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Reliability of Non-Destructive Test Results for Assessment of Concrete Using Cut and Pull Out Test & Rebound Hammer Test (A Case Study)

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ABSTRACT : *Structural assessment of an old building of Directorate of Electronic Media and Publication (DEMP), Ministry of Information and Broadcasting, Government of Pakistan was carried out to assess repair and rehabilitation works. Non-Destructive Testing (NDT) Methods were used that included thorough visual assessments, complimented with two types of NDTs i.e Cut and Pull Out Test and Rebound Hammer Test. A total of 80 tests, 40 for each Rebound Hammer and CAPO Tests were performed at various locations of the building elements. The compressive strengths of concrete obtained by both these tests at different locations were recorded and standard deviations of Hammer readings at each test location were calculated. The indirect compressive strength of concrete obtained by the Hammer Test was compared with the compressive strength of concrete obtained by the CAPO Test. The results from both these tests were tabulated and interpreted to ascertain their reliability. It was concluded that the Rebound Hammer Tests can be recommended only as preliminary Non-Destructive Testing to compliment detailed investigations by other sophisticated methods viz. CAPO Test method.*

KEYWORDS *Reliability, non-destructive testing, cut and pull out test, rebound hammer test, rebound numbers, compressive strength of concrete.*

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I. INTRODUCTION

The Ministry of Information and Broadcasting, Directorate of Electronic Media and Publications (DEMP) had approached the Council for Works and Housing Research (CWHR) in February 2021 for assessing the structural strength, integrity and fitness of an old building in Karachi constructed partially prior to 1947 and partially in 2009. Non-Destructive Testing methods were used for assessment of the building. The testing work was completed in July 2021 and a detailed assessment report was submitted to the Directorate whereby it was concluded that repair works to the building was not economically viable.

The scope of this paper is to compare the reliability of two Non-Destructive Testing methods i.e. Cut and Pull Out Test (CAPO) and Rebound Hammer Tests. The sample size is based on a total of 80 tests, 40 each for CAPO test and Rebound Hammer test on the DEMP building elements viz. foundation, load bearing wall, columns and beams and slabs at different floors.

The structural adequacy of the DEMP building was assessed by carrying out physical inspection, identifying critical locations to determine the strength of the RCC members, carrying out diagnostic tests using non-destructive testing equipments and finally drawing conclusions on the basis of test results and engineering judgment. Following equipments were used:

i. Schmidt Hammer Test for determination of surface hardened of concrete. Test performed in accordance to ASTM C-805.
ii. CAPO Test Equipment (Cut and Pull-Out Test Equipment, A/S GERMANN Instruments,) Model C-104 series was used for determining compressive strength of concrete at different locations. The test was performed in accordance with ASTM C-900.

iii. Corrosion analysis tests at accessible and corroded areas to ascertain the extent of corrosion at different parts of the roof slabs and beams.

The conclusive results were largely based on the Rebound Hammer Test and the Cut and Pull Out Test (CAPO Test). Their test procedures are briefly described as under:

II. MATERIAL AND METHODS

II(A). REBOUND HAMMER TEST

The Rebound Hammer Test is performed as per ASTM C805. This test is convenient and provides a rapid indication of the quality of concrete. The rebound hammer consists of a spring controlled mass that slides on a plunger within a tubular housing. When the plunger of rebound hammer is pressed against the surface of concrete, a spring controlled mass with a constant energy is made to hit concrete surface to rebound back. The extent of rebound, which is a measure of surface hardness, is measured on a graduated scale. This measured value is designated as Rebound Number. A concrete with low strength and low stiffness will absorb more energy to yield in a lower rebound value. Thus, the hardness of concrete and rebound hammer reading can be correlated with compressive strength of concrete. The rebound value is read off along a graduated scale and is designated as the rebound number. (See Figs. 1 and 2)

Figs. 1 and 2

The compressive strength can be read directly from the graph provided on the body of the hammer. (See Figures 3 and 4)

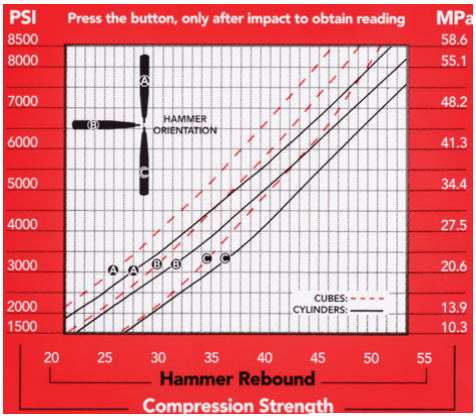


Fig. 3

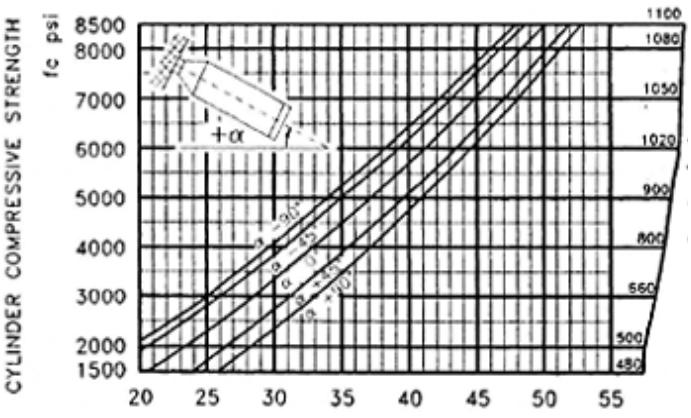


Fig. 4

Correlation

This diagram shows the relationship between the compressive strength for concrete, measured directly in a laboratory using concrete cylinders or concrete cubes, and the rebound numbers receive using Rebound Hammer.

A refers to using the Rebound Hammer against a concrete floor **(Angle = +90⁰).**
B refers to using it against a concrete wall **(Angle = 0⁰).**
C refers to using it against a concrete ceiling **(Angle = -90⁰).**

Limitations of the Rebound Hammer Test

The test has some uncertainties as different factors influence results. The main factors are concrete material ratio, aggregate size, concrete cover and moisture content etc.

In order to cater the uncertainties it is standard practice to record 10 readings at the testing location, to cater variations that occur on the surface of concrete. It is recommended to discard upto two readings (out of ten readings) if the difference of individual readings and the average readings is more than 6. If there are more than 2 readings then it is recommended to discard all the readings and select a new location. Thus the general range for standard deviation is greater than 0 and equal or less than 6.

The deviations are greatly influenced by the presence of coarse aggregate near surface at specific location. e.g carbonated layer increases the rebound variations on the surface of concrete., presence of moisture content effects the deviation value and decreases the rebound number with more variations. Similarly, partially deteriorated concrete will give variations in rebound readings.

II(B). CUT AND PULL-OUT TEST

The CAPO test permits performing pull out tests on existing structures without the need of preinstalled inserts. CAPO test provides a pull out test system for accurate on-site estimates of compressive strength. CAPO tests are performed in accordance to ASTM C900.

Typical applications of the CAPO tests include the following:

- Quality assurance testing of the finished structure.
- Verification of in-place strength, if strength of standard-cured specimens fails to meet acceptance criteria.
- Estimating strength of concrete in existing structures.
- Evaluation of fire-damaged structure.

When selecting the location for a CAPO test, it is first ensured that reinforcing bars are not within the testing region. The surface at the test location is ground using a planning tool and a 18.4 mm hole is made perpendicular to the surface using a diamond-studded core bit. A recess (slot) is routed in the hole to a diameter of 25 mm and at a depth of 25 mm. A split ring is expanded in the recess and pulled out using a pull machine reacting against a 55 mm diameter counter pressure ring, the concrete between the expanded ring and the counter pressure ring is in compression.

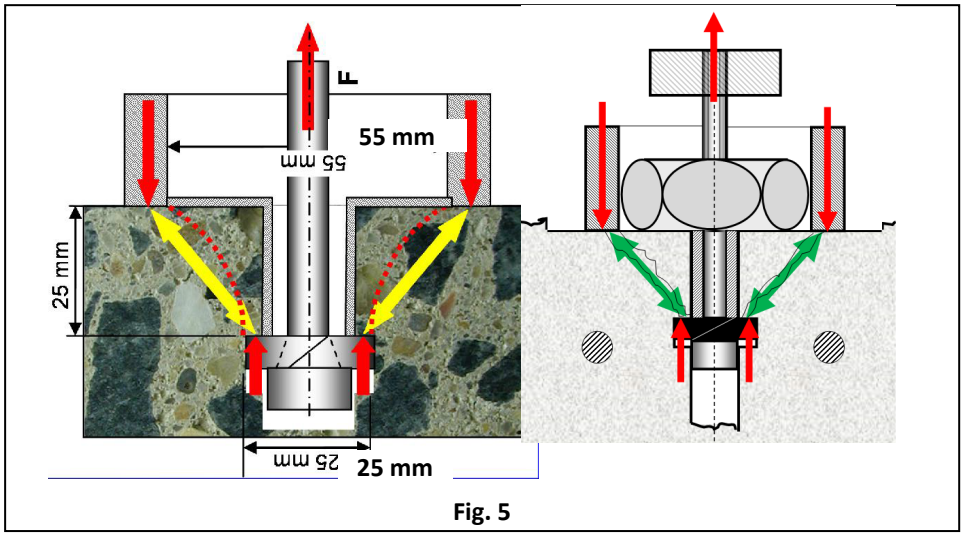


Fig. 5

Hence, the ultimate pull out force F is related directly to compressive strength. The test is performed until the conical frustum between the expanded ring and the inner diameter of the counter pressure is dislodged.
(See Fig. 5)

Limitations of the Capo Tests:

- Max pull out force for the CAPO-Test is 90 kN, equiv. to 105 MPa cylinder strength or 140 MPa cube strength.

- CAPO-Test measure compressive strength range is 2 to 130 MPA or 300 to 19,000 psi. Their strength range may be increased this limit but it needs strong correlation data for the subjective equipment.
- Total duration of one test 15-20 minutes.
- A criteria for correct CAPO testing is shown in Fig. 6.
- As shown in Fig. 7, there should be a sharp circular edge on the concrete surface corresponding to the 55 mm inner diameter of the counter pressure ring. This indicates the surface was planned properly to a flat condition and the counter pressure was in uniform contact with surface.

Fig. 6

Fig. 7

Crushed material

Sharp 55 mm diameter edge from counter pressure free from any cracks

- There is no CAPO Test acceptable near to the any type of cracks in concrete.
- The distance between the two tests should be not less than 3 to 4 feet.
- Fig. 8 shows, there is minor surface damage, which should be repaired for aesthetic reasons or to avoid potential durability problems. Alternatively, the hole may be patched with a non-shrink, polymer-modified repair mortar that is prepared in accordance with the manufacturer's instructions.

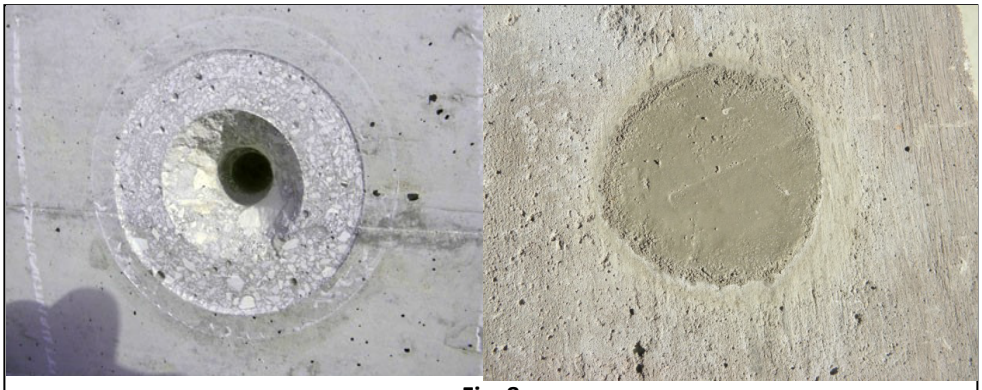


Fig. 8

- In existing building, there are many locations of beams have minimum depth 12" which are not compatible for the CAPO gun hydraulic machine as it is required the minimum space about 18" in diameter to rotate the plunger of the CAPO gun.

III. RESULTS AND DISCUSSION

III (A). SUMMARY OF TEST RESULTS

Summary of Test Results at different locations of the DEMP Building are tabulated in the Tables III/a to III/m in the following order:

TABLE III: SUMMARY OF LOCATIONS				
Table No	**Location**			**Reference Figure**
III/a	Foundation	:	RCC Framed Structure	9 - 10
III/b	Load Bearing Wall	:	Load Bearing Structure, Ground Floor	11 – 12
III/c	Load Bearing Wall	:	Load Bearing Structure, First Floor	13 – 14
III/d	Columns	:	RCC Framed Structure, Ground Floor	15 – 16
III/e	Columns	:	RCC Framed Structure, First Floor	17 – 18
III/f	Beams	:	Load Bearing Structure, Ground Floor	19 – 20
III/g	Beams	:	Load Bearing Structure, First Floor	21 – 22
III/h	Beams	:	RCC Framed Structure, Ground Floor	23 – 24
III/i	Beams	:	RCC Framed Structure, First Floor	25 – 26
III/j	Roof Slab	:	Load Bearing Structure, Ground Floor	27 – 28
III/k	Roof Slab	:	Load Bearing Structure, First Floor	29 – 30
III/l	Roof Slab	:	RCC Framed Structure, Ground Floor	31 – 32
III/m	Roof Slab	:	RCC Framed Structure, First Floor	33 – 34

TABLE III/a: LOCATION: FOUNDATION (RCC Framed Structure)							
TEST MARK No.	**REBOUND NUMBER OF HARDENED CONCRETE (ASTM: C 805)**					**CAPO TEST (ASTM: C 900)**	
	10 Rebound Hammer Readings over an area of 1sq ft Plunger angle at 0°	**Average of 10 Rebound Hammer Readings**	**Standard Deviation of Hammer Readings**	**Equivalent Cylinder Compressive Strength fc' (psi)**	**Equivalent Cube Compressive Strength fc' (psi)**	**Pull force P (kN)**	**Transformation to 150mm standard cube compressive strength in MPa (psi)**
19	12, 12, 15, 18, 16, 16, 13, 13, 18, 18	15	2.34	NA	NA	8.7	9.66 (1,401)
20	16, 16, 18, 14, 16, 12, 12, 17, 16, 16	15	1.90	NA	NA	8.5	9.40 (1,363)

TABLE III/b: LOCATION: LOAD BEARING WALL (Load Bearing Structure, Ground Floor)							
08	20, 20, 18, 21, 20, 18, 19, 18, 21, 18	19	1.19	NA	NA	2.7	2.68 (388.6)
16	19, 19, 21, 20, 19, 20, 18, 18, 20, 18	19	0.98	NA	NA	4.0	3.99 (579.2)

TABLE III/c: LOCATION: LOAD BEARING WALL (Load Bearing Structure, First Floor)							
32	18, 20, 22, 18, 20, 20, 26, 20, 21, 20	21	2.16	NA	NA	2.6	2.58 (374.3)

TABLE III/d: LOCATION: RCC COLUMNS (RCC Framed Structure, Ground Floor)							
02	19, 20, 18, 14, 16, 18, 12, 12, 14, 12	16	2.94	NA	NA	5.7	5.89 (854.0)
03	19, 19, 19, 18, 20, 22, 21, 20, 21, 21	20	1.18	NA	NA	9.2	10.31 (1,496)
05	28, 28, 26, 30, 22, 28, 28, 28, 28, 26	27	2.13	2,400	2,880	8.1	8.89 (1,288.8)
11	24, 20, 22, 22, 22, 22, 23, 22, 22, 22	22	1.04	1,500	1,800	13.9	16.40 (2,378)
13	21, 22, 22, 23, 19, 20, 23, 22, 22, 22	22	1.08	1,500	1,800	8.2	9.01 (1,307)
15	30, 34, 30, 32, 33, 30, 36, 30, 40, 30,	33	2.39	3,600	4,320	24.9	31.51 (4,570)

TABLE III/e: LOCATION: RCC COLUMNS (RCC Framed Structure, First Floor)							
Test Mark No.	**REBOUND NUMBER OF HARDENED CONCRETE (ASTM: C 805)**					**CAPO TEST (ASTM: C 900)**	
	10 Rebound Hammer Readings	**Average Of 10**	**Standard Deviation**	**Equivalent Cylinder**	**Equivalent Cube**	**Pull force**	**Transformation to 150mm**

	Over An Area of 1sq Ft Plunger Angle At 0 ⁰	Rebound Hammer Readings	of Hammer Readings	Compressive Strength fc' (psi)	Compressive Strength fc' (psi)	P (kN)	standard cube compressive strength in MPa (psi)
24	20, 26, 18, 18, 21, 28, 26, 26, 21, 23	23	3.44	1,700	2,040.0	15.2	18.13 (2,629)
27	20, 21, 23, 26, 28, 20, 28, 20, 23, 26	24	3.11	1,900	2,280	8.7	9.66 (1,401)
28	20, 23, 26, 20, 20, 22, 23, 20, 20, 26	22	2.32	1,500	1,800	24.0	30.26 (4,388)
38	28, 30, 24, 30, 28, 24, 28, 28, 26,26	27	2.04	2,400	2,880	26.1	33.21 (4,817)
39	20, 28, 20, 26, 26, 20, 20, 20, 20, 26	22	3.05	1,500	1,800	17.6	21.41 (3,105)
40	30, 26, 22, 24, 28, 22, 22, 22, 26, 24	24	2.90	1,900	2,280	13.8	16.26 (2,359)

TABLE III/f: LOCATION: BEAMS (Load Bearing Structure, Ground Floor)							
01	20, 22, 30, 20, 30, 24, 20, 20, 20, 20	23	4.12	1,700	2,040.0	7.2	7.74 (1,122.9)
04	20, 24, 22, 18, 20, 20, 20, 18, 18, 20	20	1.79	NA	NA	7.0	7.49 (1,086.5)
07	32, 36, 34, 30, 34, 36, 30, 48, 34, 30	33	2.33	3,800	4,560.0	7.0	7.49 (1,086.5)
09	26, 26, 26, 26, 26, 22, 22, 26, 28, 28	26	1.96	2,200	2,640	3.8	3.79 (549.2)

TABLE III/g: LOCATION: BEAMS (Load Bearing Structure, First Floor)							
25	23, 20, 30,20, 30, 20, 20, 30, 20, 30	24	4.73	1,900	2,280	13.7	16.13 (2,340)
29	22, 24, 25, 28, 24, 28, 28, 26, 28, 26	26	2.02	2,200	2,640	8.4	9.27 (1,345)
31	30,30, 26, 20, 30, 30, 30, 20, 20, 21	26	4.61	2,200	2,640	6.2	6.50 (942.5)
33	30, 30, 30, 26, 28, 26, 26, 28, 26, 26	28	1.79	2,600	3,120	19.9	24.63 (3,572)
34	18, 18, 20, 20, 18, 20, 18, 18, 18, 22	19	1.34	NA	NA	7.8	8.50 (1,233.1)
35	20, 20, 19, 20, 21, 20, 20, 21, 20,20	20	0.54	NA	NA	3.7	3.68 (534.3)
36	26, 26, 20, 20, 21, 20, 21, 20, 20, 20	21	2.33	NA	NA	3.9	3.89 (564.2)
37	24, 24, 22, 24, 26, 28, 24, 24, 24, 24	24	1.50	1,900	2,280	11.8	13.66 (1,981)

TABLE III/h: LOCATION: BEAMS (RCC Framed Structure, Ground Floor)							
10	36, 30, 30, 32, 36, 32, 36, 37, 36, 36	34	2.62	3,800	4,560	6.2	6.50 (942.5)
12	31, 29, 34, 28, 30, 30, 35, 35, 32, 30	31	2.37	3,200	3,840	19.0	23.36 (3,388)
14	36, 30, 36, 36, 40, 40, 36, 36, 40, 32	36	3.33	4,200	5,040	34.8	46.19 (6,699)

TABLE III/i: LOCATION: BEAMS (RCC Framed Structure, First Floor)							
Test Mark No.	REBOUND NUMBER OF HARDENED CONCRETE (ASTM: C 805)					CAPO TEST (ASTM: C 900)	
	10 Rebound Hammer Readings over an area of 1sq ft Plunger angle at +90⁰	Average of 10 Rebound Hammer Readings	Standard Deviation of Hammer Readings	Equivalent Cylinder Compressive Strength fc' (psi)	Average of 10 Rebound Hammer Readings	Pull force P (kN)	Transformation to 150mm standard cube compressive strength in MPa (psi)
26	20, 22, 26, 30, 30, 26, 22, 28, 26, 26	25	3.61	2,000	2,400.0	14.5	17.19 (2,493)

30	30,30,30, 26, 20, 21, 26, 20, 20, 21	24	4.25	1,900	2,280.0	11.7	13.53 (1,962)

TABLE III/j: LOCATION: ROOF SLAB (Load Bearing Structure, Ground Floor)							
06	20, 20, 18, 21, 18, 20, 18, 20, 21, 20	20	1.11	NA	NA	6.4	6.74 (978.2)
17	23, 20, 23, 21, 23, 21, 20, 19, 21, 22	21	1.35	NA	NA	8.4	9.27 (1,345)

TABLE III/k: LOCATION: ROOF SLAB (Load Bearing Structure, First Floor)							
21	16, 15,14, 14, 16, 18, 14, 16, 26, 14	16	2.33	NA	NA	3.2	3.18 (460.6)
23	13, 12, 18, 18, 12, 23, 20,23,18, 23	18	4.20	1,700	2,040.0	9.9	11.23 (1,629)

TABLE III/l: LOCATION: ROOF SLAB (RCC Framed Structure, Ground Floor)							
18	26, 18, 26, 20, 20, 20,20, 22, 26, 14	22	3.07	NA	NA	12.3	14.30 (2,074)

TABLE III/m: LOCATION: ROOF SLAB (RCC Framed Structure, First Floor)							
22	22, 22, 24, 22, 20, 20, 20, 22, 20, 22	21	1.28	NA	NA	8.6	9.53 (1,382)

III(B). INTERPRETATION OF RESULTS

Foundation

The 02 nos. test results for Foundation shown in Table **III/a** are graphically represented in Figs. 9 and 10.

The standard deviation of the rebound readings at Test Mark Nos. 19 and 20 are 2.34 and 1.90 respectively. The average standard deviation of these two tests is 2.12, which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data is not too scattered.

The average rebound number for Test Mark Nos. 19 and 20 are in the range of rebound number 15. This number is not defined on the correlation curve of the instrument.

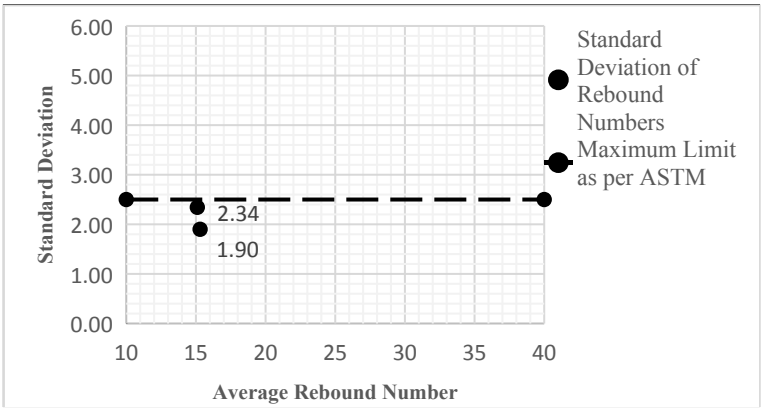


Fig. 9: Average Rebound Number VS Standard Deviation (Test Mark Nos 19 and 20)

The minimum value on the correlation curve of rebound hammer is 22 that corresponds to fc'=1500 psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said locations is less the 1,500 psi. In such cases the quality of concrete is classified as poor.

The CAPO test results at Test Mark Nos. 19 and 20 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 PSI in structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by rebound hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the rebound hammer.

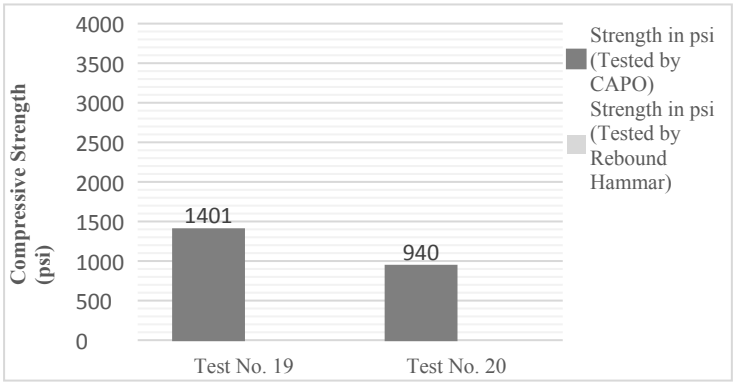


Fig. 10: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 19 and 20)

Load Bearing Walls (Ground Floor)

The 02 nos. test results for Load Bearing Walls shown in Table **III/b** are graphically represented in Figs. 11 and 12. The Two tests were conducted on walls at ground floor (Test Mark Nos. 8 and 16).

The standard deviation of the rebound readings at Test Mark Nos. 8 and 16 are 1.9 and 0.98 respectively. The average standard deviation of these two tests is 1.08, which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data is not too scattered.

The average rebound number for Test Mark Nos. 8 and 16 are in the range of rebound number 19. The 19 number is not defined on the correlation curve of the instrument. The minimum value on the correlation curve of rebound hammer is 22 that corresponds to fc'= 1500psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said locations is less the 1,500 psi. Therefore, the quality of concrete is classified as poor.

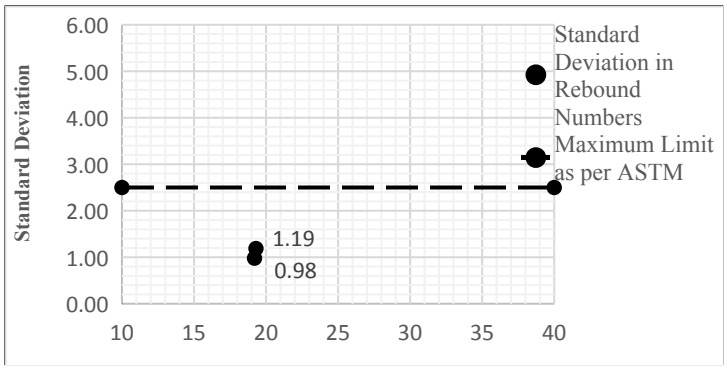


Fig. 11: Average Rebound Number VS Standard Deviation (Test Mark Nos. 08 and 16)

The CAPO test results at Test Mark Nos. 08 and 16 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi in structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the rebound hammer.

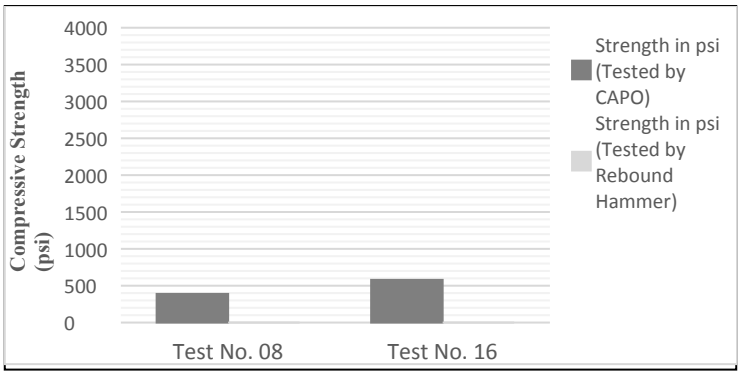


Fig. 12: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 08 and 16)

Load Bearing Walls (First Floor)

The test result for Load Bearing Wall shown in Table **III/c** is graphically represented in Figs. 13 and 14. Only one test (Test Mark Nos. 32) was conducted on walls at first floor.

The standard deviation of 10 rebound readings at Test Mark Nos. 32 is 2.16, which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data is not too scattered.

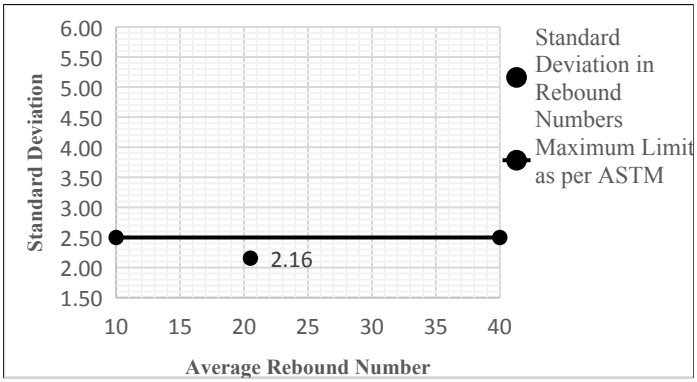


Fig. 13: Average Rebound Number VS Standard Deviation (Test Mark No. 32)

The average rebound number for Test Mark Nos. 32 are 21. This number is not defined on the correlation curve of the instrument. The minimum value on the correlation curve of rebound hammer is 22 that corresponds to fc'= 1500 psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said locations is less the 1,500 psi. Therefore, the quality of concrete is classified as poor. Therefore, in Fig 5.3.2, zero value is plotted for the compressive strength of concrete as tested by the rebound hammer.

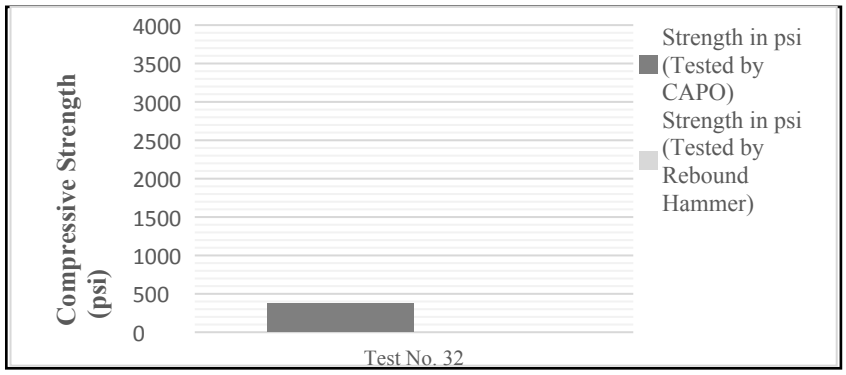


Fig. 14: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark No. 32)

The CAPO test results at Test Mark Nos. 32 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi for structural element as per ACI Code 318-14.
Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the Rebound Hammer.

RCC Columns (Framed Structure, Ground Floor)

The test results for 06 nos. Columns (Framed Structure, Ground Floor) shown in Table **III/d** are graphically represented in Figs. 15 and 16. All the tests were conducted on columns located at ground floor.
The standard deviation of the rebound readings at Test Mark Nos. 02, 03,05,11,13 and 15 are 2.94, 1.18, 2.13, 1.04, 1.08 and 2.39 respectively. The average standard deviation of all tests is 1.80 which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data is not too scattered.

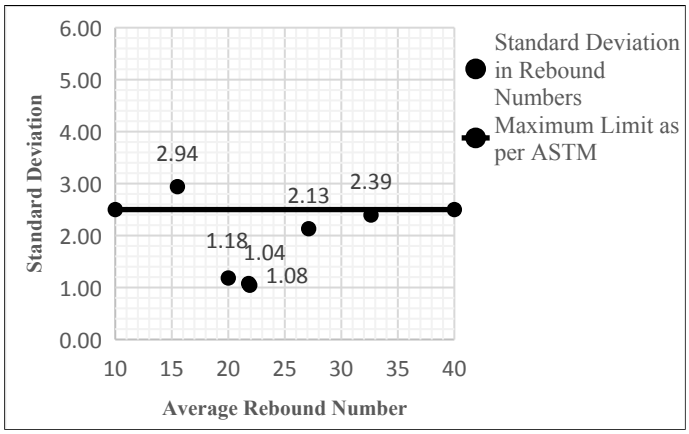


Fig. 15: Average Rebound Number VS Standard Deviation (Test Mark Nos. 02, 03, 05, 11, 13 and 15)

The average rebound number for Test Mark Nos. 02, 03, 05, 11, 13 and 15 are in the range of rebound numbers 16 to 33. Rebound number of 16 is not defined on the correlation curve of the instrument. The minimum value on the correlation curve of rebound hammer is 22 that corresponds to fc'=1,500 psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said location is less the 1,500 psi. Similarly the strength corresponding to rebound number 33 is fc'= 4,320psi. It is inferred that the strength of concrete (fc') in the tested locations ranges from 1,500 psi to 4,320 psi. Therefore, the quality of concrete is classified as poor to good layer of concrete.

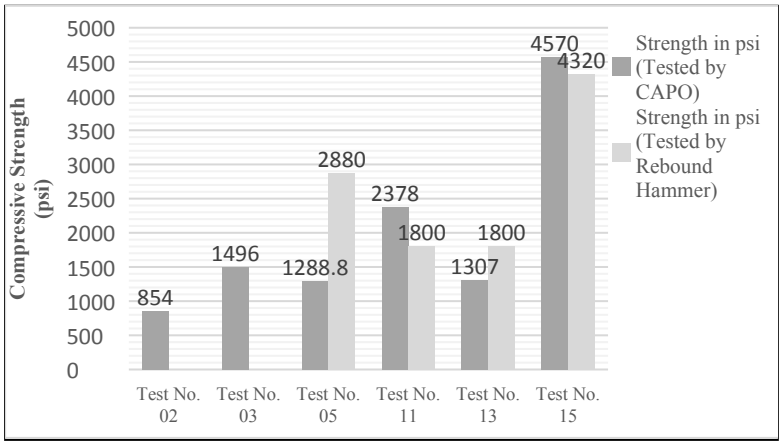


Fig. 16: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 02, 03, 05, 11, 13 and 15)

The Capo Test results at Test Mark Nos. 02, 03, 05, 11 and 13 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

However at only one location/column the cube compressive strength (at Test Mark No. 15) is 4,320 psi which is greater than minimum strength required as per ACI Code 562-19 as well as minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

% Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by CAPO test is lower than tested by Rebound Hammer and vice versa.

The comparative strength of CAPO and Rebound Hammer in percentage are as follow

	Test No. 02	Test No. 03	Test No. 05	Test No. 11	Test No. 13	Test No. 15
Compressive Strength by CAPO Test	854	1,496	1,288.8	2,378	1,307	4,570
Compressive Strength by Rebound Hammer	0	0	2,880	1,800	1,800	4,320
Difference in %	-	-	-123	24.3	-37.7	5.47

RCC Columns (Framed Structure, First Floor)

The test results for 06 nos. columns (Framed Structure, First Floor) shown in Table **III/e** are graphically represented in Figs. 17 and 18. All the tests were conducted on column at first floor.

The standard deviation of the rebound readings at Test Mark Nos. 24, 27, 28, 38, 39 and 40 are 3.44, 3.11, 2.32, 2.04, 3.05 and 2.90 respectively. The average standard deviation of all tests is 2.81 which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are too scattered.

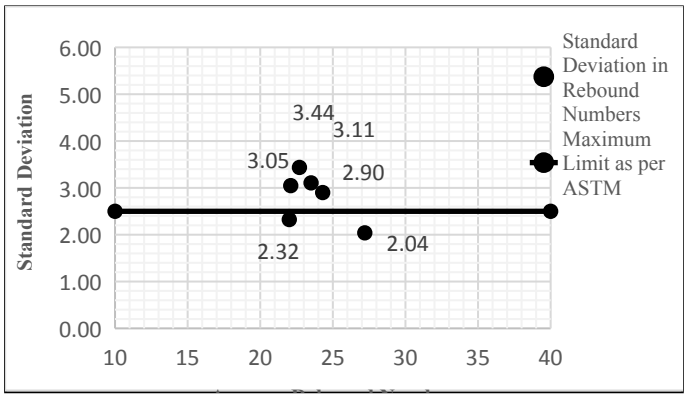
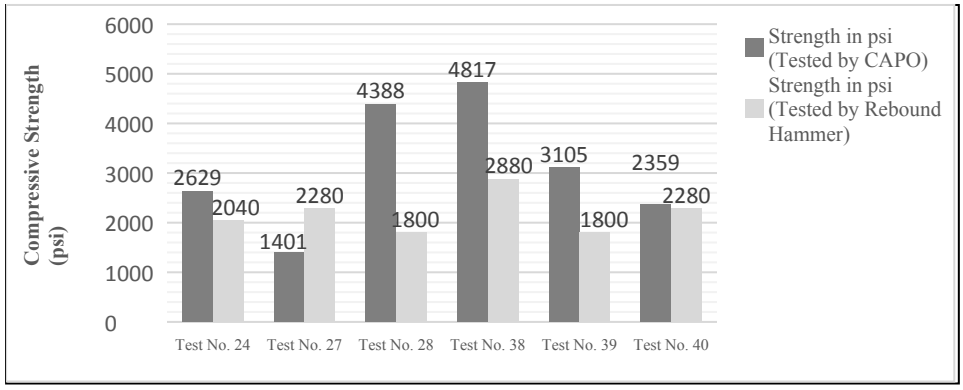


Fig. 17: Average Rebound Number VS Standard Deviation (Test Mark Nos. 24, 27, 28, 38, 39 and 40)

The average rebound number for Test Mark Nos. 24, 27, 28, 38, 39 and 40 are in the range of rebound number 22 to 27. Rebound number 22 and 27 correspond to fc'= 1,800 psi and to fc'= 2,880 psi respectively. Hence the quality of concrete at these locations is classified as fair.



The CAPO Test results at Test Mark Nos. 24, 27 and 40 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi in structural element except test Marks Nos. 24 as per ACI Code 318-14.

However, the cube compressive strength at Test Marks Nos. 28, 38 and 39 satisfy both minimum strength required as per ACI Code 562-19 as well as minimum design strength requirement for structural element as per ACI Code 318-14. % Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by CAPO test is lower than tested by Rebound Hammer and vice versa.

The comparative strength of CAPO and Rebound Hammer in percentage are as follow

	Test No. 24	Test No. 27	Test No. 28	Test No. 38	Test No 39	Test No. 40
Compressive Strength by CAPO Test	2,629	1,401	4,388	4,817	3,105	2,359
Compressive Strength by Rebound Hammer	2,040	2,280	1,800	2,280	1,800	2,280
Difference in %	22.4	-62.7	58.9	52.6	42.0	3.3

Beams (Ground Floor) in Load Bearing Structure

The test results for 04 nos. beams (Load Bearing Structure, Ground Floor) shown in Table **III/f** are graphically represented in Figs. 19 and 20. The tests were conducted on beams at ground floor. The standard deviation of the rebound readings at Test Mark Nos. 01, 04, 07 and 09 are 4.12, 1.79, 2.33 and 1.96 respectively. The average standard deviation of all tests is 2.55 which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are too scattered.

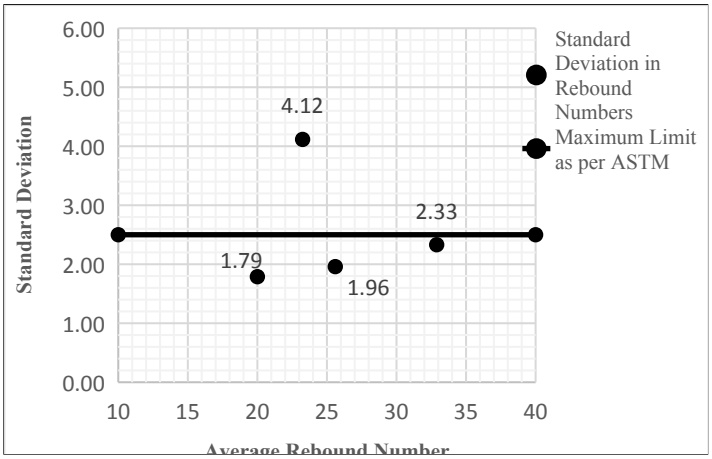
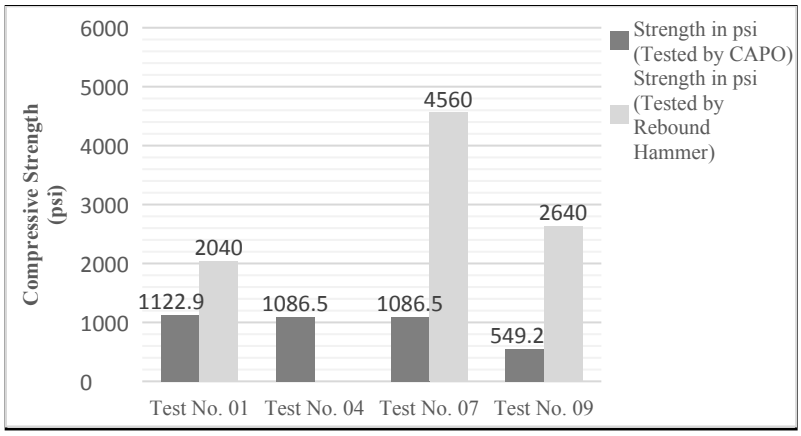


Fig. 19: Average Rebound Number VS Standard Deviation (Test Mark Nos. 01, 04, 07 and 09)

The average rebound number for Test Mark Nos. 01, 04, 07 and 09 are in the range of rebound number 20 to 26. The 20 number is not defined on the correlation curve of the instrument. The minimum value on the correlation curve of Rebound Hammer is 22 that corresponds to fc'= 1,500 psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said location is less than 1,500 psi. Similarly the strength corresponding to rebound number 26 is fc'= 2,640 psi Therefore, the quality of concrete at this location is classified as fair concrete.



The CAPO test results at Mark Nos. 01, 04, 07 and 09 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

% Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by CAPO test is lower than tested by Rebound Hammer and vies versa

The comparative strength of CAPO and Rebound Hammer in percentage are as follow

	Test No. 01	Test No. 04	Test No. 07	Test No. 09
Compressive Strength by CAPO Test	1122.9	1086.5	1086.5	549.2
Compressive Strength by Rebound Hammer	2040	-	4560	2640
Difference in %	-81.6	-	-319.6	-380.6

Beam (First Floor) in Load Bearing Structure

The test results for 07 nos. beam (First Floor) in Load Bearing Structure shown in Table **III/g** are graphically represented in Figs. 21 and 22. All the tests were conducted on beam at first floor. The standard deviation of the rebound readings at Test Mark Nos. 25, 29, 31, 33, 34, 35, 36 and 37 are 4.73, 2.02, 4.61, 1.79, 1.34, 0.54, 2.33 and 1.50 respectively. The average standard deviation of all tests is 2.36 which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are not too scattered.

The average rebound number for Test Mark Nos. 25, 29, 31, 33, 34, 35, 36 and 37 are in the range of rebound numbers 19 to 28. The 19 number is not defined on the correlation curve of the instrument. The minimum value on the correlation curve of rebound hammer is 22 that corresponds to fc'= 1,500 psi. It is therefore inferred that equivalent cylinder compressive strength of concrete at the said locations is less the 1,500 psi. Similarly the strength corresponding to rebound number 28 is fc'= 3,120 psi Therefore, the quality of concrete at locations corresponding to Test Mark Nos. 25, 29, 31, 33, 34, 35, 36 and 37 is classified as poor to fair concrete.

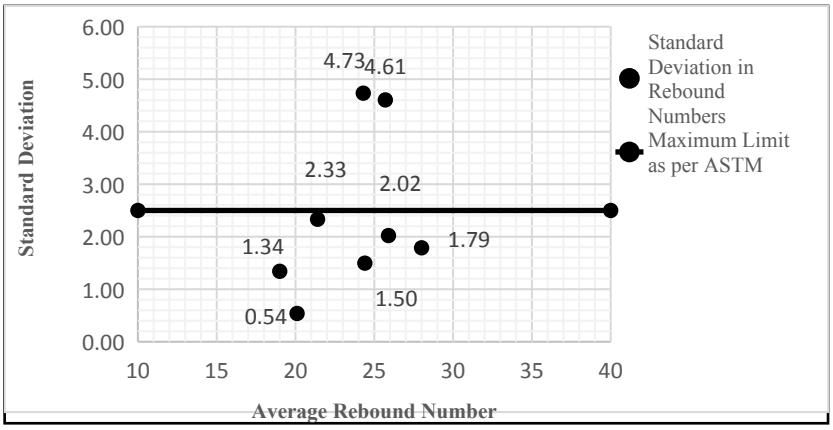


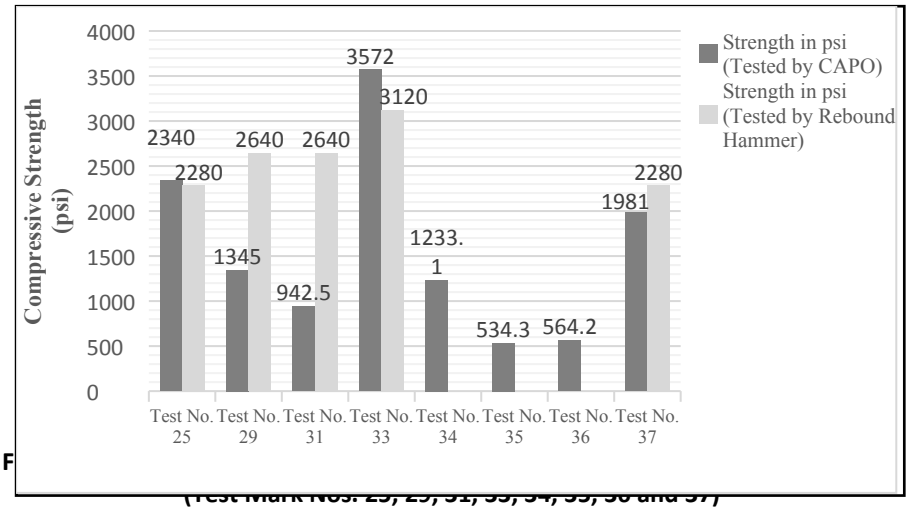
Fig. 21: Average Rebound Number VS Standard Deviation (Test Mark Nos. 25, 29, 31, 33, 34, 35, 36 and 37)

The CAPO Test results at Test strength of concrete is less than than of minimum design strength requirement of 2,500 psi as per ACI Code 318-14.

However the test Mark Nos. 33 satisfy both minimum strength required as per ACI Code 562-19 as well as minimum design strength requirement for structural element.

% Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by CAPO Test is lower than tested by Rebound Hammer and vice versa

The comparative strength of CAPO and Rebound Hammer in percentage are as follows:



F

(Test Mark Nos. 25, 29, 31, 33, 34, 35, 36 and 37)

	Test No. 25	Test No. 29	Test No. 31	Test No. 33	Test No. 34	Test No. 36	Test No. 37
Compressive Strength by CAPO Test	2,340	1,345	942.5	3,572	1,233.1	564.2	1,981
Compressive Strength by Rebound Hammer	2,280	2,640	2,640	3,120	0	0	2,280
Difference in %	2.56	-96.2	-180.1	12.6	-	-	-15

Beams in Framed Structure (Ground Floor)

The test results for 03 nos. beams (Framed Structure, Ground Floor) shown in Table **III/h** are graphically represented in Figs. 23 and 24. The standard deviation of the rebound readings at Test Mark Nos. 10, 12 and 14 are 2.62, 2.37 and 3.33 respectively. The average standard deviation of all tests is 2.78 which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are scattered.

The average rebound number for Test Mark Nos. 10, 12 and 14 are in the range of 31 to 36. The 31 number corresponds to compressive strength fc'= 3,480 psi while that of 36 is fc'= 5,040 psi. Therefore, the quality of concrete at this location is classified as good layer concrete.

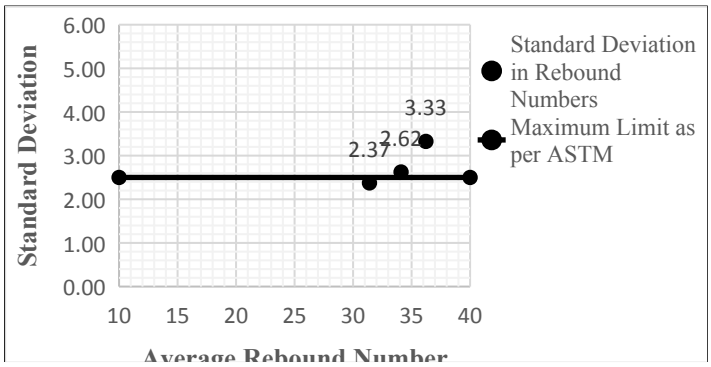


Fig. 23: Average Rebound Number VS Standard Deviation (Test Mark Nos. 10, 12 and 14)

The CAPO Test results at Mark Nos. 12 and 14 satisfy both minimum strength requirement as per ACI Code 562-19 as well as minimum design strength requirement of structural element as per ACI Code 318-14. However the CAPO Test result at Mark No. 10 indicate that the cube compressive strength of concrete is less than 3,000 psi (Minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

% Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by CAPO Test is lower than tested by Rebound Hammer and vice versa

The comparative strength of CAPO and Rebound Hammer in percentage are as follows:

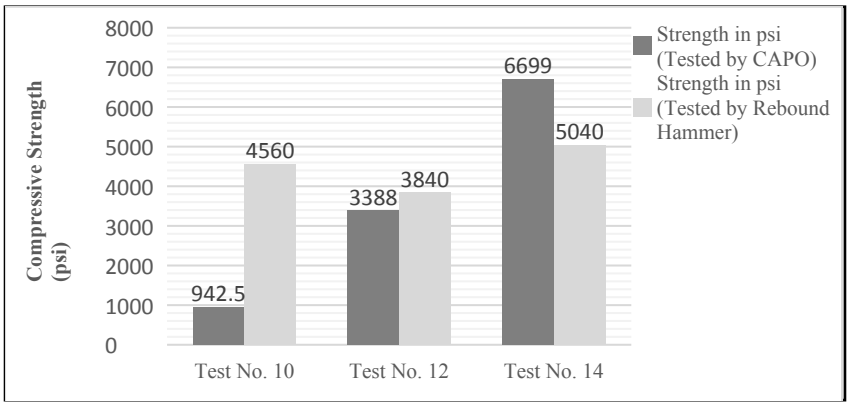


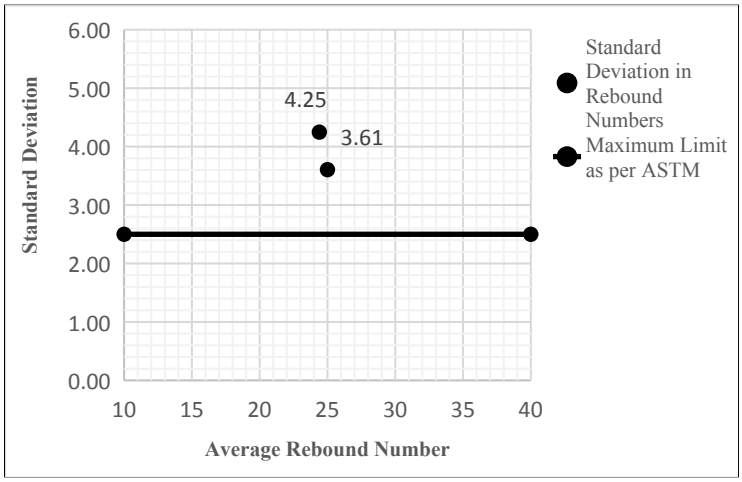
Fig. 24: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 10, 12 and 14)

	Test No. 10	Test No. 12	Test No. 14
Compressive Strength by CAPO Test	942.5	3388	6699
Compressive Strength by Rebound Hammer	4560	3840	5040
Difference in %	-383.8	-13.3	24.7

Beam in Frame Structure (First Floor)

The test results for 02 nos. beams (Framed Structure, First Floor) shown in Table **III/i** are graphically represented in Figs. 25 and 26. The standard deviation of the rebound readings at Test Mark Nos. 26 and 30 are 3.61 and 4.25 respectively. The average standard deviation of all tests is 3.93 which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are scattered.

The average rebound number for Test Mark Nos. 26 and 30 are in the range of 24 to 25. The 24 number corresponds to compressive strength fc'= 2,280 psi while that of 25 is fc'= 2,400 psi. Therefore, the quality of concrete at this location is classified as fair concrete.



ig. 25: Average Rebound Number VS Standard Deviation (Test Mark Nos. 26 and 30)

The CAPO Test results at Mark No.26 and 30 indicate that the cube compressive strength of concrete is less than 3,000 psi (minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

% Difference of concrete strength tested by CAPO and Rebound Hammer is summarized as under where negative value indicates that strength tested by capo test is lower than tested by Rebound Hammer and vice versa

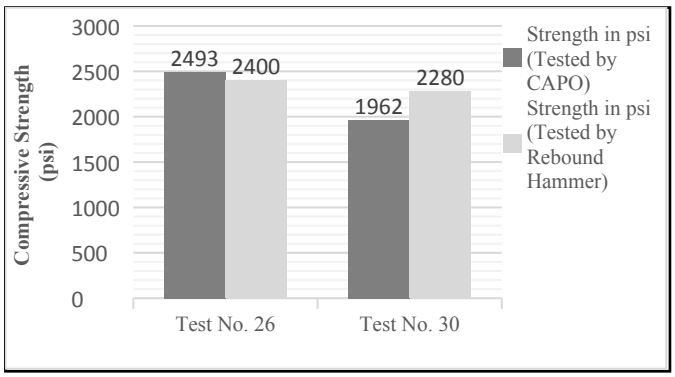


Fig. 26: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 26 and 30)

The comparative strength of CAPO and Rebound Hammer in percentage are as follows:

	Test No. 26	Test No. 30
Compressive Strength by CAPO Test	2,493	1,962
Compressive Strength by Rebound Hammer	2,400	2,280
Difference in %	3.7	-16.2

Slab in Load Bearing Structure (Ground Floor)

The 02 nos. test results for slab (Load Bearing Structure, Ground Floor) shown in Table **III/j** are graphically represented in Figs. 27 and 28. The standard deviation of the rebound readings at Test Mark Nos. 06 and 17 are 1.11 and 1.35 respectively. The average standard deviation of all tests is 1.23 which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are not too scattered.

The average rebound number for Test Mark Nos. 06 and 17 are in the range of 20 to 21. The 20 number is not defined on the correlation curve of the instrument at an instrument angle of +90°. The minimum value on the correlation curve of rebound hammer is 27 that corresponds to fc'= 1,600 psi. It is therefore inferred that for 20 to 21 rebound range the equivalent cylinder compressive strength of concrete at the said location is less than 1,600 psi. Therefore, the quality of concrete at this location is classified as fair concrete.

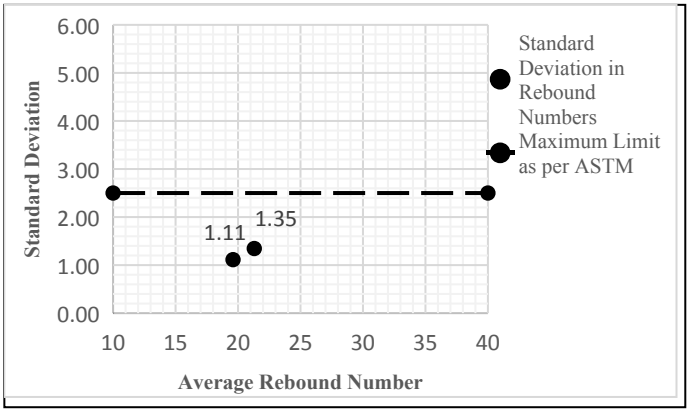


Fig. 27: Average Rebound Number VS Standard Deviation (Test Mark Nos. 06 and 17)

The CAPO Test results at Mark Nos. 06 and 17 indicate that the cube compressive strength of concrete is less than 3,000 psi (minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the rebound hammer.

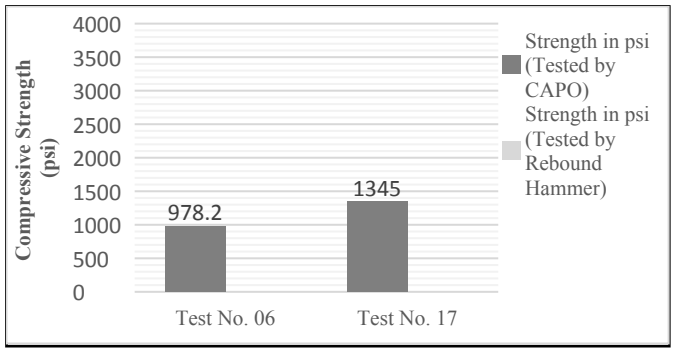


Fig. 28: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 06 and 17)

Slab on Load Bearing Structure (First Floor)

02 nos. test results for slab (Load Bearing Structure, First Floor) shown in Table **III/k** are graphically represented in Figs. 29 and 30. The standard deviation of the rebound readings at Test Mark Nos. 21 and 23 are 2.33 and 4.0 respectively. The average standard deviation of all tests is 3.26 which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are too scattered.

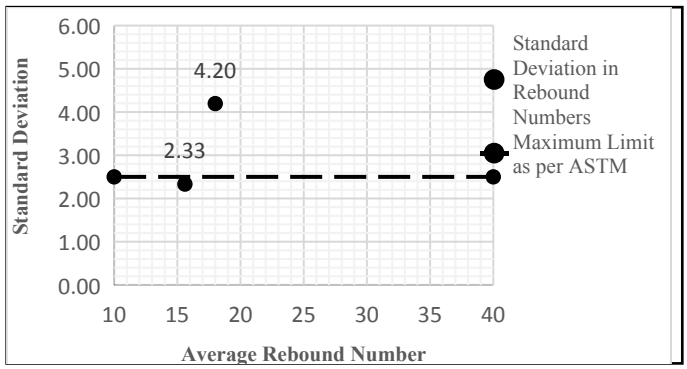


Fig: 29: Average Rebound Number VS Standard Deviation (Test Mark Nos. 21 and 23)

The average rebound number for Test Mark Nos. 21 and 23 are in the range of 16 to 18. The 16 number is not defined on the correlation curve of the instrument at an instrument angle of +90⁰. The minimum value on the correlation curve of rebound hammer is 27 that corresponds to fc'= 1,600 psi. It is therefore inferred that for 16 to 18 rebound range, the equivalent cylinder compressive strength of concrete at the said location is less than 1,600 psi. Therefore, the quality of concrete at this location is classified as poor concrete.

The CAPO Test results at Mark Nos. 21 and 23 indicate that the cube compressive strength of concrete is less than 3,000 psi (minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the rebound hammer.

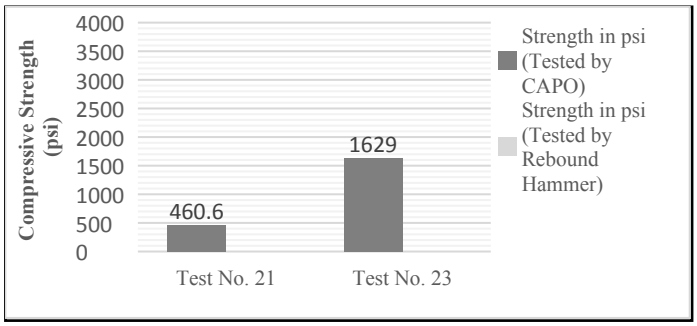


Fig. 30: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark Nos. 21 and 23)

Slab on Framed Structure (Ground Floor)

01 no. test results for slab (Framed Structure, Ground Floor) shown in Table **III/l** are graphically represented in Figs. 31 and 32. The standard deviation of the rebound readings at Test Mark Nos. 18 are 3.07, which is more than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are too scattered.

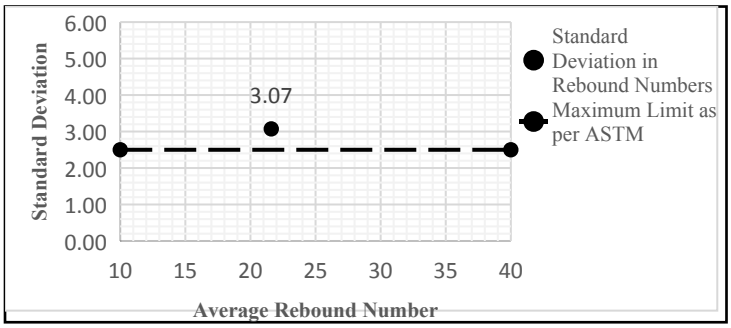


Fig. 31: Average Rebound Number VS Standard Deviation (Test Mark Nos. 18)

The average rebound number for Test Mark Nos. 18 and 22. The 22 number is not defined on the correlation curve of the instrument at an instrument angle of +90⁰. The minimum value on the correlation curve of rebound hammer is 27 that corresponds to fc'= 1,600 psi. It is therefore inferred that for 22 rebound number, the equivalent cylinder compressive strength of concrete at the said location is less than 1,600 psi. Therefore, the quality of concrete at this location is classified as fair concrete.

The CAPO Test results at Mark No. 18 indicate that the cube compressive strength of concrete is less than 3,000 psi (minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500psi of structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the Rebound Hammer.

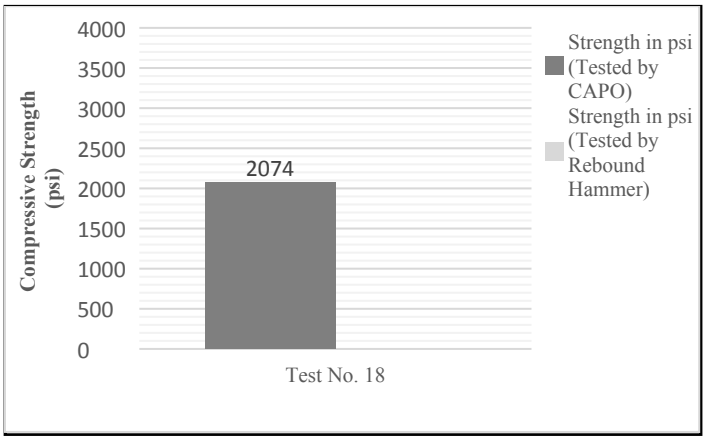


Fig. 32: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark No. 18)

Slab on Framed Structure (First Floor)

01 no. test results for slab (Framed Structure, Ground Floor) shown in Table **III/m** are graphically represented in Figs. 33 and 34. The standard deviation of the rebound readings at Test Mark Nos. 22 are 1.28, which is less than 2.5 (maximum allowable standard deviation as per ASTM C-805) which implies that the test data are not scattered.

The average rebound number for Test Mark Nos. 22 are 21. The 21 number is not defined on the correlation curve of the instrument at an instrument angle of $+90^0$. The minimum value on the correlation curve of Rebound Hammer is 27 that corresponds to fc'= 1,600 psi. It is therefore inferred that for 21 rebound number, the equivalent cylinder compressive strength of concrete at the said location is less than 1,600 psi. Therefore, the quality of concrete at this location is classified as fair concrete.

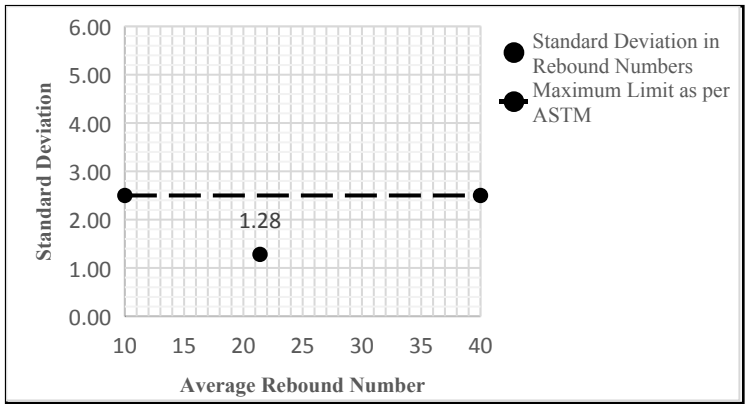


Fig. 33: Average Rebound Number VS Standard Deviation (Test Mark No. 22)

The CAPO Test results at Mark No. 22 indicate that the cube compressive strength of concrete is less than 3,000 psi (minimum strength required as per ACI Code 562-19) as well as less than of minimum design strength requirement of 2,500 psi of structural element as per ACI Code 318-14.

Note: The value of compressive strength tested by Rebound Hammer has not been plotted in the above figure as the hammer reading is not defined/not applicable on the correlation curve of the rebound hammer.

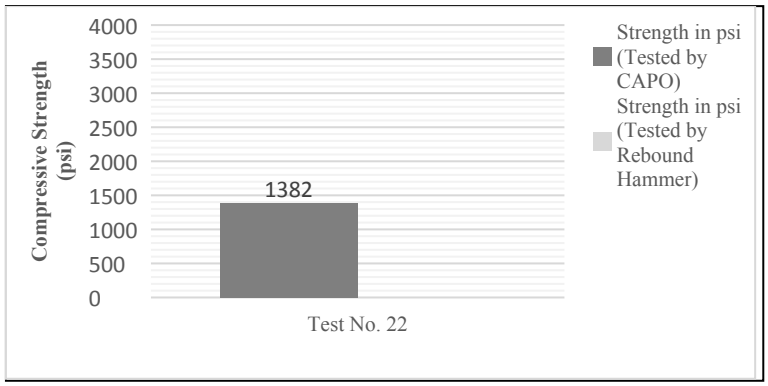


Fig. 34: Compressive Strength of Concrete Tested by CAPO and Rebound Hammer (Test Mark No. 22)

IV. CONCLUSION

The accuracy of Rebound Hammer Test cannot be relied totally as compared to the CAPO Test Method. The Rebound Hammer Test has its limitations and can only give a rough idea of the quality of concrete and surface hardness. Since CAPO Test Method is time consuming and relatively expensive, the Hammer Test can cover large areas of investigations in lesser time for identifying weak locations requiring more detailed investigative tests viz. CAPO Tests. Hence, the Rebound Hammer tests are recommended only for preliminary testing to compliment detailed investigations.

ACKNOWLEDGMENT

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