EVALUATING CONCRETE COMPRESSIVE STRENGTH USING NON-DESTRUCTIVE TEST TECHNIQUES

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ABSTRACT

Non-destructive testing procedures (NDTs) are recognized as an effective method to evaluate and ensuring concrete quality, particularly in context with of existing structures. The current study in the subject is aimed at developing reliable predictive models for the compressive strength of concrete using non-destructive testing methods (NDTs). Nevertheless, many developed models rely on calibration and/or historical context of concrete, such as mixing percentage, curing history, mechanical properties, and so on, limiting their applicability for in-situ forecasts. The objective of the study is to build up a relationship between NDT and destructive test (DT) results for concrete compressive strength. A total of 180 nos cylindrical (150mm dia×300mm height) specimens were cast using several concrete grades with varied strengths of 15 to 60 MPa complying BS 8500-2. NDTs including ultrasonic pulse velocity (UPV) and rebound hammer (RH) test were carried out on cylindrical and core cylindrical specimens in accordance with BS EN 12504-4 and BS 1881-202:1986, respectively. For the experimental part of this study, core cylinder of dia 100mm were cut from the standard cylinders. NDTs were conducted on concrete specimen before DT tests after curing times of 7, 28, and 90 days at room temperature. Both RH and core strengths were well comparable and observed to be lower than the cylinder strength ranging from 3-8% and 8-11% respectively. The Rebound numbers (RN) At 28 days show the concrete quality varied from good to excellent. The UPV test results of all grades of concrete were more than 4000m/s indicating the concrete quality varied from very good to excellent for both core and cylindrical specimens. Based on test results, predictive equations corelating compressive strength of cylinder and core cylinder to RH and UPV values were developed. Predictive equations of compressive strength with RH values provides higher accuracy (e.g., $R^2 \geq 0.99$) than the predictive equation of compressive strength made with UPV values (e.g., $R^2 \geq 0.93$). Thus, professionals can employ these predictive equations to assess the compressive strength of any existing structures without inducing any damage to the integrity of the structure.

Keywords: *Non-destructive Test (NDT), rebound Hammer (RH), ultrasonic pulse velocity (UPV), core concrete, compressive strength.*

1. INTRODUCTION

Concrete is a mixture of material made up of binding agent (cement), fine aggregate (sand), coarse aggregate (gravel or granite) and water complying with the specific mix ratios (Ajagbe et al., 2018). It is the most important and irreplaceable building material due to its high compressive strength and resilience against immense load without random failure. The strength of concrete particularly its compressive strength is its important property as all other properties are directly or indirectly related to it. There are two methods to measure the strength of a concrete structure, namely destructive tests (DT) and non-destructive tests (NDT). The more accurate and effective method for determining compressive strength is the destructive test but they also have an impact on the structure's durability and life span. (Erdoğdu et al., 2018). On the other hand, NDT provides tests that do not cause any harm or do not affect the structure's behavior thus leaving the structure in satisfactory condition. However, an efficient NDT is one that can be used on concrete structures in site and have portability and simplicity of operation with minimum cost. Leshehinsky (A. Leshchinsky, 1991) mentioned several various advantages of NDTs as compared to core concrete that include, (i) reduction in labour construction of testing and relevant preparatory works, (ii) a lesser degree of structural damage, (iii) analyzing the concrete strength where core drilling is impractical or not feasible etc. However, these advantages are null and void if the outcomes of non-destructive testing (NDT) are neither reliable nor indicative of the true strength of the tested area of the structure.

The use of non-destructive testing includes the quality control of pre-cast components such as slab, beam, column etc; investigating the workmanship associated with mixing and casting, determination of cracks, voids and honey combing, leakage and similar effect in a concrete structure; figuring out the potential failure of concrete structure; observing prolonged change in characteristics and ageing management of concrete structures.

The rebound hammer (RH) test is described in ASTM C805 (American Society of Testing and Material (ASTM), 2002) and BS 1881: Part 202 (BSI, 1986). RH test is a hardness test and the test results are expressed as a rebound number (RN). Although easier to use, the test is associated with complex impact problem due to stress-wave propagation (Akashi & Amasaki, 1984). The test requires precise selection and preparing of the concrete surface and is performed by an abrasion stone. The hammer plunger must strike the concrete surface perpendicularly. At least 10 RH test must be conducted at each test area. No unique relationship exists between hardness and strength although the experimental data relationship can be found for a given grade of concrete. However, such relationship depends on several factors affecting the strength of concrete that includes degree of saturations, carbonations, temperature, location of rebar, type of aggregate, mix ratios and type of surface finish. Amasaki (S. Amasaki, 1991) pointed out the effect of carbonation and Grieb (Grieb, 1958) showed the influences on of aggregate type in concrete on RN and hence the predicted strength. Because of the interference of the aggregate and voids immediately below plunger, it is necessary to take 10-12 reading (Neville & Brooks, 2010). As RN indicates the surface strength of concrete, BS 1881; Part 2002 (BSI, 1986) suggest that RN is an indication of about the top 30mm depth of concrete. Teodoru (Teodoru, 1989) reported that the RH measurements are only applicable to the top concrete layer having thickness of 30 to 50 mm.

The UPV method is a renowned non-destructive testing approach that is measured by the velocity of compressive stress waves (P-waves). The essential idea of the UPV test method is the velocity at which ultrasonic pulses travel through a material. For concrete construction works, The findings of UPV test are used to evaluate the uniformity; to detect cracks and voids; to maintain the quality; to detect depth of crack, conditions, and deteriorations etc. Table 1 depicts the use of UPV to categorize the quality of concrete (Whitehurst, 1951).

Core tests are commonly utilized to determine whether concerned concrete in a new structure meets strength acceptance standards. It is also important in determining the in-situ concrete strength within an existing structure for the purpose of structural capacity evaluation. However, the main objective of this study is to develop a relationship between NDT results with the compressive strength of concrete. This study will correlate the results of RH and UPV test with the compressive strength of concrete that will assist for investigating the in-situ concrete quality of the existing structure. Table 1 shows the concrete quality based on UPV.

Table 1: Concrete quality based on UPV

Pulse Velocity	Concrete Quality
>4.0 km/s	Very Good to Excellent
3.5 km/s – 4.0 km/s	Good to Very Good, slide porosity may exist
3.0 km/s – 3.5 km/s	Satisfactory, but loss of integrity is suspected
< 3.0 km/s	Poor, loss of integrity exist

2. INVESTIGATION PROGRAM

3. Materials

In this study, Ordinary Portland Cement (OPC) was used to cast the concrete test specimens. The properties of OPC is given in Table 2.

Table 2: Physical properties and chemical composition of OPC

Characteristics	Value
Blaine's Specific Surface (cm^2/gm)	4000
Normal Consistency	25%
Soundness by Le Chatelier's Test (mm)	5
Specific gravity	3.15
Setting Time	
Initial (min)	150
Final (min)	230
Compressive Strength	
3 days (MPa)	16.4
7 days (MPa)	22.7
28 days (MPa)	30.7
Calcium Oxide (CaO)	64%
Silicon Dioxide (SiO_2)	21%
Aluminum Oxide (Al_2O_3)	6%
Ferric Oxide (Fe_2O_3)	3.5%
Magnesium Oxide (MgO)	1.2%
Sulphur Trioxide (SO_3)	2.5%
Loss on ignition	1.2%
Insoluble matter	0.6%

Coarse aggregate (CA) were crushed stone chips of 19mm down grade with specific gravity (SG) 2.74. The fine aggregate (FA) were natural Sylhet sand with SG of 2.61 and FM of 2.51. All the aggregates were washed with tap water and made SSD condition before use in making concrete. A Superplasticizer (SP) MasterGlenium SKY 8632 based on polycarboxylic ether and containing no chloride additive was used to achieve high strength concrete. Specimens were cast and cured using portable/tap water.

4. Concrete Mix Design

A total 10 sets of concrete mixes were designed to accomplish the goal of study. As per BS 8500-2 British/ European standards, a total of 180 nos concrete cylinders (150mm dia×300mm height) were cast from C15, C20, C25, C30, C35, C40, C45, C50, C55 and C60 grades concrete. The summary of 10 mix design is shown in Table 3.

Table 3: Mix Proportion for 1 m³ Concrete for different Grades of Concrete

Concrete Grade	OPC kg/m³	w/c ratio	Water kg/m³	Coarse Aggregate kg/m³	Fine aggregate kg/m³	Admixture kg/m³
C15	370.00	0.50	185.00	1070.00	795.00	-
C20	410.00	0.45	185.00	1070.00	755.00	-
C25	450.00	0.40	180.00	1070.00	715.00	-
C30	480.00	0.38	180.00	1070.00	680.00	-
C35	500.00	0.36	180.00	1070.00	660.00	-
C40	510.00	0.34	175.00	1085.00	625.00	5.10
C45	520.00	0.34	175.00	1085.00	615.00	5.20
C50	530.00	0.33	175.00	1085.00	605.00	5.30
C55	540.00	0.33	175.00	1085.00	595.00	5.40
C60	550.00	0.32	175.00	1085.00	585.00	5.50

5. Specimen Casting and Testing Process

The specimens were cast from ten different mixes and tested at 7, 28 and 90 days of curing period. For each type of mix, OPC, coarse aggregate, and fine aggregate of required amount were mixed thoroughly. Water was added after one minutes of dry mixing and the mix contents were mixed properly for further three minutes. The 150mm dia×300mm height cylindrical moulds were filled in three equal layers and compacted at each layer. The specimens were demoulded after 24 hour and the exposed to curing tanks. After curing for specific periods, the specimens were removed from water and prepared for testing at SSD condition. The test conducted includes RH, UPV, core test and compressive strength test. RH test and UPV test was performed complying BS 1881-202:1986 and BS EN 12504-4 respectively. Cores (Dia 100mm & length 1.9 to 2.1 times dia) were cut from 150 dia standard cylinders for both NDT and DT test. Figure 1 shows the core cutting process and Figure 2 and Figure 3 show the RH and UPV test of the specimens, respectively.

Figure 1: Core cutting process

Figure 2: Rebound Hammer (RH) test performed over core cylinder

Figure 3: Ultrasonic Pulse Velocity (UPV) test performed over cylinder

6. RESULTS AND DISCUSSION

The test results were analysed and presented in graphical form to make it easy to interpretate. Predictive equations were developed at different ages of concrete for cylinder and core strength based on NDT results. Figure 4 and Figure 5 shows the compressive strength of cylinders and core cylinders respectively for different grades of concrete at the curing age of 7, 28 and 90 days.

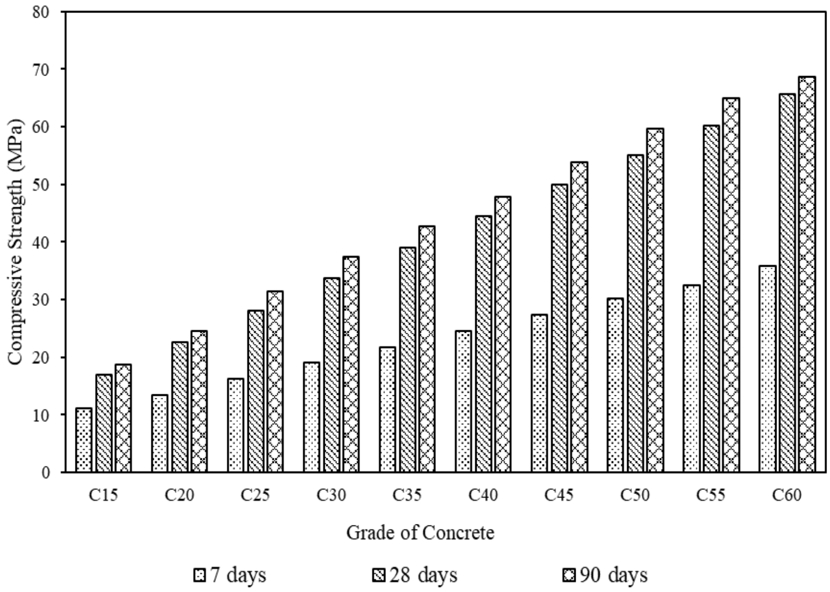

Figure 4: Compressive strength of cylinders for various grades of concrete at the curing age of 7, 28, and 90 days.

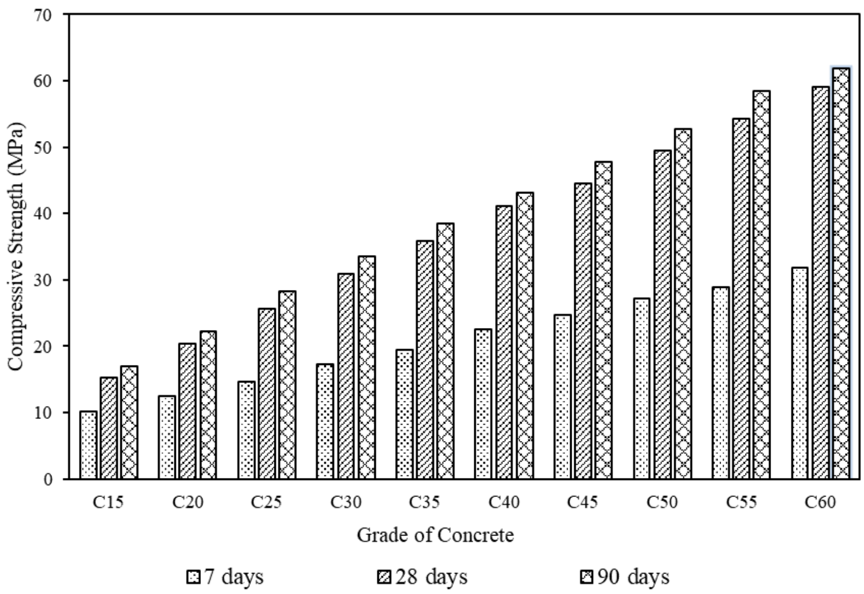

Figure 5: Compressive strength of core cylinders for various grades of concrete at the curing age of 7, 28, and 90 days.

On the other hand, Figure 6 and Figure 7 show the predicted RH strength of cylinder and core cylinder concrete strength respectively at different curing ages.

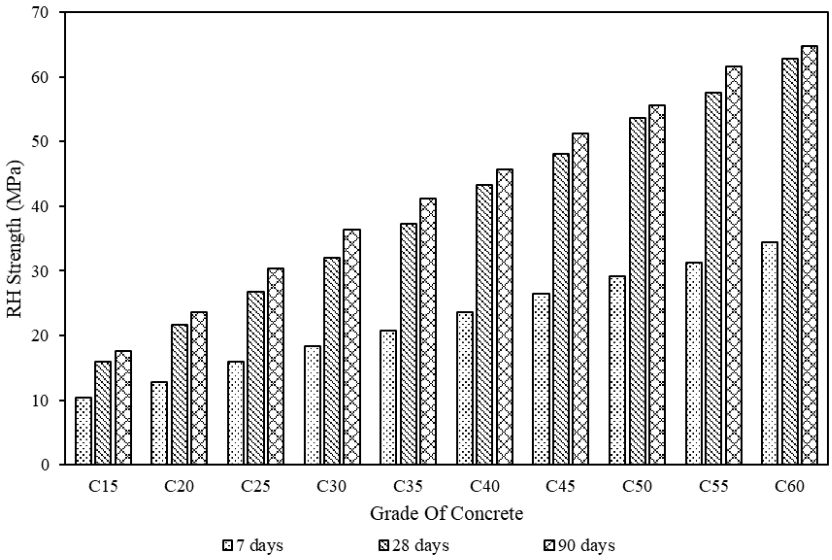

Figure 6: Rebound Hammer (RH) strength of cylinders for different grades of concrete at the curing age of 7, 28, and 90 days.

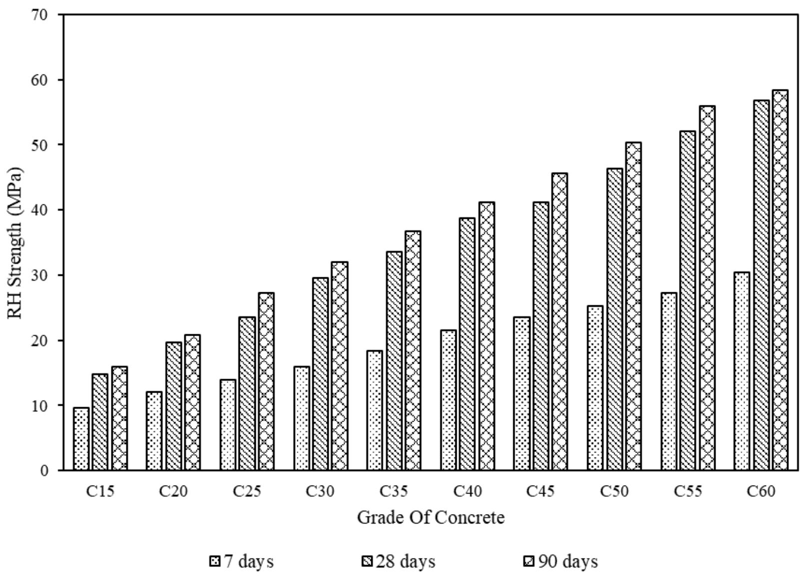

Figure 7: Rebound Hammer (RH) strength of core cylinders for different grades of concrete at the curing age of 7, 28, and 90 days.

Also, Figure 8 and Figure 9 show the UPV values of the same grades of concrete for cylinder and core cylinder concrete, respectively.

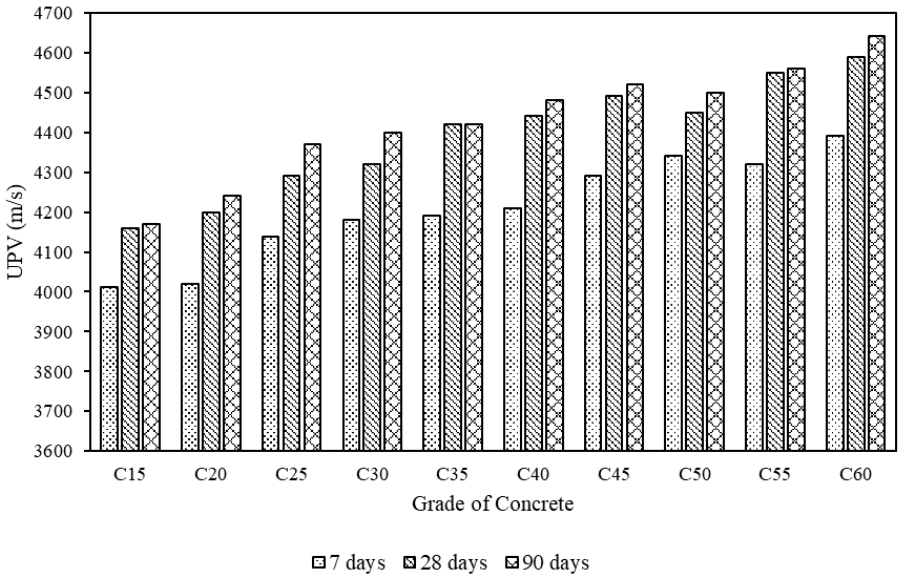

Figure 8: UPV of cylinders for different grades of concrete at the curing age of 7, 28, and 90 days.

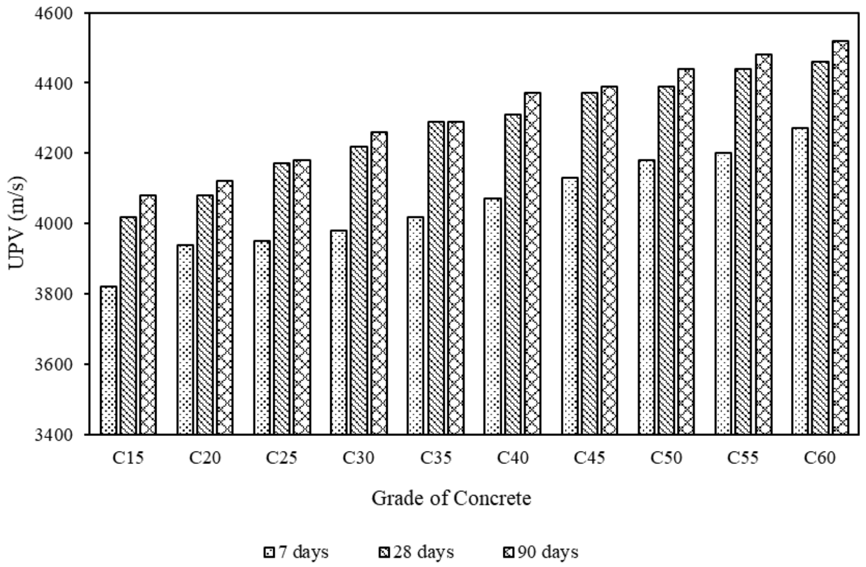

Figure 9: UPV of core cylinders for different grades of concrete at the curing age of 7, 28, and 90 days.

Figure 10 and Figure 11, respectively showing the relationship between compressive and RH strength for cylinder and core cylinder.

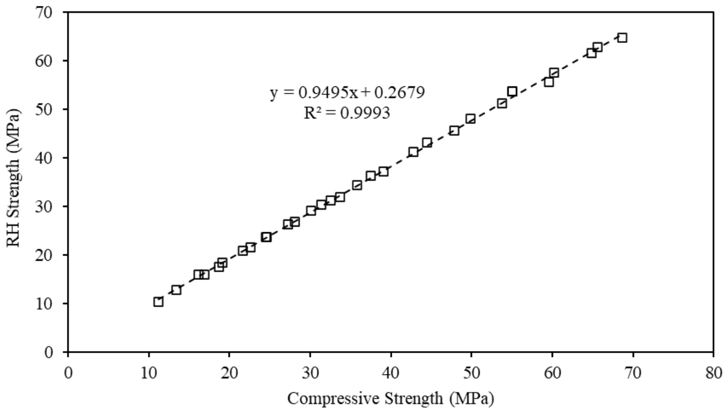

Figure 10: Relation between compressive strength and hammer strength for cylinders at the curing age of 7, 28, and 90 days.

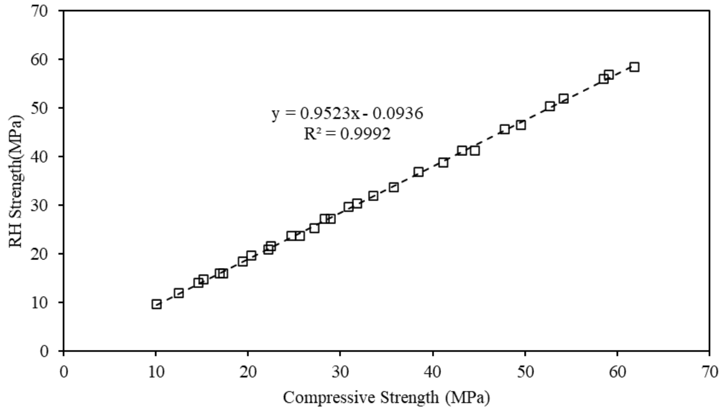

Figure 11: Relation between compressive and hammer strength for core cylinder at the curing age of 7, 28, and 90 days.

And Figure 12 and Figure 13 show the relation between compressive strength and UPV for cylinder and core cylinder, respectively.

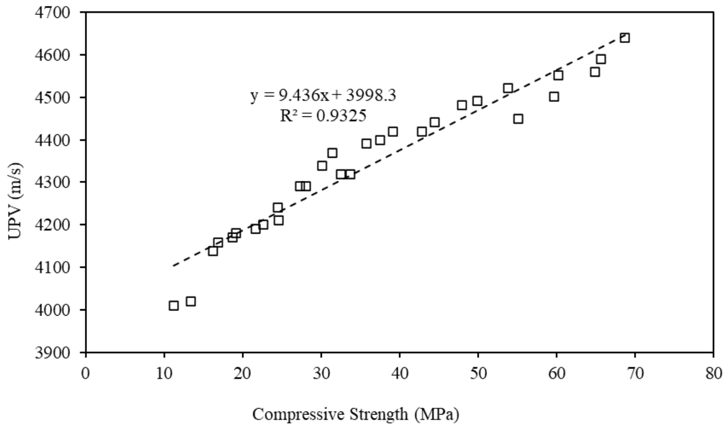

Figure 12: Relation between compressive strength and UPV for cylinder at 7, 28, and 90 days curing.

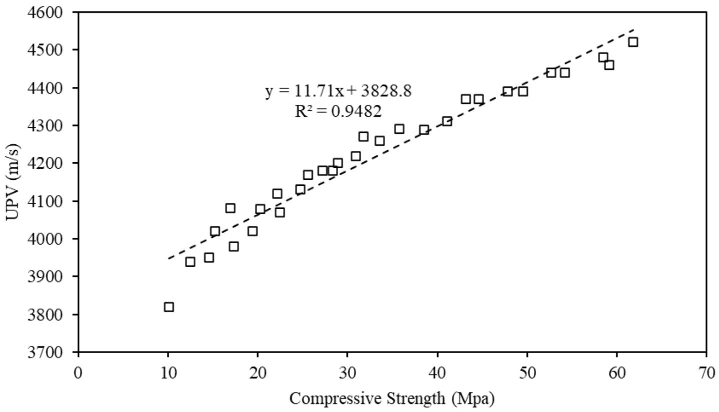

Figure 13: Relation between compressive strength and UPV for core cylinder at 7, 28, and 90 days curing.

Also, exponential relation between UPV and RH strength for cylinder and core cylinder were developed as shown in Figure 14 and Figure 15 respectively whereas Figure 16 shows the relation between the compressive strength of cylinder and core cylinder. The regression coefficient (R^2) values for all the developed relations vary within the acceptable limits (i.e., 0.957 to 0.999).

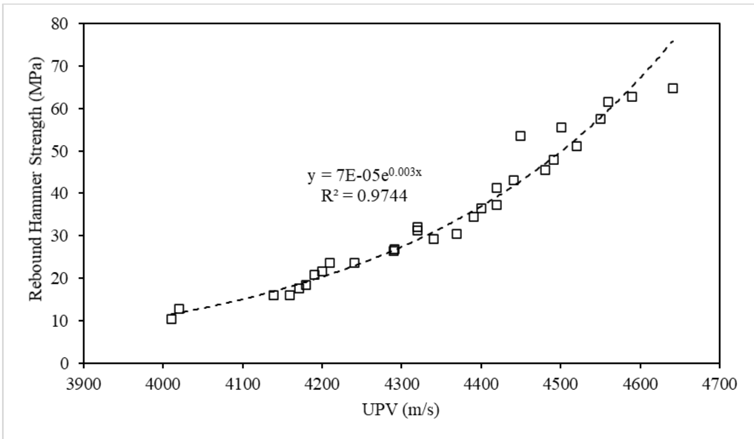

Figure 14: Exponential relation between UPV and RH strength for cylinder at 7, 28, and 90 days curing.

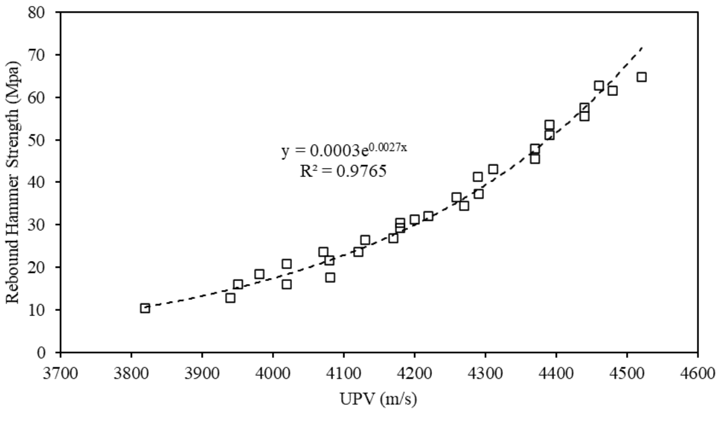

Figure 15: Exponential relation between UPV and RH strength for core cylinder at 7, 28, and 90 days curing.

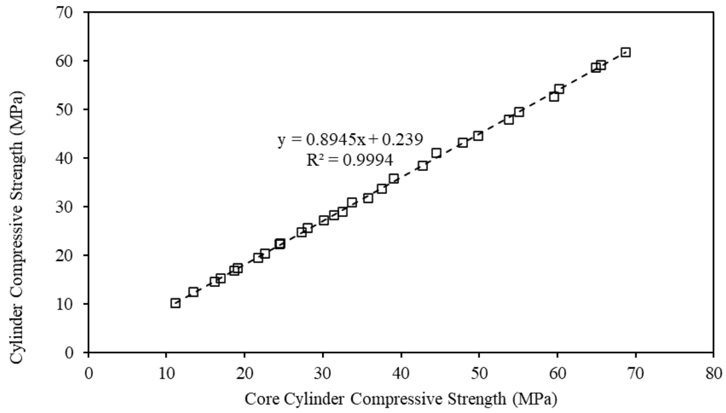

Figure 16: Linear relation between cylinder compressive strength and core cylinder compressive strength at 7, 28, and 90 days curing.

From the analysis of the test data and developed relations, it is seen that the strength obtained from Rebound hammer and core specimen in well comparable with the standard cylinder crushing strength. The strength obtained from RH predictions is found lower than the cylinder compressive strength for all grades of concrete by an amount 3 to 8%. On the other hand, core strength is found lower than the cylinder strength by an amount ranging from 8 to 11% for all grades of concrete over the period up to 90 days. Moreover, the RH number at early age (7days) shows the concrete quality varied from poor to good for all concrete grades for both cylinder and core cylinder. However, the corresponding Rebound number (RN) at 28 and 90 days shows the concrete quality varied from good to excellent for all grades of concrete. The UPV test results show the concrete quality varied from very good to excellent for both cylinder and core concrete.

7. CONCLUSIONS

On the basis of limited numbers of test findings and variables studied, the following observation/conclusions can be drawn,

(i) The Rebound numbers (RN) at 7 days show the concrete quality varied from poor to good whereas the RN values at 28 and 90 days show the concrete quality varied from good to excellent for all grades of concrete.

(ii) The UPV test results show the concrete quality varied from very good to excellent for both cylinders and core cylinders at all curing ages.

(iii) The strength obtained from RH and core cutting specimens is found to be well comparable with cylinder crushing strength. However, RH strength is found lower (about 3% to 8%) than the cylinder strength for all grades and curing ages of concrete. Whereas core strength is found lower (about 8% to 11%) than the cylinder strength.

(iv) Some linear and exponential relations are developed based on NDT and DT results with adequate accuracy, i.e., $R^2 \geq 0.95$ and hence can be used to predict the strength of the existing structures.

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