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Valorization of Dredged Sediments as a Component of Vibrated Concrete: Durability of These Concretes Against Sulfuric Acid Attack

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Abstract: Hydraulic facilities are subjected to significant siltation which, in a very short period of time, can render them unusable. In Algeria, the silting-up of a great number of dams, built for drinking water needs and for irrigation, implies the necessity and urgency to take action. Therefore, the maintenance work, which leads to dredging the deposited silt, constitutes an unbearable obligation for the preservation of the environment. Chorfa dam (western Algeria) may be mentioned as a concrete example. This study is part of a long research whose objective is to contribute to the valorization and the optimization of the formulations economically that are easy to implement and which enable to use the dredged materials in the formulation of ordinary concretes by partial substitution to cement (10, 20 and 30%) of dredged sediments, after calcination at 750 °C to make them active. Tests were carried out on concrete that was vibrated in the fresh state (setting time) and hardened state (compressive strengths and durability of concrete exposed to sulfuric acid attack) in order to determine their characteristics. The results obtained confirmed the possibility to develop concretes containing calcined silt, with proportions up to 30%, and which can meet the economic, ecological and technological objectives.

Keywords: calcined silt, vibrated concrete, setting time, compressive strength, acid attack.

1. Introduction

According to the National Agency for Dams and Transfers (ANBT 2014), Algeria has until 2014 72 dams with a total capacity of 7692.24 million m^3 whose rate of siltation reached 14.12% of this capacity (ANBT 2014). The sediment dredging operations are at the same time inevitable and destructive of the environment. This is why, in a spirit of sustainable development and for good environmental management, several areas for the use of silt from these sediments as a raw material and no longer as waste have been targeted including civil engineering.

In the cement industry, finding a less expensive binder using wastes and natural resources, such as silt from sediments dredged from dams (Benamara et al. 2013; Bourabah et al. 2015; Remini and Bensafia 2016; Remini 2017), particularly Chorfa dam (western Algeria), has become a major concern in facing the shortage in the production of Portland cement (Lin and Lin 2005; Ouhba and Benamara 2009; Aouad et al. 2012).

In a spirit of sustainable development and a better environmental management, several areas of use of silt as a raw material, and not as waste, have been investigated, and particularly in civil engineering.

The partial substitution of a certain amount of Portland cement, with one or more mineral additions, when available at competitive prices, can be useful, not only economically, ecologically, rheologically, but also from the strength and durability point of views (Agostini et al. 2007; Bel Hadj Ali et al. 2014; Naamane et al. 2014a, b, c; Frar et al. 2017).

Using calcined mud in concrete, for partial replacement of cement, offers several advantages. The most important ones are those related to the fact that cement is the most expensive component in concrete and its production requires high energy consumption. Indeed, the production of 1 ton of cement releases about as much carbon dioxide in the atmosphere whereas the calcination of the mud generates only water vapor (Manap and Voulvoulis 2014; Naamane et al. 2014a, b, c; Bates et al. 2015; Couvidat et al. 2018).

Calcined sludge, is considered as a reactive pozzolan. Lime, which is released during the hydration of the clinker compounds, reacts with the pozzolanic material inside the mixture to lead to products that contribute to the mechanical strength of concrete (Qian and Li 2001; Mtarfi et al. 2016).

Using sludge, in partial replacement of cement in concrete, has been widely studied in recent years. The literature clearly indicates that mud is an active pozzolana; it helps to improve the mechanical properties of the cement/concrete paste at the young age and in the long term (Siddique and Klaus 2009; Mymrin et al. 2017).

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Some of the recent research studies (Siline 2013; Belaribi 2015; Kazi Aoual-Benslafa et al. 2015; Senhadji 2016; Kazi Aoual-Benslafa et al. 2017) on the valuation of sediments from dam dredging have been conducted in the field of physico-chemical, mechanical and durability characterization. They have demonstrated the possibility of using these sediments as a raw material in the field of civil engineering, and especially as a partial substitute for cement. (Labiod et al. 2004; Djafari et al. 2017; Amar et al. 2018).

In this study, the setting times and mechanical strengths (compression) were measured, on pastes and concretes, respectively. The behavior of concrete subjected to sulfuric acid attack was also investigated. The concretes studied were made by replacing 10, 20 and 30% of cement by mud. The crushing of concrete specimens (10 × 10 × 10) cm^3 was carried out at 7, 14, 28, 60, 90, 180 and 360 days.

2. Identification of Chorfa Dam

The dam of Chorfa is located in the department of Mascara (Western Algeria). It is known for its springs and has always supplied the region with drinking water. The geographical location of the dam is shown in Fig. 1.

Since it has entered into operation, Chorfa dam has had an enormous siltation problem which reduced its capacity by up to 80%. Some dredging operations were carried out in order to remedy this problem. This technique gave satisfactory results; however, it was limited due to the ecological problems as a result of negligence, since this sludge was poured downstream (Belas et al. 2009).

3. Experimental Program

3.1 Materials Used

3.1.1 Sludge

All the sludge collected from the discharge area (Fig. 2) was suitably prepared and then transformed to have the desired pozzolanic reactivity for the suggested substitution. The sludge was selected, homogenized, dried in an oven at 50 °C, crushed and reduced to powder by means of a grinder, sieved (80 µm sieve opening) and then calcined at 750 °C, for 5 h (Belas et al. 2009). The contents of the chemical components in sludge are summarized in Table 1. Its absolute density is 2.65 g/cm^3 and its Blaine specific surface area is 7830 cm^2/g. The process of preparing and transforming the mud sample by heat treatment is described in the following steps (Fig. 3) (El Ouardi 2008; San Nicolas et al. 2013; Teklay et al. 2015):

(a) Drying: the sample of mud is first dried in an oven (105 °C).
(b) Crushing: then it is crushed to facilitate its grinding.
(c) Grinding: the crushed dry mud is ground by means of an electric grinder.
(d) Sieving: it is then subjected to dry sieving (80 µm opening).

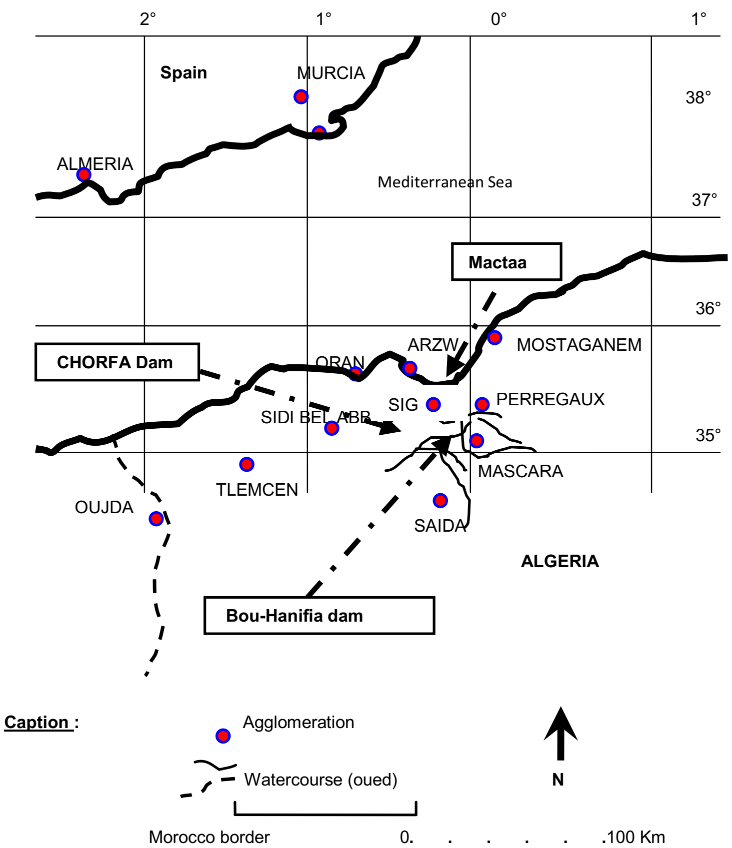

Fig. 1 Geographical location of Chorfa dam.

Fig. 2 Sludge discharge area.

(e) Calcination: mud, which was previously baked in an oven, is heat treated. Precautions are taken to avoid thermal shocks; the baking speed is set to 5° per minute. The baking temperature of 750 °C is kept constant for 5 h, to obtain the final product, i.e. calcined mud, which is stored away from air and moisture (Belas et al. 2009; Snellings et al. 2016).

The chemical and mineralogical analysis of the mud under study (Fig. 4a) reveals the presence of the essential minerals, such as silica and alumina that make up the most common hydraulic binders (Naamane et al. 2014a, b, c; Benasla et al. 2016).

Figure 4b shows the rough and porous appearance of calcinated mud grains. It would be sufficient to thermically activate the clay minerals so that they can react with water if the limestone content is adequate, to form compounds which set and harden at ambient temperature (Oh et al. 2011; Benasla et al. 2015; Claverie et al. 2015; Benzerzour et al. 2017; Moon et al. 2017; Hyeok-Jung et al. 2018).

The granulometric analysis of a sample of the mud under study is given in Fig. 5 (Mekerta et al. 2009; Duan et al. 2013; Rodríguez et al. 2013; Dia et al. 2014; Amar et al. 2017).

3.1.2 Cement

Portland CEMI 42.5 cement, provided from Zahana cement plant in western Algeria, was used in this study. Its specific surface area is 3180 cm^2/g which is according to the Algerian norms (NA442 Equiv EN 197-1 2001), and its chemical and mineralogical compositions are reported in Tables 2 and 3.

3.1.3 Aggregates

The aggregates used in the mix design of concretes are of natural limestone and come from the quarry of Sidi-Bel-Abbes, a town located in the western region of Algeria.

3.1.3.1 Sand The main physical characteristics of this sand (0/3) are shown in Table 4.

3.1.3.2 Gravel Two granular classes are used, namely 3/8 and 8/15. They have an absolute density of 2.65 g/cm^3. The grain size distribution curves of the aggregates are given in Fig. 6.

Table 1 Chemical characteristics of Chorfa mud (Benfetta and Remini 2008; Xu et al. 2014).

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	Loss on ignition
Contents (%)	47.36	15.75	7.43	23.08	0.17	2.67	2.97	0.37	1.76

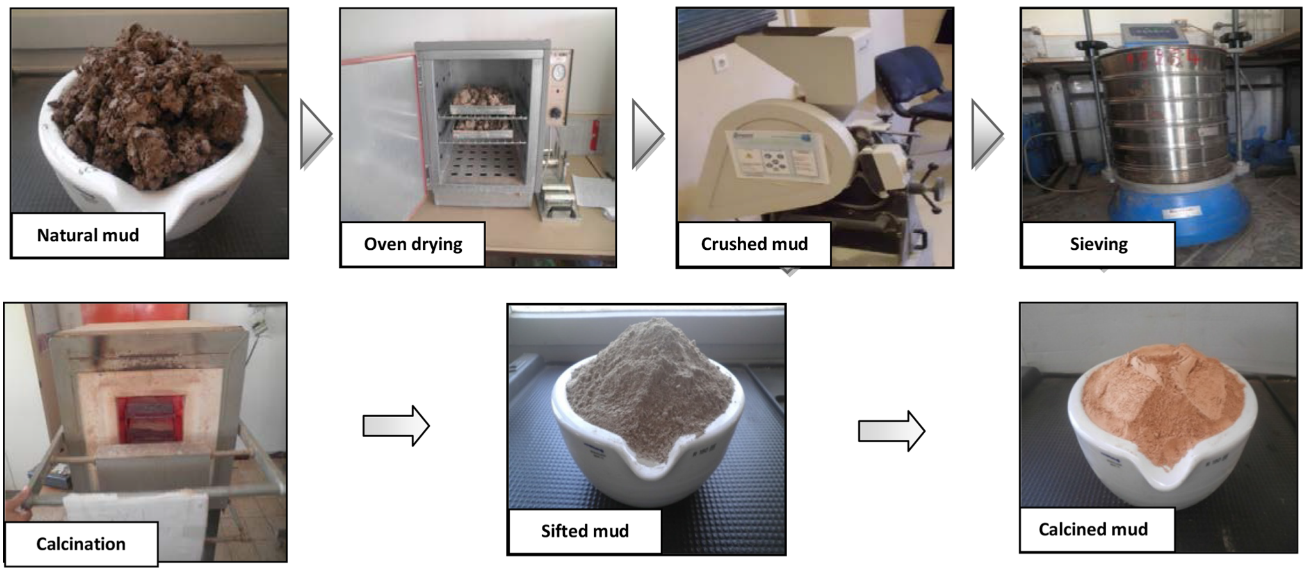

Fig. 3 Steps for mud preparation.

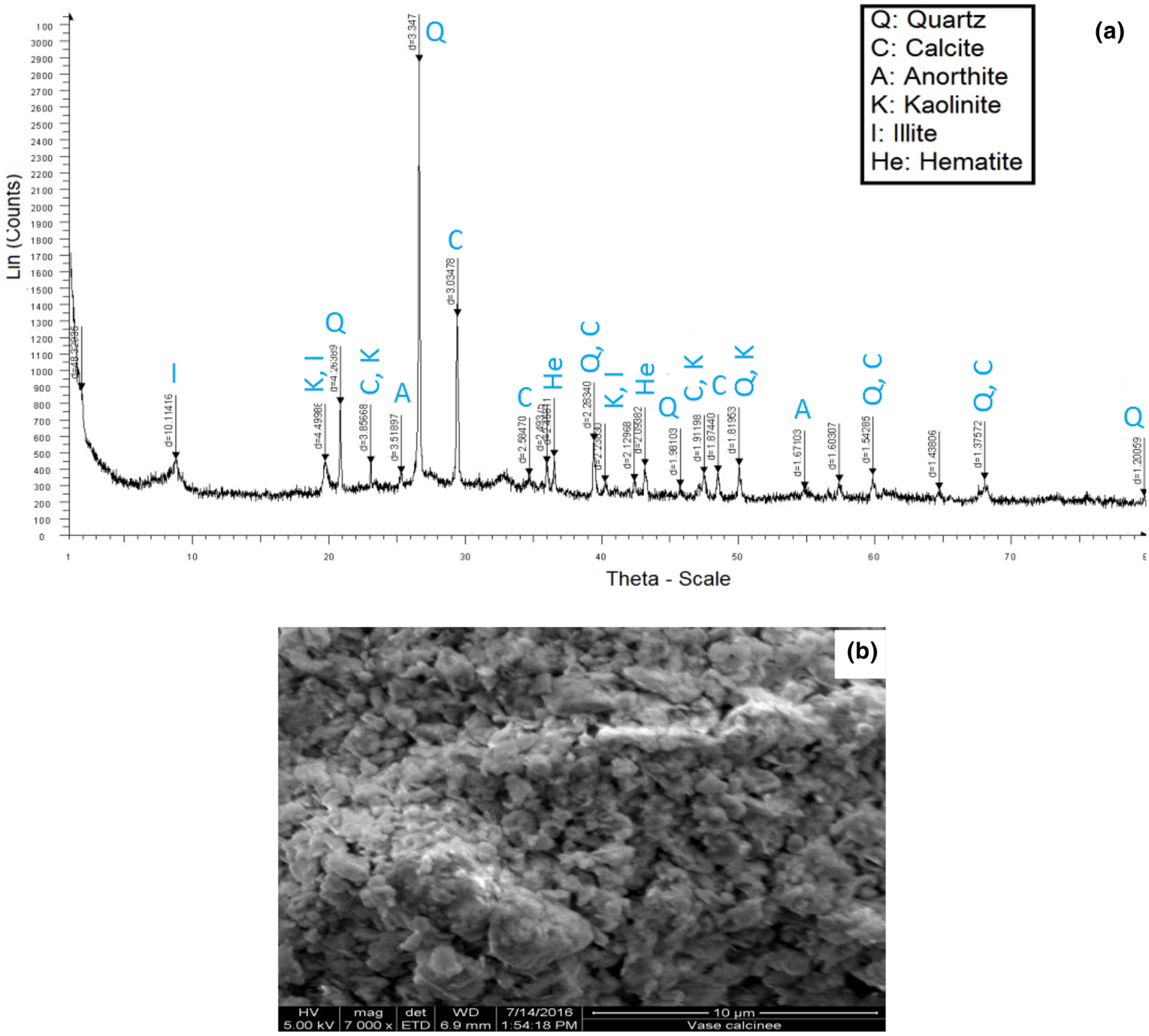

Fig. 4 **a** XRD analysis of calcinated mud and **b** EDS analysis of calcinated mud.

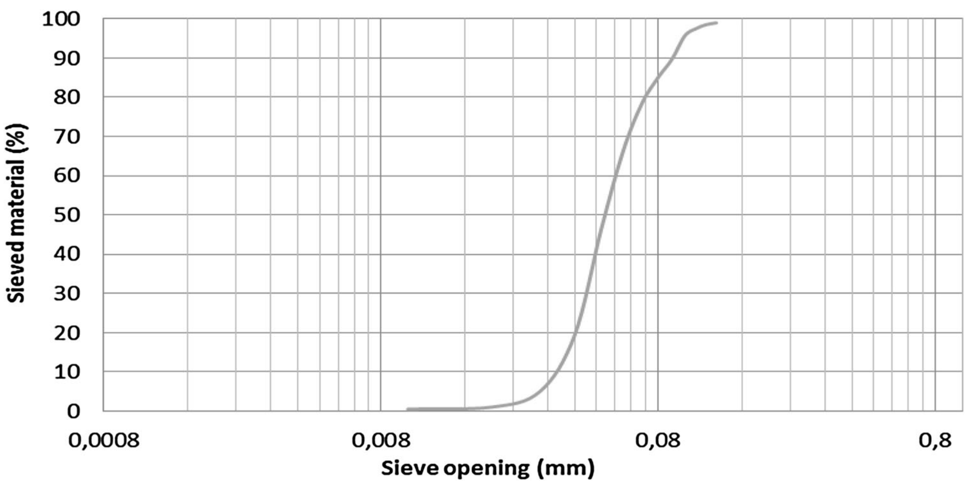

Fig. 5 Granulometric (grain-size) curve of mud.

Table 2 Chemical composition of Portland cement.

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	PF	Loss on ignition
Contents (%)	22.30	5.10	3.99	63.60	1.24	1.43	0.70	0.34	1.18	0.36

Table 3 Mineralogical composition of clinker.

Components	C_3S	C_2S	C_3A	C_4AF	CAO free
Contents (%)	53.13	23.55	6.76	12.13	< 01

Table 4 Physical characteristics of the quarry sand.

Absolute density (g/cm^3)	2.68
Sand equivalent (%)	
Visual	77.45
Piston	74.00
Fineness modulus	2.63

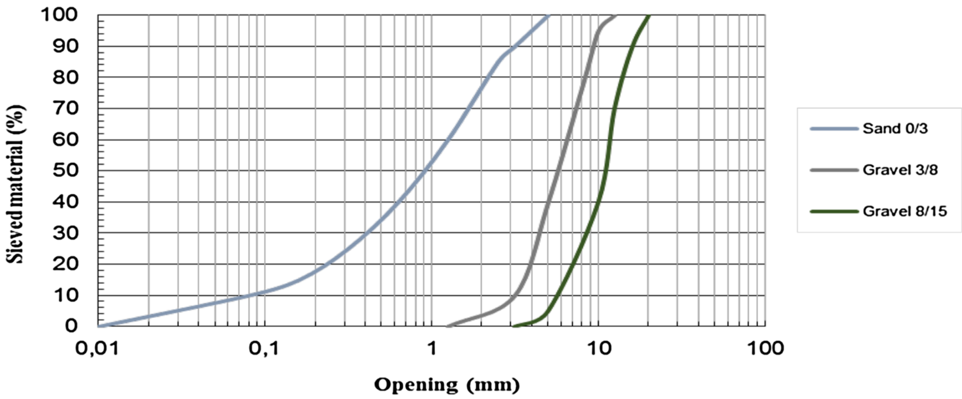

Fig. 6 Grain size distribution curves of aggregates.

3.1.4 The Additive

A water-reducing plasticizer, namely SIKA PLASTIMENT BV 40, was used for additive-based formulations in order to have concretes of the same consistency (plastic) while keeping the same W/B (water/binder) ratio.

3.2 Formulations Studied

3.2.1 Mud-Ordinary Portland Cement Concrete, MOPCC

Four concrete mixes were developed. Three of them involved various proportions of mud (MOPCC 10%, MOPCC 20% and MOPCC 30%), and the fourth one is control concrete (CC 00%) for the need of comparison. The limit of the mud substitution rate has been set at 30% because beyond this value the demand for water would be greater due to the porosity of the mud grains and consequently the dosage plasticizer risk of reaching the limit percentage. Table 5 gives the compositions of the different concretes under study.

The slump of concretes is found to be in accordance with standard NF P 18-451 and also with the slump required for the formulation of our concretes (8 ± 1 cm).

4. Results and Discussions

4.1 Setting Time

The results relative to the initial and final of setting times of the different cement pastes are displayed in Fig. 7.

Figure 7 shows a slight decrease in the setting time (beginning and end) as the percentage of addition with respect to cement rises. This may be attributed to the replacement of the cement by the addition. The initial and final setting times decrease proportionally with the increase in the finesse of cement and mud mixture. This means that the hydration kinetics of the binder becomes increasingly fast as the fineness goes up (Pan et al. 2003; Chikouche et al. 2016). In general, the setting time of pastes does not seem to be highly

Table 5 Formulation of concretes.

Designation	Cement (kg/m^3)	P/B (%)	Addition (kg/m^3)	Gravel (kg/m^3)		Sand (kg/m^3)	Water (kg/m^3)	W/B	P (kg/m^3)
				3/8	8/15				
CC 00%	402	00	00	179	912	663	201	0.5	00
MOPCC 10%	363.6	0.3	35.33	179	912	663	199.4	0.5	1.19
MOPCC 20%	324.8	0.4	71.02	179	912	663	197.9	0.5	1.58
MOPCC 30%	286.3	0.65	107.31	179	912	663	196.8	0.5	2.56

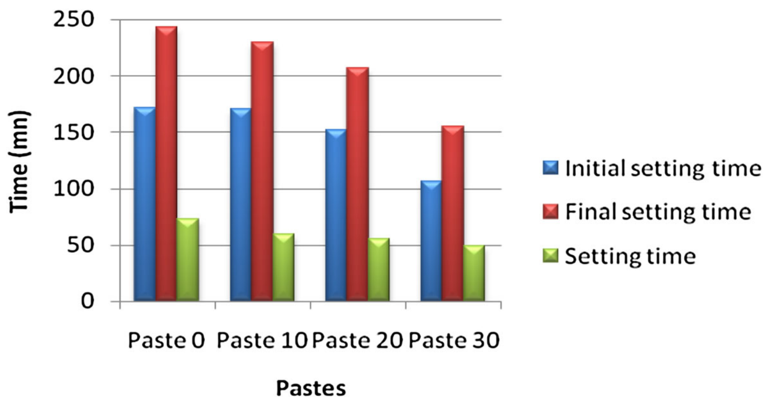

Fig. 7 Influence of mud content on the setting time.

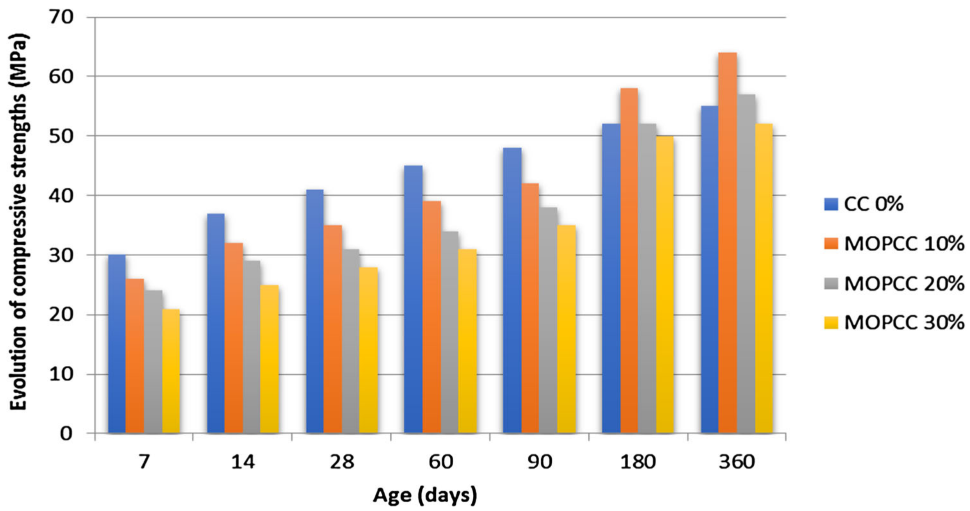

Fig. 8 Compressive strength of concretes in MPa, as a function of time.

affected by the presence of mud; hence the importance of valorizing and using dredged materials with replacement levels up to 30%.

4.2 Compressive Strength

Figure 8 displays the compressive strengths of the concretes in MPa, as a function of time.

The results indicate that the control concrete achieves good compression performance, because it did not show compression strength smaller than 55 MPa at 360 days. The mechanical strengths of concrete with 10% of cement replaced by mud are obviously the best of all mud-based concretes. At the end of the curing time, they tend to exceed those of control concrete. This concrete reaches a compressive strength around 64 MPa at 360 days (Bibi et al. 2008; Dang et al. 2013; Belaribi et al. 2014; Ouhba et al. 2014). The other concretes with mud contents of 20, and 30% also give very satisfactory results. (Belas et al. 2003; Lafhaj et al. 2008; Benkaddour et al. 2009; Limeira et al. 2011; Manap et al. 2016).

To better visualize the strength evolution, the strengths of mud-based concretes are compared with that of control concrete (0% mud), at different ages (Fig. 9).

It can easily be noted from the results obtained that, relatively to the control concrete, the compressive strengths of all tested concretes increase continuously with age and show no drop.

Indeed, the concretes with mud contents of 20 and 30% are likely to develop mechanical performances that are higher by 87 and 80% at 7 days, and 85 and 76% at 28 days, respectively, as compared to control concrete. Beyond

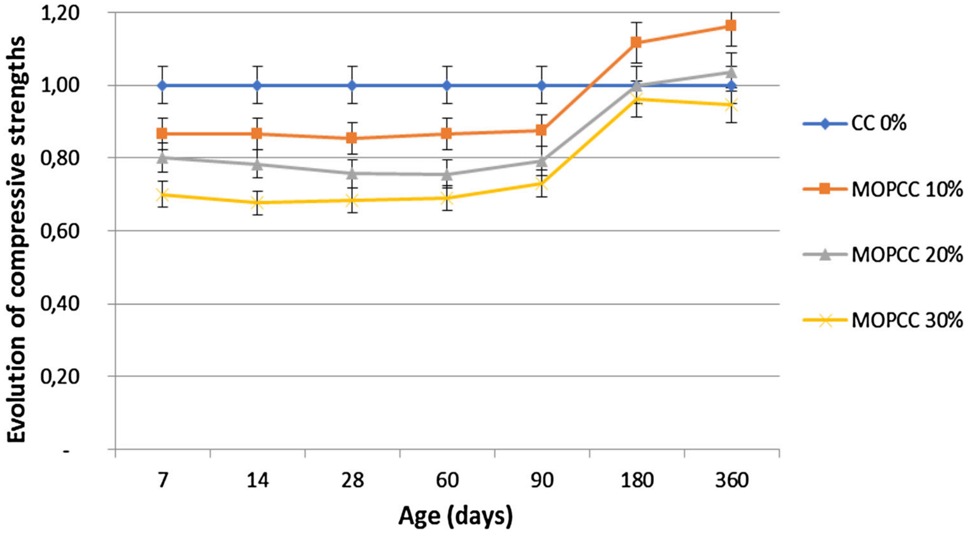

Fig. 9 Evolution of the strength of mud-based concretes with respect to control concrete.

90 days, MOPCC 10% and MOPCC 20% develop compressive strengths superior to those of control concrete. At 360 days, they are higher than that of control concrete by about 116 and 104%, respectively. This can be attributed to the slow pozzolanic activity at the young age, but which grows later.

Moreover, the mechanical behavior of concrete containing 30% of mud also exhibits high strengths, which eventually tend to approach those of control concrete. This concrete reaches a compressive strength around 70% at 7 days, 68% at 28 days, and about 95% at 360 days of hardening, as compared to that of control concrete (Zentar et al. 2012; Frar et al. 2014; Rozière et al. 2015; Laoufi et al. 2016; Naamane et al. 2016; Serbah et al. 2018). Incorporating calcined mud in concrete induces a rapid increase in the mechanical strength, at all maturities. When the particles of calcined mud whose fineness is higher than that of cement, they promote the hydration of cement and mud, mainly through a physical process, and lead to a cementitious matrix with a denser structure, all the more since mud has a high fineness. These effects have a visible influence on the mechanical strength in the medium to long term (Goncalves et al. 2009; Vejmelkova et al. 2011; Sajedi 2012; Gastaldini et al. 2015; Junakova et al. 2015; Junakova and Junak 2017).

4.3 Sulfuric Acid (H_2SO_4) Attack

A very aggressive and destructive case of acid attack occurs when the concrete is exposed to sulfuric acid (H_2SO_4). The calcium salt resulting from the reaction between sulfuric acid and calcium hydroxide is a calcium sulfate which causes increased degradation. This process is illustrated by the following equation:

$$\underset{\text{Calcium hydroxide}}{Ca(OH)_2} + \underset{\text{Sulfuric acid}}{H_2SO_4} \rightarrow \underset{\text{Calcium sulfate}}{CaSO_4} + \underset{\text{Water}}{2H_2O} \quad (1)$$

Testing for acid resistance usually consists of following the development of the mass of cylindrical concrete samples which, after 90 days of wet curing, are immersed into a solution saturated with H_2SO_4 (2% of volume), according to the standard (ASTM C 267-01 2012). Mass monitoring was conducted over a period of 12 weeks of immersion, and some digital photos were taken for visual examination.

The results are shown as a function of the immersion time in Fig. 10.

The results obtained from all four preparations tested by immersion into the acid solution of H_2SO_4 show, most importantly, that after 90 days of acid attack, the control concrete appears to be the most resistant. By comparing between the different concretes, we can notice that all the samples were damaged. The loss of mass, due to the aggressiveness of the acid H_2SO_4, varies from one type of concrete to another, depending to the mud content. we notice the same resistance of 10 and 20% of concrete to the attack of H_2SO_4. Concrete containing 30% of mud exhibits a slightly higher loss of mass compared to the other types of concrete, especially for longer periods of immersion in the acid solution. It seems that the mud is very sensitive to the attack of sulfuric acid especially for the concrete with high dosage which led to more significant damage.

The resistance of concrete to the attack of sulfuric acid depends mainly on the amount of $Ca(OH)_2$ produced during the hydration of the cement (Li and Zhao 2003; Siad et al. 2010).

In the presence of fly ash or natural pozzolana, the pozzolanic reaction reduces the percentage of portlandite to give a new hydrated calcium silicate (H-C-S) that is different from the ordinary H-C-S (Detwiler et al. 2003). Hydrated calcium silicates resulting from pozzolanic additions are more stable in a low pH environment (Aydin et al. 2007). Indeed, the pH measured in our test, over the twelve-week immersion period does not exceed 2.

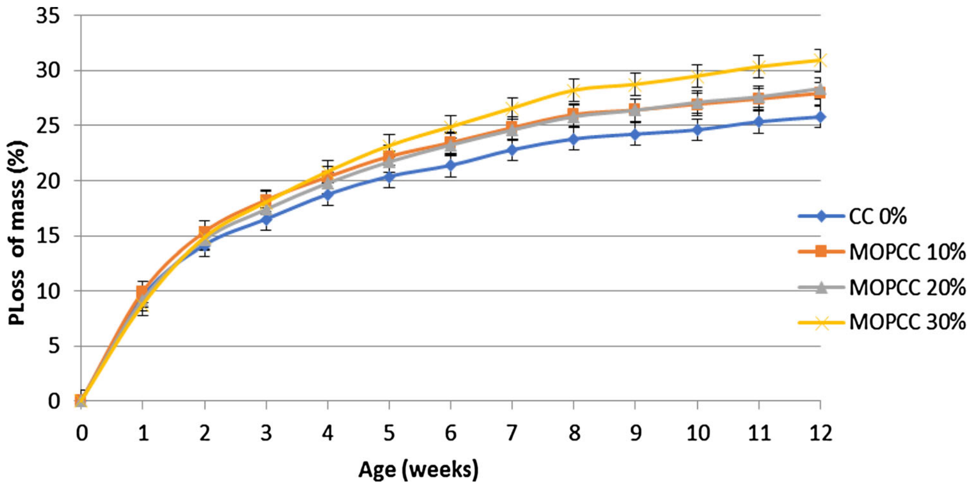

Fig. 10 Mass loss of concretes aged 90 days and immersed in H_2SO_4 solution.

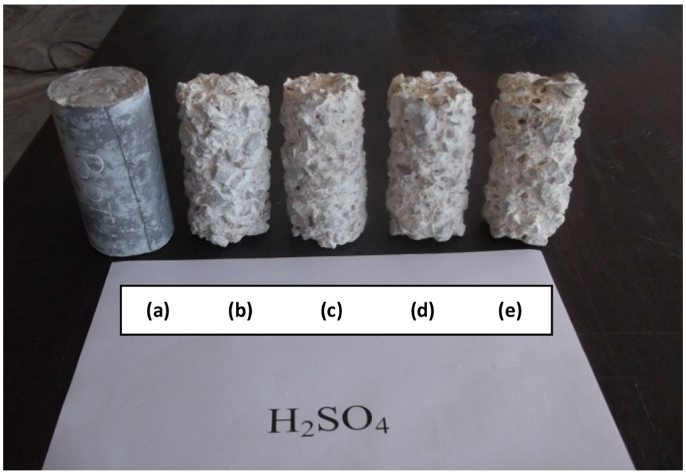

Fig. 11 Aspect of healthy concrete and attacked by the sulfuric acid solution: **a** concrete not attacked, **b** CC 00%, **c** MOPCC 10%, **d** MOPCC 20%, and **e** MOPCC 30%.

4.4 Visual Examination

Figure 11 displays the aspect of all the concrete samples, after a 12-week immersion period in the 2% H_2SO_4 solution, compared to healthy control concrete.

Before cleaning the samples removed from the sulfuric acid solution, one could notice a water washable whitish layer (O'Connell et al. 2012).

From the above figure, the degradation of all test samples of concrete can easily seen, especially the MOPCC 30% concrete which has suffered more degradation compared to the other concretes (ACI Committee 201 and ACI 201.2R-01 2001; De Belie et al. 2004; Chang et al. 2005).

Alteration of the samples can be seen in the loosening aggregates on all surfaces exposed to sulfuric acid. Indeed, no great difference is noted in the degradation of concretes with replacement levels of 10 and 20% of mud. The control concrete was the least degraded.

5. Conclusions

This study allows confirming the possibility of valorizing the mud from Chorfa dam as partial cement replacement material in concrete. This could solve the problem of its storage, thus making our country more environmentally-friendly, and at the same time may contribute to the national economic development. The possibility of valorizing mud, resulting from the dredging operations of dams, leads us to no longer consider this material as waste, but as a material meeting the principles of sustainable development.

The main conclusions reached are:

(1) In general, the setting time of concrete pastes made with different replacement rates of mud does not seem to be highly affected by the presence of mud.

(2) Compressive strengths of all tested concretes increase continuously with age and do not show any drop.

(3) The mud from Chorfa dam enhances the long-term compressive strength of concrete, as it gives rise to a second hydrated calcium silicate (H-C-S) which helps to fill in the pores, and increase the mechanical strength as well.

(4) The results obtained from the sulfuric acid attack showed that all the concrete formulations show low resistance to the aggressive acid. It is found that in general, the incorporation of mud improves the

resistivity of these concretes regarding the sulfuric acid attack. Concretes with 10 and 20% of mud exhibited performances very comparable to that of the control concrete, but slightly higher than that of the concrete that contains 30% of mud.

In the end, from all the results obtained in this work, one may conclude that the mud from Chorfa dam can be successfully used as a mineral addition in the formulation of ordinary vibrated concrete. In addition to its economic advantage, this natural material, when incorporated into concrete, generally generates appreciable compressive strength and durability.

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