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IMPACT OF SUBSTITUTION OF PORTLAND CEMENT BY UNTREATED DREDGED SEDIMENTS ON CONCRETE PROPERTIES

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ABSTRACT : In a context where the construction industry is seeking to reduce its carbon footprint, this article explores the integration of St. Lawrence River dredged sediments as a partial substitute for Portland cement in the design of low environmental impact concretes. The aim is to assess the technical and environmental feasibility of this approach in relation to construction materials management practices in Quebec. The sediments studied are highly plastic silty clays, subjected to a treatment including drying, crushing and grinding. Their physical (particle size, density, consistency), chemical (elemental analysis by X-ray fluorescence) and mineralogical (identification of crystalline phases by X-ray diffraction) characteristics were analyzed to assess their compatibility with the requirements of cementitious materials. In terms of mechanical performance and durability, compression tests were carried out on mortars substituting 20% of GU cement with sediment, with measurements taken at the ages of 1, 7, 28 and 112 days. The microstructural study assessed the pore distribution and connectivity using mercury intrusion porosimetry and computed tomography. The results show a compressive strength of 51.2 MPa for the control mortar, made up solely of GU cement, versus 50.2 MPa for the mortar containing 20% of the sediment powder after 112 days. This represents approximately 98% of the performance of mortar made from 100% GU cement. From an operational point of view, this approach offers a dual advantage: efficient reclamation of harbour sediments, thereby reducing the costs associated with their management, and a reduction in the carbon footprint associated with cement production. These results offer promising prospects for materials engineering professionals and port managers, facilitating the integration of sediments into civil engineering applications while meeting performance and sustainability requirements.

1. INTRODUCTION

Dredged sediments are geosourced materials made up of mineral and organic particles accumulated in port areas. Extracted by dredging, sediments are classified as waste. Managing dredged sediments represents a major challenge for port and waterway managers. Every year, large volumes of sediment are extracted to maintain navigation safety and the operational efficiency of port infrastructure. In Quebec alone, around 500,000 m³ of sediment is dredged annually from the St. Lawrence River (MeRLIN, 2018), but its reuse remains limited, often leading to its treatment as waste. Current disposal methods, such as transport to storage sites or treatment of contaminated materials, generate considerable costs, ranging from $10 to $50 CAD per m³, and up to $100 to $500 CAD per m³ for contaminated sediments (*Programme décennal de dragage d'entretien au quai de Rivière-du-Loup: rapport d'enquête et d'audience publique*, 2022). These practices not only add to the operational budgets of harbour authorities; they also exacerbate the environmental impact of the sector, underscoring the urgent need for more sustainable management of these wastes.

At the same time, the production of cement, a key material in the construction industry, is facing growing environmental challenges. This sector is responsible for around 7% of global CO_2 emissions per year (Barbhuiya, Kaminaris, Das, & Idrees, 2024 ; Falana, Osei-Kyei, & Tam, 2024 ; Friedlingstein et al., 2020), largely due to the clinker production process, which is extremely energy-intensive and emits CO_2. In addition, the industry's heavy reliance on virgin raw materials exacerbates the depletion of natural resources, calling for low-carbon concrete designs to reduce the ecological impact of concrete.

Faced with these two challenges, this article proposes an innovative approach: transforming dredged sediments into supplementary cementitious materials (SCM) to produce low-carbon concrete. By partially substituting cement, dredged sediments could contribute to the efforts of the construction industry:
i. Reduced costs and CO_2 emissions: incorporating sediments into low-carbon concrete formulations reduces the expense of disposal and significantly lowers the carbon footprint compared with Portland cement.
ii. Waste recovery: Dredged sediments, often considered worthless waste, become a valuable resource, meeting the principles of the circular economy.
iii. Conservation of natural resources: By limiting dependence on virgin raw materials, they promote sustainable resource management, while offering competitive mechanical performance and durability.

In addition to these technical and environmental contributions, this research also aims to popularize the potential of sediments. This article presents the technical feasibility of replacing cement with sediments. The impact on the carbon footprint will be presented in another article.

2. MATERIALS AND METHODS

2.1 Materials

In this study, dredged sediments were collected from the Port of Montreal in Contrecoeur, Quebec (Canada). Prior to physical and chemical characterization, the sediments were dried to a constant mass at 110°C, then crushed using a jaw crusher and finely ground in a vibrating bucket (Figure 1).

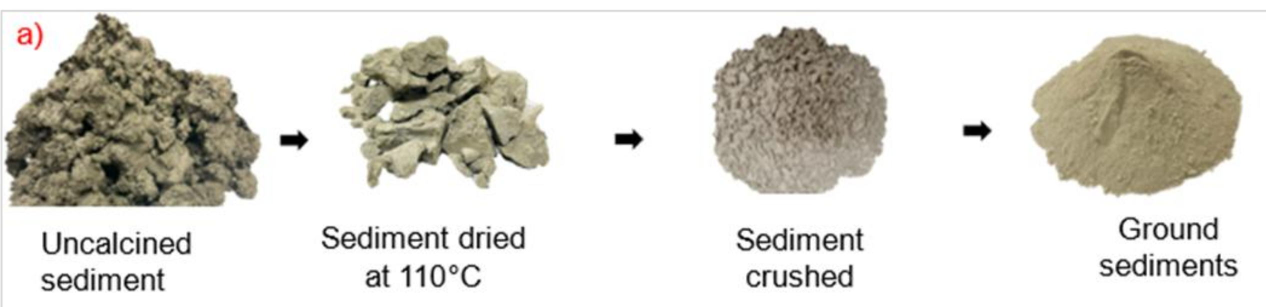

Figure 1: Sample preparation

Ordinary Portland cement (GU) was used as the reference binder for mortar preparation. The following abbreviations are used throughout this study: SB for raw sediment and GU for general-purpose Portland cement. To assess the reactivity of the raw sediments (SB), comparisons were made with two reference materials: quartz (Q), considered an inert material, and metakaolin (MK), recognized for its high pozzolanic reactivity.
Prior to drying, the Atterberg limits and initial water content of the sediments were determined to better understand their behavior in the presence of water. The chemical composition of the sediments was obtained through X-ray fluorescence (XRF) analysis and is presented in Table 1. This analysis quantifies

the major oxides present in the material, including silica (56.24%), alumina (16.06%), ferric oxide (7.81%), and other elements typically found in harbor sediments.

The mineralogical composition of the sediments, determined by X-ray diffraction (XRD), is shown in Figure 2, while that of the GU cement is provided in Table 2. The XRD analysis was performed using cobalt radiation. The sediments are primarily composed of crystalline minerals, including quartz, albite, and dolomite.

Among these phases, quartz is generally considered chemically inert under standard cement hydration conditions and therefore contributes only as a filler without participating in the hydration process. However, the presence of albite ($NaAlSi_3O_8$), a sodium-rich feldspar, suggests a potential for slow dissolution under alkaline conditions, releasing sodium and silicate ions that may promote the formation of secondary calcium-silicate-hydrate (C–S–H) phases over time (Gambus et al., 2021). This delayed reactivity could contribute modestly to the long-term pozzolanic behavior of the sediments. Additionally, dolomite ($CaMg(CO_3)_2$), though less reactive, may interact with portlandite to form secondary products such as brucite ($Mg(OH)_2$) and carboaluminates, which can influence microstructural densification and durability.

Table 1: Chemical composition of materials

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	P_2O_5	MnO_4	LOI
SB	56.24	16.06	7.81	5.36	4.69	3.19	2.94	0.71	0.13	0.12	6.05
GU	19.2	4.69	3.61	61.5	2.40	3.98	1.06	0.25	0.25	0.14	2.62
Q	91.4	4.94	1.72	0.55	0.04	0.1	1.09	0.1	0.01	-	-
MK	62,5	31,0	1,1	0,4	0,3	-	-	0,6	-	-	-

Table 2: Mineral composition of materials

	C_3S	C_2S	C_3A	C_4AF	Quartz	Anorthite	Calcite
GU	63.4	7.3	3.9	13.0	0.1		2.2
Q					98.5	1.1	

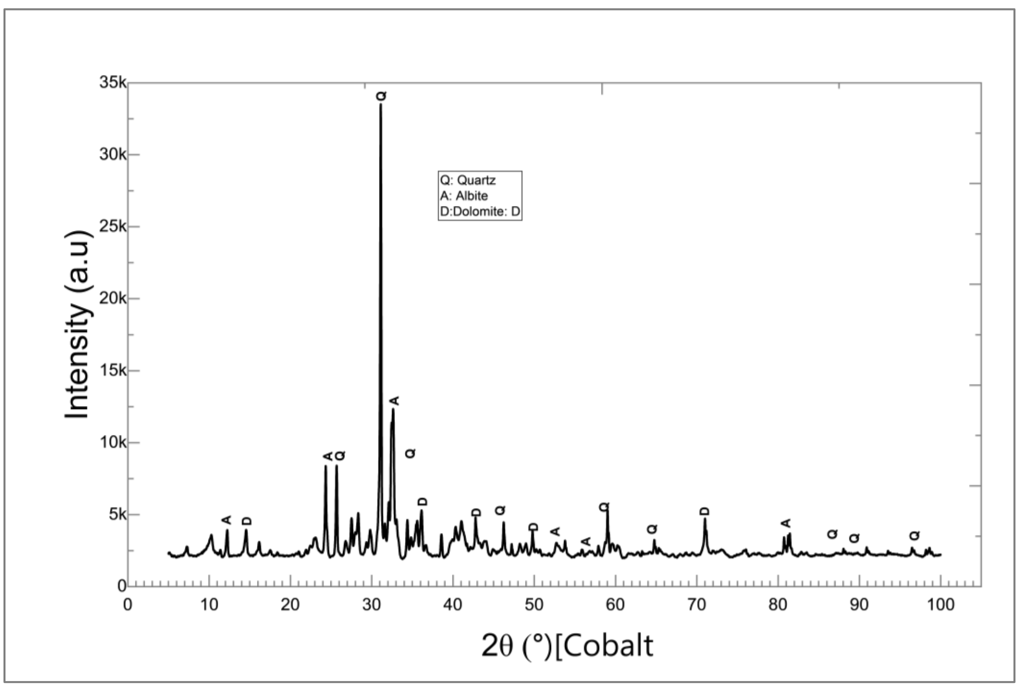

Figure 2: mineralogical composition of sediments

Loss on Ignition (LOI) is a key parameter that can influence the cement hydration process, particularly due to its potential effects of dilution or delayed reactivity. In this study, LOI was determined using two methods: X-ray fluorescence (XRF), which yielded a value of 6.05% as presented in Table 1, and thermogravimetric analysis (TGA), which gave a value of 6.14%, as shown in Figure 3. These closely aligned results are consistent with the organic matter content, also measured by TGA, and estimated at 1.81%. Although moderate, the LOI remains below the 10% threshold set by the CSA A3000 standard, and falls within a range considered suitable for use as a supplementary cementitious material (Elert et al., 2018).

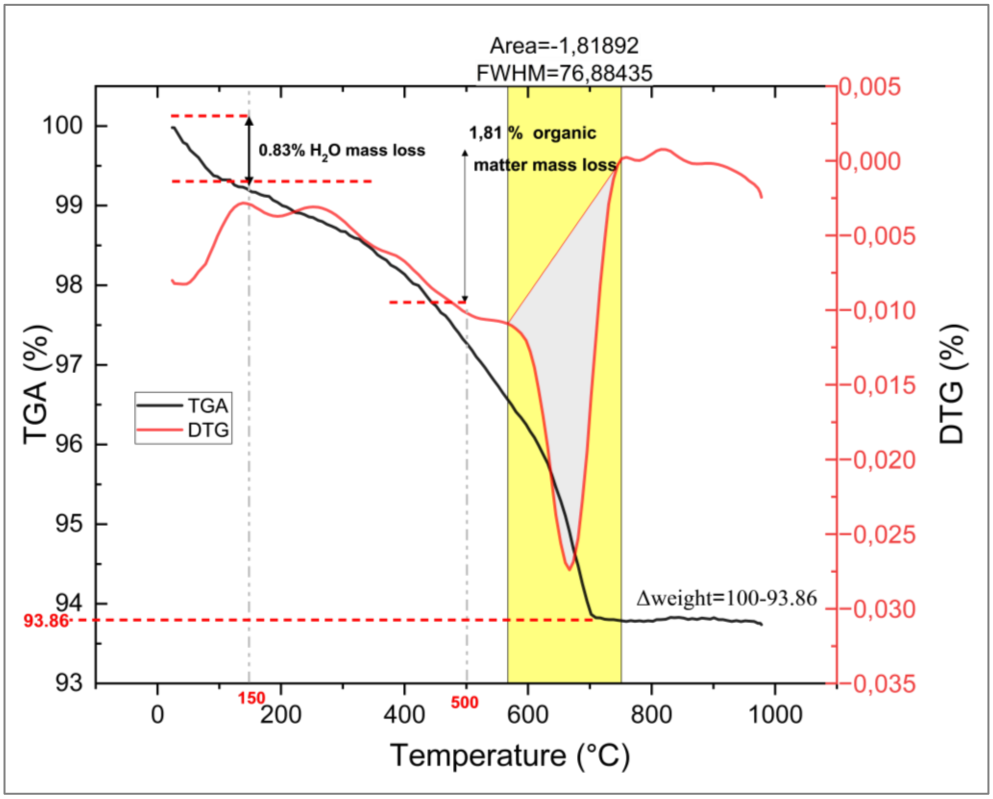

Figure 3: Organic matter obtained by TGA

The physical properties of the materials are summarized in Table 3. Sediment particle size distribution was determined using a Malvern Mastersizer laser diffraction particle sizer, using isopropanol as the dispersing agent. Density was measured by helium pycnometry, while organic matter content was assessed by thermogravimetric analysis.

Table 2: Physical properties of the cement, dredged sediments, and sand

SCM	GU	SB	Sand
d_{10} (µm)	2.25	0.03	160
d_{50} (µm)	15.00	2.60	410
d_{90} (µm)	35.00	25.80	1000
Clay (%) Ø<2 µm	-	47.39	-
Silts (%) 80 µm <ø<2 µm	-	48.61	-

Sand (%) 80 µm <ø<5 mm	-	4.00	100
Organic matter (%)	-	1.88	
Density (g/cm^3)	3	2.75	2.64
Content water initial (%)	-	35.86	-
Plasticity limit (%)	-	25.14	-
Liquidity limit (%)	-	68, 30	-
Plasticity index	-	43.16	-

2.2 Methods

2.2.1 Mechanical strength tests

To assess the contribution of alternative cementitious materials, it is essential to adopt a sufficiently significant cement substitution rate. A substitution rate of 20% by weight of cement is considered satisfactory for analyzing this contribution (Brial, Tran, Sorelli, Conciatori, & Ouellet-Plamondon, 2021a). Mortar preparation follows the procedure described in ASTM C109-16a (ASTM International, 2016). Reference mortar specimens were made by mixing 2915 g of local sand, 1060 g of type GU cement and 514 g of water, in accordance with ASTM C305-14 (ASTM International, 2015). The addition of superplasticizers maintained a spread of 110 ± 5 mm (ASTM International, 2010), with 5 ml for the reference mix and 18 ml for the specimens, while maintaining a water/binder ratio of 0.485 for the control mix and 0.5 for the modified specimens.

After 24 hours of curing, the specimens were removed from the moulds and transferred to a curing room until testing was completed. Compressive strength tests were carried out at 1, 7, 28 and 112 days to assess the evolution of the mechanical activity index over time. A second series of tests was carried out varying the rate of replacement of cement by sediment at 10%, 20%, 30%, 40% and 50%. Compressive strength tests were carried out at 1, 7 and 28 days, enabling the influence of the substitution rate on the development of mechanical performance to be analyzed.

2.2.2 R^3: Heat release

Cement hydration is an exothermic reaction, the intensity of which depends on the supplementary cementing materials (SCM) incorporated. The heat released during hydration of a cementitious paste is a reliable method for assessing their reactive potential. The R^3 model, developed by the RILEM technical committee, is now standardized under ASTM C1897 (ASTM International, 2020) and enables the reactivity of SCM to be studied independently. The method is based on a paste composed of 33.33 g portlandite ($Ca(OH)_2$), 11.11 g SCM, 5.56 g calcite ($CaCO_3$), 60 ml deionized water, 0.24 g potassium sulfate (K_2SO_4) and 1.20 g potassium hydroxide (KOH). This formulation recreates a chemical environment like that of a limestone cement without clinker, enabling isolated evaluation of SCM reactivity (Brial et al., 2021a). Two main analyses are performed on R^3 pulp: isothermal calorimetry and thermogravimetric analysis (TGA).

Isothermal calorimetry is carried out at 40°C for 7 days using an isothermal calorimeter, which continuously measures the heat flux released by the reaction of SCM with portlandite. The sample is placed in a hermetically sealed ampoule and inserted into a thermostatic chamber, where the heat released is recorded as a function of time. This measurement enables the hydration kinetics and intensity of pozzolanic reactions of SCM to be assessed. A highly reactive SCM will release a significant amount of heat in the first few hours, while a less reactive SCM will produce a more moderate heat release spread out over time.

3. RESULTS AND DISCUSSIONS

3.1 Compressive strength

Figure 4 shows the results of two series of compressive strength tests. The results of the first series (Figure 3a) of tests carried out at 1, 7, 28 and 112 days demonstrate the effect of partial replacement of cement by 20% sediment powder (20% SB) and 20% quartz (20% Q) on the compressive strength of mortars, with 100% cement mortar serving as the reference. At 1 day, the strength of the control mortar reached 21.55 MPa, while those of the formulations containing 20% quartz and 20% sediment were 16.00 MPa and 17.67 MPa respectively, reflecting an initial decrease due to the absence of an immediate contribution of these materials to hydration reactions, particularly quartz, which is chemically inert. At 7 days, the 20% SB mortar developed a strength of 40.38 MPa, very close to that of the control (40.99 MPa), in contrast to the 20% Q mortar, which remained at 32.50 MPa (21% lower than the reference), thus suggesting the participation of sediments in secondary reactions promoting compaction and improved mechanical performance. At 28 days, the 100% cement mortar reached 46.75 MPa, while the 20% SB and 20% Q formulations achieved 44.62 MPa (4.5% lower than the control) and 37.00 MPa (20.8% lower) respectively, confirming that the incorporation of sediments is more advantageous than that of quartz. This trend continues at 112 days, when the 20% SB mortar achieves 50.19 MPa, a value close to that of pure cement (51.19 MPa), while the 20% Q mortar remains lower, at 43.60 MPa. This late progression of sediment-based formulations suggests a delayed pozzolanic reaction, favoring the formation of secondary hydration products, as well as a possible filler effect improving the compactness of the pore network and long-term strength.

Figure 4b shows the results of the second series of compressive strength tests. These tests evaluate the influence of different proportions of sediment powder (10%, 20%, 30%, 40% and 50%) on compressive strength at 1, 7 and 28 days. The results show a progressive decrease in strength with increasing substitution rates, particularly marked above 30%, where the loss of active clinker significantly compromises mechanical performance. At 28 days, formulations containing 10% and 20% sediment maintained high strengths, close to those of pure cement, suggesting an optimal balance between substitution and performance. In contrast, formulations with 40% and 50% replacement show significantly reduced strengths, indicating excessive cement dilution. Compared with quartz, sediments show better reactivity, favoring the formation of secondary hydration products and improving microstructure compactness.

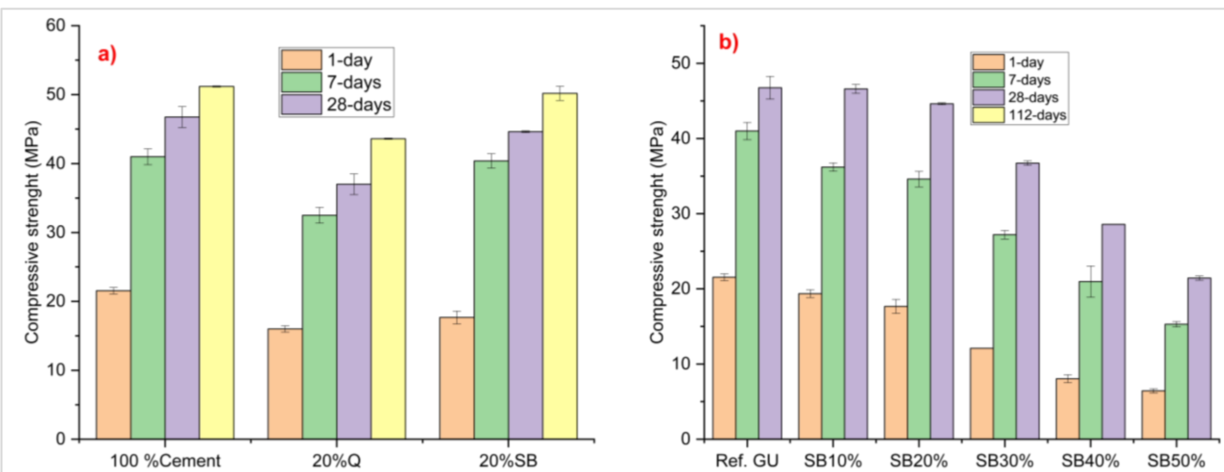

Figure 4: a) Comparison of the strength of sediment powder with that of quartz and Gu cement, including a 20% replacement of cement by the sediments ans quartz, b) influence of percentage variation of sediment on compressive strength

3.1.1 R^3: Heat release

Figure 5 shows the heat release results of R^3 paste after 7 days of hydration for three complementary cementitious materials: quartz (Q), sediment (SB) and metakaolin (MK). Heat release is a key indicator of pozzolanic reactivity in SCMs (Li, Wanner, Hesse, Friesen, & Dengler, 2024). Higher heat release suggests a more intense reaction with portlandite, leading to the formation of additional hydration products. In this context, MK shows the highest heat release (1100 J/g), followed by sediments (84 J/g), while quartz displays a significantly lower value (23 J/g). In contrast to quartz (23 J/g), which is essentially inert, sediments appear to contain a proportion of amorphous or semi-crystalline phases capable of reacting with portlandite to form secondary hydration products. These results are consistent with the literature, where metakaolin is recognized for its high reactivity due to its amorphous aluminosilicate-rich structure, favoring rapid and exothermic pozzolanic reactions (Li et al., 2024). Conversely, quartz, being a crystalline form of silica, is practically inert and does not participate significantly in cement hydration reactions (Brial et al., 2021a). This hypothesis is supported by recent studies showing that materials rich in reactive silica and partially destructured aluminosilicates can result in higher heat release than inert mineral fillers, but lower than that of highly reactive SCMs such as metakaolin (1100 J/g), known for its high pozzolanic capacity. The difference in thermal reactivity between these materials can also be attributed to their specific surface area and particle size, directly influencing the speed and intensity of hydration reactions. Thus, although sediments do not possess as marked pozzolanic activity as metakaolin, their moderate reactivity and filler effect can nevertheless contribute to improving the mechanical and microstructural performance of cementitious matrices.

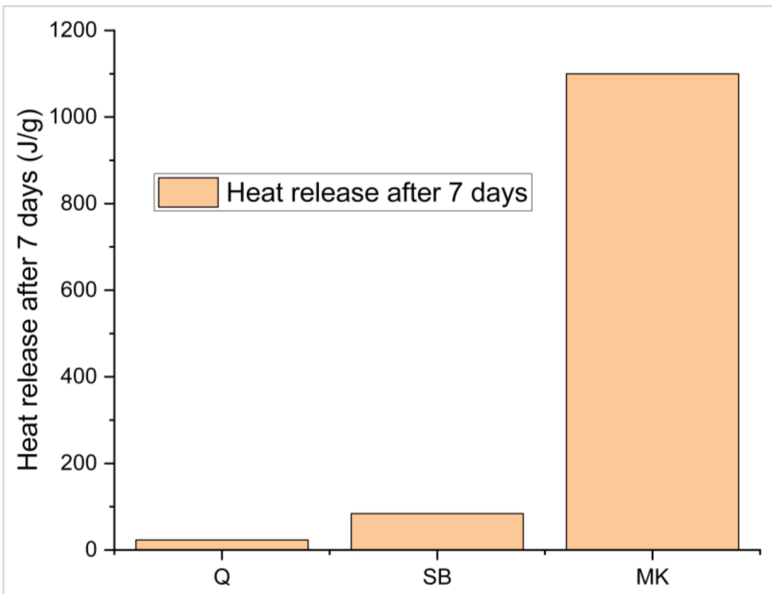

Figure 5: R^3 paste heat release after 7 days of hydration

3.1.2 R^3: CH, Consumption

The evolution of calcium hydroxide in the mixture containing 20% sediment powder was assessed by thermogravimetric analysis (TGA) and is illustrated in Figure 6a. The tangent method (Figure 6b) was used to quantify portlandite based on the dehydration peak observed between 450 and 600 °C, with the results expressed per unit mass of initial anhydrous cement, in accordance with the method proposed by Marsh and Day (1988). Peaks beyond 600 °C are attributed to decarbonation, primarily of unreacted calcite present in the mixture, but also to secondary carbonation due to atmospheric CO_2 absorption, as well as thermal effects from residual isopropanol used for hydration stopping. These reactions are associated with the formation of C–S–H, as also reported by Lothenbach et al. (Lothenbach, Scrivener, & Hooton, 2011).

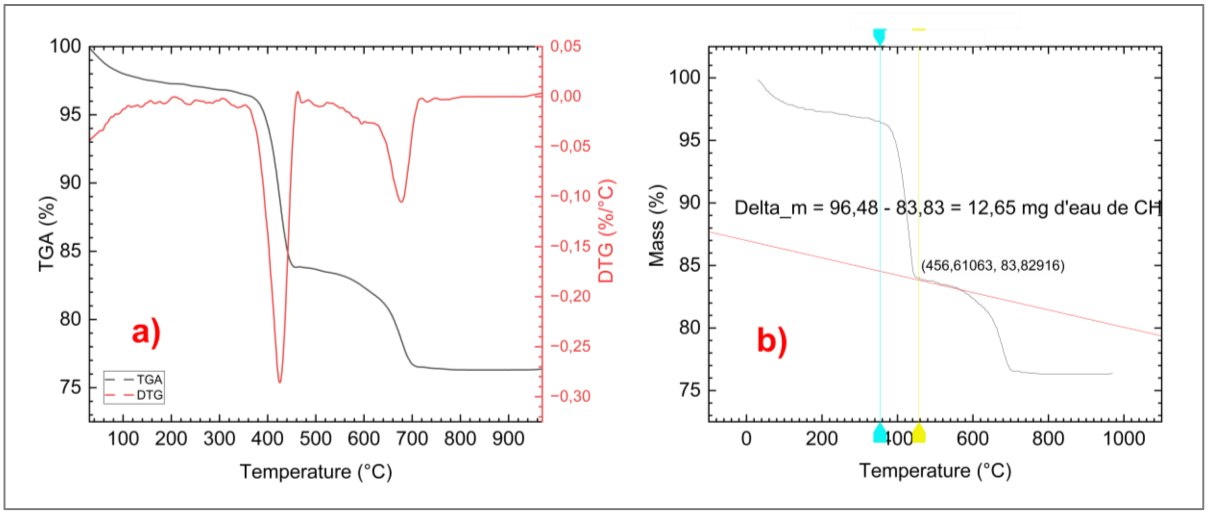

Figure 6: Derivative of mass loss (DTG) as a function of temperature increase obtained by TGA analysis of samples on the R^3 dough model after 7 days.

The portlandite consumption results, calculated using the tangent method as described by Brial et al. (2021), are presented in Figure 7. A significant portlandite consumption was observed for the sediments, compared to quartz, which is known to be inert with respect to portlandite. Quartz exhibited a consumption of approximately 45 g per 100 g of supplementary cementitious material (SCM). In contrast, the sediments, as well as other well-established SCMs such as metakaolin (MK), silica fume (SF), and ground granulated blast furnace slag (GGBS), showed a markedly higher consumption, as illustrated in Figure 7. The reference data for these materials were obtained from the study conducted by Brial et al. (2021) in the same laboratory and under similar experimental conditions

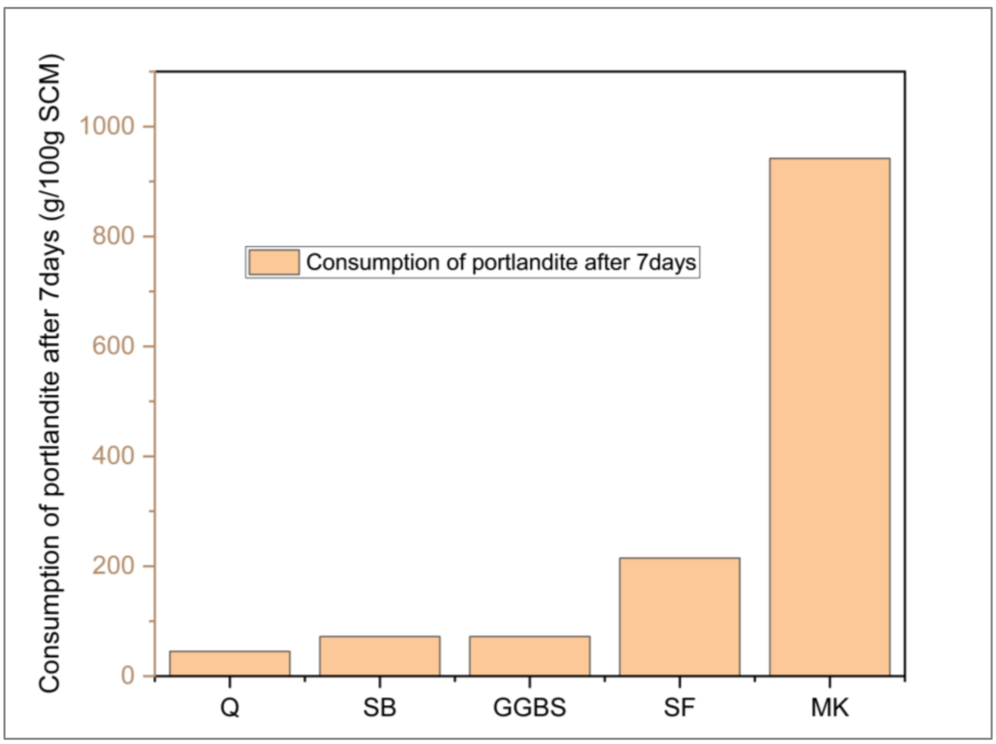

Figure 7: Portlandite consumed in the R^3 paste model, after 7 days

4. CONCLUSIONS

The aim of this study is to assess the potential of dredged sediments to contribute to reducing the carbon footprint of cement by reducing its consumption. This study demonstrates the potential of St. Lawrence River dredged sediments as complementary cementitious materials for the formulation of low carbon footprint concretes. Analysis of the mechanical and microstructural performance of mortars containing 20% sediment revealed a 112-day compressive strength of 50.19 MPa, representing 98% of that of the pure cement control mortar. In addition, the calorimetric and thermogravimetric study confirmed moderate reactivity of the sediments, with heat release higher than that of quartz but lower than that of metakaolin, indicating a certain pozzolanic activity. These results suggest that incorporating sediments into cement not only reduces dependence on virgin raw materials, but also valorizes a port waste, thus contributing to a circular economy approach and reducing CO_2 emissions associated with clinker production. However, an increase in the substitution rate beyond 20% leads to a significant reduction in mechanical performance, necessitating adjustments in the formulation of mixes to optimize their durability and workability. These results pave the way for potential applications of sediments in construction materials, subject to further studies on their long-term durability, compatibility with current standards, and assessment of the carbon reduction of concrete.

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