ASSESSMENT OF SELECTED INDICATORS OF PORTLAND CEMENT CONTAINING FLY ASH IN ROAD CONCRETE

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Abstract: Concrete is traditionally made with Portland cement, a powdery substance made of ground clinker, calcium sulfate, and other minor additives. Clinker production is energy consuming process. Fly ash, which largely consists of SiO_2 and CO, can be used as a substitute for Portland cement, or as a supplement to it. Moreover, fly ash utilization plays an important role in environmentally clean and cost effective power generation. The aim of this paper is the study of the physical-mechanical properties of hardened fly ash - concrete composites with various proportions of fly ash as well as to economic and environmental impact of its using in building industry. The results show that the using of fly ash in road concrete production seems to be the best solution to reducing consumption of cement including environmental and economic aspects.

Keywords: fly ash, road concrete, cement, secondary raw materials, compressive strength, flexural strength.

1 Introduction

Industrial utilization of fly ash from coal combustion is an important environmental and economic issue. Disposal of fly ash, e.g. in a landfill, enhances the risk of contamination the ground water by leaching of heavy metals contained in the fly ash (Pedersen, K.H. et al., 2008; Hall, M.L. & Livingston, W.R., 2002). In addition, the high taxes on landfill increase the motivation to reuse fly ash (Gieré, R. et al, 2003). Today, the primary market for fly ash utilization is as pozzolanic additive in the production of concrete (Environmental assessment report no. 10, 2003). Concrete is traditionally made with Portland cement, a powdery substance made of ground clinker, calcium sulfate, and other minor additives. Clinker is a material usually made of limestone and minerals, which are crushed and ground together, then heated. Calcium sulfate is added, and the clinker is ground into cement powder. The process requires a large amount of energy; it has a huge carbon footprint, and accounts for approximately 7% to 8% of carbon dioxide emitted every year. Fly ash, which largely consists of silicon dioxide and calcium oxide, can be used as a substitute for Portland cement, or as a supplement to it. The components from fly ash consists of are pozzolanic, meaning that they can be used to bind — or cement — materials together. Pozzolanic materials, including fly ash cement, add durability and strength to concrete.

Fly ash cement is also known as green concrete. It binds the toxic chemicals that are present in the fly ash in a way that should prevent them from contaminating natural resources. Using these supplementary cementing materials in concrete pavement has several environmental benefits. First, recovering of industrial byproducts reduces the consumption of virgin materials needed for cement manufacturing. Additionally, beneficial utilization reduces the amount disposed in landfills. However, the greenhouse gas and energy reductions achievable by using SCMs (Supplementary Cementitious Materials) to replace a portion of Portland cement are more important. CO2 and energy savings are related to the percentage of SCM used in the concrete mixture design. Lot of highway government agencies in other countries allow up to 25% of Portland cement to be replaced with fly ash and 50% to be replaced with slag cement; some states even allow higher SCM replacement levels (Rafalowski, M., 2003).

Using fly ashes in road concrete brings following benefits (Green Highways, 2007; Bačíková, M. & Števulová, 2007; Krličková, E., 1998): higher ultimate strength, improved workability, reduced bleeding, reduced heat of hydration, reduced permeability, increased resistance to sulfate attack, increased resistance to alkali-silica reactivity (ASR), lowered costs, reduced shrinkage, increased durability, resistance to traffic load, resistance to pergelation.

Care should be taken when using fly ash in concrete due to: potential for decreased air entraining ability with high carbon fly ash may reduce durability, reduced early strength, reduced heat of hydration in colder climates.

2 Materials and Methods

Experimental works were based on standards (EN 13 877 Part1 & 2). These European standards have only determined 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), given in table 1. Also lots 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. (Števulová, N. et al, 2012).

Table 1 Tested parameters and values required for road concrete (roads of classes I- II)

Properties	Method	Required value
Consistency of fresh concrete	Slump test	S1 (10-40 mm)
Air content in fresh concrete	Pressure method	4 - 8%
Fresh concrete temperature	Just after mixing	+ 5 °C ≤ T ≤ + 30 °C
Compressive strength	7, 28 and 90 days	32 MPa (in 28 days)
Flexural strength	7, 28 and 90 days	4.5 MPa (in 28 days)
De-icing salts resistance	150 freezing-thawing cycles	max. 300 g/m^2 /100 [1)]
Frost resistance	300 freezing-thawing cycles	min 0.85 [2)]

Note: [1]Rate of destruction/minimal number of cycles. Rate of destruction is expressed by scaling of tested concrete [g/m^2]; [2]Frost index - rate of flexural strength before and after freezing-thawing cycles.

In accordance to the proposed prescription, the C30/37 grade concrete made with 0 - 15% fly ash (class C - properties of FA are presented in Table 2) replacement of special kind of Portland cement CEM I 42,5 N. Water cementations material ratio was 0.36 and natural gravel aggregate from stone – pit Soporna and Hanisberk in specific ratio of the fine to coarse aggregate 40 (0/4): 10 (4/8): 50 (8/16, 16/32) was used in mixture.

Table 2 Chemical compositions of fly ash

Component [wt. %]							
SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O
37.5	15.60	7.67	1.30	22.94	2.77	1.21	0.63
MnO	P_2O_5	SO_3 (S)	S_{total}	*LOD	*LOI	*C.Sub.	*ROC
0.11	0.18	7.29 (2.91)	2.91	0.16	2.59	2.14	0.28

*Loss of drying (LOD), Loss of ignition (LOI), Combustible substances: 830 °C (C.Sub.), Residual organic carbon (ROC).

The mixtures were prepared in the laboratory mixer type ZZ 150 SH with horizontal rotary drum of 150 l capacity. Four based properties of fresh concrete: consistence, air content and temperature (EN 206-1: 2002) before the forms filing were tested according to EN 12350 (parts 3 and 7). The forms filling (the cube form with size 150 mm and the prism form with size 100 × 100 × 400 mm) were performed in two layers. Each layer was compacted on the vibration plate VSB 40 for 8 seconds. Next day the composites were taken out of the forms and saved in the water bath. 144 pieces of testing composite were cured at temperature 20 ± 2 °C. After 7, 28 and 90 days of hardening the composites were taken out of the water bath and tested for the required properties for class of concrete C 30/37 (table 1) - the composites were tested on compressive strength (CS), flexural strength (FS), determination of concrete chemical substance resistance (STN 73 1326, STN 73 6123) as well as on freezing and thawing. For the comparative study the reference sample (RS) concrete class (C 30 / 37) was prepared in accordance with requirements of Technical standards STN 73 6123 –Road Construction. Cement Concrete Pavements. Wearing Courses.

In order to meet the strict criteria of Slovak technical legislation for using of alternative materials in constructions our study was designed with 15% fly ash replacement of cement in the concrete. The Slovak cost price calculation software CENKROS was used to demonstrate the benefit of fly ash utilization. CENKROS is software for measurement and quality control of building production. This system covers all activities associated with the preparation and execution of the contract. It allows you to prepare a quality bid quickly, to calculate costs of using the effective utilization and billing of the work performed, and to prepare price estimates by financial indicators. The expected cost saving was calculated within the study of Slovak brown coal fly ash utilization in road concrete with regard to application of raw materials in the road and highway constructions. Concrete mixture with 15% fly ash compensation in a road construction was selected for our calculation.

The road construction study of two layer cement concrete (CC) pavement of T1 tunnel on Dx highway was used as a basis for this project. Its structure and dimension is full in compliance with internal technical document no. 0803/2003 "Design of concrete-cement carriageway at road communication" of actual Slovak building company. The T1 tunnel is designed as a double-pipe highway tunnel in Slovak rural area with 80 km/h maximum speed in one way traffic, or with 60 km/h maximum speed in two way traffic (in case of closure of one tunnel pipe). The pipe length is 698 m including concrete cement pavement in front of the portal with optimum length of 50 m. Width configuration of the tunnel is specified in classification T1 = 9.0 m in terms of STN 76 7507. The engineering characteristic of the T1 tunnel on Dx highway is presented in Table 4. Economic costs were calculated without production and administrative expenses and without any profit as well. Current material inputs, team and machine utilization, and transport costs were specified for Slovak Dx highway.

Table 4 Engineering characteristic of T1 tunnel on Dx highway

Two - layer concrete cover	
Coated intermediate aggregate	170/80mm
Infiltration road spray 1.0kg/m^2	50mm
Cement stabilization I	180mm
Aggregate 0-32, 0-63 (20+150mm)	270mm

3 Results and Discussion

3.1 Fresh concrete tests

The resulting measured values of fresh concrete properties (consistency, air content, temperature) in comparison with the specific requirements of Technical Standard (TS) are presented in Table 5.

Consistency: All samples comply with requirement S1, while improvement in consistency is also slightly visible with increasing amount of fly ash.

Air content: All samples comply with requirement for 4-8%, amount of fly ash does not influence the air content significantly.

Temperature: All samples comply with requirement for temperature range, while increasing amount of fly ash is causing slight decrease in temperature. It is logical, due to decrease of hydration heat causing by smaller amount of clinker.

3.2 Tests of mechanical properties of hardened concrete

Compressive (CS) and flexural strengths (FS) development of composites based on various fly ash portions after 7, 28 and 90 days are showed in Table 5. Both strengths values of experimental composites with various portion of FA are compared with values of reference sample (RS) and with requirements Technical standards (CS – 32. 0 MPa / 28d, FS – 4.5 MPa / 28d). Based on these results it can be stated that the prepared FA concrete composites with 5 % as well as 15 % of cement replacement met the required criteria of Technical standard. With increasing amount of fly ash, slight decrease in both strengths is visible, including early strengths and ultimate strengths.

3.3 Tests of water activity and chemical resistance; the freezing and thawing tests

De-icing salts resistance: Requirement for max. 300 g/m^2 of scaling in 100 cycles is not fulfilled only when replacing 15% of cement with fly ash. However, it is necessary to say that testing was done in strict conditions – with 150 cycles. In publication (Brandes, Chr. & Schiebl, P., 2006), the value of scaling 1500 g/m^2 is classifying as small damage, while according to laboratory testing such samples did not show any degradation even at real exposure.

Frost resistance - Frost index: All samples comply with requirement for min. 0.85. Increase in amount of fly ash is causing decrease of frost index.

Frost resistance - Compressive strength: Standard requirement for value of compressive strength after freezing cycles does not defined; however we did include this in our testing. As per results, compressive strengths after freezing cycles increased slightly. Increasing amount of fly ash basically doesn't influence values of strength after freezing; decrease is only visible after 15% replacement.

3.4 Economic assessment

Costs were calculated with no production and administrative expenses consideration and without any profit as well. Current inputs of materials, transport costs, team and machine utilization was specified for Dx highway space. Respecting the specific technology these results came out in this calculation (Ondová, M. et al., 2011):

Variant I. - By 100% quantity of CEM I 42.5R Portland cement utilization for CC I production according to proposed recipe designed in catalogue items of CENKROS database the unit price 93.72 €/m^2 resulted.

Variant II. - The second alternative based on utilization of 100% quantity of CEM I 42.5R Portland cement for CC I production according to our own recipe the unit price 92.46 €/m^2 resulted.

Variant III. -The variant utilization of 85% quantity of CEM I 42.5R Portland cement for CC I production and utilization of 15% ENO fly ash according to our own recipe we obtained the unit price 86.76 €/m^2.

These unit prices were used for calculation of CC I pavement construction for two - layers tunnel with 698m pipe length. Summarized results are illustrated in Table 6. The most effective alternative seems to be the number III. with 15% fly ash compensation. It represents 21 260.08 € cost savings per one kilometer of cement concrete pavement (Ondová, M. & Zeleňáková, E., 2010).

Table 5 Results of testing of fresh and hardened concrete

Parameter	Unit	Time of testing	RS	5 % of fly ash	10 % of fly ash	15 % of fly ash
Consistency	[mm]	-	30	30	40	40
Air content	[%]	-	6.0	6.0	6.4	6.5
Temperature	[°C]	-	23.5	22.5	19.5	19.5
Flexural strength	[MPa]	7	5.8	6.1	5.1	4.9
		28	6.9	6.6	6.2	5.6
		90	8.2	8.1	7.1	6.8
Compressive strength	[MPa]	7	44.2	40.0	35.7	31.0
		28	48.4	44.2	42.4	37.2
		90	57.2	53.7	52.6	41.1
De-icing salts resistance - Scaling	[g/m^2]	after freezing	47.6	90.7	209.1	557.0
Frost resistance - Flexural strength	[MPa]	before freezing	7.1	6.5	6.2	5.8
		after freezing	6.5	5.9	5.6	5.1
Frost resistance - Frost index	[%]	-	0.92	0.91	0.90	0.88
Frost resistance - Compressive strength	[MPa]	before freezing	48.6	45.3	42.7	38.2
		after freezing	50.6	50.6	50.6	42.7

Table 6 Final calculation of CC two-layer cover of pavement

Description	Total price
CC two layer reinforced cover of pavement class I. thickness to 250mm – calculation according to the CENKROS database	553 555.88 €
CC two layer reinforced cover of pavement class I. thickness to 250mm – calculation based on our own recipe with 100 % Portland cement using	549 758.76 €
CC two layer reinforced cover of pavement class I. thickness to 250mm - calculation based on our own prescriptions with 85 % Portland cement using and 15% ENO fly ash using	532 294.80 €
Cost saving with 15% fly ash in CC I production	21 261.08 €

4 Conclusion

Fly ash has wide use in highway construction, at the moment it is especially being used as replacement of primary raw materials – soil, sand and gravel-sand. It can be used for highway structures (motorways, highways, busy town roads, airports, parking areas and mountain and country roads) for stabilized base layers of road, flowable fills, in structural fills/embankments, for soil improvement and grouts for pavement subsealing. The development of these new specifications and tests (when fly ash is used in concrete construction for transport infra-structure) leads to reduction of materials related problems. Additionally the rational tests based on documented research prove that the increase of the fly ash utilization provides a net of environmental benefits as well as many of economic benefits. Partial cement replacement with supplementary cementing materials reduces greenhouse gas emission proportionately and results in a more "green" concrete, through reduced energy consumption (energy required to produce cement) and prevents the depletion of natural resources.

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