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Research paper

GEOTECHNICAL PROPERTIES OF DREDGED SEDIMENT FROM VOJVODINA FOR USE IN ROAD CONSTRUCTION

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Abstract

Deposited river sediment represents a mixture of fine clay, silt, and sand particles that accumulate at the bottom of aquatic ecosystems due to erosion of riverbanks and soil within the river basin, decomposition of plant and animal matter, as well as the accumulation of industrial and municipal waste. This process leads to large amounts of sediment forming in canals, rivers, and lakes, which can reduce water flow, decrease water quality, and disrupt waterway traffic. Disposal sites formed after regular dredging operations occupy significant land areas, making the management of this material a challenge both globally and in the region of Vojvodina. One potential reuse of this material lies in its stabilization and application as a construction material in road construction. This study analyzes a sample of dredged river sediment from the Begej River near Zrenjanin, categorizing it according to domestic standards. The application of this material is planned alone and in combination with lime binder ViaCalco F90 at a proportion of 5 and 7% relative to the dry sample mass. Afterwards, physical and mechanical tests were conducted, including the determination of maximum dry density (MDD) at optimal moisture content (Proctor test), unconfined compressive strength (UCS) test after 7 days of curing and CBR index test of the stabilized and non-stabilized samples. The results were compared with the relevant technical requirements and standards to draw a final conclusion regarding its suitability for use in pavement construction.

Key words: *dredged sediment, stabilization, pavement, waste management*

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1. INTRODUCTION

Over time, due to the process of sedimentation, large amounts of sediment accumulate at the bottom of channels, rivers, lakes, and seas. The formation of this material is associated both with the weathering of rocks or surrounding soil into finer particles, as well as with the decomposition of plant and animal matter and human activities such as the discharge of industrial or municipal wastewater. The deposited material generally consists of a mixture of sand, silt, and clay—of both organic and inorganic origin—as well as pollutants such as heavy metals and other toxic substances [1], [2]. Therefore, the regular removal of accumulated sediment is necessary to prevent potential flooding, ensure the proper functioning of waterway traffic, preserve existing ecosystems, and prevent water contamination in rivers and lakes.

In general, removing sediment from the bottom of aquatic ecosystems involves the excavation of deposited material, its transport, and, if necessary, treatment and disposal at designated landfill sites [3]. This procedure results in large quantities of dredged sediment, the further management of which can pose a challenge due to high costs, excessive land use for landfill formation, and potential pollution. Data from 2023 indicate that 160 million tons of dredged sediment were generated in Europe alone, with a rising trend [4]. In the Republic of Serbia, an average of 300,000 to 600,000 m³ of sediment is dredged annually, primarily in the Autonomous Province of Vojvodina, within the Danube–Tisa–Danube (DTD) hydro system [5]. Recently, there has been growing interest in more sustainable and cost-effective management of this material and its reuse. This type of sediment has been used worldwide in construction, agriculture, and for restoring endangered aquatic and terrestrial habitats or eroded shorelines [6].

Several analyzed studies have reported that dredged sediment is a material with low shear strength, often increased natural moisture content, a high proportion of organic matter, and high compressibility [1], [3], [7]. However, sediments cannot be considered uniform, as their physical and chemical properties depend on the specific location and their formation mechanism. Dredged sediment with a low level of contaminants and adequate physical properties, even in its raw form, can be used in concrete production—as a partial replacement for cement or fine aggregate, in the manufacturing of tiles, bricks, or blocks, as well as in road construction [3], [8]. An overview of beneficial sediment reuse is provided in *Figure 1*.

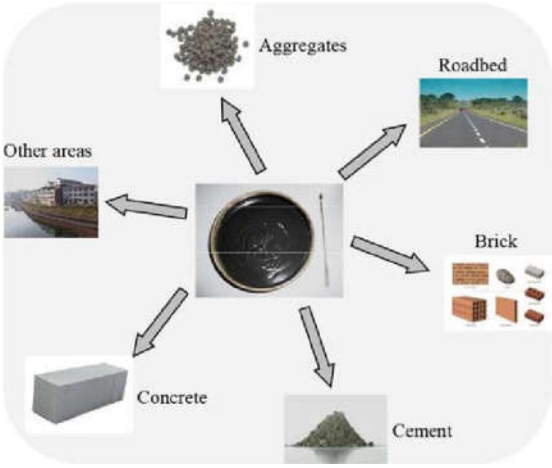

Figure 1. Beneficial reuse of dredged sediment for various purposes [8]

Since roadways are structures exposed to intensive and repetitive traffic loads, the use of raw sediment is mostly limited. In the case of contaminated and low-strength sediment, chemical stabilization can improve the material's strength while reducing its contamination level and environmental hazard [7]. Typical binders used for soil stabilization include cement, quicklime and hydrated lime, fly ash, and their combinations, and these can also be successfully applied in stabilizing dredged sediment. Sediment stabilization opens up possibilities for directly applying this material in the construction of road embankments, subbase and subgrade layers. The beneficial use of dredged sediment in infrastructure objects is presented in *Figure 2*.

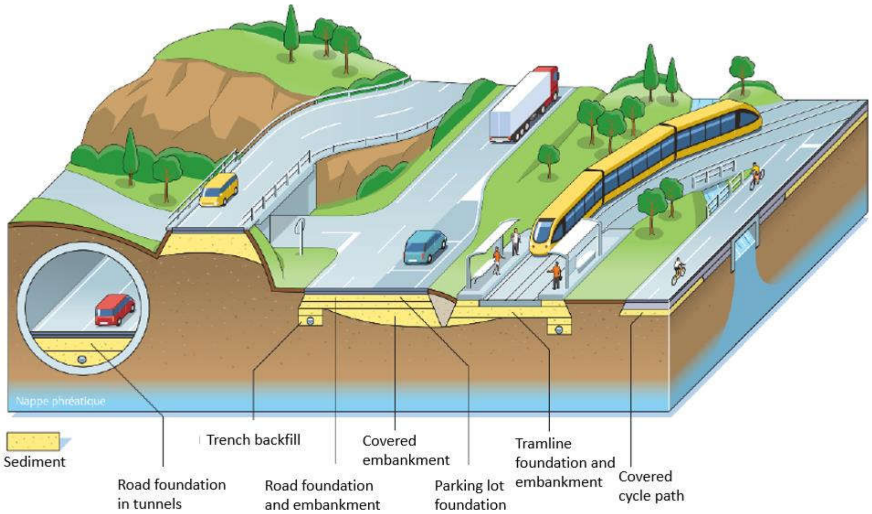

Figure 2. Beneficial reuse of dredged sediment in infrastructure objects, according to [9]

Research conducted by authors from France, India, and the USA has shown that the stabilization of dredged sediment using hydrated and quicklime significantly improves the material's physical and mechanical properties. Athira et al. [10] investigated the properties of dredged sediment stabilized with hydrated lime ($Ca(OH)_2$), fly ash, calcium lignosulfonate, and their combinations. Based on unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests, it was concluded that the optimal percentage of $Ca(OH)_2$ for achieving maximum strength was 4% by dry weight of the sample. Wang et al. [11] tested the UCS, CBR value, and indirect tensile strength of marine sediment stabilized with 3%, 6% and 9% of cement and quicklime (CaO) by dry sample mass. A significant improvement in the sediment's physical and mechanical characteristics was noticed. Minh Nguyen et al. [12] analyzed the physical and mechanical properties of dredged sediment from the Texas region that was previously stabilized with 6% $Ca(OH)_2$ and 12% CaO by dry weight. Adding binders led to a significant reduction in the plasticity index, therefore opening the possibility of using this material in embankment construction.

As part of this research, laboratory testing of the physical and mechanical properties of sediment collected from a disposal site formed after the dredging of the Begej River near Zrenjanin will be conducted. The study will focus on the analysis and comparison of the geotechnical characteristics of stabilized and non-stabilized sediment samples, as well as the assessment of whether the resulting material complies with relevant technical standards for use in pavement construction. For sediment stabilization, the binder ViaCalco F90, based on

CaO, will be used in proportions of 5% and 7% by dry weight of the sample. Additionally, the influence of the applied binder content on the physical and mechanical properties of the material will be analyzed.

2. MATHERIALS AND METHODS

Before starting the laboratory testing phase, a certain amount of the material in question was collected from a dredged sediment disposal site near Zrenjanin. The material is dried, has a brown colour, and has a very fine, silt and sandy-like texture when touched. The disposal site from which the material was collected, along with a sample of the material, is shown in *Figure 3*.

Figure 3. Landfill location and material sample

The use of the lime-based binder ViaCalco F90, produced by Carmeuse, is planned. This binder is used for soil drying, modification, and stabilization. According to the manufacturer's specifications, the binder contains more than 80% CaO [13]. By applying the binder in proportions of 5% and 7% by dry weight of the sample, long-term improvements in material strength and a reduction in natural plasticity are expected. The experimental part of the research is planned for stabilized and non-stabilized samples in order to monitor changes in the geotechnical properties of the material resulting from stabilization.

The experimental phase includes tests for determining the physical characteristics and classification of the material, specifically:

1. Determination of the particle size distribution, in accordance with SRPS EN ISO 17892-4:2017 [14];
2. Determination of bulk density and natural moisture content, in accordance with SRPS EN ISO 17892-1:2015 [15] and SRPS EN ISO 17892-2:2015 [16];
3. Determination of Atterberg limits (plastic limit, liquid limit, plasticity index), in accordance with SRPS EN ISO 17892-12:2018 [17]
4. Classification of the soil material according to the Unified Soil Classification System (USCS), in accordance with ASTM D2487 [18].

The following tests are necessary for determining the mechanical characteristics of the sediment:

1. Determination of maximum dry density and optimum moisture content using the standard Proctor test, in accordance with SRPS EN 13286-2:2012 [19];
2. Determination of the California Bearing Ratio (CBR), in accordance with SRPS EN 13286-47:2022 [20];

3. Determination of unconfined compressive strength after 7 days, in accordance with SRPS EN ISO 17892-7:2018 [21].

The described testing procedure aligns with the standard methodology for determining soil material characteristics. Particle size distribution analysis is performed by separating the soil sample into fractions of different sizes (sieving) based on a series of sieves defined by the referent standard. For particles smaller than 0.063 mm, the hydrometer method was applied. The liquid limit was determined using the Casagrande apparatus, while the plastic limit was defined as the water content at which a 3 mm diameter soil thread begins to crack during rolling. The procedure for determining the Atterberg consistency limits is shown in *Figure 4*.

Figure 4. Laboratory determination of the liquid (left) and plasticity limit (right)

The mechanical property tests presented in this study are basic test commonly performed in practice to assess the bearing capacity of materials and their potential use in pavement structures. The laboratory test used to determine the optimum moisture content (W_{opt}) and maximum compaction of the samples is the Proctor test. The standard Proctor test was conducted on both stabilized and non-stabilized samples at various moisture contents. Cylindrical samples with a diameter of Ø100 mm and height H = 120 mm were prepared, with a compaction energy of 600 kN/m³ applied. Following the Proctor test, CBR and UCS tests were performed at the W_{opt} and maximum dry density (MDD), in accordance with relevant standards. For the CBR test, cylindrical samples with a diameter of Ø200 mm and height H = 214 mm were prepared, while for the UCS test, cylindrical samples with a diameter of Ø100 mm and height H = 120 mm were used. Penetration tests in the CBR procedure were performed after 96 hours of sample submersion in water, with monitoring of linear swelling. UCS tests were carried out using a universal hydraulic press, and the results shown represent average values based on three tested samples. The measurement of sample dimensions and the UCS testing on the hydraulic press are presented in *Figure 5*.

Figure 5. Laboratory investigation of UCS after 7 days of curing

3. RESULTS

3.1. Material characterization

The results of the physical characterization of the dredged sediment are presented in *Table 1*. Granulometric analysis showed that the material predominantly consists of silty fractions, over 40%. The natural moisture content of the sample was recorded at 1.98%, and the natural bulk density was 1.34 Mg/m^3. The Atterberg liquid and plastic limits were 27.44% and 17.32%, respectively. Based on these values, it was concluded that the plasticity index is 10.12%, indicating that the material is moderately plastic. Based on the granulometric analysis and defined consistency limits, the material was classified as low plasticity clay (CL) according to the USCS classification.

Table 1. Geotechnical properties of non-stabilized dredged sediment

Material property	**Value**
Granulometric composition (%)	
Clay (<0.002 mm)	22.55
Silt (0.002 - 0.06 mm)	41.40
Sand (0.06 - 2 mm)	32.55
Gravel (2 - 6 mm)	3.50
Boulder (>60mm)	0
Initial moisture content (%)	1.98
Natural bulk density (Mg/m^3)	1.34
Liquid limit (%)	27.44
Plasticity limit (%)	17.32
Plasticity index (%)	10.12
Soil classification (according to USCS)	CL (Low plasticity clay)

The Atterberg limits were also determined for the stabilized samples in order to adequately track the changes in plasticity of the samples upon the addition of the binder. The obtained plasticity indexes did not significantly deviate from the values obtained while testing the non-stabilized sediment. This can be explained by the type of material itself. The material in question naturally has lower plasticity, so the applied lime binder loses its primary role in reducing plasticity, as is the case with highly plastic clays [22]. The consistency limits for the stabilized samples are presented in *Table 2*.

Table 2. Atterberg consistency limits of stabilized dredged sediment

Material property	**Value**	
	5% of binder	**7% of binder**
Liquid limit (%)	27.64	27.60
Plasticity limit (%)	17.04	17.00
Plasticity index (%)	10.60	10.60

3.2 Mechanical properties

The MDD and W_{opt} of the material were determined based on the bulk densities of samples prepared with different moisture contents and the corresponding diagrams formed according to the reference standard. MDD and W_{opt} were determined for both stabilized and non-stabilized samples. The recorded W_{opt} was 12.5% for the non-stabilized sediment and the MDD was 1.62 Mg/m³. The Proctor curve for the non-stabilized sediment is presented in *Figure 6*.

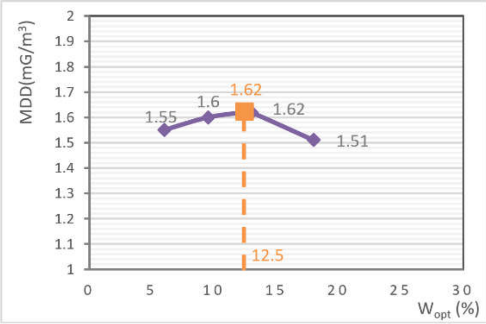

Figure 6. Proctor compaction curve of non-stabilized samples

For the samples stabilized with 5% binder based on dry mass, the MDD obtained was 1.70 Mg/m³ and the W_{opt} was 16.9%. When 7% binder was added, the MDD was recorded as 1.73 Mg/m³ and the W_{opt} as 19.4%. The increase in W_{opt} was expected due to the higher binder content and the chemical reactions occurring during stabilization. No significant changes in MDD were observed with the increase in binder percentage. The graphical representation of MDD and W_{opt} for the samples stabilized with 5% and 7% binder, based on the dry mass of the sample, is presented in *Figure 7*.

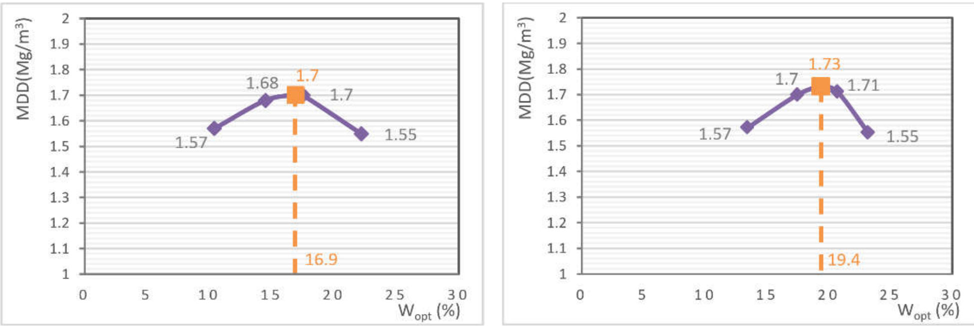

Figure 7. Proctor compaction curves of samples stabilized with 5% (left) and 7% of binder (right)

The recorded CBR index value for the non-stabilized samples was 9.70%, indicating the potential for direct application of the sediment (without prior stabilization) in the subgrade of the pavement structure. By adding lime binder, or stabilization, a significant increase in the CBR value was observed, which can be associated with the hardening of the material due to the formation of C-S-H products during the stabilization process [11]. As the binder percentage increased, a significant increase in the measured CBR value of the sample was also observed. When 7% lime binder was applied for stabilization, the CBR index reached 49.75%. The variations in the CBR values in relation to the applied binder content are presented in *Figure 8*.

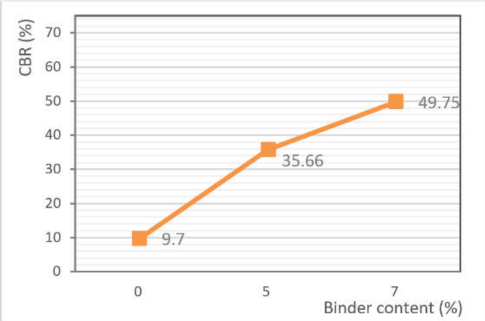

Figure 8. CBR values of sediment samples depending on binder content

Determining the UCS is an integral part of testing samples during soil stabilization and the construction of pavement structure. The UCS after 7 days could not be determined for the non-stabilized samples, nor for the sample stabilized with 5% lime binder. With the application of 7% lime binder, the strength of the samples was recorded as 0.32 MPa.

4. DISCUSSION

To assess the suitability of the material for use in the construction of embankments or subgrade, it is necessary to compare the obtained geotechnical parameters with the referent technical conditions and relevant national standards. *Table 3* provides the summarized required values of geotechnical parameters for embankment and road subgrade construction based on the valid standards SRPS U.E1.010 [23] and SRPS U.E8.010 [24].

Table 3. Technical requirements for embankment and subgrade construction and results of laboratory examination for non-stabilized sediment [23], [24]

Laboratory examination	**Required value**		**Obtained values**
	Embankment	**Subgrade**	
MDD of soil (Mg/m^3)	≥ 1.50 (*up to 3m of height*) ≥ 1.55 (*over 3m*)	≥ 1.60	1.62
W_{opt} (%)	< 25	-	12.5
Liquid limit (%)	< 65	< 50	27.44
Plasticity index (%)	< 30	< 20	10.12
Coefficient of uniformity	> 9	> 9	-
Organic matter (%)	< 6	< 6	-
CBR (%)	-	> 3	9.7

By comparing the values obtained from laboratory testing with the required values, it can be concluded that this material can be used in both the subgrade and embankment of the pavement structure, even without stabilization. The obtained CBR values, liquid limit, plasticity index, and MDD meet all the criteria prescribed by the technical conditions. The testing not covered in this study is the determination of organic matter content, which should be conducted in future research to eliminate concerns about the long-term durability of the road structure.

When it comes to sediment stabilized with lime binder, the obtained CBR values are significantly higher compared to the non-stabilized sediment. Additionally, the values of MDD, liquid limit, and plasticity index meet the requirements for use in the embankment and subgrade of the pavement structure.

Regarding the property of compressive strength, the *Technical Conditions for Earthworks* of PE Roads of Serbia from 2012 [25] require a minimum UCS of 0.5 MPa for stabilized soil after 7 days. Samples stabilized with lime binder do not meet this requirement, which may seem illogical bearing in mind the achieved CBR values of 35.66% and 49.75% for samples stabilized with 5% and 7% of binder, respectively. The reason for this inconsistency may be that the stated conditions do not differentiate between the type of binder used, nor the mechanism of strength development during stabilization with cement, lime, or fly ash. The development of strength when stabilizing with lime and fly ash can be much slower, so it would be more reasonable to test the strength of samples after a longer period [22].

5. CONCLUSION

Common materials that have been used for decades in the construction of road base, subbase and subgrade include sand, gravel, and crushed stone. Standard processes for producing these aggregates can generate large emissions of pollutant gases. Also, the distance between the sources of material and the construction site can drastically increase the cost of the roadway. Therefore, it is essential to stimulate the recycling of existing natural or artificial materials, which helps preserve existing resources, protect the environment, and reduce construction costs. Dredged sediment is one of the materials with great potential for use in these purposes, as increasing deposits of this material are forming near our rivers, and managing this waste will represent an increasing challenge in the future.

The results of this study indicate that raw river sediment originating from the Begej River can be utilized for the construction of road embankments or subgrade. The material examined in this research is a material with moderate to low plasticity, with a low content of particles smaller than 0.002 mm. It demonstrates adequate strength in terms of MDD and CBR index. Further research should include determining the organic matter content in the sediment to prevent potential negative effects on the development of material strength.

When stabilizing this material with CaO-based lime binders, additional improvement of the mechanical properties was observed, most notably through a significant increase in CBR values. A considerable rise in the W_{opt} was also recorded, attributed to lime hydration. However, stabilization with lime did not achieve the required UCS values after 7 days. This may be due to the longer curing time typically needed for strength development in lime-stabilized soils and the relatively low clay content in the material itself. Therefore, to achieve higher strength values, the use of cement-based binders for stabilization should be considered.

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