High Calcium Fly Ashes from Lignite Sources: Standardization Aspects, Current Research and Application in Practice

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Submitted for Inclusion in the Proceedings of the 10th International Conference '*Ashes from Power Plants*'

Warsaw, Poland, October 2003

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Synopsis

Since the vast majority of Hellenic lignite fly ashes are considered as high-calcium, they are not covered by any European Standard or specifications. Therefore extending their applications in several markets faces serious barriers despite the fact that the technical and economical benefits associated with their use in road and pavement construction, concrete products, as well as in high volume constructions have been repeatedly verified in laboratory and in industrial scale. The present paper comprises the current scientific work done in these fields and presents the very encouraging results obtained from the in situ application of HCFA in several projects. In this paper is also summarized the essay, in draft form, of a working group responsible for the preparation of specifications for the Hellenic High Calcium Fly Ashes.

1. Characterization of Hellenic high calcium fly ashes

According to statistical data from ECOBA (European Association for Use of the By-Products of Coal Fired Power Stations) [1], the production of Coal Production Products in Europe (EU 15) reaches approximately 60 million tons with fly ashes consisting the 67.3% of the total percentage. At the same time, more than 20 million tons of subbituminous coal/lignite fly ash are produced annually [1]. Hellenic fly ashes belong to this latter category and their generation is expected to increase during the forthcoming years as the need for lignite in Greece for the next thirty years (as the main energy source) leads inevitably to the production of large amounts of fly ash (about 10 million tons per year). The vast majority of this quantity (about 80%) is coming from Ptolemais area in Northern Greece while the rest is derived in Megalopolis in Peloponnesus.

Despite the current situation existing in EU 15, where the 70% of the fly ash is directly associated in the cement and concrete industry, summarised in Fig. 1 [2], in Greece the utilization of fly ashes is almost entirely given out in blended cements in a percentage of 10%. The main explanation for this difference is that Hellenic fly ashes are classified as high calcium fly ashes (HCFA) and their use is not specified by any European specifications as is in the case of LCFA in concrete (European Standard prEN 450-1). Hellenic ashes and especially those of Ptolemais area are classified according to ASTM as type C, i.e. ashes with high proportion of CaO (HCFA) in the form of compounds such as $3CaO{\cdot}Al_2O_3$, $CaO{\cdot}SiO_2$, $4CaO{\cdot}Al_2O_3{\cdot}SiO_2$ or sulfur-calcium-aluminates. Such ashes exhibit not only pozzolanic but also latent hydraulic behavior. In all cases the sum of Al_2O_3+SiO_2 +Fe_2O_3 is greater than 50% but certainly less than 70% by weight, as ashes which have been classified in type F. In all cases SiO_2 is greater than CaO_f (free lime) and the bigger this difference is, the greater is the tendency for the pozzolanic reaction to occur between the constituents of fly ash (principally reactive SiO_2) and the $Ca(OH)_2$ produced during the hydration of the mineral phases of clinker. It should be emphasized that the mineralogical composition and especially the amorphous siliceous and aluminous phases, in relation to the fineness of fly ash, would determine or not, how fast a material can react with lime. [3, 4, 5, 6]

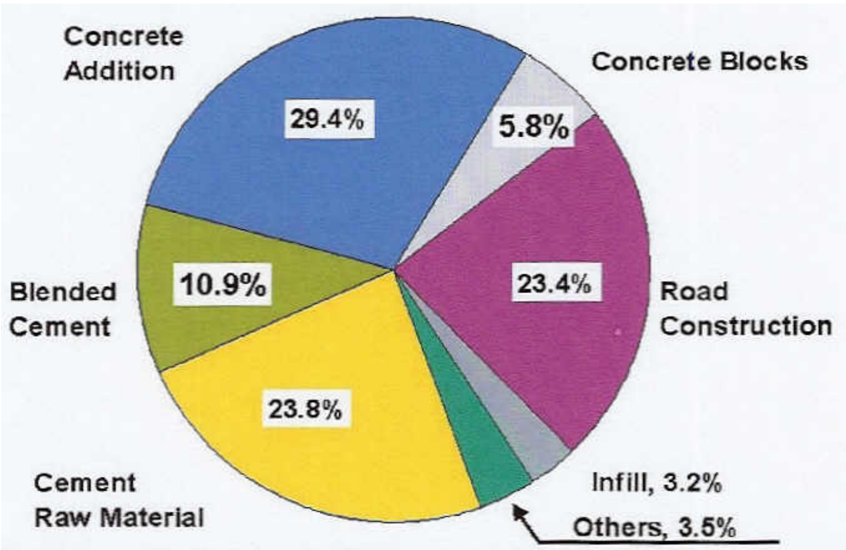

Fig 1. Utilization of fly ash in the construction industry (adopted from [2])

Although, HCFA are classified as Class C according to ASTM Standard C618 and Canadian Standard CSA-A 23.5, most of HCFA do not fully meet the requirements of the standards. As stated above, there are no specifications in Europe for the use of HCFA in concrete similar to prEN 450 for the LCFA. This makes their utilization difficult and increases the scepticism with which this material is still being handled with by a significant part of the industrial world.

However, under a tight control of the entire design-production-application process, the use of HCFA can be proved more beneficial than LCFA in terms of mechanical properties because the contribution of HCFA to the hardening of the cementitious phases is greater. In fact, numerous literature findings clearly demonstrate that high calcium fly ashes provide better early age strengths as a result of the cementitious compounds they possess. It is believed [7] that calcium substitution in the glass phase is generally increasing the reactivity of high-lime fly ashes providing for the formation of the calcium-silicate and calcium-aluminate phases in the absence of an external source of lime. It should be however pointed out that class C fly ashes differ from the class F ashes not only in that they contain more lime, but also the lime depolymerized glass phase [8].

Despite their increased reactivity and lower sensitivity to inadequate curing [9], high-lime fly ashes are generally less efficient in suppressing expansion due to ASR [10] and sulphate attack [11]. On the other hand, ashes of lower lime contents provide better resistance to ASR and sulphate attack and furthermore they usually guarantee better performance on the longer term. Concerning additional durability properties, such as carbonation and chloride penetration [12.13], both low and high calcium ashes seem to have a similar beneficial effect, with the latter presenting a slightly better resistance.

2. Standardization aspects concerning Hellenic HCFA

In Greece, at the moment, a draft concerning specifications of Hellenic High Calcium Fly Ashes has just been prepared and circulated for further comments from any interested person or organization [14]. Its structure is based on prEN 450-1 [15] incorporating any necessary modifications. It deals with two types of fly ashes: Untreated (raw) and treated (milled) fly ashes. The first type involves fly ashes which are disposed directly after collection from the thermal stations and are mainly addressed for road construction applications. Such ashes have low strength requirements. The other type comprises ashes which may substitude Portland cement in concrete and may be one of the materials foreseen in EN 206-1. Their production requires a milling plant equipped with an internal spraying system as well as with a homogenization unit. A laboratory inside the plant for the quality control either of the raw fly ash to be milled or of the final product, is considered a necessity.

Given the fact that Hellenic ashes contain low percentages of unburned carbon, the draft proposes for loss on ignition, the value foreseen in category A of prEN 450-1 that is 5% max. The same values with prEN 450-1 are also proposed for Chlorides (0.1max), Reactive Silica (>25%) and total alkalies (5% max). Concerning chemical characteristics the differences with prEN 450-1 are focused on the SO_3 and CaO_f contents. For SO_3 content the value of max 5.5% is proposed. Based on our experience gained from the construction of Platanovryssi dam, the upper limit can be expanded up to 7% but in that case: i) the other requirements for fly ash must be totally fulfilled and ii) the Canadian specifications CAN/CSA-A235-M86 must be followed. For CaO_f content, the value of 3% is proposed as the maximum percentage. In those cases where raw fly ash exceeds this upper limit the spaying system for partial hydrolization to $Ca(OH)_2$ which operates coinstantaneously with the reduction of size process, is activated inside the mill.

With regards to the physical requirements the draft proposes the following:
For fineness, expressed as the mass proportion in percent of the ash retained when dry sieved on a 0,045 mm mesh sieve, there is a diversification according to the type of fly ash. For type A the maximum value of the fineness shall not exceed 45 %, whilst in the case of ashes of type B, the respective percentage is reduced to 30%. Additionally, for activity index, soundness, setting time and particle density the same limits with those stated in EN 450-1 are foreseen. However, in the case of type B ashes and for elevated percentages of fly ash addition, the repetition of the test in mixtures of cement to fly ash of 50/50 ratio is proposed instead of mixtures with a ratio of 70-75/30-25. Finally a percentage of 1% is proposed as the maximum value for humidity.

3. Current research

3.1. Background and Objectives

During the last years, a large project concerning the utilization of Hellenic high-calcium fly ashes in the production of high volume fly ash concrete (HVFAC) is in progress in the National Technical University of Athens. In a very broad sense, HVFAC can be defined as the concrete that is prepared with a large amount of fly ash, sometimes even more than the respective amount of cement included in the mix [16,17]. Obviously, since HVFA concretes have relatively low cement content, they can be made at a significantly lower cost, whilst making a gainful utilization of substantial quantities of an industrial by-product.

Notwithstanding the fact that HVFA concretes are considered nowadays a common practice in the construction sector, the use of class C fly ashes is actually an innovative concept since the majority of such concretes is built with class F (low-lime) ashes. This is not only due to the vast global availability of these ashes, but also due to the greater heterogeneity of high-lime ashes and certain parameters inherent in class C ashes (especially high sulphur and free lime contents) that are threatening the durability of the final product [18,19]. The specific project involves the investigation of several mix design parameters such as water/binder ratio, type and dosage of superplasticizer used, attained slump and mechanical and durability performance of a HVFA concrete incorporating lignite high-calcium fly ash. Moreover, in an attempt to deal with some of the shortcomings characterizing high-lime fly ashes, lignite fly ashes of lower calcium content were used to produce lignite ash intermixtures seeking for a synergic action that will further improve the apodosis of the new-greener concrete [19,20].

3.2. Design and Experimentation

For reaching the objectives stated above, a high-calcium fly ash (from Ptolemais area), designated here as T_f, was used. A normal setting cement (CEM I 42,5 according to EN 197-1) was used during the preparation of concrete specimens, together with a naphthalene-based superplasticizer in liquid form (to compensate for the slump loss caused by fly ash addition) and normal graded limestone aggregates, including fine, medium and coarse aggregates. When fly ash was inserted in the mix, an equal unit of cement was replaced (30 and 40% by weight). The effect of w/Cm ratio on the strength development and chloride resistance of concrete samples was studied by adopting two different values (0,47 and 0,58 respectively). For each w/Cm tested and while adding such amount of superplasticizer so as to keep the slump value of the fresh concrete close to the desired one (40 and 80mm respectively), two series of concrete specimens were prepared and tested. A similar procedure was followed in the case where the second type of lignite fly ash derived in Greek power stations (that of lower calcium content, designated here as T_m,) was added in the mix in the form of a new fly ash intermixture containing equal contributions from each of the two types of ashes (specimen T_1). The chemical composition of the fly ashes and the cement used is given in Table 1, while details regarding the preparation of the specimens are shown in Table 2.

Table 1 - Chemical Composition (% by mass) of Raw Materials

	Cement	T_f	T_m	T_1
SiO_2	20.28	36.92	51.36	44.08
SiO_{2re}^*	-	29.13	31.36	30.36
CaO	65.01	29.79	13.80	21.50
CaO_f	0.63	7.01	0.95	3.95
Al_2O_3	4.75	13.50	16.73	15.70
Fe_2O_3	3.76	7.06	8.75	8.75
MgO	1.61	2.69	2.26	2.45
SO_3	2.55	5.10	1.49	3.18
Na_2O	0.17	0.92	0.77	0.81
K_2O	0.35	0.50	1.52	0.93

From the data presented in Table 1, it can be seen that both initial ashes are considered calcareous and along with the intermixture that was prepared they are covering a wide range of CaO values. This is of primal importance since the influence of this parameter is gaining increasing attention, especially in countries that are producing appreciable quantities of class C fly ashes. Indicative is the fact that recently, the Canadian Standards Association (CSA) revised the specification for fly ashes categorization, dividing them into three classes depending on their calcium content [7]. This is a classification scheme that is expected to be implemented in the national standards of other countries producing different types of fly ashes during the forthcoming years.

Testing involved, slump measurements, compressive strength at 2, 7, 28 and 90 days after casting (in cubic specimens of $100mm^3$), estimation of the efficiency factors (or *k*-values) in each case and finally resistance to chloride ion penetration (in cores from cylindrical specimens) according to the AASHTO T227 rapid test.

3.3 Slump Loss, Strength Development and Efficiency of High-lime Fly ash Concrete

In all HVFA concrete cases, it has been shown that the dosage of the superplasticizer (SP) added to compensate for the slump loss caused by the high water demand of fly ashes, especially those with high calcium content, holds a critical role during the mix design procedures [21,22]. In the present study, the amount of SP added fluctuates (for both w/Cm ratios applied) among 0,9 and 6 Kg/m^3 of concrete.

Table 2 – Proportions of the Concrete Specimens

Specimen	C	W	W/Cm	F	A	SP	Slump (mm)
C_1	*350*	*203*	*0.58*	-	*1830*	-	*80*
$30T_f$	245	203	0.58	105	1830	1.84	75
$40T_f$	210	203	0.58	140	1830	1.40	75
$30T_m$	245	203	0.58	105	1845	0.88	75
$40T_m$	210	203	0.58	140	1840	1.40	75
$30T_1$	245	203	0.58	105	1850	1.20	75
$40T_1$	210	203	0.58	140	1850	1.20	70
C_2	*350*	*203*	*0.47*	-	*1930*	*2.97*	*45*
$30T_f$	245	165	0.47	105	1925	5.00	40
$40T_f$	210	160	0.46	140	1950	5.00	40
$30T_m$	245	165	0.47	105	1925	5.00	45
$40T_m$	210	160	0.47	140	1925	5.50	40
$30T_1$	245	165	0.47	105	1922	5.14	45
$40T_1$	210	160	0.47	140	1920	6.00	45

**C, W, F, A, SP: kg of cement, water, fly ash, aggregate and superplasticizer respectively per m^3 of concrete*

Given that the fineness of the fly ashes that were utilized was similar, it seems that what determined the dosage of SP in each mix was mainly the chemical composition of each ash and the water offered in the specimens. It becomes clear that even for the pozzolanic specimens prepared with a high w/Cm ratio, SP was needed to attain similar slump with the reference sample. However, this addition was relatively small (about 1-1,5 Kg/m^3 of concrete), whilst in the samples with increased cement replacement, almost no extra SP was required. Normally, when the w/Cm ratio decreased, the SP dosage increased in all mixes. In that case, about 1 kg/m^3 more SP was introduced, with the T_2 intermixture presenting a higher need in that aspect. It is possible that the presence of two different, finely ground high-lime fly ashes enhanced the deflocculation of the cement grains and subsequently the generation of more nucleation sites [19,20]. Logically, the water demand of this new blended cement is higher and so is the need for SP to reach the slump value of the control.

The compressive strength evolution of all concrete specimens is shown in Table 3 as a function of curing time. Despite the fact that the control specimens (no fly ash addition) are exhibiting strength superiority during the first stages of hydration for both w/Cm examined, the pozzolanic samples are developing strength at a faster rate after the first week. During this stage, excessive presence of reactive CaO in high-lime T_f is accountable for its superiority. Four weeks after mixing, a significant increase in the strength values of fly ash systems is observed. In that age, fly ash concrete specimens are either approaching or outperforming the corresponding values of the reference samples. Again at this stage, T_f samples are the most efficient, especially when prepared with a low w/Cm ratio. Even after 90 days of hydration, T_f *performs better* as a result of the quicker initiation of its pozzolanic reaction (higher glass phase) and its unusually high active silica content.

Table 3 – Compressive strength evolution of the Concrete Specimens

		Compressive Strength (MPa)			
		Curing Time (days)			
Specimen	**W/Cm**	**2**	**7**	**28**	**90**
C_1	0,58	*17,2*	*26,8*	*32,8*	*39,5*
$30T_f$	0,58	12,8	23,2	31,4	42,5
$40T_f$	0,58	10,8	22,2	35,5	43,0
$30T_m$	0,58	13,3	22,7	34,7	41,4
$40T_m$	0,58	11,6	21,8	33,9	39,7
$30T_1$	0,58	9,0	20,7	31,3	37,4
$40T_1$	0,58	6,9	19,5	29,6	34,1
C_2	0,47	*28,0*	*41,8*	*50,2*	*57,8*
$30T_f$	0,47	22,1	38,0	52,1	62,1
$40T_f$	0,47	19,1	33,4	50,2	60,4
$30T_m$	0,47	23,8	34,9	46,9	57,2
$40T_m$	0,47	16,8	29,4	44,9	52,7
$30T_1$	0,47	20,0	34,4	46,5	54,6
$40T_1$	0,47	16,8	33,9	46,4	53,6

Generally, the intermixing procedure had no beneficial effect on the strength performance of concrete specimens, contrary to what was observed in the case of similarly constructed mortars [19,23]. In fact, the introduction of a different ash inside the matrix seems to bear positive consequences only in the case where low w/Cm was used. This is the case for the intermixture examined herein (T_1), where a substantial cement replacement (i.e. 40% by weight) was needed to produce an improved, in terms of mechanical properties, concrete.

The above remarks are also validated via the concept of the calculated efficiency factor (simpler). It has been well demonstrated that in the case of a pozzolanic concrete, the following equation can be used to determine the *k* factor that actually enables a first approximation of the quantity of the pozzolan that could replace an equal unit of cement to attain equal mechanical performance (obviously k=1 for the control specimen) [24-26]:

$$f_c = \mathrm{K}\left(\frac{1}{\mathrm{W} / (\mathrm{C} + \mathrm{kP})} - \alpha\right) \qquad (1)$$

where K is a parameter depending on the cement type (here 38,8MPa), C and P are the cement and fly ash contents respectively in the mortar (kg/m^3), W is the water content (Kg/m^3) kept constant in all the mixes and α a parameter depending mainly on time and curing. Inserting some of the strength values shown in Table 3 into Eq.1, the following efficiency factors were calculated and summarized in Table 4.

Table 4 – Efficiency factors of several concrete specimens

Specimen	**Age (days)**			
	2	7	28	90
$30T_f$ @*W/Cm:0,47*	0,76	0,84	1,08	1,17
$40T_f$ @*W/Cm:0,58*	0,76	0,82	1,10	1,14
$40T_f$ @*W/Cm:0,47*	0,66	0,67	1,00	1,08
$30T_m$ @*W/Cm:0,58*	0,80	0,79	1,10	1,10
$40T_m$ @*W/Cm:0,47*	0,66	0,62	0,84	0,84
$40T_l$ @*W/Cm:0,47*	0,66	0,76	0,89	0,87
$40T_l$ @*W/Cm:0,58*	0,61	0,72	0,88	0,80

In previous investigations with Hellenic high-lime fly ashes [25-27], it was shown that k-values are around unity during the early stages of hardening and exceeds it as hydration proceeds and pozzolanic reaction evolves. However, those values were calculated for moderate cement replacement levels (i.e. 20% by weight). For the advanced replacement ratios applied here, k-values present a similar trend, since the majority of the samples examined are reaching unity after the first month and exceed it at 90 days. This is quite impressive indicating the ability of high-lime fly ashes to replace a large amount of cement providing equal or even better properties to the final products.

3.4 Chloride resistance and synergy detection

With respect to resistance towards chloride ingress, the inclusion of all fly ashes in the mix, improved dramatically the concrete's performance as shown in Fig. 2, where the charge that passed through the concrete samples with 30% fly ash addition is plotted against the w/Cm used.

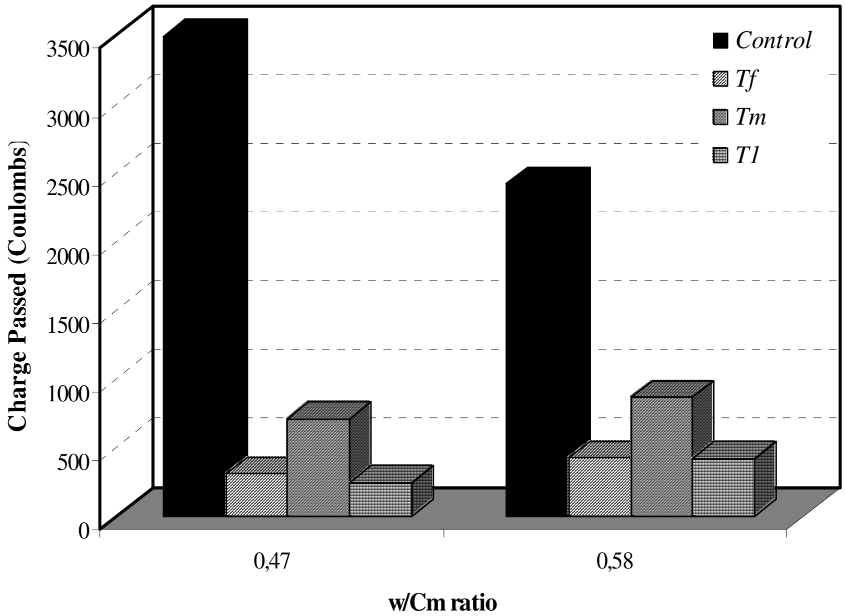

Fig. 2. Rapid Chloride Penetration Test Results (RCPT) for concretes prepared with initial ashes and their intermixture for 30% cement replacement as a function of the w/Cm applied

The advanced level of hydration applied here (120 days), ensured that fly ash systems would develop pozzolanic action. Obviously, this is the main reason that fly ash concretes are exhibiting significantly lower electrical charge for both w/Cm values adopted. Moreover, prolonged grinding of both ashes used, led to more fine particles than the ones of cement, underlining the physical effect of the pozzolans. It is widely accepted that smaller fly ash grains are causing more dense packing between the aggregates (especially the fine ones) and the cement particles, contributing to the porosity reduction [17,28]. Up to 50 percent replacement of the class C fly ash T_f by T_m ash (T_2 specimen) showed favorable resistance to chloride penetration. Somewhat surprisingly, the charge that passed through the specimens with the ashes that constitute the blend is higher. This is clearly an indication that a synergistic effect between the two ashes has taken place.

4. Application in practice

4.1 Several Applications

The most successful constructional projects with HCFA are those with optimum cost saving and technical benefits which would have hardly been achieved without HCFA. The applications of HCFA in Concrete Construction mainly refer to their use in road construction, in road pavements in high volume HCFA constructions as well in concrete products. According to bibliography, HCFA was at first used in geotechnical jobs in North Dakota 1971 [29] where a lignite fly ash-lime-aggregate road base [13pct HCFA + 2pct lime + 85pct aggregate (poz-o-pac)] was placed near the site of the Basin Electric Power Plant. Afterwards, HCFA was used for clay soil or gravel-clay stabilization and during the 80's many regional HCFA were used in constructional projects. They were tested by applying the ASTM C593 (Vacus saturation test for checking durability). Whatever the type of soil cohesive or cohesionless, the combination of lime (1-3pct) and fly ashes (7-15pct) increased strength and durability although all the HCFA used did not perform alike. Even nowadays this application, which is based on pozzolanicity and hydraulicity of HCFA, is one of the most convenient, since large quantities of low quality HCFA (considering it as binding material) are absorbed for embankments, soil amendments, subgrade stabilization, or hydraulic fills. Relevant design manual and specifications have been published in EPRI report TR-100472 Volumes 1 and 2, 1992. EPRI has sponsored the Delaware Ash Ramp Embankment Project and useful constructional details have been reported.

Table 5. Changes in the behavior of a sandy soil with the addition of HCFA

Addition of HCFA (%)	**Max. density Proctor A.A.S.H.O. T99 (kg/m^3)**	**Optimum moisture content (%)**	**C.B.R. E105-86 moist Crushing after 7 days**	**Expansion %**
0 (sand soil)	1594	4,7	2,84	0
4	1606	7,6	7,55	0
7	1622	7,8	19,43	0
10	1674	8,5	25,15	0
13	1686	11,6	34,91	0
Characteristics of sandy soil: SE: 85A.A.S.H.O. T17-6 Plasticity: NP. A.A.S.H.O. T-89, T-90 Classification: A.U.S.C.S., ASTM D-2487 : SP				

In Greece a modified with HCFA sandy soil has been used for embankment necessary for EGNATIA VIA construction purposes. In the table above [30] indicative results are given concerning the behavior (C.B.R measurements). Technically the HCFA is more advantageous compared with LCFA (in the case that both of them are locally available) because early age strength are commonly obtained without the addition of cement and the lime percentage may be the minimum required [31]. Pertinent to this field is flowable fill or Controlled Low Strength Material (CLSM), a flowable mortar or controlled density self levelling liquid mixture for easy and quick backfilling of pipe trenches and for facilitating future excavations needed [32].

Some typical mixtures mentioned in laboratory Testing Fly Ash Slurry (EPRI report CS 6100-112) are the following:

- ✓ 0,7 MPa mixt. of 5% cement and 95% Fly Ash
- ✓ 1,4 MPa mixt. of 10% cement and 90% Fly Ash
- ✓ 2,1 MPa mixt. of 15% cement and 85% Fly Ash

It is worth mentioning that the higher water retentivity of HCFA mixtures due to the hydrophilic nature of calcium-aluminate sulfate compounds of this fly ash, results in reducing settlement. The tendency to segregation of slurries with HCFA is also limited because of lower than cement specific density. In the case of using Colloidal Mixer (more than 3000 cycles per minute), the bleeding is zero and the strength development is high.

Among the outstanding case studies of HCFA applications are those of pavement and mass concrete construction. Use of very high volume fly ash concrete (i.e. 70% by weight of cement was replaced by class C Fly Ash) was made in the Wisconsin [32] and North Dakota projects [29]. In the frame of EPET program sponsored by EC + Greek Ministry of Research and Technology Development a demonstration project has been undertaken by Aristotle University of Thessaloniki in Cooperation with Public Power Cooperation (PPC) and construction Company AEGEK, for developing a Guide for the Use of Greek HCTA in concrete pavement and in stabilizing a aggregate mixture as road base for asphalt mat. Details from the results are given in table 6, below.

Table 6. Results from the EPET program concerning road construction

Place/date	**Project**	**Mix design kg/m^3**
West Macedonia/Greece /2001 Strength development 7-d 28-d 20 MPa 40 MPa	Use of Greek fly Ash in Road Construction Demonstration Project Rigid road pavement	HCFA (treated) 189 cement 81 Fines Agg. 750 Cours. Agg. 990 Vebetine : 22 sec. + Super-plasticizer HCFA data : R_{45}= 19%, CaO_f =2,9% SO_3 =4.7%
West Macedonia/Greece /2000 Strength development 7-d 28-d 18MPa 25 MPa	Use of Greek Fly Ash in road construction Road base	HCFA 126 Cement 54 Aggregates 1900 (mixed type) HCFA data R_{45}=38% CaO_{avail}=11,23% SO_3 =6.3%
Field experience: The transport of Fly Ash concrete produced at a central plant, to the site is problematic under hot weather Moist curing for 7 days is obligatory. Joints were sawed within 24 hours from bedding at intervals 4X4 m. Strength requirements Rc, 24MPa, R_t 1,2 MPa at 90 days, were overcome at earlier ages.		

The use of HCFA in structural concrete of medium grade 20- 45 MPa has a long history in research publications but a limited application since: - HCFA do not comply with existing specifications. An exception is the HCFA in Catalunia, Spain, which is used in structure under national standard regime. Its usually high content in CaO and SO_3 discourages engineers who fear about the corrosion of steel reinforcement. Therefore the percentage of HCFA addition is limited to around 20-30% of cement. However, there are many pre-cast in situ concrete products in which HCFA can be incorporated at higher than 30% percentages with remarkable benefits. As an example, the construction of New Jersey barriers and trigonal side endings for new road ways are presented below (Table 7):

Table 7. Results from New Jersey barriers and trigonal side endings in the frame of EPET

Place/Date	**Project**	**Mixture details kg/m^3**
Grevena/Kozani /2000 Strength development in situ 7-d 28-d 18.2 MPa 32,1 MPa Required strength at 28-d 25 MPa	EPET: Use of Greek Fly Ash in road construction and precast products Demonstration Project - New Jersey barriers - trigonal side endings	Cement 175 HCFA 175 Fine Agg. 1100 Coarse Agg. 670 Water 210 Superpl. 0.9lt/m^3 Slump S=3 HCFA data. R_{45} 19% CaO $_{free}$ 2.90% SO_3 4.77% + Polypropylene Fibre 600g/m^3
Field experience: The New Jersey barriers line was cured for 7 days covered with wet burlaps and plastic sheets. The finishing and appearance of the barriers were superior of those with cement only. Better resistance to leaching was measured for pre-cast road side endings		

According to CANMET project undertaken in 1994 for Electric Power Research Institute (EPRI) high volume of Class C Fly Ash (with CaO 14.8% R_{45} 46%) was used for manufacturing structural lightweight concrete. All properties of fresh and hardened concrete were determined as well as some durability characteristics in order to conclude that structural lightweight concrete (unit weight < 1900 kg/m^3 and 28-d HCFA replacing the strength grade > 35MPa) can be produced by using 60 – 70 % of the cement.

A cost effective AAC light -weight concrete without course aggregate by using high volume fly ash was promoted in US market by EPPI. It is used for manufacturing blocks in load bearing walls, partition walls, filler walls, of filling material of flooring construction. In this well-known material in Europe the incorporation of high volume HCFA in cement replacement, results in reducing bleeding and improving the technical characteristics of the final product.

Finally, high volumes of Greek HCFA have also been used in research projects for developing commercial HSC. In Table 8, indicative results are given, showing that it is feasible to achieve high strength even at earlier ages by using HCFA.

Table 8. Indicative results from high volumes Greek HCFA

Mix proportions	I	II	Mean compressive strength (MPa)		
Cement	450	350			
Fly Ash	150	300		7-d	28-Φ
Fine Agg.	-	-	**I**	50.4	71.6
Coarse Agg.	-	-	**II**	40.4	63.7
Admix.					
W/ctf	0,33	0,32			

4.2 The Platanovryssi Dam

One of the most impressive examples of the use of HCFA for the construction of a high paste RCC dam, the highest in Europe, is Platanovryssi Dam, on the Nestos river in north-eastern Greece [33, 34]. Dam construction is one of the most promising sectors in HCFA applications in which high volumes of HCFA can be used. In this type of structures the heat of hydration is low, the strength development adequate and the compactability of the mixture very good. Platanovryssi Dam is 95 m high, with a crest length of 270 m and a volume of 450.000 m^3. Its construction started in October 1995 and finished in March 1997. In this period 135000t of upgraded fly ash were produced and transported with 5500 silo vehicles for a distance of 380 Km in the place of dam in Platanovryssi. There, it was mixed with type I cement at a rate of Cement/Flyash = 20/80 and this mixture was applied for the construction of the main body of dam with RCC method. Until now (after 7 years), excellent results concerning strengths and other relevant properties have been obtained. The overall project was designed and supervised by the Hydroelectric Project Development Department of Greek Public Power Cooperation (PPC) in collaboration with worldwide specialists and specialized research centres. The decision for the use of Greek HCFA produced by PPC thermal stations of northern Greece was undertaken in 1989.

For the realization of this decision and for overcoming some particularities of high calcium fly ashes of Ptolemais origin, PPC had imposed strict requirements. These particularities are summarized to the i) variations in the chemical and mineralogical composition, ii) necessity for supplementary grinding for better reveal of their pozzolanic and hydraulic properties, iii) elevated proportion of their CaO_f as its hydration cause soundness problems as well as significant temperature increase and

iv) periodically elevated proportions of SO_3 content with negative consequences similar to cement. The handling of the aformentioned particularities had as basic assumption the construction of a milling plant with simultaneous partial hydrolization of fly ash, near Ptolemais Power Station. With the aid of this process, the problems of high CaO_f and the necessity for supplementary grinding were successfully confronted. During the period of 19 months, a very strict quality control program was followed aiming to control the four different levels of the production [35-38]. Before Platanovryssi dam, very few (3,2% of the total 157 RCC dams [39]) were constructed with HCFA. It was a historic moment for construction community that teaches how a marginal by-product may become the main cementitious material of a dam.

5. Conclusions

About 10 million tones of fly ashes are produced annually in Greece from burning lignite as the main Greek energy source. Although their chemical composition varies widely, depending on their origin, they all contain appreciable quantities of lime (in all cases above 10%). Therefore they are all characterized as High-Calcium Fly Ashes (HCFA). In Greece, from the seventies, a large number of research has been focused on the use of HCFA in blended cement, concrete and other concrete products. These efforts have led to very encouraging results with regards to basic properties of concrete (mechanical and durability) that coincide with relative published work coming from numerous researchers and especially from countries where similar ashes are generated.

Despite the absence of any National standards on the use of HC fly ashes in concrete, the introduction of such ashes into several applications (mainly road construction works and concrete products) has been successfully tested during the last 10 years, in the frame of pilot-scale programs. Unambiguously, the largest project performed with the use of HCFA, was the construction of the Platanovryssi dam, involving a large addition of such ashes (i.e. 80% by weight) into the final mix. So far and after 6 years of operation, impressive results have been obtained regarding its mechanical and other properties. It was the excellent performance of this work that actually increased the need for the development of National specifications on the use of high-calcium fly ashes in concrete. The main points of these specifications are mentioned in the text of the present study. Special attention is given on the points that are differentiated with respect to the specifications of the European standard prEN 450-1, that is, principally the upper limits proposed for the SO_3 and free lime contents of the ash.

Coinstantaneously with the standardization efforts stated above, laboratory-scale research is also in progress on the production and evaluation of High-Volume Fly Ash Concrete prepared with high-lime fly ashes. Preliminary results of this attempt, presented also here, have strengthened the belief that HCFA is an industrial by-product with great potential for use in the construction sector. It is believed that the definitive enactment of the aforementioned specifications will ensure the increase of the utilization rate of high-lime fly ashes in a manner that will benefit both the producer and the environment.

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