CONCRETE MIX AND ENVIRONMENTAL LOAD IN THE CONTEXT OF DURABILITY AND RELIABILITY

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Summary

The carbon dioxide is the primary greenhouse gas and its concentration in the environment has dramatically risen during the 20th century. According to some estimates, the Portland cement production is responsible for producing about 7 % of total global CO_2 emissions. This creates a challenge to minimize the use of Portland cement and maximize the use of industrial by-products such as silicate and aluminosilicate materials. The impacts of the use of such blended cements are the changes in physical-mechanical properties of concretes; however, it has also an effect on structure costing because industrial by-product as secondary raw materials might reduce the price of the binder. This should be taken into consideration when designing concrete structures, together with the required level of reliability and target service live. The consequences of those measures on the CO_2 emissions and structure costing together with the durability and reliability indicators are studied utilizing software developed by authors.

Keywords: Concrete structures, blended cements, carbon dioxide emissions, costs, durability, reliability

1 Introduction

In the context of **performance-based approaches, sustainability** consideration and the **whole life costing** the time is one of decisive variables; thus, the durability issue is pronounced. These facts have gained a considerable attention recently which is reflected also in ongoing standardisation activities: the ISO/WD 13823 [1], *fib*-Model Code 2007 [2] and the AIJ Recommendations [3]. All these documents are based on probabilistic approaches and will introduce (or enhance) the **design of structures for durability** – i.e. time-dependent Limit State approach and service live consideration. The utilization of design for durability may bring pronounced economical and sustainability impacts. Present paper concentrates on the blended cements' utilization considering the carbon dioxide emissions within the scope of costs of concrete structure designed for specified service life and relevant reliability index value.

European codes [4–6] deal with the design of reinforced concrete structure for durability and service life assessment only in a "prescriptive manner". The relevance of these requirements and associated reliability index values together with target service life should be ensured – this coherence is not generally covered by the European codes [7].

It should be noted, when designing the structure, the durability and reliability limits may be set depending on the client's decision (serviceability limit states) in the context of Performance-Based Design, balancing the economical and other consequences. Software tools used/developed by authors [8, 9] might be utilized for such purposes.

2 Design of concrete structures, economical and ecological assessment

Adopting appropriate analytical models for carbonation progress in concrete and taking account of the uncertainties of concrete mixture and exposition characteristics, a statistical description of carbonation progress may be gained e.g. by SW [8]. Later, this SW has been enhanced for utilization of supplementary cementitious materials (SCM) [9], where the *k*-value concept has been discussed considering and comparing recommendations of [4] and [11]. Random or deterministic input parameters are involved and the results of statistical analysis allow for the assessment of the reliability index relevant to different service life values. The software has been enhanced also by incorporating a simple way for assessment of cost and embodied CO_2 emission (OPC production). This may furnish a client (and a designer) with a user friendly tool to support his/her decisions. The specific requirements may be met in this way.

In the view of the above mentioned issues two points deserve an extra consideration:

- reflecting the idea of **life cycle costing** (LCC) and the economical and environmental consequences, the design service life should be determined (or agreed) by the client;
- consequently, the appropriate limit states and relevant reliability level (in the form of the reliability index β) have to be chosen and satisfied.

Facing the challenge to minimize the use of Portland cement, a maximization of the use of industrial by-products such as silicate and aluminosilicate materials is a suitable way. Other consequences of blended cements' utilization are the changes in physical and mechanical properties of concrete, and it might also have a considerable effect on structure costing because some industrial by-product such as secondary raw materials reduce the price of the binder.

Assessment of carbon dioxide emission: Reduction in carbon dioxide emission from cement production can be reached in two different ways. The first possibility is to add a secondary raw material, which does not release carbon dioxide upon burning, to the starting mixture for the cement production. Such raw materials are e.g. fly ash, slag or undersize particles of recycled concrete. The other and more frequently used alternative of reduction of CO_2 emission is the utilization of suitable admixtures to Portland clinker: granulated blast furnace slag (GBFS), fly ash (FA), and silica fume (SF). GBFS is a latent hydraulic material that forms calcium silicate and aluminate hydrates, when calcium hydroxide from clinker hydration is present. FA and SF are pozzolanas, which contain above all amorphous silica that reacts with $Ca(OH)_2$ and forms calcium silicate hydrates, CSH gels, at an ambient temperature. When optimum design of the concrete mixture is applied, it is possible to achieve the comparable properties of concrete with supplementary cementing material to those of ordinary Portland cement concrete. In certain cases the pronounced effect on concrete durability can be achieved. The total CO_2 emissions per tonne of cement range from about 1.1 tonne of CO_2 from the wet process to 0.89 tonne from precalciner kiln [12]. In order to get certain quantitative view about this issue we simply applied approximately an average value of 970 kg per 1 tonne of cement for CO_2 emission.

Assessment of costs: For the sake of simplicity the costs are deduced from binder amount only under the presumption of nearly constant volume and relatively low costs of aggregates; the discount rate is not considered. Consequently, the resulting costs in the present study are of relative nature and can serve for the purposes of comparison only - the problem of costs is not covered in a complex way.

Durability limit state: When assessing the service life of a concrete structure, the time passing before the initiation of rebar corrosion is usually considered being the most conservative limiting state. In the probabilistic terms the relevant limit condition can be formulated as follows:

$$P_f\left(t_D\right) = P\left\{a - x_c\left(t_D\right) \leq 0\right\} \leq P_d \tag{1}$$

where a is the thickness of concrete cover, x_c is the depth of the carbonated zone, t_D is design (target) service life and P_d the design (target) probability of “failure”. Note: the ingress of chloride ions may be another reason for reinforcement depassivation; this effect is not regarded in this paper. The index of reliability β is often used as a measure of reliability instead of the failure probability P_f, being interconnected by the transformation rule

$$\beta = -\phi^{-1}\left(P_f\right) \tag{2}$$

where Φ is the cumulative distribution function of the standardized Normal distribution.

Considering the condition (1), the probability of non-reaching the t_D value (or a design value β_D of reliability index) is assessed.

3 Comparative studies

Example 1

The authors have studied the influence of replacement of Portland cement with SCM on reliability index β, CO_2 emission, and costs of binders. The content of cement was replaced by fly ash in the designed mixtures with 5, 10, 15, 20, and 25 %, and high calcium fly ash has been taken into account. The w/c ratio was kept at 0.5 and unit content of water was 180 kg/m^3 for all mixes. Input data common for all examples are shown in **Tab. 1**, the rest of the data together with the results are listed in **Tab. 2** (mean values; standard deviation values are computed too, however not shown in the table). Some of those results are depicted in **Fig. 1**.

It should be noted the value of efficiency factor k used in this study has been fitted according to [13] as the values recommended by [4] proved to be not suitable for the purposes of carbonation prediction – see [10].

Note the reliability index value in the present context represents the probability of not exceeding the target service life of 50 years ensuring the condition (1); according to [2] the recommended limit is $\beta \geq 1.3$, but there are proposes for limit $\beta \geq 0.8$ (according to [6] it should be $\beta \geq 1.5$). In this respect only the concrete mix of the first three cases would be acceptable. In **Fig. 1** the differences in emission and economical consequences may be observed too.

Tab. 1 Input data (part 1)

Variable	**Mean value**	**COV**	**PDF**
Ambient CO_2 content [mg/m^3]	800	10	Normal
RH [%]	75	10	Normal
Unit content of cement [kg/m^3]	**Tab 2**	3	Normal
Unit content of water [kg/m^3]	175	3	Normal
Unit content of SCM [kg/m^3]	**Tab 2**	3	Normal
Efficiency factor k of SCM [-] [13]	0.5	10	Lognormal
Uncertainty factor of model	1	15	Lognormal
Cover [mm]	30	16	Lognormal
Service life [years]	50	-	Deterministic
Emission of CO_2 per tonne of binder [kg]	970	-	Deterministic
Costs of cement [Kč /t]	2500	3	Normal
Costs of fly ash [Kč /t]	26	3	Normal

Tab. 2 Input data (part 2)

Unit content [kg/m^3]		**$(w/c)_{eff}$**	**Reliability index for t_D = 50**	**CO_2 emission [kg]**	**Cost of binders [Kč /m^3]**
PC	**FA**				
360	0	0.5	2.79	349	900
342	18	0.51	1.05	332	855
324	36	0.53	0.79	314	811
306	54	0.54	0.53	297	776
288	72	0.56	0.25	279	722
270	90	0.57	–0.02	262	677

It should be noted the value of efficiency factor *k* used in this study has been fitted according to [13] as the values recommended by [4] proved to be not suitable for the purposes of carbonation prediction – see [10].

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Example 2

Perhaps, it might be of significant interest to recall here the results of a complex study presented by Itoh [14]. The energy consumption and CO_2 emission have been used as the environmental impact indicators, however, not assessing and comparing the reliability consequences. Bridges, having a length of 150 m and width of 12 m with T-type piers each having 12 m height, were considered for the purpose of this comparison. The study shows the advantage of prestressed bridge over the steel one with the respect to environmental impacts. The embodied energy consumption proved to be almost doubled in case of a steel bridge, and the same holds for CO_2 emission compared to a PC simple pre-tensioned T-girder bridge or a PC simple box girder bridge.

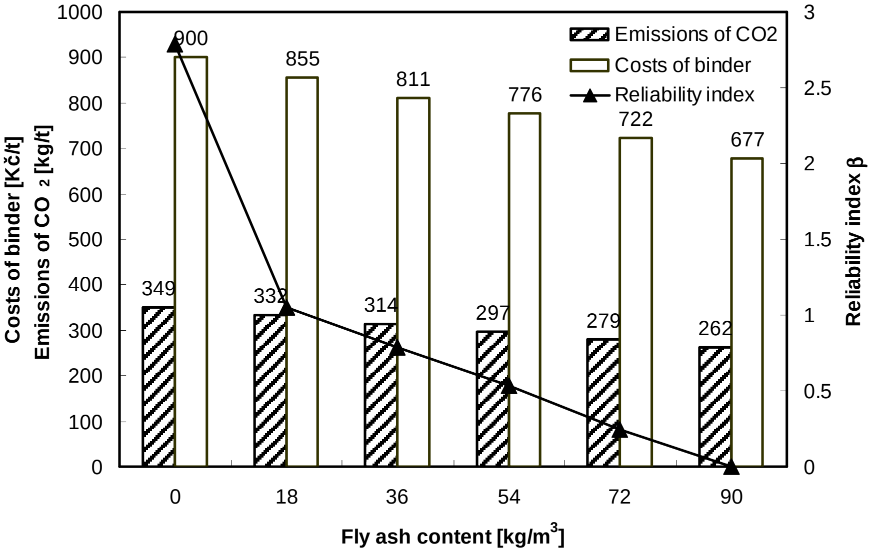

Fig. 1 Comparisons of reliability, emissions and costs for designed mixtures.

Example 3:

The study on the comparison of service life and ecological and economical aspects for different values of concrete cover has been performed. A reinforced concrete member made from concrete C20/25 (CEM I), exposition class XC3 (medium humidity: RH 75 %), and ambient CO_2 concentration N(800, 80) with concrete cover scaled from 25 to 40 mm has been suggested. The value of 25 mm was considered the basis for comparison, i.e. 100 %. The reliability index β has been kept at the constant value 1.3.

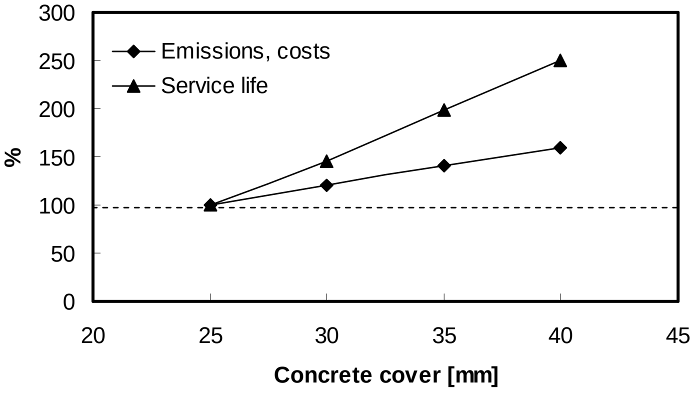

Fig. 2 Relative increase of costs, CO_2 emissions and relevant service life for constant β.

Again, the value of β represents the probability of carbonation depth reaching the reinforcement, i.e. the consideration of condition (1). The time, when $a = x_c(t)$, serves as a threshold of the depassivation of reinforcement and it is called the initiation time $t = t_{ini}$; it is often considered to be the service life.

From the results of this study shown on the **Fig. 2** it may be observed that the increase of service life due to cover increase is much more pronounced then the relevant increase of costs and emissions (about 1.6 times).

4 Conclusions

A relatively simple approach for emissions and economical load assessment, together with the reliability level of service life fulfillment has been presented. A study for different concrete mixes with fly ash addition is provided for illustrative purposes. The influence of other types of SCM may be assessed in similar way, too. This creates a basis for certain optimizations and balancing different performance indicators of the concrete structure and, in this respect, an advanced decision making at the design stage.

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