Concrete, Sustainability and Limit States

Concrete, Sustainability and Limit States

K Hrabová[1], B Teplý[1] and P Hájek[2]

[1] Brno University of Technology, Czech Republic
[1] Brno University of Technology, Czech Republic
[2] UCEEB, Czech Technical University in Prague, Czech Republic

kristyna.hrabova@usi.vutbr.cz, teply.b@fce.vutbr.cz, petr.hajek@fsv.cvut.cz

Abstract. Efficient sustainability management of concrete structures requires the use of tools which allow material, technological and construction variants to be quantified. The present contribution, apart from discussing the issue of sustainability of concrete structures, focuses on the quantification of concrete resistance to degradation. An indicator expressing quality, with regard to sustainability, is determined using information on concrete performance characteristics, service life and eco-costs, enabling the quantification and comparison of various cases. Cradle-to-gate system boundary and the full probability method are used. The aim is to propose a suitable methodology which can simplify decision-making about the design and choice of concrete mixes from a wider sustainability perspective, as an extensional and integrating approach to evaluating load-bearing capacity and durability. Two case studies of probabilistic sustainability quantification are shown using sustainability potential indicators for two different definitions of service life (due to carbonation of concrete and freeze/thaw effects), considering also the concrete performance's and impact on the environment.

1. Introduction

Sustainability approach is a key general principle to be considered in any human activity including design, construction process, operation, maintenance and repair of any structure – including any concrete structure. Concrete is the most common construction material in the world. Because of this, concrete puts a significant strain on the environment – especially in terms of CO_2 emissions. Nevertheless, since it indisputably possesses numerous advantages, there is little doubt that concrete will remain in use as a main construction material well into the future. It is thus evident that enhanced technologies and procedures for designing and/or assessing concrete structures need to be sought and developed.

General principles related to sustainability in civil engineering are described in ISO 15392 [1] – *Sustainability in building construction*. The purpose of sustainable design is to reduce the negative impacts and to improve the benefits for the society, environment and the economy. ISO 13315 [2], [3] *Environmental management for concrete and concrete structures*, aims to provide the basic rules on environmental management for concrete and concrete structures. The standard is meant to help with mitigating the environmental impacts resulting from concrete-related activities.

Sustainability is a rather complex subject that must be considered from the very beginning of construction. Webb and Ayyub [4] summarized definitions available in different contexts and introduced requirements and working sustainability definitions for constructions.

According to [1] sustainability measures consider three primary aspects (pillars): social, environmental and economic, pertaining to a relevant system boundary, i.e. cradle-to-grave. Two domains of definition can be utilized: general and construction. The first, general definitions include any definition that does not apply to a specific sector. They define sustainability in a rather broad context. The other domain – construction definitions – deal with more specific situations, e.g. with the sustainability of building structures. Also, sustainability metrics and indicators should be mentioned in this context. According to [4] construction-based indicators can be classified at the following levels:

- Scale: global, regional, national
- Country or organization
- Pillar: social, environmental, economic
- Aspect: materials, energy, water, air, financial, health or others
- Phase: design, construction, operation, maintenance, demolition. (Note the set of applied phases can determine the system boundary used).

There is a need for the implementation of sustainability criteria into a performance-based approach [5] which is currently at the centre of research all over the world, in particular in the activity of *fib* Commission 7 Sustainability [6], [7] and *fib* Commission 10 preparing Model Code 2020 with a focus on sustainability. In this context the issue of limit state has to be discussed as well and adjusted in a relevant way considering the design of reinforced concrete structures; it is closely related to sustainability assessment and its quantification. This approach can be utilised in the design and assessment of concrete mixes quite broadly, i.e. not only with regard to load-bearing capacity or durability, as is currently common in civil engineering.

The goal of the present paper is to propose a suitable decision-making methodology for working with concrete with special focus on sustainability aspects. It deals with material aspects during design and construction, analysing the sustainability of a concrete mix. The presented approach is based on Müller [8], [9], who described three sustainability pillars in terms of three quantities: performance, service life and environmental impact expressed in the form of the Building Material Sustainability Potential (BMSP). In a normalized form BMSP could be transformed into the indicator k_{SB} which enables quantification with respect to environmental conditions and the prospect of suffering degradation [10], [11], as shown further.

The paper presents examples of different concrete types which are subjected to different effects. Utilizing the sustainability indicators k_{SB} the sustainability level can be compared and quantified also within a fully probabilistic approach.

2. Limit state concept from the perspective of sustainability approach

The probability-based limit state (LS) design is a common approach in civil engineering practice today, and is described e.g. in the international documents ISO 2394, EN 1992-1-1 and *fib* Model Code 2010 [12]. The structural ultimate limit state (ULS) and serviceability limit state (SLS) are commonly utilized in current practice either as part of the semi probabilistic format (partial factor) or, in the fully probabilistic approach. Considering degradation effects, exposure conditions, and using ULS and/or SLS, the service life L can be assessed as well. This can be performed with a suitable model analysis of degradation effects with effective software tools [13], [14], which offers a number of different numerical degradation models in a probabilistic format, producing statistical, sensitivity and probability results. Generally the analysis is governed by a probability condition which in its general form reads:

$$P_f = P\left[A(t) \geq B(t)\right] < P_d \tag{1}$$

where P_d is the design probability (target, limiting, required), t is time, A is the effect of the action being analysed and B is the barrier. Generally, both A and B are time dependent and hence the probability of failure P_f is time dependent as well. The combined effect of both structural performance and ageing should be considered wherever relevant. Note the index of reliability β is frequently utilized in the practice of structural design instead of the probability of failure P_f – see e.g. ISO 2394.

Service life *L* is usually defined as a period of time after installation during which technical, functional or other requirements are met or exceeded. Different types of service life can be distinguished: the technical service life, functional, economical and aesthetic (or obsolescence) service life. However, when evaluating the sustainability of reinforced concrete structures it is advisable to work with the definition provided by the *fib* Model Code 2010. It describes service life (in years) using the relevant limit state (LS) and associated target level of reliability P_d. This expresses the technical service life, i.e. the design or remaining service life (depending on whether a new or existing structure is being evaluated). This type of limit state and the limit probability value are critical and in order to determine them it is necessary to model the degradation of materials over time or, less effectively, estimate the service life via the Factor method (ISO 15686) or by expert judgement.

The most commonly used concrete structure design today is performance-based according to *fib* Model Code 2010 [12]. Sustainable target value design can be briefly expressed as a comparison of sustainable capacity vs. sustainable impacts. This requires a new class of limit states – apart from engineering (or structural) ones, sustainability limit states have to be specified as well, as mentioned in [15] and also in *fib* Model Code 2010, where:

(i) Section 7.10.1.2 dealing with environmental performance reads "*... it shall be confined at the design stage that the environmental performance required for the structure is satisfied. This is undertaken using a Life Cycle Analysis. ... Verification: Environmental performance of a concrete structure shall be verified by confirming that the retained performance (R), defined by using appropriate indexes with regard to environment, is larger (or smaller) than the set value (S) of the relevant performance requirement.*" Note that environmental performance is also linked with e.g. global warming potential, ozone, emissions of acid-generating gases, eutrophication, waste storage, etc. Ecological criteria associated with evaluating the impacts of concrete-based structures on the environment include mainly: bound CO_2, SO_2, NO_x emissions, bound energy, the consumption of non-renewable resources, the consumption and pollution of water, waste, but also potential recyclability should be taken into consideration. Since only some of these components can be used for each of the many conceivable different cases thus only the influence of CO_2 is usually considered.

(ii) Social performance is described in a similar way in section 7.10.2.2: "*... the retained (social) performance (R)... regarding the impact on society is larger (or smaller) than the set value (S) of relevant performance requirement.*" In this respect, safety, serviceability and durability are also social aspects [16], [17]; i.e. parts of social responsibility (Life Cycle Social Performance, LCSP), and therefore SLS, ULS and L fall also into this category (albeit usually being understood and utilized as the basic criteria of safety and serviceability as well, i.e. engineering criteria according e.g. to fib Model Code 2010).

All these factors have to be verified when performing a life cycle analysis, i.e. by considering the entire life of the structure based on ISO 14040 [18]. A new, advanced *fib* Model Code 2020 is to be published in 2020 complete with an implementation of sustainability approach as is stated in [5]: "*MC2020 will take sustainability as a fundamental requirement, based upon a holistic treatment of societal needs and impacts, lifecycle costs, and environmental impacts.*" As for concrete structures specifically the future development of the sustainability approach, prospects and consequences are explained in more detail in [17].

The limit state approach is not yet commonly used for sustainability analysis and relevant limit states are not being employed in practice. A recent paper [15] discusses this, unfortunately only verbally without formulating relevant limit state equations. Such a limit state approach has to be based on the probabilistic approach combined with the life cycle approach considering a very broad and subjective sustainable development. It is a highly complex matter, as besides the construction LS, the sustainability LS (environmental and social) need to be addressed as well; it also comprises the main goal – to determine the global pollutant reduction targets which is mainly the role of policy-makers and environmental specialists. A wealth of literature dealing with this topic can be found elsewhere (see e.g. a concise text [19] and basic directory [6]). Analogous to structure failure probability, the probability that the cumulative impacts over the timeline of the construction and repair of a concrete structure do not meet the target reductions in cumulative impacts as compared to the status quo, the current cumulative impacts can be understood as a sort of sustainability limit state [20]. At the same time the service life and/or financial factors must be considered as well. Broadly speaking, an LS by which sustainability can be assessed has not yet been identified. All this greatly complicates the sustainability design of structures and places obstacles in practice. Civil engineering sorely needs tools for prioritization and decision-making.

It should be mentioned that a relatively large number of investigations all over the world have dealt with the multi-criteria evaluation of buildings or large structures and assessment of their sustainability. Analyses and assessment of sustainability, as a rule, are hampered by uncertainties which can usually devaluate the results and their applicability to a certain extent; moreover, methods, such as obtaining the opinion of a group of experts, are used, which can be rather time-consuming and costly. Therefore some simpler alternatives are sought, although they are only being utilized for more limited purposes, e.g. for aspects of material only. Also, environmental sustainability targets are often expressed as a reduction from baseline emissions and an achievement of reductions in environmental impact indicators as compared to the status quo design can likewise be applied. The probability of failing to meet a reduction goal by implementing an alternative design is discussed in [20] where a relevant limit state condition is presented. This example implies that only one sustainability pillar is involved (environment) in such an assessment; insufficiencies of this sort can be found quite often – e.g. durability is often left out of in sustainability studies [21].

3. Sustainability potential indicator

Considering the above described problems it might prove useful to focus attention first on the evaluation and comparison of simpler problems, however with sustainability defined in a complex way. A possible approach to making an approximate assessment of the sustainability potential could be based on the Building Material Sustainability Potential (BMSP) defined by Müller in Eq. (2) see [8], [22].

$$BMSP = \frac{performance \times servicelife}{environmentalimpact} = \frac{R \times L}{E} \tag{2}$$

Material sustainability (concrete specifically) can be quantified for practical purposes using all the material aspects together by normalized Eq. (2) in the form according to Eq. (3), thus creating a sustainability potential indicator k_{SB}. Quantities L (service life), R (performance) and E (eco-cost) are there divided by arbitrary reference values L_{ref}, R_{ref} and E_{ref}, thus leading to the dimensionless quantity k_{SB} whose value usually approximates 1.0.

$$k_{SB} = \frac{\frac{R}{R_{ref}} \cdot \frac{L}{L_{ref}}}{\frac{E}{E_{ref}}} \tag{3}$$

The authors of the present paper have been focusing on such sustainability quantification connected with the use of various types of concrete with regard to their resistance to degradation – e.g. [10], [11].

Note that all three pillars of sustainability are integrated in k_{SB} as both social and economic effects are associated (however partially indirectly) with service life and performance (limit levels of reliability measures and service life are, in relation with different conditions, stated in/required by standards). The environmental impact is expressed in the eco-costs (expenditures on measures to be taken so as to reduce environmental impacts to a sustainable level). The procedure can be improved further by using the probabilistic approach, i.e. by considering the input quantities L, R and E as random with known probability parameters and distribution, which produces output values of statistical parameters of k_{SB} and its probability distribution. The FReET-SB is used for this task; it enables the statistical and probability analysis of formula (3), (4) and it is a modification of the fully probabilistic tool FReET [13]. This also enables the evaluation of the probability P_{SB} with which a certain limit (acceptable) value of $k_{SB,lim}$ could be exceeded using the limit state equation

$$P_{SB} = \left[\left(k_{SB} - k_{SB,lim}\right) \leq 0\right] \leq Pd(t) \tag{4}$$

Both Eq. (3) and (4) might become useful in the design practice in near future as it is believed that tackling sustainability problems will become more important.

In Eq. (3) the performance *R* represents e.g. load-bearing capacity, deformability, resistance to degradation or other properties of the material. When analysing concrete mixtures using formula (3), it is often convenient for *R* to represent compressive strength. Eco-costs *E* (as mentioned above) are expenditures on measures to be taken so as to reduce environmental impacts to a sustainable level as explained e.g. in [23] and, in more detail, covered in various databases – e.g. the eco-cost database [24] and [25] where components of *E*, i.e. the individual elements (virtual pollution prevention costs, costs of energy, material depletion costs and some others), are listed. However, there is a whole range of other definitions of *E,* and political or local issues are often involved. When evaluating a sustainability potential indicator, service life is determined with regard to the given/chosen type of degradation or/and mechanical loading, and to exposure conditions. Numerical modelling is favourable; a number of models of several concrete degradation effects has been used, specifically the software tool FReET-D [13], [14], in agreement with *fib* Model Code 2010.

Aside from the evaluation and quantification of sustainability, it is also generally useful to carry out an economic comparison by comparing the cost of the individual implementations (concrete mixes). One way of performing this is having *R* only represent the acquisition costs of the case being evaluated (money = performance!) and omitting service life. Eq. (2) transforms into the form of a price-type BMSPe

$$BMSPe = \frac{R}{E} \tag{5}$$

This quantity can be used to compare individual variants in financial and environmental terms, if ecological cost is considered. Note equation (5) is simultaneously an inversion quantity for the "ERV indicator" (Eco-costs/Value Ratio) developed by Vogtländer et al. [23].

4. Comments about the Material Aspect implementation and examples

The above comments about limit states indicate that sustainability analyses of general aspects would require dealing with a number of limit states: structure (e.g. ULS, SLS), environmental and social type. Especially limit states of the last type are not commonly constructed; moreover, a consequence of the number of the limit states involved is the need to apply a multiobjective optimization tool, which is a labour intensive endeavour, although there are many examples in writings on LCA. The present paper concentrates on the sustainability analysis of concrete based on the material level, which is a simpler task. An effective comparison and selection can be achieved with the use of sustainability indicators related to the cradle-to-gate system boundary and analysed in the probability method. However, it should be mentioned there are also some obstacles involved:

Sustainability indicators (3) can be effectively applied as a sustainability measure for the purpose of comparing various concrete mixes under the condition that all cases in a given group of mixes must be considered as being subjected to the same type of exposure and the same deterministic reference values of L_{ref}, R_{ref} and E_{ref} have to be used. This probabilistic evaluation of sustainability of concrete mixes does not cover usage of the structure, repair or rehabilitation – it is merely a cradle-to-gate boundary condition system intended for the selection or optimization of cases of one group and considering their sustainability (note there is the exception of service life *L* which is supposed to proceed until "the grave"). Note, the applicability of Eq. (3) and (4) is limited, as the values of k_{SB} depend on arbitrarily chosen values of L_{ref}, R_{ref} and E_{ref}. Therefore the sustainability level of concretes in the studied group can be assessed according to the order of k_{SB}.

Two examples follow:

(i) Example from ISO 13315-4 [26], Annex C is discussed. The concrete structure presented in ISO (concrete A_1) is required to show a 30% reduction in CO_2, which is achieved by adjusting the formula to contain ground granulated blast furnace slag (concrete B_1) as shown in Table 1. The required reduction of CO_2 is met in this way; unfortunately without taking durability into consideration. The authors added the results of a service life analysis by modelling concrete carbonation, applying the FReET-D tool [12], option RC LifeTime, using the model created by Papadakis et al. [27]. The following input data were applied: exposition class XC3, 30 mm cover, k = 0.6, CO_2 concentration in the air is 820 [mg/m^3], RH = 75 % and reliability index β = 1.3. This analysis results in a value of service life which is approximately three times lower.

The resulting sustainability indicators assessed using Eq. (3) are shown in table 2; the resulting k_{SB} values indicate that the best choice from the point of view of sustainability is concrete A_1. This is evidently influenced by the differences in service life.

Table 1. Composition of mixtures

Components [kg/m^3]	A_1	B_1
CEM I 42.5 R	346	133
Ground granulated blast furnace slag	-	200
Water	173	150

Table 2. Concrete properties and the final values of indicators k_{SB}

Property	Concrete A_1			Concrete B_1		
	Mean	COV	Pdf	Mean	COV	Pdf
28-day cube strength [MPa]	45	0.06	Normal	42.75	0.06	Normal
Service life [years]	91	0.01	Normal	33	0.01	Normal
Eco-costs [€]	49.8	0.20	Rectangular	40.4	0.20	Rectangular
k_{SB}	1.04	0.23	Beta	0.45	0.22	Triangular

(ii) To show the effectiveness of Eq. (3) in sustainability assessment as well as its ability to distinguish differences between concrete mixes (SCMs) exposed to frost. In this case the common service life in years is replaced by a value determined for the amount of scaling ρ_a per 100 freeze-thaw cycles. When calculating k_{SB} this "non-traditional" quantity reads $L = 1/\rho_a$. Concrete mixtures A_2 to D_2 were analysed (adopted partially from [14]). Data from [28] were utilized for the frost effect. Table 4 lists the values of the resulting sustainability indicators and their statistical parameters.

Table 3. Composition of mixtures

Components [kg/m^3]	Concrete A_2	Concrete B_2	Concrete C_2	Concrete D_2
CEM I 42.5 R	389	301	301	301
Aggregate 0–4 mm	812	812	812	812
Aggregate 8–16 mm	910	910	910	910
Zeolite Zeobau 200	-	88	44	44
Fine-ground blast furnace slag	-	-	44	-
Fly ash	-	-	-	44
Microground limestone	-	-	-	-
Water	140	168	161	164

The resulting k_{SB} values (see Table 4) indicate that in terms of durability the best choice from the four concretes attacked by frost is concrete A_2.

Clearly, when the effect of other types of degradation and/or the effect of mechanical load on the service life are taken into account, the order of sustainability indicator values can change. This issue is at the focus of the authors' ongoing research.

Table 4. Concrete properties and the final values of indicators k_{SB}

Property	Concrete A_2			Concrete B_2			Concrete C_2			Concrete D_2		
	Mean	COV	Pdf	Mean	COV	Pdf	Mean	COV	Pdf	Mean	COV	Pdf
90-day cube compressive strength [MPa]	63	0.06	Normal	58	0.06	Normal	67	0.06	Normal	56	0.06	Normal
Scaling after 100 cycles [g/m^2] [28]	120	-	-	400	-	-	560	-	-	220	-	-
Eco-costs [€/m^3]	71	0.20	Rectangular	68.9	0.20	Rectangular	68.7	0.20	Rectangular	57.9	0.20	Rectangular
k_{SB}	1,04	0.29	Beta	0.30	0.25	Beta	0.28	0.26	Beta	0.55	0.27	Lognormal

5. Conclusion

The paper presents a tool for sustainability assessment, which enables the quantification of sustainability and the comparison of concrete mixture variants in this respect, with an emphasis on durability and CO_2 emission. It can be employed when making decisions in the production of concrete to understand the required properties. It utilises the cradle-to-gate system boundary and the fully probabilistic approach, dealing with simple equations in which service life, performance and environmental impact (expressed as eco-costs) are used to determine a sustainability indicator as a sustainability quantification measure. A software tool designed for this purpose is briefly introduced. The last section discusses two simple illustrative examples, considering two degradation effects – concrete carbonation and freeze/thaw cycles. The authors believe the proposed methodology can serve as a supporting policy-making tool for the cement industry.

Acknowledgement

This work has been supported by project No. 19-22708S supported by the Czech Science Foundation and by the Ministry of Education, Youth and Sports within National Sustainability Programme I (NPU I), project No. LO1605 – University Centre for Energy Efficient Buildings – Sustainability Phase.

References

[1] ISO 15392: 2008 *Sustainability in building construction – General principles*. International Organization for Standardization: Geneva Switzerland

[2] ISO 13315-1: 2012 *Environmental management for concrete and concrete structures, Part 1: General Principles,* International Organization for Standardization: Geneva Switzerland

[3] ISO 13315-2: 2014 *Environmental management for concrete and concrete structures Part 2: System boundary and inventory data.* International Organization for Standardization: Geneva Switzerland

[4] Webb D and Ayyub B M 2017 Sustainability quantification and valuation I and II. *ASCE-ASME J. Risk Uncertain. Eng. Syst.* Part A: Civil Engineering 3(3): E4016001 and E4016002

[5] Matthews S 2017 fib Model Code 2020 – A new development in structural codes *Structural Concrete Journal of the fib* 18(5) 651–2

[6] *fib* Bulletin 71. *Integrated Life Cycle Assessment of Concrete Structures*, ISBN 978-2-88394-111-3, *International Federation for Structural Concrete* (*fib*) (Lausanne Switzerland)

[7] *fib* Bulletin No. 67 2012 *Guidelines for green concrete structures, International Federation for Structural Concrete (fib)* (Lausanne Switzerland)

[8] Müller H S 2013 Sustainable structural concrete – from today´s approach to future challenge *Structural Concrete* **14 (4)** 299–300

[9] Müller H S, Haist M and Vogel M 2014 Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime *Constr.Build. Mater.* **67** 321–37

[10] Teplý B, Vymazal T and Rovnaníková P 2018 Methodology for the quantification of concrete sustainability ISBN 978-83-937864-2-8 *Polish Association of Civil Engineers and Technicians* (Opole, Poland)

[11] Teplý B, Rovnaníková P and Vymazal T 2018 Sustainability Quantification of Concrete Structures *Chapter in Advances in Environmental Research* vol 63 ed Justin A Daniels (NOVA Science Publishers, NY, USA) pp 231–48

[12] *fib* bulletin No. 65 and 66 *fib* Draft Model Code 2010 (2012) *International Federation for Structural Concrete* (*fib*) (Lausanne Switzerland)

[13] Novák D, Vořechovský M and Teplý B 2014 FReET – Software for the statistical and reliability analysis of engineering problems and FReET-D: Degradation Module *Adv. Eng. Softw.* 179–92

[14] Teplý B, Vořechovská D and Chromá M 2018[c] Probabilistic based models for material degradation processes, *Chapter 9 in fib Bulletin 86, International Federation for Structural Concrete* (*fib*) (Lausanne, Switzerland) p 205–38

[15] Geiker M, Michel A, Stang H, Vikan and Lepech MD 2019 Design and maintenance of concrete structures requires both engineering and sustainability limit states. *Life-Cycle Analysis and Assessment in Civil Engineering*: Towards an Integrated Vision (London)

[16] Hajek P, Fiala C and Kynclova M 2011. Life Cycle Assessment of Concrete Structures – Step towards Environmental Savings, *Structural Concrete* Journal of the fib **12(1)** ISSN 1464-4177

[17] Hájek P 2018 Contribution of concrete structures to sustainability – challenge for the future *IOP Conf. Series: Materials Science and Engineering* Volume 442 conference 1

[18] ISO 14040:2006 – Environmental management – *Life cycle assessment* – Principles and framework 2006 International Organization for Standardization: Geneva Switzerland.

[19] Favier A, De Wolf C, Schrivener K and Habert G 2018 A Sustainable Future for the European Cement and Croncrete Industry: *Technology assessment for full decarbonisation of the industry by 2050* 96

[20] Lepech MD, Geiker M, Michel A and Stang H 2016 Probabilistic design and management of sustainable concrete infrastructure using multi-physics service life models *1st Internal Confer on Grand Chellenges in Construction Materials IGCMAT*

[21] Tait MW and Cheung WM 2016 A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *Life Cycle Assess* 21:847–860

[22] Müller HS, Haist M, Moffatt JS and Vogel M 2017 Design, material properties and structural performance of sustainable concrete *Proceedia Eng.* 171 22–32

[23] Vogtländer J G, Brezet H C and Hendriks CH F 2000 The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. *Int. J. LCA* **3(6)** 157–66

[24] Eco Costs Data *Design-4-Sustainability*: Inspiration and knowledge by designers for designers [online] http://www.design-4-sustainability.com/ecocosts

[25] The Model of the Eco-costs / Value Ratio (EVR) [online] http://www.ecocostsvalue.com/

[26] ISO 13315-4 2017 Environmental management for concrete and concrete structures – Part 4: *Environmental design of concrete structures*

[27] Papadakis VG and Tsimas S 2002 Supplementary cementing materials in concrete Part I: Efficiency and design *Cement and Concrete Research* **32(10)** 1525–32

[28] Sedlmajer M, Hubáček A and Rovnaníková P 2014 Vlastnosti betonu s využitím přírodního zeolitu a běžně používaných příměsí do betonu In: *Sborník konference Technologie betonu, sekce B*: p 35-40 (in Czech) [Properties of concrete using natural zeolite and commonly used admixtures in concrete *Proceed conf on Technology of Concrete*, section B: p 35–40