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IMPACT OF DIFFERENT WOOD ASH FRACTIONS ON THE LOAD-BEARING CAPACITY OF SAND MIXTURES

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Abstract

Different types of natural aggregates (gravel, crushed stone, sand) are used in the construction of load-bearing layers of pavement structures, the granulometric composition of which has a great influence on the compaction and load-bearing capacity of the layer. Special care should be taken when compacting single-grain materials, such as sand, as difficulties can be expected with these. For this reason, it is useful to modify the granulometric composition of the sand by adding new material of finer fractions. The bearing capacity of mixtures for the production of unbound load-bearing layers of a pavement structure is tested by determining the California Bearing Ratio (CBR), the value of which depends on the dry bulk density achieved and the granulometric composition of the mixture. The bearing capacity of the mixture is influenced by the grain shape and grain surface characteristics of the stone material. This paper describes the testing of mixtures intended for the performance of load-bearing layers of pavement structures, consisting of Drava sand and wood ash (WA) of different fractions (bottom wood ash (WBA) and fly (cyclonic) wood ash (WFA)) and different proportions. The CBR index was determined after immersion of the samples for 4 days under water, during which time swelling was monitored. The results showed that wood fly ash (WFA) has a greater impact on the bearing capacity of the sand mixture and, using it, lower linear swelling results are achieved as well as higher CBR results.

Keywords: load-bearing capacity, stabilized mixtures, wood ash (WA), Drava sand

1 Introduction

Unbound, mechanically compacted layers are an important element of the pavement structure of all traffic surfaces. Depending on the category of the road and the traffic load, these layers can make up 40 – 80 % of the pavement structure and thus affect the total cost of the road. Such a layer is built into the pavement construction of roads for all groups of traffic loads, and is made of unbound granular stone materials that are stabilized by mechanical compaction [1]. Different kinds of materials, including natural materials (gravelly-sandy and crushed stone materials and their mixtures), industrially produced materials (such as slag and fly ash) and recycled aggregates, can be used to make mechanically-compacted layers [2]. Granular materials must have the appropriate physical and mechanical properties and, therefore, the grain shape, wear resistance and frost resistance are checked and the proportion of loose grains in the mixture is limited. An important element of the stability of the grain mixture is its granulometric composition, which ensures the required compaction and obtaining the mechanical stability and load-bearing capacity of the constructed layer, and ensures resistance of this layer to freezing. A prerequisite for mechanical stability is a con-

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tinuous granulometric curve and for easier selection of materials, a standard [3] is used to define a wider range of applications for each type of granular material. An important information for granular mixtures is the coefficient of uniformity $C_u=d_{60}/d_{10}$, which defines uniformity of the composition of the mixture, i.e. it represents a measure of good constructability of the mixture [3]. Mixtures of granular materials with a coefficient of $C_u>15$ have an uneven composition, and this is also the lower limit that granular materials must satisfy [4]. If the value of the coefficient $C_u<5$, it is considered that such material, due to its uniformly graded composition, will be harder to compact [3].

For sandy materials, in most cases is $C_u<5$, thus indicating their difficulty in compaction and construction. Therefore it is justified to consider the process of mechanical stabilization, where it is possible to add finer granular material to improve the uniform granulometric composition of sand, and thus achieve a better bearing capacity or compaction of the mixture. Adding finer material to the base material (sand) will fill the cavities and thus obtain a more stable mixture. As an additional material, fine-grained silty-clay fractions can be added to uniformly graded sand, as well as some of the industrially produced materials such as bottom ash or fly ash [5, 6].

The load-bearing capacity of granular material is determined on the basis of the California Bearing Ratio (CBR), which is also an input parameter for designing of pavement structure. The bearing capacity of the mixture is influenced by the granulometric composition of the material (whether the mixture is mechanically stable or not), but also by the grain shape and grain surface characteristics of the stone material [1]. Thus, Shalabi et al. [7] and Parylak [8] examined mixtures of sand, i.e. sand and fly ash, and found that, when compacted, irregular grains of sand with a rough surface were more suitable than smooth rounded grains. This shape of grain and surface allows the creation of a stronger bond when bonding with an additional material or binder.

The California Bearing Ratio (CBR) was determined on samples compacted at an optimum moisture using the energy of a modified Proctor test, immediately after compaction or after a specific time of curing the mixture. The standard HRN EN 13286-47: 2012 [9] allows the specimen to be cured for 1 hour, 3 days or some other period at a specific temperature, ensuring that the specimen does not dry out, after which it is immersed under water for a period of 4 days (96 hours) or longer. The General Technical Conditions for Road Works (GTR) [4] define the CBR values that mixtures must have depending on the materials of which they are composed (min CBR = 40 % for natural gravel or a gravel mixture with less than 50 % crushed stone, and min CBR = 80 % for crushed stone material). Although the GTR [4] allows for the possibility of using sandy materials (natural and crushed sand) in the performance of unbound load-bearing layers, it does not prescribe the required value of the CBR ratio for them. The reasons for omitting the prescribed values probably lie in the fact that sandy materials are less commonly used in the construction of unbound load-bearing layers compared to gravel or crushed stone, at least in areas where sand is not a locally available material. Sandy materials can be found more often in pavement structures of commercial roads or roads with lower traffic volumes and in areas where sand (river or excavated) is a local material [10]. The use of local materials and the correction of their granulometric composition using mechanical stabilization, all with the purpose of more economical construction of load-bearing layers, is prescribed by the standard HRN U.E9.020 [11]. Braunović [5] states the advantages of mechanical stabilization and describes the specifics of various applied materials, especially local materials and industrial by-products such as fly ash and slag. Author also defines that the CBR for a mechanically stabilized mixture and its application in the subbase layers of the pavement structure is at least 30 %. In the rest of this paper, we describe the laboratory determination of the CBR index on sand mixtures to which bottom ash (WBA) and fly ash (WFA) from wood biomass were added, in order to determine their stabilizing effect. Both ashes were added to replace part of the sand, in proportions of 10 %, 20 % and 30 % of the mixture.

2 Experimental part

2.1 Materials

2.1.1 Drava sand

The granulometric composition of Drava sand was determined using samples of 500 g in accordance with the standard HRN EN ISO 17892-4 [12], on a mechanical vibrating table with a set of sieves with openings ranging from 31.5 to 0.063 mm. The granulometric composition of Drava sand is shown in Fig. 1, and the physical properties of the sand in Table 1.

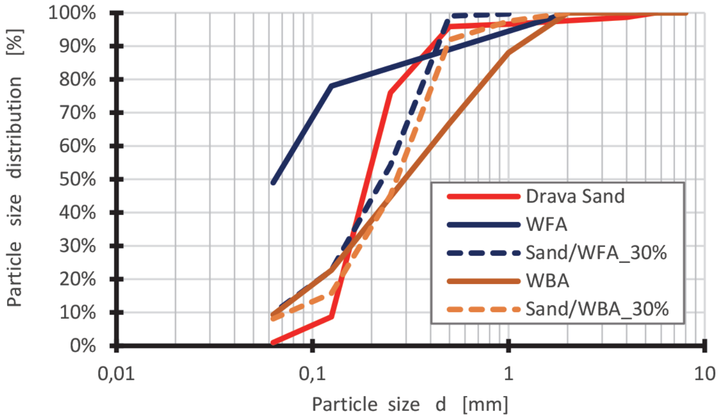

Figure 1 Granulometric composition of materials

Table 1 Physical properties of sand from the river Drava

UCSC	Density [Mg/m³]	Colour	D_{10} [mm]	D_{30} [mm]	D_{60} [mm]	C_u	C_c
SP	2.68	greyish-brown	0.13	0.16	0.22	1.68	0.895

Note: C_u = coefficient of uniformity; C_c = coefficient of curvature

Using X-ray diffraction analysis (XRD), it was determined that the main components of the sand are quartz (predominant, 71 % of the mass) then calcite, dolomite, feldspars and clay minerals [13]. Scanning electron microscopy (JEOL SEM JSM-IT200) was used for images of the shape and size of the sand particles (Fig. 2). The SEM images showed that most of the sand particles are rod-shaped and angular (according to the degree of roundness) and have a rough, porous surface.

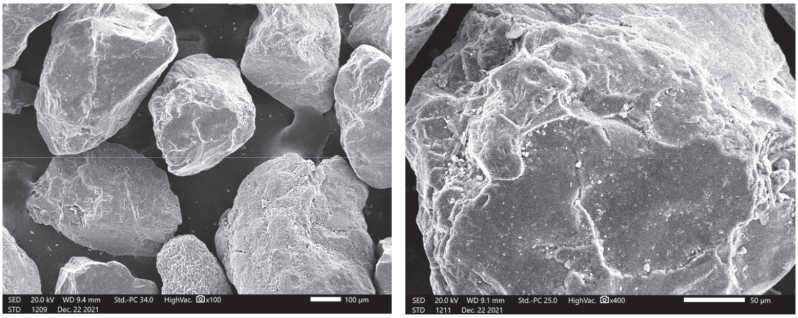

Figure 2 SEM microphotograph of the sand: a) magnification SEM_MAG = 100 x; b) magnification SEM_MAG = 400x

2.1.2 Wood ash

When burning biomass, three different fractions of ash are formed: bottom ash (the coarser fraction), cyclonic fly ash and electrostatic filter fly ash. For the purposes of this study, wood ash collected in a biomass power plant in eastern Croatia, engaged in wood processing and the production of wood products, was used. Wood bottom ash (WBA) is collected under the furnace grate, and wood fly ash (WFA) is collected on a cyclonic filter. The granulometric composition of WA is shown above in Fig. 1. and its chemical composition in Table 2.

Table 2 Chemical composition of wood ash fractions

Components mass [%]	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO
WBA	2.645	0.828	3.486	2.346	1.408	7.134	43.7
WFA	3.06	0.44	4.05	2.90	1.59	2.82	46.9

As a result of testing the mineral composition of WFA samples by the X-ray diffraction method (XRD) [14], it was determined that the main components of WA were calcite, quartz and CaO, and, in smaller quantities, portlandite $(CaOH)_2)$ and fairchildite $(K_2Ca(CO_3)_2)$. For WBA, the analysis of X-ray diffraction showed that the main components are calcite, quartz, CaO and, in a smaller amount, portlandite $(Ca(OH)_2)$ [14].

2.2 Composition of mixtures and the manufacturing process

Mixtures of sand and WA of different composition were designed for testing purposes. Mixtures were designed in the following ratios of sand to WA: 90:10; 80:20 and 70:30. The composition of the mixtures, the optimal water content (OWC) and maximum dry density (MDD) for sample preparation are shown in Table 3. OWC and MDD were determined by a modified Proctor test for each mixture. The modified Proctor experiment was conducted in accordance with the standard HRN EN 13286–2 [15]. A Proctor's cylindrical mould A was used, with a diameter of 100 mm diameter and height of 120 mm. Five layers of samples were compacted with the appropriate energy (2,7 MJ/m^3) in an automatic Proctor device.

2.3 Determination of the CBR bearing ratio

The determination of CBR on sand/WA mixtures was conducted in accordance with the standard 13286-47 [16] and three samples were used for each mixture. The samples were prepared in Proctor's cylindrical mould B with a diameter of 150 mm and a height of 120 mm. The samples were submerged under water with a load of 4.5 kg placed on top for a period of 4 days, during which time swelling was periodically recorded in order to determine the increase in linear swelling. CBR results are shown in Table 3. and in Fig. 3. and Fig. 4b.

Table 3 Results of MDD, OMC, CBR and linear swelling

No.	Mix composition	MDD [g/cm³]	OWC [%]	CBR 1 [%]	CBR 2 [%]	linear swelling [%]
0.	100 % Drava sand (control)	1.648	14.20	27.44	18.96	0.02
I.	90 % sand + 10 % WBA	1.661	14.20	50.00	0.00	0.53
II.	80 % sand + 20 % WBA	1.690	14.18	43.76	41.16	2.14
III.	70 % sand + 30 % WBA	1.706	13.81	52.35	50.83	2.33
IV.	90 % sand + 10 % WFA	1.716	13.57	48.99	59.38	0.08
V.	80 % sand + 20 % WFA	1.607	14.94	52.69	56.82	0.22
VI.	70 % sand + 30 % WFA	1.648	15.00	82.09	90.70	0.64

2.4 Comment on the results

The trend of the results of MDD and OWC in the mixtures is different for different fractions of ash in the mixtures. In mixtures with WBA, MDD increases with increasing WA content from 1.66 to 1.70 g/cm³ whilst the OWC decreases. These results suggest that WBA does indeed act as a filler and fills the pores present in uniformly graduated sand. In mixtures with WFA, the effect of different ash content on MDD cannot be clearly observed. Mixtures with 10 % WFA (1.71 g/cm³) have the highest MDD values, while mixtures with 20 % WFA (1.60 g/cm³) have the lowest MDD values. OWC shows increase with increasing WFA content in the mixture.

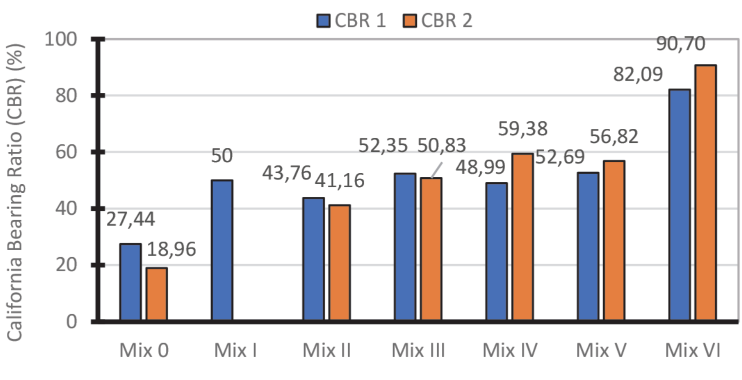

Figure 3 Effect of WA content on the CBR results of mixtures

The results of CBR test show that the WA content (regardless of the type of fraction) has a direct effect on increasing the bearing capacity of the mixture. When 10 % WBA was added to the sand, the bearing ratio increased by 85.2 %, compared to the control sand mixture (CBR = 50.00 %). In the 20 % WBA mixture, the CBR was slightly lower (43.76 %), while the highest bearing ratio for mixtures with WBA was 52.35 % (30 % WBA). Mixtures with WFA achieved higher bearing values than mixtures with WBA. The bearing capacity of the mixture with 10 % WFA (59.38 %) is 116.4 % higher than the bearing capacity of pure sand while the bearing capacity of the mixture with 30 % WFA (CBR = 90.70 %) is 231 % higher than that of pure sand. According to the results obtained, the increase in the bearing capacity of the

mixture is more influenced by WFA than by WBA (Fig. 5a). This effect is particularly noticeable for mixtures with 30 % ash, where mixtures with WFA (90.70 %) have a 73 % higher bearing capacity than mixtures with WBA (52.35 %). For mixtures with 20 % WA, the CBR of the WFA mixture is 29.8 % higher than the mixture with WBA (43.76 %). Given the fineness of the WFA particles, the increased demand for water during compaction with an increasing amount of WFA in mixtures, and significantly higher measured CBR results, indicate the potential effect of chemical stabilization (along with mechanical) in sand mixtures with this type of ash, and also indicate that further investigation should be carried out.
Similar results confirming the significant stabilizing effect of WFA (10 % and 20 %) in sand mixtures were obtained by Šķēls et al. (2016) [17] and Šķēls et al. (2017) [18]. The results showed a multiple increase in the bearing capacity of mixtures ($CBR_{(10)}$ = 34.1 %; $CBR_{(20)}$ = 48.65 %) compared to sand; without the appearance of significant swelling. Wood ash was characterized by the authors as a good independent hydraulic binder for sand stabilization, with the possibility that the result obtained can be partly attributed to the effect of mechanical stabilization.

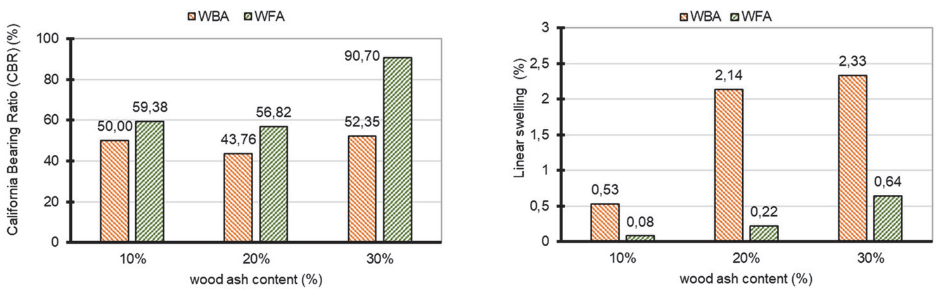

Figure 4 Effect of WA fractions on (a) CBR results; (b) linear swelling results

The results of linear swelling shown in Fig. 4b. show that, as the proportion of WA increases, regardless of the type of WA fraction, the linear swelling of the mixture also increases. Significantly higher values of linear swelling were observed for mixtures with WBA. Thus the swelling for a mixture with 10 % WBA is 0.53 %, for a mixture with 20 % WBA is 2.14 %, while for a mixture with 30 % WBA the swelling is 2.33 %. Linear swelling of mixtures with WFA ranges from 0.083 % (10 % WFA), 0.221 % (20 % WFA) to 0.64 % for a mixture with 30 % WFA. The differences are significant and suggest that WFA is more suitable for use in load-bearing sand layers because the swelling is significantly less than for the WBA mixture, regardless of the percentage of wood ash content.

3 Conclusion

Based on the tests carried out to measure the bearing capacity of sand mixtures with different proportions and types of WA, it can be concluded that WA has a significant stabilizing effect on sand. The stabilizing effect of ash is much more noticeable for mixtures with WFA than for mixtures with WBA:

1. Increasing the content of WA in mixtures (10-30 %) increases its bearing capacity. Mixtures with 30 % WFA have the highest bearing capacity (90.7 %), which is 231 % more than the bearing capacity of pure sand.
2. For the same proportion of WA in the sand mixture, WFA mixtures achieved higher bearing capacity results than WBA mixes. A particularly significant increase in bearing capacity was observed for mixtures with 30 % WA, where the CBR of the mixture with WFA increased by 73 % compared to the CBR of the mixture with WBA.

3. The linear swelling of the mixture increases with increasing WA content. For WFA mixtures it ranges from 0.083 % to 0.64 % while swelling for WBA mixtures is significantly higher (0.53 % to 2.33 %). The differences are significant and point to the conclusion that a mixture with WFA is more suitable for use in load-bearing sand layers, because the swelling is significantly less than for the WBA mixture.

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