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Use of New Industrial By-products and Mixtures for Reducing the Environmental Cost of Constructions

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Abstract

The building sector in Greece occupies prime position within the industrial / technical activities. However, given the fact that the construction sector produces more than 35% of all the greenhouse emissions, on European level, emphasis is given on adaptation of energy and emissions reducing solutions by the construction industry. Utilization of supplementary cementitious materials (SCM) in concrete design, for example, is a very promising first step in reducing considerably the fixed environmental footprint. On this note, the aim of this study is twofold. To evaluate the environmental contribution of each concrete component and to provide the best possible mix design configuration, by using analytical models developed by the authors, in terms of low environmental cost, concrete compressive strength and service life estimation under harsh environments.

It is hoped that the outcomes of this study will provide the basis for the establishment of an optimum, balanced approach, between sustainability and durability. It was proved that such a balance can be achieved through extended use of industrial by-products and their various mixtures in the concrete mix, reducing in this way the fixed environmental emissions without minimizing the long-term safety and durability of the structure.

Keywords: Industrial by-products, Concrete, Constructions, Environmental cost, Software, Supplementary cementing materials.

1 Introduction

The construction sector and cement industry, in particular, plays a major role in meeting society's needs for housing and infrastructure that are expected to increase considerably in the developing world. At the current rate of concrete consumption the demand for concrete is expected to rise to

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about 16 billion tonnes a year by 2050 [1]. The challenge we face is to develop processes and practices that will curb the intensity of CO_2 emissions per ton of cement produced in order to strike a balance between climate change risk and global growth.

From a production point of view almost every type of structural material used has a considerable impact on the local and global environment. In general, any set of construction materials entails certain aspects of environmental cost (in the form of carbon dioxide and other gasses emissions and energy consumed) from its manufacturing stage to its end-use (fixed environmental cost), or during-use of the structure (operational environmental cost) according to the particular type of construction.

In concrete production for example [2], the main emissions to air are associated with the cement-making process, where during the stage of clinker formation, CO_2 gasses and other greenhouse emissions are emitted to the atmosphere (0.873 tonnes of CO_2 gases are emitted per 1 tonne of cement produced [3-4]. Cement manufacturing is a mature industry applying the same chemical process (in principle) for more than a hundred years (thus any revolutionary breakthroughs are rendered at a slow pace). Considering the facts that, the construction sector accounts for a considerable share of the total EU final energy consumption (more than 42%) and produces more than 35% of all the greenhouse emissions [4-5], with cement manufacturing contributing 5% of the global man made CO_2 emissions, increasing emphasis should be placed on investigating and enforcing ways and methodologies to make the construction industry in general a more environmental friendly sector.

Given the availability of current raw materials in cement manufacturing, what is needed is to be able to achieve an optimum, balanced approach, between sustainability and durability when designing reinforced concrete structures. To achieve this, utilization of supplementary cementing by-products, like fly ash, rice husk ash (and others including ground granulated blast-furnace slag and silica fume) has been suggested as a solution (since they replace clinker to a great extend). Considerable amount of work on developing analytical models for the evaluation of SCM in concrete using the concept of efficiency factors (or k-values, to compare the relative performance of supplementary cementing materials on concrete durability) by Papadakis [6-8] and preliminary work undertaken by Papadakis et al. [9-11] on RHA has identified the high-added value of this materials and its pozzolanic properties on cement and mortar. Rice husk ash (RHA), an agricultural waste material, produced by controlled burning of rice husk have shown to contain reactive silica and alumina (in the form of metakaolin) which could contribute chemically to the Portland cement ingredients. In general, besides the effect they entail on early concrete strength and volume stability [12-13], they improve to a great extend the overall environmental contribution [13]. It has been calculated that 18 % replacement of Portland cement results in a 17 % reduction of the CO_2 emissions [4, 14]. It is believed that if just 30% of cement sed globally was replaced with supplementary cementing materials (SCM), the rise in CO_2 emissions from cement production could be reversed [4,14].

Under the scope of this study, an evaluation of these types of 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, in addition to their environmental output was presented. The overall aim is to portray the basis for the previously mentioned balanced approach between sustainability and durability of reinforced concrete structures (optimum solution).

2. Estimation of concrete 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 briefly 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 were made using a software tool, based on proven predictive models (according to performance-related methods for assessing durability) developed and validated by some of the authors of this study [15-17], 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 (or a mixture of 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 *FA*, *RHA* and a mixture of 50 % *FA* and 50 % *RHA*, (as Type II additives) took place, as cement and as aggregate replacement. 10, 20 and 30 % replacement levels of the control cement mass were chosen, with the water content (kg/m^3) kept constant for all specimens. The mix design configuration and the results observed are given in Table 1.

Overall it was seen that when SCM were used for aggregate replacement, the carbonation depth was decreased compared to the control mix. Incorporation of *FA* in CEM I type of cement, produced a better performance under carbonation exposure than the other SCM types and mixtures used. Addition of 30 % of *FA* reduced the carbonation depth by 50 %, compared to 23.5 % and 28.1 % reductions, when *RHA* and their mixture (50 % *RHA* and 50% *FA*) were used respectively. 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.

As far as chloride exposure is concerned, 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. *RHA* proved to inhibit chloride diffusion more efficiently than *FA*. A 89.7 % reduction of the previously mentioned adequate concrete cover was noticed, compared to 82.8 % reduction when *FA* was used, for a 30 % content of SCM.

Overall utilisation of SCM in concrete mix design produced considerable gains in the 28 days concrete compressive strength. Incorporation of FA produced an increase of 44.4 % (from 44.6 MPa to 64.4 MPa) compared to the 26.2 % and 32.5 % increases when RHA and the RHA-FA mixture were used, respectively.

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:

$$E_{conc} = C \cdot E_c + R \cdot E_R + F \cdot E_F + A \cdot E_A + W \cdot E_W + D \cdot E_D \quad (1)$$

C, R, F, A, W, D:	are the contents (in kg / m^3 of concrete) of cement, rice husk ash, fly ash, aggregate, water and admixtures, respectively, and
E_C, E_R, E_F, E_A, E_W, E_D:	the environmental cost (in kg of CO_2 / kg of cement) of cement, rice husk ash, fly ash, aggregates, water, admixtures, respectively.

For the calculation of the environmental cost of the individual concrete components the following were taken under consideration.

In terms of cement, according to the literature, the CO_2 emissions associated with cement production vary from 700 to 1000 kg CO_2/kg cement [18]. According to Hoeing et al [19] 0.65-0.92 kg of CO_2 is produced for per kg cement produced based on a cement plant with a modern technology and equipment. The CO_2 emission for cement Type I is approximately 800 g/kg cement, less for the other cement types with lower clinker contents [20].

In this study a more precise estimation was made using operational and production data from the Greek branch of a multi-national cement-manufacturing company. By taking under consideration the chemical equation of incomplete combustion of coal (Equation 2), where 94 Kcal/mol of energy is produced (Q), since it is an exothermic reaction, the amount of CO_2 produced from energy consumption of 1KWh is calculated as 0.404 kg (1 cal is equal to $1.162 \cdot 10^{-6}$ KWh, hence 94 Kcal equal to 0.109 KWh producing 44 g of CO_2).

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

By taking into account data as, 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. In addition to the later, the derived 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 [21].

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 [22-23] 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 (emissions from transportation, similar to cement transportation, should also be added).

In the case of rice husk ash, since it is available from limited regions on European level, the related emissions arise from the amounts of energy required for the controlled burning of rice husk, for the grinding of the raw material into very fine powder and for its transportation. They can be safely assumed to be twice of those of fly ash.

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. The total volume of admixtures added in a concrete mix is usually less than two litres per cubic metre of concrete. In addition, the CO_2 emissions generated from admixtures are very small (2.2 – 53 x 10^{-3} kg CO_2-e/l admixtures). Therefore, the environmental footprint of admixtures can be ignored [22]. 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 (Table 1) and on the environmental factors, as derived above, the overall environmental cost of concrete was calculated (Table 2). For reasons of comparison, the durability indicators (carbonation depth ”x_c” and adequate 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 Table 2.

A first observation is that utilization of SCM as aggregate replacements did not change significantly the environmental output of concrete, however, when SCM were used as cement replacements, considerable reductions of up to 28.9 % 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 Figure 1. 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, the mixture of FA with RHA produced the best balanced behavior, followed by the case when only FA was incorporated in the concrete mix.

A 20 % addition of RHA and FA increased the concrete compressive strength by 5.2 % (same increase as in the case of FA) and produced a 55.2 % reduction of the adequate concrete cover needed to sustain a chloride free structure for 50 years (compared to a 27.6 % when FA was used) resulting also in a 19.2 % reduction of the overall associated CO_2 emissions. However, at higher rates of cement replacement (30 %) FA proved to be more effective resulting in 7.6 % increase of concrete compressive strength and to 20.7 % and 28.7 % reductions of the concrete cover in terms of chloride attack and of the associated environmental cost. At this rate of cement replacement RHA and RHA/FA mixture gave a lesser performance than FA. The reasons for such a behavior are analyzed in the following section.

4 Discussion

A thorough design of reinforced concrete structures must be the combination of an integrated study and a techno-economic optimization. Economical, environmental and technical parameters must be taken into account for the definition of the best solution. On this note, 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 FA, RHA and its combination reduced considerably the carbonation depth values, compared to the control mix when used as aggregate replacements, on observation also reached by other researchers [24-25]. 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 [26]. While in the second case, by reducing the cement and clinker content, the amount of carbonatable materials is also reduced (due to the decrease in total CaO), resulting in higher carbonation rates [25]. 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 [27]. RHA, when used as additive, proved to be most efficient in inhibiting chloride ingress (up to 20 % replacement). RHA, 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 [11, 13]. The reactivity of RHA can be attributed to its high content of non-crystalline silica, and to its very large surface area governed by the cellular structure of the particles [28-30]. When pozzolanic materials with high active silica content are added to cement, the silica (SiO_2) present in these materials reacts with free lime released during the hydration of cement and forms additional calcium silicate hydrate (CSH) as new hydration products which improve the mechanical properties of concrete formulation [31]. However when all the available free lime is depleted, the pozzolanic reactions stops and the remaining levels of silica remain inactive. Such an observation is further reinforced by the rate of the pozzolanic reaction of RHA, which at high replacement levels drops bellow 0.8 (even bellow 0.5 when RHA is solely used).

On the contrary, when FA is used, a study pozzolanic reaction level is observed (rate of pozzolanic reaction equal to 1) resulting in higher reductions of concrete cover able to resist a chloride attack and also in further increases of concrete compressive strength, for bigger replacement levels than when RHA is used (30 %). FA, due to its high calcium oxide content, apart of being pozzolonic active, reacts faster than the siliceous reach cement replacement materials, since it contains higher amounts of aluminate-cementing compounds (C_3A, C_4AF), leading to a more increased chloride ion binding capacity [9].

Overall, by taking under consideration the environmental and economical cost, as estimated in this study (Table 2), a more complete portrait of the properties and effects of every particular mix design used was created (Figure 1). 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 (Figure 2) to achieve the best possible (optimum) solution, according to the requirements of his particular study.

5 Conclusions

The concrete industry is facing the challenge of providing and safeguarding a sustainable design of buildings and structures. To achieve that, relevant environmental, financial and service life factors should be taken under consideration.

On this note, 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 most important 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.
- The use of SCM as an addition to a concrete mix, replacing either aggregates or cement, significantly decreases the adequate concrete cover needed to sustain chloride exposure for a service life of 50 years.
- The environmental footprint of each individual concrete component can be quickly estimated, based on data from the literature or from production and operational data from cement-manufacturing companies.
- Utilisation of SCM as cement replacement reduces considerably the total concrete 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
- RHA and FA mixture proved to be the most promising SCM material, for a replacement level up to 20 %, in providing a balanced environmentally friendly durable solution (under chloride exposure).
- While FA gave the most coherent overall behavior at larger replacement levels (30 %).

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 concrete design, in other words a balance between sustainability and durability, by utilising SCM by-products (and mixtures) 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 afforded by using such types of materials.

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Table 1 Mix design and durability indicators*

SCM type	SCM (%)	C	W	w/c	A	FA	RHA	f_{cu}	Δf_{cu}	r_{FA}	r_{RHA}	X_c	Δx_c	C_{50}	ΔC_{50}
	0	300	150	0.5	1925	-	-	44.6	-	-	-	19.6	-	29	-
FA	*As aggregate replacement*														
	10	300	150	0.50	1896	30	-	51.4	15.3	1	-	15.9	-19	19	-34.5
	20	300	150	0.50	1866	60	-	58.0	30.0	1	-	12.4	-37	11	-62.1
	30	300	150	0.50	1837	90	-	64.4	44.4	1	-	9.8	-50	5	-82.8
	As cement replacement														
	-10	270	150	0.56	1920	30	-	45.8	2.69	1	-	21.3	8.7	25	-13.8
	-20	240	150	0.63	1916	60	-	46.9	5.16	1	-	23.3	18.9	21	-27.6
	-30	210	150	0.71	1911	90	-	48.0	7.62	1	-	25.5	30	17	-41.1
RHA	*As aggregate replacement*														
	10	300	150	0,5	1890	-	30	51,4	15.3	-	1	17,7	-9.7	11	-62.1
	20	300	150	0,5	1856	-	60	56,3	26.2	-	0,87	16,1	-18	3	-89.7
	30	300	150	0,5	1821	-	90	56,3	26.2	-	0,58	15	-23	3	-89.7
	As cement replacement														
	-10	270	150	0,556	1915	-	30	45,8	2.69	-	1	23,4	19.4	17	-41.4
	-20	240	150	0,625	1905	-	60	42,8	-4.04	-	0,7	28,2	43.8	13	-55.2
	-30	210	150	0,714	1895	-	90	35,9	-19.5	-	0,41	34,4	75.5	23	-20.7
	As aggregate replacement														
	10	300	150	0,5	1893	15	15	51,4	15.3	1	1	16,6	-15	15	-48.3
	20	300	150	0,5	1861	30	30	58	30.0	1	1	14,4	-26	5	-82.8
	30	300	150	0,5	1829	45	45	59,1	32.5	0,45	1	14,1	-28	3	-89.7
FA+RHA	*As cement replacement*														
	-10	270	150	0,556	1918	15	15	45,8	2.69	1	1	22,1	12.8	21	-27.6
	-20	240	150	0,625	1910	30	30	46,9	5.16	1	1	25,4	29.6	13	-55.2
	-30	210	150	0,714	1903	45	45	35,9	-19.5	0	0,82	35,1	79,1	23	-20.7

* C, cement content (kg/m^3), W, water content (kg/m^3), W/C water/cement ratio, FA fly ash content (kg/m^3) RHA rice husk ash content (kg/m^3), f_c concrete compressive strength (MPa), x_c carbonation depth (mm), C_{50} adequate concrete cover needed to sustain chloride exposure for 50 years (mm).

Table 2 Mix design and environmental indicators*

SCM type	SCM (%)	C	W	w/c	A	FA	RHA	X_c	C_{50}	E_C	ΔE_C (%)	P_C
	0	300	150	0.5	1925	-	-	19.6	29	311.47	-	44.76
FA	*As aggregate replacement*											
	10	300	150	0.50	1896	30	-	15.9	19	311.56	-	45.07
	20	300	150	0.50	1866	60	-	12.4	11	311.64	-	45.38
	30	300	150	0.50	1837	90	-	9.8	5	311.72	-	45.70
	As cement replacement											
	-10	270	150	0.56	1920	30	-	21.3	25	281.70	-9.6	42.66
	-20	240	150	0.63	1916	60	-	23.3	21	251.94	-19.1	40.56
	-30	210	150	0.71	1911	90	-	25.5	17	222.16	-28.7	38.47
RHA	*As aggregate replacement*											
	10	300	150	0,5	1890	-	30	17,7	11	311,30	-	46,96
	20	300	150	0,5	1856	-	60	16,1	3	311,13	-	49,17
	30	300	150	0,5	1821	-	90	15	3	310,95	-	51,37
	As cement replacement											
	-10	270	150	0,556	1915	-	30	23,4	17	281,45	-9.7	44,55
	-20	240	150	0,625	1905	-	60	28,2	13	251,42	-19.3	44,34
	-30	210	150	0,714	1895	-	90	34,4	23	221,39	-28.9	44,14
FA + RHA	*As aggregate replacement*											
	10	300	150	0,5	1893	15	15	16,6	15	311,43	-	46,02
	20	300	150	0,5	1861	30	30	14,4	5	311,38	-	47,28
	30	300	150	0,5	1829	45	45	14,1	3	311,34	-	48,54
	As cement replacement											
	-10	270	150	0,556	1918	15	15	22,1	21	281,58	-9.6	43,61
	-20	240	150	0,625	1910	30	30	25,4	13	251,67	-19.2	42,45
	-30	210	150	0,714	1903	45	45	35,1	23	221,78	-28.8	41,3

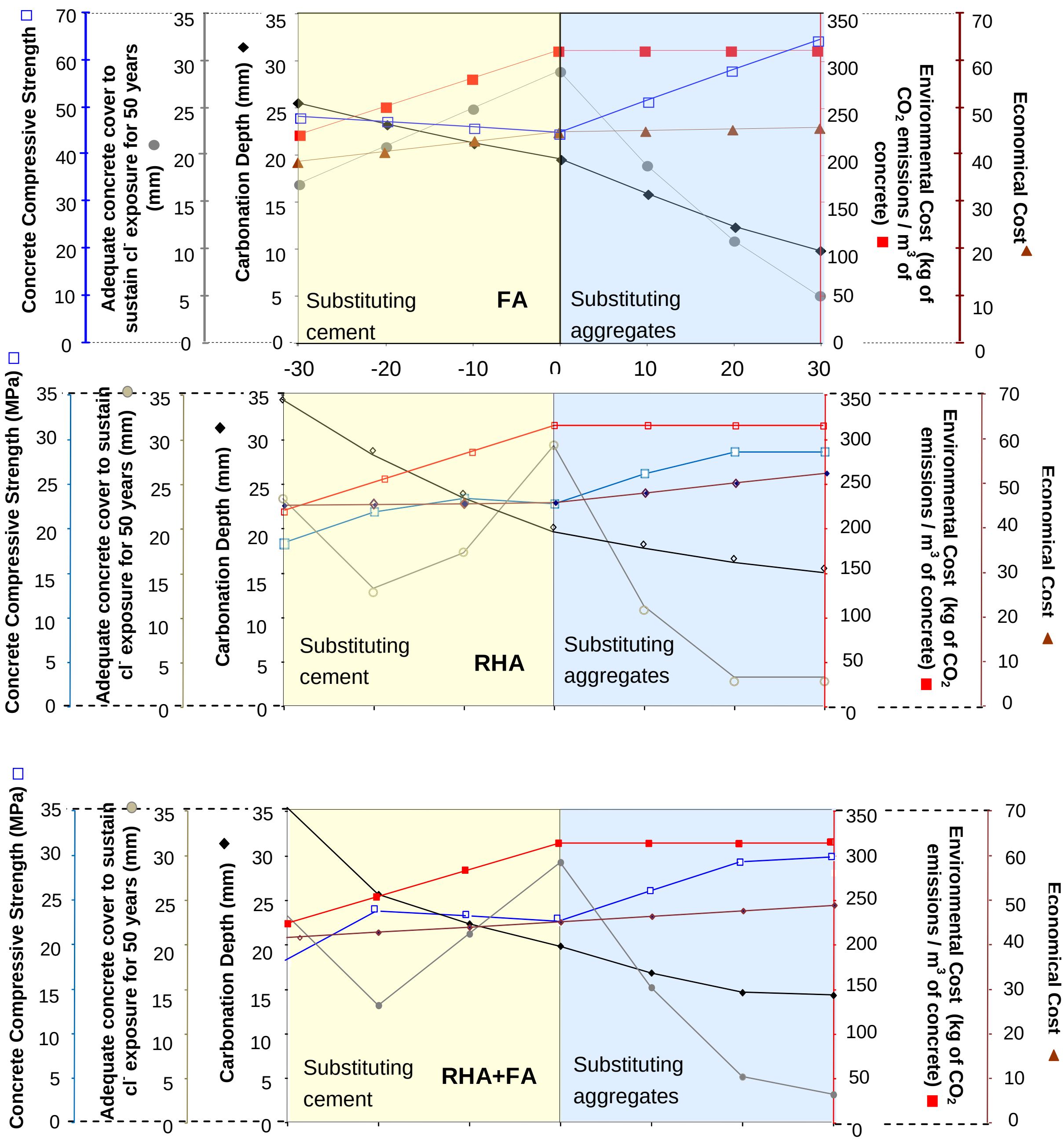

Figure 1 Durability and cost indicators for SCM mixes

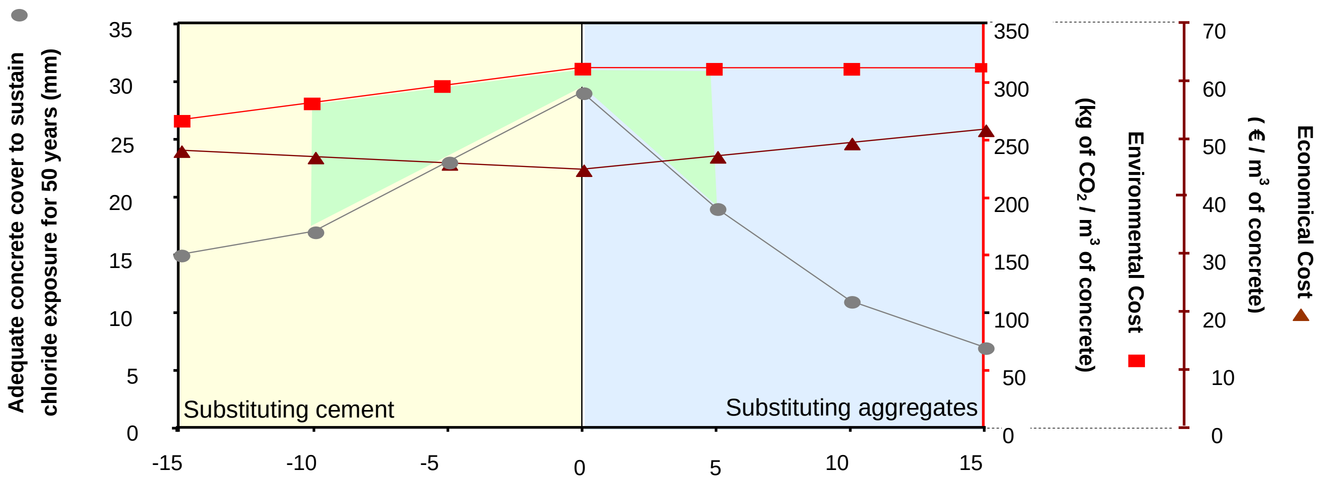

Figure 2 Area of balanced (optimum) sustainable and durable design incorporating SCM