Effect of Total Nitrogen on the Physical and Mechanical Properties and Deformation Characteristics of Soil

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Abstract. To determine the effect of total nitrogen on the physical and mechanical properties and deformation characteristics of soil, samples were tested in the laboratory after being soaked in deionized water and different concentrations of nitrogen solution. The results indicate that the total nitrogen content has a significant influence on soil characteristics. Specifically, the plasticity index, specific gravity and effective cohesive strength of the samples decrease and the effective friction angle increases with increases in the total nitrogen concentration of the solution. The strain hardening phenomenon is observed in the stress-strain relationship, and the variation of the stress-strain curve of samples soaked in deionized water and nitrogen solution are highly similar. The peak shear strength of the samples initially decreased and then increased with increases in the total nitrogen concentration of the solution. The mineral composition, particularly the composition of clay minerals, is affected by the interaction with total nitrogen in the soil, leading to changes in the soil macro-characteristics.

1. Introduction

Soil is a dispersed system composed of solid, liquid and gas phase material. The nature of soil strongly depends on the interaction between these three phases. The interactions are complex due to environmental problems resulting from population growth, higher standards of living and industrialization[1]. At present, some studies of rock and soil mechanics are difficult to explain without considering the influence of changes in the natural environment[2]. An increasing number of studies have demonstrated that the interaction between the environment and soil, particularly the chemical interaction between water and soil, not only exists but also has significant mechanical effects[3]. Thus, the ideal concept, interaction process and models used in mechanical theory and application research are unsatisfactory, as the interaction between the chemical environment and soil must be considered when studying rock and soil mechanics[4].

Water, as the most important natural resource, provides conditions for social and economic development. Society has mainly been concerned with the metal elements in water because heavy metals are commonly found in drinking water and can negatively affect the environment and human health[5-9]. However, water pollution has become increasingly serious worldwide due to rapid economic development and urbanization, and the compositions are also becoming increasingly
complex. In China, algal blooms occur in inland waters, and more than 60% of lakes have experienced eutrophication. Tai Lake, Dian Lake, Chao Lake, Baiyang Lake and several other large lakes have experienced serious eutrophication\cite{10,11}, and nitrogen and phosphorus pollution have affected the Yellow River\cite{12,13}.

In recent years, environmental geotechnology has emerged as an interdisciplinary science that aims to forecast, analyze and solve geotechnical problems involving environmental factors\cite{14}. The influence of pollutants on the mechanical properties of rock and soil has become an important issue in recent years. The relationship between the shear strength of soil and the composition of landfill leachate pollutants has been studied\cite{15}. Kamon examined the effect of acid rain on the stability of concrete\cite{16}. The influence of underground water runoff\cite{17,18} and groundwater characterization\cite{19} have been shown to be critical in changing the original structure and characteristics of rock and soil. Cheng and Kong studied the chemical corrosion of soil (mainly red clay soil) and its long-term strength and stability\cite{20,21}. Ou studied the influence of thermal effects on the thermodynamic properties of clay with different pH levels\cite{22}. Li examined the mechanical property changes of polluted foundation soil before and after corrosion in typical regions of Jinan\cite{23}. The influence of the chemical composition of water resources on the soil permeability coefficient was analyzed via laboratory tests\cite{24}. To date, the research in this field has mainly concentrated on the effect of inorganic pollutants on the properties of soil, namely, the influence of sulfate, nitrate, and chloride on soil stability.

Nitrogen is one of the most important nutrients for organisms. Many studies of nitrification in freshwater systems have been conducted over the past few decades\cite{25-27}. With the increasingly complex compositions of water, the effects of organic-inorganic hybrid pollutants, particularly nitrogen compounds, on soil mechanical properties should be investigated, particularly with regard to dam foundations, slope stability, and cavern stability. Such issues represent a new research field of geological engineering that must be expanded.

This project aims to compare and analyze the plasticity index, effective cohesion, effective internal friction angle, changing rule of the stress-strain curve and mineral composition of soil through experiments of soil soaked in deionized water and a total nitrogen compound solution at different concentrations. This work intends to provide basic data and theoretical support for safety evaluations, disease prevention and control in geotechnical engineering.

2. Materials
The monitoring data for water quality in the related literature suggest that the nitrogen pollution concentration is approximately 0.06-0.75 mol•L\(^{-1}\) in rivers, lakes, reservoirs and other water bodies\cite{10,12,13,28}. The total nitrogen solution used in this study is prepared based on this range of reference concentrations. The chemical reagents used in the test are analytically pure, with 1.00 mol•L\(^{-1}\) potassium nitrate (KNO\(_3\)), ammonium chloride (NH\(_4\)Cl) and 0.05 mol•L\(^{-1}\) L-glutamic acid (C\(_5\)H\(_9\)NO\(_4\)) used to prepare the total nitrogen (TN) aqueous solution; concentrations of 6.80×10\(^{-2}\), 3.40×10\(^{-2}\), 6.80×10\(^{-2}\), 0.17 and 0.68 mol•L\(^{-1}\) were tested. The soil used in the test is a low-liquid limit clay collected from the middle line of the south-to-north water diversion project. The main physical and mechanical indexes are shown in Table 1, and the main mineral composition obtained by X-ray diffraction is shown in Table 2.

| Table 1. Physico-mechanical index of the sample soil. |
|---------------------------------|----------------|
| γ\(_d\) (gꞏcm\(^{-3}\))         | 1.63           |
| w (%)                           | 23.0           |
| w\(_L\) (%)                     | 44.6           |
| w\(_P\) (%)                     | 23.0           |
| I\(_P\) (%)                     | 21.6           |
| Gravel (%)                      | 0.0            |
| Sand (%)                        | 6.0            |
Table 2. Mineral composition of the sample soil.

| Mineral          | Percentage |
|------------------|------------|
| Silt (%)         | 62.2       |
| Clay (%)         | 31.8       |
| Quartz (%)       | 49         |
| Montmorillonite (%) | 8         |
| Illite (%)       | 11         |
| Potassium feldspar (%) | 6    |
| Anorthose (%)    | 10         |
| Chlorite (%)     | 11         |
| Calcite (%)      | 3          |
| Dolomite (%)     | 2          |

3. Methodology

The soil used in the experiment is remolded. After natural air drying, the undisturbed soil samples are passed through a 2 mm sieve and crushed. Soils are placed in an airtight container for more than 24 h after being sprayed with water to ensure a uniform water content. The maximum dry density of the soil is 1.63 g•cm⁻³ for a water content of 23.0%, and the soil samples are divided into 5 compaction layers, each of the same quality. The specimen dimensions are φ 39.1 mm×80 mm. Four of the same samples are soaked in deionized water and total nitrogen solution with concentrations of 6.80×10⁻³, 3.40×10⁻², 6.80×10⁻², 0.17 and 0.68 mol•L⁻¹ for 14 days, thus yielding 24 samples. The saturation of the soil samples is 99% or higher according to the quality of the soil before and after soaking. Consolidated undrained shear tests are conducted under confining pressures of 100, 200 and 300 kPa, the liquid limit and plastic limit are determined after soaking in accordance with SL 237-007-1999, and the plasticity index is calculated.

4. Results

4.1. Influence of TN on the physical properties of the soil

Figure 1 presents the curves of the plasticity index and specific gravity with variations in the concentration of the total nitrogen solution. The TN solution has a similar influence on the plasticity index and specific gravity, with both decreasing with increases in the TN solution concentration. The values of the plasticity index and specific gravity of the soils soaked in TN solutions of different concentrations are lower than those of the soil soaked in deionized water. The plastic index decreases relatively slowly with increases in the TN solution concentration, as shown in Figure 1 (a). A relation between the plasticity index and TN solution concentration is developed based on the fitting curves (R²=0.982). The prediction equation is obtained as follows:

\[ I_p = -0.55 \ln(c) + 18.07 \] (1)

As shown in Figure 1 (b), the specific gravity of soil decreased from 2.73 to 2.70 with increases in the TN concentration, suggesting a trend of "desertification". A relation between the specific gravity and TN solution concentration is developed based on the fitting curves (R²=0.965). The prediction equation is obtained as follows:

\[ G_s = -0.00 \ln(c) + 2.698 \] (2)
4.2. Influence of TN on the strength properties of the soil

Figure 2 illustrates that the TN solution concentration has an important effect on the effective cohesion and effective internal friction angle of the soil samples. The effective cohesion of the soil after soaking in the TN solution tended to decrease with increases in the TN concentration. The effective cohesion of the soil soaking in a low-concentration TN solution is higher than that of soil soaking in deionized water; in contrast, soil soaked in TN solution at concentrations higher than 0.17 mol•L⁻¹ exhibit a lower effective cohesion than that of soil in deionized water (Figure 2(a)). A relation between the effective cohesion and TN solution concentration is developed based on the fitting curves (R²=0.918). The prediction equation is obtained as follows:

\[ c' = -5.64 \ln(c) + 67.38 \]  

The effective internal friction angle changes more than the effective cohesion. It increases with increasing TN solution concentration; however, at total nitrogen concentrations higher than 6.80×10⁻² mol•L⁻¹, the effective internal friction angle is greater than that of the soil in deionized water (Figure 2(b)). A relation between the effective internal friction angle and TN solution concentration is developed based on the fitting curves (R²=0.936). The prediction equation is obtained as follows:

\[ \phi' = 1.821 \ln(c) + 32.23 \]
4.3. Influence of TN on the deformation characteristics of the soil

The relationship between the axial strain and principal stress under different soaking conditions in the shear process is shown in Figure 3. The figure shows that: (1) the sample in different soaking conditions exhibits a strain hardening phenomenon, and the phenomenon becomes more notable with increasing confining pressure; (2) the stress-strain relationship curves of the samples soaked in deionized water and different concentrations of TN solution are highly similar when the strain is small, but with increasing axial strain, the difference increases gradually under all soaking conditions and eventually stabilizes at a certain value; (3) when the strain reaches a certain value, the difference in the principal stress of the samples soaked in relatively high concentrations of TN solution (≥0.17 mol·L⁻¹) has significantly improved, i.e., under the same principal stress condition, the strain of the soil soaked in TN solution is less than that of the soil soaked in deionized water. This result indicates that the strength and deformation resistance of soil increased after soaking in TN solution. The increase in intensity is related to the concentration of the TN solution.
Figure 3. Stress-strain curve of soil soaked in (a) deionized water and (b) total nitrogen of $6.8 \times 10^{-3}$ mol·L$^{-1}$ (c) $3.4 \times 10^{-2}$ mol·L$^{-1}$ (d) $6.8 \times 10^{-2}$ mol·L$^{-1}$ (e) 0.17 mol·L$^{-1}$ and (f) 0.68 mol·L$^{-1}$.

Figure 4 shows the shear peak (the axial strain reaches the peak value of 15%) under different soaking conditions. When the confining pressure is 100 kPa, the shear peak of soil soaked in $6.8 \times 10^{-2}$ mol·L$^{-1}$ TN solution is slightly lower than that of soil soaked in deionized water (Figure 4(a)). The remaining shear peaks of the samples soaked in TN solutions are greater than those soaked in deionized water under pressures of 200 kPa (Figure 4(b)) and 300 kPa (Figure 4(c)). All shear peak values increase considerably after initially decreasing. The relationships between the shear peak and TN solution concentration under confining pressures of 100, 200, and 300 kPa are developed based on the fitting curves ($R^2=0.679$, $R^2=0.965$, and $R^2=0.932$, respectively). The prediction equation is obtained as follows:

$$
\sigma_1 = 100 \text{ kPa}, \quad \epsilon_1 = 359.4 e^{0.240c} \quad (5) \\
\sigma_1 = 200 \text{ kPa}, \quad \epsilon_1 = 471.7 e^{0.348c} \quad (6) \\
\sigma_1 = 300 \text{ kPa}, \quad \epsilon_1 = 600.9 e^{0.326c} \quad (7)
$$
Figure 4. Relationship between the total nitrogen solution concentration and peak shear strength of the sample when the confining pressure is (a) 100 kPa (b) 200 kPa and (c) 300 kPa.

4.4. Influence of TN on the mineral composition of the soil

Kaolinite, montmorillonite and illite are three common clay minerals that have a significant effect on the engineering properties of soil because of their active properties\cite{29}. The macroscopic mechanical parameters of soil change to different extents after soaking in TN solution, mainly because of the differences in the reactions of the chemical compositions in the solution.

Table 3 shows the mineral composition analysis results of samples soaked in deionized water and TN solution of different concentrations. The contents of illite and potassium feldspar increase with increasing TN solution concentration, mainly because of the increased amount of K\textsuperscript{+} in the solution. In contrast, the contents of montmorillonite and chlorite exhibit a decreasing trend, decreasing by 57\% and 20\%, respectively. Although the illite content increased by 60\%, the overall content of clay minerals still exhibit a decreasing trend. The cation exchange capacity of illite is weak, whereas the capacity of cation exchange and the adsorption of organic matter of montmorillonite are relatively high. Montmorillonite has a significant influence on the plastic index, cohesion and internal friction angle. Therefore, the plasticity index and effective cohesion decrease and the effective internal friction angle increases (Figures 1 and 2) with increasing TN solution concentration because of the decreasing clay mineral content of the soils.

Table 3. Mineral composition of soaked soil.

| C (mol·L\textsuperscript{-1}) | 0  | 6.80×10\textsuperscript{-1} | 3.40×10\textsuperscript{-2} | 6.80×10\textsuperscript{-2} | 0.17 | 0.68 |
|--------------------------|----|----------------------------|-----------------|-----------------|------|------|
| quartz (%)               | 50 | 50                         | 49              | 51              | 47   | 48   |
| montmorillonite (%)      | 7  | 7                          | 5               | 3               | 4    | 3    |
| illite (%)               | 15 | 19                         | 20              | 21              | 25   | 26   |
Glutamic acid, as the acidic amino acid in TN solution, can ionize hydrogen ions in water. The following demonstrates how a weak acid causes feldspar to dissolve:\(^{30}\):

$$\text{CaAl}_2\text{Si}_2\text{O}_8\text{(calciclase)} + 8\text{H}^+ \rightarrow 2\text{Al}^{3+} + \text{Ca}^{2+} + 2\text{H}_2\text{SiO}_4$$

$$\text{NaAlSi}_3\text{O}_8\text{(sodaclase)} + 4\text{H}^+ + 4\text{H}_2\text{O} \rightarrow \text{Na}^+ + \text{Al}^{3+} + 3\text{H}_2\text{SiO}_4$$

$$\text{KAlSi}_3\text{O}_8\text{(potassium feldspar)} + 4\text{H}^+ + 4\text{H}_2\text{O} \rightarrow \text{K}^+ + \text{Al}^{3+} + 3\text{H}_2\text{SiO}_4$$

The feldspar content decreased due to the dissolution of feldspar, but large amounts of K\(^+\) in the soaking liquid make it difficult to replace the K\(^+\) in potash feldspar. Thus, the potassium feldspar content does not decrease but rather increases slightly.

H\(^+\) and K\(^+\) in the TN solution result in the transformation from montmorillonite to illite, which decreases the montmorillonite content and increases the illite content:\(^{31}\):

$$2.3\text{Ca}_{0.165}\text{Mg}_{0.33}\text{Al}_{1.67}\text{Si}_{4}\text{O}_{10}(\text{OH})_2\text{(calcium-montmorillonite)} + 1.002\text{K}^+ + 0.44\text{H}^+ \rightarrow 1.67\text{K}_{0.6}\text{Mg}_{0.25}\text{Al}_{1.8}\text{Al}_{0.5}\text{Si}_{3.5}\text{O}_{10}(\text{OH})_2\text{(illite)} + 0.3795\text{Ca}^{2+} + 0.3415\text{Mg}^{2+} + 3.355\text{SiO}_2 + 0.85\text{H}_2\text{O}$$

$$2.3\text{Na}_{0.33}\text{Mg}_{0.33}\text{Al}_{1.67}\text{Si}_{4}\text{O}_{10}(\text{OH})_2\text{(sodium-montmorillonite)} + 1.002\text{K}^+ + 0.44\text{H}^+ \rightarrow 1.67\text{K}_{0.6}\text{Mg}_{0.25}\text{Al}_{1.8}\text{Al}_{0.5}\text{Si}_{3.5}\text{O}_{10}(\text{OH})_2\text{(illite)} + 0.759\text{Na}^+ + 0.3415\text{Mg}^{2+} + 3.355\text{SiO}_2 + 0.85\text{H}_2\text{O}$$

5. Conclusions
The experimental analysis demonstrates that the TN solution is an important factor affecting the physical and mechanical properties of soil:

1. The plastic index and specific gravity decrease with increasing TN solution concentration, whereas the effective cohesion decreases and the effective friction angle increases after soaking.
2. The stress-strain relationship curves of soil soaked in deionized water and TN solution of different concentrations are highly similar and exhibit a strain hardening phenomenon. The shear peak initially decreases with increasing TN solution concentration and then increases.
3. The mineral compositions in soil, particularly the clay mineral composition, is the main factor influencing the physical and mechanical properties of soil. The clay mineral composition of soil decreases in TN solution, eventually leading to decreases in the plastic index and effective cohesion, whereas the effective internal friction angle increases.

Appendix A

Nomenclature

- \(\gamma_d\): Maximum dry density (g\cdot m\(^{-3}\))
- \(w_a\): Natural moisture content (%)
- \(w_l\): Liquid limit (%)
- \(w_p\): Plastic limit (%)
- \(I_p\): Plasticity Index (%)

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