# EXPERIMENTAL STUDY OF THE STATIC AND DYNAMIC MODULUS OF ELASTICITY OF LIGHTWEIGHT CONCRETE WITH THE USE OF EXPANDED CLAY FOR STRUCTURAL PURPOSES

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## ABSTRACT

Structural lightweight concrete has been presented as a promising solution due to its low specific mass, enabling lighter, slender and economical structures. In this research, the conventional aggregates were partially replaced by two granulometry expanded clay. Static and dynamic modulus of elasticity tests were performed for both concretes. The experimental results were also compared to the analytical predictions of the literature and norms, where the variation between these results was discussed. The lightweight concrete obtained showed a loss compressive strength of 16.5% and a tensile strength of 19.8%, a specific mass reduction of 32.6% and a gain of 24.0% in the efficiency factor, compared to normal concrete. In the first, the lightweight concrete showed a modulus of the order of 56.5% of that identified for normal concrete. The dynamic tests showed results 11.29% and 11.05% higher than the static tests for normal and lightweight concrete, respectively.

**KEYWORDS:** Lightweight concrete, Expanded clay, Experimental, Modulus of elasticity

# ESTUDO EXPERIMENTAL DO MÓDULO DE ELASTICIDADE ESTÁTICO E DINÂMICO DE CONCRETOS LEVES COM O EMPREGO DE ARGILA EXPANDIDA PARA FINS ESTRUTURAIS

## RESUMO

O concreto leve estrutural vem apresentando-se como uma solução promissora em função de sua baixa massa específica, possibilitando estruturas mais leves, esbeltas e econômicas. Neste trabalho, os agregados convencionais foram substituídos parcialmente por duas granulometrias de argila expandida. Foram realizados ensaios de módulo de elasticidade estático e dinâmico para ambos os concretos. Os resultados experimentais foram ainda comparados às previsões analíticas da literatura e normatizações, onde a variação entre esses resultados foi discutida. O concreto leve obtido apresentou perda de resistência à compressão de 16,5% e à tração de 19,8%, redução de massa específica de 32,6% e ganho de 24,0% no fator de eficiência, comparado ao concreto normal. No primeiro, o concreto leve evidenciou módulo da ordem de 56,5% do identificado para o concreto normal. Os ensaios dinâmicos apresentaram resultados 11,29% e 11,05% superiores aos ensaios estáticos para os concretos normal e leve, respectivamente.

**Palavras chave:** Concreto leve, Argila expandida, Experimental, Módulo de elasticidade

# 1 INTRODUCTION

From a structural point of view, lightweight concrete has been gaining space and competitiveness over the last few decades, especially given the reduction in its specific mass, below 2.000 kg/m³, as defined by NBR 12655 (ABNT, 2015).

Rossignolo (2009) suggests that the application of lightweight concrete allows, among other advantages, the reduction of the cross sections of several elements throughout the structure, significantly impacting the loads and dimensions of the foundations. This same author states that in the context of precast structures, in addition to the direct impact on the reduction of the structures' own weight, there is a gain in productivity regarding complementary activities of the construction process, that is, machining of concrete, internal and external transport and lifting.

The financial gain with the increase in productivity in logistics activities when using lightweight concrete is more than seven times the increased cost of the inputs necessary for machining it (ACI 213R-14, 2014).

However, the use of lightweight concrete is strongly dependent on the lightweight aggregates available in the region. According to Silva (2007), in the United States, expanded shale (Stalite) is used a lot, while in the Netherlands and the United Kingdom, the most used lightweight aggregates are produced from fly ash, commercially known as Lytag and Aardelite. While in other European countries like Norway and Germany, lightweight expanded clay aggregates are widely used, given the local availability and the great development in the field of research in this area.

LECA is the international denomination for the lightweight expanded clay aggregate, produced in more than twenty countries, having different denominations. For example: “LECA” is used in the United Kingdom, Iran, Portugal, Finland, Germany, Italy, Denmark and Switzerland; "Keramzite" is used in Sweden, China, Poland and Russia; “Liapour” is used in Spain; and "Argex" in South Africa (RASHAD, 2018).

In Brazil, expanded clay is manufactured in rotary kilns, through a process called “nodulation”. This lightweight aggregate has varied granulometry, a regular rounded shape and porous core. Its external surface is vitrified and gives it resistance and low permeability. This aggregate is the main input used in the manufacture of lightweight structural concrete in the country (ANGELIN, 2014).

Santo *et al.* (2012) identified a growth of 57,2% in the consumption of crushed natural aggregates, between 2004 and 2011, in Brazil, thus quantifying the evolution of a growing demand for a limited mineral resource that imposes significant environmental damage on its generation and processing. The exploitation of this resource causes deforestation, earth movement, vibrations on the ground, generations of polluting gases, noise pollution, dust, and impacts on local populations, among other impacts (MECHI and SANCHES, 2010; SILVA NETO *et al.*, 2021). In this context, due to its potential, expanded clay presents itself as a substitute for natural aggregates in the manufacture of structural concrete.

For Rossignolo (2009), Brazilian expanded clay is a promising solution, technically and economically, for the production of lightweight structural concrete with compressive strength of up to 50 MPa and dry specific mass of around 1.400 to 1.800 kg/m$^3$. Despite the significant advancement of its use in recent years, research related to the mechanical properties of lightweight concrete with Brazilian LECA are scarce and indicate the existence of gaps, especially with regard to its deformation modulus. This information is necessary for the technical improvement of this composite with such promising potential, enabling its greater diffusion and applicability as a constructive solution.

In this context, the use of non-destructive tests in the mechanical characterization of this material is in line with the principles of efficiency, economy and sustainability. For example, dynamic non-destructive testing is desirable in the preparation of structural projects, since the modulus of elasticity of the material can be monitored throughout the useful life of the structure from a single specimen without the need to mold several specimens (DIÓGENES *et al.*, 2011). Forigo *et al.* (2021) further reinforces that non-destructive tests can be performed on a larger number of samples, will be faster than destructive tests, making it more economically viable and without the need for structural damage in cases of in loco tests.

In this investigation, in addition to the characterization of the main mechanical parameters of lightweight structural concrete with Brazilian LECA and their correlations with normative and literature predictions, the dynamic modulus of elasticity was also investigated, through the natural frequencies obtained by the impulse excitation technique – SONELASTIC®. Thus, the modulus of elasticity obtained by destructive and non-destructive methods were correlated with each other and with predictions from the literature. This investigation enabled an expansion on the state of the art of the subject, as well as enabling the development of new research based on its findings.

## 2 BRIEF REVIEW

According to Rossignolo (2014), compressive strength and specific mass are the most used parameters in the characterization of structural lightweight concrete, and these properties are directly influenced by the type and granulometry of lightweight aggregates. Moreover, the high porosity of expanded clay has a direct impact on the lower specific masses of concrete. On the other hand, this causes the material to have a lower mechanical strength.

In general, in conventional concrete, the deformation modulus of aggregates is greater than that of mortar. Thus, normally, concrete failure starts in the transition zone, creating a fracture line around the aggregate. In this model, the aggregate is in the most resistant phase, with the compressive strength of the mortar and the paste-aggregate transition zone being the limiting factors for concrete strength. In lightweight concrete with LECA, for example, there is greater similarity between the aggregate and mortar deformation moduli. Therefore, the rupture of this concrete occurs by the collapse of the mortar, creating a fracture plane that crosses the aggregates (ROSSIGNOLO, 2009).

Hashad (2018), in his review research, identified twenty-nine works on the use of LECA in concrete and mortar found in international literature. Different authors evaluated the substitution of fine and coarse aggregates individually and simultaneously. The percentage of this substitution and the granulometry of the lightweight aggregates were tested. Of the twenty-nine investigations, only Scotta and Giorgi (2016) did not identify a reduction in the compressive strength of concrete with the use of LECA. In all other studies, the compressive strength of lightweight concrete was reduced due to the use of LECA as an aggregate. The highest compressive strength reduction factor was verified by Wegin (2012), with a reduction of 69,45%.

Thus, this significant range of compressive strength variation, from 0% to 69,45%, identified in the review by Rashad (2018), corroborates the fundamental role that the physical properties of the lightweight aggregate, combined with the dosage parameters, can influence the compressive strength of the respective lightweight concrete.

The NBR 8953 (ABNT, 2015) and NBR 12655 (ABNT, 2015) prescribe that lightweight concretes have specific dry masses of less than 2.000 kg/m$^3$. While ACI 213R-14 (2014) regulates that lightweight structural concretes have specific masses of 1.120 to 1.920 kg/m$^3$, respectively.

Hassad (2018) consolidated the results of twenty-four studies that investigated the influence of replacing (either partial or total) conventional aggregates with LECA on the specific mass of concrete, where all results pointed to a reduction in this parameter. Rashad (2005) identified a reduction of 48,6% in the apparent specific mass of a mortar, with the replacement of 100% of the conventional fine aggregate by lightweight aggregate. For concrete, Mostafa and Hossam (2010) also obtained a reduction of 44,4% in the apparent specific mass, through the total replacement of fine and coarse conventional aggregates by lightweight ones.

The tensile strength values of lightweight concrete, either by diametral compression or flexion, are globally lower than those found in conventional concrete, for similar levels of compressive strength. This is due to the high volume of voids in lightweight aggregates. For concretes with Brazilian LECA, the tensile strength by diametral compression varies between 6 and 9% of the compressive strength, while the flexural tension varies between 8 and 11% (EVANGELISTA *et al*. (1996); GOMES NETO (1998); ROSSIGNOLO and AGNESINI (2005); and ROSSIGNOLO (2009)).

Angelin (2014), in his experimental work, identified a 47,5% reduction in tensile strength by diametral compression, when replacing 100% of the conventional coarse aggregate with expanded clay (CINEXPAN 1506), of DMC 12,5 mm. This same percentage of reduction was observed for the ages of 7 and 28 days.

The deformation modulus of lightweight concrete varies between 50 and 80% of the modulus for conventional concrete, with compressive strengths from 20 to 50 MPa. This relationship is valid even for concretes that use Brazilian expanded clay. The stress-strain curve of concretes with brazilian LECA indicates linear elastic behavior up to about 80% of ultimate loading, while in conventional concrete, this value is around 60% (ROSSIGNOLO, 2009).

Assunção (2016) investigated the behavior of lightweight self-compacting structural concretes with the replacement of coarse natural aggregate by Brazilian expanded clay, with a DMC of 12,5 mm (CINEXPAN, AE1506), for different replacement rates (0, 20, 40, 60, 80 and 100%). On that occasion, the author showed greater linearity in the ascending section of the curve with the increase in compressive strength, as well as a more abrupt drop in resistance in the post-peak section.

Moravia (2007) investigated the behavior of lightweight concrete using Brazilian LECA with a DMC of 19,0 mm, used as a total replacement for conventional coarse aggregate. In this instance, the author verified that the dynamic modulus of elasticity was 15,94% greater than the static one for normal concrete and 13,75% greater for lightweight concrete. For lightweight concrete, the experimental results were significantly close to the values predicted by ACI 318 (2008). The aforementioned author also points out that the smaller magnitudes of the modulus for elasticity of lightweight concrete, were around one-third smaller than conventional concrete. This showed its greater ability to absorb small deformations, for example, those arising from retraction efforts, thus reducing internal tensions and the formation of microcracks when compared to conventional concrete.

Obtaining the dynamic modulus of elasticity using the method of natural frequencies of vibration is a relatively recent technique, having been standardized in Brazil through NBR 8522-2 (ABNT, 2021), whose first edition was published in 2021. According to the aforementioned Standard, the natural vibration frequencies are particular to each freely vibrating body, determined by its dimensions, geometry and mass, as well as the elastic properties of the material.

## 3 MATERIALS AND METHOD

The characterization of the aggregates corresponding to the first activity were developed in the experimental stage of this research.

The types investigated in this research used medium-grained sand and crushed coarse aggregate, with a commercial gravel classification (nº 1) and with a gneiss-type rock origin, such as natural aggregates. The lightweight aggregates used were of the expanded clay type, from the national manufacturer CINEXPAN, produced in the city of Várzea Paulista, São Paulo, with two granulometries, one coarse (AE1506) and one fine (AE0500). The physical characterization of these aggregates is presented in Table 1, as well as through Figure 1. It is possible to compare the order of magnitude in their granulometry.

**Table 1: Physical characterization of aggregates.**

| Physical characterization | Aggregate type | | | |
|---|---|---|---|---|
| | Sand | AE0500 | Coarse aggregate nº 1 | AE1506 |
| Fineness modulus | 2,70 | 4,89 | 5,87 | 6,50 |
| Maximum characteristic diameter (mm) | 2,40 | 6,30 | 12,5 | 19,0 |
| Unit mass (kg/m$^3$) | 1.579 | 775,7 | 1.525,1 | 596,5 |
| Real specific mass (kg/m$^3$) | 2.656 | 1.265,4 | 2.694,5 | 852,3 |
| Content of powdery material (%) | 3,0 | 0,3 | - | 0,1 |
| Water absorption (%) | - | 21,3 | 1,61 | 13,42 |

**Figure 1: Comparison between the granulometries of the aggregates used: (a) natural sand; (b) AE0500; (c) AE1506; (d) gravel nº 1 (DMC 12.5 mm).**

High initial resistance cement from the brand Cimento Nacional, CP V-ARI MAX, made of silica fume, a type of concrete mix made in China and provided by the manufacturer Ferbasa. This concrete was made in the proportion of 10% by mass in relation to cement consumption, with plasticizer additive from the manufacturer VEDACIT, called CEMIX 2000, was also used in the proportion of 1,5% in relation to the mass of cement.

The type of methodology adopted was defined by Rossignolo (2003), who seeks to combine the maximum packaging factor of the aggregates with the workability conditions that allow the use of concrete in precast parts, and the properties of concrete in its hardened state that classified it as structural. For this purpose, the total aggregate obtained by the author combined 35% of AE1506, 35% of AE0500 and 30% of natural sand. Using it, a type of lightweight concrete with compressive strength of 35 MPa was fabricated in 28 days.

The NBR NM 35 (1995), which specifically regulates lightweight aggregates for structural concrete, defines granulometric frameworks by range for these aggregates. LECA (both AE0500 and AE1506), individually, do not comply with the specifications of this standard, presenting discontinuous granulometric distributions. However, the combination of a 50-50 mixture presents a significant improvement in the granulometric distribution of said mixture, as seen in Figure 2. There is an even more expressive gain with the elaboration of the total aggregate (35/35/30% - AE0500; AE1506; and natural sand, respectively), identifying a gain in the granulometric arrangement of the particles, generating a continuous and uniform distribution.

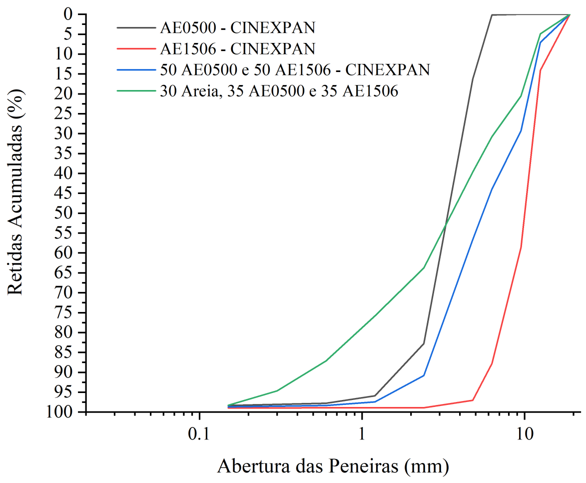

**Figure 2: Grain size distribution of lightweight aggregates and their compositions (50% AE1506 and 50% AE0500) and (35% AE1506, 35% AE0500 and 30% natural sand).**

After defining the type of lightweight concrete, the type of conventional concrete was determined by replacing AE0500 with natural sand and AE1506 with gravel nº 1, having a DMC of 12,5 mm. Said replacements were calculated according to the proportionality between the unit weights of the original and substituted aggregates. Table 2 details the consumption defined in each type.

**Table 2: Comparison between types for lightweight and normal concrete.**

| Lightweight Concrete | | Normal Concrete | |
|---|---|---|---|
| MATERIALS | Type 35 MPa (kg/m$^3$) | MATERIALS | Type 35 MPa (kg/m$^3$) |
| Cement | 394,3 | Cement | 394,3 |
| Active silica | 39,4 | Active silica | 39,4 |
| Sand | 165,6 | Sand | 607,4 |
| AE0500 | 193,2 | | |
| AE1506 | 193,2 | Gravel (12.5 mm) | 586,6 |
| Water | 216,9 | Water | 216,9 |
| Plasticizer | 5,9 | Plasticizer | 5,9 |
| a/c | 0,5 | a/c | 0,5 |

In view of the high levels of absorption of expanded clay, which were greater than 10%, pre-saturation of the same was carried out. For lightweight concrete, this moisture content absorbed by the lightweight aggregate during immersion for 24 hours was subtracted from the expected amount at the time of mixing. This procedure aimed to maintain the water-cement factor defined for each type, considering the significance of the volume of water “stored” in the expanded clay.

As a result of this procedure, there was a significant difference in the workability of lightweight and conventional concrete. Due to this peculiarity, the slump test was adopted to characterize lightweight concrete, in accordance with NBR NM 67 (ABNT, 1998), combined with the spreading and t500 tests for conventional concrete, in accordance with NBR 15823-2 (ABNT, 2017), since the latter presented similar characteristics to a self-compacting concrete.

All the concrete made in this research, regardless of type or destination, was prepared in a semi-fixed electric mixer with a capacity of 200 liters. The homogenization time of the materials used was 5 minutes. Compaction was carried out using a compaction rod in accordance with the recommendations of NBR 5738 (ABNT, 2015) in order to avoid a possible “floating” of expanded clay in lightweight concrete. The curing method adopted was wet curing by immersion and all specimens had their ends smoothed using a mechanical grinder before carrying out the tests.

The axial compression tests of lightweight and conventional concrete were carried out with the aim of obtaining only their ultimate strengths. They followed the recommendations of NBR 5739 (ABNT, 2018). A SHIMADZU UH-F universal mechanical testing machine was used, with a capacity of 1.000 kN, and data collection was carried out using the TRAPEZIUM2 Software. This same equipment was used in the tensile tests for diametral compression and static modulus of elasticity. The tensile test complied with the standards of NBR 7222 (ABNT, 2011).

In carrying out the static modulus tests, the loading speed was 0,45 MPa/s. To capture displacement data, two dial gauges were used, with a resolution of 0,001 mm. They were fixed on independent metallic bases with a measurement base of 132 mm, as shown in Figure 3. In this experimental stage, NBR 8522-1 (ABNT, 2021) was partially complied with, given that the previous cyclic loading procedure was not performed due to operational limitations of the data capture software.

Calculation methodology “A”, recommended by NBR 8522-1 (ABNT, 2021), was used to obtain the value ($E_c$) with the use of constant stress. In this work, similarly to that performed by Diógenes (2010), the secant line to the stress versus deformation curve was defined by the points corresponding to the stress of 5% and 50% of the rupture stress. The numerical results of stress and strain corresponding to this interval demonstrated the viability of this approximation through linear regressions and their respective coefficients of determination.

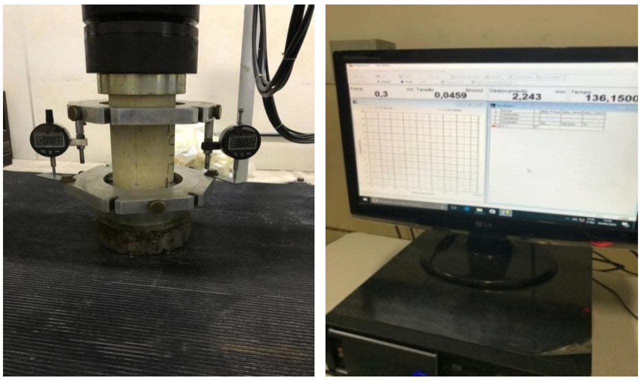

**Figure 3: Static elastic modulus test.**

To determine the dynamic modulus of elasticity in lightweight and conventional concrete, non-destructive tests were carried out using the natural frequencies obtained by the Impulse Excitation Technique – SONELASTIC®. This equipment is available at MIMME/CT/UFPB and is based on the Impulse Excitation Technique. All procedures were performed in accordance with NBR 8522-2 (ABNT, 2021) and test scheme shown in Figure 4.

**Figure 4: Dynamic modulus test.**

Tests of specific mass, absorption and void ratio were also carried out for both investigated concretes, as recommended by NBR 9778 (ABNT, 2009).

For the statistical treatment of the samples corresponding to the results of the characterization of the concretes, the “t” test was used to construct confidence intervals, with a significance level of 5%. According to Morettin and Bussab (2010), the “t” test can be used to define confidence intervals for the mean of populations that have normal distribution and unknown variance. After defining these confidence intervals, the sample mean was recalculated, excluding the extreme values, so that the calculated sample mean value is the most representative of the population referring to the variable of interest. To verify the normality of the samples, the Shapiro-Wilk test was used. This verification was carried out using Statistica software.

## 4 RESULTS AND DISCUSSIONS

The characterization in the fresh state of both concretes is presented in Table 3. It is observed, through the results presented on the right, that the normal concrete did not present fluidity or free-flow filling capacity that framed it as a self-adensable concrete according to the spreading classes recommended in NBR 15823-1 (ABNT, 2017) whose initial range is 550 to 650 mm.

As for the apparent plastic viscosity of normal concrete, measured by the parameter t500, it is observed that the results are greater than 2 (two) seconds, meaning, the concrete investigated here fits in the viscosity class VS 2 according to NBR 15823-1 (ABNT, 2017) whose classification is adequate for most current applications.

As for visual stability under free flow, qualitatively, the concrete did not present evidence of segregation, thus presenting good distribution of large aggregates and mortar in the mixture, nor exudation, and can be classified as EVI0 (Visual Stability Index) according to NBR 15823-1 (ABNT, 2017).

Table 3: Slump Test results for lightweight concrete; Slump-flow and t500 for normal concrete.

| Lightweight Concrete | | Normal Concrete | |
|---|---|---|---|
| Groups | Slump Test (mm) | Slump-flow (mm) | t500 (s) |
| 1 | 115 | 500 | 3,5 |
| 2 | 130 | 510 | 4,0 |
| 3 | 120 | 500 | 4,4 |
| 4 | 120 | 520 | 4,7 |

Regarding compressive strength, Table 4 presents the results for both lightweight concrete and normal concrete samples. The highlighted mean values were obtained through the statistical treatment already described. Therefore, it is observed that the lightweight concrete presented a resistance decrease of 16,5% when compared to conventional concrete.

Table 4: Comparison between the results of compressive strength of the lightweight and normal concretes.

| Lightweight Concrete | | Normal Concrete | |
|---|---|---|---|
| Parameter | Compressive Strength | Parameter | Compressive Strength |
| Average (MPa) | **29,55** | Average (MPa) | **35,40** |
| Sample (N) | 10 | Sample (N) | 10 |
| Standard deviation (MPa) | 1,60 | Standard deviation (MPa) | 0,57 |
| C.V. (%) | 5,4 | C.V. (%) | 1,6 |

The total replacement of the natural coarse aggregate by the expanded clay AE1506 and the partial replacement of natural sand by expanded clay AE0500 allowed a reduction of 32,6% in the apparent specific mass of the lightweight concrete compared to conventional concrete. This parameter was reduced from 2,24 g/cm$^3$ (normal concrete) to 1,51 g/cm$^3$ (lightweight concrete).

The reduction of the specific mass was related to the reduction of the porosity and permeability parameters of the lightweight concrete. It presented higher voids and absorption index than conventional concrete, at 19,2% and 38,6% higher, respectively. These results are presented in Tables 5 and 6.

The order of magnitude of the results is consistent with the literature, subject to the particularities of the mixture currently experienced. The mixing methodology of lightweight concrete, which is specific for the use of expanded clay investigated here, seeks the balance between the resistance limitation imposed by the light aggregate to the concrete and the relief of its own weight conferred by the lightness of the aggregate. This balance is exactly the concept of optimal resistance defined by Rossignolo (2003).

The highest absorption of light concrete, 38,6%, is directly related to the porous structure of the light aggregate. It should be reiterated that they presented absorption rates of 13,42% and 21,3% for both large and small granulometry, respectively, while the natural aggregate presented absorption of 1,61%. The highest void index is also predominantly justified by the porosity of expanded clay. It should be noted that the relationship between porosity and permeability is very intimate, and the latter property is made possible by interconnected or communicable pores.

The use of active silica in both mixtures combined with the internal cure conferred by the light aggregate also contributed to improving the properties of the cement matrix in the densification items and, consequently, reduction of void and porosity indexes.

**Table 5: Results of specific mass, absorption and void index for normal concrete.**

| Parameters | Dry Specific Mass (g/cm$^3$) | Saturated Specific Mass (g/cm$^3$) | Real Specific Mass (g/cm$^3$) | Apparent Specific Mass (g/cm$^3$) | Absorption (%) | Void Index (%) |
|---|---|---|---|---|---|---|
| Average | **1,85** | **2,03** | **2,26** | **2,24** | **9,78** | **15,21** |
| Sample Size | 10 | | | | | |
| Standard deviation (MPa) | 0,028 | 0,010 | 0,012 | 0,014 | 0,262 | 0,726 |
| C.V. (%) | 1,5% | 0,5% | 0,5% | 0,6% | 2,7% | 4,8% |

**Table 6: Results of specific mass, absorption and void index for lightweight concrete.**

| Parameters | Dry Specific Mass (g/cm$^3$) | Saturated Specific Mass (g/cm$^3$) | Real Specific Mass (g/cm$^3$) | Apparent Specific Mass (g/cm$^3$) | Absorption (%) | Void Index (%) |
|---|---|---|---|---|---|---|
| Average | **1,34** | **1,53** | **1,63** | **1,51** | **13,55** | **18,12** |
| Sample Size | 10 | | | | | |
| Standard deviation (MPa) | 0,024 | 0,024 | 0,024 | 0,033 | 0,388 | 0,376 |
| C.V. (%) | 1,8% | 1,6% | 1,5% | 2,2% | 2,9% | 2,1% |

Due to the different mixtures investigated in the literature, the comparison of parameters such as compressive strength and specific mass alone becomes inconclusive; so much so that the efficiency factor parameter, through the correlation between resistance and specific mass, defines a numerical variable, enabling the comparison of performance between different mixtures.

In this research, the property of light concrete sums was experimentally corroborated in presenting efficiency factors superior to conventional concrete, ratifying the investigations developed by Moravia (2007), Santis and Rossignolo (2014), Verzegnassi (2015), Bernardo et al. (2016) and Nunes (2020). The efficiency factor identified in this study for light concrete was 19,60 MPa.dm$^3$/kg, 24,0% higher than that observed for conventional concrete, 15,81 MPa.dm$^3$/kg.

A resistance class of 30 MPa at 28 days of age (as seen in Figure 5) are the concretes of resistance class like that investigated in this study. This data is consolidated for some of the most recent studies with the use of national expanded clay and verified that the research developed here presented an efficiency factor higher than that recorded in the literature.

Bernardo *et al.* (2016) recorded an efficiency factor of 22,65 MPa.dm$^3$/kg, however the author used 150 mm cubic specimens in the compressive strength and dry specific mass tests to calculate this parameter. Considering a form factor of 1,10 between the compressive strength of cubic and cylindrical specimens of 100 x 200 mm, as well as using the average result of dry specific mass of 1,34 g/cm$^3$ instead of the apparent specific mass, an efficiency factor of 24,3 MPa.dm$^3$/kg is obtained in this research, higher than that identified by Bernardo *et al.* (2016).

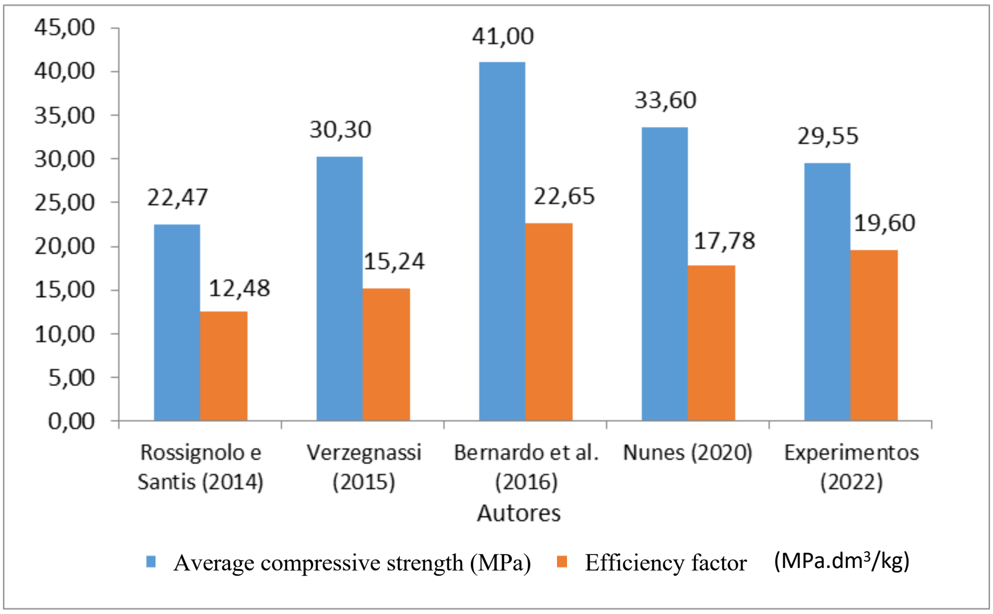

**Figure 5: Comparison of the results of compressive strength and efficiency factor of light concrete made with national expanded clay (Adapted by Nunes, 2020).**

The light concrete investigated here presented an average tensile strength by diametrical compression of 1,71 MPa, 19,8% lower than the reference concrete of normal specific mass. The mean resistance identified for normal concrete was 2,13 MPa. This loss of resistance is directly linked to the emptiness index of concrete, with the latter being a direct consequence of the type of light aggregate and mixture used. Tensile strength data is shown in Table 7.

The 1,71 MPa mean tensile strength of light concrete represented 5,8% of the average compressive strength of the light concrete, identified in the 29,55 MPa. The research of the use of expanded clay nationally developed by Evangelista *et al.* (1996), Gomes Neto (1998), Rossignolo and Agnesini (2005) and Rossignolo (2009) verified a correlation between these two parameters in the range of 6,0 to 9,0%. Thus, considering the particularities of each mixture and the approximation of the result measured with the lower limit of this range; it is considered that this result is consistent with the general state of art.

**Table 7: Diametric compression tensile strength results for lightweight and normal concretes.**

| Lightweight Concrete | | Normal Concrete | |
|---|---|---|---|
| Parameter | Tensile strength (MPa) | Parameter | Tensile Strength |
| Average | **1,71** | Average | **2,13** |
| Sample Size | 10 | Sample Size | 10 |
| Standard deviation | 0,07 | Standard deviation | 0,06 |
| C.V. | 4,1% | C.V. | 2,7% |

The experimental result of tensile strength for light concrete was compared to some analytical predictions (HOFF (1991), ACI 318 (2008) and EN 1992-1-1 (2004)), as detailed in Table 8. Through this, it is perceived that the experimental result was substantially close to the predictions of EN 1992-1-1 (2004) – Eurocode 2, with a correlation factor of 1,01. It should be noted that this standardization estimates the tensile strength by diametric compression of the light concrete as a function of its specific mass and tensile strength corresponding to the concrete of normal specific mass in an equivalent mixture. The other expressions have only the compressive strength of the light concrete as an independent variable. It is thought that this expression presented the best representation among the others due to its greater numerical complexity, a greater number of independent variables. The concept of "optimal resistance" demonstrates the existence of a balance between specific mass, positive point, resistance summation, and negative point.

**Table 8: Comparison between experimental diametric compression tensile strength and analytical predictions.**

| Reference | Tensile Strength by Diametral Compression (MPa) | Correlation Factor (Analytical Forecast / Mean Experimental Result) | Observation |
|---|---|---|---|
| HOFF (1991) | 2,66 | 1,56 | - |
| ACI 318 (2008) | 2,28 | 1,34 | Mixture with light aggregate only |
| ACI 318 (2008) | 2,61 | 1,53 | Mixture with sand and lightweight aggregate |
| EN 1992-1-1 (2004) | 1,73 | **1,01** | Calculated from the tensile strength of normal concrete with similar mixture |
| Average experimental result | 1,71 | 1,00 | - |

Figure 6 shows the stress-strain curves for the light and normal concretes investigated in this study. It is observed the greater linearity in the upward stretch of the curve to the lightweight concrete, as well as a more abrupt drop in resistance of the post-peak stretch. This behavior is consistent with the investigations of Rossignolo (2009), which verified an elastic-linear behavior for light concrete with Brazilian LECA up to about 80% of the last loading, while conventional concretes presented the same behavior up to the order of 60%.

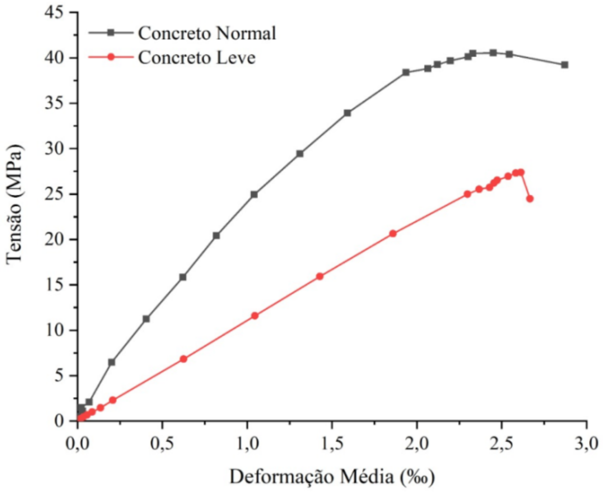

**Figure 6: Comparison between the stress versus strain curves of the normal and lightweight concrete investigated.**

The average static strain modulus obtained for lightweight concrete was around 12.231 MPa, which is 56,5% of the value identified for conventional concrete, 21.660 MPa. This percentage is in line with the literature, which predicts a ratio of around 50 to 80% between the static and dynamic modules, for concretes of 20 to 50 MPa, including the use of national expanded clay (ROSSIGNOLO, 2009). The summary of static modulus results is shown in Table 9.

**Table 9: Results for the static modulus of elasticity tests of the lightweight and normal concretes.**

| Lightweight Concrete | | Normal Concrete | |
|---|---|---|---|
| Parameter | Static Modulus of Elasticity | Parameter | Static Modulus of Elasticity |
| Average (MPa) | **12.231** | Average (MPa) | **21.660** |
| Sample Size | 10 | Sample Size | 10 |
| Standard deviation (MPa) | 297 | Standard deviation (MPa) | 1.549 |
| C.V. (%) | 2,4 | C.V. (%) | 7,2 |

The experimental mean static deformation module was compared with analytical predictions presented in academic publications and standardizations, as detailed in Table 10. Through this, it is verified that the prediction closest to the experimental result is found in the work of Rossignolo (2009), higher only in 1% than the experimental average. This result finds consistency in the fact that this research is reproducing the mixture methodology presented by the author.

It is also observed that all normative forecasts presented lower values than the experimental: NS 3473 (2003), 11% lower; EN 1992-1-1 (2004), 29% lower; and ACI 318 (2008), 11% lower. It is noted that the standards NS 3473 (2003) and ACI 318 (2008) presented almost identical predictions. On the other hand, the predictions from academic papers presented higher predictions than the experimental one: Valente (2007), 23% higher; and Assunção (2016), 59% higher.

As for the alignment of normative predictions presenting lower values, it is considered that these are the fruits of broader research, where weightings are performed between different mixtures, meaning, the predictions have a more general characteristic. It should also be noted the possible application of safety factors, as well as statistical treatments which reduce the expected numerical result. On the other hand, the results presented in academic research reflect the particularities of each case study investigated there.

**Table 10: Comparison between the experimental elasticity module and analytical predictions.**

| Author/Standard | Experimental Static Modulus of Elasticity (MPa) | Relationship between analytical estimate and the average experimental result |
|---|---|---|
| NS 3473 (2003) | 10.907 | 0,89 |
| EN 1992-1-1 (2004) | 8.633 | 0,71 |
| Valente (2007) | 15.093 | 1,23 |
| ACI 318 (2008) | 10.839 | 0,89 |
| **Rossignolo (2009)** | **12.351** | **1,01** |
| Assunção (2016) | 19.406 | 1,59 |
| **Experimental Program** | **12.231** | **1,00** |

In this research, the numerical correlation between the modulus of elasticity obtained by the static methodology, according to NBR 8522-1 (2021), and the dynamic one, recommended by NBR 8522-2 (2021), was also investigated.

In Table 11, column (4), it can be seen that the modulus obtained by the dynamic methodology was 11,29% and 11,05% higher than that obtained by the static methodology, for normal and lightweight concrete, respectively. Initially, qualitatively, these results corroborate a prediction recommended by NBR 8522-2 (2021) that the dynamic modulus of elasticity is always greater than or equal to the initial static tangent modulus.

From the quantitative point of view, the results now identified were close to the findings of Moravia (2007), who investigated the behavior of lightweight concretes with the use of Brazilian LECA of DMC 19,0 mm. At that time, the author verified that the modules of dynamic elasticity were 15,94% and 13,75% higher than the static ones, for normal and lightweight concrete, respectively.

Respecting the particularities of each survey, from the point of view of sample size and statistical treatment employed, it is believed that the order of magnitude of the results identified in both surveys is consistent. It should also be noted that the numerical proximity of the relationship identified for the two types of concrete, normal and lightweight, of 11,29% and 11,05% points to a uniformity of procedures in the experimental phase, sample preparation and collection of the data, as well as for a possible similarity of the correlations for lightweight and conventional concrete.

NBR 8522-1 (2021), in its Annex “B”, presents a calculation methodology for estimating the static modulus of elasticity as a function of the dynamic modulus of elasticity and the apparent specific mass of the concrete. This estimate was calculated and presented in column (5) of Table 11. In column (6), still in Table 11, it appears that this estimate was 24,09% and 10,60% lower than the average experimental static modulus identified in this research, for normal and lightweight concrete, respectively. In its item “B.2”, of Annex “B”, this standard discusses the uncertainty of estimating the static modulus from the dynamic one for Brazilian concretes, using the methodology recommended therein, the result of the Popovics Model, warning about an average error of around 6,7%, with a standard deviation of 7,1% for the estimation in question.

NBR 8522-1 (2021) also clarifies that the main reason for such uncertainty is due to the dispersion of results obtained from the static method, where, in interlaboratory programs carried out annually by the Brazilian Network of Laboratories of Tests of Inmetro, standard deviations of the order of 12% have been verified in this type of test. ACI 318 (2008) considers a standard deviation of up to 20% to be acceptable for this parameter.

From a qualitative point of view, the estimated values behaved as expected, reduced in relation to the experimental value obtained by the static method. From the quantitative point of view, it appears that the result for lightweight concrete preserved the order of magnitude of the estimate, according to NBR 8522-1 (2021), estimated value 10,60% lower than that obtained by the experimental static method.

Through the analysis of the raw data of the two static modulus tests (lightweight and normal concrete), before the statistical treatment, it can be seen that the variation coefficient for lightweight concrete was 7,0%, while for normal concrete it was of 18,6%. The smaller dispersion in the numerical results for lightweight concrete can be explained by the greater linearity in the stress versus strain curve in its ascending section of lightweight concrete compared to normal. This greater dispersion, still below that recommended by ACI 318 (2008), can numerically justify the percentage of 24,09% lower identified in the estimate, column (6) of Table 11, for normal concrete.

**Table 11: Relationship between static and dynamic modulus of elasticity for light and normal concrete.**

| Type of concrete | Average Compressive Strength (MPa) (1) | Experimental Static Modulus of Elasticity (MPa) (2) | Experimental Dynamic Modulus of Elasticity (MPa) (3) | Percentage Variation between Static and Dynamic Module (4) | Estimation of the Static Modulus from the Dynamic One (Annex B, NBR8522-1, 2021) (5) | Percentage Variation between Static Modulus and its estimate (NBR8522-1, 2021) (6) |
|---|---|---|---|---|---|---|
| Normal Concrete | 35,40 | 21.660 | 24.106 | 11,29% | 16.443 | 24,09% |
| Lightweight Concrete | 29,55 | 12.231 | 13.583 | 11,05% | 10.935 | 10,60% |

## 5 CONCLUSIONS

In view of the results obtained through the bibliographic review and the findings of this experimental investigation, the following final considerations were reached:

a) The lightweight concrete investigated showed a compressive strength of the order of 16,5% lower than conventional concrete of similar dosage. This particularity is in line with predictions in the literature and is due to the lower strength of expanded clay compared to natural coarse aggregate. Even with this reduction, the average resistance value obtained of 29,55 MPa allows this concrete to be classified as lightweight structural, according to the recommendations of NBR 6118 (ABNT, 2014) and ACI 213R-14 (2014).

b) In contrast to the loss of resistance, there was a reduction of 32,6% in the apparent specific mass of lightweight concrete compared to conventional concrete, this parameter was reduced from 2,24 g/cm$^3$ (normal concrete) to 1,51 g/cm$^3$ (lightweight concrete). This result allows the classification of this concrete as lightweight, according to NBR 8953 (ABNT, 2015) and NBR 12655 (ABNT, 2015). The results of strength and specific mass also made it possible to classify this concrete as lightweight, according to NBR NM 35 (ABNT, 1995). The reduction in the specific mass was linked to the penalization of the porosity and permeability parameters of lightweight concrete. It had higher voids and absorption rates than conventional concrete, 19,2% and 38,6% higher, respectively. These characteristics are also consistent with the literature review, in part, a direct impact of the high absorptions identified in the expanded clays.

c) Considering compressive strength and specific mass, lightweight concrete presented an efficiency factor of the order of 19,60 MPa.dm3/kg, 24,0% higher than that identified for normal specific mass concrete (15,81 MPa.dm$^3$/kg). This result confirms previous research and is justified by the greater impact on the reduction in the specific mass of lightweight concrete than its loss of strength.

d) Still regarding the efficiency factor, the dosage of lightweight concrete investigated in this research obtained the maximum performance compared to the other authors presented in Figure 05, recent research with the use of brazilian LECA. The efficiency factor of 19,60 MPa.dm$^3$/kg evolved to 24,3 MPa.dm$^3$/kg if calculated using the same methodology adopted by Bernardo *et al.* (2016). Thus, the efficiency of the dosing methodology developed by Rossignolo (2003) is corroborated, which seeks a balance between reducing the specific mass of the concrete and maximizing its compressive strength.

e) The structural performance of lightweight concrete with LECA corroborated in this research and expressed by its efficiency factor demonstrates the potential of this composite for its use in prefabricated structures, in line with trends in civil construction of modularization, reuse, economy and sustainability. As an opportunity for future research, it is believed that the development of new technologies that seek to reduce the permeability of lightweight concrete with LECA, reducing the communicable pores and thus making it less susceptible to attacks by external agents, is presented as a topic relevant.

f) The results of tensile strength by diametral compression pointed to an average value of 1,71 MPa, a value 19,8% lower than that presented for the reference concrete (2,13 MPa). This result represents 5,8% of the average compressive strength, a value close to the range identified in the literature from 6,0 to 9,0% for lightweight concrete with the use of national expanded clay, aligning the findings of this investigation with the research already carried out. The experimental result approached the analytical prediction predicted in Eurocode 2, with a correlation factor of 1,01. It is believed that this analytical prediction with an average error of 1% is the result of the greater mathematical complexity of the expression recommended by this normative, which has as independent variables the specific mass of lightweight concrete and the tensile strength of concrete with normal specific mass of equivalent dosage. The other analytical predictions verified here use only compressive strength as an independent variable in the expression of tensile strength, correlations that did not prove to be as strong as those predicted in Eurocode 2.

g) The average static modulus of elasticity obtained for lightweight concrete was around 12.231 MPa, a value 56,5% of that identified for conventional concrete, 21.660 MPa. This percentage is in line with the literature, which predicts a ratio of around 50 to 80% between the mentioned modules, for concretes of 20 to 50 MPa, including the use of national expanded clay. This lower modulus of elasticity allows concrete to absorb small deformations, minimizing its internal stresses, if compared to conventional concrete. This particularity of the level of concrete with LECA can be explored in lines of research that require a greater degree of cracking of the concrete in states of lower stress levels. For example, in the use of lightweight concrete in filled composite columns, the development of greater initial transverse strains can early activate the lateral restraint provided by the metallic coating and, consequently, can improve the structural performance of the confined concrete core. Thus, this investigation can subsidize other researches in the area of mixed steel-concrete elements.

h) The experimental results of the static modulus of lightweight concrete were compared to the analytical predictions, being more strongly correlated to Rossignolo's expressions (2009), with a correlation factor of the order of 1,01. This result corroborates the expectations of this research, given that the dosage of lightweight concrete adopted was based on the author's methodology. Therefore, the slightest error in relation to its analytical expression ratifies the entire process of scientific investigation developed here, as well as corroborates the work developed by that Author. It was verified that all normative predictions analyzed presented inferior results to the experimental one, evidencing more generalist studies with application of safety factors in their statistical treatments. While the estimates from academic works pointed to module results superior to those evidenced in this investigation. This divergence can be explained by the particularities of each case study investigated there, for example, variations in dosage and test methodology.

i) It was verified that the modulus of elasticity obtained by the dynamic methodology was 11,29% and 11,05% higher than that obtained by the static methodology, for normal and lightweight concrete, respectively. Qualitatively, these results ratify NBR 8522-2 (ABNT, 2021), which clarifies that the dynamic modulus is always greater than or equal to the static modulus. From the quantitative point of view, these results are close to the findings of Moravia (2007), who identified dynamic modules superior by 15,94% and 13,75% to static modules for normal and lightweight concrete, respectively. Thus, the results identified in these two studies on lightweight concrete with LECA demonstrate considerable similarity between the behavior of normal and lightweight concrete in terms of the correlation between dynamic and static modules.

j) Finally, the estimate of the static modulus from the dynamic modulus, presented in Annex B.1, of NBR 8522-1 (ABNT, 2021), which takes into account the apparent specific mass of the concrete, was 24,09% and 10,60% lower than the experimental values obtained for normal and lightweight concrete, respectively. The referred norm warns of an average error of the order of 6,7%, with a standard deviation of 7,1% for the estimation in question. It is thought that the greater linearity of the stress versus deformation curve of the elastic section for lightweight concrete allowed for a smaller dispersion of the results for the static modulus (coefficient of variation of only 7,0%). The data from the normal concrete pointed to a coefficient of variation of 18,6%. Thus, this greater dispersion identified for normal concrete can justify this percentage (24,09%). Overall, it was observed that the standard's estimates are conservative in predicting the static modulus values from the dynamic modulus. Since the dispersion of data from the static modulus of elasticity test compromises the measurement of the real value of this safety factor.

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