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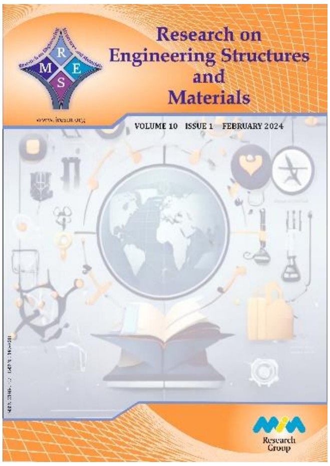

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Online Publication Date: 30 February 2024
URL: http://www.jresm.org/archive/resm2024.120me1211rs.html
DOI: http://dx.doi.org/10.17515/resm2024.120me1211rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Celerinos PJS, Frigllana SJC, Grande JJD, Ali NGH, Navarro JAC. Influence of seawater exposure at the splash zone on the reliability of the rebound hammer test in estimating concrete compressive strength. *Res. Eng. Struct. Mater.*, 2024; 10(3): 1209-1229.

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Research Article

Influence of seawater exposure at the splash zone on the reliability of the rebound hammer test in estimating concrete compressive strength

Philip Jun S. Celerinos[*,a], Sarah Jayne C. Frigillana[b], Joshua Jonielle D. Grande[c], Norfatima G. H. Ali[d], Jamie Angel C. Navarro[e]

Civil Eng. Dept., School of Engineering and Architecture, Ateneo de Davao University, Davao City, Philippines

Article Info

Article history:

Received 11 Dec 2023
Accepted 23 Feb 2023

Keywords:

Compressive strength; Direct compression; Rebound hammer; Reliability; Splash zone; Seawater

Abstract

In the face of challenging environmental conditions encompassing seawater exposure and dynamic wave forces, the evaluation of concrete's durability and structural integrity in coastal structures becomes imperative. The non-destructive test using a rebound hammer device is still commonly used up to this day to assess concrete coastal structures. However, the reliability of this test is still in question since the rebound hammer still depends on the tested environment. Thus, this study aimed to appraise the reliability of the rebound hammer test in estimating the compressive strength of concrete under specific environmental conditions, namely seawater exposure and normal room conditions—utilizing a digital version of the rebound hammer. The exposure durations included one month, two months, and three months. Results showed that the average estimated strength derived from the rebound hammer test tended to overstate the actual compressive strength obtained through the direct compression test, attaining a maximum percent error of 72.7%. This suggests a notable influence of seawater exposure on rebound readings. Additionally, it was also found that concrete samples in the first, second, and third months of exposure to seawater environment had soluble chloride content values in ppm of 250, 220, and 235, and a capillary water absorption in g/(mm^2*s$^{0.5}$) of 0.0196, 0.0151, and 0.0149, respectively. This showed that the properties of concrete used in this study could not influence the rebound reading results. Furthermore, the overestimation raises concern about the reliability of the rebound hammer test in accurately determining the actual compressive strength of concrete.

1. Introduction

Concrete structures erected in marine conditions are always directly or indirectly exposed to seawater. Direct exposure occurs on offshore and coastal structures such as seawater contact, while indirect exposure is due to winds carrying seawater sprays that may affect nearby structures. Seawater chemically reacts with concrete which results in concrete deterioration. Exposure to saltwater may also cause abrasions due to the silt and sand in shallow parts of the sea, as well the effects of wave actions [1]. Many concrete structures are being continuously built in marine environments, despite the effects on the chemical and physical properties of concrete. When seawater and concrete interact, the concrete deteriorates due to the salinity content of seawater [2]. Sulfate attack, crystallization, and mechanical action of waves are some of the phenomena that can potentially deteriorate the concrete strength over a period of time [3].

*Corresponding author: pjscelerinos@addu.edu.ph
[a] orcid.org/0009-0009-3919-2357; [b] orcid.org/0009-0006-1810-1290; [c] orcid.org/0009-0009-1430-659X; [d] orcid.org/0009-0003-2366-2808; [e] orcid.org/0009-0000-3922-1263
DOI: http://dx.doi.org/10.17515/resm2024.120me1211rs

Geographically, the Philippines being an archipelago, makes the rise of concrete infrastructure built near marine environments unavoidable. For instance, the highly anticipated proposed project in the Samal Island-Davao City Connector (SIDC) bridge had its groundbreaking ceremony in late 2022 [4], and the Davao City Coastal Road, a 17-kilometer road project, had the opening ceremony of its first section in Bago Aplaya in early 2022 [5]; hence, these two major projects built in Davao City emphasized the importance of structural integrity, particularly in these environmental conditions. Thus, its most affected area is between the atmospheric zone and the submerged zone due to the wetting and drying cycles of seawater that continuously occur in this spot. Apart from the presence of seawater itself, the waves that contact the area cause saltwater particles to infiltrate the concrete pores. As the area dries, the water will crystallize into salt particles. This repeated cycle will result in the deterioration of the concrete structure [1]. Thus, one of the tests that can be done to assess the integrity of concrete is the compressive strength test. The determination of compressive strength is a primary criterion used to assess whether the concrete mix is suitable and able to fulfill the requirements of its specific application [6].

When determining the compressive strength for destructive testing, the process involves producing a concrete cube, curing it under ideal conditions, and then destroying the cube while measuring the force required to break it. Such a procedure is commonly done using a direct compression test machine [7]. This method has the highest accuracy but takes time and effort, which can be relieved using non-destructive testing (NDT) techniques that are considered portable, less expensive, and easy to use [8]. Recent studies showed that measuring some concrete qualities and linking the measured properties to the mechanical properties of concrete is one technique that could approximately assess the compressive strength of the existing concrete structures [9]. Hence, non-destructive testing methods are used to assess the strength of concrete properties without having to break the structure or sample into pieces. Some examples of NDTs include the wireless maturity sensors, ultrasonic pulse velocity, and the rebound hammer tests. However, the most used NDT is the rebound hammer test [10]. The device used in this test can quickly determine the hardness value on the device scale without requiring the measurement of the concrete surface [11].

The rebound hammer test is an indirect method that does not measure concrete strength directly. It is frequently employed as a non-destructive technique for the evaluation of the durability and strength of concrete, specifically on historic structures, to assess their structural soundness due to the susceptibility of the country to natural disasters. It measures other properties, particularly surface hardness, where the strength is correlated and derived using conversion models provided alongside the acquired device from the manufacturer. The surface hardness of concrete must consider factors including age of concrete, calibration of the rebound hammer, carbonation, moisture content, presence of aggregates, presence of air voids and steel reinforcement, and temperature [8]. The rebound hammer uses a spring release mechanism to activate a hammer that impacts a plunger to drive into the concrete surface. The device will give a value from 10 to 100, which is called a rebound number (RN). This measurement will be correlated to estimate the compressive strength of concrete [12]. However, it has limitations that lead to a research field that studies its reliability in estimating the concrete compressive strength. Most studies proved its reliability, while some concluded that it is not dependable. Thus, a unique model cannot be all represented as a condition of concrete [10].

In the past twenty years, several research have been conducted to evaluate the performance of the rebound hammer test [13]. In the study of Li et al. [14], the impact of seawater on the development and effects of concrete were investigated. They emphasized the need to recognize that the environmental conditions during tidal seawater curing were significantly more pronounced than those of the concrete itself. Moreover, Bjegović et al.

[15] assessed the level of damage the concrete was exposed to the seawater environment and determined different mechanisms and intensities that influence the concrete during its service life. They stated that erosion and cavitation due to wave action can cause a progressive mass loss on a concrete surface, and the splash zone, which was the most exposed zone of concrete, had a higher chloride content, which allowed the deterioration of the steel reinforcement in concrete. Furthermore, Cheng et al. [16] have stated that typical physical degradations of concrete, such as leaching, wave erosion, repeated drying, and wetting, usually lead to the dissolution of hydration, increased porosity, and surface cracks. On the other hand, the experimental results by Panedpojaman & Tonnayopas [17] stated that despite a robust dataset correlating rebound numbers with compressive strength, the test was considered unreliable for accurate strength determination. Results have shown that environmental exposure impacts the concrete compressive strength, and the manufactured rebound curve often overestimates the actual compressive strength [18]. An experimental study by Sanchez & Tarranza [8] determined the reliability of the rebound hammer test in concrete cubes exposed to brackish water. They concluded that the rebound hammer test was not accurate in predicting the actual compressive strength but was still reliable in predicting the increase in compressive strength as time varied due to its rebound curve underestimating the actual compressive strength. Lastly, in more recent research conducted by Celerinos et al. [9], they assessed the use of rebound hammer in estimating concrete compressive strength when cured in three (3) specific environmental conditions: seawater, seawater in a controlled area, and potable water in a normal room condition. Their tests revealed that the rebound hammer had repeatedly underestimated the actual concrete compressive strength for the samples cured in all three (3) environments.

The abovementioned literature reviews have highlighted the importance of conducting more research and seeking further knowledge towards the specific environment on the compressive strength of concrete when using the rebound hammer test. Several researchers asserted the variables, including carbonation, concrete temperatures, maturity, surface texture, and water content may have possibly impacted the findings of performances, leading to a large data deviation [19]. Hence, a variety of rebound hammer devices are offered for sale in markets; however, their reliability is still in question. However, the studies of Li et al. [14], Bjegović et al. [15], and Cheng et al. [16] agreed that exposing concrete to fluctuating dry and wet conditions in seawater had severe effects on its properties, including heightened porosity, higher chloride content, and surface cracking. Hence, concrete structures exposed to the splash zone were the most susceptible to the effects of seawater on the characteristics and surface hardness of concrete. On top of that, Panedpojaman & Tonnayopas [17] revealed that rebound hammer test results relied on the age, carbonation, moisture content, surface smoothness, and temperature to measure the surface hardness of concrete. Yet, the device was still considered unreliable in estimating the actual compressive strength because of environmental factors and the overestimation of the manufactured rebound curves. This conclusion was consistent with the findings of Sanchez & Tarranza [8], such that the rebound hammer was not accurate in predicting the actual compressive strength, but it was reliable enough to predict the increase in compressive strength. Thus, the results obtained from using the rebound hammer test may have been affected by the conditions and factors to which the concrete was exposed to the splash zone of seawater.

This study prompted the expansion of knowledge on the rebound hammer test, since only a few studies [8-9, 14-16] had explored exposure to seawater in splash zone. Therefore, the present study aimed to determine the reliability of the rebound hammer test in estimating the compressive strength of concrete by comparing it to the direct compressive strength test after exposure to a seawater environment and normal room condition. The study also determined if the change in climate in the Philippines setting, from dry season to wet season, had any significant difference in the compressive strength of the concrete samples since the duration of experimentation was divided into three months. The three batches of concrete samples subjected to compressive strengths were done in the month of July, August, and September, respectively. Moreover, the study provided observations of any possible carbonation development that might have affected the rebound reading of the concrete samples. It also investigated the impact of prolonged exposure in seawater environment on the durability of concrete through capillary absorption and chloride content. Lastly, the study correlated the compressive strengths from the rebound hammer test and direct compression test results and compared the rebound number reading and actual compressive strength of the samples exposed to the splash zone of seawater and stored in normal room conditions. Hence, linear regression analysis was used to generate a model from acquired data and to correlate rebound number and actual compressive strength.

2. Materials and Methods

2.1. Concrete Cube Materials and Design Mixture

In the context of this study, thirty (30) samples were produced for the experimentation. A 150-mm cubic shape was used for the concrete samples [8], along with a 150-mm diameter and 305-mm height cylindrical shape samples. The cylinder concrete samples were used to derive a 150-mm diameter and 50-mm depth samples for the capillary absorption test under RILEM TC 116-PCD standard [20]. These samples were then divided into two (2) groups for seawater exposure and the normal room condition with three (3) cubes used for testing each month per group, respectively. This study prepared the requisite materials for the concrete mix, including Ordinary Portland Cement Type II, 3/4-inch (19 mm) diameter crushed coarse aggregates, washed fine aggregates, and concrete cube molds, all of which were locally outsourced. Notably, the experiment involved subjecting the concrete to seawater exposure, necessitating Type II cement under ASTM C150 standards. The properties of fine aggregates and coarse aggregates were gathered through a series of tests, shown in Table 1. These series of tests were conducted in the laboratory of the Civil Engineering Department at Ateneo de Davao University, Davao City, Philippines. Furthermore, strict adherence to a water-cement ratio of 0.6 was maintained [21]. Coarse and fine aggregates were thoroughly sieved, conforming to ASTM C33 standards [22].

Table 1. Properties of materials

Materials	Parameter	Properties
Fine Aggregates	Specific Gravity	2.7
	Moisture Content (%)	15.72
	Absorption Values	8.26
Coarse Aggregates	Specific Gravity	2.39
	Moisture Content (%)	3.21
	Absorption Values (%)	1.4

The same table exhibits the properties of the fine aggregates and coarse aggregates used in the mixture for making the concrete samples. For fine aggregates, washed sand was utilized, and was sourced from KEAN Solid Blocks & Aggregates Industries Corp. in Davao City, Philippines. The results of the laboratory tests revealed a specific gravity of 2.7, moisture content of 15.72, and absorption value of 8.26. On the other hand, coarse aggregates used in the samples were composed of 3/4-inch (19 mm) diameter gravel, and was also sourced from KEAN Solid Blocks & Aggregates Industries Corp. The results of the laboratory tests revealed a specific gravity of 2.39, moisture content of 3.21%, and an absorption value of 1.4. In addition, Figure 1 illustrates the particle size distribution of fine and coarse aggregates used in the concrete samples. These aggregates were sieved following the ASTM C33 standards [22].

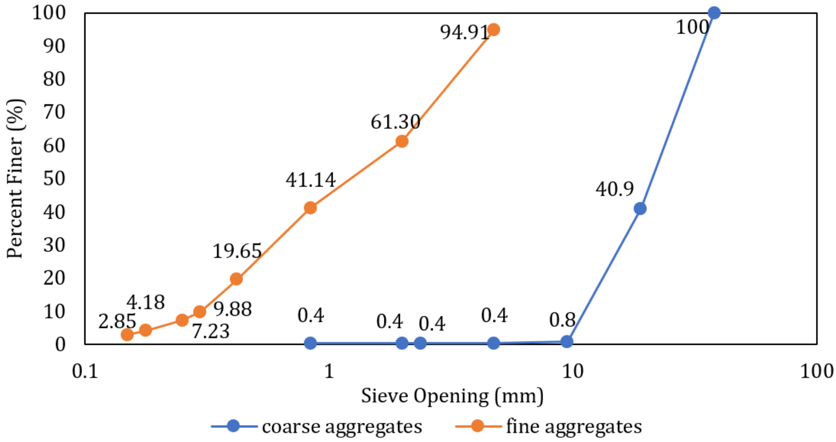


Fig. 1. Particle size analysis of fine and coarse aggregates

2.2. Concrete Mixing, Sample Making, and Curing

The concrete samples were prepared by employing the manual mixing method in accordance with the BS 1881-125:2013 standard [23]. Subsequently, the concrete mixture was integrated using clean water and was casted in a cubic mold using 3/4-inch-thick phenolic board to achieve a smooth finish concrete surface, adhering to the BS 1881-108:1983 standard [24]. All concrete samples underwent a standardized 28th-day curing process in a controlled environmental condition, following the guidelines of the BS 1881-111:1983 standard [25]. Regardless of the chosen method for maintaining moist air storage, a consistent temperature of 20.0 ± 5.0°C was meticulously upheld. Table 2 shows the quantities of the raw materials used for the making of concrete samples.

Fig. 2. Concrete samples before curing stage

This study prepared the materials for concrete mixing, including Ordinary Portland Cement Type II, crushed coarse aggregates, and washed fine aggregates. Given that the concrete was exposed to seawater, the required cement type for mixing was Type II in accordance with ASTM C150 [21]. In the same mentioned table, the volume is 0.118 m^3 and the water-cement ratio is 0.6, where 25.47 kg is water, and 42.46 kg is cement. The coarse aggregate is 0.118 m^3, and the fine aggregate is 0.059 m^3. This proportion was consistently used for casting concrete mixtures. Also, Figure 2 shows the concrete cube and cylinder samples for this study. All samples were cured for 28th days in the laboratory of the Civil Engineering Department at Ateneo de Davao University.

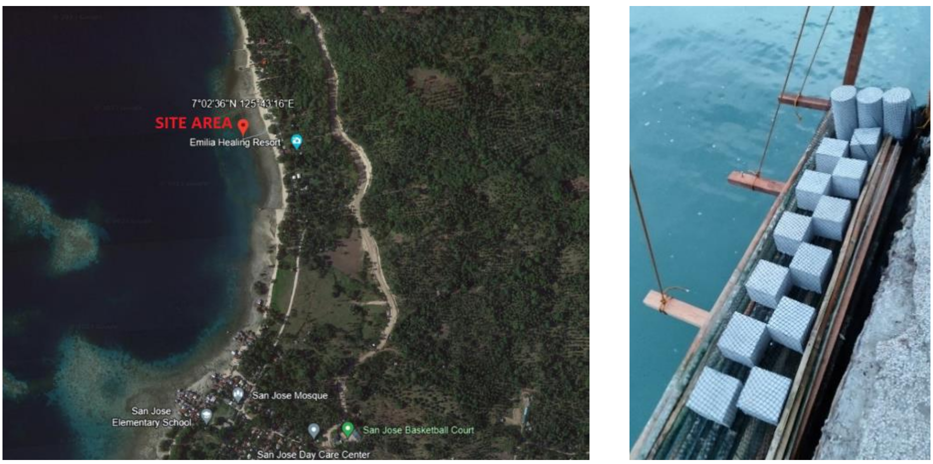
Table 2. Quantities of ingredients

Volume (m^3)	W/C Ratio	Water (kg)	Cement (kg)	Coarse Agg. (m^3)	Fine Agg. (m^3)
0.118	0.6	25.47	42.46	0.118	0.059

2.3. Exposure to Different Conditions

2.3.1. Seawater Condition

The concrete cube and cylinder samples were divided into two (2) groups and were exposed to the following different environmental conditions: 1) seawater condition, and 2) normal room condition. The samples were exposed in the months of July, August, and September in the year 2023. The authors of this study had chosen those specific months since they were under the rainy seasons of the Philippines [26]; therefore, concrete samples under this condition underwent alternate cycles of drying and wetting. First, the exposure to seawater was located at Barangay San Jose, Samal, Davao del Norte, Philippines, specifically 7° 02' 36" N 125° 43' 16" E, as shown in Figure 3a. It is situated in a private beach property, with a small dock just a few meters from the seashore. The samples were structured to be exposed and undisturbed in the small dock. Second, the experimental setup involved exposing concrete cubes in a splash zone of seawater using a platform and fish net as a stabilizing medium, as shown in Figure 3b.



(a) (b)

Fig. 3. Seawater environment in: (a) topographic view [28] and (b) concrete samples in the splash zone condition

Fifteen (15) concrete cubes and three (3) concrete cylinders were simultaneously exposed to the seawater for a specified duration. At monthly intervals, three (3) concrete cubes and one (1) concrete cylinder were taken for laboratory testing, continuing until the end of the third month. The authors conducted periodic visits to the site location to monitor and document any observable changes throughout the experiment. The specific location of the seawater exposure in this experiment is the splash zone. It was identified as the region between air and sea, where tidal changes occurred; thus, waves hit the structure. This zone was considered an optimal environment for corrosion due to the intermittent wetting and drying of this area [27]. Conforming with the studies mentioned in the earlier section, this zone allowed the exposed concrete to be more susceptible to the influences of seawater, affecting its characteristics and surface hardness [14-16]. This current study emphasized the importance of concrete exposure to the splash zone, such that the effects of seawater on the compressive strength of concrete could be measured and analyzed.

2.3.2. Normal Room Condition

The concrete samples were stored under standard room conditions after a 28th-day curing period for a predetermined duration in the laboratory storage room of the Civil Engineering Department at Ateneo de Davao University, as shown in Figure 4. They were exposed in the months similar to those samples exposed to seawater. These samples served as the control group of the study. Having this group provided a baseline reference of comparison against the samples exposed in seawater. Initially, fifteen (15) concrete cubes were placed in the designated room and were left undisturbed under normal room temperature at 20.0 ± 5.0°C. At monthly intervals, three (3) concrete cubes were systematically retrieved for testing, continuing until the third month. The authors regularly assessed the samples under this condition to monitor and note any potential alterations that might transpire during the study.

Fig. 4. Concrete samples in normal room condition after exposure

2.4. Series of Tests

After the concrete cubes were extracted from each environment during the first, second, and third months, the samples were then air-dried for forty-eight (48) hours before being weighed for its mass change, moisture content, and density. The concrete cube samples were then prepared to be subjected to the rebound hammer test adhering to the ASTM C805 standard [29]. Thereafter, the samples were systematically marked for ten (10) shots to obtain rebound readings, shown in Figure 5a. This study used a Digital Rebound Hammer Model TBT-TH225D from Nanjing T-Bota Scietech Instruments & Equipment Co., Ltd., shown in Figure 5b. To maintain the integrity of the results, precautions were taken to avoid striking areas of the concrete surface exhibiting voids and cracks. Furthermore, a minimum spacing of 50 mm between points hit by the hammer was maintained throughout the testing process. In the experimental setup, the hammer was carefully positioned at a downward angle of 90 degrees, ensuring a level ground surface supported the specimen [29-31].

(a) (b)

Fig. 5. Rebound hammer testing: (a) samples with marked zones, and (b) digital rebound hammer

Following the completion of the rebound hammer test, the concrete samples underwent loading until failure using a direct compression machine, shown in Figure 6, which was executed at TERMS Concrete and Materials Testing Laboratory Inc. in Davao City, Philippines. This process was undertaken to ascertain the true compressive strength of concrete samples.

Fig. 6. Direct compression machine

Subsequently, each sample went through a surface carbonation testing using the phenolphthalein method [32]. This step aimed to confirm the presence and degree of carbonation, a factor that significantly impacts rebound readings. The procedure involved applying liquid drops of phenolphthalein immediately after breaking the samples. A visual inspection was conducted on a cracked portion of concrete samples and sprayed with the phenolphthalein pH indicator. This indicator turned pink color on the cracked area with a pore solution higher than approximately pH 9, while the cracked with a pH lower than 9 retained a gray color [33]. The phenolphthalein used in this experiment has the following properties, as shown in Table 3. This chemical solution was purchased in Davao Mineral Laboratories, Inc. in Km. 6 Lanang, Barangay Buhangin, Davao City.

Table 3. Properties of phenolphthalein 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	0.059	Clear

In addition to the carbonation test in the concrete samples, further tests to determine the influence of the internal properties of concrete to the rebound readings were conducted. First, concrete samples of 5-mm depth from the surface was taken from the concrete cubes after carbonation for chemical analysis of chloride testing and was sent to the WVN Research and Laboratory at Elpidio Quirino Avenue, Talomo, Davao City, Philippines. The samples were turned into concrete powder to determine the soluble chloride content of the concrete (ppm). Second, the durability properties using capillary absorption test in the splash zone area of the exposed concrete cylinders in seawater were also taken using the following procedures. Three (3) samples were extracted during the first, second, and third months for the capillary absorption test as per the RILEM TC 116-PCD standard [20]. The standard test sample, with 150-mm diameter and 50-mm thick, was taken from concrete cylinders. The absorption was calculated by dividing the change in mass by the product of the cross-sectional area of the test specimen and the density of water. In this test, the temperature dependence of the water density was disregarded, and a value of 0.001 g/mm^3 was utilized. Figure 7 shows the taken samples for the capillary absorption test. The capillary absorption test was conducted in the Civil Engineering Department Laboratory at Ateneo de Davao University, Davao City, Philippines.

Fig. 7. Samples underwent in capillary absorption test

2.5. Statistical Analysis

The study utilized two statistical tools to comprehensively analyze and assess the gathered data. Specifically, the study employed Linear Regression Analysis and Two-tailed T-tests at a 95% confidence level (p<0.05). For the T-test, the average rebound numbers between the samples exposed to seawater and samples stored in normal room condition were compared, as well as their actual compressive strength. This analysis aimed to ascertain whether significant differences existed between samples subjected to these varying environments. Moreover, a paired sample T-test was also employed for the comparison between the actual concrete compressive strength versus average compressive strength derived from the rebound hammer test. Before conducting the T-test, a Shapiro-Wilk test was used to assess the normality of each group. This was done to ensure adherence to the assumption required for the T-test analysis. The regression analysis utilized a linear model to examine the relationship between the rebound number and the actual compressive strength, which described the linear relationship between the response variable of actual compressive strength and the explanatory variable of the rebound number. The statistical analysis used the IBM® SPSS® statistics software version 22.0 [36] at the University Information Technology Office in Ateneo de Davao University, Davao City, Philippines.

A total of four (4) null hypotheses were formulated in this study for T-test, and four (4) complementary alternative hypotheses were formulated in opposition to these null hypotheses. The null hypotheses were listed as:

- H_0: There is no significant difference in the actual compressive strength between the samples exposed to seawater and samples stored in normal room condition.
- H_0: There is no significant difference in the rebound number acquired from digital rebound hammer between the samples exposed to seawater and samples stored in normal room condition.
- H_0: There is no significant difference between the compressive strength of samples exposed to seawater acquired from direct compression test and digital rebound hammer test.
- H_0: There is no significant difference between the compressive strength of samples stored in normal room condition acquired from direct compression test and digital rebound hammer test.

The alternative hypotheses were listed as:

- H_1: There is a significant difference in the actual compressive strength between the samples exposed to seawater and samples stored in normal room condition.
- H_1: There is a significant difference in the rebound number acquired from digital rebound hammer between the samples exposed to seawater and samples stored in normal room condition.
- H_1: There is a significant difference between the compressive strength of samples exposed to seawater acquired from direct compression test and digital rebound hammer test.
- H_1: There is a significant difference between the compressive strength of samples stored in normal room condition acquired from direct compression test and digital rebound hammer test.

To ascertain the appropriate hypothesis based on the data, the *p*-value was compared against the significance level of 0.05. The null hypothesis is accepted if the *p*-value is greater than 0.05, while the alternative hypothesis is accepted if the *p*-value is less than 0.05. The dataset encompassed samples of varying ages, specifically samples aged one, two, and three months.

3. Results and Discussion

3.1. Direct Compression Test versus Rebound Hammer Test

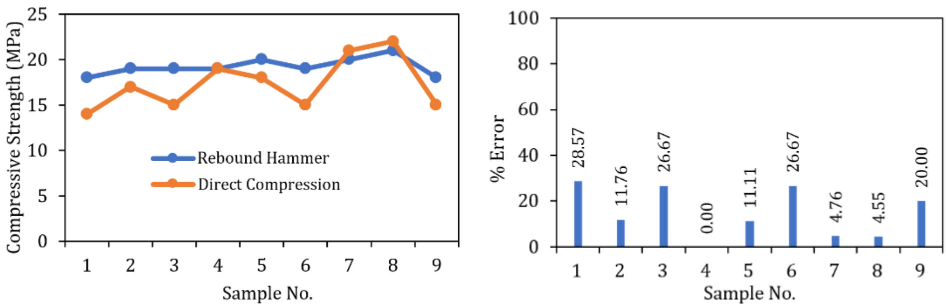
The compressive strength values of the two sample variations, which were exposed in seawater environment and stored in normal room conditions, were obtained using rebound hammer and direct compression tests. Table 4 shows the results of the estimated average compressive strength from the rebound hammer test and the compressive strength from the direct compression test of concrete samples stored in a normal room condition. The compressive strength values from the rebound hammer test were in the range between 18 MPa to 19 MPa for the 1st month exposure, 19 MPa to 20 MPa for the 2nd month exposure, and 18 MPa to 21 MPa for the 3rd month exposure. On the other hand, the actual compressive strength values of the concrete samples were in the range between 14

MPa to 17 MPa for the 1st month exposure, 15 MPa to 19 MPa for the 2nd month exposure, and 15 MPa to 21 MPa for the 3rd month exposure.

Table 4. Compressive strength results for the rebound hammer versus direct compression at 1st, 2nd, 3rd months stored in normal room condition

Months Exposure	Sample No.	Estimated Average Compressive Strength from Rebound Hammer Test (MPa)	Actual Compressive Strength from Direct Compression Test (MPa)	%Error
1st	1	18	14	28.57%
	2	19	17	11.76%
	3	19	15	26.67%
2nd	4	19	19	0.00%
	5	20	18	11.11%
	6	19	15	26.67%
3rd	7	20	21	4.76%
	8	21	22	4.55%
	9	18	15	20.00%

It can be observed that there were errors in the compressive strength results of the rebound hammer test for concrete samples for all months stored in normal room condition. The estimated average compressive strength from the rebound hammer test overestimated the compressive strength results of concrete samples stored in the normal room condition, as illustrated in Figure 8a. Conversely, the percentage error of compressive strength obtained by the rebound hammer test against the direct compressive test is plotted in Figure 8b. The minimum error has 0% on the 2nd month and the maximum error has 28.57% on the 3rd month.



(a) (b)

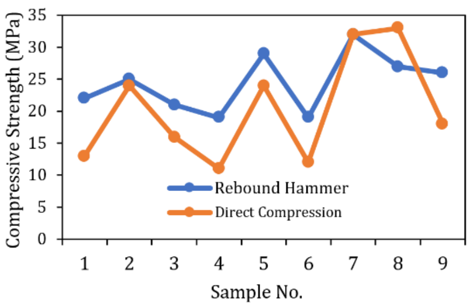
Fig. 8. Variations of concrete samples per storage period at normal room condition versus: (a) compressive strengths from the digital rebound hammer and direct compression, and (b) obtained %Error

Likewise, Table 5 shows the results of comparison of the rebound hammer test and the compressive strength obtained from the direct compression test of concrete samples exposed to seawater environment. The compressive strength values were in the range between 21 MPa to 25 MPa for the 1st month exposure, 19 MPa to 29 MPa for the 2nd month exposure, and 26 MPa to 32 MPa for the 3rd month exposure. However, the actual compressive strength values of the concrete samples were in the range between 13 MPa to 24 MPa for the 1st month exposure, 11 MPa to 24 MPa for the 2nd month exposure, and 18 MPa to 33 MPa for the 3rd month exposure.

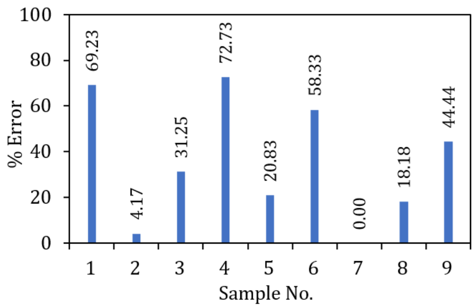
Table 5. Compressive strength results for rebound hammer versus direct compression at 1st, 2nd, 3rd months exposed in seawater environment

Months Exposure	Sample No.	Estimated Average Compressive Strength from Rebound Hammer Test (MPa)	Actual Compressive Strength from Direct Compression Test (MPa)	%Error
1st	1	22	13	69.23%
	2	25	24	4.17%
	3	21	16	31.25%
2nd	4	19	11	72.73%
	5	29	24	20.83%
	6	19	12	58.33%
3rd	7	32	32	0.00%
	8	27	33	18.18%
	9	26	18	44.44%

Similar to the previous comparison, the rebound hammer test still overestimated the compressive strength results of the direct compression test for the samples exposed in seawater environment. Figure 9a and Figure 9b show the overestimated results and the obtained percentage error for each month of exposure. Hence, the minimum error recorded 0% on the 3rd month and the maximum error recorded 72.73% on the 2nd month. In comparison with the results from the study of Celerinos et al [9], they have recorded a minimum percent error of 15.22% for all their sample variations and a maximum error of 59% that usually occurs in the latest curing period regardless of environmental condition. In this study, the minimum error obtained was 0% for both seawater environment and normal room condition. On the contrary, a maximum error of 72.73% occurred in concrete cubes exposed in the splash zone area of the seawater. The discrepancy might stem from the fact that, unlike the samples subjected to seawater exposure, the concrete samples kept in a standard room environment remained relatively stable and experienced fewer disturbances, potentially leading to a lower percentage of error. This could also be attributed to the dry-wetting cycles of the seawater waves during the duration of exposure that could led to an influence in the surface smoothness of the concrete cubes.



(a)



(b)

Fig. 9. Variations of concrete samples at normal room condition versus: (a) average compressive strength from the digital rebound hammer test and compressive strength from the direct compression test, and (b) obtained %Error

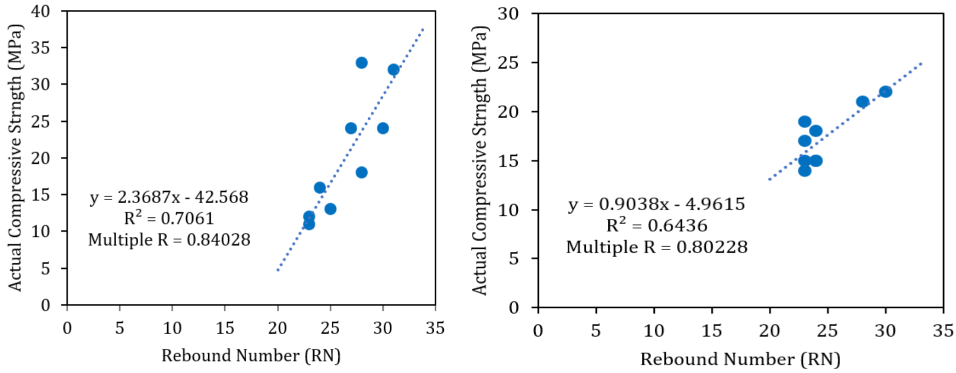
In addition, the average temperature in the site location was 31°C for the whole duration of the experiment with a weather described as mainly cloudy with precipitation. Therefore, the months wherein the samples were exposed was during a rainy season which may have further affected the surface properties of the concrete. The findings depicted in Figure 8a and Figure 9a which show that the estimated average compressive strength through the digital rebound hammer device tended to overestimate nearly all results obtained from the direct compression test. This stands in contrast to the study of Celerinos et al [9], where a manual rebound hammer device consistently underestimated the values from the direct compression test. However, when compared to Co's study [40], their results didn't demonstrate a consistent trend of overestimation or underestimation. This inconsistency suggested varying degrees of accuracy in the rebound hammer test's predictions when compared to direct compression test results.

Moreover, Table 6 shows the comparison between the actual concrete compressive strength versus the estimated average compressive strength derived from the rebound hammer test. For both comparisons, it obtained a *p*-value of 0.036273 and 0.0007921 for samples exposed to seawater and samples stored in normal room condition, respectively. The T-test results revealed that there was a significant difference between the average compressive strength from rebound the hammer test and the actual compressive strength from the direct compression test, for the two sample variations. The results consistently presented an overestimation of the estimated average compressive strength of rebound hammer. The T-test results consistently rejected the null hypothesis, which indicated that the estimated compressive strength values significantly varied from the actual compressive strength. This discrepancy was quantified in the percentage errors as shown in Figure 8b and Figure 9b, wherein a maximum error of 72.73% was attained. This observation suggests a limitation for the rebound hammer test using a digital rebound hammer device when attempting to directly estimate the concrete's compressive strength.

Table 6. T-test results for comparison between rebound hammer and direct compression test

Variations	*p*-value versus level of significance, α	Remarks
Samples exposed to seawater	*p*-value=0.036273 and α=0.05 *p*-value < α Reject the null hypothesis in favor of the alternative hypothesis	There is a significant difference between the compressive strength of samples exposed to seawater acquired from direct compression test and digital rebound hammer test.
Samples stored in normal room condition	*p*-value=0.0007921 and α=0.05 *p*-value < α Reject the null hypothesis in favor of the alternative hypothesis	There is a significant difference between the compressive strength of samples stored in normal room condition acquired from direct compression test and digital rebound hammer test.

In addition, Figure 10 shows the rebound models generated for the concrete cubes exposed to seawater and normal room condition using the rebound number obtained from the digital version. The Multiple *R* for samples exposed to seawater and normal room condition were 0.80228 and 0.84028, which indicated a strong linear relationship between the estimated average rebound number and actual compressive strength. The acquired R^2 values are 0.6436 and 0.7061 for samples exposed to seawater and samples stored in normal room condition, also the mentioned figure showed a moderate level of goodness of fit for the generated model.



(a) (b)

Fig. 10. Actual compressive strength versus rebound number: (a) stored in normal room condition, and (b) exposed to seawater environment

Furthermore, an observation of a consistent pattern emerged wherein there was a tendency to overestimate the actual compressive strength consistently. This discrepancy stems from potential inaccuracies caused by insufficient device calibration and reliance on the manufacturer's standardized graph. These outcomes underscore the critical necessity for developing a customized curve tailored to the specific characteristics of the sample being tested. This observation highlighted the significance of addressing calibration issues within the rebound hammer devices based on concrete exposed in specific environmental condition to enhance their accuracy in assessing compressive strength. Thus, this study emphasized the importance of creating individualized calibration curves that consider the unique properties of the concrete or material under examination. Developing such tailored approaches could significantly improve the precision and reliability of rebound hammer assessments in determining compressive strength, ensuring more accurate results in structural evaluations and construction quality control.

3.2. Comparison of Results from Rebound Hammer Test and Actual Compressive Strength between Two Sample Exposed to Different Conditions

Table 7 shows the comparison of estimated average compressive strength acquired from the rebound hammer test versus the actual compressive strength from the direct compression test for each pair of sample variations stored in normal room condition and exposed to seawater environment. The purpose of the comparison was to determine whether the rebound reading was affected by the type of environment where the samples were exposed to. The *p*-value of 0.3322 was attained for the first comparison, which indicated a greater value than the set confidence level considering the two-tailed T-test. Hence, this variation failed to reject the null hypothesis, indicating that there was no significant difference between the two groups of samples when compared to their actual compressive strength. This implies that the length of duration of exposure to seawater did not significantly affect the concrete, where its actual compressive strength remained relatively unchanged.

The second comparison shows the results of average compressive strength acquired from the digital rebound hammer test for each pair of sample variations exposed to different conditions. The *p*-value of 0.16644 was obtained using the two-tailed T-test, which indicated that it was greater than the significance level. Thus, there was no significant difference between the estimated average rebound number obtained from a digital rebound hammer of concrete samples exposed to seawater and stored in normal room condition. This meant that concrete cubes exposed to seawater rebound readings were partially similar compared to samples in normal room conditions.

Table 7. T-test results for comparison of rebound number and actual compressive strength between seawater exposure and normal room condition

Variations	*p*-value versus level of significance, α	Remarks
Actual compressive strength of samples exposed to seawater versus stored in normal room condition	*p*-value=0.3322 and α=0.05	Actual compressive strength of samples exposed to seawater versus stored in normal room condition
Digital Rebound Number of samples exposed to seawater versus stored in normal room condition	*p*-value=0.1664 and α=0.05	Digital Rebound Number of samples exposed to seawater versus stored in normal room condition

The comparison of findings in the first comparison concerning the actual compressive strength of two different sample variations revealed no substantial differences in their values. The outcomes presented for the second comparison corroborated that observation. Despite the digital hammer lacked precision in predicting the actual strength, its consistency in detecting variations in strength after exposure still underscores its reliability as an indicator of change. This was similarly apparent in study of Sanchez & Tarranza [8], where their findings indicated that the rebound hammer successfully anticipated the changes of concrete's strength over time.

The varied outcome of the digital iterations of the rebound hammer may be linked to the necessity for precise calibration according to its tested environment, given that the digital rebound hammer was newly purchased and underwent recent calibration. Additionally, the alignment of the digital hammer's plunger might have disrupted the concrete surface, potentially influencing the disparity in results. In the study of Celerinos et al. [9], the distributed nature of the applied plunger force was observed as the rebound hammer struck a larger zone area. Consequently, the recorded rebound readings indicated lower strength in the adjacent edges and higher strength in the central zone.

3.3. Results for Carbonation Test in Two (2) Environmental Conditions

Upon commencement of the direct compression test, visible cracks appeared in the concrete cube samples. Subsequently, a carbonation test was conducted using a phenolphthalein liquid solution. The cracked areas of the concrete cube were promptly treated with the liquid solution to assess the presence of carbonation during exposure to seawater and normal room conditions. As depicted in Figure 11, the interior of the tested cracked section turned pink in less than a second, signifying the absence of carbonation. In this study, a phenolphthalein test was employed to confirm the presence of carbonation in concrete cube samples. The results revealed the absence of carbon development in all concrete cube samples exposed to two (2) environmental conditions throughout their specified exposure duration.

One of the factors that could affect the rebound readings is the existence of carbonation if the concrete surface [29]. In the investigation conducted by Celerinos et al. [9], consistent findings were observed as the cracked segments across all sample variations exhibited a pink coloration, suggesting the lack of carbonation in proximity to the concrete surface. This parallel outcome is also evident in the experimental study conducted by Sanchez &

Tarranza [8]. The tested sections of the samples, both within the cracked areas and on the surface, rapidly transitioned to a pink hue, signifying the absence of carbonation.

Fig. 11. Concrete samples after phenolphthalein test

3.4. Chloride Content Results

Table 8 shows the results of the soluble chloride content for the concrete cube samples that were exposed in the seawater during the first, second, and third months, respectively. As per Bjegović [15], the zone with the highest exposure, the splashing zone, where waves and wind carry seawater, had an acceptable chloride content for unreinforced concrete of less than 0.15% by weight of concrete (1500 ppm). Generally, the greatest concentration of chloride ions was present in the splash zone, where wave and wind actions contributed to a significant accumulation of chloride ions in surface layers [37]. From the observation, samples from the first, second, and third month had values of 250 ppm, 220 ppm, and 235 ppm, respectively.

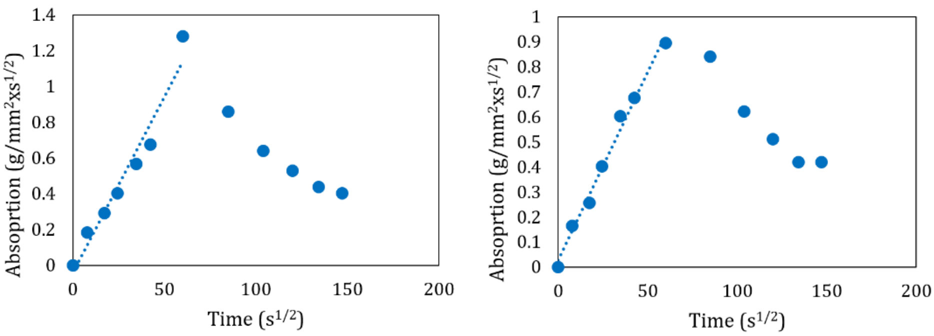
Table 8. Soluble chloride content results

Month	Soluble Chloride (ppm)
1st	250
2nd	220
3rd	235

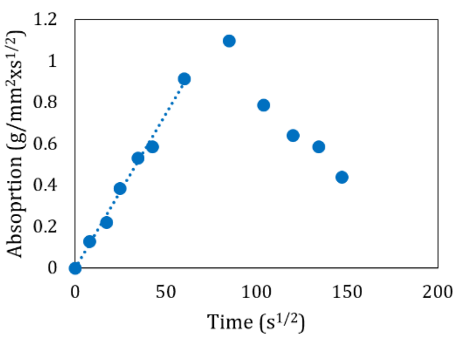
Generally, according to Arya et al. [37], at the initiation of each wetting phase, the pores near the surface were initially empty, while those farther from the surface contained varying amounts of liquid. The outcomes for all concrete samples typically indicated that the greatest depth of penetration occurred during the initial wetting cycle, and this value diminished in subsequent cycles. This trend was logical and expected until the absorbed liquid's volume equaled the volume lost during drying [15]. The results from Table 8 indicated that these values of soluble chloride were within the acceptable limit before any form of corrosion could occur on the concrete structure due to exposure to seawater for three months. As a result, the influence of the chloride content within the concrete cubes can be disregarded as one of the reasons for the accuracy of the rebound hammer test that was conducted.

3.5. Capillary Absorption Results

Furthermore, Figure 12 visualizes the capillary water absorption of the concrete cylinders exposed in the seawater splash zone. It illustrates a graph depicting the relationship between the water absorption rate and the time of absorption. The correlation between water absorption and the square root of time can be delineated into two distinct stages. Initially, during the first stage, there was a rapid linear increase in water absorption in tandem with the square root of time. Subsequently, as the concrete disc gradually reaches saturation, capillary water absorption diminishes, marking the onset of the second stage. In this stage, the water absorption curve exhibits a descending trajectory, reflecting a decrease in the water absorption rate. Therefore, it can be observed in Figures 12a, 12b, and 12c that the trendline between the three months were the same, indicating the same rate of change of absorption in the concrete cylinders during the entire duration of the experiment. It also showed the capillary water absorption coefficient of the concrete cylinders exposed in seawater in the first, second, and third month. The slope of the fitted equation during the initial stage was identified as the capillary absorption coefficient [39]. In this study, the linear fit of water absorption against the square root of time yielded a fitting correlation coefficient (R^2) exceeding 0.9.



(a) (b)



(c)

Fig. 12. Capillary water absorption results: (a) 1st month, (b) 2nd month, and (c) 3rd month

Table 9 shows the calculated capillary water absorption coefficient of the concrete cylinder for each month. The concrete cylinder in the first month had the highest coefficient of 0.0196 as the concrete was still not saturated due to its exposure to the seawater. Conversely, the second month, with a coefficient of 0.0151, and third month, with a coefficient of 0.0149, experienced lower capillary water absorption due to more prolonged exposure to the seawater. According to Balakrishna et al. [38], the absorptivity coefficient increases at initial time period due to an unsaturated pore structure, however as time goes on the pore structure may reach a fully saturated condition that led to the decrease of the rate of absorption [38]. The close values, especially in the second and third months, indicate a stable rate of capillary water absorption within the concrete samples, which shows a weak influence of the seawater in the microstructure of the concrete specimens.

Table 9. Capillary water absorption results

Month	Capillary water absorption coefficient [g/(mm^2*s$^{0.5}$)]
1st	0.0196
2nd	0.0151
3rd	0.0149

Also, as evident in Figures 12 that the absorption rate was consistently higher during the initial duration due to a differential gradient between the higher and lower concentration gradient sections. In this interval, there was a variation in the absorption rate until a specific time duration, followed by an increasing to decreasing pattern, indicating a smooth flow of the absorption rate. Upon reaching this pattern, the pore structure, cement paste, and concrete matrix became fully saturated, ultimately leading to the equilibrium state of the absorptivity coefficient [38]. In addition, according to Arya et al. [37], in all instances, with an increase in wetting-drying cycles, the net weight change decreased until it reached a constant level. At that point, the weight absorptivity value became constant. The distance absorptivity values were expected to stabilize when the value of effective porosity also reached a stable state. Therefore, from the results, the capillary water absorption has no influence in the accuracy of the rebound hammer test being conducted due to seawater exposure.

4. Conclusion and Recommendations

The compressive strength for the concrete cubes exposed to normal room showed a maximum error of 28.57% compared to the concrete cubes exposed to seawater with a maximum error of 72.73%. The results consistently overestimated the average compressive strength results using digital rebound hammer device from the actual compressive strength. The low accuracy of the percentage error between all months showed the inability of the rebound hammer to determine the actual compressive strength of the concrete samples.

The study also revealed that the carbonation, capillary absorption, and total chloride content of the concrete cube samples showed little apparent changes after being exposed to the seawater condition. This implies that the properties of concrete were not able to significantly change within the whole duration of the experimentation and did not indicate any signs of deterioration. This was also reflected on the T-test results that there is no significant difference on the actual compressive strength of samples between those exposed to seawater and those under normal room condition. Thus, there was a significant difference in relation to the estimated average rebound numbers of the concrete cubes between the sample variations.

The T-test results further showed that the estimated average compressive strength from the rebound hammer test significantly exceeded the actual compressive strength for all variations in sample groups. Hence, across both environmental exposures of the samples, the average compressive strength consistently indicated an overestimation compared to the actual compressive strength, implying potential inaccuracies in the rebound readings. However, the rebound hammer was able to show a similar trend with that of the actual compressive strength which means that the device can be relied upon in knowing the decrease or increase in compressive strength of the concrete due to the environment. Nonetheless, the digital rebound hammer was less sensitive to surface properties of concrete leading to its capability to estimate the changes in the actual compressive strength of the concrete.

Lastly, a strong linear relationship between the rebound number and actual compressive strength was evident for both sample variations as reflected on the correlation coefficient values acquired using the regression analysis. However, the coefficient of determination implies that the data has a high dispersion in both sample variations. This observation may be linked to the study's restricted availability of cube samples for analysis, potentially impacting the observed trend in the data due to the small sample size. Nevertheless, it is possible to generate a rebound hammer curve, provided a sufficient number of concrete samples are tested in order to predict a closer value to the actual compressive strength.

Acknowledgement

The authors would like to acknowledge the School of Engineering and Architecture and the Civil Engineering Department at Ateneo de Davao University for their support and guidance throughout this research work.

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