# A BALANCED APPROACH BETWEEN SUSTAINABLE AND DURABLE DESIGN OF REINFORCED CONCRETE STRUCTURES – THE WAY TOWARDS GREEN DURABILITY

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## Abstract

The internationally acclaimed efforts and expressed concern on environmental policies to reduce man-made $CO_2$ emissions into the atmosphere necessitates the need for a more rigorous approach to be adopted by the construction industry, on these matters. Given the need to provide a durable solution that guarantees a minimum service life of at least 50 years, on a common reinforced concrete structure, the issue of sustainable durability design is of paramount importance in achieving a “green” but also robust solution. Bearing in mind that the major source of emission of gasses in concrete manufacturing arise from the clinker production process, during cement manufacturing, several means of reducing the environmental footprint have been suggested, as incorporation of supplementary cementing by -products (silica fume, fly ash, etc.).

On this note, the aim of this study is by estimating the environmental contribution of each component of concrete, to provide the best possible mix design configuration in terms of low environmental cost and to assess this proposed configuration in terms of strength and durability requirements, according to the EN 206 concrete standard and the Eurocodes. It is hoped that the results of this study will provide the basis for the establishment of a balanced approach between a sustainable and durable design of reinforced concrete structures.

**Keywords:** Concrete, Supplementary Cementing Materials, Sustainability, emissions, durability

## 1 Introduction

Today, despite the high level of research and the significant advances achieved in concrete technology leading to a plethora of available construction materials, issues of unsatisfactory durability of structures appear on a frequent basis. A thorough durability design process based on, the identification of the influence of the harmful environmental agents on a reinforced concrete structure, but more important based on the correct selection of the raw building materials (cement, steel type) and of course on a systematic construction process (according to the corresponding national or European standards), is the only way forward to safeguard a prolonged service-life of any type of structure.

However, any set of construction materials entails certain aspects of environmental cost, from its production stage to its end-use (transportation, application and use of the component construction materials). In general, the footprint of each structural element on the environment is estimated based on the emissions of gases produced during their manufacturing stage. In producing concrete the main emissions to air are associated with the cement-making process, where during the stage of clinker formation, $CO_2$ and other greenhouse gases are emitted to the atmosphere. These types of emissions are both raw material-related and energy-related. Raw material-related emissions are produced during limestone decarbonation and account for about 60% of total $CO_2$ emissions. Energy-related emissions are generated both directly through fuel combustion and indirectly through the use of electrical power. It is estimated that burning of 1 tonne of clinker releases 0.97 tonnes of $CO_2$. Considering that on average 900 kg of clinker are used to produce 1 tonne of cement, the $CO_2$ emissions per tonne of cement are estimated in the magnitude of 0.87 tonnes.

Taking into consideration the internationally acclaimed efforts and expressed concern (e.g. Kyoto treaty and modifications) on environmental policies to reduce man-made $CO_2$ emissions into the atmosphere, the need for a more rigorous approach to be adopted by the construction industry, on these matters, is of paramount importance. What is needed is to be able to achieve an optimum, balanced approach, between sustainability and durability when designing reinforced concrete structures. Bearing in mind that now days, the word “green” denotes environmental sensitivity, the term “green durability” is introduced to describe the above mentioned balance in reinforced concrete design.

To achieve this, the utilization of supplementary cementing by-products, like fly ash and silica fume has been suggested as a solution. On this note, an evaluation of the previously mentioned materials, as Type II additives on CEM I type of cement, and their effects in terms of their performance in carbonation and chloride exposure, for a service life of 50 years, as well as their environmental output is presented and discussed in the current study. The overall aim is to portray the basis for the previously mentioned balanced approach between sustainability and durability of reinforced concrete structures.

## 2 Estimation of service-life

The effect of cement type on the overall durability design of concrete exposed to corrosive environments, due to carbonation and chloride diffusion, is presented in this section. As durability indicators, calculation of the carbon dioxide penetration front, for a period of 50 years, was used for carbonation exposure, while under chloride ingress, the estimation of the adequate concrete cover needed to sustain a service life of 50 years was calculated.

The service-life, and compressive strength, evaluation was made using a software tool, based on proven predictive models (according to performance-related methods for assessing durability) developed and validated by Papadakis et al. (1991; 2007) well published and awarded by the ACI, for the estimation of concrete service life when designing for durability under harsh environments. Concrete service life is reliably predicted using fundamental mathematical models that simulate the basic deterioration mechanisms of reinforced concrete (carbonation, chloride penetration).

Principles of chemical and material engineering have been applied to model the physicochemical processes leading to concrete carbonation, as well as the processes of chloride diffusion in the aqueous phase of pores, their absorption and binding in the solid phase of concrete and their desorption.

A constant volume unit (1 $m^3$) of concrete was chosen as a common basis. When an SCM was added to this unit, then an equal volume of another component, either cement or aggregate, was removed in order to keep the same total volume and the common comparison basis. A typical CEM I mix, water cured for 28 days (as it is assumed by the proven predictive model used) was selected as the reference type of cement (w/c: 0.5, cement content 300 $kg/m^3$, 31.5 mm crushed aggregates, no additives, no admixtures). Several mix design configurations were considered, where each time addition of a Type II additive took place, at certain proportions, as cement and as aggregate replacement. In the case of fly ash 10, 20 and 30 % replacement levels of the control cement mass were chosen, while in the case of silica fume, since it is a more intense pozzolanic material than fly sh (hence the rate of pozzolanic reactions drops bellow one for lesser quantities than fly ash) 5, 10 and 15% replacement levels were used. The water content ($kg/m^3$) was kept constant for all specimens. The mix design configuration and the results observed are given in **Tab 1**.

**Tab. 1** Mix design and durability indicators

| **SCM type** | **Specimen No.** | **SCM (%)** | **C** | **W** | **w/c** | **A** | **FA** | **SF** | **$f_c$** | **$x_c$** | **$\Delta x_c$ (%)** | **$C_{50}$** | **$\Delta C_{50}$ (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Control* | *0* | *300* | *150* | *0.5* | *1925* | - | - | *44.6* | *19.6* | - | *29* | - |
| **S-FA** | *As aggregate replacement* | | | | | | | | | | | | |
| | sfa-1-a | 10 | 300 | 150 | 0.50 | 1890 | 30 | - | 47.4 | 16.2 | 17.3 | 17 | 41.4 |
| | sfa-2-a | 20 | 300 | 150 | 0.50 | 1856 | 60 | - | 50.3 | 13.3 | 32.1 | 7 | 75.9 |
| | sfa-3-a | 30 | 300 | 150 | 0.50 | 1821 | 90 | - | 50.4 | 12.0 | 38.8 | 7 | 75.9 |
| | *As cement replacement* | | | | | | | | | | | | |
| | sfa-1-c | -10 | 270 | 150 | 0.56 | 1915 | 30 | - | 41.8 | 21.7 | - | 23 | 20.7 |
| | sfa-2-c | -20 | 240 | 150 | 0.63 | 1905 | 60 | - | 38.0 | 25.1 | - | 21 | 27.6 |
| | sfa-3-c | -30 | 210 | 150 | 0.71 | 1895 | 90 | - | 31.7 | 31.8 | - | 31 | - |
| **C-FA** | *As aggregate replacement* | | | | | | | | | | | | |
| | cfa-1-a | 10 | 300 | 150 | 0.50 | 1896 | 30 | - | 51.4 | 15.9 | 18.9 | 19 | 34.5 |
| | cfa-2-a | 20 | 300 | 150 | 0.50 | 1866 | 60 | - | 58.0 | 12.4 | 36.7 | 11 | 62.1 |
| | cfa-3-a | 30 | 300 | 150 | 0.50 | 1837 | 90 | - | 64.4 | 9.8 | 50.0 | 5 | 82.8 |
| | *As cement replacement* | | | | | | | | | | | | |
| | cfa-1-c | -10 | 270 | 150 | 0.56 | 1920 | 30 | - | 45.8 | 21.3 | - | 25 | 13.8 |
| | cfa-2-c | -20 | 240 | 150 | 0.63 | 1916 | 60 | - | 46.9 | 23.3 | - | 21 | 27.6 |
| | cfa-3-c | -30 | 210 | 150 | 0.71 | 1911 | 90 | - | 48.0 | 25.5 | - | 17 | 41.4 |
| **SF** | *As aggregate replacement* | | | | | | | | | | | | |
| | sf-1-a | 5 | 300 | 150 | 0.50 | 1908 | - | 15 | 50.8 | 18.4 | 6.1 | 19 | 34.5 |
| | sf-2-a | 10 | 300 | 150 | 0.50 | 1890 | - | 30 | 56.9 | 17.7 | 9.7 | 11 | 62.1 |
| | sf-3-a | 15 | 300 | 150 | 0.50 | 1873 | - | 45 | 62.0 | 16.7 | 14.8 | 7 | 75.9 |
| | *As cement replacement* | | | | | | | | | | | | |
| | sf-1-c | -5 | 285 | 150 | 0.53 | 1920 | - | 15 | 48.0 | 21.2 | - | 23 | 20.7 |
| | sf-2-c | -10 | 270 | 150 | 0.56 | 1915 | - | 30 | 51.4 | 23.4 | - | 17 | 41.4 |
| | sf-3-c | -15 | 255 | 150 | 0.59 | 1910 | - | 45 | 51.4 | 25.7 | - | 15 | 48.3 |

C: the cement content ($kg/m^3$)
W: is the water content ($kg/m^3$)
FA: the fly ash content (s: siliceous, c: calcareous) ($kg/m^3$)
w/c: is the water cement ratio
SF: the silica fume content ($kg/m^3$)
$x_c$: is the carbonation depth (mm)
$\Delta x_c$: the carbonation depth reduction compared to control (%)
$f_c$ the concrete compressive strength (MPa)
$C_{50}$: the adequate concrete cover needed to sustain chloride exposure for 50 years (mm)
$\Delta C_{50}$ the reduction of this adequate cover compared to control (%)

Overall it was seen that when SCM were used for aggregate replacement, the carbonation depth was decreased compared to the control mix. Incorporation of calcareous fly ash (CFA) in CEM I type of cement, produced a better performance under carbonation exposure than siliceous fly ash (SFA) (**Fig 1a**). Addition of 30 % of CFA reduced the carbonation depth by 50 %, compared to a 38.8 % reduction, when SFA was used. Silica fume (SF) did not prove to be as effective as fly ash (FA), in inhibiting carbonation exposure. To draw a comparison between results, 10 % addition of SF reduced the carbonation depth by 9.7 %, compared to the 17.3 and 18.7 % reductions observed when 10 % of siliceous and calcareous fly ash was added. In the case where SCM were used as cement replacement materials, the carbonation depth was increased, with the increasing content of every type of SCM used.

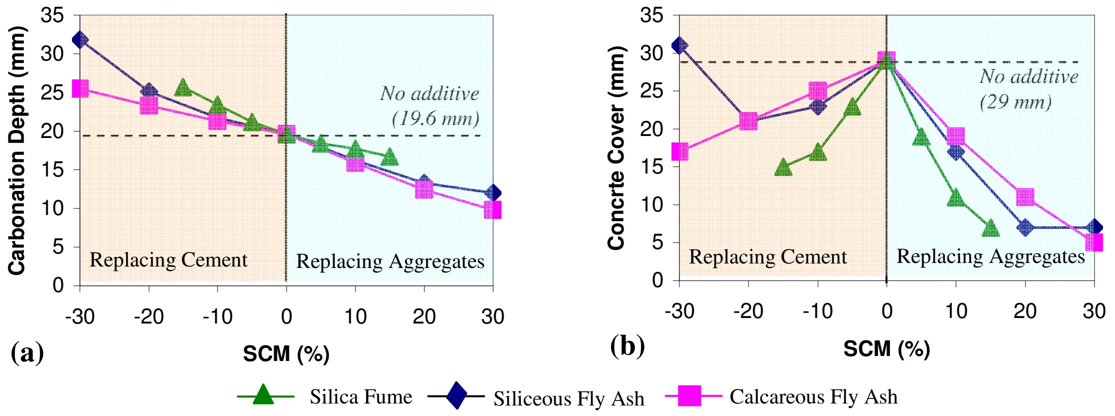

**Fig. 1** Carbonation depth and sufficient concrete cover for chloride exposure of CEM I with Type II additives

As far as chloride exposure is concerned (**Fig 1b**), specimens incorporating SCM whether aggregate or cement was substituted, produced smaller concrete cover values needed to sustain chloride exposure for a service life of 50 years, compared to control. Silica fume proved to inhibit chloride diffusion more efficiently than FA. A 62.1 % reduction of the previously mentioned adequate concrete cover was noticed, compared to 41.1 and 34.5 % reductions when siliceous or calcareous fly ash were used respectively, for a 10 % content of SCM. At higher concentration of SCM calcareous fly ash proved to be more effective than siliceous one (82.8 % reduction of the former, compared to a 75.9 % reduction of the latter).

## 3 Environmental impact of concrete

It was previously mentioned that in producing concrete the main emissions to air are associated with cement manufacturing. However, other concrete constituents also contribute in that sense. In general, it can be said that the $CO_2$ emissions from concrete production are the summation of the emissions from, the chemical conversion process in clinker production (during cement manufacturing), from the energy consumption due to fossil fuel combustion (also during cement manufacturing), from the electrical energy required for the grinding of any additive materials and from the energy required (in terms of fuel consumption) for the transportation of the raw materials and of the final product. A more precise estimation of the environmental footprint (environmental factors) of each individual concrete component, based on the literature and on data derived from the Greek branch of a multi-national cement manufacturing company, is presented in this section. The overall environmental footprint of concrete ($E_{conc}$) can be calculated as:

$$E_{conc} = C \cdot E_c + S \cdot E_S + F \cdot E_F + A \cdot E_A + W \cdot E_W + D \cdot E_D \qquad (1)$$

C is the cement content (kg of cement / $m^3$ of concrete)
$E_C$ is the environmental cost of cement (kg of $CO_2$ / kg of cement)

$S$ is the silica fume content (kg of silica fume / $m^3$ of concrete)
$E_S$ is the environmental cost of silica fume (kg of $CO_2$ / kg of silica fume)
$F$ is the fly ash content (kg of fly ash / $m^3$ of concrete)
$E_F$ is the environmental cost of fly ash (kg of $CO_2$ / kg of fly ash)
$A$ is the aggregate content (kg of aggregate / $m^3$ of concrete)
$E_A$ is the environmental cost of aggregates (kg of $CO_2$ / kg of aggregates)
$W$ is the water content (kg of water / $m^3$ of concrete)
$E_W$ is the environmental cost of water (kg of $CO_2$ / kg of water)
$D$ is the admixtures content (kg of admixtures / $m^3$ of concrete)
$E_D$ is the environmental cost of admixtures (kg of $CO_2$ / kg of admixtures)

By taking under consideration the chemical equation of incomplete combustion of coal (Equation 2), where 94 Kcal/mol of energy is produced, since it is an exothermic reaction, the amount of $CO_2$ produced from energy consumption of 1KWh is calculated as 0.404 kg.

$$C + O_2 \rightarrow CO_2 + Q \qquad (2)$$

Q 94 Kcal/mol of energy produced
1cal = $11.162 \cdot 10^{-6}$ KWh
Hence 94 Kcal – 0.109 KWh producing 44 g of $CO_2$
Hence 1 KWh produces 0.404 kg of $CO_2$.

Using operational and production data from the Greek branch of a multi-national cement-manufacturing company, the level of $CO_2$ emissions from cement manufacturing was accurately estimated. By taking into account the amount of cement produced (1,700,000 tn/year), the electrical energy required (500,000 KWh/day) the level of $CO_2$ emissions measured (3,801,000 kg/day) and the total days of operation per year (335) the total $CO_2$ emissions were calculated to be in the range of 1,341,005 tn/year. Hence in order to produce 1 tn of cement 0.79 tn of $CO_2$ are emitted into the atmosphere. On that estimate, the $CO_2$ emissions from transportation, should be added. Considering that on average 2.74 kg of $CO_2$ is emitted per litre of fuel, using vehicle transport, and that fuel consumption is estimated to be 1 lt / 3 km for 5 tn of raw materials, the overall emissions arise from transportation are estimated to be 0.183 kg / km / tn of raw material (GHG Protocol-Mobile Guide, 2001).

In order to extract, process and grind aggregates the overall $CO_2$ emissions are estimated to be 5.96 kg / tn of aggregates (considering that 2.53KWh are required for the production of 1 tone of aggregates and that 9 lt of fuel are required for the transportation of a 5 tones shipment, resulting in 4.94 kg of $CO_2$ / tn of aggregates).

When fly ash is used as a secondary cementing material, since it is a by-product of coal burning in electrical power stations, the emissions associated with power generation are not considered of being part of the environmental burden of fly ash. A small amount of energy required for the grinding of the raw material into very fine powder and for its transportation, are the only sources of greenhouse gasses. According to the literature (IPPC, 2008; US EPA, 2010) the previously mentioned energy requirement is estimated to be in the order of 20 KWh per tone of fly ash produced, hence 8.06 kg of $CO_2$ per tone of fly ash. On that amount emissions from transportation (similar to cement transportation) should be added.

In the case of silica fume, since it is available from limited regions on European level, the related emissions arise from its transportation. For reasons of simplicity, since the aim of the current study is to produce an estimation of the environment impact of concrete the previously mentioned source of emissions are assumed to be twice of those of fly ash transportation.

As far as water is concerned, the only source of emissions arises from the electrical energy required to pump the water, which in this study is considered to be negligible. Since no admixtures were used on the mix design of the different concrete configurations used in this study, the environmental impact of admixtures is ignored.

In this way, based on the proportions of the concrete constituent materials used and on the environmental factors, as derived above, the overall environmental cost of concrete was calculated (**Tab 2**). For reasons of comparison, the durability indicators (carbonation depth ”$X_c$” and concrete cover to sustain chloride exposure for 50 years “$C_{50}$”) as well as, an estimation of the economical cost of each mix design used, based on the individual prices of the raw materials are also given in **Tab 2**.

**Tab. 2** Environmental cost of concrete incorporating SCM by-products

| SCM type | Specimen No. | SCM (%) | $f_c$ | $\Delta f_c$ (%) | $x_c$ | $\Delta x_c$ (%) | $C_{50}$ | $\Delta C_{50}$ (%) | $E_C$ | $\Delta E_C$ (%) | $P_C$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Control* | *0* | *44.6* | - | *19.6* | - | *29* | - | *311.47* | | *44.76* |
| **S-FA** | *As aggregate replacement* | | | | | | | | | | |
| | sfa-1-a | 10 | 47.4 | 6,3 | 16.2 | 17.3 | 17 | 41.4 | 311.52 | - | 45.04 |
| | sfa-2-a | 20 | 50.3 | 12,8 | 13.3 | 32.1 | 7 | 75.9 | 311.58 | - | 45.33 |
| | sfa-3-a | 30 | 50.4 | 13.0 | 12.0 | 38.8 | 7 | 75.9 | 311.63 | - | 45.61 |
| | *As cement replacement* | | | | | | | | | | |
| | sfa-1-c | -10 | 41.8 | - | 21.7 | - | 23 | 20.7 | 281.67 | 9,57 | 42.63 |
| | sfa-2-c | -20 | 38.0 | - | 25.1 | - | 21 | 27.6 | 251.87 | 19,14 | 40.50 |
| | sfa-3-c | -30 | 31.7 | - | 31.8 | - | 31 | - | 222.07 | 28,70 | 38.38 |
| **C-FA** | *As aggregate replacement* | | | | | | | | | | |
| | cfa-1-a | 10 | 51.4 | 15,3 | 15.9 | 18.9 | 19 | 34.5 | 311.56 | - | 45.07 |
| | cfa-2-a | 20 | 58.0 | 30,1 | 12.4 | 36.7 | 11 | 62.1 | 311.64 | - | 45.38 |
| | cfa-3-a | 30 | 64.4 | 44,4 | 9.8 | 50.0 | 5 | 82.8 | 311.72 | - | 45.70 |
| | *As cement replacement* | | | | | | | | | | |
| | cfa-1-c | -10 | 45.8 | 2,7 | 21.3 | - | 25 | 13.8 | 281.70 | 9,56 | 42.66 |
| | cfa-2-c | -20 | 46.9 | 5,2 | 23.3 | - | 21 | 27.6 | 251.94 | 19,11 | 40.56 |
| | cfa-3-c | -30 | 48.0 | 7,6 | 25.5 | - | 17 | 41.4 | 222.16 | 28,67 | 38.47 |
| **SF** | *As aggregate replacement* | | | | | | | | | | |
| | sf-1-a | 5 | 50.8 | 13,9 | 18.4 | 6.1 | 19 | 34.5 | 311.39 | - | 47.06 |
| | sf-2-a | 10 | 56.9 | 27,6 | 17.7 | 9.7 | 11 | 62.1 | 311.30 | - | 49.36 |
| | sf-3-a | 15 | 62.0 | 39,0 | 16.7 | 14.8 | 7 | 75.9 | 311.21 | - | 51.66 |
| | *As cement replacement* | | | | | | | | | | |
| | sf-1-c | -5 | 48.0 | 7,6 | 21.2 | - | 23 | 20.7 | 296.46 | 4,82 | 45.85 |
| | sf-2-c | -10 | 51.4 | 15,3 | 23.4 | - | 17 | 41.4 | 281.45 | 9,64 | 46.95 |
| | sf-3-c | -15 | 51.4 | 14,8 | 25.7 | - | 15 | 48.3 | 266.43 | 14,46 | 48.05 |

$f_c$: the concrete compressive strength (Mpa)
$\Delta f_c$: the increase in compressive strength compared to control (%)
$x_c$: the carbonation depth (mm)
$\Delta x_c$: the reduction in carbonation depth compared to control (%)
$C_{50}$: the adequate concrete cover needed to sustain chlortide exposure for 50 years (mm)
$\Delta C_{50}$: the reduction in the adequate concrete cover compared to control (%)
$E_c$: the environmental cost of concrete (kg of $CO_2$ / m3 of concrete)
$\Delta E_c$: the reduction in environmental cost, compared to control (%)
$P_c$: the economical cost of concrete (€ / m3 of concrete)

A first observation is that utilisation of SCM as aggregate replacements did not change significantly the environmental output of concrete, however, when SCm was used as cement replacements, considerable reductions of up to 28.7 % of the environmental footprint were noticed. A comparative assessment of every durability, environmental and economical cost indicators, calculated in this study, for every type of SCM used is given in **Figs 2-4**. In this way, the reduction of environmental cost observed can be weighted against the durability and service life indicators (especially for chloride exposure) calculated. Overall, silica fume produced the best balanced behaviour. Incorporation of 15 % of silica fume led to a 48.3 % reduction of the adequate concrete cover needed to sustain chloride exposure for 50 years and to a 14.5 % reduction of the $CO_2$ emissions of concrete, compared to the 41.4 and 28.7 % corresponding reduction observed when calcareous fly ash was used and also to a 14.8 % significant increase of the concrete compressive strength.

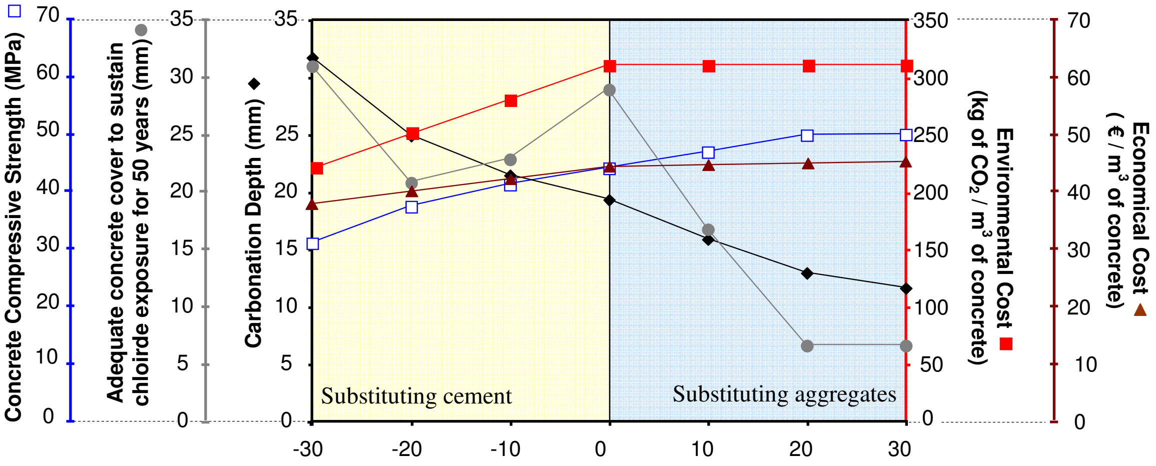

**Fig 2** Durability and cost indicators for siliceous fly ash mixes

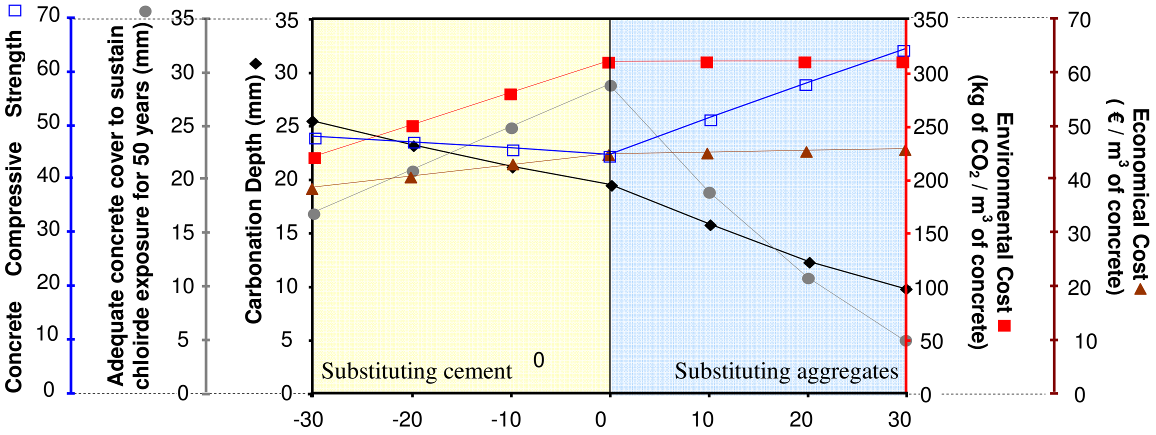

**Fig 3** Durability and cost indicators for calcareous fly ash mixes

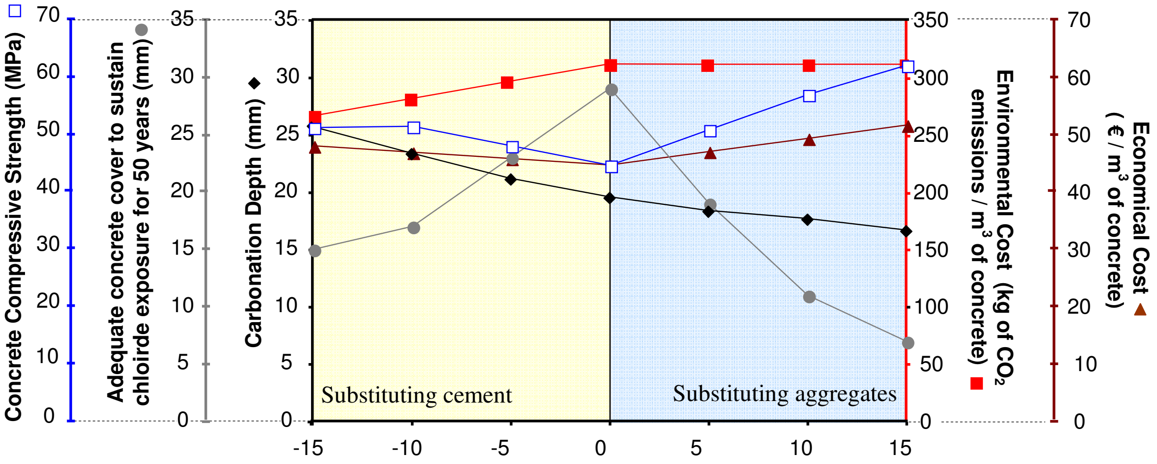

**Fig 4** Durability and cost indicators for silica fume mixes

# 4 Discussion

The aim of this study is to evaluate in terms of service life and environmental cost indicators, the effect of different supplementary cementing by-products. A software package based on proven, verified predictive models was used for the evaluation. As far as carbonation exposure is concerned, carbonation depth was estimated for a period of 50 years. In terms of chloride ingress, the adequate concrete cover needed to sustain that ingress for a period of also 50 years was estimated. The environmental footprint of concrete was calculated, based on the estimation of the range of $CO_2$ emissions of each individual concrete component, using data from the literature and from a cement production company.

The results of this study, as far as the service life estimation is concerned, showed that silica fume and fly ash reduced considerably the carbonation depth values, compared to the control mix when used as aggregate replacments, on observation also reached by other researchers (Khunthongkeaw et al. 2006; Valcuende and Parra, 2010). However, when the above mentioned materials were used as cement replacements, larger carbonation depths were produced, compared to control. The explanation for such a behaviour lays in the way these materials were incorporated into the mix. In the first case, the total amount of carbonatable constituents remains almost the same, resulting in decreased porosity and lower carbonation rates (Papadakis, 2000). While in the second case, by reducing the cement and clinker content, the amount of carbonatable materials is also reduced (due to the decrease intotal CaO), resulting in higher carbonation rates (Valcuende & Parra, 2010). In general SCM materials (as cement replacements) proved to be less resistant to carbonation, mainly due to their low binding capacity of $CO_2$, caused by their smaller concentrations of $Ca(OH)_2$, compared to control (due to the consumption by pozzolanic reaction, and lower cement content).

Under chloride exposure they all behaved much better than control. It has been noticed that specimens incorporating an SCM, whether it substitutes aggregate or cement, exhibit significantly lower total chloride content for all depths from the surface (Chalee at al. 2010; Hosam et al. 2010, Antiohos & Tsimas 2003). Silica fume, when used as additive, proved to be most efficient in inhibiting chloride ingress, followed by calcareous and silicious fly ash. Silica fume, composed by very small spherical particles, due to its ultra fineness and activity led to the formation of intense pozzolanic reaction products (with increased chloride ion binding capacity than fly ash) within the capillary pore spaces and as a consequence, a finer and more segmented pore system is produced (Hosam et al 2010, Nocjaiya et al. 2010). Calcareous fly ash, apart of being pozzolonic active, reacting faster than the silicious one, it contains higher amounts of aluminate-cementing compounds ($C_3A$, $C_4AF$), leading to a more increased chloride ion binding capacity (Antiohos & Tsimas, 2003).

By taking under consideration the environmental and economical cost (for reasons of completion), as estimated in this study (**Tab 2**), a more complete portrait of the properties and effects of every particular mix design used was created (**Figs 2-4**). Although fly ash (as cement replacement) performed extremely well under chloride exposure, reducing the environmental footprint of concrete considerably, silica fume proved to be a much more promising SCM (bearing in mind that it was utilised at lesser quantities than fly ash, due to it is a very intense pozzolanic material and hence the rate of pozzolanic reaction drops below 1, for lesser quantities than fly ash). Better reductions of both environmental cost and of the adequate concrete cover needed to sustain chloride exposure, as well as considerable increases of the concrete compressive strength, where noticed, when silica fume was used. In this way and for any type of SCM used, the designer can balance its mix design based on the properties of durability and environmental (or economical) cost (**Fig 5**) to achieve the best possible (optimum) solution, according to the requirements of his particular study.

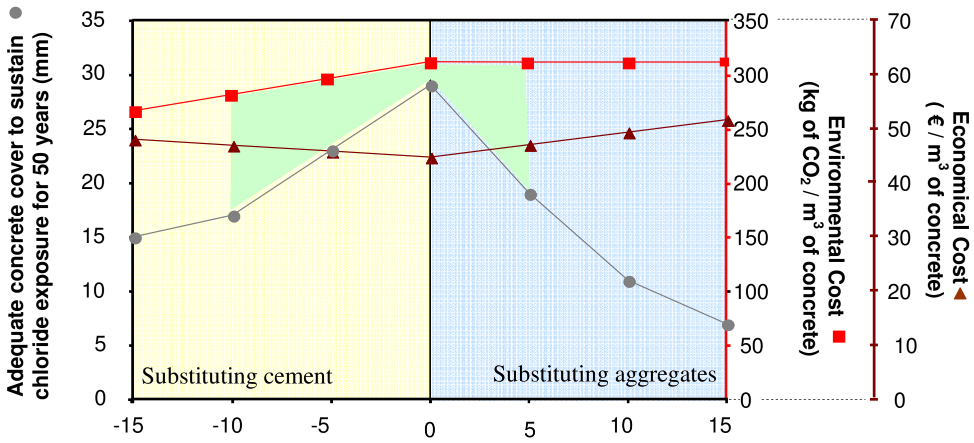

**Fig 5** Area of balanced (optimum) sustainable and durable design incorporating silica fume

## 5 Conclusions

An assessment of durability and environmental cost indicators of a concrete mix utilising supplementary cementing by-products took place, aiming to achieve a balanced level of sustainable and durable design (green durability). The finding of this study can by summarised as follows:

- The effects of the SCM materials on the behaviour of the concrete mix differ when used as aggregate or cement replacements.
- It was established that for all supplementary cementing materials tested (silica fume, calcareous and siliceous fly ash), the carbonation depth decreases as aggregate replacement by SCM increases, and increases as cement replacement by SCM increases.
- The use of SCM as an addition to a concrete mix, replacing either aggregates or cement, significantly decreases the adequate concree cover needed to sustain chloride exposure for a service life of 50 years.
- The environmental footprint of each individual conrete component can be quickly estimated, based on data from the literature or from producation and operational data from cement-manufacturig companies.
- Utilisation of SCM as cement replacmenet reduces considerably the total conrete $CO_2$ emissions.
- By taking under consideration the environmental and economical cost a complete portrait of the properties and effects of every particular mix design used, was created
- Silica fume proved to be the most promising SCM material in providing a balanced environmantaly friendly doruable solution (under chloride exposure).

Bearing all of the above in mind, it was shown that it is possible to achieve an adequate level of “green“ durability (under chloride exposure) in cocnrete design, in other words a balance between sustainability and durability, by utilasing SCM by-products in the concrete mix. It is hoped that the results of this study will pave the way for a more rigorous approach to be adopted by the research community on the level of sustainability afforted by using such types of materials.

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