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# Statistical analysis and conformity testing of concrete in port construction work

# *Análise estatística e teste de conformidade do concreto de obras portuárias*




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## Abstract

Conformity control of concrete is part of a range of control and standard methods which must be employed in all construction work to assure its compliance with quality requirements. The compressive strength of the concrete is considered as a random variable that must be controlled by standardized sampling and testing in order to ensure the structural safety. Therefore, the use of a large amount of compressive strength test results of concretes with similar characteristics has been seen as an important tool in the assessment of current standard norms. This paper describes an analysis based on the conformity control used in large port construction works which have recently been carried out in the Rio Grande Port, located in Rio Grande, RS, Brazil. Statistical analyses were performed and acceptance tests of the product were conducted. They were based on the acceptance criteria of different methodologies from different continents and showed the variations that can occur in the results of the conformity testing, depending on the adopted model. It is worth mentioning that the concrete used in port construction works in the region has been in accordance with current Brazilian norms.

***Keywords***: concrete, port structures, compressive strength conformity control.

## Resumo

O controle tecnológico do concreto faz parte de uma gama de controles e métodos normalizados que devem ser empregados em todas as obras para a garantia da conformidade deste produto, visto que a resistência à compressão do concreto é considerada uma variável aleatória que deve ser controlada através de amostragem e realização de ensaios padronizados, podendo assim, garantir a segurança da estrutura. Neste sentido, o uso de uma grande quantidade de resultados de controle tecnológico de concreto com características similares apresenta-se como uma importante ferramenta no processo de aferição das normas técnicas vigentes. O presente trabalho apresenta uma análise com base no controle tecnológico presente em grandes obras portuárias ocorridas nos últimos anos no Porto do Rio Grande, na cidade de Rio Grande - RS. Foram realizadas análises estatísticas e de aceitação do produto, com base nos critérios de aceitação de distintas metodologias de diferentes continentes, mostrando as variações que podem ocorrer nos resultados dos testes de conformidade dependendo do modelo adotado. Verificou-se que a construção das obras portuárias em concreto na região está em conformidade com as normas brasileiras vigentes.

***Palavras-chave:*** concreto, obras portuárias, resistência à compressão, controle tecnológico.

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## 1. Introduction

The seaport located in Rio Grande, in Rio Grande do Sul state, is one of the busiest ports in Brazil. This seaport has eight privately managed terminals that operate with containers, bulk grain commodities (mainly soybean and wheat), oil, petrochemicals and fertilizers. There are also shipyards for the construction and renovation of oil exploration platforms.

In order to meet market requirements, much construction work has recently been carried out in the port area to improve technical characteristics of navigability, increase its ability to receive loads, reduce time spent to load/unload containerized cargo and carry out a diversification of trading activities, as well. Current construction work comprises the enlargement of the Barra do Rio Grande Breakwater and of the container terminal, besides the construction of the Rio Grande Shipyard.

The enlargement of the Barra do Rio Grande Breakwater, with the use of tetrapods, aimed at the improvement of the technical characteristics of the access channel by deepening it; hence, the possibility of increasing the total cargo at the Rio Grande Port. The enlargement of the container terminal led to higher speed in loading and unloading operations. The bottom slab of the dry dock is an important part of the Rio Grande Shipyard ERG1, a major maritime installation whose main purpose is the construction, conversion and repair of offshore units for the oil industry.

The main structures of these construction projects were made of concrete. Therefore, the objective of this paper is to describe the statistical analyses of the results of the acceptance control of the concrete used for the manufacturing of tetrapods at the Barra do Rio Grande Breakwater, the concrete piles in the container terminal and the bottom slab in the shipyard dry dock.

Common characteristics of the concrete mixes used for these three construction projects are the compressive strength of 40 MPa at 28 days, the use of specialized concrete production plants in compliance with ABNT NBR 7212 (2012) and the use of rigorous quality control during preparation, launching, curing, molding and testing of specimens up to their final acceptance. Type A preparation condition was used in all cases. The concrete of the dry dock bottom slab and of the tetrapods is classified as exposed to class IV of environmental aggression. The concrete used for the piles of the container pier was considered to meet the specifications to be classified as class IV in compliance with ABNT NBR 6118 (2007). These characteristics were adopted because of the high risk of concrete deterioration since the construction sites are near the Atlantic Ocean.

Figure 1 – Installation of the tetrapods in the construction site of Barra do Rio Grande breakwaters expansion project (Source: Migliorini, 2011)

### 1.1 *The Barra do Rio Grande Breakwater construction project*

The Barra do Rio Grande Breakwater was built in order to ensure the navigability of the Rio Grande Access Channel and maintain its characteristics, especially its depth. The breakwater comprises two parallel marine structures which protect the entrance of the channel that takes to the Rio Grande Port: the west jetty is located on Cassino Beach, in Rio Grande, and the east one is located in São José do Norte.

The first construction project, which used irregular natural stones, was completed in 1915. Its enlargement was carried out from 2001 to 2011, with precast concrete blocks weighing 8 and 12.5 tons, called tetrapods, besides natural stones.

Both west and east jetties have been enlarged for 350 and 700 meters, respectively, with about 1.361.000 cubic meters of rock and 12.090 units of tetrapods. The concrete blocks are formed by the intersection geometry of four truncated cones which, according to Migliorini (2011), are simply juxtaposed. They overlap and form almost regular and relatively compact structures.

Figure [1] illustrates the assembly of tetrapods during their installation on site. This paper describes the statistical analyses of the data of the 8 ton concrete tetrapods with the following mix: 418 kg/m³ cement, additive Glenium 51 ® and Metacaulim (pozzolan) in the proportion of 30 kg/m³ .

### 1.2 *Berth III of Rio Grande Container Terminal construction project*

With the construction of the third berth section, the container terminal was 900 meters in length, and could handle three vessels simultaneously from 2008 on. At the same period, the installation of more equipment has made it possible to achieve the goal of reducing the time that vessels spend in the terminal by increasing handling capacity and the flow of containerized goods.

The pier structures were made of reinforced concrete, mostly precast, divided into precast prestressed piles and precast structural elements. According to Gireli (2007), the former have hollow a circular cross section, with an inner diameter of 50 cm and an outer diameter of 80 cm, and 48 meters in length. The precast pier elements have a π cross section. In this study, only the database of precast prestressed piles will be used. The ones used in the container terminal are shown in Figure [2].

The concrete used for molding the piles had the following mix specifications: pozzolanic Portland cement of domestic manufacturing (CP-32 RS-IV) in the ratio of 400 kg/m³ and water-cement ratio of 0.40. This cement is resistant to sulfates and complies with

Figure 2 – Piles of the pier (Source: FURG)

the specifications of the Brazilian norms ABNT NBR 5736 (1991). Crushed stone and natural sand were used as coarse and fine aggregates, respectively. Superplasticizer Glenium ® 51 was also employed in the concrete mix.

### *1.3 Dry dock bottom slab construction project*

Despite the need for high investment, a dry dock is one of the main parts of a shipyard not only because it makes the addition of blocks to the vessel easy, but also because it is placed on a horizontal plane and allows docking for post-release repairs (Favarin, 2011). The dry dock of the Rio Grande Shipyard interconnects directly to the Patos Lagoon. Its base is situated 13.80 meters below the water level. The dock is drained during the activities of construction and assembly. However, when vessels need to move in or out, it is flooded so that they may be floated in or out.

The dimensions of the bottom slab are 350.00 meters in length, 133.00 meters in width and from 0.56 to 1.00 meter in thickness. These dimensions demanded casting to be performed in parts. According to Larrossa et al. (2011), " due to its large size, the concrete bottom slab was executed in stages, i. e., with concrete panels; therefore, the occurrence of construction joints, which are pre-programmed and mostly impermeable, is inevitable."

The concrete was made with Uruguayan cement ANCAP (in the ratio of 380 kg/m³), strength class C40, with high similarity to the classification of normal cement Portland CP I, ABNT NBR 5732 (1991). The aggregates (coarse and fine ones) came from Pelotas, RS. The polyfunctional additive RheoTec ® 418 and silica fume were also added to the concrete mix. Figure [3] shows this structure.

### *1.4 Justification*

Considered as a basic requirement in any structural design of reinforced or prestressed concrete, the compressive strength is the most common property used as a criterion for material acceptance. However, the compressive strength of concrete is characterized as a random variable with a probability distribution that is a function of material characteristics, the production process, placement, and others. The inherent variation in acceptance tests of concrete, especially compressive strength, makes it fundamental to use statistical methods for its proper analysis.

This paper describes analyses based on the acceptance control used in large port construction work that has been carried out at the Rio Grande Port, located in Rio Grande, RS, in recent years. Acceptance criteria of different methodologies used in different continents were tested; they show the variations that can occur in the results of compliance tests depending on the adopted model. In addition, efforts that are currently made in the construction industry regarding concrete production in order to meet Brazilian norms are also described.

## 2. Methodology

The study of concrete quality control was carried out by statistical

Figura 3 – Aerial view of the Rio Grande dry dock yard - ERG1

Table 1 – Quality of the concrete according to coefficient of variation for fck > 34.5 MPa (ACI 214, 2002)

| Class | Coefficient of variation for different control standards (%) | | | | |
|---|---|---|---|---|---|
| | Excellent | Very good | Good | Reasonable | Bad |
| Test in the work | < 7.00 | 7.00 – 9.00 | 9.00 – 11.00 | 11.00 – 14.00 | > 14.00 |
| Laboratory tests | < 3.50 | 3.50 – 4.50 | 4.50 – 5.50 | 5.50 – 7.00 | > 7.00 |

analysis of the compression test results of specimens at 28 days of age. According to Azevedo and Diniz (2008 ), it is a well-known fact that the compressive strength of concrete depends on the level of quality control exerted in all stages of concrete production. During the analysis, sample specimens are collected along the time of the production process in order to verify if changes and improvement are required to comply with established norms.
In this study, a statistical analysis of the concrete specimen compressive strength was performed by determining its mean value, standard deviation, coefficient of variation, Shewhart control chart and the validity of Normal and Lognormal probability distributions by the Kolmogorov-Smirnov goodness-of-fit test.
To check the concrete production quality, the acceptance criteria of the Brazilian (ABNT NBR 12655, 2006), American (ACI 318, 2011) and European norms (EN 206-1, 2000) were applied to the three construction sites.

## 2.1 Mean value

The mean value of the compressive strength of a concrete lot is very important since it is used to calculate the estimated strength parameter ($f_{ck}$) and, consequently, to verify concrete acceptance or rejection parameters. It is calculated by Equation [1].

$$f_{cm} = \frac{\sum f_i}{n} \quad (1)$$

where:
- $f_{cm}$ is the mean value of the concrete compressive strength of the lot (MPa);
- $f_i$ is the compressive strength of the test specimen, (MPa);
- n is the number of test specimens.

## 2.2 Standard derivation

The standard deviation is a suitable measure of the dispersion of the concrete strength in relation to its mean value, playing an important role in most statistical methods (WALPOLE et al., 2009). It is calculated by Equation [2].

$$s = \sqrt{\frac{\sum_{i=1}^{n} (f_i - f_{cm})^2}{n-1}} \quad (2)$$

where:
- s is the standard deviation of the production lot (MPa);
- $f_{cm}$ is the mean value of the concrete compressive strength of the lot (MPa);
- $f_i$ is the compressive strength of the test specimen, (MPa);
- n is the number of test specimens.

## 2.3 Coefficient of variation

The coefficient of variation (CV) measures the degree of dispersion in the data analysis, indicating the quality control of the production process. The lower the value of this parameter, the closer to the mean value the results will be and the better the concrete quality will be. It is obtained by Equation [3].

$$CV = \frac{s}{f_{cm}}.100 \quad (3)$$

Where:
- CV is the coefficient of variation (%);
- s is the standard deviation of the production lot (MPa);
- $f_{cm}$ is the mean value of the concrete compressive strength of the lot (MPa).

ACI 214 (2002) provides a standardized scale to assess the quality of the concrete based on the coefficient of variation, as shown in Table [1].

## 2.4 Shewhart control charts

The Shewhart control charts were developed by physicist Walter A. Shewhart in 1924 in order to visually show the occurrence of unusual values and trends in the results. This methodology provides information on the production process that must be interpreted for decision making, thus reducing the risk of non-compliance in the final product. Control limits calculated from the data and alert thresholds based on the variation of the production process are used (HARRISSON and GIBB, 2010).
The chart consists of various horizontal lines. A center line (CL) is the reference value of the monitored characteristic. Lines that represent the upper control limit (UCL), the lower control limit (LCL), the upper warning limit (UWL) and the lower warning limit (LWL) may be added. Table [2] shows the calculation of bounds.

## 2.5 The normal probability distribution

The normal distribution is the most important distribution in

**Table 2 – Control and warning limits for formulation of Shewhart control charts**

| Limit | Identification | Equation |
|---|---|---|
| Line center | LC | $f_{cm}$ |
| Upper control limit | UCL | $f_{cm} + 3.s$ |
| Lower control limit | LCL | $f_{cm} - 3.s$ |
| Upper warning limit | UWL | $f_{cm} + 2.s$ |
| Lower warning limit | LWL | $f_{cm} - 2.s$ |

probability and statistics (WALPOLE et al., 2009). It is represented by a bell-shaped normal curve which adequately describes many phenomena that occur in nature.

According to Devore (2006), the mathematical equation for the probability distribution of the normal variable depends on two parameters, mean and standard deviation. The probability density function of the normal distribution is given by Equation [4].

$$f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma}}.e^{-\frac{1}{2\sigma^2}.(x-\mu)^2}, -\infty < x < +\infty \quad (4)$$

where:

- $\pi$ = 3.14159….;
- e = 2.71828…;
- $\mu$ = mean value;
- $\sigma$ = standard deviation.

## 2.6 The lognormal distribution

The lognormal probability distribution is the distribution of a random variable whose logarithm follows normal distribution. This model has no symmetry in relation to the mean value of the results. This probability distribution has been studied as an alternative to the model proposed by Gauss when it does not provide adequate fitness to the results. The lognormal distribution is given by Equation [5].

$$f_X(x) = \frac{1}{\sqrt{2\pi}\xi x} e^{-\frac{1}{2}\left(\frac{\ln x - \lambda}{\xi}\right)^2}, \; 0 \le x < 8$$
$$\lambda = E(\ln x)$$
$$\xi = \sqrt{Var(\ln x)} \quad (5)$$

The Kolmogorov-Smirnov goodness-of-fit test, for a 95% level of significance, was used in this study to determine which one of both distribution models, normal or lognormal, has the better fitness to the values of compressive strength test results (MAGALHÃES, 2009).

## 2.7 Acceptance of concrete in agreement with ABNT NBR 12655 (2006)

Brazilian norm NBR 12655:2006 specifies the tests and methodologies for the control and acceptance of concrete; ABNT NM 67 (1996) requires the consistency test whereas ABNT NBR 5739 (2007) recommends the compressive strength test. Lots of concrete cylinders are formed by "n" samples depending on the sampling method to be used: the partial sampling method or the total sampling method. This lot of concrete cylinders will represent the concrete volume to be analyzed. The samples consist of two (02) cylinders and the highest of both values obtained by the compressive test is considered the strength of the sample. For the acceptance of the concrete lot in both methods, $f_{ck,est}$ must be higher than the $f_{ck}$ specified in the structural design.

### 2.7.1 Concrete statistical control by partial sampling ($f_{ck,est}{}^1$)

The number of cylinders to be molded depends on the minimum requirements for the concrete class; for concrete group I (up to C50), at least six (06) pairs. The calculation equations are different, depending on the number of samples, as follows.

a) if the number of samples "n" is such that $6 \le n < 20$, the estimated characteristic strength is determined by Equation [6]

$$f_{ck,est}{}^1 = 2\frac{f_1 + f_2 + ... + f_{m-1}}{m-1} - f_m \quad (6)$$

Where:

- m = n/2;
- $f_1, f_2, ..., f_m$ are the strength values of the specimens arranged in ascending order.

The value of $f_{ck,est}$ must not be lower than $\Psi_6.f_1$, adopting the $\Psi_6$ coefficient in agreement with the values shown in Table [3] and depending on the kind of concrete preparation and the number of samples in the lot.

**Table 3 – Values of Ψ6 according to ABNT NBR 12655 (2006)**

| Condition of preparation | Number of samples in the lot | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 10 | 12 | 14 | ≥16 |
| A | 0.82 | 0.86 | 0.89 | 0.91 | 0.92 | 0.94 | 0.95 | 0.97 | 0.99 | 1.00 | 1.02 |

**Table 4 – Acceptance of concrete according to EN 206-1 (2000)**

| Production | Number "n" of test results of compressive strength in the group | Criteria 1<br>Average of "n" results ($f_{cm}$) MPa | Criteria 2<br>Any individual test result ($f_{ci}$)MPa |
|---|---|---|---|
| Initial | 3 | $\geq f_{ck} + 4$ | $\geq f_{ck} - 4.00$ |
| Continuous | ≥15 | $\geq f_{ck} + 1.48.s$ | $\geq f_{ck} - 4.00$ |

b) When the number of elements exceeds twenty, n ≥ 20, the estimated characteristic strength is given by Equation [7]:

$$f_{ck,est}{}^{1} = f_{cm} - 1{,}65.s \quad (7)$$

#### 2.7.2 Concrete statistical control by total sampling ($f_{ck,est}{}^{2}$)

Samples are taken from all concrete lots. There are two possibilities for the determination of the estimated characteristic strength.

a) If the number of samples is lower than twenty (n ≤ 20), the value of the estimated characteristic strength is equal to the lowest strength of all test specimens.

b) If n > 20, test results are arranged in ascending order and the estimated value of the characteristic strength is equal to the strength value that represents the fifth percentile.

### *2.8 Acceptance of concrete in agreement with ACI 318 (2011)*

American norm ACI COMMITTEE 318 (2011) specifies the routine sampling and manufacturing of molded cylinders that must be cured and tested in standardized procedures. Equations [8] and [9] are used to calculate the estimated compressive strength of concrete with $f_{ck} \geq 35$ MPa. The original American notation has been changed to provide better understanding for Brazilian readers.

$$f_{cm} = f_{ck,est}{}^{4} + 1{,}34.s \quad (8)$$

$$f_{cm} = 0{,}90.f_{ck,est}{}^{4} + 2{,}33.s \quad (9)$$

Where $f_{ck,est}{}^{4}$ is the lowest value calculated by both equations.

### *2.9 Acceptance of concrete in agreement with EN 206-1 (2000)*

European norms recommend the use of compressive tests and require the analysis of the results collected from individuals or from the average of test results of two or more specimens of a sample produced and tested at the same age. The acceptance of concrete is evaluated by two criteria in the test specimens at the same age:

a) Groups of "n" results of consecutive tests of mean compressive strength of concrete ($f_{cm}$), with or without overlapping (Criterion 1);

b) Each individual test result of concrete compressive strength ($f_{ci}$) (Criterion 2).

The $f_{ck,est}{}^{5}$ is calculated in accordance with the criteria adopted in Table [4].

## 3. Results and discussion

### *3.1 Data base*

In the case of the concrete used in the 8 ton tetrapods, divided into 14 lots, test results were compiled from 05/24/2008 to 12/26/2008, as shown in Table [5 (b)].

The concrete used in the piles of the pier was produced from 06/09/2006 to 02/27/2007; data were grouped into five lots for analysis, as shown in Table [6].

In the case of the concrete of the bottom slab, specimens were molded from 11/27/2008 to 10/11/2009 and tests were carried out from December 2008 to December 2009. The data were organized into thirteen lots, as shown in Table [7 (b)].

### *3.2 Statistical analysis*

Following the classification of ACI-214 (2002), the coefficients of variation of concrete are mostly classified into excellent, very good or good whereas a few lots are considered reasonable. The analysis which employed Shewhart charts shows points out of the warning limits, although there are some points outside the control limits in the three data groups. The last six lots (lots 9-14) of the tetrapod concrete had the highest mean values, i.e., higher values for the central parameter of the graphs, resulting in higher values for the control and warning limits. Lot 10 was the only set of samples that did not exceed any limit. Control limits were exceeded in eight cases by 1.299, about 0.62 %, while the alert limits were exceeded by 38 points, resulting in 2.93 %.

The concrete of the piles of the container terminal showed two cases of 327 points, about 0.61%, beyond the control limits, while the upper warning limit was surpassed by eleven points, resulting in 3.36%. Lot 5 did not have values above or below the limits, while the others had different characteristics; lot 4 surpassed the lower control limit and lot 2 surpassed the higher control limit.

Regarding the compressive test results of specimens of the dry dock bottom slab, totaling 4871 samples, seven points exceeded the upper limit in five lots (one point in lots 4, 7 and 10; two points

Table 5 (a e b) – Datas of concrete tetrapods (a – lots 1 ao 7 e b – lots 8 ao 14)

a

| Data | Lots | | | | | | |
|---|---|---|---|---|---|---|---|
| Fortnight | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Period | 05/24/08<br>06/08/08 | 06/09/08<br>06/24/08 | 06/25/08<br>07/10/08 | 07/11/08<br>07/26/08 | 07/27/08<br>08/11/08 | 08/12/08<br>08/27/08 | 08/28/08<br>09/12/08 |
| n | 33 | 33 | 63 | 167 | 262 | 122 | 131 |
| s (MPa) | 2.50 | 2.26 | 5.04 | 5.94 | 4.42 | 3.48 | 4.02 |
| CV (%) | 5.79 | 5.32 | 11.26 | 11.97 | 9.05 | 6.79 | 8.59 |
| $f_{cm}$ (MPa) | 43.09 | 42.47 | 44.76 | 49.63 | 48.84 | 51.32 | 46.84 |
| $f_{ck,est}^{1}$ (MPa) | 38.97 | 38.74 | 36.45 | 39.83 | 41.55 | 45.57 | 40.20 |
| $f_{ck,est}^{2}$ (MPa) | 40.00 | 40.20 | 40.00 | 41.37 | 41.25 | 46.73 | 41.63 |
| $f_{ck,est}^{4}$ (MPa) | 39.74 | 39.44 | 36.69 | 39.77 | 42.83 | 46.65 | 41.45 |
| $f_{ck,est}^{5}$ (MPa) | 39.39 | 39.12 | 37.31 | 40.84 | 42.30 | 46.16 | 40.89 |

b

| Data | Lots | | | | | | |
|---|---|---|---|---|---|---|---|
| Fortnight | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Period | 09/13/08<br>09/28/08 | 09/29/08<br>10/14/08 | 10/15/08<br>10/30/08 | 10/31/08<br>11/15/08 | 11/16/08<br>12/01/08 | 12/02/08<br>12/17/08 | 12/18/08<br>12/26/08 |
| n | 72 | 90 | 74 | 68 | 84 | 75 | 25 |
| s (MPa) | 3.23 | 5.26 | 5.56 | 3.95 | 4.08 | 5.51 | 4.42 |
| CV (%) | 6.85 | 9.42 | 9.89 | 7.02 | 7.33 | 9.70 | 6.84 |
| $f_{cm}$ (MPa) | 47.14 | 55.83 | 56.23 | 56.25 | 55.59 | 56.84 | 64.55 |
| $f_{ck,est}^{1}$ (MPa) | 41.82 | 47.15 | 47.06 | 49.73 | 48.87 | 47.74 | 57.27 |
| $f_{ck,est}^{2}$ (MPa) | 42.65 | 48.89 | 46.98 | 50.51 | 48.10 | 48.38 | 56.30 |
| $f_{ck,est}^{4}$ (MPa) | 42.82 | 48.42 | 48.08 | 50.95 | 50.13 | 48.88 | 58.64 |
| $f_{ck,est}^{5}$ (MPa) | 42.37 | 48.05 | 48.00 | 50.40 | 49.56 | 48.68 | 58.02 |

Table 6 – Datas of concrete piles of the pier

| Data | Lots | | | | |
|---|---|---|---|---|---|
| Month | 1 | 2 | 3 | 4 | 5 |
| Period | 10/09/06<br>11/06/06 | 11/10/06<br>12/07/06 | 12/11/06<br>01/08/07 | 01/10/07<br>02/01/07 | 02/12/07<br>02/27/07 |
| n | 39 | 72 | 81 | 99 | 36 |
| s (MPa) | 2.90 | 4.40 | 3.82 | 1.87 | 2.08 |
| CV (%) | 5.17 | 7.86 | 6.53 | 3.02 | 3.50 |
| $f_{cm}$ (MPa) | 56.13 | 55.99 | 58.56 | 61.89 | 59.50 |
| $f_{ck,est}^{1}$ (MPa) | 51.34 | 48.72 | 52.25 | 58.81 | 56.07 |
| $f_{ck,est}^{2}$ (MPa) | 51.44 | 51.44 | 53.48 | 59.21 | 55.77 |
| $f_{ck,est}^{4}$ (MPa) | 52.24 | 50.09 | 53.44 | 59.39 | 56.71 |
| $f_{ck,est}^{5}$ (MPa) | 51.83 | 49.47 | 52.90 | 59.13 | 56.42 |

**Table 7 (a e b) – Datas of concrete bottom slab (a – lots 1 ao 7 e b – lots 8 ao 13)**

**a**

| Data | Lots | | | | | | |
|---|---|---|---|---|---|---|---|
| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Period | dec/08 | jan/09 | feb/09 | mar/09 | apr/09 | may/09 | jun/09 |
| n | 35 | 130 | 106 | 162 | 364 | 441 | 593 |
| s (MPa) | 2.58 | 4.88 | 5.00 | 5.53 | 3.82 | 3.69 | 3.25 |
| CV (%) | 4.34 | 9.50 | 9.42 | 11.39 | 7.59 | 7.53 | 6.70 |
| $f_{cm}$ (MPa) | 59.45 | 51.33 | 53.03 | 48.55 | 50.39 | 49.07 | 48.52 |
| $f_{ck,est}^{1}$ (MPa) | 55.19 | 43.28 | 44.79 | 39.42 | 44.08 | 42.98 | 43.16 |
| $f_{ck,est}^{2}$ (MPa) | 55.20 | 42.20 | 43.50 | 40.80 | 44.70 | 43.30 | 42.80 |
| $f_{ck,est}^{4}$ (MPa) | 56.00 | 44.40 | 45.99 | 39.62 | 45.27 | 44.12 | 44.16 |
| $f_{ck,est}^{5}$ (MPa) | 55.63 | 44.11 | 45.64 | 40.36 | 44.73 | 43.61 | 43.71 |

**b**

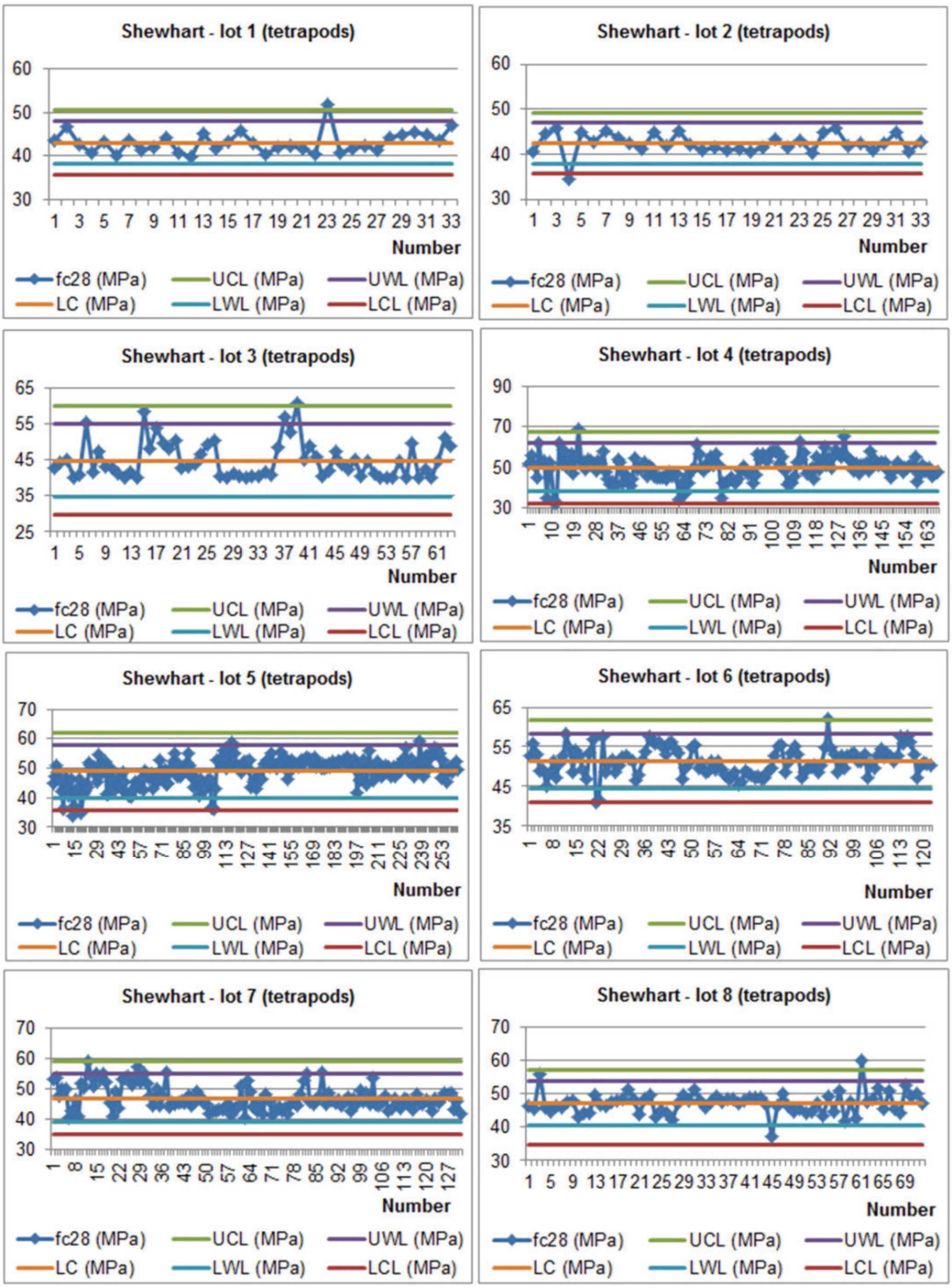
| Data | Lots | | | | | |
|---|---|---|---|---|---|---|
| Month | 8 | 9 | 10 | 11 | 12 | 13 |
| Period | jul/09 | aug/09 | sep/09 | oct/09 | nov/09 | dec/09 |
| n | 158 | 414 | 609 | 892 | 807 | 160 |
| s (MPa) | 4.66 | 3.93 | 4.35 | 3.40 | 3.76 | 4.09 |
| CV (%) | 8.84 | 7.48 | 8.83 | 7.10 | 7.84 | 8.88 |
| $f_{cm}$ (MPa) | 52.79 | 52.52 | 49.26 | 47.98 | 47.95 | 46.02 |
| $f_{ck,est}^{1}$ (MPa) | 45.09 | 46.04 | 42.08 | 42.36 | 41.75 | 39.27 |
| $f_{ck,est}^{2}$ (MPa) | 45.70 | 44.80 | 42.20 | 42.10 | 42.00 | 40.60 |
| $f_{ck,est}^{4}$ (MPa) | 46.54 | 47.25 | 43.43 | 43.42 | 42.91 | 40.54 |
| $f_{ck,est}^{5}$ (MPa) | 45.89 | 46.70 | 42.82 | 42.94 | 42.39 | 39.97 |

**Table 8 – Results of Kolmogorov-Smirnov test for concrete tetrapods**

| Lot | Number of copies (n) | s (MPa) | Maximum difference | | D (0.05; n) | Decision |
|---|---|---|---|---|---|---|
| | | | Normal | Lognormal | | |
| 1 | 33 | 2.50 | 0.1087 | 0.1033 | 0.2367 | Lognormal |
| 2 | 33 | 2.26 | 0.1009 | 0.1104 | 0.2367 | Normal |
| 3 | 63 | 5.04 | 0.1582 | 0.1512 | 0.1713 | Lognormal |
| 4 | 167 | 5.94 | 0.0495 | 0.0746 | 0.1052 | Normal |
| 5 | 262 | 4.42 | 0.1029 | 0.1164 | 0.0840 | – |
| 6 | 122 | 3.48 | 0.0496 | 0.0571 | 0.1231 | Normal |
| 7 | 131 | 4.02 | 0.1287 | 0.1135 | 0.1188 | Lognormal |
| 8 | 72 | 3.23 | 0.0868 | 0.0750 | 0.1603 | Lognormal |
| 9 | 90 | 5.26 | 0.0994 | 0.0857 | 0.1434 | Lognormal |
| 10 | 74 | 5.56 | 0.0739 | 0.0832 | 0.1581 | Normal |
| 11 | 68 | 3.95 | 0.0746 | 0.0720 | 0.1649 | Lognormal |
| 12 | 84 | 4.08 | 0.0819 | 0.0945 | 0.1484 | Normal |
| 13 | 75 | 5.51 | 0.0855 | 0.0699 | 0.1570 | Lognormal |
| 14 | 25 | 4.42 | 0.1873 | 0.1987 | 0.2720 | Normal |

in lots 5 and 8) and one point was beyond the lowest limit (lot 13), representing 0.14%. The alert limits were surpassed by approximately 3.16% of the specimens. Figures [4], [5], [6], [7] and [8] show the Shewhart charts for the lots of concrete under study. In general, both normal and lognormal distributions have shown good fitness to the values of the concrete compressive strength. The data had a few lots that did not fit satisfactorily into any of the distributions, but, when the probability distribution failed in the goodness-of-fit test, the other got the same result. Therefore, both models could represent the data properly. In the case of most of

**Figure 4 – Lots 1-8: the Shewhart chart for the data of tetrapods**

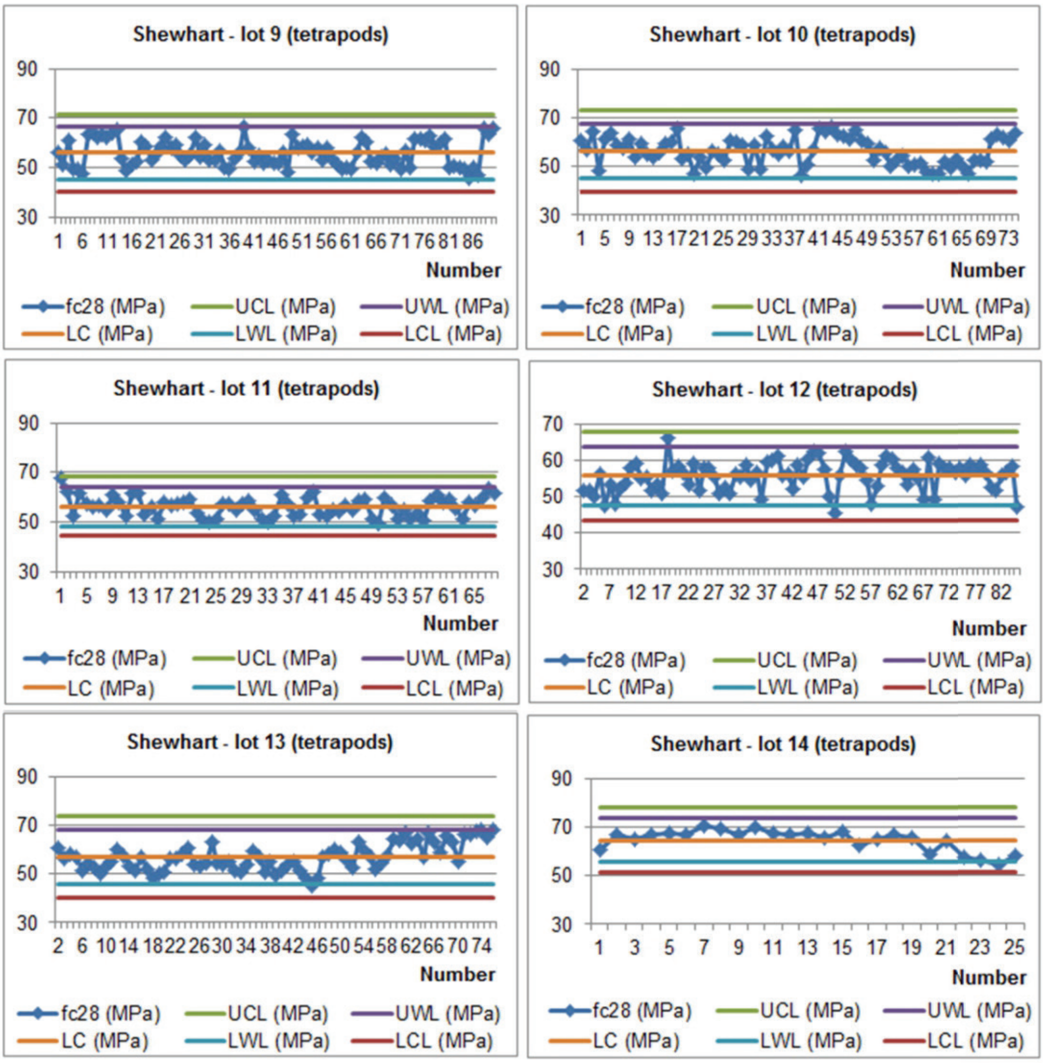


the lots, maximum difference values are lower than the limit value D (0.05, n). Tables [8], [9] and [10] show the results of the goodness-of-fit test to the concrete tests for the tetrapods, the piles of the container pier and the dry dock bottom slab, respectively.

### 3.3 Analysis of the acceptance criteria

As specified by the Brazilian norms, the construction projects under study had strict quality control in their construction stages. During the construction of the tetrapods and the dry dock bottom slab, total sampling control was applied, while for the concrete used in the container pier piles, partial sampling was used, in agreement with ABNT NBR 12655:2006, for the concrete at 28 days.
Regarding the acceptance criterion of Brazilian, North American and European norms, data showed that, for the bottom slab, two of the lots would not comply. Lot 4 would comply neither with ABNT NBR 12655 (2006), the criterion for partial sampling, not with ACI 318 (2011) whereas Lot 13 would comply neither with ABNT NBR 12655 (2006), the criterion for partial sampling, nor with EN 206-1 (2000).
Concerning data on tetrapods, Brazilian (method of partial sampling), North American and European norms would show nonconformities in four lots. Lots 1, 2, 3 and 4 would comply neither with ABNT NBR 12655 (2006) (partial sampling) nor with ACI 318 (2011). Lots 1, 2 and 3 would not comply with recommendations issued by EN 206-1 (2000).
The concrete lots of the container terminal piles complied with the three norms under analysis with good margin of safety.
Figures [9], [10] and [11] show that the strength values estimated by ACI 318 (2011) resulted in higher values than the ones issued by other norms, followed by EN 206-1 (2000) and, then, by ABNT NBR 12655 (2006), when the total sampling method is used. It can be explained by the fact that this methodology shows differences in

**Figure 5 – Lots 9-14 the Shewhart chart for the data of tetrapods**



the definition of $f_{ck}$,, by comparison with the Brazilian and European models. For the composition of the equations of ACI 318 (2011), 9 % of the values may be lower than the value of $f_{ck}$,, unlikely other norms that consider lower values of 7% and 5 % for EN 206-1 (2000) and ABNT NBR 12655 (2006), respectively.
The statistical analysis showed that all the concretes under study, the dry dock bottom slab, the tetrapods, the container terminal piles met the quality requirements for the compressive strength recommended by Brazilian norms at all stages of the production process.

## 4. Conclusions

The analyses of the coefficient of variation of the concrete lots show that good quality control was adopted during the production process and that all lots were accepted.
The application of the Shewhart control charts clearly showed the sensitivity of this methodology to detect small changes in the results during the production process . Due to the simplicity of its implementation, this type of control chart can be used not only to control many processes but also to help find changes in product characteristics and verify non-conformities .
To check the acceptance criteria of the norms under study, all 32 lots in three construction projects complied with ABNT NBR 12655 (2006), total sampling criteria , $f_{ck,est}^{2}$. The five lots of concrete of the container terminal piles were also completely accepted for the criterion of partial sampling $f_{ck,est}^{1}$, the criterion actually used during the manufacturing process of the concrete.
The criterion for partial sampling by ABNT NBR 12655 (2006) proved to be the strictest one, leading to the rejection of some lots used in the concrete bottom slab and tetrapods whereas ACI 318 (2011) was less strict than the other norms. The criteria of the European norm are at an intermediate level between the

**Figure 6 – Lots 1-5 the Shewhart chart for the data of piles**

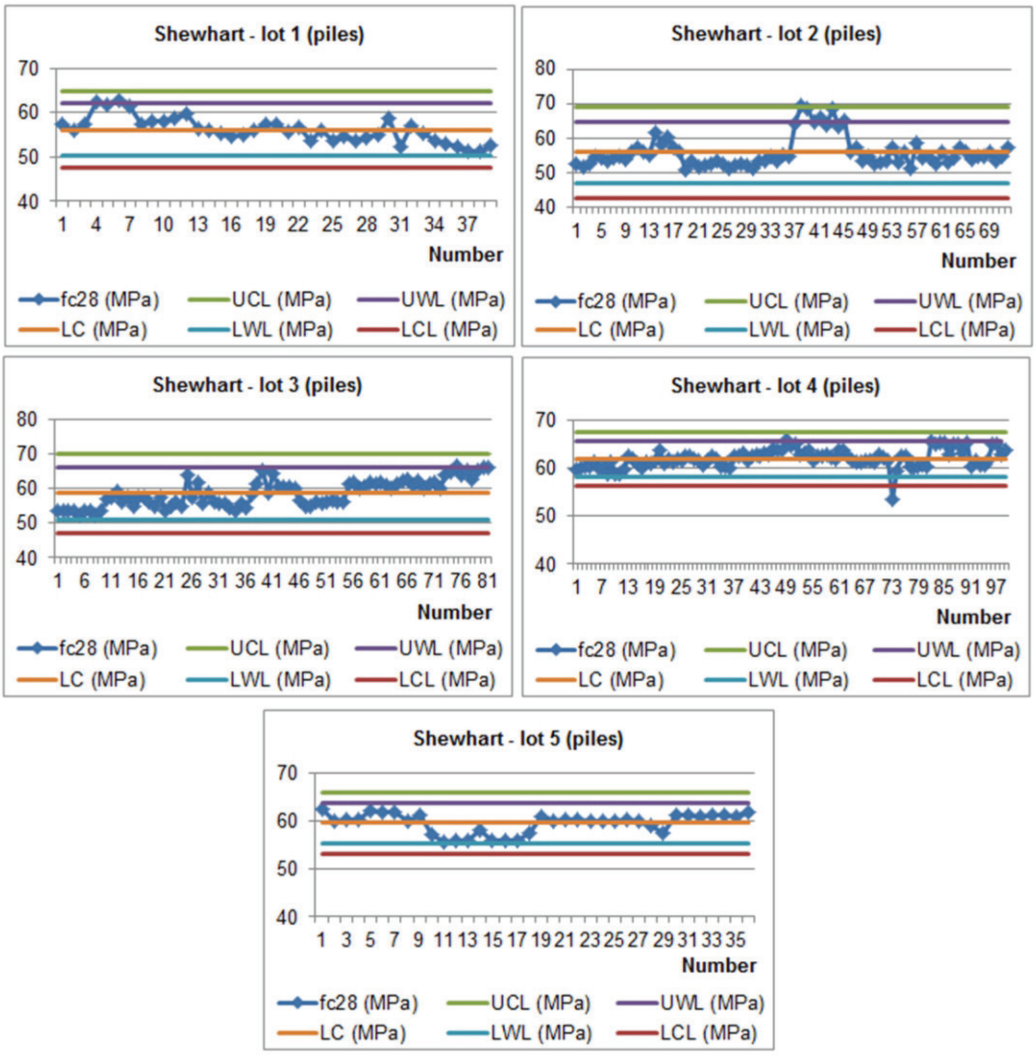


Figure 7 – Lots 1-8 the Shewhart chart for the data of bottom slab

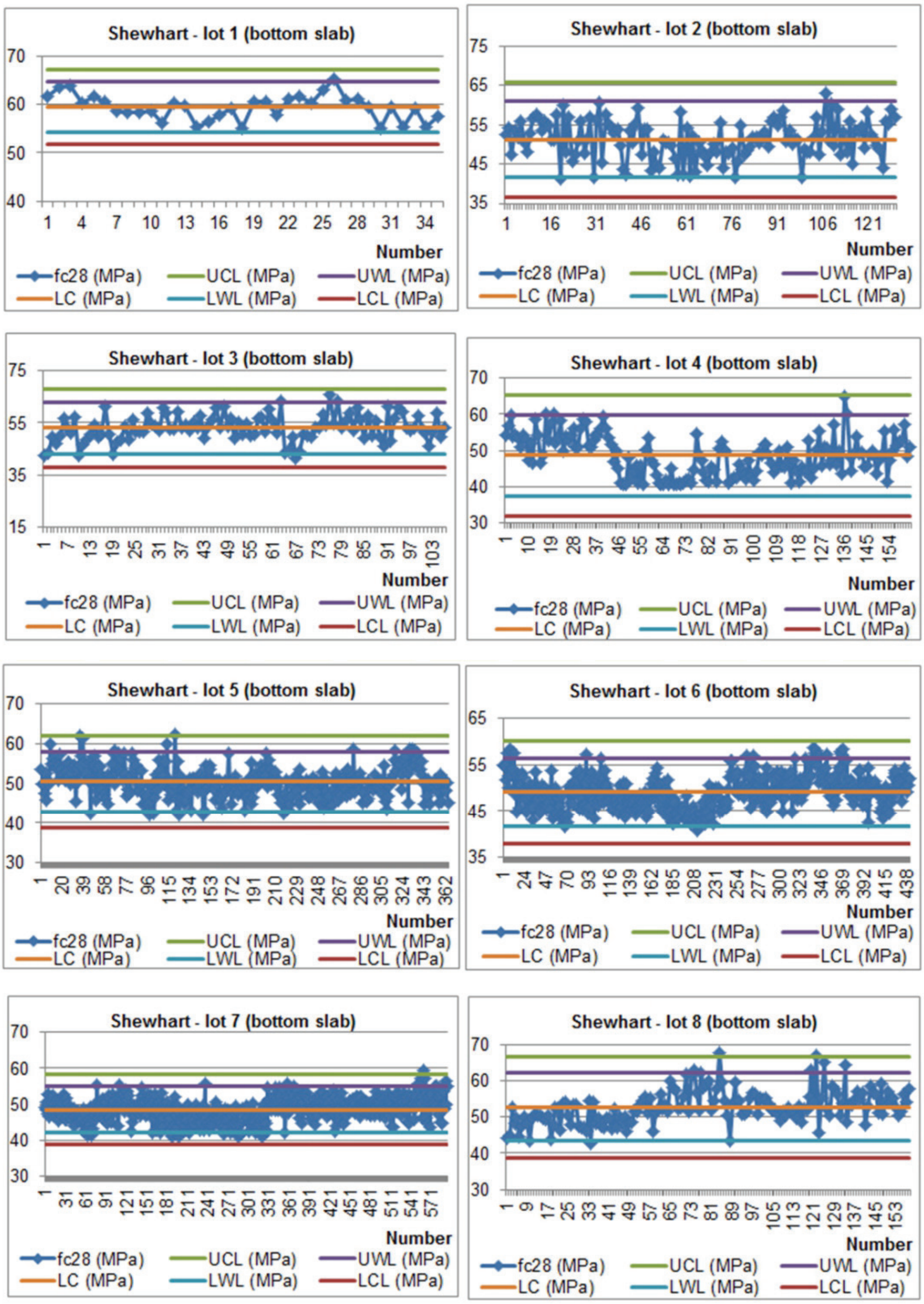


**Figure 8 – Lots 9-13 the Shewhart chart for the data of bottom slab**

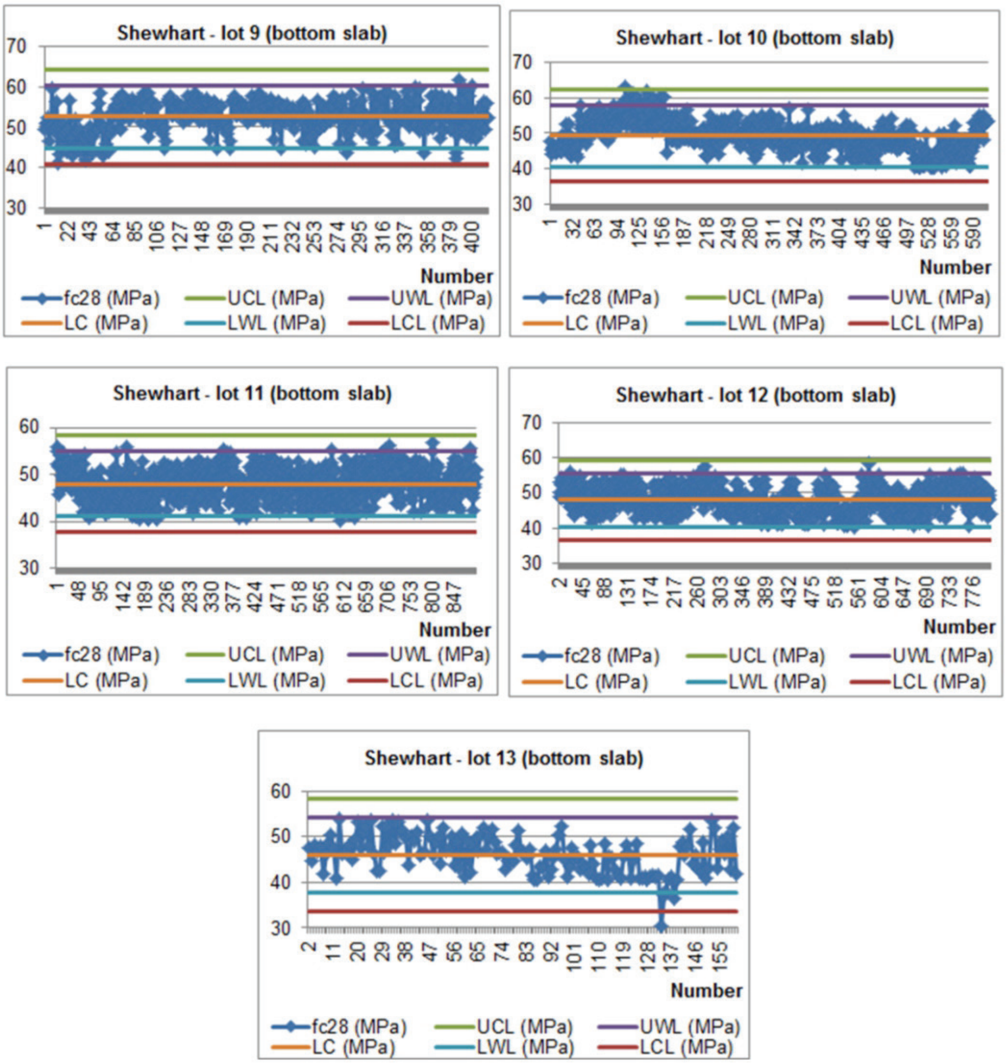



**Figure 9 – Strength values estimated by ANBT NBR 12655 (2006), ACI 318 (2011) e EN 206-1 (2000) of concrete bottom slab**

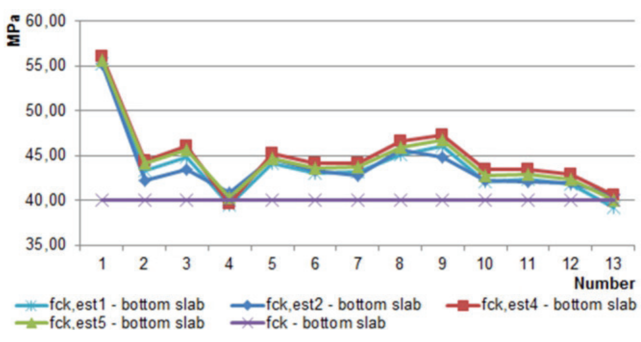



**Figure 10 – Strength values estimated by ANBT NBR 12655 (2006), ACI 318 (2011) e EN 206-1 (2000) of concrete tetrapods**

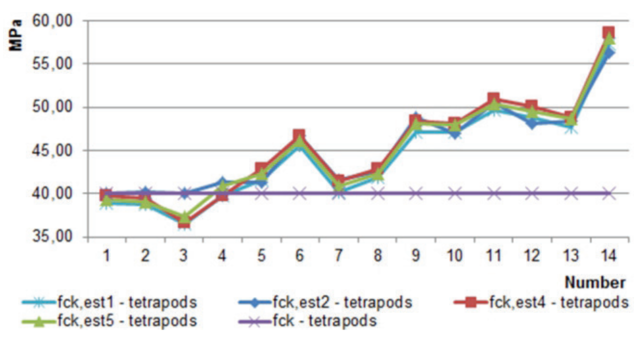


**Table 9 – Results of Kolmogorov-Smirnov test for piles of the pier**

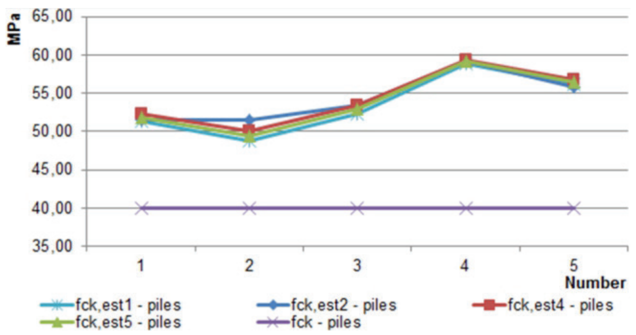
| Lot | Number of copies (n) | s (MPa) | Maximum difference | | D (0.05; n) | Decision |
|---|---|---|---|---|---|---|
| | | | Normal | Lognormal | | |
| 1 | 39 | 2.90 | 0.1123 | 0.1032 | 0.2178 | Lognormal |
| 2 | 72 | 4.40 | 0.2195 | 0.2041 | 0.1603 | – |
| 3 | 81 | 3.82 | 0.1220 | 0.1152 | 0.1511 | Lognormal |
| 4 | 99 | 1.87 | 0.1025 | 0.0995 | 0.1367 | Lognormal |
| 5 | 36 | 2.08 | 0.2310 | 0.2366 | 0.2267 | – |

**Table 10 – Results of Kolmogorov-Smirnov test of concrete bottom slab**

| Lot | Number of copies (n) | s (MPa) | Maximum difference | | D (0.05; n) | Decision |
|---|---|---|---|---|---|---|
| | | | Normal | Lognormal | | |
| 1 | 35 | 2.58 | 0.0801 | 0.0838 | 0.2299 | Normal |
| 2 | 130 | 4.88 | 0.0387 | 0.0458 | 0.1193 | Normal |
| 3 | 106 | 5.00 | 0.0568 | 0.0556 | 0.1321 | Lognormal |
| 4 | 162 | 5.53 | 0.0671 | 0.0668 | 0.1069 | Lognormal |
| 5 | 364 | 3.82 | 0.0617 | 0.0474 | 0.0713 | Lognormal |
| 6 | 441 | 3.69 | 0.0402 | 0.0370 | 0.0648 | Lognormal |
| 7 | 593 | 3.25 | 0.0384 | 0.0517 | 0.0558 | Normal |
| 8 | 158 | 4.66 | 0.0739 | 0.0578 | 0.1082 | Lognormal |
| 9 | 414 | 3.93 | 0.0696 | 0.0722 | 0.0668 | – |
| 10 | 609 | 4.35 | 0.0261 | 0.0279 | 0.0551 | Normal |
| 11 | 892 | 3.40 | 0.0504 | 0.0531 | 0.0455 | – |
| 12 | 807 | 3.76 | 0.0541 | 0.0540 | 0.0479 | – |
| 13 | 160 | 4.09 | 0.0582 | 0.0627 | 0.1075 | Normal |

American and Brazilian norms. Even though the application of the European and the American acceptance criteria resulted in the rejection of some lots, the other values obtained for the estimated concrete compressive strength were higher than those estimated by the criteria of the Brazilian norm.

**Figure 11 – Strength values estimated by ANBT NBR 12655 (2006), ACI 318 (2011) e EN 206-1 (2000) of concrete piles**




This study showed the strict control of the concrete produced and used in the structures of the dry dock bottom slab at the Rio Grande Shipyard ERG1, tetrapods used to enlarge the Barra do Rio Grande Breakwater and the piles of third berth on the pier of the Rio Grande Container Terminal. This control contributed to the acceptance of these structures, not only assuring reliability and safety but also generating a database with a large number of experimental results to prove the potential compressive strength of the concrete of these construction projects.

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