FRACTURE TOUGHNESS AND STRENGTH OF FLY ASH CONCRETE

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ABSTRACT

Solid waste as fly ash from the coal powder combustion in thermoelectric power plant is a major environmental problem that can be solved by its addition in the mixture of structural concrete in civil construction. The present work investigates the effect of substituting 10% in mass of cement by fly ash from a Brazilian thermoelectric on the fracture toughness and strength of structural concrete. 150 x 300 mm cylinders for compressive strength and 100 x 100 x 550 mm beams for flexural strength were used in the mechanical properties testing. In addition, fracture toughness K_{IC} of the fly ash concrete were measured, using the three point bending test of a notched beam, according to RILEM 1991. In the preparation of the concrete mix, the Portland cement CPV-ARI RS in conjunction with class F fly ash, plasticizer and fine sand from Joinville/SC/Brazil were employed. The raw material morphology were characterized by SEM photographs. The obtained compression strength was 46.0 MPa , K_{IC} was 1.25 MPam$^{1/2}$, indicating a high strength concrete.

1. INTRODUCTION

Concrete is the greatest structural material used nowadays in civil constructions. However, the presence of cracks and pores inside concrete material is inevitable and it is necessary to investigate if they are stable or not. In this context, the concrete Fracture Mechanics is a valuable method for studying concrete behaviour under static loading: the concepts of Linear Elastic Fracture Mechanics (LEFM) and the Non-linear Fracture Mechanics (NLFM) and its limitations. On the other hand, the solid wastes of fly ash from the combustion of powder coal in thermoelectric power plant is an environmental problem that could be solved by the addition, in small quantities, of fly ash in the concrete mixture. There are two possibilities to accomplish the addition of fly ash into the concrete paste: by partial substitution of cement or by partial substitution of sand (fine aggregate). Generally, fly ash is used in the fabrication of cement and as replacement of cement in the concrete mixture. However, in the literature, various authors [1] have reported that in fact, the effect of sand partial replacement with fly ash is to increase the mechanical properties of concrete. Siddique [1] has shown that the substitution of 10%, 20%, 30% and 50% of sand by class F fly ash from a thermoelectric has raised the compressive and flexural strengths of concrete in all test ages. The increase in compressive strength was linear with the fly ash content. At all ages, the maximum strength value occurred with 50% fly ash content. Compressive and flexural strengths have increased respectively from 26.4 MPa and 3.7 MPa for zero fly ash content up to 40 MPa and 4.3 MPa at age 28 days.

Present work investigates the replacement of 10% in mass of cement with fly ash in the concrete mixture. The mechanical properties as compressive strength, flexural strength and fracture toughness are experimentally determined for this concrete composition.

2. FRACTURE TOUGHNESS TEST METHODS

In order to apply the Fracture Mechanics concepts to concrete, it is necessary to understand and calculate the parameters that govern the tensile fracture behaviour of concrete or the resistance to crack propagation, as for example the stress intensity factor K_I and the energy of fracture G_C. The state-of-the-art in Fracture Mechanics applied to plain concrete has shown a great variety of models to simulate concrete behaviour. Therefore, it is relevant the search of different existing methodologies for fracture toughness tests for experimentally calculating fracture toughness K_{IC} and also G_C. For example, the development of the distinct methodologies as the cylindrical specimen with a V-notch, named short-rod [2,3,4], the three point bending test of prismatic beam for determining fracture parameters K_{IC} and $CTOD_C$ [5] of plain concrete and the double torsion test and the R-curve for plate of alumina refractory castables [6].

2.1 The "Short-Rod" Specimen

A methodology for fracture test of concrete aimed at determining the fracture toughness, is based on the ISRM (1988) recommendation [2]. It relies on the non-linear fracture mechanics and is carried out by loading and unloading cycles with controlled deformation. The specimen geometry utilized is the "short-rod" type. Naus and Lott [7] performed test to determine the effects of various mixture parameters on the fracture toughness in cement paste, mortar and concrete. As results, they concluded that there are an increase in the value of fracture toughness in cement paste and mortar with the test age of the specimen and increase in water content. In relation to mortar, the fracture toughness value grows with the increase in the ratio sand/cement. For concrete, an increase in the fracture toughness value with the growth in size of thick aggregate. Among the advantages of utilizing the "short rod" specimen are the shape, volume, preparation, pre-crack and symmetry, besides the fact that the sole measured parameter is the load.

In the plot obtained from the test for load F versus crack mouth openning displacement (CMOD), the points of maximum load in the two cycles of loading and unloding are marked (points A and B). Dividing by 2, the points C and D are marked on the subsequent line of reloading. In the following, two straight lines are drawn passing in the points AC and BD (line 1 and 2). These lines are extrapolated to cross the horizontal axis of CMOD: obtaining points E and F. According to ISRM, the fracture toughness for "short rod" for inelastic materials is given by:

$$K_{SR} = \sqrt{\frac{1+p}{1-p}} \cdot \quad \frac{C_K \cdot 24 \cdot \overline{F}}{D^{1,5}} \tag{1}$$

where $p = \Delta X_0 / \Delta X$; ΔX is the AB projection on the CMOD axis and ΔX_0 is the distance EF, D is the nominal diameter of the specimen, C_K is a correction factor due to dimensional variation of the specimen and $\overline{F}$ is the average maximum load at points A and B.

2.2 The Three Point Bending Test of Prismatic Beam

This method relies on RILEM 1991 recommendation [5] and covers the determination of both the critical stress intensity factor K_{IC} and the critical crack tip opening displacement $CTOD_c$ of mortar and concrete, using the three point bending test of notched beams. The critical stress intensity factor K_{IC} is defined as the stress intensity factor calculated at the effective crack tip, utilizing the measured maximum load. The critical crack tip opening displacement $CTOD_c$ is defined as the displacement of the crack tip opening calculated from the mouth notch opening , CMOD, of the specimen, using the maximum measured load and the critical size of the effective crack. The critical stress intensity factor and the critical crack tip opening displacement in conjunction with the Young modulus E, are sufficient to characterize the strength to fracture and the energy dissipation of concrete and mortar. Figure 2 shows the configuration and geometry of a notched beam for three point bending test. This is the experimental method used in the present work and it is described below.

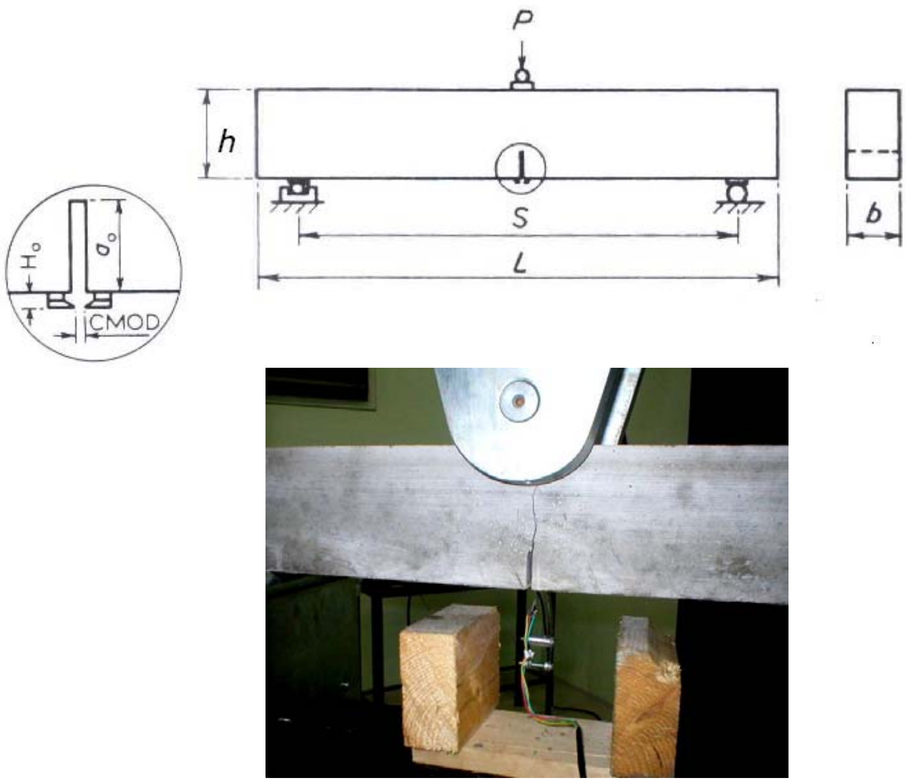

Figure 1. Three point bending test in a notched prismatic beam and its geometry:
S = 45 cm ; L = 55 cm ; h = b = 10 cm ; a_o = 2 cm; H_o= 2 mm.

3. MATERIALS AND EXPERIMENTAL PROCEDURES

The concrete mix proportion in mass for each test group of compression specimen and bending specimen were based on preliminary results. The mix proportions was:

Cement: 15% in mass (Portland cement CPV-ARI RS);
Fly ash: 10% of cement mass (fly ash from the thermoelectric Jorge Lacerda);
Aggregate (coarse): 40% in mass (rock number 1, nominal size 25 mm);
Sand (fine aggregate): 38% in mass (from Pirai region/Joinville);
Water: 6% in mass;
Plasticizer: 1% of the cement + ash mass.

The mechanical test were carried out in cylinder specimen that had dimension 100 x 200 mm, 100 mm in diameter, for the compression tests, and in prismatic beams with dimension 100 x 100 x 550 mm for the bending (flexural strength) and fracture toughness tests (see figure 1).

In the preparation of the concrete mix, Portland cement resistant to sulphate CPV-ARI RS plus fly ash, plasticizer Mastermix 393 N, sand obtained from the Joinville Pirai region and rocks size 1 (aggregate) from the local supplier Vogelsanger were used. In addition, solubilization and lixiviation tests were carried out to classify the ash in the following solid waste category as: inert solid waste. The Portland cement and fly ash particle size and shape can be seen in figure 3 and 4.

Table 1. Fine aggregate (Pirai sand) characteristics.

Material characteristic	Experim.
Modulus of fine-grained	2,11
Maximum diameter (mm)	2,40
Specific mass of grains (g/cm^3)	2,60
Material in powder (%)	1,50
Organic impurities (p.p.m)	>300
Argil as small blocks (%)	0,06

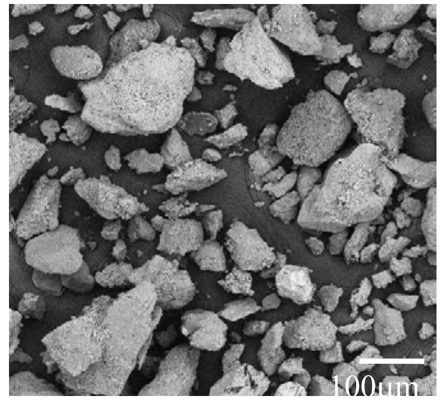

Figure 2. SEM photograph of Pirai sand.

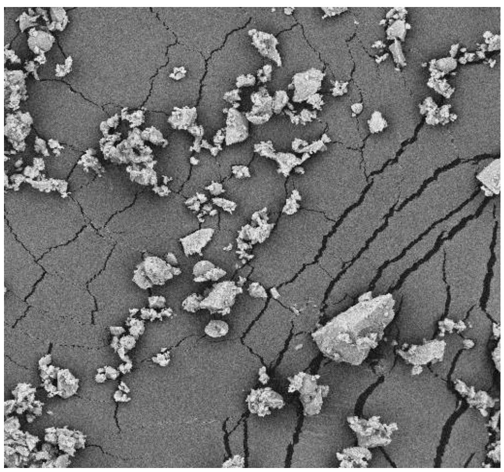
Figure 3. SEM photograph of Portland cement, showing particle size heterogeneities and the presence of residual ash. Magnification 500x.

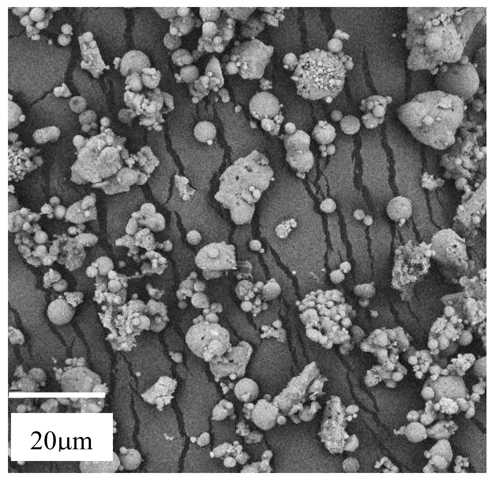

Figure 4. SEM photograph of fly ash, showing particle size and spheres that are characteristic of pozzolana cement. Magnification 500x.

A preliminary study has been performed with 120 cylindrical specimen, investigating the various factors that influences concrete strength as the ratio water/cement (w/c), fine and coarse aggregate size and the addition of fly ash in order to obtain the optimized conditions for the mix and procedure to prepare the concrete paste for obtaining a high strength concrete. The sand characteristics are shown in Table 1 and figure 2. After that, a replica with 34 cylindrical specimen for compression tests, 30 prismatic beams for four point bending or flexural strength and 10 notched prismatic beams for fracture toughness test were prepared with the optimized mix.

The concrete paste was prepared according to the Brazilian Standard Specifications NBR 5738 and NBR 9775 for determining the fine aggregate humidity. The NBR 7223 standard method was used to obtain the slump: the measured value was zero. In the procedure to made the paste, a dry mixture with cement, sand, ash and coarse aggregate was prepared inside a revolving drum. After that, water and plasticizer were added to the mix and the paste was mixed for 3 min. Following, the concrete paste was poured into the specimen moulds and vibrated at 60hz for 2 min for the cylindrical specimen and 3 min for the prismatic beams in order to obtain densification of the paste. The specimens were taken from the moulds after 24h for the cylindrical specimen and 48h for the prismatic beams. The mechanical tests were performed after 28 days of cure in lime water.

The compression tests were performed using a 200 ton hydraulic machine, made EMIC, and according to Brazilian standard. Four point bending tests for flexural strength were carried out in a 10 ton universal mechanical testing machine equipped with load cell, made EMIC, selecting the punch displacement velocity of 0.1mm/min.

Fracture toughness tests to obtain the parameter K_{IC}, the three point bending tests in a notched beam as seen in figure 2 were performed at room temperature, using the same 10 ton machine and a punch displacement velocity of 0.05mm/min. The crack mouth opening displacement CMOD was measured by a clip-gauge attached to the beam notch mouth located beneath the beam. The initial notch mouth thickness was 2 mm and the initial notch depth was a_o = 20 mm. During the test, a plot of load versus CMOD was obtained. According to RILEM recommendation [5], the loading process was stopped at near the maximum load and the load was released slowly to a low load level. Following, the specimen was loaded again with the same velocity until the final rupture. The fracture toughness parameter K_{IC} was calculated using the equation,

$$K_{IC} = 3\left(P_{máx} + 0{,}5W\right)\frac{S\left(\pi a_c\right)^{1/2} F(\alpha)}{2h^2 b} \tag{2}$$

where: P_{max} = maximum load [N] ; $W = W_o S / L$ [N] ; W_o = beam weight [N] ; S = distance between beam supports [m] ; a_c = effective critical crack length = a_o + physical crack growth [m];

$$F(\alpha) = \frac{1{,}99 - \alpha(1-\alpha)\left(2{,}15 - 3{,}93\alpha + 2{,}7\alpha^2\right)}{\sqrt{\pi^{1/2}(1+2\alpha)(1-\alpha)^{3/2}}} \quad ; \quad \alpha = a_c / h$$

4. RESULTS AND DISCUSSIONS

In table 2 below the mechanical properties results of structural concrete with replacement of 10% in mass of cement by fly ash in the concrete mixture is present. In figure 5, the fracture mechanism in concrete is shown.

Table 2. Fly ash concrete strength results.

Specimen Quantity	Mechanical test	Medium value	Weibull modulus
34	Compression strength (MPa)	46.0	13
30	Flexural strength (MPa)	5.18	17
10	Fracture toughness ($MPa.m^{1/2}$)	1.25	-

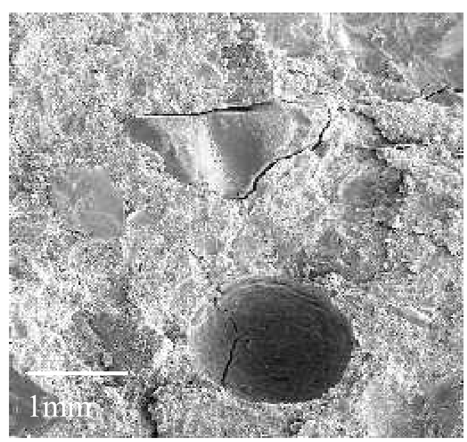

Figure 5. Fracture mechanism in concrete.

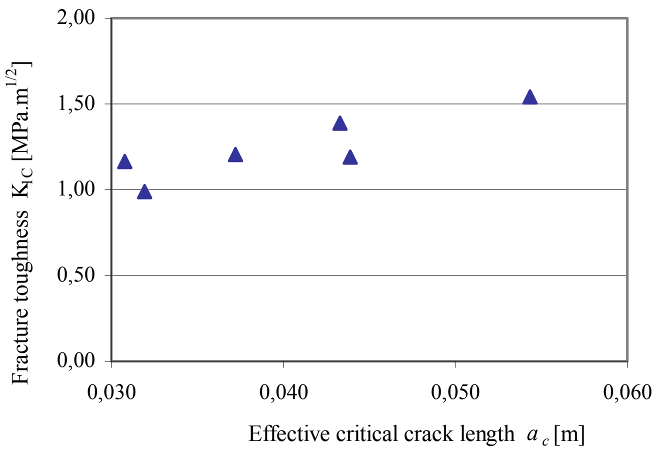

Figure 5. Fracture toughness results for three point bending tests of notched beams.

4. CONCLUSIONS

From the experimental results shown in the present work some conclusions can drawn about the replacement of 10% in mass of cement with fly ash in concrete: the compression strength was 46.0 MPa and the flexural strength was 5.2 MPa , indicating a high strength concrete. Fracture toughness was 1.25 MPa.m$^{1/2}$. Thus, it is possible to add class F fly ash to concrete. Fracture in concrete is due to rupture of the interface paste and aggregate, and the presence of pores.

5. ACKNOWLEDGEMENTS

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