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Study of the behavior in the fresh and hardened state of an eco-concrete based on dredged sediments

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- ✓ Vibrated concrete;
- ✓ Setting time;
- ✓ Compressive strength

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Abstract

All the dams in the world are exposed to the phenomenon of sedimentation, which is observed largely in Algeria. The dredging is considered as a vital activity for the exploitation of the dams. However, the quantities of the sediments (mud) evacuated by the operations of dredging will lead to the pollution of the rural environment. The aim is to suggest some economic and competitive formulations and easy to put into practice which give us an opportunity to exploit these materials in the manufacturing of the common concrete by the partial substituting with cement (10, 20 and 30%) of the mud after calcination at 750 °C to make them active. Some tests were done on concrete in the fresh and hard state in order to know their features. The obtained results have confirmed the possibility to elaborate the concretes including the calcinated mud with doses reaching till 30%.The quality of these concretes at fresh state or hard state permits to reach the economical, ecological and technological aims.

1. Introduction

In the cement industry, finding a less expensive binder using wastes and natural resources, such as sludge from sediments dredged from dams, particularly Chorfa dam (western Algeria), has become a major concern in facing the shortage in the production of Portland cement [1,2].

In a spirit of sustainable development and a better environmental management, several areas of use of sludge 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 good, not only economically, ecologically, rheologically, but also from the strength and durability point of views [3,4]. Using calcinated 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 one ton of cement releases about as much carbon dioxide in the atmosphere [5].

Calcinated sludge, such as metakaolin, is considered as a reactive pozzolana, which was confirmed by many tests as TGA/DTA [6,2]. 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 [7,8]. 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 pozzolan; it helps to improve the mechanical properties of the cement/concrete paste at the young age and in the long term [9].

In this study, the setting times and mechanical strengths (compression) were measured, on pastes and concretes, respectively. The concretes studied were made by replacing 10, 20 and 30% of cement by sludge. The crushing of concrete specimens (10x10x10) cm^3 was carried out at 7, 14, 28, 60, 90 and 180 days.

2. Experimental details

2.1. Cement

Portland CEMI 42.5 R cement, from Zahana cement plant in western Algeria, was used in this study. Its Blaine specific surface area is equal to 3180 cm^2/g according to the Algerian norms NA442 [10] and its chemical and mineralogical compositions are reported in Tables 1 and 2.

Table 1: Chemical composition of Portland cement

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	PF	RI
Content (%)	22.30	5.10	3.99	63.60	1.43	1.24	0.70	0.34	1.18	0.36

Table 2: Mineralogical composition (%) of clinker

C_3S	C_2S	C_3A	C_4AF	CaO Free
53.13	23.55	6.76	12.13	< 01

2.2. Sludge

The entire quantity of mud used was taken from the downstream discharge area of Chorfa dam.
The laser granulometric analyses of a sample of the sludge used are shown in Figure 1.

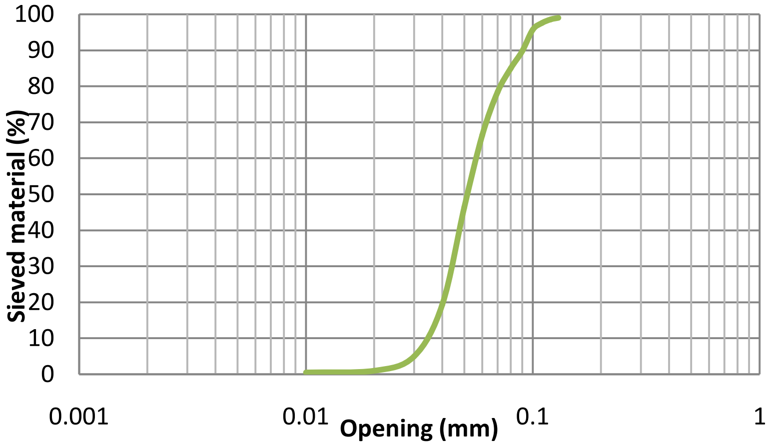


Figure 1: Granulometric curve of the sludge used.

The mud was treated according to the following steps [11].

- Mud was first dried in an oven, at 105 °C, and then subjected to dry crushing and sieving. The resulting material, which was passed through an 80 μm-mesh sieve, and amounted to more than 95% of the sample, was recovered and baked.
- Certain precautions had to be taken during the calcination processes. To avoid thermal shock, the baking temperature was increased at a rate of 5 °C per minute, until it reached the temperature of 750 °C, which was kept constant for 5 hours [12].
- The product thus obtained (calcinated mud) was kept away from air and moisture.

Figure 2 shows the appearance of mud before and after calcination.

Figure 2: Appearance of mud before and after calcinations

The chemical characteristics of mud are grouped in table 3 [13,14].

Table 3: Chemical characteristics of Chorfa mud

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	PF
Contents (%)	47,36	15,75	7,43	23,08	2,67	0,17	2,97	0,37	1,76

The chemical and mineralogical analysis of the mud under study (Fig.3a) reveals the presence of the essential minerals, such as silica and alumina that make up the most common hydraulic binders [15,16]. Figure 3b shows the rough and porous appearance of calcinated mud grains. It would be sufficient to therrmically 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 [17,18].

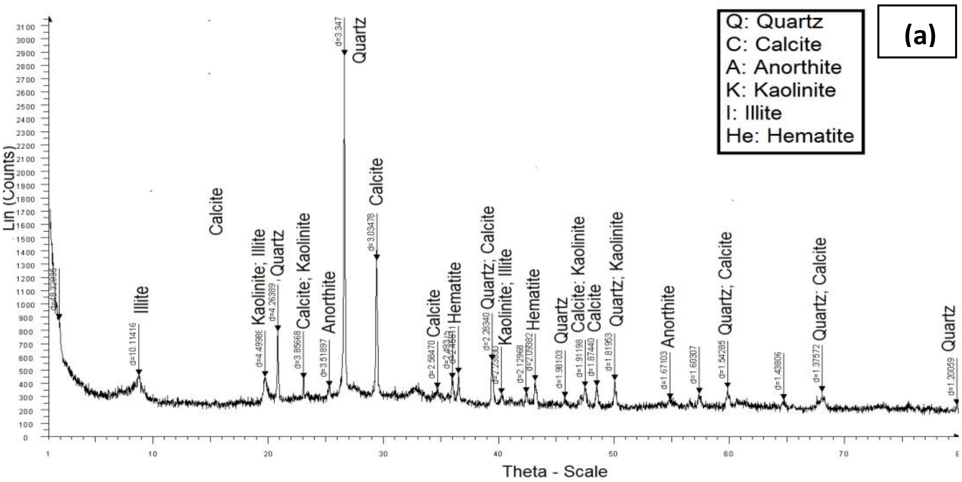


Figure 3a: XRD analysis of calcinated mud

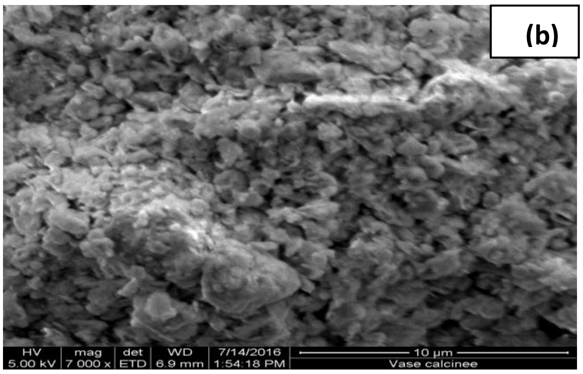
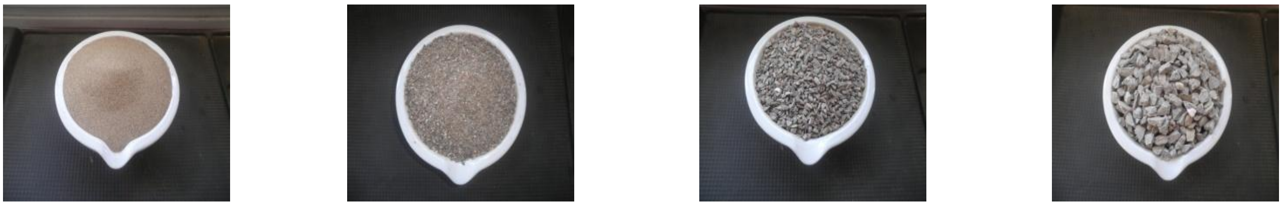


Figure 3b: EDS analysis of calcinated mud

2.3. Aggregates

The gravels used in the manufacture of concrete belong to classes 3/8 and 8/15. They are calcareous and come from the quarry of Kristel, in the region of Oran. Moreover, two types of sand, of class 0/3, were used. The first one is calcareous and was brought from Kristel, and the second is siliceous, from the beach of Sidi-Lakhdar. It is required to use both kinds of sand (with 60% and 40% of quarry sand and sea sand, respectively) in order to provide the appropriate granular correction to the mixture so that it can fit into the standardized granulometric link-pin. Figure 4 illustrates the aggregates used in the formulation of our concretes.



Sea sand Quarry sand Gravel (3/8) Gravel (8/15)

Figure 4: The used aggregates in the formulation of our concrete

The results of chemical and physical analysis of sea sand from Sidi-Lakhdar and aggregates from Kristel are given in Tables 4 and 5.

Table 4: Chemical analysis of Sidi-Lakhdar sea sand and Kristel aggregates

Chemical constituents	Sea sand (%)	QS, G3/8, G8/15 (%)
Silica SiO_2	88.78	2.06
Lime CaO	9.80	54.58
Magnesia MgO	0.42	0.14
Alumina Al_2O_3	1.37	-
Iron oxide Fe_2O_3	0.94	0.13
Sulfate SO_3	0.03	-
Nature	Siliceous	Calcareous

Table 5: Summary table of the physical characteristics of the aggregates used

Characteristics		Sea sand (SS)	Quarry sand (QS)	Gravels	
				(3/8)	(8/15)
Bulk density (g/cm^3)		1.50	1.52	1.42	1.41
Absolute density (g/cm^3)		2.64	2.65	2.59	2.63
Sand equivalent (%)	Visual	95.89	93.55	-	-
	Piston	94.03	89.26	-	-
Fineness modulus		1.39	3.2	-	-
Percentage of fines (%)		0.30	1.06	0.41	0.33
Absorption (%)		1.12	0.81	0.58	0.61

The granulometric curves of aggregates are given by Figure 5.

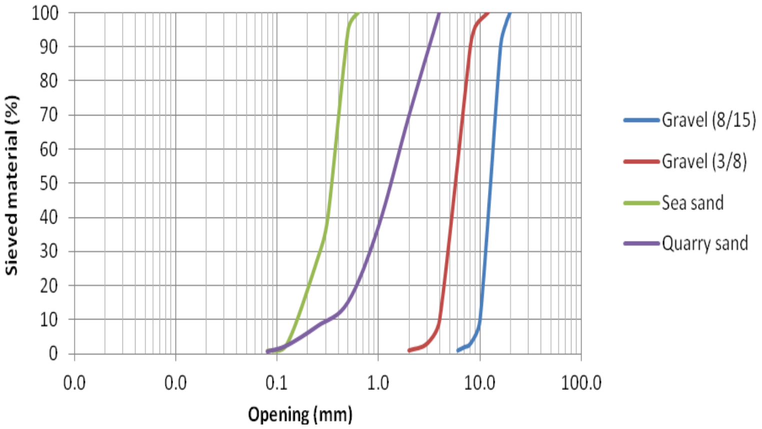


Figure 5: Grain size distribution curves of aggregates

2.4. 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.

2.5. Studied formulations

(Mud-ordinary Portland cement concrete, MOPCC)

Four concrete formulations 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. Table 6 gives the compositions of the different concretes under study.

Table 6: Formulation of concretes

Designation	Cement kg/m^3	P/B (Plasticizer/Binder) (%)	Addition kg/m^3	Gravel kg/m^3		Sand kg/m^3	Water kg/m^3	W/B (Water/ Binder)	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

The sagging 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).

2.5. Test methods

2.5.1. Cement setting test

The setting time is usually measured on a pure cement paste, of normal consistency, in accordance with the standard NF EN 196-3, using the Vicat apparatus.

2.5.2. Compression testing

The simple compression test is carried out in the laboratory on cubic specimens (10 × 10 × 10) cm^3, using a press with a maximum capacity of 3000 kN, and a loading speed of approximately 0.5 MPa/s (NF P 18-406).

2.5.3. Heat-of-hydration test

According to the standard NF EN 196-9, the heat of hydration of a cement paste is measured by semi-adiabatic micro-calorimetric. The purpose of the test is to measure, progressively, the heat of hydration of the raw cement paste and the calcinated mud, during the first few days. The heat of hydration is expressed in joules per gram of cement.

3. Results and Discussion

3.1. Setting time

The results relative to the start and end of setting times of the different cement pastes are displayed in Figure 6.

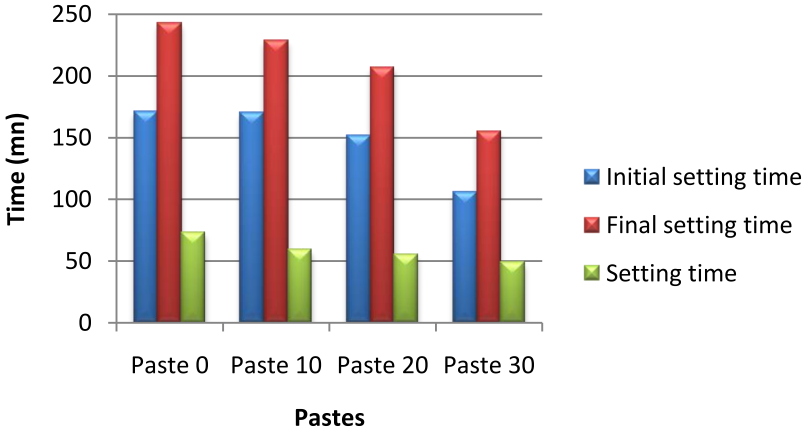


Figure 6: Influence of mud dosages on the setting time

Figure 6 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. This means that the hydration kinetics of the binder becomes increasingly fast as the fineness goes up [19]. In general, the setting time of pastes does not seem to be highly affected by the presence of mud; hence the importance of valorizing and using dredged materials with replacement levels up to 30%.

3.2. Compressive strength

Figure 7 displays the compressive strengths of the concretes in MPa, as a function of time.

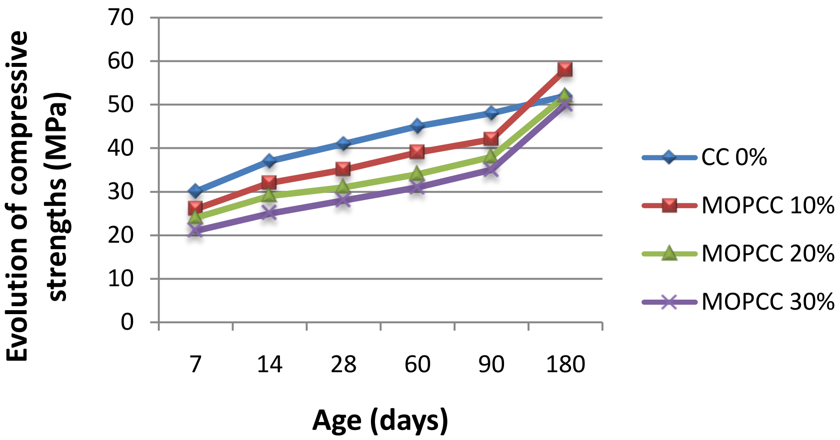


Figure 7: Compressive strengths of concretes in MPa, as a function of time

The compressive strength for all the concretes follow the same kinetics with a slight advantage for the control concrete up to 90 days, this can be explained by the dilution phenomenon which is inversely proportional to the substitution rate, where rate is important less is the amount of the cement and therefore fewer hydrates formed.

The results indicate that the control concrete achieves good compression performance, because it did not show compression strength smaller than 52 MPa at 180 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 course, they tend to exceed those of control concrete. This concrete reaches a compressive strength around 58 MPa at 180 days. The other concretes with mud contents of 20, and 30% also give very satisfactory results. [20,21].

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.8).

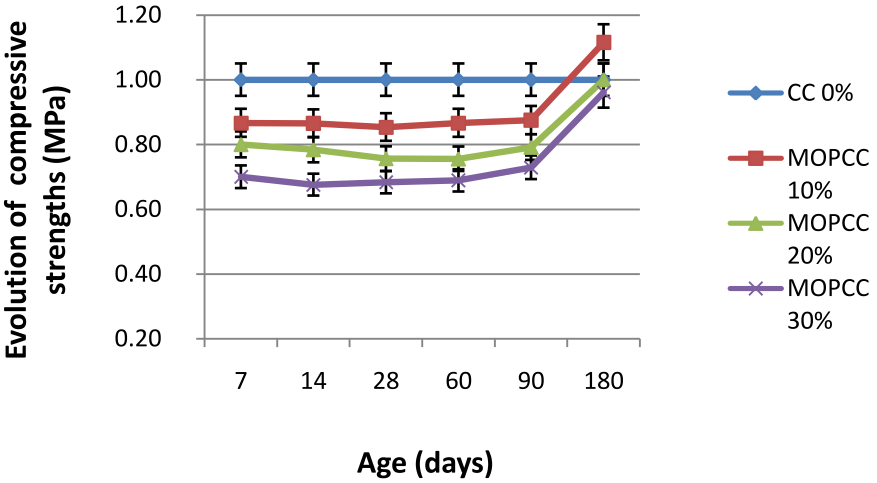


Figure 8: Evolution of the strengths of mud-based concretes with respect to control concrete

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 10 and 20% 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 90 days, MOPCC 10% and MOPCC 20% develop compressive strengths superior to those of control concrete. At 180 days, they are higher than that of control concrete by about 112% and 100%, 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 96% at 180 days of hardening, as compared to that of control concrete [22,23]. Incorporating calcinated mud in concrete induces a rapid increase in the mechanical strength, at all maturities. When the particles of calcinated mud are well deflocculated by the plasticizer, 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 [24-26].

3.3. Heat of hydration

Figure 9 illustrates the variation of heat and flux generated by the pastes containing 10, 20 and 30% of calcinated mud, as a function of time.

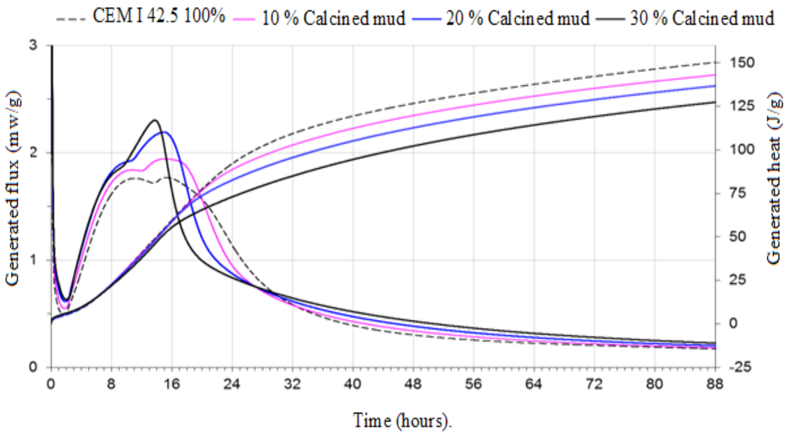


Figure 9: Evolution of hydration heat and flux generated by the pastes containing 10, 20 and 30% of calcinated mud, as a function of time

Two peaks can be observed on the above curves, which represent the evolution of the heat flow as a function of time. The first peak corresponds to the initial reactions that occur between cement and mud on one side and water on the other, within the mixture.

The initial peak is followed by a dormant period, with a very low heat release, accompanied by a gradual super saturation of lime. Then comes the acceleration period which begins with the precipitation of portlandite, and there the heat release rate increases rapidly until it reaches the main peak, with the formation of additional hydro-silicate and ettringite [27,28].

Substituting 10% of cement by an equal amount of mud from Chorfa dam provides more heat than for replacement percentages of 20 and 30%, at 88 hours. This is probably due to the slowness of the pozzolanic reaction which is triggered very late compared to the hydration reaction of C_3S.

The pozzolanic reaction is slow, because before it is initiated, portlandite must be formed first by the hydration of Portland cement. A study [29] was carried out on the effect of different percentages of mineral additions, such as fly ash, silica fume and blast furnace slag, on the heat of hydration of mortars; it showed that the process of endothermic hydration of mortar is strongly influenced by the partial replacement of cement by one of these additions.

Conclusion

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:

- Increasing the Blaine specific surface area of the cement and mud mixture slightly accelerates the setting.
- Regarding the compressive strength, all the concretes follow the same kinetics with a slight advantage for the control concrete up to 90 days due to the dilution phenomenon.
- Generally all mud-based concrete formulations give good mechanical performances.

- 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 increases the mechanical strength beyond 90 days.
- The proportions of 10 and 20% of mud, for partial replacement of cement in concrete, are found to be optimal for developing high strength in the short term, that are higher by 85% and 76% at 28 days, respectively, as compared to control concrete. Beyond 90 days, MOPCC 10% and MOPCC 20% develop compressive strength superior to those of control concrete.
- The evolution of hydration temperature shows that the maximum value of that temperature, for cement pastes with an addition, is smaller than that of the control cement paste, which means that there is a lower risk of cracking.

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