Vol. 4, No. 2, 2022

https://doi.org/10.23939/jtbp2022.02.090

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PREREQUISITES FOR THE IMPLEMENTATION OF THE EUROPEAN EXPERIENCE IN THE USE OF ASH-SLAG MATERIALS IN THE CONSTRUCTION OF HIGHWAYS: A REVIEW

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The European Green Deal is the latest climate and environmental protection program launched by the EU. This is a strategy to transform the EU into a resource-efficient economy, in which in 2050 there will be zero greenhouse gas emissions and economic growth will be decoupled from the use of natural resources. After approving the National Economic Strategy for the period until 2030, Ukraine joins and focuses on the European Green Deal and aims to achieve climate neutrality in 2060 (Natsionalna ekonomichna stratehiia, 2021).

Such ambitious goals can become a huge challenge for our country, in particular, in environmental projects of recycling in construction. Popularization of the principles of the circular economy and the introduction of the best European experience in the reuse of industrial waste is not only a requirement for the successful accession of Ukraine to the EU, but also a prerequisite for the effective implementation of infrastructure projects, especially the post-war reconstruction of the country.

Key words: recycling in construction, European green deal, highways, subgrade, ash and slag materials, fly ash.

Introduction

As of the end of 2019, about 360 million tons of ash and slag products accumulated in TPP dumps in Ukraine. Given the insufficient pace of development of other energy sources, the status of coal as an important energy resource remains in the next 15–20 years, accordingly, the scale of the problem of ash and slag accumulation will increase. If we do not increase the level of disposal today, the amount of landfills will increase by another 55 million tons by 2035, or by 15 %. Increasing the level of use of ash and slag products is a national issue, since thermal power stations (TPS) are evenly distributed throughout the territory of Ukraine and each thermal power stations has its own ash and slag dumps. The current national level of ash and slag disposal is 8.3 %, which is radically different from the EU, where no less than 44 % of ash and slag materials are disposed of annually. Achieving a high level of ash slag utilization involves the creation of a balanced environmental and economic policy of the state, namely: develop standards for ash slag products; launch a system of "green" public procurement; to initiate the implementation of the cement concrete road construction program; apply financial instruments to stimulate recycling; increase the rent for the extraction of crushed stone and sand; to approve the mechanism of compensation for the costs of transportation of slag by railway (Yevropeiska biznes asotsiatsiia, 2021).

In the EU, the main direction of utilization of ash and slag materials is the production of cement and concrete, and about 17 % of ash and slag is consumed for the needs of road construction. In Ukraine, the industry of cement and concrete production already uses the maximum amount of ash and slag products that can be achieved at the current level of construction activity. However, according to "Ukravtodor" (State Road Agency of Ukraine), Ukraine does not sufficiently use ash and slag products in road construction. Thus, road construction is an important direction that will allow to increase the level of utilization of ash and slag products in Ukraine. This is a very promising direction, since large-scale projects for the restoration of highways are being implemented in the country.

Analysis of sources on the research topic

When building a road, more than 50 % of its cost is the cost of materials. For the construction of 1 km of road, depending on its category and local conditions, from 6 to 60 thousand m3 of soil is required for the construction of the subgrade; 1.5–6.0 thousand m3 of sand for drainage and frost protection layer; 0.8–5.4 thousand m3 of crushed stone or soil reinforced with binding materials. Reducing the need for these materials, especially the most expensive and scarce ones, and increasing the efficiency of their use is one of the most urgent problems, the solution of which depends on scientific and technical progress in the road industry. The positive results of the use of ash-slag mixtures are evidenced by a large number of publications highlighting world and domestic experience (Mozghovyi, 2014; Acıkök, 2018; Smith, 2007, Abdullah, 2021; Arm, 2003)

Due to its chemical and physical properties, fly ash is used in many construction projects to reduce the cost of works, improve the environmental and operational characteristics of objects. Ash-slag products replace sand and crushed stone – in road surfaces, the price of ash-slag crushed stone is 2–5 times lower than the price of granite. Fly ash can be used for the construction of the subgrade, backfilling of embankments and soil stabilization (Maheepala, 2022; Barman, 2022; Ghadir, 2021; Spagnoli, 2022; Aboulayt, 2018), as a slow-setting, self-binding or active hydraulic additive. Crushed slag can be used for crushed stone bases and as an aggregate in highway pavement structures.

Ash and slag materials were used for road construction in the EU more than 60 years ago. During this time, ash and slag materials have proven their reliability as a construction material (Rahmat, 2011; Ferreira, 2003; Sen, 2010; Liu, 2022; Roshan, 2022). It is important that the use of ash and slag products in the construction of cement-concrete roads makes it possible not only to obtain savings due to the substitution of materials, but also to increase the strength of the structure. Thanks to this, the service life of such roads increases and there are indirect effects in the form of savings on their further repair. Therefore, ash and slag materials are now actively used in modern construction projects of high-speed highways and roads with increased traffic. The most famous road construction projects in the EU using ash-slag materials are:

– highway A1, section Aberford – Wetherby (Great Britain). Fly ash was used in road construction as an aggregate for the road subgrade. In total, 250,000 tons of ash were used. The period of performance of works – 1963–1964;

– highway A27 (Great Britain). Fly ash was added to the road embankment, which made it possible to absorb excess moisture from the materials. A total of 10,000 m3 of ash was used. The period of performance of works is 1967;

– highway M25 ring road of London (Great Britain). It is considered one of the busiest highways in Europe. In 2012, during the implementation of the road expansion project, ash residue was used;

– highway A50 (Great Britain) The highway expansion project was carried out in 2014–2016 using ash and slag products as backfill materials. The project was part of the 2014 National Road Investment Strategy;

– highway D1, section Pršerov – Lypnyk (Czech Republic). Fly ash was used as an aggregate for the subgrade, as well as for mechanical stabilization of silty clays and soil treatment. The volume of use is 120 thousand m3. The period of performance of works is 2017–2019;

– highway S17, Lubel – Kolbel section (Poland). The construction of a 24 km section of the road was carried out in 2020. The contractor was Strabag. Ash slag products were used for filling instead of a sand-crushed mixture;

– highway A1, section Strykuw – Tuszyn (Poland). Toll road, one of the largest projects in Europe in the last 10 years. Fly ash was used to stabilize the soil during road construction. As a result, the project received the status of ecological. Construction was carried out in 2014–2016.

There are 15 coal-fired power plants (TPPs) operating in Ukraine, which are evenly located throughout the territory and whose total capacity is 40.2 % of the total installed power generation capacity

in the country. The main owner of thermal power plants in Ukraine is DTEK. At the same time, Ukraine does not use all available opportunities for disposal of ash and slag materials. According to the State Highway Agency of Ukraine "Ukravtodor", Ukraine practically does not use ash and slag products in road construction. This is what limits the level of disposal of ash-slag materials. On the other hand, there is considerable potential for change.

In contrast to the European experience, the experience of building roads from ash slag in Ukraine is not widespread. Insufficient attention is paid to the development of rational ways of using ash-slag mixtures in modern economic conditions for road construction in Ukraine. Therefore, there is a need and an opportunity, using the existing assets, to show the initiative of interested organizations in improving the practical ways of using ash-slag mixtures in road construction with the help of specific developments and use in the practice of repairing and building roads and streets. The most recent, albeit insignificant, but extremely important step forward for the domestic infrastructure was the "experimental model" of a 900m long road with the use of ash and slag from the Burshtyn thermal power stations (Yatseno, 2021) [8]. 300 tons of dry and wet ash were used in the 900-meter section of the road. Ash is used both in the base for the asphalt concrete coating and in the coating itself. In the lower base layer – 25 % of wet ash. Here it acted as a substitute for sand. In the upper layer, ash is contained in the composition of asphalt concrete – instead of traditional mineral powder.

However, a number of factors hinder the increase in the level of ash and slag utilization and their use in road construction, namely the lack of special standards (Yevropeiska biznes asotsiatsiia, 2021). On the one hand, current standards do not prohibit the use of ash and slag products and mining rock in construction. On the other hand, state and communal institutions in the procurement process require confirmation of compliance of the proposed materials with current standards. In this context, the lack of standards specifically for ash and slag products becomes an obstacle to their use. The European classification of ash and slag products differs from that used in Ukraine. In the European Union, the classification is based on the method of formation of products, in Ukraine – on their properties. According to DSTU EN 14227-3:2020, which corresponds to the EU norm EN 14227-3:2013, IDT, the following concepts are highlighted:

– fly ash – finely dispersed powder, which is formed during the combustion of finely ground stone or lignite in power plants with or without combustion products (as defined in EN 450-1) and is captured with the help of mechanical or electrostatic separators;

– silicate fly ash (aluminosilicate fly ash). Fly ash, the main chemical components of which are silicate, aluminate and iron oxide in the form of SiO_2, Al_2O_3 and Fe_2O_3, and which has pozzolanic properties;

– lime fly ash is fly ash, the main chemical components of which – silicate, aluminate, calcium oxide and sulfate – are expressed as SiO_2, Al_2O_3, CaO and SO_3, and which has hydraulic and pozzolanic properties;

– pozzolanic material, which hardens and hardens when mixed with lime [$Ca(OH)_2$ or CaO] in the presence of water, and at the same time forms a stable and durable compound;

– a hydraulic material that hardens in the presence of water, and at the same time forms a stable and durable compound.

The company Recycling Solutions is one of the national leaders in the management of by-products and waste of the coal, metallurgical and thermal power industries of Ukraine and offered the following list of ash and slag materials on the national market (Recycling Solutions, 2021):

– microsphere is an ecologically clean product of high-temperature coal combustion at power stations. It is a sphere with a size of 20–50 to 400–500 microns, filled with gas. Microspheres have low density and high mechanical strength. By using them to fill cavities, manufacturers can increase the strength of the final product. In addition, the products will weigh less compared to the usual raw materials, will have less shrinkage and viscosity. The material is chemically inert, heat-resistant, has low thermal conductivity and good sound insulation. This is a promising raw material, able to function in

aggressive environments and high temperatures. The use of a microsphere slows down the burning of the final product, as it has high fire-resistant properties. The spherical shape creates the effect of a ball bearing (provides a lubricating effect) — the final product is fluid and easy to apply. It was not used in road construction. It is recommended for use in ultra-light concrete, dry building mixtures, plasters, coatings, insulating roofs and sound-insulating materials;

– dry ash or fly ash is a finely dispersed material consisting of small particles (from a fraction of a micron to 0.14 mm) and formed during the burning of solid fuels. This by-product is captured by electrostatic precipitators, after which it is removed in a dry dusty state using filters. Dry ash significantly increases the ease of placing heavy types of concrete, improves its technical characteristics (cement and sand are partially replaced with ash); improves the characteristics of concrete for highways and airfields, reduces the level of heat of hydration, which is an advantage in the case of pouring large-scale slabs and erecting buildings in the hot season; increases the strength of concrete structures that are in an aggressive environment (sulfate, marine);

– ash-slag mixture is a combination of ash and slag, which are formed as by-products during the operation of thermal power plants. They contain slag sand (particles up to 5 mm) and slag crushed stone (particles over 5 mm). Ash-slag mixtures are widely used in construction as an alternative to gravel, crushed stone, sand and similar resources, the extraction of which is time-consuming, expensive, and also negative for the environment. Also, such mixtures are actively used for multicomponent building materials and road construction. The main advantages of composite materials based on ash slag are low cost, resistance to low temperatures, ability to compact, increased strength indicators;

– boiler slag is a mineral residue formed after burning solid fuels. It does not burn and remains at the bottom of the boiler, after which it is moved to a special place for shipment. This is a valuable material that is used in various fields of construction. Most often, it looks like small black granules with sharp edges (resembles broken glass). They are used in construction for the production of: cinder blocks; road surfaces; thermal insulation materials; concrete mixtures; abrasive powder (for surface treatment);

– moistened ash is a finely dispersed material with a size of approximately 3 microns, which has a moisture content of up to 15 %. It consists of small particles that are ideal for further use without additional grinding. Moistened ash is often used in construction, its advantages are a large proportion of aluminum oxide (up to 27 %) and iron (up to 12 %); for the production of cinder blocks; as a component of clinker (instead of clay); in private construction.

In the EU, ash and slag products include:

1) fly ash is a finely dispersed material that is formed as a result of burning solid fuel and is captured by electrostatic precipitators. Fully corresponds to the domestic classification;

2) bottom ash is granular material (larger than fly ash) that is removed from the bottom of dry boilers. Has no direct correspondence with the domestic classification;

3) boiler slag is a vitreous material that is formed in the process of burning coal in boilers at temperatures from 1500 to 1700 °C. Fully corresponds to the domestic classification;

4) ash from a boiling (pseudo-liquefied) bed – fluidized bed combustion ash – is formed in boilers with a fluidized bed. It does not have a direct correspondence with the domestic classification, its properties are similar to fly ash.

In the marketing promotion of fly ash at the national level, an important role is played by the approval of state standards for their use, which would be systematically reviewed and supplemented and would directly affect the speed of innovation implementation, increasing the demand for more resource-efficient products and production technologies. In the EU, standards for the use of ash and slag products, in particular in road construction, have been developed at a sufficiently high level. For example, ASTM C0593-19 Standard Specification for Fly Ash and Other Pozzolans for Use With Lime for Soil Stabilization, ASTM D7762-18E01 – Standard Practice for Design of Stabilization of Soil and Soil-Like Materials with Self-Cementing Fly Ash. ASTM C0593-19 and ASTM D7762-18E01 describe the technology of stabilization of soil and soil-like materials using self-cementing coal fly ash for roads,

treatment of expanded subgrade or organic subgrade, and limitation of settlement of aggregates under buildings. BS EN 14227-4:2013 “Hydraulically bound mixtures. Specifications. Fly ash for hydraulically bound mixtures” – the European standard specifies silicate and lime fly ash used in hydraulically bound mixtures for roads, airfields and other areas loaded by vehicles. This European standard applies to fly ash generated by the combustion of pulverized coal or lignite in power plants.

Table 1 and Table 2 present the possibilities of using ash-slag materials in the road construction (Yevropeiska biznes asotsiatsiia, 2021).

Table 1

Possibilities of using ash and slag materials in the construction of asphalt pavements (according to the data of State Road Research Institute named by M. P. Shulgin)

Structural element	Shoulders	Subbase	Base course	Pavement
Materials used	soil and rubble	limestone and cement	sand and rubble	limestone, cement and mineral powder
Purpose	backfilling, shoulder stabilization	soil stabilization	coarse, fine aggregate and binder	coarse, fine, structural aggregate and binder
Rate of consumption for materials per 1 km of road, t	820	140	1457	263
Replacement by ash slag products	boiler slag	fly ash, bottom ash	fly ash, bottom ash	fly ash, bottom ash
Percentage of replacement	35	20	30	30
Amount of replacement, t	287	28	437	131

Ukraine has also developed regulatory documents for the use of ash-slag mixtures for road construction, in particular. However, there is a need and opportunity to develop, improve and harmonize existing state standards with EU standards using existing resources to increase the level of practical application of ash-slag mixtures in road construction, repair and reconstruction technologies of highways and streets. According to DSTU B B.2.1-2, TPS ash and slag mixtures belong to class IV – man-made dispersed soils, to type – industrial and economic waste, and to subtype – ash slag. Ash and slag mixtures of TPP can be used both independently and as granulometric admixtures to the soil to optimize its grain composition. For use in the installation of pavement layers from soils strengthened with binding materials, the TPP ash-slag mixtures meet the requirements of DSTU 8801:2018.

Table 2

Possibilities of using ash and slag materials in the construction of cement concrete roads (according to the data of State Road Research Institute named by M. P. Shulgin)

Structural element	Shoulders	Subbase	Base course	Pavement
Materials used	soil and rubble	limestone and cement	sand + rubble + cement = concrete	sand + rubble + cement = concrete
Purpose	backfilling, shoulder stabilization	soil stabilization	coarse, fine aggregate and binder	coarse, fine aggregate and binder
Rate of consumption for materials per 1 km of road, t	820	140	2500 m^3 of concrete (0.5 tons of cement)	1800 m^3 of concrete (0.4 tons of cement)
Replacement by ash slag products	boiler slag	fly ash, bottom ash	fly ash, bottom ash	fly ash, bottom ash
Percentage of replacement	35	20	3.6 (to cement)	3.6 (to cement)
Amount of replacement, t	287	28	13	18

Ash and slag mixtures of TPS can be used as fine and coarse aggregates that meet the requirements of DSTU B V.2.7-29 regarding aggregates from industrial waste in various solutions and mixtures for general construction and road purposes. In particular, the production of concrete mixtures in accordance with the requirements of DSTU B V.2.7-211, DSTU B V.2.7-211:2009, as well as in the arrangement of unreinforced and reinforced crushed stone and gravel layers of the subbase of pavement in accordance with DSTU-N B V.2.3-39:2016. Ash and slag mixtures of TPS can also be used as mineral components of organo-mineral cold and hot mixtures for the arrangement of base layers, local roads pavement layers during their construction and reconstruction, as well as major and current repairs of public roads in all road and climatic zones of Ukraine according to DBN V.2.3-4:2015.If the requirements of SOU 42.1-37641918-104 are met, fly ash and slag mixtures of thermal power plants can be used for the following types of work: as a component for cement-concrete mixtures, for layers of rigid pavements as well as for crushed stone-sand and gravel-sand mixtures reinforced with cement. Ash-slag mixtures of group I are intended for the arrangement of additional draining and frost-protective layers of the base course of pavement, as well as a component of a gravel-sand mixture or a soil mixture. Ash-slag mixtures of the II group can be used for the construction of subbases only together with an additive of not less than 50 % crushed stone or after their strengthening with inorganic binders. Group III ash-slag mixtures can be used together with lime or cement to strengthen coarse-fragmented mixtures or loose soils.

Conclusions

Without intensifying the use of ash and slag materials in road construction, it will be impossible to achieve a high level of their utilization in Ukraine. The use of ash and slag materials in road construction is characterized not only by ecological and economic effects, but also allows to significantly improve the physical and mechanical indicators of individual layers of the road surface structure and the structure of the road surface as a whole, simultaneously increasing the service life of roads. The main factors preventing the full use of ash slag materials in road construction can be named: unformed market for ash slag consumption in the road industry; conservatism of the field of road construction; lack of incentives for the use of ash residues at the state level; the need to update and supplement state standards, building regulations, and estimated pricing. When studying the European experience of using fly ash in the road industry, it is possible to single out the following stimulating measures in this field for Ukraine. Namely, "green" public procurement – where decisions are made not only based on price criteria, but also taking into account the impact on the environment. The state is the largest consumer in the economy, so state procurement can generate significant demand for environmental products and services. Development of standards for ash slag products, which will provide an opportunity to establish the requirements that ash slag materials must meet for their use in road construction. Thanks to this, road construction customers will be able to be sure that, provided they purchase ash and slag products that meet this standard, the necessary quality standards will be met in road construction. Implementation of financial incentives (grants, credit guarantees, preferential loans, tax incentives) for enterprises that use or process by-products (ash and slag materials).

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ПЕРЕДУМОВИ ІМПЛЕМЕНТАЦІЇ ЄВРОПЕЙСЬКОГО ДОСВІДУ ВИКОРИСТАННЯ ЗОЛОШЛАКОВИХ МАТЕРІАЛІВ У БУДІВНИЦТВІ АВТОМОБІЛЬНИХ ДОРІГ: ОГЛЯД

Станом на друге півріччя 2019 року в Україні у відвалах ТЕС накопичилося близько 360 млн т золошлакових продуктів. З огляду на недостатні темпи розвитку інших джерел енергії, збереження статусу вугілля як важливого енергоресурсу у найближчі 15–20 років залишається, і відповідно, масштаб проблеми накопичення золошлаків збільшиться. Якщо не підвищити рівень утилізації

сьогодні, то обсяг відвалів до 2035 року зросте ще на 55 млн т. Підвищення рівня використання золошлакових продуктів – це питання загальнонаціонального масштабу. Національний поточний рівень утилізації золошлаків становить 8,3 %, що кардинально відрізняється від ЄС, де щорічно утилізується не менше 44 % золошлакових матеріалів. Досягнення високого рівня утилізації золошлаків передбачає створення зваженої екологічної та економічної політики держави, а саме: розробку стандартів для золошлакової продукції; запуск системи "зелених" державних закупівель; ініціювання реалізації програми будівництва цементобетонних доріг; застосування фінансових інструментів для стимулювання ресайклінгу; затвердження механізму компенсації витрат на перевезення шлаків залізничними шляхами. В ЄС основний напрям утилізації золошлакових матеріалів – це виробництво цементу та бетону, і близько 17 % золошлаків споживається на потреби будівництва доріг. В Україні галузь виробництва цементу та бетону вже використовує той максимум золошлакових продуктів, якого можливо досягти за поточного рівня активності будівництва. Однак, за даними "Укравтодору", Україна практично не використовує золошлакові продукти в дорожньому будівництві. Отже, дорожнє будівництво є важливим напрямком, що дозволить збільшити рівень утилізації золошлакових продуктів в Україні. Це дуже перспективний напрямок, оскільки в країні реалізуються масштабні проєкти з відновлення автомобільних доріг.

Ключові слова: ресайклінг у будівництві, європейський "зелений курс", автомобільні дороги, земляне полотно, золошлакові матеріали, зола виносу.