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Geotechnical characteristics of soils from Tourela artisanal gold mining site in Mali and restoration proposals

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Abstract

The village of Tourela is facing progressive degradation of its soils due to unregulated mining activities. The main objective of this research is to study the evolution of the geotechnical characteristics of soils as a function of excavation depth, through field investigations followed by drilling and laboratory tests, in order to understand their mechanical and physical behavior in a post-exploitation context. Grain size analysis, bulk density, and moisture content tests were carried out to determine the physical parameters. The Atterberg limits test was conducted to determine the soil consistency parameters. The mechanical parameters, such as cohesion and the angle of internal friction, were determined through direct shear testing. In the perspective of backfilling mining excavations, the Proctor test was performed to evaluate the maximum compaction energy of the fill material, both on the soil without additives and with the incorporation of 25% and 50% of crushed gravel in the backfill mass. Based on the results obtained, technical solutions are proposed for the progressive restoration of the site, particularly through backfilling and stabilization methods, with a focus on durability, safety, and environmental rehabilitation. This study therefore aims to contribute to the sustainable management of former mining sites and to provide recommendations for future rehabilitation projects.

Keywords: Artisanal mining; Soil degradation; Geotechnical characteristics; Depth; Restoration

1. Introduction

Artisanal gold mining, also known as gold panning, is an ancient practice still observed today. As a metal of great economic value, gold has long been considered one of the most precious metals [1]. In West Africa, this activity has become inseparable from the economic development of the countries [2].

In Mali, since 1990, gold mining has become a major economic activity and constitutes the country's second largest source of export revenue after cotton. This rapid growth has raised many hopes for development, hopes further bolstered by the boom in gold prices on world markets in recent years [3]. Although artisanal gold mining generates income for communities, it has numerous consequences. The degradation of vegetation cover and the pollution of surface and groundwater resulting from mining activities have many negative impacts on social, environmental, and biological levels.[4 , 5].

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Artisanal mining in Mali plays a major economic and social role, providing livelihoods for thousands of people, particularly in gold-bearing regions such as Kayes, Sikasso,Koulikoro, Kidal and Gao [6]. However, this activity is often carried out informally, with few environmental and geotechnical risk management measures in place.

Tourela gold mining site is one of many sites where local people extract gold using traditional techniques (Figure 1).

However, the unregulated exploitation of these resources generates multiple environmental and geotechnical consequences, including progressive soil degradation and changes in their mechanical characteristics [7].

Indeed, artisanal gold mining activities, often carried out without prior studies or technical standards, result in deep excavations, the destruction of soil horizons, and the formation of unstable pits. These transformations not only create risks of collapse but also compromise any possibility of future rehabilitation. Furthermore, understanding the evolution of the geotechnical properties of soil with depth, is essential for assessing the stability of the exploited sites and ground.

Taking into account these challenges, a thorough geotechnical analysis of Tourela site is essential. This study aims to evaluate the variations in the mechanical and physical characteristics of the soil with depth, through laboratory tests. This will not only allow for a better understanding of the stability conditions of gold panning pits but also enable the formulation of technical proposals for site restoration and safety measures for future redevelopment.

It is in this context that the present study, entitled: Geotechnical characteristics of soils from Tourela artisanal gold mining site in Mali and restoration proposals, is situated.

Tourela gold mining site emerged in the 2000s, amidst a surge in artisanal gold mining in Mali, particularly in rural areas. Although Sanankoroba had been identified as potentially gold-bearing as early as the 1980s, artisanal mining truly took off around 2010 with the massive influx of unemployed youth, former farmers, and migrant workers from various West African countries (Burkina Faso, Guinea, Ivory Coast, Niger). Gold from Tourela thus became a source of informal income in a context of increasing rural poverty.

Figure 1 Tourela gold panning site

Tourela gold mining site is located in Koulikoro, second region of Mali. It covers an estimated area of approximately 25 to 40 hectares, without official boundaries. This area fluctuates depending on the intensity of mining activities and informal land use.

The overall objective of this research project is to analyze the geotechnical characteristics of soils as a function of depth and to propose suitable restoration techniques to ensure the site's rehabilitation after exploitation.

This study primarily aims to achieve the following specific objectives:

- Characterize the site's soils through laboratory tests to assess their nature and mechanical behavior.
- Analyze the variation of geotechnical properties with depth
- Propose a sustainable restoration plan integrating geotechnical, environmental and socio-economic aspects.

2. Materials and methods

2.1. Methodological approach of the study

This research is focused on three essential phases: data collection, geotechnical analysis and the proposal of restoration solutions.

The first phase is be devoted to documentary research on soil geotechnics, artisanal gold mining, and mine restoration methods. During this phase, field surveys was conducted, based on field observations and interviews with gold miners and the local community, to understand mining practices and collect study data. Soil samples were also taken at various depths in representative pits during this phase to obtain reliable data on the vertical evolution of soil characteristics.

The second phase consisted of conducting laboratory tests. The collected samples were subjected to a series of laboratory tests to determine their physical and mechanical properties. These tests included particle size analysis, bulk density, Atterberg limits, and direct shear testing. This stage also encompasses the analysis and interpretation of the test results.

Finally, the third phase was focus on proposals for restoring the site through the integration of local approaches (manual backfilling with rock waste or granular materials) and improved approaches (backfill stabilization), in order to develop recommendations adapted to the economic and environmental contexts.

3. Results and Discussion

Laboratory tests, in accordance with current standards, were carried to study particle size distribution, Atterberg limits, apparent density, water content and shear strength.

3.1. Soils Samplings

Soil samples were taken from the wells at different depths in the various layers. Table 1 summarizes the key information obtained during this field phase.

Table 1 Summary of key information's obtained during this field phase

Depth (m)		Visual observations	Photos
From	To		
0	5	Reddish-colored soil containing solid gravelly grains	
5	20	Light red powdered soil	

20	30	The soil is yellow with a sandy texture.	
30	35	Composed of yellow and grey colored elements, the solid elements can easily be reduced to fine particles under the action of a one-handed press.	
35	40	Composed of layers of grey soil and hard rocks, difficult to reduce into fine particles.	

3.2. Results of laboratory tests

3.2.1. Particle size analysis test (NFP 94-056)

The purpose of this test is to determine the particle size distribution of aggregates with dimensions ranging from 0.08 to 80 mm (Figure 2). It consists of separating a material into several granular classes of decreasing sizes using a series of sieves.[8]

The objective is to obtain the particle size distribution curve, which allows for the interpretation of soil texture and its suitability for construction and landscaping work. The equipment used includes: an oven, a series of sieves, and a balance.

Figure 2 Materials for particle size analysis

Table 2 Particle size analysis results

	Ground 1 (5m)	Ground 2 (20m)	Ground 3 (25m)	Ground 4 (35m)	Ground 5 (40m)
% fines	36.20	60.50	48.70	58.90	4.80

Table 2 indicates that soil layers 1, 3 and 5 are made up of less than 50% of material passing through a 0.075mm or 75.μm sieve. The results prove that the soils located at 5m, 25m and 40m from Tourela gold mining site are mostly made of coarser elements higher than 75 .μm

On the other hand, soil layers 2 and 4 have a percentage of fine particles greater than 50%, at 20 and 35m we encounter soils made up largely of fine elements.

3.2.2. Water content test (NF-P94-050)

The water content of a material is the ratio of the weight of water contained in that material to the weight of the same material when dry[9]. Water content is a state parameter that allows us to approximate certain mechanical characteristics and assess the consistency of a fine soil. The equipment used includes: an oven, a tare weight, and a balance (Figure 3).

Figure 3 Precision balance

The determination of water content is carried out by weighing the sample in its initial (wet) state and after passing through the oven at 105°C until constant mass is reached [10].

Table 3 Soil water content

Samples	Ground 1	Floor 2	Ground 3	Ground 4	Floor 5
Water content (%)	23.46	20.82	17.23	7.57	4.16

From the graph and table 3, the water content of the site varies from 4.16 to 23.46%, and it is observed that with the depth of the layers the water content reduces considerably.

This decrease in water content generally reflects better natural soil compaction; drier and denser soils represent better mechanical resistance (Figure 4).

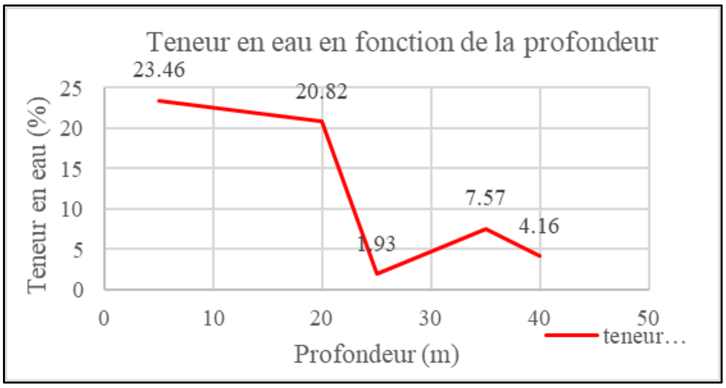

Figure 4 Water content vs depth

3.2.3. Apparent soil density by immersion (NFP 94-053)

Apparent density is an indicator of soil compaction (Figure 5). It is calculated as the dry weight of the soil divided by its volume, where, m and V are the mass and volume of the sample (g) [11]. The materials used are: Paraffin wax, a beaker, and a balance.

$$\rho = \frac{m}{V}$$

Figure 5 Hydrostatic weighing

Table 1 Apparent soil density

Samples	**Sol1**	**Sol2**	**Sol3**	**Sol4**	**Sol5**
Apparent Density (g/cm^3)	**1.91**	**1.79**	**1.93**	**1.81**	**2.41**

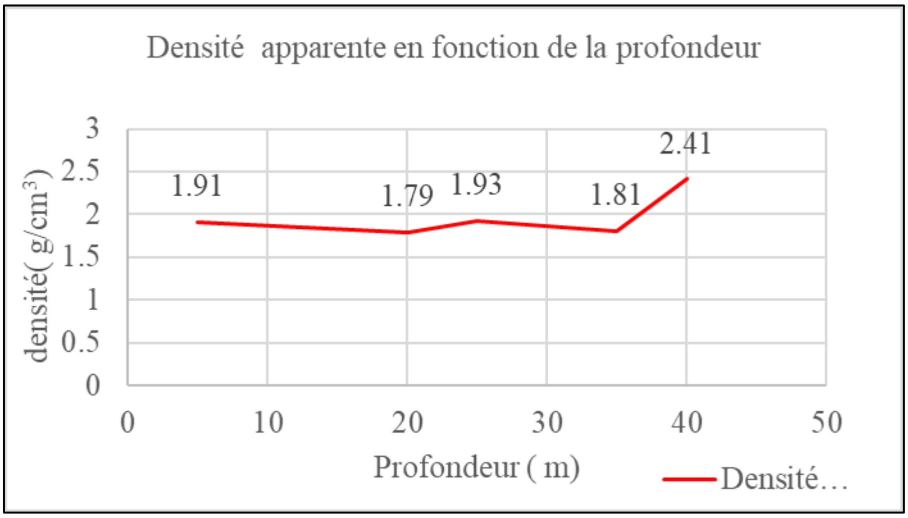

Figure 6 Density vs depth

From 5m to 35m, the apparent density of the layers varies between 1.79 and 1.93 g/cm³, followed by an increase reaching 2.41g/cm³ in the last layer (Table 4 and Figure 6).

3.2.4. The Atterberg limits (NFP 94-051)

The Atterberg limits are tests that define indicators describing the plasticity of a soil. They include:

- **Liquidity limit**: The content beyond which a soil loses its ability to maintain a given shape under the effect of its own weight.

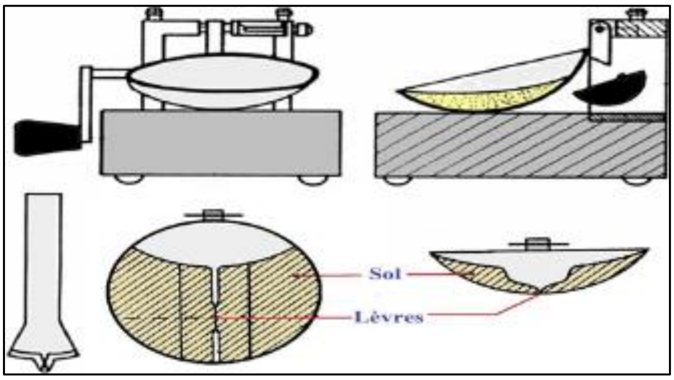

Figure 7 Casagrande cup for determining the liquidity limit[12]

Table 5 Soil liquid limit

	Sol1	Sol2	Sol3	Sol4	Floors 5
Liquid Limit (LL%)	48.71	43.20	35.44	51.94	24.40

The plastic limit: the water content at which the soil changes from a semi-solid to a plastic state. It is determined by rolling a soil sample into 3 mm diameter wires until it cracks (Table 5).

Table 6 Soil plasticity limit

	Sol1	Sol2	Sol3	Sol4	Floors 5
Plastic limit (PL%)	34.25	35.01	35.02	35.78	21.49

The Plasticity Index: which measures the plasticity of a soil (Tables 6 and 7). It is calculated as the difference between the liquid limit (LL) and the plastic limit (LP) [13].

$$IP = LL - PP$$

Table 7 Soil plasticity index

	Sol1	**Sol2**	**Sol3**	**Sol4**	**Sol5**
Plasticity Index (PI%)	14.46	8.19	3.71	16.16	2.91

- ✓ **Geotechnical classification of soils according to depth**

The particle size analysis tests and the Atterberg limits tests yielded the following results (Table 8)

Table 8 Geotechnical characterizations of soils

Floors	**Nature**	**USCS**	**AASHTO**	**Description**
		Soil type		
Sol1	Granular soil	SM	A-7-6	Silty sand
Sol2	Thin soil	SL	A-5	soft plastic
Sol3	Granular soil	SM	A-4	Silty sand
Sol4	Thin soil	CL	A-6	Lean clay
Sol5	Granular soil	SM-GM	A-2-4	Sand or silty gravel

3.2.5. Direct shear test (NFP 94-071-1)

The aim is to experimentally determine the intrinsic curve of a soil, and then to deduce the shear parameters (the angle of internal friction and the cohesion, where a normal stress $\boldsymbol{\sigma}$ is imposed and then the soil is sheared)[14]

The objective is therefore to determine the angle of internal friction (ϕ)and the cohesion (c) of the material (Figure 8).

Figure 8 Shear box

Table 9 Soil shear parameters

Shear parameters	**Sol1**	**Floor 2**	**Ground 3**	**Sol4**	**Sol5**
Cohesion C (kPa)	13.96	23.86	23.86	31.81	35.79
Angle of friction $\boldsymbol{\varphi}$ (°)	36.23	28.35	25.50	21.68	29.10

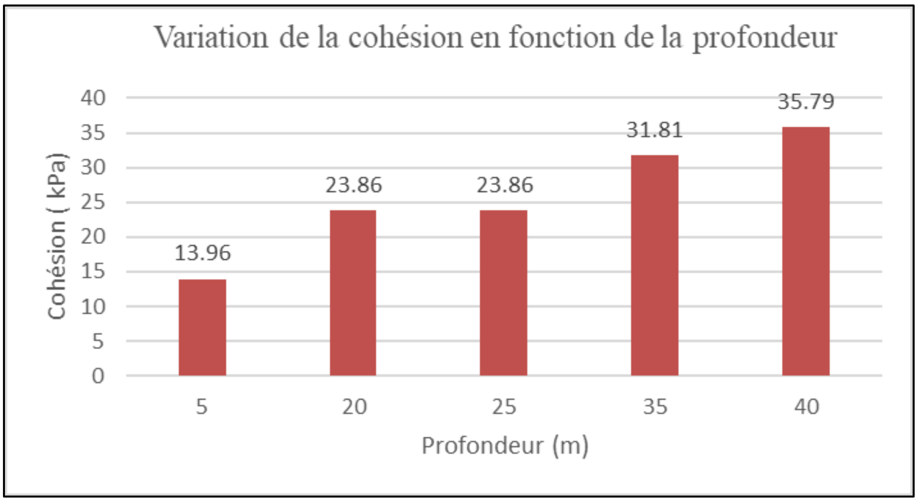

Figure 9 Cohesion vs depth for various samples

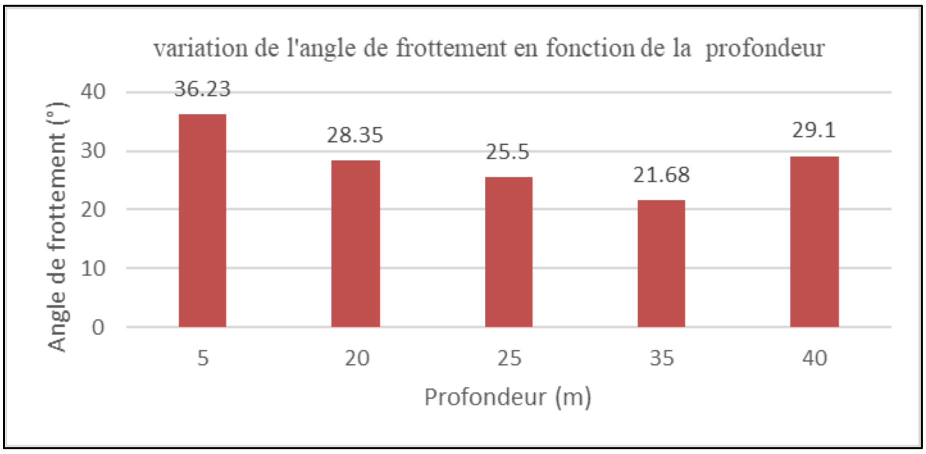

Figure 10 Angle of friction vs depth for various samples

According to Figure 9 and Table 9, there is an increase in cohesion up to a depth of 20 m, between 20 m and 25 m it is constant and an improvement up to 40 m.

In Figure 10, there is a decrease in the friction angle up to a depth of 35 m followed by a slight increase from 35 m to 40 m.

Thus, as observed, the soils are characterized by strong cohesion and a friction angle that decreases relatively with depth.

3.2.6. Proctor Test (94-093)

The Proctor test (Figure 11) is a geotechnical test used to determine the water content required to achieve the maximum dry density of a granular (or non-granular) soil through compaction. Compaction remains the most economical method still used in embankment construction to improve soil dry density[15].

Figure 11 Proctor test equipment [14]

The compaction was carried out on soil in its natural state and then on the ones improved with class 5/20 of crushed gravel at 25 and 50 % in order to evaluate the compaction performance of the embankment (Table 10 and Figure 11).

Table 10 Proctor test results on soil without additives

	Sol2 without additives			
Percentage of water %	**14**	**16**	**18**	**20**
Wet density (g/cm3)	**1.51**	**1.58**	**1.63**	**1.60**
Dry density (g/cm3)	**1.30**	**1.34**	**1.36**	**1.31**

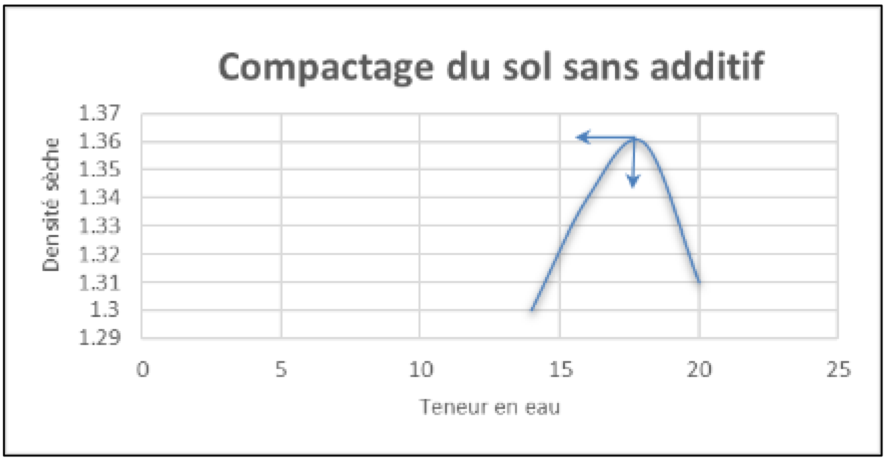

Figure 12 Soil compaction curve without additives

The compaction curve is obtained from the data in Table 9.

From Figure 12, the maximum dry density is 1.36 g/cm^3, corresponding to a water content of 18%. This is the density of the soil without additives. Compared to the results of previous studies, this value is low; for example, studies conducted by "DJEMILI Mohamed Rafik" on the same type of soil give a maximum dry density of 1.73 g/cm^3, corresponding to a water content of 16%. This highlights the need to strengthen the soil for site restoration purposes.

Table 11 Proctor test results on soil with 25% crushed gravel 5/20

	Soil + 25% gravel			
Percentage of water %	4	6	8	10

Wet density (g/cm3)	2.07	2.34	2.59	2.47
Dry density (g/cm3)	1.94	2.15	2.33	2.19

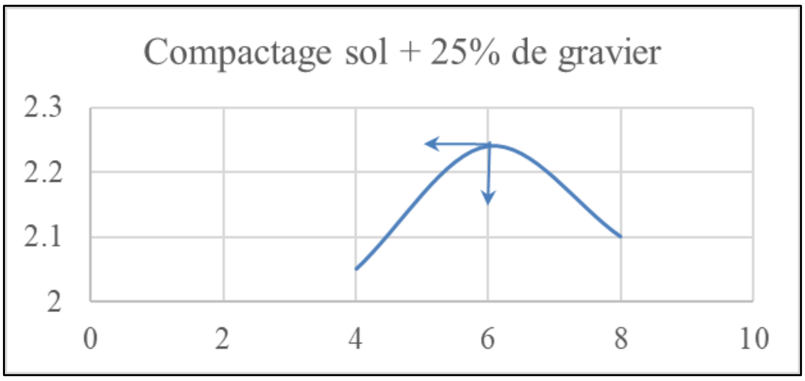

Figure 13 Soil compaction curve + 25% crushed gravel

From Table 11 and Figure 13, the maximum density is 2.24g/cm³ corresponding to the optimum water content of 6%.

Table 12 Proctor test results on soil with 50% crushed gravel 5/20

	Ground + 50% gravel			
Percentage of water %	**4**	**6**	**8**	**10**
Wet density (g/cm3)	**2.19**	**2.44**	**2.33**	**2.23**
Dry density (g/cm3)	**2.05**	**2.24**	**2.10**	**2.01**

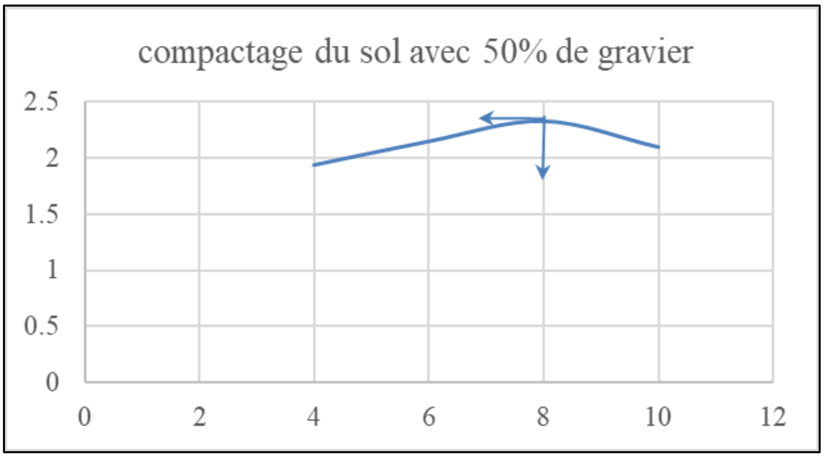

Figure 14 Soil compaction with 50% crushed gravel

From Table 12 and Figure 14, the maximum density is 2.33 g/cm³ corresponding to 8% of optimal content.

Compaction carried out on the ground without additives and with the addition of crushed gravel at 25% and 50% indicates (Table 13) that the performance of the embankment during compaction improves with the addition of gravel, with an increase in dry density and a decrease in the optimum water content, which can be related to the cohesion with granular materials (Figure 15) and the fewer water content from the added materials.

Figure 15 Sample after compaction containing crushed gravel

Table 13 Geotechnical profile with various soils layers and characteristics after tests

Depth		**Description**	**Layer Symbol**	**Atterberg Limits**			**Sieve analysis**	**Apparent Density (g/cm³)**	**Cohésion (KPa)**	**Angle of frictiont (°)**	**Samples Photos**
From (m)	**To (m)**			**LL (%)**	**LP (%)**	**IP (%)**	**Passing at 80 µm**				
0	**5**	**Silty Sand**		**48.71**	**34.25**	**14.46**	**36.20**	**1.91**	**13.96**	**36.23**	
5	**20**	**Silt**		**43.20**	**35.01**	**8.19**	**60.50**	**1.79**	**23.86**	**28.35**	
20	**30**	**Silty Sand**		**35.44**	**35.02**	**3.71**	**48.70**	**1.93**	**23.86**	**25.50**	
30	**35**	**Clay**		**51.94**	**35.78**	**16.16**	**58.90**	**1.81**	**31.81**	**21.68**	

35	**40**	**Sand or Silty Gravel**		**24.40**	**21.49**	**2.91**	**4.80**	**2.41**	**35.79**	**29.10**	

3.3. Comparative study of compaction tests

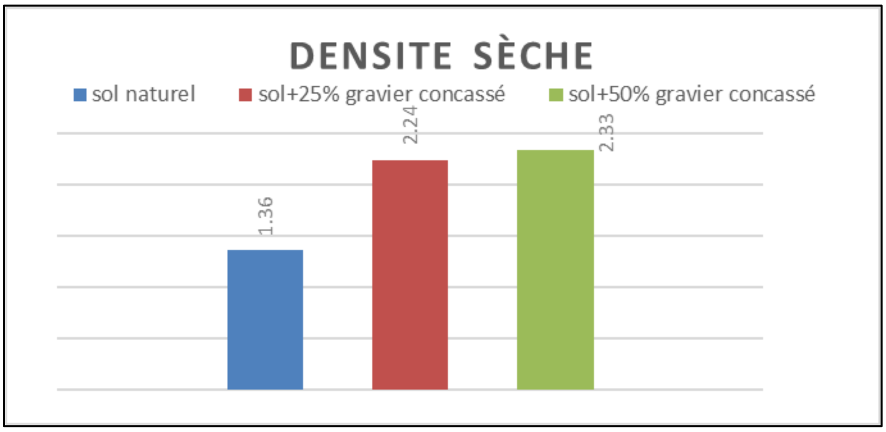

Figure 16 Density of natural soil vs density of soils reinforced by gravel after compaction

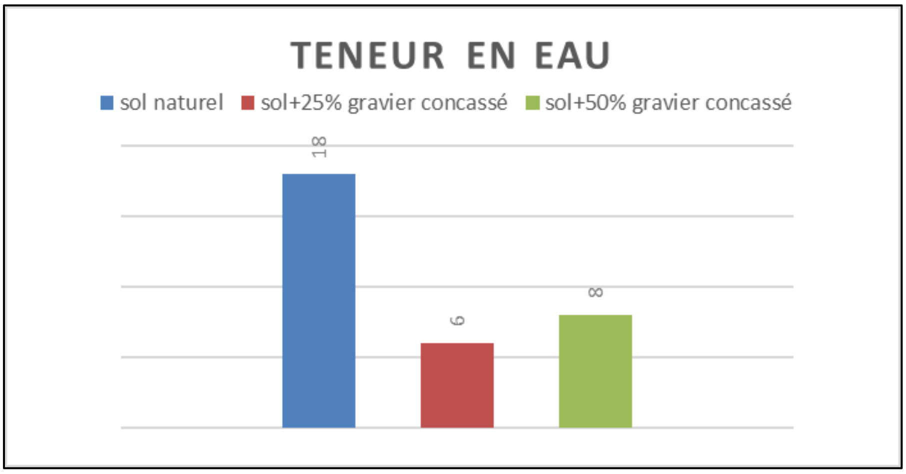

Figure 17 Water content of natural soil vs Water content of soils reinforced by gravel after compaction

From these Figures 16 and 17, the soil without additive requires a relatively high optimal water content for a low compaction value, unlike the addition of crushed gravel where the water content undergoes a considerable decrease and the maximum density increases.

3.4. Strategies for implementing the site restoration phase

The strategies presented below define the priority actions to be undertaken in order to ensure a sustainable, safe restoration that complies with safety and environmental protection requirements.

- Securing wells and excavations to prevent accidents.
- Improvement of waste rock with application of crushed gravel.
- Once the fill material has been mixed, the whole thing is transported underground through pipes, either by gravity or with the help of displacement pumps.
- Proceed with backfilling and progressive compaction in layers of reasonable thickness.

- In very deep areas, the material can be introduced as a semi-fluid paste (a mixture of water, waste rock, and binder) so that it compacts under gravity and hardens in place. Alternatively, a self-stabilizing material such as crushed gravel can be used.
- The upper part (0.5 to 1m) may be covered with a layer of well-compacted clay or laterite, serving as a waterproof barrier to limit water infiltration.
- Mine monitoring during and after rehabilitation.

4. General conclusion, recommendations

The study carried out on Tourela gold mining site highlighted the impact of mining activity on the geotechnical properties of Tourela soils.

Particle size distribution, Atterberg limits, density, direct shear strength, content and Proctor were carried out.

From the point of view of physical properties, the soils consisting of a portion of fines and coarse elements containing largely sand and silt, with an apparent density varying between 1.79 up to 2.41g/cm^3, with a water content ranging from 4.16 to 23.46 %, the Atterberg limits that the soils have low plasticity.

The mechanical aspect of the soils indicates that the cohesion parameters and friction angle are respectively from 13.96 to 35.79 kPa and 21.68 to 36.23°.

For restoration or backfilling purpose, the Proctor test yielded a required compaction density of 1.36 g/cm^3 corresponding to an optimal content of 18%.

From the stabilization of the embankment body by the percentages of 25% and 50%, the respective reference values γd max=2.24; Wopt=6% and γd max= 2.33; Wopt= 8% were found.

The results prove that adding the stabilizer allows better compaction performance of the embankment.

In light of the results obtained and the challenges related to safety, the environment, and the geotechnical stability of Tourela site, several measures are necessary to ensure more sustainable restoration. These recommendations, which involve both local communities and the relevant authorities, aim to prevent risks, improve soil quality, and guarantee more responsible management by those in charge.

4.1. To the competent authorities

- Strengthening the regulatory framework and control of artisanal mine operations
- Technical and financial support for the restoration of degraded sites
- Implementation of a geotechnical monitoring program to assess soil evolution after restoration work
- Organize awareness campaigns on geotechnical risks (collapses, landslides) and good soil management practices

4.2. To local communities

- Limit the uncontrolled opening of wells and respect the safety guidelines established by geotechnical studies.
- Active participation in restoration work under the supervision of technical services.
- Establish local monitoring committees tasked with identifying at-risk areas and collaborating with authorities for rapid intervention.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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