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EXTENDED USE OF SUPPLEMENTARY CEMENTING MATERIALS IN CONSTRUCTION FOR ECONOMIC AND ENVIRONMENTAL BENEFITS

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ABSTRACT

A sustainable development of the building sector can be achieved by extended 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 the developing countries, are dumped due to overproduction or non-conformity with the existing standards. In this work, various types of SCM are investigated, theoretically and experimentally, for a potential use in concrete. The behavior of the SCM as regards strength and durability is approached by a practical efficiency factor (k-value), based either on experimental results or calculated from fundamental characteristics of the SCM. Finally, a holistic mix design strategy ensuring optimum strength, durability, economy and ecological profile is proposed.

Keywords: Concrete; Design; Efficiency; Strength, 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 well known [1-6], these materials can be used in concrete production either as blended cement constituents or as separate concrete admixture. However, as they exhibit different activity due to significant variation in physical, chemical, and mineralogical composition, an efficient procedure has to be developed for their optimum and safe use in construction.

In previous publications [7-10], a simplified scheme was proposed, describing the activity of silica fume and fly ash (low- and high-calcium) in terms of chemical reactions, yielding quantitative expressions for the estimation of the final chemical and volumetric composition of 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 the 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 mixture 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 [11,12]. In this work, durability properties are also used, such as the resistance against chloride penetration, and relative k-values are presented. Knowing these k-values, the mix design for preparation of the building product can be easier and more accurate.

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 Puplic 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 sulfur content (fly ash from Ptolemais plant, defined as FH), and a high-calcium fly ash of high sulfur 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 rapid setting Portland cement was used (CEM I 52.5R according to European Standard EN 197) of the same fineness. Oxide analyses for all materials are presented in Table 1. The fraction of SiO_2, which is active for pozzolanic reactions, is also given

Table 1. Chemical analyses (%) of the materials used*

	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**	-	70	75	73	5	50	50

* The methods specified by EN-450, EN-196 and EN-451 were followed.

** The fraction of SiO_2 which is soluble after treatment with HCl and with boiling KOH solution (European Standard EN 197-1).

(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 80-120 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.

For the determination of these k-values (different for each SCM and each property) an experimental program 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:

a. Compressive strength measurements. The strength development versus time was measured representing the mechanical behavior of concrete.

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.

3. RESULTS AND MODELING

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

Table 2. Efficiency factors (k-values) for various supplementary cementing materials

Concrete Property	FL	FH	FHS	SL	ME	DE
Strength, 2 days	0.8	0.8	1.0	0.0	0.4	0.2
Strength, 7 days	1.0	0.9	1.0	0.0	0.3	0.2
Strength, 28 days	1.1	0.9	1.4	0.1	0.3	0.2
Strength, 90 days	1.2	0.9	1.2	0.1	0.3	0.2
Chloride resistance	2.5	2	2	-	1	1

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

where W is the water content in the initial 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 α a parameter depending mainly on time and curing. 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, α was 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:

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

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 Table 2. Also, in Fig. 1 all k-values presented here as well in earlier works [10,13] are summarized.

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 [7-9], these specific pulverized fly ashes can substitute, equivalently, for Portland cement. 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.

The specimens incorporating a fly ash, whether it substitutes aggregate or cement, exhibit significantly lower chloride permeability as compared with the control specimen [10]. 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

[10] 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 Table 2. 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 [10].

In recent works [14,15], for the first time, the k-value was correlated with the active silica content of SCM and an analytical relationship was obtained:

$$k = (\gamma_S f_{S,P} / f_{S,C})\,(1 - \alpha\, W/C) \tag{3}$$

where, $f_{S,C}$ and $f_{S,P}$ are the weight fractions of silica in cement and SCM, respectively, and γ_S is the ratio of active silica to the total silica in the SCM (see Table 1). This expression was found to be valid for artificial SCM (fly ash, slag), while overestimating the k-values for the natural materials. This exception for natural materials can be attributed either to the formation of a weaker CSH component or to the fact that the active silica measurement followed was not applicable for natural materials. Thus, the analytical relationship can be applied as a first approximation of the k-value of the artificial SCM. This approach may be used for a rapid prediction of the quantity, but most of all the quality of the SCM used in the concrete mix design so that the final product will meet certain specified requirements.

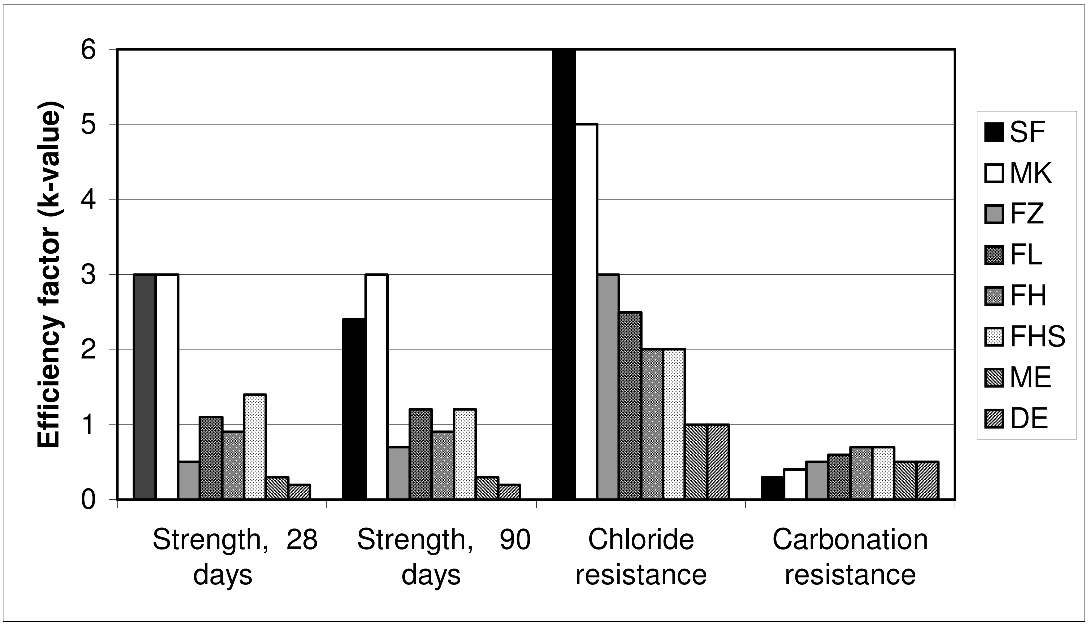

Figure 1. Efficiency factors (k-values) for various supplementary cementing materials; this work and earlier works [10,13]. SF: silica fume, MK: metakaolin, FZ: anthracite fly ash with almost zero calcium content, FL: low-calcium fly ash, FH: high-calcium fly ash, FHS: high-calcium high-sulfur fly ash, ME: Milos volcanic earth, and DE: diatomeous earth.

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:

$$C_{eq} = C + kP \qquad (4)$$

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 are proposed, respectively [11]. From the present work, new k-values (for strength) are proposed and summarized in Table 2. These values are valid for a certain amount of SCM in concrete. As given in previous publications [7-9], 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 [10] 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 [10]. 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. APPLICATION IN PRACTICE

When an SCM replaces aggregates or cement the total production cost can increase or decrease accordingly, depending on their relevant values. In the following application examples, these cost differences are given quantitatively. The real case of a Megalopolis fly ash (FL) use by a concrete ready-mix plant in Greece was selected. All figures are real (in €, April 2001, VAT not included).

A typical mix design (C 16/20 characteristic strength [11]) using only Portland cement is denoted as the reference concrete. Two different types of concrete are examined: a high-durability concrete (higher than the reference; using the maximum permitted amounts for FL) and an equal-strength concrete (equal strength to the reference mixture as the k-value concept is applied; using again the maximum permitted amounts for FL). The maximum FL content is 36% of the cement content [9], or, equivalently, about C/3.

Data:
U_C: cement value (Portland I 42.5): 0.0624 €/kg
U_P: fly ash value (20% of Portland cement; estimated): 0.0125 €/kg
U_A: aggregate value: 0.0044 €/kg
U_W: water value: 0.0015 €/kg
U_D: admixture value: 0.59 €/kg
E: additional equipment and modifications: 16,200 €
d: depreciation period: 5 years
PR: annual production: 100,000 m^3 concrete/year

Concrete mix design:
1. Definition of C and P contents.
2. Estimation of D content: 0.5% (C+P)
3. Definition of W content for the required strength and durability
4. Aggregate selection and air content estimation (e.g., 2%)
5. Determination of A content = $(1 - C/\rho_C - P/\rho_P - W/\rho_W - D/\rho_D - \varepsilon_{air})\ \rho_A$
   ρ_C: 3150 kg/m^3, ρ_P: 2600 kg/m^3 (FL), ρ_A: 2700 kg/m^3, ρ_W: 1000 kg/m^3, ρ_D: 1170 kg/m^3

The various mix designs are presented in Table 3. Using the above data, the purchase cost of the materials was calculated, added to the additional fixed cost due to fly ash use, and the total cost (expenses due to fly ash presence in concrete) was calculated.

Table 3. Examples of various concrete mix designs and comparative production costs

	Refer. Concrete (C 16/20)	**High Durability with FL**	**Equal Strength with FL**
C, kg/m^3	270	270	200
P, kg/m^3	0	90	70
D, kg/m^3	1.35	1.8	1.35
W, kg/m^3	175	175	175
A, kg/m^3	1939	1844	1926
E/(d.PR), €/m^3	0	0.032	0.032
Raw mat. cost, €/m^3	26.44	27.41	22.89
Total, €/m^3	26.44	27.44	22.92
Difference from reference, €/m^3	-	1.00 increase: 3.8%	-3.52 decrease: 13.3%

* C_{eq}=C+kP, FL=C/3, k_{FL}=1

In the above-mentioned ready-mix plant (located at Athens), fly ash was transported from Megalopolis power plant, milled and placed at a separate silo. Trial mixes were performed in the basis of the mix designs proposed in Table 3. As a general conclusion, it was observed that in the case of high durability FL-mix, a concrete of higher strength was produced and in the case of equal strength FL-mix, a concrete with similar strength to the controls was produced.

6. CONCLUDING REMARKS

In practice, the concept of an efficiency factor for the supplementary cementing materials (SCM: silica fume, fly ash, slag, natural pozzolans, etc.) may be applied in order to predict the performance of concrete incorporating SCM. 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. In this work, efficiency factors for various SCM were presented. These values are valid for a certain amount of SCM in concrete and they are different depending on the property that it concerns (strength, durability). This approach may be used for a rapid prediction of the quantity, but most of all the quality of the SCM used in the concrete mix design so that the final product will meet certain specified requirements.

Using SCM to replace cement and/or aggregates in building applications, components of strength equal or higher to a reference mixture can be obtained. At the same time, a similar or higher durability is achieved, plus significant ecological benefits, due to industrial by-product use (reduction of pollution from SCM arbitrary disposal) and decrease in the cement quantity (energy saving and CO_2-emission reduction). Especially, due to increase in durability, a significant decrease in maintenance and repair costs is expected. Focusing on economical results from the presented application in practice it was generally observed that:

- Increasing the cost of production (the purchase cost of materials plus the additional cost due to fly ash use) only by 4%, a concrete incorporating fly ash (FL) can be produced providing significantly higher durability than the reference concrete.
- Using fly ash (FL) in concrete and replacing part of the cement and aggregates, equal-strength concrete can be produced with the saving of 13% on the initial production cost.

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