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Mechanical Properties of High-Performance Concrete with Fly Ash

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Synopsis: High-performance concrete is generally produced using carefully selected high quality materials. These materials increase significantly the initial cost, hence, limiting its use. In this research work, the performance of concrete was enhanced through incorporating low cost untreated material like fly ash and crushed aggregates. Thus, it can be produced enhanced or even high-performance low cost concrete and, also, decrease significantly the use of cement and non-renewable natural resources (river/sea sand), contributing to the necessary sustainability of construction.

From experimental program, the effect of replacing cement by fly ash (up to 60%) in the mechanical properties (compressive strength, splitting-tensile strength, flexural-tensile strength and shear strength) was evaluated.

The results obtained show that it is possible to produce high-performance concrete with the selected materials replacing up to 40% of cement by fly ash. In specimens of such mixtures, cured at least 56 days, mechanical properties evaluated were similar to those of the control mixtures.

Keywords: fly ash, high-performance concrete, mechanical properties
INTRODUCTION

Nowadays, the world’s eco-system is faced with the growing problem of global warming which is associated with the emission of $CO_2$. The construction industry is responsible for a significant part of these emissions. The cement industry is a high consumer of energy and contributes with about 7% in total of $CO_2$ expelled to the atmosphere. On the whole, each ton of Portland cement produced releases about one ton of $CO_2$. With the objective of reducing these levels of $CO_2$, it is urgent to reduce the cement consumption. But, this reduction must be done without compromising the requirements of the performance of concrete structures.

Another environmental problem associated with the construction industry is the high consumption of non-renewable natural resources. The increase in construction, especially in the last decades, has provoked a significant reduction of these resources. So, it is mandatory to contribute to its maintenance.

High-performance concrete (HPC) has demonstrated to be a reliable alternative to conventional concrete, namely in special structures. In the meantime, HPC is, in general, produced using high quality selected materials, which results in a considerable increase of its initial costs and hinders its general use.

Hence, this research work was carried out with the objective of evaluating the possibility of producing low cost HPC using high quantities of fly ash (FA) for substitution of cement and using crushed aggregates, thus, reducing the consequences associated with high consumption of cement (C) and extraction of aggregates, particularly sand, from river beds, estuaries and sea coasts.
To accomplish the objectives described, an experimental program was carried out in order to evaluate the workability, mechanical properties and durability of concrete compositions, which were produced with 400 kg/m$^3$, 500 kg/m$^3$ and 600 kg/m$^3$ of binder content (C + FA) and cement substitution by FA of 0%, 20%, 40% and 60% (percentage of the binder weight).

The influence of the amount of binder, the percentage of cement replaced by fly ash, as well as the concrete age on the mechanical behaviour (compressive strength, splitting-tensile strength, flexural-tensile strength and shear strength) was assessed carrying out experimental tests. The results obtained are presented and analysed.

The durability of the mixtures produced was also evaluated, through chloride ion migration test, electrical resistivity and water absorption. The durability results obtained are presented elsewhere$^{1,2}$.

**MATERIALS, MIXTURE PROPORTIONS, MANUFACTURE AND CURING**

All the aggregates used in this research work were obtained from crushed granite of the same quarry. Two sands of maximum aggregate sizes ($D_{\text{max}}$) of 2.38 mm (fine sand) and 4.76 mm (coarse sand), and a coarse aggregate of $D_{\text{max}}$ of 9.53 mm were used as received, without any treatment.

Ordinary Portland cement (C) type CEM I 42.5R was used.

The FA was supplied by the Portuguese Thermoelectric Power Plant of Pego. The quantities of loss on ignition (LOI) varied between 6% and 9%, resulting in an average value over 7%. The LOI value is higher than the maximum allowed by the European Standard EN450$^3$ and the American Standard ASTM C618$^4$, which limit LOI to 5% and 6% respectively. This would mean that the FA used can be considered a poor quality FA, with high carbon content. However, previous studies$^4$ have shown that concrete using this FA achieved levels of performance similar to those using the same fly ash when the excess unburned carbon was removed by sieving. Table 1 indicates the principal chemical and physical properties of C and FA.

The superplasticizer (SP) used had a chemical composition based on naphthalene sulphonate formaldehyde condensates. In previous works$^5$, the optimum SP solid content was estimated to be between 0.5% and 1.0% of the mass of binder. Due to economic reasons, the value of 0.5% was adopted.

More details of the main characteristics of the materials are elsewhere$^{1,2,5}$.

Twelve different mixtures corresponding to three binder contents ($B$) and four levels of cement replacement were studied. Binder contents of 400 kg/m$^3$,
500 kg/m$^3$ and 500 kg/m$^3$ were adopted and the corresponding water/binder ratio (W/B) was maintained constant for each binder content and was determined experimentally to achieve 200 mm slump when 40% FA was used. The mixture proportions were estimated using the Faury method and are presented in Table 2, where the workability obtained using the Slump and the Flow Table test is also indicated.

Cubic specimens of 100 mm edge, cylindrical specimens of 150 mm diameter and 300 mm height and 850x100x100 mm$^3$ beam specimens were moulded.

The specimens were placed into a curing room, at a temperature of 21°C and at a constant relative humidity of 80%. The specimens were demoulded 24 hours after have been cast, and were stored immersed in water at 21°C until their preparation for testing.

**EXPERIMENTAL RESULTS AND ANALYSIS**

The influences of the age and percentage of cement replaced by FA on the studied mechanical properties were evaluated. Each value presented is the average of the results recorded in three specimens. The results obtained are presented and analysed. The possible correlations are discussed.

**Compressive Strength**

Cubic specimens with 100 mm edge and cylindrical specimens of 150 mm diameter and 300 mm height were tested for evaluating the compressive strength.

The compressive strength of the produced concretes was evaluated from uniaxial compression tests carried out in a closed-loop servo controlled compression-testing machine. A linear voltage displacement transducer (LVDT) of 5 mm linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.12 mm/min (cylindrical specimens) or 0.36 mm/min (cubic specimens).

Figs. 1, 2 and 3 show the average values obtained in cubic specimens ($f_{c,\text{cube}}$), as well as the best fit of results using the hyperbolic equation (Eq. 1), proposed by Carino$^6$ and Knudsen$^7$.

$$f_c = f_{\text{max}} \frac{k(t-t_0)}{1+k(t-t_0)}$$  \hspace{1cm} (Eq. 1)

where $f_c$ is the compressive strength predicted at a given time $t$; $t_0$ is the time needed before the strength gain begins ($t_0 = 0$ was considered); $f_{\text{max}}$ is the final strength when $t$ tends to infinity; and $k$, expressed in days$^{-1}$, is a constant.
Results obtained (see Figs. 1, 2 and 3) indicate that:

a) Low cost HPC can be produced using materials currently used for conventional concrete, achieving compressive strength in cubic specimens ($f_{cm,cube}$) around 60 MPa at 28 days and 65 MPa at 56 days for a total binder content ($B$) of 500 kg/m$^3$. Increasing $B$ to 600 kg/m$^3$, $f_{cm,cube}$ rises to about 70 MPa at 28 days and 75 MPa at 56 days;

b) The use of $B = 400$ kg/m$^3$ gives lower values of $f_{cm,cube}$. The maximum $f_{cm,cube}$ was reached when FA was not used, achieving about 45 MPa at 28 days and approximately 50 MPa at 56 days;

c) In spite of the low strengths measured in the early ages, the compositions with 60% of FA obtained relatively high compressive strength at longer curing times. The compressive strength of such compositions was about 50 MPa at 90 days for $B = 500$ kg/m$^3$ and around 65 MPa at 90 days for $B = 600$ kg/m$^3$. This is especially significant bearing in mind the low cement content of these mixtures, i.e. $C = 200$ kg/m$^3$ and $C = 240$ kg/m$^3$;

d) As expected, the rate of strength gain with the time is smaller with higher percentages of cement replacement. This is due to the lower rate of FA pozzolanic reaction;

e) The composition with $B = 500$ kg/m$^3$ and 40% FA replacement indicates strength gain far beyond the expected. However, this behaviour may be due to experimental problems. Compressive strength tests using cylindrical specimens showed that the strength gain with time for this mixture was similar to the mixture with $B = 600$ kg/m$^3$ and FA = 40%.

Splitting-Tensile Strength

The splitting-tensile strength of the studied concretes was determined from diametric compression tests carried out in a closed-loop servo controlled compression-testing machine. A LVDT of 5 mm linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.12 mm/min.

The specimens used results from the cutting of the 300 mm height cylindrical specimens moulded. They were obtained by cutting one specimen in three similar portions of 150 mm diameter and about 95.5 mm height.

The compositions with $B = 400$ kg/m$^3$ were tested at 7, 28, 56, and 330 days while the others were tested at 7, 28, 56 and 420 days.

Fig. 4 shows the variation of splitting-tensile strength ($f_{cm,sp}$) with the specimen’s age and FA content. The results obtained indicate that:

a) The $f_{cm,sp}$ is clearly affected by the presence of FA in the concrete composition. The higher the amount of FA the lower the $f_{cm,sp}$. However, this effect is detected at early ages and is attenuated with curing time;
There is a small effect of binder content on splitting-tensile strength at long curing times, i.e. longer than 28 days. For example, the difference between compositions with 20% of FA and $B = 500 \text{ kg/m}^3$ or $B = 600 \text{ kg/m}^3$ is about 10%.

The $f_{cm,sp}$ can be predicted using the compressive strength of cylindrical specimens ($f_{cm,cil}$), using expressions suggested in the available references such as:

**ACI Committee 363**\(^8\) – $21 \text{ MPa} < f_{cm,cil} < 83 \text{ MPa}$:

$$f_{cm,sp} = 0.59 \sqrt{f_{cm,cil}} \quad (\text{MPa})$$  
(Eq. 2)

**Carrasquillo, Nilson and Slate**\(^9\) – $21 \text{ MPa} < f_{cm,cil} < 83 \text{ MPa}$:

$$f_{cm,sp} = 0.54 \sqrt{f_{cm,cil}} \quad (\text{MPa})$$  
(Eq. 3)

**Ahmad and Shah**\(^10\) – $f_{cm,cil} < 84 \text{ MPa}$:

$$f_{cm,sp} = 0.462 f_{cm,cil}^{0.55} \quad (\text{MPa})$$  
(Eq. 4)

**Burg and Ost**\(^11\) – $85 \text{ MPa} < f_{cm,cil} < 130 \text{ MPa}$:

$$f_{cm,sp} = 0.61 \sqrt{f_{cm,cil}} \quad (\text{MPa})$$  
(Eq. 5)

**Iravani**\(^12\) – $50 \text{ MPa} < f_{cm,cil} < 100 \text{ MPa}$:

$$f_{cm,sp} = 0.57 \sqrt{f_{cm,cil}} \quad (\text{MPa})$$  
(Eq. 6)

Fig. 5 presents the experimental results and the predicted values using the above mentioned equations. It can be seen that, for lower strength classes, the predicted values are mostly higher than the experimental values, while this tendency is inverted for higher strength concretes. This tendency is more pronounced for the lower values of $f_{cm,sp}$ which correspond to the lower compressive strengths detected for curing times up to 7 days and for the compositions with higher quantities of FA.

Using the overall results of the tested compositions, equations (Eq. 7) and (Eq. 8) are suggested that give a better fit for the data obtained with a correlation coefficient equal to 86% and 87%.

$$f_{cm,sp} = 0.8062 \sqrt{f_{cm,cil}} - 1.7375$$  
(Eq. 7)

$$f_{cm,sp} = 35.2584 f_{cm,cil} - 40.7074$$  
(Eq. 8)
Fig. 6 indicates that both equations have similar results for $f_{cm,fl}$ between 30 MPa and 70 MPa.

**Flexural Tensile Strength**

The flexural behaviour of the produced concretes was evaluated carrying out three-point bending tests according to RILEM recommendations using $850 \times 100 \times 100 \text{ mm}^3$ beam specimens.

In the pre-test preparation phase of beam specimens, a notch of 5 mm width and 25 mm depth was sawn in a beam face parallel to the casting direction.

Loading, support conditions and the arrangement of the LVDTs are show in Figs. 7 and 8. The tests were controlled by LVDT1 of 5 mm of linear measuring length and 0.05% of accuracy. A Japanese-Yoke-system was used to avoid that LVDT1 has registered extraneous displacements (see Fig. 7). LVDT2 and LVDT3 were placed according to Fig. 7 for the estimation of the deformations at the fracture zone. LVDT2 had 5 mm of linear measuring length and 0.09% of precision, while LVDT3 had 6.3 mm of linear measuring length and 0.05% of precision. A load cell of 10000 N of bearing capacity and 0.05% of accuracy was used to measure the force. All the tests were performed with a mid-span deflection increase at a constant rate of 0.36 mm/min. The tests were carried out using closed-loop equipment developed in the University of Minho.

The compositions with $B = 400 \text{ kg/m}^3$ were tested at 155 days, while the other compositions were tested at 7, 28, 56 and 165 days.

Fig. 9 shows the variation of flexural-tensile strength ($f_{cm,fl}$) with the specimen’s age and FA content for compositions with $B = 500 \text{ kg/m}^3$ and $B = 600 \text{ kg/m}^3$. Results obtained indicate that:

a) For the designed compositions $f_{cm,fl}$ remained practically constant for ages greater than 56 days. For compositions without FA, $f_{cm,fl}$ remained constant after 28 days of curing. For compositions with $B = 500 \text{ kg/m}^3$, apart 500/FA60 mixture, marginal increments on the $f_{cm,fl}$ were observed after 28 days. Similar trend was verified for $B = 600 \text{ kg/m}^3$, but only after 56 days of curing;

b) In the compositions with 60% of FA, values of $f_{cm,fl}$ significantly smaller than the values recorded in the other mixtures were obtained. However, increasing the binder content from 500 kg/m$^3$ to 600 kg/m$^3$, $f_{cm,fl}$ became closer to that of the remaining compositions;

c) Increasing the binder content from 500 kg/m$^3$ to 600 kg/m$^3$ had a marginal effect on $f_{cm,fl}$. Only in compositions with 60% of FA, the use of higher binder contents seems to be advantageous.
Fig. 11 shows the compressive strength $f_{cm,ct}$ versus $f_{cm,ft}$. The results obtained confirm splitting-tensile strength results (see Fig. 9). Large variations are noted in the results from the flexural test.

Fig. 11 shows the splitting-tensile strength results ($f_{cm,sp}$) versus those obtained in flexural tests ($f_{cm,ft}$). The best fit of data is also presented in Fig. 11. It can be noted that values of $f_{cm,ft}$ are larger than those of $f_{cm,sp}$.

The discrepancy between the values of $f_{cm,sp}$ and $f_{cm,ft}$ has already been identified by other authors. It is noted that the fracture mechanism apparently is not the same for the two tests. Visual observation of the fractured surface of the specimens subjected to flexural tests indicates that fracture surface has occurred along the aggregate-paste interface, whereas in splitting tests, the fracture surface passes through the large aggregates. Thus, the results from the two tests may be not directly related.

The axial tensile strength ($f_{cm}$) can be estimated using the results of the splitting test as suggested by CEB-FIP, which considers that $f_{cm}$ is 90% of $f_{cm,sp}$. Using $f_{cm,ft}$ it is also possible to estimate $f_{cm}$, according to CEB-FIP:

$$f_{cm,ft} = f_{cm} \left( \frac{d}{d_0} \right)^{-0.7} \alpha_d \left( \frac{d}{d_0} \right)^{-0.97}$$

(Eq. 9)

where $d$ is the height of the specimen and $d_0 = 100$ mm. The parameter, $\alpha_d$, depends on the ductility of the concrete and decreases as the concrete becomes less ductile. If $\alpha_d$ is considered a constant and equal to 1.5, as indicated by CEB-FIP, the estimated values of $f_{cm}$ are slightly higher than the results from the splitting tests, as can be noted in Fig. 12. However, using the best fit of data for estimating the value of $\alpha_d$ ($\alpha_d = 1.7777$) it is possible to minimise the deviations (see Fig. 12).

Shear strength

The shear strength was estimated by loading 100 mm side cubic specimen conveniently cut, so that shear stress would occur on a section of 30x100 mm$^2$ (see Fig. 13). Compositions with $B = 400$ kg/m$^2$ were tested at an age of 330 days while the other mixtures were tested at 7, 28, 56 and 420 days.

The shear strength tests were performed in the closed-loop equipment used for flexural tests. A LVDT of 5 mm linear measuring length and 0.09% of accuracy was used to control the test, at a displacement rate of 0.09 mm/min.
The shear strengths ($\tau_m$) obtained are presented in Fig. 14. It is noted that shear strength gain with curing time and FA content is similar to the compressive strength gain and other properties already mentioned. However, it's still possible to state that:

a) $\tau_m$ remained approximately constant for curing times between 56 and 420 days, irrespective of the binder and FA content;

b) For early ages, increasing quantities of FA decreases $\tau_m$ of the concretes studied. This effect is particularly noticeable at 7 days curing time, becoming less significant at long curing times. Mixtures with up to 40% of FA show similar values of $\tau_m$ at 56 days curing time;

c) Compositions made with 60% of FA show values of $\tau_m$ significantly lower than the other mixtures. Mixtures with 20% of FA resulted in $\tau_m$ slightly higher than mixtures without FA. Mixtures with $B = 600 \text{ kg/m}^3$ showed practically the same shear strength for 40% of FA and 0% of FA;

d) The increase of $B = 500 \text{ kg/m}^3$ to $B = 600 \text{ kg/m}^3$ was beneficial only at short curing times and in compositions with 60% of FA content, becoming practically irrelevant at 28 days and FA up to 20%.

The best fit of data for shear strength versus compressive strength is shown in Fig. 15. The results obtained indicate that the gain in shear strength is smaller than the compressive strength gain.

CONCLUSIONS

The results showed that FA addition decrease the concrete mechanical properties, mainly when evaluated at young ages. This undesirable effect of FA decreases with the age of the concrete.

In general terms, at the age of about 56 days, the compressive strength, the splitting-tensile strength, the flexural-tensile strength and the shear strength of the compositions with FA content up to 40% (percentage of the binder weight) are not significantly different. This indicates that, HPC can be designed with the use of relatively high percentage of FA (up to 40% of the binder content) since live loads in a concrete structure are, in general, applied when the concrete is several months old.

In concrete compositions with 60% of binder replaced by FA, the mechanical properties evaluated were considerably lower than those of the corresponding reference series (0% of FA). However, it is interesting to note the relatively high values of the mechanical properties at long curing times, achieved with such a high FA content.

In most cases, a good linear correlation was obtained between the evaluated mechanical properties (splitting-tensile strength, flexural-tensile strength and shear strength) and the square root of compressive strength. This indicates that
REFERENCES


Table 1 – Chemical composition and physical properties of the cement and fly ash

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<tr>
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<th>Cement</th>
<th>Fly Ash</th>
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<tr>
<td>$SiO_2$ (%)</td>
<td>19.71</td>
<td>42.16 – 58.46</td>
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<tr>
<td>$Al_2O_3$ (%)</td>
<td>5.41</td>
<td>21.04 – 32.65</td>
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<td>$Fe_2O_3$ (%)</td>
<td>3.34</td>
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<tr>
<td>CaO total (%)</td>
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<tr>
<td>MgO (%)</td>
<td>2.58</td>
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<tr>
<td>SO$_3$ (%)</td>
<td>3.22</td>
<td>0.22 – 1.04</td>
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<tr>
<td>Cl (%)</td>
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<td>0.00 – 0.06</td>
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<tr>
<td>Free CaO (%)</td>
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<td>Loss on ignition (%)</td>
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<td>Insoluble residue (%)</td>
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<td>Specific weight (kg/m$^3$)</td>
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<td>Blaine specific surface (m$^2$/kg)</td>
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<td>Finessness (%)</td>
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<td>Water demand (%)</td>
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Table 2 – Concrete mixture proportions and workability

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<th>Fine Sand (kg/m$^3$)</th>
<th>Course Sand (kg/m$^3$)</th>
<th>Course Aggregate (kg/m$^3$)</th>
<th>Slump (mm)</th>
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<td>592</td>
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Fig. 1 – Compressive strength

\( B = 400 \text{ kg/m}^3 \)

Fig. 2 – Compressive strength

\( B = 500 \text{ kg/m}^3 \)

Fig. 3 – Compressive strength

\( B = 600 \text{ kg/m}^3 \)
Fig. 4 – Splitting-tensile strength

Fig. 5 – Compressive strength vs. splitting-tensile strength

Fig. 6 – Best fit of compressive strength vs. splitting-tensile strength
Fig. 7 – Three-point bending test set-up

Fig. 8 – Three-point bending test photo

Fig. 9 – Flexural-tensile strength

Fig. 10 – Compressive strength vs. flexural-tensile strength

Fig. 11 – Splitting-tensile strength vs. flexural-tensile strength
Fig. 12 – Estimated uniaxial tensile strength

Fig. 13 – Shear strength test

Fig. 14 – Shear strength

Fig. 15 – Compressive strength vs. shear strength