A Comparative Assessment of the Effect of Cement Type on Concrete Durability

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Abstract

In the current study, the effect of different types of cements (CEM I, II, III, IV and V), classified according to the European Standard EN 197-1, as well as the effect of different types of Type II additives on CEM I type of cement, were evaluated as far as their performance in carbonation and chloride exposure is concerned, for a service life of 50 years. Different types of supplementary cementitious materials (SCM) and water-cement ratios were examined. The evaluation was made using a software package, an analytical tool for the estimation of concrete service life when designing for durability under harsh environments, developed based on a unique analytical approach of all the parameters identifying the aggressivity of those environments, and validated using experimental data. The results showed that a range of CEM II type of cements behaved in an extraordinary fashion compared to the control mix (CEM I, water cement ratio of 0.45). A benchmarking scale was created to provide a measurable value of the effectiveness of each type of cement. It was found out that cements incorporating artificial pozzolan (CEM II/A-Q, at 15%) produced the best performance when designing for chloride diffusion, based on the adequate concrete cover value to resist that kind of attack in a depth of 50 years, followed by cement incorporating silica fume (CEM II/A-D) and blast furnace slag (CEM II/B-S). With further incorporation of slag (at 43 %), moving on to the CEM III category of cement, the best overall performance in chloride diffusion was achieved. A type of cement with low clinker content (45 %), which if adopted by the cement manufacturing companies, except of its outstanding performance in chloride exposure, minimizes further the manufacturing energy emissions. In Europe production of Portland-composite cements (CEM II) and Blast-furnace cements (CEM III) constitutes 55.5 % and 6.2 % of the total cement production. Bearing in mind that the cement production in several countries, as in Greece, is limited to a few types of cement (CEM I, CEM II/M, CEM IV) due to a number of reasons (e.g. economical, availability of raw materials, energy emmisions) and considering that the clinker burning is the most important part of the process in terms of energy use and emissions to air, it is believed that the outcome of this study will provide the basis for future consideration of further types of cement to enter the production line, based on their behavior in chloride diffusion, as well as on their lower content of cement clinker (as in the case of CEM III cement).

Originality

The results of this study, investigating the influence of the different types of cements and supplementary cementitious materials (SCM) on the durability of concrete, with emphasis on the chloride diffusion, portray a comprehensive but also comparative assessment of the performance of each individual type of SCM and cement, as categorised according to EN 197-1, on concrete durability. Furthermore, it clearly identify the need for further consideration on the decision-making process on the cement manufacturing, aiming to promote the advantages of other cement types (than the ones being already developed). Bearing all of the above in mind, this work is under the aims and scope of the 'Concrete durability' thematic area of the conference, in addition to under the subsection 'Supplementary cementitious materials' of the "Properties of fresh and hardened concrete" thematic area of the conference as well.

Chief contributions

As it was mentioned above, the results of this study portray a comprehensive but also comparative assessment of the performance of each individual type of SCM and cement, as categorised according to EN 197-1, on concrete durability. Furthermore, it clearly identifies the need for further consideration on the decision-making process on the cement manufacturing in several countries, aiming to promote the advantages of other cement types, than the ones being already developed.

Keywords: *Carbonation, Chloride Exposure, Durability, Cement Type, Supplementary Cementing Materials*

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. 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. It is estimated (Papadakis, 2000) 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 calculated to be 0.873 tonnes. It has been suggested (Papadakis, 2000) that a way of sustainable development of cement and concrete can be achieved by utilization of supplementary cementitious by-products, like fly ash, silica fume or ground granulated blastfurnace ash. In Europe, for example, production of Portland-composite cements (CEM II) and Blast-furnace cements (CEM III) constitutes 55.5 % and 6.2 % of the total cement production (Papadakis, 2000).

On this note, the effect of different types of cements, classified according to the European Standard EN 197-1 (2000), and the effect of Type II additives on CEM I type of cement, are evaluated in terms of their performance in carbonation and chloride exposure, for a service life of 50 years. The 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. (1992; 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.

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. Initially the influence of type II additives (siliceous or calcareous fly ash and silica fume) on a standard CEM I type of cement were examined, followed by an analysis of the effect of the different supplementary cementing materials (SCMs) on other cement types (CEM II, III, IV, V). As durability indicators, calculation of the carbonation depth, for a period of 50 years, is used for carbonation exposure, while under chloride ingress, the estimation of the adequate concrete cover needed to sustain a service life of 50 years are used.

2.1 EFFECT OF TYPE II ADDITIVES ON CONCRETE DURABILITY

Several mix design configurations were considered, where each time addition of 10 kg/m^3 of a Type II additive took place, for a constant w/c ratio and cement content, until the rate of SCM reaction dropped bellow 1. 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). Overall it was seen that incorporation of calcareous fly ash (cfa) in CEM I type of cement, produced a marginally better performance under carbonation exposure than siliceous fly ash (sfa)(Figure 1a). Addition of 50 kg/m^3 of cfa reduced the carbonation depth by 31.6 %, compared to a 27.6 % reduction, when sfa was used. Silica fume (sf) did not prove to be as effective as fly ash (fa), in inhibiting carbonation exposure Incorporation of 50 kg/m^3 of sf decreased the depth of carbonation by 15.8 % and reduced the diffusion coefficient of CO_2 by 29.6 %, compared to the 52 % (on average) reductions when fa was used.

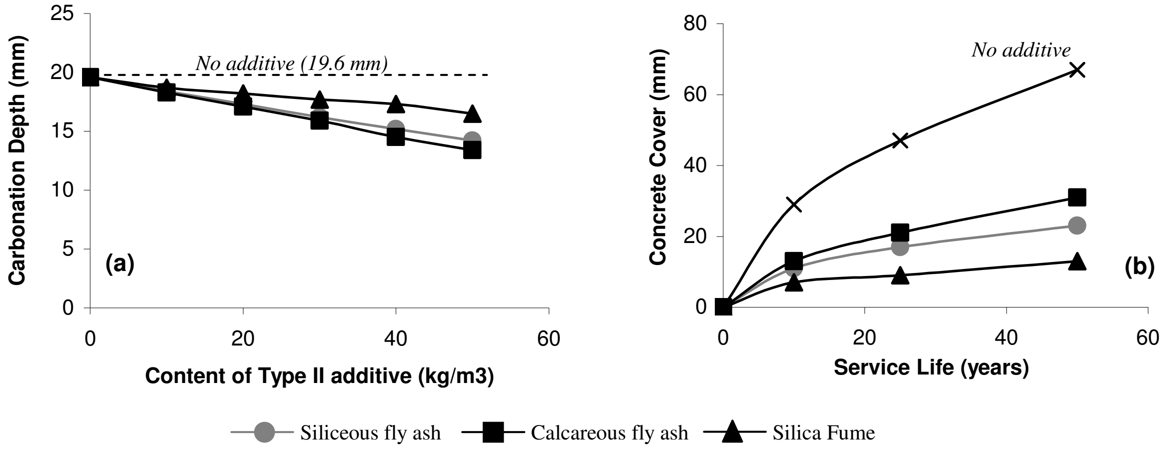

Figure 1: Carbonation depth and sufficient concrete cover for chloride exposure of CEM I with Type II additives

Silica fume proved to inhibit chloride diffusion more efficiently than fa. A 96.7 % reduction of the diffusion coefficient of chloride ions was noticed compared to 76.1 % and 87.5 % reductions when cfa and sfa were added. Incorporation of 50 kg/m^3 of sf reduced the sufficient concrete cover, needed to sustain a service life of 50 years, by 79.2 % (much higher than the corresponding reductions due to fa). Siliceous fly ash produced a slightly better performance in chloride exposure environments than the calcareous one (Figure 1b). When their combined action was considered it was seen that utilization of cfa and sf produced marginally better results in carbonation exposure (20.6% reduction than 19.2% in the case of sfa), while for chloride ingress sf with sfa produced smaller concrete cover values needed to sustain the chloride diffusion (66.7 % reduction compares to control, than 63.4% in the case of cfa).

2.2 EFFECT CEM II TYPE OF CEMENT ON CONCRETE DURABILITY

A standard CEM I mix of 0.45 water-cement ratio was selected as the reference type of cement for chloride exposure (cement content 300 kg/m^3, 31.5 mm crushed aggregates, no additives, no admixtures). The CEM II type of cements were divided to four different categories, based on the type of SCM they contain, as classified in the European Standard EN 197-1. On each type of SCM, three different content levels were considered (minimum, medium and high).

Considering their performance under carbonation exposure (Figure 2), an initial observation is that carbonation depth was increased and the critical time for initiation of corrosion (for a 30 mm concrete cover, indicated with italics in Figure 2) was reduced compared to the control values, for every type of CEM II cement used. However, closer inspection reveals that certain types of cements, with low content of SCM (6 %) produced a “tolerable” behavior. Cements (CEM II/A-Q, A-s) incorporating artificial pozzolana and blast furnace slag (at the previous mentioned low quality, produced the best behavior in carbonation (4.1 % increase of carbonation depth) followed by cement incorporating 6 % burnt shale (CEM II/A-T, 4.7 % increase of carbonation depth). Cements using pozzolanic materials with hydraulic properties (W, S, T), behaved much better than those containing normal pozzolanic materials (V, P, Q, M). The latter, produced a deviation of 8.3 % from the control value of carbonation depth, almost twice than the 4.7 % calculated to the former. Cements incorporating silica fume at low quantities produced a steady performance, regardless the SCM increase (11.5 % increase of the carbonation depth). The worst performance in carbonation exposure was calculated by cements incorporating limestone.

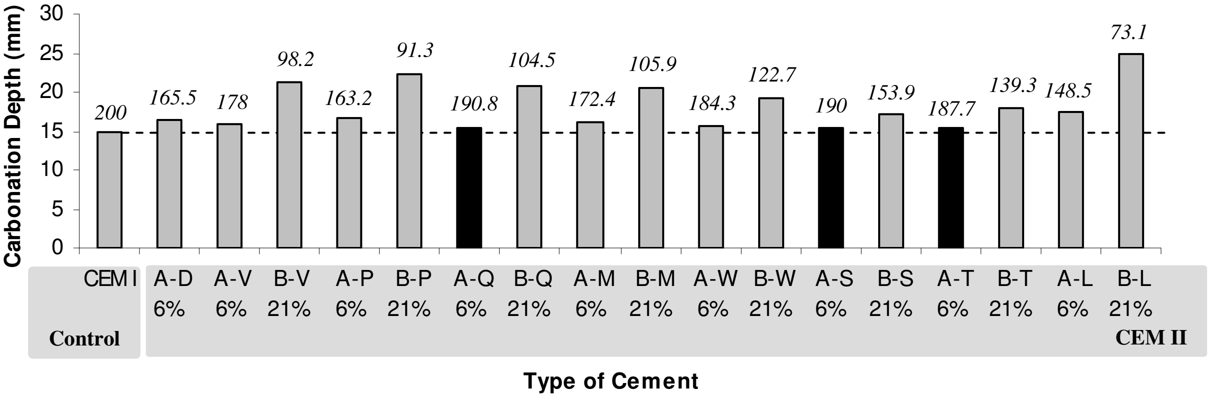

Figure 2: Best carbonation depth values calculated for a service life of 50 years for every type of CEM II (the critical time for initiation of corrosion for a concrete cover of 30 mm is illustrated with italics).

Under chloride exposure every different type of cement used (except the one with limestone, CEM II/B-LL) behaved in an extraordinary way (Figure 3). Cement incorporating 15 % artificial pozzolana (CEM II/A-Q) produced the best "behavior" (reductions of up to 62.2 % on the concrete cover). A scale of effectiveness was created, where by setting the control values as the reference/starting point of the scale and the performance of the CEM II/A-Q (15 %) in chloride exposure, as the top (best) value, the behavior of each other type of CEM II cement was benchmarked against those values. The results of this approached are illustrated in Figure 4. Cements incorporating silica fume (CEM II/A-D) produced a considerable decrease of the concrete covers, up to 57.8 % with increasing SCM content (a 71.4% overall effectiveness). Cements containing normal pozzolanic materials, except natural pozzolana, behaved in a similar manner. At low SCM quantities (up to 15 %) concrete cover was reduced, where at quantities above than 21% an increase in the concrete cover was noted.

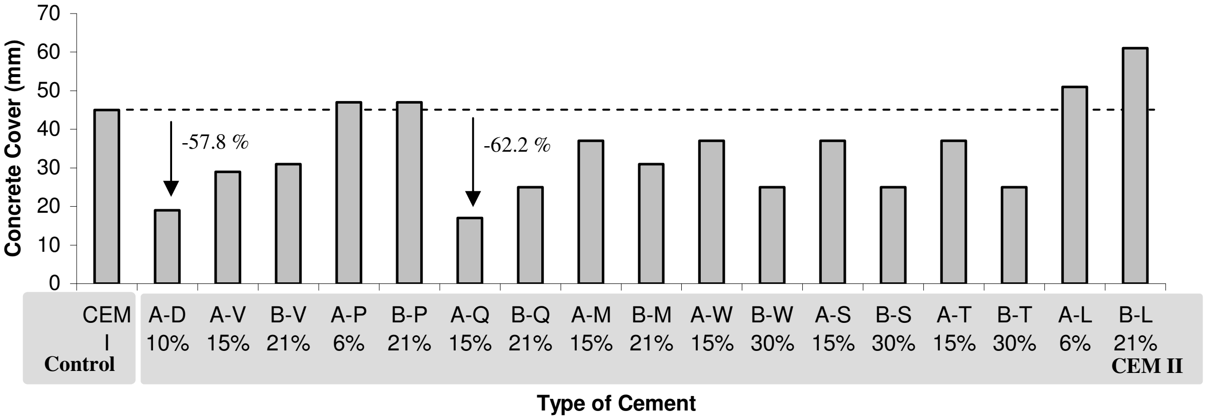

Figure 3: Best adequate concrete cover values calculated to sustain for a service life of 50 years under chloride exposure, for every type of CEM II cements

Incorporation of natural pozzolana (CEM II/A,B-P) produced a steady increase of the concrete cover. Cement containing silicious fly ash (CEM II/A,B-V) produced a similar behavior to the artificial pozzolana CEM II cement. Cement containing other SCMs (CEM II/A,B-M) produced a considerable decrease of the concrete cover (35.6 %) up to 25 % of SCM. Cements containing pozzolanic materials with hydraulic properties (calcareous silica fume, blast furnace slag and burnt shale) behaved in a similar manner, producing the best performance, overall, at low (6 % - 15 %) and high (21 % - 30 %) quantities of SCMs (the biggest reduction of the concrete cover noticed at 30 % of SCM was 44.4 %). Cement containing limestone produced the worst behavior in chloride exposure. Addition of 30 % of

SCM increased the concrete cover by 57.8 % (compared to control). Overall, the performance of the different types of SCMs in chloride exposure can be summarized as it is illustrated in Figure 4.

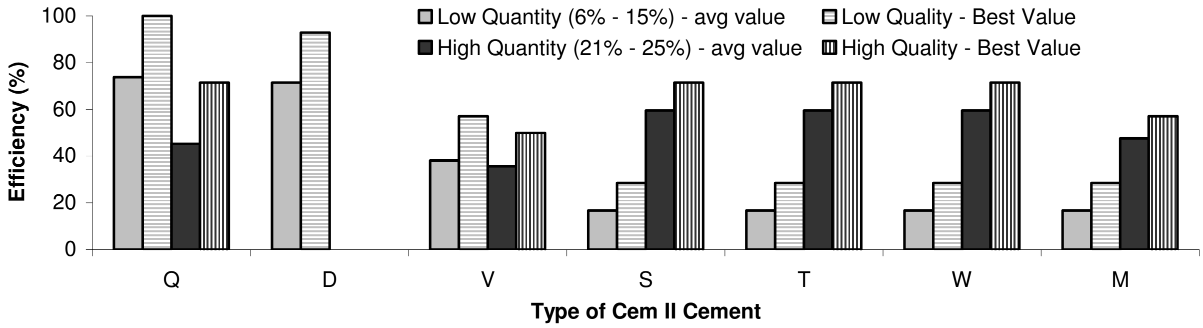

Figure 4: Comparative performance of SCMs in chloride diffusion

2.3 EFFECT OF OTHER TYPES OF CEMENT (CEM III, IV, V) ON CONCRETE DURABILITY

CEM III type of cements produced a very good performance under chloride exposure, in contrast to their carbonation behavior (Table 1). Carbonation depth kept increasing (compared to control) with the increasing percentage of SCM (up to the socking value of 466.2 % at 81 % of SCM).

Table 1: Performance of CEM III, IV, V type of cements

Cement Type	**CEM I (control)**	**CEM III/A**			**CEM III/B**	**CEM IV/A**			**CEM IV/B**		**CEM V/A**
Scm (%)	0	36	43	51	66	11	20	30	36	40	45
x_c (mm) *	14.8	18.4	19.1	22.3	42.2	17.7	20.3	25.6	26.4	30.1	34.0
c_{50} (mm) *	45	21	15	17	*75*	39	33	41	43	*53*	*63*
c_{50} (%)	-	-53.3	-66.7	-62.2	*8.9*	-13.3	-26.7	-8.9	-4.4	*17.8*	*40.0*

* x_c is the carbonation depth (mm), c_{50} the adequate concrete cover needed, for a service life of 50 years to be sustained under chloride exposure

Considering the concrete cover needed to sustain a service life of 50 years under chloride ingress, up to 43 % of slag, the cover values were reduced (maximum reduction of 66.7 %). Comparing the best behavior of CEM II and CEM III type of cements it was found out that cement type CEM III with 43 % of slag produced the best performance in designing for chloride exposure (at 50 years) than any other CEM II type of cement (Figure 6).

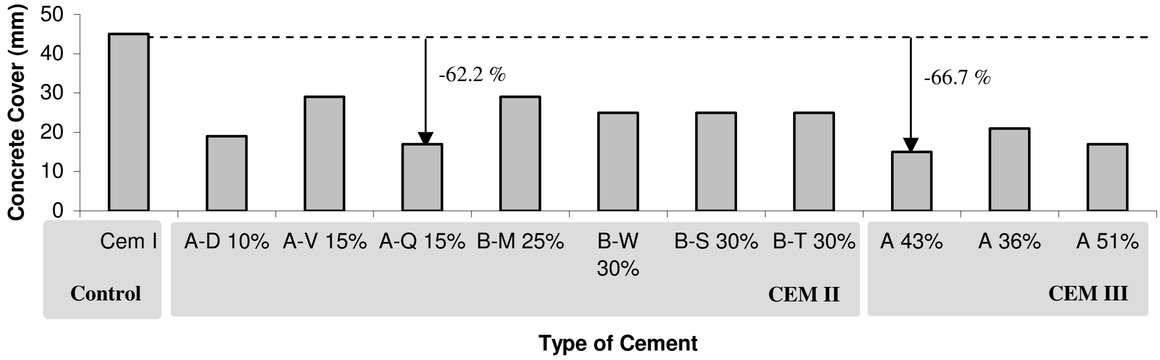

Figure 6. Comparative performance of SCMs in chloride diffusion

As far as CEM IV type of cements is concerned, carbonation depth kept increasing with an increasing percentage of SCM. However, smaller values compared to CEM III type of cements were noticed. Up to 20 % of SCM, the concrete covers (for chloride exposure) reduced by 26.7 %. Increasing the content of slag, up to 40 %, the concrete cover values started to increase but they still remained 4.4 % bellow the control value. Incorporation of slag at higher quantities, increased concrete cover considerably. Finally for CEM V type of cements considerable increases in carbonation depth were noticed, in addition to a very poor performance in chloride diffusion.

3. DISCUSSION

The aim of this study is to evaluate in terms of service life for carbonation and chloride exposure, the effect of each different cement type (different SCM) as calcified in EN 197-1. A software package based on proven, verified predictive models was used for the evaluation (Papadakis et al. 2007). As far as carbonation exposure is concerned, carbonation depth was estimated for a period of 50 years, in addition to the critical time for initiation of corrosion for a given concrete cover of 30 mm. In terms of chloride ingress, the adequate concrete cover needed to sustain that ingress for a period of also 50 years was estimated. In general, the resistance to chloride penetration is mainly governed by the porosity and permeability of concrete but also by the chloride ion binding capacity of the cementitious paste. The results of this study showed that silica fume and fly ash reduced considerably the carbonation depth values, compared to the control mix (CEM I) when used as additives. 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 (CEM II/A-S, A-V, A-W) marginally (5 %) larger carbonation depths and smaller times for the initiation of corrosion, were produced compared to control. The explanation for such a behavior lays in the way these materials were incorporated into the mix. In the first case, by keeping constant the w/c ratio and the cement content, addition of these materials acts as aggregate replacement, where 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, the cement and clinker content is reduced, hence the amount of carbonatable materials is also reduced (due to the decrease in total 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 CEM I type of cements (due to the consumption by pozzolanic reaction, and lower cement content). However, considering that for reasons of comparison certain parameters were kept unchanged (w/c ratio, cement content) better performances in carbonation exposure (than control) can be achieved by altering these parameters.

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 siliceous 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-cementitious compounds (C_3A, C_4AF), leading to a more increased chloride ion binding capacity (Antiohos & Tsimas, 2003). While utilization of artificial pozzolana (CEM II/A-Q) produced the best behavior in chloride exposure, limestone did not behave at an adequate manner, probably due to its very low aluminum concentration compared to CEM I (hence less chloride ions binding capacity). In other studies (Loser et al; 2010, Selih et al 2003) a limestone containing binder proved to increase considerably the risk of corrosion. However, when combined with blastfurnace slag, much better results have been noted (Lang, 2005). An increase in pozzolan content proved to lead to a higher resistance of concrete in chloride exposure (Kaid et al. 2009), as it was observed in this study for a level of concentration from 6% to 15%.

Considering the results of CEM II and CEM III type of cements overall, blastfurnace slag, proved to be the most beneficiary SCM (a decrease of 66.7 % on adequate concrete cover values was noticed for a 43% CEM III type of cement) in ihibiting chloride ingress. Slag replacements of up to 40% have been known to reduce drastically the chloride penetrability of concrete (Tamimi et al. 2008), mainly due to the binding characteristics of the SCM. Its increasing pozzolanic effect with time, results in more hydration products and lower diffusivity, as well as in more improved interfacial zone and a better bond between the paste and the aggregate (denser structure).

4. CONCLUSIONS

A comparative assessment of all the cement types, categorized according to the European standard for Cement, based on proven predictive models for the estimation of service life under harsh environments took place in this study. Overall the CEM II type of cements produced an effective performance in terms of chloride exposure. Utilization of blastfurnace slag, artificial pozzolana and silica fume proved to be the most effective SCMs. Taking into account the reduction in clinker achieved when a SCM is utilized and the overall performance of these materials presented in this study, utilization of these types of cement not only can guarantee a durable solution (under harmful environmental agents) but they also provide a sustainable solution, by reducing the CO_2 emissions associated with the clinker burning process during cement manufacturing. It is hoped that the results of this study will pave the way for more thorough research attempts on the durability of SCM aiding in this way on the future utilization, in large scale, of these types of materials from cement manufacturing companies.

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