Volume 10, Number 3 (June 2017) p. 547 – 567 • ISSN 1983-4195
http://dx.doi.org/10.1590/S1983-41952017000300002

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS
IBRACON STRUCTURES AND MATERIALS JOURNAL

Stress-strain curve of concretes with recycled concrete aggregates: analysis of the NBR 8522 methodology

Diagrama tensão-deformação específica em concretos com agregados reciclados de concreto: análise da metodologia proposta pela NBR 8522



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Abstract

This work analyses the methodology "A" (item A.4) employed by the Brazilian Standard ABNT 8522 (ABNT, 2008) for determining the stress-strain behavior of cylindrical specimens of concrete, presenting considerations about possible enhancements aiming it use for concretes with recycled aggregates with automatic test equipment. The methodology specified by the Brazilian Standard presents methodological issues that brings distortions in obtaining the stress-strain curve, as the use of a very limited number of sampling points and by inducing micro cracks and fluency in the elastic behavior of the material due to the use of steady stress levels in the test. The use of a base stress of 0.5 MPa is too low for modern high load test machines designed do high strength concrete test. The work presents a discussion over these subjects, and a proposal of a modified test procedure to avoid such situations.

Keywords: 8522 Standard (ABNT, 2008), Concrete, Modulus of elasticity, strength-stress behaviour.

Resumo

Este trabalho analisa a metodologia descrita no Anexo “A” (item A.4) da Norma NBR 8522 (ABNT, 2008) para a determinação do diagrama tensão-deformação específica em corpos-de-prova cilíndricos de concreto apresentando considerações sobre possíveis adequações de seu uso para concretos com agregados reciclados e com equipamentos automatizados. A metodologia especificada na norma apresenta restrições metodológicas que geram distorções na obtenção do diagrama tensão-deformação, tais como o uso de número muito limitado de pontos de leitura e a inclusão, no comportamento elástico do material, de fenômenos diferidos como microfissuração e fluência ocorridos durante os patamares de estabilização de carga. A tensão básica de 0,5 MPa, especificada para garantir a estabilização da carga, é inadequada para grande parte das prensas automatizadas modernas, projetadas para o ensaio de concretos de alta resistência. São discutidos alguns aspectos da Norma e propostas alterações metodológicas.

Palavras-chave: Norma 8522 (ABNT, 2008), concreto, módulo de elasticidade estático, diagrama tensão-deformação específica.

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Received: 21 Jun 2014 • Accepted: 01 Aug 2016 • Available Online: 12 Jun 2017

1. Introduction

Strength is a function of the capacity to withstand stress without permanent deformation or fracture, while hardness is associated with deformation under a given level of stress. Such properties should be determined in laboratory, and the common assays used include uniaxial stress, tensile, and compressive tests, which are used to determine the relationship between the means of normal stress and specific longitudinal deformation. Tensile and compressive strength data indicate where deformation occurs under a given stress level, affording to construct a curve called stress-strain curve.

The linear behavior of concrete is observed until a certain level of stress is reached. For Melo Neto and Helene [1], this happens before 50% of the ultimate strength. This behavior results from progressive microcracking, which begins on the interface between coarse aggregate and cement paste and spreads to the whole concrete with time. The typical stress-strain curve for concrete constructed using data from a simple compressive assay is shown in Figure 1.

The stress-strain curve shows that the behavior of concrete may be considered elastic up to a certain stress level, usually between 40% and 50% of the fracture strength. Stress levels over this threshold induce microscopic changes that may be easily visualized, such as the increasingly non-linear character of the stress-strain curve during the application of a load or the existence of permanent deformation when stress is removed [2]. Standard NBR 6118 [3] section 8.2.10.1 stipulates that compressive strength below 0.5 *fc* affords to presuppose a linear relationship between stress and deformation.

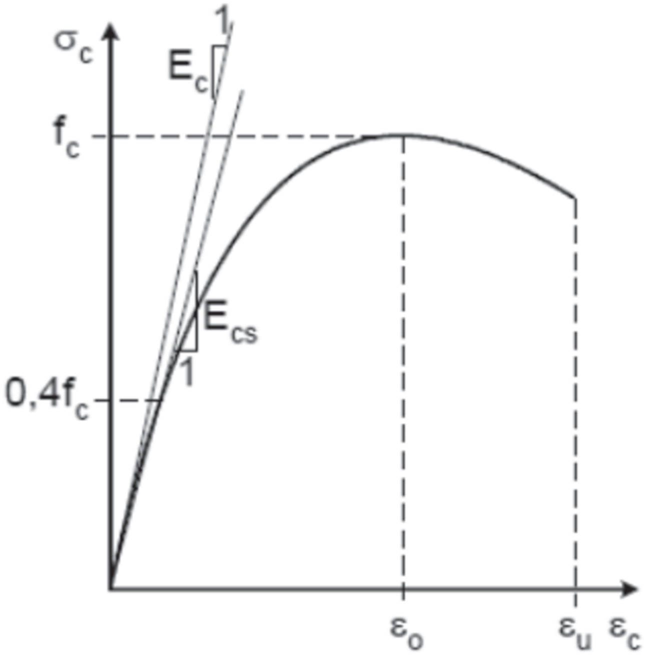

Figure 1
Stress-strain curve typical of concrete (simple compression)
Source: *Araújo (3)*

Besides the notable demand for specific landfill areas, the increasing lack of natural resources and growing environmental awareness prompt the use of construction waste as source material in the production of aggregates [4,5,6]. According to Buttler [7], concrete waste has considerable recycling potential compared with other kinds of waste, since it is relatively easy to recover information about the materials used in its formulation.

If the differences between the values of fracture strength obtained in laboratory and estimated using specific models described in standards is large already, the discrepancy between these parameters is even more substantial for concretes including recycled concrete aggregates (RCA) in their formulations. This is due to the scarcity and wide variation of data describing RCA characteristics. In concretes, elasticity modulus (E_c) varies with the amount of coarse aggregates. Substituting RCA or aggregates with low E_c values for conventional aggregates requires the appropriate investigation of fracture strength [8].

This study reviews the methodology described in the Brazilian standard NBR 8522 Anexo “A” (item A4) [9], which prescribes the construction of the specific stress-strain curve–using cylindrical specimens of concrete prepared with RCA. The factors behind distortions in the curve are analyzed, including the use of a rather low number of reading points and the consideration of time-dependent phenomena like microcracking and flow in the analysis of the behavior of the material, since the adoption of steady stress levels that may worsen distortions in concrete specimens with RCA.

2. Procedures described in NBR 8522

In Appendix A4, the standard NBR 8522 [9] describes the procedure to be used to construct the stress-strain curve of hardened cylindrical concrete specimens. According to the standard, the measurement procedure has to be calibrated before the assay. The calibration procedure includes five steps:

1. Align the sample to the platen of the equipment, when clip gauges are connected to it so as to provide independent readouts along the longitudinal axis.
2. Load to the sample until a compression rate of 20% of the predicted fracture strength. Compare the deformation values in readouts. If the difference between values is over 20% of the highest deformation value, unload the sample and spin it to realign it more centrally on the platens.
3. Repeat the loading and reading processes, and compare deformation values.
4. Repeat the procedure until the difference in deformation values is lower than 20% of the highest readout.
5. Apply increasing load rates at 0.45 ± 0.15 MPa and 60-s intervals over the values given below immediately after final alignment of the sample:
   - – Axial stress readout (σa) = 0.5 MPa
   - – Readouts at 0.2 *fc*, 0.3 *fc*, 0.4 *fc*, and 0.5 *fc*, where *fc* is the estimated fracture strength value under simple compression.

Deformation values have to be read within 30 s maximum at 60-s intervals for every steady stress level applied. According to NBR 8522, the values that represent the stress-strain behavior of concrete are obtained after the 60-s period during which stress

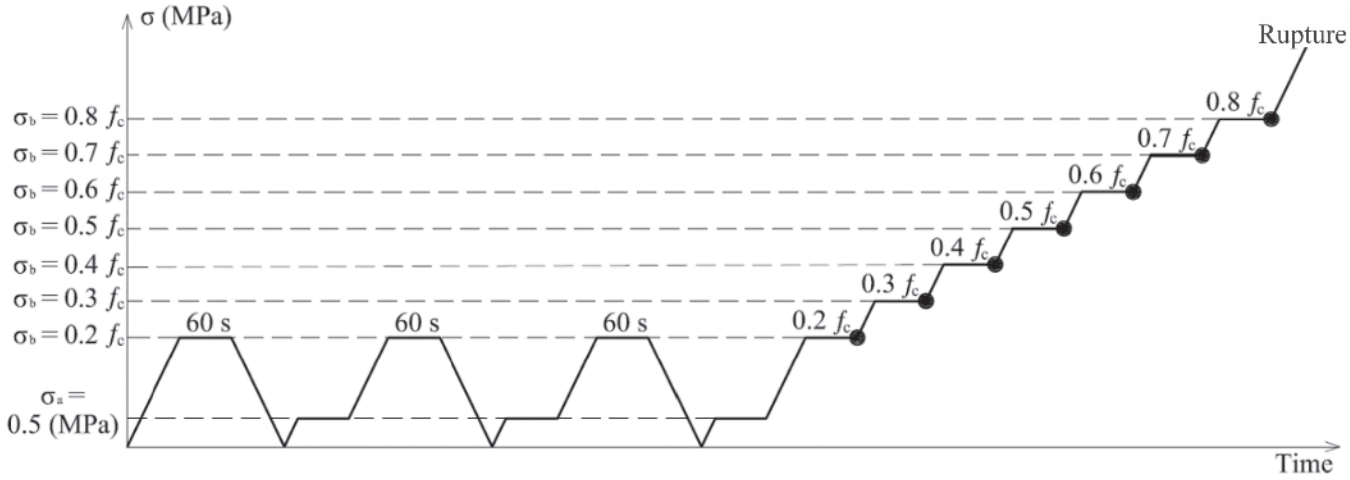

Figure 2
Location of sites for the construction of curves with no steady stress level

remains constant at each steady stress level applied (Figure 2). These values are used to construct the stress-strain curve.

Several aspects of the methodology described in the standard reviewed require improvement, since the stress-strain behavior of concrete is determined based on a limited number of readouts. Moreover, the methodology includes time-dependent phenomena like microcracking and flow during stabilization of loads in the analysis of the elastic behavior of the material. Another important aspect is that the axial stress value of 0.5 MPa is too low to guarantee the stabilization of loads in equipment designed to analyze high-resistance concretes. A discussion of these factors is given ahead.

2.1 Construction of the stress-strain curve

The curves shown in Figure 3 are constructed using the values of strain applied to three samples and the corresponding specific deformation measured automatically.

The steady stress levels on the curve are an inherent result of the experimental procedure described in NBR 8522 [9], which requires the stress and deformation readings to be made within 30 s after stress is applied for 60 s. Therefore, when instruments that allow obtaining data at short intervals between readings are used, the effect of microcracking or time-dependent deformations (flow or viscoelastic behavior) becomes evident.

If steady stress levels are not considered, the use of the criterion established in NBR 8522 (Figure 3) and of readings made applying the load for at least 60 s generates the kind of curve shown in Figure 4. Also, Figure 5 shows the curve obtained for the assay including the steady stress levels and the curve relative to the most representative sample after

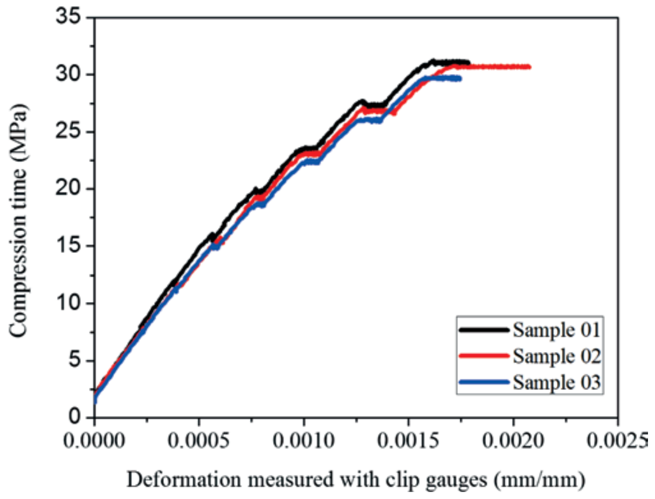

Figure 3
Strain-stress curve with steady stress levels defined in NBR 8522 (9)

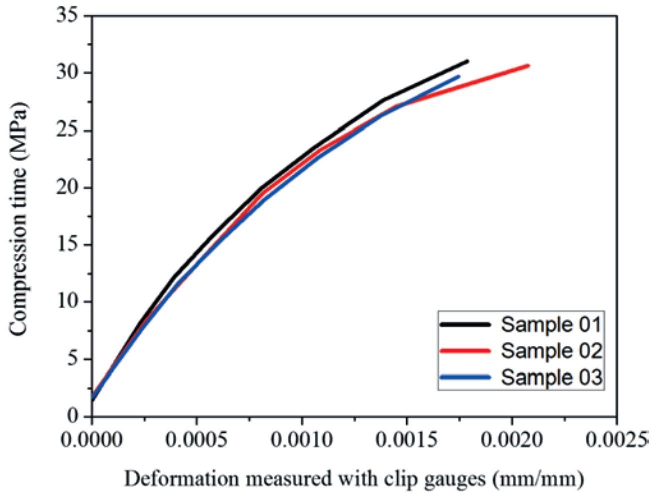

Figure 4
Strain-stress curve without steady stress levels defined in NBR 8522 (9)

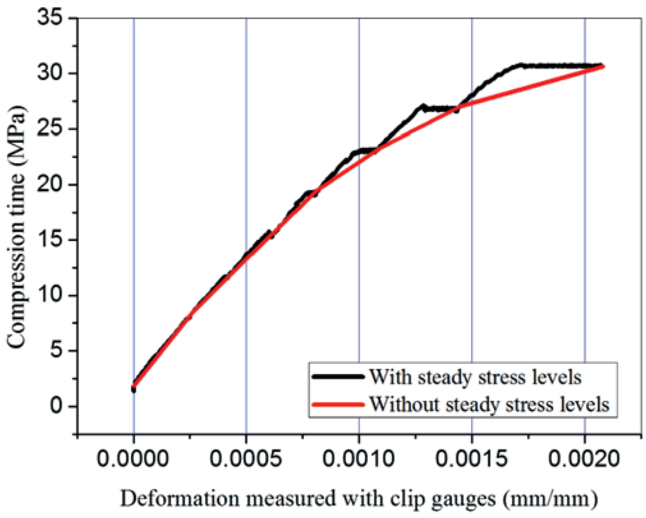

Figure 5

Stress-strain curve with steady stress levels and after they were excluded for a representative specimen of the differences in behavior of concretes

adjustment to remove the levels established in NBR 8522.

The procedures described in the standard [9] afford to determine the stress-strain curve even when the equipment used is analogic and manual, as in readings of displacement values based on one or more dial gauges (mechanical deflectors). In order to make reading times equivalent under different experimental conditions, the standard requires that a load is applied for 60 s, and this time may be extended for 30 s so that all analogical gauges may be read. This has two consequences. The first is that the stress-strain curve is constructed using a rather small number of test points. The second is that the analysis of the elastic behavior of the material tested includes time-dependent phenomena such as microcracking and flow, since each reading is made when constant loads are applied for as long as 90 s. These time-dependent phenomena become more evident as the compressive stress applied increases (as seen in Figure 2).

A different scenario is observed when automated machines and instruments are used to evaluate compressive strength of cement samples. Automated compression machines afford to set loading rates and obtain digital values of loads at short intervals. Similarly, automated instruments read digital displacement data simultaneously to the application of loads. Therefore, automated technologies do not require steady stress levels to be maintained for 60 s to 90 s at the few load levels established for the compressive strength assay, since the continuous acquisition of data affords to use loads as measurement levels, which improves the representativeness of the data obtained.

The exclusion of steady stress levels represents the stress-strain behavior of concrete more faithfully and with less variability in results. In this case, the construction of the curve that depicts the stress-strain behavior, and the initial tangent E_c may be defined based on a simple linear regression (by least squares) using all values recorded between the lowest stress value applied without adaptation of the sample on the plater (base stress) and highest stress value specified for the test.

2.2 *Starting stress used in the test*

The base stress defined in NBR 8522 is 0.5 MPa, which may lead to error in the calculation of the E_c in some situations.

Due to the high resistance of concrete formulations currently used, the compressive strength machines tend to have a high loading capacity, of approximately 200 tf or more. As a result, the base stress value at which the stress applied can be read precisely is high. For the same reason, today samples usually measure 10 cm x 20 cm, instead of 15 cm x 30 cm. Because of these two factors the starting stress of 0.5 MPa defined by the standard to calculate the initial tangent E_c may lie outside the precision range of the equipment.

In addition, the first section of the stress-strain curves obtained using data from automated equipment is always different from the other sections, due to sample adaptation and equipment limitations. Therefore, this section of the curve fails to represent the behavior of the material.

Based on the fact that the behavior of concrete in the beginning of the loading process is elastic and linear, the starting stress applied may be set over 0.5 MPa with no effect on the calculation of the initial tangent E_c, ultimately reducing the error associated with equipment limitations.

2.3 *Humidity of samples*

Consensus has been reached in the scientific community as to the need for the curing of concrete to be carried out in a humid environment. The objective is to ensure the hydration of cement compounds and reduce the porosity of the hydrated cement paste [10]. For Neville [10], relative humidity should be kept at 80% at least so as to maintain the appropriate level of hydration of cements. If a concrete is not well cured, especially at young ages, hydration may be negatively affected, permanently changing the microstructure of this concrete [13]. According to Mehta and Monteiro [11], low humidity may induce microcracking due to shrinkage during the setting process, affecting performance of the material. Drying and the consequent autogenous shrinking, especially in concretes with low cement-aggregate ratio, negatively affect the material's properties. For these reasons, most technical standards stipulate that concrete samples should be cured in saturated environments and that compressive strength should be analyzed under the same conditions. The inherent humidity of concrete samples plays a considerable role in compressive strength. Compressive strength of concrete samples cured in laboratory is approximately 15% higher than the value recorded for saturated samples of identical composition submitted to the same setting process [2].

The effect of humidity on E_c, however, is surrounded by controversy. For Li [14], saturated concrete have higher static E_c values compared to a dry concrete of identical cement-aggregate ratio and setting process. Shoukry et al. [15] claim that E_c behaves identically to compressive strength, and that E_c is up to 20% higher in samples whose humidity is in equilibrium with the surrounding environment air, compared with saturated samples. In a review study, Liu et al. [16] point to the consensus that highly saturated concretes have lower strength values and increased E_c values. The authors described a rise of up to 30% in static E_c values of a dry concrete formulation, compared with saturated samples of identical composition.

Also, NBR 8522 [9] refers to NBR 5738 [17], which describes the casting and curing process of samples for the compressive strength test, which is carried out using saturated samples. Under this condition, compressive strength values are lower than those obtained for a dry concrete sample of identical formulation. This emulates the most critical scenario a concrete sample may be subjected to, which is an important variable in the design of structures considering the ultimate limit state. However, the critical environmental conditions concerning E_c are those when the parameter reaches its lowest value, that is, under dry conditions. This means that using dry samples would lead to more significant deformation values for a given stress level, which is critical in the design of reinforced concrete structures at ultimate limit state due to the fact that stress levels of steel and of concrete become similar. The same is valid in the analysis of structures considering serviceability limit states. Salvador [18] demonstrated that relative humidity influences deformation with time, when higher relative humidity levels reduce sag in flexing samples, while lower levels increase sag. Therefore, the critical condition for the calculation of E_c is the dry condition, not the saturated condition established in NBR 8522 [9].

Testing using dry samples is difficult, because curing should be carried out at saturation, and drying has to be conducted after this period. When curing time is 28 days or less, drying under room conditions in the laboratory is not appropriate, since it takes several days, which affects the degree of hydration of samples, while fast drying in an oven induces stress, changing the microstructure and strength of concrete. Yet, if samples are removed from the curing room a few days before tests so as to allow drying, curing will be affected, rendering impossible to compare resistance values obtained at different drying times. The mechanical properties of older concretes are not significantly affected by drying times, since such samples already present high level of humidity. Dry samples of older concretes could be used so as to better represent the most critical situation to determine E_c. As an alternative, a safety factor could be used to estimate E_c under a more critical environmental condition (the dry condition) based on the value obtained in laboratory using saturated samples. This could be critical in concretes prepared with RCA, due to the high porosity as compared with formulations prepared with natural aggregates and, consequently, the higher amount of free water inside the sample.

E_c values for concretes prepared with RCA are low, compared with those of concretes with 100% natural aggregates, as observed by Xiao, Li, and Zhang [19], Katz [14], and Benetti [8]. For Leite [20], E_c of concrete depends on several factors, such as the type of aggregate used, whose deformation modulus is associated mainly with porosity of the material, which controls the restriction capacity of the concrete formulation. According to Xiao, Li, and Poon [21], E_c values of concretes prepared with RCA is always lower than that of conventional concretes due to the large amount of mortar bound to the natural aggregate, which almost always has lower E_c values. Domingo et al. [22] and Brito and Alves [23] observed that E_c values tend to decrease with increasing amounts of RCA in formulations, which lowers hardness. Topçu and Gunçan [24] observed E_c values for concretes prepared with RCA roughly 80% lower than those reported for mixtures prepared with natural aggregates. Xiao, Li, and Zhang [19] found that this reduction was of 45% in concrete prepared with 100% RCA. In other words, E_c values vary considerably when natural aggregates are replaced by RCA, since the parameter depends on the kind of aggregate used, age, resistance, amount of mortar adhered to the aggregate, among other factors. It should also be noted that estimating E_c of concretes prepared with RCA is comparatively more difficult when using the formulas that standards indicate for concretes with natural aggregates.

3. Materials and experimental program

An experimental protocol including the changes proposed was tested using concretes prepared with conventional aggregates and with the replacement of 50% of the amount of natural aggregates by RCA.

The cement used was CPV-ARI RS. The natural coarse aggregate used was the fraction of basalt rock retained in the 4.8-mm mesh and passing the 19-mm mesh with unit weight of 1.51 g/cm³ and specific weight of 2.73 g/cm³. The natural fine aggregate used was the fraction of quartz retained in the 0.075-mm mesh and passing the 4.8-mm mesh (within the optimal use range), unit weight of 1.47 g/cm³, and specific weight of 2.57 g/cm³. The RCA used was concrete beam waste obtained from a precut concrete beam manufacturer (original concrete mixture with *f*cj of 35 MPa, submitted to high-temperature curing) retained in the 4.8-mm mesh and passing the 19-mm mesh with unit weight of 1.13 g/cm³ and specific weight of 2.21 g/cm³.

The mix proportions used for all formulations were 1:1.641:2.25 (water-cement ratio: 0.45), 1:2.228:2.75 (water-cement ratio: 0.55), and 1:2.815:3.25 (water-cement ratio: 0.65), calculated using the IPT/EPUSP method described by Helene and Terzian [25]. Slump was set at 100 ± 20 mm, and water amount was 9.2%. Formulations were prepared and samples were cast in the Construction Materials Laboratory, UNISINOS, Brazil. All samples were submitted to submerged curing for 28 days. Six 70-kg batches were prepared to produce 18 samples for each water-cement ratio (0.45, 0.55, and 0.65), six of which were cured at three times (7, 28, and 63 days). Of these, two were employed in the compressive strength test, three were used in the E_c assay, and one was spared. After seven days, E_c values of concretes with RCA varied considerably, since the chemical reactions involved and the hydration conditions adopted had not reached stability. For this reason, E_c should not be determined at this age.

After the calculation of compressive strength as means of values obtained for three samples, E_c was determined according to the steps 1, 2, and 3 of section 6.2.2.1 of NBR 8522 [9]. Measurements were conducted at 20%, 30%, 40%, 50%, 60%, 70%, and 80% of fracture strength to determine the stress-strain behavior and 60-s intervals. Loads were measured in a 2,000-kN class I concrete compressive strength testing machine (Controls). Strain was measured using 100-mm-long clip gauge sensors (ER-25, MSI). Data acquired during the static E_c assay were processed using a data logger (ALMEMO 2490, Ahlborn) and recorded in a notebook, as well as applied loads, at every 3 s. Specific deformation was obtained dividing displacement values obtained with the data logger by the length of the base of clip gauges (100 mm). The corresponding compressive strength values applied were obtained dividing the loads applied by the sample cross section area.

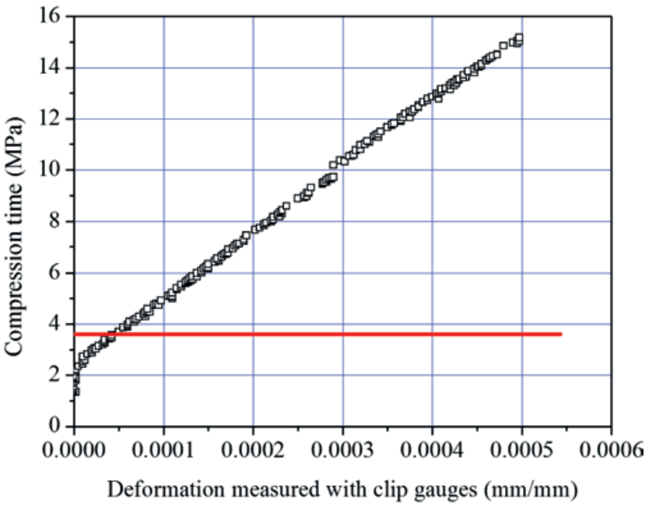

Figure 6
Stress-strain curve for concrete prepared without RCA and rupture on day 28 of curing and water-to-agglomerate ratio of 0.65

3.1 Calculation of the initial tangent E_c

NBR 8522 [9] stipulates that the initial tangent E_c is calculated using the formula:

$$E_{ci} = \frac{\sigma_b - 0{,}5}{\varepsilon_b - \varepsilon_a} \tag{1}$$

Where,
σ_b is the highest stress (MPa, σb = 0.3 *f*c)
0.5 is starting stress (MPa)
ε_b is the mean specific deformation of samples under the highest stress
ε_a is the mean specific deformation of samples under the starting stress (0.5 MPa)

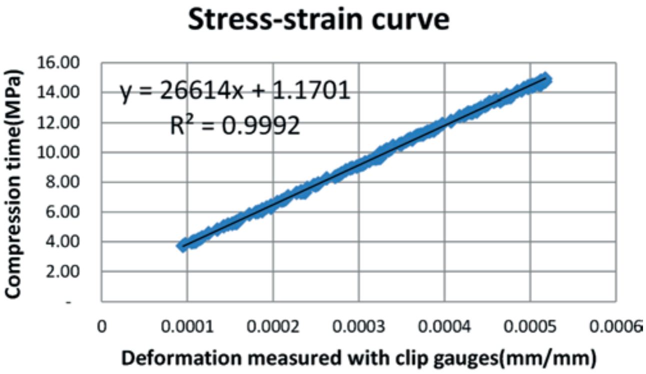

Figure 7
Stress-strain curve obtained by regression for a concrete specimen with RCA and water-to-aggregate ratio of 0.45 on day 28 of the curing process

The standard defines a starting stress value of 0.5 MPa. Samples are then submitted to increasing stress values up to 0.3 *f*c, and E_c is calculated. Also, σa and σb, which correspond to 0.3 *f*c, are obtained using the stress-strain curve constructed according to NBR 8522 [9], meaning that these values are obtained under constant stress for at least 60 s and 90 s maximum. However, it was not possible to stabilize stress to such a low value as 0.5 MPa for all samples, since the equipment's linearity threshold was below 20 kN, which corresponds to a stress of 2.55 MPa for samples measuring 10 cm x 20 cm. Besides the lower calibration threshold of the equipment, it is known that readouts do not entirely represent the behavior of the material, due to the adaptation of samples in the beginning of the assay, the poor accuracy in the first values of the stress range, and other factors. Each sample required a different value of stabilization stress, which reached 3.6 MPa in the most critical case.

The stress-strain curve shown in Figure 6 is typical of tests carried out using up to 0.3 *f*c. It becomes clear that the first points behave in such a way that is not typical of the material tested, since all samples – prepared with or without RCA – 28 and 63 days into curing. In fact, the curve obtained was influenced by the way the test is conducted and the equipment used, whose capacity is much higher than the loads applied. Therefore, E_c of all samples was obtained using a modified version of Equation 1:

$$E_{ci} = \frac{\sigma_b - 3{,}6MPa}{\varepsilon_b - \varepsilon_x} \tag{2}$$

Where
ε_x is deformation at 3.6 MPa.
If the material has linear elastic behavior throughout the stress values below 0.3 *f*c, the original and the modified equations will yield the same value of E_c.

3.2 Results and discussion

3.2.1 Elastic behavior and calculation of E_c by regression

The effect of steady stress levels was analyzed based on a simulation of stress-strain values, when the test was carried out with no steady stress levels and/or stop times to read deformation values. In this case, E_c was calculated using the slope of the regression curve using a least square regression. Figure 7 shows one example of the final result obtained.

The slope of the curve shows that E_c of the concrete samples analyzed is 26.61 MPa. Tables 1 and 2 show the differences between values obtained by linear regression and the method described in NBR 8522 [9], and list the coefficients of variation and relative differences.

The results obtained by linear regression indicate that when the test is carried out with no steady stress levels and the loading rate is controlled, the data obtained tend to scatter less. This means that E_c is not defined by two stress-strain pairs, but by all pairs obtained in the stress range used, which minimizes the effect of measurement variability compared with the pairs chosen, improving reliability. Importantly, while E_c values of samples prepared with natural aggregates varied less when the two methods are compared, confirming our previous statement, E_c values of samples prepared with RCA varied more between the two methodologies. This behavior is explained in light of the wide variability of concretes prepared with RCA. The high porosity of the mortar adhered to basalt rock in RCAs and of the transition zone between these two phases, besides the uneven distribution of RCA in the new concrete paste, increases the errors associated with a small number of stress-strain readings when the method described in NBR 8522 [9] is used, compared with the use of continuous measurements.

3.2.2 Stress-strain curve

Figure 8 compares the methods used to construct stress-strain curves, and represents all results obtained in the experimental protocol. The red curve was obtained using the procedure described in NBR 8522 [9], where representative values are only the stress-strain pairs obtained when load is kept constant for between 60 s and 90 s. The black curve was constructed using the data acquired by the automated system, simulating data obtained with constant loading rate and no steady stress levels.

The results show that the stress-strain curves obtained using the two methods differ considerably when 50% of the rupture stress is reached. The region up to 0.7 *fc* is normally used in the design

Table 1

Comparison of MMW obtained using NBR 8522 (9) and regression (concretes without RCA)

		Specimen 1	Specimen 2	Specimen 3	Mean	CV	Relative difference
w:aggl 0.45	MEE (GPa)	37.49	25.26	28.58	26.92	23.50%	3.54%
28 days	MEE (GPa) Regression	39.09	26.53	29.23	27.88	23.70%	3.54%
Without RCA	Relative difference	4.30%	5.00%	2.20%	–	–	–
w:aggl 0.55	MEE (GPa)	29.21	22.97	22.94	22.96	15.70%	6.83%
28 days	MEE (GPa) Regression	27.53	24.68	24.36	24.52	7.10%	6.83%
Without RCA	Relative difference	-5.70%	7.50%	6.20%	–	–	–
w:aggl 0.65	MEE (GPa)	18.16	21.03	20.38	19.86	7.60%	5.88%
28 days	MEE (GPa) Regression	19.17	22.14	21.77	21.03	7.70%	5.88%
Without RCA	Relative difference	5.60%	5.30%	6.80%	–	–	–
w:aggl 0.45	MEE (GPa)	24.02	29.52	24.96	26.17	11.20%	3.67%
63 days	MEE (GPa) Regression	26.06	30.25	25.08	27.13	10.10%	3.67%
Without RCA	Relative difference	8.50%	2.50%	0.50%	–	–	–
w:aggl 0.55	MEE (GPa)	24.69	26.08	24.21	24.99	3.90%	5.43%
63 days	MEE (GPa) Regression	25.04	27.47	26.54	26.35	4.60%	5.43%
Without RCA	Relative difference	1.40%	5.30%	9.60%	–	–	–
w:aggl 0.65	MEE (GPa)	22.11	23.71	23.9	23.24	4.20%	7.94%
63 days	MEE (GPa) Regression	23.217	25.15	24.85	25.08	0.80%	7.94%
Without RCA	Relative difference	5.00%	6.10%	4.00%	–	–	–

CV = Coefficient of variation. Relative difference is between mean MEE and MEE obtained by regression.

of reinforced concrete parts, which underlines the importance of predicting deformation values for these load levels. As expected, the curves obtained using NBR 8522 [9] have a smaller slope (that is, they have higher deformation values when a given load is used with the other protocol) and are highly dependent on the time stress values are maintained at one given level (between 60 s and 90 s). The curves constructed using values obtained at 60 s tend to have a smaller slope than those obtained when readings are carried out at the end of a 90-s period due to microcracking and time-dependent deformation, which are made worse when loads are kept at constant levels.

It may be concluded that compressive strength assays conducted according to NBR 8522 produce deformation values that are higher than the real measurements when the test equipment used allows applying loads at a constant rate and obtaining loads and respective deformation values using several readouts by automated gauges. This difference becomes more significant when high loads are applied to concrete mixtures prepared with RCA.

The curves shown in Figures 9 and 10 were selected randomly to illustrate that the data acquisition procedure using the automated system produces curves with smaller slopes, compared with those obtained using NBR 8522 [9]. The explanation is that applying loads at constant rates with no steady stress levels minimizes microcracking and flow (this was observed for all concretes, either with or without RCA).

Table 2

Comparison of MMW obtained using NBR 8522 (9) and regression (concretes with RCA)

		Specimen 1	Specimen 2	Specimen 3	Mean	CV	Relative difference
w:aggl 0.45	MEE (GPa)	25.63	20.77	24.74	23.71	10.90%	6.95%
28 days	MEE (GPa) Regression	26.22	23.24	26.61	25.36	7.30%	6.95%
Without RCA	Relative difference	2.30%	11.90%	7.60%	–	–	–
w:aggl 0.55	MEE (GPa)	20.2	27.62	20	20.1	21.60%	-0.16%
28 days	MEE (GPa) Regression	20.16	25.09	19.98	20.07	14.40%	-0.16%
Without RCA	Relative difference	-0.20%	-9.20%	-0.10%	–	–	–
w:aggl 0.65	MEE (GPa)	21.67	23.67	20.83	22.06	6.60%	4.96%
28 days	MEE (GPa) Regression	23.08	24.76	21.63	23.15	6.80%	4.96%
Without RCA	Relative difference	6.50%	4.60%	3.80%	–	–	–
w:aggl 0.45	MEE (GPa)	22.41	19.5	21.11	21.01	6.90%	10.63%
63 days	MEE (GPa) Regression	24.31	20.03	22.79	23.24	14.90%	10.63%
Without RCA	Relative difference	8.50%	2.70%	7.90%	–	–	–
w:aggl 0.55	MEE (GPa)	24.71	28.36	22.02	25.03	12.70%	1.79%
63 days	MEE (GPa) Regression	24.27	28.271	2.56	25.48	9.50%	1.79%
Without RCA	Relative difference	-1.80%	-0.30%	2.50%	–	–	–
w:aggl 0.65	MEE (GPa)	26.39	22.47	23.8	24.22	8.20%	2.93%
63 days	MEE (GPa) Regression	26.71	23.59	24.48	24.93	6.50%	2.93%
Without RCA	Relative difference	1.20%	5.00%	2.90%	–	–	–

CV = Coefficient of variation. Relative difference is between mean MEE and MEE obtained by regression.

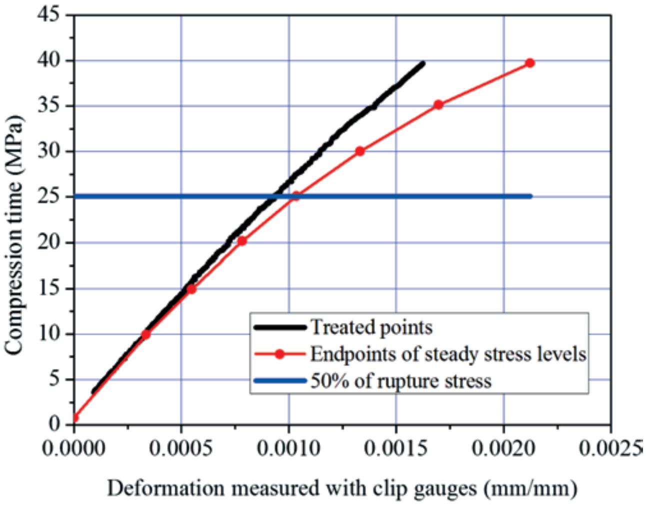

Figure 8
Comparison of stress-strain curves constructed with treated data and the endpoints of each steady stress level for a specimen with water-to-aggregate ratio of 0.45 prepared with RCA on day 28 of the curing process

4. Conclusions

The present study show that the procedure to determine static E_c described in NBR 8522 [9] was developed considering the manual reading of load and displacement in non-automated test equipment. When equipment that allows applying constant load rates and obtain data instantly is used, the drawbacks of the method become more apparent, causing microcracking and time-dependent deformations during the loading stabilization stage. In addition, when loads exceed 50% of the ultimate strength, the shape of the stress-strain curve is markedly changed. Also, the use of an automated readout system produces curves with smaller slopes, compared with the procedure described in NBR 8522 [9]. Therefore, the findings of the present study support the use of automated equipment and constant load rates (loading or deformation) throughout the assay, without steady stress levels. Similarly, E_c and the stress-strain curve should be determined using the values obtained by lest square regression. The curves obtained in the present study show that concrete mixtures prepared with RCA behave similarly to formulations made without this material, though they have a smaller slope, since they undergo higher deformation values under a given stress. Concretes prepared with RCA have higher coefficient of variation of results obtained using the methodology described in NBR 8522 [9] and the new methodology proposed in the present study.

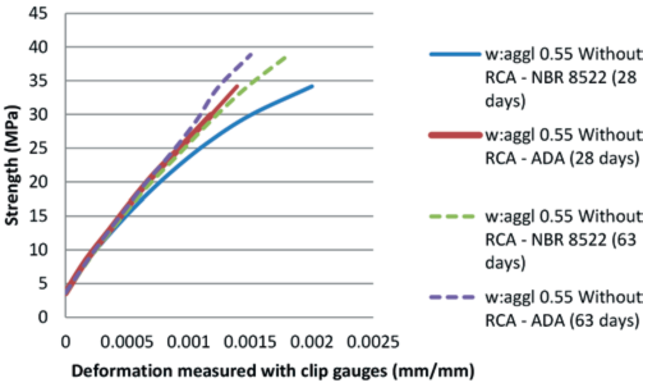

Figure 9
Mean stress-strain curves of concretes of identical water-to-agglomerate ratio (on days 28 and 63 of the curing process) constructed using data obtained according to NBR 8522 and automated data collection (ADA: automated data acquisition, w:aggl = water-to-agglomerate ratio)

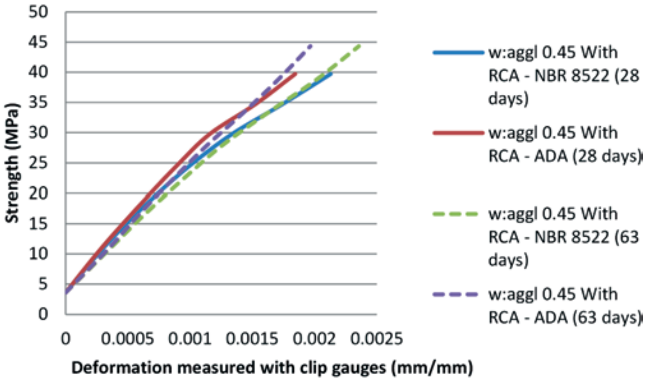

Figure 10
Mean stress-strain curves of concretes of identical water-to-agglomerate ratio prepared with RCA (on days 28 and 63 of the curing process) constructed using data obtained according to NBR 8522 and automated data collection (ADA: automated data acquisition, w:aggl = water-to-agglomerate ratio)

In concrete compressive strength testing machines that afford high loads, the stabilization of the stress applied down to levels as low as 0.5 MPa may lead to inaccurate results. Therefore, a higher stabilization load should be considered. Also, since this section of the curve is linear, changing this value would not be difficult in laboratory.

The construction of the stress-strain curve of concrete using automated data collection and increasing load rates with no steady stress levels has smaller slope (smaller deformation for a given stress level), compared with the curves constructed based on NBR 8522 [9].

5 Acknowledgements

If the authors are grateful to CAPES, FINEP, PreConcretos, and Votorantim for the support given to this work.

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