DOI: 10.2478/rjti-2020-0008
ROMANIAN JOURNAL
OF TRANSPORT INFRASTRUCTURE

SPECIAL-PURPOSE RIVER-PORT SEDIMENT VALORIZATION AS ROAD CONSTRUCTION MATERIAL EMPHASISING ENVIRONMENTAL ASPECTS

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Abstract

Special-purpose river port sediment was investigated for its potential use as a road construction material. Sediment samples were extracted from three locations in three small river ports, and detailed laboratory research was conducted to determine its basic mechanical properties and characteristics that can potentially have an adverse influence in a roadside environment. The results of the research conducted indicate that there is a need for systematic monitoring of the quality and quantity of sediment in special-purpose river ports of the Danube River Basin to maintain its mobility and prevent flooding. The basic engineering characteristics (Proctor elements, Atterberg limits, California bearing ratio, and unconfined compressive strength) determined represent the good potential of the sediment samples tested herein for use in road construction. In addition, the chemical characteristics tested indicate the need for detailed analyses of the potential environmental risk before application in civil engineering structures

Keywords: dredged sediment, river-port, road construction, chemical properties, mechanical properties

1. INSTRUCTIONS

The natural features of watercourses, such as the slope and geological characteristics or the construction of dams or barriers, cause riverbed sedimentation as a natural process in all inland watercourses. This process affects the form of the river and changes its cross sections at locations where sedimentation is a dominant process, particularly in basin river ports where the flow velocities are very low. The main river ports are usually constructed in such a way as to optimize access to land and navigable water, for commercial demand, and for shelter from the wind and waves, and are usually located along a portion of the river where the water velocity is sufficient to prevent serious sedimentation problems but allow regular and necessary maintenance activities (dredging). However, small river ports, usually organized for special purposes such as winter ports, are located on river branches or main streams protected by groins or piers. The flow velocities there are much lower, creating a more intensive sedimentation process and a requirement for more intensive maintenance. Special-purpose ports are a type of small port managed by a non-public concessionaire using the port for industrial purposes or other personal activities such as tourism and recreational activities. They are usually intended for the mooring and unmooring of ships, yachts, fishing boats, and recreational and other types of boats and vessels, as well as for other economic activities in the transportation and technological areas, including recreational and tourist activities and catering services. However, like all main ports, the sediments deposited should be monitored, and excessive amounts dredged out to maintain normal river activities, maintain the port mobility, and satisfy the minimum depth requirements, in addition to an amelioration of the channels to maintain an optimal cross section for efficient drainage. It has been estimated that several hundred million tons of dredged sediment is generated around the world annually [1], and in Europe alone, dredging activities produce about 200 million m3 per year [2]. Although large quantities of such material are available, it has been classified as waste in many countries. This is particularly owed to the fact that dredged sediment has an extremely high moisture content resulting in a very low mechanical strength and is frequently physically treated and dewatered prior to disposal [3]. In addition, it can be contaminated with organic and inorganic pollutants or toxic chemicals when dredged from heavy industrial areas or is often polluted with toxic chemicals from vessels operating in river ports. These natural characteristics of dredged sediment present a certain drawback when analyzing its potentially acceptable disposal, such as marine (ocean) disposal, deposit into landfills, or use in agriculture or geotechnical engineering.

The beneficial usage of dredged sediment in civil engineering is becoming increasingly interesting in terms of environmental protection and sustainable development because this is an activity that essentially relies on the exploitation of natural resources. However, sustainable development requires more efficient use of natural materials, and promotes the usage of unconventional waste materials in view of improving the level of environmental protection. To date, the results of previous researches have confirmed the feasible use of dredged sediments as a secondary raw material in brick production [4-7] owing to its high clay mineral content. Polluted river sediments were also investigated as a partial sand substitute for self-compacting material production to be used in backfill trench construction [8]. Sediment generated by stripped soils, violent rain, and erosion trapped behind dams as a partial substitution to clinker for manufacturing blended Portland cement has also been researched [9]. The results presented in [10] show that the production of bricks from dam reservoir sediment is feasible and promising, and that such sediment can be used directly without additional grinding and at a relatively low firing temperature. In [11], dredged sediment and basic oxygen furnace steel slag were evaluated as road construction materials with encouraging results of the mechanics and physical characteristics. On the other hand, the need for improving the mechanical behavior for sediment utilization for road construction purposes was presented in [12], which indicates the potential for obtaining adequate characteristics through the solidification and stabilization of sediments with hydraulic binders such as cement or lime. Results indicate that 10% cement addition to lake sedimentary soil creates material with satisfactory strength and durability characteristics for pavement subbase use [13]. Also, combination of cement and fly ash for reservoir dredged sediment stabilization is more effective due to a combined effect of hydration and pozzolanic reaction [14]. The highest strength and stiffness are obtained for 10% addition of fly ash regardless to cement content and curing time [15]. Stabilization of dredged sediment from commercial harbor, sand and blast furnace slag mixture by quicklime also presented potential use in road sublayers [16]. Finally, according to [17] road construction with stabilized sediment can be 1.5 times more economical than roads using conventional earthen pavement materials.

The environmental impact of polluted sediment was addressed in [18], where the material was treated through a special type of stabilization called the Novosol® process, which the paper describes in detail. The results confirm that this type of sediment treatment produces a material applicable as a substitute to the sand in road buildings. Another study dealing with the environmental impact of channel sediment was described in [19]. The adverse influence on the water quality and life conditions for channel biota can be affected based on the detected concentrations of macronutrients exceeding their content in the surrounding arable land by a few folds owing to the interactive processes between the water and sediment material. Clearly, environmental issues dealing with dredged sediment utilization in road construction is a highly relevant topic [2, 18-26] and needs to be addressed when analyzing the potential use of any kind of new material, particularly one usually classified as waste.

Within the Danube River Basin in Croatia and Serbia, there has been no systematic research or monitoring of sediment accumulation or its sustainable management. The current practice dealing with sediment treatment is its disposal near the place of origin (spreading along a channel or riverbank), leaving it to dewater under atmospheric conditions and spreading it using heavy machinery. This process can take a long time and causes some secondary pollution [3] if the original sediment is contaminated. Therefore, the regeneration and beneficial reuse of dredged sediment as cost-effective and eco-friendly disposal options are addressed in the present paper. As the main objective of this research, dredged sediment from three special-purpose river ports on the Sava, Drava, and Danube Rivers was analyzed to valorize its potential use as a building material for embankment and pavement subgrade purposes. The main motive for this investigation was the fact that, despite the Danube being the second largest and longest navigable river in Europe, there has been no monitoring of the sediment quality or quantity of the Danube River ports, or of the ports on its tributaries; however, there have been some recent investigations into the sediment quality and quantity of the Sava River [27].

2. MATERIALS AND METHODS

2.1. Sampling

Owing to the different material sources and sedimentary environment, dredged sediments vary in terms of their grain size distribution, chemical and mineralogical composition, amount of organic matter, and inorganic pollutants (heavy metals). To facilitate these differences and give full insight into the potential use of the Danube River Basin sediment in road construction, three locations were selected along the Danube (in the City of Vukovar, Croatia), as well as the Sava (in the City of Belgrade, Serbia) and Drava (in the City of Osijek, Croatia) Rivers as its main tributaries. The extraction of river port sediment samples was conducted using two methods. The first method was applied using small sampling equipment, namely, a sediment core sampler, type BEEKER (Eijkelkamp), for extraction of undisturbed materials for chemical analyses. The second method accounted for the samples using heavy machinery during port maintenance, namely, sediment dragging.

2.2. Mechanical, physical and chemical material characterizations

To evaluate the potential use for embankment and pavement subgrade construction purposes, basic mechanical and physical material characterizations were conducted. The specific gravity (Gs) was determined according to the procedure defined in the standard CEN ISO/TS 17892-3:2012. The particle size distribution was determined using a combined sieving and hydrometer (sedimentation) method, all in accordance with the procedure defined in the standard CEN ISO/TS 17892-4: 2011. As a dispersing agent, the sodium-hexametaphosphate solution was used. To obtain full insight into the material grain size distribution, acoustic spectroscopy was applied. Acoustic spectroscopy measures the attenuation and speed of ultrasound pulses as they pass through concentrated slurries. The measurements are made over a wide range of frequencies, and the resulting spectra are used to calculate the particle size distribution over a range from 10 nm to more than 10 μm. Within this test, sediment samples were weighted (about 3.0 g) and placed in a glass container. About 150 g of deionized water was added, and the mixture was stirred for 5 min with a magnetic stirrer. The dispersion was homogenized using ultrasound for 15 min (three 5 min cycles with a 1 min cooling period under 50% stirring power) and transferred to a cell for acoustic (ultrasonic) spectroscopy. For dispersion, a SONOPLUS ultrasonic homogenizer HD3100 (Bandelin), with a probe VS70T, was used (frequency of 20 kHz, power of ~35 W (50%), and amplitude of 97 microns). For the particle size determination, a DT-1200 acoustic spectrometer (Dispersion Technology, Inc.) was applied, within a frequency range of 1–100 MHz, and a piezo-element distance of 0.1 to 20 mm with a standard cell and a magnetic stirrer. The Atterberg (consistency) limits and plasticity index (PI) were determined using a Casagrande and rolling method, whereas the moisture-density relationship (compaction parameters) was determined in accordance with the standard EN 13286-2:2012. The specimens used for testing the mechanical properties (the unconfined compressive strength (UCS) and California bearing ratio (CBR)) were prepared in accordance with the procedure given in the standard EN 13286-2:2012, whereas UCS and CBR tests were conducted according to the standards EN 13286-41: 2012 and EN 13286-47:2012, respectively.

To gain full insight into the characteristics and potential environmental hazard of river port sediment, samples were analyzed based on the pH measurement using water as a reagent, the macro-element concentration using aqua regia (nitric acid + hydrochloric acid, HNO3+3HCl), and the heavy metal concentration (Cd, Pb, As, and Ni according to the standard EN ISO 15586:2008 using an electrothermal atomic absorption spectrometer; Hg level measurement using the standard AAS 019 REV; and Fe, Mn, Zn, Cu, Co, and Cr destruction using aqua regia). To determine the carbonate and organic matter content, two procedures were used: first, using a Scheibler calcimeter method and hydrogen-peroxide, and second, using a device for simultaneous thermogravimetry and differential scanning calorimetry, namely, a Mettler-Toledo TGA / DSC 1. For the thermogravimetry test, the samples (~50 mg) were heated (50–1,000° C, at 10° C/min) in Al2O3 containers in an oxygen atmosphere, and thermal decomposition occurred through a two-stage process: one from about 150 to 500° C and the second from 600 to 800° C, while measuring the weight loss (%).

2.3. Heavy metals contamination indices

For complete material valorization, potentially negative environmental influence and sediment pollution is analyzed through calculation and analyses of several factors presented in Table 1. Contamination factor (CF) as a degree of metal enrichment in sediment is calculated as the ration between total metal content in sediment (C_s) and the background concentration (C_b) taken from [28]. Ecological risk factor (E_r) is calculated by multiplying CF and toxic-response factor (T_i) suggested by Hakanson [29] (for heavy metals C_d=30; C_u=5; P_b=5; C_r=2; Z_n=1). The potential ecological risk index (RI) is presenting the sum of all ecological risk factors (E_r) considering all five heavy metals toxicity and environment responses. Geo-accumulation index (I_{geo}) as a simple quantitative measure of heavy metal pollution in sediments is used to determine metal contamination in sediment by comparing current concentrations with pre-industrial levels [30]. As stated in [31], factor 1.5 is introduced to minimize the effects of possible variations in the background values which may be attributed to lithogenic effects. The pollution load index (PLI) is calculated to determine the pollution status of heavy metals in sediment of a specific area for comparison of the pollution status of different locations [32]. There must be a space of one blank line between the last line of the text and the figure, and between the name of the figure (which is written right below the figure) and the first line of the text too.

Table 1. Sediment contamination assessment [31, 32]

CF	Er	RI	Contamination / Risk level	Igeo	Pollution level	PLI	Pollution level
< 1	< 40	< 150	Low	< 0	Unpolluted	< 0	Unpolluted
1-3	40-80	150-300	Moderate	0-1	Unpolluted to moderately polluted	0-1	Baseline levels of pollutant present
3-6	80-160	300-600	Considerable	1-2	Moderately polluted	1-10	Polluted
> 6	160-320	> 600	High	2-3	Moderately to strongly polluted	10-100	Highly polluted
	> 320		very high	3-4	Strongly polluted	> 100	Progressive deterioration of environment
				4-5	Strongly to very strongly polluted		
				> 5	Very strongly polluted		

CF=Cs/Cb ; **Er**=Ti*CF; **RI**=ΣEr; **Igeo**=log2(Cs/1,5*Cb); **PLI**=$(CF_1 * CF_2 * \ldots * CF_n)^{1/n}$

3. RESULTS AND DISCUSSION

3.1. Physical and mechanical characterization

The basic physical characteristics obtained are presented in Table 2. According to the results, all tested special-purpose river port sediments have similar specific gravity (G_s) values ranging from 2.60 to 2.69. This result indicates that the tested sediments consist mainly of inorganic matter because the density of the individual soil particle minerals largely influences the specific gravity of the soils. This indication was verified by measuring the amount of carbonate and organic matter content. According to the results in Table 2, the sediment sample from Sava River is classified as intermediate plasticity silt (MI), whereas the sediment samples from Drava and Danube Rivers are classified as low plasticity clay. The liquid limit (LL) and plasticity index (PI) are the highest for the sediment samples of the Sava River and lowest for those of the Danube River. According to the American Association of State Highway and Transportation Officials (AASHTO) classification of soils for highway construction purposes, Drava and Sava River sediments are classified as A7-6 (silt-clay materials with high plasticity indexes in relation to the LL and that are subject to extremely high changes in volume), and the Danube River sediment is classified as A6 (plastic clay soil and mixtures of fine clayey soil, with usually high changes in volume between wet and dry states). Based on the Atterberg limits of LL ≤ 65% and PI ≤ 30%, all tested sediments have potential for use in embankment construction.

According to the results presented in Table 2 and Figure 1, the Proctor (compaction) parameters, namely, the maximal dry density ($\gamma_{d,max}$) and optimal moisture content (w_{opt}), vary considerably in the sediment from the Danube, Sava, and Drava Rivers. Sediments from the Drava and Sava Rivers have very high optimal moisture content (w_{opt} > 25%), and additional treatment needs to be conducted (in terms of material stabilization using a hydraulic binder, for example) in order to use the material in embankment or road subgrade construction. In contrast, sediment from a special-purpose port on the Danube River has satisfactory compaction characteristics and has the potential to be used in embankment or road subgrade construction without additional treatment. Results of a UCS test show that all tested sediments can be classified as S4 strength class, namely, hard clay, with the UCS ranging between 0.10 and 0.25 MPa. The highest UCS was obtained for the sediment from the Drava River, and the lowest was for the sediment from the Danube River. The results of the CBR test showed that all tested sediments have a CBR > 3%, presenting a good potential for its use in road subgrade construction. The highest CBR value was obtained for the Danube River sediment and the lowest for the Sava River sediment.

Table 2. Results of sediment classification and strength characteristics

Sample Location	Gs	Atterberg limits			Classification			Proctor test		Strength	
		LL (%)	PL (%)	PI (%)	USCS	Group index	AASHTO	$\gamma_{d,max}$ (kN/m³)	w_{opt} (%)	UCS (kN/m²)	CBR (%)
Drava River	2.69	41.61	24.53	17.08	CI	8	A7-6	13.97	27.74	241.3	8
Danube River	2.67	31.10	19.34	11.76	CL	5	A6	16.88	16.89	180.3	9
Sava River	2.60	49.45	29.49	19.96	MI	14	A7-6	13.70	29.22	188.2	3

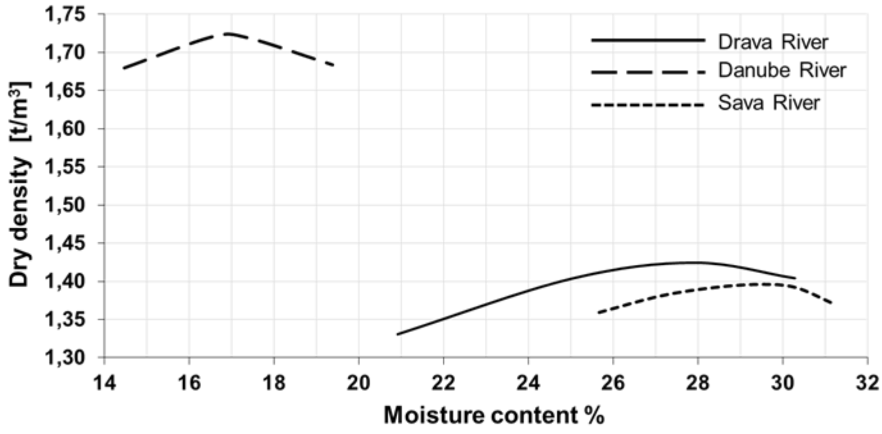

Figure 1. Compaction characteristics of tested river port sediment

As presented in Figure 2, the particle size distributions of sediment from special-purpose river ports on the Drava and Danube Rivers are similar, whereas the sediment from the Sava River has a higher content of fine particles, which is in accordance with the results of the Atterberg limit test and USCS classification. To gain more insight into the particle size distribution of fine graded sediment, additional tests were conducted using acoustic spectroscopy. Based on the results shown in Figure 3, it is clear that Drava River sediment is significantly different in terms of particle size distribution from the other two tested sediments with a lognormal particle size distribution and an average particle size of 9.185 microns. Sediment samples from the Danube and Sava Rivers show a bimodal particle size distribution. Although the Danube River also shows a bimodal particle size distribution, the sediment is coarser (0.113 microns) with a finer (0.011 microns) fraction several orders of magnitude smaller than the samples from the Sava River (Belgrade). This suggests a different origin and morphology of the tested special-purpose river port sediments. Detailed research on the sedimentation origin for all researched locations confirms this result. Namely, the problem of sludge and sediment accumulation at the location of the special-purpose river port on the Sava River is affected by the Topčider River, which carries a significant amount of mud and sludge into the Čukarica branch of the Sava River where this port is located, and from where the samples were extracted for the laboratory tests. Observed similarities and differences between analyzed sediment samples are result of a different origin and morphology of tested samples but also of a different chemical composition, minerology, grain shape and interconnectedness and more detailed analyses is needed for gaining full insights in material behavior.

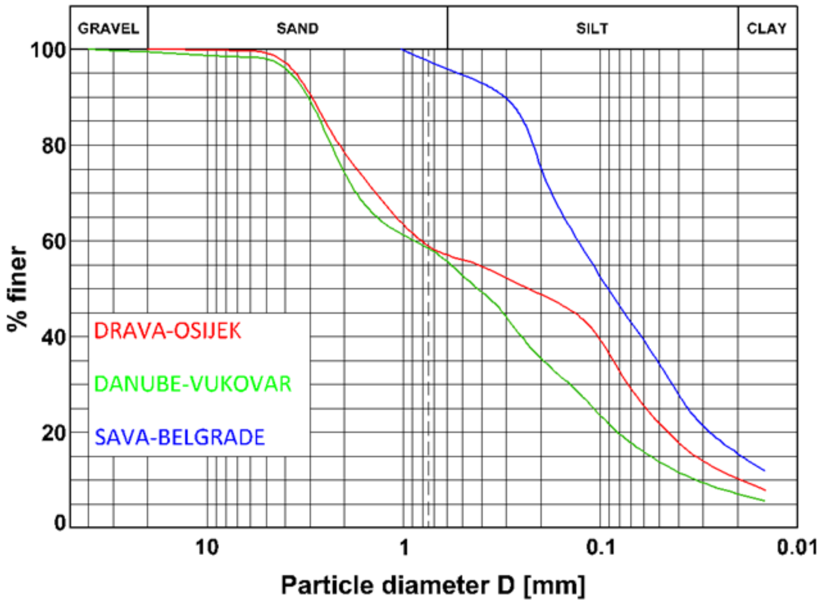

Figure 2. Particle size distribution

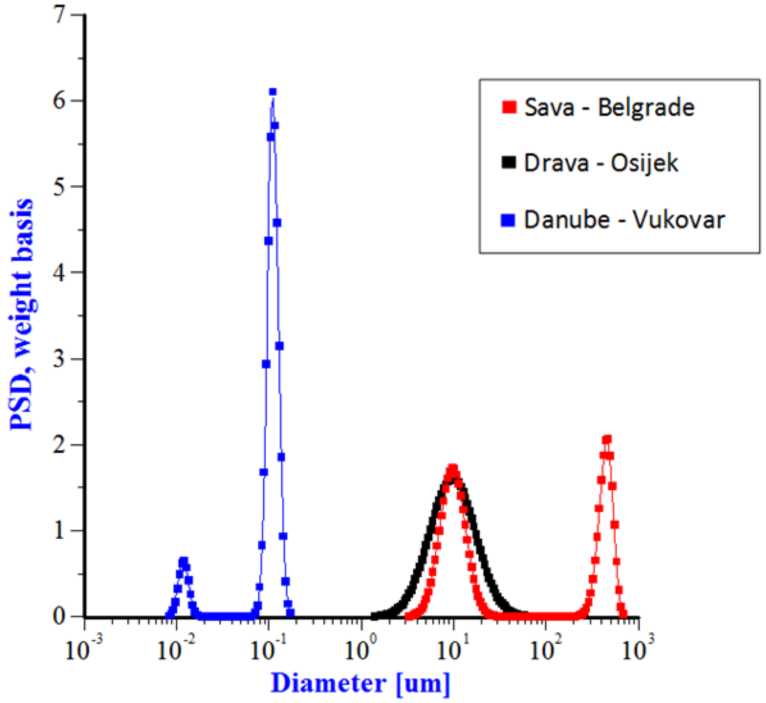

Figure 3. Particle size determined using acoustic spectrometer

3.2. Chemical characterization

The results of the pH measurement and texture classification of the different sediments are given in Table 3. The pH value of the soil is an important environmental factor, and each type of soil has a certain level of acidity and pH depending on its composition, native vegetation, and rainfall amount. The soil acidity can significantly influence the plant growth, and its change in pH influences microbial growth and activity [33]. Thus, the pH can be an important factor if soil (or in this case sediment) is used for embankment construction or protection because it may influence humus growth within embankment slope protection measures. According to the results given in Table 3, all tested sediments can be classified as neutral (pH = 6.6–7.3) to slightly alkaline (pH = 7.4–7.8). This slight increase in alkalinity is a result of the sediment chemical composition with high concentrations of Ca and Mg, as presented in Table 3. Many metals are more mobile and available for uptake in soil with a low pH, which presents favorable results. In soils with a low pH, the toxicity and bioavailability of the metal contaminants to terrestrial organisms are more pronounced compared with neutral or alkaline soils [34].

The results of the thermogravimetric study are presented in Table 4. The first stage of thermal decomposition (up to 500°C) corresponds to the disintegration (oxidation) of organic material present in the tested sediment samples. It is clear that there are very small quantities of such materials in samples from the Danube and Drava Rivers, whereas in the Sava River sediment, the quantity of such materials is significantly higher. The higher average temperature of the first stage decomposition for the Sava River sediment can be attributed to the presence of a greater quantity of aromatic organic substances, which oxidize at higher temperatures. The second stage of thermal decomposition (about 750°C) can be attributed to silicate mineral (clay) dehydration and calcination (decarbonation) of the carbonate minerals, mainly dolomite ($MgCO_3 \bullet CaCO_3$) and calcite ($CaCO_3$, biogenic and terrigenous). Mass loss within this temperature range is significantly higher for the Sava River sediment than for the Danube and Drava River sediment samples, which behave similarly.

Table 3. Results of sediment chemical analyses

Sample Location	Combustible matter content (%)	Organic matter content (%)	Carbonates content (%)	pH	Na [mg/kg]	K [mg/kg]	Ca [mg/kg]	Mg [mg/kg]
Drava	10.54	4.86	5.63	7.15	6.00	73.61	488.76	211.71
Danube	6.40	2.04	8.73	7.80	2.53	39.58	554.25	173.79
Sava	11.98	5.17	0.00	7.48	4.40	84.46	990.91	93.52

Table 4. Thermogravimetry test results

Sample Location	first stage (% mass loss)	mean temperature (ºC)	second stage (% mass loss)	mean temperature (ºC)
Drava River	0.9	308	6.5	723
Danube River	1.3	315	7.4	723
Sava River	8.3	370	11.9	747

3.3. Potential environmental influence

When analyzing the possible use of new, unconventional materials in road construction, it is necessary to consider all the pros and cons of its use in a particular area. In the application of river port sediment in pavement or embankment construction, possible harmful consequences for the environment should be considered because these layers are in direct contact with the surrounding soil, and potential pollution can easily reach the groundwater. To address the potential adverse impact on the environment, heavy metal concentrations were measured on the samples from all investigated locations, the results of which are given in Table 5. In general, for all tested sediment samples, Fe and Pb are present at the highest concentrations, whereas the lowest values are obtained for Co and Cu.

When analyzing the environmental influence of the road and its elements, Cd, Cr, Cu, Pb, Ni, and Zn metals are usually investigated, and it has been noted that the mobility and leaching potential is strongly influenced by the soil pH and organic matter content [35].

In Table 6, the limit values according to the European (Dutch and Finnish) and Australian regulations are presented, and it can be seen that there are different approaches to defining concentrations of heavy metals in soil associated with the risk levels. According to the results shown in Table 5 and the guidelines presented in Table 6, the sediment from the Sava River show the highest environmental risk in view of the total heavy metal concentrations. The Cd, Pb, As, and Hg metals exceed the limits according to Finnish and Australian guidelines, whereas Ni exceeds the limits according to all three guidelines presenting the potential environmental risk. The concentrations of Cd and As in Drava River sediment exceed the limits according to the Finnish and Australian guidelines, whereas the Pb value only exceeds the threshold value of the Finnish guidelines. Sediment from the Danube River shows the least ecological risk because only the As value exceeds the threshold according to the Finnish guidelines, and a further assessment is needed for its potential application.

Finally, it can be concluded that all analyzed sediments should be further analyzed through leaching tests and by defining the potential of heavy metal release into the environment if used in an inbuilt road embankment. In addition, the limit values presented herein are for soils, and the limit values for embankment or road subgrade application are not defined in the current legislation.

Table 5. Results of sediment chemical analyses

Sample Location	Cd	Pb	As	Ni	Hg	Fe	Mn	Zn	Cu	Co	Cr	texture
Drava River	2.55	305.0	27.2	33.9	0.49	358.7	6.89	5.28	0.52	0.14	0.74	silty loam
Danube River	0.68	35.4	13.5	24.1	0.41	195.7	5.12	1.01	0.22	0.09	0.33	sandy loam
Sava River	4.71	152.0	54.9	121.0	1.68	312.3	7.06	2.39	0.53	0.15	1.12	silty clay loam

Table 6. Heavy metal limit values for soil

(mg/kg)	Dutch Intervention Values[1] [36]	Finnish threshold and guideline values for metals in soils[2] [37]			Australia assessment levels for soil [3] [38]		
					Ecological Investigation Levels	Health Investigation Levels	
	Intervention level	Threshold value	Lower guideline value	Higher guideline value		Residential	Industrial
Cd	13	1	10	20	3	80	100
Pb	530	60	200	750	600	1300	1500
As	76	5	50	100	20	400	500
Ni	100	50	100	150	60	2400	3000
Hg	4	0,5	2	5	1	60	75
Fe	-	-	-	-	-	-	-
Mn	-	-	-	-	500	6000	7500
Zn	720	200	250	400	200	28000	35000
Cu	190	100	150	200	100	4000	5000
Co	190	20	100	250	50	400	500
Cr	180	100	200	300	1	400	500

[1] intervention values represent the level of contamination above which a serious case of soil contamination is deemed to exist.
[2] threshold value: equally applicable for all sites, and indicates the need for further assessment of the area; higher concentration levels, major land uses, i.e., for industrial or transport sites and for other land uses; lower guideline value, all other land uses.
[3] residential with minimal opportunities for soil access including dwellings with fully or permanently paved yard space such as high-rise apartments and flats; commercial/industrial includes premises such as shops and offices, as well as factories and industrial sites.

Table 7 Results of heavy metals contamination assessment

Location	Element	CF	E_r	RI	I_{geo}	PLI
Drava River	Cd	3.19	95.63	113.69	1.09	0.14
	Pb	3.59	17.94			
	Zn	0.04	0.04			
	Cu	0.01	0.07			
	Cr	0.01	0.01			
Danube River	Cd	0.85	25.50	27.63	-0.82	0.03
	Pb	0.42	2.08			
	Zn	0.01	0.01			
	Cu	0.01	0.03			
	Cr	0.00	0.01			
Sava River	Cd	5.89	176.63	185.68	1.97	0.12
	Pb	1.79	8.94			
	Zn	0.02	0.02			
	Cu	0.01	0.07			
	Cr	0.01	0.02			

The degree and extent of heavy metals contamination and potential environmental risk assessment is quantified in Table 7 comparing presented results to a limiting value presented in Table 1. For Drava River and Sava River locations, there is a considerable sediment contamination level by Cd (CF > 3) for Drava and Sava River sediment and by Pb for Drava River sediment. Considerable to high ecological risk factor is presented by high Cd content for Drava River sediment (Er > 80) and Sava River Sediment (Er > 160). However, for Drava River sediment, the total potential ecological risk index is low (RI < 150) and moderate for Sava River sediment. Drava River and Sava River can be classified as moderately polluted since Igeo values does not exceed 2. Sediment from Danube River location presents low contamination by heavy metals and according to analyzed factor can be classified as unpolluted. Comparing the pollution load index (PLI) values, it can be concluded that sediments from analyzed locations have low pollution status (PLI < 1). Finally, it can be concluded that detailed analyses on heavy metals concentrations must be conducted for river port sediment characterization and for that, site specific background concentrations for precise pollution assessment need to be established.

4. CONCLUSION

The presented study aims to enhance our understanding of the possible regeneration and beneficial reuse of dredged sediment from special-purpose river ports, and to find cost-effective and eco-friendly disposal options. Dredged sediments from three special-purpose river ports on the Sava, Drava, and Danube Rivers were analyzed and valorized for their potential use as building materials for embankment and pavement subgrade purposes. Based on the results of laboratory tests, the following conclusions can be drawn:

1. There is a need for the systematic monitoring of the quality and quantity of sediment in special-purpose river ports of the Danube River Basin to maintain mobility and prevent flooding.

2. There is variability in the optimal moisture content among the different special-purpose river port sediments, and additional treatment in terms of material stabilization may be needed for such materials to be used in embankment or road subgrade construction.

3. All tested sediments can be classified as S4 strength class, namely, hard clay with UCS ranging between 0.10 and 0.25 MPa.

4. CBR tests show that all tested sediments have CBR > 3%, presenting a high potential for use in road subgrade construction.

5. Acoustic spectroscopy can be a useful tool for obtaining more insight into the particle size distribution of fine graded sediment and suggesting a different origin and morphology of special-purpose river port sediment.

6. Before their potential use in road construction, special-purpose river port sediments should be further analyzed in view of their total heavy metal content, and leaching tests should be conducted to define their potential environmental influence. In addition, the limit values for embankment or road subgrade application should be investigated and defined based on national and international regulations.

The conclusions presented here are drawn from the research conducted on a limited number of samples and, to reach general conclusions, more tests are to be conducted such as deeper shear strength parameters analyses.

Acknowledgments

The authors gratefully acknowledge the START Danube Region Project Fund for its support of this study.

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