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THE EFFECT OF PALM OIL MILL EFFLUENT (POME) ON THE CONSOLIDATION BEHAVIOR OF COMPACTED HIGH-PLASTICITY CLAY UNDER ELEVATED TEMPERATURES

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Abstract. Palm Oil Mill Effluent (POME), a byproduct of palm oil processing, is characterized by high concentrations of suspended solids, a brownish color, and discharge temperatures ranging from 80°C to 90°C. These elevated temperatures have the potential to alter the physical and mechanical properties of the subgrade soil in waste ponds. However, research addressing this issue remains scarce, particularly regarding the consolidation behavior of high-plasticity clay. This study investigates the alterations in consolidation parameters of high-plasticity clay saturated with POME. The experiments were conducted using a modified consolidation apparatus across a temperature range of 28°C to 90°C. The results indicate that saturating the soil with POME altered the soil classification from high-plasticity clay (CH) to low-plasticity clay (CL), leading to a significant reduction in the Plasticity Index from 39.15% to 16.22%. At an elevated temperature of 90°C, the POME-saturated soil exhibited an 85.40% increase in the Compression Index (Cc). Conversely, POME saturation reduced the Swelling Index (Cs) by 25.86% and decreased the Coefficient of Consolidation (Cv) by 25.42% compared to conditions saturated with clean water.

Keywords: consolidation; elevated temperature; palm oil mill effluent; high-plasticity clay.

I. INTRODUCTION

Palm oil stands as a pivotal plantation commodity within the Indonesian economy due to its significant capacity for vegetable oil production, which is in high demand across the industrial sector. In the Kalimantan region, the geological presence of clay soil frequently intersects with palm oil plantation areas. Technical challenges emerge when this native soil serves as a subgrade or liner for ponds designed to contain liquid waste, specifically Palm Oil Mill Effluent (POME). POME discharge, a byproduct of palm oil processing, contains high concentrations of suspended solids, exhibits a brownish coloration, and is released at elevated temperatures ranging from 80°C to 90°C (Hamzah et al., 2020).

Exposure to elevated temperatures can drastically alter the mechanical characteristics of clay soil. It is established that temperature increases influence pore water seepage velocities and the interaction between clay particles, which ultimately impacts the rate and magnitude of soil settlement. Several preceding studies indicate that temperature variations can accelerate the consolidation process and modify soil permeability. However, existing geotechnical literature has predominantly focused either on the effect of temperature on soils saturated with clean water or on the effect of waste fluid at room temperature. Consequently, there is a paucity of research addressing this specific intersection, particularly regarding the consolidation behavior of high-plasticity clay subjected to elevated temperatures.

The thermal impact of POME discharge has the potential to modify the physical and mechanical properties of the waste pond's subgrade. Therefore, a comprehensive understanding of the variations in consolidation parameters such as the Compression Index (Cc), Swelling Index (Cs), and Coefficient of Consolidation (Cv), resulting from elevated temperature exposure is imperative.

The primary objective of this research is to analyze the consolidation behavior of compacted high-plasticity clay saturated with both clean water and POME across a range of temperatures: 28°C (room temperature), 40°C, 60°C, 80°C, and 90°C. Experiments were conducted using an oedometer apparatus that has been modified with a controlled heating element. The findings of this study are expected to serve as a reference for the palm oil industry in implementing more efficient and environmentally friendly POME management strategies while maintaining the quality of the supporting soil.

II. LITERATURE REVIEW

Characteristics of High-Plasticity Clay

Soil is generally defined as an assemblage of minerals, organic matter, and relatively loose sediments overlying the bedrock. Broadly, soil is categorized into three distinct groups: non-cohesive, cohesive, and organic soils. Non-cohesive soils are characterized by loose, unbonded granular structures. In contrast, cohesive soils consist of very fine particles that adhere to one another, whereas organic soils are typically friable and highly compressible (Hardiyatmo, 2002). Specifically, clay is defined as an aggregate of microscopic mineral particles, typically smaller than 0.002 mm, that exhibit plasticity when moist and harden upon drying. According to the Unified Soil Classification System (USCS), clays possessing a Liquid Limit (LL) exceeding 50% are classified as High-Plasticity Clay (CH) (Das et al., 1995)

Consolidation Theory and Mechanical Parameters

Consolidation is defined as the process of volume reduction or void space decrease in saturated, low-permeability soil resulting from applied loading, which is accompanied by the expulsion of pore water (Das et al., 1995). The primary consolidation parameters examined in this analysis are:

- Compression Index (Cc): Quantifies the magnitude of soil compressibility under applied loading.
- Coefficient of Consolidation (Cv): Governs the rate at which consolidation settlement occurs.
- Swelling Index (Cs): Indicates the potential for soil rebound or swelling upon the removal of load (unloading).

The Effect of Temperature on Geotechnical Properties

Temperature plays a pivotal role in influencing the mechanical characteristics of soil, particularly within fine-grained classifications. It is established that an elevation in soil temperature can induce alterations in pore water viscosity and modify particle-to-particle interactions (Ogawa et al., 2020). Relevant prior studies have highlighted the following effects:

- Increased Compressibility: (Rusdiansyah & Markawie, 2021) observed that rising temperatures lead to a proportional increase in both the Compression Index (Cc) and the Swelling Index (Cs). This trend indicates that under elevated temperature conditions, the soil matrix becomes more susceptible to compression.
- Consolidation Rate: Both the Coefficient of Consolidation (Cv) and permeability (k) have been demonstrated to increase concurrently with rising temperatures (Hoseinimighani & Szendefy, 2021). This amplification in Cv is primarily driven by the thermal reduction of pore water viscosity, which accelerates the expulsion of water from the soil pores (Bouazza et al., 2008).
- Conversely, Ogawa et al. (2020) noted that the Coefficient of Volume Compressibility (m_v) tends to decrease as temperatures rise. This suggests that elevated temperatures possess the capacity to attenuate variations in soil volume.

Characteristics of Palm Oil Mill Effluent (POME)

Palm Oil Mill Effluent (POME) is a brownish liquid waste generated from palm oil processing, characterized by a high concentration of suspended solids. Under standard operational conditions, POME is discharged at elevated temperatures ranging from 80°C to 90°C and exhibits slightly acidic properties (Hamzah et al., 2020). Due to its significant content of organic compounds and suspended solids, POME acts as a primary contributor to environmental pollution if discharged without adequate treatment (Nugroho, 2019).

III. RESEARCH METHODOLOGY

Materials and Specimen Preparation

Pada penelitian ini sampel tanah diuji dengan dua perlakuan yang berbeda yaitu persiapan pengujian sampel tanah yang telah dijenuhkan dengan air bersih dan air limbah *Palm Oil Mill Effluent* (POME). Selanjutnya pada tanah yang dijenuhkan dengan air bersih dilakukan pengujian konsolidasi dengan suhu normal 28°C dan suhu panas 40°C, 60°C, 80°C dan 90°C. Pada tanah yang dijenuhkan dengan air limbah *Palm Oil Mill Effluent* (POME) dilakukan pengujian konsolidasi dengan suhu panas 40°C, 60°C, 80°C dan 90°C. Variasi suhu panas berdasarkan penelitian terdahulu milik In this study, soil specimens were subjected to two distinct treatments based on the saturation fluid employed: clean water and Palm Oil Mill Effluent (POME). Consolidation tests for the soil saturated with clean water were conducted at a baseline room temperature of 28°C, as well as at elevated temperatures of 40°C, 60°C, 80°C, and 90°C. Similarly, specimens saturated with POME underwent consolidation testing specifically at elevated temperatures of 40°C, 60°C, 80°C, and 90°C. The selection of these specific temperature variations aligns with parameters established in prior studies by Rusdiansyah & Markawie (2021) and Hamzah et al. (2020).

This research utilized two primary materials: clay soil and liquid waste (POME). The soil samples consisted of high-plasticity clay (CH), obtained from a quarry located in Banjarbaru City, South Kalimantan. This sampling location was selected to represent the dominant soil characteristics of the region. Meanwhile, POME samples were collected directly from Waste Pond 1 at the PTPN XIII plantation in Pelaihari, South Kalimantan.

The soil was collected as disturbed samples and subsequently processed in the laboratory. The preparation process involved oven-drying, pulverizing, and sieving the soil through a No. 4 mesh. Subsequently, the prepared soil was mixed with distilled water to achieve the Optimum Moisture Content (OMC), as determined by the Standard Proctor compaction test in accordance with the Indonesian National Standard (SNI) 1742:2008.

Two types of fluids were utilized for the saturation phase of the consolidation tests: clean water and POME. The specific utilization of POME as a saturation fluid is intended to simulate a worst-case scenario, particularly modeling the potential impact of infiltration or leakage from waste ponds into the surrounding subgrade.

Modified Consolidation Apparatus

The testing procedures were conducted using a one-dimensional consolidation apparatus (oedometer) in accordance with ASTM D2435 and SNI 2812:2011 standards. To investigate the effects of temperature variations, the standard consolidation cell was modified by integrating an electric heating system that encircles the specimen ring. The integrated system comprises the following components:

I. Heating Unit: Installed on the external wall of the immersion cell to facilitate heat transfer to the fluid surrounding the soil specimen.
II. Digital Thermostat: Employed to regulate and maintain temperature stability at the target setpoint $\pm 1^{\circ}C$ throughout the testing duration.
III. Thermocouple: A temperature sensor positioned within the immersion fluid to monitor the actual temperature in real-time.

Testing Procedure

The soil specimens were prepared within a consolidation ring measuring 6.35 cm in diameter and 2.0 cm in height. Prior to the application of load, each specimen underwent a saturation process for 24 hours using the designated fluid (either clean water or POME), maintained at the specific temperature intended for the test. The experimental temperature variables were established as follows:

- 28°C (Room Temperature): Served as the standard control baseline.
- 40°C, 60°C, and 80°C.
- 90°C: Selected to represent the extreme conditions of waste discharge.

The loading sequence was executed using the incremental loading method with a load increment ratio (LIR) of 1 $(\Delta\sigma/\sigma = 1)$. The stress sequence commenced at 25 kPa and progressed through 50, 100, 200, and 400 kPa, culminating at a maximum pressure of 800 kPa. Each load increment was maintained for a duration of 24 hours to ensure the complete dissipation of pore water pressure. Upon reaching the maximum load, a stepwise unloading process was initiated until the specimen returned to the initial stress state. Vertical displacement (settlement) was monitored using a dial gauge throughout the process. The recorded data were subsequently analyzed to derive the key consolidation parameters: the Compression Index (Cc), Swelling Index (Cs), and Coefficient of Consolidation (Cv).

IV. RESULTS AND DISCUSSION

Alterations in Soil Physical Properties Induced by POME

The initial assessment of the physical properties revealed that the native soil exhibits an exceptionally high Liquid Limit (LL). Consequently, under the Unified Soil Classification System (USCS), the soil falls within the High-Plasticity Clay (CH) category. However, the interaction with Palm Oil Mill Effluent (POME) was found to induce significant alterations in the soil's plasticity characteristics.

Table 1 Physical Properties of Clay Soil Saturated with Clean Water and POME

Test Parameter		**Soil + Clean Water**	**Soil + POME**
Soil Properties	Gs	2,675	2,596
Atterberg Limits	LL	69,90%	38,84%
	PL	30,75%	22,62%
	PI	39,15%	16,22%
	USCS	CH	CL
Grain Size Distribution	Gravel	0,83%	0,55%
	Coarse Sand	2,92%	2,80%
	Medium Sand	2,76%	2,93%
	Fine Sand	3,32%	8,19%
	Silt & Clay	38,05%	45,44%
	Clay Fraction	52,11%	40,10%
	No. 10	99,17%	99,45%
	No. 40	95,17%	95,59%
	No. 200	91,82%	91,77%

Based on the data presented in Table 1, it is evident that the Plasticity Index (PI) experienced a drastic reduction, plummeting from 39.15% in the native soil to 16.22% following the interaction with POME. This significant decline precipitated a shift in the soil classification from High Plasticity Clay (CH) to Low-Medium Plasticity Clay (CL). The observed reductions in both the Liquid Limit (LL) and Plastic Limit (PL) are attributed to the organic chemical constituents present in POME. These organic compounds function by compressing the adsorbed water layer (diffuse double layer) surrounding the clay particles, thereby diminishing the soil's overall capacity to retain water.

Soil Compaction Characteristics

The Standard Proctor compaction test was conducted to establish the fundamental compaction parameters that serve as the reference for preparing the consolidation specimens. This procedure is critical for simulating field conditions, specifically replicating the scenario where the subgrade of waste ponds is compacted to achieve the desired stability.

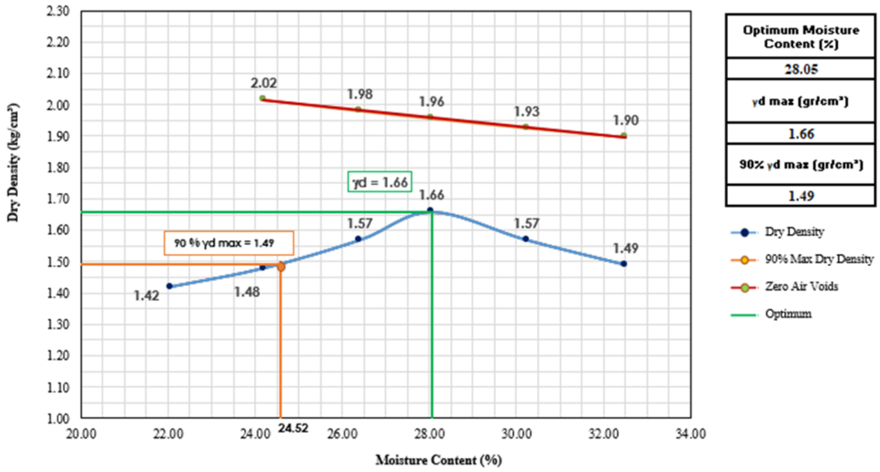

Figure 1 Soil Compaction Curve

Based on the Standard Proctor test results, the relationship between moisture content and dry density describes the compaction behavior of the tested clay. Analysis of the curve yielded an Optimum Moisture Content (W_{opt}) of 28,05% and a Maximum Dry Density ($\gamma_{d,max}$) of 1,66 gr/cm³.

These data points provide the basis for both field compaction execution and laboratory specimen preparation. For the fabrication of consolidation test specimens in this study, the compaction target was established at 90% of the Maximum Dry Density (MDD). Aligning with this target, the specific parameters utilized for molding the specimens were a dry density (γ_d) of 1.49 g/cm³ and a moisture content of 24.52%. The consistency of these parameters was strictly maintained across all samples to ensure that any observed variations in consolidation behavior could be attributed exclusively to the effects of temperature and POME saturation, rather than discrepancies in initial density.

Analysis of Compression Index (Cc) and Swelling Index (Cs)

The Compression Index (Cc) serves as a fundamental parameter for predicting the magnitude of total soil settlement. The experimental results demonstrate that the exposure of POME-contaminated soil to elevated temperatures exerts a significant impact on its compressibility characteristics.

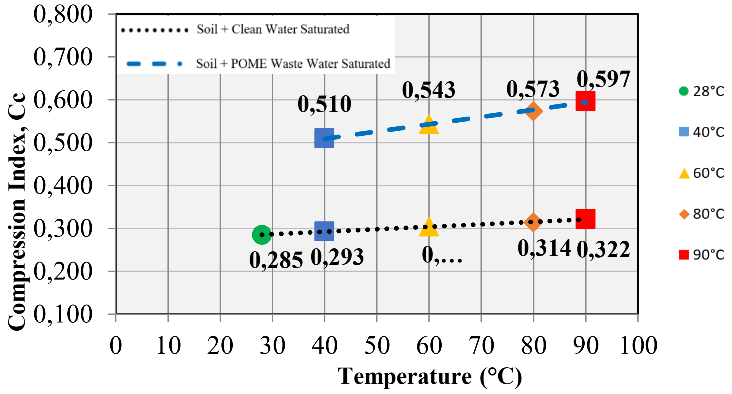

Figure 2 Relationship between Average Compression Index (Cc) and Temperature

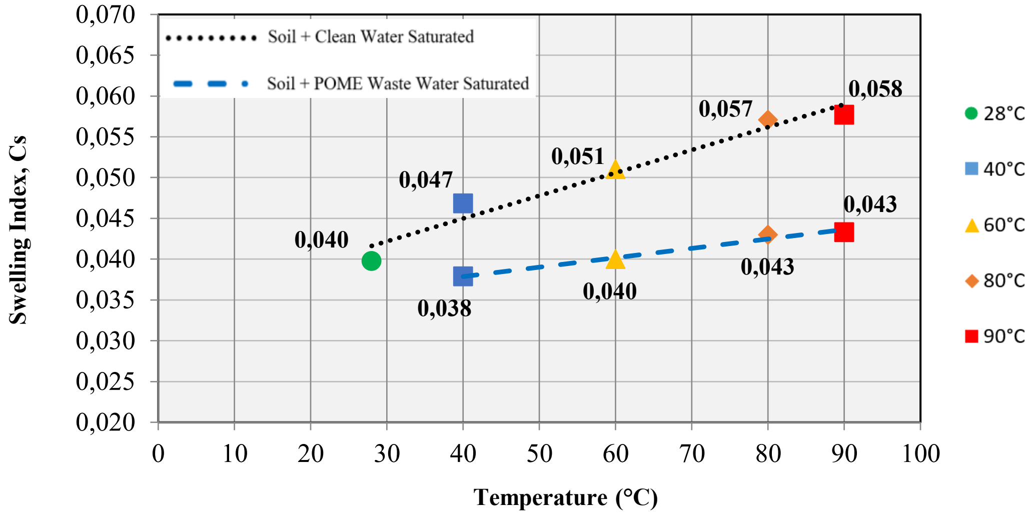

Figure 3 Relationship between Average Swelling Index (Cs) and Temperature

The experimental data indicates that the Compression Index (Cc) of POME-saturated soil exhibits a sharp increase corresponding to the rise in temperature. Specifically, at room temperature (28°C), the recorded Cc value was 0.265. However, upon exposure to an elevated temperature of 90°C, this value surged to 0.491. This substantial increase of 85.40% suggests that the synergistic effect of heat and organic contaminants renders the soil structure significantly more compressible.

Analysis of Coefficient of Consolidation (Cv)

The Coefficient of Consolidation (Cv) is the governing parameter that determines the rate of soil settlement. Theoretically, an increase in temperature reduces the viscosity of pore water, thereby facilitating faster drainage and resulting in a higher Cv value. However, the experimental results for the POME-saturated specimens revealed a distinctly different phenomenon.

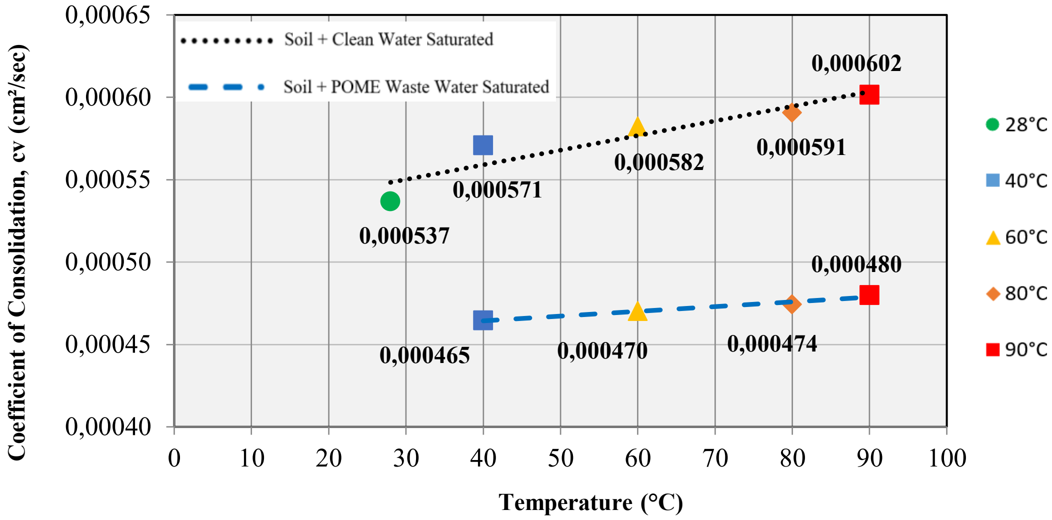

Figure 4 Relationship between Average Coefficient of Consolidation (Cv) and Temperature

As illustrated in Figure 4, the clean water specimens followed the theoretical trajectory, where Cv increased from 0.000537 cm²/s at 28°C to 0.000602 cm²/s at 90°C. In contrast, the POME-saturated samples consistently exhibited lower and more suppressed Cv values despite the thermal acceleration. Even at the maximum temperature of 90°C, the Cv for POME-saturated soil only reached 0.000480 cm²/s, remaining significantly below the control baseline. This observed retardation is attributed to the pore clogging phenomenon. POME contains a high concentration of suspended solids and viscous organic matter. These particulates create physical obstructions within the soil matrix, impeding the drainage flow paths. Consequently, this physical blockage counteracts the thermal reduction of fluid viscosity, causing the consolidation process to proceed at a much slower rate compared to clean water conditions.

V. CONCLUSION

Based on the comprehensive analysis regarding the impact of Palm Oil Mill Effluent (POME) infiltration and elevated temperature variations on high-plasticity clay, the following conclusions are drawn:

1. Alteration of Soil Classification: The infiltration of POME induced a substantial reduction in the Plasticity Index (PI) from 39.15% to 16.22%. This reduction precipitated a fundamental shift in the soil classification from High-Plasticity Clay (CH) to Low-Plasticity Clay (CL).
2. Significant Amplification of Compressibility: Elevated temperatures were found to exacerbate the mechanical degradation of POME-contaminated soil. The Compression Index (Cc) exhibited a drastic surge of 85.40% at 90°C compared to room temperature conditions. This finding

highlights a critical risk of excessive settlement for waste pond liners subjected to continuous thermal exposure from effluent discharge.

3. Reduction in Swelling Potential: While the Swelling Index (Cs) demonstrated an upward trend corresponding to temperature increases, the POME-contaminated soil generally exhibited lower swelling potential compared to clean water-saturated soil. Specifically, a reduction in the Cs value of 25.86% was observed at 90°C.
4. Impediment of Consolidation Rate: Contrary to the theoretical expectation that thermal reduction of fluid viscosity accelerates consolidation, the Coefficient of Consolidation (Cv) in POME-contaminated soil did not exhibit a consistent increase. This anomaly is attributed to the pore clogging phenomenon caused by suspended organic particulates, which physically obstruct the pore drainage pathways and retard the consolidation process.

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