International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:8, No:5, 2014

LCA and Multi-Criteria Analysis of Fly Ash Concrete Pavements

M. Ondova, A. Estokova

***Abstract*—**Rapid industrialization results in increased use of natural resources bring along serious ecological and environmental imbalance due to the dumping of industrial wastes. Principles of sustainable construction have to be accepted with regard to the consumption of natural resources and the production of harmful emissions. Cement is a great importance raw material in the building industry and today is its large amount used in the construction of concrete pavements. Concerning raw materials cost and producing CO_2 emission the replacing of cement in concrete mixtures with more sustainable materials is necessary. To reduce this environmental impact people all over the world are looking for a solution. Over a period of last ten years, the image of fly ash has completely been changed from a polluting waste to resource material and it can solve the major problems of cement use. Fly ash concretes are proposed as a potential approach for achieving substantial reductions in cement. It is known that it improves the workability of concrete, extends the life cycle of concrete roads, and reduces energy use and greenhouse gas as well as amount of coal combustion products that must be disposed in landfills.

Life cycle assessment also proved that a concrete pavement with fly ash cement replacement is considerably more environmentally friendly compared to standard concrete roads. In addition, fly ash is cheap raw material, and the costs saving are guaranteed. The strength properties, resistance to a frost or de-icing salts, which are important characteristics in the construction of concrete pavements, have reached the required standards as well. In terms of human health it can´t be stated that a concrete cover with fly ash could be dangerous compared with a cover without fly ash. Final Multi-criteria analysis also pointed that a concrete with fly ash is a clearly proper solution.

***Keywords*—**Life cycle assessment, fly ash, waste, concrete pavements.

I. Introduction

BUILDING materials were and are indispensable elements of each period. One of the most revolutionary of materials is especially the concrete. From unusual material in the nineteenth century, concrete became "the stone" of the twentieth. From construction elements to urban furniture, a large variety of concrete objects surround us nowadays [1]. Since more than 150 years, research on cement concrete have contributed to improve its mechanical (strength, durability) and casting (self-compacting.) characteristics [2]. However, environmental performances of concrete have only recently become a subject of concern. They are often improved by the incorporation of recycled industrial wastes in the mix-design, most recently [3], [4], without reducing the quality of the final product. Environmental impacts of cement production have been studied [5]-[7] because it requires high energy consumption and induces important greenhouse gas emissions.

It is known that cement production is one of the main pollution contributors. Sources of dust emission are mainly kiln, crusher, grinders, clinker cookers and material handling equipment. Crusher department is one of the major sources of environmental pollution. Fugitive dust emission, stack emission and noise have been identified as significant aspects during activities like receipt of limestone, primary crushing and screening. These significant aspects are imparting very much impact on the human health. Thus there arises a need for developing a strategy for reducing the impacts and this require more attention to be emphasized on the aspects [8].

The Portland cement manufacturing industry is under close scrutiny these days because of the large volumes of CO_2 emitted. Actually this industrial sector is thought to represent 5–7% of the total CO_2 emissions. Therefore, is implemented the evaluation of CO_2 emissions, energy consumption and other cement emissions such as SO_2 emissions using Life Cycle Assessment (LCA) method. This method refers to international standard and has been applied to the building sector since 1990 [9]. Currently, it belongs to a most used methodology of materials impact assessment to human health as well as to Environment.

Life cycle assessment involves the evaluation of some aspects – often the environmental aspects – of a product system through all stages of its life cycle. Sometimes also called „life cycle approach", „life cycle analysis", „Eco balance" or „cradle to grave analysis". It represents a rapidly emerging family of tools and techniques designed to help in environmental management and, longer term, in sustainable development [10]. Simply stated, the life cycle of a product embraces all of the activities that go into making, transporting, using and disposing of that product. The typical life cycle consists of a series of stages running from extraction of raw materials, through design and formulation, processing, manufacturing, packaging, distribution, use, re-use, recycling and, ultimately, waste disposal [11]. The term „product" refers to both goods and services [12]. LCA cannot (or at least should not) be used to claim that a particular product is environmentally friendly. At best it is only possible to say, using a specified set of criteria, that one product is better than another in certain aspects of its performance [11]. This method is an internationally standardized method (ISO 14040 and

M. Ondova is with the Technical University of Kosice, Faculty of Civil Engineering, Institute of Environmental Engineering, Department of Material Engineering, , Vysokoskolska 4, 042 00 Kosice, Slovakia (+421-55-602-4125; marcela.ondova@tuke.sk).

A. Estokova is with the Technical University of Kosice, Faculty of Civil Engineering, Institute of Environmental Engineering, Department of Material Engineering, , Vysokoskolska 4, 042 00 Kosice, Slovakia (+421-55-602-4265; adriana.estokova@tuke.sk).

14044) that can provide a rigorous approach for improving decision support in environmental management. ISO 14040 and 14044 address not only the technical, but also the organizational aspects of LCA, such as stakeholder involvement and independent critical review of studies. Methodological aspects specify the general principles and requirements for conducting an LCA [13].

The LCA process is a systematic, phased approach and consists of four phase:

- Goal and scope definition (ISO 14041) - here are explained the reasons behind the study, the intended application of the study, and the intended audience of the study. This is also the phase in which the system boundaries of the study are described and functional unit is defined (the functional unit being a quantitative measure of the functions that the product in question provides).
- Life Cycle Inventory Analysis (LCI), (ISO 14041) – in this phase of the study, a list is compiled of the inputs (resources) and outputs (emissions) from the product in question. This list considers the inputs and outputs of the product over its life cycle in relation to the functional unit.
- Life Cycle Impact Assessment (LCIA), (ISO 14042) – the goal is to understand and evaluate the magnitude and significance of the potential environmental impacts of the studied system. The impact categories are selected in order to describe the impacts caused by the considered products or product systems.
- Interpretation (ISO 14043) – is a phase, where results from the previous phases are evaluated in order to reach conclusions and recommendations [14].

Aim of our paper is assessment and comparison of two type of concrete road: concrete road with 15% wt. fly ash of cement component and standard type of road, which were assessed through methods: LCA and Multi-criteria analyses (MA1, MA2), where the decision in the theory of multi-criteria analysis means to select one or more variants from the set of acceptable variants and to recommend them to implement. The decision maker should proceed as objectively as possible, when selecting variants. For this he uses different procedures and methods to analyze variants. In the models of multi-criteria analysis of variants is given a finite set of m variants which are evaluated by n criteria. The aim is to find a variant, which is rated the best according to all criterions, eventually to arrange variants from best to worst, or to eliminate inefficient variants. The criteria by which the best variant is chosen are divided according to different aspects. According to the nature of the criteria we distinguish between:

- maximization criteria (best variants - highest values),
- minimization criteria (best variants - lowest values).

For the solution of the problem, it is very important, whether some criterion is preferred over another. Preference of criteria can be expressed in different ways, e.g. aspiration levels of criteria, ranking criteria (ordinal information on the criteria), and weights of individual criteria (cardinal information on the criteria) and compensation method of criterion values [15]. Multi-criteria evaluation methods can be classified according to the calculation principle which is used by methods, for example benefit maximization, minimizing the distance from the ideal variant, etc. For this work, four methods were selected:

- Weighted Sum Approach (WSA) - Weighted sum method is based on the principle of maximizing benefit. Variant, which reaches a maximum value of benefit, is selected as the best; but it is also possible to sort variants by decreasing value of benefit.
- Ideal Points Analysis (IPA) - This is actually the WSA method with a slight modification, thus achieving changes in the list of variants so that the value with the lowest benefit is the best, and vice-versa.
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) - This is the principle of minimizing the distance from the ideal variant. The ideal variant is the variant for which all values of criteria reach the best values. The ideal variant is mostly hypothetical. The best variant is selected the one, which is according to some metrics closest to the ideal variant.
- Concordance Discordance Analysis (CDA) - The Concordance Discordance Analysis is a widely used method in multi-criteria analysis. This method is based on the comparison of alternatives of choices in pairs and measures the degree to which alternative selection and weights factor confirms or refutes the mutual ratio between alternatives [16].

II. Materials and Methods

Experiments were based on European Standards (EN 13877-1;-2), which determine rather general conditions for materials and methods of properties evaluation, but in many ways they refer to national standards. The national standards for concrete pavements are in place. ES´s do not cancel but only partly modify them. The materials selection for experimental works, as well as testing the contribution of fly ash to quality of road concrete was performed in the terms of national standard requirements for roads of classes I – II (motorways, international roadways, parking areas). A lot of expert studies were taken into consideration; however national conditions should be respected not only in the terms of technical requirements, but also due to specific parameters of fly ash. It is well known, that properties of fly ash vary significantly and strongly depend on coal quality, conditions of combustion etc. [17].

For purposes of life cycle assessment and testing required qualitative parameters of concrete, the concrete samples were prepared with and without fly ash proportion. In accordance to the proposed prescription (grade concrete: C30/37) special kind of Portland cement CEM I 42.5 N, w/c was 0.36 and natural gravel aggregate in specific ratio of the fine to coarse aggregate 40 (0/4): 10 (4/8): 50 (8/16, 16/32) was used in the mixture [18]. In the context of studying the reduction of environmental impact through the use of secondary raw materials, the comparative samples were prepared with 15% wt. fly ash from brown coal combustion as cement replacement; other components of the prescription were unchanged. It is known that fly ash used in the experiments meets the requirements according to the STN EN 450 – Fly ash into the concrete.

Methods of evaluation were divided into four steps according to criteria of LCA.

A. Goal and Scope Definition

In this section, subjects of evaluation (fly ash concrete - FAC and standard concrete – SC roads) as well as the functional unit of LCA ($1m^3$f.c.) have been determined. System boundaries were selected from "cradle to grave" and determined to 4 areas (Fig. 1). Qualitative, environmental, economic and health-hazardous parameters were monitored in every area of life cycle (extraction – production – use – demolition). Impact of machines production and other used facilities in various processes, the use of demolition products, and effects of demolition products during the period of landfill as well as the assessment of mixing water were not included in the system boundaries.

Fig. 1 Specification of evaluated areas of Life cycle assessment

B. Life Cycle Inventory Analysis

Due existent information applicable to Slovak conditions were inventory data for the production of aggregates, chemical additives, manufacturing and demolition of concrete taken from the available literature sources on the LCA analysis of concrete [19]. For cement production data was used from the Czech catalog of building products and the impact of their production on the environment [20]. Data on emissions of transport and energy consumption have been obtained from the Network for Transport and Environment and literature [21]. Characterization factors for conversion of individual issues on categories of environmental impacts have been drawn from the database CML - IA. Due to lack of data for the production of aeration additives were used the same data as for the production of plasticizers. Price data were obtained on the basis of communication with building practice or existing price lists of individual companies. Formula for the production of concrete cover solved types differs only in the amounts of cement and fly ash. Whereas for the production of Portland cement have been available quantified environmental impacts, have added to the calculation of the final production stage.

Transport distance and mode of transportation of the individual materials within the development of the analysis were derived from the real construction of concrete cover at Mengusovce (Slovak republic). Because the goal of the analysis was to approach the most realistic outcome for all forms of transport was considered a full load vehicle, while it was necessary to consider the amount of materials needed for one cubic meter of concrete in accordance with formula (processing analysis of emissions and power consumption of the fly ash (15 %) multiplied by 1/6 and cement (85 %) 5/6 due to their dosage in concrete).

C. Life Cycle Impact Assessment

The following impact categories were considered for this study:

Primary energy intensity (PEI) – the primary energy content is called energy consumed during manufacturing of product. It is derived accounting for both renewable and non-renewable sources of energy [22].

Global warming potential (GWP) – in the LCA methodologies the potential global warming or greenhouse effect is quantified by using global warming potentials for substances having the same effect as CO_2 in reflection of heat radiation. GWP for greenhouse gases are expressed as CO_2 equivalents, i.e. the effects are expressed relatively to the effect of CO_2 [23]–[25].

Ozone Depletion Potential (ODP) – the potential depletion of stratospheric ozone is quantified by using ozone depletion potentials (ODP) for substances having the same effect as CFC's. The ODP describes the ozone depletion potential from a substance relative to CFC-11. It is one of the substances having the largest effect on ozone depletion [23].

Photochemical Ozone Creation Potential (POCP) – generally presented as a relative value where the amount of ozone produced from a certain VOC (Volatile organic compound) is divided by the amount of ozone produced from an equally large emission of ethene. The unit of POCP is grams of ethane equivalents per gram of gas (g C_2H_4/g VOC). Ethene has been chosen as a reference gas as it is one of the most potent ozone precursors of all VOC's [23].

Acidification Potential (AP) – acidification occurs primarily through the reaction of nitrogen oxides (NO_x) and sulphur dioxide with other components in the air such as hydroxyl (radical). The Acidification Potential is a measure of the tendency of component to become acidified [22].

Nutrification Potential (NP) – defined as the potential to cause over-fertilisation of water and soil, which can result in increased growth of biomass. Nutrification potential is expressed relative to PO_4^{3-} [26].

D. Interpretation

In interpretation phase, the results of both obtained LCA were compared with each other in each area. Great emphasis was placed primarily on environmental impact.

However, to obtain the resulting opinion there was a need to objectively evaluate and compare the processed analysis for each parameter (qualitative - technical, environmental, economic and health-hazardous parameters) separately. Two multi-criteria analyses (MA1 and MA2) were processed using program MCA7 for this purpose. Fuller triangle method was used to determine the weights of individual criteria for analysis of MA1. The principle of this method is gradual comparing pair – wise each criterion with each of the others. For MA2, the Saaty method was used, which is based on the continuous comparison of two criteria, while numerically expresses ratio of their importance. We have evaluated the environmental and economic criteria, parameters of strength and durability of concrete and parameters of harmfulness to human health. For MA1, environmental impacts have been preferred; the relative importance of each criterion has been assigned based on subjective view. Because of the objectification of results obtained in MA2, the same weights of importance were assigned to the environmental impacts by the same way, as to the parameters of strength and durability [27].

Within the analysis MA1 and MA2, 14 criteria (environmental impact: GWP, AP, PEI, POCP, ODP and NP; economic benefits: raw material cost, costs of silo; health-hazardous parameters: Gamma index I_γ, Cr^{VI}; technical/ qualitative parameters: frost resistance index, de-icing salts resistance, compressive strength and flexural strength) were assessed in two versions (FAC and SC).

Results and Discussion

The partial results of analyzes divided into the areas are presented in Tables I-IV. Under "extraction" phase (Table I) there are some values for FA concrete assessed as zero. It is because the fly ash is considered to be waste material and does not need to purposefully obtain it.

TABLE I
$CaO{\bullet}SiO_2$), 5 - 75 kg ($Ca{\bullet}Mg(CO_3)_2$), 6 - 50 kg ($CaCO_3$).
LIFE CYCLE ASSESSMENT OF "EXTRACTION" PHASE

Assessed area	Assessed parameters	Unit	FA / FAC	SC
Production cost	Raw material costs[1]	€/t	21	130.8
	Costs of FA modification	€/t	*	0
Hazardous elements	Radioactivity: ^{226}Ra	Bq/kg	0	13.08
	^{232}Th	Bq/kg	0	19.84
	^{40}K	Bq/kg	0	169.2
	Gamma index Iγ	-	0	0.198
	$Cr^{(VI)}$	mg/kg	0	2.46
Environmental impact	GWP	kg CO_2 ekv./kg	0	0.82
	AP	kg SO_2 ekv./kg	0	1.2 E-03
	PEI	MJ/kg	0	3.598
	POCP	kg C_2H_4 ekv./kg	0	4.3E-05
	ODP	kg CFC-11 ekv./kg	0	2.33E-08
	NP	kg$(PO_4)^{-3}$ekv./kg	0	2.6E-04

The big price difference between fly ash and cement is interesting in the first phase of the life cycle especially. Low costs per ton in case of fly ash include the certification and transport intended for the distance of 208 km to a concrete plant. The price for the adjustment of characteristics was not found out, but in this case it is irrelevant, forasmuch as fly ash with an inappropriate characteristic cannot be used for a cement-concrete pavement. The specific characteristics (radioactivity, Cr^{VI}) are considered having no value in this phase, because the intention was to highlight that the fly ash itself is not produced [28].

Table II defines the results of phase "production". The transport costs were calculated in this phase. In this case the transport by a truck is the same for both types of concrete. However, the silo cost is considered as double in the case of the concrete production with fly ash, as it needs to be stored in a separate silo. It is necessary to have a separate silo for cement and fly ash, it is merely investment cost. By modeling the costs in this phase it was found out that the optimal transport distance of fly ash, with regard on environmental impacts, is up to 426 km. For the major part of the Slovak Republic this alternative production of concrete covers is the more environmentally suitable and as can be seen, most of the partial results are evaluated in favor of fly ash concrete.

TABLE II
LIFE CYCLE ASSESSMENT OF "PRODUCTION" PHASE

Assessed area	Assessed parameters	Unit	FAC	SC
Hazardous elements	^{226}Ra	Bq/kg	39.26	-
	^{232}Th	Bq/kg	10.144	-
	^{40}K	Bq/kg	698.17	-
	Gamma index Iγ	-	0.411	-
	$Cr^{(VI)}$	mg/kg	0.03	
Environmental impact	GWP	kg CO_2 ekv./kg	1456.9	1551.47
	AP	kg SO_2 ekv./kg	2.79	2.95
	PEI	MJ/kg	2502.24	2765.82
	POCP	kg C_2H_4 ekv./kg	0.18	0.19
	ODP	kg CFC-11 ekv./kg	8.39E-06	9.83E-06
	NP	kg$(PO_4)^{-3}$ekv./kg	0.7	0.74
Transport and storage	Transport costs	€/(t.km)	2.71	2.71
	Optimal distance	km	426	0
	Containers	€	30000	15000

The durability and strength of the concrete were considered in the third phase, but the results were compared with the standard requirements only, and not with each other. In the final stage it was found out that the price for landfilling and recycling of concrete are not different. On the face of it the price for landfilling of raw material is negative for fly ash. However, the fly ash is intended for a concrete production (not storing in a landfill) and the price is informative only. However, based on the results presented in Tables III and IV it is evident that only insignificant differences were observed in both alternatives. The better values are still possible attributed to fly ash concrete [28].

[1] Fly ash costs including the certification and transport costs.

TABLE III
LIFE CYCLE ASSESSMENT OF "APPLICATION" PHASE

Assessed area	Assessed parameters	Unit	FAC	SC
Quality of concrete	Frost resistance	%	0.88	0.92
	De-icing salts resistance	g/m^2	557	47.6
	Compressive strength	MPa	40.2	42.5
	Flexural strength	MPa	6	6.9
Hazardous elements	Radioactivity: ^{226}Ra	Bq/kg	6.46	8.61
	^{232}Th	Bq/kg	24.93	22.26
	^{40}K	Bq/kg	199.41	397.18
	Gamma index Iγ	-	0.14	0.14
	$Cr^{(VI)}$	mg/kg	0.05	0.07
Environmental impact	GWP	kg CO_2 ekv./kg	104.18	104.18
	AP	kg SO_2 ekv./g	0.2	0.2
	PEI	MJ/kg	46	46
	POCP	kg C_2H_4 ekv./kg	0.011	0.011
	ODP	kg CFC-11 ekv./kg	0	0
	NP	kg$(PO_4)^{-3}$ekv./kg	0.053	0.053

TABLE IV
LIFE CYCLE ASSESSMENT OF "DISPOSAL/RECYCLING" PHASE

Assessed area	Assessed parameters	Unit	FAC	SC
Concrete recovery	Concrete recovery costs	€	12.61	12.61
Concrete disposal	Concrete disposal costs	€	12.4	12.4
	Fly ash disposal costs	€	31.7	0
Environmental impact	GWP	kg CO_2 ekv./kg	106.8	106.9
	AP	kg SO_2 ekv./g	0.21	0.21
	PEI	MJ/kg	62.22	62.72
	POCP	kg C_2H_4 ekv./kg	0,.011	0.011
	NP	kg$(PO_4)^{-3}$ekv./kg	0.053	0.054

Results obtained after including all evaluated areas are presented in Table V. Subsequently, values were recalculated and their absolute values were final normalized to concrete road of 1m (length) x 4m (width). Concluding results the optimized fly ash concrete road pavement were as follows: GWP values 42.5xE4 kg CO_2eq; PEI: 66.6xE4 MJ; AP: 819.71 kg SO_2eq; ODP: 2.14E-3 kg CFC-11eq; POCP: 48.52 kg C_2H_2eq, and NP: 206.84 kg $(PO_4)^{-3}$eq. In comparison with standard concrete road, the results values were reduced by 5-7% on the average. It should be noted that the final differences are not already insignificant as in the case of results of partial sections and the final results are presented in favor of using FA concrete and can be seen significant benefits already at its using as 15% of cement substitution in concrete.

TABLE V
LIFE CYCLE ASSESSMENT – TOTAL ENVIRONMENTAL IMPACT

Assessed parameters	Unit	Fly ash concrete	Standard concrete
GWP	kg CO_2 ekv./kg	1667.96	1762.55
AP	kg SO_2 ekv./g	3.2	3.4
PEI	MJ/kg	2610.46	2874.5
POCP	kg C_2H_4 ekv./kg	0.199	0.208
ODP	kg CFC-11 ekv./kg	8.398E-06	9.830E-06
NP	kg$(PO_4)^{-3}$ekv./kg	0.811	0.851

Figs. 2 and 3 present the results of the final multi-criteria analysis MA1 and MA2 for evaluated concrete variants (FA concrete and standard concrete).

FA concrete was identified being more suitable variant within both subjective MA1 (subjective assessment of weight setting, where the greatest weight has been assigned the environmental impact, especially PEI and GWP) and objective (MA2) assessment methods.

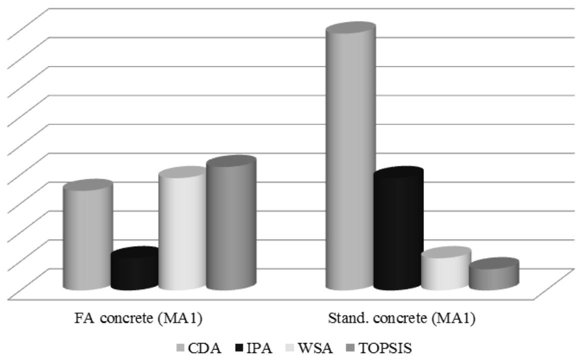

Fig. 2 Results of Multi-criteria analysis MA1

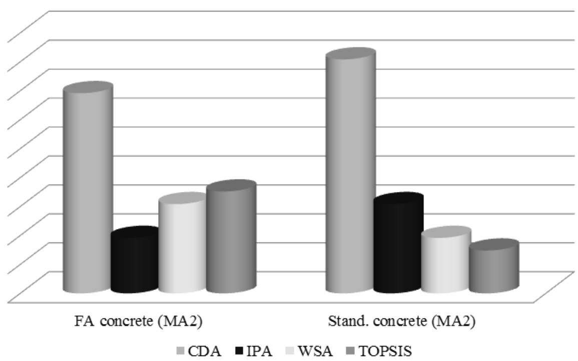

Fig. 3 Results of Multi-criteria analysis MA2

Weighting (MA 1; MA2) confirmed the results of LCA of selected variants and besides reduced environmental impacts through the concrete road pavement with a proportion of fly ash also showed number of the other benefits necessary in the construction.

III. Conclusion

The LCA proved that a concrete road pavement with a 15% fly ash replacement is more environmentally friendly compared to standard concrete roads. In addition, fly ash is cheap raw material, and the costs saving are guaranteed. Other properties obtained of previous research: strength, frost resistance, de-icing salts resistance, which are important characteristics in the construction of concrete pavements, have reached the required standards as well. In terms of human health it cannot be stated that a concrete cover with fly ash could be dangerous compared with a cover without fly ash. Multi-criteria analyses MA2 of all monitored parameters pointed that a concrete with fly ash is a proper solution. In regard to the positive results of research and a fact that the construction and reconstruction of the Slovak roads and highways are currently in progress and in view of the continuous depletion of natural resources, the use of fly ash in concrete roads seems to be highly advanced solution.

Acknowledgment

This research has been carried out in terms of the project VEGA (scientific grant agency of the Ministry of Education of the Slovak Republic and of Slovak Academy of Sciences) no. 1/0481/13 Study of selected environmental impacts of building materials.

References

[1] A.Sicakova, J. Sliwinski, I. Hager, T. Tracz, T. Zdeb, T. Zych, R. Hela, L. Bodnarova, *New generation cement concretes: ideas, design, technology and applications*. Slovakia, Kosice: Technical University, 2008.

[2] B., Cazacliu, A. Ventura, "Technical and environmental effects of concrete production: dry batch versus central mixed plant," *Journal of Cleaner Production*, vol. 18, pp. 1320–1327, 2010.

[3] A. Polettini, R. Pomi, E. Fortuna, "Chemical activation in view of MSWI bottom ash recycling in cement-based systems," *Journal of Hazardous Materials*, vol. 162, pp. 1292–1299, 2009.

[4] T. Bashar, G. Nounu, "Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement," *Construction and Building Materials*, vol. 22, pp. 713–720, 2008.

[5] A. Josa, A. Aguado, A. Cardim, E. Byars, "Comparative analysis of the life cycle impact assessment of available cement inventories in the EU," *Cement and Concrete Research*, vol. 37, pp. 781–788, 2007.

[6] C. Pade, M. Guimaraes, "The CO_2 uptake of concrete in a 100 year perspective," *Cement and Concrete Research*, vol. 37, pp. 1348–1356, 2007.

[7] D. N. Huntzinger, T. Eatmon, "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies," *Journal of Cleaner Production*, vol. 17, pp 668–675, 2009.

[8] J. K. Tiwari, A. M. Rawani, "Environmental impact analysis: a case study of acc cement plant," *Journal of Environmental Research And Development*, vol. 7 (no. 2), pp. 802–808, 2012.

[9] J.A. Fava, "Will the next 10 years be asproductive inadvancing lifecycle approaches as the last 15 years?" *International Journal of Life Cycle Assessment*, vol. 11, pp. 6–8, 2006.

[10] M. Culakova, E. B. Kridlova, S. Vilcekova, J. Katunska, "Reduction of carbon footprint of building." *Chemical engineering transactions*, vol. 29 (no. 1), pp. 199–204, 2012.

[11] M. Hauschild, H. Wenzel, *Environmental Assessment of Products*. London: Chapman & Hall, 1998.

[12] C. Benoit et al., *Guidelines for social life cycle assessment of products: a social and socio-economic LCA code of practice complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development*. Paris: United Nations Environment Program, 2009.

[13] European Commission. *Supporting Environmentally Sound Decisions for Waste Management – A technical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners*. Luxembourg: Publications Office of the European Union, 2011.

[14] G. Finnveden, "Life cycle assessment [online]". [cited 12 March 2014]. Available: http://www.eoearth.org/view/article/1542442010.

[15] M. Houska, "Multi-critarial analysis" [online]. Education materials of ZIP project. [cited 12 March 2014]. Available from Internet: http://etext.czu.cz/php/skripta/skriptum.php?titul_key=79 (in Czech).

[16] P. Korviny, "Theoretical basis of multi-criteria decision [online]". [cited 12 March 2014]. Available from Internet: http://korviny.cz/mca7/soubory/teorie_mca.pdf (in Czech).

[17] M. Ondova, N. Stevulova, "Benefits of coal fly ash utilization in the area of a pavement building," in *Proc. of the 8th International Conference Environmental Engineering*, Vilnius, Lithuania, 2011, pp. 1156–1159.

[18] M. Ondova, N. Stevulova, A. Estokova, "The Study of the Properties of Fly Ash Based Concrete Composites with Various Chemical Admixtures," in *Procedia Engineering*, vol. 42, 2012, pp. 2044-2054.

[19] J. Sjunnesson, *Life Cycle Assessment of Concrete*. Lund: Lunds Tekniska Högskola, 2005.

[20] J. Hodkova et al., "Catalog of Materials - Cement Portland 42,5 [online]". [cited 12 March 2014]. Available from <http://envimat.cz/materialy/sypke-materialy/cement-portlandsky-42-5.html>

[21] B. Berge, *The Ecology of Building Materials*. UK: Elsevier Ltd., 2009.

[22] Information on building components [online]. [cited 12 March 2014]. Available from Internet: http://www.dataholz.at/en/bauteil_info.htm

[23] H. K., Stranddorf, L. Hoffmann, A. Schmidt, *Update on impact categories, normalization and weighting in LCA*, Danish EPA, 2005.

[24] A. Estokova, M. Porhincak, R. Ruzbacky, "Minimization of CO_2 emisions and primal energy by building materials´ environmental evaluation and optimalization," *Chemical Engineering Transactions*, vol. 25, pp. 1–6, 2011.

[25] A. Estokova, M. Porhincak, "Reduction of Primary Energy and CO_2 Emissions Through Selection and Environmental Evaluation of Building Materials," *Theoretical Foundations of Chemical Engineering*, vol. 46 (no. 6), pp. 704–712, 2012.

[26] A. Azapagic, A. Emsley, I. Hamerton, *Polymers, the environment and sustainable development*. UK: John Wiley & Sons, Ltd., 2003.

[27] L. Meciarova, *Findings of environmental impact of concretes prepared with a share of fly ash in terms of assessing basic factors of their life cycle*. Slovakia, Kosice: Technical University, 2013 (in Slovak).

[28] M. Ondova, N. Stevulova, *Slovak fly ash as cement substitution in the concrete road pavements*. Saarbrücken: Verlag, 2013.