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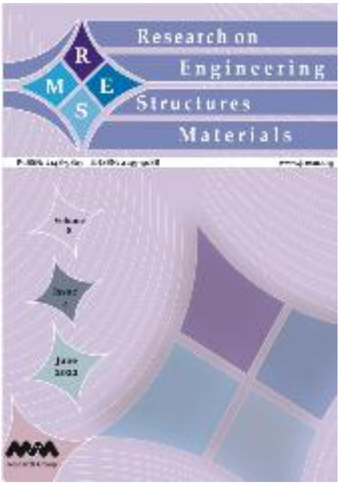

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Research Article

An assessment of rebound hammer test in estimating the concrete compressive strength in seawater

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Abstract

Currently, there is a need to assess the structural integrity of concrete structures situated near or within seawater in a faster manner using a rebound hammer test. However, this test is limited to its reliability, particularly if the rebound hammer device has not been calibrated according to its specific tested environment. Hence, this study assessed the reliability of the rebound hammer test in the compressive strength estimation of concrete cured in a specific environmental condition. As such—the seawater environment, the seawater in a controlled area, and the potable water stored in a normal room condition were the environmental conditions that were considered in the study. Results showed that the rebound hammer test consistently underestimated the direct compression test in three (3) environmental conditions. It was found that the underestimated compressive strength errors ranged from 15.22% to 59% in seawater environment, 33.33% to 58.33% in seawater in a controlled area, and 37.70% to 57.57% in potable water stored in a normal room condition, respectively. Furthermore, this study also established a rebound correlation model, both graphical curve and empirical equation, which can be the basis for concrete compressive strength estimation cured in three (3) different environments.

1. Introduction

Seawater is an aggressive and complex marine environment. If concrete structures are constructed and situated in seawater, these will cause deterioration through biological, chemical, mechanical, and physical processes [1]. Due to the perception of seawater in concrete, its durability has been a problem for many years. Hence, poor-quality cement in the concrete design mixture is not long-lasting for such aggressive and complex environments [2]. In the Philippines, particularly in Davao Region, some ongoing and upcoming major infrastructure (e.g., bridges, coastal roads, and ports) are situated near or within seawater. Most of these infrastructures are reinforced-concrete designs [3].

Generally, in the reinforced-concrete structure, the durability of concrete is determined through compressive strength. It can be measured by taking concrete samples in cylinder forms [4]. The samples are brought to laboratories and loaded in the direct compression machine until cracking failure occurs. While this method is commonly practiced in the construction industry up to this day because of its accuracy, this also requires considerable time and expenses [5]. Recently, researchers have developed a non-destructive testing technique in a faster manner to determine the in-situ concrete compressive strength. These techniques have estimated the compressive strength of the concrete structures by

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evaluating some concrete properties and then relating the measured properties to the mechanical properties of concrete [6].

One of the most widely known non-destructive testing techniques is to use a device called the Rebound Hammer. This device measures the concrete surface hardness through the rebound principle of spring, also referred to as the rebound number, to correlate with its compressive strength. Moreover, this development provided a portable, low-cost, and easy-to-use non-destructive device [6], [7]. Studies revealed that the near-surface properties of concrete could affect the rebound readings. Consequently, it came with certain drawbacks and was limited in its reliability. Factors that contributed to its accuracy are aggregates, air voids of concrete, calibration of the rebound hammer, carbonation, concrete age, surface hardness, moisture content, and environmental temperature. These factors have demonstrated that the obtained measurements are not unique for the rebound hammer device and that the test outcome is based on the tested properties of concrete [6], [8].

Many research works have verified if the non-destructive test using the rebound hammer was a reliable technique to estimate the concrete compressive strength. Some of these findings revealed that this technique provided adequate information and was an acceptable method for conducting a fast approximation in determining the concrete compressive strength [6]–[9]. Sanchez & Tarranza (2014) [6] examined the rebound hammer test of concrete samples exposed to a brackish water environment. They found out that rebound number readings were affected by the concrete surface hardness. Also, the type of environment significantly influenced the compressive strength result from the rebound hammer test compared to the actual compressive strength result in the direct compression test. In the study of Co (2019) [8], the rebound hammer test was investigated for concrete samples cured in potable water and compared to the actual test result in the direct compression test. Hence, the rebound hammer consistently underestimated the actual compressive strength result. From the consistent underestimation, the study developed an empirical model to estimate the compressive strength of concrete when using the rebound hammer device in assessing a concrete structure.

Moreover, Brencich et al., 2020 [7], investigated the reliability of the rebound hammer test in concrete structures with different water-cement ratios cured in standard clean potable water. They concluded that the irregularities of the concrete mixture within the concrete surface significantly affected the rebound hammer readings. The interaction of the plunger in the rebound hammer and concrete sample during their test provided large dispersion in the compressive strength results. However, they also inferred that the rebound hammer test was still acceptable as a non-destructive test to estimate the compressive strength of concrete if the universal calibration curve has been developed from the actual compressive strength result of the concrete sample. Jain et al., (2022) [10] used the rebound hammer device to measure the compressive strength of the concrete samples with additive materials in the standard curing procedure. The rebound hammer readings still underestimated the compressive strength result around 34.3% to 38.1% for 28th days and 84th days after the curing period. The linear correlation graph from the rebound number versus the compressive strength obtained a 0.98 coefficient. In addition, Pushpakumara & Fernando (2023) [11] assessed the existing concrete structures exposed to splash zone partially submerged in seawater using the rebound hammer test. The study found that water quality exposure achieved the highest priority for the deterioration of concrete structures in the splash zone area. Hence, the rebound hammer still provided an adequate prediction of estimating the concrete compressive strength.

The abovementioned studies also concluded that the rebound reading estimation can only be accepted if the device has undergone calibration for a particular type of concrete. Thus, the rebound hammer device relied on its physical condition and must be maintained regularly [12]. In addition, a rebound correlation curve must be developed from the laboratory experimentation, made with the concrete specimen, similar to the materials in the existing concrete structure [6], [7], [13]–[15]. With this, the rebound hammer test must also be evaluated in actual marine conditions, particularly in seawater, to investigate the concrete structure when subjected to extreme changes in weather conditions [6]. Therefore, to the author's knowledge, the evaluation of compressive strength in concrete samples cured in seawater using the rebound hammer test has never been reported in the existing literature, specifically in the Philippine setting. Furthermore, the development of the rebound correlation curve has yet to be provided in actual marine conditions for the particular type of concrete samples.

This present study aimed to assess the reliability of the rebound hammer test in estimating the concrete compressive strength cured in seawater. Thus, produced in this context were concrete cube samples that were cured in three environmental conditions: 1) seawater environment, 2) seawater in a controlled area, and 3) potable water stored in a normal room condition. Consequently, this study provided a distinction of the obtained concrete compressive strength using the tests of rebound hammer versus direct compression. The study also determined the carbonation development in the concrete cube samples cured in three (3) environmental conditions since carbonation development was one factor that influenced the rebound reading. It also determined the true relationships between the compressive strengths from the rebound hammer and direct compression tests, respectively. Furthermore, this work established a rebound correlation curve and equation models from the calculated rebound hammer estimation.

2. Methodology

2.1. Materials and Design Mixture

Twenty-seven (27) samples were produced for experimentation in this study. The concrete samples in a cubic shape form with a 150-mm size [6] for all sides were used, shown in Figure 1. The concrete design mixture was class A with a standard proportion of 1:2:3 ratio, and the minimum attainable compressive strength was 21 MPa (3000 psi). This ratio was equally divided by weights for cement in one-part, fine aggregates in two parts, and coarse aggregates in three parts. To produce all concrete cube samples, the following were the used materials: 1) Type 1 Ordinary Portland cement, 2) crushed-washed sand fine aggregates, and 3) 3/4-inch diameter crushed gravel. The properties of cement, fine aggregates and coarse aggregates were provided by the supplier, shown in Table 1.

The gradation of curves for fine aggregates and coarse aggregates used for experimentation is presented in Figure 2. The test for geometrical properties using the sieving method to determine the size distribution was based on BS EN 933-1 standards [16]. After preparing all materials and determining their properties, they were blended using a 0.45 water-cement ratio [17] with clean potable water for casting all concrete samples. Thereafter, the mixed concrete was poured into a cubic molder using a 3/4-inch-thick phenolic board to attain the fair-faced finish concrete surface. The abovementioned materials were supplied by Green Rise Marketing and Co., located in Davao City, Davao del Sur, Philippines.

Fig. 1 Concrete cube samples

Table 1. Properties of Materials

Materials	Parameter	Properties
Cement	Specific gravity	3.15
Fine aggregate	Specific gravity	2.50
	Fineness modulus	3.16
	Moisture content (%)	7.75
	Absorption values (%)	4.20
Coarse aggregate	Specific gravity	2.45
	Moisture content (%)	3.15
	Absorption values (%)	3.08

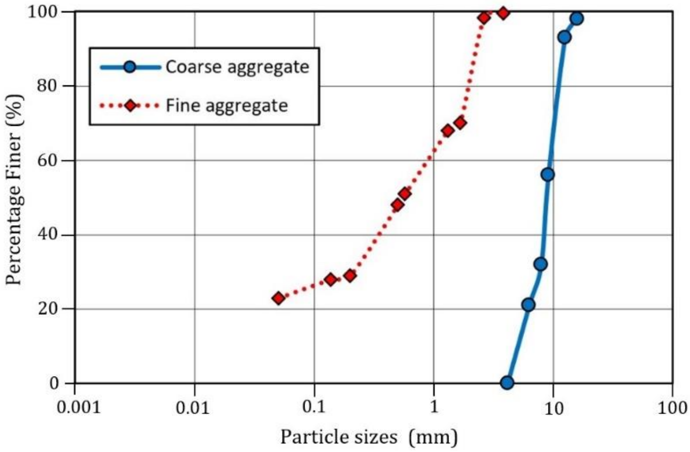

Fig. 2 Grain size distribution of fine aggregates and coarse aggregates

2.2. Curing Environments

2.2.1. Seawater Environment

The concrete cube samples were divided into three (3) groups and were cured in the following environmental conditions: 1) seawater environment, 2) seawater in a controlled area, and 3) potable water stored in a normal room condition. In the first environmental condition, nine (9) concrete cube samples were cured using the continuous immersion of seawater in a private fish cage (Figure 3b) located at Brgy. Biao, Digos City, Davao del Sur, Philippines, shown in Figure 3a. Moreover, these samples were wrapped in a fishnet and tied with a 1/4-inch nylon rope one to two meters below the surface of seawater to ensure stable conditions during the strong presence of waves. This specific procedure measured the effect of extreme changes on weather conditions in the concrete cube samples [6]. Moreover, the authors in this present work conducted this specific curing condition in June 2022 since this month had recorded a normal range and above-normal range temperature from 23°C to 31°C [18].

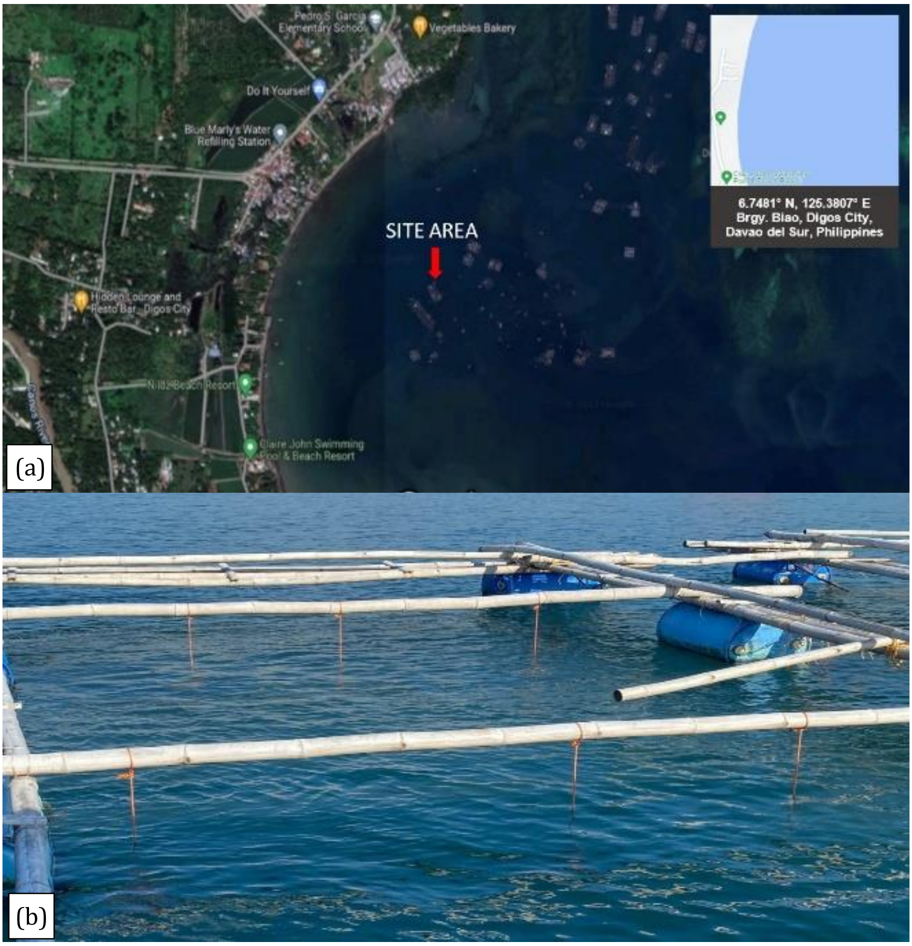

Fig. 3 Seawater environment in: (a) topographic view [19] and (b) actual curing condition of concrete cube samples

2.2.2. Seawater in a Controlled Area

The second environmental condition in this study was seawater in a controlled area, shown in Figure 4. Another nine (9) concrete cube samples were cured in a controlled area at 20°C to 26°C temperature and 75% relative humidity. The concrete cube samples were placed in an emptied container that was alternately cured and filled with seawater instead of brackish water [6]. The seawater was replaced weekly in an alternate cycle of drying and wetting, in which the concrete cubes were air-dried for six (6) hours. After air-drying, the emptied container was slowly filled with seawater to immerse all concrete cube samples fully. This condition was maintained until all nine (9) concrete cube samples were removed from the container for a rebound hammer test and a direct compression test, respectively. This procedure was consequently performed in a vacant room in Brgy. Calinan, Davao City, Davao del Sur, Philippines.

Fig. 4 Concrete cube samples cured in seawater in a controlled area

2.2.3. Potable Water in a Normal Room Condition

In the third environmental condition, the last nine (9) concrete cube samples were cured in potable water at a normal room condition, shown in Figure 5. The container with potable water was stored at a temperature from 20°C to 26°C at 75% relative humidity in a vacant room in Brgy. Calinan, Davao City, Davao del Sur, Philippines. Following the curing procedure of concrete samples in the laboratory test, this study observed the standard practice provided by ASTM C192 [20] for all nine (9) concrete cube samples. Hence, this group served as the controlled samples [6] set by the researcher as a baseline reference for the abovementioned environmental conditions.

Fig. 5 Concrete cube samples cured in potable water in a normal room condition

2.3. Equipment, Measurement and Variation of Tests

After the twenty-seven (27) concrete cube samples had been extracted from the molders and were cured in three (3) different environmental conditions, the non-destructive and the destructive tests were employed. All concrete cube samples were air-dried for twenty-four (24) hours before they were tested on the 7th, 14th, and 28th day for compressive strength. Moreover, the conventional N-type rebound hammer device, shown in Figure 6a, was used for the non-destructive test. On the other hand, the digital direct compression machine, shown in Figure 6b, was used for the destructive test with a 5000-kN maximum load capacity. The direct compression machine and the rebound hammer device used to conduct the tests were from Terms Concrete and Materials testing Laboratory Inc. in Davao City, Davao del Sur, Philippines.

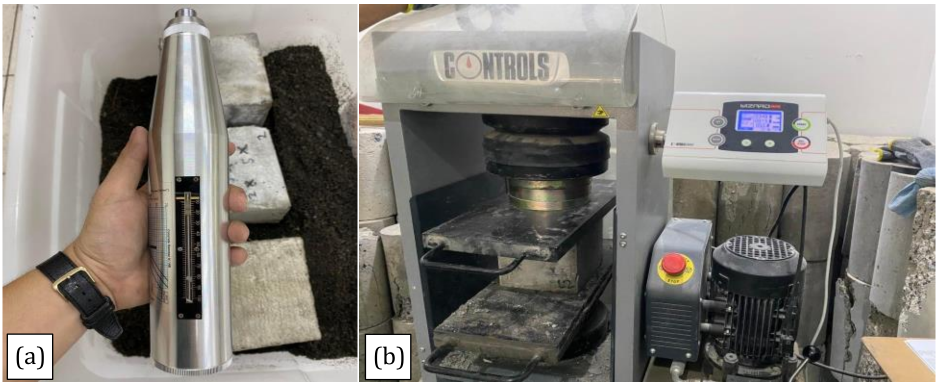

Fig. 6 Destructive and non-destructive tests using: (a) N-type rebound hammer device and (b) one unit test automatic compression machine

When the concrete cube samples were ready for testing, all samples in each group were tested first by the rebound hammer device, following the procedure set forth by ASTM (2008) [21] and ACI Committee 228 (2003) [22]. Consequently, when the rebound hammer was employed, its plunger part penetrated and struck the ten (10) marking zone [23]–[25] in each concrete cube sample. The plunger in the rebound hammer should be perpendicular to each zone and spaced 30 mm from each marked zone to achieve the desired readings. This penetration estimated the hardness of concrete for the compressive strength. All samples had visual inspection to identify the smooth surface before testing. The schematic diagram of the rebound hammer test is illustrated in Figure 7a, where the device was pressed towards the surface of each sample at the horizontal position, shown in Figure 7b. Every tested sample must lean in the solid wall so that when the rebound hammer impacted in the concrete sample, the stability condition was still achieved.

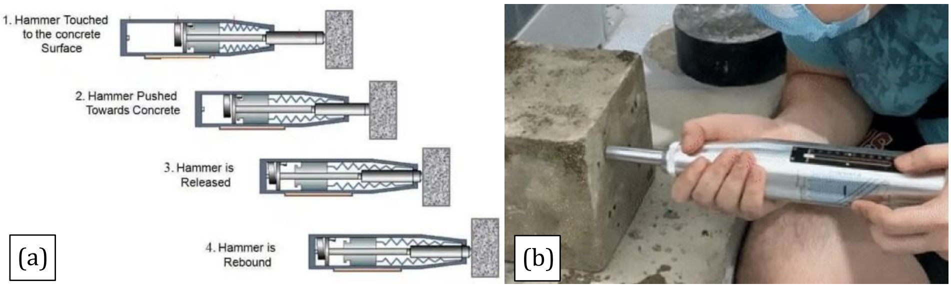

Fig. 7 Rebound hammer device in: (a) schematic diagram [26] and (b) actual position

Moreover, all concrete cube samples with the highest and lowest rebound reading numbers were discarded, and the remaining eight (8) rebound reading numbers were averaged [23], [24], [27]. The average rebound readings were taken for calculations and were compared to the rebound hammer graph provided by the manufacturer. Equation 1, shown below, was used to calculate the estimated rebound hammer compressive strength reading [7].

$$R_c(t) = R_c, 28e^{s\left(1-\sqrt{\frac{28}{t}}\right)} \tag{1}$$

where R_c is the estimated rebound hammer compressive strength reading, s is the exponential equation provided [28] at the given time t in the designated tests at 7th, 14th, and 28th days.

Henceforth, the concrete cube samples were immediately placed in the direct compression machine and loaded for failure after the rebound hammer test was performed. The destructive test was set at a gradual load rate of 140 kg/cm^2 per minute until it reached the maximum compressive failure capacity. After recording the obtained compressive strength from the direct compression machine, the percentage error (*%Error*) of compressive strength reading from the rebound hammer test was determined. The percentage error used by Co (2019) [8] was employed as presented in Equation 2.

$$\%Error = \frac{R_D - R_C(t)}{R_D} \tag{2}$$

where R_D is the compressive strength from the direct compression machine, and R_c is the estimated rebound hammer compressive strength reading at the given time t in the designated tests at 7th, 14th, and 28th days.

After the concrete samples had undergone the destructive test approach in the direct compression machine, the crushed crack part of the concrete cube sample was tested using a chemical indicator that assessed the concrete carbonation. The purpose of the carbonation test in this study was to identify if concrete cube samples have been suspected of corrosion during the curing process in three (3) environmental conditions. This procedure adopted the carbonation test using a phenolphthalein [29], [30]. The phenolphthalein liquid solution has the following properties (Table 2) and was purchased in Davao Mineral Laboratories, Inc. Brgy. Lanang, Davao City, Davao del Sur, Philippines.

Table 2. Properties of phenolphthalein indicator solution

Molecular mass (g/mol)	Purity (%)	Solution in ethanol (%)	Denatured (%)	ph balance	Density at 20°C (g/mL)	color
318.328	98	1	90	8-10	0.82	clear

When phenolphthalein is applied and sprayed around 0.1 mL to 0.3 mL in the crushed crack portion of each concrete sample at contacts in alkaline, the color of the undisturbed cracked part of the concrete cube sample turns pink if it has a high pH level. In contrast, if the concrete cube sample has the presence of carbon, it will remain uncolored.

2.4. Statistical Analysis

The relationship between the readings from the rebound hammer device versus the calculated rebound hammer compressive strength and the direct compressive strength results were determined in probabilistic and statistical analysis [6], [8], [25], [31]–[33]. The correlation and regression of the Pearson *r* coefficient equation, presented in Equation 3, has been used in this study to identify the true relationship between the test results of the rebound hammer and the direct compression in concrete compressive strength for the twenty-seven (27) concrete cubes in three (3) environmental conditions.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \tag{3}$$

where the rebound reading is the independent variable x, the calculated compressive strength estimation from the test of rebound hammer and the compressive strength from the test of direct compression are dependent variables *y*, and the twenty-seven (27) concrete cube samples are considered as *n*.

In determining the covariance of the variables considered, the computed *r* coefficient must be between -1 and +1. Hence, *r* must be a non-zero value so that the relationship between variables is evident [34]. In addition to this analysis, two (2) hypotheses were considered: 1) null hypothesis, which stated that the variables considered have no linear correlation, and 2) alternative hypothesis, which stated that the variables considered have a linear correlation. A 95% confidence level was used, with an α value equal to 0.05, in selecting the hypothesis. The α value was compared to the calculated *p*-value; hence, if the computed *p*-value was greater than α, the alternative hypothesis was accepted. In contrast, if the computed *p*-value was lesser than α, the accepted hypothesis was null.

3. Results and Discussion

3.1. Compressive Strength in Rebound Hammer and Direct Compression Tests

The compressive strength of all concrete cube samples placed in three (3) different curing environments was determined using a rebound hammer and direct compression tests. Table 3 shows the compressive strength results for the concrete samples cured in a seawater environment.

Table 3. Compressive strength results for rebound hammer versus direct compression at 7th, 14th and 28th days of curing in seawater

Curing days	**Sample**	**Strength**	***Number of readings**										**Rebound hammer (MPa)**	**Direct compression (MPa)**	**% Error**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			
7	1	Rebound Reading	20	18	22	13	20	14	18	18	14	14	10.00	15.00	33.33
		Equivalent computed compressive strength (MPa)	10	10	13	10	10	10	10	10	10	10			
	2	Rebound Reading	16	16	22	18	19	17	17	20	20	19	10.00	17.00	41.18
		Equivalent computed compressive strength (MPa)	10	10	13	10	10	10	10	10	10	10			
	3	Rebound Reading	14	17	20	16	16	20	18	20	23	18	10.00	17.00	41.18
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	14	10			
14	1	Rebound Reading	22	17	27	27	21	28	24	27	25	18	15.80	22.00	28.18
		Equivalent computed compressive strength (MPa)	12	10	20	20	12	22	16	19	17	10			
	2	Rebound Reading	26	32	30	32	21	24	23	28	20	21	16.64	24.00	30.67
		Equivalent computed compressive strength (MPa)	18	28	24	28	12	16	14	21	10	12			
	3	Rebound Reading	24	31	30	25	23	23	23	27	23	28	19.50	23.00	15.22
		Equivalent computed compressive strength (MPa)	16	26	24	17	14	14	14	20	14	21			
28	1	Rebound Reading	25	21	27	23	19	16	21	21	22	12	12.50	25.00	50.00
		Equivalent computed compressive strength (MPa)	17	12	20	14	10	10	12	12	13	10			
	2	Rebound Reading	19	20	21	19	18	15	17	18	16	22	10.25	25.00	59.00
		Equivalent computed compressive strength (MPa)	10	10	12	10	10	10	10	10	10	13			
	3	Rebound Reading	24	21	20	25	21	21	20	21	20	18	12.00	26.00	53.85
		Equivalent computed compressive strength (MPa)	16	12	10	17	12	12	10	12	10	10			

**Note that the minimum and maximum rebound readings were eliminated and the remaining eight (8) rebound readings were considered.*

For the observations herein, the direct compression test results for the concrete compressive strength samples cured in a seawater environment ranged from 15 MPa to 17 MPa for the 7th day curing period, 22 MPa to 24 MPa for the 14th day curing period, and 25 MPa to 26 MPa for the 28th day curing period, respectively. The results demonstrated that the mixture of concrete achieved a compressive strength of 21 MPa (3000 psi) from the set standard mix [20]. Moreover, in Figure 8a, the results in compressive strength for the rebound hammer test underestimated all the direct compression test results. Using Equation 2 to calculate the percent error in the rebound hammer reading, it was found that the consistent underestimation for concrete cube samples cured in a seawater environment has a minimum error of 15.22% on the 14th day and a maximum error of 59% on the 28th day curing period as illustrated in Figure 8b. In comparison, the study of Co (2019) [8] has recorded minimum and maximum errors of 5.95% to 44.18%, respectively. The recorded errors in this study provided higher results because the rebound hammer device used by Co (2019) [8] was calibrated before it was used.

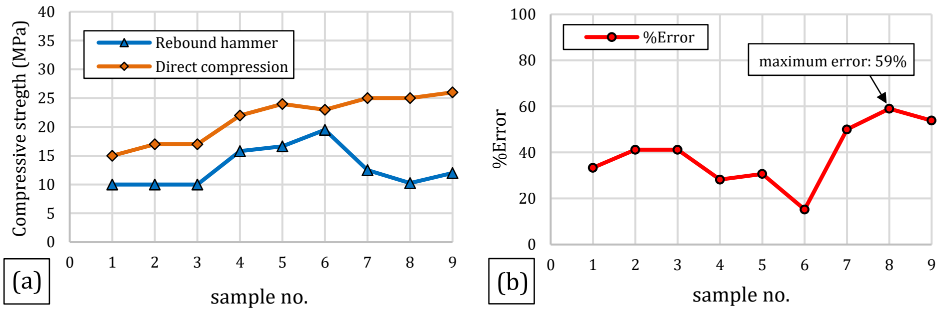

Fig. 8 Variations of concrete samples per curing periods in seawater environment versus: (a) compressive strengths from the rebound hammer and direct compression, and (b) obtained %Error

Furthermore, as the age of curing in concrete increased, the obtained compressive strength also increased. Thus, the hydration process continued [35]. The compressive strength for the rebound hammer test in this study revealed similar results to the study of Co (2019) [8], which indicated that the compressive strength results varied accordingly. However, the compressive strength of the rebound hammer test yielded only after the 14th day (Figure 8b) because the longer the concrete cube samples were cured, the higher the moisture content retained. Additionally, concrete cube samples were air-dried only after each curing period for twenty-four (24) hours instead of a much more extended period before they went through a rebound hammer test. Although the age of exposure to a particular environmental condition and the moisture content in concrete cube samples were not explored in this study, nonetheless, both factors were observed during experimentation that can influence the obtained high rebound readings percent errors [6].

Table 4 exhibits the compressive strengths of the rebound hammer and the direct compression test results of the concrete samples cured in seawater in a controlled area. Similar to Table 3, the test results of the rebound hammer underestimated all the test results in the direct compression for the compressive strength. Hence, on the 7th day curing period, when the rebound hammer test was employed, the concrete cube samples had recorded 10 MPa, while the direct compression test ranged from 15 MPa to 16 MPa compressive strengths. Subsequently, on the 14th day curing period, the rebound hammer test recorded from 10.63 MPa to 12 MPa compressive strengths, while the direct compression test ranged from 20 MPa to 21 MPa. Also, for the curing period on the 28th day, the results in the rebound hammer test obtained 10.67 MPa to 11.63 MPa. On the other hand, the direct compression test ranged from 24 MPa to 26 MPa.

Table 4. Compressive strength results for rebound hammer versus direct compression at 7th, 14th and 28th days of curing in seawater in a controlled area

Curing days	**Sample**	**Strength**	***Number of readings**										**Rebound hammer (MPa)**	**Direct compression (MPa)**	**% Error**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			
7	1	Rebound Reading	17	12	18	13	15	16	16	17	17	12	10.00	16.00	37.50
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	10	10			
	2	Rebound Reading	13	18	18	17	14	14	15	18	14	17	10.00	15.00	33.33
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	10	10			
	3	Rebound Reading	12	15	18	14	17	14	14	18	18	18	10.00	15.00	33.33
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	10	10			
14	1	Rebound Reading	20	22	25	26	22	21	18	21	18	18	12.83	20.00	35.85
		Equivalent computed compressive strength (MPa)	10	13	17	18	13	12	10	12	10	10			
	2	Rebound Reading	10	18	23	22	18	20	21	19	19	19	10.63	20.00	46.85
		Equivalent computed compressive strength (MPa)	10	10	14	13	10	10	12	10	10	10			
	3	Rebound Reading	18	20	20	18	18	22	21	22	24	24	12.00	21.00	42.86
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	13	12	13	16	16			
28	1	Rebound Reading	23	21	20	21	14	12	14	18	16	10	10.67	24.00	55.54
		Equivalent computed compressive strength (MPa)	14	12	10	12	10	10	10	10	10	10			
	2	Rebound Reading	17	22	25	23	19	18	17	16	22	22	11.63	26.00	55.27
		Equivalent computed compressive strength (MPa)	10	13	17	14	10	10	10	10	13	13			
	3	Rebound Reading	14	17	17	15	16	10	18	20	13	19	10.00	24.00	58.33
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	10	10			

**Note that the minimum and maximum rebound readings were eliminated and the remaining eight (8) rebound readings were considered.*

The underestimated compressive strength result in the second environmental condition is illustrated in Figure 9a. The results also revealed that the maximum error plotted in Figure 9b occurred on the 28th day curing period at 58.33%, the same curing period in a seawater environment where the maximum error also occurred.

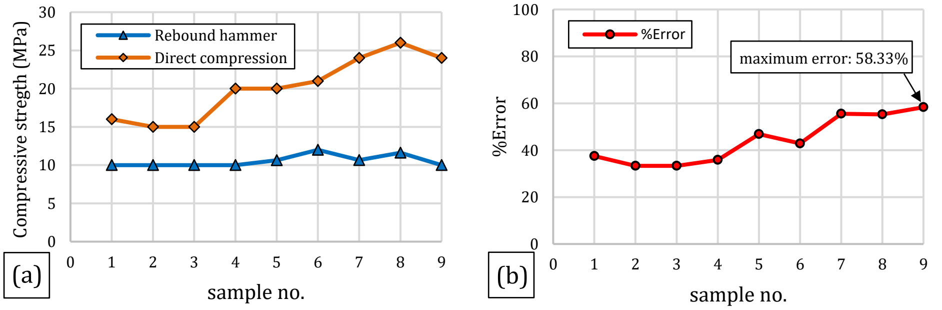

Fig. 9 Variations of concrete samples per curing periods in seawater in a controlled area versus: (a) compressive strengths from the rebound hammer and direct compression, and (b) obtained %Error

Aside from the calibration error factor and the less drying period after curing, it was also observed in the rebound hammer test that all rebound readings at the middle zones in concrete cubes had the highest results. In contrast, zones at the corner of the concrete cube samples revealed low readings. The results can be attributed to the rebound hammer device that the impact of the plunger on the nearby concrete surface edges provided a high slenderness effect [23]. Hence, the applied plunger force becomes more distributed when the rebound hammer strikes a larger zone area. Thus, the rebound readings recorded lower strength in the nearby edges and higher strength in the middle zone.

In the last environmental condition, the compressive strength results of concrete cube samples cured in potable water stored in a normal condition revealed that the compressive strengths had obtained barely higher strength, shown in Table 5. Hence, the rebound hammer test recorded 10 MPa on the 7th day of curing, while the direct compression test recorded from 17 MPa to 18 MPa compressive strengths. For the 14th day of curing, the tested concrete cube samples for the rebound hammer recorded from 13 MPa to 14.33 MPa compressive strengths.

Table 5. Compressive strength results for rebound hammer versus direct compression at 7th, 14th and 28th days of curing in potable water stored in a normal condition

Curing days	**Sample**	**Strength**	***Number of readings**										**Rebound hammer (MPa)**	**Direct compression (MPa)**	**% Error**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			
7	1	Rebound Reading	15	13	18	13	10	18	16	15	15	18	10	18	44.44
		Equivalent computed compressive strength (MPa)	10	10	10	10	10	10	10	10	10	10			
	2	Rebound Reading	20	19	22	19	18	15	14	20	17	19	10	17	41.18
		Equivalent computed compressive strength (MPa)	10	10	13	10	10	10	10	10	10	10			
	3	Rebound Reading	16	18	22	16	17	12	16	22	17	20	10	17	41.18
		Equivalent computed compressive strength (MPa)	10	10	13	10	10	10	10	13	10	10			
14	1	Rebound Reading	20	21	22	22	20	26	20	23	22	20			
		Equivalent computed compressive strength (MPa)	10	12	13	13	10	18	10	14	13	10	13	21	38.20
	2	Rebound Reading	22	21	21	20	25	20	21	24	20	22			
		Equivalent computed compressive strength (MPa)	13	12	12	10	17	10	12	16	10	13	13	21	38.20
	3	Rebound Reading	22	24	22	20	21	20	22	24	22	22			
		Equivalent computed compressive strength (MPa)	13	16	22	10	12	10	13	16	13	13	14.33	23	37.70
28	1	Rebound Reading	21	17	19	17	18	22	14	25	18.5	21			
		Equivalent computed compressive strength (MPa)	12	10	10	10	10	13	10	17	10	12	10.88	24	54.67
	2	Rebound Reading	21	13	24	18	16	19	19	26	25	19			
		Equivalent computed compressive strength (MPa)	12	10	16	10	10	10	10	18	17	10	11.88	28	57.57
	3	Rebound Reading	21	19	27	19	18	22	16	21	21	17			
		Equivalent computed compressive strength (MPa)	12	10	20	10	10	13	10	12	12	10	11.13	25	55.48

**Note that the minimum and maximum rebound readings were eliminated and the remaining eight (8) rebound readings were considered.*

In comparison, the direct compression test recorded from 21 MPa to 23 MPa. Lastly, the test results for the rebound hammer in compressive strength ranged from 10.88 MPa to 11.88 MPa for the 28th day of curing. In contrast, the direct compression test recorded from 24 MPa to 28 MPa, respectively. The test results for direct compression in three (3) environmental conditions shown in Tables 3, 4, and 5 for compressive strength have comparable results. However, in the last environmental condition, the rebound hammer test results still underestimated the compressive strength results in the direct compression, shown in Figure 10a. Likewise, the concrete compressive strength results in the rebound hammer and the direct compression tests in the last environmental condition, the maximum error reached 57.57% for the samples in potable water stored in a normal condition environment, shown in Figure 10b.

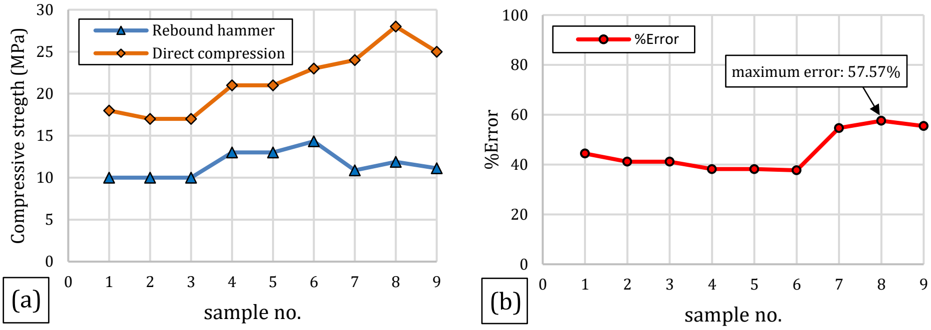

Fig. 10 Variations of concrete samples per curing periods in potable water stored in a normal condition versus: (a) compressive strengths from the rebound hammer and direct compression, and (b) obtained %Error

This maximum error is slightly lower than 1.43% compared to the maximum error of concrete cube samples in the seawater environment and 0.76% lower than the maximum error of the samples in seawater in a controlled area. The results are similar to the study of Sanchez & Tarranza (2014) [6], where the concrete cube samples cured in potable water in a normal room condition provided higher compressive strength from the direct compression test. However, compared to brackish water [6] from the seawater environment in this study, samples from the seawater environment had slightly comparable results of compressive strength versus the rebound hammer test of the samples cured in the potable water environment. Additionally, it was also observed in the rebound hammer test for all environmental conditions that the compressive strength results on the 7th day had a similar reading of 10 MPa (Tables 3, 4, and 5). This was associated with the fact that at early curing age, the rebound reading only registered and obtained a barely minimum reading from the rebound hammer device provided by the manufacturer.

Furthermore, concrete cube samples were susceptible to crack failure in nearby edge surfaces, as observed during the direct compression test. This kind of failure provided a lesser estimation of the compressive strength of concrete. Additionally, one element that influenced the inconsistent estimation of the concrete compressive strength was that when concrete cube samples were transported from one place to another, they were subjected to frequent disturbances, thereby reducing the rebound reading and compressive strength. It was advised that when using the rebound hammer device to assess the concrete structures situated in seawater, the adjustments of rebound readings and compressive strength results in a particular setting must be developed.

3.2. Results for Carbonation Test in Three (3) Environmental Conditions

After the direct compression test was performed and cracked portions of the concrete cube samples were visible, the samples went through a carbonation test. The phenolphthalein liquid solution was immediately applied and sprayed to all the cracked portions of the samples to determine the occurrence of carbon that had been developed during the consequent curing periods. As observed in Figures 11a, 11b, and 11c, all the cracked portions in concrete cube samples turned pink.

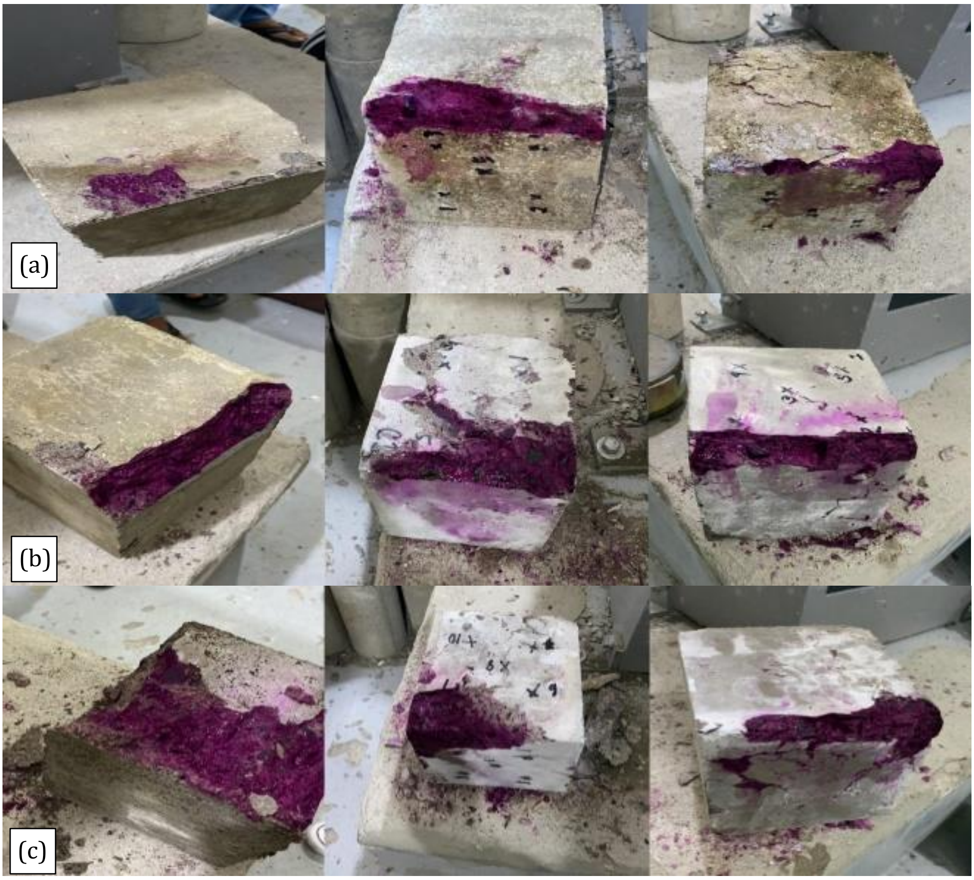

Fig. 11 Phenolphthalein solution in crack portion of concrete cube samples cured in: (a) seawater environment, (b) seawater in a controlled area, and (c) potable water stored in a normal room condition

In the carbonation test performed in this study, it can be inferred that all twenty-seven (27) concrete cube samples cured in three (3) environmental conditions had no carbon development during their designated curing periods. This test was done to verify the carbonation existence in concrete cube samples. Hence, carbon could significantly affect the rebound readings and may indicate higher than 50% inconsistency than those without carbonation [30].

Thus, the finding in this work revealed that more than 50% of the rebound reading errors were not directly influenced by carbonation development. Therefore, this contradicted the previous result in the existing literature in the aforementioned. In addition, this finding also indicated that when the concrete cube samples were in continuous immersion in the seawater environment, any acidic agents had not intruded inside the concrete during their curing periods. Thus, in this present work, only the calibration of the rebound hammer device, less drying period after curing, the high water retained in the concrete samples, and the uneven distribution of force in the plunger of the rebound hammer device to the concrete surface were the factors that can affect the high rebound readings errors.

Furthermore, as the concrete cube samples aged in the seawater environment, seashells and other marine organisms, particularly algal species, slowly grew on the concrete surface. These organisms produced extraordinarily toxic compounds [36] that could affect the rebound hammer and direct compression tests in concrete cube samples. However, weekly cleaning maintenance on the surfaces of all nine (9) concrete cube samples cured in a seawater environment was conducted as part of the methodology in this present work to maintain the smoothness of the concrete surface. Thus, the continued growth of seashells and the development of marine organisms on concrete surfaces were prevented.

3.3. Regression and Correlation Results and Development of Correlation Models

In regression analysis for the variables considered in the seawater environment, the computed p-value of 0.000000247 between the rebound reading versus the rebound hammer compressive strength test was less than the set significant level (α). On the other hand, the computed p-value of 0.141883304 for the variation between the rebound reading versus the direct compression compressive strength test was greater than the set significant level (α). These showed that both variations had contrasting results. Hence, the null hypothesis was accepted in the former variation, while the alternative hypothesis was accepted for the latter variation.

In the calculated correlation coefficient R^2 using Equation 3 for the rebound reading versus the rebound hammer compressive strength test, the result was 98.16%, which indicates a significantly high correlation. In contrast, the rebound reading versus the direct compression compressive strength test was 28.12%, which can be considered a negligible correlation. The result of the regression and correlation analysis in the latter variation can also be observed in Figure 12a. The plotted values were dispersedly unaligned in the linear trendline. This study found that rebound readings from approximately 12 to 16 had no direct effect on the direct compression compressive strength test results in a seawater environment. These findings showed that extreme weather changes in the seawater environment with a normal range and above-normal range recorded temperatures from 23°C to 31°C [18] can also significantly affect the rebound readings.

Moreover, for the variables considered in seawater in a controlled area, the computed p-values of 0.000348684 and 0.065826142 in the variations between the rebound reading versus the rebound hammer compressive strength and the direct compression compressive strength tests in concrete cube samples were less than the set significant level (α). These showed that the considered variables had linear relationships with each other. Hence, the null hypothesis in the second environmental condition was accepted. The correlation coefficient R^2 between the rebound reading versus the rebound hammer compressive strength test was computed to have 85.62%, which was considered a high correlation result. Contrary to the former variation, the correlation coefficient R^2 of 40.40% in the rebound reading and the direct compression compressive strength test indicated a low correlation. Subsequently, the regression and correlation analysis results in both variables in seawater in a controlled area can also be observed in Figure 12b. Hence, in the former variation, the plotted values were in a consolidated arrangement in the linear trendline. On the other hand, the plotted values in the latter variation were scattered in the linear trendline.

Lastly, for concrete cubes cured in potable water stored in a normal room condition, shown in Figure 12c, the regression analysis for the variables considered had a 0.001870707 computed p-value, less than the set significant level (α). On the other hand, the computed p-value for the variation between the rebound reading versus the direct compression compressive strength test was 0.162301988, which was greater than the set significant level (α). Since both variations had contrasting results, the null hypothesis was accepted. In contrast, the alternative hypothesis was accepted for the latter variation. Hence, the correlation coefficient R^2 between the rebound reading versus the rebound hammer compressive strength test was 77.02%, which was considered a high correlation result. However, the rebound reading and the direct compression compressive strength test was 25.84%, a considerably negligible correlation.

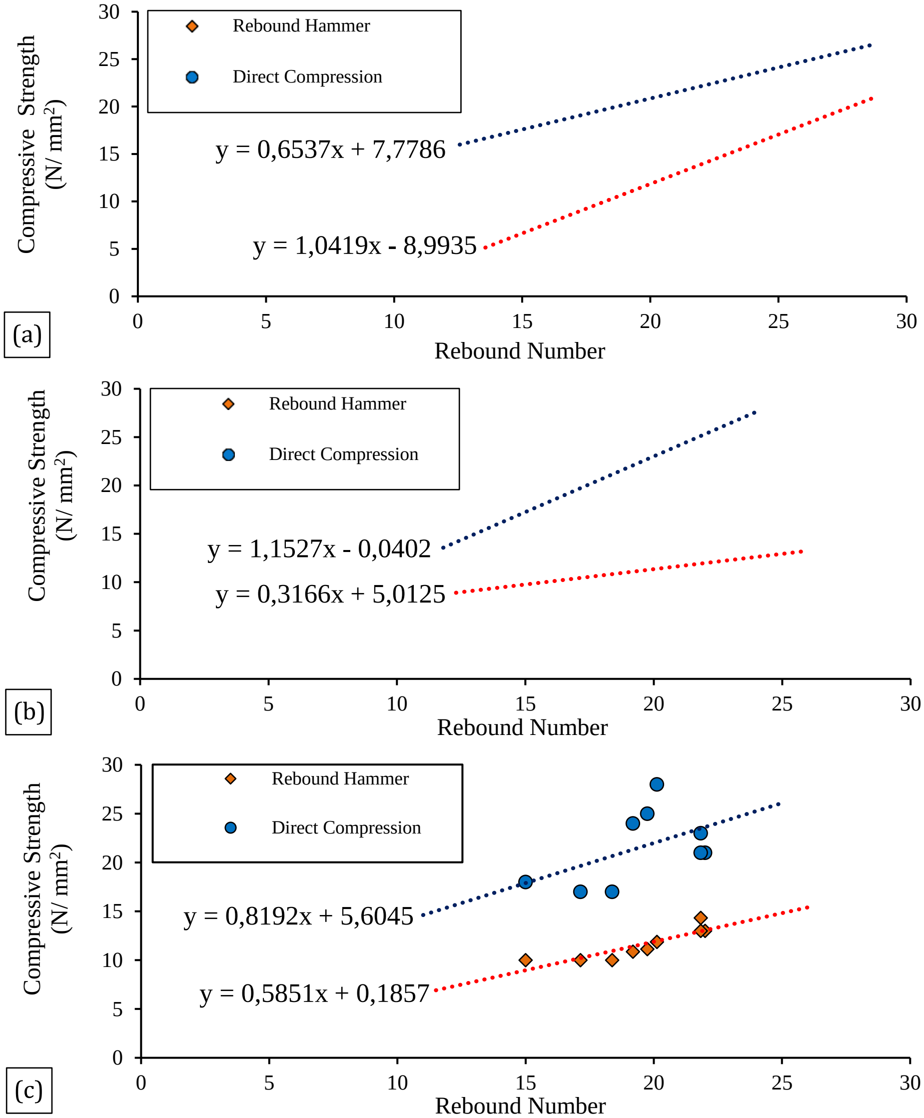

Fig. 12 Rebound correlation curve of concrete cube samples cured in: (a) seawater environment, (b) seawater in a controlled area, and (c) potable water stored in a normal room condition

The plotted values were unaligned in the linear trendline (Figure 12c) for the variation between the rebound reading versus the direct compression compressive strength test. Meanwhile, the variation between the rebound reading versus the rebound hammer compressive strength test shown in the same figure revealed that the plotted values were within the linear trendline. These indicated that the outcome of the non-destructive test using the rebound hammer in assessing all the samples was significantly far from the actual compressive strength using the correlation curve graph provided by the manufacturer. Consequently, there was a need to develop a rebound correlation model to assess the compressive strength of concrete for its reliability, either a graphical curve or an empirical equation derived from the actual compressive strength data.

Finally, this study established three (3) correlation curves for the graphical model in the rebound hammer test in concrete samples, as presented in Figure 13. The graphical model considered the rebound reading as x and the estimated compressive strength as y. The developed graphical model adopted the exponential power model of Co (2019) [8] as the rebound correlation curve graph in this work. The model increased the estimation by 7.86% in a seawater environment, 5.93% in seawater in a controlled area, and 9.15% in potable water stored in a normal room condition, respectively.

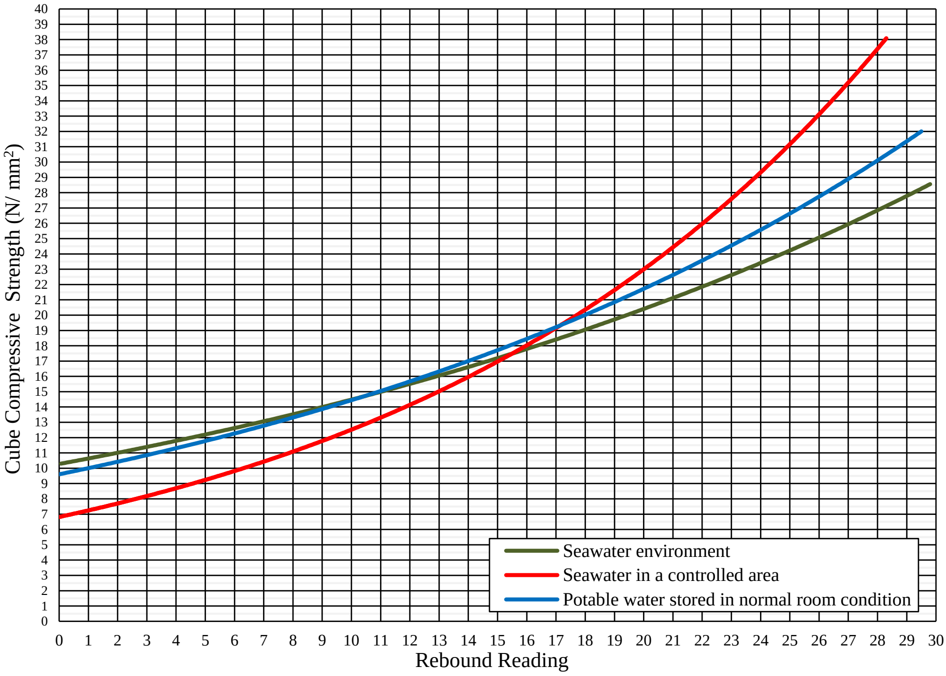

Fig. 13 Developed rebound correlation curve in three (3) environmental conditions

Aside from the graphical model, this study also established an empirical equation model for the predictor variable (rebound reading) to emerge with an outcome variable (compressive strength) when the rebound hammer test was used. The established equations can also be the basis for estimating the concrete compressive strength cured in a seawater environment (Equation 4), seawater in a controlled area (Equation 5), and potable water stored in a normal room condition (Equation 6) for rebound hammer test, respectively.

$$y_{(compressive\ strength)} = 10.2780e^{0.0343x_{(rebound\ reading)}} \tag{4}$$

$$y_{(compressive\ strength)} = 6.8166e^{0.0608x_{(rebound\ reading)}} \tag{5}$$

$$y_{(compressive\ strength)} = 9.6049e^{0.0408x_{(rebound\ reading)}} \tag{6}$$

4. Conclusions and Recommendation

The rebound correlation curve provided by the manufacturer in this study shows high dispersion in actual compressive strength results. The conventional rebound hammer device recorded low accuracy of 28.12%, 40.40%, and 25.84% in the actual concrete compressive strength estimation in three (3) environmental conditions. Therefore, the non-destructive test using the rebound hammer is inadequate to determine the actual compressive strength of concrete during the earlier days of its curing period.

The study also shows that the changes in temperature in the seawater environment, the calibration and maintenance of the rebound hammer device, less drying period of concrete samples after curing, the high water retained in the samples, and the uneven distribution of force in the plunger of the rebound hammer device to the concrete surface have greatly influenced the rebound reading which provided a high percentage error. Hence, the obtained compressive strength results were affected. It was also found that there was no carbonation development in all concrete samples in three (3) environmental conditions during their curing periods. Moreso, it was confirmed that the rebound reading was not linearly correlated with actual compressive strength results for concrete samples cured in the seawater environment and potable water stored in a normal room condition. Additionally, the rebound reading of concrete cured in seawater in a controlled area has a low correlation with the compressive strength in the direct compression test. In general, contrary to the specifications provided by the manufacturer, the rebound readings were not directly correlated with the actual compressive strength results.

Although the rebound hammer test had an inferior prediction in the actual compressive strength of concrete, still the rebound hammer device is good enough to estimate the concrete compressive strength if it is calibrated and regularly maintained to have a good condition. The study also developed rebound correlation models (graphical curve and empirical equation) as baseline references to estimate the concrete compressive strength when assessing the reinforced-concrete structure situated in seawater. The models increased the reliability estimation by 7.86%, 5.93%, and 9.15% in three (3) environmental conditions, respectively.

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