Annales de Chimie - Science des Matériaux
Vol. 45, No. 6, December, 2021, pp. 455-465
Journal homepage: http://iieta.org/journals/acsm

Behavior of Cementitious Materials under the Effect of an Eco-Cement Based on Dredged Sludge

Riad Ali Halassa[1*], Mekki Bibi[1], Mohamed-Aziz Chikouche[2]

[1] Laboratory of Development of Geomaterials, Faculty of Technology, Civil Engineering Department, Mohamed Boudiaf University, PO Box 166 Ichbilia, M'sila 28000, Algeria
[2] Laboratory of Materials and Mechanics of Structure, Faculty of Technology, Civil Engineering Department, Mohamed Boudiaf University, PO Box 166 Ichbilia, M'sila 28000, Algeria

Corresponding Author Email: alihalassa.riad@univ-msila.dz

https://doi.org/10.18280/acsm.450604

Received: 11 December 2021
Accepted: 23 December 2021

Keywords:
cementitious materials, dam, dredging sludge, hybrid binder, siltation, treatment

ABSTRACT

This paper attempts to simulate the use of green materials from the silt in a dam, and reduce the harmful impacts of siltation on Algerian dams affected by frequent droughts and irregular rainfalls, which are resulted from climate change. These harsh weather conditions are the main cause of water erosion in Algeria, leading to a high silting level in many dams across the country. Therefore, it is necessary to dredge the considerable volumes of sludge in the dam areas. This paper treats the sludge dredged from the K'sob dam, and adds the treated sludge into cement, creating a hybrid binder that can be used in composition of cementitious materials. Specifically, the sludge extracted from the K'sob dam was characterized chemically, physically, mineralogically, and mechanically, and introduced both as a substitute of cement and a component in the mixture of ordinary concrete/mortar. The sludge was firstly activated through calcination, and added to cement at the mass dosages of 10%, 15%, and 20% separately. The mechanical behavior, especially that under compression, of cementitious materials (concrete/mortar) based on the treated sludge was studied through lab tests. The test results show that this technical innovation gives the finished product three major properties, namely, high strength, economy, and a beneficial ecological impact. The results obtained are encouraging and promise an optimal exploitation of the sludge from similar dam areas.

1. INTRODUCTION

Dredging is a safe clearing technique to recover storage capacity. But the dredging operation remains very expensive and uneconomic, if a considerable volume of sludge is involved [1-3]. It is of high necessary to carry out this operation, when there are no suitable sites for the construction of new dams, or the dike is threatened by a strong sediment pressure. During each clearing operation, the problem of finding the site for discharging the dredged sludge arises. Generally, the sludge is thrown directly into the watercourse downstream of the dam, or transported to the nearest disposal area, without considering aesthetic or ecological issues. If the sludge is discharged to the downstream, the concentration of fine particles will rise in the watercourse, which harms flora and fauna. The farmers using downstream water are likely to complain about the high turbidity [4]. This is what happened right after the dredging operations of the Zardezas dam, Algeria in 1993.

Since environmental impacts are inevitable, it is important to assess and compare the benefits of dredging operations. A huge amount of sludge was disposed of in several Algerian dams, namely, the K'sob dam of M'sila in the Algerian East, but the disposal was proved destructive to the environment. In the case of this dam, considerable quantities of sludge were dumped into the wilderness at a rate of 0.3 million m^3/year, causing inevitable ecological damages [1, 5]. Downstream water users may complain about the water being disturbed by suspended particles. According to Semcha [6], particular attention is drawn to the disorders induced by the deposits and storage of fine particle materials. Take the dredging of the Fergoug dam in Algeria as an example. The deposit of sediments downstream of the dam caused an ecological catastrophe across the dam in the downstream. The National Agency for Dams and Transfers (ANBT), Algeria began a second dredge operation of the K'sob dam during 2015-2019, which extracted an additional 3 million m^3 of sludge. This operation, plus the first operation in 2006-2008, almost restored the initial holding capacity of the K'sob dam, about 29 million m^3. This volume of water is intended for the irrigation of 4,250 hectares of intensive crops and 2,000 hectares of cereals [7]. For the sake of economy and environmental protection, a potential research direction is to convert the sludge dredged from dams into construction materials.

Focusing on environmental problems, some Algerian scholars have tried to use the sludge dredged from dams, particularly the K'sob dam, as a cost-effective natural binder compared to Portland cement, the yield of which is subjected to production conditions in cement plants [8, 9]. Other researchers emphasized on the strength and durability after a portion of Portland cement is replaced with the sludge dredged from dams [10, 11].

Cement is the most expensive component of concrete. The production of cement consumes lots of energy. Each ton of cement is produced, releasing roughly the same amount of carbon dioxide into the air. By contrast, the calcination of the sludge only generates water vapor [12]. As a result, some researchers have partially replaced Portland cement in concrete with calcinated sludge [13, 14]. In the cement industry, the recent research of sludge vaporization mainly characterizes physical, chemical, mineralogical, and sustainability features. The research results demonstrate the possibility of using the sludge as an auxiliary cementitious material in civil engineering, particularly as a partial substitute for cement [15, 16].

Several researchers have studied the use of the sludge dredged from the K’sob dam as cementitious materials. For example, Chikouche et al. [17] heated the dredged sludge at 20°C/min, treated the dredged sludge at 600°C, modified cement with the treated sludge, and prepared mortars from the modified cement.

It was found that the mortars reached the highest compressive strength at an old age, indicating that the sludge treatment improves the strength of the mortar. Bibi et al. [18] added different amounts of calcinated clay into clinker materials, and made the following discoveries: the water intended for the hydration of the clinker minerals was absorbed by the additive clay; the consistency of the resulting compound cements increased with the amount of calcinated clay; the consistency and mechanical response (42-43MPa) of the compound cement with 10% of calcinated clay were the closest to Portland cement (44MPa). Chikouche [19] modified cement concrete with treated sludge, and learned that the modified concrete achieved an acceptable comprehensive strength, when the dosage of the treated sludge was 5% and 10%. However, the strength of the modified concrete was lower than that of CEM I concrete, because the treated sludge contains a low percentage of metakaolin, i.e., a limited amount of silica is supplied for the pozzolanic reaction. The same was observed in the ultrasonic study, for the voids/solid ratio of the reference concrete changed quickly, resulting in a good hydration effect.

This paper aims to achieve three goals: the ecological goal of minimizing the dredging sludge stored in nature, the technical goal of preparing mortar and concrete based on dredging sludge with interesting compressive strengths, and the economic goal of replacing much of the cement with treated dredging sludge.

For these purposes, the sludge extracted from the K’sob dam was characterized chemically, physically, mineralogically, and mechanically, and introduced as a construction material, both as a substitute of cement and a component in the mixture of ordinary concrete/mortar. The sludge was firstly activated through calcination, and added to cement at the mass dosages of 10%, 15%, and 20% separately. The mechanical behavior, especially that under compression, of cementitious materials (concrete/mortar) based on the treated sludge was studied through lab tests. Several notable results were obtained:

- The sludge could be activated at 600°C after being fully dehydroxylated through heat treatment. The dredged sludge contains essential raw minerals of common hydraulic binders.
- The setting time of the pastes was not strongly affected, as long as fewer than 20% of the cement was replaced by the sludge.
- The flexural and compressive strengths of all mortars increased steadily with age, and showed no decrease. Compared to the control mortar, the 28d flexural strength loss after the 20% of cement was substituted by calcined sludge did not surpass 7%; the 28d compressive strengths of the prepared concretes exceeded the normative value of 42.5MPa.
- The 28d compressive strengths of the prepared concretes were generally acceptable, and above the minimum characteristic value (21MPa) of the concrete on site. The mechanical strength of the concrete, of which 10% of cement was replaced by sludge, was much better than that of all sludge-based concretes. This concrete achieved a 90d compressive strength of up to 30MPa. The other concretes, with sludge contents of 15% and 20% also gave satisfactory results, exceeding that of the control concrete.

2. MATERIALS

2.1 Sludge

The sludge under investigation came from the K'sob dam, which was chosen because it is highly silted, pending a dredging operation. The dam is located in Hamman between the mountains of Kef El Ouerad and Djebel El Groun. It is 15 km north of the M'Sila Department on the national road towards the Bordj Bou Arreridj Department. The dam was constructed on the K'sob wadi between 1934 and 1940, allowing the of the agricultural perimeter of the M'Sila Department [20]. In the 1970s, a capacity of 50 million m^3 of water was intended for the irrigation of 13,000 hectares of agricultural land. However, the dam now only waters 4,840 hectares, due to its highly silted state (Figure 1) [21]. In fact, it is among the most silted dams in Algeria. The banks of the K’sob wadi, over a distance of 9 km, were washed away by erosion. The sludge from the dam results in the widening of the wadi bed from 20m to 150m [7].

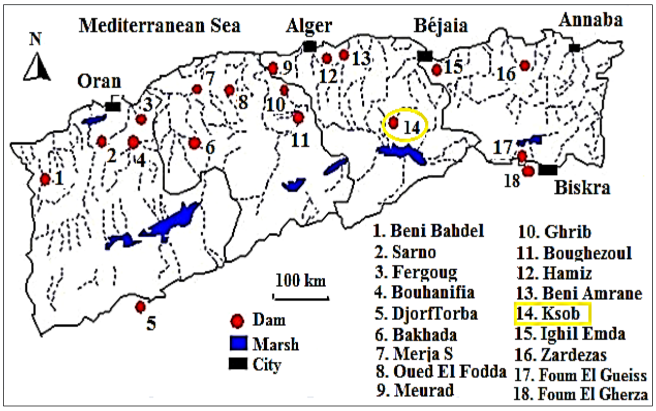


Figure 1. Geographical situation of the K’sob dam

Sludge samples were collected from the dredged sludge pumped downstream from settling ponds built on uncultivated land. The sites of these settling ponds, characterized by low slopes and low runoff velocities, represent a large surface area in the dam watershed. The low slopes promote settling, reduce the speed of water flow, control the dike height, and limit the structural size. The dredged sludge was stored in the ponds temporarily, before being transported to a disposal area away from the dam watershed. In total, six such ponds were planned for the K'sob dam. Three of them are already operational, and the remaining three are under construction. The closest pond is only 4 km from the dam.

The collected sludge was adequately prepared according to the following steps (Figure 2):

- The sludge was dried for 12h in an oven at 80°C.
- To facilitate grinding, the sludge was crushed.
- The crushed sludge was filtered by an 80µm sieve.
- The prepared sludge was calcinated as part of thermal treatment in an electric fixed bed oven called Nabertherm. The sample was heated up at the rate of 5°C/min to 600°C, and then kept constant for 5h. After the treatment, the sludge color changed from the natural greenish color to brick red color. The calcinated sludge was stored away from air and moisture.

Figure 2. Sludge preparation

2.2 Cement

The cement adopted for preparing concrete/mortar is CEM I 42.5N from the SIGUS cement plant located in the region of Oum El Bouaghi, Algerian East. It has a Blaine specific surface area (BSSA) of 4,356cm^2/g and a density of 3.10.

2.3 Aggregates

The calcareous aggregates adopted for preparing concrete come from the quarry of Ain Abid located in the region of Constantine, Algerian East. The main components are 0/3 sand with an absolute density of 2.66g/cm^3, as well as 3/8, 8/15 and 15/25 gravels, whose densities are 2.60, 2.61 and 2.64g/cm^3, respectively.

2.4 Formulations

Four mixtures of concrete and mortar were developed. Three of them contain different proportions of sludge (10%, 15% and 20%), and the fourth is the control sample (without sludge). The upper bound of sludge substitution rate was set to 20%. If the rate surpasses this bound, the water demand will rise due to the porosity of the sludge grains, and therefore the plasticity may reach the limit percentage, causing the cementitious materials to crumble and lose all their values. Tables 1 and 2 give the compositions of the different concretes and mortars, respectively.

The basic data used for our concrete formulations are inspired by the European standards EN 206-1 [22] and EN 13791 [23]. The desired consistency for a plastic concrete of current vibration, evaluated by reference to the cone slump between 6 and 9cm.

Table 1. Mortar formulations

	MS0	MS10	MS15	MS20
Sludge (%)	0	10	15	20
Cement (g)	450	400	382.5	360
Calcined Sludge (g)	0	45	67.5	90
Standardized sand (g)	1350	1350	1350	1350
Water (g)	225	225	225	225
W/ (C+S) (%)	0.5	0.5	0.5	0.5

Table 2. Concrete formulations

	CS0	CS10	CS15	CS20
Sludge (%)	0	10	15	20
Cement (g)	400	360	340	320
Calcined Sludge (g)	0	40	60	80
Sand (Kg/ m^3)	665	665	665	665
Gravel 3/8 (Kg/ m^3)	216	216	216	216
Gravel 8/15 (Kg/ m^3)	400	400	400	400
Gravel 15/25 (Kg/ m^3)	551	551	551	551
Water (Kg/ m^3)	205	210	214	219
W/ (C+S) (%)	0.513	0.525	0.535	0.547

3. METHODOLOGY

3.1 Sludge tests

Multiple tests were carried out to characterize both natural and calcinated sludge samples.

(1) Granulometric analysis

Granulometric analysis was carried out by sedimentation method according to the French-European standard NF EN ISO 17892-4 [24], aiming to determine the weight distribution of the particle size.

(2) X-ray diffractometry (XRD)

The XRD is an analysis technique based on the diffraction of X-rays by matters, particularly crystalline matters. It is a powerful technique to determine the positions of atoms in a crystal, provided that single crystals are available. With the aid of the XRD, one can distinguish products with the same chemical composition but with different atomic arrangements at the microscopic scale. As a physicochemical analysis tool, the XRD enables the determination of the nature of each crystalline phase within a sample, and the tracing of the system structure (lattice parameters, atomic positions). The quantitative result of the XRD is about the arrangement of the elements of a material, and the qualitative result is about the different crystalline compounds of a material and their crystallographic forms.

(3) X-ray fluorescence spectrometry (XRF)

The XRF is an elemental analysis technique revealing the atoms making up the sample and their proportions. However, it does not reflect the organization of these atoms or their chemical form. This global elemental analysis technique makes it possible to identify and determine most of the chemical elements making up the sample.

(4) Loss of ignition test

The loss of ignition was determined by the European standard EN 196-2 [25]. The density of solid grains of each sludge sample was determined according to the French-European standard NF EN ISO 17892-3 [26]. The BSSA of each sample was measured against EN 196-6 [27], using the air permeability method (Blaine method).

(5) Soil classification

Atterberg limits are geotechnical parameters intended to identify a soil and to characterize its state by its consistency index. The soil classification of the sludge samples was based on the French-European standard NF EN ISO 17892-12 [28].

3.2 Paste tests

The start and end times, as well as the duration of the setting of pastes were determined according to the European standard EN 196-3+A1 [29]. Table 3 lists the proportions of cement, sludge and water used to prepare the pastes.

Table 3. Mix ratios of the cement paste

	PS0	PS10	PS15	PS20
Sludge (%)	0	10	15	20
Cement (g)	500	450	425	400
Calcined Sludge (g)	0	50	75	100
Water (ml)	130 131	140 138	136 142	144 147 149
Test N°	1 2	3 4	5 6	7 8 9

3.3 Mortar tests

In accordance with European standard EN 196-1: 2016 [30], the mortar tests were conducted on standardized mortars of the formulations in Table 1. Both 4×4×16cm samples of control and sludge-based mortars (10, 15 and 20%) were subjected to flexural and then compression tests at 2, 7 and 28 days.

Considering the action power of calcined sludge, the strength activity index was determined through mechanical compression tests on mortar samples of $40 \times 40 \times 160 mm^3$. The index can be calculated by the ratio (SAI=A/B 100) between the compressive strength of a mortar with p% added sludge (A) and the compressive strength of a control mortar with 100% cement (B) at the same age.

3.4 Concrete tests

The slump concretes were found to be in line with the European standard EN 12350-2 [31], as well as that required by the concrete formulation (6 to 9cm) indicated above.

Hardened concrete was subjected to destructive and non-destructive tests. Cylindrical samples, with a diameter of 16cm and a height of 32cm, are tested at 7, 14, 28, 60 and 90 days, respectively. The concrete formulation is specified in Table 1.

The concrete was casted in cylindrical metal molds. A total of 120 samples were prepared for crushing tests at different ages (7, 14, 28, 60 and 90 days). Each mix consists of six samples (0, 10, 15 and 20% sludge), which were all stored in water at 20°C. The samples were clamped using a 25mm diameter-vibrating needle. The frequency depends on the value of the Abrams cone drop and the angularity of the aggregates.

According to NF EN 12504-4, a sonic auscultation test was carried out on each sample [32]. During the test, the direct transmission method was employed to ensure that the direction of measurement of the transit time is perpendicular to the direction of the preparation. This test was implemented to measure the propagation time of ultrasonic waves between two points in the concrete. The ultrasonic velocity V (m/s) can be derived from the transmitter-receiver distance L (sample length), and the propagation time T (µs) of ultrasonic waves in the concrete:

$$\mathrm{V} = \frac{L}{T}$$

The obtained ultrasonic velocity is the mean of the measurements on the area of the sample. It allows empirical formulas to determine the presumed strength Scu (MPa) of the concrete as a function of the dynamic modulus of elasticity, E_d [33]:

$$\mathrm{S_{cu}} = 16.7 \times \frac{\mathrm{E_d}}{\mathrm{exp.\,122500}}$$

where, E_d can be calculated by:

$$\mathrm{E_d} = \mathrm{V}^2 \times \frac{\gamma}{\mathrm{g}} \times \frac{(1+\mu_\mathrm{d})(1-2\,\mu_\mathrm{d})}{(1-\mu\mathrm{d})}$$

where, μ_d is the dynamic Poisson coefficient (0.25 for young concrete; 0.20 for concrete older than 28 days); γ (kg/m^3) is the bulk density of the concrete (the mean of all samples whose volume was measured and weighted on an electronic balance); g (m/s^2) is the acceleration of gravity.

Then, the rebound hardness tests (sclerometer) were carried out by NF EN 12504-2 [34] on all the samples. Finally, destructive tests were performed by crushing the surfaced sample according to NF EN 12390-3 [35].

4. RESULTS AND DISCUSSIONS

4.1 Sludge test results

4.1.1 Physical and geotechnical results

The physical and geotechnical properties of the prepared samples are shown in Table 4.

Table 4. Physical and geotechnical properties of the dredging sludge of the K'sob dam

	Sieved natural sludge	Calcined sludge
ρ_s (g/cm^3)	2.65	2.67
ω (%)	60	50
W_L (%)	39.11	37.28
W_P (%)	20.44	19.11
I_P (%)	18.67	18.17
Elements by Weight < 80 µm. (%)	98	89

The samples were denominated according to the L.C.P.C classification [36]. More than 50% of the elements by weight were less than 80µm. The granulometric curves (Figures 3 and 4) show that the sludge of the K'sob dam is a fine soil.

Fine soils are usually classified with the plasticity criteria linked to the Atterberg limits. By this criterion, the sludge dredged from the K'sob dam is clay soil, which features a water-dependent plasticity, and a liquidity limit of the water content equivalent to 25 strokes of the Atterberg test [37]. The volume weight of the solid grains of the sludge varied from 2.65 to 2.67g/cm^3. Besides, the sludge is mainly composed of soil phases like silica and alumina. These simple elements have very similar atomic masses. Hence, the volume weight of the sludge evolved within a very narrow range. Organic and metalliferous soils are exceptions to this phenomenon: soils are metalliferous above 2.7g/cm^3 [37]. The above results confirm that the sludge contains a certain level of organic matter. Finally, the BSSA was 6,664cm^2/g for natural sludge, and 7,879cm^2/g for calcined sludge.

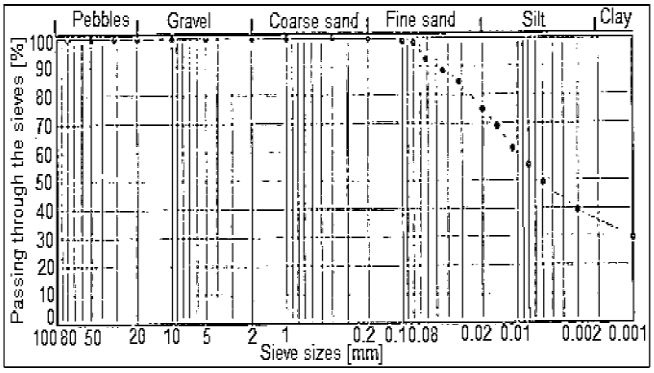


Figure 3. Granulometric curve of sieved natural sludge

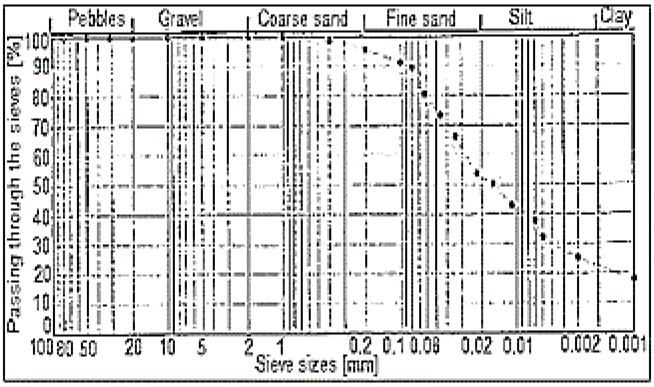


Figure 4. Granulometric curve of calcined sludge

4.1.2 Mineralogical results

Table 5 reports the results of the mineralogical analyses of the prepared dredging sludge from the K'sob dam.

As shown in Table 5, the two samples are mainly composed of quartz, calcite, illite and muscovite. Three types of phyllosilicates coexist in the dredged sludge. The top component is illite and muscovite (around 50%), followed by kaolinite. Quartz is the main element of the silt and clay fractions. According to Chikouche [19, 20] and Bibi et al. [18], sludge can be activated after being heated up at different rates to more than 550°C, and the dihydroxylation would be fairly complete at 600°C.

Table 5. Mineralogical composition of the dredging sludge from the K'sob dam

Oxides	Mineralogical composition (%)	
	Sieved natural sludge	Calcined sludge
Quartz	16.2	18
Calcite	21.2	15
Kaolinite	6.1	/
Illite	26.3	32
Muscovite	24.2	28
Amesite	3	/
Merlinoite	1	4
Gobbinsite	1	/
Albite	1	3

4.1.3 Chemical results

The chemical analyses intend to quantify the composition of the oxide sludge, and confirm the results of the mineralogical analysis. The analysis results are presented in Table 6.

Table 6. Results of the chemical analysis of the dredged sludge of the K'sob dam

Chemical composition (%)			
Oxides	Chemical formula	Sieved naturel sludge	Calcined sludge
Silica	SiO_2	37.67	39.54
Alumina	Al_2O_3	9.71	9.96
Iron oxide	Fe_2O_3	3.80	4.09
Lime	CaO	20.83	22.77
Magnesia	MgO	3.60	4.00
Sulfur trioxide	SO_3	0.07	0.09
Potassium oxide	K_2O	1.24	1.31
Sodium oxide	Na_2O	0.37	0.40
Chloride	Cl	0.010	0.011
Loss On Ignition	LOI	22.12	15.05
Sulfate	SO_4^{2-}	None	None

Note that the heat treatment changed the chemical composition of the sludge: more silica and free lime were recorded, with a significant decrease in the loss on ignition. Silica and alumina account for a great portion of sludge. The presence of the two oxides confirms the mineralogical results of the sludge, and the existence of kaolinite and illite, two clayey minerals composed mainly of alumina and silica leaflets. The percentage of the loss on ignition was remarkable, justified by the content of organic matter from 22.12 to 15.05%, and the percentage of lime from 20.83 to 22.77%. The thermal activation of the sludge allows the mineral structures, which are in a naturally stable state, to transform into amorphous structures through the rearrangement of the hydroxide structure. It also allows clay minerals to react with water, forming compounds that harden at ordinary temperatures. To reach the target temperature, the processing speed needs to be adjusted to improve the chemical activity of alumina and silica.

4.2 Paste test results

4.2.1 Consistency

Table 7 reports the results of the consistency tests on the cement pastes.

Table 7. Consistency measurements

Paste	Test N°	Water (ml)	W/ (C+S) (%)	d (mm)
PS0	1	130	0.26	9*
PS0	2	131	0.262	7
PS10	3	140	0.28	3.5*
PS10	4	138	0.276	7
PS15	5	136	0.272	12*
PS15	6	142	0.284	8
PS20	7	144	0.288	15*
PS20	8	147	0.294	9*
PS20	9	149	0.298	8

(*) failed test

For sinks of d > 8mm, there is insufficient water; For d<4mm: there is too much water. In both cases, the dough in question was discarded, while the equipment was cleaned and dried, and restarted with a new volume of water. This process was repeated until obtaining the values whose dough is of normal consistency.

As shown in Table 7, replacing 10-20% of the cement by the calcined dredging sludge increased the amount of water needed to obtain a normal consistency of the binder. This is due to the large specific surface presented by the mixture (cement-calcined sludge). Thus, a strong appeal to water molecules is noted in order to wet the entire surface.

Table 8 presents the BSSA results of the mixtures (cement-sludge), which highlight the probability of the large specific surface area of the mixture, and its influence on the water content.

Table 8. BSSA of mixtures cement-calcined sludge (cm^2/g)

Cement + 10% sludge	Cement + 15% sludge	Cement + 20% sludge
5058	5509	5776

4.2.2 Setting time

Figure 5 records the start and end times of the setting of different cement pastes.

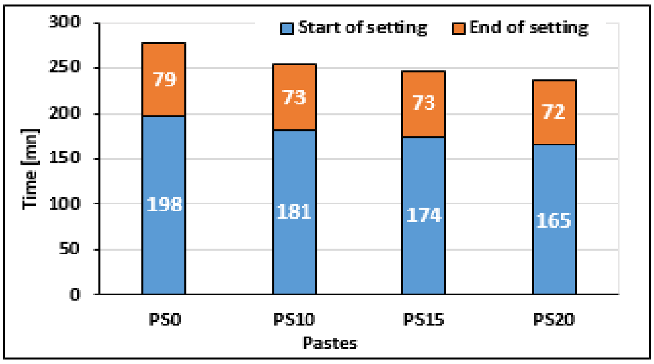


Figure 5. Influence of the sludge content on the setting time of the different mixtures of the pastes

As shown in Figure 5, the setting time (start and end of setting) decreased slightly, as the sludge-cement ratio increased. This is because the substitution of cement by sludge affects cement minerals, especially C_3S and C_2S, which are responsible for the precipitation of the calcium silicate hydrate (CSH) gel as well as the start of setting. The decrease in setting time was proportional to the increase in fineness of the cement-sludge mixture (Table 8). This means the hydration kinetics of the binder picks up speed as the fineness increases. When up to 20% of cement was replaced by sludge, the setting time of the pastes was not significantly affected. This highlights the importance of valorizing and using this dredged sludge as a setting accelerator of concrete in cold weather.

4.3 Mortar test results

4.3.1 Flexural strength

Table 9 displays the flexural strengths (MPa) of the MS0 control mortars as a function of time.

Table 9. Flexural strength of the MS0 control mortar (MPa)

at 2 days	at 7 days	at 28 days
$4.52^{\pm0.04}$	$6.76^{\pm0.05}$	$7.80^{\pm0.06}$

For clarity, Figure 6 compares the strengths of the sludge-based mortars with those of the control mortar (0% sludge) at different ages. For the mortars with 10, 15 and 20% cement replaced by calcined sludge, the strengths evolved similarly as those of the control mortar. Compared to the control mortar, the flexural strengths of all mortars increased steadily with age and showed no decrease. At 28 days, the loss of strength did not exceed 7% at the substitution rate of 20%, compared to the control mortar. This MS20 mortar became noticeable in strength, and was likely to surpass the strength of the control mortar after 28 days. Note that the mortar test aims to characterize the materials and judge their quality for use.

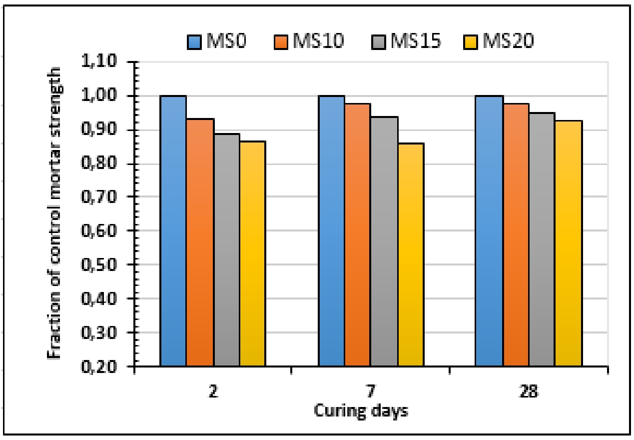


Figure 6. Evolution of the flexural strengths fraction of sludge-based mortars compared to control mortar (MS0)

4.3.2 Compressive strength

Table 10 present the compressive strengths (MPa) of the mortars as a function of time.

Table 10. Compressive strengths of mortars (MPa)

Age	MS0	MS10	MS15	MS20
at 2 days	$22.65^{\pm0.18}$	$18.09^{\pm0.18}$	$17.25^{\pm0.13}$	$15.25^{\pm0.06}$
at 7 days	$48.96^{\pm0.39}$	$40.72^{\pm0.42}$	$39.91^{\pm0.29}$	$35.23^{\pm0.15}$
at 28 days	$63.98^{\pm0.51}$	$53.76^{\pm0.55}$	$51.88^{\pm0.38}$	$47.36^{\pm0.20}$

The compressive strengths of all mortars increased steadily with age, showing no decrease. The compressive strengths were low in the short term (2 and 7 days), but surpassed the requirement of EN 197-1 [38], which recommends a nominal 28d compressive strength of mortars ≥ 42.5MPa.

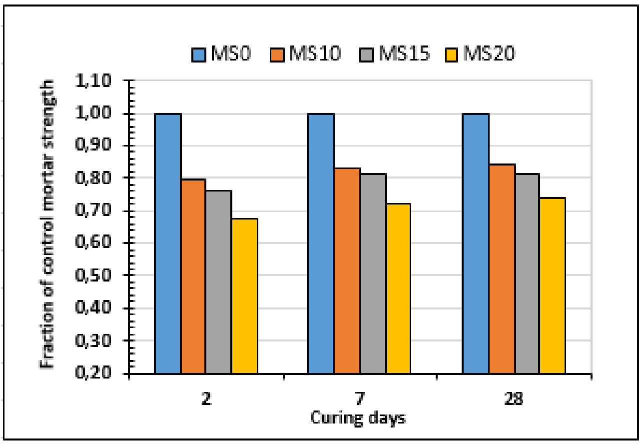


Figure 7. Evolution of the compressive strengths fraction of sludge-based mortars compared to control mortar (MS0)

Figure 7 compares the compressive strengths of sludge-based mortars with those of control mortar (0% sludge) at different ages.

As shown in Figure 7, the compressive strengths of the mortars decreased with the growing substitution rate. The mortars with sludge contents of 15 and 20% were likely to loss 19% of strength at 7 days, and between 26% and 28% at 28 days, compared to the control mortar. During the first days, the strength evolved less rapidly for mortars with calcined sludge. Thus, the hydration speed was smaller than that of the Portland cements. This decrease in compressive strength is due to the substitution of cement with dredging sludge. Another reason is the lack of reactive silica. Among the detected phyllosilicates (illite, muscovite and kaolinite), only a very low percentage (6%) kaolinite is transformed into metakaolinite, inhibiting the feeding of new cements to the mortars with new dissolution sites in the solution. As a result, the silicates in solution interact with the portlandite to form silico-hydrated aluminates, and the alumina even interact to produce hydrated calcium aluminates called CASH.

As shown in Table 11, the strength activity was not poor. The 28d strength activity indexes of the three mortar mixes (10, 15 and 20% of cement replaced by sludge) varied from 74 to 84%. Several standards, including ASTM C618 [39], agree that a material is active when the index is above 75% at 28 days.

Table 11. Compressive strength of mortars (MPa) and strength activity index at 28 days

	MS0	MS10	MS15	MS20
CS	63.98	53.76	51.88	47.36
SAI		0.84	0.81	0.74

4.4 Concrete test results

4.4.1 Slump test

Table 12 presents the results of the concrete slump test, which attempts to verify the consistency of the concrete with the workability determined in the plastic concrete with a cone slump of 6 to 9cm.

To achieve the desired consistency of plastic concrete (6 to 9cm), it is necessary to add mixing water at different volumes in relation to the percentage of calcined sludge replacing the cement. Thanks to its absorption power, the treated sludge in the various mixtures diverts part of the water intended for the hydration of the cement. This part of water does not contribute to fluidity, which affects the handling of concrete and hydration reactions.

Table 12. Slump as a function of mixing water volume and calcined sludge percentage for ordinary concrete

Concrete	Water volume (kg/m^3)	slump (cm)
CS0	205	6
CS10	205	4*
CS10	210	8
CS15	205	3.5*
CS15	214	7.5
CS20	205	2.5*
CS20	219	7.5

(*) failed test

4.4.2 Results of destructive and non-destructive tests

Table 13 displays the mean values of the design parameters of the compressive strength of the samples at different ages. These parameters were measured in the destructive and non-destructive tests. The specific parameters are introduced below:

- **W:** weight sample; **γ**: bulk density of concrete; **V**: ultrasonic velocity; **E_d**: dynamic modulus of elasticity given by formula (3); **I**: sclerometric index.

Note that:

- The propagation velocity of the ultrasonic wave in concrete depends on the modulus of elasticity and density of the concrete.
- The sonic velocity evolves in relation to the dynamic modulus of elasticity and the compressive strength. This relationship is the logical basis for estimating the compressive strength of concrete based on wave velocity measurements.
- Ultrasonic wave velocities through concrete are resulted from the time for the waves to pass through the hardened binder paste (cement and silt) and aggregates.

Table 13. Mean values of the design parameters of the compressive strengths of the samples

Age	Concrete	Calculation parameters	
		W (Kg)	γ (Kg/dm^3)
at 7 days	CS0	15.08	2.34
	CS10	14.84	2.31
	CS15	15.08	2.34
	CS20	15.03	2.33
at 14 days	CS0	15.31	2.38
	CS10	15.17	2.36
	CS15	14.93	2.32
	CS20	15.18	2.36
at 28 days	CS0	15.47	2.40
	CS10	15.11	2.35
	CS15	15.04	2.33
	CS20	14.94	2.32
at 60 days	CS0	15.16	2.35
	CS10	15.11	2.35
	CS15	15.13	2.35
	CS20	15.10	2.35
at 90 days	CS0	15.31	2.38
	CS10	15.21	2.36
	CS15	15.29	2.37
	CS20	15.15	2.35

Table 13. Mean values of the design parameters of the compressive strengths of the samples (to be continued)

Age	Concrete	Calculation parameters		
		V (Km/s)	Ed (Kg/cm^2)	I
at 7 days	CS0	4.42	389 411.93	27
	CS10	4.28	359 377.27	26
	CS15	4.21	352 881.43	26
	CS20	4.13	339 080.19	25
at 14 days	CS0	4.62	430 862.74	29
	CS10	4.42	391 323.17	27
	CS15	4.41	383 039.61	27
	CS20	4.28	366 831.86	26
at 28 days	CS0	4.78	464 804.81	31
	CS10	4.48	400 069.09	29
	CS15	4.54	409 360.41	28
	CS20	4.44	388 938.25	28
at 60 days	CS0	4.86	508 556.29	32
	CS10	4.42	420 044.47	30
	CS15	4.50	436 983.10	29
	CS20	4.54	443 630.19	30
at 90 days	CS0	4.86	515 138.44	33
	CS10	4.62	463 453.90	31
	CS15	4.63	467 659.98	31
	CS20	4.69	474 973.87	32

As shown in Table 13, the concrete densities generally decreased with the growth of sludge percentage, as compared to the control concrete. The possible reason lies in the slightly expansive character of the particles, which swell compacting the cement particles, causing an increase in volume. Bibi et al. [18] reached the same conclusions (the particles have a slightly expansive character), when they studied on muddy clay and sandstone clay from the M'sila region.

It can also be seen from Table 13 that the velocity of ultrasonic waves passing through the concrete increased with the age of all types of concrete. The velocity at 7 and 14 days of curing decreased with the growing percentage of treated sludge in all types of concrete. CS10 and CS15 concretes witnessed a slight decrease in velocity at 60 days, and a rapid increase at 90 days. This phenomenon can be explained by the following fact: During the curing process, the concrete structure becomes denser due to the hydration reaction.

For CS10 concrete, the rapid growth of ultrasonic velocities during the first days is resulted from the pore filling by hydration products and the change in the empty/solid ratio. Meanwhile, the concretes based on cement and dredging sludge mixing binder (CS10, CS15, CS20) develop in the first days another property to compensate for the loss of production of the hydrate: the filler effect of dredging sludge [19].

Therefore, it can be concluded that the velocity of wave propagation may depend on changes in the behaviour of the hardened binder paste. In CEM I cement, the proximity between cement particles facilitates hydration, and speeds up void reduction. In cements mixed with dredged sediments (sludge), the particles are farther apart, requiring the hydration products must fill more pores. In other words, these cements tend to have a high void-to-solid ratio. The voids are responsible for the faster movement of the waves. Therefore, the reduction in ultrasonic velocities is proportional to the substitution rate.

The sclerometric index I sheds light on the hardness of the concrete surface. The rebound height of a mass projected at a certain speed on the surface of the concrete raises the strength on the surface of the concrete. The higher the hardness, the stronger the concrete. The hardness values recorded for the different concrete mixtures were close in each curing period.

Table 14. Mean compressive strengths of concretes (MPa)

	CS0			CS10		
	Scc	**Scu**	**Scs**	**Scc**	**Scu**	**Scs**
at 7 days	18.30	19.53	22.84	17.75	18.02	21.13
at 14 days	21.30	21.62	26.13	19.90	19.63	23.63
at 28 days	25.90	23.37	29.71	22.70	20.06	26.28
at 60 days	28.55	25.66	31.56	23.15	21.07	28.12
at 90 days	30.10	25.84	34.03	26.40	23.24	31.01

1. Scc: crush compressive Strength; 2. Scu: ultrasonic compressive Strength; 3. Scs: sclerometer compressive Strength.

Table 14. Mean compressive strengths of concretes (MPa) (to be continued)

	CS15			CS20		
	Scc	**Scu**	**Scs**	**Scc**	**Scu**	**Scs**
at 7 days	17.10	17.70	20.95	15.15	17.01	19.79
at 14 days	19.60	19.21	22.50	17.80	18.40	21.67
at 28 days	21.13	20.47	25.48	19.20	19.51	23.92
at 60 days	22.84	21.93	27.19	22.70	22.25	28.57
at 90 days	25.20	23.45	30.25	24.98	23.82	32.00

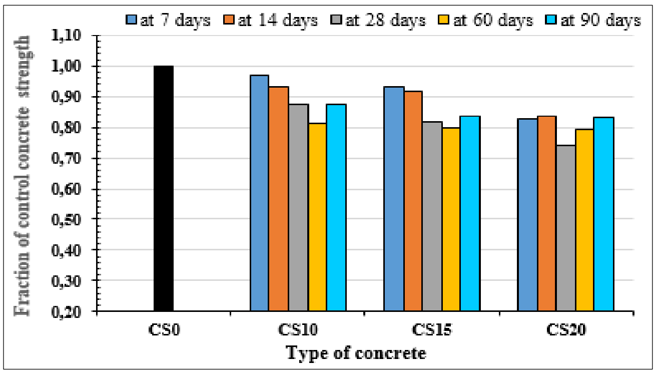
1. Scc: crush compressive Strength; 2. Scu: ultrasonic compressive Strength; 3. Scs: sclerometer compressive Strength.

Table 14 displays the mean compressive strengths measured by compressive test, ultrasound test, and sclerometer test.

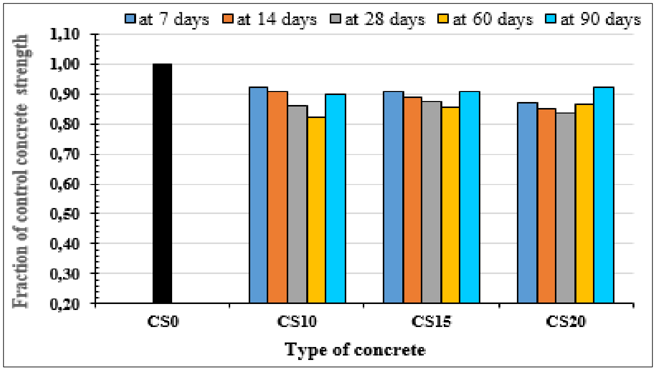
As shown in Table 14, the mechanical strengths of all concretes subjected to destructive and non-destructive testing increased steadily with the age, without any decline. The 28d compressive strengths are generally acceptable, all of which were above the minimum characteristic value (21MPa) of the concrete on site [22].

At 90 days, the control concrete achieved a good compressive performance as an ordinary concrete: its compressive strength never fell below 25MPa. In some cases, the strength even exceeded 30MPa. The mechanical strength of the concrete with a 10% substitution rate was obviously the best of all sludge-based concretes. This concrete achieved a compressive strength of up to 30MPa at 90 days. The other concretes with sludge contents of 15, and 20% also gave satisfactory results.

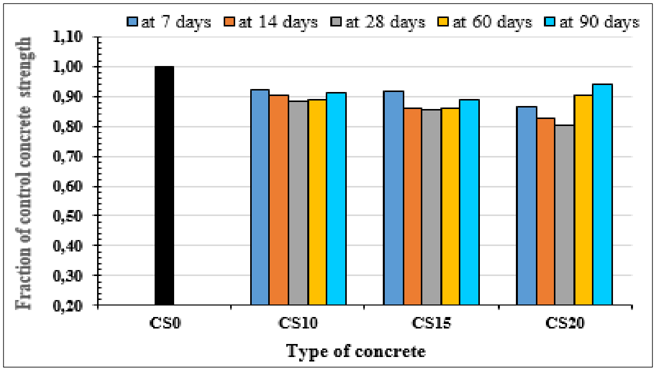
To better display the evolution of the compressive strength, the strengths of sludge-based concretes were compared with those of control concretes (0% sludge) at different ages (Figure 8).



(a) Crush test



(b) Ultrasonic test



(c) Sclerometer test

Figure 8. Evolution of the compressive strength of sludge-based concrete compared to control concrete CS0

Indeed, the concretes with 15 and 20% sludge contents achieved mean mechanical performances respectively higher than 92 and 86% at 7 days, and higher than 89 and 84% at 14 days, compared to the control concrete. It was also noted that the strength generally developed less rapidly for calcinated sludge-based concretes in the early days, which means that hydration is slower in these concretes than in Portland cements.

The effect of the sludge became noticeable beyond 28 days for CS20, and 60 days for CS10 and CS15, as the strengths of the calcined sludge concretes approached the strength of the control concrete. At 90 days, the CS20 concretes achieved the strengths of approximately 90% compared to the control concrete. If the curing age surpasses 90 days, it is very likely that the strength of the prepared concretes will exceed that of the control concrete. More research is needed to confirm this expectation.

The above compressive strength development can be explained by power of action of the calcined sludge, as well as the following fact: the hydraulic properties are only sensitive at the most advanced ages; then, it is easy to fix the lime released by cement hydration, forming new hydrated calcium silicates that contribute to the compressive strength. These hydraulic properties consist of the creation of stable hydrated compounds that are not very soluble in water, with a strong adhesion to each other and to the aggregates. These compounds progressively increase the cohesion of mortar and concrete pastes. In addition, the particles of calcined sludge, which are finer than cement particles, promote the hydration of cement and sludge, mainly through a physical process, and produce a cement-area matrix with a dense structure.

5. CONCLUSIONS

The following conclusions can be drawn from the above results on the behavior of cementitious materials under the effect of the proposed eco-cement based on dredging sediment:

(1) The incorporation of treated sludge increases the demand for water, ensuring the normal consistency of the paste.

(2) Adding the calcined sludge to the mixture of concrete accelerates the setting, facilitating the concreting in cold weather.

(3) The flexural strengths of MS20 mortars (20% calcined sludge) at 28 days were noticeable, as they approached the strengths of the control mortar. The substitution of cement by calcined sludge can be used to produce fragile elements. The compressive strengths of the mortars at 28 days and with 10, 15 and 20% calcined sludge exceeded the requirement of the current standards.

(4) During hydration, the calcined sludge reacted well with the cement, and achieved certain mechanical performances in the concrete and mortar. Hence, the sludge is a reactive material and not an inert material, especially as its strength activity index surpassed 75% at 28 days.

(5) No remarkable changes in the mechanical strengths of concrete samples with 10 and 15% of calcined sludge were observed through destructive and non-destructive testing. Meanwhile, the compressive strengths increased in the medium term for the concrete with 20% calcined sludge, exceeding 83% of the control concrete. The long-term performance of the prepared concretes is promising.

This research makes it possible to obtain cementitious materials (concrete/mortar) at a lower cost, providing a solution to the high cost of cement and the storage of dredged sludge. Thus, the research results contribute to ecological and economic development. In the field of construction, the proposed hybrid cement-based binder and dredging sludge can be used to produce concrete for structural elements with moderate loads, as well as self-lacing concrete and masonry elements, decorations, and coating. In addition, the proposed material can be used in masonry and cladding as a bonding element for sealing, or coating.

REFERENCES

[1] Remini, B., Hallouche, W. (2004). Le dragage des retenues de barrages : Quelques exemples algériens. La Houille Blanche, International Water Journal, 90(5): 95-100. https://doi.org/10.1051/lhb:200405012

[2] Bianchini, A., Cento, F., Guzzini, A., Pellegrinia, M., Saccani, C. (2019). Sediment management in coastal infrastructures: Techno-economic and environmental impact assessment of alternative technologies to dredging. Journal of Environmental Management, 248: 109332. https://doi.org/10.1016/j.jenvman.2019.109332

[3] Hammadi, L., Ponton, A., Belhadri, M. (2011). Rheological study and valorization of waste sludge from wastewater treatment plants in the dredging operation of hydraulic dams. Energy Procedia, 6: 302-309. https://doi.org/10.1016/j.egypro.2011.05.034

[4] Remini, B. (2006). Valorisation de la vase des barrages quelques exemples algériens. LARHYSS Journal, 5: 75-89. https://archimer.ifremer.fr/doc/00000/1040/, accessed on Nov. 19, 2021.

[5] Belas, N., Belaribi, O., Mebrouki, A., Bouhamou, N. (2011). Valorisation des sédiments de dragage dans les bétons. Proceedings of the II International Seminar on innovation and valorization in civil engineering and construction materials, INVACO2: Rabat, Morocco. https://www.asmatec.org/index.php/, accessed on Nov. 19, 2021.

[6] Semcha, A. (2006). Valorisation des sédiments de dragage : Applications dans le BTP, cas du barrage de Fergoug. Ph.D. dissertation. Université de Reims, Champagne-Ardenne, France. http: //theses.univ-reims.fr/exl-doc/GED00000521.pdf/, accessed on Nov. 19, 2021.

[7] Algerian National Agency for Dams and Transfers, ANBT [on-line]. Appropriate technology, water saving, surface planning, basin management. https://www.soudoud-dzair.com/, accessed on Jan. 8, 2021.

[8] Benamara, L., Ouhba, K., Hamwi, A. (2013). Elaboration d'une pouzzolane de synthèse à partir des sédiments de barrage. Environnement & Technique Journal, 330(5): 40-44. https://doi.org/10.4267/dechets-sciences-techniques.1144

[9] Aouad, G., Laboudigue, A., Gineys, N., Abriak, N.E. (2012). Dredged sediments used as novel supply of raw material to produce Portland cement clinker. Cement and Concrete Composites, 34: 788-793. http://dx.doi.org/10.1016/j.cemconcomp.2012.02.008

[10] BelHadj Ali, I., Lafhaj, Z., Bouassida, M., Said, I. (2014). Characterization of Tunisian marine sediments in Rades and Gabes harbors. International Journal of Sediment Research, 29(3): 391-401.

https://doi.org/10.1016/S1001-6279 (14)60053-6

[11] Frar, I., Belmokhtar, N., El Ayadi, H., Ammari, M., Ben Allal, L. (2017). Valorization of port dredged sediments in cement mortars. Journal of Materials and Environmental Sciences, 8(9): 3347-3352. http://www.jmaterenvironsci.com.

[12] Safer, O., Belas, N., Belaribi, O., Belguesmia, K., Bouhamou, N., Mebrouki, A. (2018). Valorization of dredged sediments as a component of vibrated concrete: Durability of these concretes against sulfuric acid attack. International Journal of Concrete Structures and Materials, 12(1): 44. https://doi.org/10.1186/s40069-018-0270-7

[13] Bates, M., Fox-Lent, C., Seymour, L., Wender, B.A., Linkov, I. (2015). Life cycle assessment for dredged sediment placement strategies. Science of the Total Environment, 511: 309-318. http://dx.doi.org/10.1016/j.scitotenv.2014.11.003

[14] Couvidat, J., Chatain, V., Bouzahzah, H., Benzaazoua, M. (2018). Characterization of how contaminants arise in a dredged marine sediment and analysis of the effect of natural weathering. Science of the Total Environment, 624: 323-332. http://dx.doi.org/10.1016/j.scitotenv.2017.12.130

[15] Djafari, D., Semcha, A., Zentar, R., Mekerta, B., Touzi, A., Hannache, H., Elharti, M., Zarrouk, A. (2017). Characterization and valorization of sludge of wastewater treatment plant (WWTPs) into cement industry. Journal of Materials and Environmental Sciences, 8(4): 1350-1358.

[16] Amar, M., Benzerzour, M., El Mahdi Safhi, A., Abriak, N. (2018). Durability of a cementitious matrix based on treated sediments. Case Studies in Construction Materials, 8: 258-276. https://doi.org/10.1016/j.cscm.2018.01.007

[17] Chikouche, M.A. Ghorbel, E. Bibi, M. (2016). The possibility of using dredging sludge in manufacturing cements: Optimization of heat treatment cycle and ratio replacement. Construction and Building Materials 106: 330-341. http://dx.doi.org/10.1016/j.conbuildmat.2015.12.128

[18] Bibi, M., Belouahri, B., Chikouche, M.A., Hattab, M. (2009). Etude des propriétés mécaniques et physico-chimiques de l’argile vaseuse et de l’argile gréseuse provenant de la région de M’sila. 19th French Congress of Mechanics. http://documents.irevues.inist.fr/bitstream/handle/2042/36523/548.pdf.

[19] Chikouche, M.A. (2021). Valorization of heat treated dredged sludge in the cement matrix of ordinary concrete. Annales de Chimie - Science des Matériaux, 45(3): 251-257. https://doi.org/10.18280/acsm.450309

[20] Chikouche, M.A. (2016). Optimisation des ajouts à base d’argiles vaseuses et leurs effets sur les propriétés des matériaux cimentaires. Ph.D. dissertation. Département de génie civil, Faculté de technologie, Université de M'sila, Algérie.

[21] Remini, B., Hallouche, W., Achour, B. (2009). L’Algérie plus d’un siècle de desenvasement des barrages. GEB-Environnement, UNESCO : Etat des ressources en eau au Maghreb, pp 130. https://rabat.unesco.org/.

[22] NF EN 206+A1 Standard. (2016). Concrete-Specification, performance, production and conformity. https://standards.iteh.ai/catalog/standards/cen/b22aa5df-b7d0-4073-a729-d8e0653c4c49/en-206-2013a1-2016.

[23] NF EN 13791 Standard. (2019). Assessment of in-situ compressive strength in structures and precast concrete components. https://standards.iteh.ai/catalog/standards/cen/3209bcc7-df9a-4eb2-904d-e690e79b7452/en-13791-2019.

[24] NF EN ISO 17892-4 Standard. (2018). Geotechnical investigation and testing-Laboratory testing of soil, Part 4, Determination of the particle size distribution. https://standards.iteh.ai/catalog/standards/cen/eb256e27-684c-46f9-ac31-0d7c307ab226/en-iso-17892-4-2016.

[25] EN 196-2 Standard. (2013). Methods of Testing Cement, Part 2, Chemical Analysis of Cement. https://standards.iteh.ai/catalog/standards/cen/47283941-90a2-43dc-8b2c-dea6208712a6/en-196-2-2013.

[26] NF EN ISO 17892-3 Standard. (2018). Geotechnical investigation and testing-Laboratory testing of soil, Part 3, Determination of particle density-Pycnometer method. https://standards.iteh.ai/catalog/standards/sist/e7ffce9c-8dc7-4e3d-9389-5edcc7a61c77/sist-en-iso-17892-3-2016.

[27] EN 196-6 Standard. (2012). Methods of Testing Cements, Part 6, Determination of Fineness. https://standards.iteh.ai/catalog/standards/cen/9feaed91-485e-4e0b-93c6-36357e1580ec/en-196-6-2012.

[28] NF EN ISO 17892-12 Standard. (2018). Geotechnical investigation and testing-Laboratory testing of soil, Part 12, Determination of liquidity and plasticity limits. https://standards.iteh.ai/catalog/standards/cen/c3d39b6a-748d-43da-8a18-21a361d77e1e/en-iso-17892-12-2018

[29] NF EN 196-3+A1 Standard. (2017). Methods of testing cement - Determination of setting times and soundness. https://standards.iteh.ai/catalog/standards/cen/e4921eca-8101-4261-b066-25d19b9b8e8a/en-196-3-2016.

[30] NF EN 196-1 Standard. (2016). Methods of testing cement, Part 1, Determination of strength. https://standards.iteh.ai/catalog/standards/cen/37b8816e-4085-4dcc-a642-a383d9bddd6c/en-196-1-2016.

[31] NF EN 12 350-2 Standard. (2019). Testing fresh concrete, Part 2, Slump test. https://standards.iteh.ai/catalog/standards/sist/5594b26b-bc7f-474b-8cf5-db4dcc90966b/sist-en-12350-2-2019.

[32] NF EN 12 504-4 Standard. (2005). Testing concrete in structures, Part 4, Determination of ultrasonic pulse velocity. https://standards.iteh.ai/catalog/standards/cen/203a1a36-d5df-4f4c-9ab8-f6700e74e02c/en-12504-4-2004.

[33] Redjel, B., Khelifi, W., Jaubertie, R. (2014). Mesure de la résistance à la compression du béton, influence des méthodes destructives (écrasement) et non destructives (ultrason) et des géométries des corps d’épreuves. Ecole Nationale Supérieure des Travaux Publics, Algérie équipement 53: 8. http://www.entp.edu.dz/revue/files/article/53/article/8.pdf/, accessed on August 02, 2021.

[34] NF EN 12 504-2 Standard. (2003). Testing concrete in structures, Part 2, Non-destructive testing, Determination of rebound number. https://standards.iteh.ai/catalog/standards/cen/e5f4aab2-1f21-4823-985a-c09983b86f92/en-12504-2-2012.

[35] NF EN 12 390-3 Standard. (2012). Testing hardened concrete, Part 3, compressive strength of test specimens. https://standards.iteh.ai/catalog/standards/cen/7eb738ef-44af-436c-ab8e-e6561571302c/en-12390-3-2019.

[36] Magnan, J.P. (2015). Description, identification et classification des sols. Techniques de l’ingénieur, Ti541, C208 (3), pp. 17-20. http://www.techniques-ingenieur.fr.

[37] NF P 11-30 Standard. (1992). Classification of materials usable in the construction of embankments and subgrade of road infrastructure.

[38] NF EN 197-1 Standard. (2016). Cement, Part 1, composition, specifications and conformity criteria for common cements.

[39] ASTM C618. (2003). Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in Portland cement concrete. https://www.astm.org/Standards/C618.