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Valorization of Dam Sediments as Building Materials: A Study on Their Characteristics

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***Abstract*— The silting of dams in Tunisia is a phenomenon that increases year by year, resulting in considerable losses. As of March 2023, these losses amounted to approximately 22.36% of their storage capacity. Dredging the reservoirs could be a potential solution to preserve the structures and extend their lifespans. However, sustainable management of dredged sediments involves exploring avenues for their utilization. Utilization in construction materials could potentially offer an acceptable solution. This study, conducted in this context, firstly presents a characterization of sediments from three dams located in northern Tunisia through laboratory tests. Secondly, the potential for utilizing the sediments in road materials and ceramic products is investigated. The test results indicate that the sediments consist of moderately plastic, low-organic, predominantly clayey soils, with the presence of quartz and carbonates. Identification of the sediments based on their geotechnical characteristics revealed that they cannot be used as standalone road materials; they require pre-treatment either with lime alone or a combination of hydraulic binders. Similarly, for the valorization of sediments in ceramic material manufacturing, a mixture with mineral modifiers is necessary to achieve more suitable shaping properties.**

***Keywords*—dams silting, dredged sediments, characterization, valorization, road material, ceramic material.**

I. INTRODUCTION

The silting of dams is one of the concerning issues in the mobilization and utilization of surface water in Tunisia. The accumulation of sediments at the bottom of reservoirs reduces the storage capacity of dams and causes damage to sediment removal and drainage structures. Silting is a direct consequence of watershed erosion in dam catchment areas. In Tunisia, the catchment areas of dams are characterized by young reliefs, consisting of marl formations and erosion-prone soils on one hand, and limited forest cover in the most well-watered parts and seasonal vegetation cover on the other hand [1], [2]. In addition to these natural conditions, the torrential nature of precipitation, which occurs at the end of the dry season, contributes to erosion and a significant solid load during flood events. As a result, the reservoirs of various hydraulic structures are all confronted with alluviation to varying degrees in the long term [3], [4].

Currently, Tunisia has 36 operational dams, with 22 dams in the north, 8 dams in the central region, and 6 dams in Cap Bon. According to the "Hydraulic State of Dams - March 2, 2023" report from the General Directorate of Dams and Large Hydraulic Works under the Ministry of Agriculture, Hydraulic Resources, and Fisheries, the total initial capacity of the dams is 2988 million cubic meters (Mm^3), while the current usable capacity is 2320 Mm^3. These values indicate a trapped sediment volume of 668 Mm^3 and, consequently, a loss of 22.36% of the storage capacity.

To reduce the siltation rate and extend the lifespan of dams, effective dredging operations are highly demanded. However, sustainable management of dredged sediments should be anticipated. Utilizing dredged sediments in a sector that consumes aggregates from non-renewable deposits, such as the construction industry, can offer an interesting solution. Numerous studies have been conducted in this regard, considering various potential valorization options [5-8]. Among the most developed options, we can mention road construction techniques, concretes/mortars, and ceramic materials.

Several studies have been conducted on the valorization of dredged sediments in road materials, including those by Anger et al. [9], Banoune et al. [10], Benaissa et al. [11], Tribout [12], and Achour [13]. The latter tested a formulation based on treated marine sediment with 1% lime and 6% hydraulic binder, initially developed in the laboratory and then applied to a real road section measuring 550 meters in length. The mechanical results obtained

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after one year of service were consistent with those obtained in the laboratory and were satisfactory for valorization as a sub-base layer.

The valorization of dredged sediments in the production of concrete and mortar has been the subject of several research projects [13-18]. Indeed, sediments can be treated and used as a mineral addition in mortar manufacturing [19]. Research conducted by Amar [20] has shown that substituting cement with treated dredged sediment (physically and thermally treated) in a cementitious matrix is feasible and maintains good mechanical performance while complying with current environmental thresholds. The research by Ben Othman et al. focused on studying the characteristics of sand concrete composed mainly of marine sediment dredged sand, aiming to use it as a material for rigid pavement construction [21], [22]. They demonstrated that the compressive strength of compacted sand concrete, comprising 60% dredged sand and 40% crushed sand, is suitable for road applications. Zdiri et al. studied the use of marine or river sediments in roller-compacted concrete formulations as partial replacement of ordinary limestone aggregates [23], [24]. The proportions used range from 12% to 14.6% of the total mass, allowing the addition of sediment quantities ranging from 264.88 to 321.20 kg per m^3 of concrete. The compressive and tensile strengths obtained for the studied mixtures are sufficient to enable the application of this material in road engineering.

The aim of this study is to investigate different local sediments and explore their potential as alternative materials for total or partial substitution of conventional construction materials, with a focus on sustainable development. In Tunisia, dredged sediments are often classified as waste, and their storage poses environmental hazards.

This study focuses on dredged sediments from three different dams located in northern Tunisia. The geotechnical, mineralogical, and environmental characteristics of these sediments were examined through various tests. The classification of sediments was based on the characterization test results, which guided their suitability for different valorization pathways. Specifically, the valorization of the studied sediments in road materials and ceramic materials was examined and discussed based on the characterization test results.

II. EXPERIMENTAL STUDY

A. Origin and sampling of sediments

This study focuses on sediments that originate from three dams located in northern Tunisia, namely the Joumine, Sejnene, and Masri dams.

Joumine Dam, inaugurated in 1983 on the Joumine River, is located approximately 15 km northeast of Joumine in the Mateur region. The water from the dam is mainly used for drinking purposes. The total initial capacity of the dam is 129.9 million cubic meters (Mm^3), while the current usable capacity (March 2023) is 118.77 Mm^3, indicating a sedimentation rate of 8.57%.

Sejnene Dam is located in the northeastern part of Sejnene, in the Bizerte governorate. It is an earth dam, inaugurated in 1994 on the Sejnene River. The water from the dam is primarily used for drinking purposes. The total initial capacity of the dam is 137.5 Mm^3, while the current usable capacity is 134.01 Mm^3. Fig. 1 shows the geographical location of Sejnene and Joumine Dams.

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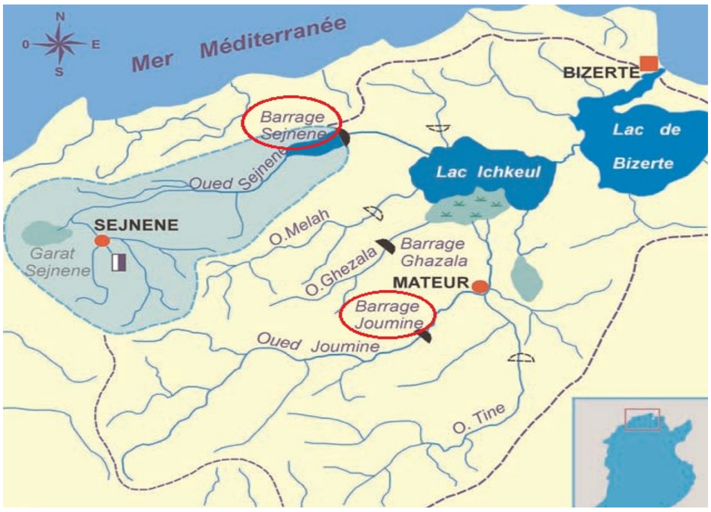

Fig. 1 Geographic localization of Sejnene and Joumine dams [4]

Masri Dam is situated on Djebel Sidi M'Hamed Latrach and was impounded in 1968 on the Masri River, 10 km south of Grombalia. The water from the dam is used for irrigating citrus crops in the Béni Khalled and Bou Argoub areas. Currently, the sedimentation rate of Masri Dam reaches 24.74%.

The main characteristics of the three dams are summarized in Table I. The hydraulic characteristics are obtained from reference [25].

TABLE I
MAIN CHARACTERISTICS OF DAMS

Dam	**Joumine**	**Sejnene**	**Masri**
Gouvernorate	Bizerte	Bizerte	Nabeul
River	Wadi Joumine	Wadi Sejnene	Wadi Masri
Watershed (Km^2)	418	363	53
Year of impoundment	1983	1994	1968
Purpose	Drinking water	Drinking water	irrigation
Initial capacity (Mm^3)	129.9	137.5	6.9
Current capacity (Mm^3)	118.77	134.01	5.19
Siltation rate (%)	8.57	2.54	24.74
Annual siltation rate (Mm^3/an)	0.37	0.13	0.04
Watershed erosion (mm/an)	0.89	0.50	0.75

The sediments, the subject of this study, were collected from the surface upstream of the dams. They were transported in airtight bags to the laboratory, as shown in Fig. 2 In the laboratory, before conducting the characterization tests, the sediments were dried at a temperature not exceeding 50°C to prevent any alteration of their chemical components, particularly organic matter. Subsequently, the sediments were disaggregated and homogenized.

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Fig. 2 Studied sediments

B. Sediment Characterization tests

The first step, essential and mandatory, in the search for material valorization is their characterization. A good understanding of the sediment's characteristics is crucial to assess its potential for valorization in the most suitable pathways. The objective of this experimental study is to determine the grain size, geotechnical, mineralogical, and environmental characteristics of the sediments from the Joumine, Sejnene, and Masri dams.

Grain size analysis is used to determine the distribution of particles within the material based on their dimensions. Given the fine size of sediment grains, the adopted technique is laser diffraction following the criteria of ISO 13320 standard [26]. This technique relies on the diffraction of a laser beam by particles suspended in a liquid and allows for the exploration of a wide range of particle sizes. The diffraction angle is inversely proportional to the size of the assumed spherical particles. Thus, the laser granulometry analysis technique accurately identifies the particle size of the sediment constituents.

Geotechnical parameters are necessary for the identification, classification, and selection of the sediment valorization process. The parameters considered in this study include the solid grain density, Atterberg limits, methylene blue value of the soil, and organic matter content, which were determined according to applicable standards. Each test was conducted on three sediment samples from each dam, after they were dried and homogenized, to obtain a representative average value. Fig. 3 shows the visual appearance of the sediments after drying and grinding.

Fig.3 visual appearance of sediments after grinding

The bulk density (ρs) of solid particles was determined using a pycnometer following the guidelines of standard EN ISO 17892-3 [27].

The Atterberg limits of the studied samples were determined in accordance with standard NF EN ISO 17892-12 [28]. The plastic limit (WP) and the liquid limit (WL) of each sediment sample were initially measured using the Casagrande apparatus and by rolling a soil ribbon of well-defined dimensions. The plasticity index (IP), which defines the plasticity range of the sample, was then calculated (IP = WL - WP).

The blue value of the sediments (VBS) was determined in accordance with standard NF P 94-068 [29]. The blue value of methylene blue in sediments is expressed in grams of blue dye absorbed per 100g of sediment.

The amount of organic matter present in the sediments was determined through a loss-on-ignition test, conducted following standard NF EN 15935 [30]. The principle is to measure the weight percentage of organic matter after the dry matter is incinerated at 550°C. Indeed, for any valorization of sediments in construction materials, the organic matter content (OM) is a highly influential parameter. It should be noted that a higher content of organic matter predicts undesirable characteristics for sediment valorization.

The mineralogical composition was then determined using X-ray Diffraction (XRD). This method allows for the identification of micro and poly-crystalline mineral phases in materials. The sediment sample is bombarded with X-rays, and the intensity of the diffracted X-rays is measured as a function of their angle of deviation (2θ) in space. XRD analyses were performed using an X-ray Diffraktometer, as shown in Fig. 4, (Siemens, Diffraktometer D5000), equipped with a cobalt anti-cathode, a rotating sample holder, and an automatic 42-position sample changer. The measurement chamber (PW 1710) is controlled by a microcomputer using FPS software.

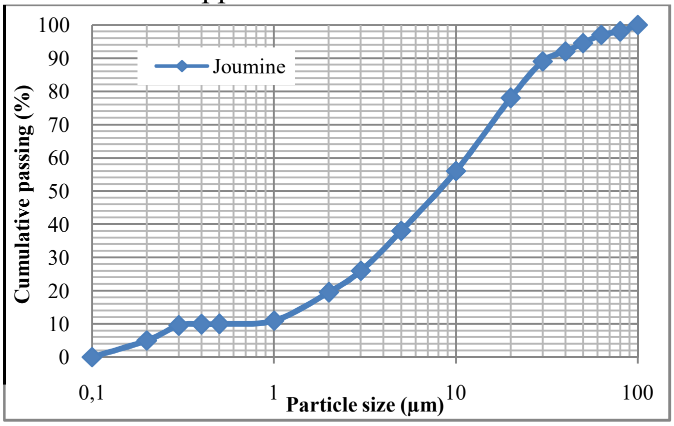
Fig.4 X-ray Diffraktometer used

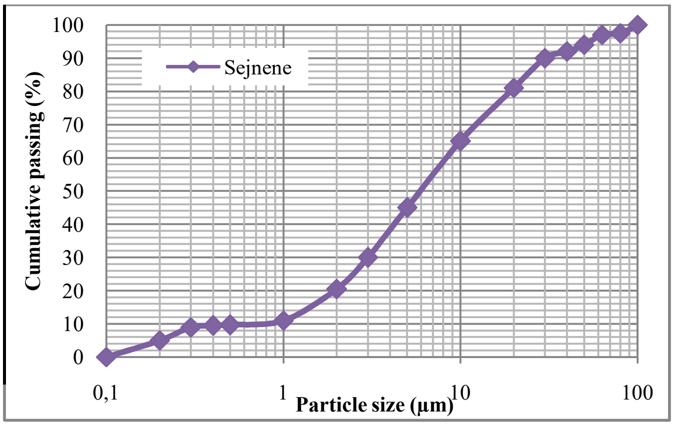
Finally, soil contamination by heavy metals, which is one of the most pressing environmental issues, was studied to assess the concentration of trace elements considered as pollutants, such as cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), and chromium (Cr). The analysis was conducted using inductively coupled plasma mass spectrometry (ICP/MS). The different sediment samples from the three dams were air-dried, then crushed and sieved through a 2 mm sieve before being subjected to laboratory analysis. The mineralization of the heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) was performed by hot digestion using a mixture of hydrochloric acid, nitric acid, and hydrofluoric acid on a hot plate for three hours.

III. RESULTS, DISCUSSION AND POTENTIAL OF VALORIZATION

A. *Results and discussion*

Grain size analysis describes the sediment based on different mineral fractions grouped into classes: clay particles smaller than 2µm, silt particles ranging from 2µm to 63µm, and sand particles between 63µm and 2mm. Fig. 5 presents the laser granulometry results of the sediments from the three dams.





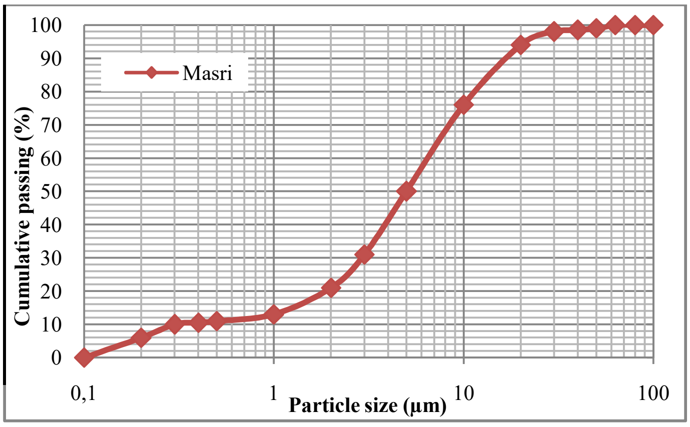


Fig. 5 grading curves for dam sediments

Fig. 5 shows that the sediments collected from the Joumine, Sejnene, and Masri dams are characterized by semi-logarithmic cumulative curves with an irregular and spread-out S-shape. Their appearance indicates a high percentage of silt. Furthermore, the three curves resemble each other and have the same overall shape. They all exhibit a inflection point corresponding to the transition from clay to silt. The grain size characteristics derived from the interpretation of the grain size curves are summarized in Table II.

TABLE II
GRANULOMETRIC CHARACTERISTICS

Dam	Joumine	Sejnene	Masri
Clay fraction < 2µm (%)	19	20	21
Silt fraction 2 à 63µm (%)	78	77	79
Sand fraction > 63µm (%)	3	3	0
Passing 80µm (%)	98	97.8	100
Median diameter (µm)	8	5.5	5

Coefficient of uniformity Cu	16.67	13.33	17.5
Coefficient of curvature Cc	2.04	1.87	3

The results of the grain size analysis lead to the following comments:

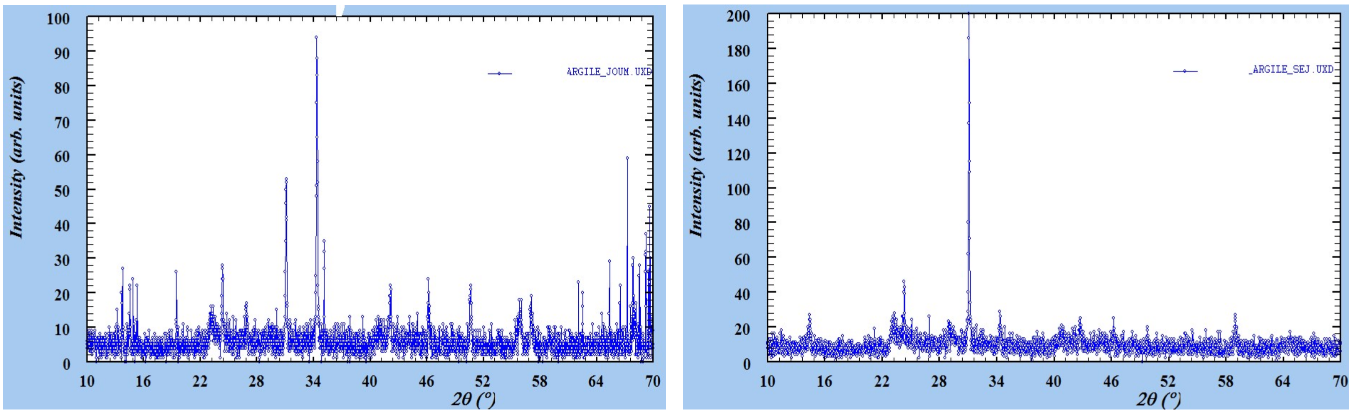
- The silt fraction is the most dominant. For all three dams, the silt content in the sediments is very similar and exceeds 77%.
- The ultra-fine clay fraction accounts for an average percentage of approximately 20% of the total grain size ;
- The sand fraction is negligible for the Joumine and Sejnene dams, while the Masri dam is completely devoid of this fraction. Therefore, all three dams have predominantly fine sediments.
- The median diameters for the Masri and Sejnene dams are close and lower than that of the Joumine dam (8µm).
- The coefficients of uniformity obtained are significantly higher than 2. Consequently, the grain size distribution of the sediments from all three dams is widely spread.
- The coefficients of curvature have values ranging between 1 and 3, indicating a well-graded grain size distribution for the sediments from all three dams.

The geotechnical parameters were subsequently determined. They are necessary for the identification, classification, and selection of the sediment valorization process. The results displayed in Table III indicate that the sediments are loamy soils with medium plasticity and low organic content, as the organic matter content for all three dams is below 10%. The bulk densities of the three sediments are close and comparable to those of materials from quarries.

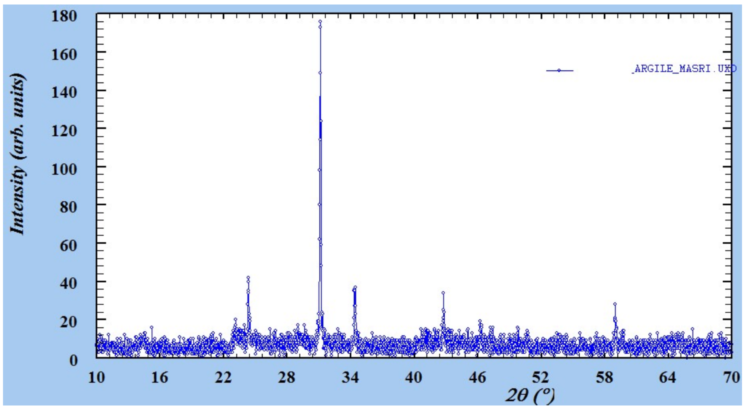
TABLE III
GEOTECHNICAL PARAMETERS

Dam	Joumine	Sejnene	Masri
Liquid limit W_L (%)	39	33,5	45,9
Plastic limit W_P (%)	30	26,0	30,0
Plasticity index I_P (%)	9	7,5	15,9
Bleu value VBS (g/100g)	4,4	2,6	3,8
Organic matter content (%)	4.4	3.8	3.4
Bulk density (g/cm^3)	2,75	2,74	2,61

The mineralogical analysis was performed using X-ray diffraction (XRD), and the obtained diffractograms are shown in Fig. 6.



a. b.



c.

Fig. 6 XRD Diffractograms of dam sediments
a. Joumine, b. Sejnene, c. Masri

Table IV is established based on the diffractograms shown in Fig 7, and it presents the main minerals found in the sediments of the three dams. The results of the mineralogical characterization show that:

- The studied sediments are mainly composed of clay minerals, quartz, and carbonates (predominantly calcite and dolomite).
- The proportions of quartz are high in all three dams, while calcite is predominantly present in the sediments of the Sejnane and Masri dams.
- The sediments from the Joumine dam are the richest in clay minerals and the poorest in carbonates.
- Low levels of feldspar and ferruginous minerals are observed.

TABLE IV
MINERALOGICAL ANALYSIS

Minerals	Joumine	Sejnene	Masri
Quartz	38	35	28
Calcite	2	19	24
Dolomite	5	3	7
Illite	16	13	10
Kaolinite	19	14	13
Chlorite	9	2	5
Albite	2	3	2
Anorthite	5	4	6
Minéraux ferrugineux	4	7	5

The average concentrations measured in trace metal elements are provided in Table V. The results are expressed in mg/kg of soil dry weight.

TABLE V
CONCENTRATIONS OF TRACE METAL ELEMENTS (MG/KG)

Trace metal element	Concentration (mg/kg)			Limit value in soil
	Joumine	Sejnene	Masri	
Cd	0.315	0.719	0.872	2
Cu	11.17	13.05	15.12	100
Pb	62.92	29.11	34.64	100
Ni	27.371	26.738	27.025	50
Zn	124.98	119.86	125.39	300
Cr	96.19	106.16	104.36	150

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The data from Table V demonstrate that the studied sediments contain varying amounts of trace metal elements, and all concentrations are below the usual limit values. This proves the absence of sediment contamination by heavy metals in the three dams.

B. POTENTIALS FOR VALORIZATION

According to the results of the characterization tests, the identification of sediments is carried out using specific classifications based on the intended valorization pathway. The potentials for valorization of the sediments in the road material and ceramic material sectors will be discussed in this section.

1) *The Road Materials Sector:* For use as road material and similar applications, the characteristics of fine sediments that need to be considered are grain size distribution, clay content, and organic matter content. These three parameters are required for various geotechnical classifications that help identify fine soils for road or non-road use. They are particularly important in the classification system provided in the Technical Road Guide (GTR) (SETRA-LCPC, 2000) [31]. The classification also follows a standard, which is the NF P 11 300 standard [32].

According to the GTR technical guide (2000), the studied sediments belong to class F and subclass F11, and they are considered to have low organic content since their organic matter content ranges between 3% and 10%. Referring to the grain size distribution, the sediments from the Joumine and Sejnene dams belong to class A1, while the sediments from the El Masri dam fall under class A2, with a significant fine fraction (< 80 µm), as shown in the Fig. 7.

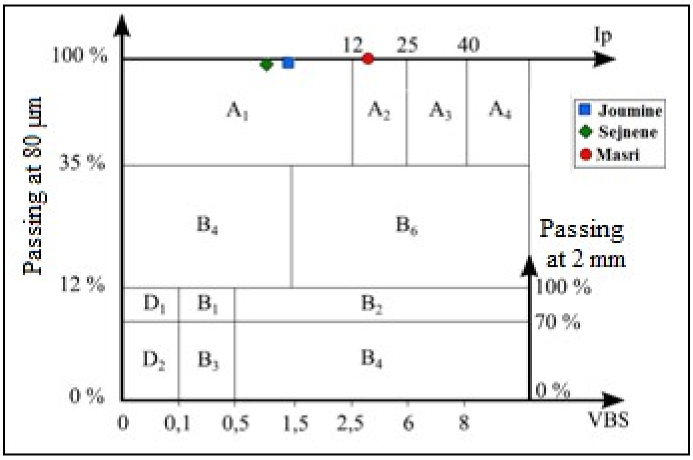

Fig. 7 Sediments classification according to the GTR [31]

Based on the knowledge of the sediment's Atterberg limits, classifications can be performed. The most commonly used diagram in geotechnical engineering to classify fine soils is the Casagrande plasticity chart according to the LCPC (Laboratoire Central des Ponts et Chaussées). Fig. 8 represents the summary of all the values obtained for the sediments from the three dams.

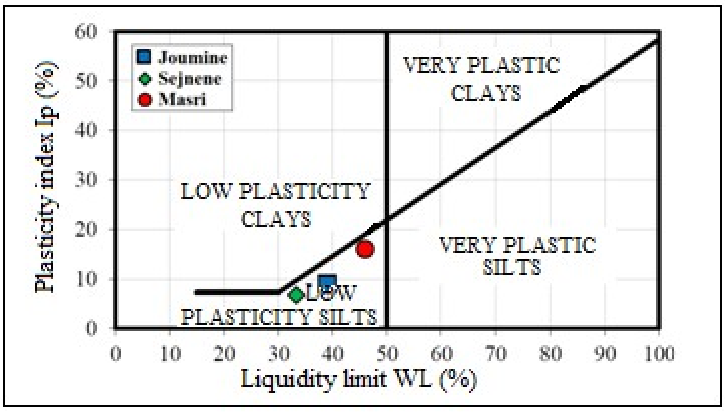

Fig. 8 Classification des sédiments sur le diagramme de plasticité de Casagrande selon LCPC (1965)

Based on the Casagrande classification, it can be observed that the studied sediments can be classified as low plasticity silty soils, as their liquidity limit is below 50%.

In conclusion, the studied sediments can be classified as low-clay content, low plasticity, and low organic content fine soils. The low organic matter content and low plasticity are favorable characteristics for their use in the road material sector. However, the low proportion of coarse elements will result in a weak internal skeleton. Nonetheless, these fine sediments cannot be used directly. Pre-treatment with lime alone or a combination treatment with hydraulic binders is recommended to use them as road material in applications such as subbase layers, bicycle paths, or pedestrian walkways. Similar observations have been made by researchers [33] and [34].

2) *The Ceramic Materials Sector:* Ceramic materials are made from clays. After extensive preparation, the mixture is shaped, dried, and finally fired. For use as ceramic material, the characteristics of fine sediments that need to be considered are the particle size distribution and plasticity. The particle size distribution of the mixtures plays a significant role in their properties. A certain content of clays and silts is therefore sought in the production mixtures, depending on the desired products.

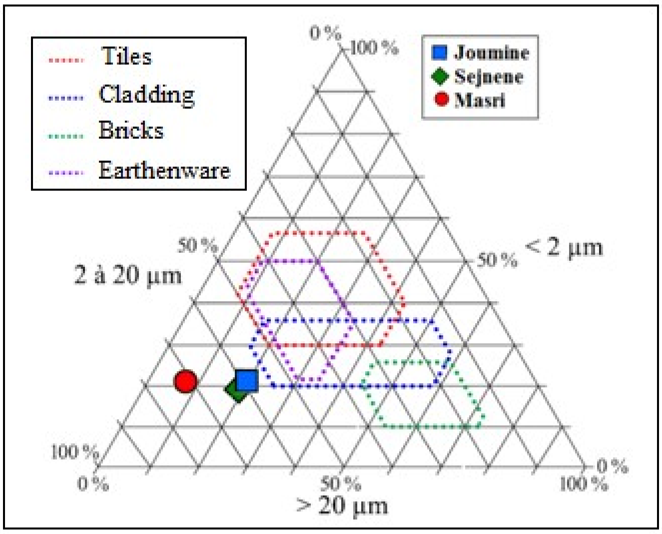

Fig.9 Particle size distribution of sediments and Winkler diagram.

The Winkler diagram incorporates industrial data that relates optimal particle size distribution to application for extrusion processing. Fig. 9 demonstrates that the analyzed dam sediments, based on their particle size distributions, do not appear suitable for standalone use as a material. This is generally the case with traditional materials sourced from quarries as well since a production blend must be prepared to achieve a paste with optimal characteristics.

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Indeed, ceramic pastes can consist of one or several clays mixed with "non-plastic" mineral modifiers that have a degreasing effect [35].

The shaping of ceramic materials for the production of ceramic components is almost always accomplished through extrusion. Gippini [1969] established limits of plasticity/plasticity index ranges to determine the characteristics of mixtures and achieve optimal shaping. The sediments from the three dams are placed on this plasticity chart shown in Fig. 10.

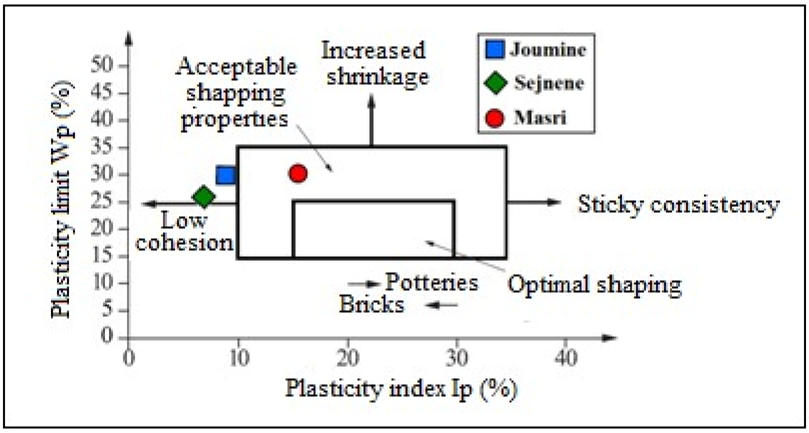

Fig.10 Classification of sediments according to the Gippini diagram (1969)

Among the studied sediments, the Masri sediment exhibits acceptable shaping properties and is the most suitable for use as an alternative raw material in the production of earthenware. For the other sediments, a mixture should be considered to achieve more suitable shaping properties.

IV. Conclusion

This study is carried out within the framework of sustainable management of dam sediments by examining their characteristics. The characterization of these materials allows for their efficient utilization in the most suitable channels. A comprehensive characterization of sediments from three dams was conducted based on geotechnical, mineralogical, and environmental analyses. The results of the characterization tests on the three studied sediments led to the following conclusions:

- The silty fraction is the most dominant (77 to 79%), the clay fraction is moderate (19 to 21%), and the sandy fraction is nearly absent. Therefore, the studied sediments are fine silty soils.
- The three studied sediments have low organic content.
- Based on the methylene blue value, they are soils with moderate plasticity.
- The mineralogical analysis reveals that the studied sediments are mainly composed of clay minerals, quartz, and carbonates.
- The content of trace metal elements indicates the absence of metal pollution in sediments of the three dams.

The first sediment valorization pathway focused on road materials. The identification of these materials showed that they cannot be used alone, but require pre-treatment with lime alone or a combination treatment with hydraulic binders.

The valorization of sediments in the production of ceramic materials represents the second explored avenue of valorization. The ElMasri dam sediments exhibit acceptable properties, whereas for the Sejnene and Joumine dam sediments, a mixture is necessary to achieve more suitable shaping properties.

While land-managed sediments have a regulatory waste status, they deserve to be considered as a potential alternative resource for raw materials in the construction sector, which is a major consumer of aggregates.

Furthermore, it is proposed to further investigate this study by conducting chemical analyses of sediments and exploring their potential for valorization in the production of cement, mortar, and concrete.

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