Life cycle assessment and sensitivity analysis of a clayey sediment-based geopolymer concrete

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ABSTRACT: This article evaluates, through a life cycle assessment (LCA), the environmental impacts of a sediment-based geopolymer mortar mixed with alkaline reagents. The obtained results were compared to the use of classic Ordinary Portland Cement (OPC) for treating dredged sediment with similar compressive strength. Dredging methods as well as transport were taken into account in addition to the mix-design and fabrication methods. In order to quantify the sensibility of the chosen hypothesis, a sensitivity analysis was also conducted to make the methodology more robust. Throughout the analysis, it could be concluded that the use of alkaline reagent reduces the impact on climate change but does not lead to better impact results than OPC for all other categories considered. Therefore, the use of alternative local precursors is not sufficient and market potential of geopolymer mortars will depend on an alternative to the alkaline reagents currently used for geopolymerization.

1 INTRODUCTION

In 1978, the French chemist Davidovits (2005) coined the term geopolymer to describe a class of aluminosilicate inorganic materials obtained by reaction between a precursor, aluminosilicate material, and alkaline reagents. Considered as mineral binders due to their properties similar to OPC, geopolymers represent a potential replacement for cement. For this reason, their low carbon impact is an important leitmotif in the studies published to date. Davidovits (2013) estimates that the manufacturing process of geopolymers requires 9 times less energy than the production of Portland cement and emits 8 to 10 times less greenhouse gases. Indeed, the materials used for geopolymerization do not require a calcination process, contrary to clinker production. In the most favourable case, when the manufacture of the precursors is not taken into account, it achieves an 80% reduction in CO_2 emissions compared to Portland cement. These results, although similar to other studies (Robayo-Salazar et al., 2018; Salas et al., 2018), are highly dependent on the assumptions made in LCA. In the literature, CO_2 emission reduction values ranging from 9% to 80% are observed. The factors responsible for these variations are: the variability of the precursors used, the different transport distances considered, the high alkali content, whether or not the solid fraction of the silicate is taken into account, and the requirement for high-temperature processing. Despite diverging results, there is a general consensus towards the same conclusion: geopolymer production produces less CO_2 than cement production.

One of the strategies identified as essential to the competitiveness of geopolymers on the market, is the use of local resources that allow to decrease the costs related to the manufacture of materials and their transport. Among the identifiable local resources, dredged sediments are a source of interest due to their adequate mineralogical composition and their significant quantity. Annually in Bordeaux, 9 million m^3 of sediments are dredged. Several studies have successfully evaluated the potential of dredged sediments for use in geopolymer matrices (Ferone et al., 2013; Komnitsas, 2016; Lirer, 2017). Using sodium silicate (Na_2SiO_3), Ferone et al. (2013) obtain a value of 3.44 MPa at 28 days for a mortar with calcined sediments. Similarly, Mograhbi et al. (2018) obtained at the age of 28 days 0.2 MPa for untreated sediments from the Grand Port Maritime of Dunkerque. However, despite the technical viability, to the authors' knowledge, there is no study on the LCA of such process. Furthermore, existing studies on the ecological impact of geopolymer applications focus on the impact regarding climate change, but the true environmental profile of these materials goes far beyond that and will define the true limits for the development of this technology in a sustainable construction industry.

Through a LCA, this paper fills a knowledge gap by presenting the impacts of the full LCA of a geopolymer mortar formulated from untreated dredged sediments taking into account the activities associated with the extraction of raw materials, transport and the manufacture of 1 m^3 of mortar. In addition, in order to minimise the uncertainties associated with the assumptions and choices made in the study, a Monte-Carlo sensitivity analysis was performed. Three different scenarios were considered for two different mortars based on untreated dredged sediments: a reference cement-based mortar and a geopolymer-based mortar. The impact of mortars was evaluated based on four environmental indicators: climate change, acidification, eutrophication and water pollution.

2 SCOPE DEFINITION AND METHODOLOGY

2.1 *Goal, scope definition and life cycle assessment*

The objective of this study is to compare the ecological performance of two different treatments to formulate a mortar from untreated dredged sediments from the Garonne. The functional unit retained in this study is the production of 1m^3 of mortar with cement or alkaline reagents with similar proportion (10%) and with a compressive strength of, at least, 1.5 MPa. It was decided in this study to focus on the early parts of the life cycle with a "cradle to gate" approach. The boundaries of the system are therefore the extraction and production of materials, the dredging and processing of sediments in addition to the transport and manufacturing energy required to produce 1 m^3 of mortar. Other processes related to on-site implementation, sustainability, end-of-life and recycling were not considered in this study. Sensitivity analyses were performed to take into account market developments in geopolymerization and circumstantial changes in transport distances of activators.

The scenarios of the different mortars were established according to ISO 14 040 and ISO 14 044 and were modelled in SimaPro using the EcoInvent 3.2 database. The calculations were then carried out according to the NF EN 15804+A1/CN (2014) and CML-IA method (2016).

2.2 *Mix design*

The geopolymerized mortars were obtained from untreated dredged sediments from the Garonne River as a precursor. The sediments are used at a water content of 30% to limit the additional external water input and to facilitate the treatment by eliminating additional operations such as screening and crushing. The production of geopolymerized mortar from dredged sediments is based on the alkaline activation of 70% sediment with 30% activator by mass. The activator mixture is a combination of a 4M solution of NaOH and Na_2SiO_3 with an optimum weight ratio of SiO_2/Na_2O solution of 1.2. Sodium hydroxide (NaOH) was used in the form of pellets (99% purity) which were dissolved in a ready-to-use silicate solution (Na_2SiO_3) supplied by Xatico. The choice of these activators is motivated by their classical use in most studies, allowing the results obtained to be compared with those known in the literature. A first formulation of geopolymer-based sediments (GBS) was established using this methodology. The reference formulation with OPC is a mixture of 80% sediment and 20% conventional Portland cement. The formulations and mechanical strengths of the two solutions are detailed in Table 1. The volume and the water/solid ratio are kept constant at 1 m^3 and 0.40 respectively.

Table 1. Mix design and compressive strength of the studied mortars

Mix	Mix proportions for 1m³				Mechanical Strength [MPa]
	Sediment	OPC	NaOH	Na_2SiO_3	
OPC	1319.00	172.70	-	-	1.67
GBS	1138.18	-	14.43	153.10	4.78

2.3 *Life cycle assessment*

The data for cement and alkaline reagents (NaOH, Na_2SiO_3) are taken from the EcoInvent database. The data for OPC in EcoInvent corresponds to the production of cement consisting of 0.9 kg of clinker for one kg of cement. The molarity of the NaOH solution was taken into account according to the mass of pellet added. For sodium silicate (Na_2SiO_3), only the solid fraction of the silicate is considered in this study. There is no dredging process for sediments on EcoInvent so the impact of dredging was modelled as follows:

- Moving the dredger in the estuary to the dredging area in Pauillac, Gironde (*transport, freight, inland waterways, barge*)
- Hydraulic suction dredging operation (*sand quarry operation, sediment extraction from river bed*)
- Dumping of sediments with shovels and skips (*excavation, hydraulic digger + transport, freight, lorry 3.5-7.5 metric ton)*
- Natural dewatering of the sediments in landfills (*process-specific burdens, inert material landfill*).

For transport, it is assumed that the concrete production plant is located in Bassens next to the Port of Bordeaux, while the dredging of the sediments is located in the Pauillac area upstream of the estuary. The material suppliers were chosen as close as possible to the concrete production plant. The distance assumptions are presented in Table 2.

Table 2. Transport inventory

Materials/Process	Supplier	Distance from supplier	Mode
Portland cement	Lafarge (France-Bassens)	1.4km	Road
NaOH	Sigma Aldrich (Germany)	1146km	Road
Na_2SiO_3	Xatico (Spain – Saint Gugat del Vallès)	638km	Road
Sediment	-	-	-
Round trip	-	75km	Estuary
Unloading platform	-	0.2km	Road
Landfill deposit	-	48.8km	Road

3 RESULTS AND DISCUSSIONS

3.1 *Global impacts*

Table 3 presents the calculated impact values for each category related to the production of 1m³ of the formulations compared in this study. Figure 1 shows the comparison of the values in relative terms for each impact category. Considering the Climate Change impact, which represents the CO_2 emissions emitted per 1 kg of mortar produced, a clear decrease is observed for geopolymerized solutions. OPC emits 227.54 kg.CO_2.eq against 180.1 kg.CO_2.eq for GBS. The use of a geopolymer binder relative to the use of OPC, allows a reduction of carbon emissions by 21%. Although the GBS shows a lower performance for the climate change category than OPC, results shows that geopolymer treatment has a higher environmental score regarding the other impact categories such as Acidification (A), Eutrophication (E) and Water Pollution (WP) which increases by 47%, 68% and 56% respectively. Thus, this questions the ecological benefit of using alkaline reagent in order to develop the mechanical strength. The use of local sources of materials has been identified as one of the major keys to reduce the environmental impact of geopolymer (Turner & Collins, 2013) yet, despite the use of local and alternative precursors such as dredged sediments, high impact in A, E and WP were observed. Alkaline reagents are often targeted when questioning the environmental potential of geopolymer. Indeed, sodium silicate (Na_2SiO_3) process, through the electrolysis, is responsible for the high value in those categories. The reduction of environmental scores for geopolymers will require the search for new, more environmentally friendly activators which are often identified as the major source of contribution.

Table 3. Results for each impact category

Impact category	Unit	OPC	GBS
Acidification (A)	kg.SO_2.eq.	0.57	1.06
Eutrophication (E)	kg.PO_4.eq.	0.14	0.44
Water Pollution (WP)	m^3	2.39	5.50
Climate Change (CC)	kg.CO_2.eq.	227.53	180.06

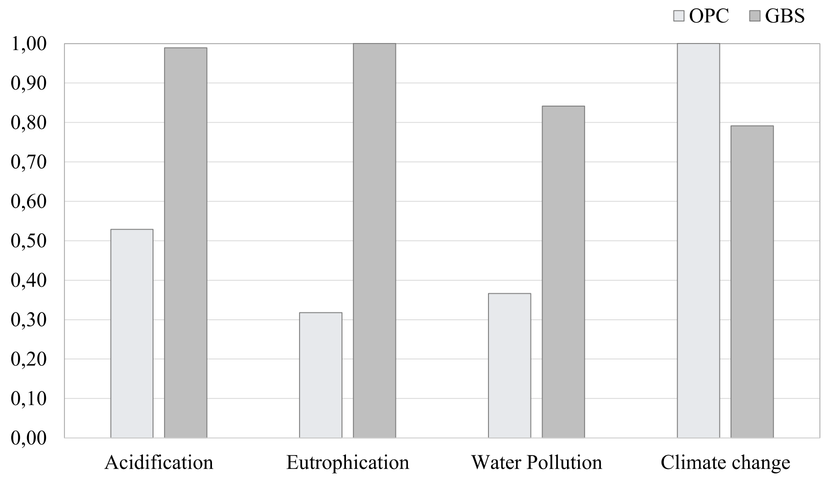


Figure 1: Global impacts of each mortar calculated with the EN 15-806 and CML-IA

3.2 *Sensitivity analysis*

3.2.1 *Deterministic model*

In order to test the robustness of the results and their sensitivity to the chosen initial hypotheses, a deterministic sensitivity analysis was carried out. The objective is to define the limit values of the study in order to be able to study the sensitivity of the results related to the input parameters. Among the hypotheses defined in the study, the transport distances and the extraction of the sediments are considered. As Davidovits (2013) pointed out, it is difficult to compare the cement industry, implemented in France for several years now with hundred cement factories which implies an easy proximity supply in France, with the importation of alkaline reagent. For the sake of comparison and in anticipation of market forces, the new impacts of geopolymer mortars should be calculated assuming nearby suppliers. Concerning sediments, it can be assumed that, as sediments are considered as waste and because their extraction is linked to port activities, the consideration of this process can be neglected in the sensitivity analysis. Table 4 shows the results for OPC and GBS impact categories when transport distances for GBS are considered similar as cement and when sediment extraction is not taken into account for both mixtures.

Table 4. Results for each impact categories after sensibility analysis

Impact category	Unit	OPC	GBS
Acidification (A)	kg.SO_2.eq.	0.43	0.88
Eutrophication (E)	kg.PO_4.eq.	0.13	0.38
Water Pollution (WP)	m^3	0.45	3.94
Climate Change (CC)	kg.CO_2.eq.	202.35	138.95

The reduction of transport distances and the non-inclusion of sediment extraction lead to an environmental gain for every impact category. Transport and sediment extraction are identified as key parameters in this first analysis. A study including uncertainties for these parameters is carried out to analyse their impact in the following section.

3.2.2 *Stochastic model*

In order to observe the sensitivity of the emissions for the different impact categories in Table 3, three scenarios, y_{sci}, are considered. Each scenario is defined by Equation 1 below:

$$y_{sci} = \sum_1^k F_j \cdot X_j \quad (1)$$

where F_j is the emission factor (defined in EcoInvent 3.2 database) for each input parameter X_j, that are stated for OPC mortar as follows:
- X_{OPC1}: amount of cement (kg)
- X_{OPC2}: amount of electricity (kWh)
- X_{OPC3}: amount of excavation (m^3)
- X_{OPC4}: amount of landfill of inert material (kg)
- X_{OPC5}: amount of sediment extraction (kg)
- X_{OPC6}: transport, freight, inland waterways, barge (t.km)
- X_{OPC7}: transport, freight, lorry 16-32 metric ton (t.km)
- X_{OPC8}: transport, freight, lorry 3.5-7.5 metric ton (t.km)

and for GBS mortar:
- X_{GBS1}: amount of electricity (kWh)
- X_{GBS2}: amount of excavation (m^3)
- X_{GBS3}: amount of landfill of inert material (kg)
- X_{GBS4}: amount of sediment extraction (kg)
- X_{GBS5}: amount of NaOH (kg)
- X_{GBS6}: amount of $Na_2\ SiO_3$ (kg)
- X_{GBS7}: transport, freight, inland waterways, barge (t.km)
- X_{GBS8}: transport, freight, lorry 16-32 metric ton (t.km)
- X_{GBS9}: transport, freight, lorry 3.5-7.5 metric ton (t.km)

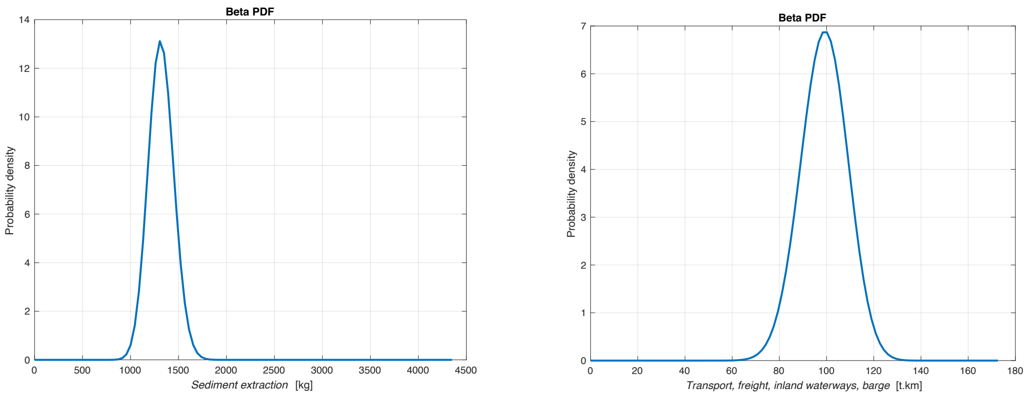
The three scenarios, y_{sci}, that have been identified are listed below:
- y_{sc1}: this scenario is considered the baseline scenario with all the input parameter X_j where current distance from raw material suppliers for activators (Table 2) are taken into account
- y_{sc2}: this scenario is similar to y_{sc1} for OPC mortar but for GBS mortar we consider a market of raw material suppliers located in the region, the impact of transport (X_{GBS8}) being therefore minimal
- y_{sc3}: this scenario considers that the extraction of sediments is a necessary action for the maintenance of the waterways and is therefore not a source of emission allocated to the production of mortars from the dredged sediments (X_{OPC5} and X_{OPC6}, for OPC mortar, and X_{GBS4} and X_{GBS7}, for GBS mortar, are not considered in Equation 1).

For the following input parameters, X_j, an uncertainty range was identified which allowed us to define them as random variables: X_{OPC5}, X_{OPC6}, X_{OPC7}, X_{GBS4}, X_{GBS7} and X_{GBS8}. Indeed, using the Monte-Carlo method, we perform a sensitivity analysis to measure their impact on the calculation of different scenarios defined above. Having identified three values characterizing the uncertainty: a minimum, a most likely and a maximum value, as shown in Table 5, we have modeled these variables with Beta probability distributions. For example, Figure 2 shows the probability distributions for the variables X_{OPC5} and X_{OPC6} by considering a coefficient of variation (ratio between standard deviation and mean value), $COV = 10\%$. The interval values correspond, for transport (t.km), to the minimum and maximum distances that lorry must travel to transport the materials. For X_{OPC5} and X_{GBS4}, the minimum corresponds to the non-consideration of sediments in the analysis, the most likely interval represents the minimum to be dredged for 1m[3] of the defined formulation and the maximum value corresponds to the total quantity of sediment dredged per operation.

Table 5. Uncertain input parameters with their value intervals

Random variable	Value intervals		
	Minimum	Most likely	Maximum
X_{OPC5} (kg)	0.00	1319.00	4350.00
X_{OPC6} (t.km)	0.00	98.93	172.60
X_{OPC7} (t.km)	0.12	64.69	83.97
X_{GBS4} (kg)	0.00	1138.18	4350.00
X_{GBS7} (t.km)	0.00	85.36	149.01
X_{GBS8}* (t.km)	55.79	169.76	225.79

*For y_{sc2} this variable is not random but deterministic with the minimum value



(a) X_{OPC5} (b) X_{OPC6}

Figure 2: Beta probability distributions for the variables X_{OPC5} and X_{OPC6}, $COV = 10\%$

3.2.3 *Results of sensitivity analysis*

1000 Monte Carlo simulations were performed to assess the sensitivity of each scenario, using the model in Equation 1, for each mortar and for the different impact categories. An uncertainty of ±5% was assumed for the emission factor, F_j. A uniform probability distribution was used to model this uncertainty. Table 6 ($COV = 10\%$) and Table 7 ($COV = 30\%$) present the overall results obtained, where μ and σ are the mean and standard deviation values respectively, and the values in square brackets is the 95% confidence interval.

Table 6. Results of the sensitivity analysis for each impact category, $COV = 10\%$

Impact category	OPC y_{sc1}	OPC y_{sc2}	OPC y_{sc3}	GBS y_{sc1}	GBS y_{sc2}	GBS y_{sc3}
Acidific. [kg.SO_2.eq]	$\mu = 0.569$ $\sigma = 0.014$ [0.544; 0.593]	$\mu = 0.570$ $\sigma = 0.014$ [0.545; 0.593]	$\mu = 0.511$ $\sigma = 0.013$ [0.490; 0.534]	$\mu = 1.064$ $\sigma = 0.026$ [1.016; 1.108]	$\mu = 1.001$ $\sigma = 0.024$ [0.960; 1.039]	$\mu = 1.015$ $\sigma = 0.026$ [0.969; 1.060]
Eutrophic. [kg.PO_4.eq]	$\mu = 0.139$ $\sigma = 0.003$ [0.132; 0.145]	$\mu = 0.139$ $\sigma = 0.003$ [0.132; 0.144]	$\mu = 0.119$ $\sigma = 0.003$ [0.114; 0.124]	$\mu = 0.436$ $\sigma = 0.009$ [0.420; 0.453]	$\mu = 0.420$ $\sigma = 0.009$ [0.405; 0.436]	$\mu = 0.419$ $\sigma = 0.009$ [0.404; 0.435]
Wat. Pollut.	$\mu = 2.397$	$\mu = 2.391$	$\mu = 0.506$	$\mu = 5.581$	$\mu = 5.524$	$\mu = 3.957$

[m^3]	$\sigma = 0.204$	$\sigma = 0.193$	$\sigma = 0.013$	$\sigma = 0.192$	$\sigma = 0.188$	$\sigma = 0.092$
	[2.026; 2.823]	[2.014; 2.779]	[0.482; 0.527]	[5.224; 5.970]	[5.171; 5.901]	[3.795; 4.109]
Clim. Chan.	$\mu = 227.3$	$\mu = 227.5$	$\mu = 219.4$	$\mu = 180.1$	$\mu = 160.5$	$\mu = 173.4$
[kg.CO_2.eq]	$\sigma = 5.839$	$\sigma = 6.103$	$\sigma = 6.085$	$\sigma = 4.676$	$\sigma = 3.635$	$\sigma = 4.681$
	[217.5; 237.1]	[217.1; 237.7]	[209.4; 229.4]	[171.0; 188.7]	[154.3; 166.8]	[163.9; 182.1]

Table 7. Results of the sensitivity analysis for each impact category, $COV = 30\%$

Impact	OPC			GBS		
category	y_{sc1}	y_{sc2}	y_{sc3}	y_{sc1}	y_{sc2}	y_{sc3}
Acidific.	$\mu = 0.569$	$\mu = 0.568$	$\mu = 0.514$	$\mu = 1.064$	$\mu = 0.999$	$\mu = 1.016$
[kg.SO_2.eq]	$\sigma = 0.020$	$\sigma = 0.021$	$\sigma = 0.017$	$\sigma = 0.040$	$\sigma = 0.026$	$\sigma = 0.037$
	[0.526; 0.606]	[0.523; 0.607]	[0.478; 0.541]	[0.980; 1.132]	[0.954; 1.047]	[0.940; 1.081]
Eutrophic.	$\mu = 0.139$	$\mu = 0.139$	$\mu = 0.119$	$\mu = 0.436$	$\mu = 0.421$	$\mu = 0.420$
[kg.PO_4.eq]	$\sigma = 0.006$	$\sigma = 0.006$	$\sigma = 0.004$	$\sigma = 0.012$	$\sigma = 0.010$	$\sigma = 0.012$
	[0.128; 0.149]	[0.127; 0.149]	[0.110; 0.125]	[0.413; 0.458]	[0.403; 0.438]	[0.396; 0.439]
Wat. Pollut.	$\mu = 2.407$	$\mu = 2.385$	$\mu = 0.504$	$\mu = 5.587$	$\mu = 5.517$	$\mu = 3.957$
[m^3]	$\sigma = 0.586$	$\sigma = 0.576$	$\sigma = 0.016$	$\sigma = 0.500$	$\sigma = 0.484$	$\sigma = 0.093$
	[1.361; 3.633]	[1.380; 3.609]	[0.470; 0.532]	[4.735; 6.604]	[4.631; 6.518]	[3.801; 4.126]
Clim. Chan.	$\mu = 227.4$	$\mu = 227.5$	$\mu = 219.8$	$\mu = 179.8$	$\mu = 160.8$	$\mu = 173.2$
[kg.CO_2.eq]	$\sigma = 6.971$	$\sigma = 6.968$	$\sigma = 6.800$	$\sigma = 9.754$	$\sigma = 3.899$	$\sigma = 9.451$
	[213.5; 240.1]	[213.4; 239.6]	[206.4; 231.4]	[159.6; 194.5]	[153.8; 167.7]	[153.2; 187.4]

3.2.4 *Discussion*

With regard to the above sensitivity analysis, the obtained results shows that a strong dependence exist between the final impact category score and the subjective choice of input parameters. Furthermore, results found for both sensitivity analyses are similar to the one calculated with a deterministic approach even more when the coefficient of variation is set to 30%. It can be estimated that for OPC, Climate change is the less sensitive category with a variation range of -11% to 6% from the referring value of 227.535 kg.CO_2.eq, followed by Acidification that can vary from -16% to 7% compared to an initial value of 0.569 kg.SO_2.eq. Eutrophication present similar range value as a variation of -21% to 8% has been observed. However a relevant variation from -80% to 52% is observed for the Water Pollution impact. As for GBS, results shows that Eutrophication is characterized by low variation (-9% to 5%) followed by Acidification (-12% to 6%) and Climate Change (-15% to 8%). Water Pollution for GBS also presents the highest variations ranging from -31% to 19% from the referring value of 5.500 m^3. Despite the variations observed in the final life cycle analysis results, conclusions remain the same. In all three of the scenarios, GBS presents a lower impact in Climate Change and higher impact on Acidification, Eutrophication and Water Pollution.

4 CONCLUSION

Throughout this study, life cycle analysis score of a geopolymer-based sediments mortar has been compared with an OPC-based sediments mortar. In accordance with the results obtained for the climate change impact category, this article argues that geopolymer can be a better option for reducing CO_2 emissions in comparison with the traditional use of OPC. However, in comparison with the traditional use of OPC, the Acidification, Eutrophication and Water Pollution impact categories were observed highest for GBS due to the use of alkaline reagent. In order to analyze the sensibility of the results toward the chosen scenarios, a sensitivity analysis was performed on the input parameters. High range of variation were observed for Water Pollution when transport and sediment extraction were taken into account however conclusion toward the environmental score of GBS compared to OPC remains unchanged.

If climate change scores could make geopolymers viable competitors to cement, it is appropriate, in perspective, to study the use of alternative alkaline reagent in order to improve the environmental scores of geopolymerized mortars from dredged sediments.

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