INFLUENCE OF FLY ASH ON THE COMPRESSIVE STRENGTH AND YOUNG'S MODULUS OF CONCRETE

P. R. Lustosa[1], M. S. Magalhães[2*],

[1] Engineering faculty, State University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil

[2] Department of Civil Construction and Transportation, Engineering faculty, State University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil

*Corresponding author; e-mail: margareth.magalhaes@uerj.br

Abstract

This experimental research focus on determining how the addition of industrial waste affects the mechanical properties of concrete when partially replacing cement. The cement industry is currently one of the most polluting industries, contributing negatively and significantly to the emission of toxic gases into the atmosphere. There is, therefore, a general need to reduce the dependence and the use of cement in order to mitigate its effects on the environment. One way of reducing its needs is partially to replace it by waste or industrial by-products in the form of supplementary cementing materials (SCM). Therefore, the proposed project focuses on the influence of the cement substitution by SCM in the concrete manufacturing and establishing a relation with the characteristics of a standard concrete. The SCM used in this study is an in-nature fly ash, a by-product of Brazilian thermoelectric plants. The influence of fly ash on the concrete was analysed according to the substitution content at the age of 28 days. This study comprised the production of 50 specimens casted with 0%, 10%, 20%, 40% and 50% cement replaced by fly ash and with a water/binder ratio of 0.4 and 0.6. Slump, compressive strength and Young's modulus tests were carried out on the mixes. Experimental results indicated an increase in compressive strength at the age of 28 days for 10% and 20% in-nature fly ash replaced cement and reduced for 40% and 50% in-nature fly ash. A drop in the modulus of elasticity was also noted in accordance with the increase in the ash substitution rate. Relationship between Young's modulus and compressive strength were also determined.

Keywords:

Fly ash; cement; concrete; compressive strength; Young's modulus

1 INTRODUCTION

Talking about the greenhouse effect, it is established that CO_2 is a major contributor and therefore responsible for global warming of the planet. The environmental damage to cement production is substantially higher; it contributes for approximately 7% of global CO_2 emissions [Mehta 1999]. In addition, production of cement requires more amount of energy.

In recent years, many studies attempted to develop new Supplementary Cementing Materials (SCMs), aiming to solve environmental problems linked to the disposal of solid waste [Babu 2004, Chatveera 2009, Chindaprasirt 2007, Thomasa 1999, Magalhães 2017, Khatib 1998]. The re-use in construction industry is seen as an attractive alternative to landfill.

Positive results were already obtained during the last decades with pozzolana, limestone, fly ashes, silica fume and blast furnace slag, which are currently considered as conventional additions, and their use is regulated by several standards [ASTM C595 2016, EN 197-1 2011].

Fly ashes are pozzolanic materials obtained from thermal power plants, with their economic advantages and potential for improving fresh and hardened concrete performance.

A fundamental issue that should be investigated when using supplementary fuels relates to the quality of fly ash produced during the combustion, as it may be a valuable resource in concrete industry. Fly ash has been successfully used in concrete industry worldwide since more than 50 years, primarily as mineral admixture in Portland cement concrete and also as a component of blended cement [Bouzoubaâ 1999]. Concerning its first use, fly ash can either partially substitute Portland cement or be applied as an addition into ready-mix concrete at the batch plant [Siddique 2010, Siddique 2011]. It is generally accepted that the use of this SCM promotes sustainability of concrete industry.

In Brazil, large quantities of fly-ash are generated as a by-product in thermal power plants, increasing year by year by the increasing demand of electricity, but usage is low in the industry and, its use is restricted to partially replacing clinker in the manufacture of cement. There are two reasons; Inadequate information about the fly ash properties and fly ash properties are not always uniform [Tokyay 1998, Bayat 1998].

According to the above concepts, the aim of this study has been to explore the potential of fly ash produced by the power plant of Capivari de Baixo, Santa Catarina, Brazil, for use in concrete mixture.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The raw materials used on the preparation of the concrete mixes were: Portland cement; fly ash; sand; gravel; and tap water. The cement used is a high early strength Portland cement type V, as defined in NBR 16697 [2018], with a density of 3.04 g/cm³, fineness index of 0.54% and loss on Ignition (LOI) < 6.5% [NBR 11579 2012]. The fly ash is used in as-received condition from the ash collection system of a thermoelectric plant in south of Brazil, and has a density of 2.26 g/cm³, fineness index of 35.91% and (LOI) < 2%. This waste product is classified as type C, following the specifications from NBR 12653 [2015]. Specific gravity of the powdered material was determined according to NBR 16605 [2017]. The natural sand has 6.3 mm maximum particles size and density of 2.51 g/cm³. The gravel has 19 mm maximum particles size and density of 2.66 g/cm³.

Fig. 1 shows particles size distribution of cement, fly ash, sand and gravel. Particles size distribution of cement and fly ash were obtained using Mastersizer 2000 equipment. The fly ash has a wide range of particles size, with coarse particles having size up to 417 µm. The distribution has the following characteristics: d_{10} equal to 4.37 µm; median particle size d_{50} of 45.71 µm and d_{90} is 158.49 µm. The cement's characteristics is instead by d_{10} = 1.96 µm, d_{50} = 12.29 µm and d_{90} =36.54 µm, being finer than the fly ash used in this work.

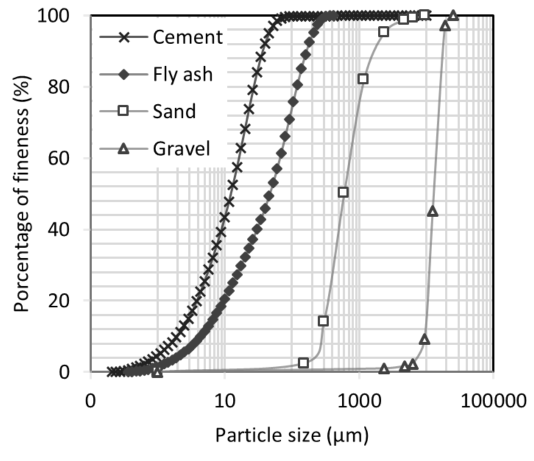


Fig. 1: Particles size distribution of cement, fly ash, sand and gravel.

Scanning electron microscope (SEM) images were taken in the secondary-electrons mode, with an acceleration voltage of 15 kV, and in the backscattered electrons mode, using an accelerating voltage of 25 kV.

Fig. 2 shows images of fly ash, taken at a magnification of 800x, samples appear as composed of small round-shape particles. The texture of the fly ash appears smooth, despite the relative low LOI value, indicating that they underwent an incomplete burning.

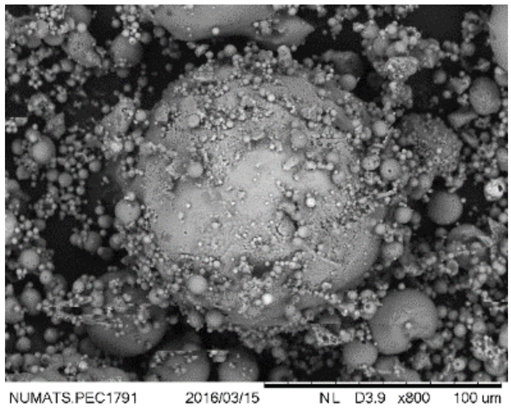


Fig. 2: SEM image of gross fly ash.

Tab. 1 shows the chemical composition of Portland cement and fly ash, which was obtained with X-ray Fluorescence (XRF) analyses. As it is possible to see, the composition of this fly ash is rich in Si and Al oxides, with few quantities of calcium oxide.

Tab. 1: Chemical compounds in Portland cement and fly ash.

Compound	Cement (wt %)	Fly ash (wt %)
Al_2O_3	3.772	32.242
SiO_2	14.317	53.640
SO_3	3.923	1.664
K_2O	0.626	3.475
CaO	72.160	1.973
MnO	0.127	0.039
Fe_2O_3	4.320	5.478
ZnO	0.052	0.041
SrO	0.307	0.023
TiO_2	0.324	1.330
Rb_2O	-	0.026
ZrO_2	-	0.087
Y_2O_3	-	0.015
V_2O_5	-	0.069

2.2 Mixture details

Ten mixtures were produced to investigate the influence of fly ash on the compressive strength and Young's modulus of concrete. Two mixtures are without fly ash (labelled as Ref). The other eight mixtures contain 10% (M10), 20% (M20), 40% (M40) and 50% (M50) of fly ash as cement substitute. Mixture proportions are listed in Tab. 2. Binder to sand ratio and binder to gravel ratio were maintained constant in all the mixes, and is equal to 1:1.51 and 1:1.7, respectively. Substitution ratios are expressed in weight percentage. Water to binder ratio (w/b) of 0.4 and 0.6 was used in all mixtures. A superplasticizer based on polycarboxylate and nanosilica was added to some mixtures, to allow a good workability for mixtures with w/b ratio equal to 0.4. In all the cases, slump value, according to NBR NM 67 [1998], ranges between 180 mm and 250 mm. All the concrete specimens were casted in steel molds, and after 24 h from the mixing they are demolded and cured until testing in 100% relative humidity (RH) conditions, at 23 ± 2°C temperature, according to NBR 9479 [2006].

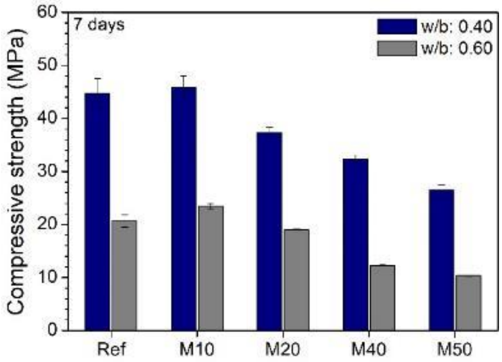
Tab. 2 : Mixture proportions of concretes.

Mix	Cement (%)	Fly ash (%)	w/b	Quantities (kg/m^3)					
				Cement	Fly ash	Sand	Gravel	Water	SP
Ref-0.40	100	-	0.40	506.7	-	765.2	866.5	202.7	2.8
M10-0.40	90	10	0.40	453.4	50.4	760.8	861.5	201.5	2.8
M20-0.40	80	20	0.40	400.7	100.2	756.4	856.6	200.4	2.8
M40-0.40	60	40	0.40	297.1	198.1	747.8	846.9	198.1	2.8
M50-0.40	50	50	0.40	246.2	246.2	743.6	842.1	197.0	2.7
Ref-0.60	100	-	0.60	460.1	-	694.8	786.8	276.1	-
M10-0.60	90	10	0.60	411.9	45.8	691.1	782.7	274.6	-
M20-0.60	80	20	0.60	364.2	91.1	687.5	778.6	273.2	-
M40-0.60	60	40	0.60	270.4	180.2	680.4	770.5	270.4	-
M50-0.60	50	50	0.60	224.1	224.1	676.9	766.6	269.0	-

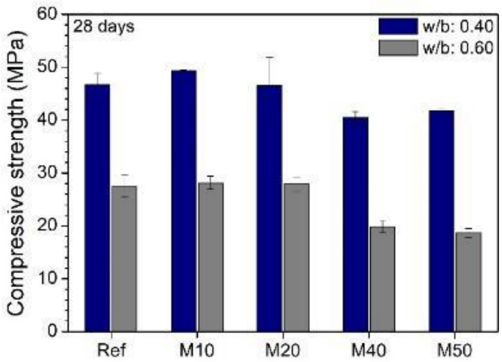
w/b: water/binder ratio; SP: superplasticizer.

2.3 Experimental methods

Tests were carried out on cylindrical specimens with 100 x 200 mm (diameter x height). The Compressive strength of specimens was determinate according to NBR 5739 [2018] at 7 and 28 days and the Young's modulus by NBR 8522 [2017] at 28 days.



(a)



(b)

Fig. 3: Compressive strength of concretes, with w/b ratios of 0.40 and 0.60, at (a) 7 and (b) 28 days.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Compressive strength

Fig. 3 shows the dependence of compressive strength on the w/b ratio for all mixtures, both at 7 and 28 days. Average results and standard deviation (in parentheses) are presented in Tab. 3. Compressive strength of the tested concrete specimens depends on the w/b ratio, following the Abrams' law. According to Neville [2011], concrete strength at a given age depends mainly on w/b ratio, as well as on the degree of compaction. Here, the use of the superplasticizer in the mixtures with the lowest water amount was fundamental to ensure that specimens could be considered as fully-compacted, similarly to the other mixtures.

Tab. 3: Compressive strength and Young's modulus results.

Mix	Young's Modulus (GPa)	Compressive strength (MPa)	
		7 days	28 days
Ref-0.40	33.92 (0.81)	44.76 (2.79)	46.66 (2.14)
M10-0.40	31.76 (1.04)	45.86 (2.19)	49.29 (0.20)
M20-0.40	30.67 (2.39)	37.36 (0.94)	46.57 (5.24)
M40-0.40	29.80 (0.80)	32.28 (0.83)	40.53 (1.06)
M50-0.40	29.38 (0.70)	26.50 (0.91)	41.82 (0.52)
Ref-0.60	26.35 (1.22)	20.63 (1.18)	27.46 (2.06)
M10-0.60	25.23 (0.63)	23.46 (0.52)	28.16 (1.24)
M20-0.60	23.86 (0.21)	18.94 (0.19)	27.97 (1.34)
M40-0.60	24.45 (0.61)	12.31 (0.14)	19.88 (1.04)
M50-0.60	19.99 (1.27)	10.36 (0.32)	18.64 (0.82)

It is possible to observe from Tab. 3 that the increase of w/b from 0.40 to 0.60 lowers the compressive strength of both reference (Ref) and fly ash concrete (M10, M20, M40 and M50). The decrease ranges between 49% and 62% at 7 days, and between 41% and 55% at 28 days of curing. The porosity of the concretes increases in the hardened state with the increase of w/b ratio, thus it directly affects the mechanical strength of the mortars.

Data shown in Fig. 4 highlight that the compressive strength at 7 days increases when 10% of fly ash was used as SCM, whereas it decreases at other fly ash contents (20%, 40% and 50%) of substitution, regardless the w/b ratio. The maximum strength gain observed is 2.5% in M10 concrete with 10% of fly ash and w/b: 0.40 and the highest loss occurred is 49.8% in M50 concrete with 50% of fly ash and w/b: 0.6. At 28 days, compressive strength also increases when 10% of fly ash was used as SCM; whereas it didn't change when 20% was used and, as expected, decreased when 40% and 50% fly ash was replaced cement. The maximum strength gain was 5.6% in M10 concrete with 10% of fly ash and w/b: 0.40 and the highest loss occurred is 32.1% in M50 concrete with 50% of fly ash and w/b: 0.6.

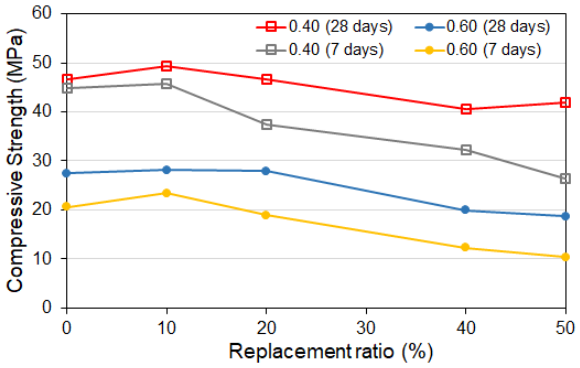


Fig. 4: Compressive strength vs. replacement ratio curves with varying w/b at 7 and 28 days.

Other observation is that the reduction of the gap between reference and fly ash concrete in time, often reported in literature, was observed in this work. For instance, the compressive strength at 7 days of Ref mixture with w/b: 0.40 was 96% of its compressive strength at 28 days, whereas, compressive strength of M10, M20, M40 and M50 at 7 days were, respectively, 93%, 80%, 79% and 63% of their compressive strength at 28 days. To w/b: 0.60, similar behaviour was observed: the compressive strength at 7 days of ref, M10, M20, M40 and M50 mixtures were, respectively, 75%, 83, 68, 62 and 56% of their compressive strength at 28 days.

3.2 Young's modulus

The Young's modulus of concretes was determined experimentally at 28 days. Fig. 5 and Tab. 3 shows the average values and respective standard deviations. It is possible to observe that when the w/b ratio increases from 0.4 to 0.6, the elastic modulus of reference (Ref) and fly ash concretes (M10, M20, M40 and M50) decreases. The reduction varied between 18% - 32%.

With regard to influence of fly ash, the results presented in Tab. 3 and Fig. 4 indicate that Young's modulus was slightly reduced up to 13%. This finding is consistent with the works of other researchers. According Mehta [2008], the Young's modulus is dependent of w/b ratio and mineral additions.

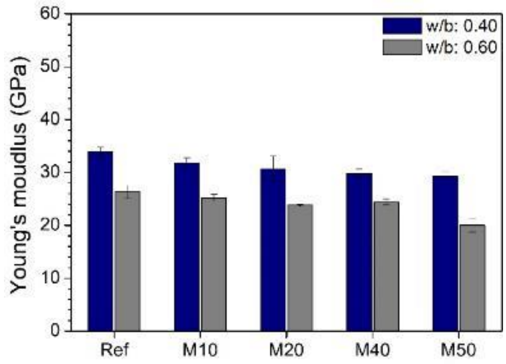


Fig. 5: Experimental Young's modulus of concretes, with varying w/b ratios and fly ash replacement, at 28 days.

Fig 6 shows the regression equation obtained from the average values of compressive strength (f_c) and Young's modulus (E), shown in the previous Fig. 3b and Fig. 5. The relationship is derived to predict the Young's modulus of concrete, as a function of compressive strength. The regression equation with the highest correlation coefficients (R^2 = 0.86) is a power function (Eq. (1)) of compressive strength:

$$E = 6.59 f_c^{0.41} \qquad (1)$$

The result obtained was compared with the empirical equations from Brazilian standard [NBR 6118 2014] and American standard [ACI 318-14 2014], also showed in Fig 6. The trend line calculated with the values found came out near of the existent equations provided from the Brazilian and American standards.

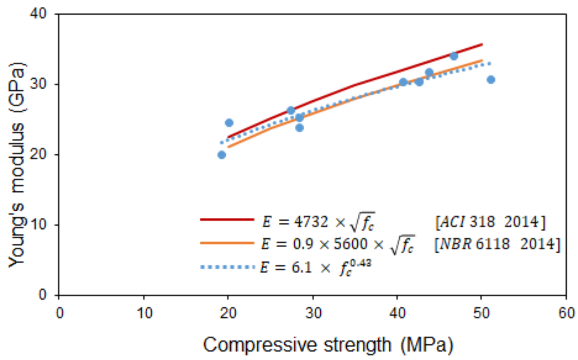


Fig. 6: Correlation between Young's modulus and compressive strength of concretes.

4 CONCLUSIONS

The use of fly ash can make construction process more sustainable, because not only using it as a mineral addition in concrete mixture reducing the use of cement and the impact of the cement industry in the environment, but also will give a new destination for an industrial waste. Using fly ash in the concrete mixture will be also good in an economic way, because the fly ash has a lower added value.

The experimental campaign carried out in this work provides information about the influence of a Brazilian fly ash on the compressive strength and Young's modulus of concretes, when used as a supplementary cementing material (SCM). Conforming to the experimental results, the following conclusions can be derived.

- Compressive strength increased with curing age for all fly ash replacements, irrespective of fly ash percentage.
- The influence of fly ash depends on the quantity of fly ash used. When is used a replacement ratio of 10% fly ash, the compressive strength is higher than the reference mixture. In a concrete mixture with 20% fly ash, the compressive strength not change and with 40% and 50%, the compressive strength is lower than the reference concrete.
- A reduction of the gap between reference and fly ash concrete in time was observed.
- Young's modulus reduces with a higher w/b ratio for all concrete mixtures, irrespective of fly ash replacement ratio.
- The Young's modulus decreases as the fly ash content increases.
- The relationship between Young's modulus and compressive strength of fly ash concretes was in good agreement with the existing empirical equations by Brazilian and American standard for normal concretes.

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