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Physiomechanical of Residual Soil Contaminated with Zinc Heavy Metals

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ABSTRACT

The rapid industrialization and radical development that has taken place in today's modern society, be it agriculture, construction, industry, soil degradation or heavy metal contamination of soil, is one of the most serious ecological and environmental problems, which continuously poses a serious threat to sustainable development. Heavy metals may change the geotechnical properties of soils, making it difficult to reconstruct buildings on those sites because the parameters of the contaminated soil are unknown. Contamination by heavy metals will lead change soil's structure, pore characteristics and behaviour, resulting in changes in soil permeability, plasticity, compressibility, in terms of strength and eventually affecting the structural integrity. The main objective of the present investigation is to enhance the understanding of the impact of the significant and hazardous heavy metal, zinc (Zn), on the geotechnical properties. The residual soil was subjected to Compaction Test and Atterberg Limit Test for each analysis, which was assigned a number up to six samples, one of which was left uncontaminated. The remaining samples were combined with a ZnSO4 solution, with values ranging from 0 mg/L to 4000 mg/L and increased by 500 mg/L intervals. The findings reveal that as the penetration increases in liquid limit test, moisture content also increases where at the same time, plasticity index increases proportional to concentration of zinc contaminant producing soil with high plasticity. This outcome is in contrast with the increasing of concentrations where the pattern is more likely to shift to a lower value of moisture content. Based on the findings, the presence of heavy metal contaminants in soils leads to degradation of geological properties, including changes in mechanical behaviour and geotechnical properties based on the double diffuse layer theory. Increased zinc heavy metal concentrations lead to reduced water adsorption capacity of soil particles.

1. Introduction

The rapid industrialization and heavy development that takes place in modern society nowadays such as agriculture, construction and industry and land degradation or contamination of soil by heavy metals, has become one of the most serious ecological and environmental problems which lead to serious threat on the sustainable development of the world [2,3,12,14,27]. Soil's health is becoming an increasing concern [17]. It is known that a considerable number of abandoned industrial sites that

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exist in urban areas worldwide have been contaminated with prominent levels of heavy metals. Land or soil pollution caused by heavy metals contamination has become threats, as soil becomes an increasing demand for the purpose of future development for the usage of various economic sectors.

Zinc (Zn) is classified as a transition metal listed in chemistry periodic table with atomic number 30 and density greater than 5 g/cm^3 [2,3,28], which naturally exists within the soil. However, additional zinc is added unnaturally due to various industrial activities which lead to the amount of increase in the environment that could negatively affect soil's behaviour [9]. The two main categories of heavy metal sources identified by scientists are natural and anthropogenic sources [2,5,8,10,14,25]. Natural sources include sedimentary rocks, volcanic eruptions, soil formation and rock weathering which are rarely regarded as toxic. It is in contrast to anthropogenic sources which include industry, agriculture, mining and domestic effluents discharged from the factories [1,9,18]. Heavy metals can accumulate in topsoil through atmospheric deposition by sedimentation, impaction and interception. The atmospheric dust and aerosol deposition, automobile exhaust emissions and various industrial activities are important sources of heavy metals contamination of soil [1,16]. In general, heavy metals deposition on the soil surface is due to natural formation on the earth as well as human activities like industrialization and agricultural activities [5,20]. In addition to being harmful to the ecosystem and public health [1-3,17,18,25], heavy metals may also change the geotechnical properties of soils, making it difficult to reconstruct buildings on those sites because the parameters of the contaminated soil are unknown [8,15]. The structure, pore characteristics and soil quality of soil that have been contaminated by heavy metals will change the soil's permeability, plasticity, compressibility and strength [2,4,13].

Therefore, evaluation and testing need to be conducted to examine the possible deterioration of properties of the contaminated soil sample. This brings us to the aim of studying the effects of increment of concentration of zinc heavy metals toward the physical and mechanical properties of residual soil contaminated with zinc heavy metals.

2. Methodology

2.1 Materials Methods

Soil was taken from Suling Hill, Kubang Semang, Penang. It is then washed, oven-dried at 105°C and sieved through a 2 mm sieve for sample storage, preparation and laboratory tests. The initial physical properties such as natural moisture content, specific gravity, particle size distribution, liquid limit, plastic limit, compaction characteristic, unconfined compressive strength (UCS) and pH of natural soil were tested prior to the testing on the addition of zinc heavy metal. The heavy metal contaminant chosen for this study is zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$).

2.2 Experimental Methods

The concentration levels of zinc heavy metal were 500 mg/L, 1000 mg/L, 2000 mg/L, 3000 mg/L, 4000 mg/L. The soil samples were synthesized by exposing them to variation concentrations and by taking the 23.58% weight of dry soil based on the natural moisture content of uncontaminated residual soil. To evaluate the impact of heavy metal contaminants on the physical, mechanical and chemical properties of residual soil, the Atterberg Limits (Liquid limit and Plastic limit), pH test and compaction test were done on the sample according to BS 1377-2:1990, BS 1377-3:1990 and BS 1377-4: 1990, respectively.

3. Results

3.1 Atterberg Limits

Percentage of soil moisture in which the soil starts to behave like a liquid and starts to flow is known as the liquid limit, or WL [24]. Cone penetration testing was the procedure employed in the experiment. A soil sample was applied with various amounts of moisture to get a penetration value between 10 and 30 mm. The moisture content (%) that indicates the sample's liquid limit would be determined by the value of 20 mm penetration.

The Plastic Limit (WP) is the moisture level in which the soil starts to behave like plastic. A crucial characteristic of fine-grained soils is their plastic limit. Using the common thread rolling technique, the plastic limit is calculated. The boundary between the non-plastic and plastic is stated after rolling out a thread of the fine fraction of a soil on a flat non-porous ground to determine the plastic limit.

Figure 1 shows the relationship trend between average cone penetration values and the moisture content of soil. As the penetration increases, the moisture content also increases. Each line represents the trend for soil samples contaminated with different concentrations. As concentration increases, the pattern is more likely to shift to a lower value of moisture content.

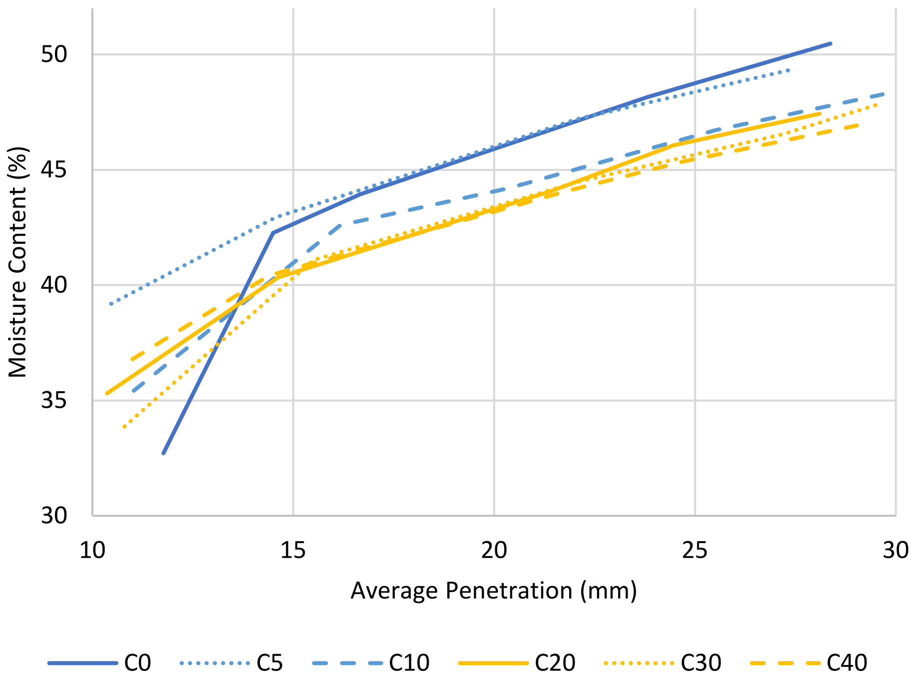


Fig. 1. Relationship trend between average cone penetration values and the moisture content of soil content

Figure 2 and Figure 3 illustrate that as the concentration of zinc heavy metals increases, both liquid limit and plastic limit of soil decrease. It can be observed that the plasticity index for the soil produces the relationship between concentration of zinc contaminant and plasticity index of soil.

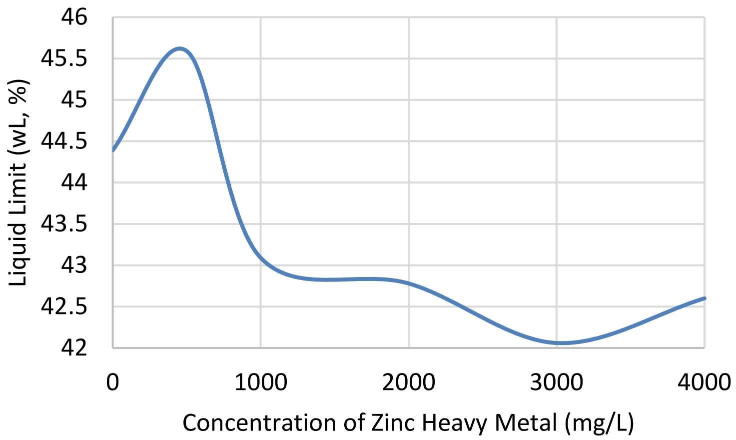


Fig. 2. Relationship between liquid limit and concentration of zinc heavy metal

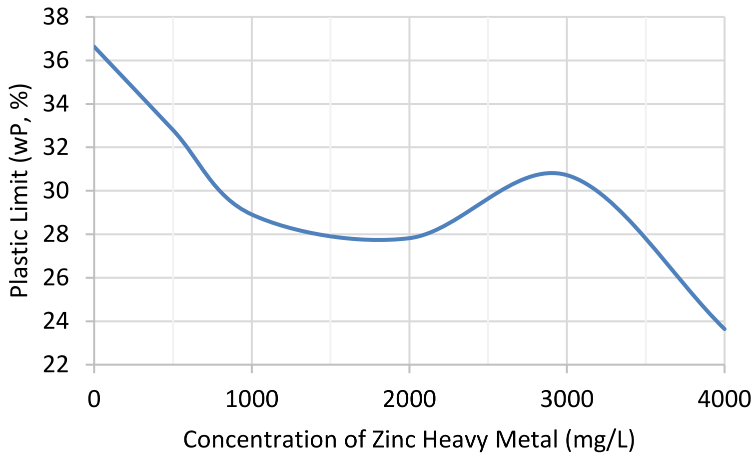


Fig. 3. Relationship between plastic limit and concentration of zinc heavy metal

In Figure 4, it increases as the concentration of zinc contaminant is increased.

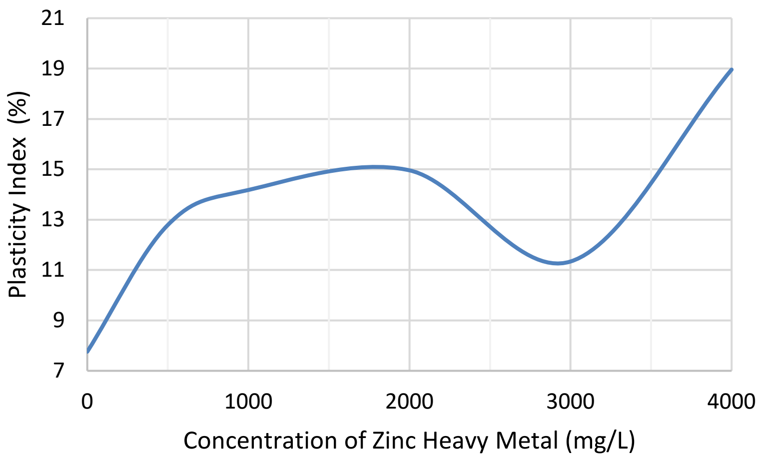


Fig. 4. Relationship between plasticity index and concentration of zinc heavy metal

Table 1 shows the summarization of results obtained for Atterberg Limits of residual soil contaminated with zinc heavy metal.

Table 1
Plasticity index

Concentration of Zinc Heavy Metal (mg/L)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
0	44.39	36.63	7.76
500	45.59	32.8	12.79
1000	43.09	28.91	14.18
2000	42.78	27.82	14.96
3000	42.06	30.72	11.34
4000	42.6	23.64	18.96

3.2 Compaction Test

The experiment to study the effect of different concentrations of zinc heavy metal towards the residual soil's compaction behaviour was conducted via the standard proctor test using mechanical 2.5 kg rammer. The results are presented in Figure 5 and Figure 6, where Figure 5 shows a significant reduction in the value of the optimum moisture content of residual soil. However, the overall pattern indicates a downward trend as concentration increases.

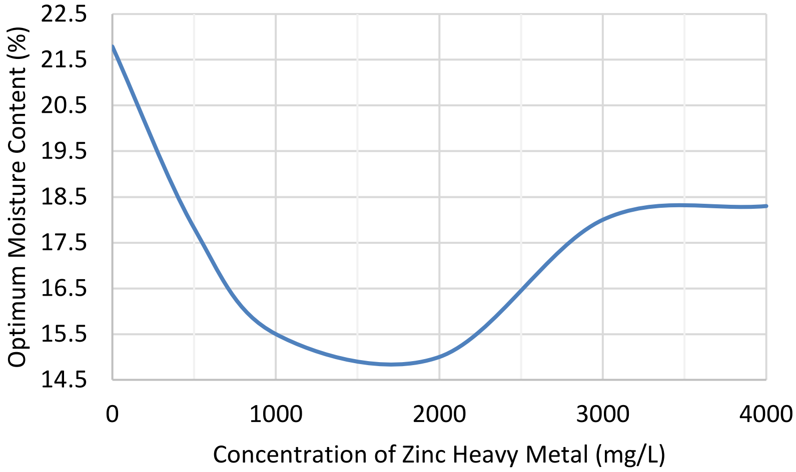


Fig. 5. Relationship between moisture content and the concentration of zinc heavy metal

Meanwhile, Figure 6 shows a strong upward trend of maximum dry density as the concentration of zinc contaminant increases.

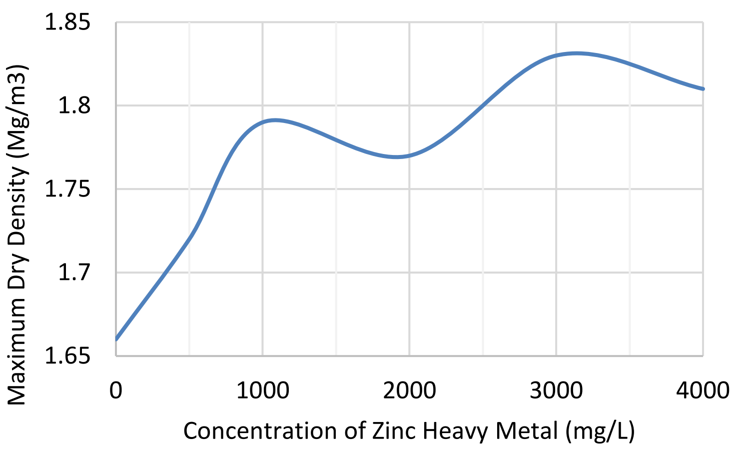
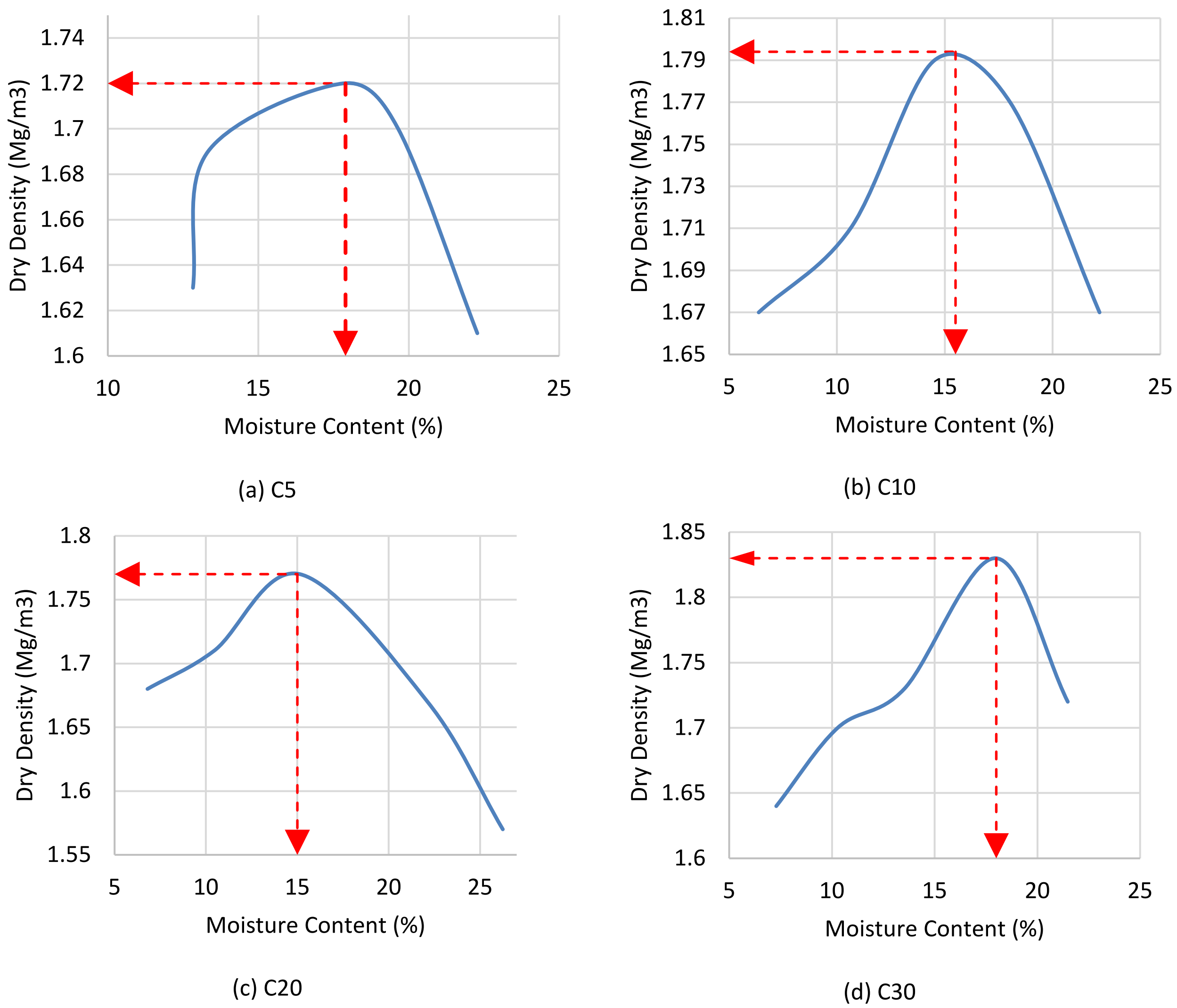
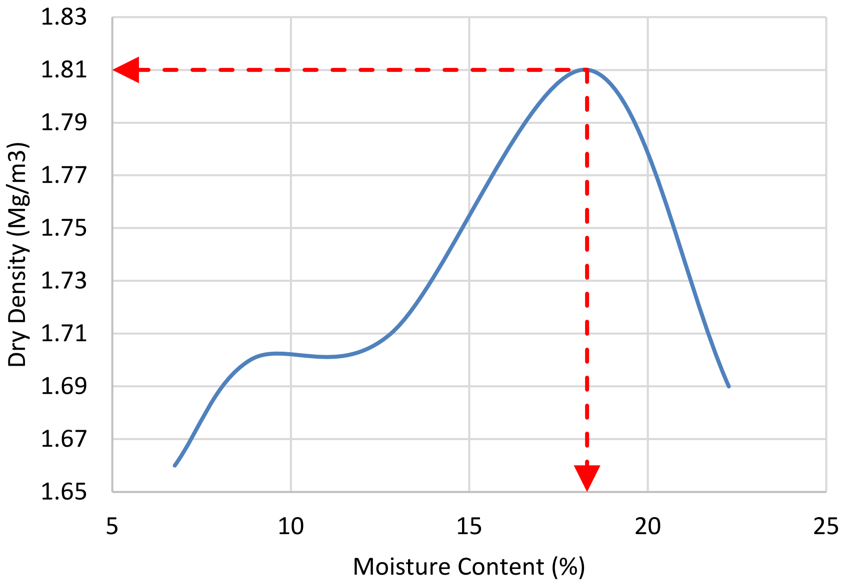


Fig. 6. Relationship between maximum dry density and the concentration of zinc heavy metal

As can be seen from the compaction curve diagram in Figure 7, with the increase of moisture content, the dry density first increases and then decreases and the value for optimal water content and the maximum dry density can be determined.





(e) C40

Fig. 7. Compaction curve of contaminated sample respective to concentration of zinc heavy metal (a) C5 (b) C10 (c) C20 (d) C30 (e) C40

3.3 pH Test

The pH test was conducted to determine the pH level of contaminated soil test for the acidity or alkalinity of soil. By analysing the soil pH, geotechnical engineers can gain insights into chemical reactions that occur within the soil, which can influence its stability, durability and engineering properties. The soil sample was tested using a calibrated pH meter, with the accuracy of ±0.005. Table 2 shows the results of pH value of the soil recorded with the variations of zinc heavy metal concentrations.

Table 2
Results for soil pH test

Concentration (mg/L)	pH
C0	6.063
C5	5.980
C10	5.859
C20	5.839
C30	5.810
C40	5.835

As shown in Figure 8, the pH of residual soil can be seen to be decreasing as the added concentration of zinc heavy metal is increased. Natural residual soil has the natural pH of 6.05 which significantly drops to the pH value of 5.98 as soon as the soil is spiked with 500 mg/L of zinc heavy metal. The pH value continues to reduce as the concentration increases to 4000 mg/L.

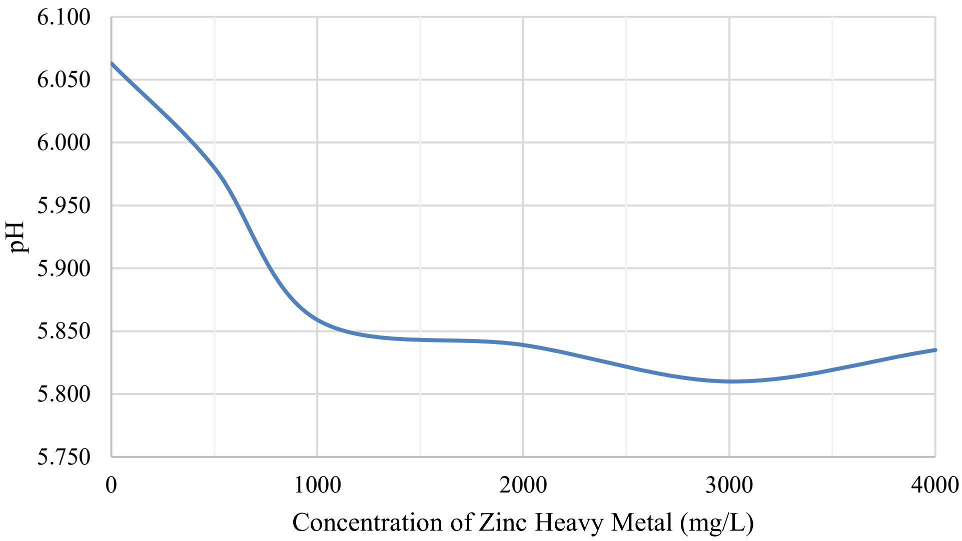


Fig. 8. Relationship between soil pH and the concentration of zinc heavy metal

4. Discussion

4.1 Atterberg Limits

Based on the results, the presence of heavy metal ions in soil has a significant impact on soil liquid limit and soil plasticity limit [22,30]. The results are related to the Theory of Diffuse Double Layer. The liquid limit and plastic limit of the soil are controlled essentially by the thickness of diffuse double layer (DDL) and the amount of bound water at particle surface [9]. The increase in the concentration of heavy metal contaminants would cause further reduction of double-layer thickness [7]. The effects are attributed to two mechanisms. Firstly, heavy metal contamination causes significant pH to drop due to heavy metal hydrolysis reactions. It refers to chemical reactions that occur between water molecules and certain compounds that are present in the soil which can affect the behaviour of soil minerals. This leads to soil pH reduction of the thickness of the double layer around the clay and forms an entangled (agglomerated) structure in the soil [22]. As a result, it reduces both the water adsorption capacity and liquid limits of the soil sample. The second mechanism simply suggests that the decrease in clay platelet double layer thickness may be due to the presence of heavy metal contaminants. Therefore, as the concentration of heavy metal contaminants increases, the thickness of the double layer around the clay platelets decreases. Increasing concentration enhances the aggregation behaviour and reduces inter-particle repulsion, which in turn allows the particles to move more freely at lower water levels, lowering the liquid limit value and reducing the tendency for water adsorption.

4.2 Compaction Test

Effects on the diffuse double layer (DDL) is due to a significant decrease in the strength of the zinc-contaminated soil through strong adsorption of heavy metal ions by the clay particles. A decrease in the thickness of the DDL creates the disturbing elements between the clay particles that affect the void [30]. This is mainly due to the presence of heavy metal ions within the soil, which leads to the formation of a velvety structure and the rearrangement of the soil particles [32]. According to the theorem of DDL, clay minerals can adsorb water molecules around themselves. High plasticity due to clay mineral in soil can adsorb much more water than low plasticity clays [23].

4.3 pH Test

The pH of the soil samples decreases with the addition of contaminant due to its acidic nature and the presence of more free ions in contaminated soils [23]. In addition, heavy metals have positive charges on their outermost surfaces and adding such ions to a soil solution triggers the pH to fall towards the acidic range [9,19]. This results in the reduction of liquid limits through the promotion of a flocculated structure. Heavy metal ions are adsorbed in the DDL, creating inner and outer layers sphere complexes as well as a collection of hydrated ions. As concentration increases, cation adsorption can turn the particle to become neutral or potentially positively charged [29,30]. Therefore, the accumulation of positively charged particles around the surface lowers the pH value.

5. Conclusions

This research aims to study the effects on the increment of concentration of Zinc heavy metals toward the physical and mechanical properties of residual soil contaminated with zinc heavy metals. Throughout the research effort, standard test method for experimental work was conducted according to BS 1377: 1990 Soils for Civil Engineering Purposes to help evaluate the compaction characteristics, plasticity and chemical characteristic of residual soil contaminated with zinc heavy metals. In addition, the heavy metal contaminants decrease the liquid limit and plastic limit of the soil but at the same time increases the plasticity which leads to high adsorption of water affecting the Atterberg's limits values. Soil's mechanical and chemical behaviours are also affected by the addition of zinc heavy metal contaminants. As the level of contamination increases, optimum moisture content decreases and maximum dry density increases with soil pH significantly dropping due to the presence of more acidic ions. Thus, the presence of heavy metal contaminants in soils leads to the degradation of geological properties, including the changes in mechanical behaviour and geotechnical properties based on the double diffuse layer theory. The increase of zinc heavy metal concentrations leads to reduced water adsorption capacity of soil particles but increases the adsorption of heavy metal ions which disrupts the residual soil's geotechnical properties.

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