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Investigation of the Strength Development in Tunisian Phosphogypsum-Stabilized Sensitive Clayey Soils: Assess of Geotechnical Properties and Environmental Impact

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Abstract

According to the previous works, the addition of Tunisian phosphogypsum and cement to the clayey soils is able to improve the geotechnical properties of these soils. This addition reduces the swelling problems by making the soil more resistant to water. The degree of success of such a treatment remains dependent on several parameters such as particle size, plasticity, and the chemical and mineralogical composition of soils and the dosage of hydraulic binders. The experimental approach adopted within the framework of this study was oriented towards the characterization of the behavior of three different soil samples in the presence of phosphogypsum and cement at different proportions. To observe this effect, some geotechnical tests were performed such as the Proctor test and the CBR test. The results have shown the improvement in the maximum dry unit weight and the optimum water content depends on the quality of the soil (% clay fraction). The CBR index was influenced by this addition taking into account the properties of the studied soils especially the mineralogical composition. Therefore, to confirm our results, an application of this technique was realized on a real scale.

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This work proved the reliability of the addition of phosphogypsum and cement to a clay soil with well-defined characteristics. Knowing that the use of the phosphogypsum did not introduce any contamination at the lower layers, either by the heavy metals or by the radioactive elements. The stabilization of sensitive clayey soils with phosphogypsum and cement depends on the quality of the soil to be stabilized, the criteria of the phosphogypsum to be used and the appropriate dosage.

Keywords: CBR index; environment; phosphogypsum; Proctor test; road; sensitive clayey soils; stabilization.

1. Introduction

The reutilization of fine soils, water sensitive and / or often wet, proves difficult, in general, during the execution of earthworks and road construction. Therefore, to re-use them, treatment of the soil with a hydraulic binder is necessary and more economical than the use of noble materials.

The stabilization of soils by means of chemical additives, in order to improve their properties, has been worldwide used since the sixties [1]. The chemical stabilization allows making soils insensible to water in an irreversible way and confers them suitable mechanical properties [2].

Among the objectives of the stabilization we identify the increase of the wet strength of the soil, a sufficient cohesion, the increase of durability, the acquisition of strength to the erosion and the decrease of permeability [1]. In previous work, the additives used for the stabilization of soils are the cement, the lime, the mixture cement/lime and the fly ash.

Phosphogypsum (PG) is a byproduct from the processing of phosphate rock by the “wet acid process” of fertilizer production, which currently accounts for over 90% of phosphoric acid production [3].

The valorization of PG by the various developed sectors up to the present day is capable of absorbing at least 20% of the quantities produced [4]. The PG can be used in line with previous search as building materials, agricultural fertilizers, stabilizing agent of soil and as set controller in the manufacture of Portland cement.

The remaining 85% is disposed of without any treatment. This byproduct is usually dumped in large stockpiles exposed to weathering processes, occupying considerable land areas [3].

Degirmenci and his colleagues (2007) [5] have studied the effect of the addition of phosphogypsum mixed with the cement on clayey soils. The effect of this treatment was observed by the measure of the optimal moisture content, the maximal dry density and the Atterberg limits. The addition of cement only to the soil with 5 to 15% has no effect on plasticity index (Ip). However, when it is mixed with the phosphogypsum with a proportion of 2.5% or 5%, improvements have been recorded. The addition of phosphogypsum gives a decrease of the Ip and increases the strength, which is more significant for the high than the low plastic soils. Thus, the phosphogypsum reacts with the soil by creating the hydrated forms in the presence of cement, which supplies a favorable alkaline environment for the release of the reaction between soil and phosphogypsum, increasing the mechanical properties of soils.

The present research project is based on these last studies to further push the understanding of the process of stabilization, and the tool of conception to improve the properties of the fine sensitive soils to water. This study tends to define a model generalizing the behavior of the stabilized soils, and to develop a method allowing the prediction of the gain of strength and the pressure of soils treated with phosphogypsum and cement according to the percentage of additive, the chemical and mineralogical composition and the particle size of soils.

The addition of phosphogypsum only does not present an improvement of the mechanical properties because of its acidity. Hence, the addition of cement makes the environment basic allowing the phosphogypsum to react with the soil and to produce new forms. . The Hydrates (such as CSH, CAH, etc.) would be formed during this reaction, which, during the hardening phase, would increasingly create dense layers around the anhydrous silicate grains, thus obstructing the diffusion of ions and water [6]. The formation of ettringite, starting from the solubilisation of the gypsum and Tricalcium Aluminate, can be indicative of the change in soil status, which becomes more resistant. The presence of such components helps to improve the bearing pressure of the soil, which also depends on the nature and reactivity of the clayey minerals present in the soil as well as the quantity of added PG.

Therefore, to observe this phenomenon, clayey soils are collected from different regions in Tunisia and are, subsequently, treated. To investigate the effect of the presence of phosphogypsum and cement mixed at various proportions in the mechanical properties of soils, some tests were performed such as Proctor test and CBR test. This research could also enhance the effect of cement/phosphogypsum treatment from an environment viewpoint. This was done by applying this technique on a real plane under varying climatic conditions, and measuring the levels of heavy metals and the radioactivity.

2. Materials and Methods

2.1. Materials

- Soils:

Three samples of Tunisian soil were collected and investigated for their relative responses and behavior after PG-cement treatment.

- Soil “Id” was collected from Jbel Aidoudi in the region of Gabes, south of Tunisia. It belonged to the Aleg formation, dating back to Coniacien-companien age.
- Soils “B2” and “B3” were collected from the city of El Hamma in the region of Gabes, south of Tunisia. They belong to the Ben Kralouf formation, dating back to Barremien age. The point of difference between these soils is the level of depth of each soil which causes the change in their characteristics.

- Additives:

Phosphogypsum, an industrial by-product, is characterized by the high acidity that causes a high solubility and a decrease of strength in the case of immersion [7]. For this reason, a CEM II 32.5 type cement is often added.

This addition increase the pH environment by encapsulating the impurities promotes the reaction of PG with the particles of soils, resulting in the change of the properties of treated soils.

The PG, used in this study, is a few decades older, which influences its chemical composition essentially its acidity where the content of P_2O_5 determined is 0.7%.

2.2. Methods

This work is of a particular interest with regard to the investigation of soil behavior in response to the addition of PG and cement. To observe the effect of the addition of PG and cement on the behavior of soils, a series of tests were carried out. Bearing in mind that this behavior differs from soil to soil according to their mineralogical, chemical and physical properties. Therefore, this study presented the variation of soil response by the presentation of the results of some mechanical tests such as Proctor test and CBR test.

Table 1 presents the different mixtures (soils treated with different percentage of PG) and the tests applied on these soils.

Table 1: The tests conducted on the treated soils

<table>
<tr><td>Soils</td><td>Conducted tests</td></tr>
<tr><td>Id
Id+7.5%C
Id+7.5%PG+7.5%C
Id+17.5%PG+7.5%C</td><td rowspan="3">Proctor test
CBR test</td></tr>
<tr><td>B2
B2+7.5%C
B2+7.5%PG+7.5%C
B2+17.5%PG+7.5%C</td></tr>
<tr><td>B3
B3+7.5%C
B3+7.5%PG+7.5%C
B3+17.5%PG+7.5%C</td></tr>
</table>

The soil samples treated with various concentrations of PG and cement were mixed with water proportions equal to their corresponding liquid limits. The Proctor test (NF P 94 093) was carried out to determine the maximum dry unit weight and the optimum water content of treated and compacted soils. The CBR test (NF P 94-078) was used to define the capacity of soils to support the machines of the traffic after treatment.

In order to observe the effectiveness of the treatment in a real scale, an application of this technique was made by realizing a bank test, of 9.5m of length and 2m of width, divided into four compartments. Every compartment possesses a distinctive mixture of soil B2 and additives.

During the application of the treatment in the real plan, some samples were performed from the layer of soil situated below the layer of clay implemented in various treated and untreated cases. These samples were examined by realizing some analysis to observe the effect of the addition of PG in the environment: the determination of the radioactivity, essentially the activity of the Raduim-226, and the determination of heavy metal existing in leachates by the ICP (Inductively Coupled Plasma).

The work carried out in the field requires the preparation of four mixtures which will establish the section to be produced. These mixtures will subsequently be subjected to some analyses in order to determine the effect of the treatment from the point of view environment and resistance (Table 2)

Table 2: Presentation of realized mixtures

<table>
<tr><th>Prepared mixtures</th><th>Conducted test</th></tr>
<tr><td>B2</td><td rowspan="4">CBR test
Measure of Ra-226
Determination of heavy metals by ICP</td></tr>
<tr><td>B2+7.5%CEM II</td></tr>
<tr><td>B2+7.5%CEM II+7.5%PG
(10cm)</td></tr>
<tr><td>B2+7.5%CEM II+7.5%PG
(20cm)</td></tr>
</table>

3. Results and Discussion

3.1. Characterization of selected soils

Each soil has its own specific characteristics. Table 3 presents the results of the physical and mineralogical tests.

The method of particle size analysis showed the abundance of the silt fraction in the particle size distribution of the studied soils.

The determination of the plasticity was carried out by the application of Atterberg limit. Since the soils B2 and B3 have of the same origin, there is therefore no significant difference from the point of view particle size distribution and plasticity.

However, this difference is outstanding by observing their mineralogical composition. The soil B2 is richer in kaolinite (21%) than the soils B3 and Id, the presence of this mineral may cause the difference in soil B2 behavior with other soils.

The soil Id is characterized by the presence of smectites (≈50%), modest contents of kaolinite and calcite and a little quartz, the important content of smectites can cause an unsatisfactory effect during application of treatment.

Table 3: Characterization of studied soils

Soils	Particle size distribution			Atterberg limit			Clay mineral			Other minerals			USCS Classification
	sand	silt	Clay	Wl	Wp	IP	Kaolinite	Illite	Smectite	Quartz	calcite	Dolomite	
ID	0	65	35	86	52.4	33.6	20.5	0	48.4	9.1	22	0	Lt
B2	0	55	45	46.4	33.4	13	21.3	69.9	0	7.3	0	1.5	Ap
B3	0	61	39	43.7	29.2	14.5	9.1	58.8	0	32.1	0	0	Lp

Wp: plastic limit; Wl: liquid limit; Ip: plasticity index

3.2. Application of the treatment of laboratory scale

- Proctor test:

The proctor test was carried out for all clays proposed with or without treatment.

The optimum water content, the maximum dry unit weight as well as the profile of the proctor curve were analyzed. Table 4 shows the Wopt and γd for each clay.

Table 4: Proctor test of soils with different treatments

	$\rho_d(g/cm^3)$	Wopt(%)
Id	1.45	28
Id+7.5%C	1.49	9.4
Id+7.5%PG+7.5%C	1.46	13
Id+17.5%PG+7.5%C	1.4	17
B2	1.39	17
B2+7.5%C	1.38	27
B2+7.5%PG+7.5%C	1.4	22.5
B2+17.5%PG+7.5%C	1.39	22
B3	1.48	12.5
B3+7.5%C	1.43	21
B3+7.5%PG+7.5%C	1.46	15
B3+17.5%PG+7.5%C	1.45	17

The tight shape of the Proctor curve of the soil Id indicates its high sensitivity to water (Figure 1). The addition of 7.5% PG + 7.5% CEM II makes this curve more flattened, with a slight increase in the maximum dry unit weight "ρd" and in the optimum water content "Wopt". Noting that the increase in maximum dry density is considered as an indicator of improvement in soil behavior towards treatment [5]. On the other hand, the addition of 17.5% of PG in the presence of cement did not cause an improvement.

For the soil B2, the addition of PG and cement makes the soil denser. (Figure 2) The increase in dry unit weight gives the soil, after treatment, a greater compact and a lower sensitivity to water. This is observed with the addition of 7.5% PG + 7.5% CEM II associated with a flattening of the Proctor curve. Even the addition of 7.5% CEM II increased the optimum water content but the dry unit weight remains weak with a tight curve. The presence of a more important clay fraction (45%) in the particle size distribution contributes to having, during the treatment, a soil that is more compact and more resistant to water.

The Proctor curve of soil B3 without addition has the flattened shape; thus the soil has a resistance to water. (Figure 3) The addition of cement alone or with 17.5% PG changes the shape of the curve. It becomes tighter; hence the soil becomes more sensitive to water. However, the addition of 7.5% PG + 7.5% CEM II improved the optimum water content by making the soil more resistant to water.

The slope of the wet side is different from that of the dry side. This variation is probably due to the partial dissolution of the PG in the presence of high water content and of PG.

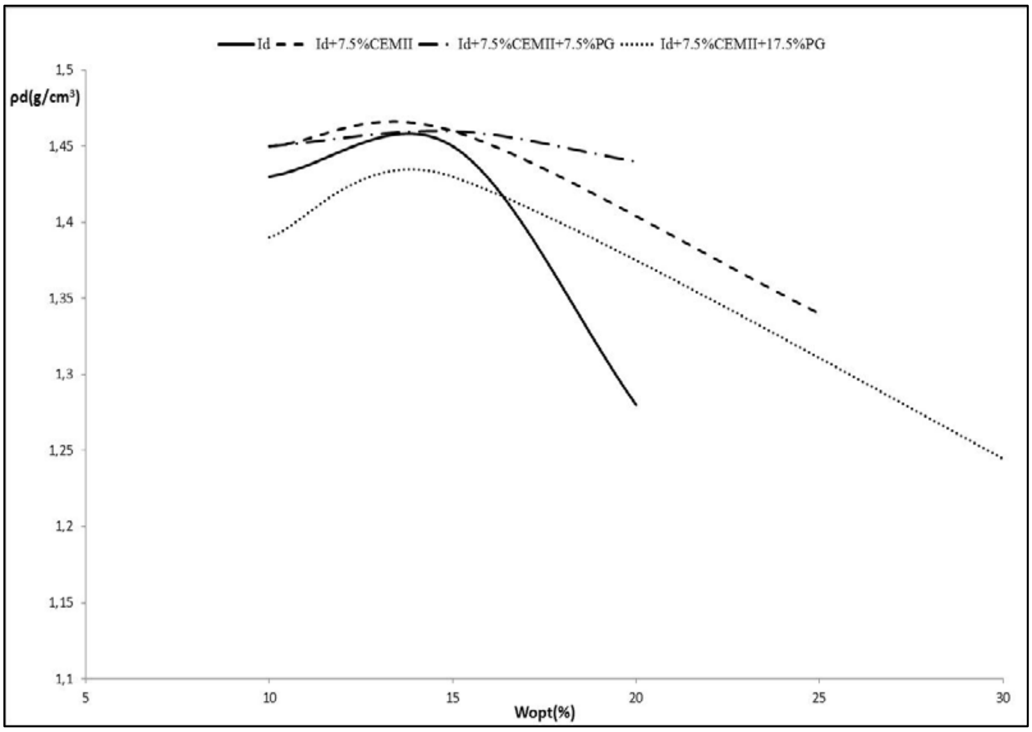

Figure 1: Proctor curves of soil Id with different additives

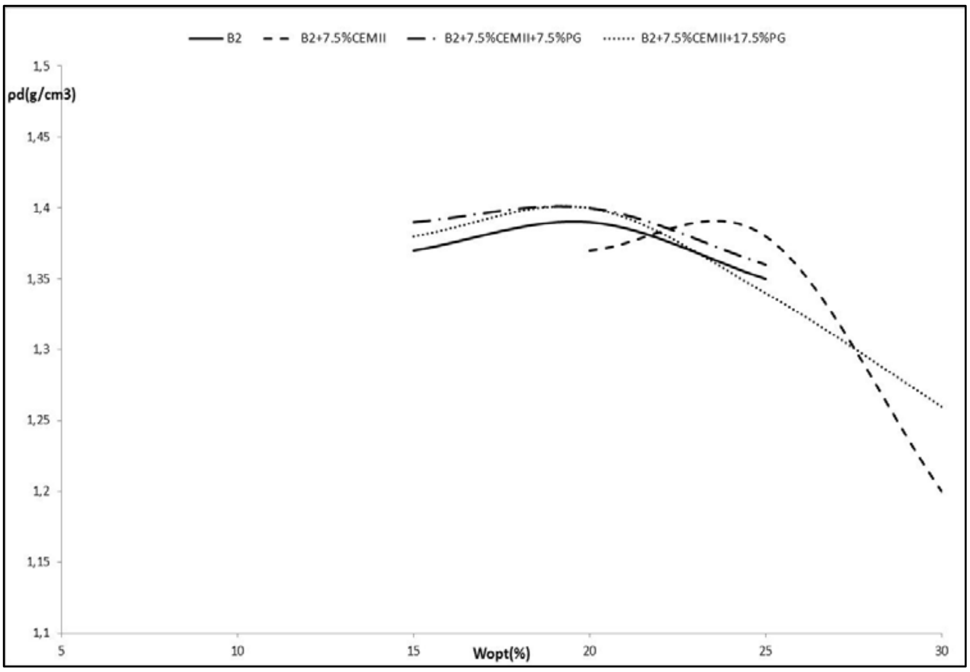

Figure 2: Proctor curves of soil B2 with different additives

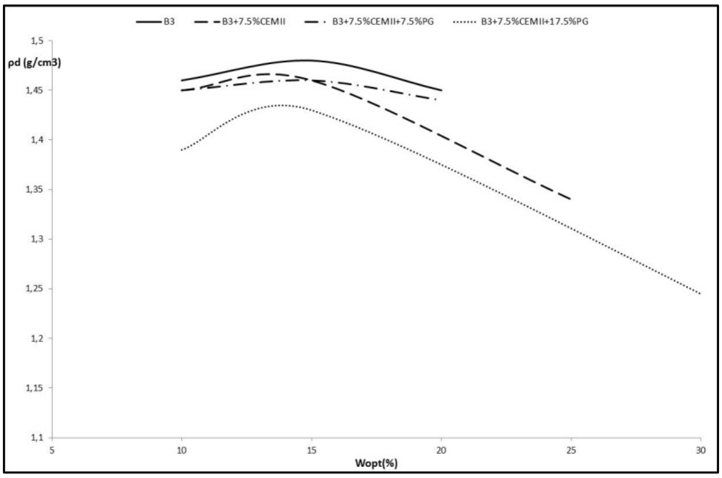

Figure 3: Proctor curves of soil B3 with different additives

- CBR test:

A CBR test was carried out on the study soils stabilized with cement and PG, mixed with a water content equivalent to optimum moisture content. The mean values of CBR (%) are shown in table 5. These results are coherent with the results obtained in Proctor test. The CBR values of the soil Id treated with the PG and the cement showed an improvement, especially with 7.5% PG + 7.5% CEM II (after 24h of compaction of the mixture in the CBR mold). On the other hand, the CBR index is canceled after the immersion of the mixture in water for four days. This result is assigned to the presence of smectites in this soil, which gives a swelling aspect to this soil in the presence of water and makes it unfit for use to build a road. Although they are of the same origin, the soils B2 and B3 have a different mineralogy. This difference influenced the CBR results. The soil B2 reacted with the treatment mainly with 7.5% PG + 7.5% CEM II after 24h. After four days of immersion, the CBR index increases more. On the other hand, the soil B3 treated with 7.5% PG + 7.5% CEM II, its CBR index decreases slightly after immersion compared to that obtained after 24h.

Table 5: CBR value of studied and treated soils

	CBR Value (%)					
	0%PG+ 0%CEMII	0%PG+7.5%CEMII	7.5%PG+7.5%CEMII	17.5%PG+7.5%CEMII	7.5%PG+7.5%CEMII (after 24h)	7.5%PG+7.5%CEMII (after 4 days of immersion)
Id	1.5	29.2	21	19.5	46.4	0.5
B2	24.3	2.4	2.4	2.2	55.2	76.2
B3	15	6.3	24.3	15	67.4	47.9

3.3. Application of the treatment in the real scale

In order to showcase the work carried out in the laboratory, an application of the soil stabilization technique with hydraulic additions was made on a pilot scale. Given that this application applies mainly to soils which, in their natural state, cannot be used (difficulties in carrying out earthworks, problems in vehicles traffic, difficulty in obtaining sufficient compact). The application of this technique avoids the use of expensive solutions (dumping of excavated soil and supply of replacement materials) [8]. To perform this work and in order to obtain a layer of stabilized clay, different operations must be realized: initial preparation of mixture; manufacture of the mixture (application of the product of the treatment and then the mixing and the adjustment of the hydric state); Adjustment (adjust the surface of the layer to be treated and its thickness) and finally compaction [9]. Hence, to apply the treatment of PG and cement, soil B2 was used on a real scale to observe the improvement brought by the treatment to this soil. Taking into account that the addition of PG, considered as stabilizing agent, to this soil raises certain environmental doubts and more precisely its effect on the groundwater in case of rainfall. Measurements of the heavy metal contents and the radioactivity of the layers below the treated clay layer were made in order to observe the impact of this by-product on these layers

- Realization of the section of a road:

A section, 9,5m of length and 2m of width, divided into four compartments was realized. These compartments are separated between them by trenches 0.5m of width and 1m of depth, filled with the existing soil and insulated by a polyethylene film. (Figure 4)

1st compartment: Layer of clay B2 of thickness 10 cm, named « B ».

2nd compartment: Layer clay B2 treated with 7.5%CEM II of thickness 10 cm, named « BTC ».

3rd compartment: Layer clay B2 treated with 7.5%PG+7.5%CEM II of thickness 10 cm, named « BTCP 10 ».

4th compartment: Layer clay B2 treated with 7.5%PG+7.5%CEM II of thickness 20 cm, named « BTCP 20 ».

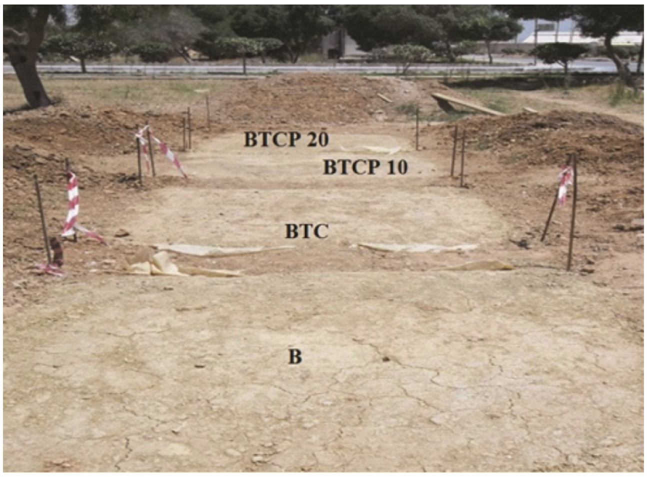

Figure 4: Photo of finished section of a road

The half of the compartments was subjected to a regional climate while the other half was periodically doused and covered throughout the study period.

Table 6: Results of measurement of maximum dry density on site

	1st compartment	2nd compartment	3rd compartment	4th compartment
	B	BTC	BTCP 10	BTCP 20
Dimensions	2m*2m*0.1m	2m*2m*0.1m	2m*2m*0.1m	2m*2m*0.2m
Composition	Clay B2	Clay B2+7.5%CEMII	Clay B2+7.5%CEMII +7.5%PG	Clay B2+7.5%CEMII +7.5%PG
In laboratory $\gamma_d (g/cm^3)$	1.39	1.38	1.4	1.4
On site $\gamma_d (g/cm^3)$	1.25	-	1.25	1.35
Compaction index (%)	91.8	-	91.6	98.6

- Environmental impact:

In order to verify the effect of the application of the treatment on the soils situated below the layer of clay treated with the PG and the cement, analyses were carried out on samples taken from the soil in a depth of 40 cm. (After 28 and 90 days for the case of an intense rainfall)

❖ Determination of the heavy metals:

The determination of the heavy metal contents was made by the ICP of the leachates obtained by the leaching test (NF X 31-210). The samples were taken from the soils below the three compartments B, BTCP 10 and BTCP 20 after 28 and 90 days of the date when the test bench was placed. According to analysis, no significant concentration of heavy metals has been detected. Hence, no contamination of the soil below the treated clay layer was recorded.

❖ Measurement of the Radioactivity:

The use of the PG in roads domain is considered as a potential way for mobilizing large quantities of this material. For example, in the USA, It has been determined that the use of phosphogypsum in road base applications could consume 25 000 t per lane kilometre, which would translate into an annual phosphogypsum consumption of some 140 million. It has also been determined from the pilot studies carried out that the use of phosphogypsum as a road bed material is no more expensive than the use of more traditional materials, and may actually be less expensive when the full life cycle cost is considered [10].

A measurement of the radioactivity was made on seven samples. This measurement concerns the activity of raduim-226 which, according to previous work, is the most concentrated element in the PG. This analysis was realized within the National Center for Tunisian Nuclear Science and Technology (CNSTN).

Seven samples were prepared, which are:

- Sample of PG.
- Sample of clay B2.
- Existing soil sample before execution or control soil noted S_B.
- Two samples of the existing soil below of the layer of clay treated with the PG and the cement of the compartments BTCP 10 et BTCP 20 after 28 days, expressed, respectively, $S_{(BTCP\ 10)28j}$ and $S_{(BTCP\ 20)28j}$.
- Two samples of the existing soil below of the layer of clay treated with the PG and the cement of the compartments 3 et 4 after 90 days, expressed, respectively, $S_{(BTCP\ 10)90j}$ and $S_{(BTCP\ 20)90j}$.

The activity of the Ra-226 is very important for the used PG. It is moderately low for the clay soil B2. (Table 7) This activity is low for the soil S_B. Thus, by comparing this activity of this soil with those of the other soils ($S_{(BTCP\ 10)28j}$; $S_{(BTCP\ 20)28j}$; $S_{(BTCP\ 10)90j}$; $S_{(BTCP\ 20)90j}$), no remarkable difference is observed, where this activity remains almost stable.

This proves that the existing soils below the layer of the clay treated with the cement and the PG at any thickness are devoid of any radioactivity. Clay plays a crucial role, as well as cement, in the encapsulation of radioactive elements and prevents them from passing into infiltration waters.

Table 7: Determination of the activity of Ra-226 (Bq/Kg) (±uncertainty (%))

	PG	B2	S_B	$S_{(BTCP\ 10)28j}$	$S_{(BTCP\ 20)28j}$	$S_{(BTCP\ 10)90j}$	$S_{(BTCP\ 20)90j}$
Ra-226*	198.4±8.62	38.76±8.13	17.75±8.1	23.52±7.23	22.46±5.86	19.95±5.96	23.53±5.8
Pb-214	201.49±5.62	41.08±5.83	18.42±5.83	22.27±4.76	22.05±3.56	18.58±3.84	23.53±4.26
Bi-214	195.26±6.85	36.44±6.52	17.07±5.63	24.77±5.45	22.86±4.32	21.33±4.56	23.52±3.95

- Determination of the portance of realized section of the road:

In order to prove the effectiveness of the addition of the PG and cement to the clay B2 to support the traffic machines, a study of the portance of this soil was carried out. The measurements of CBR index in situ are absent and difficult to perform, thus determining the CBR index is made by realizing a laboratory test. This test was carried out for sample B2 mixed with 7.5% PG + 7.5% CEM II and compacted in the CBR mold at the optimum moisture content of the compaction of the Proctor test. The CBR index, to be taken into account, is that corresponding to the punching of mixture after 28 days of the preparation date of the mold.

The CBR index increased from 24.5% before treatment to 105.4% with treatment and after 28 days. This passage is important, reflecting the effectiveness of treatment for long-term. According to the recommendations of the technical guide for road works LCPC /SETRA [11], the CBR index of a rural road must be of the order of 120%. However, the CBR index found in the mixture of clay, PG and cement is close to 120%. Thus, we can conclude that the realized section is capable of supporting the machines of traffic during the years and the addition of PG in the presence of cement reacted effectively with the clay soil.

4. Conclusion

The PG, considered as a by-product, was used in the field of road construction. According to the previous work, the PG added to the materials (sand or clay) could change their mechanical properties.

In this research, an addition of PG to different percentages in the presence of cement was made for clay soils collected from different stations in Gabes region, Tunisia.

The effect of PG on these treated soils was observed by realizing the mechanical tests: proctor test and CBR test. Following the realization of these tests, a change in the geotechnical properties of the treated soils was recorded. This change is observed by the improvement of parameters such as maximum dry density, optimum moisture content and CBR index. This reflects the obtaining of more compact mixtures with a high bearing capacity. We also tried, in this study, to predict the effect of the PG when applying this technique to the pilot scale by realizing a section of a road. In order to observe the environmental impact of the PG on the layers situated below the treated clay layer, some tests were carried out. The results of these tests showed the absence of any contamination by heavy metals and the presence of low Ra-226 content. Indicating that this realized section has a very high CBR index close to that of a rural road. Since our research tends to optimize the use of PG in road construction, we can, supported on the results obtained, determine the quantities of PG needed. This application consumes 250Kg per 1 kilometer for a linear lane. In other cases, by varying the type of clay, the PG consumption can vary between 167kg and 500kg per 1kilometer for a linear lane with PG percentages respectively between 5% and 15%, depending on the degree of sensitive of clayey soil to water.

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