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Physical and mechanical properties of stabilised river sediment: case study of the Begej river in Serbia

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Research Paper

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Physical and mechanical properties of stabilised river sediment: case study of the Begej river in Serbia

Using recycled and waste materials in construction instead of natural aggregates contributes to the conservation of natural resources and reduction of construction costs. River sediment obtained via dredging represents one such material which, following appropriate stabilisation, is likely suitable for road construction applications. This study analysed the physical and mechanical properties of both unstabilised and hydraulically stabilised sediments sourced from the Begej River in the Republic of Serbia. Based on the evaluation of the measured properties and their comparison with technical criteria for road construction of Republic of Serbia, the results indicated that unstabilised sediment is suitable for subgrade and embankment construction. Furthermore, specific stabilised mixtures met the 7-day compressive strength requirements for application as stabilised subgrades and stabilised subbase layers in lower-category roads.

Key words:

river sediment, stabilization, road construction, waste management

Prethodno priopćenje

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Fizikalna i mehanička svojstva stabiliziranoga riječnog sedimenta: studija slučaja rijeke Begej u Srbiji

Korištenje recikliranih i otpadnih materijala umjesto prirodnih agregata u graditeljstvu doprinosi očuvanju prirodnih resursa i smanjenju troškova gradnje. Riječni sediment dobiven jaružanjem jedan je takav materijal koji je, nakon odgovarajuće stabilizacije, potencijalno prikladan za primjenu u cestogradnji. U ovome radu analizirana su fizikalna i mehanička svojstva nestabiliziranih i hidraulički stabiliziranih sedimenata iz rijeke Begej u Republici Srbiji. Na temelju rezultata istraženih svojstava i njihove usporedbe s tehničkim kriterijima za cestogradnju Republike Srbije dokazana je prikladnost primjene nestabiliziranog sedimenta za izgradnju posteljice i nasipa. Nadalje, pojedine stabilizirane mješavine zadovoljile su zahtjeve tlačne čvrstoće nakon sedam dana za izvedbu stabilizirane posteljice i stabiliziranih donjih nosivih slojeva cesta niže kategorije.

Ključne riječi:

riječni sediment, stabilizacija, cestogradnja, gospodarenje otpadom

1. Introduction

River sediments form via the accumulation and deposition of weathered rock or soil particles at the bottoms of water bodies. Additional processes, including the decomposition and settling of organic matter from flora and fauna, as well as the discharge of industrial and municipal wastewater, further influence sediment formation in aquatic environments. Consequently, the deposited sediment may contain substantial quantities of organic matter, heavy metals, and other pollutants. Dredged sediments typically comprise a mixture of solid particles, organic and inorganic constituents, heavy metals, various contaminants, and a considerable amount of interstitial water [1-4]. From a geotechnical perspective, sediment is predominantly composed of fine-grained fractions, typically representing a mixture of clay, sand, and silt. This material is also commonly characterised by a high void ratio, high compressibility, and low strength and bearing capacity [5-7]. Therefore, the direct use of this material without chemical stabilisation during construction remains highly limited [8, 9].

Sediments constitute highly heterogeneous materials whose properties vary significantly depending on the watershed geology, hydrological regime, land use, and anthropogenic influences. Grain size distribution, mineralogical composition, and organic matter content are strongly controlled by the upstream lithology, soil erosion processes, and river flow dynamics, whereas the concentration of pollutants, such as heavy metals, nutrients, microplastics, and hydrocarbons, depends on the surrounding industrial activities, agriculture, and urban wastewater inputs. Consequently, sediment behaviour significantly differs across regions. Some deposits exhibit predominantly sandy or silty characteristics with relatively low contaminant loads, whereas others contain high fractions of clay, organic matter, or hazardous substances that influence their plasticity, compressibility, and environmental risk profiles. These differences directly impact the feasibility of reuse and the type of stabilisation treatment required.

The management of dredged marine and river sediments represents a global challenge. Data from 2023 indicate that annual sediment dredging in Europe amounts to approximately 160 million tonnes, representing a substantial increase over the past two decades [10, 11]. In many Western European countries, beneficial reuse options, such as land reclamation, construction materials, and habitat restoration, are increasingly prioritised within circular economic frameworks. By contrast, some countries continue to predominantly rely on landfilling or temporary storage, as observed for sediments from the Begej River, owing to regulatory, economic, or technical limitations. Other regions implement treatment methods such as washing, thermal desorption, or solidification–stabilisation prior to reuse. The global variability in sediment characteristics and management approaches highlights the necessity for site-specific analyses to determine the sustainability and suitability of dredged materials for construction applications. In the United States, the annual volume of sediment dredged from navigable waterways is approximately 200 million cubic yards (≈ 153 million m^3), of which nearly 30 to 35 % is utilised in a sustainable manner that delivers environmental and societal benefits [12]. In the Republic of Serbia, annual dredging volumes range between 300,000 and 600,000 m^3, primarily within the Danube–Tisa–Danube (DTD) hydrosystem in the Autonomous Province of Vojvodina. The material is predominantly stored at temporary disposal sites, and projections suggest that dredged quantities may reach approximately 1 million m^3 per year in the near future [2, 13].

Conventional sediment management processes involve material excavation, transport, eventual treatment, and subsequent disposal in designated landfills, which can be challenging owing to high transport costs and land occupation [7, 14]. Moreover, the storage of materials in landfills can cause up to ten times more negative impacts on the environment than when no measures are implemented to remove the sediment [15]. Therefore, the development of alternative management strategies that prioritise beneficial reuse is essential. This approach aligns with the basic principles of the circular economy, such as reuse, renewal, sharing, and recycling, which aim to extend the life cycle of materials [16].

Numerous studies demonstrate that chemical stabilisation of dredged sediment can produce materials with adequate physical and mechanical properties, thereby enabling applications in road subgrades and embankment construction. Chemical stabilisation involves mixing and combining additives (binders) in a specified proportion with the subject material (soil), initiating chemical reactions between the mineral components of the material and binder. These reactions promote material hardening via cementation and the formation of hydration products. In general, chemical stabilisation significantly increases material strength, reduces porosity and moisture sensitivity, decreases plasticity, and increases frost resistance. Prior studies indicate that the typical binders used for sediment stabilisation are quicklime, hydrated lime, Portland cement, fly ash, and their mixtures in different proportions [9, 17-21]. A review of the available literature reveals the predominant use of cement or cement–fly ash for sediment stabilisation compared with other binders. Cement is preferable as a binder for sediment stabilisation because of its rapid strength development and superior performance, particularly in silty and low-plasticity materials [22].

The evaluation of dredged sediment for road construction requires consideration of key parameters that provide insight into its mechanical properties, such as maximum dry density (MDD) at optimum moisture content (W_{opt}), unconfined compressive strength (UCS), California bearing ratio (CBR), and indirect tensile strength (ITS). These parameters, which reflect strength and bearing capacity, have been extensively investigated for stabilised dredged sediments from the port of Dunkirk, France [3, 23]. Wang et al. [3] analysed these parameters for unstabilised and sediment-stabilised soils using a hydraulic binder and fly ash. Almokdad and Zentar [23] evaluated the use of recycled and raw sediments stabilised with 6 % Portland cement (by dry mass), demonstrating the suitability for highly performing pavement layers. Additional studies conducted in Thailand analysed stabilisation of dredged sediment using cement, fly ash, and their combinations, as well as the impact of stabilisation on the development of several mechanical characteristics of the material [5-6, 8, 24]. In [5] and [8], the investigations reported maximum strength development for cement–fly ash mixtures, and the stabilised material satisfied the reference criteria for application in the subgrade and, in some cases, subbase and base layers of the pavement.

This study investigated the physical and mechanical properties of sediments collected from a local material landfill formed after the riverbed cleaning of the Begej River, Zrenjanin, Republic of Serbia. Following the characterisation of the sediment, stabilisation was performed using hydraulic road binders BeoBond and BeoSol, produced by Lafarge, in accordance with relevant standards. Stabilisation was performed using different binder contents to monitor changes in the mechanical properties, specifically in terms of strength and bearing capacity. The planned tests for evaluating the mechanical properties included determining the MDD at W_{opt} (via the Proctor test) and the CBR for all samples, as well as UCS and ITS tests for the stabilised sediment. Finally, the obtained results are compared with relevant technical regulations for the use of materials in pavement structure layers in the Republic of Serbia.

2. Materials

The sediment was collected from a local landfill near the Begej River in Zrenjanin. The disposal site was established in 2021 during riverbed cleaning operations aimed at restoring navigability. The landfill location and a satellite image of the sampling site are shown in Figure 1. The subject landfill was created during cleaning of the riverbed and banks over a length of 780 m. The landfill is composed of material deposited during a single dredging campaign, resulting in relatively homogeneous composition. Dredged material was extracted from the river utilising hydraulic excavators mounted on amphibious crawlers, transferred to floating vessels, transported to a transshipment site, loaded onto trucks, and conveyed to pre-prepared cassettes located approximately 2 km downstream. Material sampling for the study was conducted in stages throughout 2024, in parallel with the experimental program. To ensure better representativeness, the material was collected from four different locations within the landfill and mixed to achieve additional homogeneity. During material sampling, the material exhibited characteristics of dry, silty-sandy soil with brown colour. The samples were stored in plastic bags to preserve their natural moisture content and other properties during transport. Subsequently, the physical characteristics of the material were determined in accordance with relevant standards, including particle size distribution, bulk density, natural moisture content, particle density of soil, organic matter content, Atterberg consistency limits, and soil classification according to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification. A summary of the physical characteristics of the materials, in conjunction with the applied standards for their determination, is presented in Table 1.

Figure 1. Sediment landfill location on the map of Serbia (left) and a satellite image of the sampling area (right)

Table 1. Physical characteristics for unstabilised dredged material

Physical property	Value	Standard
Natural moisture content [%]	2.12	SRPS EN ISO 17892-1:2015 [27]
Bulk density [Mg/m^3]	1.42	SRPS EN ISO 17892-2:2015 [28]
Particle density [g/cm^3]	2.67	SRPS EN ISO 17892-3:2016 [29]
Liquid limit [%]	26.91	SRPS EN ISO 17892-12:2018 [30]
Plasticity limit [%]	16.88	
Plasticity index [%]	10.03	
Organic matter content [%]	2.48	SRPS U.B1.024:1968 [31]
Soil classification (USCS)	CL	ASTM D2487 [32]
Soil classification (AASHTO)	A-6	AASHTO M145 [33]

BeoBond (BB) and BeoSol (BS) binders were utilised for stabilisation at percentages of 3, 5, 7, and 9 % by dry weight of the sample. Binder dosages were selected to align with the objective of practical applicability of the results. Given the commercial availability of the binders and the intended use of stabilised sediment for large-scale earthwork in road construction, 9 % of the dry weight of the material was selected as the maximum binder content. Although stabilisation with higher binder percentages has been reported in the literature, this approach compromises improvements in the geotechnical properties of the material as well as the economic and ecological sustainability of the procedure. Owing to commercial constraints, detailed chemical compositions of the hydraulic binders are not presented in this paper. Based on the information available to the author, BS is produced as a conventional hydraulic binder from Portland cement clinker (approximately 45 %) with the addition of up to 15 % fly ash. The remaining BS binder is composed of a mixture of slag, gypsum, and limestone. The BB binder consisted of approximately 35 % cement clinker, 20 % fly ash, and 20 % quicklime (CaO), calculated relative to the dry binder mass. Similar to the BS binder, the remaining binder composition consisted of a mixture of slag, gypsum, and limestone. Both binders are

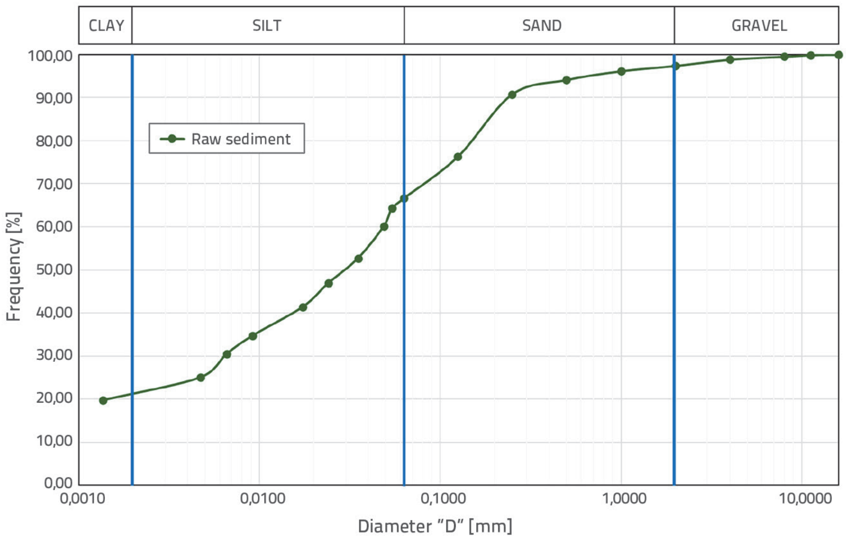

Figure 2. Particle size distribution for unstabilised dredged material

commercially available and are actively used for soil stabilization/ modification via cold recycling [25].

Particle size distribution was determined via sieve analysis using a set of sieves in accordance with the SRPS EN ISO 17892-4:2017 standard [26]. The hydrometer method was employed to determine the size of particles smaller than 0.063 mm. The final grain size distribution curve was obtained as the average of the results from the sieve analyses performed on the four sediment samples. The particle size distribution of the unstabilised sediment is shown in Figure 2.

The measured natural moisture content and bulk density of the material were 2.12 % and 1.42 Mg/m^3, respectively. The organic matter content was determined employing the loss-on-ignition method at 700 °C, yielding a relatively low organic matter content of 2.48 %. Particle density was determined via the pycnometer method, with a measured value of 2.67 g/cm^3, which corresponds to typical values for clayey soils [34].

Atterberg consistency limits were determined in accordance with the SRPS EN ISO 17892-12:2018 standard [30], which specifies the Casagrande cup method for determining the liquid limit, and the rolling method for determining plastic limit, in which soil threads are rolled to a diameter of 3 mm until visible cracking. Based on the obtained consistency limits, a plasticity index of 10.03 % was recorded. According to Burmister's soil classification based on plasticity (cited in [35]), the obtained plasticity index indicates soil at the boundary between very low and low plasticity. Comparison of the measured consistency limits with the classification thresholds for cohesive soils by Dahms and Fritz (cited in [35]) confirmed that the tested material corresponds to clayey soil with a low degree of plasticity. Soil classification according to USCS, as per ASTM D2487 [32], was confirmed as previously mentioned. Based on its physical properties, the material is classified as a low-plasticity clay (CL). According to the AASHTO M145 standard [33], the material belongs to Group A-6 (clayey soil with low-to-moderate plasticity).

The changes in the consistency limits depending on the type and percentage of the applied binder are shown in Figure 3. Comparison of the obtained values indicates that the addition of a binder does not significantly influence the plasticity of the material or the consistency limits. A limited increase in the plasticity index was observed when the binder was initially added at a content of 3 % relative to the dry mass. However, further increases in the binder content resulted in no significant changes in plasticity. This behaviour is attributed to the lower content of the clay fraction in the sediment and the lower content of the montmorillonite mineral in the clay, which is typically responsible for cationic exchange between soil particles and the binder [22, 36]. Similar results were reported in a study conducted by Nguyen et al. [20], who observed that treating sediments with Portland cement did not significantly change the plasticity of the material.

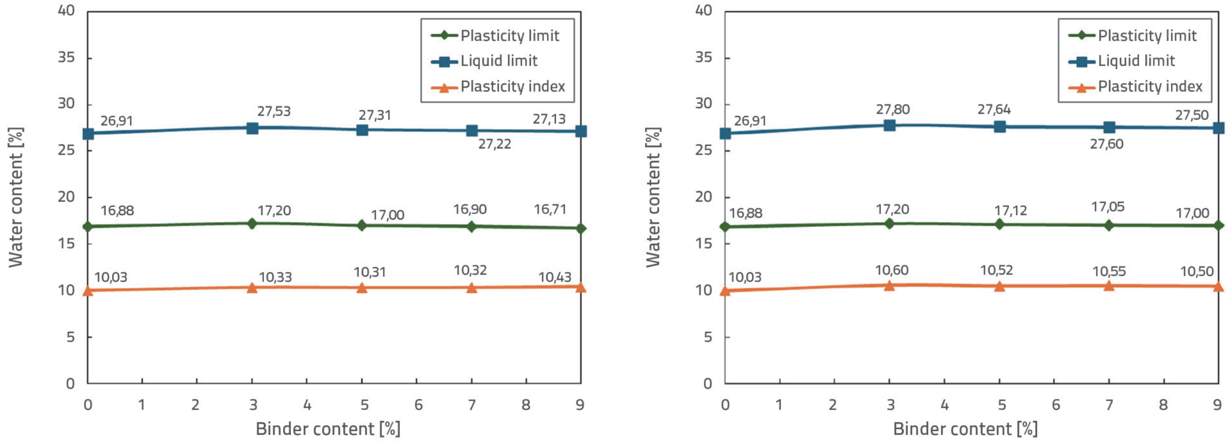

Figure 3. Consistency limits for samples stabilised with hydraulic binder: BS (left) and BB (right)

3. Methodology

Laboratory testing of the mechanical properties was performed on a series of unstabilised samples and samples individually stabilised with BS and BB binders. Unstabilised sediment samples (Mix S.0) were prepared to determine the MDD at W_{opt} and the CBR index. For the stabilised samples, in addition to the MDD and CBR tests, laboratory tests of UCS after 7 and 28 d and ITS after 28 d were conducted. A list of mixtures with the applied binder percentages is presented in Table 2. Nine mixtures comprising 117 samples were prepared for the testing. The samples were prepared by manually mixing the sediment material with a binder according to a predefined proportion.

Table 2. Mixture proportions for sample formation

Mixture symbol	BS [%]	BB [%]
S.0	-	-
BS.3	3	-
BS.5	5	-
BS.7	7	-
BS.9	9	-
BB.3	-	3
BB.5	-	5
BB.7	-	7
BB.9	-	9

Determination of the MDD at W_{opt}, performed using cylindrical samples with a diameter of 100 mm and height of 120 mm, in accordance with the standard SRPS EN 13286-2:2012 [37]. The samples were prepared with four different moisture contents, and a compaction energy of 600 kN/m³ (standard Proctor test) was applied. The material was dynamically compacted in a cylindrical mould in three layers, with 25 blows per layer using a standard rammer. The samples were subsequently extruded from the mould, and the MDD was determined according to the standard procedure based on the moisture content, mass of the sample with the mould, and mass of the mould. Thirty-six samples were prepared for the Proctor test.

Compressive strength and ITS represent basic tests for evaluating the strength of stabilised materials [38]. To test the UCS after 7 and 28 days, as well as the ITS after 28 days, a total of 72 cylinders with a diameter of 100 mm and a height of 120 mm were prepared in accordance with the SRPS EN ISO 17892-7:2018 [39] and SRPS EN 13286-42:2012 standards [40]. During sample preparation, water was added to a percentage corresponding to W_{opt} to achieve maximum compaction, following the Proctor procedure. The samples were then stored in plastic bags to preserve moisture at a temperature of 20 ± 2 °C, for 7 and 28 days, depending on the testing schedule.

UCS testing was conducted using a standard hydraulic press, with peak load recorded at specimen failure. The apparatus used for UCS laboratory testing is shown in Figure 4. The same hydraulic press was used to determine the ITS, whereby the samples were placed in a horizontal position and a metal semi-cylinder loading strip was placed between the sample and load transfer plate. The peak load at the failure of the sample was recorded, and the ITS was obtained using the following equation [40]:

$$ITS = \frac{2F}{\pi DH} \qquad (1)$$

where ITS denotes indirect tensile strength (MPa), F represents the failure load (N), D is the specimen diameter (mm), and H is the specimen height (mm).

The obtained UCS and ITS values represent the average results based on testing three specimens.

The CBR index serves as a primary indicator of bearing capacity for subbase and lower pavement layers. It is obtained based on a penetration test, during which the pressure is recorded as a 2.54 mm and 5.08 mm plunger penetrates the soil sample, in accordance with the SRPS EN 13286-47:2022 [41] standard. The obtained stress values are divided by the reference stresses

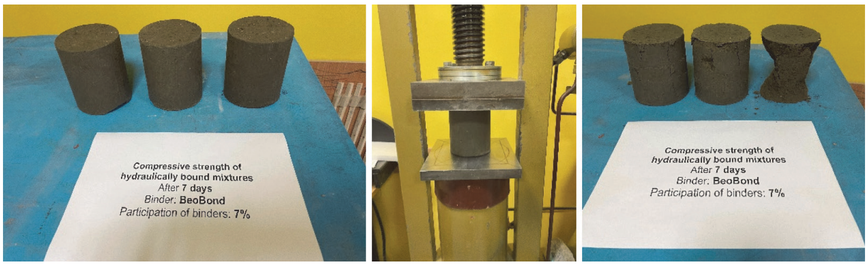

Figure 4. Samples stabilised with 7 % of BB binder before (left), during (middle) and after (right) UCS testing after 7 days of curing

Figure 5. Laboratory examination of ITS (left) and CBR index with determination of linear swelling (center and right)

defined by the standard. Typically, the adopted (higher) CBR value corresponds to a penetration of 2.54 mm. After repeating the test, a higher value was obtained at a penetration of 5.08 mm, which was adopted as the reference value. For the CBR test, eight samples of stabilised sediment with different binder percentages and one sample of unstabilised sediment were prepared. The samples were fabricated in cylindrical moulds with a diameter of 200 mm and height of 212 mm. The percentage of moisture added to the samples corresponds to W_{opt}, which was previously determined for the stabilised and unstabilised samples as part of the Proctor test. The sample moulds with loads were soaked in water for 96 h, and the linear swelling of the samples was monitored to evaluate the behaviour of the material under wet conditions. The recorded values of linear swelling for all samples varied from 0.03 to 0.12 %, indicating a substantially low sensitivity of the material to swelling (less than 1.5 %) and suitability for use in pavement construction, according to Seed et al. [42]. Figure 5 shows the laboratory tests conducted for determining the ITS and CBR indices.

4. Results and discussion

4.1. Compaction characteristics

The MDD and W_{opt} values determined from Proctor compaction curves for the unstabilised and stabilised mixtures (Figure 6) are summarised in Table 3. In general, MDD for all mixtures ranged from 1.62 to 1.77 Mg/m^3, whereas W_{opt} varied from 12.50 to 19.40 %. For unstabilised sediment, MDD was recorded as 1.62 Mg/m^3, and W_{opt} was 12.50 %. The addition of the binder BS to the contents at 3, 5, 7, and 9 % (by dry mass of the sample) yielded an increase in both MDD and W_{opt}. The highest recorded MDD was 1.71 Mg/m^3 at a W_{opt} value of 16.20 % for sediment stabilisation with the 9 % BS binder. The Proctor curves shown in Figure 5 exhibit a rightward shift of the compaction curve, indicating an increase in water demand to achieve maximum compaction. This phenomenon is likely attributed to the ongoing cement hydration process, which requires higher water-to-cement ratio to hydrate a higher cement content. Wang et al. [9], Nguyen et al. [20], and Chompoorat et al. [43] reported similar trends. The increase in MDD when cement is added coincides with the results of a study by Nguyen et al., who explained this phenomenon by the higher specific gravity of cement compared with that of pure sediment [20]. Similar material behaviour was recorded for mixtures made with the BB binder. Greater increases in MDD and W_{opt} were observed for higher binder percentages (5, 7 %, and 9 %) than for mixtures stabilised with the BS binder. The additional increase in W_{opt} is attributed to the chemical composition of the BB binder itself; specifically, the need for an additional amount of water during CaO hydration [20, 43]. Rai et al. reported an increase in MDD, in conjunction

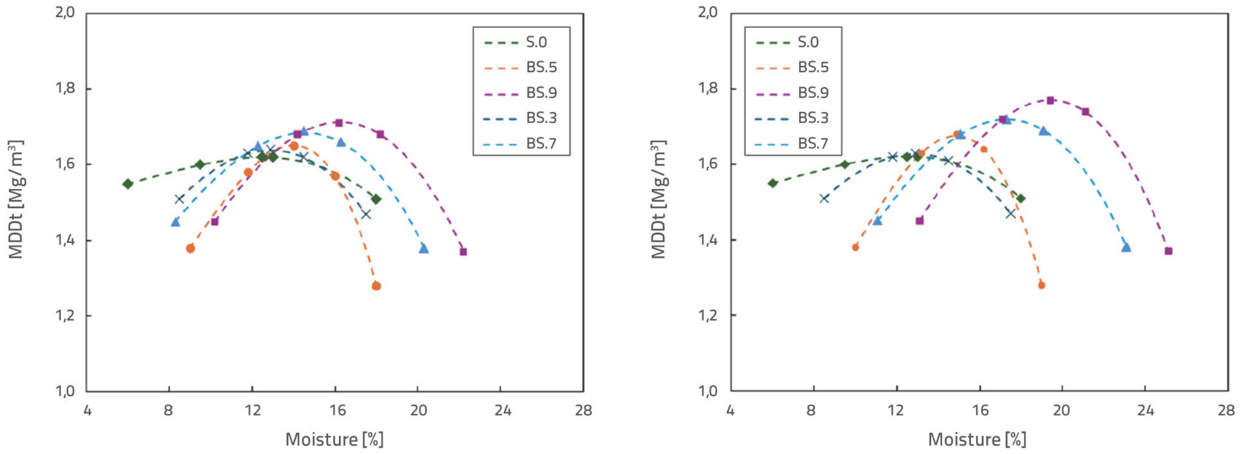

Figure 6. Compaction curves for sediments treated with BS binder (left) and BB binder (right)

Table 3. MDD and W_{opt} values obtained from compaction tests

Mixture symbol	**BS** [%]	**BB** [%]	**W_{opt}** [%]	**MDD** [Mg/m^3]
S.0	-	-	12.50	1.62
BS.3	3	-	12.90	1.64
BS.5	5	-	14.00	1.65
BS.7	7	-	14.50	1.69
BS.9	9	-	16.20	1.71
BB.3	-	3	12.90	1.63
BB.5	-	5	14.90	1.68
BB.7	-	7	17.30	1.72
BB.9	-	9	19.40	1.77

with a partial decrease in W_{opt}, when increasing the content of fly ash and cement as binders for silty soil stabilisation [44]. When observing all mixtures, the highest MDD value of 1.77 Mg/m^3 was recorded for samples stabilised with 9 % BB binder, based on the dry weight of the sample.

4.2. Unconfined compressive strength

After adding a hydraulic binder to stabilise and achieve the optimal moisture content of the sediment material, strength development primarily occurs via two fundamental chemical reactions: cement hydration (Equation (1)) and pozzolanic reaction (Equation (2)) [6, 8]. Prior to these processes, CaO hydration occurs during the mixing of the materials, binders, and water. This reaction produces calcium hydroxide ($Ca(OH)_2$), which reacts with silicon and aluminium minerals of the sediment, contributing to an immediate reduction in the plasticity of the material owing to the dislocation of Ca^+ and OH^- ions and the subsequent pozzolanic reaction [22].

$$C_3S,\ C_2S,\ C_3A + H_2O \rightarrow CSH + Ca(OH)_2 \tag{2}$$

$$Ca(OH)_2 + SiO_2 \rightarrow CSH \tag{3}$$

An increase in strength during sediment stabilisation is expected owing to the formation of a denser sediment matrix and interparticle bonding induced by binder addition. When a cement-based binder is applied, a chemical hydration reaction occurs between the calcium silicates (C_3S, C_2S) and calcium aluminates (C_3A) in the clinker, leading to the formation of cement paste, namely calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H). The C–S–H gel governs rapid strength development and imparts cementitious characteristics to the material. A specific amount of free $Ca(OH)_2$ forms as a secondary product of this reaction and participates in long-term pozzolanic reactions with SiO_2 obtained from the sediment or from additives (e.g., fly ash), resulting in additional strength development owing to further formation of C–S–H gel. The hydration-driven C–S–H gel contributes to short-term strength development (7, 14, and 28 days), whereas the C–S–H gel formed via pozzolanic reactions contributes to long-term strength development (60 and 120 days) [5, 6, 8, 22].

The compressive strength test results for the stabilised samples, conducted after 7 and 28 days of curing, are shown in Figure 7. UCS tests were not performed on unstabilised samples because of sample disintegration under loading, indicating lack of a coherent structure suitable for testing.

The obtained values indicate an increase in UCS over time. After 7 days of curing, the highest strength was recorded for samples stabilised with 9 % BS binder (1.63 MPa), followed by stabilisation with 9 % BB binder (1.50 MPa). The lowest strengths after 7 days of curing were recorded in samples stabilised with 3 % binder BB and binder BS, at 0.18 and 0.34 MPa, respectively. As expected, an increase in UCS was observed as binder content was increased. A sharp increase in strength was observed when the BB binder content increased from 5 % to 9 % (by dry mass). Specifically, the UCS after 7 days increased by approximately 105 % when the BB binder content was raised from 5 % to 7 %, and by approximately 103 % when increased from 7 % to 9 %. The strength development with increasing BB content followed a quadratic trend, as shown in Figure 5. Unlike the BB binder, the BS binder showed an extremely linear increase in strength as percentage of the binder increased.

After 28 days of curing, the highest UCS was recorded for samples stabilised using the 9 % BB binder, followed by those stabilised with the 9 % BS binder. Similar strength growth trends were observed with increasing binder percentages. The largest increase was observed when comparing the strengths of the samples stabilised with 7 % and 9 % BB binders, where the strength increased by approximately 127 %. Comparing the strengths after 7 and 28 days of curing, an increase in strength was observed, particularly when using the BB binder. When applying the 9 % BB binder (by dry mass), a 54 % increase in strength was recorded because of the longer curing time of

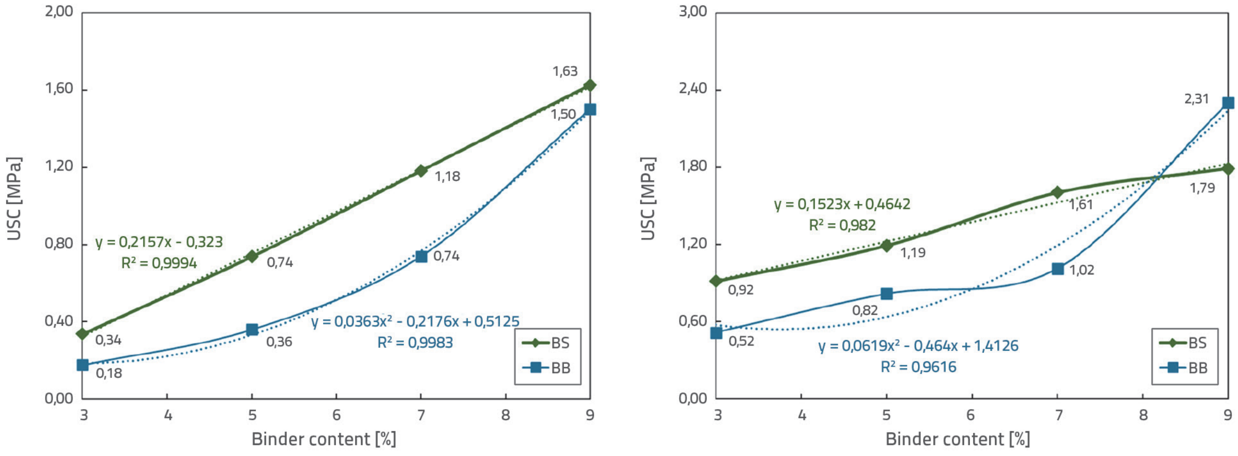

Figure 7. UCS of stabilised samples after 7 days of curing (left) and 28 days of curing (right)

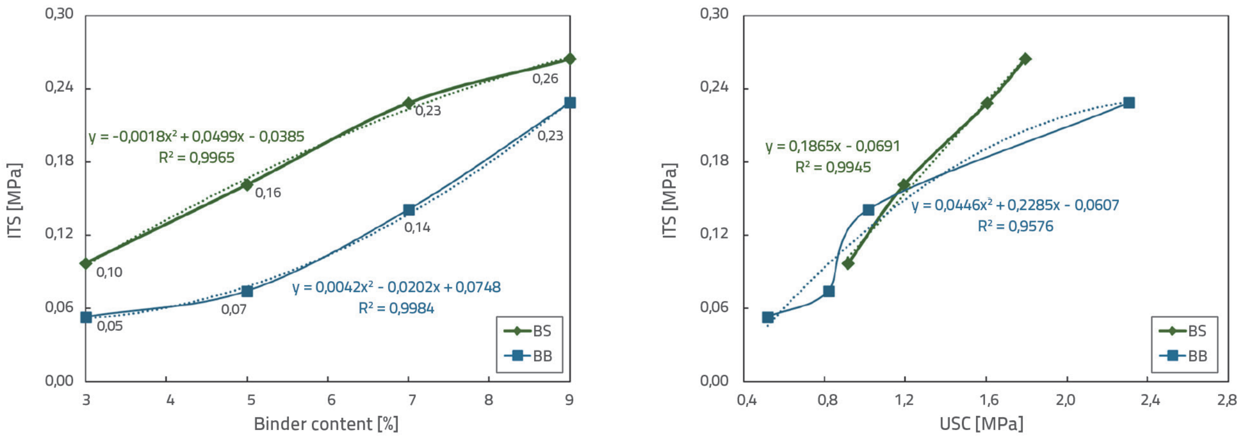

Figure 8. ITS of stabilised sediments after 28 days of curing (left) and correlation ITS-UCS after 28 days (right)

the samples (28 days instead of 7 days). This phenomenon is attributed to the binder composition; the BB binder contains, in addition to cement clinker, higher proportions of fly ash content and CaO, which enhance strength development via the pozzolanic reaction [6, 45]. Several studies have confirmed the assumption that higher strengths can be achieved with the combination of cement and fly ash at optimal doses [5, 6, 8, 24, 46]. In the case of BS, the increase in strength during longer curing times was significantly lower, and the differences in strength between 7 and 28 days of curing decreased as binder content increased.

4.3. Indirect tensile strength

The results of the ITS test for the stabilised samples after 28 days are shown in Figure 8. The results indicate a significant increase in the ITS as the binder content increased. Several studies have also reported a significant increase in the ITS when stabilising sediments [6, 8, 23]. Higher strengths were achieved when using the BS binder, with tensile strength values ranging from 0.1 to 0.26 MPa for the applied binders at proportions of 3, 5, 7, and 9 % (by dry mass of the sample). In the case of BB-stabilised mixtures, the tensile strengths ranged between 0.05 and 0.23 MPa for the same binder percentages. The growth of ITS with an increase in the BS binder was more pronounced when the binder content increased from 3 to 7 % and was significantly more moderate when the percentage of binder increased from 7 to 9 % (by dry mass). For BB-stabilised mixtures, a moderate increase was observed in the ITS when the binder content increased from 3 to 5 %, and the increase in the ITS was more pronounced when the binder content increased from 5 to 9 %. The difference in the ITS of the mixtures stabilised with 9 % BS and 9 % BB binders was negligible, amounting to approximately 13 %. The UCS (after 28 d)–ITS relationship for the mixtures stabilised with BS and BB binders is presented in Figure 7. ITS increased linearly with an increase in UCS when the BS binder was applied, whereas ITS increased as a quadratic function of UCS growth when the BB binder was applied for stabilisation.

4.4. California bearing ratio

The results of CBR index testing on the stabilised and unstabilised mixtures are shown in Figure 9. The measured CBR value of 10.16 % for the untreated sediment corresponds to subgrade materials of fair to good quality [47], indicating the high potential of using untreated sediment in road embankments or subgrades. Upon the stabilisation of the material, a significant increase in the CBR index was observed, wherein the CBR value increased as the binder content increased. By stabilising the dredged material with BS binder at contents of 3 and 5 % (by dry mass), the CBR value increased by approximately 11 and 26 times relative to the non-treated sediment, respectively.

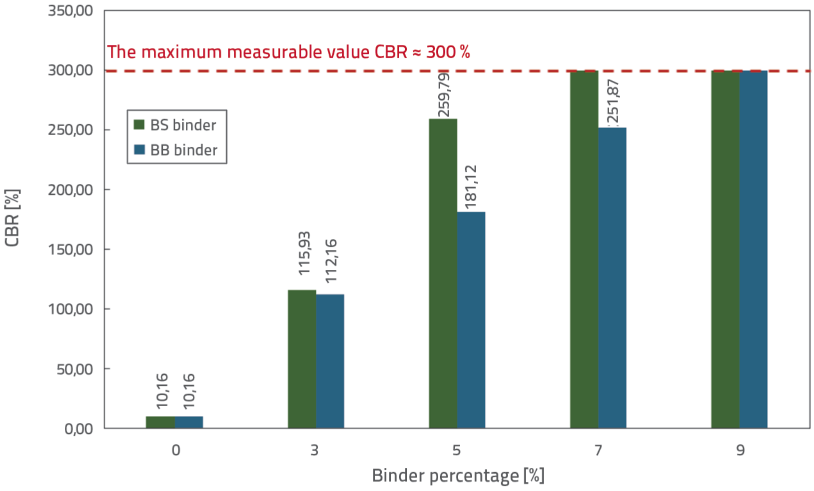

Figure 9. CBR index of unstabilised and stabilised sediment specimens

Table 4. Required properties for use of unstabilised/stabilised materials in various pavement layers according to Serbian standards [48-51]

Material property	Required value				Research results
	Embankment	Subgrade	Subbase (roads class III and IV)	Base course and subbase (roads class I and II)	
MDD tla [Mg/m³]	≥ 1.50 (up to 3 m of height) ≥ 1.55 (over 3 m)	≥ 1.60	-	-	1.62 (US) 1.63 – 1.77 (SS)
W_{opt} [%]	< 25	-	-	-	12.50 (US) 12.90 – 19.40 (SS)
Liquid limit [%]	< 65	< 50	-	-	26.91 (US) 27.13 – 27.80 (SS)
Plasticity index [%]	< 30	< 20	-	-	10.03 (US) 10.31 – 10.60 (SS)
Organic matter [%]	< 6	< 6	-	-	2.48 (US) -
CBR [%]	-	> 3	-	-	10.16 (US) 112.16 – 300* (SS)
UCS after 7 days [MPa]	-	0.5	1.5 - 4.5	2 – 5.5	- 0.18 – 1.63 (SS)
UCS after 28 days [MPa]	-	-	2.5 – 6.0	3 – 6.5	- 0.52 – 2.31 (SS)

* Maximum measurable value on the press
US = unstabilised (raw) sediment; SS = stabilised sediment

The increase in the CBR value for the samples stabilised with the BB binder was marginally milder, and the CBR index for the same applied percentages of binder increased by approximately 11 and 18 times, respectively. In general, the samples stabilised with the BB binder exhibited lower load capacity parameters than the samples stabilised with the BS binder at the same percentages. This phenomenon is likely attributed to an insufficiently long curing time for the development of the strength of the samples (test plan of 7 d according to the standard procedure), particularly for stabilisation with a mixture of cement, fly ash, and CaO. Therefore, in further studies, the CBR test should be performed after 28 d or longer to better compare the values for samples stabilised with BS and BB binders. For samples stabilised with 7 and 9 % binder BS and 9 % binder BB (by dry mass), measuring the CBR index was not feasible because of the extremely high strength of these samples and the 50 kN loading limit of the CBR penetration plunger. This limitation indicates the exceptional bearing capacity of the samples stabilised at the specified percentages.

4.5. Potential of use as a pavement material

Table 4 presents the technical requirements for the use of unstabilised/stabilised materials in the construction of embankments and pavement subgrade layers in Serbia, in accordance with standards SRPS U.E1.010 [48], SRPS U.E8.010 [49] and the Technical Conditions for Earthworks Execution issued by PE 'Roads of Serbia' (2012) [50]. The referenced technical conditions [50] identify 7-day UCS as the only relevant criterion for assessing the adequacy of stabilised soil and its application in pavement structures, prescribing a minimum value of 0.5 MPa for use in subgrade layers of the highest road categories (primarily state roads). The earlier standard SRPS U.E9.024 [51] defines the criteria in greater detail, specifying different minimum compressive strength values at 7 and 28 d depending on the road category and position within the pavement structure (base or subbase layer).

To evaluate broadest possible applicability of the stabilised sediment, including its potential use in lower-traffic infrastructure, such as local streets and bicycle paths, both standards were considered in parallel. Stabilised sediment demonstrates greater potential for use in roads with lower loads, where the required material strength and bearing capacity are less stringent.

Comparison of the required and experimental values obtained in this study indicates that unstabilised sediment material can be used in the construction of embankments and subgrade layers, as the obtained values correspond to the minimum requirements outlined in Table 4 in terms of the CBR value, MDD, and other physical characteristics of the material. For stabilised specimens, an additional requirement for subgrade construction is achieving a UCS value of 0.5 MPa after 7 d of curing, in accordance with standard [50]. This requirement was met by stabilising the sediment with 5, 7, and 9 % binder BS and 7 and 9 % binder BB (by dry mass of the sample). Therefore, these mixtures can be considered suitable for use as stabilised subgrades. Higher values of UCS after 7 days, when stabilising the sediment with the BS binder compared with BB, can be attributed to a faster mechanism of soil hardening in the case of the cement binder. Nevertheless, despite the insufficient UCS values of certain mixtures after 7 days of curing, the obtained CBR values for all stabilised mixtures indicated a more than satisfactory bearing capacity for road subgrade materials.

Standard SRPS.U.E9.024 [51] requires a minimum UCS value of 1.5 and 2 MPa after 7 days for the installation of stabilised material in the subbase and base layers of the pavement, depending on the road category. By stabilizing the sediment with BS and BB binders in a percentage of 9 % of the dry mass, strengths of 1.63 and 1.5 MPa were achieved after 7 days, respectively. Based on this property, these two mixes were the only ones that satisfied the requirement for installing materials in the subbase layer for roads classified as categories III and IV. Simultaneously, no mixture met the requirement for installing the material in the base layer of the pavement or the subbase of higher-category roads. Considering the UCS of all mixtures after 28 days, none of the mixtures met the criteria of a minimum of 2.5 MPa, i.e., 3 MPa of compressive strength, for using the material in the subbase or base layer of the pavement structure. Although current engineering practice primarily relies on the 7-day UCS as the governing parameter of a stabilised material, these findings indicate potential limitations regarding the long-term strength development of the material. This phenomenon is likely attributed to the limited pozzolanic activity of materials stabilised with higher binder content, where rapid increase in strength and stiffness after 7 days is followed by a slowdown in strength development. Future investigations of the strength (after 56 or 90 d) may facilitate assessment of the long-term strength development of the material and optimisation of the sediment stabilisation process. Additionally, for the use of sediment in the base or subbase layers, higher binder percentages should be considered, depending on the cost-effectiveness of the procedure.

5. Conclusion

The construction industry represents a resource-intensive economic sector with substantial dependence on natural resources. The constant extraction of natural resources has led to their gradual depletion, with additional adverse impacts on the environment. This problem can be addressed by replacing traditional materials with wasteful and environmentally sustainable alternatives. Dredged sediment, obtained by removing deposits from the bottoms of rivers, lakes, and sea basins, constitutes a promising candidate for such applications. This study evaluated the physical and mechanical characteristics of sediments sourced from the Begej River in the Republic of Serbia. Additionally, physical-mechanical tests were conducted on samples of sediment stabilised with hydraulic binders BS and BB at percentages of 3, 5, 7, and 9 % (by dry mass of the sample). Physical characterisation of the raw material revealed a clayey material with low plasticity and organic matter content. The addition of binders to the sediment material did not significantly change its plasticity and consistency limits. The examination of mechanical characteristics included the determination of MDD at W_{opt} and CBR values for all mixtures, as well as the determination of UCS after 7 and 28 days and ITS after 28 days for the stabilised samples. Based on the tests conducted, the following conclusions were drawn:

Stabilisation of the sediment with hydraulic binders BS and BB increases both MDD and W_{opt} across all mixtures. In addition, increasing the binder content produces a partial increase in MDD and a significant increase in W_{opt}, resulting in a rightward shift of Proctor compaction curve of the mix owing to the hydration process during stabilisation. For binder contents at a percentage of 3 to 9 % (by dry mass), the initial MDD of the untreated sediment increased by 1.23 to 5.56 % when applying binder BS and 0.62 to 9.26 % when applying binder BB. Additionally, in the same case, the W_{opt} increases by 3.2 to 29.6 % for sediment stabilisation with the BS binder and 3.2 to 55.2 % for stabilisation with the BB binder.

The CBR value of the unstabilised material (10.16 %) indicated an adequate bearing capacity for untreated sediment and the potential for using this material without stabilisation in the construction of road embankments and subgrade layers. The stabilisation of the sediment specimens resulted in an additional increase in the bearing capacity, with multiple increases in the CBR index as the percentage of the binder increased. By applying BS and BB binders at a percentage of 3 to 5 % of the dry mass, the CBR value increased by approximately 11 to 26 times compared with the initial CBR. For samples stabilised with 7 to 9 % BS and 9 % BB binders (by dry mass), the upper measurable limit of the CBR value was 300 %.

The use of a hydraulic binder for stabilisation results in material hardening and improves mechanical performance. As the binder content increased, the UCS of the samples also increased; this growth was extremely linear in the case of the BS binder and described by a quadratic function in the case of the BB binder. The recorded strength values after seven days indicated faster hardening and higher strengths of samples stabilised with binder BS compared with those stabilised with binder BB at the same percentage. However, when testing the UCS after 28 d of curing for the samples stabilised with the 9 % BB binder, the highest strength of 2.31 MPa was recorded. This phenomenon indicates an additional strength development and a pozzolanic reaction owing to the presence of CaO and fly ash in the BB binder.

ITS test results after 28 d of curing exhibit similar trends consistent with UCS behaviour; mechanical strength increased as binder content was increased. Higher ITS values were obtained for the samples stabilised with binder BS than for those stabilised with binder BB at the same binder percentage. For higher percentages of binder (7–9 %), BB-stabilised mixtures exhibit a more pronounced increase in ITS compared with that of BS-stabilised mixtures. A linear dependence of UCS (28 days) and ITS was observed for BS-stabilised mixtures, whereas a quadratic dependence of UCS (28 days), ITS was established for BB-stabilised mixtures.

Comparison of these results with the relevant technical criteria for using different materials in pavement construction (Republic of Serbia) indicated that the unstabilised sediment met all the stated conditions for application in the subgrade or embankment of the pavement. The stabilisation of the sediment resulted in additional strengthening and an increase in the bearing capacity. The achieved compressive strength values after seven days for samples stabilised with 5, 7, and 9 % binder BS and 7 and 9 % binder BB (by dry mass), indicate the potential for using the material in the stabilised road subgrade for all road categories. When considering the use of stabilised sediment in pavement-bearing layers, two mixtures (BS.9 and BB.9) met the 7-day strength criterion but not the 28-day criterion for application in the subbase layer of lower-category roads. These findings indicate the need for further investigation of mixtures with potentially higher binder contents, as well as the evaluation of long-term strength development and durability of the material. Despite the promising mechanical performance of both untreated and stabilised sediments, dredged materials frequently contain high concentrations of pollutants such as heavy metals, hydrocarbons, nutrients, and other organic contaminants. These substances may pose environmental risks, particularly via leaching during construction or long-term exposure to rainfall and groundwater interactions. Therefore, the wider application of dredged sediment in road construction should always be preceded by detailed chemical characterisation and leaching assessments in accordance with environmental regulations. In cases where pollutant concentrations exceed acceptable thresholds, additional stabilization/solidification, encapsulation techniques, or restrictions on use (e.g. only in low-permeability embankments or below impermeable layers) are likely required. These environmental considerations represent an important limitation for the universal reuse of dredged sediment and highlight the need for an integrated mechanical–environmental evaluation before practical application.

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