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Compressive strength assessment of normal and self-compacting concrete made with recycled coarse aggregate using in-situ tests

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ABSTRACT

There is an increasing trend in construction for using recycled coarse aggregate (RCA) concrete, which is a more sustainable approach for reducing natural resource consumption. One typical method for developing more environmentally friendly structures is to partially substitute natural aggregate. limited studies investigated the use of in-situ tests to assess the compressive strength of concrete made with RCAs. In this study, ultrasonic pulse velocity (UPV) and core sampling (CST) tests were used to evaluate the compressive strength of normal vibrated (NVC) and self-compacting (SCC) concretes made with recycled coarse aggregates (RCAs). Four different compressive strengths ranging from 25 to 55 MPa were adopted for each concrete type to consider the effect of replacing 0, 20%, 40%, 60%, 80%, and 100% of the required natural coarse aggregates (NCAs) with (RCAs). Exponential relationships were adopted to relate the UPV values with the compressive strength for both RCA-NVC and RCA-SCC. Also, suggested factors were adopted to correct equivalent core strengths for both RCA-NVC and RCA-SCC. The results of both test methods (UPV) and (CST) showed good correlations to estimate the compressive strength of RCA-NVC and RCA-SCC with confidence limits of 93%.

Keywords: Recycled coarse aggregate, Ultrasonic pulse velocity, Concrete core, Self-compacting concrete

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1. Introduction

Globally, there is a growing trend of using industrial wastes as a useful raw material for construction providing a more sustainable solution to minimize the natural material consumption. Concrete made with recycled coarse aggregate (RCA), which may produce from concrete waste generated by demolition processes of aging buildings, as partial replacement of natural aggregate is one common means for achieving more environment-friendly constructions. Several experimental studies have investigated the mechanical properties of normal vibrated concrete with recycled coarse aggregate (RCA-NVC) at the material level. It was found that the compressive strength, tensile strength, and modulus of elasticity of RCA-NVC are lower compared with those of conventional concrete. This reduction may be reached to 25% in the compressive or tensile strength and 35% in the modulus of elasticity [1-6]. Moreover, due to its rheological properties that lead to a reduction in the cost and vibrating energy associated with the casting process [7-8], several studies examined the mechanical properties of self-compacting concrete made with recycled coarse aggregate (RCA-SCC) to achieve the best environmental performance and to produce the so-called green concrete [9-13].

On the other hand, the need to assess the efficiency and durability of concrete structures during and after the construction stage may require due to several reasons. Some of these reasons may occur during the construction stage of a concrete structure when a variation in the results of the concrete mechanical properties obtained through the standard laboratory tests than those required in the design or the unacceptable deterioration may happen after the construction stage or during the structure service life. The concrete effective compressive strength is usually a key property that is required to perform this assessment. The use of in-situ test methods to evaluate the concrete quality or to estimate its compressive strength has been well known for some decades. The range of available in-situ tests varies from non-destructive, economical, and easy to use test methods (e.g., ultrasonic pulse velocity test, rebound hammer test, and surface hardness test) to destructive, expensive, and complicated to use test methods like core sampling test. The selection of the type of test is critical to achieve both cost-saving and results in accuracy [14-16]. The core sampling test (CST) and ultrasonic pulse velocity test (UPV) represent the most popular techniques to evaluate the new or old concrete compressive strength. The review of literature shows there are several studies that have been made to estimate the correction factors for the concrete strength that were evaluated by using CST or to develop a relationship between the concrete compressive strength and the ultrasonic pulse velocity for both normal vibrated and self-compacting concrete [17-23]. However, very limited studies investigated the use of such in-situ tests to assess the compressive strength of concrete made with RCA. Therefore, the purpose of the present work was to explore the use of CST and UPV tests to evaluate the compressive strength of normal vibrated and self-compacting concretes made with recycled coarse aggregates.

Forty-eight test specimens were created and tested. Twenty-four specimens were constructed with RCA-NVC, and the others with RCA-SCC. The concrete compressive strength and RCA ratio represent the main parameters considered in the present study, where the compressive strength values were 25, 35, 45, and 55 MPa, whereas the RCA ratio ranged from zero to 100%. New factors were adopted to correlate the estimated concrete compressive strength using CST. Moreover, two relationships were developed to evaluate the concrete compressive strength by using UPV test for both RCA-NVC and RCA-SCC.

2. Experimental program

2.1 Materials and concrete mixtures

In order to achieve the goals of the present work, twenty-four mixes were designed for each of the normal vibrated and self-compacting concrete. Four different compressive strengths ranging from 25 to 55 MPa were adopted for each concrete type to consider the effect of replacing 0, 20%, 40%, 60%, 80%, and 100% of the required natural coarse aggregates (NCAs) with RCAs. Ordinary Portland cement (OPC) was used as a base material in each concrete mix, which is available in the local markets with chemical and physical characteristics conforming to ASTM C150-04, as shown in Table 1. Crushed stone natural coarse aggregates (NCAs) and river fine aggregates (sand) were used in the present study, whereas the adopted RCAs were obtained from the demolition of different reinforced concrete structural members with a compressive strength ranging between 30 to 40 MPa that were tested in previous experiments at the faculty laboratories. Based on the ASTM C33-03 specification, the physical properties and size grading of sand, NCAs, and RCAs were chosen, as shown in Table 2 and Figure 1, respectively. After numerous trials, the details of the adopted mixes for RCA-NVC and RCA-SCC are shown in Table 3, where the commercially known “ViscoCrete-180 GS” was used as superplasticizer (SP), which is chlorides free and compatible with all Portland cements as stated in ASTM C494 types G and F specifications. A limestone powder (LP) with maximum particle size and a specific gravity equal to 0.125 mm and 2.69, respectively was used for developing RCA-SCC. The adopted designation of the concrete mixes was achieved by considering four or five digits numbers preceded by the letter (N) for normal vibrated concrete or (S) for self-compacting concrete. The first two digits refer to the target compressive strength, whereas the last two or three digits represent the replacement ratio of RCAs.

Table 1. Physical properties and chemical composition of cement

Characteristics	Value
MgO (%)	2.01
Fe_2O_3 (%)	4.4
SO_3 (%)	2.01
C_3A (%)	4.20
C_4AF (%)	13.60
Loss on ignition	2.45
Insoluble residue	0.65
Specific gravity	3.16
Specific surface area (m^2/kg)	300

Table 2. Physical characteristics of fine and coarse aggregates

Characteristics	Sand	NCA	RCA
Max. Size (mm)	2.36	12.5	12.5
Loose bulk density (kg/m3)	1590	1555	1310
Specific gravity	2.63	2.55	2.41
Sulfate content (%)	0.109	0.063	0.075
Absorption (%)	0.95	1.14	6.49
Aggregate crushed value* (%)	----	18.9	29.3
* Based on BS 812-110:1990.			

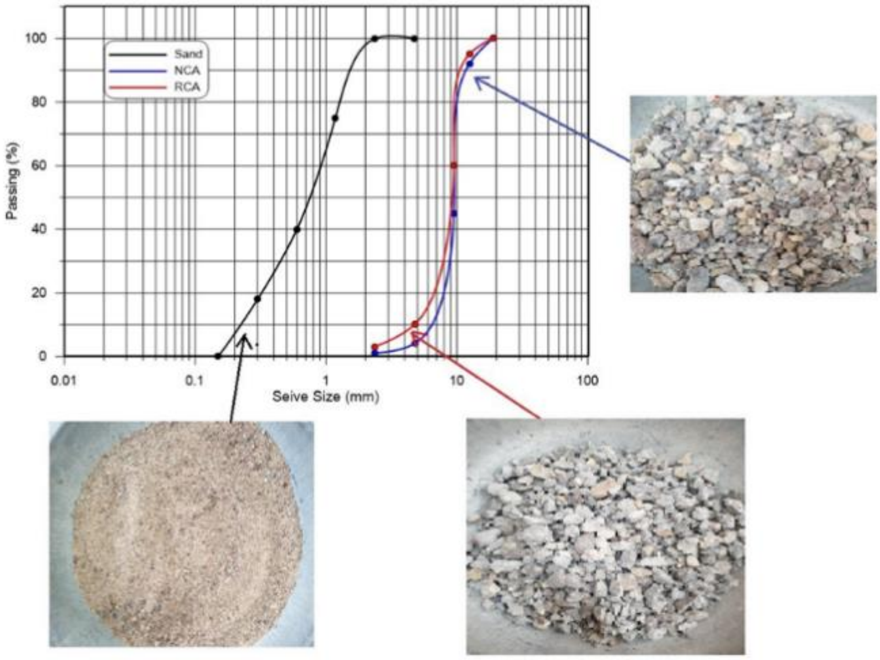

Figure 1. Particle size distribution of aggregates.

Table 3. Details of concrete mix materials

Designation	Target f_c' (MPa)	Cement (kg/m^3)	Sand (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	RCA (%)	Water (kg/m^3)	W/C ratio	LP (kg/m^3)	SP (L/m^3)
N2500	25	320	750	1200	0	0	160.0	0.50	0	5.0
N2520		325	750	960	232	20	156.0	0.48	0	5.3
N2540		330	750	720	464	40	151.8	0.46	0	5.6
N2560		335	750	480	696	60	147.4	0.44	0	6.0
N2580		345	750	240	928	80	144.9	0.42	0	6.5
N25100		355	750	0	1160	100	142.0	0.40	0	7.0
N3500	35	360	750	1200	0	0	172.8	0.48	0	7.0
N3520		370	750	960	232	20	173.9	0.47	0	7.5
N3540		375	750	720	464	40	168.8	0.45	0	7.8
N3560		385	750	480	696	60	165.6	0.43	0	8.0
N3580		390	750	240	928	80	163.8	0.42	0	8.5
N35100		420	750	0	1160	100	163.8	0.39	0	9.0
N4500	45	430	750	1200	0	0	197.8	0.46	0	8.0
N4520		440	750	960	232	20	189.2	0.43	0	8.5
N4540		455	750	720	464	40	182.0	0.40	0	9.0
N4560		465	750	480	696	60	181.4	0.39	0	9.5

Designation	Target f_c' (MPa)	Cement (kg/m^3)	Sand (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	RCA (%)	Water (kg/m^3)	W/C ratio	LP (kg/m^3)	SP (L/m^3)
N4580		470	750	240	928	80	178.6	0.38	0	10.0
N45100		490	750	0	1160	100	176.4	0.36	0	10.5
N5500	55	520	750	1200	0	0	234.0	0.45	0	10.0
N5520		520	750	960	232	20	218.4	0.42	0	11.0
N5540		535	750	720	464	40	214.0	0.40	0	11.5
N5560		540	750	480	696	60	205.2	0.38	0	12.0
N5580		550	750	240	928	80	198.0	0.36	0	12.5
N55100		550	750	0	1160	100	192.5	0.35	0	13.0
S2500	25	340	1250	700	0	0	156.4	0.46	160	6.0
S2520		350	1250	560	135	20	154.0	0.44	160	6.5
S2540		375	1250	420	270	40	161.3	0.43	160	7.0
S2560		385	1250	280	405	60	161.7	0.42	160	7.3
S2580		390	1250	140	540	80	156.0	0.40	160	7.5
S25100		400	1250	0	675	100	156.0	0.39	160	8.0
S3500	35	400	1250	700	0	0	180.0	0.45	160	7.5
S3520		410	1250	560	135	20	176.3	0.43	160	8.0
S3540		420	1250	420	270	40	172.2	0.41	160	8.3
S3560		435	1250	280	405	60	174.0	0.40	160	8.6
S3580		445	1250	140	540	80	173.6	0.39	160	9.0
S35100		460	1250	0	675	100	170.2	0.37	160	9.5
S4500	45	450	1250	700	0	0	202.5	0.45	160	10.0
S4520		465	1250	560	135	20	195.3	0.42	160	10.5
S4540		475	1250	420	270	40	190.0	0.40	160	11.0
S4560		490	1250	280	405	60	186.2	0.38	160	11.5
S4580		510	1250	140	540	80	188.7	0.37	160	12.0
S45100		490	1250	0	675	100	176.4	0.36	160	12.5
S5500	55	500	1250	700	0	0	210.0	0.42	160	12.0
S5520		515	1250	560	135	20	206.0	0.40	160	12.5
S5540		525	1250	420	270	40	199.5	0.38	160	13.0
S5560		538	1250	280	405	60	193.7	0.36	160	13.5
S5580		552	1250	140	540	80	187.7	0.34	160	14.0
S55100		565	1250	0	675	100	186.5	0.33	160	14.6

2.2 Test specimens

For each concrete mix, a concrete block with dimensions (500 × 500 × 150 mm) was poured with three 150 mm dia. × 300 mm standard cylinders according to ASTM C 873-02 in order to use them in the experimental tests that required in the present study. All the test specimens were moist cured for seven days and then left in the air until they were tested at the age of 28 days. Moreover, the fresh properties of RCA-NVC and RCA-SCC were examined by the slump test for NVC and by the slump flow, L-box, and sieve segregation tests for SCC, where the ASTM C1611 and EN 206-9:2010 specifications were used to verify the test results for RCA-NVC and RCA-SCC, respectively.

2.3 Experimental tests

The first part of the experimental tests was represented by using the ultrasonic pulse velocity test (UPV), which is one of the non-destructive tests to estimate the concrete compressive strength by measuring the travel time of a pulse of ultrasonic waves over a fixed path length in the concrete. According to ASTM C597, the ultrasonic pulse velocity can be determined as follows;

$$V = {}^{L}\!/_{t} \tag{1}$$

Where, V is the ultrasonic pulse velocity (km/s); L is the path length in the concrete (mm); and t is the traveling time of the ultrasonic pulse (μs). Hence, it is possible to estimate the concrete compressive strength by relating it to the calculated ultrasonic pulse velocity.

In the present study, the opposite faces (direct transmission) UPV test was adopted for each concrete mix to measure the ultrasonic pulse velocity by testing the (500 × 500 × 150 mm) concrete blocks at the age 28 days along with the poured standard cylinders., as shown in Figure 2. One point reading was considered for each cylinder, whereas three point readings were adopted for the concrete blocks. The average recorded velocity for each concrete mix is shown in Table 4.

Figure 2. UPV test for concrete block and cylinder specimens

Table 4. UPV values for RCA-CC and RCA-SCC test specimens

RCA-NVC		RCA-SCC	
Specimen	UPV (km/s)	Specimen	UPV (km/s)
N2500	4.354	S2500	4.482
N2520	4.265	S2520	4.465
N2540	4.187	S2540	4.421
N2560	4.154	S2560	4.238
N2580	4.151	S2580	4.421
N25100	4.037	S25100	4.354
N3500	5.016	S3500	5.102
N3520	5.001	S3520	5.013
N3540	4.883	S3540	5.053
N3560	4.839	S3560	4.987
N3580	4.858	S3580	4.979
N35100	4.895	S35100	4.973
N4500	5.387	S4500	5.513
N4520	5.364	S4520	5.327
N4540	5.301	S4540	5.349
N4560	5.332	S4560	5.503
N4580	5.276	S4580	5.438
N45100	5.301	S45100	5.349
N5500	5.807	S5500	5.746
N5520	5.694	S5520	5.762
N5540	5.642	S5540	5.769
N5560	5.651	S5560	5.807
N5580	5.686	S5580	5.803
N55100	5.686	S55100	5.746

On the other hand, the core sampling test (CST), which represents one of the in-situ destructive test methods to estimate the concrete compressive strength, was adopted in the second part of the experimental tests in the present work. In accordance with ASTM C42, concrete cores are extracted from the existing concrete structural elements and axially compressed until failure after being subjected to a series of laboratory processes. The resulting core compressive strength (fcore), which is measured in MPa, is corrected by four different factors, as described in Equation 2 below;

$$f_{eq} = F_{l/d} \ \ F_{dia} \ \ F_{mc} \ \ F_d \ \ \ f_{core} \tag{2}$$

where, feq is the equivalent concrete compressive strength (MPa), Fl/d, Fdia, Fmc, and Fd factors for considering the effects of core length to diameter ratio, core diameter, core moisture content, and core damage due to drilling, respectively.

As shown in Figure 3, core samples were taken from the poured concrete blocks at the age 28 days in order to test under compression with the related cylinders for each concrete mix. The compression tests were carried out by using a universal testing machine with a loading rate of about 0.02 mm/s. Table 5 listed the results of the compressive strength for the tested specimens. It must be noted that the reported cylinder compressive strengths represent the average value of three test specimens, whereas the adopted values for the Fl/d, Fdia, Fmc, and Fd factors to correct the core compressive strength were 1.0, 1.03, 1.0, and 1.06, respectively, as specified by ASTM C42 and ACI 214.4R-10 for conventional concrete.

Figure 3. Concrete core sampling and testing

Table 5. Compression test Results of concrete specimens

Designation	Cylinder Compressive Strength, f_c' (MPa)	Core Strength, f_{core} (MPa)	Equivelant Core Strength, f_{eq} (MPa)	f_{eq} / f_c'
N2500	25.4	21.3	23.3	0.916
N2520	25.3	20.4	22.3	0.880
N2540	24.9	19.1	20.9	0.837
N2560	25.3	18.7	20.4	0.807
N2580	26.1	18.3	20.0	0.766
N25100	25.1	16.8	18.3	0.731
N3500	36.2	31.1	34.0	0.938
N3520	35.2	29.3	32.0	0.909
N3540	35.7	27.7	30.2	0.847
N3560	34.7	26.4	28.8	0.831
N3580	34.9	25.5	27.8	0.798
N35100	35.6	25.3	27.6	0.776
N4500	45.7	40.2	43.9	0.960
N4520	45.2	37.9	41.4	0.915
N4540	44.8	35.7	39.0	0.870
N4560	46.1	36.4	39.7	0.862
N4580	45.3	34.8	38.0	0.839
N45100	46.7	33.6	36.7	0.786
N5500	57.4	51.3	56.0	0.976
N5520	56.3	48.6	53.1	0.942

Designation	Cylinder Compressive Strength, f_c' (MPa)	Core Strength, f_{core} (MPa)	Equivelant Core Strength, f_{eq} (MPa)	f_{eq} / f_c'
N5540	55.2	46.3	50.6	0.916
N5560	54.7	44.8	48.9	0.894
N5580	56.1	45.2	49.3	0.880
N55100	54.8	43.8	47.8	0.873
S2500	26.4	22.8	24.9	0.943
S2520	25.3	21.3	23.3	0.919
S2540	25.7	21.4	23.4	0.909
S2560	24.6	19.8	21.6	0.879
S2580	24.8	19.8	21.6	0.872
S25100	25.1	19.7	21.5	0.857
S3500	37.2	32.4	35.4	0.951
S3520	36.2	31.1	34.0	0.938
S3540	36.8	31.5	34.4	0.935
S3560	35.7	30.1	32.9	0.921
S3580	35.9	29.5	32.2	0.897
S35100	34.8	28.2	30.8	0.885
S4500	46.7	41.1	44.9	0.961
S4520	45.1	39.2	42.8	0.949
S4540	45.9	39.7	43.3	0.944
S4560	46.3	39.2	42.8	0.924
S4580	45.6	37.6	41.1	0.900
S45100	44.8	36.8	40.2	0.897
S5500	57.1	50.6	55.2	0.968
S5520	56.3	48.9	53.4	0.948
S5540	57.4	49.7	54.3	0.945
S5560	55.8	47.9	52.3	0.937
S5580	54.2	45.2	49.3	0.911
S55100	55.1	45.6	49.8	0.904
Mean				0.8926
Standard deviation				0.0567

3. Results and discussion

3.1 UPV test results

Figure 4 illustrates the relationships between the compressive strength and UPV for the RCA-NVC and RCA-SCC test specimens. For low values of concrete compressive strengths, it can be seen that ultrasonic wave transmission velocities in RCA-SCC are higher than those in RCA-NVC. However, this variation may reduced with increasing of concrete compressive strength. This may related to the fact that the RCA-SCC is more homogenous compared with RCA-CC due to its ability to compact by itself. Moreover, it was noted that the UPV values were inversely proportional with RCA ratio for both normal vibrated and self-compacting concretes. Exponential relationships were suggested to relate the UPV with the compressive strength for both RCA-NVC and RCA-SCC with mean squared error equals to 0.9863 and 0.9888, respectively. The tested specimens’ compressive strengths were compared with those evaluated by using the suggested relationships along with the UPV test results, as shown in Table 6. It can be seen that the ratio of the predicted compressive strength by using UPV test to the cylinders values were ranged from 0.88 to 1.03 with a mean value of about 0.9525 for RCA-NVC, whereas the ratio was ranged from 1.01 to 0.91 with a mean value of about 0.9629 for RCA-SCC.

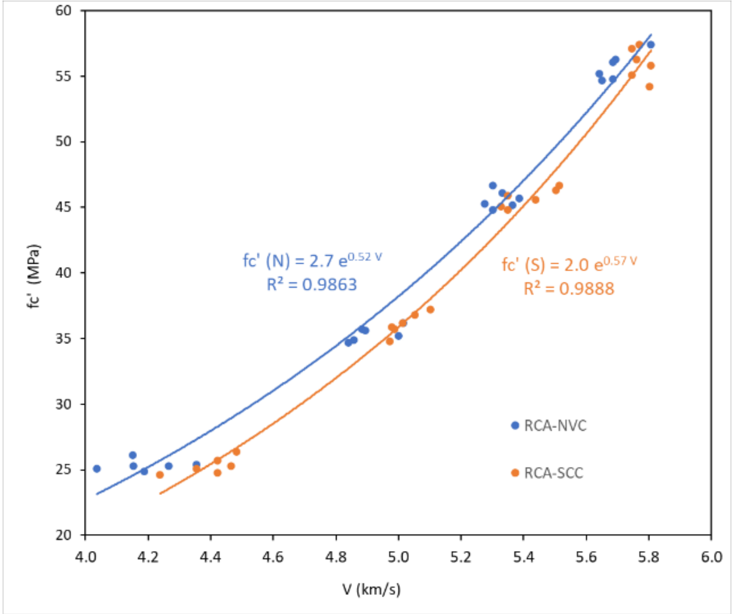

Figure 4. Relationships of concrete compressive strength with ultrasonic pulse velocity

Table 6. UPV values for RCA-NVC and RCA-SCC test specimens

RCA-NVC					RCA-SCC				
Specimen	Cylinder Compressive Strength, f_c' (MPa)	UPV (km/s)	f_{UPV} (MPa)*	f_{UPV} / fc'	Specimen	Cylinder Compressive Strength, fc' (MPa)	UPV (km/s)	f_{UPV} (MPa)*	f_{UPV} / fc'
N2500	25.4	4.354	26.0	1.02	S2500	26.4	4.482	25.7	0.97
N2520	25.3	4.265	24.8	0.98	S2520	25.3	4.465	25.5	1.01
N2540	24.9	4.187	23.8	0.96	S2540	25.7	4.421	24.9	0.97
N2560	25.3	4.154	23.4	0.93	S2560	24.6	4.238	22.4	0.91
N2580	26.1	4.151	23.4	0.90	S2580	24.8	4.421	24.9	1.00
N25100	25.1	4.037	22.0	0.88	S25100	25.1	4.354	23.9	0.95
N3500	36.2	5.016	36.7	1.01	S3500	37.2	5.102	36.6	0.99
N3520	35.2	5.001	36.4	1.03	S3520	36.2	5.013	34.8	0.96
N3540	35.7	4.883	34.2	0.96	S3540	36.8	5.053	35.6	0.97
N3560	34.7	4.839	33.4	0.96	S3560	35.7	4.987	34.3	0.96
N3580	34.9	4.858	33.8	0.97	S3580	35.9	4.979	34.2	0.95
N35100	35.6	4.895	34.4	0.97	S35100	34.8	4.973	34.0	0.98
N4500	45.7	5.387	44.5	0.97	S4500	46.7	5.513	46.3	0.99
N4520	45.2	5.364	43.9	0.97	S4520	45.1	5.327	41.7	0.92
N4540	44.8	5.301	42.5	0.95	S4540	45.9	5.349	42.2	0.92
N4560	46.1	5.332	43.2	0.94	S4560	46.3	5.503	46.1	0.99
N4580	45.3	5.276	42.0	0.93	S4580	45.6	5.438	44.4	0.97
N45100	46.7	5.301	42.5	0.91	S45100	44.8	5.349	42.2	0.94
N5500	57.4	5.807	55.3	0.96	S5500	57.1	5.746	52.9	0.93
N5520	56.3	5.694	52.2	0.93	S5520	56.3	5.762	53.4	0.95
N5540	55.2	5.642	50.8	0.92	S5540	57.4	5.769	53.6	0.93
N5560	54.7	5.651	51.0	0.93	S5560	55.8	5.807	54.8	0.98
N5580	56.1	5.686	51.9	0.93	S5580	54.2	5.803	54.6	1.01
N55100	54.8	5.686	51.9	0.95	S55100	55.1	5.746	52.9	0.96
Mean				0.9525					0.9629
Standard deviation				0.0351					0.0278
* The evaluated concrete compressive strength by using the suggested formulae along with UPV values.									

3.2 Core sampling test results

The main issue in the estimation accuracy of concrete compressive strength by using CST is the selection of correction factors to correct the core compressive strength. As previously discussed, the adopted values of these factors by ASTM C42 and ACI 214.4R-10 were for conventional concrete. It can be seen for the results in Table 5 that the mean value of the ratios of equivalent core to cylinder compressive strength for the tested specimens was about 0.8926 with standard deviation of about 0.0567. Moreover, it can be noted form Figure 5 that the replacement ratio of RCA in test specimens was inversely effect on the accuracy of the equivalent core compressive strengths comparing with the values of the standard cylinders, but this effect may reduce with increasing the concrete compressive strength. On the other hand, it was observed that the ratios of equivalent core compressive strengths to cylinder compressive strength of RCA-SCC test specimens were higher than those of RCA-NVC test specimens. The present study, therefore, suggested a new correction factor to take into account the effect of RCA replacement ratio in the normal vibrated or self-compacted concretes. This suggested factor was adopted by using the method of squired residuals of equivalent core and cylinder strengths, which can be evaluated as follows;

$$F_{SR} = e^{(A.R/S)} \tag{3}$$

where; S: the core compressive strength, fcore (MPa), R: replacement ratio of RCA, and A: a constant. It was found that the value of A can be taken equals to 7.11 for RCA-NVC and 4.24 for RCA-SCC. The use of the suggested factor improved the evaluated values of equivalent core compressive strength comparing with the cylinder ones, where, as shown in Table 7, the mean value of the ratios of equivalent core to cylinder compressive strength for the tested specimens was increased to be 0.9842 with standard deviation of about 0.0355.

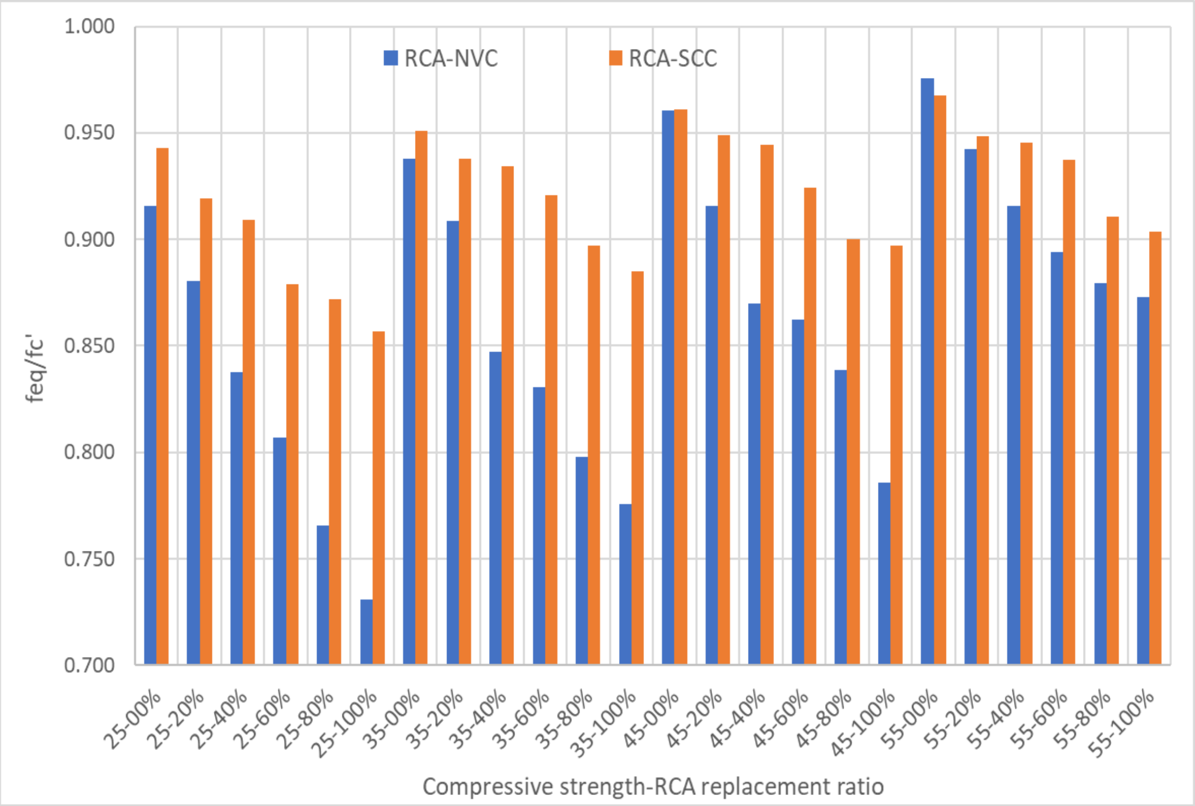

Figure 5. Mean value of the ratios of equivalent core to cylinder compressive strength for RCA-NVC and RCA-SCC.

Table 7 Comparison of evaluated to corrected concrete core compressive strength

Designation	RCA (%)	Cylinder Compressive Strength, f_c' (MPa)	Core Strength, f_{core} (MPa)	Equivalent Core Strength, f_{eq} (MPa)	F_{SR}	$f_{corrcted}$ $(F_{SR} \times f_{eq})$ (MPa)	$f_{orrected}$ / f_c'
N2500	0.0	25.4	21.3	23.3	1.00	23.3	0.92
N2520	0.2	25.3	20.4	22.3	1.07	23.9	0.94
N2540	0.4	24.9	19.1	20.9	1.16	24.2	0.97
N2560	0.6	25.3	18.7	20.4	1.26	25.6	1.01
N2580	0.8	26.1	18.3	20.0	1.36	27.3	1.04
N25100	1.0	25.1	16.8	18.3	1.53	28.0	1.12
N3500	0.0	36.2	31.1	34.0	1.00	34.0	0.94
N3520	0.2	35.2	29.3	32.0	1.05	33.6	0.95
N3540	0.4	35.7	27.7	30.2	1.11	33.5	0.94
N3560	0.6	34.7	26.4	28.8	1.18	33.9	0.98
N3580	0.8	34.9	25.5	27.8	1.25	34.8	1.00
N35100	1.0	35.6	25.3	27.6	1.32	36.6	1.03
N4500	0.0	45.7	40.2	43.9	1.00	43.9	0.96
N4520	0.2	45.2	37.9	41.4	1.04	43.0	0.95
N4540	0.4	44.8	35.7	39.0	1.08	42.2	0.94
N4560	0.6	46.1	36.4	39.7	1.12	44.7	0.97
N4580	0.8	45.3	34.8	38.0	1.18	44.7	0.99
N45100	1.0	46.7	33.6	36.7	1.24	45.3	0.97
N5500	0.0	57.4	51.3	56.0	1.00	56.0	0.98
N5520	0.2	56.3	48.6	53.1	1.03	54.6	0.97
N5540	0.4	55.2	46.3	50.6	1.06	53.8	0.97
N5560	0.6	54.7	44.8	48.9	1.10	53.8	0.98
N5580	0.8	56.1	45.2	49.3	1.13	56.0	1.00
N55100	1.0	54.8	43.8	47.8	1.18	56.2	1.03
S2500	0.0	26.4	22.8	24.9	1.00	24.9	0.94
S2520	0.2	25.3	21.3	23.3	1.04	24.2	0.96
S2540	0.4	25.7	21.4	23.4	1.08	25.3	0.98
S2560	0.6	24.6	19.8	21.6	1.14	24.6	1.00
S2580	0.8	24.8	19.8	21.6	1.19	25.7	1.03
S25100	1.0	25.1	19.7	21.5	1.24	26.7	1.06
S3500	0.0	37.2	32.4	35.4	1.00	35.4	0.95
S3520	0.2	36.2	31.1	34.0	1.03	34.9	0.96
S3540	0.4	36.8	31.5	34.4	1.06	36.3	0.99
S3560	0.6	35.7	30.1	32.9	1.09	35.8	1.00
S3580	0.8	35.9	29.5	32.2	1.12	36.1	1.01
S35100	1.0	34.8	28.2	30.8	1.16	35.8	1.03
S4500	0.0	46.7	41.1	44.9	1.00	44.9	0.96
S4520	0.2	45.1	39.2	42.8	1.02	43.7	0.97
S4540	0.4	45.9	39.7	43.3	1.04	45.2	0.99
S4560	0.6	46.3	39.2	42.8	1.07	45.7	0.99
S4580	0.8	45.6	37.6	41.1	1.09	44.9	0.99
S45100	1.0	44.8	36.8	40.2	1.12	45.1	1.01
S5500	0.0	57.1	50.6	55.2	1.00	55.2	0.97
S5520	0.2	56.3	48.9	53.4	1.02	54.3	0.96
S5540	0.4	57.4	49.7	54.3	1.03	56.1	0.98
S5560	0.6	55.8	47.9	52.3	1.05	55.1	0.99
S5580	0.8	54.2	45.2	49.3	1.08	53.2	0.98
S55100	1.0	55.1	45.6	49.8	1.10	54.6	0.99
Mean							0.9842
Standard deviation							0.0355

3.3 Validation of suggested relationships

By adopting the same test procedure that previously discussed in this study, twelve concrete mixes was fabricated randomly in order to validate the suggested corrections of UPV and CST tests by pouring six specimens for each of RCA-NVC and RCA-SCC with different RCA ratios and compressive strengths. As shown in Table 8, the RCA-NAC specimens were designated as N1 to N6, whereas, the adopted designation of RCA-SCC specimens were S1 to S6 It is obvious that the ratios of corrected compressive strength measured by UPV or CST tests to the standard cylinder compressive strength were equal or greater than 0.93, which represents a good assessment.

Table 8. Validation of suggested corrections for UPV and CST tests

Specimen's Designation	RCA (%)	Cylinder Compressive Strength, f_c' (MPa)	Ultrasonic Pulse Velocity Test			Core Sampling Test				
			UPV (km/s)	f_{UPV} (MPa)*	f_{UPV} / fc'	Core Strength, f_{core} (MPa)	Equivalent Core Strength, f_{eq} (MPa)	F_{SR}	$f_{corrcted}$ $(F_{SR} \times f_{eq})$ (MPa)	$f_{orrected}$ / f_c'
N1	75	27.8	4.378	26.3	0.95	17.2	18.8	1.36	25.6	0.92
N2	50	33.2	4.681	30.8	0.93	25.4	27.7	1.15	31.9	0.96
N3	35	38.1	4.971	35.8	0.94	31.8	34.7	1.08	37.5	0.99
N4	45	46.2	5.406	44.9	0.97	36.5	39.9	1.09	43.5	0.94
N5	90	50.4	5.531	47.9	0.95	35.7	39.0	1.20	46.6	0.93
N6	25	54.3	5.718	52.8	0.97	46.3	50.6	1.04	52.5	0.97
S1	30	23.6	4.191	21.8	0.92	19.6	21.4	1.07	22.8	0.97
S2	45	32.8	4.848	31.7	0.97	26.3	28.7	1.08	30.9	0.94
S3	55	40.8	5.211	39.0	0.96	33.8	36.9	1.07	39.5	0.97
S4	85	47.6	5.435	44.3	0.93	36.4	39.7	1.10	43.9	0.92
S5	45	51.3	5.583	48.2	0.94	42.7	46.6	1.05	48.8	0.95
S6	65	58.7	5.849	56.1	0.96	50.2	54.8	1.06	57.9	0.99

4. Conclusions

Forty-eight concrete mixes were designed in the present study to pour 500×500×150mm concrete specimens along with three standard cylinder for each mix in order to assess their compressive strength by using UPV and CST tests. The normal vibrated and self-compacting concretes having four compressive strengths (25, 35, 45, and 55 MPa) made with recycled coarse aggregates ranged from zero to 100% were adopted to examine the effect of concrete type, concrete compressive strength, and RCA ratio on the accuracy of UPV and CST tests. The following points can be drawn;

- For low values of concrete compressive strengths, UPV values in RCA-SCC are higher than those in RCA-NVC. However, this variation may reduce with the increasing of concrete compressive strength.
- The UPV values were decreased with increasing the RCA ratio of the tested specimens.
- Exponential relationships were adopted to relate the UPV values with the compressive strength for both RCA-NVC and RCA-SCC with mean squared error equals to 0.9863 and 0.9888, respectively.
- It was found that the equivalent core compressive strengths of the tested specimens were inversely proportional with the RCA ratio.
- The ratios of equivalent core compressive strengths to the cylinder ones for RCA-NVC specimens were lower than those for RCA-SCC.
- A suggested factor was adopted to re-correct the core compressive strength for RCA-NVC and RCA-SCC in addition to the correction factors that specified by ASTM C42.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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