numbers having reading differences as much as 10 points are included in calculating the average rebound numbers. This is contrary to the recommendations of accepted standards that usually advise lower and upper outliers to be discarded [5]. Secondly, it contradicts standard testing procedures by incorporating readings that are lower by more than 6 units from the average of 10 readings [5], [6].

The third anomaly of the result is related to the calculation of the estimated compressive strength. Without giving any correlation curves or any corrections whatsoever, Lab I reported with a single page directly equating the average rebound number as the magnitude of the compressive strength.

Comparing and contrasting the results reported in light of the cube test result of Block F is worth considering here. Had some kind of correction been made, the difference in compressive strength between the actual cube test and the rebound hammer test of Block F would have been closer. The difference here is about 8.49MPa. This amounts to 26.7% of the 28 days strength. Although, it is a general truth that concrete made up of Portland Pozzolana Cement gains discernible strength until about 45days from casting, expecting a strength gain of over a quarter of its strength in the period after 28days of age casts doubt.

Relating the average rebound numbers with the actual cube test data is necessary in having a quick calibration. In the absence of post 28 days cube test data for Block F, the post 28 day strength gain was deliberately neglected. Accordingly, Block F cube test and hammer test results were directly equated and evaluated. Direct proportioning has given that in order the average rebound number to approach the 28days strength, it has to be multiplied by a factor of about 0.78.

Using this quick and direct (but not precise) method, it was seen that calibrating the machine for site specific conditions would serve as a good indicator in relating average rebound numbers to in-place

strength of concrete. Employing this simple calibration approach and rejecting some outliers of the rebound readings, quality engineers of the contractor estimated the in-place compressive strength of Blocks G & I as 30.08MPa and 32.29MPa respectively. A comparison will be made later with the core compressive strength results.

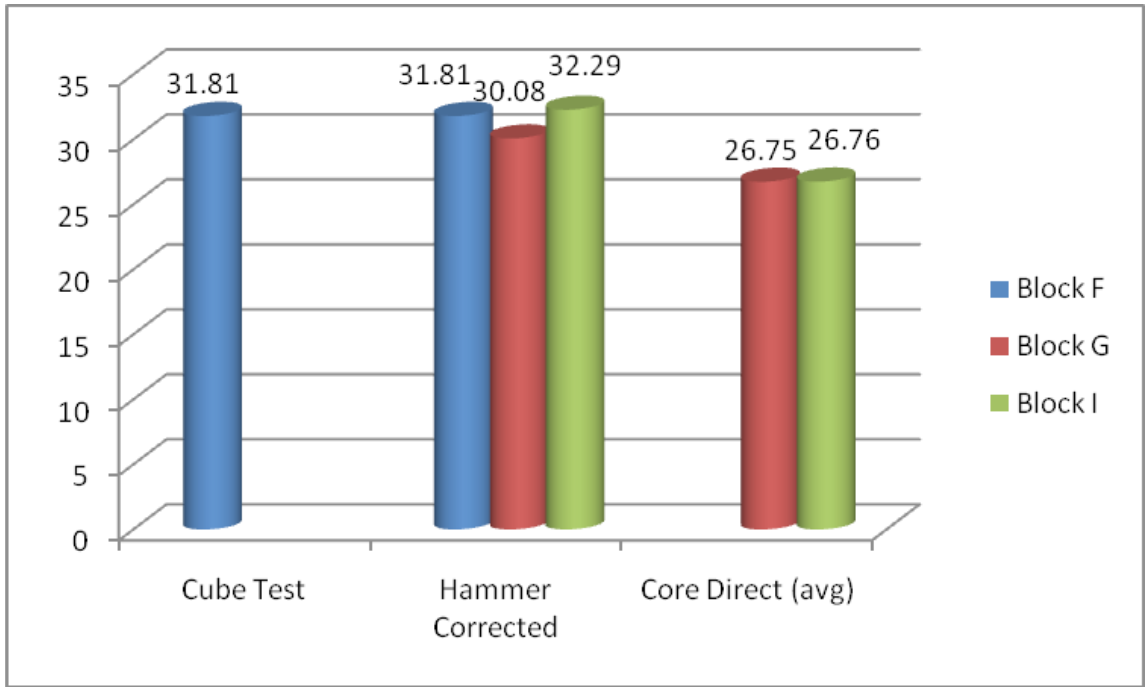


Figure 3: Cube, hammer and core test results

Figurer 3 above indicates cube test for block F, site specific calibrated and corrected hammer test for Blocks F, G & I and average of direct core test on Blocks G & I. Hammer test results appearing above are all secondary data generated from the field data. These post-Lab report analyses figures by quality engineers of the contractor may be important for professional and academic discussions. Nevertheless, being secondary data, they could not help in convincing a high quality expecting Employer that manages the project in strict compliance with provisions in the contract. For obvious reasons of grave professional inco nsistencies, com pressive strength calculated and reported by Lab I was thus rejected and order for core drilling was given to Lab II.



Figure 4: Drilled Core Samples from Block I.

Lab II drilled and tested four cores from each block rejecting the damaged ones (Figure 4 above). The diameter and height of drilled cores were identical for each block but vary from block to block. The Laboratory reported showing the dimension of each core from each block, the failure load and calculated the direct compressive strength of each drilled cylinder. Unlike the previous one, Lab II did not indulge into converting core test results to standard cube or cylinder compressive strength. Quality engineers of the Contractor accepted this approach of Lab II for the reason that the laboratory has only the onus to sample and conduct the test in accordance with standard procedures. Interpretation and analysis should always be the territory of the specifier of the tests [1], [6]. Table 2 shows the summarized data of the report from Lab II.

Table 2: Summarized strength of four cores per block

No	Block	Dimensions (cm)		Area (cm^2)	Failure Load (KN)	Average Compressive Strength (MPa)
		D	H			
Four cores	G	7.50	15.00	44.16	118.14	26.75
Four cores	I	5.00	10.00	19.63	54.48	26.76

4. Analysis and interpretation

The report on compressive strength calculation of Lab I is rejected for the anomalies discussed above. But the raw data was manipulated in order to generate secondary data. This section deals with analysis and interpretation of drilled core test results and compares them with the secondary data of the rebound hammer test. Evaluation of a new construction with low strength test results and an existing structure consisting of concrete with considerable age are separately treated.

4.1 Low strength concrete verification

When 28 days compressive strength tests are non-compliant with the specified strength, taking cores may be one of the options of ascertaining in-place strength. However, various factors affect the interpretation of concrete core test results [1], [3], [6]. To cite few;

- The length to diameter ratio (L/D)
- Diameter of the core
- Location of the concrete in the structure
- The moisture condition
- The direction of coring
- Maximum aggregate size of the concrete
- Presence of reinforcing bars
- The thickness of the concrete under investigation

All of these factors may ultimately need their own correction factors. Moreover, core samples are cylindrical in shape and converting them to standard cubes may be necessary when the specified characteristic compressive strength is in cubes. Generally, correction factors alter the raw data by a certain margin.

Various authors attempted to establish a relationship between cores and standard molded specimens. But, having a universally acceptable method of correlating the two has so far been unattainable. Some standards like ASTM C42 provide procedures on the testing and state that "there is no universal relationship between the compressive strength of a core and the corresponding strength of standard-cured molded specimens" [7]. The difficulty is not only attributable to the lack of easy to use methods of mathematical or statistical formulae but also to the possibility of compounding of errors and associated reliability issues in doing so.

It can rather be argued that relating the two is inappropriate due to differences in the inherent properties of standard specimens and core samples. Cores represent concrete from the very start of batching, mixing & transporting all the way to placing, consolidating and curing making them different from standard specimens that are restricted to the first three steps only. The method of sampling, handling the samples and testing them is also another point of difference.

ASTM C42-04 provides standard test methods for obtaining and testing cores [7]. The method further suggests that the preferred length to diameter ratio for core specimens is between 1.9 and 2.1. The same test method gives length to diameter correction factors for those ratios below the preferred ratio range as shown in Table 3. The correction factor for a length to diameter ratio of 2 can be considered as unity and that for intermediate ones can be interpolated. The test method states nothing on other factors that affect the interpretation of cores.

Table 3: Length to Diameter Ratio Correction factors [7]

Length to diameter (l/d) ratio	Strength Correction Factor
1.75	0.98
1.50	0.96
1.25	0.93
1.00	0.87

Multiplying core compressive strength test results with correction factors appearing above may be good in incorporating one of the factors. Nevertheless, it lags far behind in presenting the true or closer to the actual in-place strength of concrete. Rather, ACI 318-11 gives a better approach to evaluating core test results for new construction. Under sub-clause 5.6.5.4, it states the following [8].

Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85% of f'_c and if no single core is less than 75% of f'_c.

Core test results of the above mentioned health center project were evaluated for fulfilling the ACI 318 requirement. Here, care should be taken that the 25MPa characteristic compressive strength specified in the contract is cube strength. Lending the above stated ACI recommendations and multiplying this figure with a conversion factor from EBCS2 of 1.25 yields the approximate equivalent cylinder strength of 31.25MPa [9].

Table 4: Checking compliance of cores in accordance with ACI 318-11 [8]

Item	Compressive Strength (MPa)		Expected Cylinder Strength (MPa)	Actual Core Strength MPa)	Remarks
	Cube	Cylinder			
	a	b=1.25xa	c= 85% of b	d	
Characteristic Strength	25	31.25	26.56		
Block G			26.56 or greater	26.75	Accepted
Block I			26.56 or greater	26.76	Accepted

All eight core strength tests as well as the average of any three exceed the characteristic compressive strength and no single core is below 75% of f'_c. According to the provision, the Contractor's concrete would be accepted if the average of any three cores were greater or equal to 85% of the characteristic strength (26.56MPa for cylinder and 21.25MPa for cube). This shows that the Contractor maintained good quality control in meeting strength above the specified characteristic strength, albeit marginally.

4.2 Comparison of Core and Hammer Test Results

Converting the cylinder strength of the cores to standard 15cm cube strength for blocks G & I gives 33.40 and 34.70 Mpa respectively, (Figure 5). These figures can be compared with the results obtained from the rebound hammer test corrected using the results of Block F as indicator. As shown in Figure 3 above, the corresponding figures for Blocks G & I were estimated at 30.08 and 32.29MPa respectively. Comparing the two approaches equates to a difference of 11% and 7.5% respectively. The differences in these figures may emanate from the crudeness of the site calibration, the age difference between the cube and hammer test dates and above all hammer tests are on the surface and concrete strength is lower at the surface and stronger deep inside [10].

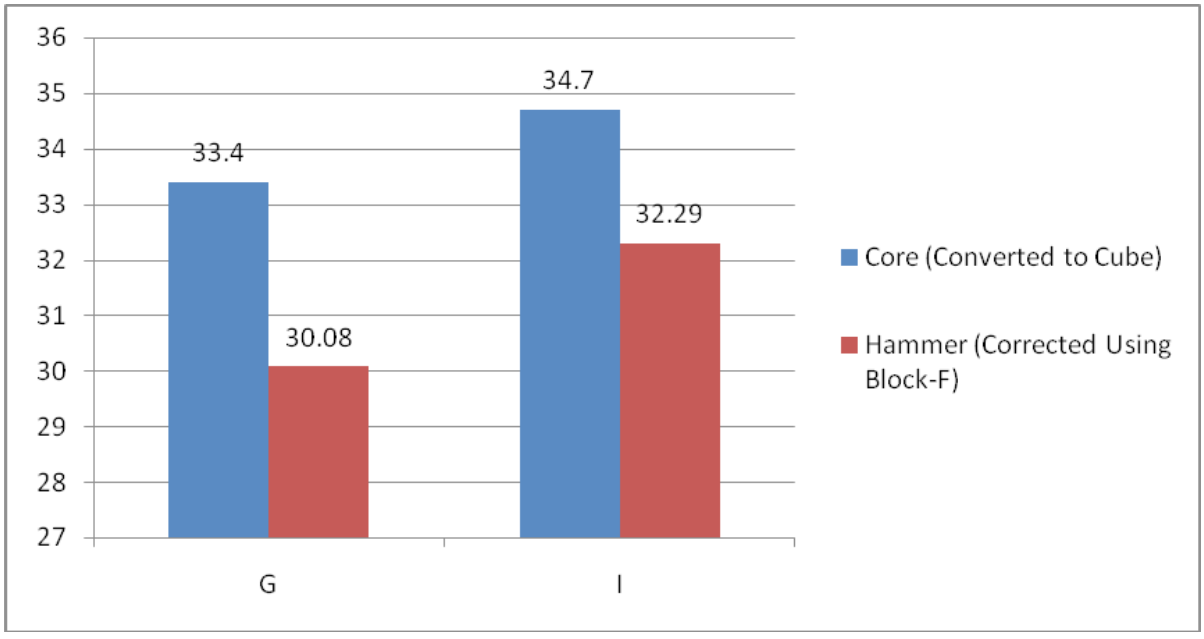


Figure 5: Core and Hammer compressive strength expressed in terms of cube strength (MPa)

Given these possible causes of differences, the two approaches yielded relatively closer figures. It can therefore be stated that, albeit a crude approach, calibrating the hammer test using available cube test data from the site could serve as a quick indicator of the strength of concrete in Blocks G & I.

4.3 Evaluating strength of an existing structure

Evaluating concrete from an existing structure has certain differences from that under construction. The thermal and chemical environment it has been exposed to, the moisture condition, the depth of carbonation, etc. may be distinctly different from concrete that is under construction.

Sometimes, for evaluation of the structural soundness of an existing structure, determining an equivalent characteristic strength may be required. Under such a case, the following formula can be helpful [10].

$$f_c = F_{l/d} F_{dia} F_{mc} F_d f_{core} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where,

f_c is the equivalent in-place strength;

f_{core} is the core strength;

$F_{l/d}$ is length to diameter ratio correction factor;

F_{dia} is correction factor for diameter

F_{mc} is correction factor for moisture condition of the core, and

F_d accounts for the effect of damage sustained during drilling including micro-cracking and undulations at the drilled surface and cutting through coarse-aggregate particles that may subsequently pop out during testing.

Citing a research by Bartlett and MacGregor, ACI Report ACI 214.4R.03 presented mean correction factors for length to diameter ratio, diameter, moisture condition and damage sustained during drilling. The coefficient of variation for each is also indicated. For ease of practical applications, Table 5 shows extracted correction factors for diameter, moisture condition and damage.

Table 5: Correction factors extracted from Reference [10]

Factor	Mean Value for each Condition of the factor			Remarks
	As Received	Soaked 48h	Air Dried	
Length to Diameter Ratio ($F_{l/d}$)				Is given as long formula. ASTM C42 provisions may be used instead.
Diameter *(F_{dia})*				
50mm	1.06			Similar under the three conditions.
100mm	1.00			
150mm	0.98			
Moisture Condition *(F_{mc})*	1.00	1.09	0.96	
Damage *(F_d)*	1.06			Similar under the three conditions.

Although ACI Report 214.4R-03 provides formulae for determination of the mean correction factors for length to diameter ratio under the three conditions, it appears relatively a complex approach for job site application. For ease of practical use, applying ASTM C42 correction factors indicated under Table 3 above can serve in lieu of those formulae. The replacement can be considered consistent since the provisions of ASTM C42 are applicable for both concrete in new construction and that in an existing structure.

For instance, if a core of 100mm diameter and a length of 200mm is taken from an existing structure; tested in air dried condition it yields a compressive strength of 22MPa. Then the correction factors from Tables 3 and 5 will be 1.0, 1.0, 0.96 and 1.06 for length to diameter ratio, diameter, moisture condition and damage respectively. The equivalent strength, $f_{c,}$ in equation (1) above will be about 22.39MPa, in terms of cylinder strength. Using the conversion factor from EBCS2, this translates to 17.91Mpa cube strength. The result can be used in analyzing and evaluating the safety and stability of the existing structure.

5. Process of acceptance and rejection

It is a common practice that construction standards and codes provide acceptance and rejection criteria. When the strength of a structure is in doubt, different

methods may be called for. In Ethiopia, the rebound hammer and core tests are commonly employed. Before going to costly demolition and reconstruction, following the process indicated in Table 6 may be of practical importance.

Table 6: Proposed process of acceptance and rejection

No.	Test Type	Shortcomings	Description
1	Rebound Hammer Test	• Indirect method • Calibration is often difficult • Dependent on surface characteristics • More human error involved • Reliability is questionable	i. This test is easy to use, non-destructive and is readily available in Ethiopia. ii. Make sure that manufacturer's correlation curves are available and all recommendations are applicable to the site [6], [11], [17]. ✓ Use them if applicable. iii. In case of any doubt on its reliability, test other locations of the structure where cube test results are available. a) Establish a relationship between cube tests and rebound numbers [12], [13], [14]. b) The established relationship can be used in estimating the strength of other sections where test is carried out. ❖ Stop here if acceptable or continue to No.2 below if unacceptable.
2	Core test	• Destructive, at least partially • May cut bars • Yields disturbed sample	• Drilled cores will be sampled and tested just like cubes [6], [15], [16]. • Use correction factors from Tables 3 and 5 above. • Make sure that the proper conversion from cube to cylinder or vice versa is done. ❖ Stop here if accepted or proceed to No.3 below if not accepted.
3	Strengthening	• Time taking • Requires due care, precision and accuracy	• Strengthen the structure. • Requires complementary design. ❖ Stop here if accepted or proceed to No. 4 below.
4	Demolition	• Both costly and time taking	❖ Demolish the structure and reconstruct.

6. Implications to Dispute Handling

Conducting hammer tests and taking cores from a structure are simple jobs to perform. Unless the interpretation procedures are clearly stated in the contract specification, the results from these tests may come out to be the cause of misunderstanding. There is a possibility that each party in the contract may either intentionally or out of ignorance on the subject misinterpret the results [1].

As discussed herein above, analyzing and interpreting the results of both hammer and core tests involve assumptions, corrections and conversions. Any intentional misinterpretation will certainly create confusion and a dispute may flare up. Clearly specifying the procedures to be followed in testing, analyzing and interpreting test results averts a potential dispute. Laboratory technicians, under a close supervision of a materials/structural engineer, should only provide test results as specified by the specifier of the tests. Planning the tests, anlaysing the results, interpreting them and forwarding a recommendation shall always be left to the structural or materials engineer having profound knowledge on concrete technology.

7. Conclusions

The use of core and rebound hammer tests for determining the in-place strength of hardened concrete is discussed. The following conclusions are drawn from the discussion.

- Hammer tests are quick and easy indirect strength measurement methods. Properly following manufacturer's recommendations as well as site level calibration with a known concrete strength improves their reliability.
- Core testing needs careful planning from selecting the location of coring to the methods of interpretation, acceptance and rejection. They need to be made by a professional structural or materials engineer with robust knowledge on concrete technology.
- Including the methods of in-place strength measurement methods and interpretation approaches in contract specifications helps in averting potential misunderstandings and disputes.
- In testing in-place strength of concrete, the duty of laboratory technicians shall squarely be restricted to sampling and testing as per the specified standard. They should neither specify tests nor interpret results. Basing one's engineering judgment on interpretation and/or recommendations of laboratory technicians will not only be of grave professional ignorance but also of civil engineering nonsense.

8. References

1. Neville, A. M.(2001), *Core Tests: Easy to Perform Not Easy to Interpret,* Concrete International.
2. Cited in ACI SP-144 (1994), *Concrete Technology-Past, Present and Future,* P.K. Mhetta Ed., American Concrete Institute, Detroit, MI, PP 623-678.
3. Neville, A. M. (1995), *Properties of Concrete,* 4th Edition, Pearson Education and Dorling Kinderslay Publishing Inc., Thirteen Impression.
4. NRMCA (2014), *Concrete in Practice What, Why & How?, CIP10-Strength of In-Place Concrete,* National Ready Mix Concrete Association, Silverspring MD20910, USA.
5. ASTM C 805-02 (2007), *Standard Test Method for Rebound Number of hardened Concrete,* Annual Book of ASTM Standards.
6. Bungey J. H., Millard S. G. and Grantham M. G.(2006), *Testing of Concrete in Structures,* 4th Edition, Taylor & Francis e-library, New York.
7. ASTM C 42-04 (2007), *Test for obtaining and testing drilled cores and sawed beams of concrete*, Annual Book of ASTM Standards.
8. ACI (2011), "*Building code requirements for structural concrete and commentary"*, Report ACI 318-11, American Concrete Institute, USA.
9. EBCS2 (1995), *Structural Use of Concrete, Ethiopian Building Code Standards*, Ministry of Works and Urban Development, Ethiopia.
10. ACI 214.4R-03 (2003), *Guide for Obtaining Cores and Interpreting Compressive Strength Results*, American Concrete Institute, USA.
11. www.humboldtmfg.com, H-2987 *Concrete Rebound Hammer, Product Manual*, Accessed on February 28, 2015.
12. Brencich A. et al (2013), *Calibration and Reliability of the Rebound (Schmidt) Hammer Test*, Civil Engineering and Architecture 1(3):66-78.
13. Ayden F. and Sarabiyik M. (2010), *Correlation between Schmidt Hammer and destructive compressions testing for concretes in existing buildings*, Scientific Research and Esssays Vol. 5(13), pp. 1644-1648.
14. Liu J.C., Sue M.L. and Kou C.H.(2009), *Estimating the Strength of Concrete Using Surface Rebound Value and Design Parameters of Concrete Material*, Tamkang Journal of Science and Engineering, Vol. 12, No. 1, pp, 1-7.
15. Mustafa T. M. et al (2007), *Assessing concrete strength by means of small diameter cores*, Construction and Building Materials 22 (2008) 981–988, Elsevier Science Limited.
16. Yamamoto D. et al, *Evaluation of comp ressive strength of concrete using small diameter core,* Third International Conference on Sustainable Construction Materials and Technologies, http://www.claisse.info/proceedings.htm, accessed February 28, 2015.
17. IAEA (2002), *Guidebook on non-destr uctive testing of concrete structures*, INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, Austria.

i The author is not authorized to disclose the name of the project.

ii Mentioning their names is intentionally excluded for fear that it may have unintended consequences.