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Concrete Compressive Strength Estimation by Means of Nondestructive Testing: A Case Study

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Abstract

Estimation of the mechanical properties of concrete in an existing structure is possible with the results of surface hardness and ultrasound tests (nondestructive tests (NDTs)). For both the use of correlation curves is necessary, it is established between NDT and the results of the compressive strength of test specimens or extracted from structure. The objective of this study is to produce correlations between the results of surface hardness and ultrasound NDTs and the compressive strength of the structural concrete in the bleachers of a soccer stadium in the city of Cianorte, which is located in the northwest part of the state of Paraná, Brazil. This concrete structure, which is approximately 26 years old, has some defects, such as corrosion, concrete segregation and cracks. Concrete spalling in one of the slabs has recently raised some concern. Another significant issue is the absence of records regarding concreting of the bleachers' structure. Therefore, mapping the reinforcement was initially performed according to the results of a surface hardness test, as recommended by standard [1]. An ultrasound test was simultaneously performed according to standard [2] for the same points employed in the surface hardness test. The concrete specimens were extracted according to the recommendations of standard [1] to determine compressive strength, perform the NDT and construct the correlation curves for the results. A total of 26 concrete specimens were obtained from all structures of the bleachers. From the methodology and the results of the study, highly reliable equations were obtained from the correlation curves among the compressive strength of the concrete specimens and the values of the surface hardness index and the ultrasound wave propagation velocity.

Keywords

Concrete, Soccer Stadium, Strength, Ultrasound, Surface Hardness

1. Introduction

The measurement of ultrasound and surface hardness comprises practical tests that do not damage a structure's surface: the instruments are light and easy to handle and use. Ultrasound is employed to verity the homogeneity of concrete, to detect defects (concreting, depths of cracks and other imperfections) and to monitor variations in the concrete quality over time. Surface hardness is measured according to standard [3] to verify the uniformity of a concrete's surface hardness to compare it with a reference concrete and to estimate its compressive strength.

According to [3], a reliable correlation, which is obtained with local materials and with special attention to factors such as type of cement, type of aggregate, surface humidity conditions, carbonation and concrete age, must be available to have a direct assessment of a concrete's compressive strength.

The results of surface hardness measurement and ultrasound tests (nondestructive tests (NDTs)) enable the estimation of the mechanical properties of concrete in an existing structure. In this study, that estimation is performed using correlation curves that are established from the NDT results and the compressive strengths of specimens from the structure.

Correlations between the results of nondestructive tests (surface hardness and ultrasound tests) and the compressive strength of the concrete in the bleachers of the Albino Turbay soccer stadium in the city of Cianorte, which is located in the northwestern part of the state of Paraná, Brazil, are developed in this study.

2. General Characteristics of the Stadium and the Structure

The Albino Turbay Olympic Municipal Stadium ("Estádio Olímpico Municipal Albino Turbay") in the city of Cianorte, which is located in the northwestern section of the state of Paraná, Brazil, was inaugurated in April 1958. At that time, the land on which the stadium was built consisted of a simple grassy field that was surrounded by a natural hedge. The stadium is currently being employed for state and national professional soccer championships.

The reinforced concrete structure of the bleachers consists of modules (**Figure 1**) that are separated by cold and expansion joints. Module 1 was constructed in July 1991; each of the other modules was constructed in a subsequent stage. Module 5 was the last module to be constructed.

The structure of each module consists of porticos; each portico has three pillars (PT) and an upper sloped beam that receives the cross beams (VT). These beams provide support for the unidirectional slabs that are used as seats (**Figure 2**). Because the porticos are sloped, the space below them is used for restrooms, a gym, a medical department and the main entrance to the stadium.

3. Materials and Experimental Program

Preliminarily, the entire structure of the stadium was inspected to detect existing defects in the concrete and the corresponding degree of damage. The following defects

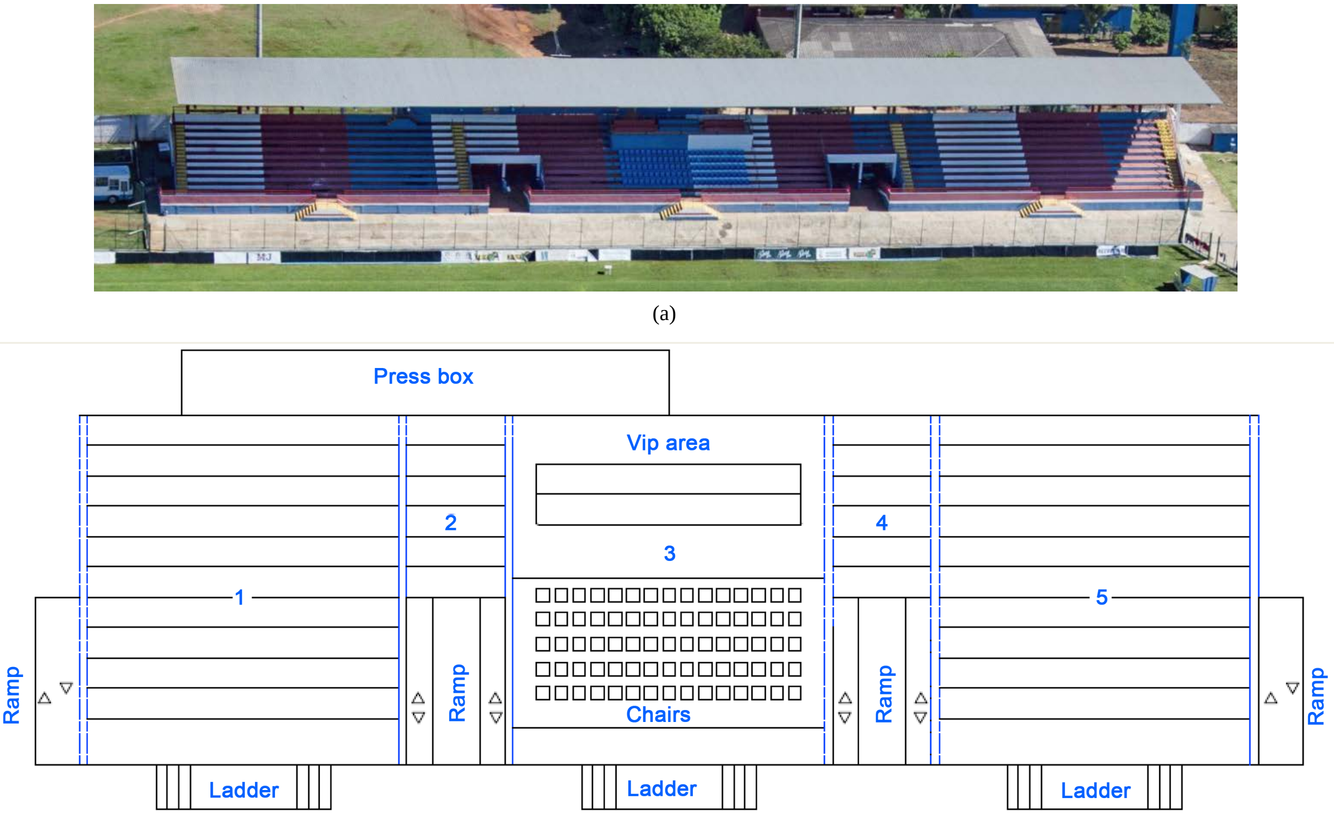


Figure 1. Total view and schematic of the bleachers. (a) Total view of the stadium's bleachers; (b) Schematic of the bleacher modules.

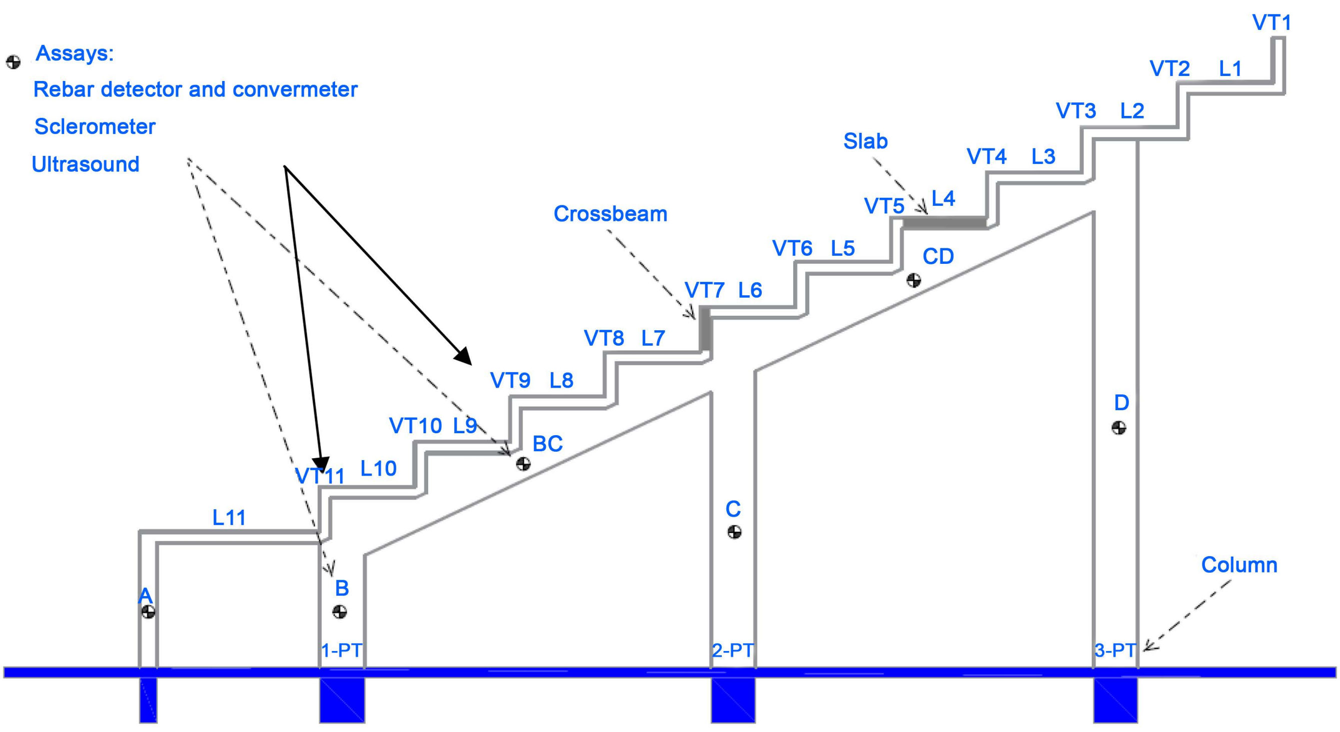


Figure 2. Cross-section of the porticos' structure.

were recorded: rebar corrosion (especially at the base of the pillars), concrete voids (more evident in the ends of the sloped beams of the porticos) and cracks in the unidirectional slabs.

An electromagnetic detection test (**Figure 3**) was performed to locate the rebar in the structural element to reduce its interference on the results of the ultrasound and surface hardness tests.

3.1. Rebar Mapping of the Structure and Definition of Lots

No records of the technology control of the structural concrete of the bleachers are available. In the preliminary inspection phase, all structures were divided in lots based on the importance of the structural elements and the homogeneity of the concrete according to standard [1]. The homogeneity of the structural concrete was subsequently assessed by the surface hardness test, following the procedures of standard [3].

3.2. Surface Hardness Test

To perform the surface hardness test, the concrete surface was prepared with a silicon carbide (*carborundum*) disc that was applied in circular movements to render it flat and perfectly smooth. All dust that was generated during the process was removed. Care was taken to avoid regions that were affected by segregation, exudation, rebar concentration, cold joints, cracks, pillar tops and regions close to the supports.

The position of the test area was defined in a manner that it was geometrically and uniformly distributed along the structure. As shown in **Figure 4**, the test area was defined by a grid that was drawn on the surface of the structure (exposed concrete). The instrument that was employed in the test was a Schmidt "N" Type scelerometer.

Seventeen surface hardness tests were performed in the structures of modules 1, 3 and 5, whereas nine hardness test areas were included in each structure of modules 2

Figure 3. Electromagnetic detection test of the structural elements' rebar.

Figure 4. Indication of the hardness test areas on the exposed concrete surfaces of the structural elements under the bleachers (insert scelerometer).

and 4. The tests in the points that were distributed in all structural elements (unidirectional slabs, cross beams, sloped beams and pillars) were performed in each module. The maximum and minimum surface hardness indices (SIs) of each module are listed in **Table 1**.

Based on the values of **Table 1**, the concrete's characteristics are homogeneous within each module. The minimum and maximum SIs for each module of the structure are within ±15% dispersion of the average value, as recommended by standard [1]. The SI results for modules 1, 2 and 4 and modules 3 and 5 are also homogeneous. For structural concrete mapping purposes, to define the number of specimens and to construct the correlation curves, the modules were separately considered due to their different ages.

3.3. Specimens' Extraction

The extraction of the concrete specimens followed the recommendations of standard [1] and was performed with a 100 mm diameter Hilti drill with a diamond crown (**Figure 5**). A total of 26 concrete specimens were extracted from the entire structure. The specimens were duly identified and sent to the Laboratory of Civil Construction Materials of the State University of Maringá in Umuarama for testing.

The propagation velocity of the ultrasound wave was determined by a direct transmission mode for each specimen at the laboratory, as shown in **Figure 6**. The Pundit Lab+ ultrasound instrument that was employed in the test was manufactured by Proceq, with 50 mm diameter transducers and a frequency of 54 kHz. Three readings in the direct transmission mode were performed.

The concrete specimens were submitted to simple compression until rupture in an Emic press, model PC200, with a capacity of 200 tons. The test adhered to the recommendations of standard [4].

Figure 5. Extraction of specimens from the bleacher's structure.

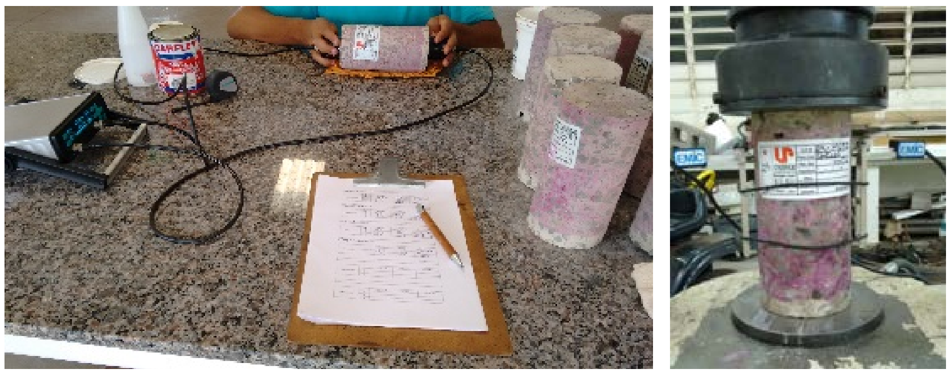


Figure 6. Ultrasound and simple compression tests of the concrete specimens.

Table 1. Surface hardness indices for each module (minimum and maximum values).

Module 1		Module 2		Module 3		Module 4		Module 5	
$SI_{minimum}$	$SI_{maximum}$	$SI_{minimum}$	$SI_{maximum}$	$SI_{minimum}$	$SI_{maximum}$	$SI_{minimum}$	$SI_{maximum}$	$SI_{minimum}$	$SI_{maximum}$
38	42	37	43	36	41	35	40	36	41

4. Results and Discussion

Correlation curves between the NDT results (surface hardness and ultrasound) and the compressive strength of the specimens were constructed. The curves are displayed for each module of the stadium structure. Only the curve that better represents the correlation that is defined by a nonlinear regression and its correlation coefficient (R^2) are shown,

The number of specimens to be extracted from the stadium's structure was defined according to the guidelines of standard [1]: six specimens for each of modules 1, 3 and 5 and 4 specimens for each of modules 2 and 4. Table 2 shows general information about the tests: quantity and maximum and minimum values.

In the case of module 4, a correlation between the NDT that was directly performed on the structure and the results of the compression of the concrete specimens was not feasible for different reasons: excessive rebar concentration, the impossibility to perform the test in the direct transmission mode for the chosen points of the structure and

Table 2. Information about the tests of the stadium's structure.

	Ultrasound	Surface Hardness	Concrete Specimens
Quantity	207	207	26
Maximum	V = 5528 m/s	SI = 48.2	f_c = 40.4 MPa
Minimum	V = 1211 m/s	SI = 24.1	f_c = 13.1 MPa

V = propagation velocity of the ultrasound wave; f_c = compressive strength of the concrete specimen.

significant concrete degradation in this module (cracks and corrosion) as previously detected in the preliminary inspection of the structure.

Correlation between surface hardness (SI) and compressive strength (f_c)

The correlations between SI and f_c are shown in Figure 7 and Figure 8. The curves were defined by the correlation of the values of SI obtained in the tests that were directly performed at the points of the structure of each module and the f_c values obtained in the tests of the specimens collected from the same points.

The regression equations that represent the correlation between SI and f_c and the respective correlation coefficients (R^2) are indicated in each curve.

The correlation coefficients of the curves varied between 0.69 (module 3) and 0.98 (module 2). This range is not substantially different from the range obtained in a study by [5] in which the lowest correlation coefficient was 0.78 and the highest correlation coefficient was 0.90 for a series of five different concrete compositions.

The observation of the curves reveals that the higher the f_c value is, the higher the SI of the structure's concrete. The best correlation was obtained for module 2, with R^2 almost equal to 1, which indicates that the equation has a high reliability.

The curve in Figure 9 was constructed to obtain a total evaluation of the correlation between the SI and the f_c of all points from which the specimens of the stadium's structure were collected. The total correlation was not as acceptable as the correlations for the individual modules.

The regression for the entire structure had a coefficient of correlation (R^2) of 0.3037, which is lower than the R^2 of 0.446 obtained by [6], which is explained by the authors as a consequence of the heterogeneity of the concrete.

Correlation between the ultrasound velocity (V) and compressive strength (f_c)

Figure 10 and Figure 11 show the correlations between V and f_c. The curves were constructed by correlating the values of V obtained in the test that was performed in the concrete specimens with the values of f_c obtained in the compression tests of the same specimens. A correlation between of the velocity tests could not be directly established for the structure and the strength of the specimens due to the influence of the rebar and the difficulty of performing the tests in the direct transmission mode, which directly affected the readings of the wave propagation velocity in the structure.

The regression equations that represent the correlation between V and f_c and the respective coefficients of the correlations (R^2) are indicated in each of the curves.

The coefficients of the correlations of the obtained curves ranged from 0.46 (module 5) to 0.89 (module 1). Better correlations between 0.69 and 0.96 were obtained in

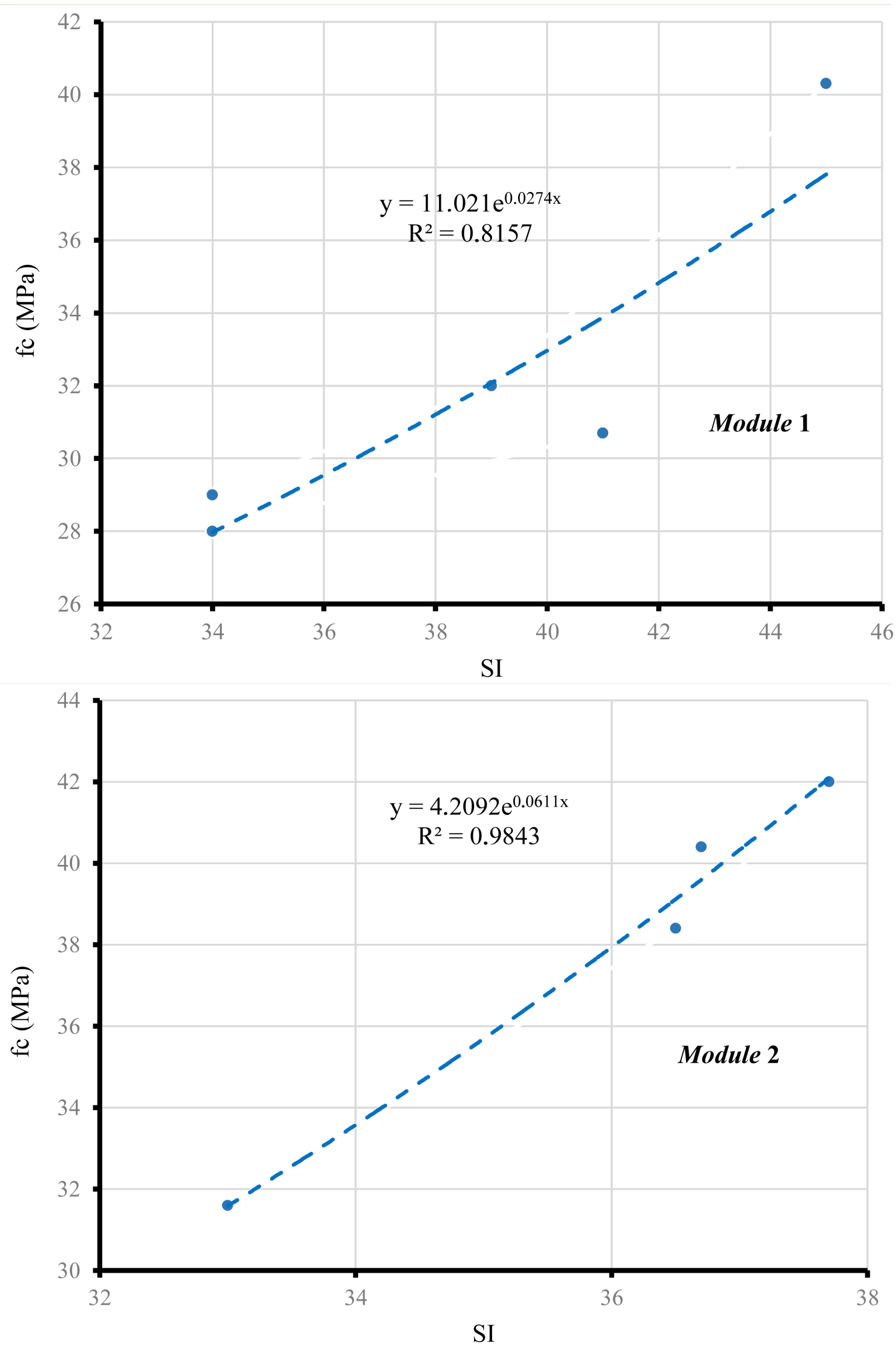


Figure 7. Correlation curves between the SI of the structure and the f_c of the concrete specimens (modules 1 and 2).

the study by [5] for five different concrete compositions.

The curves indicate that the higher the wave propagation velocity is, the stronger the concrete, which is demonstrated by the high correlation between the strength and the ultrasound velocity.

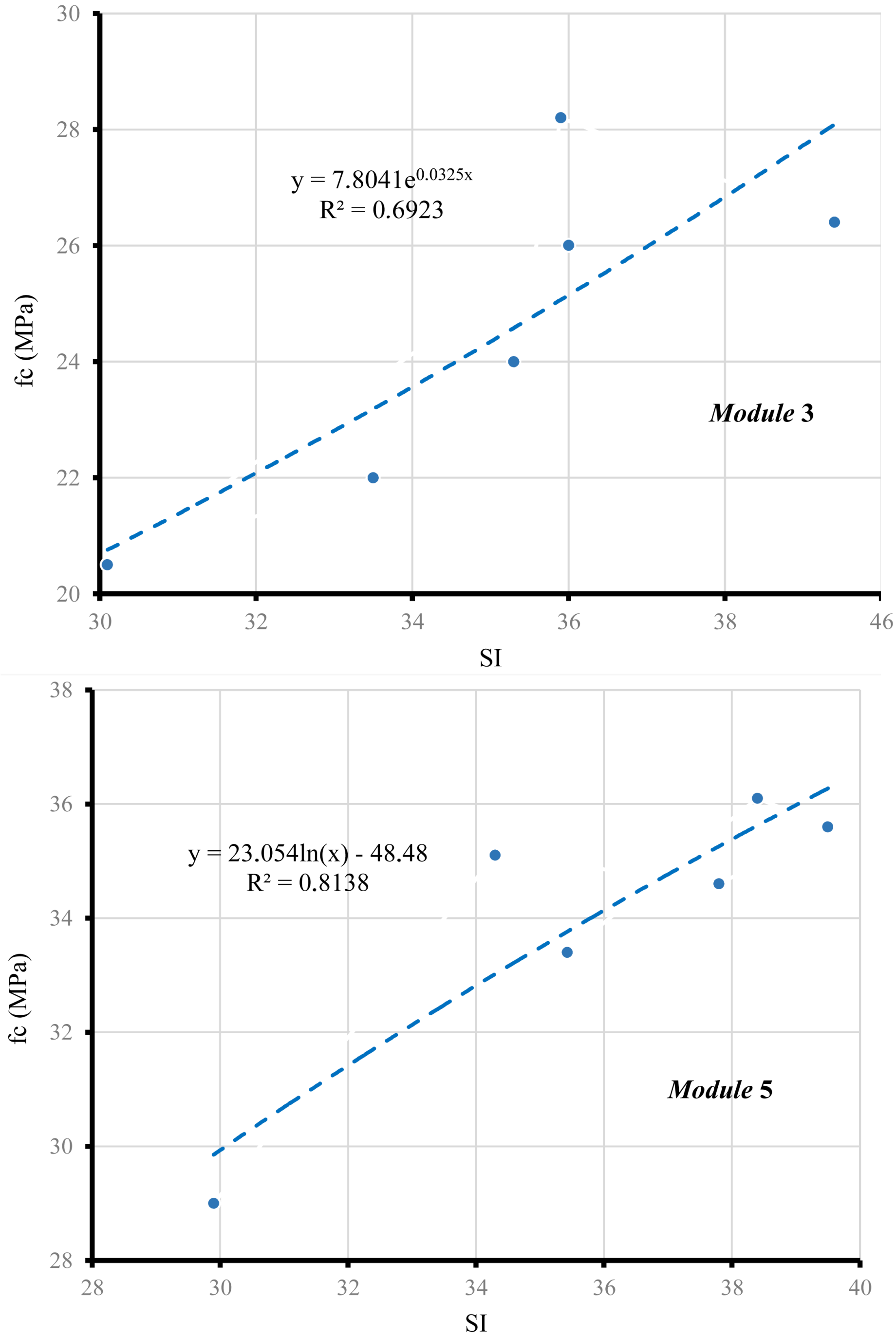


Figure 8. Correlation curves between the SI of the structure and the f_c of the concrete specimens (modules 3 and 5).

As with the surface hardness curves, different behaviors among the correlation curves obtained by ultrasound are observed. Module 2 yielded the strongest correlation with surface hardness, whereas Module 1 had the best correlation with the ultrasound test the weakest correlations from the surface hardness test and the ultrasound test were obtained for module 3 and module 5, respectively.

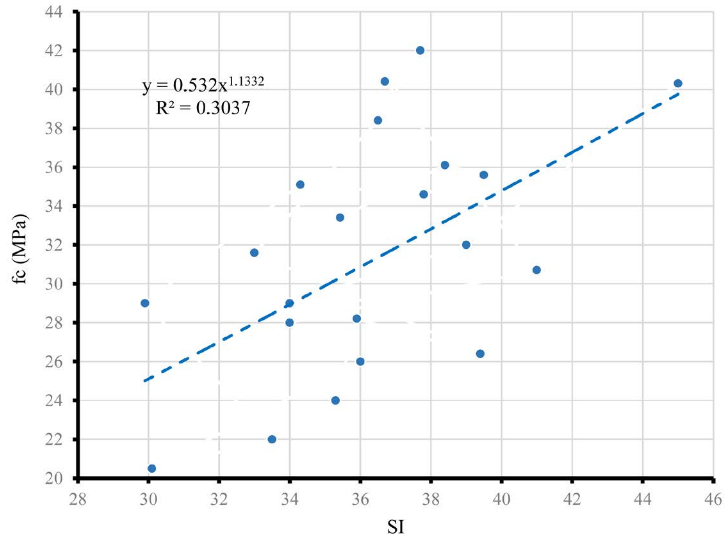


Figure 9. Correlation curves between the SI and the f_c of the concrete specimens (all modules).

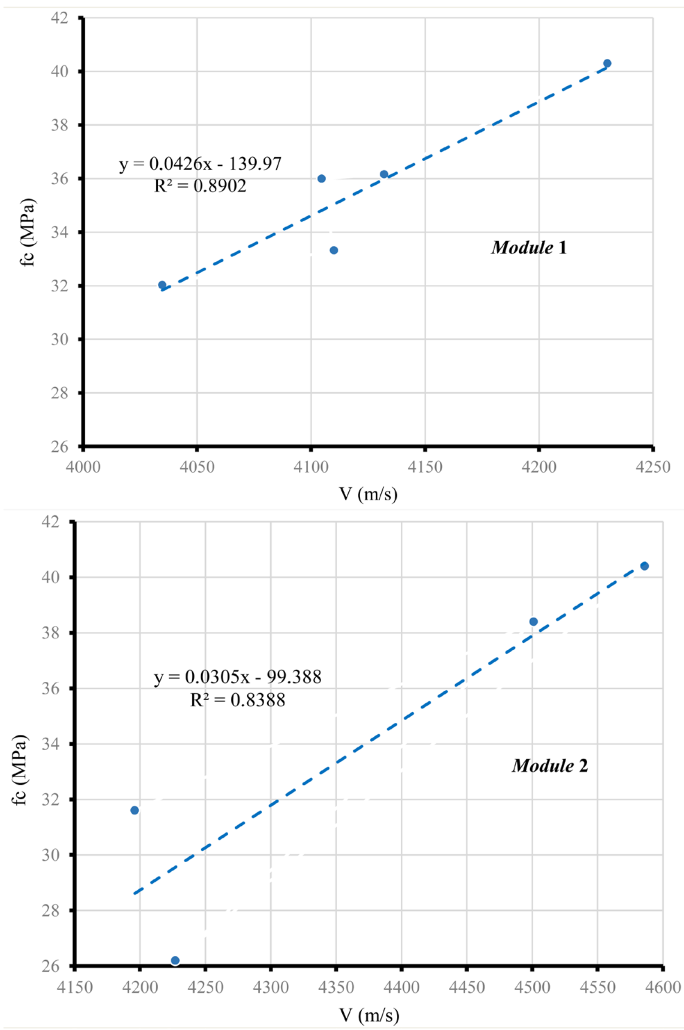
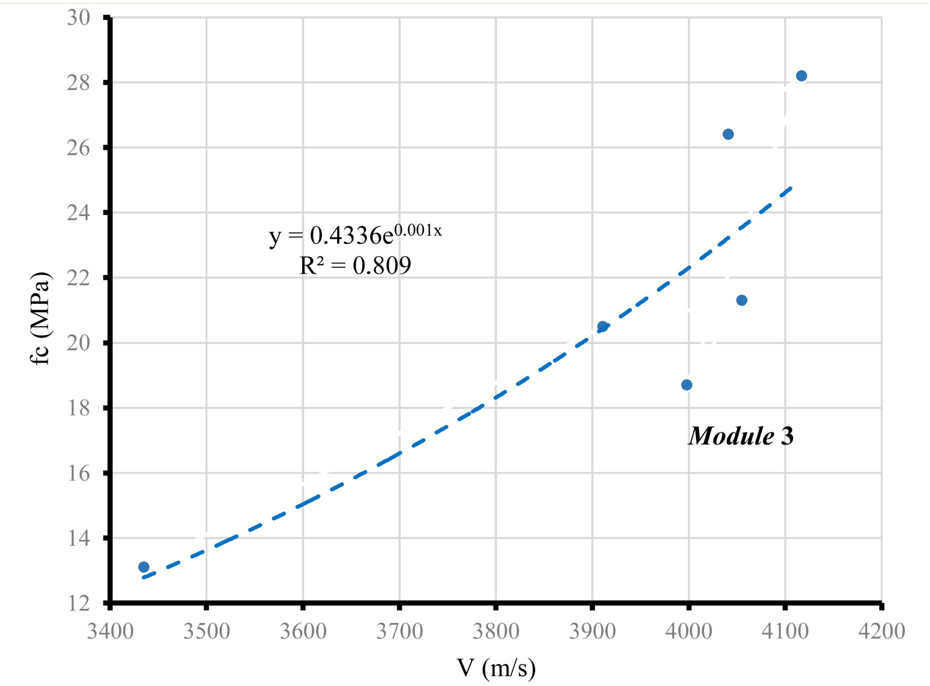


Figure 10. Correlation curves between V and f_c of the concrete specimens (modules 1 and 2).



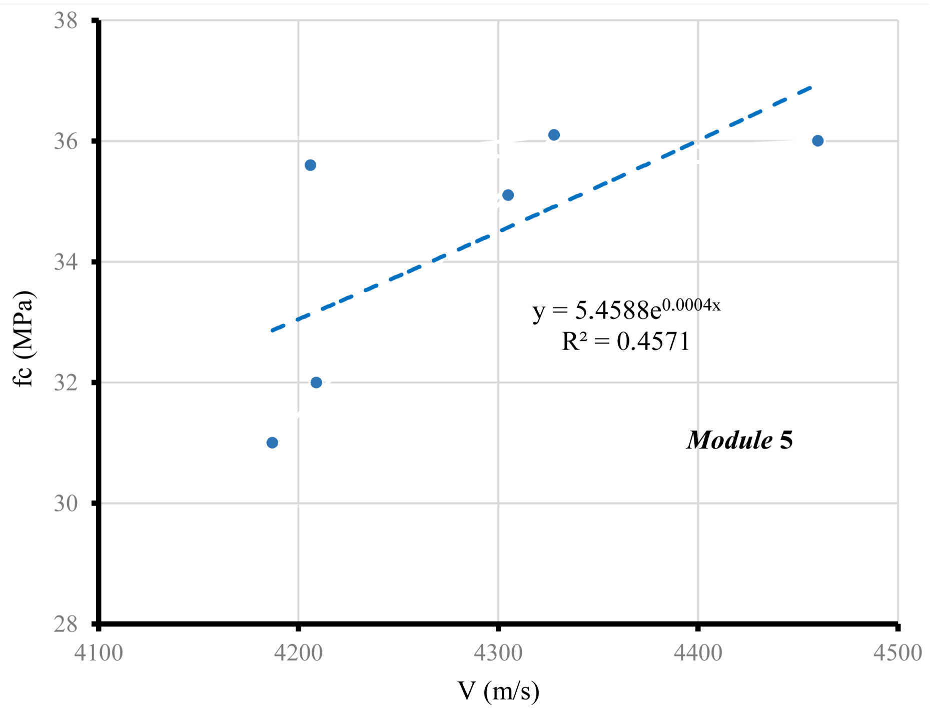


Figure 11. Correlation curves between V and f_c of the concrete specimens (modules 3 and 5).

The curve of **Figure 12** was constructed to obtain a total evaluation of the correlation between V and f_c for all concrete specimens that were collected from the structure. The correlation for the entire structure is only stronger than the correlation for module 5. The total correlation of the ultrasound tests was better than the total correlation of the surface hardness tests.

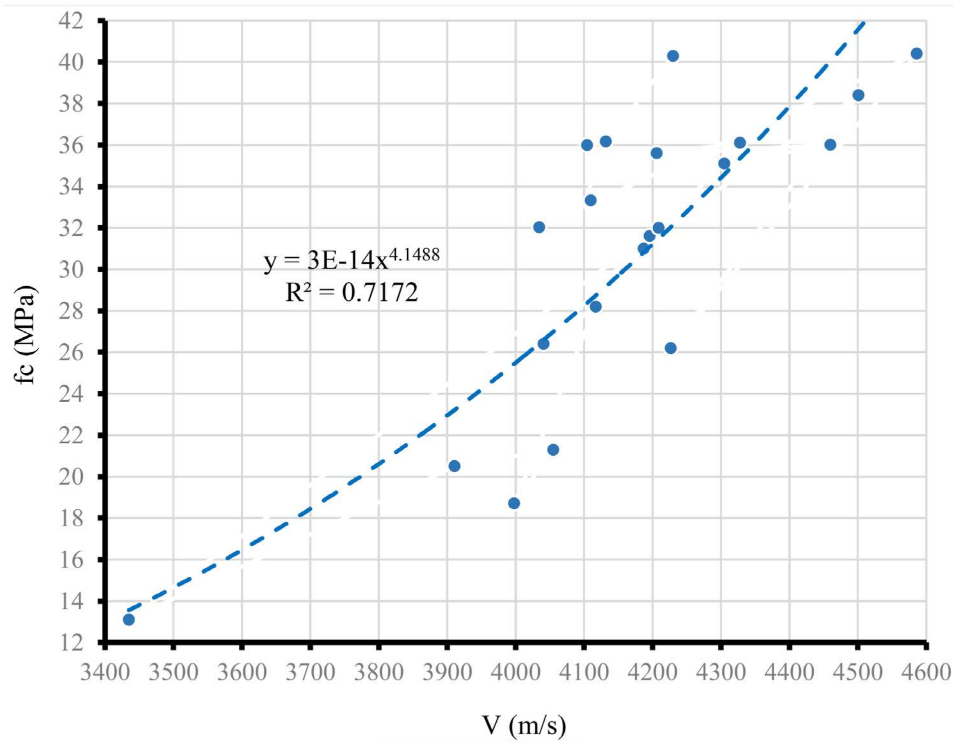


Figure 12. Correlation curves between V and f_c of the concrete specimens (all modules).

The regression of the entire stadium's structure had a coefficient of correlation (R^2) of 0.7172, which exceeds the coefficient of correlation that was obtained by [6] of 0.3011.

5. Conclusions

From the results, the following conclusions are formed:

Surface hardness measurement:

- A correlation between the results of the direct measurements of surface hardness for the same points of the structure at which the concrete specimens were collected and the specimens' compressive strengths was established;
- The stronger the concrete is, the higher the surface hardness index is;
- The curves obtained in the tests had similar behaviors, especially in the case of modules 1, 2 and 5 of the structure that was analyzed in the study. A strong correlation between the two variables, with a correlation coefficient of 0.98 for module 2, was observed.

Ultrasound:

- A correlation between the results of the ultrasound tests of the concrete specimens collected from the stadium's structure and the compressive strengths of the same specimens was established;
- The results indicated that the stronger the concrete was, the higher the wave propagation velocity was;

- The curves obtained in the tests revealed similar behaviors for each of the modules of the structure that was analyzed in the study, with the exception of the curve of module 5;
- The best correlations were obtained for modules 1 and 2, for the surface hardness and ultrasound tests. The correlation coefficients of the curves of these two modules were similar for both types of NDTs;
- In the case of the structure of module 3, the correlation of the ultrasound test was reasonable ($R^2 = 0.809$), whereas the correlation coefficient of the surface hardness test—$R^2 = 0.6923$—was lower. In the case of module 5, the best correlation was obtained by the surface hardness test ($R^2 = 0.8138$), whereas the correlation coefficient of the ultrasound test was $R^2 = 0.4571$;
- When the data of all modules were grouped, the correlations of both the surface hardness test and the ultrasound tests worsened, and the ultrasound test achieved the best result ($R^2 = 0.7172$);
- The curves obtained in this study can be used to estimate the strength of the concrete of other elements of the structure, considering that the corresponding equations were highly reliable. In addition, the equations obtained in this study will be very useful for identifying regions in other structures.

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