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Compressive strength assessment of recycled aggregate concrete using Schmidt rebound hammer and core testing

Mostafa Kazemi [a], Rahmat Madandoust [b] Jorge de Brito [c] [*]

[a] MSc Graduate Student, Department of Civil Engineering, University of Guilan, Rasht, Iran,
kazemi.civil68@gmail.com

[b] Associate Professor, Department of Civil Engineering, University of Guilan, P.O. Box 3756, Rasht, Iran,
rmadandoust@yahoo.com

[c] Full Professor, CERIS, Department of Civil Engineering, Architecture and Georresources, Instituto Superior Técnico,
University of Lisbon, Portugal, jb@civil.ist.utl.pt

Corresponding author *

Abstract

The main objective of this study was to estimate the compressive strength of recycled aggregate concrete (RAC) by means of Schmidt rebound hammer and core testing. The use of recycled aggregate in concrete has been shown to lead to a decrease in the construction cost and it can reduce the burden on the environment by saving natural aggregates. On the other hand, some non-destructive and semi-destructive techniques, such as Schmidt rebound hammer and core testing, are long-established methods for strength estimation of materials. Thus, the present study intended to obtain the compressive strength of RAC using these methods and then compare it with the results of 150 mm cube specimens. To achieve this goal, after producing concrete mixes with 70% replacement of recycled coarse aggregate, 96 cube specimens and 8 concrete slabs were cast to perform Schmidt rebound hammer, core and cube testing. In addition, the combination of the methods was used to obtain correlations between Schmidt rebound hammer and core testing. The results demonstrate that a multi-variable equation using these tests' results can efficiently predict the compressive strength of RAC and conventional concrete and is more promising than single-variable equations based on the Schmidt rebound hammer test results.

Keywords: Recycled aggregate, Schmidt rebound hammer, Core testing, Compressive strength of concrete

1. Introduction

The extensive amount of construction and demolition wastes produced has imposed a heavy burden on the environment in recent years, and it is estimated that about 67% of total construction waste materials in the United States is crushed concrete [1-3]. One of the solutions to prevent this serious environmental concern is to recycle waste construction materials and use them in the building process again. These construction materials have drawn the attention of researchers to recycled aggregate concrete (RAC), having both positive economic and environmental impacts [4-9]. RAC has been known as a viable solution in which natural aggregates is replaced with crushed waste. As a new concrete mix design, it was proposed by Frondistou-Yannas [10] over 40 years ago, and the concept of RAC was subsequently analysed and developed by other researchers. Regarding this, Ajdukiewicz and Kliszczewicz [11] assessed the effect of recycled aggregates on the mechanical properties of high-performance concrete. They showed that the compressive strength slightly increased by replacing natural sand with fine recycled aggregates (0-2 mm).

Zhang et al. [12] and Zaetang et al. [7] showed that the utilization of recycled aggregate led to a decrease in the compressive strength and flowability of concrete. On the other hand, a study by Zhu et al. [13] demonstrated that the presence of coarse recycled aggregate in concrete led to an increase in slump and that 70% was the optimum replacement level to achieve suitable compressive and splitting tensile strengths. Tam et al. [14] reported similar results, where 50% to 70% substitution levels of natural aggregate with recycled aggregate improved the compressive strength of concrete.

There has always been a need for determining the strength of concrete specimens by means of standard test methods in the laboratory. However, some conditions including compaction, curing, and bleeding will vary in existing concrete at the building site compared to those in the laboratory. So, semi-destructive and non-destructive testing methods have been proposed to realistically estimate the in-situ strength of concrete [15-17]. Of all non-destructive testing methods, the Schmidt rebound hammer test was first developed by a Swiss engineer in the late 1940s [18]. The device of this test is cheap, portable and easy to operate and its components include hammer, plunger, outer body, and spring. As indicated in Fig. 1, the plunger is pressed forcefully and steadily against the concrete at right angles to its surface. After moving the spring-loaded mass from its locked position, the scale index, known as the rebound number, can be read, while the hammer is still in the test position. This number is dependent on the energy accumulated in the spring and in the mass used [18, 19]. The feasibility of the Schmidt rebound hammer test was evaluated by Kolek [20], where it was suggested to use it in two types of application, namely precast works and building sites. Victor [21] showed that the rebound numbers of concrete incorporating coarse limestone aggregate were found to be 7 points lower than those of concrete incorporating coarse gravel aggregate, which led to 7 MPa difference in compressive strength of concrete. According to the results of Greene [22], the rebound numbers of lightweight concrete varied remarkably. In addition, there was a difference between the rebound numbers of two concrete samples incorporating the same aggregate from different sources as reported by Grieb

[23]. However, the rebound numbers at different locations of a plain concrete member were found to be close to each other as observed recently by Xu and Li [24].

Among the semi-destructive tests on concrete, the core testing method can be employed at the building site to obtain drilled core specimens using a rotary cutting tool with diamond bits, and reliably assess the on-site strength of concrete elements. In this test, the measured strength of cylindrical core specimens can be affected by some factors including the direction of drilling, length to diameter (L/D) ratio of core, and the presence of reinforcement in concrete [18]. For most practical in-situ testing, the diameter of core specimen has been proposed between 100-150 mm, and it is recommended by ASTM-C42-77 [25] that the L/D ratio of core is close to 2 to reduce uncertainties of correction factors. According to ASTM-C42-77 [25] and BS 1881 [26], the results of compressive strength for a L/D ratio below 1.75 should be modified using some correction factors, as presented in Table 1. As per a study by Sharma et al. [27] on different L/D ratios of drilled core specimens, by changing the L/D ratio, the results of 50 mm core specimens were affected more than those of 75 mm core specimens. Meanwhile, the measured strength of concrete increased with decreasing L/D ratio. Similar results were reported by Madandoust and Alizadeh [28], where the effects of diameter, concrete strength level, drilling direction, and L/D ratio on the compressive strength of concrete were detected. They also concluded that the correction factors of L/D ratios for low strength drilled core specimens were found to be close to those of BS1881, while for high strength drilled core specimens these factors were close to those

of ASTM C 42. Gaynor [29] demonstrated that the presence of reinforcement in concrete led to a decrease in compressive strength of drilled cores between 4 and 18 MPa. In addition, Loo et al. [30] showed that the effect of reinforcement on core testing results decreased by decreasing the L/D ratio of drilled core specimens. Furthermore, they showed that the effect of reinforcement ratio up to 4% on the strength of drilled core specimens with L/D ratio of 1 was negligible.

Some studies have been performed to assess the effects of recycled aggregate on the properties of concrete in laboratory. In addition, a limited number of studies have been conducted to predict in-situ strength of RAC by means of reliable non-destructive and semi-destructive testing methods. Concerning this, the effect of crushed bricks aggregates on mechanical properties of concrete was evaluated by Debieb and Kenai [31], where there was a good correlation among the compressive strength estimated by the ultrasonic pulse velocity test, Schmidt rebound hammer and the compression destructive test. Al-Mufti and Fried [32] measured the early age strength and the surface hardness of RAC using non-destructive testing methods. The results showed the similar behavior with age between RAC and normal concrete by means of ultrasonic pulse velocity test and Schmidt rebound hammer. Mukharjee and Bari [33] assessed the effects of Nano-Silica on the properties of RAC using the ultrasonic pulse velocity test and Schmidt rebound hammer. They showed that the properties of RAC were similar to those observed in natural aggregate concrete incorporating 3% of Nano-Silica. For further investigation, the present study is an effort to realistically estimate the in-situ strength of

concrete made with 70% coarse recycled aggregate using Schmidt rebound hammer and core testing. To achieve this goal, cores were extracted from slab samples to prepare cylindrical specimens, where different diameters and L/D ratios of core specimens were tested at 11 and 28 days. In addition, cubic specimens were cast and prepared and tested with the Schmidt rebound hammer at 11, 28, 42 and 90 days. Since the curing regimes can affect the mechanical properties of concrete materials [34-37], plain concrete slabs and cubic specimens were cured under both wet and dry conditions. The results of Schmidt rebound hammer and core testing were compared with those of standard cube tests. In addition, a two-variable equation was proposed between Schmidt rebound hammer and core testing to realistically estimate the compressive strength of conventional concrete and RAC under both wet and dry curing conditions.
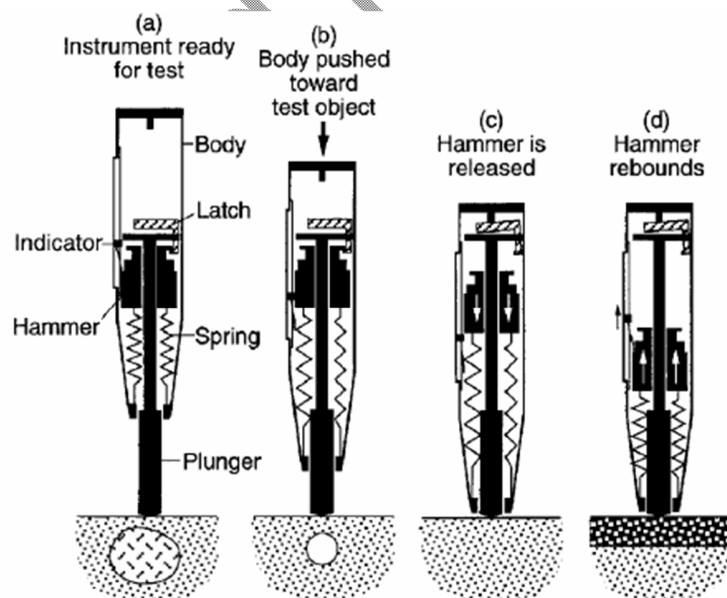
Fig. 1. Schematic illustration of the operation of the Schmidt rebound hammer [19]

Table 1. Correction factors to modify the compressive strength of drilled core specimens

L/D	Correction factors	
	ASTM C42-77	BS1881
1.75	0.98	0.97
1.5	0.96	0.92
1.25	0.93	0.87
1	0.87	0.8

2. Experimental program

2.1. Materials

The chemical composition of Type II Portland cement, with a density of 3.2 g/cm^3 and surface area of 2900 cm^2/g, is shown in Table 2. Crushed gravel was used as coarse aggregate, with a density of 2.65 g/cm^3 and water absorption of 1.1%. Natural river sand, with a density of 2.72 g/cm^3 and water absorption of 5.1%, was used. The size grading curves are indicated in Fig. 2, where the coarse recycled aggregate, with a nominal size of 5-20 mm, was obtained from crushed concrete to produce RAC. A superplasticizer of polycarboxylic ether-type from the Feroplast Company was used in order to obtain the intended concrete workability [38-41].

Table 2. Chemical composition of the Portland cement

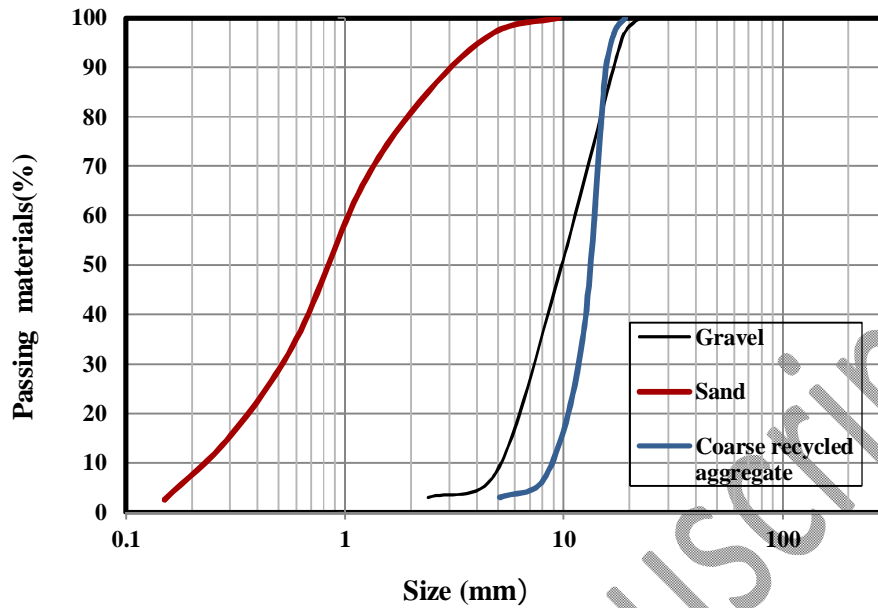| XRF	Cement (%)
SiO_2	21.54
Al_2O_3	4.85
Fe_2O_3	1.55
CaO	64.86
MgO	1.55
SO_3	2.43
LOI	1.15

Fig. 2. Aggregates' size distribution.

2.2. Mix proportioning

In this study, two concrete mix designs were considered as in Table 3. Mix A is the control mix made with coarse natural aggregate, and Mix B is defined as RAC, where the coarse natural aggregate was replaced at 70% with coarse recycled aggregate to achieve an optimum mix design as proposed by Zhu et al. [13] and Tam et al. [14]. The effective water-binder ratio was 0.4 for all mixes. All aggregates were used in the saturated surface-dry condition to prevent further water absorption.

For mix preparation, first, the sand, coarse natural and recycled aggregates were mixed for 30 s at normal speed. Then, half of the tap water was added into the mixer and mixing went on for 1 min. Thereafter, cement was added and mixed for one more minute. Then, the remaining water

and superplasticizer were introduced in the mixer, and mixing went on for 3 min. Finally, 15 cm cubes and 100×100×30 cm concrete slabs were cast to estimate the compressive strength of concrete using Schmidt rebound hammer, core, and cube testing.

Table 3. Mixes composition

Mix ID	Water (L/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Recycled coarse aggregate (kg/m^3)
Mix A	160	400	154.76	703.84	-
Mix B	160	400	154.76	210.94	492.9

2.3. Sample preparation

The compressive strength cube test was conducted under both wet and dry curing conditions at 11, 28, 42 and 90 days. At each age and curing condition, six concrete specimens were cast and tested. So, the results of cube testing were the average of 6 15 cm cubic specimens, and the total number of cubes was 96. Before testing in the compression testing machine, two sides of each cubic specimen were tested with the Schmidt rebound hammer and the result of each test was the average of 12 rebound numbers. Therefore, the total number of rebound numbers was 192 under both wet and dry curing conditions at 11, 28, 42 and 90 days. In this study, a manual Type N hammer was used and the test procedure was based on the recommendations given by ASTM C805 [42]. To securely clamp the cube specimens to the compression testing machine and perform the Schmidt rebound hammer test, a minor load was applied to the cube specimens from two sides using clamp jaws.

On the other hand, four concrete slabs were cast and cured under each curing condition to drill core specimens at 11 and 28 days, where 2" and 4" core diameters with L/D ratios of 1 and 2 were considered. At each age and curing condition, seven cylindrical specimens were drilled and tested. So, each result of core testing was the average of 7 cylindrical specimens, and the total number of drilled cores was 224. It is noteworthy that both slabs and cubes were compacted using concrete vibrating table to achieve a similar compaction. This vibrating method was helpful as well to prevent the generation of difference between concrete properties at low and high depths of slabs. Since the strength of the core specimens can be affected by the location of the drilling and the results of drilled cores in the corner zone can be lower than those in the central zone of a slab, a minimum distance of 150 mm was considered between the hollow core and the slab edges to reduce the effect of location of the drilling on the strength of core specimens.

3. Results and discussion

3.1. Slump

In this study, the slump of concrete control mix (Mix A) and RAC (Mix B) was equal to 78 mm and 69 mm, respectively. The slump of RAC in this study was nearly within the range of the results given by Ferreira et al. [43], where the slump of concrete with different substitution levels of recycled aggregate was 80 ± 10 mm. In addition, the slump value of 60 mm was obtained by Adnan et al. [44] for concrete with the water-binder ratio of 0.4 and 75% incorporation of coarse

recycled aggregate. In this study, the results showed that the slump of control mix (Mix A) was about 13% higher than that of RAC (Mix B). This could be due to the fact that the coarse recycled aggregate, obtained from crushed concrete, was more angular and rough-textured compared to coarse natural aggregate, although there was no significant difference between the slump values of Mixes A and B, because both recycled and natural aggregates were used in the saturated surface-dry condition to prevent further water absorption. So, the amount of free water in Mix B was nearly the same in Mix A as expected.

3.2. Cube compressive strength

Fig. 3 shows the cube compressive strength of the control mix (Mix A) and RAC (Mix B) with 70% incorporation of coarse recycled aggregate under wet and dry curing conditions at 11, 28, 28, 42 and 90 days. According to the experimental results, the cube compressive strength of the control mix and RAC under wet curing conditions was in the range of 24.7-40.2 MPa and 14.8-27.9 MPa, respectively. The corresponding values of the control mix and RAC under dry curing conditions were in the range of 18.2-29.7 MPa and 11-20.6 MPa, respectively. In the study of Wang et al. [45], the 28-day cube compressive strength of RAC with 75% incorporation of coarse recycled aggregate was 26 MPa under wet curing conditions. This value in the present study, 23.6 MPa, had less than 10% difference. In addition, the compressive strength of concrete under wet curing conditions was on average about 35% higher than that under dry curing conditions. So, as

expected, the curing regimes affect the compressive strength of concrete specimens [46-51] and the difference between wet and dry curing conditions can go up to 50% as reported by Mamola and Zaniewski [52]. Under wet curing conditions, the cube compressive strength of the control concrete was on average about 47.6% greater than that of RAC. Nearly the same difference was observed under dry curing conditions. The increase in cube compressive strength, particularly for RAC specimens, was higher at early ages than that at older ages. Regarding this, as revealed by Belin et al. [53] and Zhang et al. [12], the surface of recycled aggregate is more porous compared to that of coarse natural aggregate, and the former can somewhat absorb more water in concrete, leading to a decrease of the hydration process. Therefore, the poor interlock between recycled aggregates and cement paste is inevitable, particularly at older ages.
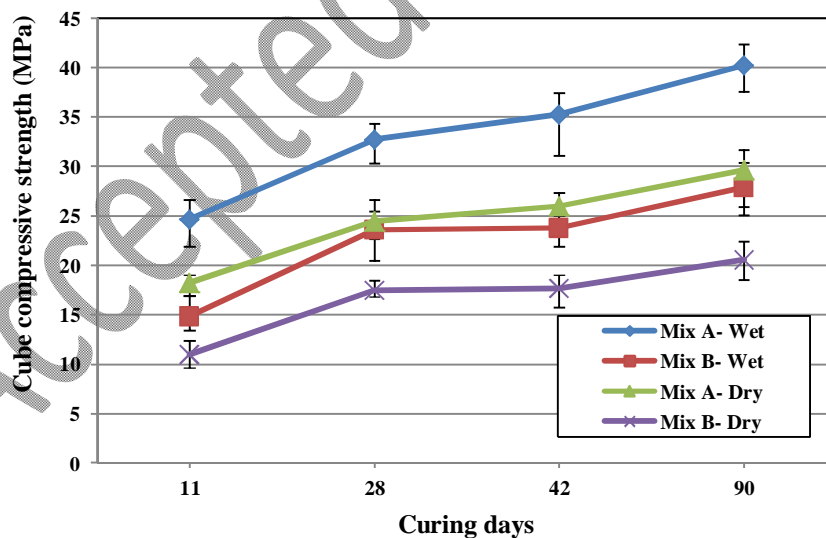

Fig. 3. Cube compressive strength of the control mix (Mix A) and RAC (Mix B) under wet and dry curing conditions

The mid-values of standard deviation (SD) of the control mix and RAC under wet curing conditions were 2.1 MPa and 1.45 MPa, respectively. The corresponding mid-values under dry curing conditions were 2.5 MPa and 1.9 MPa, respectively. So, there was no significant difference between the SD values under wet and dry curing conditions.

3.3. Core testing

Fig. 4 shows the core strength of the control mix (Mix A) and RAC (Mix B) under wet and dry curing conditions at 11 and 28 days. For different L/D ratios, the compressive strength of the control core specimens (Mix A) with a diameter of 2" was 39% to 49% higher than that of the RAC specimens (Mix B) at different ages. These values were between 42% and 50% for the core diameter of 4". The core strength of both the control and RAC specimens increased 32-45% from 11 days to 28 days.

To compare the results of core testing with those compressive strength cube test, Khoury et al. [54] measured the 28-day compressive strength of conventional concrete. They showed that a stress concentration around the core specimens was generated during the coring operation, which was associated with damage in the drilled cylindrical specimens and a subsequent decrease in the strength of cores up to 20% for diameters less than 100 mm (4"), compared to the compressive strength cube tests. This may be the reason why the strength of the control and RAC specimens were lower than those of the cubic specimens up to 19% in the present study.

As mentioned above, the compressive strength results for an L/D ratio below 1.75 need to be corrected using factors, proposed by ASTM-C42-77 [25] and BS 1881 [26]. As shown in Table 1, the correction factors for L/D ratios of 1 and 2 are 0.8 and 0.87 respectively. In this study, the ratios of core strength between L/D=2 and L/D=1 can be obtained using the results of Fig. 4. These ratios were between 0.83 and 0.87, within the range of the correction factors proposed by ASTM-C42-77 [25] and BS 1881 [26]. Madandoust and Alizadeh [28] revealed that, for wet curing conditions, core strengths for a diameter of 4" were 10% to 11% higher than those for a diameter of 2". This range was 9-12% in the present study, which is in agreement with Madandoust and Alizadeh [28].

As seen in Fig. 4, there was no significant difference between the SD values under wet and dry curing conditions, similarly to the standard cube test. The mid-values of SD for 2" and 4" core diameters with an L/D ratio of 1 were 1.3 MPa and 1.2 MPa, respectively. The mid-values for an L/D ratio of 2 were 1.2 MPa and 1.1 MPa, respectively. According to the results, the mid-values of SD for a 2" core diameter were 9-18% lower than those for 4" core diameter. This shows that the SD values can be affected by the size of the specimens, as reported by Madandoust et al. [16], and they have a higher scatter for lower core diameters.
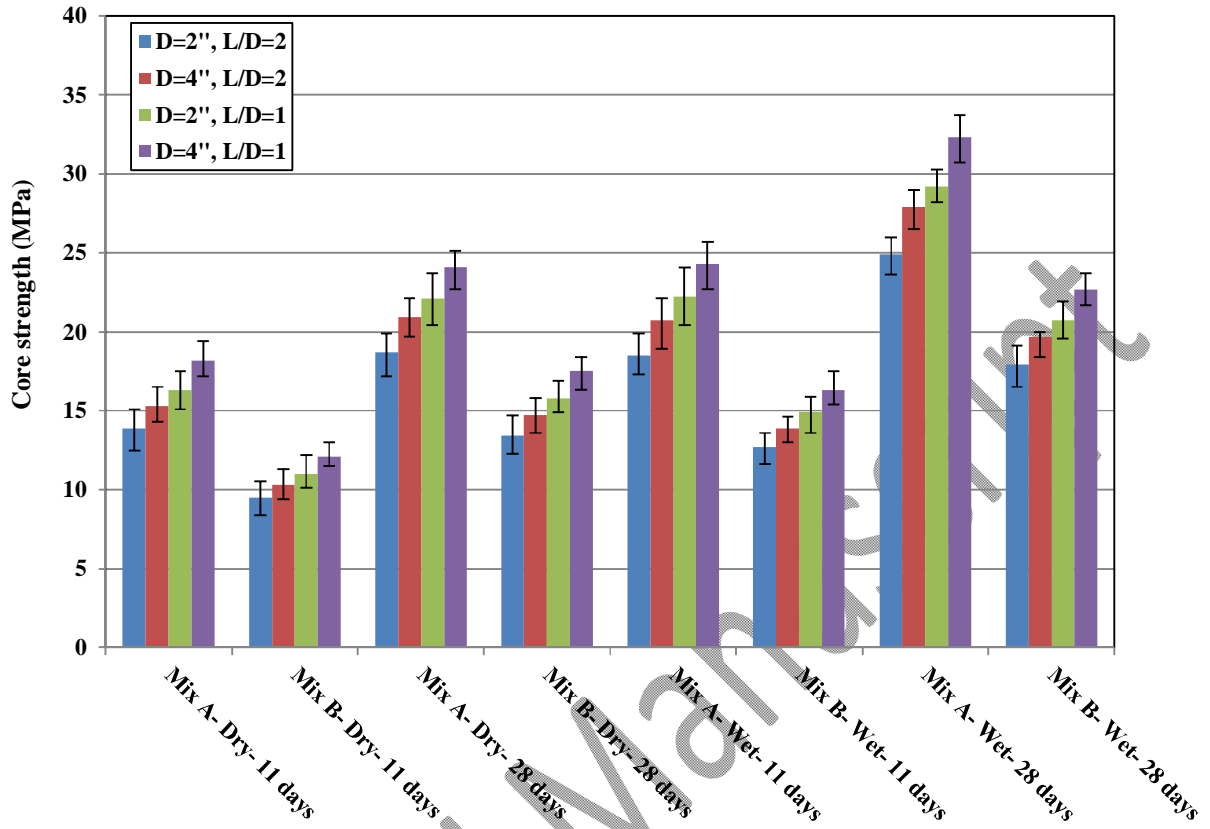
Fig. 4. Core strength of the control mix (Mix A) and RAC (Mix B) under wet and dry curing conditions

3.3.1. Estimation of in-situ cube strength using core testing results

Eq. 1 has been proposed by BS1881 [26] for drilled vertically cores, to calculate the estimated in-situ cube strength using core testing results, specifically for plain concrete.

$$f_c = \frac{3}{1.5 + \frac{1}{\frac{L}{D}}} f_{\frac{L}{D}} \tag{1}$$

Where f_c is the estimated in-situ cube compressive strength and $f_{\frac{L}{D}}$ the measured core compressive strength for different L/D ratios. The estimated in-situ cube compressive strength

using Eq. 1 and cube compressive strength obtained in this study were compared under wet

curing conditions as seen in Table 4.

Table 4. Comparison between the cube compressive strength and the estimated cube compressive strength

Mix ID	Age (day)	11				28			
	L/D	1		2		1		2	
	D	2"	4"	2"	4"	2"	4"	2"	4"
Mix A	Cube compressive strength	24.6	24.6	24.6	24.6	32.7	32.7	32.7	32.7
	In-situ cube compressive strength estimated by BS1881	26.6	29.1	27.7	31	35	38.7	37.3	41.8
	Difference between cube compressive and estimated cube compressive strength (%)	8	18	12	26	7	18	14	28
Mix B	Cube compressive strength	14.8	14.8	14.8	14.8	23.6	23.6	23.6	23.6
	In-situ cube compressive strength estimated by BS1881	17.8	19.5	19	20.8	24.8	27.2	26.8	29.5
	Difference between cube compressive and estimated cube compressive strength (%)	20	31	28	40	5	15	13	25

For both the control and RAC specimens, the cube compressive strength was between 16%

and 22% higher than the estimated in-situ cube compressive strengths, obtained using Eq. 1. This

difference can be explained by the results of Khoury et al. [54], where they reported that the

values of cube compressive strength estimated by various standards are different. These

differences can be due to the fact that not all correction factors of the results of core testing are

considered by the standards. These factors include the particle size distribution, curing

conditions, dimensions of core specimens, direction of drilling, and damages generated by the

coring bit. By considering this, although Eq. 1 considered the direction of drilling and L/D ratio,

there are other significant factors ignored by BS1881 [26]. This seems to be the reason why there

was a difference between the cube compressive strength and estimated in-situ cube compressive

strength in our study.

3.4. Schmidt rebound hammer test

The results obtained in the Schmidt rebound hammer test for the control mix (Mix A) and RAC (Mix B) under wet and dry curing conditions at 11, 28, 42 and 90 days are presented in Table 5.

Table 5. Average values of the rebound number and of its standard deviation

Mix ID	Curing conditions	11 days	28 days	42 days	90 days	SD
Mix A	Wet	21	-	-	-	+1.8 -1.5
	Dry	18	-	-	-	+1.5 -1.6
	Wet	-	25	-	-	+1.4 -1.6
	Dry	-	23	-	-	+2.1 -2.1
	Wet	-	-	27	-	+1.6 -1.5
	Dry	-	-	26	-	+1.4 -1.5
	Wet	-	-	-	31	+1.9 -2.3
	Dry	-	-	-	28	+2.5 -1.6
Mix B	Wet	15.5	-	-	-	+1.2 -1.1
	Dry	12.5	-	-	-	+1.2 -1.2
	Wet	-	22	-	-	+1.5 -1.4
	Dry	-	19	-	-	+1.4 -1.5
	Wet	-	-	25	-	+1.7 -1.5
	Dry	-	-	22	-	+1.6 -1.9
	Wet	-	-	-	27.5	+1.4 -1.6
	Dry	-	-	-	24.5	+1.4 -1.8

The general trends of the rebound number under both wet and dry curing conditions were similar to those observed in the cube compressive strength. As seen in Table 5, the rebound number of the control mix and RAC under wet curing conditions was in the ranges 18-28 and 15.5-27.5,

respectively. The corresponding values of the control mix and RAC under dry curing conditions were in the ranges 21-31 and 12.5-24.5, respectively. As expected, the rebound number of RAC was lower than that of the control concrete, due to the porous interfacial zone in the concrete specimens generated by the presence of recycled aggregate, based on a study at the microscopic scale by Poon et al. [55]. This led to poor interlock between recycled aggregate and cement paste and lower compressive strength in the RAC specimens relative to the control concrete specimens.

The mid-values of SD for the control mix and RAC under wet curing conditions were 1.8 and 1.4, respectively. The mid-values under dry curing conditions were 1.8 and 1.5, respectively. Similarly to what Xu and Li [24] observed, the mid-values of SD for the control mix and RAC showed that the rebound number at different locations of cubic concrete specimens were close.

3.4.1. Comparison of calibration curves

In Fig. 5, the calibration curves of this study were compared with those of Kaushal [56] for conventional concrete under both wet and dry curing conditions. Two exponential equations (single-variable equations) of $f_c=10.39e^{0.04r}$ and $f_c=7.977e^{0.05r}$ with high correlation coefficients (R^2) of 0.92 and 0.97 for wet and dry curing conditions, respectively, were obtained for the control mix (Mix A), where r is the rebound number and f_c is the estimated compressive strength. The results showed that the estimated compressive strengths of conventional concrete using these two equations were close to the compressive strength obtained by Kaushal [56] and that the trends were similar.

The calibration curves of the control concrete and RAC were compared under both wet and dry curing conditions, as seen in Fig. 5. Two exponential equations (single-variable equations) of f_c=6.813$e^{0.05r}$ and f_c=5.958$e^{0.05r}$ with high correlation coefficients (R^2) of 0.941 and 0.94 for wet and dry curing conditions, respectively, were obtained for RAC (Mix B). Generally, all equations for the control concrete and RAC can reliably predict the compressive strength.
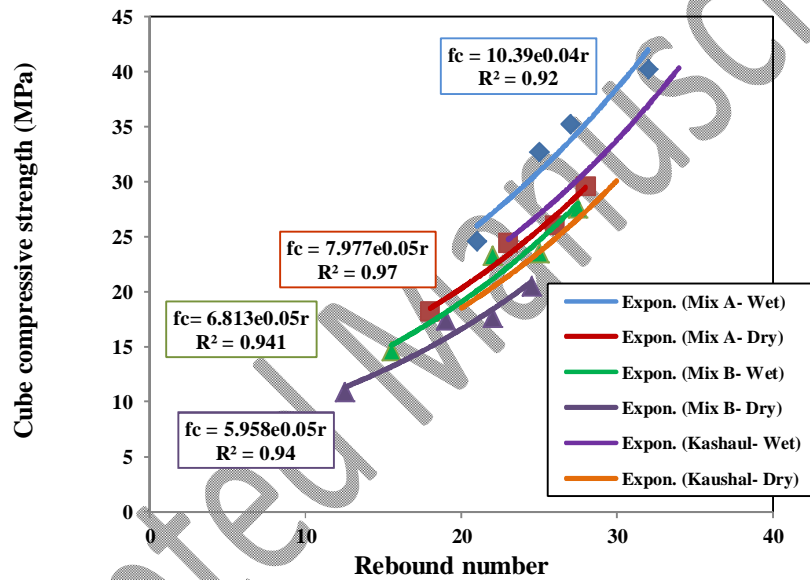

Fig. 5. Comparison between the calibration curves of the Schmidt rebound hammer test

3.4.2. Schmidt hammer compressive strength

As shown in Fig. 6, the values of Schmidt hammer compressive strength were obtained for the control concrete and RAC using the equations proposed in Fig. 5.

Under wet curing conditions, the Schmidt hammer compressive strength of control concrete was on average about 44.9% higher than that of RAC. This value under dry curing conditions was found

to be 46.1%. Similarly to what was observed in the cube compressive strength, the Schmidt hammer compressive strength of RAC under both wet and dry curing conditions remarkably increased at early ages, while a moderate increase occurred in most cases at older ages. For instance, the compressive strength of RAC under wet curing conditions increased up to 39.1% from 11 to 28 days. This increase was equal to 16.7% from 28 to 42 days and thereafter, a 12.2% enhancement was obtained from 42 to 90 days. According to microscopic studies by Tam and Tam [57] and Li et al. [58] on recycled aggregate, recycled aggregate absorbs water from the mix and over time this trapped water can lead to bleeding of concrete. Then, after water evaporation, more porous transition zone is generated in the RAC specimen. Therefore, the quality of the bond between recycled aggregate and cement paste decreases, leading to the lower Schmidt hammer compressive strength of RAC. Another aspect is that the recycled aggregate was used in the saturated surface-dry condition in this study to prevent further water absorption. Therefore, at early ages, the trapped water molecules in the recycled aggregate were given back to the empty capillary pores to increase the amount of free water in the concrete mixes, leading to an increase in the rate of the hydration process. This process led to a remarkable increase in compressive strength of concrete at early ages. Over time, the free water in concrete mixes evaporated and the remaining water decreased in concrete mixes. So, there was no sufficient water to react with the cement particles and complete the hydration process. That is why a moderate increase occurred in most cases at older ages.
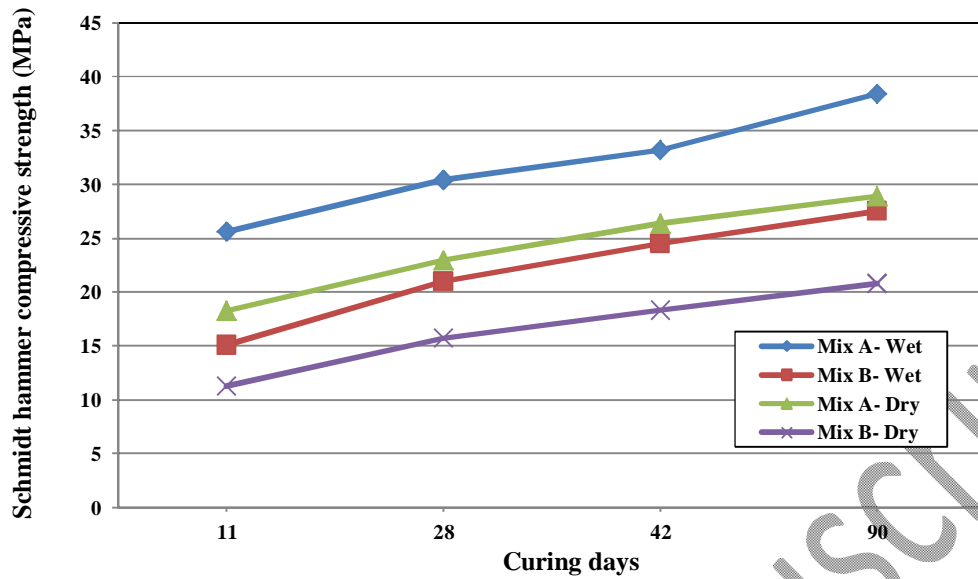
Fig. 6. Schmidt hammer compressive strength

3.5. Two-variable equation between Schmidt rebound hammer and core testing

The results of the control concrete and RAC, obtained by the Schmidt rebound hammer, core and cube testing, were used under both wet and dry curing conditions 11 and 28 days to determine a reliable two-variable equation to estimate the compressive strength of concrete specimens. In Table 6, the results of specimens No. 4 to 8 were randomly selected and used to obtain the two-variable equation (Eq. 2) with high correlation coefficient (R^2) of 0.99.

$$f_c = 1.073\ C + 0.229\ R - 2.755 \tag{2}$$

Where f_c is the estimated compressive strength, C is the drilled core compressive strength with L/D ratio of 2, and R is the rebound number. Then, results No. 1 to 3 in Table 6 were employed to test the reliability of Eq. 2. It is noteworthy that the drilled core compressive

strengths in Table 6 were for the L/D ratio of 2. Table 7 compares the results of the standard cube test with those of the Schmidt hammer, core testing, and the two-variable equation, where the differences between them are expressed as percentages in parentheses. The differences between the standard cube test and the Schmidt hammer test results were 10% at the most and increased to 15.5% between the standard cube test and the core testing results, while there was less than 5.4% difference between the results of the standard cube test and those of the two-variable equation. Therefore, it seems that the estimated compressive strength by two-variable equation is more reliable than that of either the Schmidt hammer or the core testing.

Table 6. Results used to obtain and test the two-variable equation

No.	Cube compressive strength (MPa)	Drilled core compressive strength (MPa)	Rebound number
1	17.4	14.7	19
2	14.8	13.9	15.5
3	32.7	27.9	25
4	18.2	15.3	18
5	10.9	10.3	12.5
6	24.4	20.9	23
7	24.4	20.7	21
8	23.6	19.7	22

As mentioned previously, the cube compressive strength was between 16% and 22% above the estimated in-situ cube compressive strength using Eq. 1, proposed by BS1881 [26]. On the other hand, although some reliable exponential equations were obtained using the Schmidt rebound hammer test to estimate the compressive strength as seen in Fig. 5, these equations were different for the control concrete and RAC and for the two curing conditions. So, considering the fact that the differences between the estimated compressive strength estimated by the two-variable equation and the cube compressive strength were less than 5.4%, as seen in Table 7, it

can be inferred that the this equation can reliably predict the compressive strength of conventional concrete and RAC under both wet and dry curing conditions, and it seems to be more promising than the exponential equations of the Schmidt rebound hammer test.

Table 7. Comparisons between measured and estimated in-situ cube strength

No.	Measured cube strength (MPa)	Estimated cube strength		
		By Schmidt hammer (MPa)	By core test (MPa)	By the two-variable equation (MPa)
1	17.4	15.7(10%)	14.7(15.5%)	16.6(4.6%)
2	14.8	15.1(2%)	13.9(6%)	15.6(5.4%)
3	32.7	30.4(7%)	27.9(14.7%)	34.1(4.3%)

4. Conclusion

In this study, the Schmidt rebound hammer, core and cube testing were used to assess the compressive strength of RAC under wet and curing conditions at different ages. The following conclusions can be drawn from the experimental investigation:

- The cube compressive strength of concrete specimens under wet curing conditions was on average about 35% higher than that under dry curing conditions. In addition, the strength of the control concrete specimens was on average about 47% higher than that of the RAC specimens under both wet and dry curing conditions;

- The core strength of the control concrete and RAC specimens was up to 19% less than that of the cubic specimens. Moreover, the 4" diameter strength was between 9-12% higher than that of the 2" diameter core;

- The range of the correction factors for drilled core specimens of the control concrete and RAC was between 0.83 and 0.87, which were within the values proposed by ASTM-C42-

77 and BS 1881. For both the control concrete and RAC specimens, the results showed that the cube compressive strength was 16-22% higher than the in-situ cube compressive strength estimated using the equation proposed by BS1881;

- The Schmidt hammer compressive strength of the control concrete was on average about 44.9% and 46.1% higher than that of RAC under wet and dry curing conditions, respectively;

- Based on the results of the Schmidt rebound hammer, core and cube testing, the compressive strength of RAC under both wet and dry curing conditions remarkably increased at early ages, while a moderate increase occurred in most cases at older ages;

- In core testing, there was no significant difference between the SD values under wet and dry curing conditions, similarly to the standard cube test. In addition, the mid-values of SD for 2" diameter core were 9-18% less than those for 4" diameter core. In the Schmidt rebound hammer test, the rebound number at different locations of cubic specimens was close;

- According to the data calibrations, for specific situations similar to what was considered in this study, the differences between the standard cube test and the Schmidt hammer test results increased to 10%, while there was less than 5.4% difference between the results of the standard cube test and those of the two-variable equation. Therefore, the two-variable equation between Schmidt rebound hammer and core testing reliably estimated the compressive strength of conventional concrete and RAC under both wet and dry curing conditions at different ages, and it was more promising than the exponential equations of

the Schmidt rebound hammer test.

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