Influence of the moisture content on the dynamic modulus of elasticity of concrete made with recycled aggregate

Influência do teor de umidade no módulo de elasticidade dinâmico de concreto produzido com agregado reciclado

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Abstract

The elastic behavior of the concrete is estimated from its strength or determined by static or dynamic tests. However, because the codes of practice do not standardize the internal moisture content of the concrete and disregard the use of recycled aggregates when proposing equations for the estimation of the modulus of elasticity, discrepancies between the values measured and estimated are frequent. The influence of the moisture content of concrete containing basaltic coarse aggregates and coarse recycled concrete aggregate in the dynamic modulus of elasticity is discussed in this paper. A basalt coarse aggregate and two recycled coarse aggregates where used. For each type of coarse aggregate, concrete with compression strength between 25 MPa and 55 MPa were produced. The dynamic modulus of elasticity of the saturated samples were determined and range from 26 GPa to 46 GPa. There is a significant difference in the value of the dynamic modulus of elasticity for dry concrete versus saturated concrete, also influenced by the type of aggregate. Estimations of the modulus of elasticity from the compressive strength equations proposed by the codes of practice must be improved considering its characteristics.

Keywords: Dynamic modulus of elasticity. Concrete moisture content. Concrete with recycled concrete aggregate.

Resumo

O comportamento elástico do concreto é estimado a partir de sua resistência a compressão ou determinado por ensaios estáticos ou dinâmicos. Como a maioria das normas não consideram o teor de umidade interna do concreto e desconsideram o uso de agregados reciclados ao propor equações para a estimativa do módulo de elasticidade, é frequente se observar divergências entre os valores determinados. Nesse trabalho, a influência da umidade do exemplar e do uso de agregados reciclados no módulo de elasticidade dinâmico são avaliadas. Foram utilizados um agregado basaltico e dois agregados provenientes da cominuição de concreto, sendo produzidos concretos com resistência entre 25 MPa e 55 MPa. Os módulos de elasticidade dinâmicos dos exemplares foram determinados nos estados saturado e seco, variando entre 26 GPa e 46 GPa. Conclui-se que há sensíveis diferenças de módulo de elasticidade dinâmico entre o concreto seco e saturado e em função do tipo de agregado utilizado, sendo imprescindível que esses fatores sejam considerados nas equações propostas pelas normas para a estimativa do módulo de elasticidade.

Palavras-chave: Módulo de elasticidade dinâmico. Umidade interna do concreto. Concreto com agregado reciclado graúdo de concreto.

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Introduction

The elastic modulus of concrete is a fundamental parameter in the design of a reinforced concrete structure. The dynamic moduli can be performed subjecting the concrete to a longitudinal vibration and obtaining their pulse velocity through the concrete, in a non-destructive testing. The use of the dynamic modulus has the advantages of being simple and fast to measure and obtained by a non-destructive test that allows repetitive testing in the same sample (COSSOLINO; PEREIRA, 2010).

Many factors influence the modulus of elasticity of concrete, as the aggregates properties (type, shape, content, its own modulus, surface characteristics), the cement paste (strength, content, age) and the transition zone (porosity, composition, age, strength); the test procedure (specimen characteristics, moisture content, device used) and the structure construction behavior (BATTAGIN, 2008).

The procedure for determining the dynamic modulus of elasticity using ultrasound devices is specified in codes of practice, as BS 1881, part 203 (BRITISH…, 1986), C 597-16 (AMERICAN…, 2016) and NBR 8802 (ABNT, 2013), and consists in obtaining the ultrasound pulse velocity through the concrete, and estimating the dynamic modulus of elasticity using a formula where the variables are the pulse velocity, the specific gravity and the Poisson ratio of the concrete. However, the codes of practice don't standardize features of the concrete that impact on the result but must be considered, as the use of recycled aggregates and the concrete moisture content (MALHOTRA; CARINO, 1991).

Therefore, it is common to find works where the modulus of elasticity determined in concrete with recycled aggregates by means of dynamic tests presents contradictory results.

Nowadays, the use of recycled aggregates as an alternative to natural aggregates in concrete is a subject of great interest. However, the new concrete is impacted by the characteristics of the recycled aggregates, particularly the coarse aggregates, which has a strong influence on the modulus (SHEHATA, 2005). The modulus of elasticity of a concrete prepared with recycled concrete aggregate usually is lower than those of conventional concrete. According to the studies of Hansen (1986), Rahal (2007), Cabral *et al*. (2010) and Ghorbel and Wardeh (2017), the reduction varies between 5 to 35%, when a total replacement on natural coarse aggregate by recycled concrete aggregate is done. The decrease occurs mainly due to the mortar from the original concrete remaining attached to the stone particles in the coarse recycled aggregate (HANSEN, 1986) and the properties of its interfacial transition zone (the concrete prepared with coarse recycled aggregate has two different transition zones: an old ITZ between the original aggregate and the old matrix paste and a new ITZ between the old mortar and the new matrix (XIAO *et al*., 2013)).

Many codes of practice propose equations to estimate the static modulus of elasticity from algebraic equations that associate the moduli with the compression strength. In a few, such as NBR 6118 (ABNT, 2014), in Brazil, and others such as ACI 209.2R-08 (AMERICAN…, 2008), MC90-99 (COMITÉ…, 1999) and Eurocode 2 (EUROPEAN…, 2004), the characteristics of the raw aggregate are also considered. However, they recommend the use of prediction models for only concretes made with natural aggregates. Some standards, as the MC90-99 (COMITÉ…, 1999) also specify procedures for determining the dynamic elasticity module and specify that it can be 20% higher than the static module. Different equations have been proposed to describe the relationship between the static modulus of elasticity of the concretes prepared with recycled aggregate and their corresponding compressive strength (FONTEBOA *et al*., 2011; ANDREU; MIREN, 2014; CHOUBEY; KUMAR; RAO, 2016; MEDJIGBODO *et al*., 2018). However, there is a great diversity in the results and discrepancies are frequent, and this behavior should be similar in the dynamic modulus. Some authors, as Malhotra and Carino (1991), affirm that the estimation of the dynamic modulus of elasticity from ultrasonic pulse velocity measurements is not valid for inhomogeneous composite materials.

The mechanical properties of concrete are affected by the moisture content of their pores. The strength of concrete decreases with saturation, but the static modulus of elasticity increases (MEHTA; MONTEIRO, 1993). The same happens in non-destructive tests determining the dynamic modulus of elasticity, because the water increases the sound wave speed, impacting on the dynamic modulus of elasticity (QIXIAN; BUNGEY, 1996; LIU *et al.*, 2014). The pulse velocity for saturated concrete is 4 to 5% higher than for air-dry concrete with high w/c ratio (MALHOTRA; CARINO, 1991; AMERICAN…, 2016).

According to Payan, Garnier and Moysan (2010), there are many quantitative and qualitative publications regarding the mechanical properties of saturated concrete, but only a few quantitative analyses of unsaturated concrete. Aguilar *et al.* (2006) found that the modulus of elasticity can be

15% higher in saturated concrete compared to dry concrete. Payan, Garnier and Moysan (2010) and Popovics (2005) indicate that the difference in the elastic moduli due to the moisture content of the pores is between 15% and 20%, depending on the moisture content and on the characteristics of concretes.

According to C597 (AMERICAN…, 2016) the moisture generally has higher influence on the velocity in low-strength concrete than on high-strength concrete because of the difference in the porosity. As a consequence, in concrete with recycled concrete aggregate, the influence of the moisture content may have a higher impact than in concrete prepared with natural aggregates, because concrete with recycled concrete aggregate have a higher volume of pores.

Then, the correlation between the various methods of determination or estimation of the elastic module is hampered because important aspects such as the previous knowledge of the concrete moisture content are not specified in the codes of practice. Because many factors influence the modulus of elasticity of concrete and the research studies are usually performed for a specific type of concrete, it is not possible to establish a single prediction model to be used with all types of concrete (GRAFT-JOHNSON; BAWA, 1969; VOGT, 2006, CORINALDESI, 2010).

This paper analyses the influence of two characteristics that influence the modulus of elasticity of concrete: the use of coarse recycled aggregate and the moisture content of the specimen in the estimation of the dynamic modulus of elasticity of concrete.

Materials and methods

Cement CPV-ARI, a Brazilian equivalent to American Type III Portland Cement, and quartz natural river fine aggregate with a fineness modulus of 2.73 were used in the admixtures in this study. Fly ash was added in a proportion of 15% in all admixtures. Three coarse aggregates were used, a basalt coarse aggregate (REF) and two recycled coarse aggregates made from the reuse of concrete rejected in a precast plant (RCO – from the crushing of ordinary concretes with fc = 40.0 MPa, and RCT - from the crushing of concretes that had thermal cure, with fc = 45.7 MPa). The precast concrete was produced with the same basalt coarse aggregate of the reference concrete, but their mix proportion is unknown. The pieces of concrete were transported to the laboratory and then crushed in a jaw crusher and graded between #19 mm and #4.75 mm. The main coarse aggregates characteristics are presented in Table 1.

For each type of coarse aggregate, concrete with water/binder ratios of 0.42, 0.50 and 0.58 were produced, resulting in concrete specimens with compression strength between 25 and 55 MPa. The mix proportions are listed in Table 2. To achieve good workability the recycled aggregates had an internal amount of water corresponding to 80% of their porosity, cited on Table 2 as “supplementary water”, and superplasticizer. Cylinders ø100 mm × 200 mm were molded and cured in a saturated chamber under a temperature of (22 ± 2) °C.

After 63 days of curing, the strength to axial compression and the dynamic modulus of elasticity of the saturated samples was determined. Next, the wet samples used to determine the dynamic moduli were conditioned in a ventilated oven at 60 °C until achieving mass equilibrium (at least one month) and the dynamic moduli of the dry specimens were determined.

The ultrasound pulse velocities of the samples were obtained according to C 597 (AMERICAN…, 2016) using an ultrasonic device Pundit Lab+ Proceq with 54 kHz transductors. The dynamic modulus of elasticity was calculated in accordance with BS 1881: Part 203 (1986), using Equation 1.

$$Ed = \rho V^2 \times ((1+\mu) \times (1-2\mu)) /(1-\mu) \qquad \text{Eq. 1}$$

Where:

Ed = dynamic modulus of elasticity (MN/m²);

ρ = specific gravity (kg/m³);

V = ultrasound pulse velocity (km/s); and

μ = Poisson ratio. A Poisson ratio of 0.2 was used in the study. This value is specified by NBR 6118 (ABNT, 2014) and has been used by many authors, as Ajdukiewiewicz and Kliszczewicz (2002) and Lee and Park (2008).

Table 1 – **Coarse aggregates characteristics**

Aggregate	Origin of the aggregate	NBR NM 53:02 (ABNT, 2009) absorption (%)	NBR NM 53:02 (ABNT, 2009) specific gravity (g/cm³)	NBR NM 45:02 (ABNT, 2006) bulk density (g/cm³)
REF	Basalt	3.46	2.55	1.57
RCO	Precast concrete, 40 MPa	10.47	2.33	1.07
RCT	Precast concrete, thermal cure, 45.7 MPa	10.93	2.37	1.16

Table 2 – **Concrete mixtures**

Type of aggregate	Mix proportion (cement:fine aggregate:coarse aggregate)	w/b (total)	Proportion							
			Cement	Fly ash	Fine aggregate	Coarse aggregate*		Water	s.w.**	Super plasticizer (%)
						Basalt	Recycled aggregate			
REF	1:2.78:3.10	0.58	1	0.15	2.780	3.100	0	0.58	0	0.46
RCO	1:2.78:3.10	0.61	1	0.15	2.780	1.550	1.416	0.58	0.03	0.42
RCT	1:2.78:3.10	0.62	1	0.15	2.780	1.550	1.441	0.58	0.04	0.27
REF	1:2.23:2.65	0.50	1	0.15	2.230	2.650	0	0.50	0	0.46
RCO	1:2.23:2.65	0.52	1	0.15	2.230	1.330	1.215	0.50	0.02	0.44
RCT	1:2.23:2.65	0.53	1	0.15	2.230	1.330	1.236	0.50	0.03	0.25
REF	1:1.68:2.20	0.42	1	0.15	1.680	2.200	0	0.42	0	0.35
RCO	1:1.68:2.20	0.44	1	0.15	1.680	1.100	1.005	0.42	0.02	0.55
RCT	1:1.68:2.20	0.45	1	0.15	1.680	1.100	1.022	0.42	0.03	0.53

Note: *the aggregate replacements were done keeping the same volume occupied by basalt; and
** supplementary water added to the recycled aggregate.

A descriptive statistical analysis was performed. Student's t-test, ANOVA and Tukey tests were applied to check the difference between the averages in relation to the modulus of elasticity and the concrete axial compressive strength. Correlation and regression between the compressive strength and the dynamic modulus of elasticity were also determined.

Results and discussion

Compressive strength and dynamic modulus of elasticity of all concretes are presented at Table 3.

In this paper, the behavior of the dynamic modulus of elasticity is analyzed by the relationship between the compressive strength and the dynamic modulus of elasticity, and by the influence of moisture content on the modulus of elasticity.

Figure 1 shows the dynamic elastic modulus obtained with the concrete with natural aggregates (diamond markers, in gray) and recycled aggregates (round markers, in black) in saturated specimens, associated with their respective compressive strengths. Their dynamic moduli of elasticity obtained for saturated concrete samples is compared to static modulus of elasticity predicted according to the equation proposed by NBR 6118 (ABNT, 2014) for natural aggregate and for sandstone aggregate. The comparison was carried out with saturated specimens because this is recommended by NBR 5739 (ABNT, 2018) for the determination of the compressive strength.

In concrete samples made with natural aggregate, the dynamic modulus of elasticity tends to increase with the increase in the compressive strength (following the behavior of the static moduli predicted using the NBR 6118 (ABNT, 2014) equations - "static moduli for natural aggregate" on Figure 1).

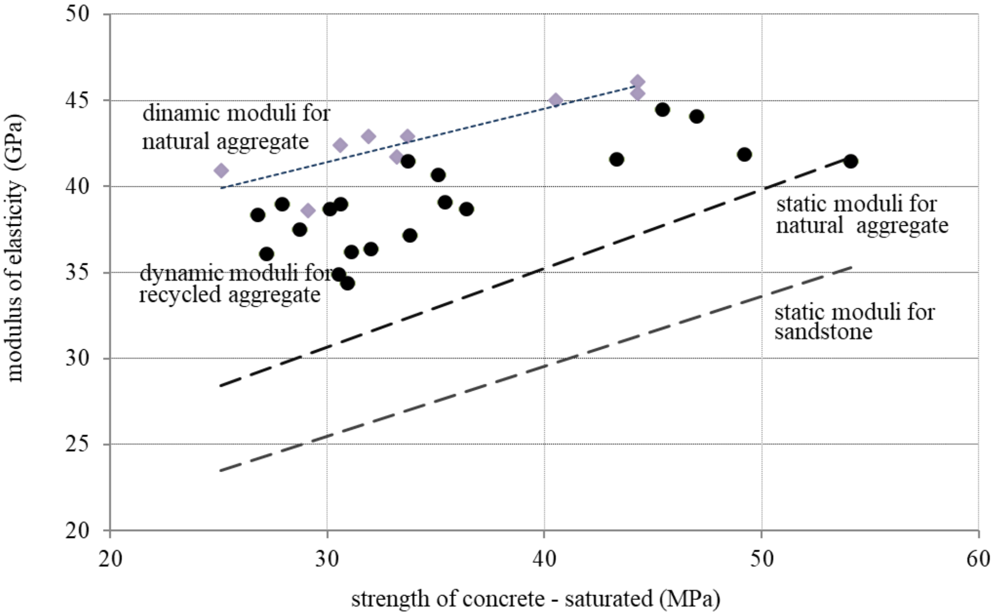
The standard specifies an equation for estimating the static modulus of concrete with natural basalt aggregate and uses a correction coefficient for concrete made with more porous aggregates. The dynamic moduli found in the research ("dynamic moduli for natural aggregate") are consistent with the specifications of NBR 6118 (ABNT, 2014) and MC90-99 (COMITÉ…, 1999).

NBR 6118 (ABNT, 2014) presents correction coefficients for estimating static moduli for porous aggregates, such as sandstone (shown on Figure 1). As the recycled aggregates have similar characteristics (greater porosity and lower elastic modulus), it is reasonable to assume that the static moduli of the concrete with the recycled aggregates would have the same behavior. However, samples produced with RCO and RCT do not exhibit the same behavior than the concrete with natural aggregates: for concrete with these recycled aggregates, the dynamic moduli is lower, but it is not possible to establish a model relating the compressive strength to the dynamic modulus of elasticity. Considering the same compressive strength, the dynamic modulus of elasticity of the saturated specimens are higher than those estimated by the standards and present a higher dispersion. According to the studies of Hansen (1986), Rahal (2007), Cabral *et al.* (2010) and Ghorbel and Wardeh (2017), the increase may range from 5 to 35%. The use of recycled aggregates (with high porosity and a double interfacial transition zone) justify the higher difference between the moduli.

Table 3 **- Concrete strength and dynamic modulus of elasticity**

Aggregate	Strength (MPa)	Dynamic modulus of elasticity (GPa)		
		Saturated	Dry	Difference between saturated and dry (%)
REF	25.1	40.9	33.4	18.51
	30.6	42.4	34.6	18.55
	31.9	42.9	35.1	18.09
	33.2	41.7	34.4	17.42
	33.7	42.9	36.3	15.58
	29.1	38.6	32.0	16.95
	40.5	45.0	37.4	16.89
	44.3	46.1	37.2	19.34
	44.3	45.4	37.1	18.27
RCO	30.9	34.4	27.4	20.38
	30.5	34.9	26.2	24.87
	47.0	44.1	36.5	17.32
	49.2	41.9	35.4	15.52
	45.4	44.5	36.3	18.46
	43.3	41.6	34.0	18.32
	54.1	41.5	33.7	18.93
RCT	28.7	37.5	27.9	25.68
	26.8	38.4	30.0	21.92
	27.9	39.0	30.5	21.85
	32.0	36.4	29.4	19.14
	36.4	38.7	32.9	15.03
	35.4	39.1	33.4	14.68
	33.8	37.2	31.7	14.85
	30.6	39.0	31.2	19.94
	33.7	41.5	29.6	28.53
	35.1	40.7	32.1	21.07
	27.2	36.1	32.0	11.56
	31.1	36.2	31.2	13.80
	30.1	38.7	32.7	15.53

Figure 1 **- Relationship between the static moduli determined using the prediction models of ABNT NBR 6118:2014 for natural and sandstone aggregates and the dynamic modulus of elasticity in saturated concrete samples**



The relationship between the compressive strength and the dynamic modulus of elasticity determined for each specimen tested, dry and saturated, are shown in Figure 2.

For each dynamic modulus of elasticity found in dry specimens (in the bottom group) it is possible to draw a vertical line and identify the dynamic modulus of elasticity in the same specimen, saturated (upper group).

As seen on Figure 2, there is a clear distinction between the dry and the saturated specimens, which have a dynamic modulus of elasticity up to 28,53% higher than those made in the respective dry concrete. The decrease in the ultrasound pulse velocity in dry specimens was expected because the ultrasound waves propagate faster in saturated materials. However, the difference was greater than indicated in the literature, which points to a difference between 15% and 20%, depending on the moisture content of the concrete samples (which varies from dry to saturated) and on the characteristics of concretes (POPOVICS, 2005; PAYAN; GARNIER; MOYSAN, 2010).

In Figure 3 the compressive strength of the concrete for each aggregate is related to their respective dynamic moduli of elasticity.

The difference in the dynamic moduli of elasticity using dry or saturated specimens in concrete with natural basalt aggregates is between 15% and 19%, similar to those specified in the literature. However, in concrete with recycled aggregates the difference between dry and saturated concrete increases, being between 11.56% and 28.53%. Also, in concrete with recycled aggregates, the distance between the modulus of elasticity at wet or saturated concrete is highly variable.

It is possible to verify, in Figures 4 and 5, that while the correlation coefficient between the dynamic moduli of wet and dry concrete with natural aggregate is 93%, in concretes with recycled aggregates the coefficient drops to 64%, which makes it evident that for concrete with recycled aggregates there isn't a significant relationship between the elastic modulus obtained in saturated and in dry concrete.

The most probable reason for the variation between the dynamic modulus in dry and saturated concrete is the increase on the porosity of the concrete with recycled aggregate, which is confirmed by C 597 (AMERICAN…, 2016), which states that the wave velocity increases according to the porosity of the concrete.

The differences due to the moisture content of the concrete are more significant than those due to the strength, which clearly divides the dynamic modulus of elasticity into two distinct groups (as shown in Figure 2). Estimating the dynamic modulus of elasticity through a direct correlation with the compressive strength without considering the moisture content results in substantial inaccuracies.

Figure 2 – **Dynamic modulus of elasticity of dry and saturated concrete**

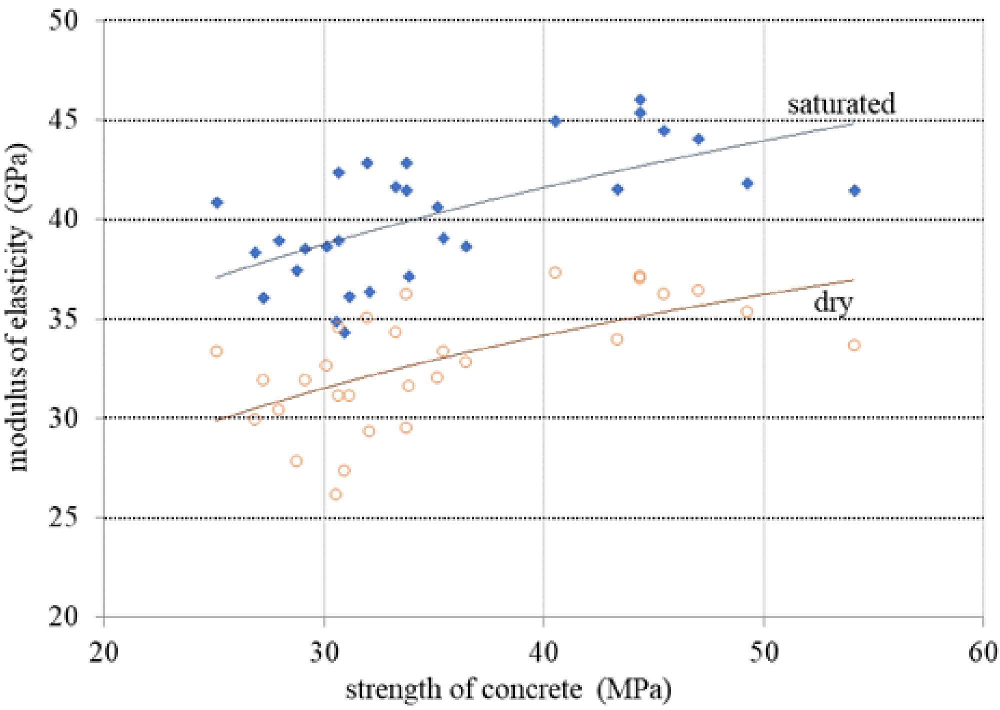


Figure 3 - **Dynamic modulus of elasticity versus the compressive strength of concrete for each kind of aggregate**

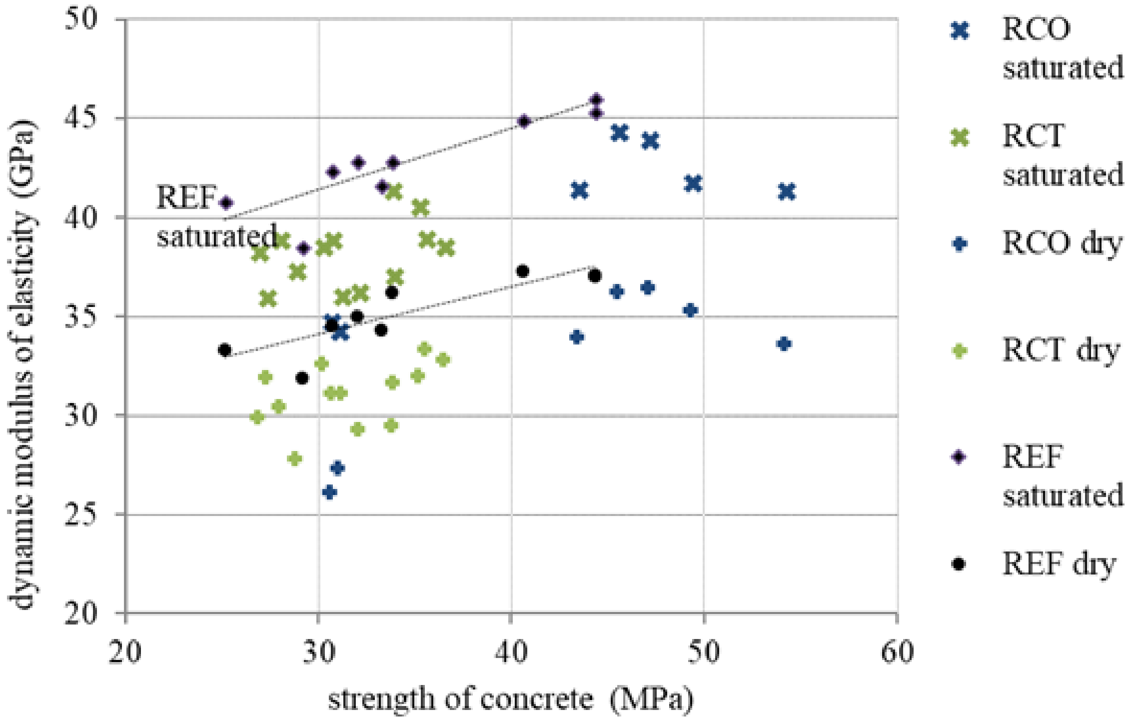


Figure 4 - **Wet and dry moduli - natural aggregate**

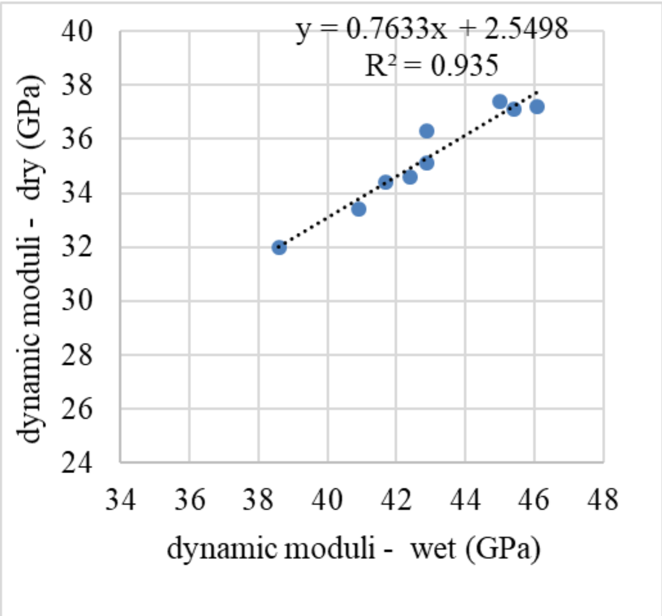


Figure 5 - **Wet and dry moduli - recycled aggregate**

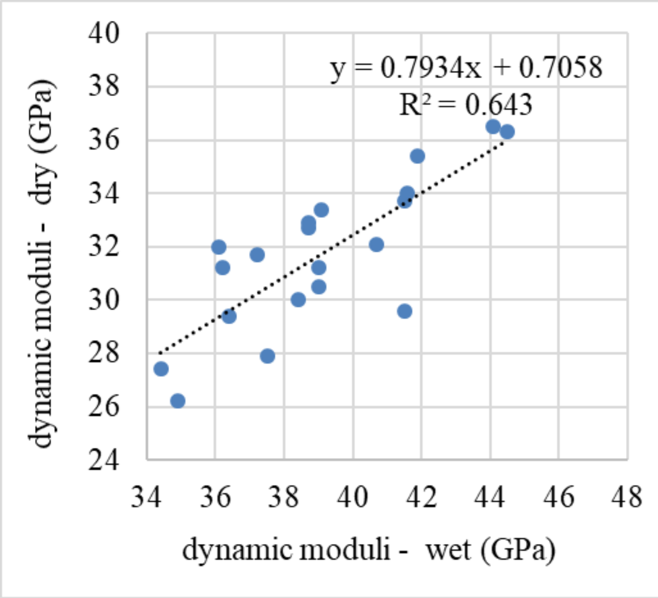


Table 4 - **Regression analysis between the compression strength and the dynamic modulus of elasticity**

Type of aggregate	Moisture condition		R^2	Regression	ANOVA	Gradient and level of significance
REF	dry	**	0.76	y=0.2425x+26.846	0.002	0.2425(p=0.002) 26.846(p=0.000)
	saturated	**	0.78	y=0.3126x+32.024	0.002	0.3126 (p=0.002) 32.024(p=0.000)
RCO	dry	*	0.74	y=0.4042x+15.41	0.013	0.4042(p=0.013) 15.41 (p=0.021)
	saturated	*	0.71	y=0.3863x+23.8	0.017	0.3863 (p=0.017) 23.8 (p=0.004)
RCT	dry		0.25	y=0.2445x+23.412	0.099	0.2445 (p=0.099) 23.412 (p=0.000)
	saturated		0.17	y=0.2084x+31.779	0.171	0.2084 (p=0.171) 31.779 (p=0.000)

Note: *level of significance p<0.05;
**high level of significance p<0.01; and
R^2=coefficient of determination.

There are also differences in the dynamic moduli of the elasticity of the concrete samples due to each type of aggregate used. Several studies demonstrated that the modulus of elasticity of concrete depends on the porosity of the aggregate (LEITE, 2001) because it determines the restriction on the deformation of the concrete matrix and, for the dynamic modulus of elasticity, interferes with the ultrasound pulse velocities. This high variation does not allow the use of one algebraic equation to estimate the modulus of elasticity from the resistance to compression. However, by classifying the concrete by the type of aggregate, it is possible to estimate an equation to predict the dynamic modulus of elasticity of concrete made of each type of aggregate, as presented in Table 4.

The highest coefficient of determination (R^2) obtained by regression analysis between the compression strength and the dynamic modulus of elasticity was found in concretes with natural basalt aggregate - REF (0.76 in dry and 0.78 in saturated concretes); in these concretes, almost 80% of the variability of the modulus of elasticity can be explained by the variability of the compressive strength.

In concrete with recycled aggregates, the coefficient of correlation achieved by regression analysis is variable. In concrete with RCO, which is a hi-quality recycled aggregate, although there is a decrease in the coefficient of correlation, there is still a good relationship between the modulus of elasticity and the compressive strength, as concluded by Estolano *et a*l. (2018). In concrete with RCT, however, it is not possible to determine a significant relationship between the modulus of elasticity and the compressive strength.

Conclusions

(a) there is a significant difference in the value of the dynamic modulus of elasticity for dry concrete versus saturated concrete, regardless of the type of aggregate used. This difference was observed in all groups of concrete analyzed and often surpassed the influence of the other variables. The greatest difference between dry versus saturated concrete was approximately of 19%, which demonstrates that this parameter must be considered when determining the dynamic modulus of elasticity of concretes;

(b) the type of aggregate used in the concrete significantly influences the dynamic modulus of elasticity of the concrete. The correlation between the dynamic modulus of elasticity and the compressive strength of concrete can only be established for each specific type of concrete (considering individually the type of aggregate), and the use of all types of concrete simultaneously results in an inadequate coefficient of correlation; and

(c) ordinary estimations of the modulus of elasticity from the compressive strength equations should not be adopted in concrete prepared with a recycled concrete aggregate.

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