



Mechanical and thermo-physical characterization of mortars made with uncontaminated marine sediments

Amani Abdallah, Hassina Kada, Abdelwaheb Amrouche

► To cite this version:

Amani Abdallah, Hassina Kada, Abdelwaheb Amrouche. Mechanical and thermo-physical characterization of mortars made with uncontaminated marine sediments. *Journal of Material Cycles and Waste Management*, 2022, 10.1007/s10163-022-01497-4 . hal-03784499

HAL Id: hal-03784499

<https://hal.science/hal-03784499v1>

Submitted on 27 Sep 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Metadata of the article that will be visualized in OnlineFirst

ArticleTitle	Mechanical and thermo-physical characterization of mortars made with uncontaminated marine sediments	
Article Sub-Title		
Article CopyRight	Springer Japan KK, part of Springer Nature (This will be the copyright line in the final PDF)	
Journal Name	Journal of Material Cycles and Waste Management	
Corresponding Author	FamilyName	Abdelwaheb
	Particle	
	Given Name	Amrouche
	Suffix	
	Division	Junia, ULR 4515 – LGCgE, Laboratoire de Génie Civil Et Géo-Environnement
	Organization	Univ. Artois, Univ. Lille, Institut Mines-Télécom
	Address	Technoparc Futura, F-62400, Béthune, France
	Phone	
	Fax	
	Email	abdelwaheb.amrouche@univ-artois.fr
	URL	
	ORCID	http://orcid.org/0000-0003-2173-409X
Author	FamilyName	Abdallah
	Particle	
	Given Name	Amani
	Suffix	
	Division	Junia, ULR 4515 – LGCgE, Laboratoire de Génie Civil Et Géo-Environnement
	Organization	Univ. Artois, Univ. Lille, Institut Mines-Télécom
	Address	Technoparc Futura, F-62400, Béthune, France
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	FamilyName	Kada
	Particle	
	Given Name	Hassina
	Suffix	
	Division	Junia, ULR 4515 – LGCgE, Laboratoire de Génie Civil Et Géo-Environnement
	Organization	Univ. Artois, Univ. Lille, Institut Mines-Télécom
	Address	Technoparc Futura, F-62400, Béthune, France
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Schedule	Received	24 Feb 2022
	Revised	
	Accepted	26 Aug 2022
Abstract	<p>In a context of sustainable development, civil engineering must increasingly use recyclable materials to preserve natural resources. Sediments could be a solution in the context of their recovery in several areas. Uncontaminated marine sediments were used to partially substitute sand aggregate in the formulation of mortars. Five mortars were manufactured with different percentages of sand substitution. Physical, chemical, mineralogy, and mechanical characterization were carried out in order to investigate their possible use and impact in cemented-based materials. The mechanical strengths and the elastic modulus of mortars were analyzed. The hydration kinetics of the mortars were studied at different temperatures. The acceleration of the chemical reactions was also assessed through the determination of the apparent activation energy of mortars. Finally, the microstructure of two formulations of mortars was observed by Scanning Electron Microscope (SEM). Results show a drop of the mechanical properties with the increase of the percentage of substitution. This can be attributed to the natural composition of sediments and to the increase of the total porosity of the mixtures. The measured heat released of mortars increase with the increase of sediment content. This result suggests an additional chemical activity linked to the presence of sediments within the matrix.</p>	
Keywords (separated by '-')	Dredged sediments - Mortars - Sand substitution - Mechanical properties - Thermo-physical properties	



Mechanical and thermo-physical characterization of mortars made with uncontaminated marine sediments

Amani Abdallah¹ · Hassina Kada¹ · Amrouche Abdelwaheb¹

Received: 24 February 2022 / Accepted: 26 August 2022
 © Springer Japan KK, part of Springer Nature 2022

Abstract

In a context of sustainable development, civil engineering must increasingly use recyclable materials to preserve natural resources. Sediments could be a solution in the context of their recovery in several areas. Uncontaminated marine sediments were used to partially substitute sand aggregate in the formulation of mortars. Five mortars were manufactured with different percentages of sand substitution. Physical, chemical, mineralogy, and mechanical characterization were carried out in order to investigate their possible use and impact in cemented-based materials. The mechanical strengths and the elastic modulus of mortars were analyzed. The hydration kinetics of the mortars were studied at different temperatures. The acceleration of the chemical reactions was also assessed through the determination of the apparent activation energy of mortars. Finally, the microstructure of two formulations of mortars was observed by Scanning Electron Microscope (SEM). Results show a drop of the mechanical properties with the increase of the percentage of substitution. This can be attributed to the natural composition of sediments and to the increase of the total porosity of the mixtures. The measured heat released of mortars increase with the increase of sediment content. This result suggests an additional chemical activity linked to the presence of sediments within the matrix.

Keywords Dredged sediments · Mortars · Sand substitution · Mechanical properties · Thermo-physical properties

Introduction

The accumulation of sedimentary particles at the bottom and on the edges of watercourses and shipping lanes as well as in seaports leads to their clutter. For navigable waterways, it slows the flow and prevents activities of transportation. In order to maintain and restore these accesses, it is necessary to dredge or clean up regularly from coast and estuarine lines around the world.

Each year, several millions of tons of materials are dredged throughout the world [1]. In France, around 50 million m³ of sediments are produced from ports. These materials, which range from rocks to clays, can contain various types and amounts of pollutants and organic matter.

Currently, the French, European and international legislation aims to preserve the environment. Traditional solutions for the management of dredged sediments, such as dumping the sediments at the sea, are constrained.

In this context, due to the shortages of natural resources and the environmental restrictions on the establishment of new quarries as well as the sustainable development approach adopted by several countries, sediment management is increasingly oriented toward valorization processes by respecting technical, environmental, and economic criteria.

The beneficial use of dredged sediments has gained a large acceptance in various domains such as civil engineering, agriculture, and manufacturing.

However, various factors influence the effective use of dredged material, including mineral composition, grain size distribution, and physical and chemical characteristics [2]. Furthermore, there are a number of scientific challenges that must be overcome in order to achieve this beneficial application. Among these, inorganic contaminants, such as heavy metals (copper, chromium, lead, etc.), salts, as well as organic hydrocarbons, such as PAHs (polycyclic aromatic

✉ Amrouche Abdelwaheb
 abdelwaheb.amrouche@univ-artois.fr

¹ Junia, ULR 4515 – LGCgE, Laboratoire de Génie Civil Et Géo-Environnement, Univ. Artois, Univ. Lille, Institut Mines-Télécom, Technoparc Futura, F-62400 Béthune, France

hydrocarbons), PCBs (polychlorinated biphenyls), and TBT (Tributyltin), may be present in sediment [3, 4].

Various treatments and reuse possibilities are available, such as brick production [5–8] or to replace a portion of raw materials in the production of Portland cement clinker [9, 10], sometimes after applying an effective treatment, such as the Novosol process. Aouad et al. [9] showed comparable compressive strengths of a commercially produced Portland cement and a manufactured cement based on sediment.

Many studies on the reuse of sediments as a new material resource in some geotechnical applications as in road basement construction or backfill were conducted [11–15]. The results showed that the use of additives, such as cement, lime, fly ash, and slag, for the solidification/stabilization of sediments can meet the mechanical characteristics requirements as well as the environmental impact standards [15–17]. Depending on the final use, the cost/performance ratio can be assessed by adjusting the proportions of cement and admixtures addition.

In literature, the reuse of sediments in the formulations of mortars or concretes were less studied compared to their reuse in road construction [18–20]. Large amounts of cement, aggregate, and water are necessary for the manufacture of concrete. Many studies have investigated the possibility of the use of sediments in the cement-based materials [21, 22]. Due to the mineralogical and chemical constitution (siliceous, limestone, clayey, etc.) of sediments, their valorization in such cementitious mixtures is very promising. It was demonstrated that treated sediment could be introduced with various proportions into the production of mortars or concretes. Concrete valorization provides some flexibility in terms of granular size distribution and the quantities and types of materials that can be substituted (binder or aggregates).

Most of these studies relies on the substitution of cement by the sediment for the formulations of mortars and concretes [23–27]. However, few studies were conducted on the replacement of sand by sediments in the cement-based materials [18, 28, 29]. Most studies deal with a simple stabilization–solidification process [30–33]. Dredged sediments can fully or partially substitute the sand aggregate [34, 35]. This valorization is very interesting in order to solve a current environmental and economic issue related to the pollution generated by cement industry, a major emitter of CO₂, and the depletion of natural aggregates. The construction industry in France consumes 400 million tons of aggregates per year where 40% are used for concrete structures.

Agostini et al. [28] substituted sand by treated sediment at replacement percentage of 33%, 66%, and 100%. They obtained a compression strength enhancement of 33% with up to 20% of sediment replacement. This result can be explained by the formation of a denser interfacial transition zone in the presence of treated sediment despite the high porosity linked

to the presence of a fine fraction and its constitution in the sediments [28, 29]. This porosity can lead to high amount of absorbed water and high drying shrinkage of mortars.

The full substitution of sand by the coarse fraction of marine sediment was the subject of Couvidat et al. [18]. The authors confirmed that the use of an 80 µm-sized sediment offered an interesting valorization potential as a replacement of sand in mortars for non-structural applications. These studies focus on the valorization of contaminated and treated marine sediments.

The main objective of this paper is the valorization of uncontaminated marine sediments, not subjected to any specific high-cost pre-treatments and the preservation of natural resources. Sediments are used to replace sand in the manufacture of mortars where five formulations were studied. This research was carried out to demonstrate the feasibility of substituting sediments by sand aggregate. These sediments were dredged from the port of Dunkirk, north of France. Physical, chemical, mineralogy, and mechanical characterizations of the dredged sediments were assessed in order to ensure a sustainable management of sediments and investigate their possible use and impact in cemented-based materials.

This impact was evaluated through the evolution of the mechanical properties, such as flexural, compressive, and elastic modulus.

In addition, in order to understand the phenomena behind this substitution, a complete thermo-physical study was conducted. The hydration kinetics was studied by isothermal calorimetry at three different temperatures 20°, 30°, and 40 °C. The activation energy that describes the acceleration of the chemical reactions was determined in order to explain the reactivity issues in the presence of sediments. Therefore, this study was completed by the determination of the thermal conductivity and the specific heat capacity of mortars. Finally, the microstructures of a reference mortar and a sediment-based mortar were given in order to identify the cementitious mineral phases which participate in the mechanisms mentioned above.

This paper describes in Materials and methods, the materials used for the formulation of mortars and the corresponding methods for the characterizations. In the Experiments, the mechanical and thermo-physical experiments are presented. Results of the different performed tests are then reported in Results. At the end, an Interpretations and discussion is dedicated to analyze and discuss the obtained results, followed by the conclusions of this contribution.

Materials and methods

Sediments characterization

The used marine sediments were dredged from the Grand Port Maritime of Dunkirk (GPMD) located in the North of

France. This port dredges about 4 million cubic meters of sediments per year. The characterization of such materials is essential in order to understand their influence and behavior in cemented matrixes and explain some mechanical and physico-chemical properties that can be altered.

Physical characterizations of sediments were performed and results are summarized in Table 1.

The particle size distribution was conducted by laser particle size analysis presented in Figure. 1.

Chemical analysis was also conducted on the used sediments. The proportion of each chemical element was determined by X-ray Fluorescence (XRF). The major chemical elements are Oxygen (~ 50%), Silicon (~ 18%), and Calcium (~ 12%). PAHs value was 5.5 mg/kg and PCBs value was 0.04 mg/kg, which were below the limited value according to AMATR [36].

In addition, leaching tests of the raw sediments were conducted in accordance with the European standard EN 12457-2 (2002). The proportions of heavy metals, pollutants leached and major ions are shown in Table 2. A comparison of the obtained values with the inert waste reference thresholds ISDI (Decree of October 28, 2010 concerning inert waste storage facilities) was made. For the used sediments, the determined values are below the threshold values with the exception of molybdenum (Mo). The studied raw sediments were not contaminated with heavy metals, but they contained high chlorides and sulfates content.

The mineralogical characteristics of the used sediments were also investigated using Siemens D5000 diffractometer (Fig. 2). The XRD analysis provides the presence of crystalline phases. The major elements detected were quartz (SiO_2) and calcite (CaCO_3).

Table 1 Physical characterization of marine sediments

Density (g/cm^3)	Surface area BET (cm^2/g)	Organic matter—LOI (450°C) (%)	Water content (%)	Liquid limit LL (%)	Plastic limit PL (%)	Fine fraction ($D < 63 \mu\text{m}$) (%)	Clay fraction ($D < 2 \mu\text{m}$) (%)
2.45	134,472	10.9	23.64	107	46	72.06	7.13

Fig. 1 Particle size distribution of sediment and sand

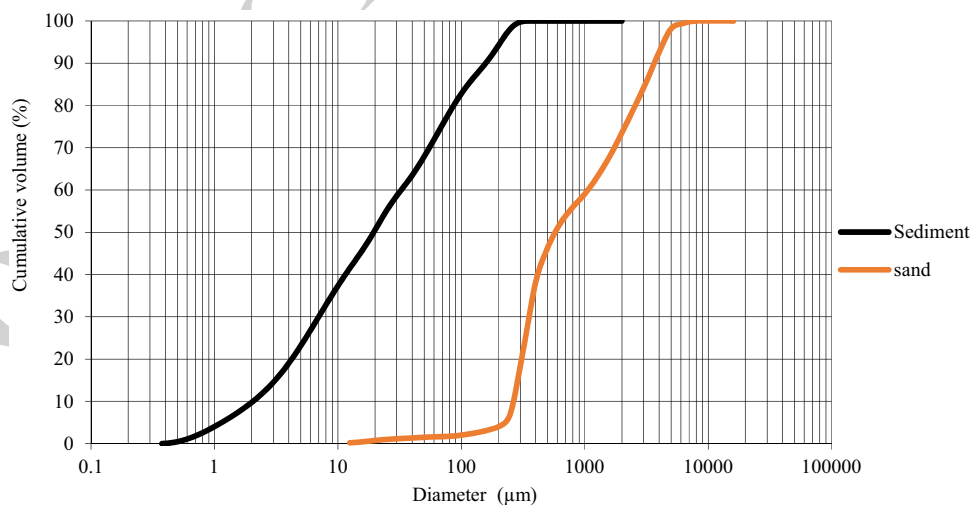


Table 2 Contaminant concentrations in sediments (mg/kg)

Element	Antimony (Sb)	Arsenic (As)	Barium (Ba)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Mercury (Hg)	
Concentration (mg/Kg)	0.066	<0.08	0.370	<0.008	<0.03	0.192	0.004	
ISDI limits	0.1	0.5	20	0.04	0.5	2	0.01	
Element	Lead (Pb)	Molybde- num (Mo)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)	Fluorides	Chlorides	Sulfates
Concentration (mg/Kg)	<0.03	0.618	<0.03	<0.07	<0.06	<2.5	14,900	12,580
ISDI limits	0.5	0.5	0.4	0.1	4	10	800	1000

Formulations

Five mortars were formulated for which the sand being replaced by the same volume of sediment at replacement percentages of 0%, 5%, 15%, 30%, and 40%, referred to MT, MT5, MT15, MT30, and MT40, respectively. The reference mortar MT is a standard mortar mixed on a ratio basis of 1 part of cement to 3 parts of sand and half part of water.

The slump of mortars was measured using the Abrams' mini-cone (see Table 3). It can be seen that all formulations have almost the same consistency.

Table 3 presents the composition of the various formulations studied in 1 L of volume. The effective water-to-cement (W/C) ratio was kept constant (0.5) for all formulations. The absorption coefficient of sediments was determined according to standard NF EN 1097-6. A value of 35% was obtained. The sediments were pre-saturated for 2 h before mixing in order to prevent the main issue of porous aggregate linked to their high water absorption capability. The formulations were prepared according to the mixture procedure described in the European standard EN 196-1 [37]. For each formulation, three prismatic samples of $4 \times 4 \times 16 \text{ cm}^3$ were prepared and cured until 28 days. The slump of mortars was measured using the Abrams' mini-cone (see Table 3). It can be seen that all formulations have almost the same consistency.

Portland cement CEM I 52.5R (Calcia Cement from Couvrot) was used. The mortar aggregate was CEN siliceous sand (according to EN 196-1), with rounded grains (Class 0/5). This sand has a silica content of at least 98%. Its density is 2.60 g/cm^3 measured by helium pycnometer and it has an absorption coefficient equal to 0.7%. The particle size distribution of sand is presented in Fig. 1.

Table 3 Composition of the sediment-based mortars (in 1L)

Mortar	MT	MT5	MT15	MT30	MT40
Cement (g)	507	507	507	507	507
Sand (g)	1526	1450	1298	1068	916
Effective Water (g)	253	253	253	253	253
Sediment (g)	0	95	285	570	760
W/C	0.5	0.5	0.5	0.5	0.5
Density (g/cm^3)	2.11	2.09	2.07	2.04	1.98
Slump (cm)	0	1.0	1.1	1.2	3.1

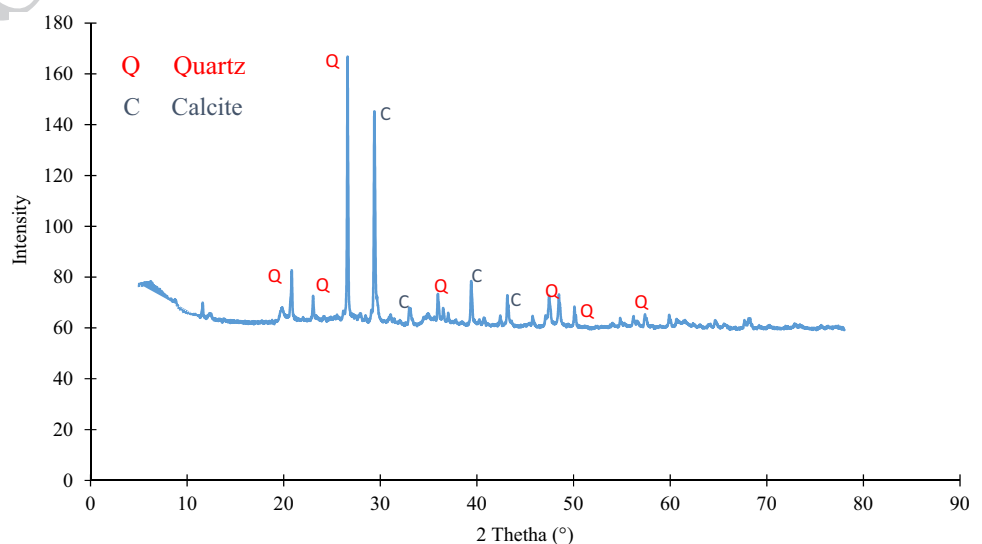
Experiments

The mechanical strengths of the prismatic mortar samples were determined in accordance with the European standard EN 196-1. Flexural and compressive tests were carried out using a mechanical INSTRON testing machine (loading capacity of 1500 kN). These tests were performed on the reference and sediment-based mortars after being cured in water for 7, 14, and 28 days. Results are the averages of three samples.

A method was developed to determine the elastic modulus E of the mortars using strain gages. It consists in recording the deformation of the tested specimen when subjected to a compression imposed by the INSTRON testing machine with a displacement control. Optimization works were realized in order to obtain accurate values of the elastic modulus. These optimizations concern the length of the used strain gages ($L = 20 \text{ mm}$) and their installation on the specimen's surface, the rate of displacement, and the compensation of temperature effect.

The pore size distribution of mortars was measured with a Micrometrics Auto pore IV using Mercury Intrusion

Fig. 2 XRD analysis on the studied sediment



Porosimetry (MIP) technique (Standard NF P 94-410-3). Measurements were taken for the reference mortar and for the sediment-based mortars. The samples were stored under the same conditions as those mechanically tested at 20 °C and cured in water for 28 days.

Heat of hydration

Many previous research is limited on the study of the mechanical properties of cemented-based materials. In this paper, a further study on the thermo-physical properties was conducted in order to better understand the influence of sediments and the mechanisms that can occur when incorporated in mortars.

The hydration reaction being thermoactive, an isothermal calorimeter was used at three imposed temperatures (20 °C, 30 °C, and 40 °C) that correspond to usual concrete applications [38]. For each formulation of mortar, the total flux, the heat of hydration, and the activation energy were determined.

The activation energy of the formulated mortars was determined in order to understand the reactivity issues when substituting a given proportion of sand by sediment in cementitious matrix [39, 40]. The hydration reactions being exothermic, at a given time, the amount of heat released is the reflection of the overall state of progress of the various chemical reactions between cement constituents and mixing water. Previous studies have shown that in the case of concrete, the Arrhenius law was the most suitable to describe the acceleration of the chemical reactions. It is of the form:

$$K(T) = A \exp\left(-\frac{E_a}{RT}\right), \quad (1)$$

where $K(T)$ denotes the kinetic constant at temperature T , A the constant of proportionality (1/s), R the perfect gas constant = 8.314 J/mol K, E_a the apparent activation energy (J/mol), and T temperature (°Kelvin).

The apparent activation energy is specific to the studied composition and must be determined before each maturo-metric study. The apparent activation energy must be calculated for a range of temperatures representative of those encountered on the site. For two different thermal histories, the apparent activation energy can be determined from the progress of the hydration reaction or from the quantities related to this progress, such as the compressive strength or the heat released by hydration.

The method used in this study is the “superposition” method. It consists in determining a constant value of the apparent activation energy allowing to superimpose as much as possible two curves of resistance or heat evolution as a function of the equivalent age.

The equivalent age t_{eq} corresponds to the time during which a concrete must be kept at a reference temperature T_{ref} (generally 20 °C) to reach the same maturity as under real curing conditions. It can be written as

$$t_{eq} = \int_0^t \exp\left(-\frac{E_a}{R}\left(\frac{1}{T(\tau)} - \frac{1}{T_{ref}}\right)\right) d\tau, \quad (2)$$

where $T(\tau)$ is the absolute temperature at the moment τ (°Kelvin), R the perfect gas constant = 8.314 J/mol K, T_{ref} the reference temperature, E_a the apparent activation energy (J/mol).

The target is finding the value of the apparent activation energy that minimizes the differences between the different pairs of equivalent ages (t_{eq1i} , t_{eq2i}) over the targeted range. This optimization is performed using the least squares method. The value of the apparent energy sought is the one that meets the following criterion:

$$\min_{E_a} \left(\sum_{X_i \in [X_{inf} - X_{sup}]} |t_{eq1i} - t_{eq2i}|^2 \right), \quad (3)$$

where t_{1i} and t_{2i} correspond to the actual curing ages for the same amount of heat Q_i (or the same resistance R_{ci}), t_{eq1i} and t_{eq2i} are the corresponding equivalent ages.

Thermal conductivity and specific heat capacity

The thermal conductivity is a measurement of a material's capacity to conduct heat. It is often used in the construction industry to assess its thermal performance. It measures the amount of heat transmitted due to a unit temperature gradient through a unit thickness in a direction normal to the surface of a unit area in a steady condition. Thus, to evaluate the influence of sediments on mortars, the thermal conductivity (λ) of samples was determined with the heat flux meter method, based on the EN 12664 standard [41]. This method involves measuring temperatures and heat flow on both sample faces at the same time. Surface temperatures are measured by T-type thermocouples and heat flux are measured by flux meters. The temperatures are applied on both sides of the sample thanks to two exchanger plates and controlled by bath thermostats. The sample and flux meters are surrounded by an insulating boundary to ensure unidirectional flow in the central measurement area. To determine λ , a temperature gradient is generated ($\Delta T = 10$ °C) and the thermal conductivity is calculated for an almost zero heat flux difference on both sample sides. The thermal conductivity is expressed by Eq. 4:

$$\lambda = \frac{\sum \phi \times e}{2 \times \Delta T}, \quad (4) \quad C_p = \frac{Q}{\rho \times A \times e \times \Delta T}, \quad (5)$$

with λ : thermal conductivity of the material ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), e : sample thickness (m), $\sum \phi$: sum of both recorded heat flux at the sample surface ($\text{W} \cdot \text{m}^{-2}$), and ΔT : temperature gradient ($^{\circ}\text{C}$).

The specific heat capacity is also an important parameter for construction materials. It depends on the density and the nature of the material in study. It characterizes the ability of a material to store heat and represents the amount of heat per mass unit required to raise the temperature by one degree. To determine the thermal capacity of a material, the method is based on the process of heat storage of the material. In the initial state, the system is isothermal: the exchange plates are at temperature (T_{init}). The final system is also in an isothermal state (T_{fin}). The sample stores an amount of energy that represents the system's internal energy variation between these two states (Q). The material's specific heat (C_p) can then be calculated using Eq. (5). A higher specific heat capacity value means that the material can store more heat and contribute more effectively to building insulation.

with C_p : specific heat capacity ($\text{J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$), e : sample thickness (m), ρ : density ($\text{kg} \cdot \text{m}^{-3}$), A : surface of the material in contact with the exchange plates, Q : stored energy (J), and ΔT : temperature gradient ($^{\circ}\text{C}$).

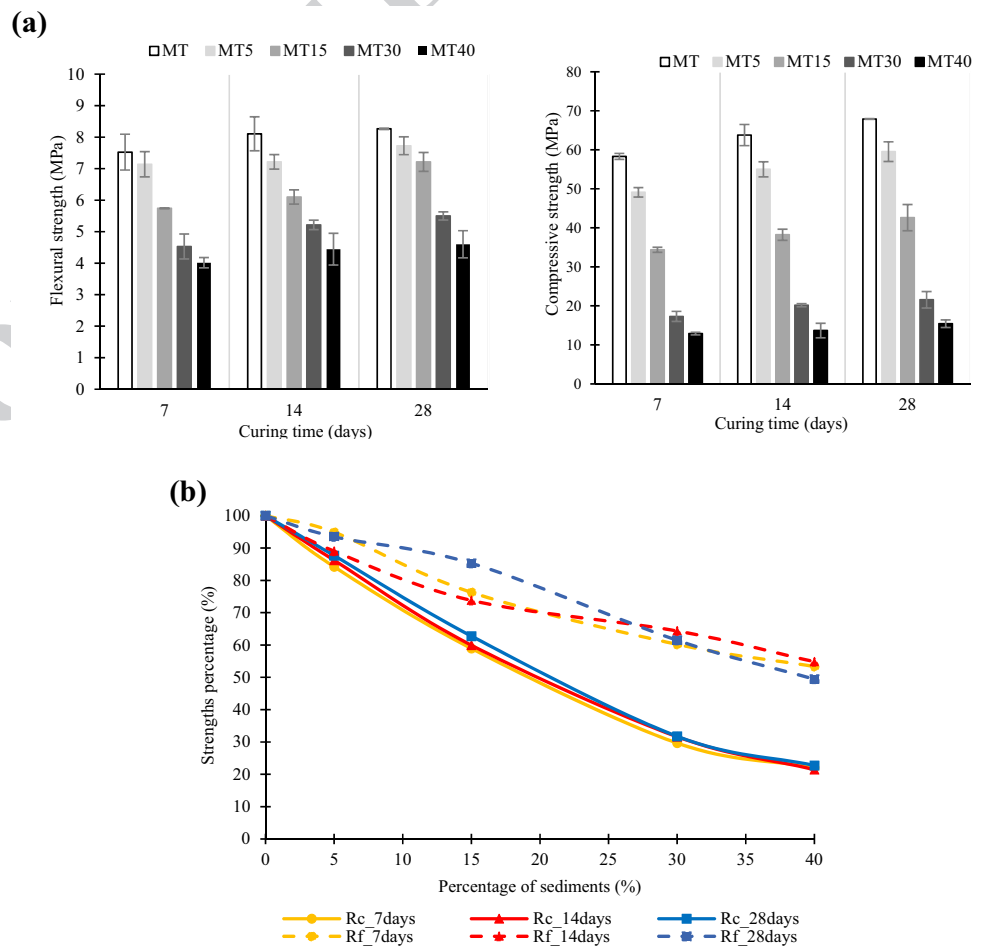
Results

Mechanical properties

Flexural and compressive strengths

The flexural and compressive strengths of the reference and sediment-based mortars are presented in Fig. 3a. Average values obtained by three measurements for flexural strength and six measurements for compressive strength are shown with the corresponding standard deviation. The mechanical strengths of all the formulated mortars increase with the curing time as expected.

Fig. 3 **a** Flexural and compressive strengths of mortars at 7, 14, and 28 curing days. **b** Flexural strength (Rf) and compressive strength (Rc) percentage of mortars at 7, 14, and 28 curing days



Both the flexural and compressive strengths of mortars decreased with the proportion increase of sediment for 7, 14, and 28 days of curing in water.

This decrease is linear with the amount of substitution of sand by sediment up to 30% of replacement, independently of the curing time as illustrated in Fig. 3b. Rc and Rf stand for the compressive and flexural strengths, respectively. For MT5, the compressive strength dropped by 13%, while 38% for MT15, 69% for MT30, and 77% for MT40. For the flexural strength, it dropped by 10% for MT5 to 50% for MT40.

Elastic modulus

The average elastic modulus of three measurements for each formulation of sediment-based mortars are presented in Fig. 4, for 7, 14, and 28 curing days. The errors on the measurements are less than 5%. The elastic modulus E decreases when the percentage of replacement of sand by sediment increase independently of the curing time. The mortars became more deformable with the increase of substitution percentage. The elastic modulus of the reference mortar is equal to 35000 MPa, while the sediment-based mortar MT40 has a value around 8000 MPa at 28 days.

The percentage of decrease of the elastic modulus at 28 days with respect to the reference mortar MT is similar to the results obtained for the compressive strength. 10% of decrease was noticed for MT5 whereas approximately 80% for MT40 (see Fig. 4b).

In addition, it is remarkable that the elastic modulus of MT and MT5 increase between 7 and 28 curing days contrary to the other formulations. This can be linked to the formation of an internal cracking for high substitution rate of sediments due to the presence of some disruptive elements that will be discussed in Interpretations and discussion.

Mercury porosity

The porosity of a cement matrix is a fundamental measurement for characterizing the microstructure and determining the material's durability. This test yields a global result ("total porosity"), which is an indicator of the quality of the material [42]. It evaluates the percentage of connected voids. The test results at 28 curing days are given in Table 4. The results confirm that the presence of sediments modifies the pore structure. The average pore diameter is smaller for mortars having high percentage of sediments. However, the total intrusion volume and total pore area are higher for MT40 than for mortars with low percentage of replacement. This result can be refined by presenting the pore size distribution of mortars in Fig. 5. The mortars with high percentage of sediments (MT30 and MT40) have higher proportion of small pores but lower large pores. This highlights the porous nature of the used marine sediments. The total porosity of

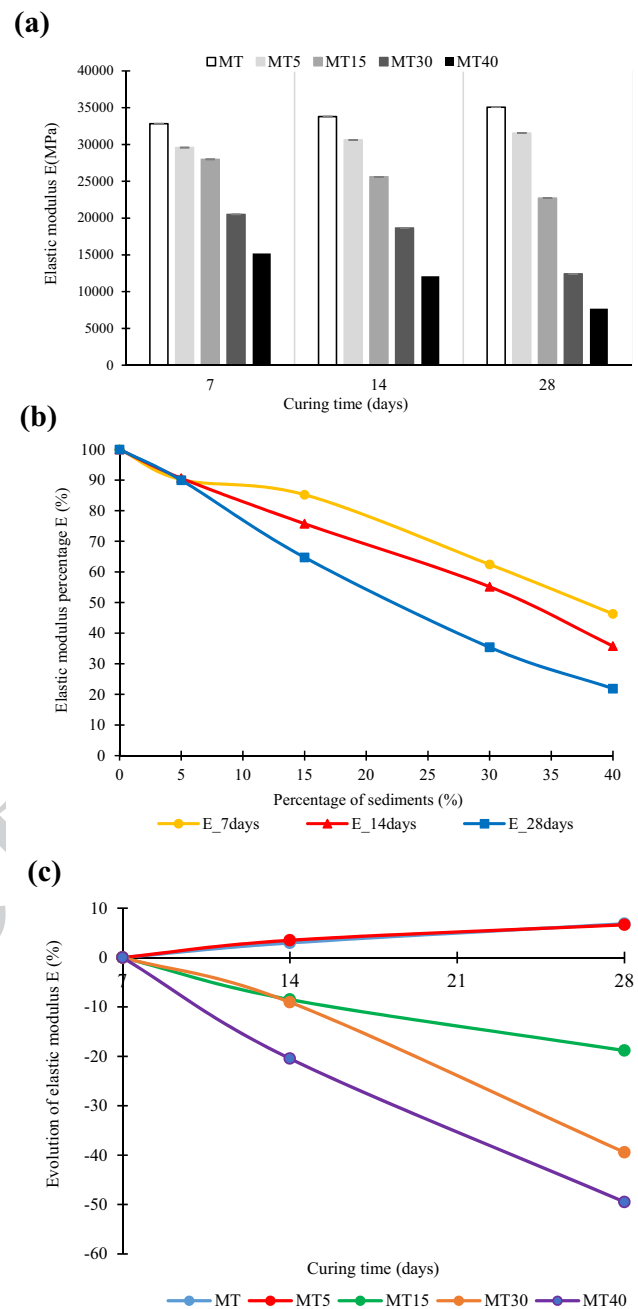


Fig. 4 a Elastic modulus of mortars at 7, 14, and 28 curing days. b Percentage of elastic modulus of mortars at 7, 14, and 28 curing days. c Evolution in time of the elastic modulus (%) of mortars

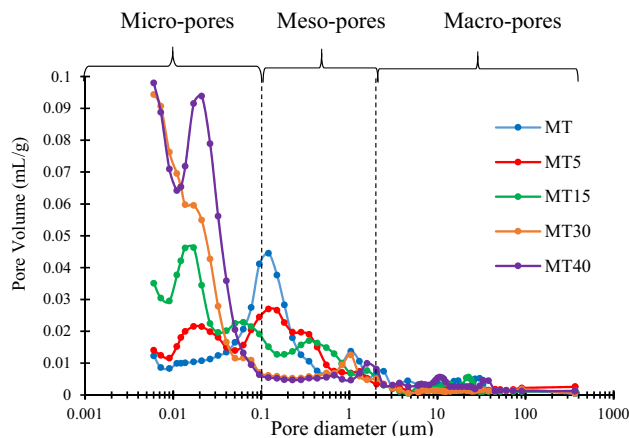
mortars increases with the percentage of sediments. MT presents 9.92%, whereas MT40 is equal to 16.56%. MT is the least porous mortar in this study.

Heat of hydration measurements

The results of the hydration kinetics observed on the five formulations of mortars are presented in this section. The

Table 4 Mortars porosity using a mercury porosimetry analysis at 28 curing days

Formulations	MT	MT5	MT15	MT30	MT40
Average pore diameter (4 V/A) (μm)	0.05372	0.03851	0.02470	0.01510	0.01704
Total intrusion volume (mL/g)	0.0458	0.0446	0.0559	0.0658	0.0841
Total pore area (m^2/g)	3.41	4.63	9.05	17.42	19.75
Porosity (%)	9.92	9.85	11.95	13.45	16.56

**Fig. 5** Pore size distribution of mortars measured by MIP at 28 days

total flux and the heat of hydration Q (J/g) of the formulated mortars at the three imposed temperatures 20, 30, and 40°C are presented in Fig. 6a–f, respectively. The heat of hydration Q (J/g) can be determined by an integration of the heat flux. The start time of the hydration reaction is calculated for each mortar at 20°C and 30°C (Table 5). It represents the end of the “latent period” where the flux changes are very small and the beginning of the “acceleration period” where the flux starts to evolve. It is difficult to determine such period for the formulated mortars at 40°C due to the accelerating effect of temperature on the hydration reactions of cement as it is clearly shown in Fig. 6a–c. Thus, the latent period is very short at 40°C compared to 20°C . It can be noticed a delay when the percentage of sediments increase for both temperatures. At 20°C , the hydration reaction started after 163 min for the reference mortar MT while after 200 min for the sediment-based mortar MT40. Nearly the same delay effect was observed at 30°C , the reactions begins after 54 min for MT while 96 min for MT40.

One can also notice an increase of the maximum heat flux with the increase of sediment substitution. Same trend was observed for the total heat flux at the imposed temperatures 20, 30, and 40°C . However, at high temperature (40°C), there is an acceleration of the hydration reactions of cement. This effect can be highlighted by presenting the results of the activation energy in the upcoming section.

Comparing the heat curves of the formulated mortars, it is apparent that the heat released of mortars increases with

the increase of sediment content. At 20°C , the heat released for MT is 333 J/g whereas 383 J/g for MT40. At 30°C , it is 315 J/g for MT and 367 J/g for MT40 while at 40°C , 315 J/g for MT and 376 J/g for MT40. The reaction is much more accelerated when the temperature increases. These results could suggest an additional chemical activity due to the presence of sediments within the matrix [43].

In order to describe more precisely these observed phenomena, a parameter was determined which refers to the apparent activation energy E_a described previously in Results. In this paper, a superposition method for determining this parameter for the formulated mortars is presented. This method is based on the evolution curves of the heat released which define the maturity of the hydration reaction of cement.

An apparent activation energy value is calculated for each pair of temperatures (20 – 30°C), (30 – 40°C), and over the entire temperature range (20 – 40°C) for the different formulated mortars. These results are presented in Table 6.

It can be noticed that the apparent activation energy is higher when the substitution percentage of sediments is high. At the range (20 – 30°C), E_a for MT is 31.4 kJ/mol , whereas E_a for MT40 is equal to 36.8 kJ/mol . In addition, one can observe that the apparent activation energy varies with the temperature. It is obvious that E_a is higher for higher temperatures.

The evolution of the apparent activation energy is highlighted in Fig. 7. A quasi-linear evolution of E_a is observed as function of sediment percentage for the three pairs of temperature. This evolution is small up to 5% of substitution. Therefore, the hydration reaction is little affected by this introduction of sediments. However, the evolution of E_a is much more important for MT15, MT30, and MT40. E_a increases around 9%, 15%, and 18%, respectively, for each pair of temperature. One can say that the effect of sediments is not modified with the increase of temperature.

Thermal conductivity and specific heat capacity

Figure 8 presents the evolution of the thermal conductivity and the specific heat capacity of the reference mortar (MT) and sediment-based mortars.

The thermal conductivity of (MT) is $1.25 \text{ W.m}^{-1} \cdot \text{K}^{-1}$ in conformity with the values obtained in literature [44–46], while it decreases to $0.66 \text{ W.m}^{-1} \cdot \text{K}^{-1}$ for MT40. This

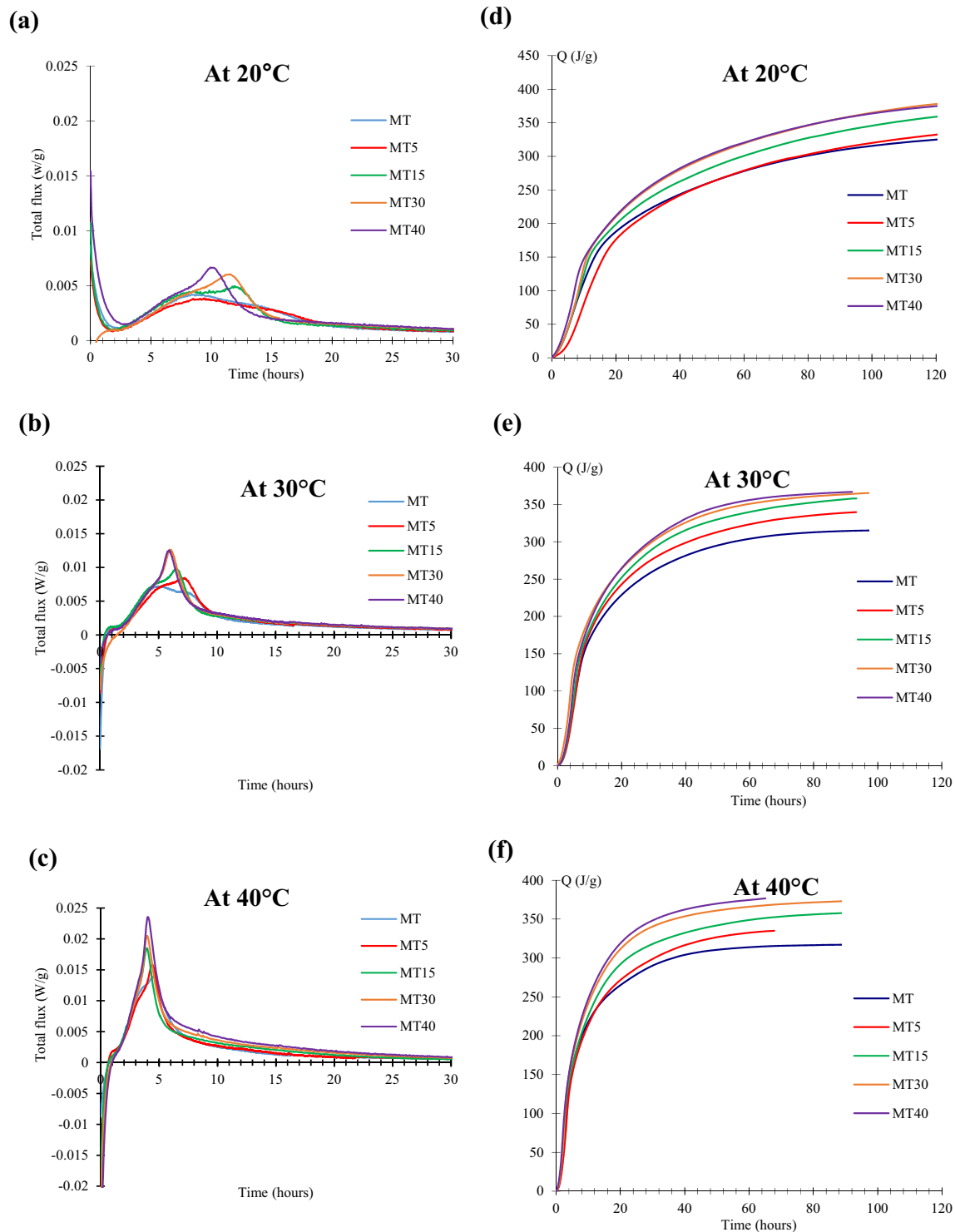


Fig. 6 Total flux (a,b,c) and heat of hydration Q (J/g) (d,e,f) of the formulated mortars at imposed temperatures 20°, 30° and 40 °C

decrease is linear with the percentage of sediments incorporated in the formulated mortars. It ranges from 10 to 50% for MT5 and MT40, respectively.

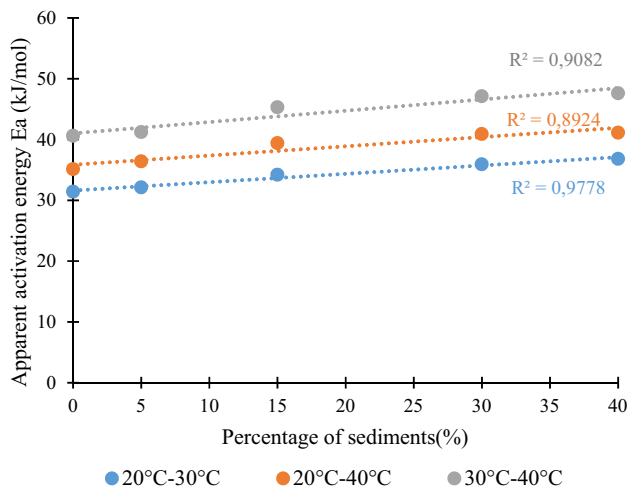
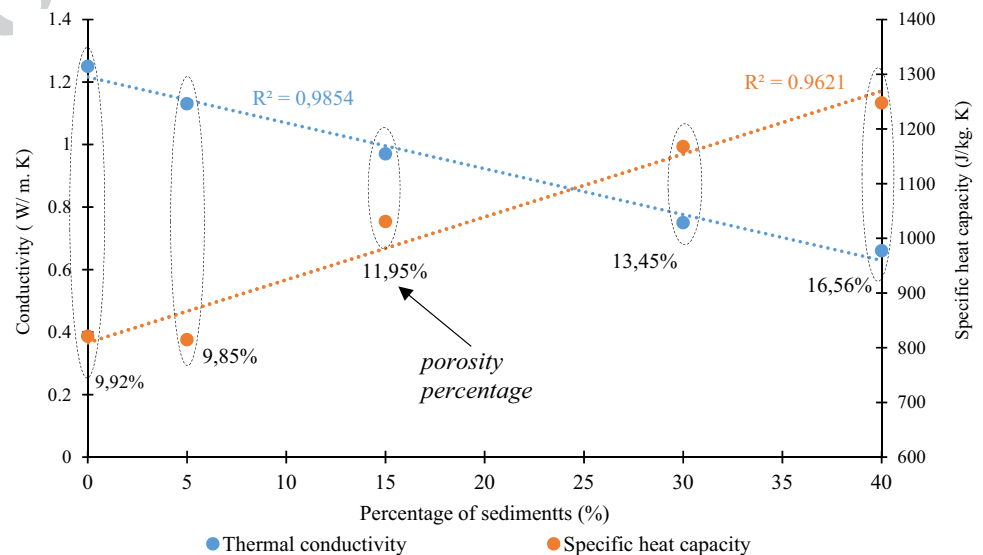
Contrary to the thermal conductivity, the specific heat capacity increase in the presence of sediments. C_p increases from 821 J/kg. K for MT to 1247 J/kg. K for MT40. An increase of 50% was observed for 40% of sand replacement.

Table 5 Hydration start time of mortars (min)

Temperatures	MT	MT5	MT15	MT30	MT40
20 °C	163	165	170	180	200
30 °C	54	57	78	90	96

Table 6 Values of the apparent activation energy E_a (kJ/mol) determined by superposition method

Range of temperatures (°C)	MT	MT5	MT15	MT30	MT40
20–30	31.4	32.1	34.2	35.9	36.8
20–40	35.1	36.4	39.4	40.9	41.1
30–40	40.6	41.2	45.3	47.1	47.6

**Fig. 7** Evolution of the apparent activation energy of mortars**Fig. 8** Evolution of the thermal conductivity and the specific heat capacity of mortars

Microstructural properties: scanning electron microscopy observations.

The microstructures of the reference mortar MT and the sediment-based mortar MT30 were observed by Scanning Electron Microscope (SEM) with back-scattered electron diffraction.

After 28 days curing in water, pieces of 1cm³ were cut from the core of the mortar samples. All samples were epoxy impregnated and polished according to a standardized process.

Figure 9 displays the textures and cementitious phases microstructures obtained for the studied mortars MT and MT30.

From a qualitative point of view, no major differences in terms of cement matrixes can be observed between the reference and the sediment-based mortar in the SEM images. Crystalline portlandite, needle-shaped ettringite and amorphous calcium-silicate-hydrates (C-S-H) can be clearly recognized. Pores of various sizes can also be seen among the solids.

However, C-S-H gel was found in greater amounts in samples of the reference mortar compared to MT30. It was observed that the C-S-H mineral phases were well formed, and large amounts of hydration products covered the particles forming a dense and homogeneous microstructure. The well formation of C-S-H improved the microstructure by improving the solid-to-solid phase connectivity and minimizing the pore-to-pore connectivity.

Diverse CH crystallization was observed in the sediment-based mortar MT30, with thin hexagonal and globular-shaped portlandite crystals (alite and belite).

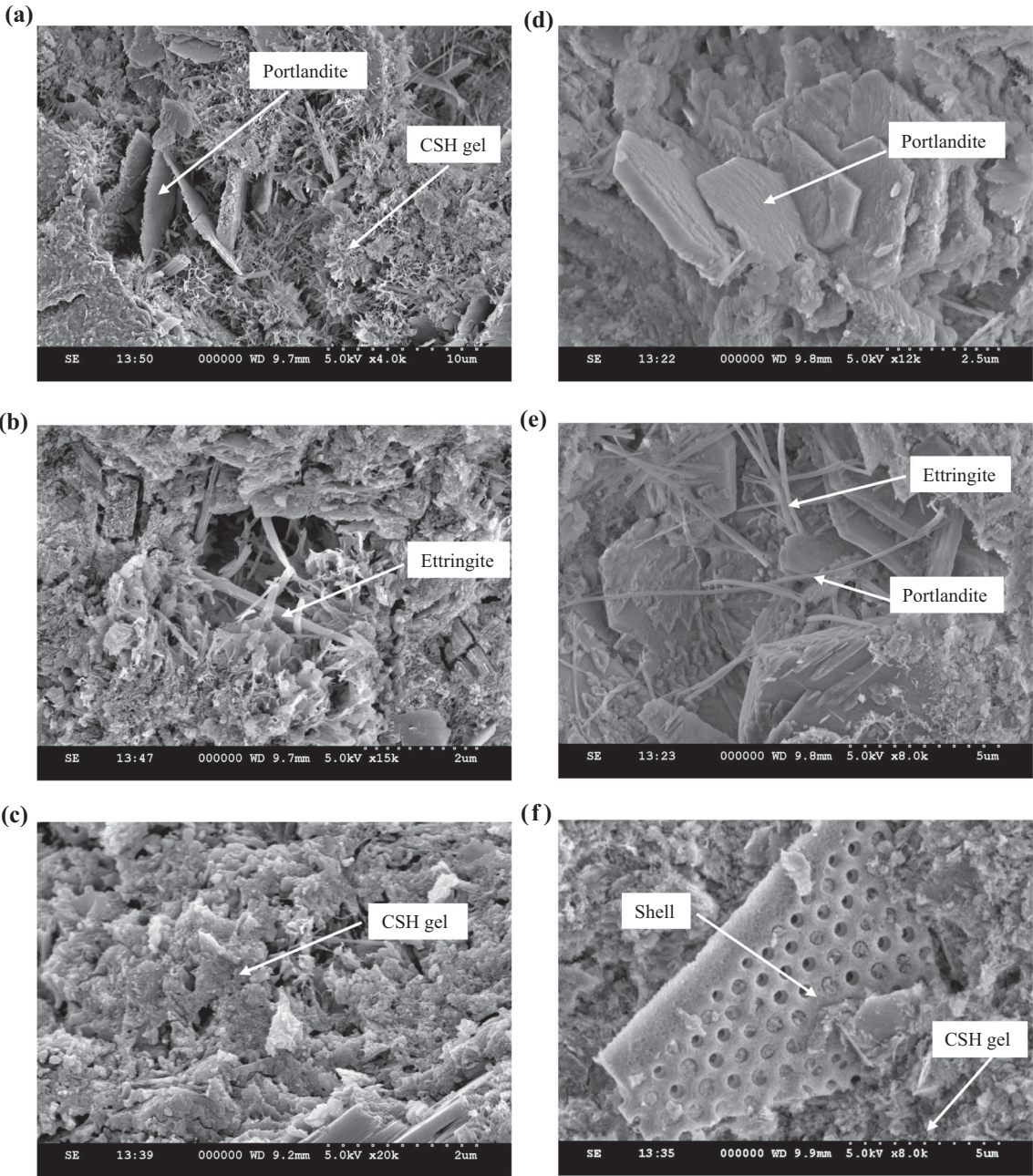


Fig. 9 SEM with back-scattered electron pictures of MT (a, b, c) and MT 30 (d, e, f) samples at 28 days of curing time

Interpretations and discussion

The feasibility of the uncontaminated marine sediments used in the formulation of mortars as a replacement of

sand aggregate was assessed.

The mechanical strength is an important characteristic that has to be determined for the purposes of valorization.

It allows the evaluation of the material's physical integrity as well as the determination of its potential reuses.

The mechanical strength comes mainly from the formation of cemented products. The hydrating processes are affected by introducing the sediments as aggregates.

The used sediments contain 10.9% of organic matter (Table 1). These latter are known to interfere with the hydration process of cement as mentioned in previous works [47, 48]. In particular, it is known that the most acidic fraction prevents the formation of CSH phases by lowering the pH of water.

The marine sediments contain also chloride salts (Table 2). Their high salinity has a negative impact on the mechanical strength development of cement-based materials. The influence of salts was the subject of a previous study conducted by Kamali et al. [13]. The authors have found a low mechanical performance of mortars mixtures made with unwashed sand. They demonstrated that the effect of chloride contained in sediments can be reduced by a washing process.

Besides, traces of metals are contained in the studied sediments (Table 2). Although their concentrations are low, they can influence the quality of the obtained mortars.

The presence of constituents, such as Zinc (Zn), Cadmium (Cd), or Chromium (Cr), may alter the hydration processes and have a negative impact on the mechanical strength by affecting the mortar's average porosity according to Arliguie and Grandet [49]. Zinc presents the largest impact out of all the other pollutants. Its presence causes a significant reduction in the compressive strength by affecting the hydration of C_3S and C_3A [55, 56]. Bhatti [52] previously investigated the impact of all trace elements in cement production and consumption. The mechanisms that normally lead to the development of hydrates (CSH) or the pores network can be disturbed [51, 53, 54].

Same trend was observed for the elastic modulus which decreases in the presence of sediments (Fig. 4). It is known that the elastic modulus is highly influenced by the aggregates modulus that compose the cemented materials as well as by their form and texture [55]. The decrease with the sediment substitution can be explained by the means of two factors. Sediments are known to have low resistance compared to natural aggregates like sand. In addition, sediments are high porous by nature. This high internal porosity generates an increase of the mortars porosity as it is given in Table 4 where the sediment-based mortar MT40 has the highest total porosity (16.56%).

As described previously, the hydration in presence of sediments is modified due to the existence of some heavy metals, organic matter, salts, such as chlorides, sulfates, etc. This modification is accentuated with the quantity of such elements which is directly correlated to the substitution rates of sediments in the cement matrix. In the presence

of these elements, we have a dissolution of the portlandite and a progressive decalcification in time of the CSH leading to an increase in their porosity [56, 57]. These phenomena cause internal cracking, which explains the decrease of the elastic modulus as a function of time, particularly for mortars MT30 and MT40 [58–60]. The elastic modulus is more sensitive to these variations compared to the resistances. For the latter, these effects are masked due the continuation of hydration and the increase of the bonds between the CSH. It is noticed that we have almost no evolution of resistances for the mortars with high substitution rates of sediments.

The micro-porosity of the sediments can be observed when comparing the distribution of porosity (Fig. 5). The pore structure can be divided into three main ranges as it was reported in Cheng et al. [61]. The micro-pores which correspond to the pore diameter $< 0.1 \mu m$, the meso-pores for pore diameter ranging between $0.1 \mu m$ and $2 \mu m$, and the macro-pores for pore diameter $> 2 \mu m$. The mortars with high percentage of replacement have a porosity distribution ranged in the first domain representing micro-pores. This can be explained by the internal porosity of the used marine sediments.

The meso-pores and macro-pores which come mainly from water loss are low. This can be attributed to the fact that the sediments were pre-saturated before mixing. Thus, the water added for saturation is sufficient to respond to the water demand of sediments due to the presence of high concentrations of organic matter and clays.

There exists a certain link between the mechanical properties discussed. Figure 10 represents the link between the compressive strength, the total porosity, and the elastic modulus of the formulated mortars. A clear correlation is observed. When porosity is high, the mechanical strength and the elastic modulus are low. The mechanical strength decrease is linked to the total porosity [62].

According to Verbeck and Helmuth [63], a change in porosity ratio of 1% can result in a 10% loss in elastic modulus. Same result was obtained in this study where the elastic modulus of MT40 decreases by 80% when its porosity increases by around 8%. The resistance of mortars is primarily a consequence of their porosity. Up to 30% of sand replacement by sediment, the decrease of the mechanical properties is significant. Between 30 and 40%, this effect is reduced. Similar results were obtained by Couvidat et al. [18], who fully replaced sand by sediments. The authors obtained a linear correlation between the increase in total pore area and the decrease in compressive strength.

The hydration kinetics of the formulated mortars were investigated by means of the isothermal calorimeter. The heat released is higher in the presence of the used sediments (Fig. 6). The physical characterization presented in Table 1 shows that 70% of the sediments have a diameter lower than $63 \mu m$ and mineralogical characteristics of

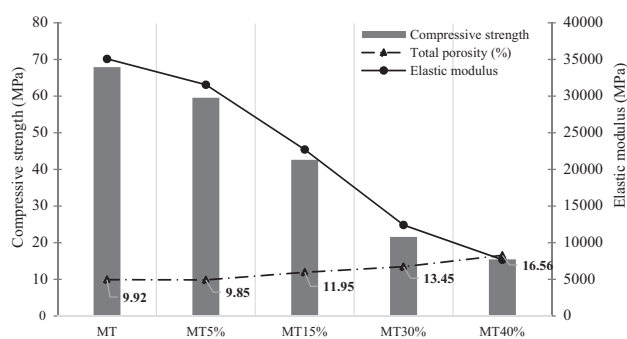


Fig. 10 Compressive strength of mortars linked to the total porosity and elastic modulus at 28 days of curing time

sediments revealed that the major elements are calcite and quartz. Regarding these findings, it seems that sediments are not totally considered as inert admixture. However, they have a certain chemical activity linked to their granulometry and mineralogical composition. They can participate in the exothermic reactions of hydration. It seems also that the quality of the bonds between the hydrates formed in the presence of sediments are altered despite the increase of heat released. This assumption is confirmed by the degraded properties determined previously.

A small delay of the hydration was observed (Table 5) in the presence of sediments. This can be associated to the presence of some heavy metals, such as Zinc (Zn) [49], and also to the presence of marine salts in sediments as shown by Minocha et al. [50].

Apparent activation energy was calculated for the formulated mortars. An increase was observed when the percentage of replacement of sand by sediments increase. This can be explained by the fact that higher energy is necessary to activate the hydration reaction of cement in the presence of the used sediments. This result confirm the decrease of the mechanical strengths observed previously. Bresson [64] have found a correlation between the activation energy of a cement and its actual class at two days. Waller [65] compared values of the activation energy for different types of cement and demonstrated that the activation energy is inversely proportional to the mechanical strength.

The high porosity observed in the sediment-based mortars has also an influence on the thermal conductivity and the specific heat capacity (Fig. 8). The available voids inside the cement-based materials and the sediment's internal porosity have a significant effect on the thermal conductivity due to the low thermal conductivity of air [66]. In addition, the rise of the specific heat capacity when substituting sand by sediment can be explained by the decrease of the density of mortars as shown previously in Table 3 [67, 68].

Conclusions

This study investigated the potential use of uncontaminated marine sediments to replace sand aggregate in mortars. Five mortars were formulated for which the sand being replaced by the same volume of sediment at replacement percentage of 0%, 5%, 15%, 30%, and 40%.

Based on the different experimental tests carried out, the following conclusions can be drawn:

- The used sediments had important fine particles content ($70\% < 63 \mu\text{m}$). They were classified as uncontaminated sediments containing high amount of salts. They were mainly composed of quartz (SiO_2) and calcite (CaCO_3).
- The mechanical properties of mortars decreased with the increase of sediments percentage. Up to 30% of sand replacement, the decrease is significant. It attained 70% for the sediment-based mortar MT40.
- The total porosity increased as the sediment substitution content increase, but the pore size distribution was shifted toward smaller particles. This highlights the porous nature of the used marine sediments. MT is the least porous mixture (9.92%). The increase in total porosity is linked to the decrease of the mechanical strengths.
- The total flux and heat released measured were higher in the presence of sediments. A delay of the exothermic hydration reactions was also observed. Sediments had a certain chemical activity linked to their granulometry and mineralogical compositions.
- A linear evolution of the apparent activation energy E_a was observed as function of sediments percentage. An increase of 18% was observed for MT40. Higher energy was necessary to activate the hydration reactions in the presence of sediments which confirm the decrease of the mechanical strengths.
- The thermal conductivity λ of mortars decreased, while the specific heat capacity C_p increased with the percentage of sand replacement. An evolution of 50% was observed for MT40. This can be attributed to the high porosity and low density of the sediment-based mortars. MT is the mixture having the highest density correlated to the lowest value of C_p and highest value of λ . The higher the C_p value, the more the material retains the stored heat and contributes to the insulation of the construction.
- Cementitious mineral phases (CSH, portlandite, ettringite) were identified in the reference (MT) and sediment-based (MT30) mortars. In particular, CSH were well formed and were found in greater amount in MT.

From the mechanical and thermo-physical experimental results of this study, the uncontaminated marine sediments

can be used as cementitious materials in mortars. The obtained properties confirm the possibility of sediments valorization depending on the intended applications. The sediment-based mortar MT40 has the lowest compressive strength of 15 MPa. This value is higher than the minimum strength required for structural applications (8 MPa).

One can mention that the origin of sediments (marine or fluvial) could influence the properties of recovered materials especially concerning the salinity in presence. Supplementary experiments would be needed to assess the durability of mortars.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- R. Boutin (1999), "Amélioration des connaissances sur le comportement des rejets en mer de produits de dragage de type vase : phénomènes à court terme et dans le champ proche," thesis, Lyon, INSA.
- Junakova N, Junak J, Balintova M (2015) Reservoir sediment as a secondary raw material in concrete production. *Clean Techn Environ Policy* 17(5):1161–1169. <https://doi.org/10.1007/s10098-015-0943-8>
- Rozière E, Samara M, Loukili A, Damidot D (2015) Valorisation of sediments in self-consolidating concrete: mix-design and microstructure. *Constr Build Mater* 81:1–10. <https://doi.org/10.1016/j.conbuildmat.2015.01.080>
- He J, Shi X, Li Z, Zhang L, Feng X, Zhou L (2020) Strength properties of dredged soil at high water content treated with soda residue, carbide slag, and ground granulated blast furnace slag. *Constr Build Mater* 242:118126. <https://doi.org/10.1016/j.conbuildmat.2020.118126>
- Hamer K, Karius V (2002) Brick production with dredged harbour sediments. an industrial-scale experiment. *Waste Manage* 22(5):521–530. [https://doi.org/10.1016/S0956-053X\(01\)00048-4](https://doi.org/10.1016/S0956-053X(01)00048-4)
- Cappuyns V, Deweirt V, Rousseau S (2015) Dredged sediments as a resource for brick production: possibilities and barriers from a consumers' perspective. *Waste Manage* 38:372–380. <https://doi.org/10.1016/j.wasman.2014.12.025>
- Xu Y, Yan C, Xu B, Ruan X, Wei Z (2014) The use of urban river sediments as a primary raw material in the production of highly insulating brick. *Ceram Int* 40(6):8833–8840. <https://doi.org/10.1016/j.ceramint.2014.01.105>
- Samara M, Lafhaj Z, Chapiseau C (2009) Valorization of stabilized river sediments in fired clay bricks: factory scale experiment. *J Hazard Mater* 163(2):701–710. <https://doi.org/10.1016/j.jhazmat.2008.07.153>
- Aouad G, Laboudigue A, Gineys N, Abriak NE (2012) Dredged sediments used as novel supply of raw material to produce Portland cement clinker. *Cem Concr Compos* 34(6):788–793. <https://doi.org/10.1016/j.cemconcomp.2012.02.008>
- Dalton JL, Gardner KH, Seager TP, Weimer ML, Spear JCM, Magee BJ (2004) Properties of Portland cement made from contaminated sediments. *Resour Conserv Recycl* 41(3):227–241. <https://doi.org/10.1016/j.resconrec.2003.10.003>
- Wang D, Abriak NE, Zentar R (2017) Dredged marine sediments used as novel supply of filling materials for road construction. *Marine Georesources Geotechnol* 35(4):472–480. <https://doi.org/10.1080/1064119X.2016.1198945>
- Rekik B, Boutouil M (2009) Geotechnical properties of dredged marine sediments treated at high water/cement ratio. *Geo-Mar Lett* 29(3):171–179. <https://doi.org/10.1007/s00367-009-0134-x>
- Siham K, Fabrice B, Edine AN, Patrick D (2008) Marine dredged sediments as new materials resource for road construction. *Waste Manage* 28(5):919–928. <https://doi.org/10.1016/j.wasman.2007.03.027>
- Wang D, Abriak N-E, Zentar R, Xu W (2012) Solidification/stabilization of dredged marine sediments for road construction. *Environ Technol* 33:95–101. <https://doi.org/10.1080/09593330.2011.551840>
- Dubois V, Abriak NE, Zentar R, Ballivy G (2009) The use of marine sediments as a pavement base material. *Waste Manage* 29(2):774–782. <https://doi.org/10.1016/j.wasman.2008.05.004>
- Zentar R, Dubois V, Abriak NE (2008) Mechanical behaviour and environmental impacts of a test road built with marine dredged sediments. *Resour Conserv Recycl* 52(6):947–954. <https://doi.org/10.1016/j.resconrec.2008.02.002>
- Ennahal I, Maherzi W, Mamindy-Pajany Y, Benzerzour M, Abriak N-E (2019) Eco-friendly polymers mortar for floor covering based on dredged sediments of the north of France. *J Mater Cycles Waste Manag* 21(4):861–871. <https://doi.org/10.1007/s10163-019-00843-3>
- Couvidat J, Benzaazoua M, Chatain V, Bouamrane A, Bouzahzah H (2016) Feasibility of the reuse of total and processed contaminated marine sediments as fine aggregates in cemented mortars. *Constr Build Mater* 112:892–902. <https://doi.org/10.1016/j.conbuildmat.2016.02.186>
- Meyer C (2009) The greening of the concrete industry. *Cem Concr Compos* 31(8):601–605. <https://doi.org/10.1016/j.cemconcomp.2008.12.010>
- Kasmi A, Abriak N-E, Benzerzour M, Azrar H (2017) Environmental impact and mechanical behavior study of experimental road made with river sediments: recycling of river sediments in road construction. *J Mater Cycles Waste Manag* 19(4):1405–1414. <https://doi.org/10.1007/s10163-016-0529-5>
- Benslafa FKA, Kerdal D, Ameur M, Mekerta B, Semcha A (2015) Durability of mortars made with dredged sediments. *Procedia Eng* 118:240–250. <https://doi.org/10.1016/j.proeng.2015.08.423>
- Zhao Z, Benzerzour M, Abriak N-E, Damidot D, Courard L, Wang D (2018) Use of uncontaminated marine sediments in mortar and concrete by partial substitution of cement. *Cement Concr Compos* 93:155–162. <https://doi.org/10.1016/j.cemconcomp.2018.07.010>
- Benzerzour M, Maherzi W, Mouhamadou AA, Amar N-E, Damidot D (2018) Formulation of mortars based on thermally treated sediments. *J Mater Cycles Waste Manag* 20(1):592–603. <https://doi.org/10.1007/s10163-017-0626-0>
- Benzerzour M, Amar M, Abriak N-E (2017) New experimental approach of the reuse of dredged sediments in a cement matrix by physical and heat treatment. *Constr Build Mater* 140:432–444. <https://doi.org/10.1016/j.conbuildmat.2017.02.142>
- Amar M, Benzerzour M, Safhi AEM, Abriak N-E (2018) Durability of a cementitious matrix based on treated sediments. *Case Stud Constr Mater* 8:258–276. <https://doi.org/10.1016/j.cscm.2018.01.007>
- Benkaddour M, Kazi Aoual F, Semcha A (2009) Durabilité des mortiers à base de pouzzolane naturelle et de pouzzolane artificielle. *Rev Nat Tecnol* 1(1):63–73
- Dang TA, Kamali-Bernard S, Prince WA (2013) Design of new blended cement based on marine dredged sediment. *Constr Build*

- Mater 41:602–611. <https://doi.org/10.1016/j.conbuildmat.2012.11.088>
28. Agostini F, Davy CA, Skoczylas F, Dubois Th (2010) Effect of microstructure and curing conditions upon the performance of a mortar added with treated sediment aggregates (TSA). *Cem Concr Res* 40(11):1609–1619. <https://doi.org/10.1016/j.cemconres.2010.07.003>
 29. Agostini F, Skoczylas F, Lafhaj Z (2007) About a possible valorisation in cementitious materials of polluted sediments after treatment. *Cement Concr Compos* 29(4):270–278. <https://doi.org/10.1016/j.cemconcomp.2006.11.012>
 30. Chen QY, Tyrer M, Hills CD, Yang XM, Carey P (2009) Immobilisation of heavy metal in cement-based solidification/stabilisation: a review. *Waste Manag* 29(1):390–403. <https://doi.org/10.1016/j.wasman.2008.01.019>
 31. Gardner KH, Tsiatsios CJ, Melton J, Seager TP (2007) Leaching behavior of estuarine sediments and cement-stabilized sediments in upland management environments. *Waste Manag* 27(11):1648–1654. <https://doi.org/10.1016/j.wasman.2006.09.002>
 32. Paria S, Yuet PK (2011) Solidification–stabilization of organic and inorganic contaminants using portland cement: a literature review. *Environ Rev*. <https://doi.org/10.1139/a06-004>
 33. Zentar R, Wang D, Abriak NE, Benzerzour M, Chen W (2012) Utilization of siliceous–aluminous fly ash and cement for solidification of marine sediments. *Constr Build Mater* 35:856–863. <https://doi.org/10.1016/j.conbuildmat.2012.04.024>
 34. Benzaazoua M, Fall M, Belem T (2004) A contribution to understanding the hardening process of cemented pastefill. *Miner Eng* 17(2):141–152. <https://doi.org/10.1016/j.mineng.2003.10.022>
 35. Yan DYS, Tang IY, Lo IMC (2014) Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction. *Constr Build Mater* 64:201–207. <https://doi.org/10.1016/j.conbuildmat.2014.04.087>
 36. Sétra Amatr (2012), Guide méthodologique : Acceptabilité de Matériaux Alternatifs en Techniques Routière, Evaluation environnementale.
 37. EN 196–1:(2005), Standard Methods of Testing Cement - Part 1: Determination of Strength, CEN.
 38. H. Kada-Benameur (1998), “Techniques de mesures fluxmétriques appliquées à l’étude de la cinétique d’hydratation des bétons : calorimétrie isotherme et mesures directes sur ouvrages,” These de doctorat, Artois.
 39. Kada-Benameur H, Wirquin E, Duthoit B (2000) Determination of apparent activation energy of concrete by isothermal calorimetry. *Cem Concr Res* 30(2):301–305. [https://doi.org/10.1016/S0008-8846\(99\)00250-1](https://doi.org/10.1016/S0008-8846(99)00250-1)
 40. Wirquin E, Broda M, Duthoit B (2002) Determination of the apparent activation energy of one concrete by calorimetric and mechanical means: influence of a superplasticizer. *Cem Concr Res* 32(8):1207–1213. [https://doi.org/10.1016/S0008-8846\(02\)00770-6](https://doi.org/10.1016/S0008-8846(02)00770-6)
 41. AFNOR, NF EN 12664 (2001), Performance thermique des matériaux et produits pour le bâtiment, Détermination de la résistance thermique par la méthode de la plaque chaude gardée et la méthode fluxmétrique.
 42. Nielsen LF (1993) Strength development in hardened cement paste: examination of some empirical equations. *Mater Struct* 26(5):255–260. <https://doi.org/10.1007/BF02472946>
 43. M. Amar (2017), “Traitement des sédiments de dragage pour une valorisation dans les matrices cimentaires,” These de doctorat, Lille 1.
 44. J. G. Ndong Engone (2015), “Développement de matériaux cimentaires à base de sous-produits bois : mise en forme par extrusion et vibrocompactage,” These de doctorat, Artois.
 45. Demirboğa R (2003) Influence of mineral admixtures on thermal conductivity and compressive strength of mortar. *Energy Build* 35(2):189–192. [https://doi.org/10.1016/S0378-7788\(02\)00052-X](https://doi.org/10.1016/S0378-7788(02)00052-X)
 46. Shafigh P, Asadi I, Akhiani AR, Mahyuddin NB, Hashemi M (2020) Thermal properties of cement mortar with different mix proportions. *Mater Construcc* 70:339–224. <https://doi.org/10.3989/mc.2020.09219>
 47. Tremblay H, Duchesne J, Locat J, Leroueil S (2002) Influence of the nature of organic compounds on fine soil stabilization with cement. *Can Geotech J* 39:535–546. <https://doi.org/10.1139/t02-002>
 48. Beddaa H, BenFraj A, Lavergne F, Torrenti JM (2019) Effect of potassium humate as humic substances from river sediments on the rheology, the hydration and the strength development of a cement paste. *Cem Concr Compos* 104:12. <https://doi.org/10.1016/j.cemconcomp.2019.103400>
 49. Arliguie G, Grandet J (1990) Influence de la composition d’un ciment portland sur son hydratation en présence de zinc. *Cem Concr Res* 20(4):517–524. [https://doi.org/10.1016/0008-8846\(90\)90096-G](https://doi.org/10.1016/0008-8846(90)90096-G)
 50. Minocha AK, Jain N, Verma CL (2003) Effect of organic materials on the solidification of heavy metal sludge. *Constr Build Mater* 17(2):77–81. [https://doi.org/10.1016/S0950-0618\(02\)00098-3](https://doi.org/10.1016/S0950-0618(02)00098-3)
 51. Park C-K (2000) Hydration and solidification of hazardous wastes containing heavy metals using modified cementitious materials. *Cem Concr Res* 30(3):429–435. [https://doi.org/10.1016/S0008-8846\(99\)00272-0](https://doi.org/10.1016/S0008-8846(99)00272-0)
 52. Bhatti JI and Portland Cement Association (1995), Role of minor elements in cement manufacture and use. Skokie, Ill.: Portland Cement Association.
 53. Malviya R, Chaudhary R (2006) Factors affecting hazardous waste solidification/stabilization: a review. *J Hazard Mater* 137(1):267–276. <https://doi.org/10.1016/j.jhazmat.2006.01.065>
 54. Minocha A, Jain N, Verma CL (2003) Effect of inorganic materials on the solidification of heavy metal sludge. *Cem Concr Res* 33:1695–1701. [https://doi.org/10.1016/S0008-8846\(03\)00146-7](https://doi.org/10.1016/S0008-8846(03)00146-7)
 55. Carlos A, Arruda A, Silva T, Carvalho P, Trautwein L (2017) Influence of coarse aggregate on concrete’s elasticity modulus. *Acta Sci Technol* 39:17–25. <https://doi.org/10.4025/actascitechnol.v39i1.29873>
 56. J. Perreault-Chabot (2010), “Modélisation de la pénétration des chlorures dans les stationnements multiétages,” <https://corpus.ulaval.ca/jspui/handle/20.500.11794/21347>.
 57. Neville A (2004) The confused world of sulfate attack on concrete. *Cem Concr Res* 34(8):1275–1296. <https://doi.org/10.1016/j.cemconres.2004.04.004>
 58. Regourd M. (1975) L’action de l’eau de mer sur les ciments ». *Annales de l’ITBTP, supplément au n° 329, Série « Lians hydrauliques » n° 25*, p. 86–102.
 59. Bonnell DGR, Nottage ME (1939) Studies in porous materials with special reference to building materials: I. The crystallisation of salts in porous materials. *J Soc Chem Ind* 58:16–21
 60. La durabilité des bétons. Bases scientifiques pour la formulation de bétons durables dans leur environnement, Chapitres 2–3–12, Jean-Pierre Ollivier, Angélique Vichot.
 61. Cheng S, Shui Z, Sun T, Yu R, Zhang G (2018) Durability and microstructure of coral sand concrete incorporating supplementary cementitious materials. *Constr Build Mater* 171:44–53. <https://doi.org/10.1016/j.conbuildmat.2018.03.082>
 62. N. T. Tran (2009), “Valorisation de sédiments marins et fluviaux en technique routière,” These de doctorat, Artois.
 63. F. Marot (1997), “Caractérisation et traitement de sédiments de dragage contenant des polluants métalliques,” These de doctorat, Le Havre.

64. J. Bresson (1980), "La prévision des résistances des produits en béton : Facteur de maturité - Temps équivalent". Publication Technique N° 56. 1000
65. V. Waller (1999), "Relations entre composition des betons, exothermie en cours de prise et resistance en compression," phdthesis, Ecole des Ponts. 1001
66. Asadi I, Shafigh P, Abu Hassan ZFB, Mahyuddin NB (2018) Thermal conductivity of concrete – a review. J Build Eng 20:81–93. <https://doi.org/10.1016/j.jobbe.2018.07.002> 1002
67. Uysal H, Demirboğa R, Şahin R, Gül R (2004) The effects of different cement dosages, slumps, and pumice aggregate ratios on the thermal conductivity and density of concrete. Cem Concr Res 34(5):845–848. <https://doi.org/10.1016/j.cemconres.2003.09.018> 1003
68. Demirboğa R, Türkmen İ, Burhan Karakoç M (2007) Thermo-mechanical properties of concrete containing high-volume mineral admixtures. Build Environ 42(1):349–354. <https://doi.org/10.1016/j.buildenv.2005.08.027> 1004

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. 1005

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law. 1006
1007
1008

Journal:	10163
Article:	1497

Author Query Form

Please ensure you fill out your response to the queries raised below and return this form along with your corrections

Dear Author

During the process of typesetting your article, the following queries have arisen. Please check your typeset proof carefully against the queries listed below and mark the necessary changes either directly on the proof/online grid or in the 'Author's response' area provided below

Query	Details Required	Author's Response
AQ1	Please check and confirm that the authors and their respective affiliations have been correctly identified and amend if necessary.	
AQ2	Kindly provide volume details for reference [58] and amend if necessary.	
AQ3	Author names: Please confirm if the author names are presented accurately and in the correct sequence Author 3 Given name: [Amrouche] Last name [Abdelwaheb]. Also, kindly confirm the details in the metadata are correct.	
AQ4	Please check the spelling of the word 'maturometric' in the sentence 'The apparent activation... each maturometric study.' for clarity and amend if necessary.	
AQ5	Please check the terms 'C-S-H' and 'CSH' for consistency throughout the article and correct if necessary.	