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Fly ash from coal power plants and its application - a step towards green building

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ABSTRACT

The utilization of fly ash, a byproduct from thermal power plants, in construction materials such as concrete, mortar, bricks, asphalt mixes, and binders for stabilization offers significant environmental and economic benefits. This comprehensive technical review delineates the historical background, current applications, and future potential of fly ash in reducing the construction industry's carbon footprint, particularly in Serbia. It outlines the successful integration of fly ash in various construction scenarios, emphasizing its role in enhancing material properties while contributing to sustainability by repurposing industrial waste. The document further explores the environmental advantages of fly ash use, highlighting its impact on lowering the carbon emissions associated with traditional cement and aggregate production. Through a detailed comparison of carbon footprints, the text argues for the adoption of fly ash in construction practices as a pathway towards achieving a carbon-neutral future. The discussion on the variable CO2 footprint of fly ash, influenced by production methods, underlines the importance of optimizing these processes to fully leverage its environmental benefits. This review underscores the need for the construction industry to embrace fly ash as a key component in materials, aiming for both performance improvement and sustainability, aligning with global efforts towards a CO2-neutral environment.

Keywords: fly ash, construction, sustainability, circular economy.

1. Status and Domestic Experiences in Research and Application of Fly Ash

TPP (thermal power plant) "Kolubara A", as the first thermal power plant within the current structure of Elektroprivreda (EPS) AD, Serbia conducted research on the utilization of ash to produce cement, lightweight concrete, aerated concrete, light aggregate, and sintered blocks. As a result of these activities, ash was supplied for the needs of the following companies: "Grmec" Belgrade, "Alkaloid" Skopje, "Kamnik" Slovenia, and other smaller consumers.

On June 6, 1980, an industrial trial production of cement with added ash was carried out at the Kosjeric Cement Factory, with a quantity of about 100 tons. During 1984, activities related to the application of ash were discontinued due to the lack of support from the management at the time (Miletić and Ilić 2007).

At the beginning of the 1970s, fly ash was used for soil stabilization in combination with cement when experimental sections were constructed on the route Lazarevac – Ibarski road, Beogradski bataljon street on Banovo Brdo, and then for making roads within the precincts of the Mining Institute in Belgrade, etc. Apart from announcing the results obtained on these test sections, there were no further advancements in the application of fly ash (Miletić and Ilić 2007).

During the 1980s, about 15 kilometers of roads were constructed around the ash landfills of "TENT A" and "TENT B" in Obrenovac, as well as on the streets of Obrenovac. All data on the methods and technology of embankment construction and aggregate mixtures with ash are unknown. The experts who worked on these projects are no longer alive, and it is not precisely known which companies were the contractors. Also, fly ash was used for the construction of access roads around the ash landfills in Kostolac (Miletić and Ilić 2007).

At that time, and currently, ash was practically only supplied to cement factories and, to a lesser extent, to brick and concrete prefab manufacturers.

As part of the reconstruction of the technology for receiving, low-water transport, and depositing ash and slag, reception capacities – silos from which dry fly ash shipment to potential customers was enabled for the first time have also been constructed. Currently, such facilities are operational at TPP Nikola Tesla B, TPP Kolubara A, TPP Kostolac B, and TPP Kostolac A, and construction is underway at TPP Nikola Tesla A.

With the data that around 300 million cubic meters of ash are in ash landfills, it should be mentioned that the "occupied" area under

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landfills exceeds 1400 hectares, with current production between 5 and 6.7 million tons annually (Miletić and Ilić 2007).

Since 1994, a series of activities have been undertaken to market fly ash, resulting in deliveries of ash to brickworks 'Trudbenik' and 'Komgrap', as well as to cement plants in Beocin, Kosjeric, and Novi Popovac.

By 2006, mostly from the ash landfills of the entire TENT, over 400,000 tons were delivered, including shipments from TPP "Kolubara" and TPP "Morava", which are part of the entire TENT complex, and today about 120-150,000 tons are delivered annually (Miletić and Ilić 2007).

2. Construction and Building Materials Made with or Including the Addition of Fly Ash

2.1. Building Infrastructure (such as roads, railways, and dams)

According to exceptional research by the Road Institute from Belgrade and Arcadis-Geotechnica from Prague, Czech Republic, for the needs of PE "Roads of Serbia", for the construction of embankments from fly ash with a height of 3 to 8 meters on bearing soil, when building a road 10 meters wide, around 100,000 tons of fly ash can be integrated per kilometer (Institute for Roads 2008). This means that for a length of up to 100 km (which is conditionally considered cost-effective for ash transport), it's possible to integrate about 10 million tons of fly ash. Compared to conventional materials, the savings in such a process range from 30 to 80%. For the construction of the trial section of the E 763 motorway ("Milos the Great Highway"), the Road Institute in 2015 prepared Technical Conditions for the construction of embankments from fly ash (Roads Institute 2015).

These technical conditions are intended for the use of fly ash produced by the combustion of coal in thermal power plants and stabilized fly ash - a mixture of fly ash with a binder (lime and/or cement) and water (SLP), for the purposes of road construction. They provide guidelines for design and determine the conditions for execution and control of the characteristics of the installed layers of embankments and active zones as well as conditions for safe work and environmental protection. For the work defined in these technical conditions, fly ash can be used from the point of collection directly at the power plants (dry ash without water treatment) or at central mixing facilities. The suitability of using fly ash, both with and without additives, for embankment construction is assessed (considering the purpose and location of the embankment and the significance of the communication), based on the knowledge of the geotechnical properties of the local soil at the construction site, properties of fly ash and stabilized fly ash, and the distance from the sources where it is obtained. Fly ash and stabilized fly ash are particularly suitable for constructing embankments on weak and compressible substrates with high groundwater levels, and for use in the transition zone between the embankment and bridge structures. As a result of the lower soil load from the embankment, smaller settlement values are also achieved.

In 2014, the Institute for Material Testing, in collaboration with the Faculty of Civil Engineering, conducted a study for the needs of PE EPS: "Use of Fly Ash and Slag Produced in the Thermal Power Plants of PE EPS for Railway Purposes" (Institute for Materials Testing 2015). The aim of the study was to conduct tests and research based on the most important common characteristics (chemical and mineral composition) of fly ash and slag from the Kolubara and Kostolac coal basins. This involved examining fly ash and slag produced in the Nikola Tesla A and B thermal power plants in Obrenovac and the A and B thermal power plants in Kostolac. The research was intended to define methods for rapid and technologically simple stabilization by adding basic components (lime, cement, etc.), so that the fly ash and slag incorporated into the substructure of the railway track, i.e., the solid track bed, would have appropriate stability and load-bearing capacity.

The widespread use in railway construction in Serbia would have significant environmental, economic, and practical importance. Railways are large linear construction projects that require substantial amounts of natural building materials (earth materials, sand, gravel, and crushed stone). A good portion of these materials can be replaced with fly ash and slag, contributing to environmental protection. The use of fly ash and slag also results in significant economic effects because they are inexpensive materials, and the method of installation is relatively simple. The study's results provide an assessment of the possibilities for using fly ash and slag in the construction and reconstruction of roadways such as main, regional, and local tracks, as well as railway handling and access areas in industrial and other facilities.

Based on the analysis of the results from conducted tests, the conclusions regarding the physical and mechanical characteristics relevant for assessing the applicability of fly ash and slag in the construction and reconstruction of railways are as follows (Institute for Materials Testing 2015):

1. The tested fly ashes belong to the silicate ashes (Class F) and mainly do not have self-cementing properties. Such fly ashes are most used with the addition of cement or lime. The research conducted has shown that the tested fly ash, even without binder additives, have acceptably good mechanical characteristics:
   - shear strength parameters (f and c) are within the ranges of f' = 31-330 and c' = 20-28 kPa for fly ash. For the stability of embankments, such shear strength parameters satisfy the design conditions related to the inclines of slopes.
   - based on the deformability parameters expressed through the modulus of compressibility, fly ash and slag can be classified in the category of soils with low compressibility. For instance, the moduli of compressibility for a stress range of 100-200 kPa range from 20,000 to 29,000 kPa for fly ash.
   - CBR (California Bearing Ratio) values, depending on the origin of the fly ash, can reach up to 55%.
2. The addition of binders to all tested materials has shown a clear trend of increase in all mechanical characteristics (Institute for Materials Testing 2015):
   - A moderate increase in the effective angle of internal friction over time and with an increase in the percentage of binders has been recorded f28 = 39-440, while in the case of cohesion, the trend of increase is moderate to significant c28 = 40-260 kPa.
   - Research has shown that some of the tested materials have significant CBR values even without the addition of binders. With the addition of binders, CBR values increase, and there is a general trend of significant increase over time (CBR28=75-235%).
   - The frost resistance index ranges from 70-86%. Although it is lower than the required 80% for some materials, it can be considered acceptable considering the high absolute values of uniaxial strength after 15 cycles of freezing and thawing.
   - Deformability parameters significantly increase over time and with an increase in the percentage of additives (for a stress range of 100-200kPa, Ms28=25000-90000 kPa).
3. The results indicate that the addition of lime as a binder or activator generally achieves a more significant improvement in engineering properties compared to the addition of cement, except in the case of deformability parameters, where cement has proven to be a more efficient stabilizer.
4. Based on the correlations between Ev2 and CBR values, it was concluded that the mixture of ash and slag from the landfill – TENT A without the addition of a binder can be used for embankment layers below the transition layer at a depth greater than 2.0 m. With the addition of 2% cement or 5% hydrated lime, this material meets the bearing capacity conditions of the transition layer and embankment layers at depths less than 2.0m below the transition layer. Fly ash from the silo - TENT B without binders meets the requirements for the

bearing capacity of embankment layers at depths less than 2.0m below the transition layer. With the addition of 2% cement or 5% hydrated lime, this material also meets the bearing capacity conditions of the transition layer (Technical Conditions for Substructure Layers - Draft Regulation on Technical Conditions and Maintenance of the Subsystem Infrastructure Substructure).

5. Although the presented results show a clear trend of positive effects, it is necessary to perform additional laboratory tests in each specific application to determine the properties of the selected materials (with or without binders) and define the optimal technology for executing the works.

6. Given that the tests have shown that the examined materials are suitable building materials for use in the construction of railway infrastructure, the following uses of ash and slag are proposed:

7. Stabilization of weak bearing subsoil (subgrade).

8. Construction of embankments from soil stabilized with ash (ash with the addition of lime or cement).

9. Construction of embankments from ash and with a core of ash.

10. Construction of a transition layer from ash with the addition of lime or cement (mandatory proof of frost resistance), during the construction of a new body or during rehabilitation/reconstruction

11. Construction of a transition layer by soil stabilization during the construction of a new body or during rehabilitation/reconstruction.

12. It is possible to apply stabilization with the addition of ash in the construction of the bearing layer under concrete or asphalt track bed.

13. The possibility of using ash and stabilization with ash at the transition from the bridge to the embankment needs to be examined. Railway regulations provide for cement stabilization.

14. Construction of roadway structures for access roads and manipulative surfaces at official sites.

2.2. Concrete

Fly ash has been successfully used in concrete production worldwide for more than 50 years. In Europe and the USA, about 30% of the produced fly ash is used as an additive in concrete, replacing part of the cement necessary for concrete production. Technical requirements for the use of fly ash in concrete are given in the SRPS EN 450-1 standard. This standard applies only to silicate ash, like the fly ash produced in thermal power plants in our country. When mixed with lime and water, fly ash has properties very similar to Portland cement (pozzolanic properties). Its price ($5 to $7 per ton in the USA) is very competitive with the price of cement, which is an additional incentive for its use in concrete.

Fly ash improves the properties and quality of concrete. It fills pores, and the spherical ash particles behave like balls in bearings, improving the workability of concrete. The binding rate of concrete with added ash is slower, allowing for longer workability in transportable concretes. Fly ash affects the plastic properties of concrete by reducing segregation and bleeding (leaching of calcium hydroxide from concrete) and lowering the heat of hydration in concrete. It increases the final strengths of concrete, density, reduces permeability, corrosion of reinforcement, increases sulfate resistance, and reduces the possibility of alkali-aggregate reaction.

Given the benefits of using fly ash for concrete production, concrete in its hardened state—with the addition of fly ash—exhibits improved properties:

- Higher strength. Fly ash contributes to an increase in strength over time as it continuously combines with the lime released in the hydration reaction of cement and water.
- Reduced permeability. The increased density and the prolonged pozzolanic action of fly ash result in a reduction of bleeding channels and lower permeability.
- Enhanced durability. The lower permeability of concrete with added fly ash also prevents the penetration of aggressive compounds, thereby reducing their destructive impact. Concrete with added fly ash is also more resistant to sulfate attacks, mild acids, and soft waters.
- Reduced alkali-silica reaction. Fly ash combines with the alkalis from the cement, which would otherwise combine with the amorphous silica from the aggregate, thus preventing destructive expansion.
- Reduced heat of hydration. The pozzolanic reaction between fly ash and lime generates less heat, resulting in reduced cracking due to heat development when fly ash is used as a partial replacement for Portland cement in concrete.
- Reduced efflorescence. Fly ash chemically binds free lime and salts that can create efflorescence. The reduced permeability of concrete with the addition of fly ash can help retain compounds that cause efflorescence within the concrete.
- Improved workability. Concrete is easier to place with less effort, reacts better to vibration, and fills molds more completely.
- Easier pumping. Pumping requires less energy, and greater pumping distances are possible.
- Enhanced finish quality. Sharp, clear architectural definitions are easier to achieve with less concern about the integrity of the finished product - concrete.
- Reduced bleeding. A reduction in bleeding channels decreases porosity and chemical aggression. Bleeding is reduced, which is particularly important for architectural finishes (exposed concrete). Improved paste and aggregate contact results in enhanced bond strengths.
- Reduced segregation. Improved cohesion in concrete with added fly ash reduces segregation, which can lead to pockets of unbound aggregate.
- Decreased slump loss. Adding fly ash to concrete allows for a longer workability time, especially at higher external temperatures, which is essential for more demanding concrete applications.

In high-performance concrete, it is possible to incorporate more than 20% fly ash without degrading the concrete's properties. On the contrary, some properties (e.g., resistance to corrosion) are noticeably improved. In structural concrete without high demands, it is possible to replace up to 50% of cement with fly ash. When fly ash is added to concrete, it reacts with calcium hydroxide to create stable hydrates of calcium silicate and calcium aluminate. The resulting concrete is not only stronger and more durable but also more impermeable (there is a notable reduction in the penetration of chlorides and sulfates). This makes the concrete more resistant to chemical agents and their aggressive effects. The addition of fly ash to massive concrete plays a significant role in reducing the formation of cracks due to the decreased heat of hydration release. The spherical shape of fly ash particles acts like ball bearings in the mixture, improving the workability and flow of the concrete.

Numerous significant constructions in Europe and around the world have been executed with the application of fly ash.

At the IMS Institute, preliminary tests of concrete with the addition of fly ash were conducted in accordance with the Regulations for Concrete and Reinforced Concrete (Institute for Materials Testing, 2011). The designed consistency is within the limits of 15±2 cm according to SRPS ISO 4109 (Determination of Consistency – Slump Test). The aggregate mix line was designed based on the nominal maximum aggregate size and the method of concrete installation, according to the boundary lines A and B from the standard SRPS U.M1.057. Such a designed line of aggregate mixture enables the production of concrete suitable for transport and installation.

For the preparation of preliminary tests, the following materials were used:

- Aggregate: "Moravac" river aggregate, washed, separated, fractions 0/4, 4/8, 8/16, 16/32 mm,
- Cement: PC 42.5R Lafarge, Beocn,
- Water: from the municipal water supply.

To examine the impact of ash on concrete properties, concrete samples were prepared by replacing 30% of the cement in the concrete mix with ash. Fly ash (from TENT A, TENT B, TPP Kolubara, TPP Kostolac A, TPP Kostolac B) was used in its original state, without any prior preparation such as sieving, grinding, etc. The testing of concrete samples was conducted according to the standards SRPS ISO 4848; SRPS ISO 6275; SRPS ISO 6276; SRPS ISO 4109; SRPS U.M1.032; SRPS ISO 4012; SRPS U.M1.015; SRPS U.M1.016; SRPS ISO 6274. The results of the concrete tests, considering the size of the ash particles, the fact that the ash does not comply with the requirements of the standard EN 450-1, and the amount of added ash, show that very satisfactory results were obtained. All concrete samples prepared with ash achieved satisfactory compressive strengths (above 30 MPa), indicating its possible and justified application in the preparation of concrete mixes.

2.3. Mortars

Mortars for masonry and plastering are exceptionally suitable for the application of fly ash, regardless of whether they are pre-prepared in a plant or on the construction site itself. It is possible to incorporate more than 50% fly ash into these materials. For the "in-situ" application of fly ash in mortars, it is necessary to prepare the appropriate fraction of dry fly ash in processing plants. This ash is then transported to the construction site in bags or tankers. It is used in standard mortar mixes for masonry and plastering as a replacement for a portion of cement and/or the fine fraction of aggregate. Sometimes, due to a potential increased need for water, the use of plasticizers may be necessary.

For testing, a standard cement mortar with ash, PC 42.5R Lafarge cement from Beocn, standard sand (SRPS B.C1.001:1976), and water in a ratio of 1:3:0.5 was prepared (Institute for Materials Testing, 2011). Mortars with ash were prepared by replacing 30% of the cement in the mortar with ash, while the ratio of other components remained the same. Fly ash (TENT A, TENT B, TE Kolubara, TE Kostolac A, TE Kostolac B) was used in its original condition, without any prior preparation such as scattering, grinding, etc. All mortar tests were conducted in accordance with the SRPS EN 1015-1 to 1015-19 standards, and the strength after 28 days was determined according to the SRPS EN 196-1 standard (Institute for Materials Testing, 2011).

The test results of mortars prepared by replacing 30% of the cement with ash show that all mortars prepared with fly ash achieved satisfactory compressive strengths (30 – 50 MPa), indicating its possible and justified application (Institute for Materials Testing, 2011).

2.4. Brick

In our country, ash, mainly from landfills, has been used for years in several brick manufacturing factories, where it replaces clay by 10 to 50%, mostly as a filler. In addition, numerous research projects have shown that by using a semi-dry pressing process, high-quality bricks can be produced by completely replacing clay with fly ash, and even producing lighter bricks with significantly improved thermal insulation properties (Institute for Materials Testing, 2011).

Fig. 1. Brick produced from 100% fly ash using semi-dry pressing technology (Institute for Materials Testing, 2011)

To define the application of fly ash in the production of brick products, mixes of brick clay (50 vol.%) and samples of fly ash from TENT A, TENT B, TE Kolubara, TE Kostolac A, and TE Kostolac B (50 vol.%) were prepared.

To determine the ceramic characteristics of the sample, the following tests were conducted:

1. Properties of the raw material after processing and homogenization,
2. Properties and behavior of the raw material in the shaping process,
3. Behavior of the raw material in the drying process and characteristics of dry products,
4. Behavior of the raw material in the firing process and characteristics of fired products.

By its granulometric characteristics, fly ash is classified in the group of fillers for use in the production of brick products. Therefore, mixes with ashes have a higher residue on the sieve than pure brick clay.

Additionally, ash as a filler leads to a reduction in drying shrinkage. All tested mixes of brick clay and ash have less sensitivity during drying than the original brick clay. Based on the position of the critical point on Bigot curves, all mixes are classified as sensitive during drying, while

Table 1. Physical-Mechanical Properties of Concrete Prepared with Fly Ash (Institute for Materials Testing, 2011)

Tested Parameter		TENT A	TENTB	TPP Kolubara	TPP Kostolac A	TPP Kostolac B
Concrete temperature	°C	17.0	17.0	18.0	17.0	17.5
Consistency, slump measure	cm	15	14	16	14	16
Bulk density of fresh concrete	kg/m3	2290	2288	2290	2295	2293
Bulk density of hardened concrete	kg/m3	2292	2298	2301	2298	2302
Contents of entrained air	%	1.0	1.0	0.8	0.9	1.1
Compressive strength after 28 days	MPa	29.9	30.5	33.1	32.8	30.3

Table 2. Physical-Mechanical Properties of Mortars Prepared with Fly Ash (Institute for Materials Testing, 2011)

Tested Parameter		TENT A	TENT B	TPP Kolubara	TPP Kostolac A	TPP Kostolac B
Spread of Fresh Mortar on Vibration Table	mm	194	193	194	194	195
Bulk Density of Fresh Mortar	kg/m3	2062	2065	2120	2102	2100
Bulk Density of Hardened Mortar	kg/m3	2115	2130	2140	2140	2140
Water Retention Capacity	%	84.5	84.5	83.5	81.1	80.7
Entrained air content	%	4.5	4.5	3.8	3.9	3.9
Flexural Strength after 28 Days	MPa	7.4	7.5	8.4	8.4	7.5
Compressive Strength after 28 Days	MPa	35.3	32.2	43.4	40.9	36.5

pure brick clay is classified as a very sensitive material. The addition of ash from power plants causes an increase in the plasticity of the mixes (Fefferkorn method). The plasticity coefficient of brick clay is 33.55, and the plasticity coefficient for mixes with ash ranges from 36.6 to 41.5. The compressive strength of dry samples made from mixes of clay and ash ranges from 3.03 to 4.14 MPa. The mechanical characteristics of fired samples were monitored through compressive strength, determined on full cube-shaped samples and block-shaped samples with vertical cavities. The impact of firing temperature on the change in mechanical characteristics was also monitored. For all tested samples, an increase in firing temperature results in an increase in the compressive strength of the samples. The compressive strength of cube-shaped samples made from mixes of brick clay and ash ranges from 13.47 to 53.26 MPa. The compressive strength of hollow block-shaped samples with vertical cavities made from mixes of brick clay and ash ranges from 8.17 to 26.73 MPa (Institute for Materials Testing, 2011).

Regarding the porosity of the fired samples, it increases for all mixes of brick clay and ash compared to fired samples made from pure clay. The porosity of the fired samples was monitored through the determination of water absorption and bulk density. The porosity of all tested samples decreases with increasing firing temperature, which results in reduced water absorption and increased bulk density of the fired samples. The water absorption for fired samples made from mixes of brick clay and ash is 17.61 – 27.27%. Correspondingly, with the increase in porosity, the net bulk density decreases. The bulk density for fired samples made from mixes of brick clay and ash is 1.39 – 1.85 g/cm³. Based on the results of the conducted tests, it can be concluded that the examined fly ashes from power plants can be used as raw material in mixes with brick clays to produce brick products. Tests have shown that ash can be mixed with clay in amounts exceeding 50 volumetric %, and still produce brick products that meet domestic and EN standards (Institute for Materials Testing, 2011).

With the application of semi-dry pressing technology, it is possible to produce bricks of satisfactory quality with 100% ash content - Figure 1. Considering the capacities of existing brick product manufacturers in our country as well as the possible share of fly ash in production, the application of fly ash in quantities of up to a million tons per year is possible.

2.5. Binders for stabilization

In all prepared samples of binders for stabilization, whether lime and/or cement were used as the binder, satisfactory test results were obtained. It is noted that for each specific project, it is necessary to optimize the ratio of binder and ash according to the project requirements.

2.6. Asphalt Mixes

Tests were conducted on the feasibility of using fly ash as a component in the production of asphalt mixes for the wearing layer of asphalt concrete AB 8. The preliminary composition of the asphalt mix for the wearing layer of asphalt concrete AB 8 was determined using fly ash samples from TPP Kolubara, TPP Kostolac A, TPP Kostolac B, TENT A, and TENT B. The mix design was guided to ensure that the mixes meet the prescribed quality criteria according to the SRPS U.E4.014 standard. For determining the preliminary composition of the asphalt mix AB 8, the following component materials were used (Institute for Materials Testing, 2011):

Mineral materials:

- Stone flour “Batocina”-Batocina.
- Crushed sand 0/4 mm “Ladne vode” - Petrovac na Mlavi, Serbia.
- Stone trinkets 4/8 mm “Ladne vode” - Petrovac na Mlavi, Serbia.
- Fly ash originating from thermal power plants TENT A, TENT B, TPP Kolubara, TPP Kostolac A, TPP Kostolac B
- Bitumen BIT 60 Pancevo, Serbia.

For the preparation of the preliminary composition of the asphalt mix AB 8, bitumen BIT 60 Pančevo was used, which meets the quality conditions according to the SRPS U.M3.010 standard. The BIT 60 Pancevo bitumen sample was tested according to the parameters necessary for determining the preliminary composition of the asphalt mix AB 8, and the obtained results satisfy the quality conditions given in SRPS U.M3.010. Mixes in which stone flour was replaced with ash were made to test the possibility of using ash for the preparation of asphalt mixes AB 8 (Table 5).

Table 3. Physical-Mechanical Characteristics - Hydraulic Binder for Road Stabilization (Institute for Materials Testing, 2011)

Fineness of Grinding, %		Volume Stability	
• sieve residue 0.09 mm	6.50	• cakes	steady
• specific surface area (Blaine), cm²/g	5180	• Le Chatelier, mm	0.5
Bulk density, g/cm³	2.92	Strengths, MPa,	
Bulk density, g/cm³, kg/m3		• flexural, after	
• loose state	960	3 days	2.3
• compacted state	1520	7 days	3.9
Water for Standard Consistency, %	24.2	28 days	5.5
Setting Time, h, min • start • end	03:15 04:15	• compressive, after 3 days 7 days 28 days	8.4 14.4 20.6

Table 4. Physical-Mechanical Characteristics - Hydraulic Binder for Road Stabilization 2 (Institute for Materials Testing, 2011)

Fineness of Grinding, %		Volume Stability	
• sieve residue 0.09 mm	9.50	• cakes	steady
• specific surface area (Blaine), cm²/g	6220	• Le Chatelier, mm	1.0
Bulk density, g/cm³	2.89	Strengths, MPa,	
Bulk density, g/cm³, kg/m3		• flexural, after	
• loose state	860	3 days	-
• compacted state	1420	7 days	4.8
Water for Standard Consistency, %	28.7	28 days	6.3
Setting Time, h, min • start • end	02:15 03:15	• compressive, after 3 days 7 days 28 days	- 18.8 26.4

Table 5. Physical-mechanical properties of designed asphalt mixtures - fly ash (Institute for Materials Testing, 2011)

Characteristic	TENT A	TENT B	TPP Kolubara	TPP Kostolac A	TPP Kostolac B
Stability at 60°C, (kN)	14.4	13.8 (13.7)	14.8	14.9	13.8
Flow at 60°C, (mm)	3.7	3.8 (3.9)	3.8	4.2	4.8
Ratio of Stability to Flow at 60°C, (kN/mm)	3.9	4.0 (3.5)	3.9	3.5	2.9
Voids in Asphalt Sample, % (v/v)	4.8	4.7 (3.8)	3.7	3.9	3.4
Voids in the asphalt sample, % (v/v)	78	78 (82)	81	82	83.5
Bulk density of the asphalt sample, (g/cm3)	2.281	2.313 (2.324)	2.365	2.340	2.340
Apparent volume mass of asphalt mixture, (g/cm3)	2.396	2.427 (2.416)	2.456	2.435	2.422
Optimum binder content, %	7.7	7.5 (7.7)	6.9	7.2	7.8

Mineral mixes were tested with BIT 60 Pancevo bitumen content ranging from 5.0 to 8.0%, depending on the optimal bitumen content in the asphalt mix. For the applied BIT 60 Pancevo bitumen, the optimal temperatures of the asphalt mix are:

- Exiting the asphalt plant mixer 160±10°C, max 175°C,
- At the installation site 150±10°C, min 140°C,
- Marshall specimens were compacted with 2x50 blows at a temperature of 150±3°C.

Asphalt mixtures with the addition of fly ash met the requirements in terms of the granulometric composition of the mineral mixture for the asphalt mixture type AB 8, and the physical-mechanical properties of the asphalt mixture (stability parameter, flow, void content in the asphalt sample, and void content in the mineral mixture filled with binder).

2.7. Innovative Solutions - Wastewater Filter

Ash has always been officially recognized as a handy or auxiliary means for fire extinguishing, as stated in the fire protection regulations in Serbia, Montenegro, and other European countries in the past. Examples of using ash to extinguish fires have been present in the mines of EPS in Kosovo since the 1980s, with the use of machinery in both underground and surface mining. Since the ash produced by EPS ad contains a low organic material content (below 2%) and the loss on ignition is almost negligible, it serves as an ideal medium for traditional methods of extinguishing surface fires by covering, in places where sand, soil, or similar materials were used. With the addition of ash-based mixtures, they have proven successful in sealing fires on slopes and layers, by cutting off the oxygen supply that enables combustion at greater depths of the landfill. For the specific extinguishing of landfill underground fires and aboveground mixtures of mineral raw materials with ash, it has been tested on multiple sites and used to extinguish fires below the surface (coal pits, coal landfills, industrial and municipal landfills) (Karanac et al. 2018).

A technical solution has been chosen for extinguishing fires at landfills in Niksic, Becej, as well as one of the selected solutions for the remediation of an underground fire in Vinca, Belgrade. Ash is mentioned in the Fire Extinguishing Report for the Mislov Do Niksic landfill as the most favorable technical solution offered for closing the decades-long fire at this landfill. A new method for extinguishing underground fires at the Vinca landfill was presented as a solution based on an ash hydraulic mixture, which was approved by the Client. The mineral mixture was applied from 30 to 60 meters away. For this purpose, the company Tekon techno-consulting from Belgrade developed special equipment and a formula for this application, and this project completed all competition cycles for obtaining development funds from the Innovation Fund. This solution is especially useful in situations where water cannot be used or is ineffective, or when extinguishing with water leads to the washing away of layers and re-ignition of underground fires. Dry and wet ash-based mixtures have recorded excellent results under all conditions. Leaching tests showed that the product is within the LCV for the stated application (Karanac et al. 2018).

Fig. 2. Ash-based mineral mixture for fire extinguishing purposes - test

3. *Carbon Footprint*

Sustainability is today widely recognized as an economic, social, and environmental issue. A major challenge for all assessments is balancing various factors that often have different units of measurement; for example, how to compare biodiversity, health and safety, and CO_2 emissions from transport? As a result, it is accepted best practice for designers not only to adhere to a mindset of using assessment tools but to also understand the factors and take a holistic and life-cycle view of sustainability when considering their projects. Europe harbors an ambitious vision for a carbon (CO_2) neutral future, a vision that integrates energy-intensive industries as well as the construction sector and its entire value chain. Cement, the binder in concrete, is central to turning this vision into reality (European Cement Association, 2023, UK Quality Ash Association, 2023).

These solutions cover the entire life cycle of the cement and concrete value chain: from raw materials to production, use, reuse, and recycling. As part of the effort to move toward a construction sector without a carbon footprint, the progress of the cement industry since the publication of the roadmap to 2050 and mapped pathways to a resource-efficient and CO_2-free built environment have been considered (European Commission 2023).

Over the past decades, continuous improvements in Europe have led to a reduction in the energy used in cement production by about 30%. Five years ago, the European cement industry published its low-carbon roadmap outlining how to reduce CO_2 emission intensity by 32% (compared to 1990 levels) by 2050 using conventional technologies, and potentially by 80% if revolutionary technologies become widely available (European Commission 2023). Due to the European decarbonization agenda, there is less availability of clinker substitutes, such as blast furnace slag and fly ash from the energy sector, compared to other regions of the world. Importantly, differences in cement quality arising from different performance and durability requirements of constructions worldwide make the direct comparison of clinker-to-cement ratios in different regions challenging. From the perspective of the entire construction value chain, the quality of cement and its performance in concrete also complicate global comparisons of clinker-cement ratios (European Commission 2023).

The European industry, including the construction sector, needs to be neutral, circular, yet remain competitive. This is no easy task, especially in a globalized world. Therefore, there's an interest in looking beyond the factory gates, focusing on how a neutral approach to materials and performance based on the lifecycle that considers the entire value chain can yield tangible results.

Efforts to reduce the amount of clinkers in cement are well underway, with the clinker-to-cement ratio reduced to 76.4%. The uncertain sustainable availability of clinker substitutes is a major limitation. CEMBUREAU has forecasted an average clinker-to-cement ratio of 70% by 2050. The cement industry continuously reduces the clinker content in cement, replacing it with other active elements such as fly ash, blast furnace slag, pozzolans, or limestone to reduce CO_2 emissions. The cement industry is also exploring the potential for developing low-CO_2 binders (European Cement Association 2023).

Cement is primarily used as a binder in concrete. Thanks to its durability, concrete structures can last 100 years or more, meaning resources and emissions are dramatically reduced compared to construction materials with shorter lifespans. Not least, concrete can be 100% recycled at the end of its life. Nonetheless, the carbon footprint per ton of concrete can be further reduced by using low-clinker cement, more efficient usage, mix optimization, aggregate packaging, and additives for fine-tuning, while still delivering the same performance and strength. The use of fly ash in concrete, either as an additive or through factory-produced cement, can significantly reduce the total greenhouse gas emissions associated with concrete production. Table 6 and 7 shows carbon footprint in cement and aggregates.

Table 6. Carbon Footprint in Cement Without and With Additives (European Coal Combustion Products Association Home 2023)

Cement and Additives		Carbon Footprint (kg CO2/ton)
Portland cement, CEM I		930
Mineral additives to cement	Granulated blast furnace slag	52
	Fly ash	0
	Limestone	32
	Minor additives (gypsum, etc.)	32

Table 7. Carbon Footprint of Aggregates (European Coal Combustion Products Association Home 2023)

Material	Production of material kg CO2/ton	Transport kg CO2/ton	Total kg CO2/ton
Natural aggregates	6.6	2.7	9.3
Recycled aggregates from construction and demolition	7.9	0.0	7.9
+ Distance for delivery	7.9	2.7	10.6

According to the latest data from the ECOBA General Assembly held in November 2023, it is expected that by early 2024, a CO_2 footprint ranging from 0 - 20 (kg CO_2/ton) will be adopted for fly ash, depending on the operational costs of producing fly ash (due to a lack of fly ash in the market, there is an increasing use of processed (crushing, drying, milling, etc.) ash from old landfills, which contributes an additional emission of about 20 kg CO_2/ton). According to EUROSTAT data, the value of CO_2 Allowances, i.e., EU Carbon Permits" in the EU has reached 100 EUR/t.

Conclusion

This technical review presents a comprehensive overview of the research, application, and benefits of fly ash in various construction materials and environmental solutions, highlighting its potential in reducing the carbon footprint of the building industry. Initially, the document outlines the historical and recent developments in fly ash utilization in Serbia, illustrating its application in concrete, mortar, brick, asphalt mixes, binders for stabilization, and innovative solutions such as wastewater filters and fire extinguishing. The engagement with fly ash not only diversifies the use of construction materials but also contributes to environmental sustainability by repurposing waste products from thermal power plants. The latter sections delve into the environmental and economic benefits of incorporating fly ash into construction materials, significantly highlighting its role in lowering the carbon footprint associated with cement production and usage. By comparing the carbon footprints of traditional cement and aggregates to those with added fly ash, the text underscores the importance of adopting fly ash in construction practices to achieve a carbon-neutral future. The acknowledgment of fly ash's variable CO_2 footprint, based on operational costs, emphasizes the need for sustainable production methods to maximize its environmental benefits. In summary, the article supports the idea of using more fly ash in the building sector to improve material characteristics, cost-effectiveness, and environmental sustainability. This aligns with Europe's goal of achieving a carbon dioxide-neutral future.

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