Road building using wood ash

Dimter, Sanja; Kuburić, Goran; Ević, Ernest; Vrhovac, Goran

Source / Izvornik: **Građevinar : časopis Hrvatskog saveza građevinskih inženjera, 2024, 76, 1077 - 1086**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.14256/jce.4157.2024

Primljen / Received: 17.10.2024.
Ispravljen / Corrected: 18.11.2024.
Prihvaćen / Accepted: 25.11.2024.
Dostupno online / Available online: 10.1.2025.

Road building using wood ash

Autohrs:

Prof. **Sanja Dimter**, PhD. CE
Josip Juraj Strossmayer University of Osijek
Faculty of Civil Engineering and Architecture Osijek
sdimter@gfos.hr
Corresponding author

Goran Kuburić, ing.mech.
Strizivojna Hrast d.o.o., Strizivojna
goran.kuburic@strizivojna-hrast.hr

Ernest Ević, MCE
Institut IGH d.d. RC Osijek
ernest.evic@igh.hr

Goran Vrhovac, MCE
Institut IGH d.d. RC Osijek
goran.vrhovac@igh.hr

Preliminary note

Sanja Dimter, Goran Kuburić, Ernest Ević, Goran Vrhovac

Road building using wood ash

This paper describes the specifics of constructing a test section of an internal road where wood ash was used to improve the bearing capacity of the subgrade and to construct the base layer of the pavement structure. Laboratory testing and field control testing were conducted during the construction. The results showed that the increase in the bearing capacity of the subgrade by applying stabilization with wood ash ranges from 155 to 235 % compared to the natural clay subgrade. Due to the binding properties of wood ash, the bearing capacity of the subgrade continues to increase even after construction, with an observed increase of 31 to 39 % in bearing capacity within 14 days of construction. The base layer made of wood ash of different fractions achieved compressive modulus Ms = 60 to 80 MN/m², thus meeting the bearing capacity criteria. The experiences from the test section confirm the potential of wood ash for use in improving subgrade bearing capacity and in the construction of the base layer of pavement structures. This could encourage more rational and economical design and construction of pavement structures, especially in areas with large amounts of waste ash from wood biomass, such as the region of Slavonia.

Key words:
sustainable development, wood ash, internal road, test section, quality control

Prethodno priopćenje

Sanja Dimter, Goran Kuburić, Ernest Ević, Goran Vrhovac

Izgradnja ceste primjenom drvnog pepela

U radu su opisane posebnosti izgradnje pokusne dionice interne ceste u kojoj je drvni pepeo upotrijebljen za poboljšanje nosivosti posteljice te za izvođenje nosivog sloja kolničke konstrukcije. Tijekom izgradnje provođena su laboratorijska ispitivanja te terenska kontrolna ispitivanja. Rezultati su pokazali kako povećanje nosivosti posteljice primjenom stabilizacije drvnim pepelom iznosi 155 do 235 % u odnosu na prirodnu glinovitu posteljicu. Zbog vezivnih svojstava drvnog pepela nosivost posteljice nastavlja rasti i nakon izvedbe te uočeno povećanje nosivosti posteljice (14 dana nakon izvedbe) iznosi od 31 do 39 %. Nosivi sloj izveden od drvnog pepela ostvario je module stišljivosti Ms = 60 do 80 MN/m² te tako udovoljio kriterijima nosivosti. Iskustva s pokusne dionice potvrđuju potencijal drvnog pepela za primjenu u poboljšanju nosivosti posteljice i za izradu nosivog sloja kolničke konstrukcije te mogu biti poticaj za racionalnije i ekonomičnije projektiranje i izgradnju kolničkih konstrukcija, posebno u područjima s velikim količinama otpadnog pepela iz drvne biomase kakvo je područje Slavonije.

Ključne riječi:
održivi razvoj, drvni pepeo, interna cesta, pokusna dionica, kontrola kvalitete

1. Introduction

The application of local materials, natural or improved, in the pavement structures of road can significantly rationalize the cost of construction, primarily through the cost of transportation, which in the cost of materials can be significant. In addition to local materials, the economical construction of the pavement structure can also be achieved by exploiting the potential of waste materials and industrial by-products that arise as technological waste. These are materials that require complex disposal of significant amounts in landfills, whose application has significant economic justification and is clearly encouraged by the Sustainable Development Guidelines [1]. The application of some local material, if not covered by existing standards, requires detailed laboratory tests and the performance of the test section and the fine-tuning of the execution technology. The same is true for waste materials or industrial by-products. To be applicable, these materials must meet certain engineering characteristics, demonstrate an acceptable level of performance and be cost-effective comparable to traditional materials [1].

The concept of the use of local materials, natural or improved, has a special role in the construction of economic roads [2]. Economic roads, unlike public roads, are simple buildings for the transport of vehicles and machines for agriculture and forestry. In addition to economic roads, the use of local materials is also significant for the construction of site roads, which must ensure undisturbed dynamics of construction with their bearing capacity and condition of the surface. Both groups of these roads are almost always carried out with minimal costs and usually as earth roads. This method of performance is certainly the most cost-effective, however not the best from the point of view of load-bearing capacity. The earth road is made from the local soil at the construction site, to which coarser or finer grains of sandy-gravel material or dust material can be added to improve the bearing capacity and granulometric composition. These roads, although of sufficient load-bearing capacity in dry weather, become significantly deformable in rainy weather and especially in the case of clay soils, make it difficult or impossible to move vehicles or machines. Therefore, increase of strength and resistance to deformation is necessary, and to achieve it, one should resort to various stabilization procedures. In addition to mechanical stabilization, it is possible to improve the local soil chemically, by adding various standard binders such as cement, lime or bitumen. This stabilized soil can serve as driving surface for the movement of vehicles and machines or as a base for the pavement structure above. The suitability of each binder is conditioned by the basic properties of the soil, so lime will be used for clay soils, while cement and bitumen will be used to stabilize fine grain incoherent soils. In addition to the traditional binders, it is possible to use binders based on synthetic polymers, enzyme-based products, ionic products, as well as lignin and resin [3] for stabilization. These are the products that can be used independently or in combination with traditional binders (cement, lime), which significantly enhance their action. Regardless of the modern product type in soil stabilization, their price is significantly higher than the price of standard binders and perhaps that is why these products are used very rarely in our country.

Unlike the binders mentioned above and the costs of their application, in the economical construction of roads, waste materials and industrial side-products are offered which are free of charge and have a great potential as well as various applications. Some of the materials, particularly fly ash generated from coal combustion in thermal power plants or metallurgical slag, and more recently various types of bio-ash produced from the combustion of biomass from agriculture and forestry, possess good pozzolanic properties, making them suitable as standalone binders or as additives to binders. The application of these materials offers multiple benefits and rationalization of construction costs through:

- reducing the amount of required hydraulic binder in the mix
- improving the properties of mixtures
- reducing the amount of waste material in landfills
- adding value to the waste material [4].

Given that such non-standard material, wood ash, used in the construction of the test section, which is the subject of the paper, a brief overview of the properties of wood ash and its potential application in road construction will be provided in the following sections of the paper.

2. Wood ash: properties and possibility of application

Wood ash is formed as a residue when burning wood biomass to produce electricity and heat and consists of existing (part of organic structure or mineral particles due to biomass during collection and processing) and newly formed inorganic substances that arise in the process of burning and often a smaller proportion of unburned organic matter, moisture and gases [5]. According to the European Waste Catalog, wood ash is classified as non-hazardous waste (currently it is mostly treated as such) and is disposed of in waste landfills and (to a much lesser extent) in agricultural and forested areas. The quantities, quality, physical and chemical properties of wood ash depend on the type and burned part of the wood biomass, the mineral impurities content, the location where biomass grew, the method of collecting and processing biomass, the technology and the combustion temperature [5]. During the combustion of biomass, three different fractions of ash are formed: bottom ash, cyclone fly ash and filter fly ash. Bottom ash consists of the coarsest fractions of ash (particles larger than 100 μm) that are collected beneath the boiler grid. It is often mixed with impurities such as sand, soil, or material from the seat when burning in a fluidized bed. Cyclone fly ash is the coarser fraction of fly ash (particles ranging from 5 μm to 100 μm) that is carried by the flue gases into the secondary combustion zone. The finest fraction is filter fly ash, which is collected on electrostatic filters (particle size from 1 to 5 μm).

The potential of application of wood ash in construction was early recognized and was the subject of numerous studies that have determined that the effect of ash in mixtures can be indirect and immediate. In immediate action, ash with its granulometric composition repairs the composition of the basic material of the mixture (mechanical stabilization), while in indirect action, ash with its chemical composition initiates certain chemical reactions because of pucolan activity or hydraulic binding of ash, which ultimately improve the properties of the mixture. The content of CaO and Pozzolana in the chemical composition of wood ash suggests the possibility of partial or complete replacement of binders (cement and lime) when stabilizing poorly load-bearing materials of subgrades, in the base courses of pavement structures, or in concrete mixes. In the case of a slightly weaker effect in the mixture, cement or lime can be added to the ash as an activator. In addition to being used as a binder, wood ash can be used as a replacement for mineral filler in asphalt mixtures or as an aggregate in the base courses of pavement structures. The place of application will depend on the fraction of the wood ash.

The most numerous studies on the application of bioash in road construction have been conducted on the stabilization of clayey and sandy materials in the subgrade, and the results have shown that the proportion of traditional binders for subgrade stabilization (lime or cement) can be significantly reduced or completely replaced with wood ash, while still maintaining the engineering properties of the mixtures within the required limits [9-16].

Cyclone fly ashes and bottom ashes have found their application in the base courses of the pavement structure where they can improve the load-bearing capacity and behavior of the layer through mechanical stabilization effect or their binding properties. The potential application of different fractions of bioash in unbound and cement-stabilized base courses of pavement structures has also been investigated, and the results obtained indicated improved physical-mechanical engineering properties of mixtures with the addition of bioash.

Good foreign experience and results of research on the application of wood ash have encouraged the cooperation of the Faculty of Civil Engineering and Architecture Osijek with the company Strizivojna Hrast d.o.o. from Strizivojna in 2017 when the first ash stabilization tests were carried out [9]. The cooperation was intensified and expanded by the implementation of a scientific research project entitled "Application of ash from wood biomass in the base courses of pavement construction (BioPAV)" in 2019 [24]. The interest in cooperation was mutual: To determine the extent to which it is possible to use the potential of wood ash in sustainable construction of roads and thus to encourage more economical and rational construction of roads and ultimately contribute to the well-being of the economy of the region or county. After conducting complete laboratory research with wood ash, on different mixtures and for different layers, a test section was performed on the internal road in the circle of the factory Strizivojna Hrast d.o.o.

3. Performance of the test section of the internal road with wood ash

3.1. In general

Strizivojna Hrast d.o.o. is a company founded in 1996 in Strizivojna near Đakovo in Osijek-Baranja County, which deals with wood processing and production of parquet and other wood products. The industrial plant of the company Strizivojna Hrast d.o.o. covers an area of 5.6 hectares and consists of a sawmill, workshops to produce wood products, covered sheds for the natural drying of wood elements, and other supporting buildings, as well as a cogeneration plant for the production of electrical and thermal energy [25] (Figure 1.).

Each day, about 110 t of wood biomass is burned in the cogeneration plant and the amount of wood ash that is produced daily is considerable. On an annual level, the amount of wood ash generated is about 700 t. The wood mass used as fuel consists of wood waste and bark generated during the processing and production of wood products, as well as wood chips (forest biomass), where only clean, untreated wood biomass is used. The 3.3 MW cogeneration plant for electricity and 2x3 MW for thermal energy is also the first biomass cogeneration plant commissioned in Croatia in 2011 [25]. Currently, wood ash is registered in the by-products register under serial number NUS 268 [27], and it is used for agricultural purposes as fertilizer, soil conditioner, and for neutralizing soil acidity.

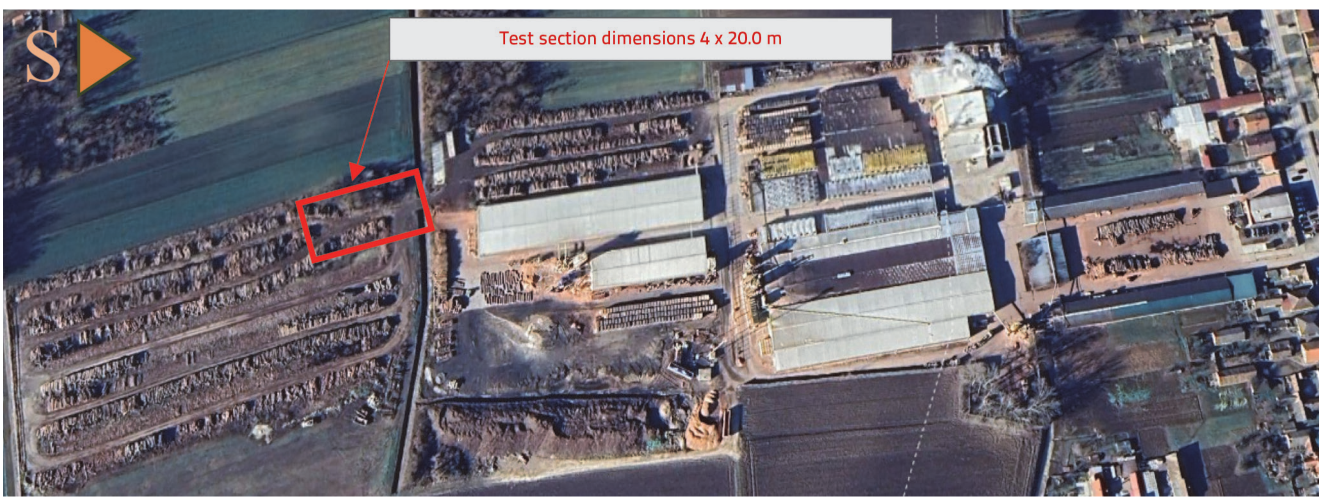

Figure 1. Industrial complex of the company "Strizivojna Hrast d.o.o." in Strizivojna with the position of test section [26]

Since 2013, on several occasions, base courses made of wood ash have been used in the construction of road structures for internal roads and traffic surfaces within the Strizivojna Hrast d.o.o. factory complex [25]. The idea for this application was motivated by the large quantity of wood ash at the landfill, and the company's employees, without prior knowledge of the suitability of wood ash for road construction, decided to construct roads and traffic surfaces with minimal investment. The pavement structures were of different thickness and composition; the base course made of wood ash was constructed in thicknesses of 50-100 cm, while the surface layer was made of a mixture of crushed stone with a thickness of 10 cm. Some pavement structures were constructed without a crushed stone surface layer, only with a base course of wood ash. By monitoring the behavior of internal roads and traffic surfaces constantly exposed to the movement of heavy trucks and controlling their load-bearing capacity, it was determined that the roads meet the load-bearing requirements and allow for the smooth passage of vehicles. The measured compressive modulus on the unbound stone surface layer ranged from 50 to 100 MPa [25].

3.2. Performance of the test section

The location of the test section was chosen based on interviews with representatives of the factory, and it is located at the branching of access roads (Figure 1.), which daily move heavy vehicles. Access roads (five of them) are 4 m wide and 200 m long and traffic on them is organized circular. Wooden logs are being deposited on both sides of the access roads, and every day, 8 to 10 heavy trucks with forestry trailers, weighing 36 to 40 tons, travel on the roads.
In June 2023, the construction of a test section began, in which wood ash was used for the construction of the base course and for the improvement of the subgrade [28]. Mixed wood ash (a mixture of all three fractions of wood ash) was used in the construction from a landfill near the test section.
Test section of 80 m^2 was performed in two phases:
Test field 1, in which the pavement structure was performed in a natural subgrade, was performed in June 2023, and in September 2023 Test field 2 was performed with a subgrade enhanced by adding wood ash (Figure 2.). All the work related to excavation, planning, mixing and compaction was carried out by employees of "Strizivojna Hrast d.o.o.", with a mechanization available at the time.

3.2.1. Properties of soil in which the test section was performed

The test section was performed in the medium plastic inorganic clay CI whose natural moisture was 24.4 %. The yield point of the material was 39.99 %, the plasticity limit was 22.20 % and the plasticity index was 17.79 % [29]. The laboratory-determined value of the California bearing ratio (CBR) index was 2.0 % while the swelling was not (0.0 %) [30].
The tests related to bearing capacity of the subgrade as well as the tests related to bearing capacity of the base course on the test section were carried out by a dynamic plate and the resulting dynamic deformation module (EVD), and correlation with the static compressibility modulus determined the value of the compressive modulus (MS)

Figure 2. Test section with test fields [26]

3.2.2. Test field 1 from km 0+000 to 0+010.00

On Test field 1 the pavement structure is performed on a natural subgrade, and its composition is shown in Figure 3.

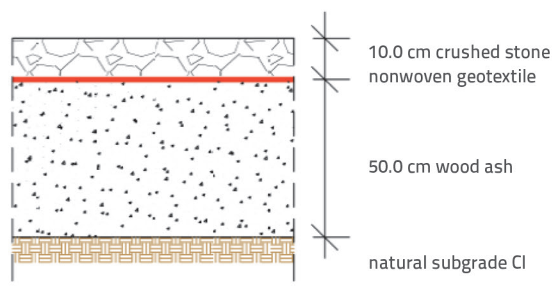

Figure 3. Composition of the pavement structure – Test field 1

The test section had to be cleared of various (waste) construction materials (broken bricks, crushed remains of concrete slabs and blocks) as well as remnants of roots and branches before the actual excavation. After cleaning, excavation of the soil was carried out, followed by leveling and compaction of the subgrade (Figure 4.). When planning the subgrade, a cross slope of 4 % was taken into consideration to allow for the drainage of percolated

Figure 4. Planned and compacted subgrade at Test field 1

Figure 5. Filling of the base course with wood ash

water. The load bearing capacity of the subgrade was controlled in several places and the average compressive modulus was MS = 12.0 MN/m^2. Mixed wood ash from the landfill was applied and planned on the compacted and tested subgrade (Figure 5.). The ash was deposited in layers, with a final thickness of 50 cm, and the compaction of the wood ash was carried out using a 5-ton roller with vibration (Figure 6.).

Figure 6. Compaction of the base course with wood ash

After the control of the bearing capacity of the wood ash layer (MS = 60 to 80 MN/m^2), a non-woven geotextile 100 g/m^2 (Figure 7.) was implemented on which an unbound layer of crushed stone was installed in the thickness of 10 cm. The granulometric curve of the stone mixture was used to perform the surface layer deviated from the curve defined by the General technical conditions for road works OTU [31] because crushed stone was used to create the surface, which was available in stock at the factory. The maximum grain in the crushed stone mixture was 200 mm. After spreading and leveling the surface layer, compaction of the layer was carried out, as well as testing its load-bearing capacity (Figure 8.). The compressive modulus measured at 6 points on the unbound stone layer ranged from 55.5 to 72.0 MN/m^2. The compressive modulus as a load-bearing indicator was measured again in the same places three months after its implementation and then the load-bearing capacity of the surface layer was higher, more uniform, and was 71.5 to 80.90 MN/m^2.

Figure 7. Geotextile on the base course with wood ash [32]

Figure 8. The constructed unbound pavement of the internal road made of crushed stone [32]

3.2.3. Test field 2 from km 0+010.00 to 0+020.00

On Test field 2, a subgrade stabilized with wood ash was performed, and the composition of the pavement structure is shown in Figure 9.

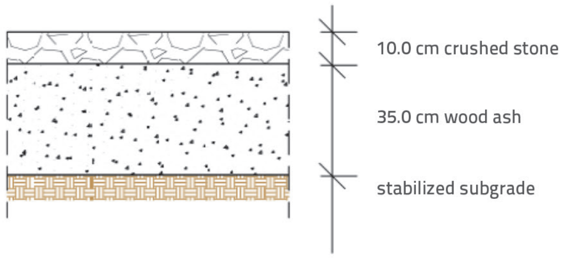

Figure 9. Composition of pavement structure – Test field 2

After the soil was dug up, in the immediate vicinity of the Test field, the crushed material from the excavation with mixed (all three fractions) wood ash was mixed with an excavator (Figure 10.). After achieving a sufficiently homogeneous mixture of soil and ash in equal proportions (50 % : 50 %), the mixture was scattered (Figure 11.) and planned on the subgrade and compacted in a layer of 15 to 17 cm thick (Figure 12.). The bearing capacity was tested using a dynamic plate immediately after compaction at multiple locations on the subgrade, which showed compressive modulus Ms = 30.7 to 8.4 MN/m². Because wood ash has binding properties that develop over a corresponding period of time, the bearing capacity was controlled even after 14 days from compaction, and the obtained results of the compressive modulus were higher and amounted to MS = 35.4 to 49.3 MN/m². After the bearing capacity of the subgrade was checked, a mixed wood ash layer, 35 cm thick, was placed, leveled, and compacted. The wood ash layer was compacted using a 5-ton vibrating roller. An unbound crushed stone layer, 10 cm thick, was placed over the base course, and the compressive modulus measured on the unbound stone layer ranged from 72.8 to 83.9 MN/m². Despite the absence of a nonwoven geotextile, the measured moduli of compressibility were like those measured three months after the construction of the first test field.

Figure 10. Mixing of wood ash and crushed material from excavation [32]

Figure 11. The spreading of the mixture of wood ash and material from the excavation

Figure 12. The compaction of the subgrade stabilized by wood ash

From the moment the test section was performed, heavy duty vehicles with forestry trailers loaded with wood logs are driven daily (Figure 13.). The construction of the test section is in an excellent condition, no deformation or other types of damage to the curtain is observed. In June 2024 (one year after performing the first test field of the test section), the load-bearing capacity of the traffic surface was measured again, and the values of the compressive modulus were between Ms = 75.00 to 85.00 MN/m².

Figure 13. Test section appearance in June 2024 [32]

3.3. Quality control at construction

The field-testing program planned only the testing of the bearing capacity of the subgrade and road base courses using a dynamic plate, and from the obtained dynamic deformation modulus (Evd) and the correlation with the static compressive modulus, the value of the compressive modulus (Ms) was determined. The scope of laboratory testing was significantly broader, in accordance with the General Technical Works on Roads OTU Book II [33] and Book III [31].

3.3.1. Field tests

The dynamic deformation modulus test was performed immediately after the compaction of each layer, at several different locations on the layer as well as after the corresponding period of time. The compressive modulus of the natural subgrade made of medium-plasticity soil was 12 MN/m^2, which is significantly lower than the prescribed minimum bearing capacity of earth materials according to OTU [33] which is 30.0 MN/m^2. However, it is common for the contractors to encounter a reduced load-bearing capacity of the subgrade on clay soils (materials of the excavated category "C") and to resort to some of the procedures for improving load-bearing capacity.

Significantly better load-bearing results were achieved on the subgrade stabilized with wood ash. The addition of wood ash with pronounced hydraulic properties, in an amount of 50 % in the soil mixture, improved the bearing capacity of the clay subgrade immediately after compaction, when the compressive modulus were Ms = 30.7 to 48.4 MN/m^2. The bearing capacity of the subgrade continuously increased over time, reaching Ms = 35.4 to 49.3 MN/m^2 after 14 days. The bearing capacity of the subgrade improved with wood ash was measured at 6 points on two occasions: immediately after compaction and 14 days later, and the results are shown in Table 1.

Table 1. The values of the measured deformation modulus (compressive modulus) on the subgrade [34]

Testing site	**Evd** [MN/m^2]	**Evd** [MN/m^2]	**Increase of the load-bearing capacity of the subgrade** [%]
	20.09.2023.	3.10.2023.	
1	31.8	35.4	11.32
2	25.9	40.7	57.14
3	40.3	44.8	11.17
4	35.7	49.3	38.10
5	30.7	42.7	39.09
6	48.4	36.1*	-
*a wet area. reduced load-bearing capacity of the subgrade after 14 days			

Table 2. Laboratory test results [29, 30, 35, 36]

Properties		Test by:	Soil	Wood ash	Soil/ash mixture
Natural humidity [%]		ASTM D 2216-10	24.4	23.7	-
Density of solid particles [Mg/m^3]		ASTM D 854-14 method B. clause 9.3	2.58	2.65	2.60
Granulometric composition	Coefficient of non-uniformity U	ASTM D 422-63	-	30.90	262.4
	Maximum grain diameter (mm)		4.75	8.0	60.0
Soil consistency	Yield point [%]	BS 1377:1990 part 2. points 4.5 and 5	39.99	-	-
	Plasticity limit [%]		22.20	-	-
	Plasticity index [%]		17.79	-	-
Standard Proctor	Optimal water content [%]	HRN EN 13286-1	22.6	14.1	19.0
	Maximum dry density [Mg/m^3]		1.49	1.13	1.27
California bearing ratio, CBR [%]		HRN EN 13286-47	2	22	9
Swelling [%]			0	0.1	0.5

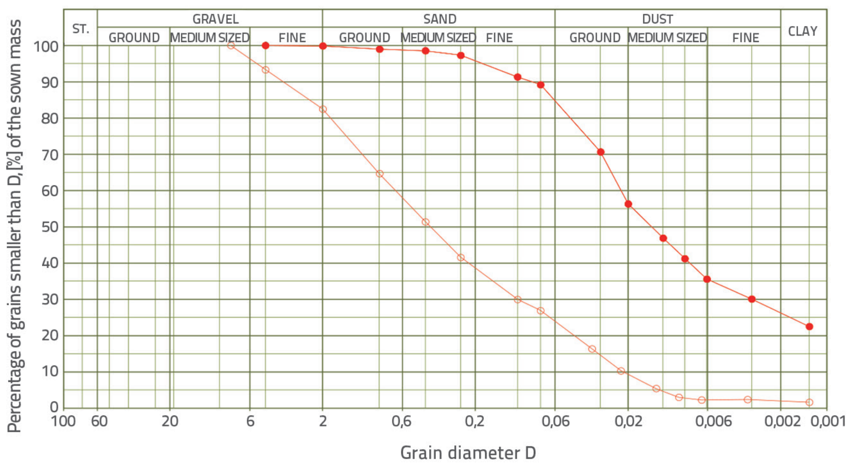

Figure 14. Granulometric diagram [35]

According to the results of the measurements, it is evident that the load-bearing capacity was slightly lower in only one measuring spot due to higher wetness, however, such capacity still met the minimum required load-bearing capacity required for the earth subgrade (30 MN/m^2 according to OTU II [33]), while all other subgrade bearing capacity values were higher. A 14-day increase in the load-bearing capacity of the subgrade is noticeable from 11 % to 57 % compared to the load-bearing capacity measured immediately after the subgrade is compacted.

3.3.2. Laboratory tests

Laboratory tests included determination of soil moisture and wood ash, density, granulometric composition, soil consistency, optimal water content and maximum dry unit weight according to Standard Proctor's Compaction Test, CBR index and swelling (results of all these studies are shown in Table 2) and compressive strength of soil and ash mixture (results are shown in Table 4).
The curves of the soil material (upper granulometric curve) and mixed wood ash (lower granulometric curve) were obtained by granulometric analysis of the sample which are shown in Figure 14.

Besides the physical properties, the effect of wood ash in the mixture is also affected by its chemical composition which depends on the inorganic composition of the wood biomass. The chemical composition of wood ash is presented in Table 3, and as shown in the composition, calcium oxide (CaO) predominates, with a content ranging from 33.38 % to 43.74 % by mass, depending on the ash fraction. This indicates the binding capacity of the ash [12, 22].
Compressive strength testing was performed on samples of a mixture consisting of soil and wood ash in equal proportions, according to HRN EN 13286-41. The mixture samples were prepared following the standard Proctor method (HRN EN 13286-2) and cured for 7 and 28 days in a moisture chamber at 20 °C ± 5 °C and 90 to 95 % relative humidity. Three mixture samples were tested for each curing period, and the average compressive strength values are presented in Table 4.

3.3.3. Analysis of test results

The basic material (soil) of the test section belongs to the group of medium plastic inorganic clay symbolized as CI with a density of solid particles 2.58 (mg/m^3). The soil's natural humidity is 24.4 %. Wood ash used in the construction of the test section is a mixture of three fractions of ash that are formed during combustion in different proportions. The density of mixed wood ash is 2.65 (mg/m^3).
The granulometric diagram in Figure 12 shows good gradation of the wood ash mixture with a maximum particle size of 8 mm and a non-uniformity coefficient of U = 30.9. The particles are described as angular, hard, and durable. In addition to physical properties, the chemical composition of the ash is also important for the behavior of wood ash in a mixture with soil (or on its own). According to authors Sarkkinen et al. [12] and Bohrn et al. [22], when used as a binder in the stabilization of various materials, bio-ashes must

Table 3. Chemical composition of wood ash [24]

Components		MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO
Furnace bottom ash	mas. %	2.64	0.82	3.48	2.34	1.40	7.13	43.74
Cyclone ash		3.06	0.44	4.05	2.90	1.59	2.82	46.9
Electrostatic filter ash		2.39	0.22	1.25	3.61	21.55	25.99	33.38

Table 4. Compressive strength test results for soil and wood ash mixture [37]

Sample care [days]	**Compressive strength of mixture** [MN/m^2]	**Minimum compressive strength of mixtures stabilized with lime** [MN/m^2]
	HRN EN 13286-41	**According to the 2-11 OTU Book 2**
7	0.48	0.40
28	0.55	0.50

contain at least 20 % CaO to exhibit good binding properties. The presence of different oxides in the chemical composition is visible in Table 3; calcium oxide CaO dominates in the amounts of 33.38 - 46.9 mas. %, and wood ash acts as an independent binder. The effect of mixed wood ash in the mixture is visible in the improvement of the bearing capacity expressed by the CBR index (Table 2) and the results of the compressive strength (Table 4).

The California Bearing Ratio (CBR) for clay soil is 2 %, while for the mixture of soil and ash (50/50 %), the bearing ratio is CBR = 9 %, indicating an increase in bearing capacity of 350 %. By adding wood ash to the clay soil, the optimal water content in the mixture decreased (19.0 %), as did the maximum dry density (1.27 Mg/m³).

Comparisons are made in Table 4 to better detect the effect of wood ash with the results of the compressive strength of the soil-ash mixture; minimum compressive strength criteria prescribed by OTU II [33] for lime-stabilized mixtures are also presented. The required amount of lime to achieve the minimum compressive strength of the mixture typically ranges from 3 % to 5 % of the dry soil mass. The results show that the compressive strengths of the soil and ash mixture after 7 and 28 days are higher than the required minimum compressive strengths for lime stabilization. The compressive strength after 7 days is 20 % higher compared to traditional lime stabilization, while the compressive strength after 28 days is 10 % higher than that of lime stabilization with the same curing period. Although the HRN EN 13286-41 standard does not specify this, the compressive strength of the samples was also tested immediately after preparation, and it was 0.3 MN/m².

The effect of wood ash is evident in both laboratory and field bearing capacity parameters (Table 1.), showing its contribution compared to the traditional binder for clay materials – lime. The clay material with weaker properties was improved by adding a mixed wood ash at a 50 % ratio. Since the test section was constructed without a laboratory-derived pre-determined working composition, and the proportion of ash in the mixture was chosen for practicality and ease of execution, even better bearing capacity results can be expected. However, this would require additional laboratory testing with varying ash contents in the soil mixture.

The base course of the road, which was made of wood ash on both test-section fields, met the load-bearing criteria and confirmed its application in the pavement structure. The measured moduli of compressibility were from 60 to 80 MN/m². In comparison, the base courses made of sand (common in pavement structures in Slavonia and Baranja) have modules of compressibility MS = 60 to 80 MN/m² [22]. The reasons for the good bearing capacity results of the base course with ash lie in the physical properties of the ash mixture (three ash fractions with varying proportions in the mixture) and the good gradation of the ash mixture. Additionally, the chemical composition of the wood ash, with its calcium oxide (CaO) content which gives binding properties to the material.

4. Conclusions

This paper presents the experiences from the construction of a test section of a road with wood ash, which was carried out within the industrial facility of Strizivojna Hrast d.o.o. as part of an internal road used daily by heavy trucks loaded with wooden logs. Mixed wood ash from the landfill next to the plants was used to improve the bearing capacity of the clay subgrade and to build the base course of the pavement structure. During the construction of the test section, laboratory and field tests were carried out for quality control purposes. A special effect of wood ash was observed in stabilization of clay subgrade where its load-bearing capacity is increased up to 4 times compared to the load-bearing capacity of natural, unstabilized clay subgrade, and the increase in the load-bearing capacity of stabilized subgrade is continued. Wood ash could successfully replace natural aggregate (such as gravel, sand or crushed stone), which is otherwise used in the construction of base courses of the pavement structure.

The state of the test section is visible in Figure 13., and the moduli of compressibility measured one year after the performance of the test section confirm a stable and load-bearing structure without damage, which fully meets the requirement of daily traffic of heavy vehicles.

When considering the costs of road construction with standard aggregate and binder, without specifically analyzing the current prices of materials and binders and comparing them with the costs of constructing a test section using (free) wood ash, the potential for significant cost rationalization and savings becomes clear. Furthermore, this approach meets the requirements of sustainable development by promoting the reuse/recycling of wood ash, aiming to reduce the substantial amounts of ash in landfills, which are expected to continue increasing.

Acknowledgements

No special funds were allocated for the construction of the test section; it was carried out solely through the goodwill and personal involvement of all those interested and involved in its creation. The organization and execution of the test section was made possible by the courtesy of Mr. Mate Ravlić, owner of the Strizivojna Hrast d.o.o. factory in Strizivojna. All the work related to the construction of the subgrade and pavement structure was carried out by the factory's employees. The quality control and implementation of field and laboratory testing involved employees from the Material and Structure Laboratory of the IGH Institute d.d., RC Osijek.

REFERENCES

[1] Dimter, S., Rukavina, T., Barišić, I.: Alternative, environmentally acceptable materials in road construction. In Handbook of Research on Advancements in Environmental Engineering, Ed.: Gaurina-Međimurec, N., IGI Global: Hershey, PA, USA, 2014, pp. 557–583.

[2] Šikić, D., et al.: Tehnički uvjeti za gospodarske ceste, Znanstveni savjet za promet JAZU, Zagreb, 1989.

[3] Rukavina, T., Dragčević, V., Lopuh, S., Rajič, S.: Metode stabilizacije slabo nosivog tla pri izgradnji prometnica, Građevinar 59 (2007) 4, pp. 301-309.

[4] Dimter, S., Zagvozda, M., Tonc, T., Šimun, M.: Construction of economical pavement structures with wood ash, 30th International Baltic Road Conference (IBRC 2021) IOP Conf. Series: Materials Science and Engineering, 1202 (2021) 012048, https://doi.org/10.1088/1757-899X/1202/1/012048

[5] Zagvozda, M., Dimter, S., Rukavina, T., Netinger Grubeša, I.: Mogućnosti primjene biopepela u cestogradnji, Građevinar, 70 (2018) 5, pp. 393-402. https://doi.org/10.14256/JCE.2074.2017

[6] Dimter, S., Šimun, M., Zagvozda, M., Rukavina, T.: Laboratory evaluation of the properties of asphalt mixture with wood ash filler, Materials, 14 (2021) 3, pp. 1-17, https://doi.org/10.3390/ma14030575

[7] Šimun, M., Dimter, S., Grubješić, G., Vukelić, K.: Contribution to the Research on the Application of Bio-Ash as a Filler in Asphalt Mixtures, Applied sciences (Basel), 13 (2023) 11, pp. 6555, https://doi.org/10.3390/app13116555

[8] Dimter, S., Zagvozda, M., Milovanović, B., Šimun, M.: Usage of Wood Ash in Stabilization of Unbound Pavement Layers, Road and Rail Infrastructure VI, Proceedings of the Conference CETRA 2020*, ed. Lakušić, S., 20-21 May 2021, Zagreb, Croatia, pp. 981-987, https://doi.org/10.5592/CO/cetra.2020.1016

[9] Zagvozda, M., Rukavina, T., Dimter, S.: Wood bioash effect as lime replacement in the stabilisation of different clay subgrades, International Journal of Pavement Engineering, 23 (2020) 8, pp. 2543-2553, https://doi.org/10.1080/10298436.2020.1862839

[10] Zagvozda, M., Dimter, S., Rukavina, T.: Subgrade Bearing Capacity Improvement With Bioash. Proceedings of the 26th World Road Congress, Abu Dhabi, 2019, Connecting Cultures, Enabling Economies, 10p.

[11] Supancic, K., Obernberger, I.: Wood ash utilisation as a stabiliser in road construction, First results of large-scale tests, 19th European Biomass Conference and Exhibition, 43 (2011), pp. 859–870, Berlin

[12] Sarkkinen, M., Kujala, K., Kemppainen, K., Gehör, S.: Effect of biomass fly ashes as road stabilisation binder, Road Materials and Pavement Design, (2016), pp. 1–13.

[13] Ureña, C., Azañón, J.M., Caro, J.M., Irigaray, C., Corpas, F., Ramírez, A., Rivas, F., Salazar, L.M., Mochón, I.: Use of Biomass Ash as a stabilization agent for expansive marly soils (SE Spain), EGU General Assembly, 2012, (2012).

[14] Emeh, C., Igwe, O.: The combined effect of wood ash and lime on the engineering properties of expansive soils, International Journal of Geotechnical Engineering, XX (2016) X, pp. 1-11, https://doi.org/10.1080/19386362.2015.1125412

[15] Okagbue, C.O.: Stabilization of Clay Using Woodash, Journal of Materials in Civil Engineering, 19 (2007) pp. 14-18, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:1(14)

[16] Šķēls, P., Bondars, K., Plonis, R., Haritonovs, V., Paeglītis, A.: Usage of Wood Fly Ash in Stabilization of Unbound Pavement Layers and Soils, Proceedings of 13th Baltic Sea Geotechnical Conference, Vilnius, pp. 122-125 (2016) https://doi.org/10.3846/13bsgc.2016.017

[17] Sarkkinen, M., Luukkonen, T., Kemppainen, K.: A wasterock and bioash mixture as a road stabilization product, Selected papers from the 3rd Edition of the International Conference on Wastes: Solution, Treatments and Opportunities, Viana do Castelo, pp. 283-288, (2015)

[18] Vestin, J., Arm, M., Nordmark, D., Lagerkvist, A., Hallgren, P., Lind, B.: Fly ash as a road construction material, WASCON 2012 Conference proceedings, Gothenburg, (2012), pp. 1-8.

[19] Kaakkurivaara, T., Kolisoja, P., Uusitalo, J., Vuorimies, N.: Fly Ash in Forest Road Rehabilitation, Croatian Journal of Forest Engineering, 37 (2009) 1, pp. 119-130.

[20] Bohrn, G., Stampfer, K.: Untreated Wood Ash as a Structural Stabilizing Material in Forest Roads, Croatian Journal of Forest Engineering, 35 (2014), pp. 81–90.

[21] Šķēls, P., Bondars, K., Haritonovs, V.: Wood fly ash stabilization of unbound pavement layers, 19th International Conference on Soil Mechanics and Geotechnical Engineering, ICSMGE 2017, Coex Convention CenterSeoul, South Korea, 2017.

[22] Dimter, S., Zagvozda, M., Tonc, T., Šimun, M.: Evaluation of Strength Properties of Sand Stabilized with Wood Fly Ash (WFA) and Cement, Materials, 15 (2022) 99, Paper No.: 3090, https://doi.org/10.3390/ma15093090

[23] Dimter, S., Zagvozda, M., Tonc, T., Zvonarić, M.: Impact of different wood ash fractions on the load - bearing capacity of sand mixtures, Road and Rail Infrastructure VII, Proceedings of the Conference CETRA 2022, ed. Lakušić, S., 11-13 May 2022, Pula, Croatia, pp. 449-456, https://doi.org/10.5592/CO/CETRA.2022.1473

[24] Primjena pepela iz drvne biomase u slojevima kolničke konstrukcije - Bio PAV, znanstveno istraživački projekt Građevinskog i arhitektonskog fakulteta Osijek IZIP-GrAFOS-2018:, voditeljica prof.dr.sc. Sanja Dimter https://www.croris.hr/projekti/projekt/5444

[25] Dimter, S., Kuburić, G., Ević, E., Vrhovac, G.: Contribution to green (road) construction displayed in wood production factory Strizivojna Hrast d.o.o, 9. Congress of Croatian Builders, ed. Lakušić, S., 21-24 April 2024, Cavtat, Croatia, pp. 267-276, https://doi.org/10.14256/9SHG.2024.214

[26] https://earth.google.com/web/@45.22313493,18.41769939,81.61644031a,1654.05343212d,35y,0h,0t,0r/data=OgMKATA (20.02.2024.)

[27] https://mingor.gov.hr/o-ministarstvu-1065/djelokrug/uprava-za-procjenu-utjecaja-na-okolis-i-odrzivo-gospodarenje-otpadom-1271/gospodarenje-otpadom/ocevidnici-7589/7589 (29.02.2024.)

[28] Stjepanović, V.: Osiguranje kvalitete materijala i radova pri izvođenju nosivih slojeva kolničkih konstrukcija / Dimter, Sanja (mentor), Kuburić, Goran (neposredni voditelj, Osijek, Građevinski i arhitektonski fakultet Osijek, 2023. (in Croatian)

[29] Izvještaj o ispitivanju granice tečenja, granice plastičnosti i indeksa plastičnosti br. 72501-GP-23 0104, Institut IGH d.d. RC Osijek, 7.07.2023. (in Croatian)

[30] Izvještaj o ispitivanju bubrenja i kalifornijskog indeksa nosivosti (CBR) s opterećenjem nakon 96 sati potapanja u vodi br. 72501-0325/23, Institut IGH d.d. RC Osijek, 28.08.2023.(in Croatian)

[31] Opći tehnički uvjeti za radove na cestama, knjiga 3, Hrvatske ceste- hrvatske autoceste 2001. (in Croatian)

[32] Dimter, S., Kuburić, G., Ević, E., Vrhovac, G.: Iskustva izgradnje pokusne dionice ceste s drvnim pepelom, Zbornik sažetaka predavanja - 18. Dani Hrvatske komore inženjera građevinarstva / Štimac Grandić, Ivana, Dražin Lovrec, Nina (ur.). Zagreb: Hrvatska komora inženjera građevinarstva, 2024. pp. 123-123 (in Croatian)

[33] Opći tehnički uvjeti za radove na cestama, knjiga 2, Hrvatske ceste- hrvatske autoceste 2001. (in Croatian)

[34] Izvještaj o ispitivanju dinamičkog deformacijskog modula br. 72501-0334/23, Institut IGH d.d. RC Osijek, 3.10.2023. (in Croatian)

[35] Izvještaj o ispitivanju granulometrijskog sastava tla br. 72501-GS-23 0104_23 0105, Institut IGH d.d. RC Osijek, 7.07.2023. (in Croatian)

[36] Izvještaji o ispitivanju laboratorijske suhe gustoće i udjela vode - zbijanje po Proctoru, br. 72501-23 0104 (tlo), 72501-23 0105 (pepeo), 72501-23 0106 (mješavina tla i pepela), Institut IGH d.d. RC Osijek, 12.07.2023. (in Croatian)

[37] Izvještaj o ispitivanju tlačne čvrstoće br.72501-0327/23, Institut IGH d.d. RC Osijek, 7.11.2023. (in Croatian)