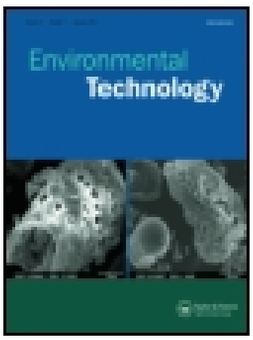

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Geotechnical and mineralogical characterisations of marine dredged sediments before and after stabilisation to optimise their use as a road material

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Geotechnical and mineralogical characterisations of marine dredged sediments before and after stabilisation to optimise their use as a road material

Dredging activities to extend, deepen and maintain access to harbours generate significant volumes of waste dredged material. Some ways are investigated to add value to these sediments. One solution described here is their use in road construction following treatment with hydraulic binders. This paper presents the characterisation of four sediments, in their raw state and after 90 days of curing following stabilisation treatment with lime and cement, using a combination of novel and established analytical techniques to investigate subsequent changes in mineralogy. These sediments are classified as fine, moderately to highly organic and highly plastic and their behaviour is linked to the presence of smectite clays. The main minerals found in the sediments using X-rays diffraction (XRD) and automated mineralogy are quartz, calcite, feldspars, aluminium silicates, pyrite and halite. Stabilisation was found to improve the mechanical performances of all the sediments. The formation of cementitious hydrates was not specifically detected using automated mineralogy or XRD. However, a decrease in the percentage volume of aluminium silicates and aluminium-iron silicates and an increase of the percentage volume of feldspars and carbonates was observed.

Keywords: marine sediment; physical properties; mineral composition; stabilisation; hydraulic binders

1. Introduction

Marine clay deposits encountered in the world's coastal regions are soft in consistency, highly compressible with low shear strength. The properties of these deposits are complex, diverse and highly dependent on the minerals present and microstructural arrangement of constituent particles. Build-up of these fine grained sediments necessitates dredging and in the English Channel area alone, 2.1 million m^3 is currently disposed of from local ports by immersion at sea [1]. Meanwhile, the shortage of construction materials available from quarries is compelling civil engineers to explore new solutions for the production of road materials.

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Previous authors have considered the use of marine dredged sediments in road construction [2-14]. However this option is only viable if improvements in mechanical performance can be achieved. To this end, stabilisation with lime and hydraulic binders was appraised.

Standard physical characterisation tests used to classify a new and unusual road material such as dredged sediment include initial water content, organic matter (OM) content, specific gravity (Gs), particle size distribution (PSD), consistency limits (plasticity index). The parameters are interdependent and the physical characteristics will in turn influence compaction, plasticity, bearing capacity, permeability and capillarity of the material [15-18]. In civil engineering, for road construction, the determination of these initial physical parameters is the starting point of any study into improvements in mechanical performance.

The mineralogy and microstructure of a raw material also influence its geotechnical properties. The analysis of hydrated cementitious products by X-rays diffraction (XRD) is not straightforward due to the presence of many phases, some of which may crystallise as different polymorphs which will each have their own XRD pattern [19-21]. Previous studies have therefore used techniques such as scanning electron microscopy (SEM) and optical microscopy to inform their investigations into the geotechnical properties of harbour dredged sediment stabilised with hydraulic binders [22-23]. Whilst automated mineralogy (Quantitative Evaluation of Minerals by SCANning electron microscopy QEMSCAN®) has been widely used in the mining industry for over 30 years and is gaining increasing recognition in other areas of research [24-25], its use in stabilisation and solidification studies has not previously been reported.

This paper presents the evaluation of physical, geotechnical, microstructural and mineralogical changes induced on sediments following stabilisation with lime and cement.

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2. Material and methods

2.1. Sampling

Four sediments (S1, S2, S3 and S4) were obtained from four French ports on the Channel coast. Sampling methods were constrained by dredging practices. At each port a large sample of between 500 and 650 litres of material was collected, transported to laboratory, homogenised and dried at 40°C yielding between 150 and 300 kg of dry material per sample. Untreated sediments are referred to as “raw sediments” or “sediments” whilst sediments after addition of binders are referred to as “stabilised” sediments. Two of the raw sediments (S1 and S3) have metal concentrations that exceed the relevant GEODE N2 levels (Hg and Pb, and Cu respectively) [26], preventing their disposal at sea without suitable disposal management techniques [27].

2.2. Physical characterisation

2.2.1. Standard tests

Standard tests were used to determine the initial physical characteristics of the sediments. These included initial water content (ASTM D2216 standard [28]), OM content (ASTM D2974standard [29]), specific gravity (ASTM D7263 standard [30]), particle size distribution (by sieving according to the ASTM D6913 standard [31] for particles ranging from 80 μm, by Berkman Coulter granulometer according to the ISO 13320-1 standard [32] for particles ranging from 0.04 to 2000μm), consistency limits and plasticity index (Atterberg limits) (ASTM D4318 standard [33]), compaction parameters, optimum moisture content (OMC) and maximum dry density (MDD) (standard EN 13286-2 [34]). The Unified Soil Classification System (USCS) [35] uses information on the fine fraction (0/80 μm), the liquid limit and the OM content to classify the soil. The raw sediments are also subjected to mineralogical characterisation, detailed in the following paragraphs.

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2.2.2. Clay Activity estimation

The clay activity (AC) allows the risk of shrinkage or swelling of a material due to minerals from different clay families (kaolinite, illite or smectite) to be predicted. The activity ranges are: AC <0.75, inactive; 0.75≤AC <1.25, normal and AC≥1.25, active. The Atterberg limits (ASTM D4318 standard [33]), liquid limit (LL) and the plastic limit (PL), are used to calculate the plasticity index (PI = LL – PL) which is then used to calculate the activity of the clay fraction (AC) using Equation 1. C2 (%) is the clay fraction (0/2 µm) of the material.

$$AC = PI / C2 \qquad \text{(Eq. 1)}$$

2.3. Sediment treatment

2.3.1. Preparation and treatment

The sediments contained a large amount of sea water (>100% with respect to dry mass). In practice, sediment intended for treatment and use in road construction would dry naturally in a storage area until the water content is <20% before treatment. For this study, dehydration was accelerated in the laboratory by oven drying (40°C). Clumps formed during this process were removed by crushing to disaggregate and sieving to 2 mm. The sediments were not washed: the oven drying induces the formation of solid salts.

Treatment formulations were designed with reference to the French technical guide for soil treatment [36] in order to achieve the required performance for sediment use in subgrade layer. Lime and cement additions were optimised according to the lime fixation point test (lime content to reach a pH of 12.4, a pH at which the formation of cementitious hydrates is favoured) (ASTM D6276 standard [37]) and to economic criteria. The sediments were stabilised with 3% of quicklime CaO and 6% of cement CEMII/B 32.5R with respect to the

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dry mass of the mixture (Maherzi [38] from NF P94-093 [39] and ASTM C977 [40] standards).

2.3.2. Sample preparation for mechanical tests and mineralogical analysis

In the laboratory, the geotechnical behaviour of stabilised sediments is evaluated according to the protocol described in the French technical guide for soil treatment [36] and detailed in European standards EN 13286 [41-44]. After mechanical tests at 90 days, samples were oven dried at 40°C for 7 days for mineralogical characterization.

2.4. Mineralogical characterisation

2.4.1. X-rays diffraction (XRD)

Bulk qualitative powder XRD characterisation was achieved using a Siemens D5000 diffractometer with Cu-Kα radiation (λ = 1.54184 Å) operating at 40 kV, beam current 30 mA in step-scan of 0.02° 2θ steps with 1s per step from 2 to 70°. Prior to analysis, samples were ground to <50 μm in a tungsten carbide Tema mill. Approximately 5 g of powder was loaded into a plastic sample holder and carefully flattened to avoid preferred orientation. Peak profiles were processed using EVA software and estimates of relative abundances made by comparison of the intensity of the main peaks. Crystalline phases detected were recorded as being either major or minor constituents.

2.4.2. Automated mineralogy

Quantitative identification of the minerals and phases in the samples and false colour maps of the samples were achieved using the QEMSCAN® 146 4300 system using procedures outlined in Rollinson et al. [25]. Data were processed to produce a simplified mineral/phase list using

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iDiscover software. Mineralogy was inferred from collected chemical spectra using a database of known mineral and phase spectra [45].

Samples were mounted in cylindrical resin blocks (30 mm diameter x 15 mm). Granular samples were prepared by mixing 1g of sample with 1.5 g of pure graphite powder to promote particle dispersion and prevent settling bias [46]. Monolith sample volume was reduced to 2 x2x2 cm^3 before resin mounting. Cold epoxy resin (Epofix) was added to the sample in a plastic mould and the mixture was allowed to cure under pressure over night to minimize bubble formation. Sample blocks were polished to a 1 μm finish using a water and diamond solution and then carbon coated to 25 nm thickness. In particle mineralogical analysis (PMA) operating mode used on the particulate samples, each resin block was measured for 4 hours using a pixel spacing of 5 μm for the >100 μm fraction and a further 4 hours using a pixel spacing of 2 μm for the <100 μm fraction. Approximately 2.5 million X-ray analysis points were taken per sample. In field scan (FS) operating mode used on the monoliths of stabilised sediment, the entire block was scanned using a pixel grid spacing of 10μm. Approximately 1.8-3.2 million X-ray analysis points were taken per sample. Operation of the QEMSCAN® follows quality control procedures developed in-house for sample preparation, instrument calibration, operation and data processing.

2.5. In summary

Figure 1 summarizes the previous informations.

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3. Results and discussion

3.1. Raw sediments

3.1.1. Physical and geotechnical properties

Physical and geotechnical properties of the sediments are summarised in Table 1. Their initial water content is very high, in most cases exceeding 100% of the dry sediment mass, preventing use of the sediments in road construction without de-watering. The OM content of the sediments ranges from 7.6 to 14.0%. These high percent values of OM may influence the physical properties of the raw sediments [4,10,47-50]. The presence of OM, which is lighter than the mineral particles, could explain the fact that the G_s was lower than expected from the mineral particles which constitute the sediments (≈ 2.65 $t.m^{-3}$ according to Holtz and Kovacs [51], Philiponnat et al. [52] and Robitaille and Tremblay [53]).

The grain size range was 0/2 mm and the grading curves of all the samples were well distributed (Figure 2). The sediments were all fine grained materials since the fine fraction (0/80 μm) constitutes more than 62.5% of all four sediments. The clay fraction (0/2 μm) represents 3.4 to 8.0% of the sediments. The PSD allows rapid classification and comparison of fine sediments with Dmax≤2 mm [54-55]. According to this classification, S1 is silt and S2, S3 and S4 are silt loam.

The liquid limit (LL) values ranged from 55 to 130%, the plasticity index (PI) values from 20 to 70%. The sediments were classified as “inorganic silts and organic clays with high compressibility” according to the Casagrande plasticity chart using the Atterberg limits. The clay activity AC indicated that the four sediments were active and influenced by the presence of smectite [56-58].

According to this USCS [35], the sediments are classified as high plasticity organic clay or silt (OH) (fine fraction>50%, LL>50%, OM>3%).

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High LL and PI values have been linked by some authors to high OM contents [59-60]: however, in this study, these parameters were not found to be directly correlated. However, the influence of OM was verified using the compaction parameters: an increase in OM content would lead to an increase in OMC and decrease in MDD. This is because the OM may retain water and prevent compaction [5-6,61]. The water sensitivity of the sediments can be determined by the shape of the standard Proctor curves (Figure 3). Water sensitivity is important when a weak variation in the water content induces a large variation in the dry density. For the sediments, the curves of S4 was the flattest, indicating that the sensitivity of the sediment to the water variations in the environment was the weakest.

3.1.2. Microstructure and mineralogy

Minerals identified using XRD as being present in the sediment samples as major or minor phases are presented in Table 2. Quartz was a major phase in all samples, calcite was a major phase in all samples except S4 where it was a minor phase. Halite was present in samples S2 to S3 but could not be unambiguously identified in S4. Minor phases include aragonite, muscovite/illite, clinochlore, spinel and pyrite.

QEMSCAN® analysis identifies minerals according to their chemistry (Appendix; Table 2). Polymorphs such as e.g. calcite and aragonite will be classified in the same category, carbonates, and given the same false colour in images. Quartz was identified as a major constituent of the four sediments using both XRD and QEMSCAN® analysis. XRD analysis identified calcite in all samples whilst carbonates were found to range from 2 to13 % using QEMSCAN®. Feldspars minerals with similar elemental composition (potassium feldspars, albite and anorthite) are grouped together in the QEMSCAN® analysis which identifies feldspar phases as the largest mineral phase in sediments S1, S2 and S3 ranging from 42 to 48%. Sample S2 had a particularly low mica/illite QEMSCAN® percentage

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volume of 2%, this was also the only sample not to have minor levels of muscovite/illite identified in the XRD analysis. Gypsum and apatite which were not identified using XRD were found to be present using QEMSCAN® with the largest amounts in samples S4 and S3 respectively. Pyrite was found to be present at minor levels in S1 and S3 by XRD and was found in all samples using QEMSCAN®, but at >1% only in samples S1 and S3. Very low levels of halite, crystallised out from the sea water during de-watering in oven, were observed using QEMSCAN® analysis compared to the samples analysed using XRD, possibly due to the water based polishing method used to prepare the QEMSCAN® sample blocks which may have re-dissolved the very soluble halite mineral. The QEMSCAN® analytical system identified mineral phases which are below the limit of detection for XRD analysis. QEMSCAN® analysis involves identifying minerals on a spot by spot basis; the limit of elemental detection is typically 3% on individual X-ray energies for the elemental spot analysis [25,62]. The reporting limit for mineral phases in this study for QEMSCAN® was set at 0.01%. In XRD analysis the diffraction patterns from different minerals in a sample can lead to low level mixed spectra which are difficult to interpret and may be obscured by the peaks from minerals present in greater quantities or those with a well-defined crystal structure such as quartz.

3.2. Stabilised sediments

3.2.1. Compaction parameters

Theoretically, due to flocculation and water consumption caused by the addition of lime, the OMC should increase and the MDD should decrease following stabilisation with quicklime and cement. This assumption is verified for the four sediments (Table 3). Moreover, the standard Proctor curves are flatter, indicating a lower sensitivity to the water of the stabilised sediments compared to that of the raw sediments.

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3.2.2. Stengths and elasticity modulus evolution

Figure 4 presents the unconfined compressive strength (UCS), indirect tensile strength (ITS) and elastic modulus (E) evolutions of the stabilised sediments, between 7 and 360 days.

The mechanical performances of the four sediments increase with time. Judging from the curves shape, mechanical performances still developing after 360 days, even slowly.

The mechanical performance of the stabilised sediments is ranked in the descending order as S1 > S2 > S3 > S4, whatever curing time or test performed are.

At 90 days, curing time at which mineralogical analysis are performed, the hydration of the hydraulic binders ensures a strength gain compared with raw sediments (soft and low consitency). Mechanical performances at 90 days are given in Table 3. More details in performance values and means in terms of use in road construction are given elsewhere [38,63-64].

3.2.3. Organic matter content influence on stabilisation

OM content appeared to affect geotechnical performances: where the OM content increased, the OMC increased and the MDD, the UCS, the TS and the E decreased (i.e. the susceptibility to stress and strain is higher). In the literature, OM is recognised as having disturbing effects on sediment stabilisation as it can delay or inhibit the hydration process, preventing amelioration of the mechanical charactersitics [5-6,61,65-68]. OM, which is not detectable by mineralogical analysis, can influence the development of mechanical performances through its effect on the hydraulic binders, hydration, texture and microstructure of the stabilised material.

3.2.4. Mineralogy and microstructure evolution

The XRD analysis results are presented in Table 4. The three main crystalline phases detected

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in the stabilised sediments were quartz, calcite and halite, the same three major minerals detected in the raw sediments. Minor clinochlore and rutile were observed in the stabilised sediments. Minor aragonite, spinel and rutile were found in raw sediments but were not detected from the corresponding stabilised sediments. It is also the case for pyrite in S1 and S3. Peak profiles matching known cementitious hydrates were not observed using XRD. These signals may have been drowned out by the dominant minerals.

False colour maps generated for the stabilised sediment using the QEMSCAN® analytical system are presented in Figure 5 along with charts displaying data for the per cent mineral volume in the stabilised and raw sediments. The matrix was very fine consisting mainly of quartz (pink), feldspars (blue), carbonates (maroon) and mica/illite (fuschia). Shells (carbonates in maroon) and fishbones (apatite in turquoise) were clearly seen. Porosity, shown in grey on the false colour images, ranged from 12 for S2 to 22% for S4. Porosity may be due to the formation of lumps due to flocculation following the stabilisation treatment but could be caused also by sample preparation (shrinkage during resin curing, plucking during polishing). Lumps were clearly observed on the false colour images for S2, S3 and S4.

Quartz has a consistently smaller per cent mineral volume in stabilised than the raw sediment. This decrease could be attributed to dilution due to the addition of material during treatment (3% quicklime and 6% cement). It could also be attributed to the reaction of quartz (SiO_2) in the formation of calcium silicate hydrates such as tobermorite ($Ca_5Si_6O_{16}(OH)_2.7H_2O$) and jennite ($Ca_9Si_6O_{18}(OH)_6.8H_2O$). These minerals, classified in the "other silicates" phase in QEMSCAN® analysis, increased slightly in the stabilised compared with the raw phases.

Pyrite is not detectible in the stabilised sediments using XRD, but it was detected using QEMSCAN® in all four sediments at 0.2 to 1.6%, showing an increase after treatment for S2 to S3 and a decrease for S4.

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The feldspar mineral phase in QEMSCAN® includes K-Feldspars ($KAlSi_3O_8$) and the plagioclase series from albite ($NaAlSi_3O_8$) to anorthite ($CaAl_2Si_2O_8$). There was a consistent increase in the percent mineral volume of feldspars phase post treatment; this could be attributed to the formation of hydration products such as katoite ($Ca_3Al_2(OH)_{7.6}(SiO_4)_{1.1}$) and gehlenite hydrate ($Ca_4Al_2(OH)_{12}[AlSi(OH)_8]_2.2H_2O$) or other phases present in blended cements such as gehlenite ($Ca_2Al_2SiO_7$) and yoshiokaite ($Ca_{5.5}Al_{11}Si_5O_{32}$). These phases are classified as feldspar minerals by the QEMSCAN® analytical system because they have similar chemistry and thus are not separable using inferred mineralogy by chemistry. If the grain size of the minerals is very small (<5 μm) mixed spectra may be produced from the electron beam which can confound separation of phases using chemistry [25]. In the stabilised sample this may led to very fine grained mixtures of e.g. alite (Ca_3SiO_5-Mg, Al), belite (Ca_2SiO_4) and aluminate ($Ca_3Al_2O_6$) being assigned to the feldspar mineral phase as they would have a similar spectra to this mineral.

There was a consistent increase in the carbonate and gypsum phases detected by QEMSCAN® after stabilisation. The increase in the gypsum phase, which includes anhydrite and phases comprising Ca, S and O (as ettringite), could be due to anhydrite, hemihydrate or gypsum present as additional phases in the blended cement using for treatment, possibly indicating that these phases were not fully involved in hydration reactions at the time of analysis. The increase in the carbonate phases could be due to the presence of calcium oxide in the quicklime and of calcite and dolomite as additional phases in the cement added during treatment. It could be also due to the carbonation of the cementitious hydrates as portlandite by reaction with carbon dioxide CO_2.

High silicates content is an important factor in the evolution of the mechanical performances of the stabilised sediments by reacting to form calcium silicate hydrates, CSH. These minerals reinforce the links between the sediment grains thus improving the strength of

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the stabilised material. However, they can have an amorphous structure, which is not detected by XRD and are also likely to be fine grained which will affect QEMSCAN® analysis. The release of silica and alumina by clay minerals contained in the fine sediments allows pouzzolanic reactions over several years which improves long term mechanical strengths due to the formation of calcium silicate hydrates, CSH, and calcium aluminate hydrates, CAH.

4. Conclusions

This paper gives the physical and mineralogical characteristics of four marine dredged sediment before and after stabilisation. The conclusions drawn from this work are listed below:

- The four sediments are fine materials (>62.5% have a gain size of <80 μm), moderately to highly organic and highly plastic, classified as high plasticity organic clay or silt (OH) according to the USCS.
- The clay activity of the sediments indicate that behaviour is influenced by the presence of smectite clay type; the three main crystalline phases detected by XRD are quartz, calcite and halite; the lower detection limits of the QEMSCAN® analytical system allow pyrite, feldspars and other aluminium silicates to be detected in addition.
- Stabilised sediments, with 3% of CaO and 6% of cement, show long term improvement of their physical and mechanical properties.
- The mineralogical changes following stabilisation are not significant enough to be detected by XRD analysis; QEMSCAN® analyses show that quartz, Al and Al Fe silicate phases decrease following stabilisation, probably due to their reaction to form cementitious hydrates, and that feldspar and carbonate mineral phases increase, probably due to the inclusion in this phase of hydration products and other phases present in blended cements.

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To confirm these changes, the mineralogy of the stabilised sediments should characterised at each mechanical test curing time. Moreover, the use of stabilised sediments in road construction should be associated with chemical and environmental follow-up to ensure stabilisation has been achieved.

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Captions

Table 1. Physical and geotechnical characterisation of the sediments

Table 2. Mineralogical characterisation of the sediments (by XRD and QEMSCAN® analysis on powder, 0/2 mm)

Table 3. Geotechnical characterisation of the raw and stabilised sediments

Table 4. Mineralogical characterisation of the raw and stabilised sediments (by XRD analysis on powder, 0/2 mm)

Figure 1. Progress of the study

Figure 2. Particle size distribution of the sediments

Figure 3. Standard Proctor curves of the sediments

Figure 4. Mechanical behaviour of the stabilised sediments

Figure 5. QEMSCAN® analysis of the stabilised sediments

Appendix. Mineral categories used in QEMSCAN® analysis

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Figure captions

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Appendix. Mineral categories used in QEMSCAN® analysis

Mineral Category	Mineral Description
Background	All resin mounting media related/edge effects: Cl??, Si Cl?? Carbon, Cl?, Al Metal (block holder, but includes the odd metal sh
Pyrite	Fe sulphides, pyrite/marcasite and pyrrhotite
Rutile	Any phase with Ti, O such as rutile, brookite and anatase
Ilmenite	Any phase with Ti, Fe, O possibly with Mn, includes minor titano-magnetite
Titanite	Any phase with Ca, Ti, Si, O and minor Al, F, Fe
	Includes Fe-oxides such as hematite, magnetite, goethite, siderite, limonite, trace chrome/chromite. May include rust and Fe sl
Mn phases	Mn Fe oxides & Mn silicates
REE phases	Monazite, trace xenotime
Zircon	Any phase with Zr, Si and O
Quartz	Quartz and other silica minerals/polymorphs
Feldspar	K-feldspars and plagioclase feldspar (incl. albite)
Mica/Illite	Muscovite, biotite and any other mica, includes illite and other similar silicates
Al silicates	Any Al silicate such as kaolinite, andalusite/siliminite/kyanite, may include topaz. May include clays
Fe Al silicates	Includes chlorite, nontronite, tourmaline, and any other Fe Al silicate. May include clays
Other silicates	Any silicates not listed elsewhere, such as clays, serpentine group, hornblende and silicates too fine to be distinguished (boun
Carbonates	Calcite, lesser dolomite (Mg rich calcite), ankerite. Includes shell debris
Ca Ox/CO_3/Cl	Any phase with Ca, C, O, Cl
Gypsum	Any phase with Ca, S, O
Apatite	Any phase with Ca, P, minor Al
NaCl	Any phase with Na, Cl such as halite
Porosity	Includes pores, holes and cavities that do not connect with the outside edge of the sample (converts background to this catego
Others	Any other mineral/phase not included above. Boundary effects, indistinguishable minerals.

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Publications on geochemical behaviour of soils and sediments

SETARMS project

Stabilisation of sediment with hydraulic binders

Review paper

Saussaye L., Hamdoun H., Leleyter L., Van Veen E., Coggan J., Rollinson G., Maherzi W., Boutouil M., Baraud F. (2016). Trace element mobility in a polluted marine sediment after stabilisation with hydraulic binders. Marine Pollution Bulletin, 110(1):401-408.

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Baraud F., Leleyter L., Hamdoun H. (2016). Accumulation of metals in harbor sediments: a comprehensive assessment of the environmental risk thanks to the combined estimations of anthropogenic enrichment, bioavailability and potential adverse biological effects. 5th International Symposium on Sediment Management (I2SM), Montreal, Canada, July 10-13.

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Van Veen E., Coggan J., Andersen J., Hopkinson L., Matthewson E., Baraud F., Leleyter, Hamdoun H., Le goff P.-A., Olivier A. (2013). An overview of metal concentrations in dredged sediment across the channel. Congrès Gestion Environnementale des Sédiments de Dragage (GESeD), Caen, France, April 10-12.

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Saussaye L., Hamdoun H., Boutouil M., Baraud F., Leleyter L., Le Goff P.-A. (2012). Evaluation de la réutilisation de sédiments de dragage en tant que matériau alternatif. XXII^{ème} Journées Nationales Génie Côtier - Génie Civil (JNGCGC), Cherbourg, France, June 12-14.

Hamdoun H., Baraud F., Basset B., Leleyter L., Lemoine M. (2010). Environmental impact of reused dredged sediment. Sustainable Approaches to remediation of Contaminated Land in Europe (SARCLE), Gent, Belgium, June 08-10.

Others studies

Soil stabilisation

Review paper

Saussaye L., Leleyter L., Baraud F., Boutouil M. (2016). Trace and major elements' stabilisation in soils treated with hydraulic binders. European Journal of Environmental and Civil Engineering, *on line*

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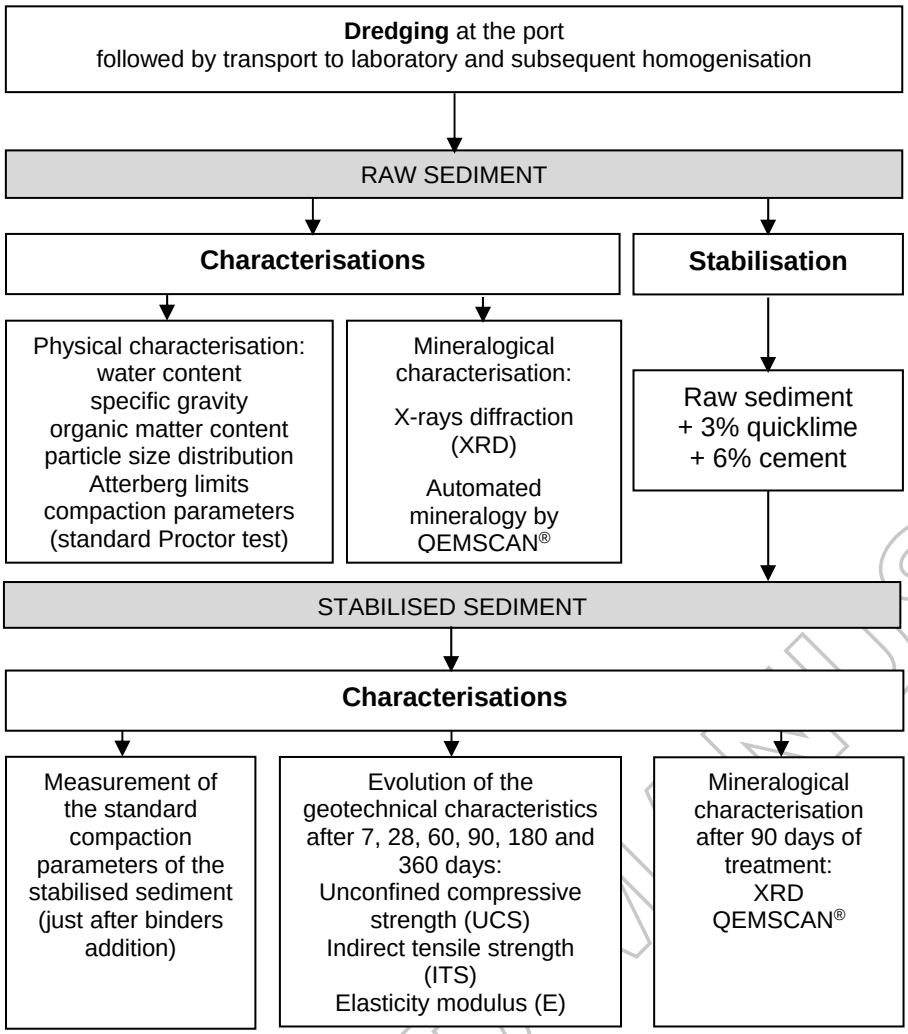

Figure 1. Progress of the study

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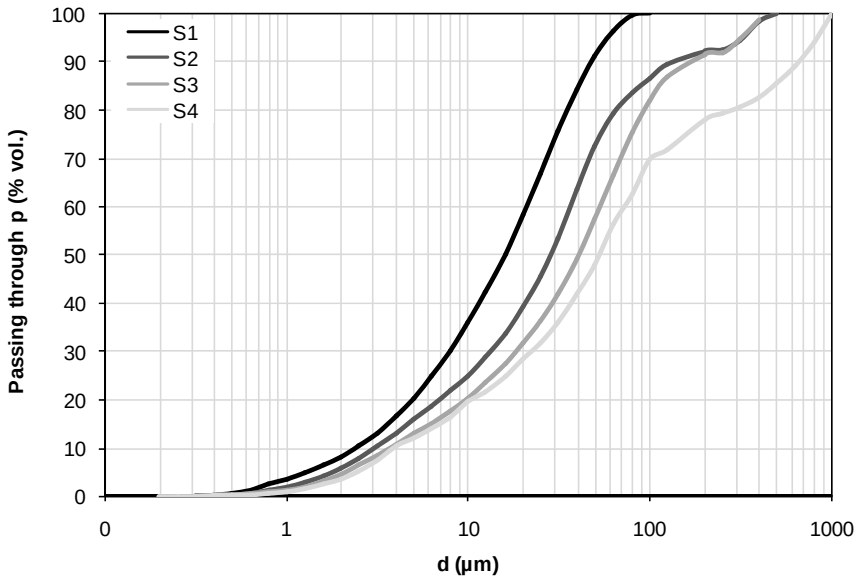

Figure 2. Particle size distribution of the sediments

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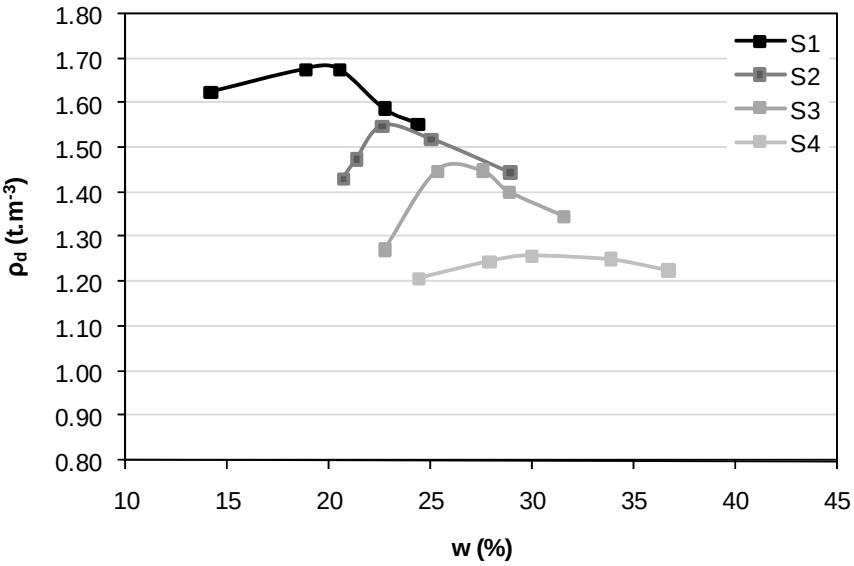

Figure 3. Standard Proctor curves of the sediments

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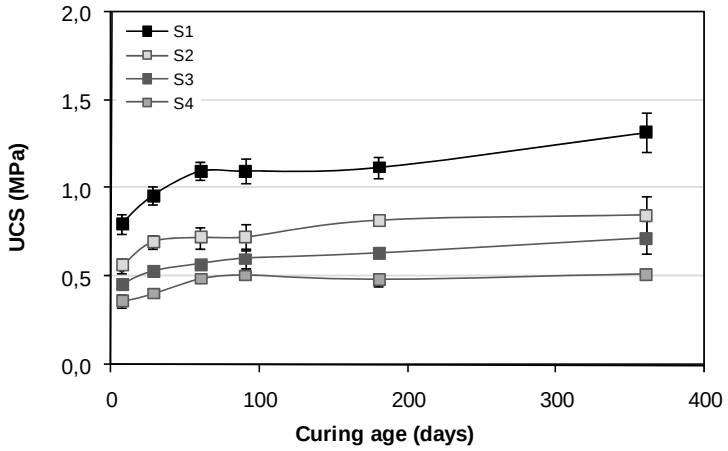
(a)



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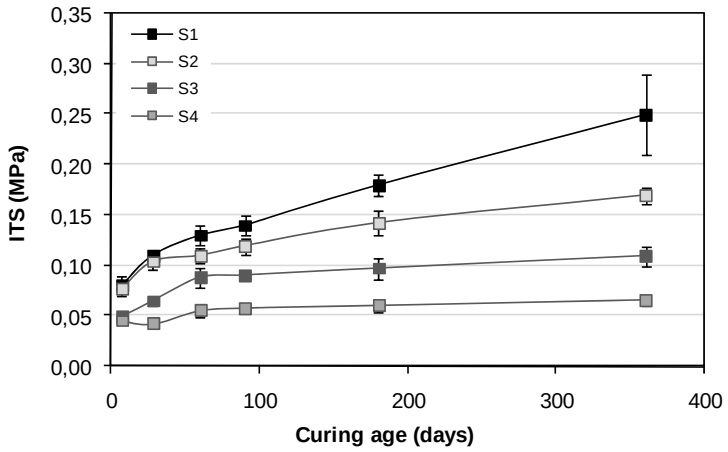

(c)

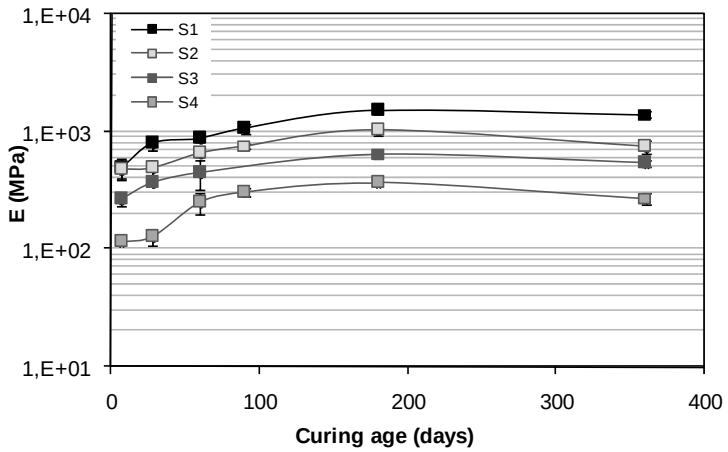

Figure 4. Mechanical behaviour of the stabilised sediments

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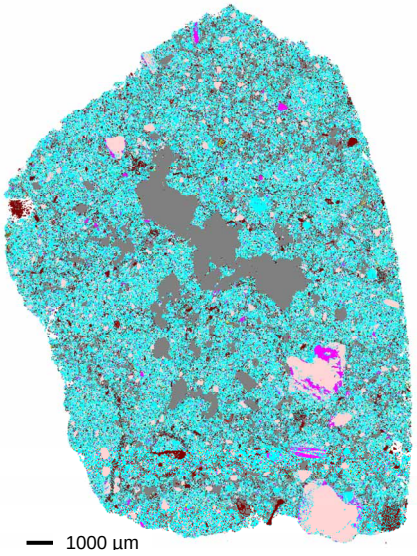
False color image S1 stabilised – monolith – porosity 18%



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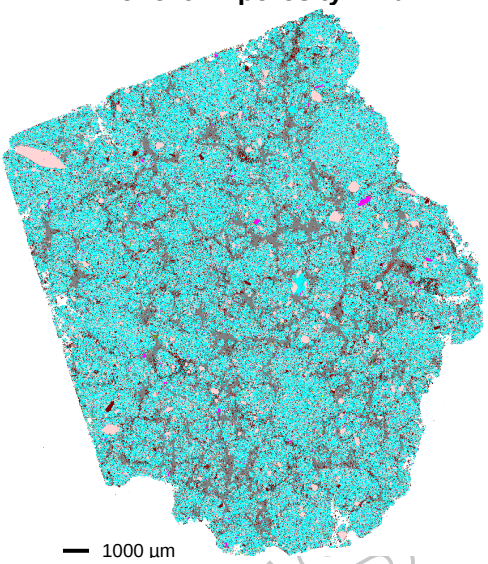
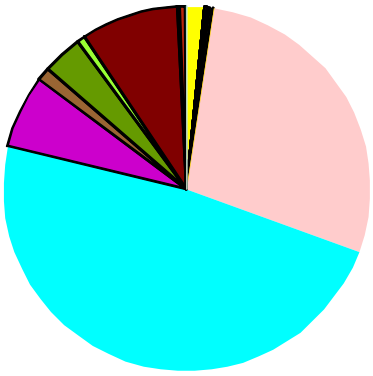
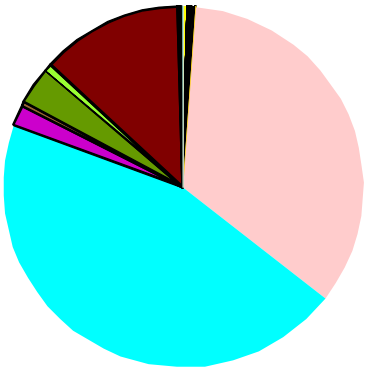


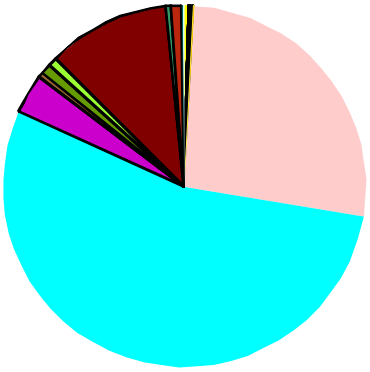
Minerals composition of the S1 raw sediment



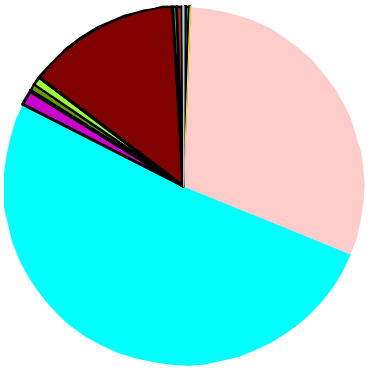
Minerals composition of the S2 raw sediment



Minerals composition of the S1 stabilised sediment



Minerals composition of the S2 stabilised sediment



Mineral Name

- Background
- Pyrite
- Pyrite (Ox)
- Chalcopyrite
- Sphalerite
- Galena
- Arsenopyrite
- Barite
- Cassiterite
- Rutile
- Ilmenite
- Titanite
- Fe-Ox/CO3
- Mn phases
- REE phases
- Zircon
- Quartz
- Feldspar
- Mica/Illite
- Al silicates
- Fe Al silicates
- Other silicates
- Carbonates
- Ca Ox/CO3/Cl
- Gypsum
- Apatite
- NaCl
- Others

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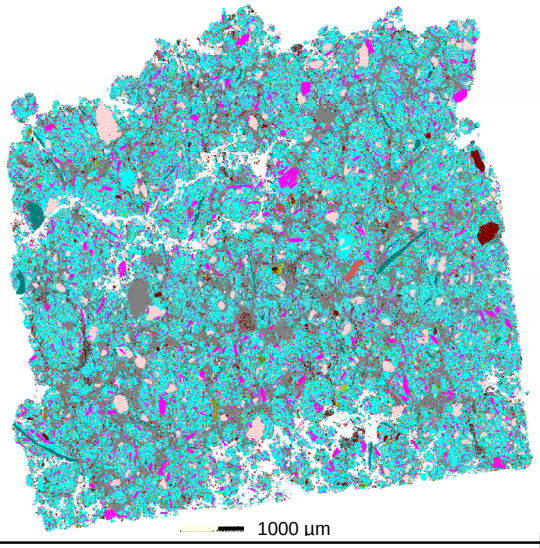
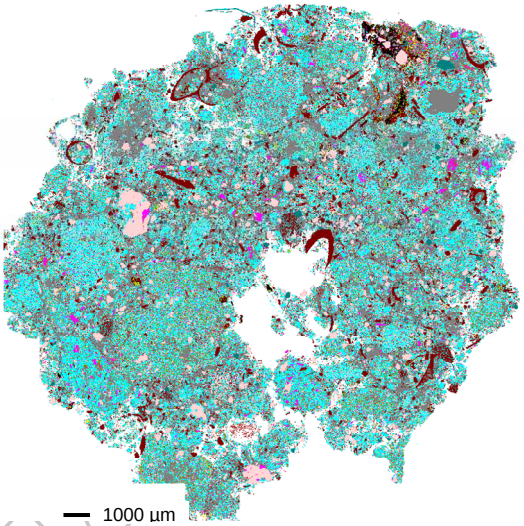
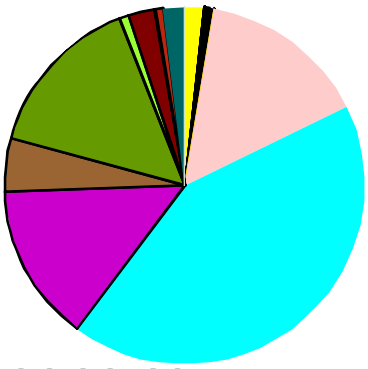
False color image S3 stabilised – monolith – porosity 18%



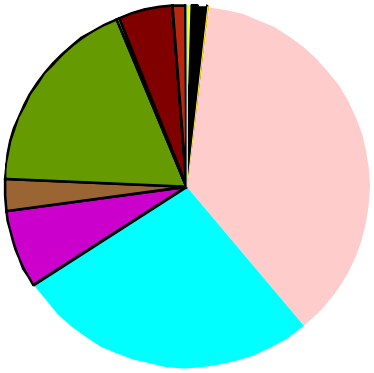
False color image S4 stabilised – monolith – porosity 22%



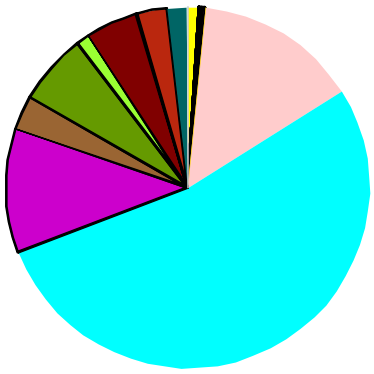
Minerals composition of the S3 raw sediment



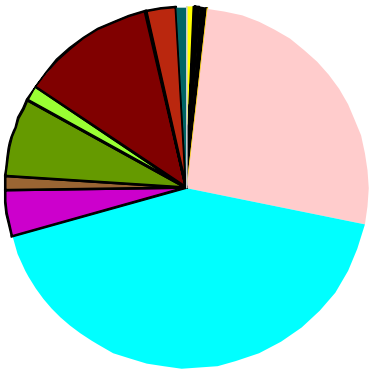
Minerals composition of the S4 raw sediment



Minerals composition of the S3 stabilised sediment



Minerals composition of the S4 stabilised sediment



Mineral Name

- Background
- Pyrite
- Pyrite (Ox)
- Chalcopyrite
- Sphalerite
- Galena
- Arsenopyrite
- Barite
- Cassiterite
- Rutile
- Ilmenite
- Titanite
- Fe-Ox/CO3
- Mn phases
- REE phases
- Zircon
- Quartz
- Feldspar
- Mica/Illite
- Al silicates
- Fe Al silicates
- Other silicates
- Carbonates
- Ca Ox/CO3/Cl
- Gypsum
- Apatite
- NaCl
- Others

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Figure 5. QEMSCAN® analysis of the stabilised sediments

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Table 1. Physical and geotechnical characterisation of the sediments

	S1	S2	S3	S4
Water content				
Mean initial water content (%)	99	115	235	230
Range of initial water contents measured	93-104	115-116	233-236	170-333
Organic matter				
Organic matter (OM) content (%)	7.6	10.3	11.3	14.0
Specific gravity (or density)				
Specific gravity Gs (t/m^3)	2.44	2.39	2.39	2.57
Grain size				
Gravel (> 2000 µm) (%)	0.0	0.0	0.0	0.0
Sand (63/2000 µm) (%)	3.6	20.7	33.6	43.8
Silt (2/63 µm) (%)	88.4	73.5	61.9	52.8
Clay (0/2 µm) (%)	8.0	5.8	4.5	3.4
Fine (0/80 µm) (%)	99.6	83.6	75.3	62.5
Atterberg limits				
Liquid limit LL (%)	55	71	130	70
Plasticity Index PI (%)	22	35	70	20
Activity AC	2.74	6.09	15.49	5.87
Compaction parameters				
Optimum moisture content OMC (%)	20.5	22.6	27.5	30.0
Optimum dry density ODD (t/m^3)	1.68	1.55	1.45	1.26
Unified Soil Classification System (USCS)				
Class	OH	OH	OH	OH

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Table 2. Mineralogical characterisation of the sediments (by XRD and QEMSCAN® analysis on powder, 0/2 mm)

	Sediment code							
	S1		S2		S3		S4	
	XRD	QEM.[a]	XRD	QEM.	XRD	QEM.	XRD	QEM.
Quartz	M[b]	28	M	34	M	15	M	37
Carbonates (calcite C, argonite A, others o)	C: M A: m[b]	9	C: M A: m	13	C: M	2	C: m	5
Halite	M	0.02	m	0.02	M	<0.01	-	0.01
Mica / illite (muscovite, illite, others)	m	6	-	2	m	14	m	7
Feldspars (albite A, orthoclase O, others o)	A: m	48	-	45	A: m	42	A: m	27
Al silicates (kaolinite, others)	-[c]	1.2	-	0.4	-	4.8	-	2.7
Spinel	m	-	-	-	-	-	-	-
Pyrite	m	1.6	-	0.4	m	1.7		0.5
CaOx/CO3/Cl (clinochlore, others)	-	0.17	-	0.16	-	0.05	-	0.02
Fe Al silicates	-	4	-	3	-	15	-	18
Gypsum	-	0.5	-	0.2	-	0.7	-	1.2
Apatite	-	0.07	-	0.04	-	1.91	-	0.06
Rutile	-	0.13	-	0.11	m	0.15	-	0.24

[a]QEM.: QEMSCAN® analysis
[b]M: major; m: minor
[c]-: unambiguous identification not possible

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Table 3. Geotechnical characterisation of the raw and stabilised sediments

	S1	S1	S3	S4
Initial moisture content (%)	99	115	235	230
OM content (%)	7.6	10.3	11.3	14.0
Compaction parameters of raw sediments				
Optimum moisture content OMC (%)	20.5	22.6	27.5	30.0
Optimum dry density ODD (Mg/m^3)	1.68	1.55	1.45	1.26
Compaction parameters of stabilised sediments (3% CaO + 6% cement)				
Optimum moisture content OMC (%)	21.9	24.9	28.3	31.8
Optimum dry density ODD (Mg/m^3)	1.57	1.47	1.39	1.23
Unconfined compressive strength at 90 days of stabilised sediments				
Unconfined compressive strength UCS (MPa)	1.1 (0.1)	0.7 (0.1)	0.6 (0.1)	0.5 (<0.1)
Mechanical class at 90 days of stabilised sediments				
Indirect tensile strength ITS (MPa)	0.14 (0.01)	0.12 (0.01)	0.09 (<0.01)	0.06 (<0.01)
Tensile strength TS = 0.80 ITS (MPa)	0.11	0.10	0.07	0.05
Elasticity modulus E (10^3 MPa)	1.06 (0.10)	0.76 (0.04)	NM	0.31 (0.03)

(x): standard deviation
NM: non measured

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Table 4. Mineralogical characterisation of the raw and stabilised sediments (by XRD analysis on powder, 0/2 mm)

	S1		S2		S3		S4	
	Raw[a]	Stab.[b]	Raw	Stab.	Raw	Stab.	Raw	Stab.
Quartz	M[c]	M	M	M	M	M	M	M
Calcite	M	M	M	M	M	M	m	M
Halite	M	m	m	M	M	M	-	m
Aragonite	m[c]	m	m	-	-	-	-	-
Muscovite/illite	m	m	-	-	m	M	m	-
Clinochlore	-[d]	-	-	-	-	m	-	-
Albite	m	m	-	-	m	M	m	-
Pyrite	m	-	-	-	m	-	-	-
Spinel	m	-	-	-	-	-	-	-
Rutile	-	-	-	m	m	-	-	-

[a]Raw: sediment before treatment

[b]Stab.: sediment following treatment with 3% CaO and 6% cement

[c]M: major; m: minor

[d]-: unambiguous identification not possible

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