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Optimization of the methodology for valorization of mud retained by dams: Morocco case study

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Abstract

Dams are mainly built to store water, but they also accumulate a lot of sediment that consolidates over time. This mud harms the functioning and safety of dams and neighboring communities.

In addition to preventive measures to mitigate siltation, dam managers often resort to de-siltation as a corrective approach. However, this method generates significant volumes of mud, causing environmental damage and significant land losses.

Faced with the scarcity and increasing costs of raw materials, the use of the mud retained by dams as a resource in various fields is becoming essential. By exploiting the potential of sludge, we can alleviate the pressure on traditional raw materials and promote sustainable practices in all industries.

This article proposes a new optimal methodology for the use of mud retained by dams, based on global research. It specifies the laboratory tests to be carried out, the limit values to be respected, and a systematic process to improve the efficiency of the use of mud while respecting standards and best practices.

In addition to the presentation of the optimal methodology developed, the article includes a case study to illustrate its practical application. Focusing on the Moroccan context, we show how our approach can be adapted in real situations, providing a useful resource for professionals involved in the extraction of mud from dam reservoirs.

Keywords: Dam; Mud-Silting; De-Siltation; Valorization; Civil Engineering; Environment.

1. Introduction

Once sediments are deposited in dam reservoirs, they undergo a consolidation process, forming layers that contain varying degrees of coarser formations known as mud. The presence of mud in dam reservoirs poses several detrimental effects, including Deterioration of water quality, risk to dam safety and nearby populations, blockage of bottom outlets, reduction in reservoir capacity, loss of invested resources…

While mud remains deposited, it poses continuous harm, prompting dam managers to actively seek methods for its removal. This can be achieved through practices such as releasing water laden with sediment during floods or conducting de-silting operations. According to White R., approximately 40,000 large reservoirs worldwide experience

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siltation issues, resulting in an estimated annual loss of 0.5% to 1% of total storage capacity due to sedimentation [1]. To compensate for this loss, around 45 cubic kilometers of new reservoirs need to be constructed each year globally. The associated costs, excluding environmental and social impacts, would amount to approximately 13 billion US dollars annually (Palmieri A. & Al, 2003) [2].

De-silting operations involve the removal of large volumes of deposited mud from the reservoir by mechanical or hydraulic means. The extracted mud is then transported and disposed of at a considerable distance from the watercourse and reservoir. While de-silting operations offer advantages, such as mud removal, they also come with several disadvantages, like high cost, land occupation, and environmental pollution.

However, the potential utilization of this mud in various industries could potentially offset some of the disadvantages associated with de-silting operations. Several researchers have carried out investigations in this sense, more particularly in arid and semi-arid countries where water resources are becoming increasingly scarce.

This article recapitulates these research works and presents as result an optimal approach for valuing the mud stored in dam reservoirs.

In the first part of this article, we present the possibilities of using these muds in different industrial sectors.

We describe in the second part an optimal methodology developed for valuing the mud stored in dam reservoirs, the results of our research.

The last part is devoted to the application of this optimal methodology for dam reservoirs in Morocco, taking into account the standards, laws, and regulations applied in this country.

2. Materials and method

2.1. Potential sectors of the possible use of mud

The significant accumulation of mud within dam reservoirs, often reaching tens of millions of cubic meters per dam, naturally leads us to contemplate harnessing this valuable resource for various industries and sectors with high demands for raw materials. Considering these circumstances, our research has been predominantly directed toward exploring potential applications in civil engineering, agriculture, environmental conservation, and artisanal crafts.

2.1.1. Civil engineering uses

In general, infrastructure and civil engineering projects require large amounts of materials. Natural materials are scarce and expensive, and their extraction is harmful to the environment.

The need to find aggregates in large quantities at low cost will push companies to invest in recycling materials.

Any material intended for use in civil engineering or public works must comply with the standards defining the technical characteristics required.

To be able to use as building materials, mud extracted from dam reservoirs must meet the standards given for their fields of use.

The presence of large quantities of stored mud in dam reservoirs opens up numerous possibilities for its application in civil engineering activities, including backfilling roads and trenches, using it as fillers or expanded aggregates in concrete production, creating clinker for cement, and manufacturing terracotta bricks.

Using mud in road works: Several superimposed layers make the structure of a roadway, of which generally only the one on which the vehicles are traveling is visible.

The physical aspects of the mud extracted from dam reservoirs lead us to think that it can be used as a top layer in the construction of roadways (Seklaoui O., 2016) [3]. However, the potential use of these raw sediments in road engineering can only be assessed after identifying the physical, chemical, mineralogical, and environmental characteristics of the material in question.

Using mud as aggregates for concrete: Concrete production is one of the big consumers of materials. Aggregates are the basic materials of this industry. They come largely from quarries and alluvial deposits (ballast pits).

Aggregates are becoming a scarce resource and the operation of quarries and ballast pits is becoming difficult and expensive.

Manufacturers must develop the use of mud retained by dams as a concrete component to meet the growing needs of the concrete manufacturing industry.

Using mud in the manufacture of bricks: Bricks are terracotta products. The raw materials with the addition of water constitute a plastic paste, the rheology of which must be adapted to the forming process. Drying of raw parts is done in a ventilated cell or a tunnel dryer. The firing temperature is between 900 and 1160°C (Bonnet J.P and Gaillard J.M, 2001)[4].

The raw materials are clay, sand, limestone, feldspar, and other additions.

Since the mud in most dams is clay, we can exploit it as a raw material in the red brick industry. Depending on its mineralogical and chemical composition, we can use mud alone or by mixing it with another clay if it contains clay of the required quality in sufficient quantity.

Using mud in the manufacture of cement: The method of producing cement, based on calcination at high temperatures, is expensive and emits greenhouse gases, which are extremely damaging to the environment. The need for a substitute is urgent.

On the other hand, the reduction in the costs of a building depends on the fall in the costs of building materials. The classic composition of cement is 80% limestone and 20% clay. These two elements are crushed, cooked at a very high temperature, and the result (clinker) is crushed again. We can use mud stored by dams as a base for the clinker if it contains sufficient clay of the required quality.

Cement based on these additions provides a timely solution. The solid fraction of the mud from the dams constitutes a very attractive local economic material because of its fine granularity, saving the costly stages of crushing and sieving.

2.1.2. Agriculture uses

Applying sediment to arable land offers a practical approach to effectively utilize this material, serving several agronomic objectives. These include fertilization, as sediment provides essential nutrients for plants, both in mineral and organic form. Additionally, incorporating sediment into the soil improves soil quality, enhancing physical, chemical, and biological properties. Furthermore, sediment application supports ecological rehabilitation efforts, aiding the restoration of disturbed areas like industrial wastelands and demolished sites, promoting vegetation growth and ecological recovery. The feasibility of using sediment for different purposes depends on its pollutant content, which requires an assessment before determining its suitability for various applications.

2.1.3. Environmental protection uses

Watertightness layer for a lagoon or landfill: The settling basins of a wastewater treatment plant must be watertight to avoid the pollution of groundwater by the infiltration of wastewater. They are generally sealed by geomembranes, a synthetic material that is impervious but very expensive.

Because it contains a large fraction of clay, the mud can be used to improve the sealing of settling ponds as well as a geomembrane mat.

The same goes for technical landfills where waste is backfilled in basins that must be waterproof to protect groundwater from leachate infiltration (Benasla M., 2015) [5].

The waterproofing characteristics of floor materials are influenced by several factors. These include the material's nature, encompassing grain size, mineralogical composition, pH, and organic matter content. Additionally, the homogeneity at the farm level and the potential for improvement or homogenization play a role. The initial state and implementation aspects, such as compaction and humidity, also come into consideration. Lastly, the nature of the fluids that may come into contact with the floor is a crucial factor in determining suitable waterproofing materials.

Soil amendment: The application of substantial amounts of mud to cover eroded or infertile soils can facilitate their transformation into permanent grasslands within a few years. This process helps in the restoration of degraded areas and promotes the establishment of sustainable vegetation.

In addition to that, mud can be employed as a versatile material for creating reliefs, landscaping, and modifying specific terrains. It offers opportunities for various projects such as industrial spaces, leisure parks, railway/road developments, and the creation of artificial islands for land reclamation and urban/environmental purposes (Levacher D., 2006)[6].

2.1.4. Craftwork uses (Ceramic products, tiles, and glass manufacturing)

Ceramics are defined as "the art of making pottery, based on the property of clays to give with water a plastic paste, easy to shape, becoming hard, solid and unalterable after firing" (Larousse P, 1878)[7].

We can use mud stored by dams in the manufacture of ceramics if they meet certain conditions, which will be detailed in the following paragraphs.

Glass, a non-crystalline substance primarily composed of silicon oxide (SiO_2) and fluxes, can potentially benefit from the utilization of mud sourced from dam reservoirs. The mud can be employed in glass production provided it possesses a specific and adequate concentration of these constituent materials.

2.2. Decisive characteristics for the use of mud

When considering the usability of mud in the aforementioned sectors and activities, several key characteristics should be taken into account. These include:

Clayey or Clay Content: The presence of clay or a certain clay content is an important factor, as it contributes to the cohesive and binding properties of the mud, making it suitable for various applications.

Granularity or Particle Size Analysis: The particle size distribution of the mud, determined through a granularity analysis, provides insight into its physical properties and potential uses.

Mineralogical Characteristics: Understanding the mineral composition of the mud is essential, as different minerals can have varying effects on its behavior and suitability for specific applications.

Organic Matter Content: The amount of organic matter present in the mud plays a role in its nutrient content, stability, and potential impact on the environment.

Water Content: The moisture content of the mud affects its consistency and workability. It is important to consider the optimal water content for the desired application.

Mechanical Characteristics: The mechanical properties of the mud, such as shear strength, compaction ability, and stability, are crucial factors to assess its usability in different projects.

Chemical Characteristics: Evaluating the chemical composition of the mud, including pH, cation exchange capacity, and nutrient content, helps determine its potential impacts and applications.

Traces of Metals: The presence of trace metals in the mud should be considered, as they can affect its suitability for certain uses and pose environmental concerns.

Traces of Organic Compounds: The presence of organic compounds, even in trace amounts, should be assessed to ensure the compatibility of the mud with the intended applications and potential environmental impacts.

Considering these decisive characteristics allows for a comprehensive evaluation of mud's suitability for specific sectors and activities.

2.3. Laboratory tests to be performed and limit values

The laboratory tests to be carried out to identify the aforementioned characteristics can be classified into three categories:

Physical tests that include among others: The limits of Atterberg, the Casagrande cup, the roller method, the dry sieving method after washing, sedimentometry, the calcination method…

Chemical tests like the methylene blue test, Chemical method of determining the organic matter content…

Radiation and spectroscopy tests that include: X-ray diffraction, Fluorescence X, Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES), Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-MS)

The limit values to be observed for each laboratory test are determined by the laws and regulations used in the country concerned.

3. Result and discussion

3.1. The optimal approach to valuing mud stored in dam reservoirs

Through our research, we have developed an effective and practical approach for assessing the value of mud retained by dams. This approach involves the creation of a comprehensive guide specific to each country. The guide consists of three main components:

Grid of Tests and Limit Values: This component outlines a set of tests to be conducted on the mud samples and specifies the corresponding limit values that need to be observed. These tests are crucial in evaluating the mud's suitability for various applications.

Matrix of Characteristics: This component provides a matrix that highlights the key characteristics to be studied when assessing the mud. These characteristics may include clay content, particle size analysis, mineralogical composition, organic matter content, water content, mechanical and chemical properties, trace metals, and organic compounds.

Procedure Diagram: This component presents a step-by-step diagram illustrating the procedure to be followed when evaluating and valuing the mud. It outlines the necessary stages, such as sample collection, laboratory testing, data analysis, and decision-making.

To provide a practical example, we present here the specific guide for valuing the mud extracted from dam reservoirs in the case of Morocco.

This approach ensures a systematic and standardized valuation of the mud, enabling informed decision-making regarding its utilization.

3.1.1. Grid of tests and limit values

The grid provides a systematic approach for evaluating the mud extracted from dam reservoirs, considering the regulations, laws, and standards applicable in the relevant country. It outlines the necessary tests and analyses based on the specific characteristics required for utilizing mud in various sectors, such as civil engineering, crafts, environment, and agriculture.

The grid in question is in the form of a table whose rows designate the different activities and its columns indicate:

- Sector: Identify the sector or industry to which the activity belongs.
- Activity: Specify the particular activity or application related to the use of mud.
- Use: Describe the purpose or intended use of the mud in the given activity.
- Characteristics: List the relevant characteristics of the mud that need to be considered for the specific activity.
- Wanted Value: Define the desired value or acceptable range for the specified characteristics
- Tests to be Carried Out: Identify the specific tests or analyses that need to be conducted to assess the characteristics of the mud for the given activity.

3.1.2. Matrix of the characteristics

Based on the grid provided and the activities associated with different sectors, you can optimize the selection of laboratory tests by dividing them into two phases: the first phase and the second phase. The choice of tests in each phase can be determined based on the targeted activities. To facilitate this process, you can use the matrix of characteristics to be examined.

An example of this matrix for the case of Morocco is given below in Figure 4.

In the first phase, you can select tests that are relevant to the targeted activities and that provide initial insights into the mud's characteristics. In the second phase, more specific and detailed tests can be conducted based on the results and requirements of the selected activities.

By utilizing this matrix and the two-phase approach, you can optimize the testing process and ensure that the chosen tests align with the characteristics targeted for each activity.

Case of a single activity: For a single activity, selecting tests in the first phase involves choosing the least expensive and quickest ones. The same principle applies to classifying the remaining tests in the second phase.

Case of several activities: In this case, the preceding matrix serves to prioritize the tests required for most or all of the activities planned during the first phase. For example, when considering applications in civil engineering or craftsmanship, the first phase of tests will focus on the study of the clay content and the granularity of the mud. Conversely, laboratory tests would favor detecting metallic traces for applications in the environment or agriculture. The cost of testing remains a determining factor in determining the priority of testing during each phase.

Cases where no activity is targeted: In the case of an undefined activity, it is essential to consider all the tests of the evaluation grid. For the first phase, the priority tests would be the least expensive.

3.1.3. Procedural Flowchart

Here is the procedure to follow, as defined sequentially, for utilizing the guide (Fig. 5):

1. Choice of dam
   a. Consider the quantity of extractable mud available in the reservoir.
   b. Assess mud deposition and storage areas.
   c. Evaluate proximity to the intended reuse area.
2. Selection of Activity Sectors
   a. Conduct market research and analyze supply and demand.
   b. Perform technical, economic, and feasibility studies, including profitability analysis.
   c. Assess the project environment across six dimensions: political, economic, social, technological, ecological, and legal.
3. Consultation of Databases on Sediments
   a. Refer to local databases, whether in physical or electronic format.
   b. Utilize Geographic Information System (GIS) databases.
4. Laboratory Testing
   a. Define the tests to be conducted for each phase.
   b. Collect mud samples for testing.
   c. Conduct trials in the first phase.
   d. Analyze the results obtained from the first phase trials.
   e. Perform additional trials in the second phase if the first phase trials yield conclusive results.
   f. Analyze the results obtained from the second phase trials.
5. Decision making
   a. If the results and assessments are favorable, consider retaining the dam for mud valorization.
   b. Reject the idea of mud valorization for the selected dam if it is deemed unsuitable or not economically viable.
6. Database management:
   a. Enter the results into the local database.
   b. Enter the results into the GIS database.

By following this procedure, you can systematically assess dams, select appropriate sectors of activity, consult relevant databases, conduct laboratory tests, make informed decisions, and maintain comprehensive records in local and GIS databases.

3.2. Possible uses of mud retained by dams in Morocco (Case study)

3.2.1. Mud-silting and desilting in Morocco

All regions of Moroccan territory are affected by soil erosion with varying intensities. According to the 2008 National Water Plan (PNE), erosion concerns 75% of 23 million hectares in mountainous areas, one-third of which is very critical (SEEE/METLE, 2008) [8].

This situation leads to the silting dam reservoirs that lose about 73 Mm^3 of their storage capacity per year according to the same PNE.

Considering the high cost of de-silting operations, the Moroccan government proceeded with this solution for only one dam: Mechrâa Homadi Dam in the Province of Berkane located in the Northeast of Morocco.

The reservoir's capacity has decreased from 42 Mm^3 to 4.9 Mm^3 due to mud siltation and is currently around 8.0 Mm^3 after desilting operations.

The desilting work allowed the extraction of about 8.8 Mm^3 of mud by dredging with suction pumps to an area arranged to store mud and recover water.

The cost of this operation executedbetween1997 and 2009 has exceeded 29 million dollars, which raises the cost of removing the cubic meter of mud to around 3.76 dollars without taking into account the costs of studies, monitoring of works, and, expropriation of land, and the discount rate of currencies (SEEE, 1997, 2004, 2005, 2006 and 2008) [9].

The studies conducted on the utilization of mud, as presented below, have been carried out by Moroccan laws, regulations, and standards. Additionally, French laws and regulations have been followed for sectors where Moroccan regulations are not fully developed.

3.3. Valorization of Mud in Civil Engineering

3.3.1. Road works

The standard to be applied in this case is AFNOR NF P11-300 [22]. It concerns the geotechnical classification of materials that can be used in sub-layers and road embankments (Association Française de Normalisation AFNOR, 1992). This classification is based on the parameters of the nature of the materials: granularity, plasticity index, and clayey.

Considering their organic matter (OM) content, dredging mud belongs to class F according to this standard. This class concerns materials called organic soils and industrial by-products.

This class includes, in particular, bottom ash for incineration of non-hazardous waste (F6), demolition materials (F7), and steel slags (F8).

The sediments belong to the F1 class of organic materials OM (P. Bataillard & al., 2017) [10].

They are divided into two subclasses according to the OM content (% OM): F11 (The OM content of the analyzed soil is between 3 and 10%) and F12 (The OM content of the analyzed soil is greater than 10%).

Dredged sediments generally fall into subclass F11, the OM content of which is between 3 and 10% (by dry mass), although sediments with even higher OM contents may be encountered (Piou S. & al. 2009) [11].

The aforementioned standard recommends that materials of class F must carry out a classification similar to non-organic materials. Given their granularity, dredged sediments fall within class A of fine soils characterized by a maximum grain size Dmax<50 mm and passing through the sieve at 80 µm of 35% minimum (Bataillard P. & al. 2017)[10].

3.3.2. Valorization of mud as aggregates for concrete

The classification of French standard NF P18-545[23], relating to the definition, conformity, and codification of aggregates (AFNOR, 2011), and French standard NF EN 12620[24] relating to aggregates for concrete (AFNOR, 2008), consider that sediments are fillers (granulate most of whose grains pass through a 0.063 mm sieve and which can be added to construction materials to give them certain properties).

Fillers play a crucial role in completing the grain-size curve of aggregate mixtures used in concrete production. They offer several benefits in improving various properties of concrete, like avoiding segregation, increasing compressive strength, reducing porosity, and enhancing surface appearance.

The French standard NF EN 12620 precisely defines the particle size characteristics of a filler to ensure that the fillers meet the specified criteria and contribute effectively to achieving the desired properties in concrete.

The limit values in question are given in Table 1 below.

The physical characteristics mentioned by French standard NF EN 12620[24] for concrete aggregates mainly concern gravel. The following specifications apply to fillers:

- Water absorption, freeze-thaw cycle: According to French standard NF EN 12620[24], a water absorption coefficient of less than 1% makes it possible to consider an aggregate as insensitive to the freeze-thaw action. This parameter is defined (in percentage) as the ratio of wet mass to dry mass according to the same standard.

- Alkali-silica reaction: This reaction takes place between the alkali hydroxides present in the interstitial fluids of concrete and certain forms of silica or silicates in aggregates. In the presence of moisture, it can lead to swelling, cracking, or breaking concrete. The FD P 18-542 [25] standard (AFNOR, 2004), relating to the qualification of aggregates for concrete concerning alkali-reaction, defines the Non-Reactive (NR) class by SiO_2<4% according to the aforementioned standard.

We can measure the chemical characterization of mud by X-ray diffraction coupling them by X-ray fluorescence spectrometry:

- Sulfur and sulfates: According to standard NF EN 12620[24], the total sulfur content of aggregates other than air-cooled blast furnace slag must not exceed 1% by mass. If the sulfur is present as pyrrhotite (FeS), the total sulfur content should not exceed 0.1% by mass.
- Chlorides: According to standard NF EN 206 [26] (AFNOR, 2014), the maximum content of chloride ions in concrete can reach 1% for unreinforced concrete, but is reduced by 0.4% for reinforced concrete and 0.2% for pre-stressed concrete.

3.3.3. Valorization of mud in the manufacture of bricks

The particle size distribution significantly affects the properties of terracotta mixes. Good plasticity and high water absorption are associated with the fraction of particles smaller than 2 µm, primarily composed of clay minerals. A higher proportion of elements smaller than 2 µm results in increased plasticity but can lead to challenges during molding due to high molding humidity and significant shrinkage during drying. Conversely, a lower proportion of particles smaller than 2 µm leads to reduced plasticity, low molding humidity, and lower shrinkage (Mazen Samara, 2006) [12].

To assess the plasticity of dough, its Atterberg limits must be determined (AFNOR NF P 94-051 standard) [27].

For use as a raw material for terracotta, Gippini in 1969[13] defined an abacus to obtain a mixture with the best molding and drying properties.

The common chemical composition thresholds of the mixtures used in the manufacture of terracotta in Morocco are given by the research works of Kornmann in 2009[14]. They define the minimum and maximum limits of the presence in clay of SiO_2, TiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O, K_2O, sulfur, and iron (Table 1).

It is therefore possible to refer to these values for the design of a clay mixture. The trace levels of metals not to exceed for the manufacture of bricks are 0.005 mg/kg for Chromium, 0.010 mg/kg for Lead, Mercury, Cadmium, and Tin, and 0.050 mg/kg for Arsenic (GEODE, 2016) [15].

3.3.4. Valorization in the manufacture of cement

According to A. PRAX from the Geological and Mining Research Office of France (BRGM), it is estimated that approximately 1.55 to 1.60 tons of raw materials are required to produce one ton of clinkers for the production of

Portland cement. This indicates that the CaO (calcium oxide) content of the clinkers implies that the $CaCO_3$ (calcium carbonate) content of the raw materials ranges from approximately 73% to 78% (PRAX A., 1979) [16].

It is, therefore, necessary as a priority to be able to have:

- The main source of raw materials, therefore: $CaCO_3$ content> 80%
- One (or more) additional raw material resources making it possible to adjust the composition (CaO, SiO_2, Al_2O_3, FeO_3, etc.) of the raw material to the required characteristics.
- The other selection criteria can be summarized as follows (PRAX A., 1979):
- MgO magnesia content <5% (or even <3%)
- Alkaline content Na_2O <0.5% and K_2O <1%
- Sulfates and sulfides content: SO_3<2%
- Iron content in the form of pyrite (FeS_2): FeS_2<< 2%
- Free silica: it is prohibited in the form of coarse elements that we cannot combine with lime during cooking:
- Flint in kidneys and nodules,
- Quartz (sand D> 80μm)
- Phosphate elements are often prohibited.

3.4. Valorization of mud in agriculture

In the deficiency of a Moroccan law governing the use of mud in agriculture, we refer to the French Decree of January 8, 1998[29] that specifies the limit levels of trace elements for agricultural recovery of sediments for Cadmium, Chrome, Copper, Mercury, Lead, Zinc, and Nickel… These limit values are summarized in Table 1.

3.5. Valorization of mud for environmental protection

3.5.1. Watertightness layer for a lagoon or landfill

Marcoen J.M. & al. (2000) [17] defined the main criteria of nature, permeability, and workability of the clay layer necessary to be used for waterproofing floors. It's about organic matter content, liquidity limit, plasticity index, and coefficient of permeability. The limit values in question are given in Table 1 below.

3.5.2. Soil amendment

The values not to be exceeded for the chemical elements present in the sediments according to the social use of the land (Children's play areas, Residential areas, Parks and leisure facilities, Industrial and commercial areas) were established by Delcour and Lefebvre in 2013[18]. These chemical elements are Arsenic, Lead, Cadmium, Cyanide, Chromium, Nickel, Mercury, Benzo[a]pyrene, and DDT (Table 1).

3.6. Valorization of mud in craftworks

3.6.1. Ceramic products and tiles

According to Guerraoui F. & al. (2008) [19], the ideal particle size composition of the soil and the recommended limits for adequate stabilization and obtaining finished products of acceptable quality are 40% clay or 70% sand (0.2-0.5mm) for tiles and Diameter (d)<50μmm2 for fine ceramic.

Regarding silica, alumina, magnesia, oxides, and other elements, the permissible limits for the use of clayey ceramic raw materials are given in table 1 (Jourdain A., 1966) [20].

3.6.2. Glass manufacturing

According to Olivier E. 1978[21], we can use mud as clay to make glass if it contains the elements SiO_2, Al_2O_3, MgO, CaO, Fe_2O_3, TiO_2, Na_2O, K_2O defines in Figures 1, 2 & 3.

3.7. Guide for valuing mud extracted from dam reservoirs in Morocco (Case study)

By referring to the laws and regulations adopted in Morocco, and using the optimal approach to valuing mud stored in dam reservoirs, we have established the guide for valuing mud stored by dams in Morocco. This guide in the form of its three components (the grid of tests to accomplish and limit values to observe, the matrix of the characteristics to study, and the flowchart of the procedure to follow) is presented below.

3.7.1. Grid of tests to perform and limit values to observe

In the absence of clear regulations dedicated to reusing sediments, several references were used during the development of this grid (standards, decree of law, guides, average values from a compilation of mud analyses, and scientific publications).

The grid that we have developed presents in an exhaustive way in its first 3 columns all the sectors, activities, and possible uses for the mud. In the other 3 columns, we have listed for each use the characteristics sought, the laboratory tests to be carried out, and the limit values not to be exceeded, extracted from the laws and regulations applied in Morocco.

The grid in question is presented in the following images.

Sector	Activity	Use	Characteristics	Wanted value	Test to be carried out
Civil engineering	Road works	Form layer	Granularity	maximum grain size Dmax< 50 mm	• Dry sieving after washing + sedimentometry
				passing 80 µm sieve of 35 % maximum	
			Clayey	2,5 < MBV < 8(g/100g)	• The methylene blue value test (MBV)
				12% < Ip < 40%	• The limits of Atterberg • The Casagrande cup • The roller method
			Water content	W(%)Fine soil conditions A1, A2, A3	• Steaming method
			Organic Matter Content	3% < OM < 10%	• Chemical method or Calcination method
	Concrete and mortars	Aggregates	Granularity	Passing 2 mm sieve: 100 %	• Dry sieving method after washing
				Passing 0,125 mm sieve: 85 to 100 %	
				Passing 0,063 mm sieve: 70 to 100 %	
			Mechanical characteristics	a water absorption coefficient < 1%	• Steaming method
				SiO_2< 4%	• X-ray diffraction • + Fluorescence X
			Chemical characteristics	total sulfur<0,1%	
				0,2%<Cl <1%	
	Bricks	Terracotta mixes	Clayey	10 % <Ip< 35%	• The limits of Atterberg • The Casagrande cup • The roller method
				15 % < Wp < 35%	• Plasticity limits • The roller method
			Mineralogical characteristics	35 %< SiO_2< 80 %	• X-ray diffraction • + Fluorescence X
				8 %< Al_2O_3<30 %	
				0,3 %< TiO_2< 2%	
				2% <Fe_2O_3<10%	
				0,5%<CaO<18 %	
				0<MgO<5%	
				0,1 %< Na_2O <1,5%	
				0,1%< K_2O <4,5 %	
				0<S <0,5 %	
				0< F <0,15 %	
			Levels of trace elements in (mg/kg)	Lead (Pb) <0,01	• ICP-OES and ICP-MS
				Mercury (Hg) <0,01	
				Chromium (Cr) <0,005	
				Cadmium (Cd) <0,01	
				Arsenic (As) <0,03	
				Tin <0,01	
	Portland cement	Raw of Clinker	Mineralogical characteristics	73% <$CaCO_3$< 78%	• X-ray diffraction • + Fluorescence X
				MgO< 5% (<3%)	
				Na_2O < 0.5%	
				K2O < 1%	
				SO_3< 2%	
				FeS_2<<2%	
			Granularity	Quartz (sand D> 80µm)-proscribed- 40% clay or 70% sand	• Dry sieving method after washing + sedimentometry
				Nodules of flint-proscribed-	
CraftWorks	Ceramic products	Roof tiles	Granularity	40% clay or 70% sand	• Dry sieving method after washing + sedimentometry
				0,2<d<0,5mm	
		Fine ceramic	Granularity	d <50µm	• Dry sieving method after washing + sedimentometry
		Clay mixture for ceramic + glass products	Mineralogical characteristics	35<SiO_2<85	• X-ray diffraction • + Fluorescence X
				9<Al_2O_3<45	
				0<MgO<5	
				0<Fe_2O_3<9	
				0.3<TiO_2<2	
				1<Na_2O + K_2O <5	
The environmental domain	Lagoon basins or landfills	Waterproofing layer	Granularity	Passing 2 µm sieve > 15% (clay fraction)	• Dry sieving method after washing + sedimentometry
				Passing 60 µm sieve > 30%	
				Refusal 10 mm sieve <10%	
				no element> 50 mm	
			Organic matter content	OM < 15 % with C/N< 20	• Chemical method or Calcination method
			Clayey	Wl< 80%	• The Casagrande cup
				10%<Ip<30%	• The limits of Atterberg • The Casagrande cup • The roller method
	Soil amendment	Children's play areas	Levels of trace elements in mg/kg of DM	Arsenic <25	• ICP-OES and ICP-MS
				Lead <200	
				Cadmium <10	
				Cyanide <30	
				Chromium <200	
				Nickel <70	
				Mercury <10	
				Aldrin<2	
				Benzo(a)pyrene< 2	• Fluorescence X
				Hexachlorobenzole< 4	
				DDT < 40	
				Hexacyclohexane<5	
				Pentachlorophenol<50	
				PCB6 = 0	
		Residential areas	Levels of trace elements in mg/kg of DM	Arsenic < 50	• ICP-OES and ICP-MS
				Lead <400	
				Cadmium <20	
				Cyanide <50	
				Chromium <400	
				Nickel <140	
				Mercury <20	
				Aldrine<4	
				Benzo(a)pyrene< 4	• Fluorescence X
				DDT <80	
				Hexachlorobenzole< 8	
				Hexacyclohexane<10	
				PCB6 < 1	

The environmental domain	Soil amendment	Parks and leisure facilities	Levels of trace elements in mg/kg of DM	Arsenic < 125	• ICP-OES and ICP-MS
				Lead < 1000	
				Cadmium < 50	
				Cyanide <50	
				Chromium <1000	
				Nickel <350	
				Mercury <50	
				Aldrine<10	
				Benzo(a)pyrene<10	• Fluorescence X
				DDT <200	
				Hexachlorobenzole<20	
				Hexacyclohexane<25	
				Pentachlorephénol<250	
				PCB6 <2	
		Industrial and commercial areas	Levels of trace elements in mg/kg of DM	Arsenic < 140	• ICP-OES and ICP-MS
				Lead <2000	
				Cadmium <60	
				Cyanide < 100	
				Chromium < 1000	
				Nickel < 900	
				Mercury <80	
				Aldrine<6	
				Benzo(a)pyrene<12	• Fluorescence X
				DDT = 0	
				Hexachlorobenzole<200	
				Hexacyclohexane<400	
				Pentachlorephénol<250	
Agriculture	Agricultural soil spreading	Spreading materials	Levels of trace elements in mg/kg of DM	Cadmium < 20	• ICP-OES and ICP-MS
				Chromium < 1000	
				Copper < 1000	
				Mercury < 10	
				Nickel < 200	
				Lead < 800	
				Zinc< 3000	
				Chromium + Copper + nickel + zinc < 4000	
			Content of organic trace compounds in mg/kg of DM	Total of the 7 main PCBs <0.8 mg/kgM	• Fluorescence X
				Fluoranthene< 5	
				Benzo(b)fluoranthene< 2.5	
				Benzo(a)pyrene2 < 2	

Figure 1 Tables of laboratory tests and limit values relating to the case of Morocco

3.7.2. Matrix of the characteristics to be studied

We present the matrix of characteristics to observe as follows:

Sector and Activity			Clayey	Granularity	Mineralogical characteristics	OM content	Water content	Mechanical characteristics	Chemical characteristics	Traces of metals	Organic compounds - traces
Civil Engineering	A1.1	Road works	X	X		X	X				
	A1.2	Concrete and mortar						X	X		
	A1.3	Bricks	X		X					X	
	A1.4	Cements		X	X						
Craft Works	A2.1	Tiles		X							
	A2.2	Fine ceramic		X							
	A2.3	Ceramic and glass			X						
Environment	A3.1	Lagoon basins and landfills	X	X		X					
	A3.2	Children's play areas								X	
	A3.3	Living areas								X	
	A3.4	Leisure parks								X	
	A3.5	Industrial zones								X	
Agriculture	A4.1	Soil spreading				X				X	X

Figure 2 Matrix of characteristics to observe

3.7.3. Procedural Flowchart

We abridge the process diagram in the following flowchart:

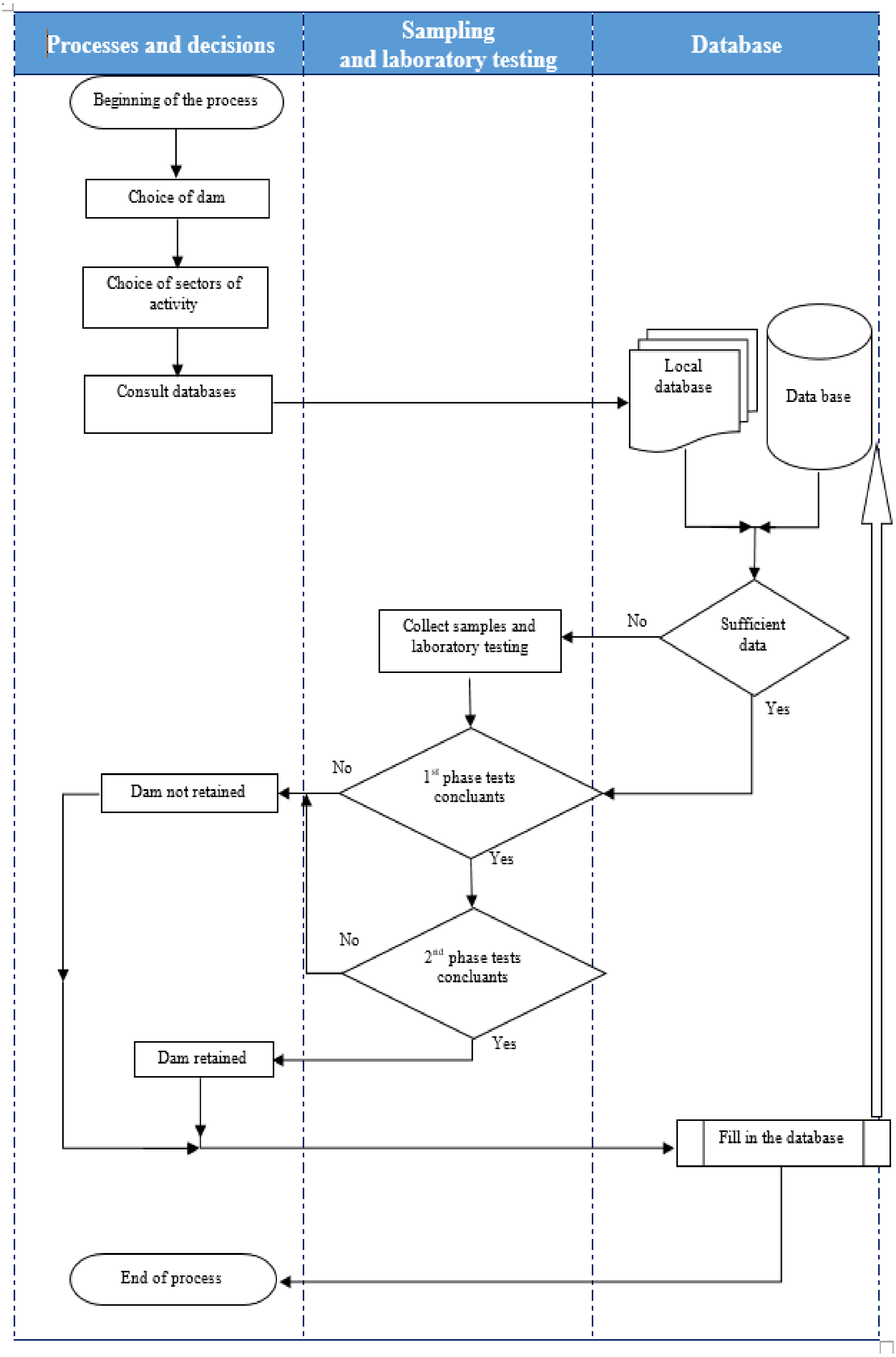

Figure 3 Flowchart of valuing mud process

4. Conclusion

The methodology proposed in this article provides an optimal framework that empowers dam managers to recover costs associated with desilting operations. It also challenges the perception of mud as an environmentally harmful material and a risk to populations, emphasizing its potential as a valuable resource for various industries.

Considering the particular context of Morocco, we intend to enrich the application of this approach through a comprehensive and detailed study following the guidelines outlined in this article. This study will focus on selected dams in Morocco, with mud samples collected for laboratory testing. The results obtained from these tests will provide valuable insights for future publications.

Moreover, our ongoing research involves a well-defined second-phase that aims to delve deeper into this optimal methodology. This phase involves the comprehensive definition and completion of databases, enhancing the overall effectiveness and applicability of the approach. The findings from this phase will be the subject of future articles, contributing to the advancement of mud valuation practices and expanding our knowledge in this field.

By implementing this methodology and continuing our research efforts, we strive to contribute to the sustainable management of dams, promote the beneficial utilization of mud, and advance the understanding of its potential applications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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