DOI: 10.23968/2500-0055-2023-8-4-99-117

VALORIZATION OF DREDGED SEDIMENTS FROM DAMS IN PAVEMENT DESIGN

Boumediene Serbah[1,2]*, Maghnia Asmahane Bourabah[2], Joanna Eid[3], Salima Bouchemella[4], Moussaab Hariche[5], Nabil Abou-Bekr[2], Said Taibi[6]

[1]University of Tiaret, Algeria
[2]University of Tlemcen, Algeria
[3]Ai Environnement FACÉA Group, R&D Department, Noisy-le-Grand, France
[4]University of Souk Ahras, Algeria
[5]University of Djelfa, Algeria
[6]University of Le Havre, France

*Corresponding author's e-mail: boumediene.serbah@univ-tiaret.dz

Abstract

Introduction: This study is part of research aimed at valorizing dredged sediments through the development of formulations for use in road engineering. The **purpose of the study** was to determine if the materials selected for pavement layers comply with road design standards, in particular, with specific requirements for density, grain size, plastic properties, organic matter, and mechanical performance. **Methods**: To determine the physical-chemical and mechanical characteristics of the dredged sediments obtained from samples taken from the Bakhadda dam located in western Algeria's semi-arid climate, the sediments were treated with binders in small amounts (3% lime (L), 6% cement (C)) for reuse in road construction. The study focused on the evolution of physical and mechanical characteristics of the treated sediments, including LL, PI, VBS, immediate bearing index (IBI%), UCS, tensile strength σ_t, as well as small strain modulus E_{SS} and large strain modulus E_{50}. The **results** showed that adding lime and cement to the dredged sediments improved their strength, as evidenced by the increased compressive strength (UCS) over time for the samples containing different amounts of binders (3%L, 6%C, and 3%L + 6%C). Additionally, the effect of the water content on the mechanical properties of the formulations was demonstrated. The study showed that the strength increased when the water content decreased.

Keywords: valorization, dredged sediments, compaction, modulus of elasticity, UCS, tensile strength, eco-geo-material, road construction.

Introduction

The dredged sediments from western Algeria provide a new source of materials for pavement layers. This study aims to investigate the feasibility of using raw dredged sediments as a road construction material and improving their mechanical properties. One of the methods used is to amend them with binders such as lime and cement (Hussan et al., 2022; Tribout et al., 2011; Wang et al., 2013). Large quantities of dredged sediments pose a significant challenge for their valorization in road engineering. However, these sediments from dams are ecologically sustainable and recyclable materials. The Bakhadda sediments are also advantageous because they are uncontaminated, allowing for direct reuse without any decontamination treatment. Nevertheless, the weak geotechnical properties of dredged sediments often hinder their use in road techniques due to their low resistance and durability (Larouci et al., 2021; Wang et al., 2013; Zentar et al., 2021). Therefore, we will explore potential solutions to enhance their properties and increase their potential use in road construction.

In order to overcome these limitations, it is essential to understand the criteria required for road construction materials (Association Française de Normalisation, 1992a; LCPC, SETRA, 1992, 2000) such as:

- Controlling particle size is crucial as it can affect the physical and mechanical properties of pavement layers.
- Compressive strength (UCS > 1 MPa) is an important parameter in determining the material capacity to support the circulation of construction machinery on the treated layer (Association Française de Normalisation, 1992a, 2003b; Qureshi et al., 2021; Wang et al., 2013; Zentar et al., 2021). As per the NF P11-300 standard, the recommended minimum and maximum compressive strength (UCS) is 2 to 4 MPa to ensure the bearing capacity of vehicles and 8 MPa for re-excavation of the base coat, subgrade, and sub-base layer.
- Indirect tensile strength and E_{SS} modulus shall also be verified since the (σ_t, E) pair at 28, 90, and 360 days should show a minimum of mechanical material class 5. Tensile strength is a significant mechanical parameter that controls the development of tensile cracking (Gajewska et al., 2017; Jamsawang et al., 2021; LCPC, SETRA, 2000; Zentar et al., 2021).

For citations: Serbah, B., Bourabah, M. A., Eid, J., Bouchemella, S., Hariche, M., Abou-Bekr, N., Taibi, S. (2023). Valorization of dredged sediments from dams in pavement design. Architecture and Engineering, No 4 (8), pp. 99-117. DOI: 10.23968/2500-0055-2023-8-4-99-117.

- The minimum recommended values of Immediate bearing capacity IBI vary from layer to layer (Association Française de Normalisation, 1997, 2012; Banoune et al., 2016), which also determines the material capacity to support the weight of construction machinery on the treated layer. The CBR test is both simple and cost-effective, offering advantages that vary depending on such factors as the road class and material placement within the pavement structure (Association Française de Normalisation, 2012; Banoune et al., 2016; Hamouche and Zentar, 2018).
- The ability of treatment depends on volume swelling (LS(%) ≤ 5) and mechanical performance represented by the Brazilian tensile strength $\sigma_t \geq 0.2$ MPa (Association Française de Normalisation, 2015).

To achieve the target strength, dredged sediments shall be treated with a specific ratio of cement or lime. Various studies (Jamsawang et al., 2021; Tribout et al., 2011; Zentar et al., 2021) showed that cement and lime are the binders most frequently utilized in laboratory experiments aimed at reinforcing dredged sediments. Macroscopic changes in clayey soil are caused by the addition of binders at the microscopic scale, which involves interactions at that level (Eid, 2017; Jamsawang et al., 2021). The strength of sediments and hardened stabilized layer is reliant on the cement and water content. When cement is added, the formation of calcic hydrates (Banoune et al., 2016; Baston et al. 2012; Jamsawang et al., 2021; Zentar et al., 2021) can enhance the soil strength. Hussan et al. (2022), found that the increase in the unconfined compressive strength (UCS) of the soil was noted at 7, 14, and 28 days, with an increase of 10 to 15% per day following the replacement of 3% and 5% of ordinary Portland cement (OPC) with lime. the results showed that sediments treated with traditional hydraulic binders did not achieve the required UCS values for use in road layers. However, the development of a geopolymer using alkali-activated GGBS and the incorporation of 30% sediments yielded a UCS value above 2 MPa at 28, 60, 90, and 180 days. Furthermore, the addition of 5% lime and 3% granular calcium carbonate in the same mixture (geopolymer + 30% sediments) increased the UCS by up to 60% and 90%, respectively. Gajewska et al. (2017) showed that the compressive strength UCS of the tested cement-soils ranged from 0.74 to 9.19 MPa, but most of the UCS results were within the 0.74–4.00 MPa range.

In studies by Wang et al. (2012, 2013), the effects of cement and lime on Dunkirk sediments were evaluated using modified Proctor compaction and UCS tests. The researchers classified the sediments as sandy soil and concluded that 6% cement is a cost-effective and practical amount for enhancing the mechanical properties of the sediments, particularly for use in road construction. This finding is consistent with the recommendations from the French guide on the treatment of soils with lime and/or hydraulic binders and application to the construction of pavement base layers (LCPC, SETRA, 2000). This guide divides lime stabilization into two phases: short-term reactions, which include cation exchange (studied by Baston et al. (2012), Eades and Grim (1966), Khattab et al. (2007), and Townsend (1979)), and flocculation and agglomeration. Khattab et al. (2007) also investigated the second phase, i.e., long-term pozzolanic reactions and carbonation. The fundamental parameters for designing road layers are tensile strength σ_t and modulus E (Tribout et al., 2011; Zentar et al., 2021). Most researchers (Gajewska et al., 2017; Tribout et al., 2011; Zentar et al., 2021) observed a sharp increase in σ_t from the beginning of the treatment, making it possible to achieve a better mechanical class, and a slow increase in modulus (E) preventing a decline in mechanical class. Gajewska et al. (2017) also found that the elastic modulus increased by 2.5 times when the cement content increased from 6 to 8%. According to Venkatarama and Gupta (2005) as well as Gajewska et al. (2017), the relationship between σ_t and E is primarily influenced by the type and quantity of the binder used as well as the grain size distribution in the material. Interestingly, the universal correlation E = f(R) can be applied to various cement-stabilized soils regardless of their grain size.

Many Maghreb researchers (Banoune et al., 2016; Larouci et al. 2021; Loudini et al., 2020) showed the possibility of using these dredged sediments in road construction materials, which allows for better use of this natural resource. The study by Achour et al. (2014) focused on the use of fine dredged sediments in road construction. The tests showed that the chemical properties of the sediments are acceptable for use in road construction, but their bearing capacity is insufficient. To improve the mechanical properties, a mix of 1/3 fine sediments, and 2/3 dredged sand with 6% cement and 1% lime was proposed. The tests showed that the mixture meets the mechanical requirements for use in the road , subgrade and sub-base layer.

This paper discusses the technique of using dredged sediments from dams for road construction, which has several advantages such as reducing waste and cost. However, it is important to conduct specific studies for each case as sediment composition can vary depending on the dam's location and nature. The example of the Bakhadda dam is mentioned as a particular case where feasibility studies should be conducted. In our research, we examined the effect of binders on the mechanical strength parameters of the treated sediments, which will enable us to characterize the behavior of the treated sediments in the short and long term. This will also allow us to determine their appropriate age for machinery to circulate on the treated layer and the frost resistance. In this paper, we study the possibility of valorization in pavement design with regard to the sediments dredged from a dam in western Algeria. The originality of the study is related to the fineness and high plasticity of the sediments, which requires double treatment with hydraulic binders to meet the updated recommendations and standards for pavement design.

Material and Methods

The materials consist of a deposit of fine particles. Raw dredged sediments (RDS) were taken from the area on the upstream side (settling basin of the Bakhadda dam in north-west of Algeria), where the dredged sediments are found accumulated in remarkable quantities. The dam is located near the village of Machraa Sfa, 25 km west of Tiaret, on the upper reaches of the Mina river, a tributary of the Oued Chéliff river. This basin receives annually 38×10^6 m^3 of water with a specific degradation of 860 $t\cdot km^{-2}\cdot year^{-1}$ (Hallouz et al., 2018).

Due to the siltation rate of approximately 30% of its total capacity, a dredging operation was assigned to Hydrodragage-C-T-Systems, a company specializing in dredging, with a goal of removing 20 million m^3 of material (Fig. 1) (hydrodragage-c.t.systems, 2005). A number of identification tests were carried out on the collected sediments, making it possible to classify the sediments according to French standard NF P11-300 (Association Française de Normalisation, 1992a) and GTR 92 (LCPC, SETRA, 1992).

The RDS samples were oven-dried at 50°C for 48 hours prior to testing, with the aim of preventing any damage to the soil structure and organic matter that could potentially impact the accuracy of the test results. Then they were crushed and sieved through 5 mm sieves without any additional treatment. The set of samples was then evaluated for geotechnical properties, including specific gravity, water content, particle-size distribution, Atterberg limits, methylene blue absorption (VBS), organic matter content, calcium carbonate content ($CaCO_3$), and pH, as well as compaction properties with the immediate bearing index (IBI). These geotechnical properties allowed for the classification of the material in its natural state.

Grain-size analysis

The particle size distribution of the RDS was analyzed by wet sieving in accordance with French standard XP-P94-041 (Association Française de Normalisation, 1995). This analysis separated the particles with dimensions greater than 80 μm by sieving, and then the fraction less than 80 μm — by sedimentation test, according to French standard NF P94-057 (Association Française de Normalisation, 1992b). Fig. 2 presents the particle size curves of the RDS, which show that the material is fine particles in almost all its composition, with nearly 32% of clay and 60% of silt, while the presence of sandy particles greater than 63 μm is the least significant (% sand ≤ 8%).

The calculation of the coefficients of uniformity ($Cu = D_{60}/D_{10}$) and curvature ($C_c = d^2_{30}/(d_{10}\cdot d_{60})$) indicates that the RDS are well-graded (Cu = 16).

Atterberg limits tests

The Atterberg limits tests of the RDS were carried out in accordance with French standard NF P94-051 (Association Française de Normalisation, 1993a). The RDS sediments exhibited a high liquidity limit of 55% and a plasticity limit of 33%, resulting in a plasticity index of 22. When plotted on the Casagrande plasticity chart (Fig. 3), the material was found to be located below the line A of equation $PI = 0.73(LL - 20)$. This position falls outside the recommended range in terms of road engineering

Fig. 1. View of the reservoir of the Bakhadda dam and the Djebel Debbagh stationary dredger

due to a high plasticity index of PI > 20, indicating highly plastic silt.

Other parameters

Methylene blue test

The methylene blue absorption (VBS) and the specific surface area (SSA) were investigated on the RDS samples according to French standard NF P94-068 (Association Française de Normalisation, 1993c). The test results indicate that the VBS and SSA are significantly high, with values of approximately 2.4 (g/100g, dry) and 50.4 (m^2/g), respectively. According to the Unified Soil Classification System (USCS), the RDS could be classified as silt of high plasticity, implying potential sensitivity of the tested soil to water invasion. Thus, the results suggest that the VBS is enough for accurate swelling potential estimates (Çokça, 1993; Seed et al., 1962; Yukselen and Kaya, 2008).

Organic matter content (OM%)

The OM content was estimated by two methods, the calcination method (CMOC) and the chemical method, according to French standards XP-P94-047 (Association Française de Normalisation, 1998), NF-EN-12879 (Association Française de Normalisation, 2000) and NF P94-055 (Association Française de Normalisation, 1993b). The sediments have organic content values ranging from 0.5 to 2.6%. Moreover, these are slightly below the maximum limit of 3% recommended by French standards NF P11-300 (Association Française de Normalisation, 1992a) and GTR 92 (LCPC, SETRA, 1992) for using them in pavement design. According to these standards, the F11 subclass refers to weak organic materials with an organic content ranging from 0.5 to 3%.

Calcium carbonate content ($CaCO_3$%)

The volumetric calcimeter method in accordance with French standard NF P94-048 (Association Française de Normalisation, 1996) was used to determine the percent calcium carbonate ($CaCO_3$%) content of the RDS sample. The results showed that the calcium carbonate level in the sediments is 18%, indicating the presence of a small amount of limestone (10% < $CaCO_3$% < 30%). The presence of calcium carbonate in the sediments creates hard points within the material, leading to a significant reduction in swelling, as noted in previous studies (Molnár et al., 2021).

Specific density (γ_s)

The specific density of the RDS determined using a pycnometer according to French-standard NF-P94-054 (Association Française de Normalisation, 1991) is 2.66 g/cm^3.

Material acidity determination (pH meter test)

The acidity of the material was determined using the pH meter test according to NF EN ISO 10390:2022 (NF EN, 2022). The suspensions of the sediments showed an average pH value of 8.4, indicating that the sediments from Bakhadda dam exhibits an alkaline nature. Table 1 presents the geotechnical characteristics of the RDS, which initially fall under class F according to LPC-USCS, GTR 92 (LCPC, SETRA, 1992), and French standard NF P11-300 (Association Française de Normalisation, 1992a) classifications for natural materials with an organic matter content less than 3% (OM = 2.6%). The sediments contain a dominant fine fraction less than 63 µm (silt and clay), which accounts for almost 90% of the material. The sediments have a poorly-graded particle size distribution with a low density due to the lack of sand particles. The coefficient of uniformity Cu is 16, and the coefficient of curvature C_c is 0.81, indicating well-graded and poorly-graded fine sediments. The particle size analysis, methylene blue value (VBS), and Atterberg limits (PI) indicate

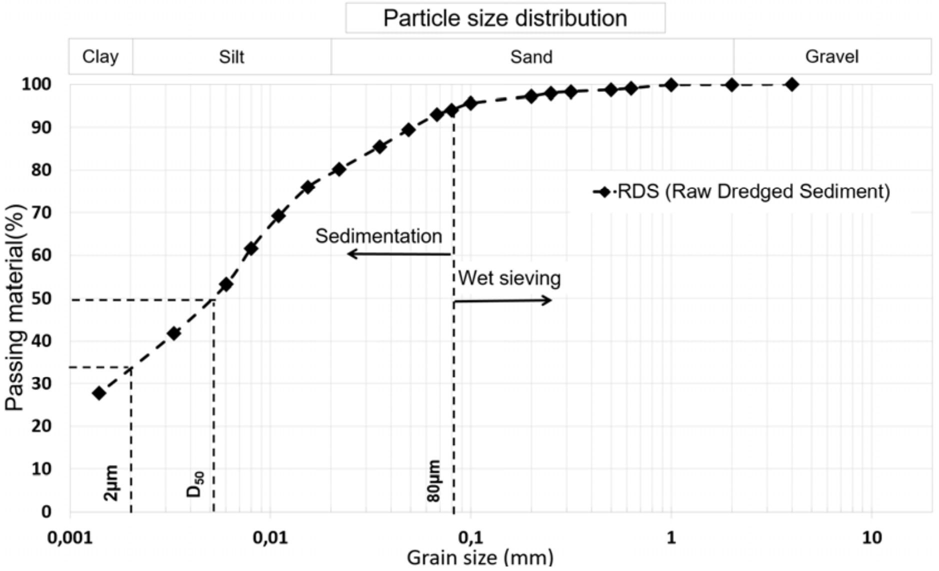

Fig. 2. Particle size distribution of the RDS

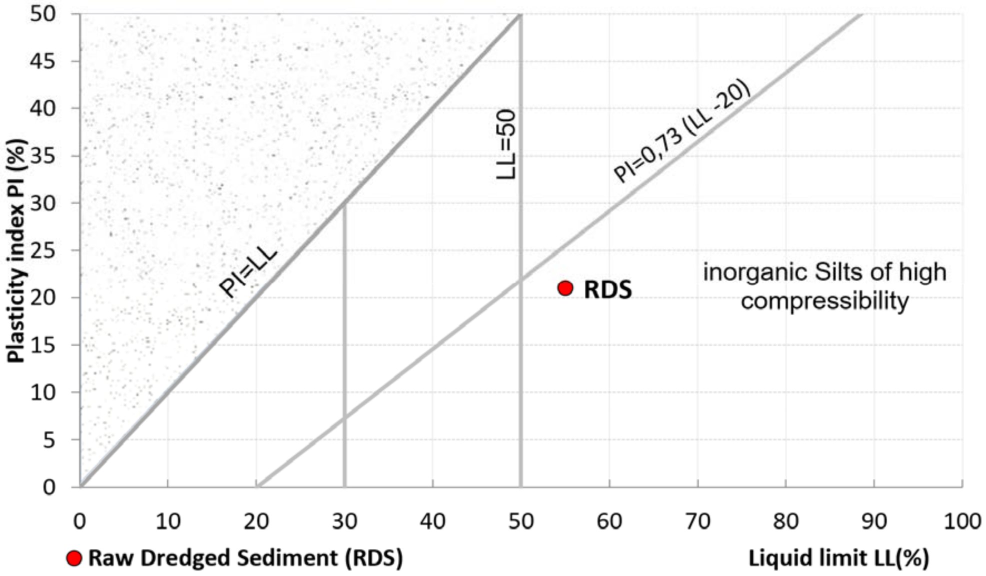

Fig. 3. Position of the RDS on the Casagrande plasticity chart

Table 1. **Characterization parameters of the Bakhadda dam RDS**

<table>
<tr><th>Bakhadda dam sediment</th><th colspan="2">Sand (%)</th><th colspan="2">Silt (%)</th><th colspan="2">Clay (%)</th><th colspan="3">Cu</th><th>C_c</th></tr>
<tr><td>Particle size distribution</td><td colspan="2">8</td><td colspan="2">60</td><td colspan="2">32</td><td colspan="3">16</td><td>0.81</td></tr>
<tr><td rowspan="5">characterization parameter</td><td colspan="10">Atterberg limits</td></tr>
<tr><td>LL (%)</td><td>PL (%)</td><td>IP (%)</td><td>Wn (%)</td><td>IL (%)</td><td colspan="2">Ic (%)</td><td>Ac</td><td colspan="2">γs (kN/m3)</td></tr>
<tr><td>55</td><td>33</td><td>22</td><td>20</td><td>–1.1</td><td colspan="2">1.14</td><td>0.69</td><td colspan="2">26.57</td></tr>
<tr><td colspan="2">VBS</td><td colspan="2">S.S.T (m²/g)</td><td colspan="2">$CaCO_3$ (%)</td><td colspan="2">OM (%)</td><td colspan="2">pH</td></tr>
<tr><td colspan="2">2.4</td><td colspan="2">50.4</td><td colspan="2">18</td><td colspan="2">0 – 2.6</td><td colspan="2">8.4</td></tr>
</table>

that the material falls under class A2 (silty, clayey) as per the classification guide for fine soils (French-standard NF P11-300 (Association Française de Normalisation, 1992a), GTR 92 (LCPC, SETRA, 1992)).

Compaction tests

The modified Proctor compaction test was performed on the RDS in accordance with French standard NF P94-093 (Association Française de Normalisation, 1993d) to determine the optimal water content and maximum dry density. The immediate bearing index (IBI_{MPO}) of the samples compacted in the CBR Mold was evaluated in accordance with French standards NF P94-078 (Association Française de Normalisation, 1997) and NF EN-13286-47 (Association Française de Normalisation, 2012).

Figs. 4, 5 show the modified compaction and IBI curves, respectively. It can be noted that the clear appearance of the peak on the compaction-bearing curve of the RDS indicates sensitivity to the water content. The IBI_{MPO} at modified compaction is low, approximately 16%, indicating a low bearing capacity of the RDS, which cannot ensure the trafficability of compaction machinery on the site. In terms of the IBI, the value remained below the minimum value required for use as an alternative road material (the IBI greater than 20%). According to GTR 92 (LCPC, SETRA, 1992) and GTS 2000 (LCPC, SETRA, 2000), the sub-base layer and base layer of pavement should have a minimum value of 35 and 45%, respectively.

Results and Discussion

The RDS has high plasticity and swelling potential due to its fineness and was classified as Lt (MH), a highly plastic silt. The densification and bearing capacity (γd_{MPO}, W_{MPO}, IBI_{MPO}) were lower than the values prescribed for use in road engineering, indicating the need for prior treatment for its use in pavement layers. The RDS in its current state is not suitable for road construction and requires treatment, particularly with binders. Various mixtures of sediments, cement, and lime in different proportions were tested to meet the recommendations of French standard NF-P11-300 (Association Française de Normalisation, 1992a), GTR 92 (LCPC, SETRA, 1992), GTS 2000 (LCPC, SETRA, 2000) and Bourabah et al. (2013).

RDS treatment with binders

Treatment protocol

For this study, a CPJ CEMII/A 42.5 compound Portland cement and quicklime were chosen. It is crucial to consider the added percentage of these binders, as it provides an additional fine fraction

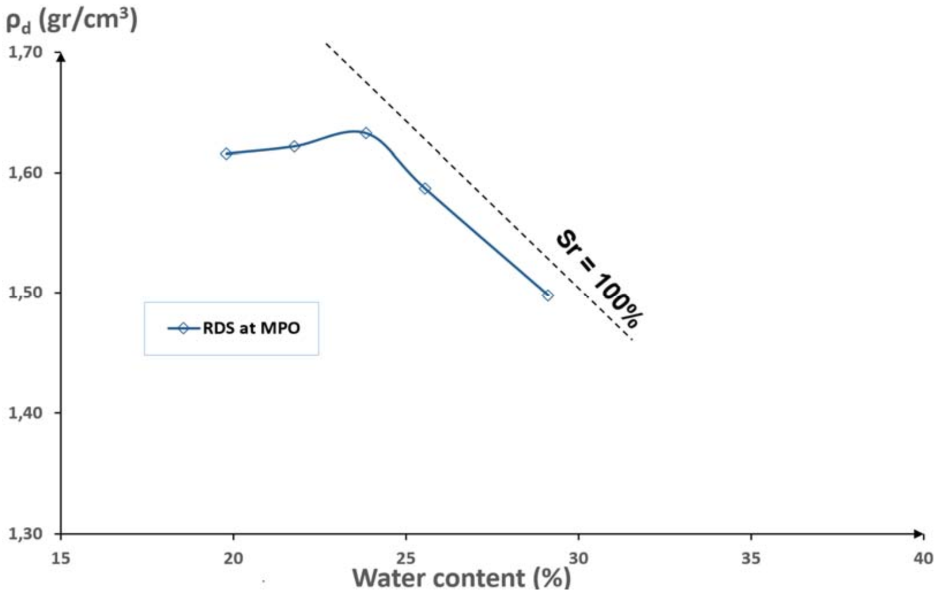

Fig. 4. Compaction tests at MPO for the RDS

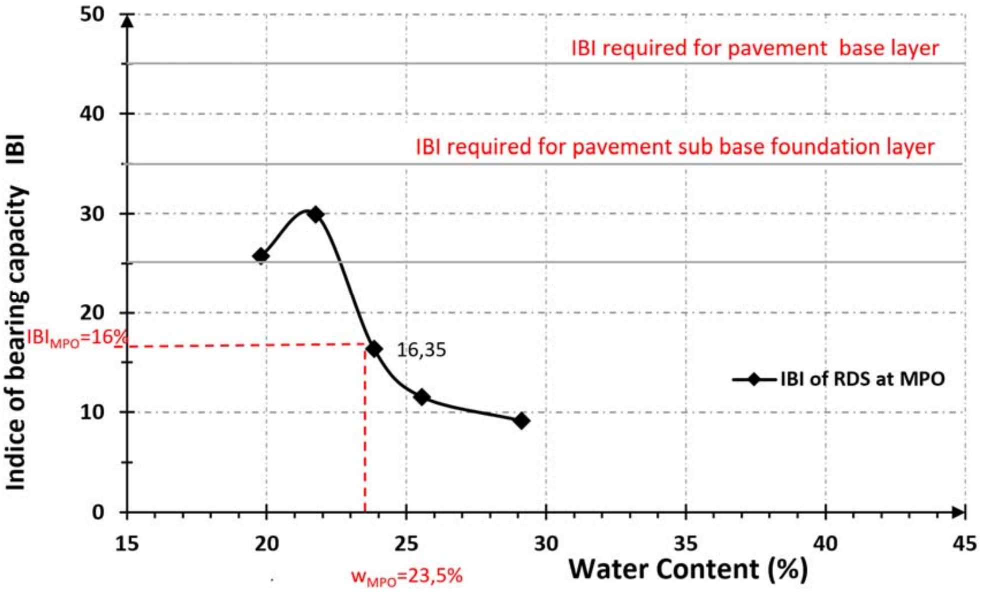

Fig. 5. Compaction-bearing curves (IBI) of the Bakhadda dam RDS

in the granular skeleton. Various studies were conducted on the optimum percentage of lime for different types of soils, based on pH testing (ASTM, 2006; Djelloul et al., 2017; Eades and Grim, 1966; Eid, 2017; Khattab et al., 2007; Makki-Szymkiewicz et al., 2015; Sivapullaiah et al., 2000). These studies showed that the minimum effective dosage of lime required for stabilization, called Lime fixation point (PFC), ranged from 1 to 4%. It is important to note that treating soil with a lime content equal to or greater than the PFC of the soil can ensure better homogeneity of the treatment and long-term structural resistance, regardless of the humidity conditions. Most studies (Akula et al., 2021; Baston et al. 2012; Eades and Grim 1966) showed that the pH increases to approximately 12.45 at 25°C. The pozzolanic reaction continues with time and results in consistency changes and strength gain. In response to the release of OH^-, the pH of the soil increases to high alkaline pH (>10), which partially dissolves clay minerals, releasing soluble silica and alumina. C-S-H and C-A-H are strength-enhancing pozzolanic products formed by free Ca^{2+} ions reacting with soluble silica and alumina (Akula et al 2021; Baston et al., 2012; Hilt and Davidson, 1960).

Khattab et al. (2007) discussed two methods proposed by Eades and Grim (1966) as well as Hilt and Davidson (1960) for determining the optimum lime percentage for FoCa soils. To activate the pozzolanic reaction between lime and soil, a pH value of 12.4 is required for a soil-water mixture containing varying masses of lime, as suggested by Eades and Grim (1966). Adding lime to the soil increases alkalinity, which, in turn, leads to better flocculation during the pozzolanic reaction by increasing the pH value. To achieve a pH value of 12.4 or higher, 3% lime is required. The second method related to the minimum lime content (L_m), suggested by Hilt and Davidson (1960), involves an empirical expression given by them as the minimum lime percentage or lime fixation point in Eq. (1). The expression is as follows:

$$L_m = \frac{Clay\ content(< 2\mu m)}{35} + 1.25. \qquad (1)$$

Moreover, Khattab et al. (2007) confirmed that the treatment efficiency is excellent, sometimes reaching more than 90%, in the presence of an optimal lime percentage of 4% and optimal compaction conditions. On the one hand, it is important to note that there is a limit to the amount of cement that can be used in soil stabilization, depending on the clay content of the soil. However, GTS 2000 (LCPC, SETRA, 2000) states that adding a reasonable quantity of lime and cement (not exceeding 9%) can increase the unconfined compressive strength (UCS) of the soil and reduce volumetric shrinkage strains. Based on this analysis, the RDS was treated with 3% lime and 6% cement to improve its mechanical properties. The proposed formulations were F1 (97%RDS + 3%L), F2 (94%RDS + 6%C), and F3 (91%RDS + 6%C + 3%L) for use in road sub-base layers and/or backfills.

RDS identification after treatment

After treatment with binders, the properties of the treated RDS (TRDS) were measured, including the soil suitability for treatment and determination of the grain size distribution curves, consistency limits, and methylene blue value for each formulation.

Suitability for treatment based on volume swelling

The evaluation of soil suitability for treatment is frequently carried out in accordance with French standard NF P94-100 (Association Française de Normalisation, 2015). The evaluation process includes two steps. First, the volume swelling (LS) of the soil samples immersed in water at 40°C for 7 days is determined using cylindrical specimens (ø = 5 cm, h = 5 cm), which are made with an optimal water content W_{MPO} and 96% $\gamma d(_{MPO})$ dry density by static compaction according to French standard NF P98-230-2 (Association Française de Normalisation, 1993e). The demolding of each specimen is carried out immediately after its making. Table 2 shows the results of volume swelling (L_S) and splitting tensile strength σ_t (in immersion) for the formulations studied. The average value of three test specimens is taken. This value is calculated using the Eq. (2), which measures the variation in volumes V_1, V_2, and V_0:

$$L_S(\%) = \frac{(V_1 - V_2) - V_0}{V_0} \times 100. \qquad (2)$$

Volume V_0 is the initial volume of the specimen. Volumes V_1 and V_2 are measured by performing hydrostatic weighing of the test specimens both in open air and under water, while taking into account the Flexible Plastic Mesh + elastic bands. Then tensile strength σ_t is measured through a Brazilian splitting test (BST), which involves curing the soil samples (ø = 5 cm, h = 5 cm) in water at 40°C until the 7-day crushing deadline is met. It is important to note that each recorded result is an average of three separate samples.

Table 2 shows the results of volume swelling (L_S) and resistance σ_t (in immersion) for the treated sediments, based on the type of binder used. The formulations of the raw sediments treated with binders are found to be suitable for treatment, as they meet the relevant criteria (i.e., low volume swelling (L_S) of 5% and good development of resistance σ_t > 0.25 MPa) and can be used for the remainder of the study. Furthermore, the frost resistance is deemed satisfactory, since resistance σ_t at the age corresponding to the first statistical appearance of freeze is greater than 0.25 MPa, as per GTS 200 (LCPC, SETRA, 2000).

Granulometry

The particle size distribution of the treated materials is presented in Fig. 6. It can be observed that the sediments mainly consist of the silt fraction. The particle size distribution of the sediments treated with binders shows a slightly improved granularity, compared to the curve of the raw sediments without treatment. Additionally, the values of the uniformity coefficient Cu exceed the reference value of 4, satisfying the spread particle size of the mixtures.

On the other hand, the recommended values for the curvature coefficients of the sediments treated with binders are verified according to their uniformity coefficients (Cu = 11 for cement, Cu = 10 for combined lime-cement, and Cu = 5.5 > 4 for lime), C_c = 1.61 > 1 and C_c = 1.41 > 1 for cement and combined lime cement, respectively (Table 3). They indicate that the materials generally have a well-graded character.

Effect of treatment on the Atterberg limits

Fig. 7 illustrates the effect of binder addition on the Atterberg limits of TRDS, revealing the following findings: adding binders significantly decreases plasticity, indicating particle flocculation.

Lime, once added to the RDS, acts on the electric charges through cation exchange, where calcium (Ca^{++}) cations from the lime replace exchangeable cations, such as sodium (Na^+), hydrogen (H^+), potassium (K^+), etc., on the soil's exchange sites. This alteration of inter-particle electric fields leads to particle flocculation and agglomeration (Cabalar et al., 2014; Townsend,

Table 2. **Results of volume swelling (L_s) and splitting tensile strength σ_t (in immersion) for the formulations studied**

No.	Formulations studied	Volumetric swelling L_S (%)	Tensile strength σ_t	Suitable for treatment
1	97%RDS + 3%L	2.74	0.26	adapted
2	94%RDS + 6%C	3.38	0.275	adapted
3	91%RDS + 6%C + 3%L	1.66	0.29	adapted
4	100% RDS	8.23	0.14	Unsuitable

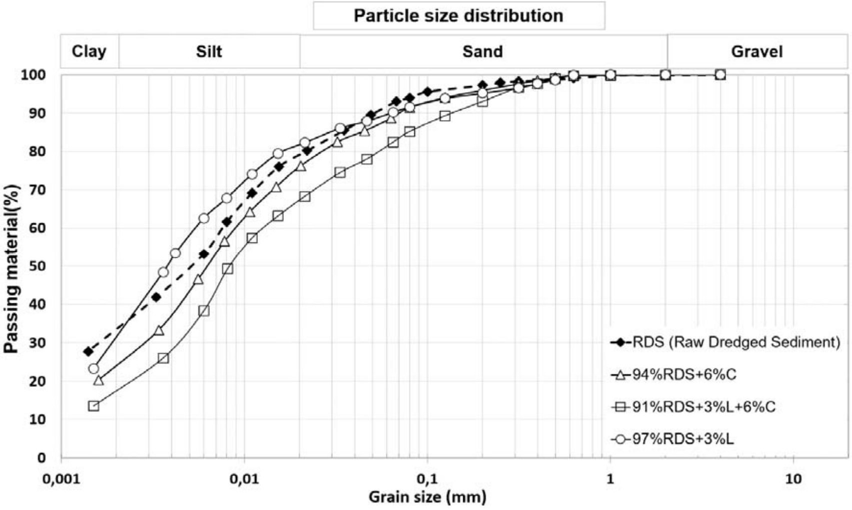

Fig. 6. Particle size distribution of the RDS and RDS treated with lime and cement

Table 3. **Influence of the addition of binder on the treated RDS**

No.	Formulations studied	% > 63 µm		% < 63 µm		Cu	C_c
		Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)		
1	97%RDS + 3%L	4	15	54	27	5.5	0.73
2	94%RDS + 6%C	3	21	60	16	11	1.61
3	91%RDS + 6%C + 3%L	7	26	57	10	10	1.41

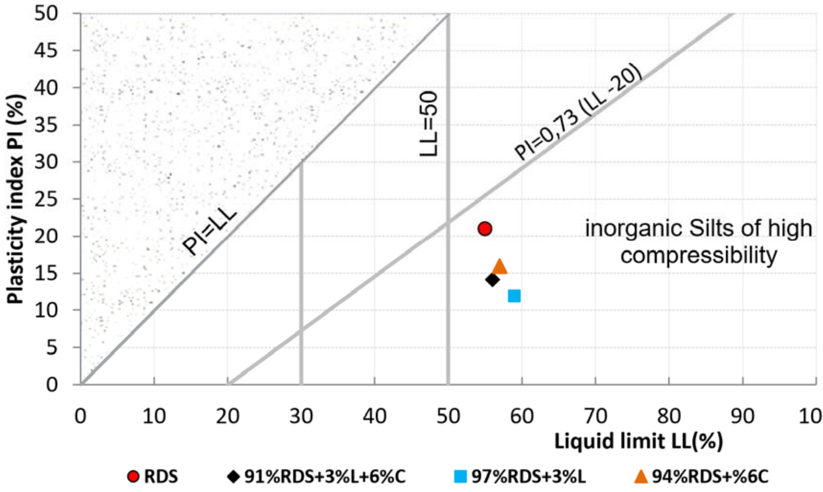

Fig. 7. Atterberg limits of the RDS and RDS with lime and cement

1979). This flocculation results in an increase in the soil plastic limit without significantly affecting its liquid limit, leading to a reduction in the plasticity index (PI). This confirms that the sediment plasticity is significantly reduced by the binder treatment. As a result, the concurrent reduction of the water content and plasticity index radically modifies the material behavior.

Classification according to GTR 92, NF P11-300 / LPC-USCS

Fig. 8 shows the treated material positioned in class A1 as loamy sand. The addition of binders such as 3% lime and 6% cement to the sediments reduced their plasticity, which positively influenced the flocculation of the particles.

Additionally, the identification test results showed a good reduction in the plasticity degree with a notable decrease in the plasticity index (PI = 11.89%) and the percentage of swelling-shrinkage. The plasticity index was significantly reduced, making it suitable for use as a road layer.

Characterization of the TRDS mechanical properties

Compaction after treatment

Fig. 9 shows the modified Proctor optimum for the TRDS curves, while Table 4 summarizes the results of the optimum parameters (w_{MPO}, γ_{dmax}) and bearing tests (IBI_{MPO}) of the TRDS. The compaction-bearing tests showed that the modified Proctor curve of the RDS exhibited a peak shape, indicating the sensitivity to the water content enhancement.

The addition of binders (lime and cement) resulted in an increase in the optimum water content at MPO and a significant reduction in the maximum dry density. If the curing time is not allowed in the compaction test, the densification may be negatively influenced, but the immediate bearing index can be greatly improved.

It should be noted that Fleureau et al. (2002), presented the correlations between the optimal water content and maximum dry unit weight of soils compacted under modified Proctor conditions (MPO), as well as their liquid limit LL in %. The regression equations (3, 4) for these correlations are as follows:

$$W_{MPO}(\%) = 4.55 + 0.32LL - 0.0013LL^2; \quad (3)$$

$$\gamma_{d\max}(kN/m^3) = 20.56 - 0.086LL + 0.00037LL^2. \quad (4)$$

The compactness and bearing parameters obtained at modified Proctor optimum (MPO) for the RDS are compared with those given by the correlations in Table 4. Consistency is observed between the values, despite a notable difference in the water content of approximately 6% for MPO. Good agreement is shown for the maximum dry density. Besides, the results for the treated materials in Table 4 show that the water content values for cement-treated and lime-treated sediments are approximately 4.5 and 6%, respectively, greater than the values given by the correlation.

As shown in Table 4, the maximum dry unit weight of the treated sediments γ_{dmax} was approximately 0.7 to 1.2 kN/m^3 less than the correlated values.

Concerning the IBI, adding of 6%C and 3%L to the RDS resulted in a reduction in the plasticity index, leading to an increase in the IBI (16% for RDS to 30.75%; 33.15%; 35.25% for RDS+3%L; RDS + 6%C; RDS + 3%L + %6C, respectively) (Fig. 10). These results confirm the feasibility of the beneficial reuse of treated dredged sediments in road layers.

UCS tests on the treated RDS

The unconfined compressive strength (UCS) test was performed according to French standard NF EN 13286-41 (Association Française de Normalisation, 2003a). The UCS was measured on the samples compacted at MPO. The samples 50 mm in diameter and 100 mm in height were compacted in a mold equipped with two pistons, upper and lower ones, to ensure homogeneous compaction. The unconfined compressive strength tests were carried out until failure. To assess reproducibility, three samples were tested for each state. Using the stress-strain curve, two parameters were derived: the secant modulus E and the unconfined compressive strength.

The secant modulus decreases with the axial strain E(ε), and the mean secant modulus E_{50} (Daheur et al. 2023; Taibi et al., 2009) is defined at a strain level ε_{50} corresponding to 50% of the maximum strength (Fig. 11). The results of the UCS measurements of the RDS and RDS treated with binders (lime, cement) are presented in Fig. 12. The curves show good reproducibility, but low stiffness is observed for the RDS. Three formulations of the treated sediments met the French criteria (UCS ≥ 1 MPa) according to GTS 2000 (LCPC, SETRA, 2000) to authorize the circulation of machinery on the treated layer, and the mechanical strength increased with the binder content.

The strength increased from 0.69 MPa for the RDS to 2.64, 3.72, and 3.84 MPa for 3% lime and 6% cement and their combination (3%L + 6%C), respectively. At a curing time of 90 days, the mechanical strength stabilized at 3.20, 4.13, and 4.06 MPa (Table 5).

The influence of 3% lime addition was initially weak but increased in the long term. In comparison of the treated RDS with the untreated RDS, the stiffness of the treated material and the elasticity modulus increased. Overall, the study demonstrated the feasibility of the beneficial reuse of treated dredged sediments in road layers. The values of the compressive strength of the treated materials increased with increasing curing time, as expected. The use of binders had a significant influence on the durability of this treated material, particularly on strength and modulus of elasticity. Finer particle size sediments were found to be more reactive with pozzolanic binder (lime and cement), producing higher strength in terms of mechanical properties. Overall, the study provides insights into the mechanical performance of treated sediments, with specific recommendations for their use in road construction based on their classification and performance values.

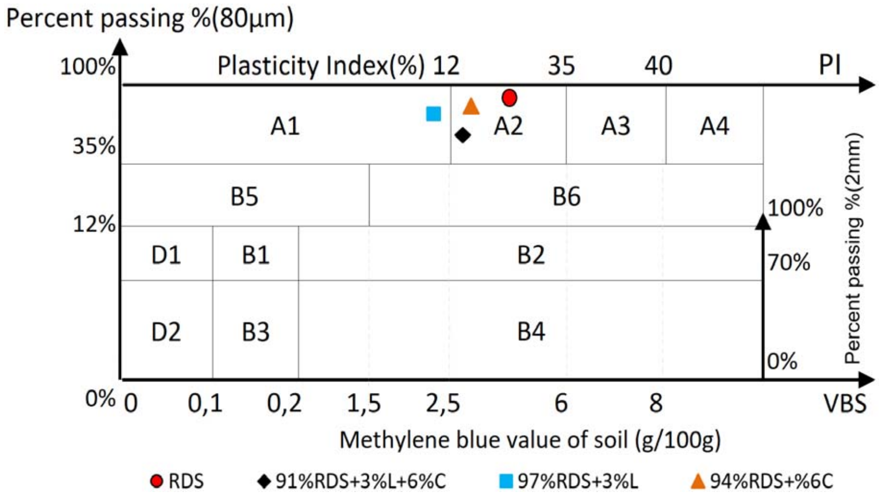

Fig. 8. Classification of the RDS according to the soil classification table of the NF P11-300 standard (Association Française de Normalisation, 1992a) (fraction 0/50 mm)

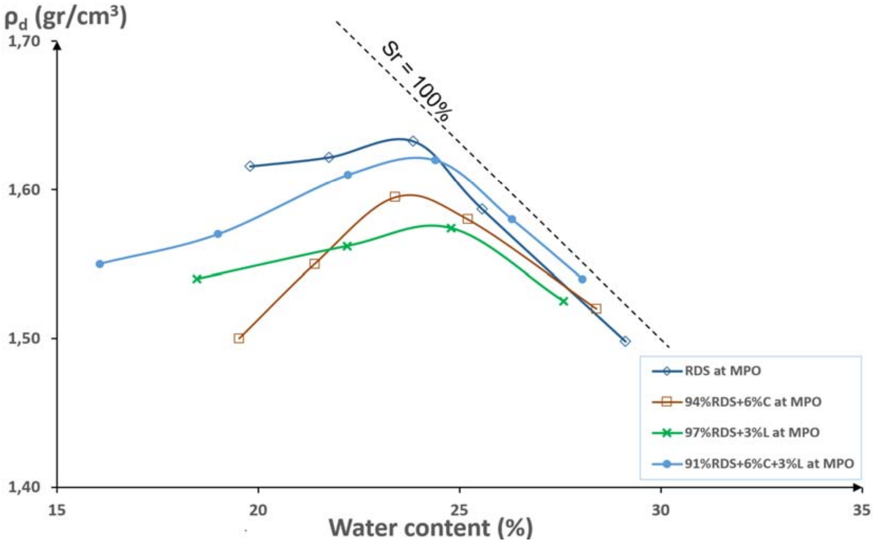

Fig. 9. Compaction tests of: RDS, RDS + 3%L, RDS + 6%C, and RDS + 3%L + 6%C at MPO

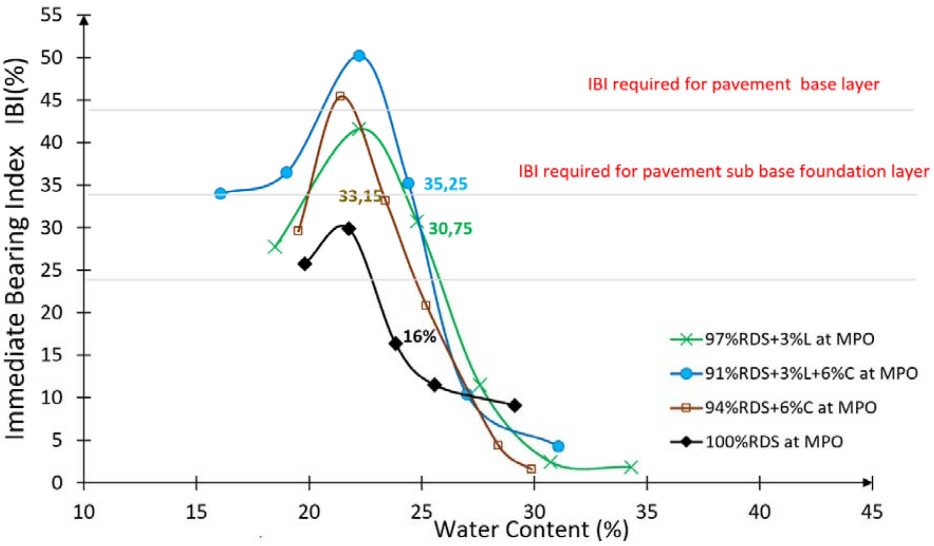

Fig. 10. Compaction-bearing curves (IBI) of the material after treatment with binder

Table 4. **Compaction parameters of the RDS and RDS treated with binders**

Type	**Compaction parameters**		**IBI_{MPO}**	**Correlation of Fleureau et al. (2002)**	
Natural sediments (RDS) with LL = 55%	γ_{dmax} (kN/m^3)	W_{MPO} (%)	(%)	γ_{dmax} (kN/m^3)	W_{MPO} (%)
RDS at MPO	16.33	23.5	16	16.95	18.20
97%RDS + 3%L at MPO	15.74	24.79	30.74	16.8	18.91
94%RDS + 6%C at MPO	15.95	23.38	33.15	16.56	18.51
91%RDS + 6%C + 3%L at MPO	16.2	24.4	35.25	16.90	18.40

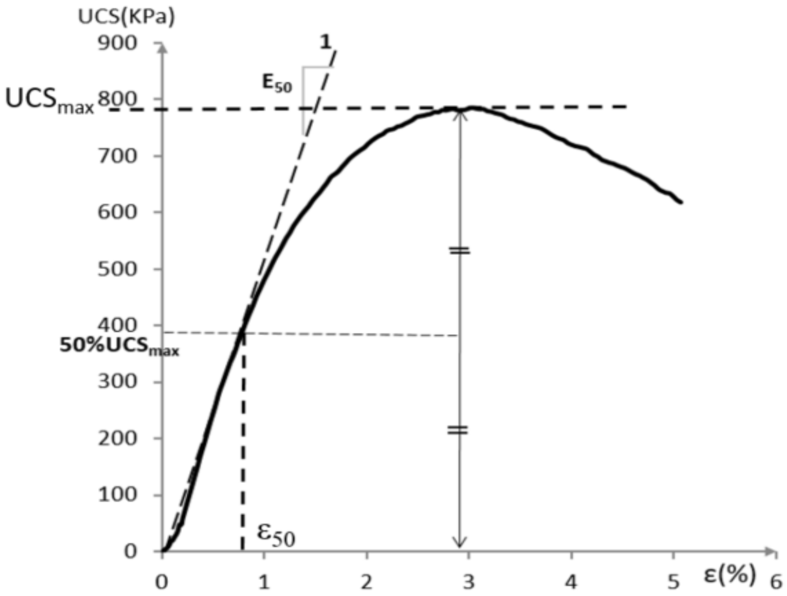

Fig. 11. Secant modulus E_{50} versus strain (ε)

Table 5. **Results of the UCS and E_{50} on the dredged sediments and sediments treated with binders**

Mechanical parameters	**RDS**	**Curing (days)**	**97%RDS + 3%L**	**94%RDS + 6%C**	**91%RDS + 6%C + 3%L**
UCS (MPa)	0.688	7	1.687	1.565	1.841
		14	2.516	3.279	2.838
		28	2.644	3.724	3.84
		90	3.19	4.128	4.057
E_{50} (MPa)	0.10	7	0.30	0.26	0.21
		14	0.37	0.44	0.39
		28	0.39	0.49	0.54
		90	0.60	0.54	0.63

Tensile strength σ_t and small strain modulus E_{SS}

The tensile strength σ_t was derived from the Brazilian splitting test (BST). The BST was carried out on cylindrical specimens, with diameter ϕ = 50 mm and a height h = 50 mm, according to NF EN 13286-42 (Association Francaise de Normalisation, 2003b). The tensile strength and modulus of elasticity at 360 days of curing (σ_{t360} and E_{SS360}) were estimated according to NF EN 14227-1 (Association Française de Normalisation, 2013) and NF EN 13286-42 (Association Francaise de Normalisation, 2003b), using Eqs. 5, 6:

$$\sigma_{t360} = \sigma_{t28} / 0.60 \tag{5}$$

$$E_{360} = E_{28} / 0.65 \tag{6}$$

where σ_{t28} and E_{28} are the tensile strength and modulus of elasticity at 28 days of curing, respectively.

Furthermore, the modulus of elasticity at very small strains of the samples was measured using the ultrasonic wave propagation method. The velocity of sound wave propagation was used to estimate Young's modulus and Poisson's ratio of the material, according to the following Eq. 7:

$$E_{SS} = \frac{V^2 \times \rho \times (1+\nu) \times (1-2\nu)}{g(1-\nu) \times 10^6}, \tag{7}$$

where V is the velocity [m/s], ρ is the density [kN/m^3], g is the gravity [m/s^2], and ν is Poisson's ratio.

The relationships (σ_t, E_{SS}) were plotted according to standards GTR 92 (LCPC, SETRA, 1992) and GTS 2000 (LCPC, SETRA, 2000), which exhibit five mechanical performance classes ranging from S1 to S5. The objective of the treatment was to achieve the highest possible mechanical class, i.e., the one closest to zone 3 (Fig. 13). The results show that the RDS samples belong to class S0, while the samples treated with 3%L and 6%C at 90d, 360d belong to class S2 and are suitable for use as a sub-base material for roads (Fig. 13). The samples at 28d belong to class S1 and can be used as road bed filling materials or subgrade layers for roads. The maximum mechanical performance was reached quickly between 28 and 90 days.

Discussion

Effect of curing time

Fig. 14 presents the ratio of tensile (σ_t) to compressive (UCS) strength as a function of curing time for the treated sediments, which ranges from 10–15% for all treated sediments. The objective of this report is to evaluate the effectiveness of lime and cement in soil stabilization by examining the mechanical properties of the treated sediments.

Specifically, the report presents the relationship between tensile and compressive strength as a function of curing time for the treated sediments and compares them with expected values for similar materials (Baldovino et al., 2018; Gajewska et al, 2017; Zentar et al., 2021). The findings indicate that the use of lime and cement significantly improved the mechanical properties of the treated sediments. However, it is worth noting that the specific values of σ_t/UCS may vary depending on such factors as the type of sediment, treatment method, and curing conditions. In addition, the report provides a linear equation that relates the two parameters, enabling the determination of one in terms of the other. The bar graphs in Fig. 15 show the relationship between curing time and the compressive strength UCS, mean modulus E_{50}, and small strain modulus E_{SS}, which increased with increasing curing time, indicating improved durability of the treated materials.

1.1.1. Relationship between the UCS and modulus E_{SS}, E_{50}

Fig. 16 shows that there are linear and proportional relationships between the compressive strength (UCS) and the small and large strain moduli (E_{SS}, E_{50}) for all treated materials. It can be seen that there is a relatively good linear relationship between the UCS and E_{SS}, E_{50} for all treated dredged sediment samples. The correlations between the small strain and large strain moduli and the compressive strength (UCS) are proposed in Table 6 as a way to reduce the time and cost of advanced laboratory experiments used to determine the modulus. It was observed that the moduli increased with the UCS.

Additionally, the use of binders (3%L and 6%C) had a positive effect on the UCS, IBI, σ_t, E_{50}, and E_{SS} at all times.

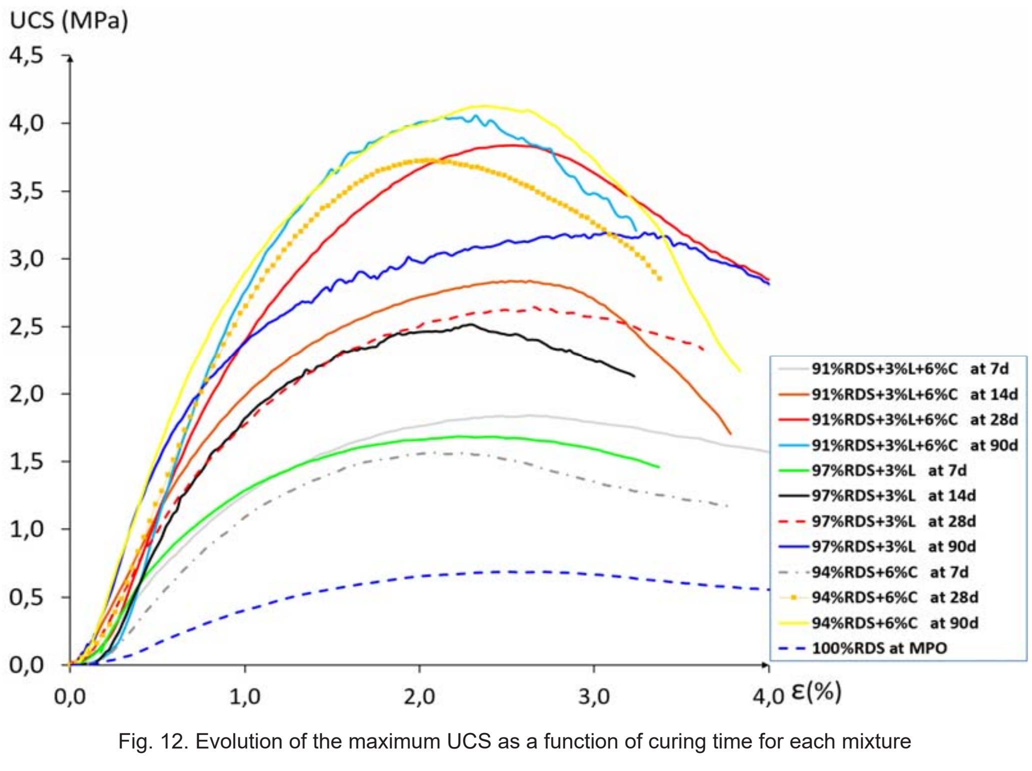

Fig. 12. Evolution of the maximum UCS as a function of curing time for each mixture

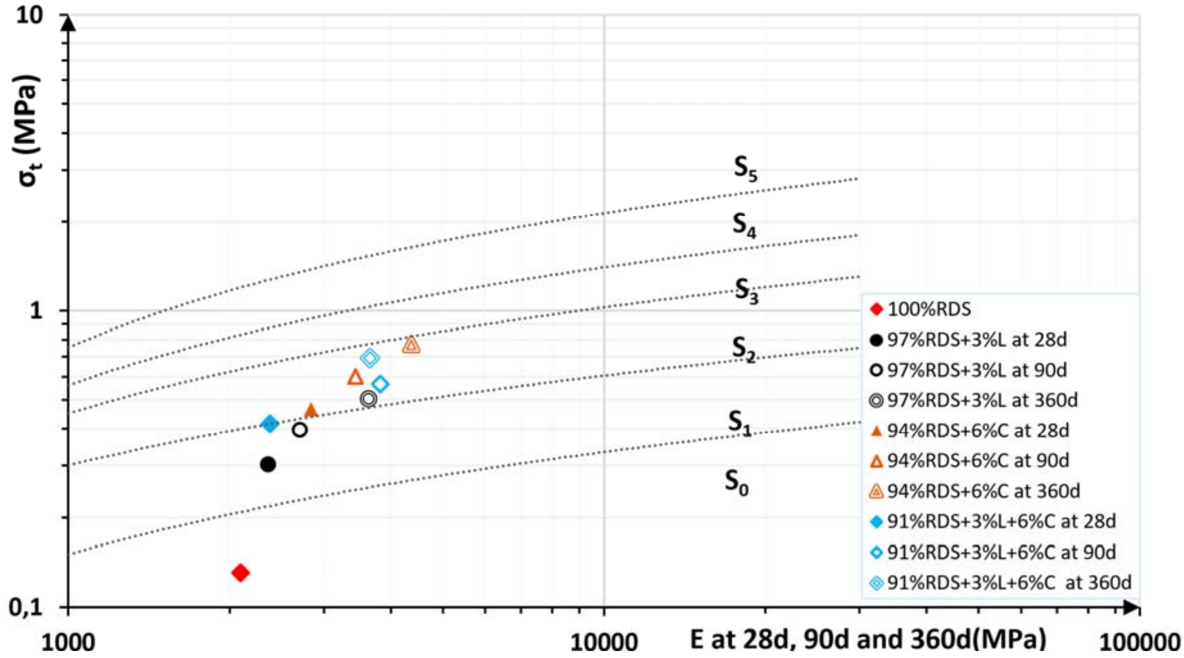

Fig. 13. Positioning of the raw sediments and three formulations studied at 28, 90 and 360 days in the GTS classification chart

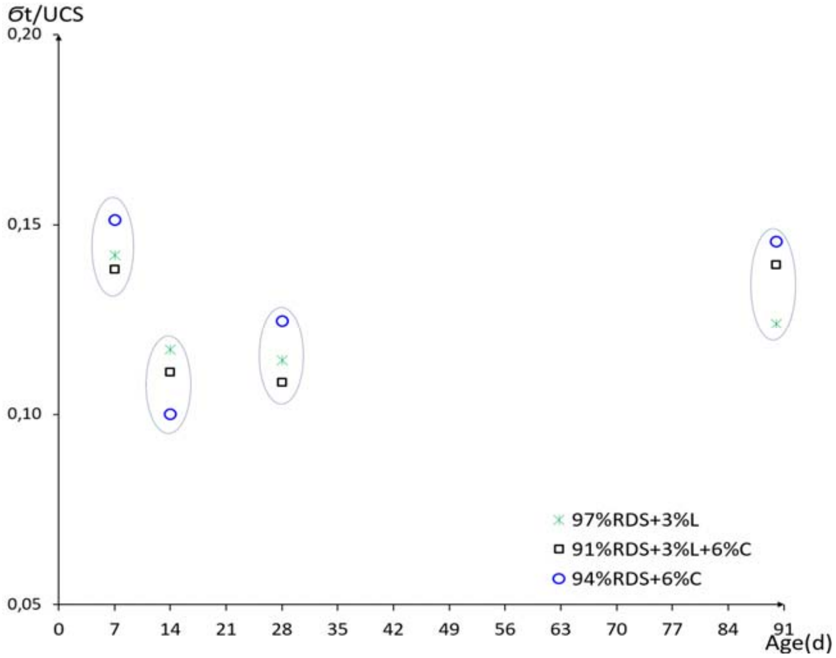

Fig. 14. Ratio of tensile (σ_t) to compressive (UCS) strength versus curing time for the sediments treated with binders

Conclusion

The valorization of the dam dredged sediments showed promising results for their use in road engineering. The addition of binders, specifically 3%L and 6%C, improves significantly the mechanical properties of the sediments, resulting in increased values of the UCS, IBI, σ_t, E_{50}, and E_{SS}. The use of treated sediments as a pavement layer is now feasible, with better durability and non-swelling properties. The addition of 3%L to 97%RDS led to the highest mechanical performance, with significant reduction in the plasticity index and swelling shrinkage. The formulations of 97%RDS + 3%L and 91%RDS + 3%L + 6%C were found to be suitable for use as a, subgrade layer, with maximum mechanical performance achieved between 28 and 90 days of curing. At 90 days, it was located in class S2, with high values of the IBI and σ_t. The addition of 6% cement to this formulation further improved its compressive strength, porosity,

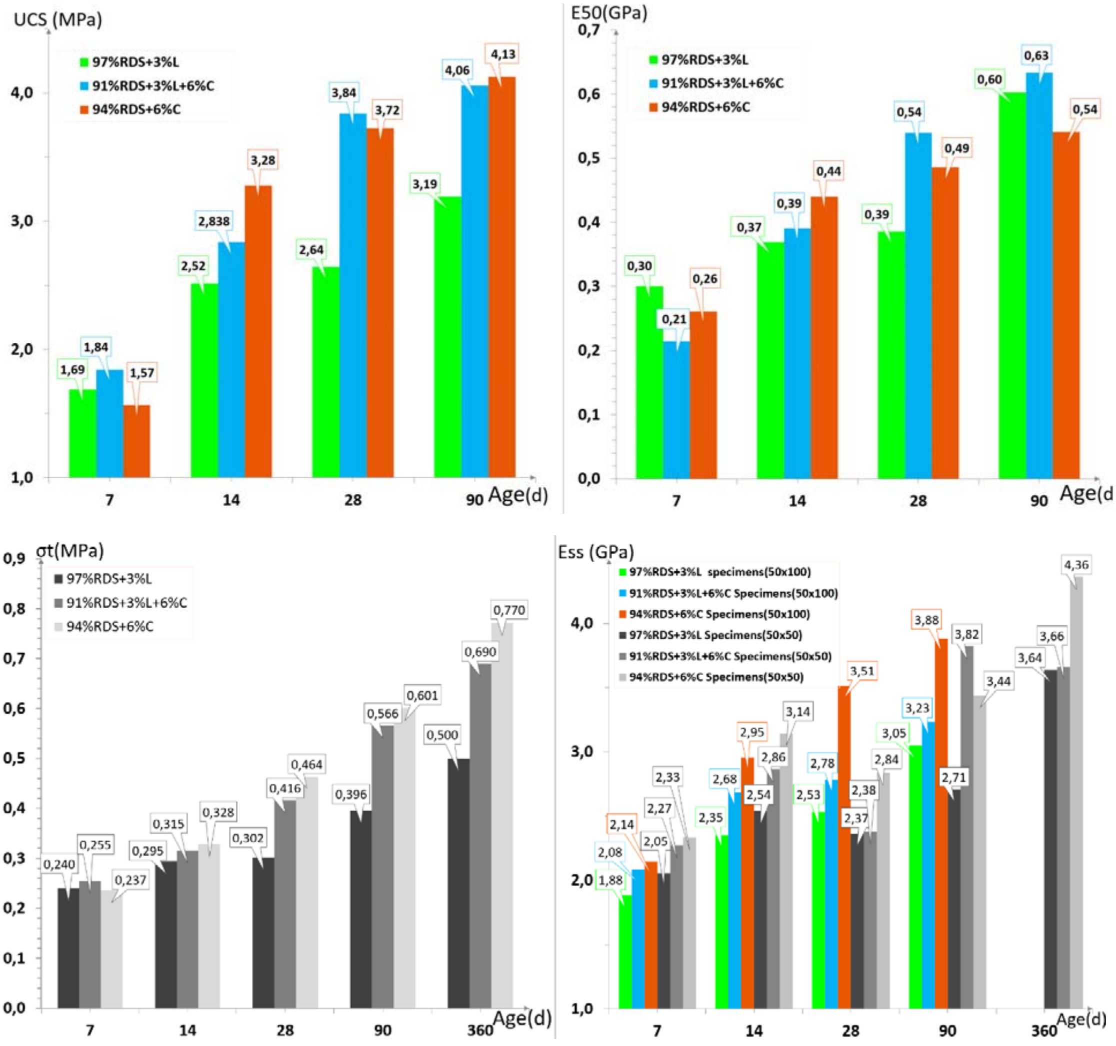

Fig. 15. Bar graphs of the relationship between curing time and the compressive strength UCS, modulus E_{50}, E_{SS}

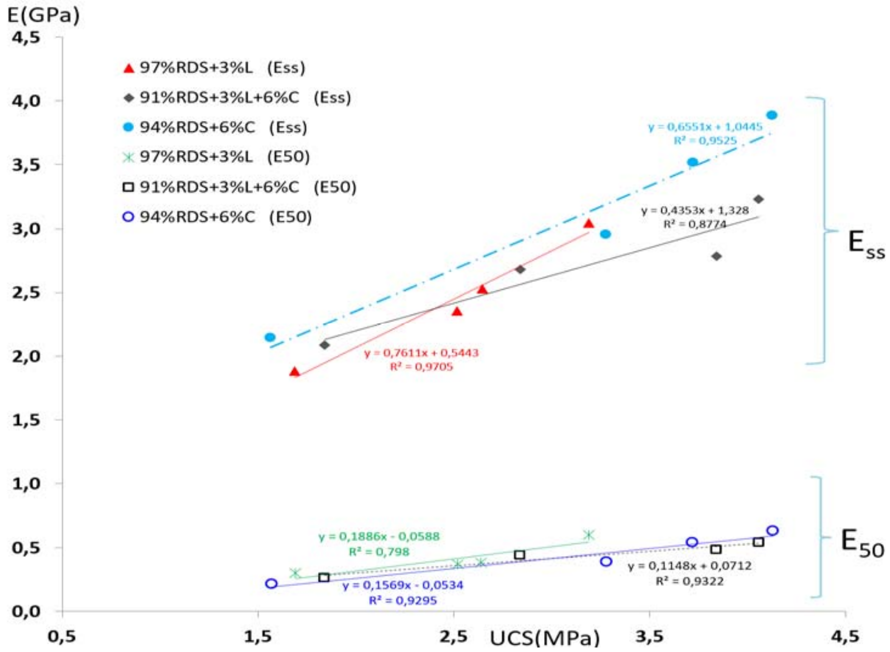

Fig. 16. Variation of the small strain modulus function of the UCS of the sediments treated with binders

and tensile strength. Although the 94%RDS + 6%C formulation had good mechanical properties, it was located close to class S3 at 360 days. It is recommended to avoid using cement alone for the improvement of fine soils, according to the GTS 2000 standard. The study shows that adding lime to dredged sediments improves its compressive strength over time in samples containing 3%L. It can also help reduce the water content in dredged sediments by promoting the processes of hydration and contribution of dry matter, which can lead to increased strength and durability. Overall, the RDS treatment with binders is an effective method for improving mechanical properties and suitability for use as a pavement layer.

Acknowledgments

The project presented in this paper was supported by the Faculty of Applied Sciences at the University of Tiaret, the EOLE Laboratory at the University of Tlemcen, and the Waves and Complex Media Laboratory at the University of Le Havre. We would like to extend our sincere thanks to all the participants for their valuable contributions. We also extend our appreciation to various institutions, including the LTPO of Tiaret, for their collaboration, support, and expertise in making this project a success.

Table 6. **Correlations between the small strain and large strain moduli and the compressive strength (UCS) for the treated sediments**

Formulations	Relationship between E and UCS	Coefficient of determination
97%RDS + 3%L	E_{SS} = 0.761 UCS + 0.544	$R^2 = 0.97$
	E_{50} = 0.189 UCS – 0.059	$R^2 = 0.80$
91%RDS + 3%L + 6%C	E_{SS} = 0.435 UCS + 1.328	$R^2 = 0.88$
	E_{50} = 0.115 UCS + 0.071	$R^2 = 0.93$
94%RDS + 6%C	E_{SS} = 0.655 UCS + 1.045	$R^2 = 0.95$
	E_{50} = 0.157 UCS – 0.053	$R^2 = 0.93$

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ВАЛОРИЗАЦИЯ ИЗВЛЕЧЕННЫХ ОТЛОЖЕНИЙ ПЛОТИН ПРИ ПРОЕКТИРОВАНИИ ДОРОЖНОЙ ОДЕЖДЫ

Бумедьен Сербах[1,2]*, Магния Асмахане Бурабах[2], Джоанна Ид[3], Салима Бушмелла[4], Муссааб Хариче[5], Набиль Абу-Бекр[2], Саид Таиби[6]

[1]Университет Тиарета, Алжир
[2]Университет Тлемсена, Алжир
[3]Группа Ai Environnement FACÉA, Нуази-ле-Гран, Франция
[4]Университет Сук-Ахраса, Алжир
[5]Университет Джельфы, Алжир
[6]Университет Гавра, Франция

*E-mail: boumediene.serbah@univ-tiaret.dz

Аннотация
Введение: данная работа является частью исследования, направленного на валоризацию извлеченных отложений путем разработки составов для использования в дорожном строительстве. **Цель исследования** заключалась в том, чтобы определить, соответствуют ли материалы, отобранные для слоев дорожной одежды, стандартам проектирования, в частности, требованиям к плотности, гранулометрическому составу, пластичности, органическому веществу и механическим характеристикам. **Методы**: с тем чтобы определить физико-химические и механические характеристики извлеченных отложений, полученных из проб, отобранных на плотине Бахадда, расположенной в полузасушливом климате западного Алжира, отложения были обработаны вяжущими в небольших количествах (3% извести (L), 6% цемента (C)) для повторного использования в дорожном строительстве. В ходе исследования была изучена динамика физико-механических характеристик обработанных отложений, включая предел текучести (LL), показатель пластичности (PI), абсорбционную емкость по методу метиленового синего (VBS), индекс текущей нагрузки (IBI%), неограниченную прочность на сжатие (UCS), прочность на растяжение $б_t$ и модуль упругости при малых деформациях E_{SS} и больших деформациях E_{50}.
Результаты показали, что добавление извести и цемента в извлеченные отложения повышает их прочность, о чем свидетельствует увеличение прочности на сжатие (UCS) с течением времени для образцов, содержащих различные объемы вяжущего (3%L, 6%C и 3%L + 6%C). Кроме того, было продемонстрировано влияние содержания воды на механические свойства составов. Исследование показало, что прочность увеличивается при уменьшении содержания воды.

Ключевые слова: валоризация, извлеченные отложения, уплотнение, модуль упругости, неограниченная прочность на сжатие (UCS), прочность на растяжение, экогеоматериал, дорожное строительство.