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COAL FLY ASH IN ROAD CONSTRUCTION AND MAINTENANCE

Abstract

Introduction. There is a general worldwide aspiration to increase the sustainability in every national economy branch, including road engineering. The growing use of various industrial by-products as economical and eco-friendly road construction and maintenance techniques can be observed in many countries. Coal fly ash is a worldwide available industrial by-product that can be advantageously used in road sector.

Problem Statement. The utilization of various types of fly ash in road sector can be not only environmentally friendly, but also cost effective; however, eventually several special technological measures must be taken.

Purpose. Presenting best practices and development trends for the use of coal fly ash in various road construction and maintenance techniques based on decade-long Hungarian and foreign experiences.

Materials and Methods. The main types investigated here are coal fly ash, eventually with acid or basic modification, also in treated forms, as well as bottom ash. The main utilization areas in road construction and maintenance are asphalt layers (principally the filler of the mixture), cement production, cement concrete pavements, other hydraulically bound pavement layers and subgrade material. (Additionally, the by-product can be used, among others, for bricks and blocks, wastewater treatment, and scrubber sludge solidification).

Results. Presenting best practices for the use of various types of fly ashes in road construction and maintenance can be beneficial for the experts of countries with limited experience in the field. The development directions (trends) outlined in the paper can supply with useful information for every interested road expert all over the world.

Keywords: coal fly ash, bottom ash, industrial by-products, cement production, road construction, environmental protection

Introduction

There is a global trend to increase the sustainability of road construction and maintenance technologies. The growing use of various industrial by-products as economical and eco-friendly construction and maintenance techniques can be seen in many countries. The elimination of waste products of various industries is a serious problem, since they pollute the environment. Fly ash is an industrial waste of coal burning [1]. Its actual application is based on specific technical, economic, and ecological criteria. It is obvious that the utilization of coal fly ash (e.g. in road engineering) can avoid environment-polluting landfills and, at the same time, can limit the use of scarce natural aggregates [2]. The paper shows the forms of fly ashes, presents their road-related application areas with their requirements in the road sector. A considerable part of the paper is dedicated to Hungarian laboratory and site experiences in the field, besides some important relevant foreign best practices are summarized. Some relevant specifications are also outlined. Finally, conclusions are drawn on the use of fly ash in road construction and maintenance projects, mentioning some development trends, as well.

Generalities of fly ash

Coal power plants generate electricity by burning pulverized coal, which creates a by-product known as fly ash [3]. Fly ash is separated in electrofilters or mechanical dust separators, with pozzolanic properties, or powdery, predominantly amorphous (glassy) residue with pozzolanic activity. It is generally finer than cement (average particle size is usually 10–30 μm), whose particle distribution depends on the properties of the coal, its grinding fineness, and the characteristics of the dust separation systems. The shape of the grains is usually spherical. The reaction between $\text{Ca}(\text{OH})_2$ and the active substance of fly ash (primarily SiO_2) is called pozzolanic reaction. Bottom ash (slag) is the residual material (glued lumps) produced in the combustion chamber from the incombustible (inorganic mineral) material of the raw coal. Ash is the combustion residue of the organic part of the raw coal (mostly fine dust). Acid fly ash has a SiO_2 content of 45–60 %, and its CaO content does not exceed 10–15 %. Basic fly ash has 30–40 % CaO (active CaO >10–15 %) and only 20–25 % SiO_2 . Fly ash can be divided in two categories: ASTM class C fly ash (with high calcium produced from lignite or subbituminous coals) and ASTM class F fly ash (with low calcium percentage and normally produced from bituminous coals) [3]. According to various studies, only high calcium fly ash affects the rate of strength development in concrete at later ages.

The main factors determining the quality of coal fly ash are as follows: coal and accompanying rock, coal grinding, burning method, type of boiler, lingering in fire pit, redox conditions, temperature distribution and ash removal method.

There are many reasons to re-utilize fly ash, some of them: disposal costs are minimized; less area is reserved for disposal; there may be financial returns from the sale of the by-product or at least an offset of the processing and disposal costs; the by-products can replace some scarce and/or expensive natural sources [5].

Fly ash utilization, especially in concrete, has significant environmental benefits including:

- longer life of concrete roads and structures by improving concrete durability;
- less energy use and greenhouse gas air emissions when fly ash is used to replace manufactured cement;
- less coal combustion products that must be disposed in landfills, and conservation of other rare natural resources and materials.

Every coin has two sides; it is true also for fly ash. The use of fly ash in concrete has advantages as well as disadvantages [6]. It is mandatory to understand the difficulties you may end up with when using fly ash. Firstly, fly ash affects concrete in many ways. There are several parameters going to effects due to the addition of fly ash. Surely, professional involvement is necessary for concreting works with fly ash addition. Another disadvantage with fly ash is low early strength and slow strength gain. Of course, this is helpful in some cases like mass concrete pours. When it comes to structural concretes, the slow rate of strength badly affects the progress. It increases the formwork removal time and curing period. Although you can introduce lime and accelerators to improve strength gaining rate, it will complex the work in other ways. When concreting in cold-weather conditions, this strength gain is critical to generate enough heat for the rest of hydration. Too cold concrete will not achieve the desired strength in-time. Fly ash reduces the pour volume in the concrete microstructure. This will make the concrete vulnerable to freeze-thaw attack. So, you may add air-entraining admixtures into the concrete. Finally, fly ash is hazardous. Inhaling the fly ash dust will cause throat irritations as well as lung diseases. Eye and skin contact also can cause severe health problems.

Main application areas in road sector

There are a lot of areas in the road sector where the coal fly ash directly or indirectly can be utilized. The most important ones are as follows [1]: cement concrete mixtures; asphalt mixtures, mainly as filler; soil stabilization; subgrade material as fills. (Some more application areas: phytoremediation, crop plants,

high-performance lithium-ion batteries, polymeric media, rubber industry, syntactic foams [2]). This paper concentrates on the road-related issues.

Fly ash in cement concrete pavements

Coal fly ash can be re-used indirectly or directly in cement concrete mixtures (pavements). The typical indirect utilization can be found in cement industry. There are three applications for fly ash in cement, the binder of cement concrete mixture: replacement of cement in Portland cement; pozzolanic material in the production of pozzolanic cements and set retardant ingredient with cement as a replacement of gypsum [4]. It is well-known that cement is the most cost and energy intensive component of concrete. The unit cost of concrete mixture can be considerably decreased if cement is partially replaced by fly ash. Generally, 15–30% of the Portland cement is replaced with fly ash. An equivalent or greater weight of fly ash is substituted for the cement removed. Using fly ash is an effective way to make concrete much more sustainable with less impact on environment, energy and reduces CO₂ emissions as well [7].

High performance concrete mixes using a blend of 53 grade cement and class F fly ash as cement replacement material up to 30 % level, having mean compressive strength above 75 MPa at 28 days, were studied in India [8]. It is found that the same compressive strength as that of control mix at 28 days is obtained in concrete having fly ash up to 25 % level. Thus, cement content in concrete could be reduced by having fly ash to produce concrete having mean target strength of 85 MPa at 28 days.

A Canadian researcher [9] investigated the impact of fly ash on the properties of concrete with a view to optimizing the level of fly ash used for a given application. The optimum amount of fly ash varies not only with the application, but also with composition and proportions of all the materials in the concrete mixture (especially the fly ash), the conditions during placing (especially temperature), construction practices (for example, finishing and curing) and the exposure conditions. Thus, the optimum fly ash content will vary on a case-by-case basis. Fly ash contents of up to 50 % may be suitable for most elements provided the early-age strength requirements of the project can be met and provided that adequate moist-curing can be ensured. If adequate curing cannot be provided or if the concrete is exposed to freezing and thawing in the presence of de-icer salts, the amount of fly ash should be limited, for example, $\leq 25\%$.

Fly ash as asphalt mixture filler

Mistry et al. investigated the effect of using fly ash (FA) in asphalt mixture as replacement of common filler [10]. In view of the same, samples were prepared for different bitumen content (3.5–6.5 % at 0.5 % increments) by using 2 % hydrated lime (HL) in control mix as well as varying percentage of FA ranging from 2 to 8 % as alternative filler in modified mixtures. The optimum bitumen content (OBC) was then determined for all the mix using Marshall mix design. Experimental results indicated higher stability value with lower OBC for the mixture having 4 % FA as optimum filler content in comparison with conventional mix and standard specification.

In the countries where the energy industry is based mainly on coal, the management of the waste generated in the process of its combustion (fly ash) is a serious problem. An article of Wozzuk et al. presented the properties of mix asphalt where the traditional limestone filler was replaced by fly ash in 25 %, 50 % and 75 % [11]. Class F and class C fly ashes were used for the tests. The ashes were characterized in terms of chemical composition, mineralogy and grain size. The tests were made for 7 mix asphalt types, AC 11 S type was selected as the reference one. For the samples with fly ash addition, the air voids ranged from 1.2–1.6 % for class F and from 1.3–2.8 % in the case of class C fly ash. Water and frost resistances were 96–104% and 102–104 %, respectively. The results indicate that both classes of fly ash can be applied as alternative mineral filler, since the air voids as well as resistance to water and frost of the obtained mix asphalt fully met the relevant standards.

Fly ash can be used as a cost-effective mineral filler in hot mix asphalt (HMA) paving applications, where available locally, fly ash may cost less than other mineral fillers [12]. Also, due to the lower specific

gravity of fly ash, similar performance is obtained using less material by weight, further reducing the material cost of hot mix asphalt. Mineral fillers increase the stiffness of the asphalt mortar matrix, improving the rutting resistance of pavements. Mineral fillers also help reduce the amount of asphalt drain down in the mix during construction, which improves durability of the mix by maintaining the amount of asphalt initially used in the mix. Fly ash will normally meet mineral filler specification requirements for gradation, organic impurities and plasticity. Also, fly ash is hydrophobic (non-water wettable), reducing the potential for asphalt stripping; the presence of lime in some fly ashes may also reduce stripping. Mineral fillers have become more necessary as mixture gradations have become coarser. Asphalt pavements with coarse gradations are increasingly being designed because they perform well under heavy traffic conditions. The findings of this study confirm that it is possible to obtain satisfactory properties and performance of asphalt mixtures with partial replacement of mineral filler with fly ash. The optimal replacement percentage depends on type and chemical composition of fly ash, as well as its properties and affinity to bitumen. Fly ash can be used as a bitumen extender or to improve stability, resistance to moisture, and permanent deformation of asphalt mixture as economic solution instead of using polymer modified bitumen and at the same time reduce negative environmental impact [13].

Earlier Hungarian research work identified that dry fine coal fly ash can substitute fully or partly limestone filler in asphalt mixtures [14]. An important precondition for this replacement is that the quality of novel mixture should not be lower than that of the reference mixture with traditional filler, the binder need cannot increase considerably. It was shown that the applicability of fly ash depends on, among others, its grading, organic material content, moisture content, sensitivity to water and swelling behaviour.

Fly ash as hydraulic binder

Coal fly ash can be the binder of base courses or frost protection layers if several requirements are met, mainly those of a cement stabilization layer [15]. Binder can be hydraulic, cementitious (Class C) or acid fly ash, pozzolanic (Class F) or basic fly ash + hydrated lime. In case of sand soils, tentative binder need is 3–7 % hydrated lime and 15–30% pozzolanic fly ash; for other soil types: 3–6% hydrated lime and 10–20 % pozzolanic fly ash. Fly ash bound base courses can be mixed on-site or in a plant. Its manufacturing procedure and machinery are identical with those of cement bound version. The thickness of fly ash bound base layer should not exceed 300 mm. Fly ash is often transported by bulk trucks or trailers, which are specifically designed to transport these kinds of materials; these trucks may have a compartmentalized design or a single large tank to transport the fly ash [16].

Fly ash stabilized base courses are proportioned mixtures of fly ash, aggregate, and – if it is needed - an activator (cement or lime) that, when properly placed and compacted, produce a strong and durable pavement base course [17]. Fly ash stabilized base course is suitable for both flexible and rigid pavements. Class C fly ash can be used as a stand-alone material. Class F fly ash can be used when blended with lime, Portland cement or cement kiln dust. Typical proportions for the Class F fly ash lime blends are 2–8 % lime blended with 10–15 % Class F fly ash. Also, 0.5–1.5 % Portland cement can be blended with Class F fly ash to produce the stabilizing agent. The stabilization of aggregate bases provides several advantages: significant strength and durability increase, the use of marginal or low-quality aggregates; reduction in project cost. It is important to ensure that adequate resistance to freeze-thaw cycling is achieved before the onset of colder months. The following steps are to be taken for determination of mix proportions in a laboratory:

- Determine the particle size distribution of the aggregate, use the portion passing 20 mm sieve for testing.
- Add fly ash to the aggregate portion in five different proportions, between 10 and 20 % for coarse aggregate. Mold one test specimen at each fly ash content in accordance with ASTM C 593 Proctor compaction procedures [18] at an estimated optimum moisture content.

- Determine the dry density of each blend of aggregate and fly ash. Plot the test results to identify a peak value or maximum dry density.
- Select an optimum matrix content at least 2 % above the matrix content at the maximum dry density; determine the optimum moisture content and maximum dry density for that blend.
- Determine the most suitable proportions of activator to fly ash. Use five different activator-to-fly ash combinations at the optimum matrix content. The five combinations should span the recommended range of ratios for each activator. The typical range of activator to fly ash ratio is 1:3 to 1:4 using lime or Portland cement.
- Prepare six Proctor-size specimens for each combination in accordance with the compaction procedures in ASTM C 593 [18]. Cure all six test specimens for 7 days in sealed containers. For lime activators, cure at 37.8 °C. For Portland cement as the activator, cure in a moist room at 22.8 °C and 100 % relative humidity.
- Test 3 specimens for compressive strength and test the other 3 specimens for durability at the end of the seven-day curing period [18].
- Plot a curve of compressive strength as a function of activator % for each of the five activator-to-fly ash combinations. Only test mixtures with a seven-day compressive strength exceeding 2,760 kPa and acceptable durability should be considered as a candidate for field use.
- Select the most economical (lowest % activator) mixture that exceeds the compressive strength and durability requirements. The mixture used in the field should contain a higher % of activator (0.5 % increase for lime or Portland cement) than the most economical mixture identified in the laboratory. This assures an adequate factor of safety for placement techniques available in the field [17].

The valid Hungarian specification in the field [19] deals with acid fly ash (V), basic fly ash (W), treated fly ash (VK or WK), lime donor powder (MP), bottom ash (VN), and lime donor fluid (MF). Exclusively, the fly ash separated from the flue gases of pulverized coal-fired boilers is allowed to be used in road construction. The 1-hour loss on ignition of fly ash should not exceed 5% wt. loss. The active CaO content of acid, pozzolanic fly ash cannot be above 10% wt; it can be deposited, transported, and used either in dry or wet condition. The basic fly ash is a powder with hydraulic and pozzolanic properties. It contains at least 10 % wt. active CaO, SiO₂, Al₂O₃, Fe₂O₃ and some other compounds. The material can be stored, transported, and used just in dry condition. If the fly ash is not appropriate to the direct utilization as road binder, it should be treated (washing, leaching, thermal treatment, solidification, chemical stabilization, etc.). Bottom ashes are the solid combustion residues of coal dust. The maximum grain size of this wet-settled material amounts to 2.0–2.5 mm, with higher coal and moisture content. Active lime donors can be the powders or solutions, which mixing with pozzolans, create a self-hardening system due to its active CaO or Ca(OH)₂ content. The chemical requirements of various fly ash types are shown on **Table 1**, while their main physical ones in **Table 2**. The pozzolanic requirements of fly ash types are presented in **Table 3**.

Table 1

Some chemical properties of fly ash types [19]

Property	Product type			
	V	W	VN	WK
SiO ₂ (% wt.)	≥35	≤30	≥35	≤30
Al ₂ O ₃ (% wt.)	≥15	≤25	≥15	≤25
Fe ₂ O ₃ (% wt.)	≥5	≤15	≥5	≤15
CaO (% wt.)	≤20	≥20	—	≥20
Total sulphur in SO ₃ (% wt.)	≤4	≤10	≤5	≤10
Loss on ignition (% wt.)	≤5		≤8	≤5
Active CaO (% wt.)	≤10	≥10	—	≥15

Table 2

Some physical properties of fly ash types [19]

Property	Product type			
	V	W	VN	VK
Blaine specific surface area (cm ² /g)	≥2,000		≥1,800	≥2,000
Passing portion through 45 μm sieve (% wt.)	≥45		≥40	≥45
Density (g/cm ³)	≥2.0	≥2.5	≥2.8	≥0.7
Bulk density (g/cm ³)	≥0.7	≥0.9	≥0.6	
Other contamination	Free of foreign matter and of right fineness			

Table 3

Pozzolanic requirements of fly ash types [19]

Property	Product type			
	V	W	VN	WK
Pozzolanic activity (MgCaO/g)	≥30	—	≥25	—
Strength of pozzolanic mixture at the age of 28 days (MPa)	≥12.5			
Swelling (% vol)	≤10			

Some rules of fly ash storage and transport [19]:

— Storage methods include bulk storage, bag storage, and silo storage. The longer the storage time, the greater the strength reduction. Under normal conditions, the strength of fly ash will decrease about 10–20 % after stored for 3 months.

— If the CaO content of wet fly ash does not exceed 5%, the maximum storage time amounts to 1 month; above 5 %, the material should be utilized in 3 days due to the starting of binding.

— Fly ash can be transferred using air slides, bucket conveyors and screw conveyors, or it can be pneumatically conveyed through pipelines. Fly ash including bottom ash is transported to markets in bulk tanker trucks, rail cars and barges/ships.

Fly ash as a subgrade material

The assessment of potential effects of the application of fly ash in road construction was based on the results of tests of fly ash from two thermal power plants in Serbia and three characteristic soil types: medium plasticity clay, silty-sandy clay, and high plasticity clay [20]. The physical and mechanical characteristics of the stabilization of the three soil types with different percentages of fly ash and stabilizers (cement/lime) were determined in the study, and pavement designs for three traffic levels, from 1,000 to 10,000 vehicles/day were developed. The savings that can be achieved by using fly ash are going up to 16.8 % depending on subgrade material type and traffic volume. The potential savings are higher by weaker subsoil and lower traffic.

The use of bottom ash in the building of road embankment was investigated by Gáspár et al. [21, 22]. Several bottom ash embankment projects were monitored, besides the total energy consumption and costs were compared to those of traditional (soil) fills. The ages of tested projects were between 9 and 24 years. The moisture contents of most bottom ash embankments were below the optimum values proving the lack of wetting leading to bearing capacity loss. No shrinkage was identified. Bearing capacity generally increased as a function of time, besides density grew or at least retained its initial favourable level. Cone Penetration testing results proved that this kind of embankment can be compacted much more homogeneously than a traditional soil one. Chemical tests showed that bottom ash embankment is not

hazardous at all. It could be concluded that the novel technology investigated can be applied economically and environmentally friendly, even in motorway structures.

A recent Hungarian specification on the geotechnical rules of road construction [23] allows the use of inert materials – among others, fly ash – for the construction of road embankments if the following requirements are met:

- fly ash is classified into relevant soil grading class (typically, some kind of silt class),
- compactibility, workability, water and frost resistance, drainage and durable load-bearing capacity criteria are to be fulfilled,
- volume change ability and the eventual presence of organic component are also checked,
- ability of embankment material to withstand the high contact pressures of heavy earthwork construction equipment.

Kaskiv et al. presented the first Ukrainian experiences on the use of fly ash as filler substitute of asphalt mixtures [24]. A comprehensive analysis of the composition and acid-base properties of fly ash from thermal power plants of various origins suggested that all the studied samples have a sufficiently high potential for use as filler in asphalt mixture. It was concluded that the use of fly ash for the production of asphalt mixtures would significantly reduce the amount of waste and improve the ecological state of the environment.

Figure 1 presents the fly ash embankment construction of a Hungarian motorway in the 1990's, while **Figure 2** shows the completed embankment in the same project.



Figure 1 — Construction of fly ash embankment in a Hungarian motorway M35

Environmental challenges

As it was mentioned before, the use of fly ash in road engineering has several significant environmental benefits including longer pavement life, less energy consumption and air pollution, less valuable areas needed for fly ash deposits and conservation of other natural resources and materials that are available in limited quantities. But at the same time, there are some environmental drawbacks (or at least challenges) in this field [25]:

- storage of fly ash in tailings and deposits results environmental burden,
- amorphous phase of acid fly ash encloses toxic heavy metals (for instance, As, Cr, Cu, Ni, Pb) and significantly inhibits their interaction with water and thus their dissolution,
- the toxic heavy metals in coal, Hg and Cd, which easily evaporate, are removed with the flue gases during the burning process, but the other, less volatile metal pollutants are significantly enriched in the fly ash and their average concentration can be in the range of 200–300 mg/kg,
- the concentration of heavy metals relatively enriched in the fly ash exceeds the element concentrations typical of normal soils by almost half or an order of magnitude, but due to the inhibited

dissolution resulting from the "glassy" structure, this does not represent an environmental risk, does not result in environmental pollution,

— considering the average particle size of fly ash (10-30 μm), the range below 10 μm , which is harmful to human health, is not a defining fraction within the fly ash [26].

— considering the average particle size of fly ash (10-30 μm), the range below 10 μm , which is harmful to human health, is not a defining fraction within the fly ash [26].



Figure 2 — Completed fly ash embankment in a Hungarian motorway M35

Conclusions

Nowadays the countries all over the world strive to concentrate on the highest possible sustainability in each branch of national economy. Of course, this statement is true for the road sector, as well. To reach this goal, an effective procedure is the utilization of various industrial by-products in road construction and maintenance technologies. Coal fly ash is one of the most widely used industrial by product in the road sector. Its various types (acid and basic fly ash, as well coarser bottom ash) have different application areas in road construction and maintenance techniques. It can partly replace Portland cement and be the binder of a high-quality concrete; fly ash can substitute – usually limestone – filler in asphalt concrete mixtures; the by-product can be also used as the binder of road base courses or frost protection layers; it can be utilized as subgrade (embankment) material. These novel techniques can be highly energy and cost saving options. They are usually environmentally friendly options, however, eventually some environmental challenges have to be treated [26].

As a summary, it can be stated the main question of fly ash utilization in road construction and maintenance is the decision-makers' attitude in this field. They have to decide whether they will be able to pursue long-term interests at the level of the national economy, or whether they will stick to the usual, traditional technologies until the end [27].

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ВИКОРИСТАННЯ ВУГІЛЬНОЇ ЗОЛИ ВИНЕСЕННЯ В БУДІВНИЦТВІ ТА УТРИМАННІ ДОРІГ

Анотація

Вступ. У всьому світі існує загальне прагнення до підвищення стійкості в кожній галузі національної економіки, включаючи дорожнє будівництво. В багатьох країнах можна спостерігати зростаюче використання різних промислових побічних продуктів для забезпечення як економічних та екологічно чистих методів будівництва та утримання доріг. Вугільна зола винесення є доступним у всьому світі промисловим побічним продуктом, який може бути вигідно використаний у дорожньому секторі.

Постановка проблеми. Використання різних видів золи винесення в дорожньому секторі може бути не тільки екологічно чистим, але й економічно ефективним; однак, в кінцевому підсумку, необхідно вжити кілька спеціальних технологічних заходів.

Мета. Представлення найкращих практик і тенденцій розвитку використання вугільної золи винесення в різних технологіях будівництва та утримання доріг на основі десятирічного угорського та зарубіжного досвіду.

Матеріали і методи. Основними видами, що досліджуються тут, є вугільна зола винесення, в кінцевому підсумку з кислотною або основною модифікацією, в тому числі в оброблених формах, а також зола з доменної печі. Основними сферами використання в будівництві та утриманні доріг є шари асфальтобетону (головним чином, заповнювач суміші порошковидний), виробництво цементу, цементобетонних покриттів, інших гідравлічно зв'язаних шарів дорожнього покриття та матеріалів земляного полотна. (Крім того, побічний продукт можна використовувати, зокрема, для виробництва цегли та блоків, очищення стічних вод і тверднення осаду на скрубєрних установках).

Результати. Представлення найкращих практик використання різних видів золи винесення в будівництві та утриманні доріг може бути корисним для експертів країн з обмеженим досвідом у цій галузі. Окреслені в статті напрямки (тенденції) розвитку можуть стати корисною інформацією для кожного зацікавленого фахівця в галузі дорожнього господарства в усьому світі.

Ключові слова: виробництво цементу; вугільна зола винесення; дорожнє будівництво; зола доменної печі; охорона навколишнього середовища; промислові побічні продукти.