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LOW COST HIGH PERFORMANCE CONCRETE USING LOW QUALITY FLY ASH

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ABSTRACT
High performance concretes (HPC) usually have been produced using silica fume, high quality fly ash and carefully chosen aggregates. These constituents increase drastically the initial cost of HPCs. The objectives of this research work were twofold. On one hand, it intended to study the possibility of producing low cost HPC, with 28 day strengths in the range of 65 MPa, using low quality fly ash and locally available crushed aggregates. On the other hand, to verify the impact of carbon content of fly ash on the strength and durability of HPC. For this purpose it was decided to enhance the ‘as received’ fly ash by eliminating particles coarser than 75μm, thus reducing the carbon content by 50%.

Compressive strength and diffusion coefficient of concretes replacing 0, 20%, 40%, and 60% of Portland cement by ‘as received’ fly ash, and 20% and 40% replacement by ‘enhanced’ fly ash, were determined. Comparing the results obtained, it was found that HPC with up to 65 MPa can be made by replacing up to 40% of cement by ‘as received’ and ‘enhanced’ fly ash and using the crushed granite aggregates. It was also observed that the carbon content did have little impact on the strength and durability of concrete. Furthermore, it was observed that the durability of concrete, as measured by diffusion coefficient, increased drastically when fly ash replaced partially Portland cement.

Keywords: High Performance Concrete, Crushed Aggregates, Low Quality Fly Ash.

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1. INTRODUCTION

High Performance Concrete, HPC, is becoming a viable alternative to the conventional concrete for special structures. Compressive strengths up to 120 MPa are used with some frequency in special construction works around the world and researchers are working on High Performance Concretes with compressive strengths above 200 MPa.

Although the application of such HPCs, apparently does not pose serious difficulties for special structures, its generalised usage clearly calls for a major adaptation of the construction industry. Traditionally, construction industry has been slow in adapting to innovations. Hence, it would be reasonable to assume that high volume usage of HPC will continue to be an exception rather than the rule.

In many countries the traditional concrete has a compressive strength in the range of 25 to 35 MPa. Therefore, it is suggested here that a High Performance Concrete with a 28 day strength of 65 MPa could be accepted as an intermediary stage for general application in ordinary structures, before the industry can move to general application of High Performance Concretes 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 concrete industry, especially the Ready Mix Concrete, 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 HPCs have been a relatively higher costs of production due to the fact that it requires the application of silica fume and selected high quality fly ash and aggregates. In many countries the cost of silica fume is several time the cost of ordinary Portland cement (OPC). For example, in Portugal, it is ten times more expensive 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 local fly ash and aggregates.

In order to reduce the overall costs of production, it was decided to use high percentage of fly ash to replace OPC. On the other hand, due to high carbon content of the fly ash available, it was decided to investigate the effect of enhancing ‘as received’ fly ash by removing part of the carbon content. The ‘as received’ and ‘enhanced’ fly ashes were used for replacement of up to 40% weight of OPC.

2. MATERIALS AND MIX PROPORTIONS

2.1. Aggregates

It is widely accepted that fine aggregates with a round particle shape and smooth texture have been found to require less mixing water in concrete and for this reason are preferable in HPC [1]. Cánovas et al. [2], while confirming the same principle, added that the fineness modulus of sand should be around 3. De Larrard [3] affirming the importance of porosity and water absorption of the aggregate indicates that porosity is the critical point concerning the aggregates and that the water absorption should be less than 1% for the coarse aggregate. The shape coefficient of the coarse aggregate has been recommended [4] to be above 0.25, while the Los Angeles factor should be kept less or equal to 15.

The aggregate used in this research work was crushed granite locally available, which departs from the characteristics recommended for HPC. Table 1 presents the characteristics of the aggregate employed.

Table 1 - Characteristics of aggregates

Sieve	Sand 1	Sand 2	Gravel
3/8”	0	0	3.42
4	0	9.82	94.72
8	2.51	68.32	98.54
16	28.69	87.80	98.85
30	53.41	93.95	99.03
50	75.99	96.51	99.18
100	86.65	97.84	99.35
200	97.38	98.65	99.53
Maximum Size (mm)	2.38	4.76	9.53
Fineness Modulus	2.47	4.54	5.93
Shape Coefficient	-	-	0.21
Specific Gravity	2.61	2.53	2.39
Water Absorption (%)	0.51	1.88	2.35
Los Angeles (%)	-	-	21

2.2. Fly ash

It is widely accepted that the water required for workability of mortars and concretes depends on the carbon content of fly ash, the more water is needed to produce a paste of normal consistency when carbon content of fly ash is high. Some of this carbon is indicated [5] to be able to adsorb significant quantities not only of water, but also of chemical admixtures in concrete, such as air-entraining admixtures, water – reducing admixtures and retarders.

Most standards limit the carbon content of fly ash to 5% while few admit values as high as 7% [6]. Some researchers [7] have indicated that in HPC fly ash must comply with ASTM C618 or AASHTO M295 that limit loss on ignition to 6% and 5%. The European norm EN450 limits this amount to 5% and admits a maximum level of 7% on a national level provided local regulation and arrangements exist. This would mean that fly ashes with higher carbon content can not be used in concrete.

Fly ash used in this research work is from a Portuguese power plant with a carbon content varying from 6% to 9% with an average value over 7%. Table 2 shows the characteristics of this fly ash and Table 3 shows the concentration of unburned carbon in ‘as received’ and particles coarser and finer than 75 μm.

Table 2 - Characteristics of fly ash

Moisture (%)	0.09	Total: $S_iO_2 + AL_2O_3 + Fe_2O_3$ (%)	87.73
Loss on Ignition (%)	7.03	Na_2O (%)	0.44
Fineness > 45 μm (%)	27.53	K_2O (%)	1.53

Fineness > 75 μm (%)	14.30	MgO (%)	1.45
free CaO (%)	0.00	SO_3 (%)	0.25
total CaO (%)	2.25	Chloride (%)	0.00
S_iO_2 (%)	58.46	P_2O_5 (%)	0.16
AL_2O_3 (%)	21.47	TiO_2 (%)	0.93
Fe_2O_3 (%)	7.81	Specific Gravity	2.36

Table 3 - Loss on ignition of fly ash

Fly Ash	L.O.I. (%)
Total 'as received'	7
Particles > 75μm	26.5
Particles < 75μm (enhanced fly ash)	3.5

It is noted that unburned carbon is concentrated particularly in particles larger than 75μm, with a LOI of 26.5% while particles smaller than 75μm, i.e. 'enhanced' fly ash have only 3.5% unburned carbon. Hence, it was decided to compare the effect of the two fly ashes, i.e. 'as received' and 'enhanced' fly ash.

2.3 Portland cement

A Type I, Class 42.5 ordinary Portland cement was used in this research work. The chemical composition, mechanical and physical properties of this cement are presented in Table 4.

Table 4 - Characteristics of Portland cement

Loss on Ignition (%)	2.52	Specific Gravity	3.15
S_iO_2 (%)	19.71	Blaine Fineness (m^2/kg)	384.3
AL_2O_3 (%)	5.41	Fineness > 90 μm (%)	1.7
Fe_2O_3 (%)	3.34	Water Demand (%)	28.3
total CaO (%)	61.49	Initial Setting Time	3h05
MgO (%)	2.58	Final Setting Time	4h03
SO_3 (%)	3.22	Expansibility	1.0
Chloride (%)	0.01	Compressive Strength: 2 days (MPa)	33.1
free CaO (%)	0.81	Compressive Strength: 7 days (MPa)	44.9
Insoluble Residue (%)	1.94	Compressive Strength: 28 days (MPa)	53.6

2.4 Concrete mix proportions

Six different concretes using a constant amount of binder and water/binder ratio were used. The amount of binder was kept constant at 500 kg/m^3 with water to binder ratio of 0.28. The mix proportions were estimated using Faury method [8]. Table 5 summarises the mix proportions of concretes used. FA indicates the usage of 'as received' fly ash while EFA denotes 'enhanced' fly ash.

Table 5 - Mix Proportions of concrete (kg/m^3)

Mix	Cement	Fly Ash	Gravel	Sand 2	Sand 1
FA 0	500	0	863	306	516
FA 20	400	100	857	327	469
FA 40	300	200	851	349	423
FA 60	200	300	850	370	374
EFA 20	400	100	857	327	469
EFA 40	300	200	851	349	423

The amount of superplasticizer (SP) was estimated using a series of tests determining the water content required for standard consistency test according to EN 196-3:1987. The results are summarised in Figure 1. It is interesting to note that results from Marsh Cone Test for estimating the amount of SP showed similar results.

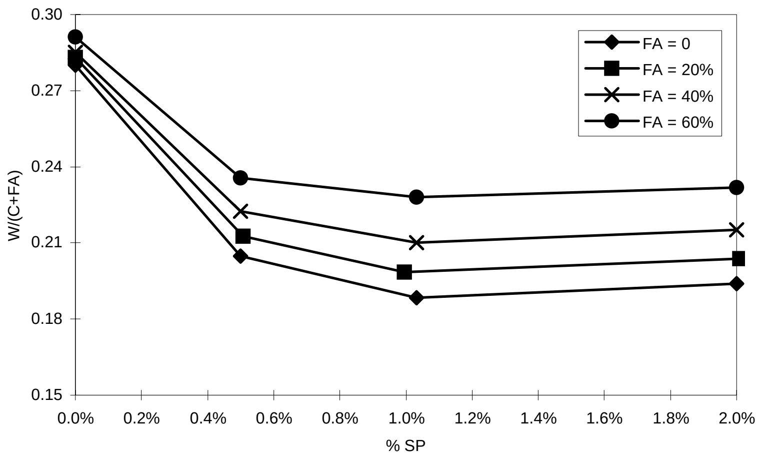

Figure 1 - Water Demand x Superplasticizer in Standard Consistency Tests

It is interesting to note that water to binder ratio w/(c+fa), increases with increasing the amount of ‘as received’ fly ash. The increase, however, is higher when fly ash is increased from 40% to 60%. There is also a clear decrease of w/(c+fa) when the amount of SP is increased from 0 to 1%. The change of SP from 0.5% to 1% has little effect on the w/(c+fa). Any increase of SP beyond 1% does not lower the water needed for standard paste and it increases slightly the water demand. Hence, the amount of SP used throughout this research work was fixed at 0.5%.

3. COMPRESSIVE STRENGTH DEVELOPMENT

The compressive strength was estimated using 100x100x100 mm cubes moulded from different batches of concrete. Results of specimens cured from 3 to 56 days at 21 ºC with

100% RH are summarised in Table 6. Three specimens were used for each age and the mean value was determined.

Table 6 - Concrete: Slump Test and Compressive Strength

Mix	Slump (cm)	f_c (MPa)			
		3 days	7 days	28 days	56 days
FA 0	0	53.3	57.3	64.5	67.5
FA 20	3.5	44.7	47.3	59.0	64.8
FA 40	6.0	33.4	35.6	55.8	60.4
FA 60	3.5	13.5	20.1	35.1	43.0
EFA 20	3.5	36.8	49.6	62.5	65.9
EFA 40	5.0	29.9	38.7	57.3	60.5

It is noted that the strength gain of concretes with fly ash replacing Portland cement is slower for early ages, i.e. up to 7 days, due to the induction period for the possolanic reactions. It is noted that at 56 days the strength is around 90% of the reference batch, with no fly ash, but with a tendency to increase further. This confirms the well - known fact that the strength gain of fly ash concretes is slower than the comparable reference concretes with no fly ash. No significant difference is noted when comparing results from concretes using ‘as received’ fly ash, i.e. FA 20 and FA 40, with those using ‘enhanced’ fly ash, i.e. EFA 20 and EFA 40.

In order to analyse the strength gain at higher ages, i.e. at 90 days, a theoretical model [9] was used. Equation 1 is suggested for the prediction of strength gain with time. The results of the best fit of the data from Table 6 using a non-linear regression analysis are presented in Table 7 and Figure 2 and 3.

$$f_c = f_{max} [1 - Exp (-k t^n)] \qquad (1)$$

where: f_c is the strength at a given time, t, f_{max} is the final strength when age tends to infinity, k is the rate constant which designates the effect of curing temperature and n is a parameter related to the morphology of the hydrated cement.

It is expected that 90 day strength of all batches will be superior to 67.5 MPa.

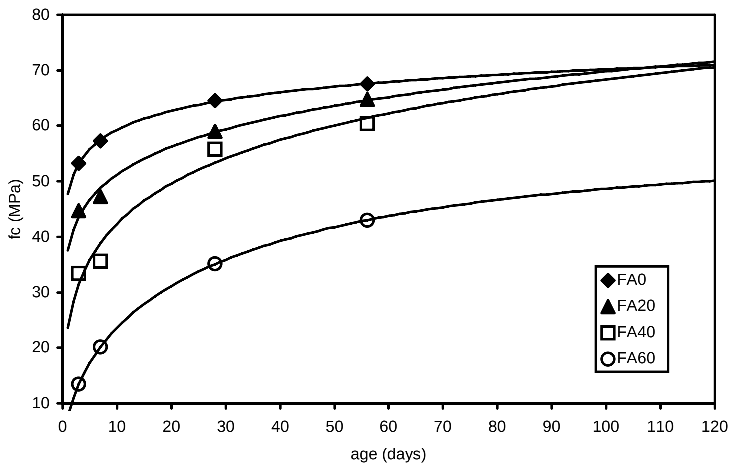

Figure 2 - Strength Gain of Concretes with Increasing Fly Ash Content and the Predicted Values Using Equation 1

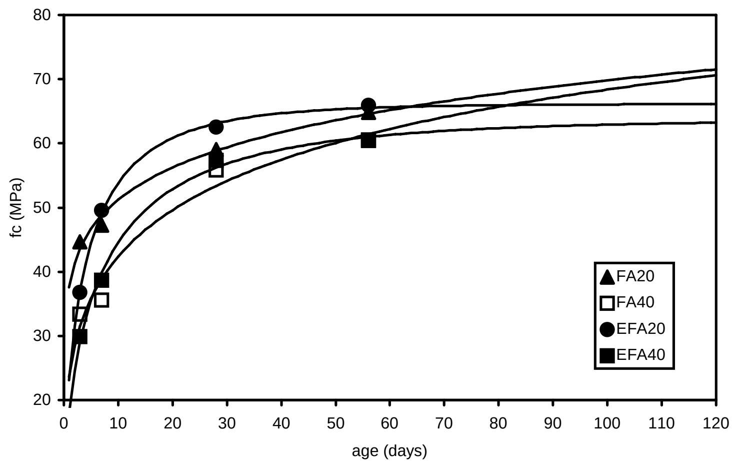

Figure 3 - Strength Gain of Concretes Using 'As Received' and 'Enhanced' Fly Ash and the Predicted Values Using Equation 1

4. CHLORIDE ION PENETRATION

In order to verify the effect of fly ash content as well as its unburned carbon content on durability of concrete, cylindrical specimens, 100 mm in diameter and 200 mm height, were moulded using different percentage of 'as received' and 'enhanced' fly ashes. The durability was measured using the CTH rapid method [10]. This method involves applying a potential of 30 – 40 Volts across a 50 mm thick specimen for a certain test duration. Then after splitting the specimen the penetration depth of chlorides is measured using a calorimetric method. The diffusion coefficient can be obtained using equation 2.

$$D = (RTL / z FU) [(x_d – a x_d^{½}) / t] \quad (2)$$

Where:
D: diffusion coefficient, m^2/s;
z : absolute value of ion valence, for chloride ions, z=1;
F: Faraday constant, F=9.648x10^4;
U: absolute value of potential difference, V;
R: gas constant, R=8.314 J/(K mol);
T: solution Temperature, K;
L: thickness of the specimen, m;
x_d: penetration depth, m;
t: test duration, second, t = t_{CTH} x 3600;
erf^{-1} : inverse of error function;
c_d: chloride concentration at which the colour changes, c_d =0.07 N;
c_o: chloride concentration in the upstream cell, c_o = 2 N and
a = 2 (RTL/zFU) 1/2 erf^{-1} [1 – (2 c_d / c_o)]

Table 7 summarises the results of CTH tests the calculated diffusion coefficient using equation 2.

Table 7 - Results of CHT Chloride Ion Penetration Test and Estimated Diffusion Coefficient

Age (Days)	Reference	Position Top / Middle	Duration (second)	x_d (m)	D (10^{-12}) m^2/s	D_{mean} (10^{-12}) m^2/s
87	FA0	T	86400	0.0195	7.48	6.58
84	FA0	M	86400	0.0155	5.68	
86	FA0.2	T	172800	0.0175	3.31	3.15
82	FA0.2	M	172800	0.0155	3.00	
89	FA0.4	T	176400	0.0140	2.66	2.27
80	FA0.4	M	176400	0.0100	1.87	
96	EFA0.2	T	172800	0.0155	2.95	3.23
110	EFA0.2	M	86400	0.0100	3.51	
97	EFA0.4	T	117000	0.0065	1.78	1.47
102	EFA0.4	M	172800	0.0065	1.17	

Table 7 shows that the mean diffusion coefficient, as determined by CTH chloride ion penetration test, decreases with increasing fly ash content. The mean diffusion coefficient increases from 1.47E-12 m/s to 6.58 E-12 m/s when the fly ash content is reduced from 40% to 0. It is also interesting to note that the value of the diffusion coefficient is higher for the top part of the sample (T) compared with the middle (M) section of the samples, except in one case. This is of course expected as usually the middle portion of the specimen is cured with higher water content and the top portion of the specimen is expected to lose water during the curing period.

5. CONCLUSIONS

The results obtained from this research work indicate that:

- It is possible to produce low cost HPC, with 90 day strength in the range of 70 MPa, using low quality fly ash and crushed sand.
- There is an optimum superplasteciser content beyond which its contribution is nil.
- It is possible to replace up to 40% of cement by low quality fly ash with carbon content up to and slightly higher than 7%.
- Separation of fly ash and eliminating the coarser size particles, thus, lowering the carbon content by 50% did have significant effect on the strength gain or diffusion coefficient of the concrete. This may well indicate that the limit of carbon content for acceptance of fly ash could be increased from the present 5 or 7%.

6. REFERENCES

[1] *State-of-the-Art Report on High Strength Concrete*, Reported by Committee 363, American Concrete Institute, 1992.

[2] M.F. Cánovas, P.A. Gutiérrez, *Composición y Dosificación de los Hormigones de Alta Resistências y sus Aplicaciones*, Cemento-Hormigon, Número 709, Agosto 1992.

[3] F. De Larrard, *High-Performance Concrete: From the Laboratory to Practical Utilization*, Concrete Technology: New Trends, Industrial Applications, E&FN Spon, Barcelona, November 1994.

[4] P.A. Gutiérrez, M.F. Cánovas, *High-Performance Concrete: Requirements for Constituent Materials and Mix Proportioning*, ACI Materials Journal, Vol. 93, N.3, May-June 1996.

[5] V.M. Malhotra, A.A. Ramezanianpour, *Fly Ash in Concrete*, 2nd Edition, Canmet, Ottawa, Canada, 1994.

[6] R.N. Swamy, *Fly Ash and Slag: Standards and Specifications - Help or Hindrance?*, Materials and Structures, Vol. 26, 1993.

[7] Roy H. Keck, Eugene H. Riggs, *Specifying Fly Ash for Durable Concrete*, Concrete International, April 1997.

[8] J. Faury, *Le Béton*, Editions Dunod, Paris, 1958.

[9] Jalali S., *Modelling the Overall Rate of Reaction in Lime-Fly Ash Systems*, Proceedings of the 10th International Congress on the Chemistry of Cement, Vol. 3, pp 3ii084, Gothenburg, Sweden, June 2-6, 1997.

[10] Luping T., *Chloride Transport in Concrete – Measurement and Prediction,* PhD Thesis, Chalmers University of Technology, Gotenborg, Sweden, 1996.