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Mechanical characterization of treated harbor sediments for road applications

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Abstract:
In road engineering, cement used as a treatment product for dredged fine sediments, has shown satisfactory results. In the present study, an industrial waste (Cement Kiln Dust) from Gabes cement plant (CKD) is used to substitute a fraction of cement used in a basic formulation F0 (30% sediment + 62% sand + 6% cement + 2% lime). Two formulations F1 and F2 are tested with 3% and 8% CKD respectively.
The results of compressive strength, indirect tensile strength and stiffness modulus obtained for the two CKD treated formulations, were compared to those of the F0 mix design. The compressive strengths Rc at 28 days was improved by the addition of CKD. The increase of Rc is 30% for F1 and 56% for F2. Nevertheless, the tensile strengths Rt were slightly lower than those obtained with cement alone (F0). An ultrasonic device is used to estimate the modulus at 28 days from the speed of propagation of longitudinal waves. From these results, the modulus E and the tensile strengths at 360 days were deduced from empirical formulas adapted in case of sediments treated with hydraulic binders. The location of the points (E, Rt) on the classification chart of treated soils for road application (GTR, 2000), showed the evolution of treated sediments from zone 4 to zone 3 for the two formulations F1 and F2. This authorized their use in the pavement base course.

Keys words:
Harbor sediment, Cement, Cement kiln dust, Tensile strength, Stiffness modulus

1. Introduction

For nearly ten years, dredged sediments, previously considered as waste, have been used in several recovery processes. The latter combined an economic advantage and an environmental issue. Indeed, this material is no longer stored or dumped because it exceeds the threshold values for storage on land or at sea. Hence, recovery channels in civil engineering have been sought in road engineering (DUBOIS, 2006; TRAN, 2009; ZENTAR *et al*., 2009; ACHOUR, 2013).

In Tunisia, attention is given to the management of dredged sediments as it is a signatory of the LONDON CONVENTION (1972) and the STOCKHOLM CONVENTION (2001). Recovery works are carried out on Rades sediments to recycle them as cement material (BEL HADJ ALI, 2013). In 2009, part of dredged sediments from the commercial port of Sfax are used to fill the coast in the Taparura project. In 2018, a full-scale test road was carried out as part of research work on the use of sediments dredged from the harbor of Zarzis as a foundation layer. The sediments of the harbor of Zarzis are composed of 67% sand, 23% silt and 10% clay and a content of 12% organic matter (ZELLEG, 2018). These sediments treated with 3% lime showed good mechanical performance at 90 days corresponding to zone 2 on the classification chart (SETRA, 2000).

In this same axis, the present study aims to use cement kiln dust (CKD) in a formulation adapted for the sediments of Dunkerque (France). CKD are used as an alternative to the traditional stabilization agents such as lime, cement and fly ash, or as alkali activators for different alumosilicate materials, including ground-granulated blast furnace slag, low-calcium fly ash and metakaolin (PARSONS *et al*., 2004; BUCHWALD & SCHULZ, 2005; AL-BAKRI *et al*., 2022). The sediments are collected in the basins of the commercial harbor of Sfax. On these samples are carried out studies of physical, chemical and environmental characterization (BEN SLAMA *et al*., 2021). The mechanical performances of treated sediments by cement and CKD are assessed by compressive tests, indirect tensile tests and measures of stiffness modulus. Classification of the treated sediments is presented to get their suitability for a given treatment.

2. Experimental procedures

2.1 Sediment characteristics

Sediments were collected from the different basins of Sfax harbor (figure 1). The samples were washed with fresh water to minimize the content of sulphates and chlorides. The sediments were dried at ambient air then in oven at temperature under 50°C. The physical characteristics were summarized and compared to those of Rades, Gabes and Zarzis harbors in table 1. The sediments were mainly composed of silt, sand and low clay fraction. Their average content of organic matter was 12 %. According to the guide of materials classification in use in France (GTR, 2000), the fine sediments were classified as A1F12 material. Previous study performed to assess the performances of Sfax harbor sediments (BEN SLAMA, 2021) has shown a very low Immediate Californian Bearing Ration (I-CBR = 13%). The evolution of I-CBR as a function of the sand content is shown on figure 2. The penetration tests are conducted with Modified Proctor characteristics (dry density and water content). An index I-CBR> 20 is obtained for a content of 70 %, which ensure an execution without deformation of the layer. The same percentage was used by DUBOIS (2006) and ACHOUR (2013).

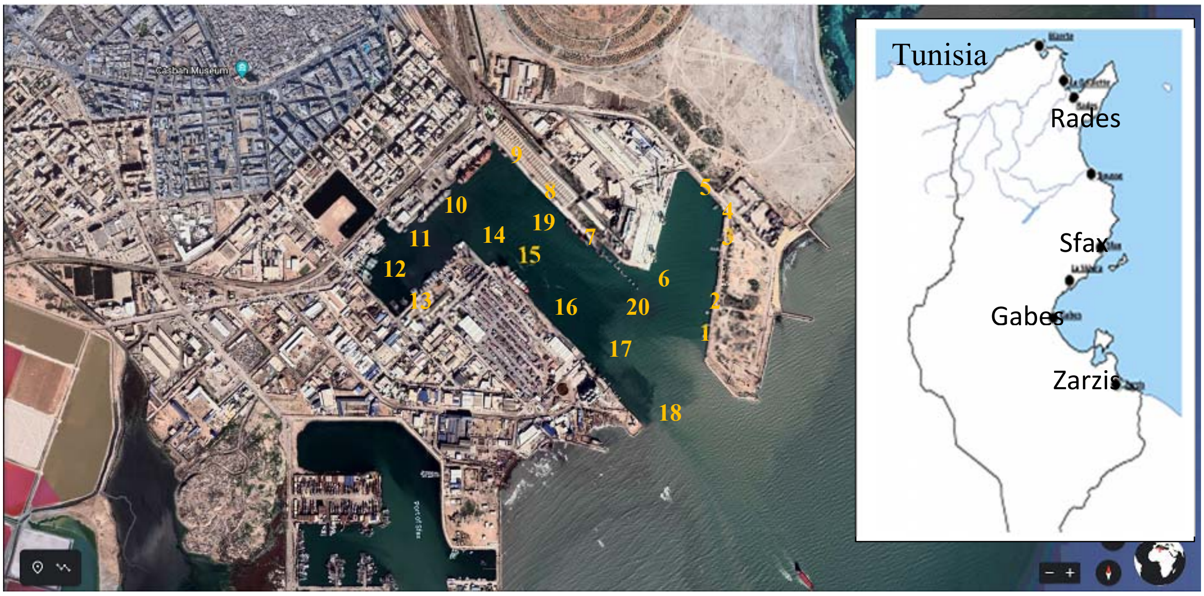

Figure 1. Localization of collected samples in Sfax harbor.

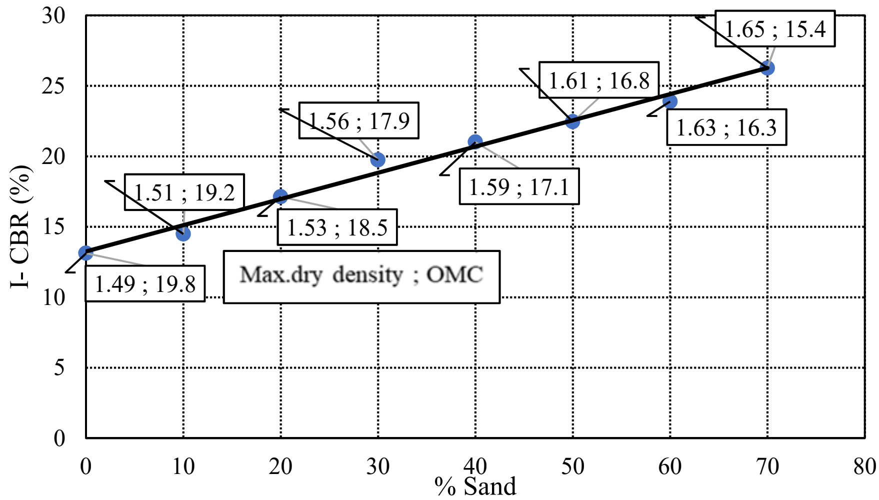

Figure 2. Influence of sand content on I-CBR index.

Table 1. GTR classification of different harbor sediments in Tunisia.

Parameter	*Sediments of Sfax*	*Sediment of Radès [Bel Hadj Ali]*	*Sediment of Gabès [Bel Hadj Ali]*	*Sediment of Zarzis [Zallej]*
$_s$ (g/cm^3)	2.11 – 2.78	2.27 - 2.62	2.13	2.56
Methylene Blue	0.72	1.66 - 1.42	0.7 - 0.63	1.2
W_L (%)	46.3 – 54.7	73.5 - 87.5	100.6	83.5
W_P (%)	37.8 - 45	22.3 - 28	57.5	66.13
PI (%)	9.2 – 10.4	51.2 - 59.5	43.1	17.37
% < 2 m (clay)	5 - 9	30 - 39	12.5	7
2 m < % < 63 m (silt)	37 - 73	74 - 58	34.5	18
63 m > % (sand)	18 - 58	11.6 - 13.5	52.7	75
Organic matter (%)	11.1 – 13.1	9.07 - 9.75	16.1	12.52
GTR class	A1	A4	A4	A2
Type behavior	A1F12	A4F11	A4F12	A2F11

2.2 Mixture components characteristics

In road construction engineering, cement used as a treatment product for dredged fine sediments has shown satisfactory results. So, the performance of the mixture (sediment/sand) is enhanced with cement. With the objective of reducing the cost of treatment, recovering industrial waste and limiting the release of CO_2, an industrial waste (cement kiln dust) from Gabes cement plant is used as a binder.

Cement CEMII 32.5 is selected according to GTS (2000) prescriptions. The chemical compositions of the CKD and cement are given in table 2. The percentage of gypsum in cement is 0.22%. The CKD grain size distribution is compared to those of sediments and sand on figure 3.

Table 2. Mineralogical compositions of cement and CKD by DRX.

	ΣAlite	**Calcite**	**Ferrite**	**Belite_beta**	**Quartz**	**Arcanite**	**ΣAlum**
Cement II	47.69	24.85	7.59	10.96	0.7	0.97	4.73
CKD	73.1	-	5.22	12.72	0.13	0.25	7.82

Note: ΣAlite: $3CaOSiO_2$, Belite : $2CaOSiO_2$, Alum: Al_2O_3, Ferrite: Fe_2O_3, Calcite: $CaCO_3$, Quartz: SiO_2, Arcanite: K_2SO_4.

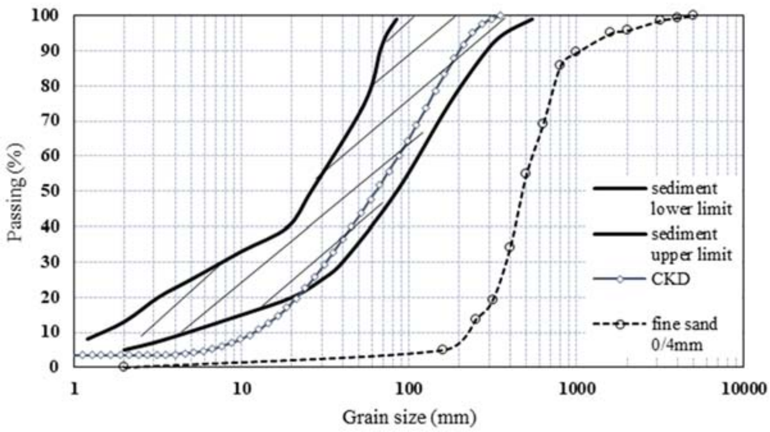

Figure 3. Grain size distributions of sediments, CKD and sand.

3. Mechanical strengths of treated sediments

A formulation given by ZENTAR *et al.*, (2008), composed of 30 % of sediment, 62%, 2 % of lime and 6% cement, is adopted in this study as a basic formulation F0. A first formulation F1 is tested where 3% of cement are substituted by 3% of CKD. The percentage of lime is increased to 4 % to ensure the activation of the CKD supposed to have pozzolanic properties. In order to improve the cohesion of the treated sediments, 5 % of sand are replaced by the CKD in a second formulation F2. The percentages of the different components in each formulation are given on table 3.

Table 3. Component fractions in tested formulations.

Formulation	*% Sediment*	*% Sand*	*% Lime*	*% Cement*	*% CKD*
F0	*30*	*62*	*2*	*6*	-
F1	*30*	*60*	*4*	*3*	*3*
F2	*30*	*55*	*4*	*3*	*8*

In addition to the I-CBR values required to be used in pavement layers, the treated materials must acquire sufficient mechanical performance to sustain the stresses brought by traffic. These performances are evaluated through measurements of compressive strength, stiffness and indirect tensile strength. These compressive and tensile strengths and stiffnesses are measured on specimens made in accordance with the recommendations of standard NF P 98 114-3 (2003).

3.1 Cylindric samples characteristics

A steel mold is made for the production of cylindric samples. The samples are first compacted manually and then under mechanic press to a density of 95 % of the maximum Modify Proctor density (Max.dry density) and at the optimal moisture content (OMC) (figure 4).

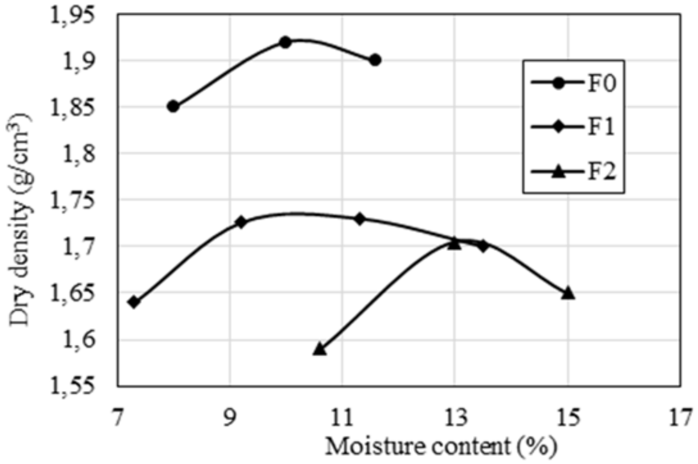

Figure 4. Compaction parameters of treated sediments.

3.2 Short term strength

The compressive strengths were performed on monolithic cylindrical samples with a diameter of 45 mm and a height of 90 mm (NF P98-232-1, 1991; NF P98-232-3, 2001). The specimens are removed from the molds just after compaction and are stored in the ambient air. The storage temperature is above 20°C. The average strengths obtained after 7 and 14 days of curing are given in table 4. The required threshold needed for circulation at young age (> 1MPa) is verified for F0. For the two formulations, the strengths are slightly decreased but remained quite close to the threshold value.

3.3 Classification of treated sediments for road applications

3.3.1 *Influence of CKD on compressive strength*

The press used for sample crushing is equipped with a data acquisition system which allows to record the applied force in function of sample deformation (displacement). The evolutions of the applied forces on the specimens curded until 28 days are presented on figure 5. It showed that the stiffnesses of treated sediment by lime-cement or lime-cement-CKD are quite similar. While the compressive strengths are improved by the insertion of CKD (figure 6).

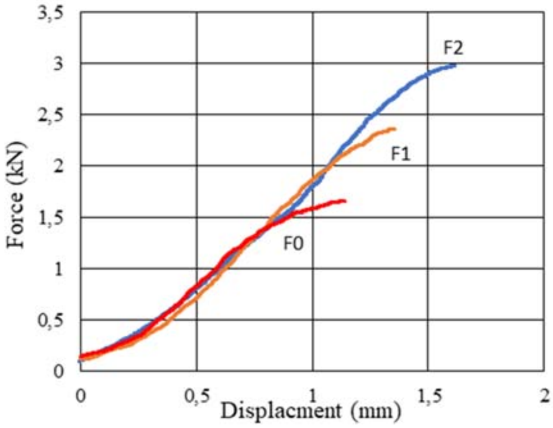

Figure 5. Stiffness of specimens treated with the three formulations.

3.3.2 *Influence of CKD on tensile strength*

The tensile strength is estimated from indirect tensile tests. The specimens with a height (*H)* of 4,5 cm and a diameter (ϕ) of 4,5 cm, are made and then stored as described above (NF P 98-232-3). The maximum value of the applied force (F_r *in N*) is used to calculate the indirect tensile strength (R_{ti}) according to the equation 1. The tensile strength (R_t = 0.8 R_{ti}) after 28 days are given on table 4 for the different formulations.

$$R_{ti}(MPa)tableau = 2\frac{F_r}{\pi \emptyset H}10^{-2} \qquad (1)$$

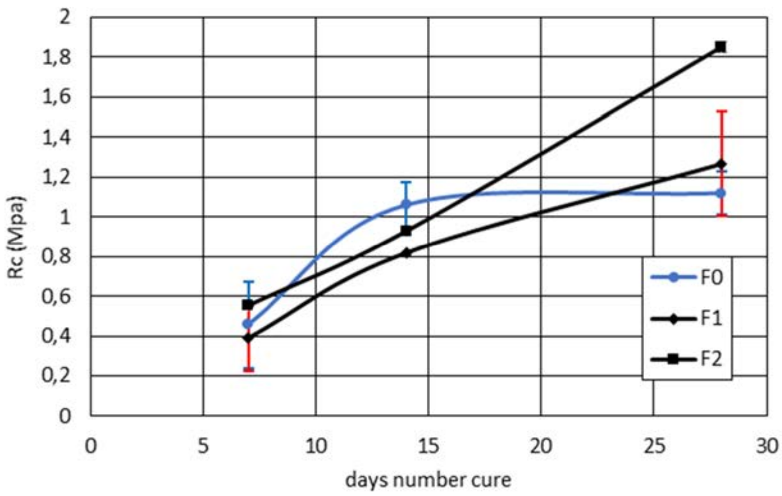

Figure 6. Compressive strengths of tested formulations.

Table 4. Tensile strength of tested formulations.

Formulation	***Max.dry density (g/cm³)***	***OMC (%)***	***Rc 7j (MPa)***	***Rc 14 (MPa)***	***Rti_{28} (MPa)***	***Rt_{28} (MPa)***
F0	*1.90*	*10.25*	*0,456*	*1.06*	*0.27*	*0.22*
F1	*1.73*	*10.00*	*0.387*	*0.816*	*0.22*	*0.18*
F2	*1.71*	*12.80*	*0.55*	*0.925*	*0.21*	*0.17*

An ultrasonic device is used to estimate the stiffness modulus of cohesive soil and rocks. The principle of the method is to measure the propagation time of longitudinal waves propagating over a length L which allows to obtain the velocity of the wave Vp (m/µs). The Young's modulus *E* is calculated by equation 2.

$$E = \rho V_p^2 \frac{(1+\nu)(1-2\nu)}{(1+\nu)} \quad (2)$$

where ρ is the material density and ν Poisson coefficient (ν = 0.2).

3.3.3 *Mechanical classification of treated sediments*

The class of the treated material is obtained by placing its tensile strength R_t and its stiffness *E* at 360 days on the classification chart of treated materials (GTR, 2000). For this study, only one experimental point is available (at 28 days) for each formulation. The strengths and stiffness modulus at 360 days are estimated from empirical equations (equations 3 and 4) deduced from research studies on sediments treated with hydraulic binder. The position of points on the chart (figure 7), showed an evolution from class 4 to class 3 for the two formulations F1 and F2. This showed their suitability to be used in the pavement foundation layer, which is recommended by the NF P98-113 standard (1999).

$$\frac{R_{t28j}}{R_{t360j}} = 0.6 \quad (3)$$

$$\frac{E_{28j}}{E_{360j}} = 0.65 \quad (4)$$

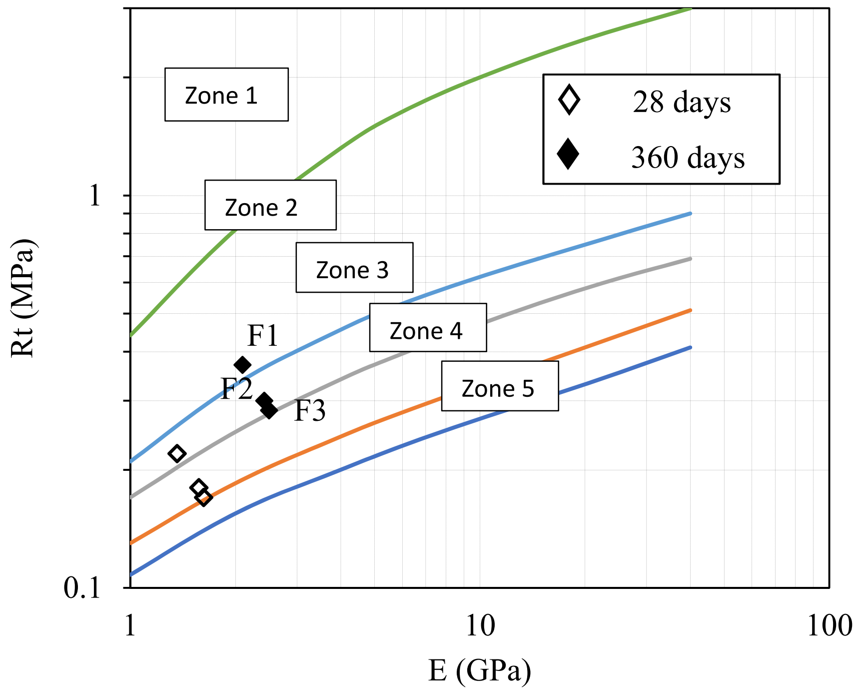

Figure 7. Classification of treated sediments (SETRA, 2000).

4. Conclusion

The substitution of cement by CKD, has given satisfactory results for use in pavement layers. The compressive strength and stiffness were improved. However, a slight decrease in tensile strength seems to be related to sulfates and chlorides

It would be interesting to measure the characteristics (tensile strength and modulus) at long term (after 90 days) and to verify their behaviors after immersion (after 60 days).

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