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Probabilistic analysis of the fiber reinforced concrete used in the construction of the Estaleiro Rio Grande dry dock

Análise probabilística do concreto reforçado com fibras utilizado na construção do dique seco do Estaleiro Rio Grande

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Abstract

Due to the variability of the concrete strength, it is fundamental to use statistical methodologies to establish the parameters for the concrete structures acceptance. The utilization of a large number of strength test results is very important to the validation and calibration of the existing standard codes and technical specifications. The objective of this study is to make a statistical analysis of the strength test results of the concrete reinforced with metallic and propylene fibers used in the construction of the Estaleiro Rio Grande dry dock, in Rio Grande-RS. A correlation model between the concrete tensile and compressive strengths was proposed. A model to predict the increasing of the concrete strength with time was also established both for the case of compression, as in the case of tension. Furthermore, it was made a comparison among the concrete characteristic strength calculated estimates according to the NBR 12655 [9] and EN-206-1 [17] standard codes and to the ACI COMMITTEE 318 [2].

Keywords: FRC, dry dock, probabilistic analysis.

Resumo

A variabilidade da resistência do concreto torna fundamental a utilização de metodologias estatísticas capazes de estabelecer parâmetros para a aceitação das estruturas. A utilização de um número grande de resultados práticos de ensaios de resistência é de grande importância para a validação e calibração das normas e especificações técnicas existentes. Desta forma, o presente trabalho busca realizar uma análise estatística das propriedades de resistência do concreto com adição de fibras metálicas e de polipropileno utilizado na construção do dique seco do Estaleiro Rio Grande, em Rio Grande-RS. Foram propostos modelos de correlação entre as resistências à tração e à compressão do concreto e correlações entre estas e o tempo. A seguir, foram realizadas comparações entre as estimativas de resistência característica definidas pelas normas NBR 12655 [9] e EN-206-1 [17], assim como pelo ACI COMMITTEE 318 [2].

Palavras-chave: CRF, dique seco, análise probabilística.

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1. Introduction

Due to concrete strength variability, it is fundamental to use statistical methods to establish parameters for the acceptance of concrete structures. The use of a large number of strength test results, especially those obtained in actual construction sites, is of great importance for the validation and calibration of existing standards and technical specifications.

According to DINIZ *apud* AZEVEDO e DINIZ [10], the fact that the current technical standards and specifications for the design of concrete structures are based on the Limit State Method, or on semi-probabilistic methods, makes the statistical description of all variables involved in the design a basic requirement for calibrating these methods. This paper presents a statistical analysis of the compressive strength and flexural tensile strength of the fiber reinforced concrete (FRC) used in the construction of the dry dock of the Rio Grande Shipyard, located in Rio Grande-RS, southern Brazil.

The fiber reinforced concrete has an increasingly use in Brazil, especially in the construction of rigid pavements. It consists in the addition of fibers with low or high elasticity modulus (or both) to the concrete during its dosage in order to improve its technical characteristics when compared to the plain concrete.

Dry docks are structures built in port areas that are used for the manufacture, renovation or maintenance of naval equipment, such as ships, submarines and oil drilling platforms. The dry dock of the Rio Grande Shipyard was built in the expansion area (Superporto) of the Port of Rio Grande-RS. It is 350 m long, 133 m wide and 14 m deep. It is positioned in the Port of Rio Grande Channel, which connects the Patos Lagoon with the Atlantic Ocean. This structure is intended to reform and construction of oil platforms, and this is the first large dry dock to be built in the country.

The Rio Grande Shipyard is positioned close to the sea, and its environment is classified as Class of Environmental Aggressiveness IV, according to NBR 6118 [6]. The concerns about the performance of the structure, both in terms of strength and durability, were evidenced through the strict technological control adopted from the initial phase of the project.

This rigorous quality control used in the construction of the Rio Grande Shipyard have taken samples of every ready mixed concrete truck, as it is established in the article 6.2.3.2 of the Brazilian standard NBR 12655 [9]. This methodology for assessing the strength of concrete provided a large amount of experimental results that are rarely available in the Brazilian port construction sites. These results were used in this work, which conducts a statistical analysis of strength properties of concrete with addition of steel and polypropylene fibers. Comparisons were made among the estimates of the concrete characteristic strength through the models defined by NBR 12655 [9] and EN-206-1 [17] and also by ACI COMMITTEE 318 [2]. Additionally, it was investigated the correlation between the tensile and the compressive strength of concrete as well as the correlation between concrete strength and age.

2. Fiber-reinforced concrete

The use of fibers to improve the technical characteristics of the materials has been performed successfully in several areas. In construction there are many applications, such as fibrocement roof tiles, sealing systems, thermal and acoustic insulation with glass fibers, and especially in concrete for tunnels and industrial flooring.

CHODOUNSKY and VIECILI [12] explain that the Fiber Reinforced Concrete (FRC) is a composite consisting of two phases: the matrix and the fiber. According to these authors, the properties of this composite material are determined by the interaction between the matrix and fibers properties.

The use of FRC dates back to the 1960s, and the addition of fibers to concrete can be performed with different materials such as steel, polypropylene, nylon, acrylic and carbon. However, the steel and polypropylene fibers are the most used in the preparation of FRC.

The polypropylene fibers have a low elasticity modulus compared to the elasticity modulus of the hardened concrete, thus, its function is restricted to the early hours after concrete casting. The introduction of this type of fiber in concrete is justified by the minimization of concrete cracking that occurs when it is in the plastic state and in the first stage of hardening.

The steel fibers are another means used to provide reinforcement to structures made of concrete. When added to concrete, steel fibers hinder crack propagation due to its high elasticity modulus. On the use of steel fibers, FIGUEIREDO [19] says (translation): "For the post-cracking load bearing capacity of composite features, the fibers allow a redistribution of stresses in the material even when used at low levels."

HOLLANDA and PINHEIRO [22] advocate the use of fibers because they act as obstacles to the development of cracks; intercepting the microcracks that develop during the hardening of the paste, preventing its progression and avoiding the appearance of premature macrocracks.

GAVA et al. [21] reported that (translation): "The steel fibers are added to Portland cement concrete to increase its performance against cracking, increasing its ability to absorb energy, called tenacity, and ensuring strength and cracking control."

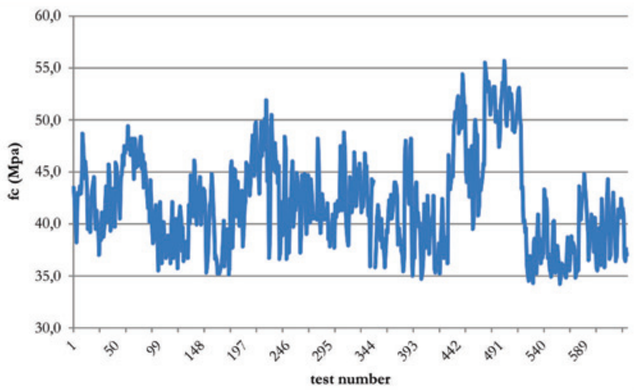
With the increasing of the cracking performance of the concrete reinforced with fibers it ceases to show the brittle behavior of plain concrete. Thus, according CHEN *apud* GAVA et al. [21], the FRC exhibits a pseudo-ductile behavior, i.e., it presents a certain load bearing capacity even after cracking. MEHTA and MONTEIRO [25] state that for concrete with low to moderate fiber content, the contribution of reinforcement is greater for the flexural tenacity of the material than for the actual strength.

Rigid pavements and concrete industrial floors are the largest applications of steel and polypropylene fibers. The introduction of fibers of high elasticity modulus increases the capacity of concrete panels to resist loads, since they redistribute the stresses on massive concrete preventing fractures in it. On the other hand, the introduction of low modulus fibers decreases the probability of occurrence of cracks in the first hours after concrete casting, a common occurrence due to the large volume of water lost in floors and pavements. According to CHODOUNSKI and VIECILI [12], the synthetic fibers such as polypropylene have been used in industrial floors to control the restrained shrinkage experienced by the still plastic concrete and later at the beginning of the cement hydration reaction.

The influence of fibers on the strength of concrete is not easy to evaluate. There are several factors that influence the strength of concrete. The water-cement ratio, chemical and physical characteristics of aggregates and additives, densification, curing conditions and temperature are some of the factors affecting this property.

The concrete is a material whose ability to resist tensile stresses is reduced. When a structure is subjected to stresses that produce

Figure 1 – Variation of the 28-day compressive strength of fiber reinforced concrete



tension above the tensile strength of concrete, cracks will appear. The introduction of steel fibers in concrete permits a stress transfer through these cracks, reducing the cracking process.
However, the addition of fibers to concrete may generate some problems: ISAIA [23] reports that the use of fibers in concrete, besides the reduction of concrete cracking, affects the concrete consistency conditions thus influencing its workability. In general, the addition of fibers to concrete occurs in the central mix plant, during the addition of aggregates. The addition in the central mix plant is advisable, as it allows more time for homogenization of materials. Nevertheless, it is possible to have the addition of fibers in the job site. In all cases, the fibers should be distributed as uniformly as possible, avoiding the formation of agglomerations of fibers, which are known by professionals as hedgehogs.
CHODOUNSKI and VIECILI [12] reported that (translation): "[...] if the mixing equipment provides a uniform mixing of concrete without fibers, it will certainly lead to a good quality mixture of fiber reinforced concrete."

3. Probabilistic analysis

This work made the probabilistic analysis of the compressive and tensile strength of the fiber reinforced concrete based on a total of 318 sets of test specimens molded according to NBR 5738 [4] and tested according to the recommendations of NBR 5739 [5]. The values of compressive strength obtained with the test at the age of 28 days of 636 specimens are shown in Figure 1. Although the samples studied in this case are of concrete with fiber addition, steel and polypropylene, it was used the same statistical treatment recommended by the standard codes for the concrete without fiber addition.

3.1 Characteristic compressive strength of concrete according to NBR 12655

The NBR 12655 [9] establishes the methods to control the compressive strength of concrete. This document provides the criteria for the choice of the batches of concrete to be sampled for the acceptance of concrete structures and two methods for controlling its strength: the statistical control by partial sampling and the statistical control by total sampling. The ABNT (Brazilian Technical Standards Association) methodology defines that each sample should consist of two specimens of the concrete taken from the discharge of a truck or a batch of concrete, and then the largest value of strength between these two is taken as the compressive strength (f_c) of the batch. In other words, the lowest score of the pair is discarded.

3.1.1 Statistical control by partial sampling

The statistical control by partial sampling consists in drawing random samples from some fresh concrete castings. In this case, the minimum number of specimens is 6 and 12 for the concrete classified according to NBR 8953 [7] as group I and II, respectively.
In case that the number of specimens n is such that $6 \leq n < 20$, the estimated characteristic strength ($f_{ck,est}$) is determined by the following equation:

$$f_{ck,est} = 2.\frac{f_1+f_2+...+f_{m-1}}{m-1} - f_m \quad (1)$$

Where $m = n/2$, and $f_1, f_2, ..., f_m$ are the strength values of the test specimens in ascending order.
When the number of specimens exceeds twenty, $n \geq 20$, the estimated characteristic strength is given by:

$$f_{ck,est} = f_{cm} - 1.65.s \quad (2)$$

Where f_{cm} is the average of strength test results expressed in MPa and s is the sample standard deviation expressed in MPa.

3.1.2 Statistical control by total sampling

The statistical analysis by total sampling consists in the sampling and testing of 100 % of the concrete batches or truckloads.
For $n \leq 20$, the estimated value of the characteristic strength of the batch is equal to the least strength among the specimens tested, i.e., $f_{ck,est} = f_1$.
For $n > 20$, $f_{ck,est} = f_i$, where $i = 0.05.n$. That is, the estimated characteristic strength is equal to the value of the element that represents the fifth percentile among the specimens placed in ascending order. When the value of i is not an integer number, we must take the integer value immediately above.

3.2.3 Characteristic strength of FRC according to NBR 12555

The control method by partial sampling, proposed by the NBR 12655 [9], uses the half of the results bellow the median strength of the specimens tested for estimating the characteristic strength of a concrete batch. It is based on the assumption that the concrete strength is modeled by a normal distribution. This methodology assumes that all specimens, whose strength values are used in the calculation, were extracted from a homogeneous population. According to Fusco [20], this estimate is centered on the characteristic value of the population studied. The author adds that the function of equation (1) is the result of two averages, the average of a set of specimens whose strength value is less than the mean value of the sample, and another average of all specimens of the sample represented by the median of the sample. The variance of this function is significantly smaller than the variance of estimators that consider the population variance.

The methodology by total sampling of the concrete batches has a more simplified calculation, based on the polygon of frequencies of the strength values. The value 0.05.*n* refers to the percentage of 5% of *n* specimens and it is related to the definition of f_{ck}.

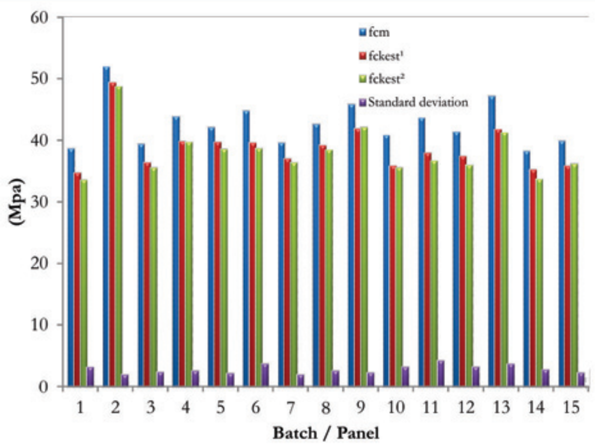
Aiming to contribute to scientific discussion, the data obtained from tests of the concrete used in the construction site of the Rio Grande Shipyard were analyzed by the two methodologies. BAUER et al. [11] presented a case study of a concrete batch using the estimators proposed by the NBR 12655 [9], highlighting the differences evidenced by each. AZEVEDO and DINIZ [10] also presented an analysis of estimates from different methodologies, encouraging further studies on the topic.

As previously reported, it was used the total sampling methodology for the control of the FRC batches executed in the construction site. Thus, for all concrete batches, specimens were molded and tested to determine the compressive strength at the age of 28 days. The construction of the Prefabrication Area of the Rio Grande Shipyard was done in stages and consists of 15 concrete panels. These floor panels were executed on different days and they meet the requirements of NBR 12655 [9] regarding the formation of concrete batches for control and acceptance. Thus, the acceptance of the rigid pavement of the shipyard was treated statistically. The pavement was divided into 15 panels. Each floor panel corresponds to a batch, which had a number of tested specimens between 20 and 23.

Using the method of dividing the pavement into panels corresponding to each of the concrete batches, the statistical parameters of each batch were determined. Figure 2 shows the mean value of strength, the standard deviation and the estimated characteristic strength by the two methods proposed by ABNT for each concrete batch.

It can be seen through the results shown in Figure 2, that the value of $f_{ck,est}$ can vary upwards or downwards, depending on the characteristics of the batch that is being analyzed and the methodology considered. However, one can observe that the results of both methods were similar; the biggest difference between the results was 1.5 MPa on the panel 14. Another important aspect is that in only two of the fifteen batches the strength obtained by equation (2) ($f_{ck,est}^2$) showed a higher value than the $f_{ck,est}^1$, which is the value adopted by the NBR 12655 [9] when the sampling is total. The similarity between the results of both methods was expected because of the definition of characteristic strength used in both approaches.

Figure 2 – Mean strength, estimated characteristic strength and standard deviation of batches according to NBR 12655 (9)



NOTE: $f_{ck,est}^1 = f_i$; $f_{ck,est}^2 = f_{cm} - 1.65.s$

3.2 Characteristic compressive strength of concrete according to ACI-318

The American method of estimating the characteristic compressive strength of concrete has basically three equations. The ACI-318 [2] divides the statistical control of concrete in two cases: one when the characteristic compressive strength is less than or equal to 34.5 MPa and the other when the concrete characteristic strength is higher than 34.5 MPa. The relationship between the required average strength (f'_{cr}) and the characteristic (or specified) compressive strength (f'_c) is established according to the following equations:

$$f'_{cr} = f'_c + 1.34.s \quad (3)$$

$$f'_{cr} = f'_c + 2.33.s - 3.45 \quad (4)$$

$$f'_{cr} = 0.90.f'_c + 2.33.s \quad (5)$$

Equations (3) and (4) are equivalent when the standard deviation reaches a value of about 3.45 MPa. Both equations refer to the concrete with characteristic strength less than or equal to 34.5 MPa. For the concrete with characteristic compressive strength exceeding 34.5 MPa, the ACI-318 Building Code requires the use of equations (3) and (5), and the highest value for f'_{cr} between the two results must be adopted. Considering that the concrete of the rigid pavement studied in this work has a specified compressive strength of 35 MPa, the equations (3) and (5) were used. In this case, we adopted for f'_c the lowest value obtained from the equations (3) and (5), using the values of the average strength (f'_{cr}) and standard deviation (*s*) of each batch, in a procedure to be on the safe side.

In the case of the American methodology, the concept of specimen is replaced by the term "*strength test*" which corresponds to the average of two single-cylinder strengths of specimens and not the

Figure 3 – Mean strength (f'cr), estimated characteristic strength (f'c) and standard deviation of batches according to ACI-318 (2)

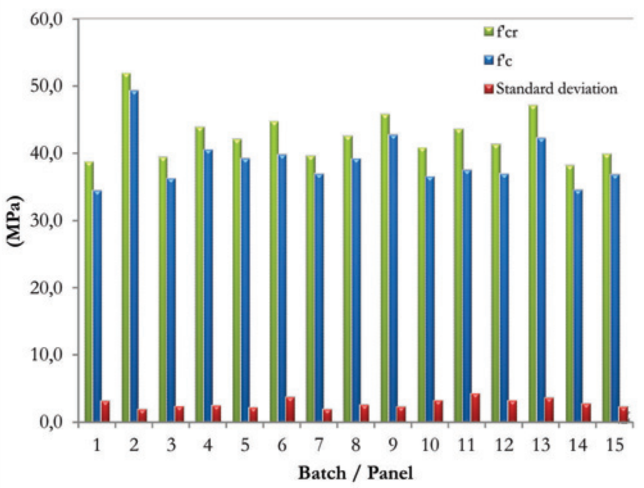
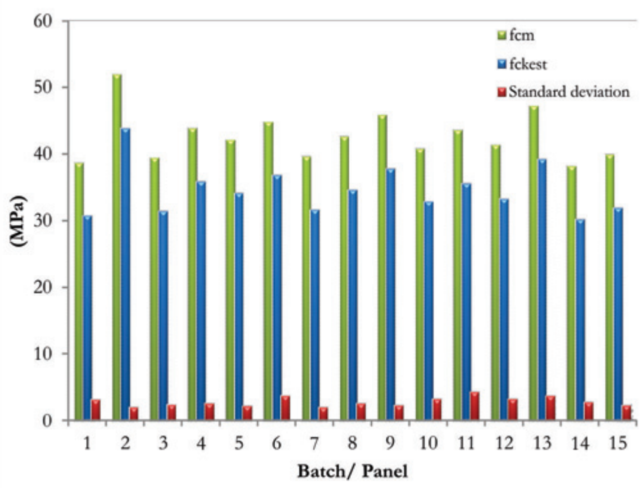


Figure 4 – Mean strength, estimated characteristic strength and standard deviation of batches according to EN-206-1 (17)



greatest value as in the case of the Brazilian methodology. In this respect, the ACI-318 [2] is more rigorous than the NBR 12655 [9]. Figure 3 shows the estimated characteristic strength values obtained by the American methodology for each batch analyzed.

3.3 characteristic compressive strength according to EN-206-1

The European standard EN-206-1 [17] establishes the criteria for conformity control of the concrete production. This standard determines how the sampling should be carried out and the criteria for acceptance of concrete structures.
To validate a given batch of concrete, EN-206-1 [17] presents two different criteria. A structure whose conformity is evaluated using the European methodology will be considered approved when the two criteria are satisfied.
The conformity criteria for the compressive strength of concrete according to the European model are presented in Table 1.
The characteristic concrete compressive strength of all the batches were calculated according to the Criterion 1 of the European code in order to compare these values with those obtained by the Brazilian and American models. Figure 4 presents the estimated values of the characteristic compressive strength of each of the fifteen batches studied by this criterion of EN-206-1 [17].

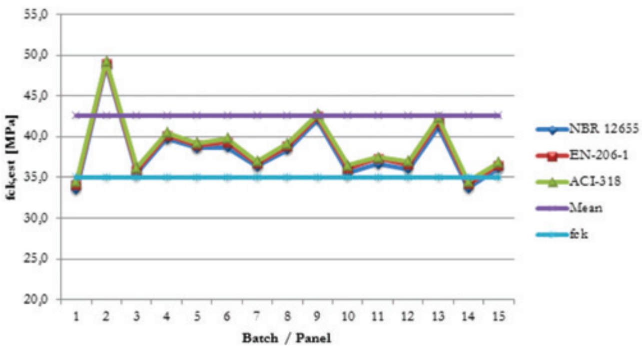
3.4 Comparison among the estimated characteristic compressive strength obtained by different standards for the FRC

The methodologies developed by the Brazilian ABNT were analyzed and compared with the American ACI-COMMITTEE 318/214 and European EN-206-1 models. It became evident that the Brazilian model provides estimates of the characteristic strength lower than the others for the same batch analyzed. It was also found that the American methodology produced estimates higher than the others for the same batch studied. Figure 5 shows the comparison among the estimators of the characteristic compressive strength according to the three models analyzed.
The ABNT prediction model presented values of the estimated characteristic strength very close to the European proposal. When comparing the two ABNT models to estimate the characteristic compressive strength, it was determined that the total sample model provides higher values in most of the batches in question. However, it was found that the two models of acceptance provided

Table 1 – Conformity criteria for compressive strength (EN-206-1 (17))

Production	Number "n" of compressive test results of the group	Criterion 1 Average of "n" results	Criterion 2 Any individual test result
Initial	3	$\geq f_{ck} + 4$	$\geq f_{ck} - 4$
Continuous	≥ 15	$\geq f_{ck} + 1.48.\sigma$	$\geq f_{ck} - 4$

Figure 5 – Estimated characteristic strength of each batch according to different standards



by the ABNT have very similar results, a fact that makes irrelevant the choice of which one of these two criteria is adopted at the moment of the batch acceptance.

However, AZEVEDO and DINIZ [10] suggest that before we hastily conclude that a norm is more conservative than another, we must be aware of the reliability levels implied in each case; without treating the variables involved in an isolated manner. PEREIRA [27] adds, saying that an efficient estimator should be able to distinguish between the concrete of good quality from that of poor quality, avoiding rejections or acceptances in error.

4. Variation of compressive strength of frc with age

There are several studies that seek to determine a correlation between the compressive strength of concrete and its age. Among these may be cited the expressions found in FALCÃO BAUER [18], NBR 6118 [6], CEB-90 [13] and MEHTA and MONTEIRO [25]. Such studies indicate that there are several factors that influence the strength of concrete during its first months of life. Curing conditions, temperature and humidity of the environment are some of these factors. MEHTA and MONTEIRO [25] add that: "At a given water-cement ratio, the longer the moist curing period the higher the strength, assuming that the hydration of anhydrous cement particles is still going on."

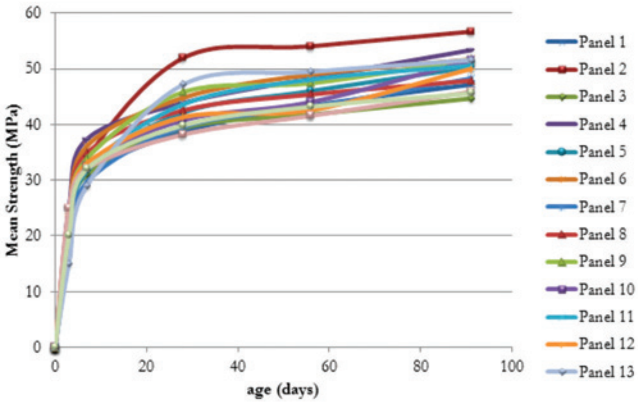
NEVILLE [26] reports that the Portland cement whose composition had high dicalcium silicate (C2S) content, typical of the early twentieth century, showed an increase in the strength of concrete exposed to the environment on a logarithmic scale up to 50 years. However, the cements made with the lower content of C2S currently used, and with increasing specific surface afforded by the best manufacturing techniques, reach their peak strength between 10 and 25 years.

The 15 batches that compose the sampling of concrete reinforced with fibers studied in this work had specimens molded and tested at the ages of 3, 7, 28, 56 and 91 days. With the test results it was possible to evaluate and generate a mathematical model capable of representing the variation of compressive strength of FRC with age. Table 2 shows the mean strength values and standard deviations for each age, as well as the number of tests in the sample.

Table 2 – Number of elements in the sample, mean strength and standard deviation of batches at the ages of 3, 7, 28, 56 and 91 days (MPa)

PANEL	3 days			7 days			28 days			56 days			91 days		
	n	mean	st dev	n	mean	st dev	n	mean	st dev	n	mean	st dev	n	mean	st dev
1	10	22.0	1.30	10	31.2	2.54	20	38.7	3.15	7	43.4	3.93	7	47.2	2.74
2	11	17.0	1.30	10	33.7	1.06	21	52.0	1.93	7	54.1	1.71	7	56.7	1.65
3	10	21.0	2.10	11	31.0	1.39	21	39.4	2.36	7	41.8	2.59	7	44.7	2.36
4	11	25.0	2.20	10	37.4	3.35	21	43.9	2.53	7	48.3	3.25	7	53.4	5.50
5	11	19.0	2.60	10	31.7	2.12	21	42.2	2.13	7	46.0	2.79	7	50.3	2.70
6	11	23.0	1.60	10	36.2	1.56	21	44.8	3.70	6	49.0	2.81	7	51.7	1.87
7	11	17.0	3.00	11	29.7	1.96	22	39.6	1.94	8	43.1	2.23	8	48.3	2.14
8	11	22.8	2.02	11	34.9	2.02	22	42.6	2.02	7	45.4	2.02	7	47.9	2.02
9	11	22.9	0.86	11	33.9	2.38	22	45.8	2.26	8	47.4	1.44	8	51.7	1.87
10	12	21.0	3.00	11	32.5	3.81	23	40.8	3.18	8	44.1	3.02	8	51.5	5.03
11	10	22.0	2.30	11	32.1	2.89	21	43.7	4.22	7	48.1	4.19	7	50.6	4.26
12	11	24.0	1.70	10	33.1	1.61	21	41.3	3.21	7	42.6	1.99	7	50.0	5.27
13	11	15.0	1.90	10	29.0	3.43	21	47.2	3.64	7	49.5	2.95	7	51.6	2.38
14	11	25.0	1.60	10	32.2	2.19	21	38.2	2.73	8	41.6	3.14	8	45.9	4.20
15	10	20.0	1.10	10	32.1	2.07	20	39.9	2.28	7	43.2	2.02	7	45.6	2.23

Figure 6 – Variation of compressive strength with age for the concrete with fiber addition



The data presented in Table 2 provide the curves of evolution of the mean strength of concrete with time shown in Figure 6. Based on the curves of Figure 6, it could be determined a correlation that permits to predict the compressive strength of concrete in a given age:

$$f_c(t) = 7.974.\ln(t) + 14.630\ \text{Mpa} \quad (6)$$

where *t* represents the concrete age, expressed in days.

Table 3 shows the relationship between the compressive strength of concrete at age *t* obtained by equation (6) and the strength at 28 days. The average results for the relations f_{ct}/f_{c28} obtained in the construction site are presented in Table 4.

It should be noted that the mathematical model fits very closely to the experimental data for ages $t \leq 28$ days, but it has little precision for other cases. It is important to note that this expression was established for a concrete executed with ordinary Portland cement and fiber addition, so that for a concrete with a different composition the equation (6) shall not be valid.

Several models are presented by the current standards and authors of the field to predict the behavior of the compressive strength of concrete with increasing age. However, the vast majority of these equations presented in these studies are based on concrete without fibers.

Figure 7 presents the graph of the strength values obtained from compressive strength tests made according to NBR 5739 [5] for different ages. This figure shows also the results obtained by the models for prediction of the compressive strength of concrete recommended by NBR 6118 [6] and the ACI-318 [2], expressed by equations (7) and (8), respectively:

$$f_c(t) = f_{c28}\exp\left\{s\left[1-\left(\frac{28}{t}\right)^{1/2}\right]\right\} \quad (7)$$

Table 3 – Relationship f_{ct}/f_{c28} determined by the proposed model for the concrete with fiber addition

Concrete composition	Age						
	1 day	3 days	7 days	14 days	28 days	56 days	91 days
Portland Cement CP-I, addition of steel fibers and polypropylene fibers, f_{ck} = 35 MPa	0.31	0.54	0.72	0.94	1.00	1.15	1.26

Table 4 – f_{ct}/f_{c28} mean ratio for the concrete with fiber addition determined by tests made in the construction site

Concrete composition	Age				
	3 days	7 days	28 days	56 days	91 days
Portland Cement CP-I, addition of steel fibers and polypropylene fibers, f_{ck} = 35 MPa	0.49	0.77	1.00	1.07	1.16

$$f_c(t)= f_{c28}\left(\frac{t}{4+0.85.t}\right) \quad (8)$$

It can be seen by Figure 7 that the models presented in the current standards can be adapted to concrete with addition of steel fibers and polypropylene. This statement can be applied to the concretes executed with cement classified by ABCP (Brazilian Portland Cement Association) as CP-I and with additions of steel fibers on the order of 30 kg / m³.

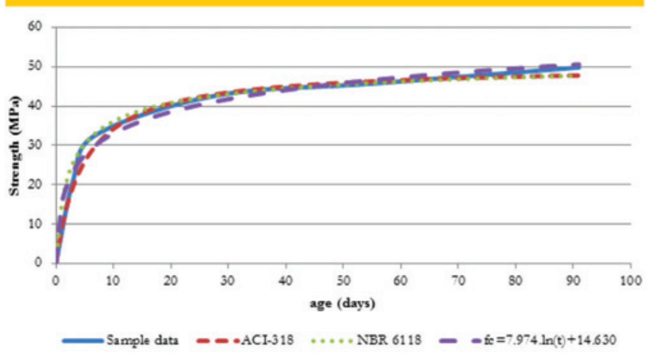
The variation of concrete strength is closely related to the type of cement used in the preparation of concrete. In the case analyzed, one can see a large increase of concrete strength in the first four weeks of age, but this increase is much lower in the following weeks till the first three months of age are completed. On average, the increase in the concrete compressive strength between the third and the twenty-eighth day was approximately 95%. For the period between the 28th and 91th days, the average increase in compressive strength was approximately 15%.

5. Variation of tensile strength of frc with age

The tensile strength of concrete is a property increasingly required by the designers, especially in the cases of pavements and concrete floors. Therefore the knowledge of the variation in its characteristics with time becomes increasingly important. The increase in tensile strength of concrete does not occur with great intensity after the concrete is 28 days old. Furthermore, the tensile strength of concrete is more sensitive to changes in external factors, such as improper curing and insufficient densification. This increase in tensile strength after 28 days of age is even less known when the concrete has the addition of fibers.

Among the factors that influence the tensile strength of concrete, we highlight the interaction between aggregates and cement paste, the geometry of the coarse aggregates, curing conditions, densification, fiber content and form factor (for FRC).

Figure 7 – Models for predicting the variation of the compressive strength with age for the concrete with fiber addition and average results obtained from the sample



The determination of the tensile strength of concrete can be done by three different tests. The direct tensile test consists of a clamping mechanism that pulls a cylindrical specimen of concrete, which is similar to the tensile test of steel rebar for construction. This test is rarely performed, since the fixtures introduce secondary stresses that are difficult to measure. The test by diametral compression is known worldwide as the Brazilian Test, since it was developed in Brazil, in 1943, by Professor Fernando Lobo Carneiro. It consists in compressing a cylindrical specimen along two diametrically opposed axial lines, determining the strength of the plane where rupture occurs by tensile stresses. This test is widely used because of its simplicity of execution in the laboratory. The flexural strength test consists in loading a prismatic beam at each third of the span length. This loading system results in pure tension on the underside of the prism, i.e., there are no shear force effects at the place of rupture.

In the case of tests of concrete with fiber addition, the use of cylindrical specimens are less recommended, particularly in diametral compression, because of the dimensions of the molding forms, in most cases, do not allow an uniform distribution of fibers. The prismatic forms used in flexural tensile strength test allow a more realistic reproduction of the local conditions of utilization of FRC.

The control of conformity of the concrete tensile strength in this work was done by the flexural strength test employing prismatic specimens with the dimensions 15 x 15 x 50 cm. Figure 8 shows the increase in the average tensile strength, corresponding to the maximum load (flexural strength) among the sampled specimens of concrete with fibers.

Through the established ratios between the flexural tensile strength of specimens older than 28 days and of specimens tested at the age of 28 days, we arrive at a correlation between the flexural tensile strength and age, for ages greater than 28 days, for the concrete with fibers object of this study:

$$f_{ct}(t)= 4.257.e^{0.002.t}\ \text{Mpa} \quad (9)$$

Where f_{ct} is the flexural tensile strength in MPa and *t* is the concrete age, expressed in days, with $t \geq 28$ days.

Figure 8 – Increase of the flexural tensile strength of fiber reinforced concrete as a function of age

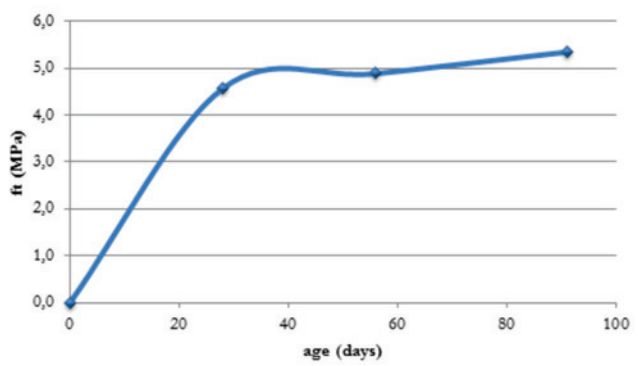
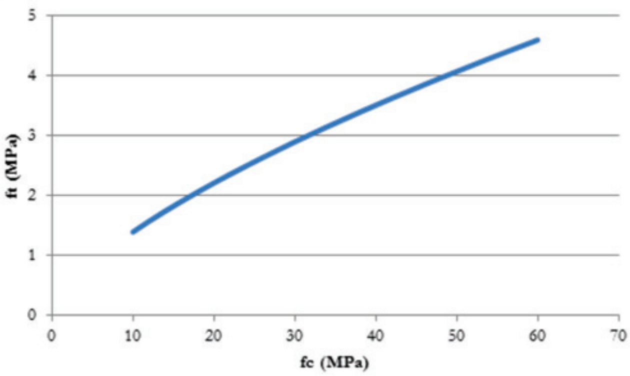


Figure 9 – Relationship between the tensile strength f_t and the compressive strength f_c according to the model adopted by ABNT



It can be seen through the relationship established in equation (9) that the flexural tensile strength of concrete has a little increase after the age of 28 days until the first three months after casting. During this time, the increase in tensile strength is just over 15% on average, less than 1.0 MPa. The increase in compressive strength is also around 15 to 20%, reaching values of 7.0 MPa on average during this same period.

However, one should take into account that the type of cement used in this concrete corresponds to the CP-I classification of ABCP. Thus, the increase in strength in ages older than 28 days is not very relevant. This fact, in general, does not happen with the concrete made with cement which has additions of pozzolanic materials such as the CP-IV, for example.

6. Correlation between compressive strength and flexural tensile strength of FRC

There are few consistent data on the correlation between compressive strength and tensile strength of a single concrete batch. The compressive strength, as previously stated, is the most valued property of concrete and it is the most tested by the constructors. However, in many cases the knowledge of the capacity of concrete to resist tension becomes essential for the proper use of the structure. Failing to measure this quantity by means of laboratory tests, the correlations are presented as a great help to estimate unmeasured data.

SOUZA et al. [29] reports that (translation): "In the relationship of the compressive strength to tensile strength, we have the works undertaken by ACI (1991) and the CEB (1990), pointing to the decrease of this ratio with increasing compressive strength". For these authors, this fact causes that many correlations between the tensile and compressive strength do not provide satisfactory results, especially when related to high-strength concrete.

NEVILLE [26] argues that when the compressive strength of concrete f_c increases, the tensile strength f_t increases also, but at a decreasing rate. Furthermore, he states that the ratio f_t/f_c decreases with time because the compressive strength increases more rapidly than the tensile strength from the first month after the execution of the concrete.

RAPHAEL *apud* NEVILLE [26] suggested a model of relationship between the tensile and compressive strength of concrete. This model was adopted by the Brazilian standards in the norm NBR 6118 [6]. The relationship is shown by the graph of Figure 9.

SOUZA [29] presents a relationship f_t/f_c obtained by testing the tensile strength by diametral compression and bending for a concrete with metakaolin addition and comparing this results with the relations proposed by the ACI, the ABNT and by the researchers DAL MOLIN (1995) and SENSALE (2000). The latter relationships were determined with the use of concrete with silica fume and rice husk ash additions, respectively.

Based on these data, SOUZA [29] proposed an equation that correlates the flexural tensile strength (f_{tF}) with the compressive strength (f_c):

$$f_{tF} = 0.1733 \, . \, f_c^{0.9191} \text{ Mpa} \quad (10)$$

Other results presented in the literature show similar relationships to those provided by the Brazilian standard, each one referring to a type of tensile test. Figure 10 presents a series of results collected by OLUOKUN *apud* NEVILLE [26] establishing the correlation between compressive strength and tensile strength of concrete obtained by the diametral compression test.

It is important to note that, once again, none of the considerations presented so far relates to the fiber reinforced concrete (FRC), a fact that can cause large variations in strength, especially in relation to tension. The introduction of fibers to the concrete creates a composite whose strength tends to change significantly, especially in tension.

Figure 10 – Relationship between the concrete tensile strength by diametral compression test and the concrete compressive strength (NEVILLE (25))

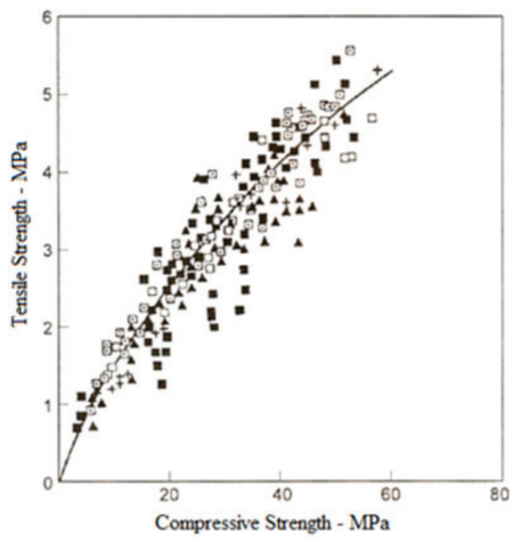


Figura 11 – Scatter plot of the flexural tensile strength and the compressive strength of the concrete with fiber addition for the test results at the ages of 28, 56 and 91 days

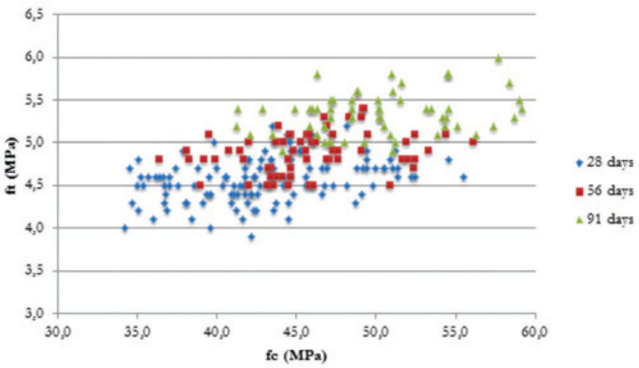


Figure 11 summarizes the relationships between the tensile and compressive strength of FRC at the ages of 28, 56 and 91 days. The results of this figure allow to establish a correlation between f_{tF} and f_c on the basis of the strengths determined in these three test ages:

$$f_{tF}=1.069.f_c^{0.395}\ \text{Mpa} \tag{11}$$

Where f_{tF} and f_c are the flexural tensile strength and the compressive strength of concrete in MPa, respectively.

The correlation between f_{tF} and f_c defined in this work for the fiber reinforced concrete is very close to the correlations made by the authors presented in SILVA et al. [28] for plain concrete. This fact shows that the relationship between the tensile and compressive strength of FRC, with a fiber content similar to that of the concrete here studied, can be estimated with a percent error less than 8% through the expressions defined for concrete without fibers.

7. Conclusions

The variations of the values of mechanical properties of concrete measured in tests, especially its strength, make the use of a large amount of sample data extremely useful to establish parameters for the acceptance of structures.

Currently, there are several models proposed to establish statistical control of the materials used in concrete structures. This diversity in the models adopted in each region or country reflects the great variability that is observed in the execution of concrete. Technological controls, dosing methodologies and material characteristics are factors that make the concrete to have peculiarities related to the region of the planet where it is produced.

A good technological control is critical to ensure the safety conditions established by standards to a concrete structure. This control must be reliable enough to avoid the rejection of good concrete batches and the approval of structures whose safety conditions may have been neglected during the execution. Although there are different methodologies for the acceptance of concrete structures, they must adequately reflect the results established in actual construction sites. This work has applied various methods of control and acceptance of concrete structures to the concrete used in the construction of the dry dock of the Rio Grande Shipyard that was built in the city of Rio Grande - RS.

Based on the analysis of the results of 1885 compressive strength tests and 245 flexural strength tests, this study determined the acceptance parameters of the concrete batches that were subject to sampling during the construction of the Prefabrication Area of the Shipyard.

The methodologies developed by the Brazilian ABNT were analyzed and compared with the models of the American-ACI COMMITTEE 318 [2] and the European EN-206-1 [17]. It became evident that the Brazilian model provides estimates of the characteristic strength lower than all others for the same batch analyzed. This fact, while not conclusive as to classify it as a more rigorous methodology than others, may reflect the quality of production and control used in each region, since these tend to reflect the construction practice of a given location. It became evident that the present American methodology gives more generous estimates of the characteristic strength for the same concrete batch studied, compared with the other standards tested. The prediction model presented by ABNT provided estimated characteristic strength values very close to those given by the European proposal.

It was also carried out a comparative analysis between the methods of concrete acceptance defined by the NBR 12655 [9] for the total sampling and partial sampling of the concrete batches. It was determined that the total sampling model provides higher values in most of the batches in question. However, it was found that the two models of acceptance provided by the NBR have very similar results, as it can be expected by the origin of both models. This fact makes irrelevant the choice of the criterion adopted at the moment of acceptance of a concrete batch.

It was defined for the fiber reinforced concrete (FRC) that is the object of this study, a correlation model between the compressive strength and age, through the rupture of specimens with 3, 7, 28, 56 and 91 days old. This correlation presented a great compatibility with the models provided by the Brazilian standard NBR 6118 [6] and the American ACI-318 [2] for plain concrete. Thus, it was observed that the prediction models for the variation of the compressive strength of plain concrete over time, when applied to fiber reinforced concrete have a good fit to the experimental results. This indicates that the models for plain concrete can be applied to this type of CRF with the same strength level and the same fiber content. It was also established a model for the evolution of the flexural tensile strength of CRF with age.

The correlation between the tensile and compressive strength of concrete with addition of fibers was determined and compared with the models provided by researchers and standards. The results showed that the prediction models of the standards ACI-318 [2], CEB-1990 [13] and NBR 6118 [6] (that were established for plain concrete) showed a good correlation to the CRF test results for this strength level and fiber content.

Finally, the statistical analysis showed that the concrete with fiber addition used in the industrial floor of the Prefabrication Area of the Rio Grande Shipyard, with f_{ck} = 35 MPa, has met the quality requirements in relation to strength prescribed by Brazilian standards.

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