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Influence of coarse aggregate on concrete's elasticity modulus

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ABSTRACT. The modulus of elasticity of concrete is an important property because it is crucial for the control of deformation. The impossibility of obtaining concrete with higher elasticity modulus rates may cause economic liabilities due to the need for larger structural elements. Current paper evaluates three compressive strength classes (20, 30 and 40MPa) of concrete produced with two types of coarse aggregate, basalt and dolomite rock from the Triângulo Mineiro region, Brazil. Further, 459 cylindrical test specimens were cast for the experimental study. The experimental results of the elasticity modulus rates were compared and with formulations prescribed by four standards: ABNT NBR 6118, ACI 318, Eurocode 2 and FIB Model Code. Comparisons demonstrated that the effect of coarse aggregate on the elasticity modulus was negligible when compared to the concrete's resistance class.

Keywords: deformation, properties, standards, experimental results.

Influência do agregado graúdo no módulo de elasticidade do concreto

RESUMO. O módulo de elasticidade do concreto é uma propriedade importante para os profissionais envolvidos na indústria da construção civil, uma vez que seu valor é determinante para o controle das deformações. A impossibilidade de se obter concretos de maior valor de módulo de elasticidade pode resultar em perda econômica pela necessidade de elementos estruturais de maior dimensão. Este trabalho avaliou o módulo de elasticidade de três classes distintas de concreto (C20, C30 e C40) produzidas com dois tipos morfológicos de rochas, basalto e dolomito, da região do Triângulo Mineiro. Como parte do estudo experimental, foram moldadas 459 amostras cilíndricas. Os valores de módulo de elasticidade obtidos foram comparados entre si e com formulações propostas em quatro normas: ABNT NBR 6118, ACI 318, Eurocode 2e FIB Model Code. Essas comparações indicaram que o efeito do tipo do agregado graúdo no módulo de elasticidade foi pouco expressivo quando comparado com a mudança da resistência do concreto.

Palavras-chave: deformação, propriedades, normas, resultados experimentais.

Introduction

The modulus of elasticity of concrete (E_c) is associated with structural deformations that must be kept within limits to prevent excessive deformations that cause cracks and other pathologies in concrete structures. Coupled to strength, the elasticity modulus, denoting material stiffness, is one of the most important characteristic of concrete (Chunsheng, Kefei & Fu, 2014). The interface between matrix and aggregate (fine or coarse), established by the aggregate, is known as the interfacial transition zone (Scrivener, Crumbie & Laugesen, 2004). Concrete is a composite, tri-phase, anisotropic and brittle material whose behavior varies according to the load applied (Topçu & Uğurlu, 2007). Determining the modulus of elasticity of concrete is not a simple task since the material is not completely elastic, even though its behavior is elastic at low loads between 30 and 40% of its ultimate load.

The nonlinear behavior of the concrete's stress-strain curve (σ-ε) makes it difficult to accurately determine a specific rate for the static elasticity modulus (Diógenes, Cossolino, Pereira, Debs & Debs, 2011). The types of static modulus of elasticity of concrete, associated with different load designs, comprise initial tangent modulus (E_{ci}), tangent modulus at a generic point, and secant modulus (E_{cs}).

The factors that influence the modulus of elasticity of concrete depend on the characteristics of cement paste matrix, transition zone, aggregate, and test parameter. Larrard and Belloc (1992) reported that the weakest components in concrete are the hardened cement paste and the transition zone between the cement paste and the coarse aggregate rather than the coarse aggregate itself. The porosity of the matrix affects the individual strength of the cement paste, causing variations in the elastic modulus (Helene, Monteiro & Kang, 1993). According to Mehta and Monteiro (2014), as maturity increases, the modulus of elasticity of concrete increases at a faster rate than its compressive strength (f_c) owing to the interfacial transition zone's greater density. Beshr, Almusallam and Maslehuddin (2003) studied the effect of four types of coarse aggregates, namely calcareous, dolomitic, quartzitic limestone and steel slag, on compressive strength and elastic modulus of high strength concrete, and concluded that the effect of the type of coarse aggregate is more significant on the modulus of elasticity when compared to that of compressive strength.

Studies in various regions of Brazil (Alhadas, Calixto & Ferreira, 2010; Machado, Shehata & Shehata, 2009) have reported that the mineralogical composition of coarse aggregate strongly affects the modulus of elasticity of concrete. In fact, the elasticity modulus varies by as much as 30%, according to the type of aggregate and to the concrete composition.

The main difficulty in using theoretical models to determine the modulus of elasticity of concrete is that they require previous knowledge about the modulus of elasticity of the aggregate and the cement paste. To solve this problem, normative empirical approaches have emerged which estimate E_c based on the rates of the concrete's compressive strength.

Associação Brasileira de Normas Técnicas-ABNT NBR 6118 (2007), Federation Internationale du Beton-FIB Model Code (2010), American Concrete Institute - ACI 318 (2014) and Eurocode 2 (2004) standards propose the use of Equations (1 to 4), respectively. In these equations, E_{ci} is the initial tangent modulus in GPa; E_c is the secant modulus, defined as the slope of the straight line that connects points corresponding to zero stress and a stress of 0.45 f_{ck} of the diagram; E_{cs} is the secant modulus between stress points 0 and 0.4 f_{cm} after 28 days, in MPa. The code equations are given below.

$$E_{ci} = 5600 \times f_{ck}^{(1/2)} \quad (1)$$

$$E_{ci} = E_{c0} \times \alpha \times \left(\frac{f_{ck} + \Delta f}{10} \right)^{1/3} \quad (2)$$

where:

E_{ci}- initial tangent modulus in GPa;

f_{ck} - characteristic compressive strength of concrete in MPa.

α - a factor that depends on the type of aggregate;

Δf = 8 MPa;

E_{co} = 21.5 × 10^3 MPa.

$$E_c = 4.700 \times f_{ck}^{1/2} \quad (3)$$

where:

E_c- secant modulus.

$$E_{cs} = 22000 \times \alpha_E \times \left(\frac{f_{cm}}{10} \right)^{1/3} \quad (4)$$

where:

E_{cs}- secant modulus between stress points 0 and 0.4 f_{cm};

f_{cm}- average concrete strength, in MPa;

α_e- correction factor that depends on the type of aggregate.

When Equations (3 and 4) proposed by American Concrete Institute - ACI 318 (2014) and Eurocode 2 (2004), respectively, are employed to calculate the secant elastic modulus, the corresponding equations for E_{ci}, shown in Equations (5 and 6), may be obtained from Equation (7).

$$E_{ci} = 25882.35 \times \alpha_E \times \left(\frac{f_{cm}}{10} \right)^{1/3} \quad (5)$$

$$E_{ci} = 5529.41 \times (f_{ck})^{1/2} \quad (6)$$

$$E_{cs} = 0.85 \times E_{ci} \quad (7)$$

Although empirical models proposed by standards cannot determine initial tangent modulus E_{ci} accurately as a function of the strength and type of aggregate, they provide approximations (Helene et al., 1993). True rates are those that previously considered the elastic modulus of cement paste and aggregates. Attempts have been made to include other correction factors linked to the nature of coarse aggregate and the consistency of fresh concrete.

Current study analyzed the influence of coarse aggregates – basalt and dolomite – on the elasticity modulus of three different strength classes of concrete. The experimental results of elastic modulus were compared with the modulus of elasticity estimated by Equations (1 and 2, 5 to 6) proposed by the standards Associação Brasileira de Normas Técnicas - ABNT NBR 6118 (2007), Federation Internationale du Beton (FIB, 2010), American Concrete Institute - ACI 318 (2014), and Eurocode 2 (2004). A total of 459 cylindrical concrete specimens were tested to determine their compressive strength, elasticity modulus and tensile strength by the diametrical compression test and Poisson's ratio.

Material and methods

Experimental Procedure

Compressive strengths (f_{ck}) of 20, 30 and 40 MPa and two types of aggregate, basalt and dolomite, extracted from three different sites in Brazil, were selected to determine the influence of coarse aggregate on E_{ci}. A total of 459 concrete cylinders, 10 x 20cm, were cast: 153 concrete cylinders for each type of aggregate and 51 concrete cylinders for each type of concrete mix. Tests were performed at ages 7, 14, 28 and 56 days to determine compressive strength, elasticity modulus, and tensile strength by diametrical compression and Poisson's ratio. Since the last two tests are outside the scope of current study, their methodologies and results will not be given. The nomenclature adopted for the specimens included the concrete compressive strength f_{ck} (C20, C30, C40), the type of coarse aggregate (BA, basalt; DO, dolomite), and the three sites from which the aggregates were extracted: 1, 2 and 3, respectively the municipalities of Uberlândia, Patos de Minas and Uberaba, in the state of Minas Gerais, Brazil. For example, specimen C20-BA-1 corresponds to the concrete cylinders cast with class 20 MPa concrete, using coarse basalt aggregate, extracted from the site in Uberlândia.

The hardened concrete tests were performed on an EMIC® DL-60000 universal testing machine in the Construction Materials Laboratory of the Federal University of Uberlândia, Uberlândia, Minas Gerais State, Brazil. The 600 kN-load capacity machine was locked to a computer interface and instruments for data retrieval of load, strain and displacement. The load-measuring system consisted of a hydraulic pressure transducer and strain was measured with two strain gauge channels.

The concrete cylinders' diameter was determined with an accuracy of ± 0.1 mm, based on the average of two diameters measured orthogonally at mid-height. The height of the cylinders was also determined with ± 0.1 mm accuracy and their loading surfaces (top and bottom) were evened with sulfurcapping. The compressive strength tests were performed with a load applied continuously and uniformly at a constant loading rate of 0.45 ± 0.15 MPa s^{-1}. The three concrete mix designs (20, 30 and 40MPa) were subjected to three tests at each age (7, 14, 28 and 56 days).

For the initial modulus of the elasticity test, clip-on strain gauges were attached to the top and bottom sides of the foil sheet anchor on the cylinder (see Figure 1). The strain, which corresponded to the vertical displacement of the balanced end of the sheet, was determined by the deformation measured by the strain gauges.

Figure 1. Position of clip-on strain gauges on the CS for the concrete modulus of the elasticity test.

The elasticity modulus test was performed according to Brazilian standard Associação Brasileira de Normas Técnicas - ABNT NBR 8522 (2008). Five concrete cylinders were used to test each concrete mix design and age. First, two concrete cylinders were used to determine the compressive strength to calculate the amount of load to be applied in the test with the other three cylinders. Each of these three concrete cylinders was centered on the plate of the testing machine and the strain gauges were positioned equidistant from the ends of the test specimen (Figure 1). The load was applied at a rate of (0.25 ± 0.05) MPa s^{-1} up to 0.3 f_{cm} (σ_b) and stress level was maintained for 60 seconds, after which the load was reduced at the same rate as the loading process until the basic stress level (σ_a equal to 0.5 ± 0.1 MPa) was reached. The loading/unloading cycles were repeated twice again at the same rates and stress levels (σ_a and σ_b). Specific strains were measured after the last preloading cycle and for a 60-second period under stressσ_a. After reading the strains, the concrete cylinders were loaded up to rupture. Results were discarded if there was a >20% difference between the compressive strength obtained in the compressive strength test performed on the first two concrete cylinders and the compressive strength of the elasticity modulus test of the other three cylinders. Equation (8) was used to determine E_{ci} in GPa.

$$E_{ci} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_b - \sigma_a}{\varepsilon_b - \varepsilon_a} \quad (8)$$

where:

ε_b- average specific strain at stress level σ_b;

ε_a- average specific strain at stress levelσ_a.

Materials and concrete mix design

The concrete specimens were cast with type II Portland cement with an average compressive strength 31.27 MPa at 28 days. The fine aggregate was natural river sand with a fineness modulus of 2.53, while the coarse aggregates had a maximum diameter of 19 mm. Table 1 describes the physical characteristics of each type of coarse aggregate.

Table 1. Physical properties of BA-1, BA-3 and DO-2 coarse aggregates.

Properties	BA-1	BA-3	DO-2
Specific density (g cm^{-3})	2.84	2.90	2.69
Unit weight (g cm^{-3})	1.53	1.53	1.42
Maximum size (mm)	19	19	19
Fineness modulus	6.98	7.73	6.96
Content of pulverulent materials (%)	0.77	0.52	0.33

Mix comprised apolycarboxylate-based superplasticizer and tap water. Water/cement ratioswere 0.53, 0.45 and 0.35, selected to reach the proposed rates of 28-day concrete compressive strength. Table 2 describes the mix design and consumption of cement per m^3.

The sand's moisture content in each mix was calculated and the amount of water in the mix was adjusted accordingly. The materials were weighed on a digital scale. Approximately 0.130 m^3 of concrete of each mix design was produced. The materials were placed in the concrete mixer in the following sequence: coarse aggregate, approximately 30% of the mixing water, fine aggregate, cement, and the remainder of the water mixed with the additive. The mixer was turned off after 5 minutes, and all the material adhering to the blades and to the internal surface was removed. The mixer was then turned on again for another 15 min., after which part of the mixture was removed for a concrete cone slump test to determine its specific density. The concrete mixer was then switched on again for another 2 minutes before casting the cylinders.

After casting, all the cylinders were placed in a moisture curing room for up to 24 hours, after which they were submerged in a water tank until the date of each test.

Results and discussion

Tables 3 and 4 describe the results of average compressive strength (f_{cm}), average elasticity modulus (E_{cm}) and respective standard deviations (S_d). The compressive strength and the elasticity modulus average were obtained by 3 cylinders results.

Table 2. Proportions of ingredients used in each concrete mix design prepared for current study.

Concrete mix design	C20			C30			C40		
	1:2.5:3.5:0.53			1:2:3:0.43			1:1.5:2.5:0.35		
Cement consumption	BA-1	DO-2	BA-3	BA-1	DO-2	BA-3	BA-1	DO-2	BA-3
(kg m^{-3})	329	322	332	389	380	392	470	459	474

Table 3. Average compressive strength (f_{cm}) and respective standard deviation (S_d) of all the concrete mix designs.

Concrete mix design	Compressive strength (MPa)				
	age	7 days	14 days	28 days	56 days
C20-BA-1	f_{cm}	22.87	24.44	25.57	26.19
	S_d	1.63	1.59	2.24	2.12
C30-BA-1	f_{cm}	32.22	35.67	35.78	36.29
	S_d	1.98	2.65	3.15	2.12
C40-BA-1	f_{cm}	46.49	51.72	53.63	56.00
	S_d	5.39	4.98	3.83	5.85
C20-DO-2	f_{cm}	25.65	28.73	29.48	29.82
	S_d	1.06	1.81	1.7	1.65
C30-DO-2	f_{cm}	32.1	35.63	35.61	36.72
	S_d	2.44	2.11	1.08	1.39
C40-DO-2	f_{cm}	49.86	50.44	49.54	52.04
	S_d	3.87	4.47	2.00	4.98
C20-BA-3	f_{cm}	26.88	29.69	35.50	36.61
	S_d	1.67	2.33	1.36	1.89
C30-BA-3	f_{cm}	36.26	39.33	42.18	46.04
	S_d	1.73	1.48	0.85	3.93
C40-BA-3	f_{cm}	47.46	49.90	49.50	50.29
	S_d	3.35	2.81	2.89	2.12

f_{cm} = average compressive strength, S_d= standard deviation.

The concrete made with dolomite coarse aggregate, regardless of the strength class, showed the lowest gain in compressive strength from day 7 to day 56, with a 11.67% average. Among the specimens produced with basalt coarse aggregate, except for concrete strength class C40, the BA-3 specimen had the highest gain in compressive strengthover time, reaching an average of 31.58%.

The concrete produced with dolomite coarse aggregate also had the lowest gain in E_{ci} from day 7 to day 56, or rather, an average of 5.81%. Among the concrete mixes produced with BA coarse aggregate, except for concrete strength class C20, the BA-3 concrete had the highest gain in E_{ci} over time, or rather, 19.73%. Since C20 concrete mix design had a more porous cement matrix than the other concrete strength classes, the latter factor was decisive in determining the difference in E_{ci} between the concrete mixes produced with basalt and dolomite aggregates. In this case, the effect of the cement paste was more important than the effect of the aggregate. In the C30 mix design, the three types of aggregate had similar gains in E_{ci}. In the C40 mix design, the C40-BA-3 showed a gain in E_{ci} twice as high as inthe C40-BA-1. In other words, the less porous matrix from the low w/c ratio caused the load to be transferred to the aggregate, whose higher specific density contributed to the composite´s stiffness. This factor reinforces the theory that the higher the compressive strength, the greater is the influence of the type of aggregate on the elasticity modulus.

Table 4. Average elasticity modulus (E_{cim}) and the respective standard deviations (S_d) of all the concrete mix designs.

Concrete mix	Elasticity modulus (GPa)				
	age	7 days	14 days	28 days	56 days
C20-BA-1	E_{cim}	31.3	32.4	35.06	37.77
	S_d	1.58	3.64	1.91	1.06
C30-BA-1	E_{cim}	38.39	39.47	40.96	43.65
	S_d	2.92	1.83	3.16	1.95
C40-BA-1	E_{cim}	46.72	46.13	52.80	52.73
	S_d	2.02	1.59	2.90	4.10
C20-DO-2	E_{cim}	36.35	36.98	37.24	37.68
	S_d	1.72	1.51	2.3	1.98
C30-DO-2	E_{cim}	40.08	39.90	41.50	42.00
	S_d	1.72	0.44	0.92	4.66
C40-DO-2	E_{cim}	48.97	48.53	52.45	53.38
	S_d	2.10	1.25	3.18	2.59
C20-BA-3	E_{cim}	36.50	42.32	42.38	43.02
	S_d	2.88	4.39	1.25	4.24
C30-BA-3	E_{cim}	40.65	42.35	43.17	46.40
	S_d	3.71	4.06	5.72	4.30
C40-BA-3	E_{cim}	45.26	45.72	53.70	56.72
	S_d	2.01	4.74	5.07	2.14

E_{cim} = average modulus of elasticity, S_d= standard deviation

The evolution of initial tangent modulus over time may be estimated by Equation 9 proposed by Federation Internationale du Beton (FIB, 2010).

$$E_{cj} = \left\{ \exp\left[s \times \left(1 - \sqrt{\frac{28}{t}} \right) \right] \right\}^{1/2} \times E_{c28} \qquad (9)$$

where:

E_{cj}- elasticity modulus of concrete at age *j*;

E_{c28} - elasticity modulus of concrete at 28 days;

t–age of concrete;

s – coefficient of strength gain as a function of the type of cement (0.2, 0.25 and 0.38 for Portland cement CPV ARI, CP I and II, and CP III and IV, respectively).

Figure 2 shows the elasticity modulus obtained by Equation 9 and the experimental rates for the concrete mix designs with coarse aggregates (a) BA-1, (b) DO-2 and (c) BA-3. The rate of the strength gain coefficient *s* adopted for this calculation was 0.25. The initial tangent modulus rates of the C30-BA-1 mix design exceeded those estimated by Equation (9), regardless of the age of concrete, while the C40-BA-1 mix design remained lower than (an average 6%) or equal to that estimated by the equation, at all ages. The growth rate of E_{ci} in the C20-BA-1 mix design, at 28 days, was 70% higher than that of the C30-BA-1, probably due to greater water availability in the former, which enabled continuous cement hydration. Results of C20-DO-2, C30-DO-2 and C40-DO-2 concrete mixes after 28 days were overestimated by Equation (9), at an average of 2.5%. In the case of the concrete mixes produced with the coarse aggregate BA-3, Equation (9) overestimated (at an average of 2.19%) only the elasticity modulus rate of the C20-BA-3 mix after 28 days.

Figure 3 shows E_{ci} versus f_c graphs of the concrete specimens at all ages. The compressive strength and elasticity modulus varied in the same proportion, that is, the elasticity modulus increased with the increase of compressive strength. The equations that best fit the observed results were obtained by exponential regression (Figure 3). Except for the BA-3 concrete, the rates of the exponent of the compressive strength were close to 0.5 and its use may be considered acceptable. The adjusted coefficients of determination for concretes BA-1 and DO-2 were 0.83 and 0.81, respectively. However, the concrete prepared with the BA-3 coarse aggregate showed a higher dispersion than the others, with the adjusted coefficient of determination for the concrete at 0.37.

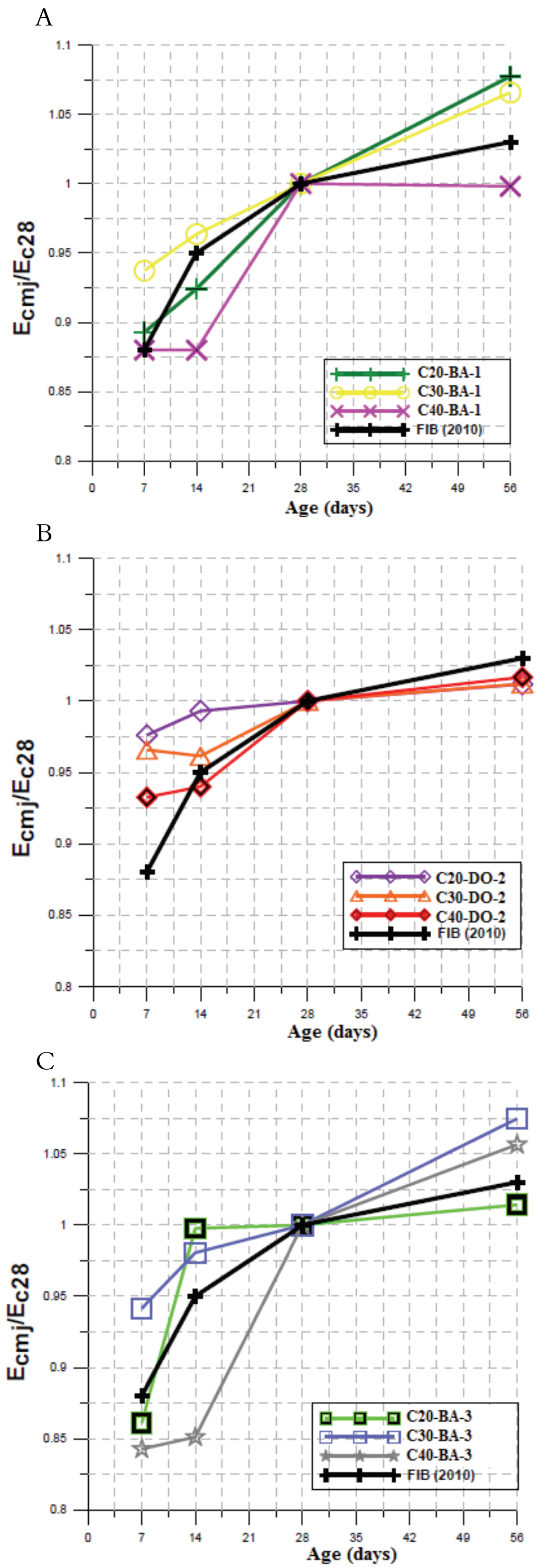

Figure 2. Elastic modulus obtained by Equation 9 and experimental rates for the concrete mix designs with coarse aggregates (a) BA-1, (b) DO-2 and (c) BA-3.

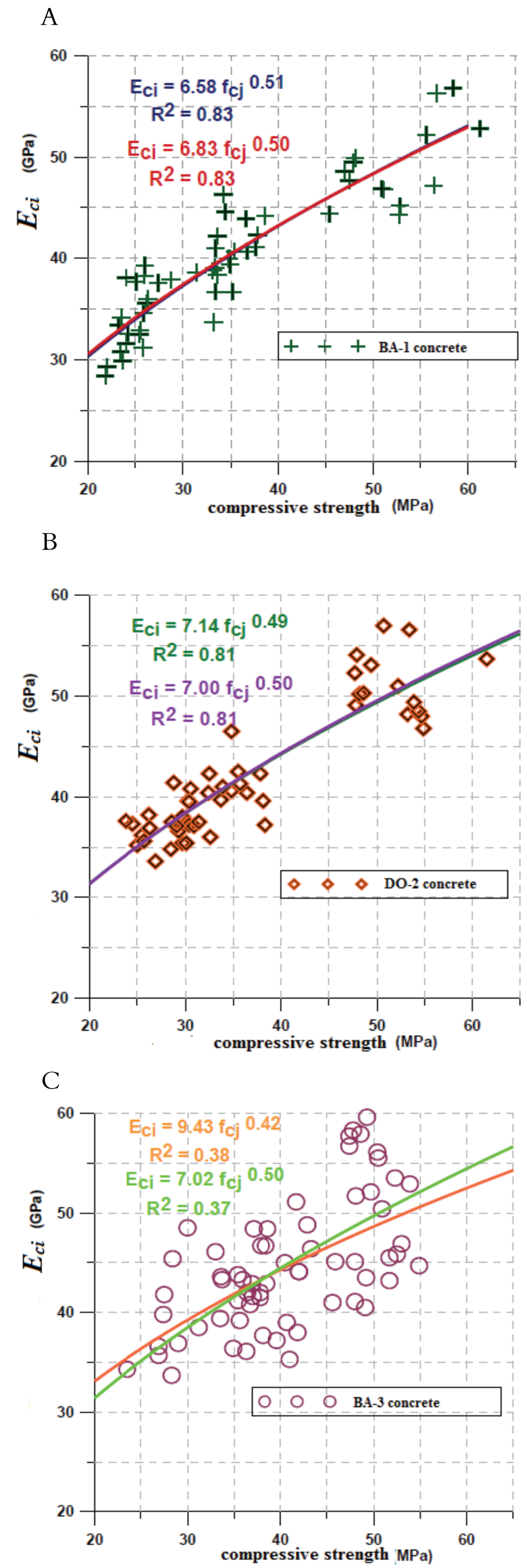

Figure 3. E_{ci} versus f_c of concrete: (a) BA-1, (b) DO-2, and (c) BA-3, at all ages.

Section 1 of current paper presented Equations (1 to 4), some of which estimated the elasticity modulus from f_{ck}. To allow for comparisons, rates of f_{ck} rates were obtained by Equation 10.

$$f_{ck} = f_{cm} - 1.65 \times S_d \qquad (10)$$

where:

f_{cm}- average compressive strength

S_d- standard deviation for each set of strength classes of concrete.

Figure 4 shows current study's results of the experimental elasticity modulus and the E_{ci} rates obtained by Equations [1 and 2, 5 to 6] for each type of concrete, regardless of age. Equation (11), recommended by the Brazilian Concrete Institute (Ibracon, 2003), was also used. The equation proposes a correction of Equation (1) to include data pertaining to the consistency of fresh concrete and the influence of the various types of aggregate, following the trend of other international standards.

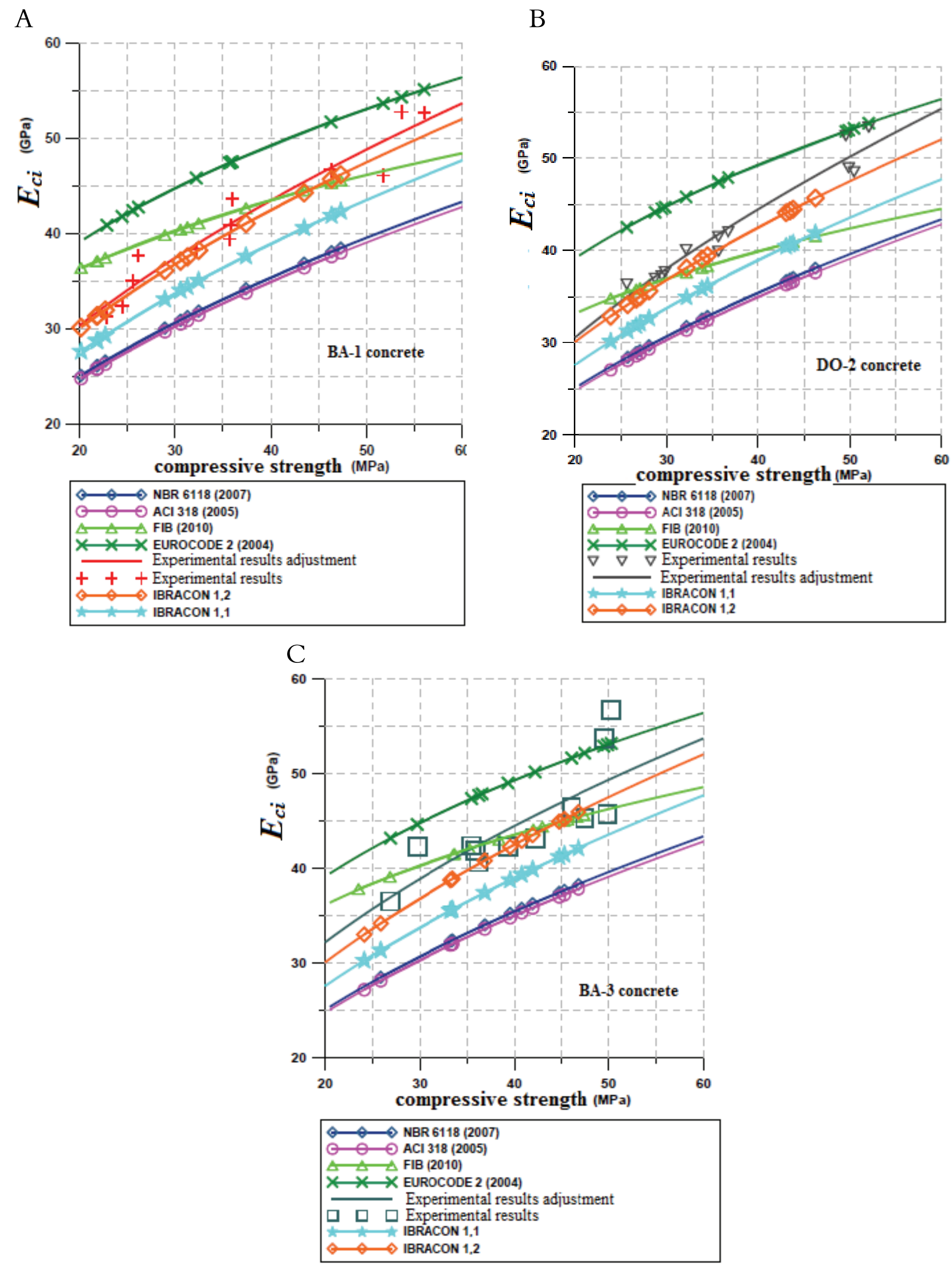

Figure 4. Comparison of current study's experimental E_{ci} results and E_{ci} rates obtained by Equation [1 and 2, 5 to 6] for concrete: (a) BA-1, (b) DO-2 and (c) BA-3, where $a_1 = 1.1$ and$a_1 = 1.2$.

$$E_{ci} = a_1 \times a_2 \times 5600 f_{ck}^{1/2} \quad (11)$$

where:

a_1 - correction index that takes into account the type of aggregate (1.1 or 1.2 for dense basalt and dense sedimentary limestone, 1.0 for granite and gneiss, 0.9 for metamorphic limestone, and 0.7 for sandstone)

a_2 - correction index determined by the consistency of the concrete, equal to 1 in current study.

An analysis of the results illustrated in Figure 4 reveals that the equations proposed by Associação Brasileira de Normas Técnicas - ABNT NBR 6118 (2007) and American Concrete Institute - ACI 318 (2014) showed similar elasticity modulus rates, albeit lower than experimental results, at an average of 24%. On the other hand, E_{ci} rates obtained by Eurocode standard (2004) were higher than elasticity modulus results (average 13%) and rates estimated by the other equations. Equation (2), proposed by Federation Internationale du Beton (FIB, 2010), was closer to the experimental results than Equations (1, 3, 4). On an average, the equation proposed by Federation Internationale du Beton (FIB, 2010) obtained elasticity modulus rates 94, 85 and 90% of the experimental results at 28 days respectively for BA-1, DO-2 and BA-3 concretes.

Conclusion

Current study analyzed the influence of coarse aggregates on E_{ci}. Results demonstrated that f_c and E_{ci} of the concrete produced with dolomitic aggregate showed lower gain rates from 7 to 56 days. According to the experimental results, the most effective way to increase E_{ci} was to increase the concrete strength class, since the changing of the mineralogical source of the coarse aggregate had little effect on E_{ci} when compared to the effect obtained by changing the concrete strength class.

The proposed addition of correction factors as a function of the type of aggregate proved to be efficient, since results by FIB equation were closest to the experimental results.

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