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Microstructural Analysis of Thermally Induced Changes in Permeability Coefficient and Settlement of Marl Soils

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ABSTRACT: Temperature changes the engineering behavior of clay soils. Clay soils are used as a protective cover for burial of high-level wastes (HLWs), where the soil is exposed to medium to high temperature regimes. Marls are a type of sedimentary deposits consisting of clay minerals and calcium carbonate. These two components can substantially influence the behavior of marl soils from an engineering standpoint. The present study focuses on the engineering characteristics of marl soils under various temperature regimes with an emphasis on the microstructural changes in permeability coefficient, settlement, and compressive strength Therefore, after determining the geotechnical properties of the marl soil, its samples were exposed to temperatures from 25°C to 900°C. The changes in marl soil properties were analyzed via mechanical tests (measuring permeability, consolidation, and uniaxial compressive strength), and microstructural tests (measuring pH and X-Ray diffraction), and scanning electron microscopy (SEM). The microstructural analysis of marl soil samples indicates that due to the deterioration and formation of new minerals as well as soil particle arrangement and microscopic texture; temperature regimes increase the permeability coefficient. However, at 700 °C the formation of cement compounds reduces permeability coefficient by an approximate factor of 50,000.

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1. INTRODUCTION

Increased global use of shallow geothermal energy systems including nuclear waste disposal facilities, ground source heat pumps (GSHPs), groundwater heating pumps (GWHPs) and aquifer thermal energy storage systems raise concerns about the effects of temperature on the geotechnical properties of the soil. Therefore, understanding the engineering behavior of heat-affected soils is essential to minimize the adverse effects of heat [1].

Marl soils are highly specialized soils which may be observed in many parts of the world, such as Italy, Spain, the United States, Britain, Canada, France, Persian Gulf marginal countries and Iran (from north and northwest to southeast) [2, 3]. Due to their structural nature, such as the presence of degradable particles and chemicals (calcium carbonate, gypsum, anhydrite and salt), marl deposits are more erodible than other deposits. Palygorskite and Sepiolite are clay minerals that form marl soils, leading to instability, reduced bearing capacity and swelling in the soil [4, 5].

Temperature variations cause the differentiation of the soil hydraulic conductivity and behavior which consequently changes the desired properties of clay soils as a natural barrier against the transport of high-level wastes [6]. So, it is important to evaluate and predict the engineering properties of marl soils when exposed to heat. Therefore, the purpose of this study is to investigate changes in the permeability coefficient, setteability and engineering properties of marl soils from the microstructural perspective at different temperatures.

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2. MATERIALS AND METHODS

In the present study, the behavioral tests have performed on the marl soil sampled from west of Bandar Abbas specifically from the area of the railway station located in the northern margin of the Persian Gulf. The purpose of this study was to evaluate the permeability coefficient, Settlement and geotechnical properties of marl soils from the microstructural perspective and to present an approach for utilizing marl soils in regional environmental geotechnical issues. These specimens are geologically belonging to the Mishan formation and are of lower to middle Miocene age [7]. According to the Unified Soil Classification System (USCS), marl soil is a low plasticity clay (CL) with 99% pass of sieve No. 200. Most of the experiments performed in this study are based on the ASTM standard [8]. The titration method has been used to determine soil carbonate content. XRD analyses performed on natural marl soil show that palygorskite, kaolinite and sepiolite are the main clay minerals and quartz, calcite and dolomite are non-clay minerals existing in marl soil. Table 1 provides some of the geotechnical and environmental geotechnical characteristics of the marl soils studied in this paper.

With the aim of evaluating heat effects on geotechnical

Table 1. Some of the geotechnical and environmental geotechnical characteristics of marl soils

Physical properties of South Marl	Quantity measured	References for method of measurement
Clay (%)	34.12	ASTM, D422-63
pH (1:10; soil: water)	8.74	ASTM D4972
Carbonate content (%)	38.5	Hesse, 1971
Unconfined Compression Strength (UCS) (kg/cm²)	0.7	ASTM D2166-06
Liquid limit (%)	28	ASTM, D4318
Plastic Limit (%)	18	ASTM, D4318
Plasticity Index (%)	10	ASTM, D4318
Maximum dry density (g/cm3)	1.65	ASTM D698
Optimum water content (%)	16	ASTM D698
Permeability coefficient (k) (cm/s)	$1.1*10^{-07}$	ASTM D2434-87
G_s	2.77	ASTM, D85487
Classification	CL	ASTM, D3282
Color	Green	
Soil composition	Palygorskite, Sepiolite, Calcite, Dolomite, Quartz	ASTM, D2216

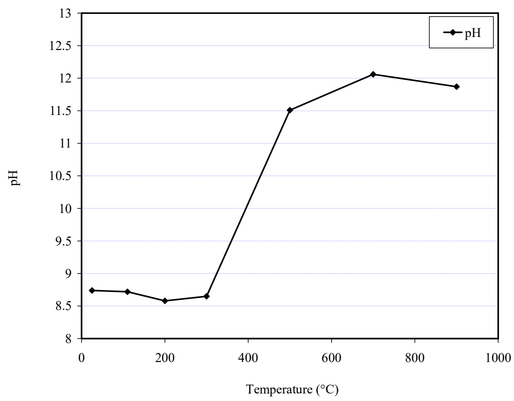

Fig. 1. pH changes of heat exposed marl soil

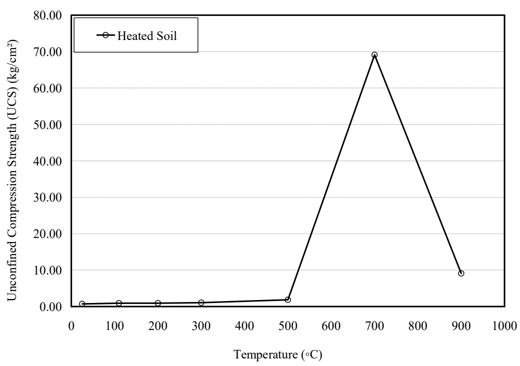

Fig. 2. Infinite compressive strength variations of marl soil exposed to heat

and environmental geotechnical parameters, in accordance to ASTM standard, some experiments done on soils which have experienced the temperatures of 25, 110, 200, 300, 500, 700 and 900 °C for determination their permeability, consolidation, granularity, infinite compressive strength and pH [8]. The furnace temperature was automatically increased at a rate of 5 °C/min up to the desired temperature and remained for 2 hours at this temperature and the furnace was switched off after that.

3. RESULTS AND DISCUSSION

3.1. Examination pH changes of the heat exposed soil

Fig.1 shows the pH changes of marl soil under different temperatures. Based on the results, the pH of the natural soil is about 8.74, which does not change with increasing temperature to 100 °C. Rising the temperature to 300 °C changes pH to 8.6, which shows no significant difference. By increasing the temperature to 500 °C, the heated soil pH increased by about 3 units to 11.51. In this temperature range, Dolomite decomposition at about 370 °C can be the main reason for the increase in pH of the reaction medium. By increasing the temperature to 700 °C, the pH of the studied marl reached to about 12.06. The release of carbonate at about 700 °C, the formation of cementitious compounds at this temperature and the occurrence of pozzolanic reactions in the presence of water can be the main reasons for increasing the soil pH. Based on the presented results, with increasing temperature to 900 °C due to the formation of glass structures, soil pH decreased up to a small extent.

3.2. Evaluating the changes of infinite compressive strength of heat exposed marl soil

Fig.2 shows the infinite compressive strength curve of marl soil under different temperatures. According to the presented results, the strength of natural marl is 0.7 kg/cm^2. By increasing the temperature to 200 °C, the soil strength increased by 1.31-fold and reached to 0.92 kg/cm^2. The compressive strengths at temperatures of 300 °C and 500 °C rose to 1.5 and 2.6 times, reaching to 1.05 kg/cm^2 and 1.84 kg/cm^2, respectively. In this temperature range, the soil has dehydrated and its strength increased. At 700 °C, the strength reaches to 69.1 kg/cm2, which is 37.5 times greater than the strength of the soil at 500 °C and about 100 times in comparison to the natural soil strength. This is due to the occurrence of dihydroxylation in this temperature range, change of the soil structure and the formation of alite cement (C_3S) and bilit (C_2S) cements. In fact, marl clay minerals are dihydroxylated, the folded structure of the particles is substituted with a stuck-together and homogeneous structure and subsequently, the homogeneous structure increases the strength. As the temperature increases to 900 °C, the soil strength decreases sharply regarding the modified sample at 700 °C and reaches to 9 kg/cm2. The studied marl soil contains 38.5% carbonate. Calcium carbonate decomposes in the thermal range of 700 °C to 870 °C and produces carbon dioxide gas that makes porous the soil structure. On the other hand, the glass-like and highly porous gehlenite compounds reduce the compressive strength of the soil.

4. CONCLUSION

Based on the performed laboratory study, the most important results are as follows:

1. At the temperature of 700 °C due to the occurrence of the dihydroxylation phenomenon and with the onset of calcite decomposition, the porosity increased sharply to about 0.81. However, the formation of cementitious (C_2S) and (C_3S) compounds and the occurrence of pozzolanic reactions and the phenomenon of pozzolanic consolidation increased the pre-consolidation stress to more than 800 kPa. Hence, while the porosity ratio increased, the setteability rate has decreased.

2. Generally, the geotechnical and environmental geotechnical properties of marl soils are strongly influenced by the temperature history, especially the maximum temperature at which they have been exposed.

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