An optimum design of reinforced concrete structures for prolongation of service life time at the lowest environmental cost

J. Tapali
Civil Engineer MSc., PhD candidate, Department of Environmental and Natural Resources Management, University of Western Greece, Agrinio, Greece

V.G. Papadakis
Associate Professor, Department of Environmental and Natural Resources Management, University of Western Greece, Agrinio, Greece

ABSTRACT: The internationally acclaimed efforts to reduce man-made CO_2 emissions require a more rigorous approach to be adopted by the construction industry. Given the need to provide a durable solution that guarantees a minimum service life, on a common reinforced concrete structure, the issue of sustainable durability design is of paramount importance. 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 cement replacement materials. On this note, the aim of this study is twofold. To evaluate the environmental contribution of each component of concrete and to provide the best possible mix design configuration (by means of a holistic analytical software tool) in terms of low environmental cost, as well as, to assess this proposed configuration in terms of strength and durability requirements.

1 INTRODUCTION

The construction activity is a major contributor to environmental pollution and especially to greenhouse gases emissions (GHG). At world level, civil works and building construction consumes 60% of the raw materials extracted from the lithosphere (Bribian et al., 2011). Buildings through their construction, use and demolition, consume approximately 50% of the final energy consumption in the members states of the European Union and contribute almost 50% of the CO_2 emissions released in the atmosphere, Dimoudi & Tombra (2008). According to previous studies the Portland cement manufacturing industry represents 5-7% of the total CO_2 anthropogenic emissions (Hendricks et al. 1998, Humphreys & Mahasenan, 2002).

Concrete is second only to water in total volume produced and consumed annually by society. The fact that concrete has very good mechanical and durability properties explains why it has become the most important building material. Nevertheless, concrete has an enormous environmental footprint, Meyer (2008).

First of all production of concrete each year creates a major need for natural resources. The production of Portland cement is energy intensive and is also responsible for CO_2 emissions. The cement subsector consumes approximately 12–15% of the total industrial energy use. Therefore, this subsector releases CO_2 emissions to the atmosphere as a result of burning fossil fuels to produce energy needed for the cement manufacturing process. Moreover, the concrete industry requires large water consumption. Construction and demolition waste have a high environmental impact as well.

At the Kyoto Conference in December 1997, developed countries agreed to cut their emissions of greenhouse gases by an average of 5.2 % in the period 2008 to 2012. The target for the European Union is an 8% reduction, shared out amongst Member States.

All these useful information in combination with other interesting data have been gathered after an extensive literature survey. However, many aspects of the environmental cost in construction have not been analyzed yet. The concrete industry faces a great challenge which is the sustainable design of buildings and structures by taking into account environmental and financial factors. The competition among constructors imposes the application of "green" technology in the production process and the marketing of new and more durable building materials.

Therefore, since environmental issues have become really important, construction industry must adjust to the principles of sustainable development. The implementation of specific environmental policies and the adoption of proper methods by industries can result in the reduction of CO_2 emissions from reinforced concrete constructions.

The principal objective of this study is to provide an integrated approach of the environmental impacts in concrete industry by using an innovative and commercially available software tool. The guidelines outlined here would be very helpful for the engineers and the companies, whereas the manufactures would be encouraged to promote "green" concrete and sustainable methods of building.

A great challenge nowadays is the construction of durable concrete structures which are friendly to the environment and live longer. The basic conclusions that arise from this particular presentation must affect, apart from the scientific community, all other social and political groups, since the environmental problems caused by constructions have become really worrying.

2 SERVICE LIFE TIME OF REINFORCED CONCRETE STRUCTURES

Concrete service life may be achieved either due to initial good quality, or due to repeated repair of a not so good structure. It is a crucial parameter which actually defines the period of time during which the performance of the concrete structure will be kept at a level compatible with the fulfillment of the performance requirements of the structure, provided it is properly maintained. Service life is strongly related with the environmental footprint of constructions. It is obvious that a structure with a longer service life is less harmful to the environment during the phase of operation.

Nowadays, an issue of importance is the durability design of reinforced concrete structures with a minimum service life of at least 50 years. However, a great number of concrete structures especially in coastal and urban areas begin to deteriorate in 20 to 30 years or even less time. This fact has serious economic impacts, as the repair of structures demands large financial amounts. Freyermuth (2001) has emphasized on these matters and suggested a service life time of 100 to 120 years for future structures. For the assessment of durability two basic indicators are used: in order to evaluate the carbonation exposure, carbon dioxide penetration front is calculated, while for chloride ingress, the adequate concrete cover needed to sustain that ingress for a period of also 50 years is estimated.

During the past years, a lot of experimental work has been conducted in this scientific field since durability is considered as one of the most serious issues that concern engineers all over the world. Nowadays, there is an increasing awareness of the durability problems that appear in many concrete structures. Three main factors define the concrete durability: the initial mix design (quality and relevant quantity of the concrete constituents), structure design, construction and maintenance, and the specific environmental conditions.

Many software tools have been developed for the estimation of service life and the computation of environmental cost in the construction sector. The combination of these models with new technologies can contribute in the establishment of sustainable building.

One of these tools, the EUCON® software package, is a complete and comprehensive solution in calculating: (a) concrete mix design, (b) concrete service life under harsh environmental agents, (c) corrosion prevention measures. EUCON is a useful tool based on proven predictive models (according to performance-related methods for assessing durability), developed and validated by Papadakis et al. (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.

The procedure suggested in order to export the desired results is the following: First, the essential parameters that characterize a concrete composition (mix design) are selected. Thereafter, the main chemical and volumetric characteristics of concrete are calculated (chemical composition of hydrated cementitious materials, porosity and related characteristics).

Based on the selected mixture proportions the compressive strength class of concrete is estimated. For each significant deterioration mechanism, according to the specific environment where the structure would be found, an appropriate proven predictive model is used. The service life of the structure in these environments, which cause either carbonation or chloride penetration, is calculated. Finally, cost and environmental aspects regarding concrete composition are analyzed. The designer evaluates the values of predicted properties (strength, service life, cost) and modifies the initially selected concrete composition, if necessary, in order to improve one or more of these properties.

3 ENVIRONMENTAL COST OF CONCRETE

The main environmental impacts of construction activity are: air pollution, waste pollution, noise pollution and water pollution. More specifically, the most harmful environmental effects of energy consumption due to construction are: global warming, acid rain, resource depletion, habitat destruction by fuel extraction, environmental damage from processing and transportation, photochemical smog.

The concrete industry in particular is not compatible with the demands of sustainable construction because of the CO_2 emissions. Environmental cost of concrete can be analyzed separately as fixed cost and operational cost. The fixed environmental cost is related with the production process of building materials, while the operating cost has to do with the environmental impacts caused by structures during the stage of their operation. According to previous studies all the life cycle phases (construction, operation maintenance, disposal) cause serious environmental impacts, but operational phase has the highest percentage of energy consumption and emissions (80-85% of total energy consumption and emissions) in a building's life (Gerilla et al., 2006). Durability can be used as an indicator for operational cost as durable buildings tend to have a lower environmental impact.

The main way to estimate the environmental cost of construction is by measuring the emissions of CO_2 during the production, transport and use of materials in construction. In addition, the calculation of energy consumed by industries contributes to the estimation of environmental cost of construction. This energy (kWh) is responsible for CO_2 emissions to the environment. In addition, other factors like the consumption of raw materials, noise pollution, emissions of other gases or dust are counted in the total environmental cost.

Cement production is an energy-intensive process in which energy represents 20 to 40% of total production costs. The production of cement clinker from limestone and chalk is the main energy consuming process in this industry. The most widely used cement type is Portland cement, which contains 95% cement clinker. Clinker is produced by heating limestone to high temperatures. Most of the energy used is in the form of fuel for the production of cement clinker and electricity for grinding the materials and finished cement. Since cement production consumes on average between 4 to 5 GJ per tone of cement, this industry uses 8 to 10 EJ of energy annually (Taylor et al., 2006).

There are two basic sources of CO_2 emissions

Table 1. Mix design and durability indicators*.

SCM type	Specimen No.	SCM (%)	C	W	w/c	A	FA	SF	f_c	x_c	Δx_c (%)	C_{50}	ΔC_{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 = the water content (kg/m^3), W/C = the water/cement ratio, FA = the fly ash content (kg/m^3) (S for siliceous, C for calcareous), SF = the silica fume content (kg/m^3), f_c = the concrete compressive strength (MPa), x_c = the carbonation depth (mm), C_{50} = the adequate concrete cover needed to sustain chloride exposure for 50 years (mm)

during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source: approximately $^3/4$ tons of CO_2 per ton of cement. But the chemical process of calcining limestone into lime in the cement kiln also produces CO_2: $CaCO_3 = CaO + CO_2$. This chemical process is responsible for roughly 1/2 ton of CO_2 per tonne of cement, according to researchers at Oak Ridge National Laboratory.

Emissions of CO_2 in the process of cement production depend mainly from: type of production process, type of the used fuel as well as the clinker/cement ratio that is the proportional content of additives (Hendriks et al., 1998).

An effective way for reducing the fixed cost of concrete is the use of materials with hydraulic properties. Thus, the effect of supplementary cementing by-products like fly ash and silica fume on the behaviour of the concrete mix has been examined. Table 1 presents the results from EUCON software for specific data given: 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 ash (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.

3.1 *Estimation of environmental footprint*

Although, the main CO_2 emissions from concrete production are associated with cement manufacturing, other concrete constituents entail environmental loads. 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. The overall environmental footprint of concrete (E_{conc}) can be calculated as:

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

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:

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

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.

There are a lot of references concerning the environmental impact of each component:

(a) Cement: there are a lot of references concerning the environmental cost of cement. Generally, the CO_2 emissions associated with cement production vary from 700 to 1000 kg CO_2/kg cement (Flower et al, 2007). According to Hoeing et al (2007) 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 (Josa et al. 2003). Using operational and production data from the Greek branch of a multinational 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).

(b) Aggregates: according to data from the Greek cement-manufacturing company, the CO_2 emissions from the production of aggregates are estimated to be 5.96 kg/tn of aggregates (considering that 2.53 kWh 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.

(c) Fly ash: 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, is the only source 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. Of course, CO_2 emissions from transportation (similar to cement transportation) should be added. According to Heindrich et al. (2005) the emission factor for fly ash (F-type) is 0.027 kg CO_2-e/kg.

(d) Silica fume: 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, the previously mentioned sources of emissions are assumed to be twice of those of fly ash transportation.

(e) Water: the only source of emissions arises from the electrical energy required to pump the water, which in this study is considered to be negligible.

(f) Admixtures**:** 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 (Flower et al. 2007).

Table 2 presents the range of values and other comments for CO_2 emissions per each component of concrete. Defining the environmental cost of each component is a complex task, as the emission values are not steady. Table 2 summarizes all these information and presents a range of estimated values for each separate concrete constituent based on data from previous research and on operational and production data from the Greek branch of a multinational cement-manufacturing company. Equation 1 in combination with Table 1 provide the basis for assessing the environmental cost of concrete and help the designer to examine alternative solutions, in case that the cost is high, in order to decrease the concrete footprint. The final decision concerning the concrete mix depends on many factors and must be taken after serious consideration, as it is explained later on.

Table 2. Environmental cost for each concrete component.

Concrete Component	Environmental cost ($kgCO_2$/kg component)	Comments
Cement	E_C=0,7-1kg CO_2/kg cement	For cement type I (the most common) the environmental cost is approximately 0,8 $kgCO_2$/kg cement For other cement types with lower clinker rates, CO_2 emissions are less.
Silica fume	E_S=0.366 kg/km/tn silica fume (emissions from transportation)	Emissions are assumed to be twice of these of fly ash transportation.
Fly ash	E_F=0,027-(0,0081+0.183 kg/km/tn fly ash) kg CO_2/kg fly ash	The source of CO_2 emissions is the energy for grinding and transportation. The value 0,027 refers to fly ash (F- type).
Aggregates	E_A=0.0049-0.041 $kgCO_2$/kg aggregates	For coarse aggregates the environmental cost is 0.04 $kgCO_2$/kg aggregates approximately For fine aggregates the environmental cost is 0.014 $kgCO_2$/kg aggregates approximately.
Water	E_W≈0 (Negligible)	The electrical energy for pumping the water is the only source of emissions.
Admixtures	E_D= 2.2 –53 x 10^{-3} $kgCO_2$/l admixtures	The CO_2 emissions due to admixtures are negligible – can be ignored

3.2 *Measures for reducing the environmental impact of concrete*

Since decreasing the environmental cost is a matter of importance, a lot of measures are proposed such as restriction of residue production and emission responsible for the greenhouse phenomenon, extended use of industrial by- products and their various mixtures, more efficient use of mineral and metallic sources, increased use of recycled materials in conjunction with lengthening of the construction durability. Several different studies IEA (2008), (2009), CSI (2009), ECRA (2009), CCAP (2008), McKinsey (2008) have focused on potential cement industry emissions reduction.

Generally, there are four main levels concerning the reduction of carbon emissions:

(1) Thermal and electric efficiency

(2) Use of alternative fuels- use of less carbon-intensive fossil fuels and more alternative (fossil) fuels and biomass fuels in the cement production process

(3) Clinker substitution

(4) Carbon capture and storage (CCS) – capturing CO_2 before it is released into the atmosphere and storing it securely so it is not released in the future (Cement Technology Roadmap 2009).

In order to achieve a balance between sustainability and durability in concrete design incorporation of supplementary cementing by –products, such as silica fume and fly ash has been suggested. It was found that when SCM are used as aggregate replacement materials, the carbonation depth is decreased. However, when SCM are used as cement replacement materials, there is an increase of carbonation depth. In addition, the use of these materials (SCM) in the concrete mix decreases the adequate concrete cover needed to sustain chloride exposure for a service life of 50 years.

4 OPTIMUM DESIGN OF REINFORCED CONCRETE STRUCTURES

A thorough design process must be based on the identification of the influence of the harmful environmental agents on a reinforced concrete structure, 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). Of course, the final decision of the designer must be the result of an integrated study and a techno-economic optimization.

4.1 *Life Cycle Analysis*

Life-cycle analysis (LCA) is a process whereby the material and energy flows of a system are quantified and evaluated. Environmental life cycle analysis (LCA) can actually access the environmental burden caused by buildings and show measures of reduction as well. Moreover, numerous environmental assessment tools have been developed to allow scientists analyze the environmental performance of buildings.

LCA attempts to quantify the full range of environmental impacts associated with a product by considering all inputs of resources and materials and all outputs of wastes and pollution at each stage of the product's life — including acquiring raw materials (e.g., mining), manufacturing and distributing the product, the consumer's use and maintenance of the product, and its ultimate disposal (Anand et al. 2006).

Figure 1 shows the system boundary in a life cycle analysis which means the inputs and outputs and of course all the intermediary stages that must be taken into account.

Life cycle assessment involves three stages:

(1) An inventory of materials and energy used and environmental releases from all stages in the life of a product or process

(2) Impact assessment examining potential and actual environmental and health effects related to the use of resources (materials and energy) and environmental releases.

(3) An improvement assessment, identifying the changes needed to bring about environmental improvements in the product or process.

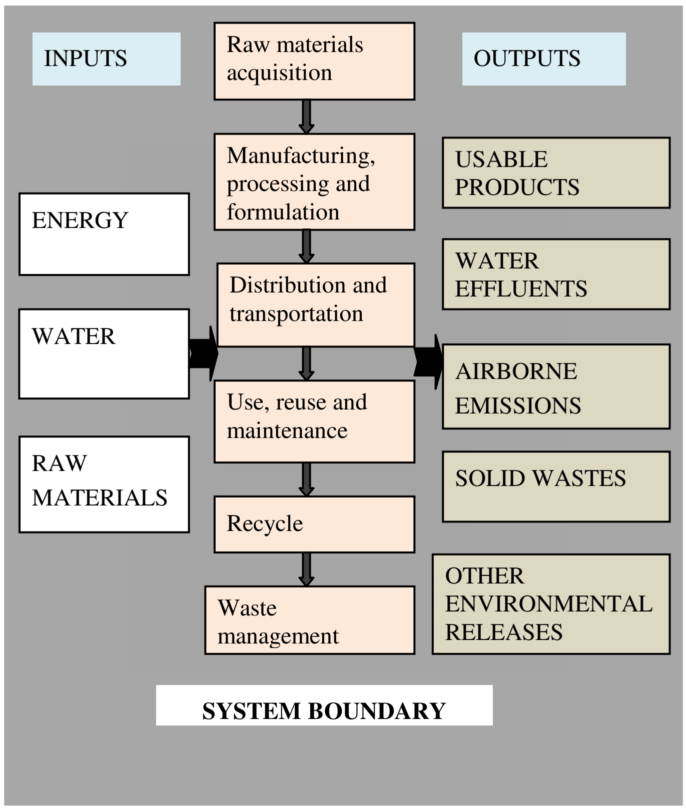

Figure 1. Life Cycle Analysis (LCA) scheme.

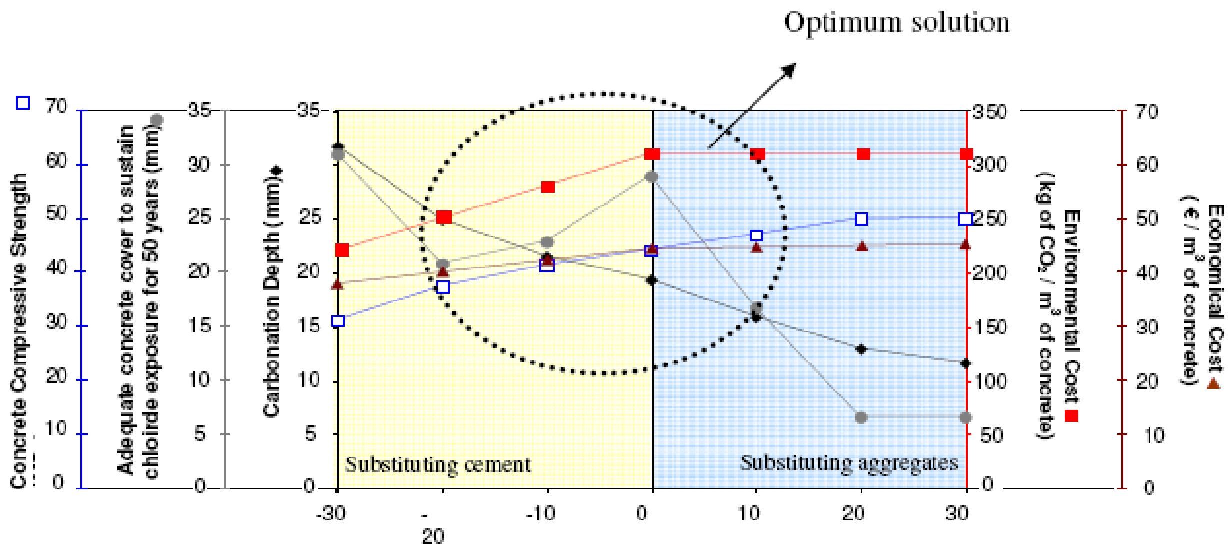

Figure 2. Durability and cost indicators for siliceous fly ash mixes.

4.2 *Optimization*

"Green" durability can be achieved by examining both the environmental and economical cost of the concrete mix. For example, Figure 2 allows an assessment of durability, environmental and economical cost indicators for siliceous fly ash mixes. The circular area designed into Figure 2 indicates the combination of values that offer an acceptable solution. The environmental cost and the economical cost seem to "behave in a similar way. Addition of siliceous fly ash as cement replacement material in the concrete mix up to 20% is acceptable as the mix is durable, economical and environmentally friendly. When siliceous fly ash replaces aggregates the replacement level accepted is about 10%. If the percentage of cement replacement is 30% environmental and economical cost are quite low, whereas the values for the carbonation depth and the concrete cover are very high. On the contrary, a concrete mix with 30% replacement of aggregates has good durability but it is not affordable.

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 the environmental footprint were noticed. 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.

Generally, the carbonation depth decreases as aggregate replacement by SCM increases, and increases as cement replacement by SCM increases. Also, replacing aggregates results in concrete mixes with high compressive strength, but increasing the percentage of cement substitution affects the values of concrete compressive strength in a negative way. Defining the optimum solution when designing reinforced concrete structures is a complex matter and EUCON is a software tool that can actually offer a lot to the scientific community in this field.

5 CONCLUSIONS

Governments should give financial and legislative incentives to manufactures and industries and urge them to apply new methods and a more sustainable technology. There are many different ways for the reduction of CO_2 emissions due to building industry. Numerous environmental assessment tools have been developed to allow scientists analyze the environmental performance of buildings.

The environmental cost of each individual concrete component can be estimated, based on data from the literature or from production and operational data from cement-manufacturing companies. Therefore, it is possible to estimate the environmental footprint of concrete and achieve an adequate level of sustainability and durability in the design of reinforced concrete buildings and structures.

The optimum solution can be defined by EUCON software which calculates the environmental cost, the economical cost, the concrete compressive strength and two basic technical indicators: the adequate concrete cover to sustain chloride exposure for 50 years (mm) and the carbonation depth (mm). Supplementary cementitious materials can replace either cement or aggregates in the concrete mix. 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 to achieve the best possible (optimum) solution, according to the requirements of his particular study. Of course, the effects of the SCM materials on the behaviour of the concrete mix differ when used as aggregate or cement replacements.

The methodology presented in this study can forward the development of new policies in the construction industry and the adoption by engineers and technicians of a sustainable perception for designing reinforced concrete structures. A characteristic phrase of Henri David Thoreau summarizes all mentioned above: “What's the use of a fine house if you haven't got a tolerable planet to put it on?”

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