2003 International Ash Utilization Symposium, Center for Applied Energy Research, University of Kentucky, Paper #43.
http://www.flyash.info

Durability of Low Cost High Performance Fly Ash Concrete

A. Camões[1], B. Aguiar[1], S. Jalali[1]

[1]University of Minho, Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

KEYWORDS: durability, high performance concrete, fly ash, low cost

ABSTRACT

High-performance concrete (HPC) is usually produced using high quality materials. These constituents drastically increase the initial cost of HPC, thus hindering its more widespread usage. This research work intends to investigate the possibility of producing low cost enhanced performance concrete or even low cost HPC, with 28 day strengths in the range of up to 60 MPa, using low-quality-as-received materials like 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 the amount of fly ash was evaluated using 0, 20%, 40% and 60% cement replacement in mixtures with different quantities of total binder (400 kg/m^3, 500 kg/m^3 and 600 kg/m^3). Workability, mechanical and durability properties of the produced concretes were studied.

The results obtained indicate that it is possible to produce HPC with up to 60 MPa by replacing up to 40% of cement by fly ash and using locally available crushed granite aggregates. Based on the results obtained, it is possible to conclude that the use of fly ash in concrete is beneficial in terms of the workability and durability properties but has some disadvantages because early strengths are reduced.

The research work also indicates ways and means to improve the performance of concretes without having its costs increased.

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.

Furthermore, the use of conventional concrete, even in common current constructions, has revealed itself to be technically and economically inadequate. The reinforced concrete structures deteriorate too rapidly, causing high maintenance and repairing costs, in addition to the related decrease of the structures' service life.

In many countries, traditional concrete has a compressive strength in the range of 25 to 35 MPa. It is suggested here that a HPC with 28 day strength of 60 MPa could be acceptable as an intermediary stage for general application in ordinary structures, before the industry can move to the general application of HPC with higher strengths. Such concrete in the lower range of HPC will be clearly easier for the concrete industry to adapt to and will markedly improve the durability of small and medium size concrete structures. It is estimated that more than 80% of concrete produced is applied in ordinary structures. Consequently, it is expected that the concrete industry will find this concrete easy to produce and market, resulting in a high volume application of HPC with obvious advantages.

The major draw back for HPC have been a relatively higher cost of production due to the fact that it requires the application of silica fume and selected high quality fly ash (FA) and aggregates. In many countries the cost of silica fume is several times that of ordinary Portland cement (OPC). In Portugal, for instance, it is ten times more costly than OPC and a 10% addition would mean doubling the price of the cementitious material. Thus this research work has focused on the possibility of using locally received FA and aggregates. In order to reduce the overall costs of production, it was decided to use a high percentage (up to 60%) of FA to replace OPC.

MATERIALS AND MIXTURE PORPORTIONS

All aggregates used in the mixes were locally available crushed granite from the same quarry. It is noted that two different crushed sands (FS: D_{max} = 2.38 mm and CS: D_{max} = 4.76 mm) and a crushed coarse aggregate (CA: D_{max} = 9.53 mm) were used as received, i.e., without any previous treatment such as washing.

The used cement was an OPC of the Type I, class 42.5R. The used FA was of class F, according to ASTM standards, and was produced by the Portuguese Thermoelectric Power Plant of Pego, with quantities of loss on ignition (LOI) varying between 6% and 9%. The LOI value is more than the maximum allowed by the European Standard EN450[1] and the ASTM C618[2], which limit LOI to 5% and 6% respectively. The European norm admits a maximum limit of 7% at national level provided that local regulation and arrangements exist.

Table 1 indicates the principal chemical and physical properties of cement and FA, and Table 2 shows the potential components of cement (C), estimated according to the expressions of Bogue[3].

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

	C	FA
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 total (%)	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 CaO (%)	0.81	0.00 – 0.12
Loss on ignition (%)	2.52	5.60 – 9.28
Insoluble residue (%)	1.94	—
Specific weight (kg/m^3)	3150	2360
Blaine specific surface (m^2/kg)	358.4	387.9
Fineness (%)	1.7 (> 90 μm)	14.1 – 31.6 (> 45 μm)
Water demand (%)	28.0	29.7

Table 2 – Estimated compound composition of the cement

C_3S (%)	61.61
C_2S (%)	4.55
C_3A (%)	8.69
C_4AF (%)	10.15
$C\overline{S}$ (%)	5.47

The superplasticizer (SP) used was naphthalene sulphonate formaldehyde condensates. In previous works[4-5], the optimum SP solid content was estimated to be between 0.5% and 1.0% of the mass of binder. For economic reasons, the value of 0.5% was adopted in this research work.

Twelve different concrete compositions corresponding to three quantities of binder (B) (400, 500 and 600 kg/m^3) and four levels of substitution of cement by FA (0%, 20%, 40% and 60%) were studied. The water/binder (W/B) was maintained constant for each dosage of binder and it was determined experimentally to achieve 200 mm slump when 40 % FA was used. The amount of the aggregates was estimated using the Faury method[6]. The mixtures proportions used are presented in Table 3, as well as the workability results obtained using the Slump Test (SL) and the Flow Table test (FL).

The concrete specimens were cured at 21ºC and constant relative humidity of 80%. At the age of 24 hours, the specimens were removed from the moulds and stored in water, at the same temperature, until the date of testing.

Table 3 – Concrete mixture proportions and workability

Concrete	W/B	C (kg/m^3)	FA (kg/m^3)	FS (kg/m^3)	CS (kg/m^3)	CA (kg/m^3)	SL (mm)	FL (mm)
400FA0	0.40	400	0	613.56	233.55	857.45	105	450
400FA20		320	80	591.96	262.38	878.58	210	485
400FA40		240	160	552.99	284.75	875.65	180	550
400FA60		160	240	503.44	300.96	855.01	205	535
500FA0	0.30	500	0	502.92	308.43	865.61	25	315
500FA20		400	100	461.85	334.01	869.82	105	395
500FA40		300	200	406.91	349.01	847.11	205	474
500FA60		200	300	364.24	373.70	848.70	230	550
600FA0	0.25	600	0	377.30	367.85	850.73	35	350
600FA20		480	120	326.57	399.51	856.01	125	365
600FA40		360	240	271.28	407.93	832.76	200	510
600FA60		240	360	223.26	421.23	824.23	230	530

COMPRESSIVE STRENGTH

The compressive strength was evaluated by tests performed on cubic specimens ($100x100x100\ mm^3$) in a displacement-controlled universal testing machine. In Fig. 1, the average values of three specimens tested, $f_{cm,cube}$, versus curing times are presented, as well as the curves that best fit the results using the hyperbolic equation (1), proposed by Carino[7] and Knudsen[8].

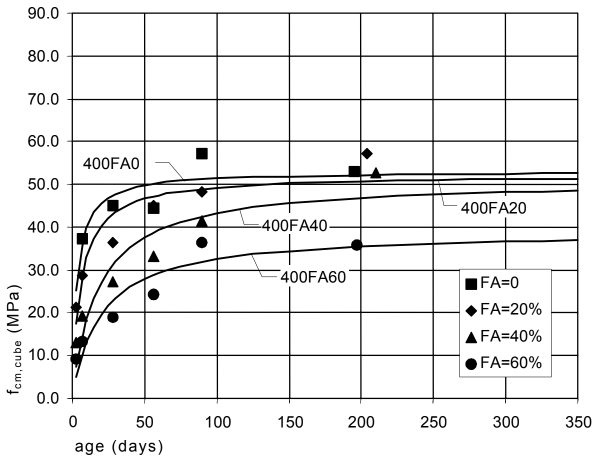
$$f_c = f_{máx} \frac{k(t - t_0)}{1 + k(t - t_0)} \tag{1}$$

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_{max} is the final strength when t tends to infinity; and k, expressed in $days^{-1}$, is a constant.

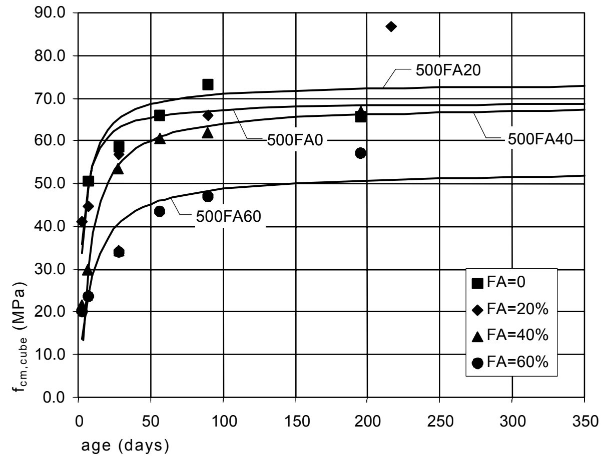
Results obtained (see Fig. 1) indicate that:

- Low cost HPC can be produced with materials currently used for conventional concrete achieving a compressive strength of around 60 MPa at 28 days and 65 MPa at 56 days for a total binder amount of 500 kg/m^3. Increasing the binder content to 600 kg/m^3, $f_{cm,cube}$ rises to about 70 MPa at 28 days and 75 MPa at 56 days;
- The use of B = 400 kg/m^3 gives lower values of $f_{cm,cube}$ and the maximum values were reached when FA was not used achieving about 45 MPa at 28 days and approximately 50 MPa at 56 days;
- In spite of the low strengths measured in early ages, the compositions with 60% FA obtained relatively high compressive strength at higher curing times, 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;

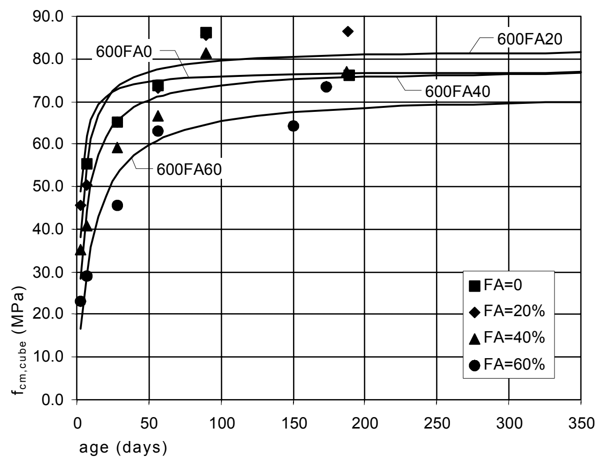
- The initial strength gain with time is smaller with the higher percentage of cement replacement due to the lower rates of pozzolanic reactions of FA.



(a) B = 400 kg/m^3



(b) B = 500 kg/m^3



(c) B = 600 kg/m^3

Fig. 1 – Compressive strength

IMMERSION AND CAPILLARY WATER ABSORPTION

The capillary water absorption test consists of registering the increase in mass of a cubic specimen (100x100x100 mm^3) at given intervals of time when permitted to absorb water by capillary suction along one surface. The values of the coefficient of capillarity absorption correspond to the slope of the curves representing water absorbed per unit area versus square root of time during the initial four hours of testing. Each coefficient of capillary absorption presented in Fig. 2 is the average of four tests performed on four nominally identical specimens (S_{cam}).

The results presented in Fig. 2 show that:

- The addition of FA causes a reduction in S_{cam};

- An increase in the quantity of binder leads to a decrease in S_{cam}, particularly in mixes with up to 500 kg/m^3 of binder;
- The S_{cam} does not seem to change significantly when binder content is increased from 500 to 600 kg/m^3.

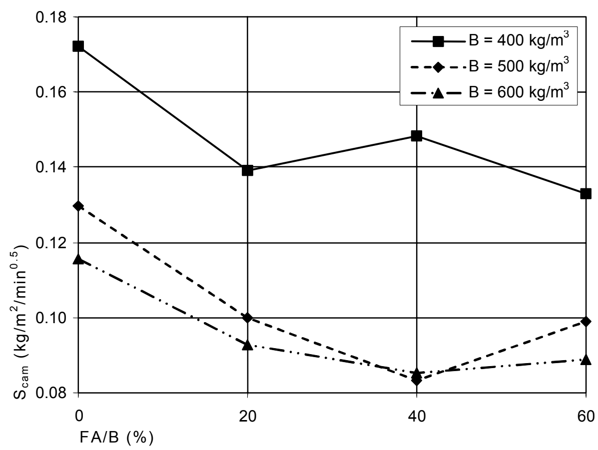


Fig. 2 – Relation between coefficient of capillarity absorption and fly ash content

Water absorption tests by immersion were also performed and led to similar conclusions.

CHLORIDE ION PENETRATION

The evaluation of the resistance to the migration of chloride-ion into concrete was made through Chalmers Teknisca Hösgskola (CTH) rapid test method. This test is performed in a non-steady state regime based on the procedure developed by Luping[9]. The test consists of submitting 100x100x50 mm^3 specimens, at an age of approximately one year, to an electrical potential difference of 40 $\pm$ 0.2 V, for a period of time calculated according to the intensity of the initial current, as suggested by the author. The coefficient of diffusion was obtained measuring the depth of chlorides penetration using a colorimetric process[9]. The average values obtained from six nominally identical specimens of the coefficient of chloride-ion diffusion (D_{nsm}) are presented in Fig. 3.

The results obtained indicate a favourable effect of FA addition:

- All the mixtures with FA presented a smaller D_{nsm} compared to those obtained from control mixes (without FA);
- A 20 % replacement of cement by FA indicates a significant reduction in the D_{nsm} for the concrete with B = 400 kg/m^3 and to a lesser degree for the remaining concretes. Further increase of FA content seems to have a marginal effect on the diffusion coefficient;
- Even for the mixtures with the poorest binder, i.e, 400FA60, the D_{nsm} obtained is lower than that of the mixture with higher cement content, 600FA0;
- The favourable effect of increasing the binder quantity becomes unimportant for mixes with 500 kg/m^3 or more. This is even more obvious in mixes without FA.

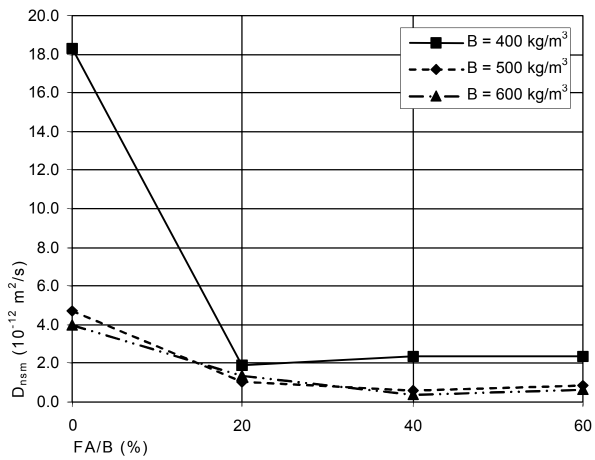


Fig. 3 – Relation between coefficient of chloride-ion diffusion and fly ash content

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 (ρ_m) (Fig. 4).

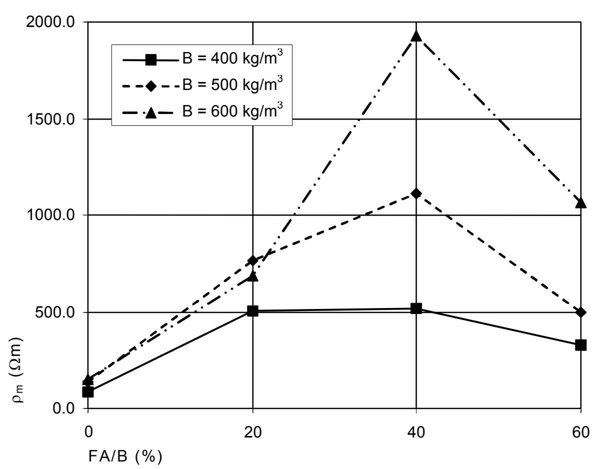


Fig. 4 – Electrical resistivity

Fig. 4 indicates that:

- The replacement of cement by FA increases the resistivity of all the mixes studied and is more significant for high binder content concretes;
- For binder contents of 500 kg/m^3 and 600 kg/m^3 there is a significant increase for up to 40% cement replacement and a rapid decrease for higher FA content;
- The highest resistivity values are obtained for 40% FA content, irrespective of binder content. This does not match the compressive strength tests, but is in general agreement with the estimated coefficient of chloride-ion diffusion.

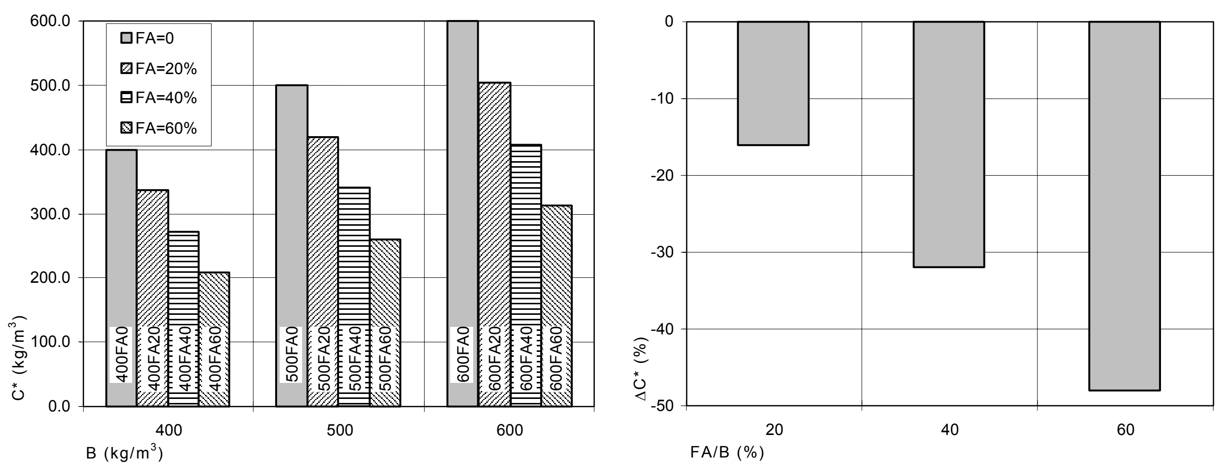
COST ANALYSIS

Concerning the cost of the materials used in the studied mixes, the main differences are related to the total binder content as well as to the quantity of cement replaced by FA. The quantities of aggregates and SP also influence the cost of the final product (concrete), albeit at a much lower level. Thus, the analysis of the main cost variations of the studied mixes can focus on the cost of the materials that most influence it and more specifically can be related to the cost of the binder.

Given that the cost of FA is almost equal to 20% of the cost of cement, it is possible to express the total price of the binder in relation to the price of cement and percentage of cement replaced by FA. The cost of the binder can therefore be evaluated according to the price of equivalent cement content (C*):

$$C^* = B\left(1 - 0.8\,\frac{FA}{B}\right) \tag{2}$$

Fig. 5 presents the equivalent cement content that correspond to the concretes produced (Fig. 5(a)) as well as the relative variation of C* associated with the use of FA, determined by comparison with the control mixes, made without FA (ΔC*) (Fig. 5 (b)).



(a) absolute values (b) relative values

Fig. 5 – Equivalent cement content

Through the analysis of Fig. 5 it is possible to verify that FA considerably reduces the cost of the binder: an inclusion of 20% FA allows a 16% reduction in cost, and an increase of FA to 40% leads to a decrease of 32% in cost. With the highest quantity of FA used (60%) the decrease in costs reaches 48%.

When comparing the different values of C* achieved, it is possible to place the different mixes studied in six different cost classes (Table 4).

Table 4 – Similar cost classes

Class	Concrete	C* (kg/m^3)
I	400FA60	≅ 210
II	400FA40; 500FA60	≅ 270
III	600FA60; 400FA20; 500FA40	≅ 330
IV	400FA0; 500FA20; 600FA40	≅ 410
V	500FA0; 600FA20	≅ 500
VI	600FA0	600

Comparing the compressive strength reached in the mixes (see Fig. 1) with the suggested classes it is possible to conclude that:

- For each class of similar cost it is the 400 kg/m^3 binder content that leads to smaller values of compressive strength;
- Generally, it seems preferable to use the mix with a larger FA content for each class;
- Mixes that belong to the same class and with 400 or 500 kg/m^3 binder content usually present similar compressive strength except for those of class V, where 600FA20 shows $f_{cm,cube}$ higher than 500FA0;
- The use of more expensive mixes does not necessarily increase the concrete's compressive strength. For instance, a 70 MPa at 56 days compressive strength concrete may not justify the use of mixes of a superior class to IV. The use of a class VI concrete (relative to the one of class IV) would imply a cost increase of about 45%. However, the need to obtain high compressive strength at early ages may require the use of more expensive mixes.

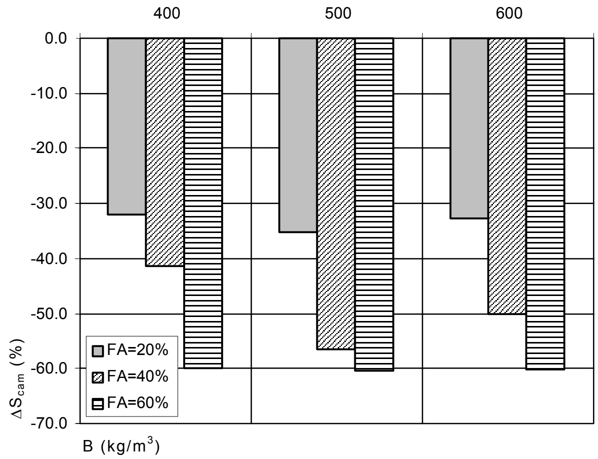
The durability of the mixes was evaluated through tests that were made in specimens of concrete of around one year age. When expressing the cost of the mixes through equivalent cement content (C*) it is possible to evaluate the cost/benefit ratio related to each one of the durability tests performed.

Fig. 6 indicates the different cost/benefit relations, which are determined as the variation of the quantity related to the control mixture (made without FA). Thus, ΔS_{cam}, ΔD_{nsm} and $\Delta\rho_m$ are representing the variation related to the control mixture of C^*/S_{cam}^{-1}, C^*/D_{nsm}^{-1} and C^*/ρ_m.

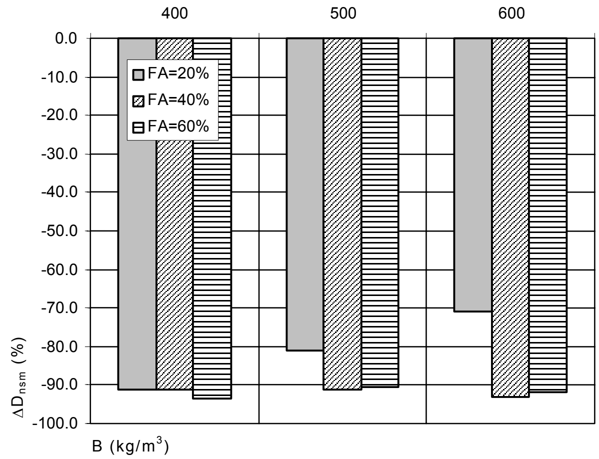
As Fig. 6 demonstrates:

- The inclusion of FA benefits the economic performance of the studied mixes;
- The decrease of the relative cost of the concretes is mainly a result of the presence of FA. The increase of the binder content is basically irrelevant as far as the possibility of change of the economic efficiency of the mixes is concerned;
- The relative cost of the mixes decreases when the quantity of FA increases when the results of the water absorption tests are considered;
- The results related to the penetration of chlorides show a stability of the relative value of C^*/D_{nsm}^{-1}, for the several quantities of FA and binder contents used;

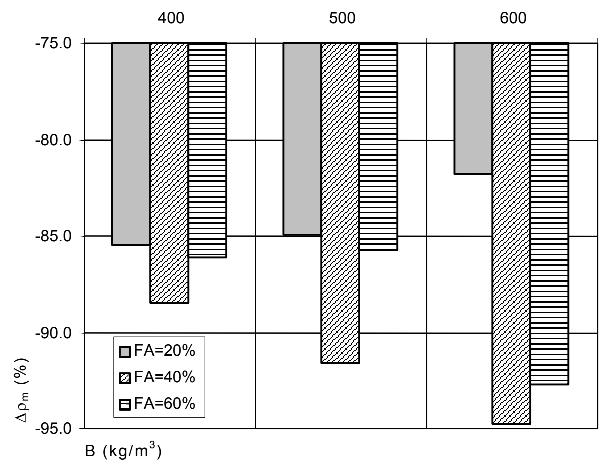
- The results of the electrical resistivity tests point to the existence of an optimum content that corresponds to the replacement of 40% of cement by FA.



(a) coefficient of capillary absorption



(b) coefficient of chloride-ion diffusion



(c) electrical resistivity

Fig. 6 – Durability cost/benefit results

Finally it is also important to draw attention to the economic efficiency of the FA concretes, which is particularly evident with relation to the chloride ion penetration and electrical resistivity. On these parameters, the presence of FA leads to an effective decrease of the relative cost of over 80%.

CONCLUSIONS

The compressive strength tests indicate that concrete with 60 MPa strength at 28 days and 65 MPa at 56 days can be produced using B = 500 kg/m^3 with up to 40% cement replacement. Increasing the binder content to 600 kg/m^3, the compressive strength rises to about 70 MPa at 28 days and 75 MPa at 56 days.

When evaluating the durability of concrete through the chloride ion diffusion coefficient, the electrical resistivity, the coefficient of capillary absorption and the water absorption by immersion, the addition of FA is seen to be beneficial, leading to more durable concrete. This effect is particularly noticeable with regard to the chloride-ion diffusion coefficient and electrical resistivity, indicating its special aptitude for environments that promote degradation of reinforced concrete due to chloride ion penetration.

Adding 60% FA renders concrete considerably weaker in terms of compressive strength, relative to other mixes studied here. However, both its workability and the durability were improved when compared to the control concrete mix. Thus, even in this case such mixtures can be rated as enhanced-performance concrete with regard to environmental and economic aspects. The research work demonstrates that it is possible to improve the concrete's performance, namely its durability, without having increased costs.

REFERENCES

[1] EN450 1994, Fly Ash for Concrete – Definitions, Requirements and Quality Control, CEN, European Committee for Standardization, September 1994.

[2] ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete, 1999 Annual Book of ASTM Standards, Volume 04.02 – Concrete and Aggregates, July 1998.

[3] Bogue, R. H., Chemistry of Portland Cement, Reinhold, New York, 1955.

[4] Camões, A., High Performance Concrete Incorporating Fly Ash, Doctoral Thesis, University of Minho, Guimarães, July 2002 (in Portuguese).

[5] Camões, A.; Rocha, P.; Pereira, J.C.; Aguiar, B.; Jalali, S., Low Cost High Performance Concrete Using Low Quality Fly Ash, ERMCO98, 12th European Ready Mixed Concrete Congress, Lisbon, June 1998, pp. 478-486.

[6] Faury, J, Le Béton, Dunod, ed., Paris, Troisième Édition, 1958.

[7] Carino, N. J., The maturity method: theory and application, Cement, Concrete and Aggregates, ASTM, Vol. 6, N. 2, Winter 1984, pp.61-67.

[8] Knudsen, T., On particle size distribution in cement hydration, Proceedings of the 7th International Congress on the Chemistry of Cement, Ed. Septima, Paris, Vol. 2, 1980, pp.I-170-175.

[9] Luping, Tang, Chloride Transport in Concrete – Measurement and Prediction, Doctoral Thesis, Chalmers University of Technology, Gotemborg, Sweden, 1996.