DURABILITY OF HIGH-PERFORMANCE CONCRETE WITH FLY ASH

Aires Camões, Rui Miguel Ferreira, J. Barroso de Aguiar, Saíd Jalali

ABSTRACT. High-performance concrete (HPC) is usually produced using high quality materials. These high quality constituents drastically increase the initial cost of HPC, hence hindering its more widespread use. Therefore, the main goal of this research project was to produce a low cost enhanced performance concrete or even a low cost HPC, using low quality fly ash and locally available crushed aggregates. In this way, a significant reduction in the use of Portland cement, as well as that of scarce natural resources, would be obtained. The effect of high percentages of fly ash and crushed aggregates on concrete performance was studied by comparing the mechanical and durability performances of such concretes with nominally similar types of concrete with no fly ash incorporated. The results obtained indicate that it is possible to produce concrete in the low range of HPC with up to 65 MPa at 56 days by replacing up to 40% of cement with as received fly ash using crushed granite aggregates. Furthermore, it was observed that workability and durability both increased significantly when fly ash partially replaced Portland cement.

Keywords: High performance concrete, High volume fly ash concrete, Durability, Sustainability, Chloride diffusion, Electrical resistivity, Capillary absorption.

A Camões is Research Assistant in the Department of Civil Engineering at the University of Minho, Guimarães, Portugal, presently researching high performance concrete material properties.

R M Ferreira is Research Assistant presently researching durability design and quality assurance in concrete construction.

J B Aguiar is Associate Professor, teaching construction materials at the University of Minho and is principal research area is focused in adhesion between polymers and concrete.

S Jalali is Associate Professor, teaching construction materials at the University of Minho, is coordinator of EU and of nationally funded research projects on Eco-efficient and innovative construction materials.

INTRODUCTION

The world's eco-system is faced with the growing problem of global warming which is associated with the emission of CO_2 into the atmosphere. It is a well known fact that for every ton of Portland cement produced, approximately one ton of CO_2 is released. To reduce the CO_2 emissions related to cement production, the use of Portland cement needs to be reduced without compromising the performance of the concrete structures.

The emission of CO_2 is only one of the many problems presently facing the construction industry. The increase in the volume of construction in the last few decades has resulted in a rampage of our natural resources. The natural resources employed in concrete are finite, and so the sustainability of construction needs to be taken into consideration.

High-performance concrete (HPC) is a viable alternative to the conventional concrete for special structures. It is usually produced using high quality materials. These constituents drastically increase the initial cost of HPC, hence hindering its more widespread use.

The main goal of this research project was to produce a HPC in which a significant percentage of Portland cement was replaced by fly ash, and in which the aggregates used were obtained from locally available crushed granite, thus eliminating the use of river sand or natural coarse aggregates. In Portugal, the massive utilisation of natural aggregates during the last decades is causing environmental problems associated with alterations in river morphology, which in turn affect the safety of infrastructures.

In order to achieve the aims of this research, an experimental program was performed which included the evaluation of the mechanical properties, workability and durability of the proposed concretes. The research work studied performance of concretes with 0, 20%, 40% and 60% Portland cement replacement by fly ash, while the total binders employed were 400 kg/m^3, 500 kg/m^3 and 600 kg/m^3.

The effect of a high volume of fly ash was studied by evaluating the mechanical and durability performances of the designed concretes. The durability of the concretes produced was evaluated through a capillary water absorption test, an electrical resistivity test and an apparent coefficient of diffusion using non-steady state chloride migration tests (CTH rapid method).

EXPERIMENTAL PROGRAM

Materials

Aggregates

All the aggregates used in this research work were obtained from crushed granite. Two sands with maximum aggregate sizes (D_{MAX}) of 2.38 mm and 4.76 mm, and a coarse aggregate with a D_{MAX} of 9.53 mm were used as received, with no previous treatment.

Cement and fly ash

The cement used was an ordinary Portland cement type CEM I 42.5 R. The fly ash came from the Pego Power Plant in Portugal, with a loss on ignition (LOI) which varied between 6% and 9%. The LOI exceeded the maximum values established by European standards [1]. However, studies have shown that, at least for this fly ash, a high LOI does not have a deleterious effect on the cement pastes and mortars [2]. Table 1 shows the oxide content of the cement and the fly ash used. Table 2 presents the estimated compound composition of the cement using Bogue's expressions [3]. Table 3 shows some physical characteristics of the cement and the fly ash.

Table 1 – Oxide composition of the cement and fly ash

Chemical Composition	Cement (%)	Fly Ash (%)
SiO_2	19.71	42.16 – 58.46
Al_2O_3	5.41	21.04 – 32.65
Fe_2O_3	3.34	3.51 – 9.13
CaO	61.49	1.67 – 9.18
MgO	2.58	0.65 – 2.59
SO_3	3.22	0.22 – 1.04
Cl^-	0.01	0.00 – 0.06
Free Lime	0.81	0 – 0.12
Loss on ignition	2.52	5.60 – 9.28
Insoluble residue	1.94	–

Table 2 – Estimated compound composition of the cement

Compound Composition	(%)
C_3S	61.61
C_2S	4.55
C_3A	8.69
C_4AF	10.15
CSH	5.47

Table 3 – Physical characteristics of the cement and the fly ash

Physical Characteristics	Cement	Fly Ash
Specific Weight (kg/m^3)	3150	2360
Blaine Specific Surface (m^2/kg)	358.4	387.9
Fineness - µm (%)	(>90) 1.7	(>45) 14.1 – 31.6
Water demand (%)	28.0	29.7

Superplasticizer

The superplasticizer used had a chemical composition based on naphthalene sulphonate formaldehyde condensates. The amount of SP used was estimated measuring the fluidity of mortars and pastes. Results indicated the saturation point (optimum quantity of SP) to be between 0.5% and 1.0% weight of binder [4,5]. For economic reasons, the value of 0.5% was adopted in this research.

Mix Design

Twelve different mixes corresponding to 3 binder contents and 4 levels of cement replacement were used. The binder contents, B, were fixed at 400 kg/m^3, 500 kg/m^3 and 600 kg/m^3 whilst the water/binder ratios, W/B, were respectively 0.40, 0.30 and 0.25. The aggregate composition was determined using the Faury method. The mix designs used are presented in table 4 as well as the workability obtained using the Slump and the Flow Table tests.

Table 4 – Concrete mix proportions and workability

Mix	W/B	C (kg/m^3)	FA (kg/m^3)	Sand 1 (kg/m^3)	Sand 2 (kg/m^3)	Course Aggregate (kg/m^3)	Slump (cm)	Flow Table (cm)
B400FA0	0.40	400	0	613.56	233.55	857.45	10.5	45.0
B400FA20	0.40	320	80	591.96	262.38	878.58	21.0	48.5
B400FA40	0.40	240	160	552.99	284.75	875.65	18.0	55.0
B400FA60	0.40	160	240	503.44	300.96	855.01	20.5	53.5
B500FA0	0.30	500	0	502.92	308.43	865.61	2.5	31.5
B500FA20	0.30	400	100	461.85	334.01	869.82	10.5	39.5
B500FA40	0.30	300	200	406.91	349.01	847.11	20.5	47.4
B500FA60	0.30	200	300	364.24	373.70	848.70	23.0	55.0
B600FA0	0.25	600	0	377.30	367.85	850.73	3.5	35.0
B600FA20	0.25	480	120	326.57	399.51	856.01	12.5	36.5
B600FA40	0.25	360	240	271.28	407.93	832.76	20.0	51.0
B600FA60	0.25	240	360	223.26	421.23	824.23	23.0	53.0

The specimen moulded from the concrete mixes was stored in a chamber with a temperature of 21ºC and a constant relative humidity of 80%. At the age of 24 hours, the specimen were removed from the moulds and stored in water, at the same temperature, until the date of testing.

EXPERIMENT RESULT AND DISCUSSION

Compressive Strength

The effect of fly ash on the mechanical properties of the concrete was evaluated by compressive strength tests performed on a 100x100x100 mm^3 cube specimen in a displacement-controlled universal testing machine. In Figs. 1-3, the compressive strength test results versus curing times are presented for the B400, the B500 and the B600 concretes.

The equation proposed by Jalali [6,7] for the prediction of strength gain with time was used to evaluate the overall strength gain behaviour of the mixes studied. The best fits of data are presented in Figs. 1-3.

The results obtained indicate that during the initial curing period the strength gain is slower as the amount of fly ash increases. For B500 and B600, a 20% replacement of cement by fly ash positively influences the compressive strength for curing times of 150 to 200 days. For B600 concrete, even a substitution of up to 40% enhances the compressive strength. This can be explained by the large amounts of calcium hydroxide produced, due to the large amount of cement which fly ash could react with. Results from the B400 mix indicate a reduction in compressive strength, even for 20% replacement, for up to 200 days curing. This result was not expected, as it is widely accepted that the compressive strength for 20% replacement is usually equal to that of concrete with no fly ash. The low quality of the fly ash used is probably responsible for the results obtained.

Fig. 2 clearly indicates two levels of strength: B500 with no fly ash and 20% fly ash exhibit similar compressive strengths, while 40% and 60% replacements present a clearly lower level of strength. This distinction is not apparent in the case of B400 concrete. For B600 concrete, two distinct levels of strength, one for 60% replacement and one for the rest of the mixes, can be seen. It is interesting to note that the percentage of cement replacement, while strength is maintained, increases as binder content is increased.

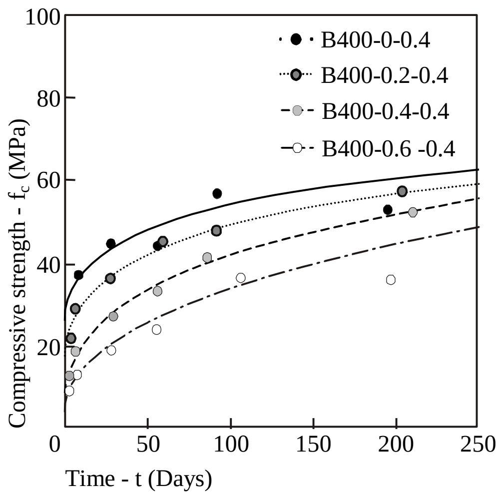

Figure 1 – Compressive strength with time for concrete B400.

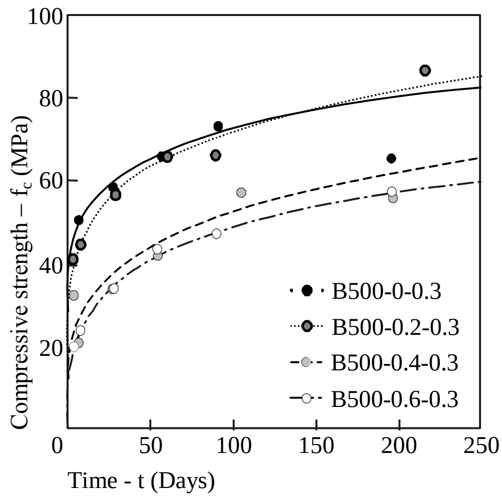

Figure 2 – Compressive strength with time for concrete B500.

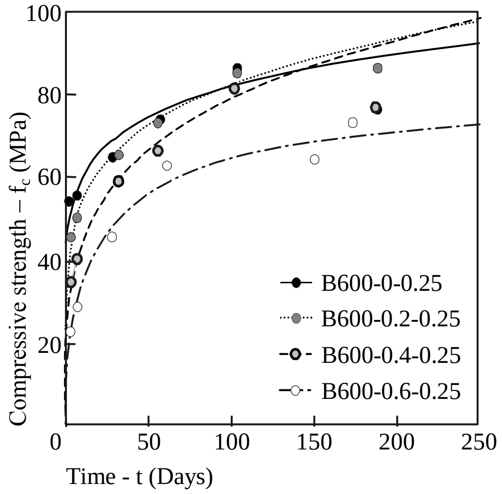

Figure 3 – Compressive strength with time for concrete B600.

Considering the effect of binder content on strength, it can be seen that higher compressive strengths are achieved with higher binder contents. B400, B500 and B600 mixes achieved 60, 80 and 90 MPa at 200 days, while at 250 days they achieved 62, 85 and 100 MPa. When comparing these strength gains it can be seen that 5 kg and 6.7 kg of binder rendered a 1 MPa increase of strength for B500 and B600 at 200 days, while at 250 days only 4.4 and 5.3 kg were needed. It can be stated that the efficiency of the binder in terms of compressive strength increases as the curing time increases.

Chloride Migration Test

The durability of mixes used was evaluated by estimating the chloride diffusion coefficient using the CTH Rapid Method procedure, developed by Luping [8]. In this method the diffusion coefficient is determined for a non-steady state when a potential of 40 V across a 50 mm thick specimen for a recommended duration, based on the initial current, is applied. The depth of penetration of the chloride front is determined by a colorimetric method using silver nitrate. The average penetration, measured with a precision of 0.5 mm, was considered to be the depth of penetration. The diffusion coefficient is obtained using the equation:

$$D = \frac{R \cdot T \cdot L}{z \cdot F \cdot U} \cdot \frac{x_d - \alpha \cdot \sqrt{x_d}}{t} \tag{1}$$

with:

$$\alpha = 2 \cdot \sqrt{\frac{R \cdot T \cdot L}{z \cdot F \cdot U}} \cdot erf^{-1}\left(1 - \frac{2 \cdot c_d}{c_0}\right) \tag{2}$$

where:

D: diffusion coefficient, m^2/s;
z: absolute value for ion valence, for chlorides, $z = 1$;
F: Faraday constant, $F = 9.648 \times 10^4$ J/(V.mol);
U: absolute value of potential difference, V;
R: gas constant, $R = 8.314$ J/(K.mol);
T: solution temperature, K;
L: specimen thickness, m;
x_d: penetration depth, m;
t: test duration, seconds, $t = t_{CTH} \times 3600$;
erf^{-1}: inverse of error function;
c_d: chloride concentration at which the colour changes, $c_d \approx 0.07$ N;
c_0: chloride concentration in the upstream cell, N;

Each coefficient of chloride diffusion obtained is the average of six tests done on 6 nominally identical specimens.

Figure 4 presents the results of the diffusion coefficients for one year old specimen. The effect of fly ash content on the diffusion coefficient is clearly visible. A 20 % replacement of cement by fly ash indicates a significant reduction in the diffusion coefficient for the concrete with a binder content of 400 kg/m^3 and to a lesser degree for the remaining concretes. Further increase of fly ash content seems to have a marginal effect on the diffusion coefficient. With respect to durability and the diffusion coefficient, there seem no be no gains in increasing the overall content of binder from 500 kg/m^3 to 600 kg/m^3. It is interesting to note that even for the lowest binder content, B400, with 60% fly ash, the diffusion coefficient (D) obtained is lower than that of the mixtures with the higher cement content, B600FA0 with no fly ash.

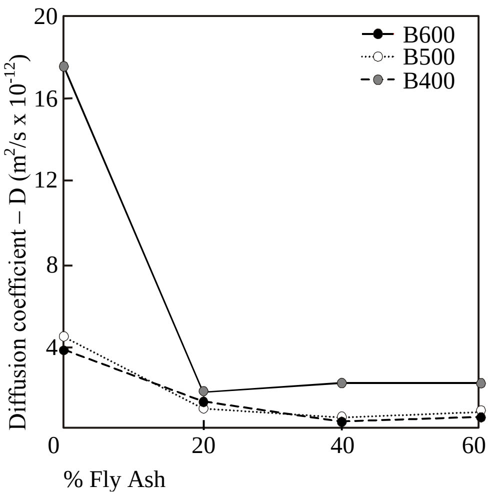

Figure 4 – Evolution of the diffusion coefficient with fly ash and binder contents.

Based on the classification presented by Gjørv [9] in which the diffusion coefficient values are divided into five categories (i.e.: from low to extremely high) based on the concrete's resistance against chloride diffusion (see Table 5), the substitution of up to 20% of cement by fly ash in the case of the B400 concrete results in the qualitative improvement of the concrete's chlorides diffusion resistance, moving it from a classification of low to very high. For the other concretes, B500 and B600, the qualitative improvement is less pronounced and moves them from the very good classification to extremely good.

Table 5 – Relationship between accelerated chloride diffusivity based on non-steady state migration testing and resistance against chloride diffusion [9]

Chloride diffusivity ($m^2/s \times 10^{-12}$)	Resistance
> 15	Low
10 – 15	Moderate
5 – 10	High
2.5 – 5	Very high
< 2.5	Extremely high

Electrical Resistivity

The electrical resistivity was determined using the initial current intensity values of the CTH Rapid Method test. Ohm's Law was used to estimate the resistivity values.

Each value of electrical resistivity represents an average of six tests done on individual specimens.

Fig. 5 indicates that the replacement of cement by fly ash increases the resistivity of all the mixes studied and is more significant for high binder content concretes. For B500 and B600 there is a significant increase for up to 40% cement replacement and a rapid decrease for higher fly ash content. Results indicate the highest resistivity values for 40% fly ash content, irrespective of binder content. This does not match the compressive strength tests, but is in general agreement with the apparent coefficient of diffusion estimated.

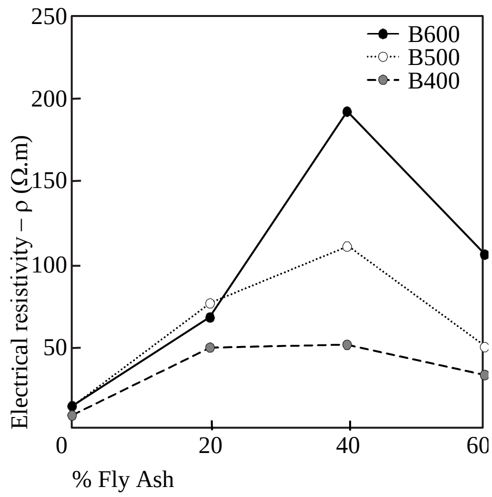

Figure 5 – Variation of the electrical resistivity with fly ash and binder contents.

It is interesting to note that this test can not distinguish between plain concretes with different cement content, while the CTH Rapid test clearly distinguished B400 from the other concretes. For the concretes with fly ash, however, the electrical resistivity test seemed more sensitive and clearly distinguished the different concretes. It remains to be determined what part of this effect is due to the presence of fly ash and what portion is due to a more compact structure, resulting from the finer hydration products from fly ash lime reaction.

Capillary Absorption

The capillary water absorption test was performed to obtain more data regarding the durability behaviour of the mixes studied. The test followed the LNEC specification E393 [10], which is based on the RILEM CPC11.2 draft recommendation [11]. The coefficient of capillarity absorption, S, is the slope of the curves representing water absorbed per unit area versus square root of time during the initial four hours of testing for all the mixes studied. Each coefficient of capillary absorption is the average of four tests performed on four nominally identical specimens.

The results presented in figure 6 indicate that the addition of fly ash decreases the coefficient of capillary water absorption (S). The increasing of the quantity of binder, associated with a lower W/B ratio, also decreases this coefficient (S). This effect is, however, only pronounced up to 500 kg/m^3 binder content. Higher binder contents do not seem to affect S significantly.

CONCLUSIONS

In order to evaluate the possibility of producing high performance-low cost concrete, laboratory tests were performed on specimen of concrete with increasing binder contents and cement replacements by fly ash. The compressive strength tests indicate that concrete with 65 MPa strength at 56 days can be produced using B500 with up to 20% cement replacement and B600 with up to 40% cement replacement. This strength was obtained with the specimens cured in water until 56 days. If these curing conditions were not maintained during this time, surely the strength would decrease. The other mixes studied did not achieve this level of strength at this age. It is noted that the efficiency of the binder, i.e. the amount needed for each 1 MPa increase in strength compared to B400, increases with increasing curing time. Furthermore, it was noted that the optimum amount of cement replacement increases with curing time and binder content.

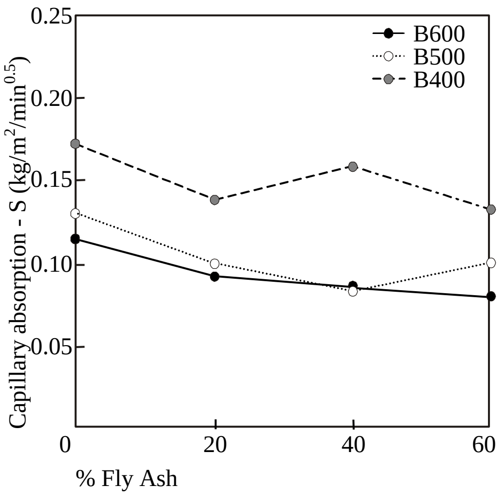

Figure 6 – Variation of the capillary absorption with fly ash and binder contents.

The addition of FA = 60% allows the obtaining of concrete with considerably lower mechanical characteristics, in comparison of the others. However, concerning the low quantities of cement existing in the mix, those may be considered as concrete with a good economic performance.

The durability of the mixes was evaluated using three different tests. They were selected between those commonly considered to characterise durability. All the tests indicate a better performance for concretes with fly ash. However, the optimum percentage of replacement varies between the performed tests. While the resistivity test indicates higher values for 40% substitution, the other two tests showed a tendency towards amelioration of durability without indicating a specific optimum point. Further research is needed to determine the effect of fly ash on the resistivity of concrete by itself and after changing the microstructure of concrete when reacted with lime.

The CTH Rapid test is sensitive to the quality of concrete with no fly ash content, but is only marginally sensitive to the level of cement replacement or even to the binder content when fly ash has been added. On the contrary, the electrical resistivity test is not sensitive when fly ash is not used, but is clearly sensitive to the amount of binder content and level of cement replacement, when fly ash is used.

The resistivity tests performed indicate that the optimum fly ash content, for studied mixes, is 40 %. This may be due to the fact that for higher amounts of substitution enough lime is not formed for complete pozolanic reaction.

The capillary water absorption test is capable of distinguishing concretes with different binder contents and is somehow sensitive to the amount of fly ash present in the mix.

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