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Greek supplementary cementing materials and their incorporation in concrete

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Abstract

Sustainable development of the building sector can be achieved by a significant incorporation of cementitious and pozzolanic by-products, such as fly ash and slag, as well as some natural pozzolanic materials (supplementary cementing materials—SCM). Millions of tons of SCM, especially in Greece, are dumped due to overproduction or non-conformity with the existing standards. In this work, various types of SCM produced in Greece are investigated for a potential use in concrete. Their behavior as regards strength and durability is approached by a practical efficiency factor (*k*-value). The work is further focused on fly ashes, as they constitute the vast and more active majority of Greek SCM. The effectiveness of the Greek fly ashes in concrete improvement is widely proved through strength and durability measurements at laboratory and pilot-plant scale. However, they contain high amounts of free lime and sulphates, which may cause durability problems. In addition, they exhibit inadequate fineness and composition variations. Thus, an appropriate treatment is required and proposed by the present study in order to eliminate or reduce any harmful factors. Finally, a mix design strategy ensuring optimum strength, durability and ecological profile is proposed.

Keywords: Concrete; Efficiency; Greece; Supplementary cementing materials

1. Introduction

Supplementary cementing materials (SCM) may be divided into natural materials and artificial ones. To the former belong true pozzolanas and volcanic tuffs. To the second category belong siliceous by-products, such as fly ashes, condensed silica fume and metallurgical slags (blast furnace slag, steel slag, non-ferrous slags). As is well known [1–6], these materials can be used in concrete production either as blended cement constituents or as separate concrete admixture.

In Table 1 the category, location, industry, production rates, way of disposal, etc., for all SCM produced in Greece are given. In the main category of natural materials about 700,000 t/year are quarried and the vast majority is used in the cement industry as additions in the production of pozzolanic cements. These materials are mainly volcanic deposits located in Cyclades Islands and Macedonia. Some other materials, such as diatomeous earth, are being investigated for use in cement production. In the other main category of industrial by-products about 12,000,000 t/year are produced and only the 13% is used, mainly in the cement industry, leaving a vast amount of 10,500,000 t/year unexploited. The main part of these materials is fly ash produced by Public Power Corporation (PPC). The total production of fly ash is 9,500,000 t/year and only about 10% is used; the rest is placed back to the lignite quarries. About 77% of this fly ash amount is produced in various plants in Macedonia (Agios Dimitrios, Kardia, Ptolemais, Amintaio: Fly ash Ptolemais) and the rest in Peloponnese (fly ash Megalopolis). The second in the importance, is a nickel slag produced by LARKO SA in Larymna, Central Greece at a rate of 1,500,000 t/year. A 42% of this slag is used mainly by the cement industry. Various other slags (steel and pig iron slags) are produced at much lower rates. Finally, red mud, a by-product with potential pozzolanic properties is produced by the aluminium industry (Aluminium of the Greece, Central Greece) at a rate of 650,000 t/year and this remains totally unexploited.

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Table 1
Category, location, industry, production rates and way of disposal for all Greek SCM (2000)

Greek SCM	Industry/location	Production (t/year)	Disposal/use
Natural materials			
Milos earth	Milos Island, Cyclades	500,000	100% in the cement industry
Skydra earth	Skydra, Macedonia	100,000	100% in the cement industry
Kaolin	Milos Island, Cyclades	60,000	35% in the cement industry, 40% in the paper industry, 25% other applications
Diatomeous earth	Samos Island, etc.	–	Under research
Artificial by-products			
Fly ash Megalopolis	PPC[a]—Megalopolis plant, Peloponnese	2,200,000	10% in the cement industry the rest is unexploited
Fly ash Ptolemais	PPC—North Greece plants, Macedonia	7,300,000	10% in the cement industry the rest is unexploited
Bottom ash	PPC	200,000	It is unexploited
Nickel slag LARKO	LARKO, Larymna	1,500,000	35% in the cement industry, 7% in shipyards the rest is unexploited
Steel slag	Chalivourgiki, Elefsis	6000	100% in the cement industry
Iron slag SIDENOR	SIDENOR, Salonica	71,000	It is unexploited
Blast furnace slag	Greek Steel Industry, Aspropyrgos	52,000	100% in road construction
Red mud	Aluminium of the Greece, Centr. Greece	650,000	It is unexploited

[a] PPC: Public Power Corporation.

Table 2
Typical composition and classification for main Greek SCM

SCM	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	RILEM classification
Milos earth	58	14	4	7	1.5	2.2	1.3	1.2	–
FA Megalopolis	45–52	12–22	5–10	5–15	1.5–3	1.5–3	0.3–0.7	3–5	II, IV
FA Ptolemais	28–41	13–19	4–7	23–39	2–4	1–1.5	0.3–1	5–8	I
Slag LARKO	36	10	40	5	3	–	–	0.2	V
Slag SIDENOR	17	4	25	40	5	–	–	–	V
BFS	25	1.5	19	35	8	0.3	0.7	–	V
Red mud	7	18	48	6	–	–	3.4	–	V

FA: fly ash, BFS: blast furnace slag.

A typical composition of the main Greek SCM in terms of oxide analysis is given in Table 2. As regards Greek fly ashes, they exhibit high contents in calcium due to lignite form of the burnt coal. However, they may be divided into two sub-categories, according to the total calcium content:

(a) *Fly ash Megalopolis*. The CaO content in these ashes varies between 5% and 15% and thus they may be characterized as cementitious and pozzolanic mineral admixtures (category II, according to RILEM classification [3]) or as normal pozzolans (category IV). They could also be characterized as Type F according to ASTM C 618 [5], as the sum of the oxides $SiO_2 + Al_2O_3 + Fe_2O_3$ is greater than 70%.
(b) *Fly ash Ptolemais*. The CaO content in these fly ashes of Northern Greece is always greater than 20% and thus they can be characterized as cementitious mineral admixtures (category I, according to RILEM classification [3]). They could also be characterized as Type C according to ASTM C 618 [5], as the sum of the oxides $SiO_2 + Al_2O_3 + Fe_2O_3$ is between 50% and 70%.

The most serious problem in the use of these fly ashes, especially of fly ash Ptolemais, is the high contents in sulphur, which may introduce expansion problems in a concrete made by these materials. Another potential problem is the high content in free lime (1/4–1/3 of the total CaO), which also may create problems of expansion at early ages. Both types of ashes contain titanium, phosphorous, unburnt carbon, organic materials and other trace elements. Another indicative component is that both ashes are coarse with a retained amount in the 45 μm sieve between 50% and 60%, and thus they do not comply with the European Standards (<35% [7]). Their density varies between 2300 and 2600 kg/m^3. Finally, the large variation in the quality of these ashes (chemical and physical characteristics) introduces skepticism in their efficient use.

The Greek fly ashes have been used since 1980 in the production of pozzolanic cement, and their efficiency has been proved in practice. Since there are no regulations for their use in concrete and other related applications, their exploitation is limited only in cement production, in spite of the accumulated knowledge and the successful applications in practice [8–11]. The only application until today was the construction of a dam (Platanovrissi, Drama, Macedonia) by PPC and AEGEK (a construction company) using the method of roller compacted concrete (RCC). Fly ash Ptolemais was the main cementitious material (80%), which was selected, homogenized and treated (by grinding with partial hydration) in order to fulfill special requirements [12,13].

The rest of the materials presented in Table 2 (slags and red mud) can be characterized as mineral admixtures of low reactivity (category V, according to RILEM classification), as they are slowly-cooled by-products. They consist essentially of crystalline materials, and relatively small amounts of non-crystalline matter. These materials are extremely coarse and must be pulverized to very fine particle size in order to develop satisfactory cementitious or pozzolanic activity.

Based on the above classification for the Greek SCM, these can be used in the same construction applications as all the corresponding materials which belong to the same category, e.g. as a separate constituent in concrete (for common buildings, foundations, dams, tunnels, reservoirs, bridges, highway pavements, silos, stadiums, etc.), prefabricated and prestressed concrete, in mortars, as soil stabilizers, etc. [5,6,14–18]. However, the suitability of the Greek SCM has to be proved by experiments, their effect on durability has to be studied in detail, and, finally, an appropriate mix design strategy has to be proposed; all these are exactly the main objectives of the present work.

2. Experimental investigation and modeling of Greek-SCM effect on concrete

2.1. SCM efficiency factor

In previous publications [19–23], a simplified scheme describing the activity of silica fume and fly ash (low- and high-calcium) in terms of chemical reactions was proposed, yielding quantitative expressions for the estimation of the final chemical and volumetric composition of such SCM-concretes. Further, a practical approach to the effect of SCM on the strength of Portland cement systems and on their resistance against carbonation and chloride penetration was presented, using the concept of the SCM efficiency factor.

The efficiency factor (or k-value) is defined as part of the SCM in a pozzolanic concrete which can be considered as equivalent to Portland cement, having the same properties as the concrete without SCM (obviously $k = 1$ for Portland cement). The quantity of the SCM in the mix can be multiplied by the k-value to estimate the equivalent cement content, which can be added to the cement content for the determination of the water-to-cement ratio, minimum required cement content, etc. The compressive strength was so far used as the property for the estimation of k-values [24,25]. In this work, durability properties are also used, such as resistance against carbonation and chloride penetration, and relative k-values are calculated. Knowing these k-values, the mix design for preparation of the building product can be easier and more accurate.

2.2. Experimental

Six typical Greek SCM were used; two natural materials and four industrial by-products: The natural materials were: a volcanic tuff from Milos Island (Milos earth, defined as **ME**), and a diatomeous earth from Samos Island (defined as **DE**). Three different fly ashes from Greek power plants (produced by Public Power Corporation) were used, i.e., a fly ash of relatively lower calcium content than the other fly ashes (fly ash from Megalopolis plant, defined as **FL**), a high-calcium fly ash of normal sulphur content (fly ash from Ptolemais plant, defined as **FH**), and a high-calcium fly ash of high-sulphur content (fly ash from Ptolemais plant, defined as **FHS**). Finally, a nickel slag produced by LARKO SA was used (defined as **SL**). All these SCM were ground prior to use up to a fineness of 400 ± 20 m^2/kg according to Blaine's test. A CEM I 52.5R, according to European Standard EN 197, Portland cement was used of the same fineness as above. Oxide analyses for all materials are presented in Table 3. The fraction of SiO_2 which is active for pozzolanic reactions is also given (active silica). Normal graded limestone aggregates, including fine (37%), medium (21%) and coarse (42%) aggregates, were used. The water content for all specimens was kept constant (175 kg/m^3). A common superplasticizer was used at a content of 0.5% of the total cementitious materials in order to retain the slump of the fresh concrete between 80 and 120 mm. For the control specimen, the water-to-cement ratio (W/C) was 0.5 and the aggregate-to-cement ratio (A/C) was 5.4. A constant volume unit (1 m^3) of concrete was chosen as a common comparison basis. When an SCM was added to this unit, then an equal mass of another component, either cement or aggregate, was removed in order to keep a similar total volume (the replacement ratios were 10% and 20% by cement weight).

For the determination of these k-values (different for each SCM and each property) an experimental programme was developed. The above Greek SCM were incorporated in test specimens and their k-values were determined, based on strength and durability properties. The program included the following measurements:

Table 3
Chemical analyses (%) of the materials used[a]

	Cement	FL	FH	FHS	SL	ME	DE
SiO_2	20.73	44.92	33.37	31.33	36.22	58.23	22.33
Al_2O_3	4.78	18.47	17.35	15.89	10.34	14.22	0.96
Fe_2O_3	3.87	7.90	5.57	5.37	40.19	4.31	1.00
CaO	64.73	14.87	25.21	27.38	5.08	7.40	45.89
MgO	2.05	2.22	3.05	3.02	3.12	1.43	1.54
K_2O	0.50	1.71	1.20	1.07	0.47	2.24	0.10
Na_2O	0.10	0.77	0.75	0.53	0.28	1.30	0.32
SO_3	2.47	3.89	5.57	7.90	0.23	1.16	1.24
Active SiO_2[b]	–	70	75	73	5	50	50

[a] The methods specified by EN-450, EN-196 and EN-451 were followed.
[b] The fraction of SiO_2 which is soluble after treatment with HCl and with boiling KOH solution (European Standard EN 197-1).

(a) Compressive strength measurements. The specimens were cast in cubes of 150 mm, vibrated for 20 s on a vibration table and then covered to minimize water evaporation. The molds were stripped after 24 h, and the specimens were immersed in lime-saturated water at 20 °C, until testing. The testing age was after 2, 7, 28, and 90 days. For each age, three specimens of each mixture were tested for compressive strength and the mean value of these measurements is reported.

(b) Durability measurements. Deterioration of building materials in service may be the result of a variety of mechanical, physical, chemical or biochemical processes. Especially, for concrete the most serious deterioration mechanisms are chloride penetration, carbonation, sulphate and alkalis attack, and frost action. In this work, the durability of concrete incorporating SCM was investigated focusing on chloride penetration.

2.3. Results and modeling

In order to estimate the *k*-values, the following procedure was followed. The compressive strength, f_c (MPa), of a Portland cement concrete can be estimated by the following empirical equation:

$$f_c = K\left(\frac{1}{W/C} - a\right) \tag{1}$$

where W is the water content in the fresh concrete mix (kg/m^3), C is the cement content in the concrete (kg/m^3), K is a parameter depending on the cement type (MPa) and a a parameter depending mainly on test time and curing procedure. For the Portland cement used in this work, the K was calculated as 38.8 MPa. Using the mean measured values of the compressive strength of the control specimen, a is estimated as 1.06, 0.72, 0.5, and 0.23, for 2, 7, 28, and 90 days, respectively.

In the case of SCM-concrete, the following expression for compressive strength can be used involving the concept of *k*-value:

$$f_c = K\left(\frac{1}{W/(C + kP)} - a\right) \tag{2}$$

where P is the SCM content in the concrete (kg/m^3). Using this equation, the measured values of the compressive strength, and the W, C and P contents, the *k*-values for the SCM of the present work were calculated and given in Fig. 1.

For fly ashes, the *k*-values are around unity (1) at early ages and they exceed it, as time proceeds. This means that up to a certain level [20–22], these specific fly ashes can substitute, equivalently, for Portland cement. Especially, for fly ash with almost zero calcium content the maximum content is about 25% of the cement content, for FL (fly ash Megalopolis) the maximum content is calculated as 36% and for FH (fly ash Prolemais) as 50%. The natural SCM exhibit much lower efficiency factors (0.3–0.4 for ME and 0.2 for DE). This is correlated with their low level of active silica content. Similarly, in the case of the nickel slag (SL) very low *k*-values of 0–0.1 were calculated, proving that the lack of active silica due to slowly-cooled production plays a dominant role in the pozzolanic activity.

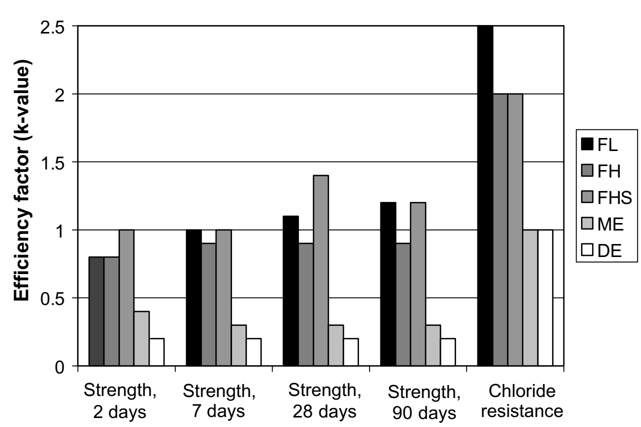

Fig. 1. Efficiency factors (*k*-values) for various supplementary cementing materials.

The specimens incorporating a fly ash, whether it substitutes aggregate or cement, exhibit significantly lower chloride permeability as compared with the control specimen [23]. Among all fly ashes tested, FL exhibited the lowest degree of chloride penetration, then FH, and FHS the highest. As the fly ash content in the concrete volume increases, the chloride permeability decreases. There is a similarity in the results for natural pozzolans (ME and DE), however, in this case the permeability is higher as compared to fly ash specimens. A mathematical model developed earlier [23] was applied to simulate the experimental results. In order for these predictions to fit the experimental data, the following optimum efficiency factors were estimated and given in Fig. 1. These significantly higher *k*-values for SCM efficiency against chlorides as compared with the corresponding values for strength can be explained as due to important interactions of Cl^- with the pore walls, or by the electrical double-layer at the pore walls-pore solution interface [23].

3. Greek fly ashes: deviations, treatment, and standardization

3.1. Deviations from the standards

The work will further focus on fly ashes, as they constitute the vast and more active majority of Greek SCM. The main deviations of Greek fly ashes from the EN-450 standard are the following:

Sulphate content. The fly ash Megalopolis content in sulphates (SO_3) varies between 3% and 5%, a little higher than the EN-450 upper limit (3%). If, however, the ASTM standards apply, where the maximum permitted sulphate content is 5%, the fly ash Megalopolis complies with this standard. The fly ash Ptolemais with a sulphate content to vary between 5% and 8% is far from the upper limits specified both by EN and ASTM.

Free calcium content. The Greek fly ashes, especially fly ash Ptolemais, contain large amounts of free calcium oxide much higher than the 1% specified by EN. The total calcium content also is much higher than the 10% specified by the same standard.

Fineness. The Greek fly ashes exhibit lower fineness than that specified by EN. The retained amount in the 45 μm sieve varies between 50% and 60%, and thus they do not comply with the upper limit of 35%.

3.2. Treatment of Greek fly ashes

As given above, the Greek fly ashes must be treated in order to eliminate or reduce any harmful factors and to comply with the EN or national standards. In addition to the above-mentioned main deviations, they also exhibit significant compositional variations. There are possibly two ways of treatment: appropriate modifications during fly ash production and specific treatment after production. Focusing on the main deviations, the following treatment and improvement techniques are proposed.

3.2.1. Sulphates

The lignite contains high contents of sulphur, which unavoidably are bound by fly ash, due to its high-calcium oxide content. As the establishment of a desulphurization unit is expensive, simpler solutions must be sought. The simplest and the most environmental-friendly way is to use these fly ashes with Portland cement of low content in gypsum. The Portland cement usually contains 5% gypsum, a material necessary to avoid flash setting of cement. The sulphur in fly ash is mainly in the form of anhydrite or semi-hydrite gypsum and may contribute to the gypsum requirements of the cement. Thus, a Portland cement with lower gypsum content can co-operate with high-sulphur fly ash without risk of sulphate expansion. In addition, a gypsum saving can be also achieved for the cement industry.

3.2.2. Free lime

Lignite contains also high amounts of calcium, where some of them are converted into free lime during the combustion process. A successful technique, that was applied in the preparation of fly ash for the construction of Platanovrissi's dam in Northern Greece [12,13], was the partial hydration of the fly ash prior to use. This process took place simultaneously with the grinding process to increase the fineness. However, the ground-hydrated fly ash exhibited lower activity as a significant part of its self-cementitious activity was released during the hydration process. For this reason, an in situ hydration of fly ash must be examined, for instance, the addition of fly ash in the mixer as the first material together with water only and their retention for a certain time. In this way, the major part of free calcium oxide will be hydrated to calcium hydroxide and thus the risk of a further expansion will be reduced.

3.2.3. Fineness

The Greek fly ashes must be pulverized to very fine particle size in order to develop acceptable levels of strength in combination with cement. For this purpose, the fly ash producer should establish a mill to grind the fly ash and thus to increase its fineness.

Thus, an appropriate treatment is required to confront the potential risks that fly ash may introduce to concrete. Most of the techniques proposed are related with treatment after fly ash production. However, long-term experiments are further required in order to establish a continuous use of larger quantities of fly ash in concrete. Some of the SCM due to specific production process, such as slowly-cooled slag (SL) and bottom ash, exhibit low or zero reactivity and their production process might be modified to improve reactivity. The increase of glass-reactive phases can be achieved by rapid water quenching of slag.

The complementarity of SCM, i.e., the simultaneous use of various SCM, to maximize their total in concrete is also a subject for investigation. Some of the materials may co-operate with others and thus their total content in an application could be maximized. For instance, low-calcium fly ash (FL) can be used together with high-calcium fly ash (FH or FHS) eliminating harmful factors, increasing early strengths, and substituting more conventional building materials (cement and aggregates). In addition, the nickel slag (SL) can be used to substitute the fine part of aggregates decreasing further the environmental cost during concrete production.

3.3. Standardization of Greek fly ashes

As shown above, Greek fly ash due to its particular chemical (high free calcium and sulphur contents) and physical (low fineness) composition, does not comply with the EN-450 specifications. However, its effectiveness in cement production and concrete improvement has been widely proved (including the present research results). It is, therefore, absolutely necessary for the existing European Standard (or national standards) to include the use of high-calcium fly ash in concrete. The present results and the proposed treatment techniques can be considered in the formulation of specifications for the use of Greek SCM in construction. As general guidelines for the future work regarding the development of specifications, the fly ash produced in the Greek power plants has to be treated as follows:

Milling. The fly ash must be milled in order to meet the EN fineness requirement: the retained amount in the 45 μm sieve has to be less than 35%. During this process an adequate mixing and homogenizing must take place to reduce any compositional variations.

Partial hydration. An appropriate procedure has to be specified and followed (either during the milling process or in the mixer prior to use) in order the free lime to be hydrated and the risk of early expansion to be avoided.

Portland cement of low-gypsum. The high-sulphur fly ash must be specified for use with a Portland cement of lower gypsum content. The total sulphate content of the cementitious materials could have a specified maximum limit.

Obviously, from this short introduction in the application of Greek fly ashes in the construction practice, the co-operation of all interested parties (fly ash producer, cement industry, concrete producers, etc.) is absolutely necessary.

4. Design of concrete incorporating SCM

With the term mix design it is meant the definition of the concrete compositional parameters (cement, different type and gradation of aggregates, SCM, water, additives) in order to maintain a required general performance (strength expectations and standards' fulfillment) at a designed service lifetime. Economic aspects and ecological benefits should also be considered. SCM additions may be taken into account in the concrete composition using the *k*-value concept. In all specifications for concrete production, among the main design parameters are the cement content (C) and the water-to-cement ratio (W/C). Thus, minimum values of cement content and maximum values of W/C ratio are specified according to the aggressiveness class of the surrounding environment. Despite the exposure classes, whenever SCM is used in concrete, the total equivalent cement content should be taken into account using the expression:

$$C_{eq} = C + kP \tag{3}$$

where C and P are the contents of Portland cement and SCM in concrete, respectively (kg/m^3), and k the SCM efficiency factor. Usually, k-values of 2 and 0.5 for silica fume and low-calcium fly ash respectively are proposed [24]. From the present work, new k-values (for strength) are proposed and summarized in Fig. 1. These values are valid for a certain amount of SCM in concrete. As given in previous publications [20–23], the maximum fly ash content in concrete shall be 25–50% of the cement weight depending on calcium content of the fly ash. Especially, for FL (fly ash Megalopolis) the maximum content is calculated as 36% of the cement content and for FH (fly ash Prolemais) as 50%. Further experiments are required for an accurate approach in the case of multi-component SCM use in concrete.

After having specified the concrete composition (primarily C, W, P and A contents of Portland cement, water, SCM and aggregate respectively, in kg/m^3) that fulfils the strength expectations and standard requirements (e.g., minimum equivalent cement content, maximum W/C_{eq} ratio, etc.), the concrete durability should be examined. Let us suppose that the design service lifetime is L years. Thus, this specific concrete composition must be examined to determine whether it ensures a service lifetime greater than the design life in the deterioration environment in which the concrete will be exposed.

First the case of concrete carbonation, if any, must be taken into account. The concrete cover, c, must be deeper than the expected carbonation depth within the lifetime L. If an unacceptable (for technical or economical reasons) cover is predicted [23] then either a different concrete composition (e.g., lower W/C ratio, higher cement content, etc.) or a protective coating application should be proposed. Then the calculation must be repeated until a satisfactory result is obtained.

Having specified the concrete composition and cover as above, the case of chloride penetration, if any, must then be considered. The k-values for resistance against chloride ingress must be used. Using the Cl-profile in the time equal to L, the minimum concrete cover can be found at which and onwards the chloride concentration has lower values than the critical threshold for corrosion [23]. If an unacceptable cover is predicted then again either a denser concrete composition or a coating application should be considered and the calculation must be repeated until a satisfactory result to be obtained. The design parameters that ensure full protection, e.g., a deeper concrete cover or a denser concrete composition for resistance against carbonation and chloride penetration, must be finally proposed. If any other deterioration mechanism could arise, it has to be considered in a similar way.

5. Concluding remarks

Sustainable development of the building sector can be achieved by significant incorporation of cementitious and pozzolanic by-products, such as fly ash and slag (supplementary cementing materials—SCM). Millions of tons of SCM (especially in Greece) are dumped due to overproduction or non-conformity with the existing standards. In this work, different types of SCM produced in Greece are investigated for a possible use in the building sector. Greek SCM are significantly different from common SCM, e.g., fly ash contains high amounts of free lime, sulphates, etc., which may cause durability problems. Moreover, all these materials exhibit inadequate fineness and compositional variations. Thus, an appropriate treatment is required and proposed by this work to eliminate or reduce any harmful factors.

For comparing the relative performance of various SCM as regards Portland cement, the concept of the efficiency factor may be applied. The efficiency factor (k-value) is defined as the part of the SCM in an SCM-concrete, which can be considered as equivalent to Portland cement. From the present work, efficiency factors for various Greek SCM were calculated and are summarized in Fig. 1. These values are valid for a certain amount of SCM in concrete and they are different depending on the property that it concerns (compressive strength at various ages, chloride resistance, carbonation resistance, etc.).

When SCM substitute aggregates, strengths higher than the controls are succeeded. When SCM replace cement, the strength is reduced, at first, but as time proceeds this gap is gradually eliminated and the strength becomes higher than that of the control for these SCM with higher active silica content in comparison with the cement. By introducing the efficiency factor concept, the fly ashes of this work can substitute, equivalently, for Portland cement ($k = 0.9$–1.2). The natural SCM exhibit much lower efficiency factors ($k = 0.2$–0.3). The concrete incorporating SCM, whether used as partial replacement for aggregate or cement, exhibited significantly lower total chloride content. Higher k-values for SCM efficiency against chlorides as compared with the corresponding values for strength were calculated ($k = 2$–2.5 for fly ashes and $k = 1$ for natural pozzolans). The use of SCM as an addition to Portland cement mixtures, replacing either aggregate or cement, should therefore significantly enhance the chloride-induced corrosion initiation stage. Finally, a mix design strategy, ensuring strength, specifications, and service lifetime is presented, by applying the concept of the SCM efficiency factor. Using SCM to replace cement and/or aggregates in building applications, components of strength equal or higher than the reference mixture can be obtained. At the same time, a similar or higher durability is achieved, plus significant ecological benefits, due to the use of industrial by-products (reduction of pollution from SCM arbitrary disposal) and decrease in the cement quantity (energy saving and CO_2-emission reduction).

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