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Research Article

INVESTIGATION OF FACTORS AFFECTING CORE COMPRESSIVE STRENGTH AND NON-DESTRUCTIVE TESTING OF CONCRETE

Nihat KABAY*[1], Fevziye AKÖZ[2]

[1]*Yildiz Technical University, Dept. of Civil Engineering, Esenler-ISTANBUL;* ORCID: 0000-0003-4587-7095
[2]*Hasan Kalyoncu University, Department of Civil Engineering GAZIANTEP;* ORCID: 0000-0002-0042-4079

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ABSTRACT

This paper investigates several factors such as the effect of drilling, moisture content and presence of reinforcement on the compressive strength of core samples and the effect of reinforcement and concrete age on the rebound number and ultrasonic pulse velocity of concrete. Test results show that the effect of moisture on core strength was lower than the other factors. Due to the drilling effect, the core compressive strength was reduced by 11%. The presence and the number of reinforcement in core samples significantly affected the compressive strength. On average, the reduction in strength of cores that contain single and two bars was found as 12% and 16% respectively. The rebound number and ultrasonic pulse velocity values increased with the age of concrete. The reinforcement did not have a significant effect on the non-destructive test results. However, direct and indirect ultrasonic pulse velocity results differed significantly and on average this ratio was found to be 1.16 and 1.17 for plain and reinforced concrete members, respectively.
Keywords: Core correction factors, compressive strength, non-destructive testing.

1. INTRODUCTION

Concrete is one of the major building materials used in the construction industry. One of the reasons for the wide use of reinforced concrete structures in the modern world is the availability of its ingredients. Therefore, in most parts of the world, the number of reinforced concrete structures has been increasing day by day. However, like every material, reinforced concrete has a service life and in some certain cases estimating the in-situ compressive strength of existing reinforced concrete structures becomes essential. One of these cases is the repair and strengthening of the structure due to i.e. seismic movements (earthquakes) where a detailed study should be performed including the assessment of in-situ concrete compressive strength. EN 13791 [1] standard addresses the following examples where the in-situ strength of concrete might be required as: when an existing structure is to be modified or redesigned; to assess structural adequacy when doubt arises about the compressive strength in the structure due to defective workmanship, deterioration of concrete due to fire or other causes; when an assessment of the in-situ concrete strength is needed during construction; to assess structural adequacy in the case of non-conformity of the compressive strength obtained from standard test specimens. The

* Corresponding Author: e-mail: nkabay@yildiz.edu.tr, tel: (212) 383 52 44

estimation of concrete strength in existing structures is usually determined by uniaxial compression tests carried out on cylindrical specimens extracted from the structural elements. However there are several factors that influence the compressive strength of core samples. Some of these factors are referred in the standards [1-3]. These factors can be named as; moisture content, direction of coring, presence of reinforcement, core diameter, core length to diameter ratio, flatness and capping of core end surfaces, effect of drilling, etc. Therefore, it is important to consider these factors during the assessment of core compressive strength.

Meininger et al. [4] and Bar tlett and MacGregor [5] studied the effect of length to diameter ratio on core compressive strength and developed correction factors for different length to diameter ratios. Bartlett and MacGregor [6] conducted an experimental research on the effect of core diameter on the compressive strength. They analyzed the test results of 50, 100 and 150 mm diameter cores from available literature and found conversion factors according to core diameter. Bartlett [7] finally developed a two-step method for converting core strength to the in-place strength using strength correction factors. The first step was the conversion of a non-standard core to a standard core and the second step was the conversion of standard core strength to the equivalent in-place strength. Yip and Tam [8] conducted an intensive experimental study on 50 mm and 100 mm core specimens. Their research showed that the factors which affect the strength of l00 mm diameter cores also influence 50 mm diameter cores to similar extents and that for the same grade of concrete, the measured strengths of 50 mm diameter cores did not differ significantly from those of l00 mm diameter cores tested under the same conditions. They also noted that small cores offer considerable economic and practical advantages such as reduced cutting effort, time and damage, and wider spread of sample location. However, EN 12504-1 [3] states that the ratio of the maximum aggregate size in the concrete to the diameter of the core has a significant influence on the measured strength when it approaches values greater than about 1:3 and gives numerical information on how the aggregate size and core diameter affect core strength. The same standard also gives some equations to calculate the correction factors for core samples with different length to diameter ratios (Eq. (1)) and for core samples that contain single or multiple reinforcing bars (Eq. (2)), aiming to determine the standard core strength.

$$K_{is,cube(cylinder)} = \frac{2.5(2.0)}{1.5+1/\alpha} \tag{1}$$

where α represents the length to diameter ratio of the core sample. In Equation 1, the standard suggests the use of 2.5 and 2.0 for cube and cylinder conversion, respectively.

$$K_s = 1.0 + 1.5\left[\frac{\sum(\varphi_r \times h)}{\varphi_c \times L}\right] \tag{2}$$

where φ_r, φ_c, h and L represents the diameter of the bar, the diameter of the core, the distance of axis of bar from the nearer end of core and the length of the core respectively.

Although testing core samples is the most reliable way to determine the compressive strength of concrete in existing structures, it is usually not feasible and/or cost effective to take large amounts of core samples from the structural elements. The experimental study conducted by Masi et al. [9] showed that even after an accurate restoration, the effects of core drilling can be dramatically high in structural elements with very low concrete strength which could remarkably reduce the capacity of the structural elements. Therefore the authors suggested avoiding or limiting core testing on members showing poor quality and using non-destructive tests. Non-destructive test (NDT) methods have been used as supplementary tests which help to compare and control the quality of concrete in different parts of the structure, reduce the number of cores, improve the information about the structure, reduce quality control costs (Pucinotti 2015), and to establish relationships between NDT methods and the core strength [10-15]. The European standard EN 13791 [1], allows the use of rebound hammer (RH), ultrasonic pulse velocity (UPV) and the pull-out tests as NDT methods. The estimation of concrete strength with NDTs has been the topic of many researches and the NDT methods mostly adopted in these experimental researches are the UPV and RH probably because of their simplicity.

NDT methods used in concrete are well documented by Malhotra and Carino [16] where some factors that affect non-destructive testing of concrete are also addressed. The main factors that affect RH measurements can be summarized as the smoothness of test surface; size, shape, and rigidity of the specimens; age of test specimens; surface and internal moisture conditions of the concrete; type of coarse aggregate and cement; and carbonation of the concrete surface [14,17]. The factors that affect UPV can be summarized as the aggregate size, grading, type, and content; type of cement; water to cement ratio; age of concrete; moisture content; presence of reinforcing steel; etc [14,18]. Therefore the NDT measurements require careful selection of test points and quite an experience on how to evaluate the test results, since they are affected by several factors as depicted above.

In the present paper, the factors affecting core compressive strength are experimentally researched. The core diameter and the length to diameter ratio of core specimens was kept constant to mainly focus on the moisture effect, core drilling effect, and reinforcement effect on core compressive strength at different ages. The development of UPV and RH values was also measured on laboratory manufactured plain concrete and reinforced concrete members at the ages of 28, 90 and 180 days. The results are compared with the available literature to evaluate destructive and non-destructive tests.

2. EXPERIMENTAL STUDY

2.1. Materials and Mix Proportions

The materials used in concrete mixes are limestone coarse aggregate with a particle density of 2.88 kg/dm^3, natural river sand with a particle density of 2.63 kg/dm^3, cement and superplasticizer. Maximum particle size of the coarse aggregate and the natural river sand was 16 mm and 4 mm respectively. The type of cement was CEM I 42.5R and its properties are presented in Table 1. A modified polycarboxylate polymer based superplasticizer was used to obtain a slump value of 15 cm. A single type of concrete was used to manufacture plain concrete and reinforced concrete members and mix proportions and fresh concrete properties are shown in Table 2. Reinforced concrete members were constructed using Ø8 mm stirrups and Ø12 mm ribbed bars as shown schematically in Fig. 1.

Table 1. Chemical, physical and mechanical properties of cement

Chemical composition (%)		Physical properties	
Insoluble residue	0.29	Specific gravity	3.12
SiO_2	20.22	Setting time (start, min)	143
Al_2O_3	5.36	Setting time (end, min)	186
Fe_2O_3	3.33	Volume expansion (mm)	2
CaO	64.39	Blaine surface area (cm^2/g)	3470
MgO	1.04		
SO_3	2.44		
K_2O	0.87	Compressive strength	
Na_2O	0.21		
Cl^-	0.03	28 days (MPa)	52.4
Loss of ignition	1.60		
CaO (free)	1.50		

Table 2. Mix proportions and fresh properties of concrete

Cement (kg/m^3)	w/c ratio	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Super plasticizer (kg/m^3)	Slump (cm)	Fresh density (kg/m^3)
290.1	0.45	1267.0	771.7	0.44	15	2460

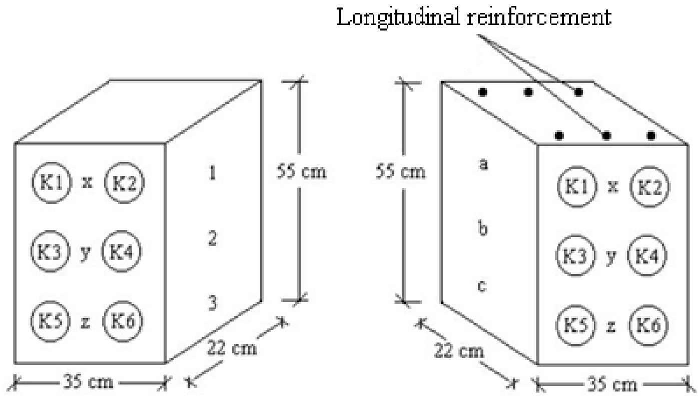

Figure 1. Test locations on (a) concrete and (b) reinforced concrete members.

2.2. Sample Preparation, Curing and Testing Procedure

The development of compressive strength of concrete was determined on 100/200 mm cylindrical samples at 28, 90 and 180 days. The samples were kept in water until the testing date and 3 samples were used to determine the average compressive strength at each age. Three plain concrete and three reinforced concrete members were constructed with dimensions of 220×350×550 mm as shown in Fig. 1, where the test points and core locations are also shown. These members were covered with wet clothes for seven days and then kept at the laboratory conditions at 20±3 ºC and 60±5% relative humidity until testing date. Before taking core specimens, non-destructive tests were performed on these members.

The non-destructive tests employed were the RH (by Schmidt rebound hammer) test and the UPV test. RH test was performed on pre-specified locations, and at each location 12 measurements were taken. Direct and indirect pulse velocity measurements were taken at pre-determined locations and two measurements were taken at each test point by switching the probes of the instrument. After the completion of non-destructive tests, a total of 6 core specimens were taken at specific locations (labeled as K1-K6 in Fig. 1) from these members at the ages of 28, 90 and 180 days (Fig. 2).

Figure 2. Extraction of core specimens from the members

Each end of the cores were cut with a diamond blade and then capped with a fast setting cementitious material. The thickness of the caps was adjusted to provide that the final length of the cores was 195±5 mm. Three of the core samples were kept in air and the other three were kept in water for 72 h to determine the effect of moisture and drilling on the core compressive strength. The cores taken from the reinforced concrete members contained reinforcing bars (three of them contained one reinforcing bar and the other three contained two reinforcing bars) in order to determine the effect of reinforcement on the core compressive strength. Table 3 gives the details on how the samples were coded.

Table 3. Sample coding

Sample code	Definition
R	Reference specimens cured in water until testing day
CA	Core specimens kept in air for 72 h after extraction
CW	Core specimens kept in water for 72 h after extraction
1R	Core specimens containing 1 reinforcing bar
2R	Core specimens containing 2 reinforcing bars

3. RESULTS AND DISCUSSION

Compressive strength test results of core samples extracted from plain and reinforced concrete members were compared to that of the standard molded cylinder specimens to determine the effect of drilling (k_d), moisture (k_m) and reinforcing bar (k_{1R}, k_{2R}) on core strength. The k_d, k_m, k_{1R} and k_{2R} values were calculated by proportioning the corresponding compressive strength values. The effect of concrete age, reinforcement and measurement configuration (in UPV testing) on NDT results is also analyzed. The values given in parenthesis in Tables 4-7 represent the standard deviation of the test results.

3.1. The Effect of Drilling on Core Compressive Strength

Table 4 presents the compressive strength test results of control specimens (R) and core specimens extracted from plain concrete members (CA) at 28, 90 and 180 days. Test results show that due to the drilling effect (k_d) the core strength was reduced by 11-24% depending on the test day. The early age (28 days) test results show that due to the drilling effect, the core compressive strength reduces about 11%. Khoury et al. [19] reported a similar strength reduction of 14–20% on core samples with a length to diameter ratio of two. Masi et al. [20] studied the effect of drilling damage on core strength by comparing the strength of standard cubes (after converting to standard cylinder) with the cores (after converting to equivalent cylinder with length to diameter ratio of two) extracted from existing structures. In order to quantify the drilling damage, the authors used some other correction factors (such as type and amount of cement and curing) to eliminate the effects that would cause strength variations between standard cubes and the core samples. The results of their study showed that the correction coefficient due to drilling damage varied between 1.0 and 1.3 and that the strength of the core was the main governing factor affecting this coefficient, i.e the higher the core strength the lower the coefficient. The results found in the present study (k_d varied between 1.11 and 1.24) are close to that found by Khoury et al. [19]. However it should also be noted that the reference concrete (R) was continuously cured in water until the testing date which might have increased the k_d values. This can be realized from Table 4 where it can be seen that the k_d coefficient remains constant after 90 days, indicating that the strength development reduces by concrete age, especially after 90 days, for both R and CA samples at similar levels (about 10% from 90 to 180 days) and that the main reason for the higher k_d values at 90 and 180 days is due to the higher strength increase of the reference concrete cured in water continuously, compared to that of the CA samples kept in the laboratory conditions. Therefore the k_d value determined at 28 days might better represent the drilling effect.

Table 4. Compressive strength test results and the k_d coefficient

Test day	Compressive strength (MPa)		k_d
	R	CA	
28	29.3 (1.85)	26.3 (2.82)	1.11
90	38.5 (1.22)	31.1 (1.13)	1.24
180	42.3 (3.10)	34.2 (0.88)	1.24
	Average		1.20

3.2. The Effect of Moisture on Core Compressive Strength

Table 5 shows the compressive strength test results of core specimens cured in air (CA) and water (CW). The moisture content of the samples is also shown in Table 5. The moisture content of the specimens was calculated by the following equation.

$$Moisture\ content\ (\%) = 100 \times \frac{(W_w - W_d)}{W_d} \tag{3}$$

where W_w and W_d represent the wet mass and the laboratory dry mass of the specimen respectively.

Table 5. Compressive strength test results to determine the k_m coefficient

Test day	Compressive strength (MPa)		Moisture content (%)	k_m
	CA	CW		
28	26.3 (2.82)	24.1 (4.34)	1.27	1.09
90	31.1 (1.13)	29.7 (0.94)	0.77	1.05
180	34.2 (0.88)	32.4 (5.06)	0.81	1.06
	Average			1.07

Test results show that the compressive strength is reduced due to the moisture content of core specimens. The k_m (moisture correction factor) values, representing the compressive strength ratio of CA samples to CW samples, varied between 1.05 and 1.09 and decreased with respect to the decrease in the moisture content (Fig. 3).

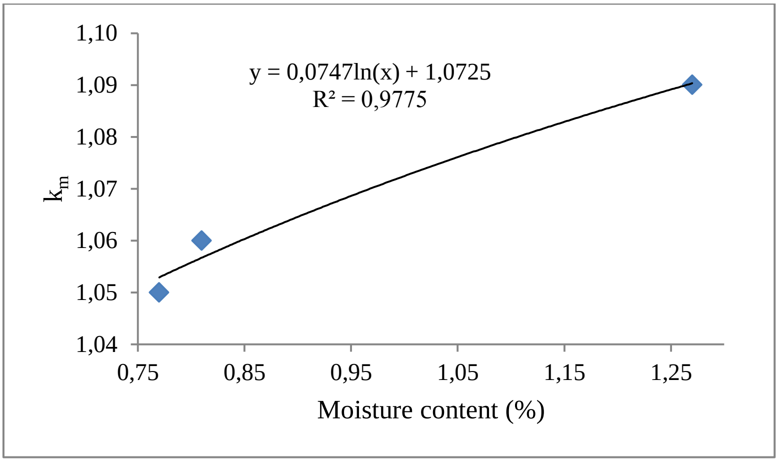

Figure 3. The relationship between moisture content and the k_m value

Bartlett [7] reported that the average strength of air dried cores were 1.14 times larger than the average strength of soaked cores and attributed this to the moisture gradient within the test specimen which affects the strength. Yip and Tam [8] reported that the strength of air dried cores might be 10% higher than the saturated cores, probably owing to the same phenomenon. The experimental study conducted by Khoury et al. [19] showed that the strength of cores left to dry in air for 7 days was on average 13% greater than that of cores soaked at least 40 h before testing. EN 13791 [1] reported that the moisture content of the core will influence the measured strength and that the strength of a saturated core is 10% to 15% lower than that of a comparable air-dried core. The available data on the effect of moisture on core compressive strength indicates that the expected reduction in the core strength is between 10-15%. The results of the present study shows that due to the moisture effect, the reduction in core strength at 28 days would be 8%, close to the values reported in the literature. However the reduction in the strength was found to be lower at later ages and to be constant at 5% due to the reduction in the moisture content. Therefore using a constant conversion factor proposed by several researchers [7,8,19] for moisture effect may not be an accurate way of reflecting this factor. The moisture content of a core sample due to water absorption will be mainly affected by its pore structure, and the duration of soaking period and it might differ from one sample to another. Therefore, determining the moisture content of each core specimen before testing for compressive strength and using a pre-established relationship between moisture content and k_m (as in Fig. 3) might be a better way of taking this factor into account.

3.3. The Effect of Reinforcing Bars on Core Compressive Strength

The effect of reinforcing bars on core compressive strength was investigated on samples which contain one (1R) and two (2R) reinforcing bars. The results were compared with plain core samples (CA) and the effect of reinforcing bars on core compressive strength was determined by simply proportioning the corresponding strength values with each other. Table 6 shows the k_{1R} and k_{2R} results which represent the strength ratio (in other words strength correction factors due to reinforcing bars) of cores that contain one (1R) and two bars (2R) to the laboratory dry cores (CA).

Table 6. Compressive strength test results to determine the k_{R1} and k_{R2} coefficients

Test day	Compressive strength (MPa)			k_{1R}	k_{2R}	EN 12504-1*	
	1R	2R	CA			k_{1R}	k_{2R}
28	22.6 (0.29)	20.7 (2.84)	26.3 (2.82)	1.16	1.27	1.06	1.05
90	27.0 (0.59)	27.5 (2.61)	31.1 (1.13)	1.15	1.13	1.06	1.06
180	31.4 (0.51)	29.0 (2.48)	34.2 (0.88)	1.09	1.18	1.05	1.06
Average				1.13	1.19	1.06	1.06

* The k_{1R} and k_{2R} values are calculated according to Eq. (2)

The k_{1R} and k_{2R} values varied between 1.09-1.16 and 1.13-1.27 respectively; indicating that the presence of reinforcing bars and their numbers significantly reduces the core compressive strength. It is also evident that the equation proposed in EN 12504-1 [3] underestimates the k_{1R} and k_{2R} coefficients. Bartlett [7] proposed the correction factors of 1.08 and 1.13 for cores containing one and two bars respectively. Khoury et al. [19] reported that the presence of reinforcing bar in drilled cores caused a reduction on core strength up to 25%, and attributed the strength reduction to the damage through cutting operation and the developed stress concentration around the bars. The experimental study conducted by Durmuş et al. [21] showed that the reduction in core compressive strength due to reinforcement was between 14-21%. The available literature review demonstrates that the presence of reinforcement in core samples certainly reduces the core strength; however there is no constant value to be considered in the assessment of this effect. Therefore, as stated in EN 12504-1 [3], the drilling through reinforcement shall be avoided wherever possible which would help to better characterize the core compressive strength.

3.4. Non-destructive Test Results

Table 7 shows the NDT results performed on plain and reinforced concrete members at 28, 90 and 180 days. As shown in Fig. 1, the direct UPV measurements were taken at the x-k, y-l, z-m and a-1, b-2 and c-3 directions and the indirect UPV measurements were taken at the core locations (K1-K6). The points k, l and m, not seen in Fig. 1, are located at the opposite end of the member to symmetrically match with x, y and z points respectively. The RH measurements were conducted at the locations where core samples were taken (K1-K6). Since the mix compositions of plain concrete and reinforced concrete members were the same, the only factors affecting the NDT results was the age and the presence of reinforcement in the members. Direct and indirect UPV measurements were conducted on both plain concrete and reinforced concrete members to determine the effect of different measurement configurations on UPV.

Table 7. NDT results of plain and reinforced concrete members

Test day	Plain concrete (1)				Reinforced concrete (2)			
	UPV (km/s)			RH value	UPV (km/s)			RH value
	Direct	Indirect	Direct/Indirect		Direct	Indirect	Direct/Indirect	
28	4.47 (0.35)	3.65 (0.38)	1.22	34.4 (2.34)	4.52 (0.14)	3.64 (1.02)	1.24	33.2 (3.18)
90	4.59 (0.08)	3.95 (0.19)	1.16	36.7 (0.67)	4.47 (0.13)	3.87 (0.33)	1.16	36.3 (3.03)
180	4.76 (0.22)	4.28 (0.29)	1.11	42.9 (0.69)	4.60 (0.08)	4.11 (0.16)	1.12	44.0 (1.16)
Average	4.61	3.96	1.16	38.0	4.53	3.87	1.17	37.8

The RH values are usually assumed to represent the first 30 mm of concrete and is therefore sensitive to surface properties [14]. Therefore, the application of RH requires significant attention since it is affected by several factors such as voids, aggregates, surface moisture, etc. Szilágyi et al. [15] introduced a constitutive model that can be formulated for the surface hardness of concrete as a time dependent material property and considered the effect of hydration, water to cement ratio and carbonation. Therefore the development of NDT values by time might be a useful input for the strength prediction models. Test results conducted on plain and reinforced concrete members indicate that the NDT values are dependent on the age of concrete and that there is an increasing trend in the UPV and RH values by age with respect to the increase in the strength (Figs. 4 and 5).

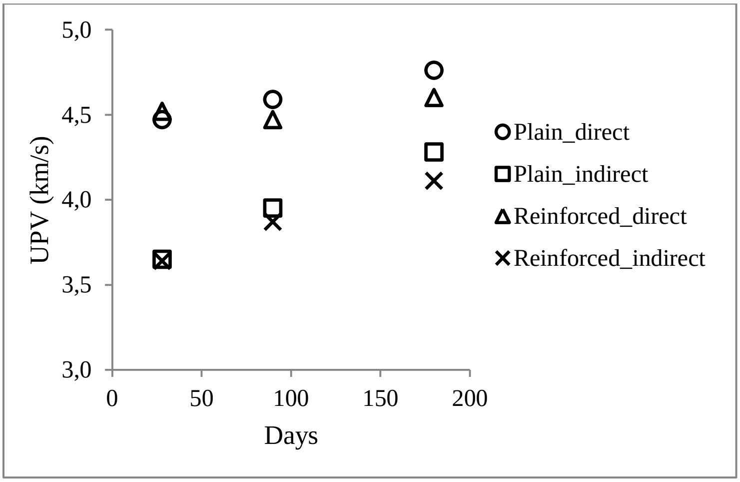

Figure 4. UPV test results of plain concrete and reinforced concrete members

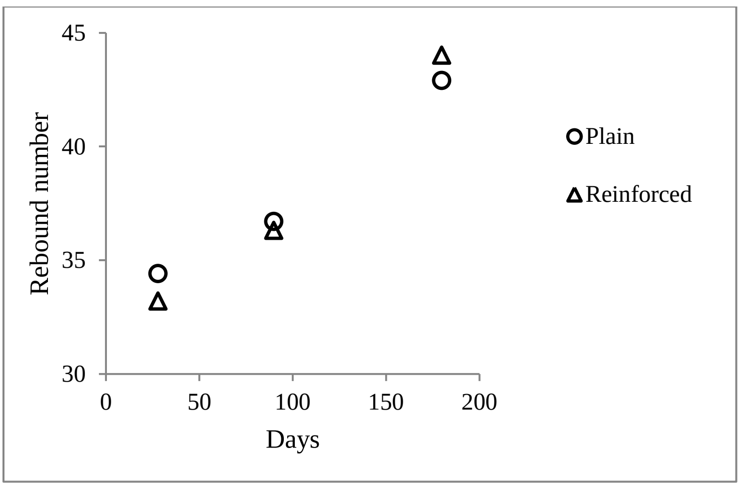

Figure 5. RH test results of plain concrete and reinforced concrete members

The comparison of the results in Table 8 demonstrates that direct and indirect UPV and RH values are similar in both plain (1) and reinforced concrete (2) members, indicating that the reinforcement did not have a significant effect on the NDT results.

Table 8. Comparison of NDT results of plain and reinforced concrete members

Test day	Plain concrete/Reinforced concrete (1/2)		
	UPV		RH value
	Direct	Indirect	
28	0.99	1.00	1.04
90	1.03	1.02	1.01
180	1.03	1.04	0.98
Average	1.02	1.02	1.01

Breysse [14] reported that rebar are known to have a significant influence in reinforced concrete and that they can offer an easier path for wave propagation at higher velocity. This might be true if the reinforcing bar is parallel to the direction of propagation, which might increase the UPV value and can be explained by the fact that the compressional pulse velocity in steel is 1.4 to 1.7 times that in plain concrete and, under certain conditions, the first pulse to arrive at the receiving transducer travels partly in concrete and partly in steel [18]. ASTM C 597 [22] reports that the pulse velocity in steel is up to double that in concrete and that the UPV measured in the vicinity of the reinforcing steel will be higher than in plain concrete of the same composition. The standard also recommends avoiding measurements close to steel parallel to the direction of pulse propagation. It is clear that the effect of reinforcing bars on the UPV measurements are significant when the reinforcing bars are parallel to the direction of propagation. However if the reinforcing bars are perpendicular to the direction of propagation, as in this study, then the effect will be reduced and the factors affecting UPV would be the diameter and the number of bars within the testing area. Since the diameter of the bar was 12 mm and there was only one bar in the testing area, the effect of reinforcing bar on UPV appeared to be insignificant. In most buildings, only indirect UPV measurements can be performed due to structural and geometrical restrictions. Therefore the transformation or calibration of indirect UPV measurements to direct measurements might be necessary. Table 7 shows that the ratio of direct UPV to the indirect UPV is in the range of 1.11-1.22 and 1.12-1.24 for plain and reinforced concrete members, respectively. It can also be noticed from the same table that this ratio reduces with the concrete age for both members. The ratio was found to be independent of the presence of reinforcement and on average it was 1.16 and 1.17 for plain and reinforced concrete members respectively.

4. CONCLUSIONS

This paper analyzes the factors that affect core compressive strength and non-destructive testing of concrete. The effect of drilling, moisture content and reinforcement on core strength was experimentally researched on laboratory manufactured plain and reinforced concrete members. On the same members ultrasonic pulse velocity and rebound hammer tests were performed at 28, 90 and 180 days to investigate the development and variation of results on each member. The conclusions from this study are summarized as follows:

- The reduction in the core strength due to the drilling effect was found to be between 11-24% depending on the age of concrete. The 28 days test results show that, due to the drilling effect, the core compressive strength reduces about 11%.
- The effect of moisture content on core compressive strength was significant especially at 28 days where the core strength was reduced by 8%. The reduction due to moisture was rather insignificant at 90 and 180 days due to the reduction of the moisture content of the core samples and the strength loss was determined as 5%.
- The presence of reinforcement in core samples significantly reduced the compressive strength. On average, the reduction in strength of cores that contain a single bar was 12%. The

reduction was higher when there were two bars in the core samples and the loss in compressive strength was 16%.

- Non-destructive test results showed that the rebound number and ultrasonic pulse velocity values are dependent on the age of concrete and that there was an increasing trend in the values by age with respect to the increase in the strength.

The comparison of the non-destructive test results in plain and reinforced concrete members demonstrated that the reinforcement did not have a significant effect on the ultrasonic pulse velocity and rebound number values. On the other hand, direct and indirect ultrasonic pulse velocity test results differed significantly, though not affected by the reinforcement. The ratio of direct ultrasonic pulse velocity to the indirect pulse velocity values decreased by age of the concrete and on average this ratio was found to be 1.16 and 1.17 for plain and reinforced concrete members, respectively.

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REFERENCES

[1] EN 13791, (2007) Assessment of in-situ compressive strength in structures and precast concrete components. *European Standard*, Brussels.
[2] ASTM C42, (2018) Standard test method for obtaining and testing drilled cores and sawed beams of concrete. *ASTM International*, West Conshohocken, PA, USA.
[3] EN 12504-1, (2009) Testing concrete in structures Part 1: Cored specimens-Taking, examining and testing in compression. *European Standard*, Brussels.
[4] Meininger RC., Wagner FT., Hall KW., (1977) Concrete core strength-the effect of length to diameter ratio. *Journal of Testing and Evaluation* 5 (3), 147-153. doi: 10.1520/JTE11631J.
[5] Bartlett FM., MacGregor JG., (1994) Effect of core length-to-diameter ratio on concrete core strengths. *Materials Journal* 91 (4), 339-348.
[6] Bartlett FM., MacGregor JG., (1994) Effect of core diameter on concrete core strengths. *Materials Journal* 91 (5), 460-470.
[7] Bartlett FM., (1997) Precision of in-place concrete strengths predicted using core strength correction factors obtained by weighed regression analysis. *Structural Safety* 19, 397-410.
[8] Yip WK., Tam CT., (1988) Concrete strength evaluation through of small diameter cores. *Magazine of Concrete Research* 40, 99-105. doi: 10.1680/macr.1988.40.143.99.
[9] Masi A., Nigro D., Vona M., (2012) Effect of core drilling and subsequent restoration on RC column strength. *15th World conference on earthquake engineering*, 24-28 September 2012, Portugal, Lisbon.
[10] Pucinotti R., (2015) Reinforced concrete structure: Non destructive in situ strength assessment of concrete. *Construction and Building Materials* 75, 331-341. doi:10.1016/j.conbuildmat.2014.11.023.
[11] Amini K., Jalalpour M., Delatte N., (2016) Advancing concrete strength prediction using non-destructive testing: Development and verification of a generalizable model. *Construction and Building Materials* 102:762-768. doi:10.1016/j.conbuildmat.2015.10.131.
[12] Alwash M., Breysse D., Sbartaï ZM., (2015) Non-destructive strength evaluation of concrete: Analysis of some key factors using synthetic simulations. *Construction and Building Materials* 99, 235-245. doi:10.1016/j.conbuildmat.2015.09.023.

[13] Bogas JA., Gomes MG., Gomes A., (2013) Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method. *Ultrasonics* 53, 962-972. doi:10.1016/j.ultras.2012.12.012.

[14] Breysse D., (2012) Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods. *Construction and Building Materials* 33, 139-163. doi:10.1016/j.conbuildmat.2011.12.103.

[15] Szilágyi K., Borosnyói A., Zsigovics I., (2011) Rebound surface hardness of concrete: Introduction of an empirical constitutive model. *Construction and Building Materials* 25, 2480-2487. doi:10.1016/j.conbuildmat.2010.11.070.

[16] Malhotra VM., Carino NJ., (2004) *Handbook on Nondestructive Testing of Concrete*. CRC Press, second ed., London, UK.

[17] Malhotra VM (2004) Surface hardness methods. *Handbook on Nondestructive Testing of Concrete*, second ed. CRC Press, London, UK, pp 13-27.

[18] Naik TR., Malhotra VM., Popovics JS., (2004) The Ultrasonic Pulse Velocity Method. *Handbook on Nondestructive Testing of Concrete*, second ed. CRC Press, London, UK, pp. 181-199.

[19] Khoury S., Aliabdo AAH., Ghazy A., (2014) Reliability of core test - Critical assessment and proposed new approach. *Alexandria Engineering Journal* 53, 169-184. doi:10.1016/j.aej.2013.12.005.

[20] Masi A., Digrisolo A., Santarsiero G., (2013) Experimental evaluation of drilling damage on the strength of cores extracted from RC buildings. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering* **7**, 525-531.

[21] Durmuş A., Öztürk HT., Durmuş A., (2013) A reliable approach for determining concrete strength in structures by using cores. *Computers and Concrete* 11, 463-473. doi: 10.12989/cac.2013.11.5.463.

[22] ASTM C597, (2009) Standard test method for pulse velocity through concrete. *ASTM International*, West Conshohocken, PA, USA.