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ORIGINAL ARTICLE

Mechanical behaviour study of soil polluted by crude oil: case of Sidi El Itayem oilfield, Sfax, Tunisia

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Abstract The pollution of soils by xenobiotic organic substances such as crude oil constitutes major environmental risks, which are still badly evaluated. The environmental risks are caused by the direct contamination of the surrounding areas or by an effect on the living organisms in the soils, thus acting directly on man via the food chains. For these reasons, it is essential to study the effects of these pollutants in the soil. The general objective of the work was to better characterize the mechanical behaviour of sites polluted by crude oil in the short and medium terms (case of oilfield of Sidi El Itayem, Sfax, Tunisia under the supervision of the Franco-Tunisian Oil Company). The process consists of determining and comparing the physicochemical, mechanical and geotechnical characteristics of virgin soil and soil artificially polluted by crude oil according to various pollution rates reaching 15% of the weight of virgin soil. This process made it possible to generate scientific knowledge and data, which could allow the prediction of the effects of the latter in interaction with the soil.

Keywords Contamination · Crude oil · Mechanical behaviour · Prediction

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Introduction

Most industrialized countries include in their territories many polluted sites. The presence of organic xenobiotic substances in the soil, such as crude oil, constitutes a major risk, which is still not well evaluated (Bouazza et al. 2005a). So it is essential to study the effects of the organic pollutants in the soils (Bouchez et al. 1996). Among the studied organic compounds, aromatic polycyclic hydrocarbons (HAP) top the list, firstly, because of the carcinogenic and mutagenic character of some of these and, secondly, because of the important number of sites polluted by crude oil (Demougeot-Renard 2004; Jeannée 2001).

The prediction of the effects of these types of pollutant in soils is one of the biggest problems that face many researchers and engineers in the domain (Demougeot-Renard 2004; Fredlund and Rahardjo 1993). Questions that they logically ask are the following:

- What is the behaviour of these polluted soils?
- Is it necessary to treat the site?
- If necessary, what is/are the most adequate treatment technique(s)?
- For how long is it necessary to treat a given site?
- What is the level of treatment to be reached?
- What will the cost of treatment be?

Generally, combinations of several techniques help to obtain satisfactory results. A unique, even though effective, technique does not generally help to solve a whole set of pollution problems (Ouimet 1996; Bouazza et al. 2005b).

In the case of HAP, the mobility of long-term pollutants is controlled mainly by the dissolution of components of HAP in water, and by processes of adsorption/desorption of these pollutants in soil (Bocard 2006; Electric Power Research Institute 1993; Richards and Bouazza 2001).

The general objective of the study was a to contribute to a better characterization of the short and medium-term mechanical behaviour of soil polluted by crude oil, by generating scientific data to predict the effects of the latter in interaction with soil (Delage and Schrefler 2005; Jeannée and de Fouquet 2003).

The followed experimental approach used samples, ranging from a few hundreds of grams to some kilograms, from the oilfield of Sidi El Itayem in Sfax. On the basis of the obtained results, hypotheses concerning mechanical behaviour of soils polluted by crude oil were elaborated. The process taking place on a geological scale was not considered in this work.

Framework of the study/research problems and methods

Framework

The region of Sidi El Itayem is a part of the oriental "Sahel" of Tunisia. The oilfield of Sidi El Itayem, situated at about 30 km northwest of Sfax, covers a surface of 180 km^2 (C·F.T.P. 1998). The surveyed area represents the centre of production and its vicinities (Fig. 1). This pollution is essentially at the surface. It only concerns a layer of a few tens of centimetres of thickness, not exceeding 1 m at the most (C·F.T.P. 2005).

Aware of the problems and environmental risks caused by the pollution of the ecosystem by crude oil, the Franco-Tunisian Oil Company, operating in the domain in the northwest of the city of Sfax, decided to carry out a scientific study. This study evaluated the behaviour of soil polluted by crude oil, making sure that the movement of the engines in the oilfield were secure (Cuisinier and Masrouri 2003).

Fig. 1 Preview of soil polluted by crude oil in Sidi El Itayem's oilfield

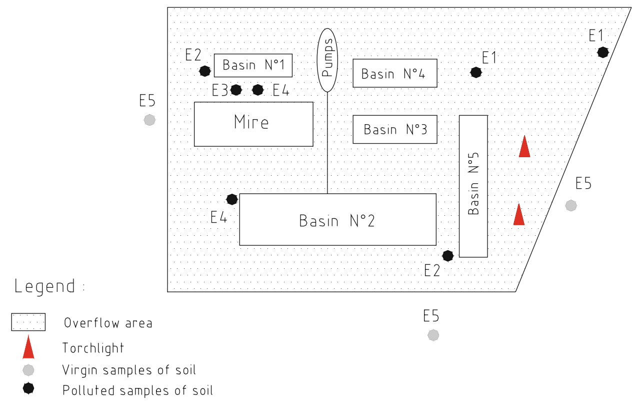

Fig. 2 Locations of the samples taken around Sidi El Itayem oilfield

Methodology

We first carried out a physical, chemical and mechanical characterization of the virgin soil taken from the site under study. We then added to this same virgin soil crude oil in order to study the resulting behavioural changes. Rates of pollution with crude oil in the different samples ranged from 5 to 15% of the total weight of the soil. A decontamination of soil samples polluted with crude oil on site was done to determine the pollution rate at the different zones of the site and to properly select the appropriate rates of pollution applied to samples of virgin soil for laboratory test requirements.

Sampling

In the present work, we used a manual sample tube for holding cylindrical samples of soil in the open air according to the French norm X 31-210 (diameter = 4 cm). Samples were taken during our visits on site in the period lasting from October to December 2005 (Fig. 2).

Characterization

The characterization tests were applied to virgin soil samples as well as to samples artificially polluted by crude oil. Table 1 specifies the composition of used crude oil (C·F.T.P. 1998).

Virgin soil samples underwent the following identification tests:

- water content,
- particle size distribution,
- particle density,
- permeability,
- Atterberg limits,

Table 1 Chemical composition of used crude oil

Saturated components	48.3
n-Alkenes	9.1
Iso-alkenes	8.7
Naphthenes (1 cycle)	8.2
Naphthenes (2 cycles)	7.4
Naphthenes (3 cycles)	4.8
Naphthenes (4 cycles)	3.8
Naphthenes (5 cycles)	3.3
Naphthenes (6 cycles)	3
Aromatic components	35.2
One cycle	8.3
Two cycles	6.5
Three cycles	4.5
Four cycles	2
Five cycles	1.5
Aromatic sulphur compounds	6.7
Non-identified aromatic compounds	5.7
Resins	9
Asphaltenes	7.5

Table 2 Variations of pollution rates in samples of polluted soil

Sample of polluted soil	Pollution rate (%)
E1	5.3
E2	9.2
E3	11.9
E4	17.7

- sulphate content,
- carbonate content,
- CBR test,
- Proctor test,
- odometer consolidation test,
- direct shear test.

As for the artificially polluted samples, only permeability, Atterberg, CBR, Proctor, odometer consolidation and shear strength tests were applied.

Results

Measurement of the rates of soil pollution

The results of decontamination carried out on samples of soil polluted by crude oil taken from the site show that the pollution is spread on the area of the oilfield of Sidi El Itayem at different rates ranging from 5 to 17% (Table 2).

Characterization of the virgin soil

The tests were applied on samples of virgin soil taken from well-chosen locations in the oilfield under study in order to compare their initial results with those drawn from tests applied on artificially polluted soil.

Physical characterization

The results of physical characterization tests carried out on virgin soil are summarized in Table 3.

According to the Central Laboratory of Bridges and Pavements (LCPC) classification of the granular soils (AFNOR 1999) and with reference to the curve of particle size distribution and the results summarized in Table 3, we observe:

- a rate of 98.35 of elements superior to 80 µm having a diameter less than 2 mm,
- a rate of 22.30 of elements lower than 80 µm,
- a limit of liquidity lower than 30%,
- a relatively elevated permeability equal to 1.85×10^{-5} m/s.

These observations affirm that the studied virgin soil is a slightly slimy granular sand.

Chemical characterization

The results of tests of chemical characterization showed that:

- the sulphates content is of about 0.409%,
- the calcium carbonate content is equal to 12%,
- magnesium carbonate is inexistent.

Table 3 Physical characteristics of the virgin soil

Test type	Water content	Particle density	Bulk density	Sand equivalent (%)	Particle size analysis	Atterberg limits	Permeability
Magnitude	$W = 1.83\%$	$\rho_S = 2.59$ g/cm^3	$\rho = 1.698$ g/cm^3	ESV = 41	CU = 9.43	LL = 15.42%	$K_{Tmoy} = 1.89 \times 10^{-5}$ m/s
							$K_{20°} = 1.85 \times 10^{-5}$ m/s
				ESP = 16	CC = 2.42	LP (undetermined)	$\mu_T = 0.986$ m^2/s
							$T = 20.4$°C

Table 4 Mechanical characteristics of the virgin soil

Test type	Odometer consolidation test	Direct shear test	Proctor test	CBR test (%)
Magnitude	$C_C = 0.140$ $C_s = 0.016$ $e_i = 0.621$ $e_o = 0.612$	$C' = 0$ KPa	$W_c = 8.03\%$	Immediate CBR indicator = 1.35 Post-immersion CBR indicator = 2.05
	$\sigma'_\rho = 7.7$ KPa $\sigma'_{vo} = 8.49$ KPa	$\Phi' = 34.67°$	$\gamma_{ds} = 1.996$ g/cm^3	CBR indicator = 2.41

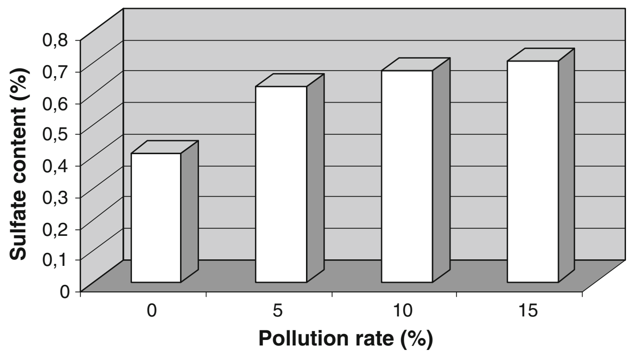

Fig. 3 Variation in the percentage of the sulphate content according to the rate of pollution

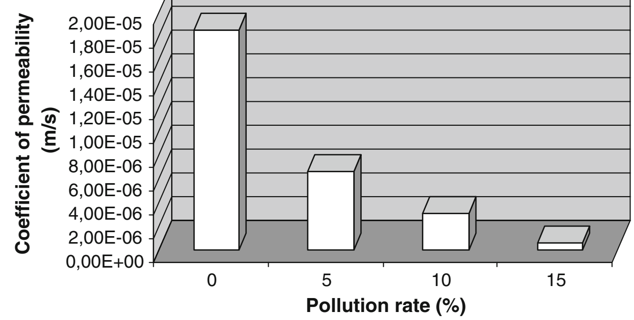

Fig. 5 Variation in the coefficient of permeability according to the rate of pollution

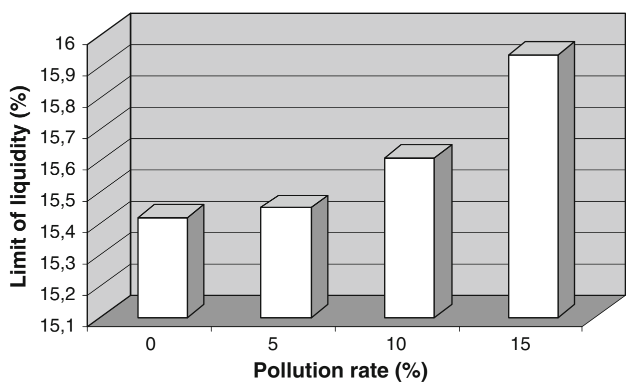

Fig. 4 Variation in the limit of liquidity according to the rate of pollution

This allows us to classify the soil as a little chalky and nonaggressive.

Mechanical characterization

The mechanical features of the virgin soil are mentioned in Table 4.

These results show that the virgin soil has:

- a weak CBR ratio equal to 2.4%,
- a C_C coefficient of compression positioned between 0.1 and 0.2,
- a preconsolidation stress σ_p equal to 7.7 kPa and inferior to the vertical effective stress σ_{v0} equal to 8.49 kPa.

These results show the mediocrity of the soil (Bayon 1998); they clearly show that it is fairly compressible and underconsolidated.

Characterization of the artificially polluted soil

The characterization of the artificially polluted soil was performed on samples of virgin soil to which crude oil was added at well-defined rates, as indicated in "Framework of the study/research problems and methods".

Physical and chemical characterization

The results of the physical and chemical characterization of the artificially polluted soil are presented in Figs. 3, 4, 5.

Adding the crude oil to the virgin soil leads to a considerable increase in the sulphates content up to 0.705% (Fig. 3). The results of the variation of the limit of liquidity according to the different rates of pollution clearly indicate (Fig. 4) that the limit of liquidity increases according to the addition of pollutant. It is necessary to indicate that the limit of malleability always stays undetermined whatever the rate of pollution.

The permeability coefficient, as shown in Fig. 5, falls considerably with the addition of the pollutant. We note that the test is inapplicable at a rate of pollution over 15% (overflow of the pollutant from the mould).

Mechanical characterization

The results of the mechanical characterization of the artificially polluted soil according to different rates of pollution are presented in the Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14.

The mechanical tests results offered by the odometer consolidation test clearly demonstrate the influence of the addition of the pollutant on the mechanical and geotechnical features of the soil. Indeed, we observe:

- A considerable fall of the preconsolidation stress and the initial and the in situ void indicators according to the rate of pollutant.
- An evolution of the C_C compression indicator up to 5% of pollutant.

While exceeding this pollution rate, the C_C compression indicator falls suddenly. These results clearly confirm that the soil remains, after the addition of crude oil, fairly compressible and underconsolidated.

The results of the Proctor test show that:

- The optimum water content decreases progressively with the addition of crude oil.
- The optimum dry density is invariable with a rate of pollution lower than 5%. Beyond this limit, the density falls considerably and the compaction of soil becomes subsequently difficult.

The direct shear test shows that there is an improvement of the angle of shear resistance of the soil from 34.67° up to 56.68° at a pollution rate reaching up to 5%. Beyond this rate, the angle of shear resistance decreases rapidly and reaches the value of 43.44° at a pollution rate equal to 10%.

The results of the CBR tests also show (Fig. 14) that the soil stays mediocre and that the addition of pollutant decreases the bearing capacity of the same soil even with weak rates of pollution.

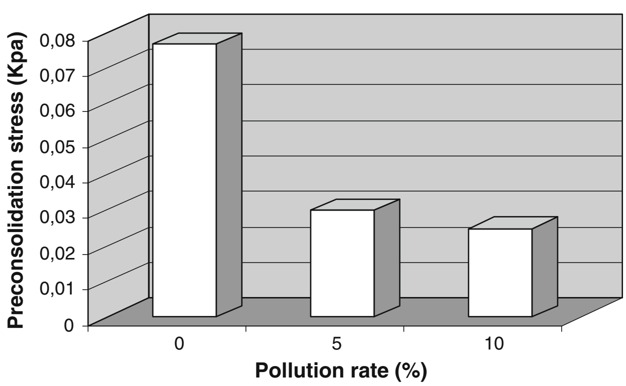

Fig. 6 Variation in the preconsolidation stress according to the rate of pollution

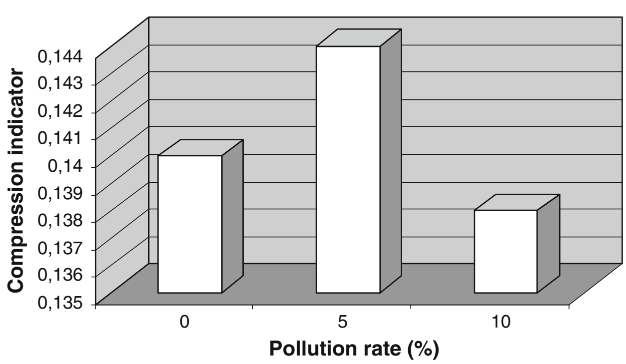

Fig. 7 Variation in the compression indicator according to the rate of pollution

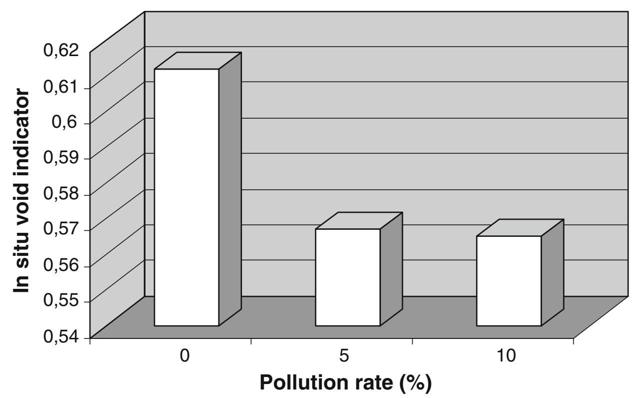

Fig. 8 Variation in the in situ void indicator according to the rate of pollution

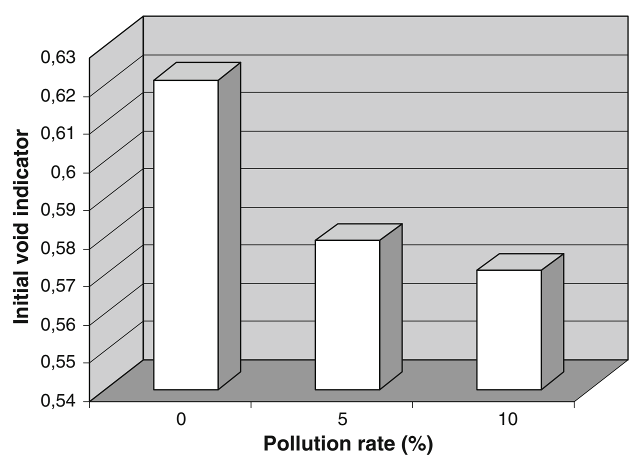

Fig. 9 Variation in the initial void indicator according to the rate of pollution

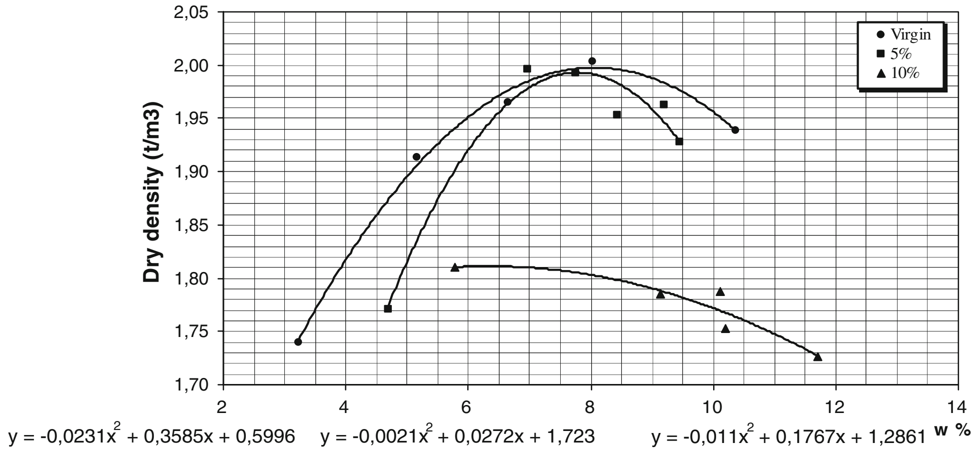

Fig. 10 Assemblage of the curves of compressibility of virgin and polluted soil

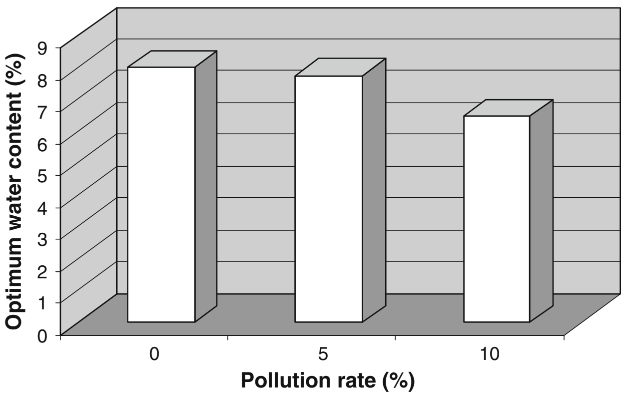

Fig. 11 Variation in the water content optimum according to the rate of pollution

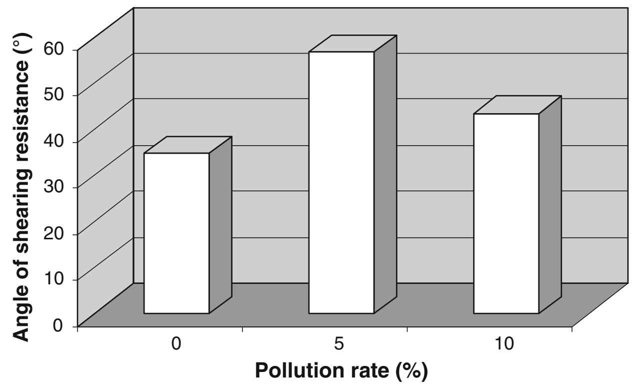

Fig. 13 Variation in the angle of shear resistance according to the rate of pollution

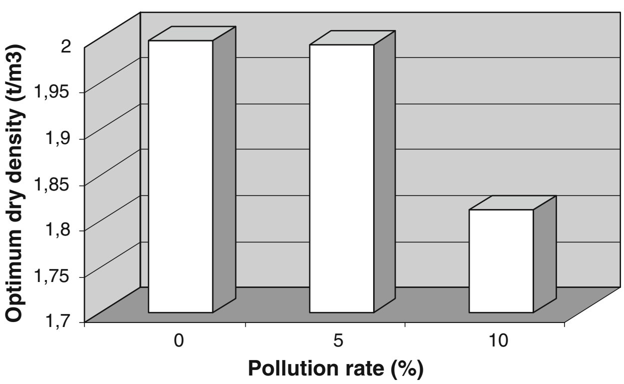

Fig. 12 Variation in the dry density according to the rate of pollution

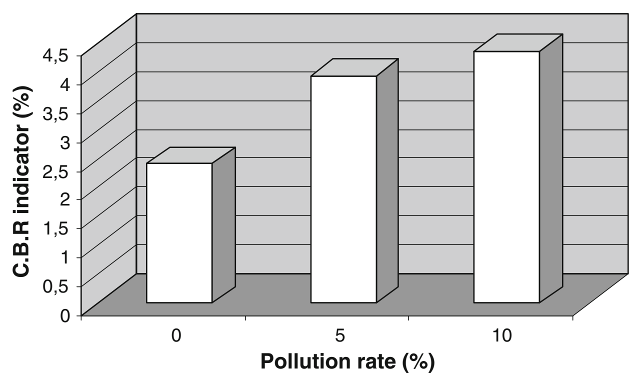

Fig. 14 Variation in the CBR indicator according to the rate of pollution

Discussion

Although the contamination of soil with crude oil represents a serious environmental problem, results of the tests carried out on virgin and artificially polluted soils show an unexpected beneficial effect of the addition of crude oil on some mechanical characteristics of the soil at short and medium terms, mainly when the rate of pollution does not exceed the limit of 5% of its weight.

The beneficial effects of adding crude oil to soil within the limit of 5% are:

- the compression indicator increases,
- the optimum water content and the optimum dry density in polluted soil stay almost the same as compared to virgin soil,
- the shearing resistance angle also increases.

These benefits are essentially due to the fact that a thin crude oil film that covered the soil grains played the role of a binder; which contributed to the agglomeration of grains into a more compact and resistant aggregate.

Experimental results of the odometer tests demonstrate that the compression indicator, which is an indicator of resistance (Gasmi et al. 2000), is positively influenced by the addition of crude oil. On the other hand, the Proctor test on the optimum water content and dry density in polluted soil proves that the soil becomes more susceptible to compacting. At this stage, the bearing quality of the polluted soil might be even better than that of virgin soil. Furthermore, the obtained results of the direct shear test provide evidence of the fact that crude oil plays the role of a binder between the soil grains. Such a phenomenon leads to a substantial improvement of the angle of shear resistance of the soil.

With the addition of crude oil at a rate over the limit of 5% of the soil weight, the mechanical characteristics of the soil deteriorate more and more. In fact, this is explained by the fact that the thin oil film covering the soil grains gets thicker and contributes to the inversion of the role of the pollutant from binder into a lubricant that facilitates the movement of soil grains, thus making the soil more and more slippery.

The remaining parameters (limit of liquidity, coefficient of permeability and CBR indicator) are also influenced by the addition of crude oil. Once the crude oil added to the soil covers the grains, it then occupies the interstices between them and makes the soil much less permeable. This phenomenon would limit a further in-depth infiltration of crude oil (Illangasekare et al. 1995). However, in genuine field conditions, the soil gets more vulnerable with the risk of surface dispersion of crude oil, especially in case of rainy weather conditions. The CBR indicator, initially weak for the virgin soil, shows that adding crude oil further decreases the bearing capacity of the soil. This consequently leads to a deterioration of the behaviour of the soil.

As for the variation of the sulphates content in the polluted soil, the increase could only come from the aromatic sulphur components emanating from the used crude oil.

Conclusion

Based on the results of the different tests done on virgin and artificially polluted soil, hypotheses were elaborated concerning the short and medium-term mechanical behaviour of soil polluted by crude oil. The addition of crude oil to the studied virgin soil up to the limit of 5% of its weight seems to improve its short and medium-term mechanical and geotechnical characteristics. Beyond these limits, the addition of the pollutant considerably disrupts the mechanical properties of the soil and decreases its bearing capacity. As for the long-term behaviour, the effect of microbial activity is to be taken into consideration. The longer the contact between the soil and the crude oil remains, the more powerful the process of biodegradation becomes.

It is useful for future research to take into consideration not only the understanding and assessment of the interaction processes between the crude oil and the soil in terms of time (ageing effect), but also the methods enabling us to predict the effects of the latter on a long term.

References

AFNOR (1999) Géotechnique, Tome 1: Essais en laboratoire, 2nd édn

Bayon R (1998) Aide mémoire du concepteur; terrassements -espaces verts (voirie réseaux divers), Editions Eyrolles (Paris)

Bocard C (2006) Marées noires et sols pollués par des hydrocarbures: Enjeux environnementaux et traitement des pollutions. Editions TECHNIP, p 295

Bouazza A, Delage P, Wojnarowicz M (2005a) Nature et reconnaissance de la pollution des sols. Géomécanique Environnementale Sols Pollués et Déchets. In: Delage P, Schrefler B (eds) Hermes Science Publications, chapter 1, pp 17–49

Bouazza A, Wojnarowicz M, Manassero M (2005b) Méthodes de Dépollution. Géomécanique Environnementale Sols Pollués et Déchets. In: Delage P, Schrefler B (eds) Hermes Science Publications, chapter 5, pp 137–177

Bouchez M, Blanchet D, Haeseler F, Vandecasteele J-P (1996) Les hydrocarbures aromatiques polycycliques dans l'environnement: propriétés, origine, devenir, Rev. IFP 51 3, pp 407–419

C.F.T.P. internal report (1998) Study of the environmental impact of the realization of petroleum drilling: SIT-46: Sidi El Itayem Sfax

C.F.T.P. internal report (2005) Environmental diagnostic of Sidi El Itayem Oilfield, Franco-Tunisian Petroleum Company

Cuisinier O, Masrouri F (2003) Comportement hydromécanique d'un sol gonflant compacté sous très fortes succions. Comptes Rendus Mécanique, vol 331, pp 203–210

Delage P, Schrefler B (2005) Géomécanique environnementale, sols pollués et déchets, p 248

Demougeot-Renard H (2004) De la reconnaissance à la réhabilitation des sols industriels pollués: estimations géostatistiques pour une optimisation multicritère. Edirion vdf Hochschulverlag AG, p 205

E.P.R.I. Electric Power Research Institute (1993) Chemical and physical characteristics of four samples from selected manufactured gas plant sites. Project 2879-12. Final report, Atlantic Environnemental Services Inc., Colchester, CT, p 75

Fredlund DG, Rahardjo H (1993) Soils mechanics for unsaturated soils. Wiley, New York

Gasmi N, Almukthar M, Kbir Arigib N, Bergaya F (2000) Rheological behavior of clays depending on the nature of the compensator cation. CR Acad Sci Earth Planet Sci 330:385–390

Illangasekare TH, Armbruster EJ, Yates KH, Butts MB (1995) Experimental study of movement and distribution of dense organic contaminants in heterogeneous aquifers. J Contm Hydrol 20:1–25

Jeannée N (2001) Caractérisation géostatistique de pollutions industrielles de sols. Cas des HAP sur d'anciens sites de cokeries, thèse, École des mines de Paris

Jeannée N, de Fouquet C (2003) Apport d'informations qualitatives pour l'estimation des teneurs en milieux hétérogènes: cas d'une pollution de sols par des hydrocarbures aromatiques polycycliques (HAP). Comptes rendus Géoscience 335(5):441–449

Ouimet N (1996) Etude en vue de la mise au point de la chaîne de la pyrolyse de la houille, PhD thesis at INSA, Lyon, ISAL

Richards S, Bouazza A (2001) Comparison of contaminant transport parameters derived from batch adsorption, diffusion cell and column tests. Proceedings of the 3rd BGA conference on geoenvironmental engineering, Edinburgh, U.K, pp 361–366