

ANALYSIS OF THE EFFECT OF CH₃COOH ADDITION ON SOIL IMPROVED WITH 10 % LIME CONTENT

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ABSTRACT

Acid rain is a serious threat to the durability of geotechnical infrastructure, particularly in highly polluted industrial areas such as Jakarta. This phenomenon may damage the stability of chemically improved road subgrade through the dissolution of binding materials. This study aims to evaluate the strength degradation of subgrade soil stabilized with 10% lime under acid exposure. A laboratory experimental method was conducted by comparing native Puri Indah soil with lime-stabilized soil under three immersion conditions: no immersion (control) to determine initial strength, normal water immersion (pH 7.02) to simulate typical flooding, and acetic acid immersion (pH 5.21) to simulate extreme acid rain. The results indicate that 10% lime stabilization in the control condition produced a high CBR value of 46%. Normal water immersion caused a slight decrease to 44%, while acid exposure resulted in severe degradation with CBR dropping sharply to 27%. The significant gap between water and acid immersion confirms chemical deterioration due to neutralization reactions dissolving lime binders. It is concluded that although 10% lime effectively increases initial strength, this content lacks sufficient alkalinity to withstand long-term acid attack.

Keywords: Acid rain; chemical degradation; 10% lime; soaked CBR; soil stability.

ABSTRAK

Hujan asam merupakan ancaman serius bagi durabilitas infrastruktur geoteknik, khususnya di kawasan industri padat polusi seperti Jakarta. Fenomena ini berpotensi merusak stabilitas tanah dasar jalan yang telah diperbaiki secara kimiawi melalui mekanisme pelarutan bahan pengikat. Penelitian ini bertujuan untuk mengevaluasi degradasi kekuatan tanah dasar yang distabilisasi dengan kapur kadar 10% akibat paparan asam. Metode eksperimental laboratorium dilakukan dengan membandingkan karakteristik tanah asli Puri Indah dengan tanah campuran kapur pada tiga kondisi perendaman: tanpa rendaman (kontrol) untuk mengetahui kekuatan awal, rendaman air biasa (pH 7,02) sebagai simulasi genangan normal, dan rendaman larutan asam asetat (pH 5,21) sebagai simulasi hujan asam ekstrem. Hasil pengujian menunjukkan bahwa stabilisasi kapur 10% pada kondisi kontrol menghasilkan nilai CBR yang tinggi sebesar 46%. Perendaman air biasa menyebabkan sedikit penurunan kekuatan fisik menjadi 44%. Namun, paparan asam menyebabkan degradasi yang jauh lebih parah dengan nilai CBR jatuh drastis hingga 27%. Selisih degradasi yang signifikan antara perendaman air dan asam membuktikan terjadinya kerusakan kimiawi struktur tanah akibat reaksi netralisasi yang melarutkan bahan pengikat kapur. Disimpulkan bahwa meskipun kapur 10% efektif meningkatkan kekuatan awal, kadar ini belum memiliki kapasitas alkalinitas yang cukup untuk menahan serangan asam dalam jangka panjang.

Kata kunci: Hujan asam; degradasi kimia; kapur 10%; CBR rendaman; stabilitas tanah.

1. INTRODUCTION

Background

Jakarta, as a dense metropolitan center with industrial and transportation activities, faces serious environmental challenges in the form of high air pollution levels. Pollutant gas emissions, specifically Sulfur Dioxide (SO₂) and Nitrogen Oxide (NO), are released into the atmosphere and react with water vapor, triggering the acid rain phenomenon with acidity levels (pH) below 5.6.

This phenomenon poses a real threat to geotechnical infrastructure, particularly to subgrade soil layers that have undergone physical and mechanical improvements through lime stabilization. Subgrade soils with poor physical properties, such as high plasticity and low bearing capacity, often require such stabilization to mitigate risks of

settlement (Kuswanda, 2015). Furthermore, if left untreated, these conditions pose significant risks of structural failure to the pavement above (Tafonao, 2017).

Chemically, lime-stabilized soil possesses strong alkaline properties due to the formation of Calcium Hydroxide (Ca(OH)₂) compounds and Calcium Silicate Hydrate (CSH) gel, which function as binders between soil particles. This stabilization process has been proven effective in increasing soil density and compressive strength by inducing cation exchange and pozzolanic reactions (Istanto et al., 2022). Consistently, previous studies confirmed that adding stabilizing agents significantly improves the unconfined compressive strength of soft soils (Fathonah et al., 2022). Beyond compressive strength, recent research also highlights that lime stabilization effectively improves the California Bearing Ratio (CBR) of clay soils, making it suitable for subgrade reinforcement (Yulianti et al., 2023). Similar mechanical improvements have been observed in studies utilizing volcanic ash and lime (Latif et al., 2017). However, this stability is threatened when acid rain infiltrates the soil pores. The contact between the alkaline soil and acidic rainwater triggers a destructive neutralization reaction. The acid attacks the calcium binding components, converting them into water-soluble calcium salts, thereby inducing the leaching process, or the washing out of binding materials from the soil matrix.

Therefore, this research is crucial to specifically evaluate the vulnerability of soil stabilized with an optimum lime content (10%). An in-depth analysis is required to determine whether the 10% content provides sufficient alkalinity reserve to survive, or if it will instead undergo degradation of cementation bonds and significant structural failure when exposed to such an aggressive acidic environment.

Literature Review

Pollution Sources and Atmospheric Gas Emissions

The problem of soil degradation due to environmental factors originates from anthropogenic activities on the earth's surface, particularly in dense industrial megacities like Jakarta. Massive fossil fuel combustion activities, whether from factory smokestacks, power plants, or millions of motor vehicles, continuously release pollutant gas emissions into the air. The two main precursor gases for this problem are Sulfur Dioxide (SO₂) and Nitrogen Oxide (NO) (Sivaramanan, 2015). The accumulation of these gases in the atmosphere creates a pollutant layer ready to react with weather elements, marking the initial stage of the destructive acid rain formation cycle.

Chemical Process of Acid Rain Formation

In the atmospheric layer, SO₂ and NO gases do not remain static; instead, they undergo a series of complex chemical reactions triggered by solar radiation and the presence of water vapor (H₂O). Oxidation and hydrolysis reactions convert these gases into strong acidic compounds, namely Sulfuric Acid (H₂SO₄) and Nitric Acid (HNO₃). These mineral acids dissolve in cloud water droplets, causing a drastic drop in rainwater acidity (pH) to below 5.6 (Sivaramanan, 2015). This figure serves as the critical threshold distinguishing acid rain from normal rain (which is slightly acidic due to natural carbonic acid), indicating a high corrosive potential when the water falls to earth.

Threats to Alkaline Construction Materials

Sivaramanan (2015) emphasizes in his study that low-pH rainwater acts as an aggressive agent capable of degrading various types of construction materials, especially those with alkaline properties. Soil that has undergone stabilization or improvement using lime falls into this highly vulnerable category. This is because the primary goal of lime stabilization is to create a strong alkaline environment within the soil to facilitate inter-particle bonding. Therefore, acid rain exposure is not merely a wetting issue, but a direct chemical attack on the components constituting the soil's strength. Similar degradation mechanisms have been observed in concrete structures, where acid deposition leads to significant material loss (Okochi et al., 2000).

Initial Defense Mechanism of Stabilized Soil

To understand the damage, the soil condition prior to the attack must first be understood. The addition of lime (CaO) to the soil triggers a hydration reaction that produces Calcium Hydroxide (Ca(OH)₂). This compound serves a dual function: first, raising the soil pH to above 12.4, and second, providing calcium ions (Ca²⁺) that react with soil silica and alumina to form Calcium Silicate Hydrate (CSH) cementation gel (Tafonao, 2017). It is this CSH gel that hardens, fills pores, and binds soil grains into a rigid and stable structure. Thus, Calcium Hydroxide acts as the "primary line of defense" maintaining soil stability. Achieving this stable state requires adequate curing time for the pozzolanic reaction to reach maturity (Afriani, 2018).

Infiltration and Acid-Base Encounter

Damage begins when acid rain falls onto the soil surface and infiltrates (seeps) into the subgrade soil pores (Kamon et al., 1996). Within these microscopic soil cavities, a meeting occurs between two substances with opposing chemical

properties: Acid from rainwater (simulated in this study using Acetic Acid or CH_3COOH) and Base from Calcium Hydroxide ($\text{Ca}(\text{OH})_2$) present in the soil matrix. This encounter is unavoidable because soil, even when compacted, retains a certain permeability that allows water ingress. Studies utilizing various additives have shown that controlling density and permeability is vital (Mangelep & Simanjuntak, 2020). Yet, chemical stability under aggressive conditions and density maintenance remains a critical variable (Amran & Pradana, 2023).

Destructive Neutralization Reaction

The encounter between the acid and base triggers a spontaneous chemical reaction known as neutralization. The entering acetic acid aggressively attacks and binds the calcium components of the Calcium Hydroxide. The chemical reaction equation is: $2\text{CH}_3\text{COOH} + \text{Ca}(\text{OH})_2 \rightarrow \text{Ca}(\text{CH}_3\text{COO})_2 + 2\text{H}_2\text{O}$. In this reaction, the lime that should function to maintain high pH and serve as raw material for CSH cementation is instead "consumed" or depleted to neutralize the incoming acid (Jawahar & Bhavana, 2016). Consequently, the amount of active binder in the soil is significantly reduced.

Formation of Soluble Byproducts and Leaching Phenomenon

The most fatal impact of the neutralization reaction is not only the loss of lime but the formation of a new byproduct: Calcium Acetate salt ($\text{Ca}(\text{CH}_3\text{COO})_2$). The physical properties of this salt differ greatly from CSH cementation gel. While CSH is solid, hard, and water-insoluble (thus able to bear loads), Calcium Acetate has very high solubility in water (Izzat et al., 2013). Due to its soluble nature, the formed Calcium Acetate salt does not remain in place. As rainwater continues to seep through the soil, these salts dissolve and are washed out of the soil matrix. This mass transport process is known as leaching (Kamon et al., 1996). The loss of solid material leaves behind micro-voids, severing contact between soil grains and rendering the soil structure porous and weak. Even without acid, mere water saturation can physically reduce strength (Andrean A. et al., 2016). Acid further exacerbates this damage chemically, a vulnerability also noted in two-stage stabilization processes under soaking conditions (Suaryana & Fransisko, 2018).

Critical Vulnerability at 10% Lime Content

The impact of the aforementioned processes becomes critical in soil stabilized with optimum lime content (10%). At this percentage, the amount of added lime is generally just enough to meet basic cementation reaction needs without leaving much alkaline reserve. As shown by (Kamon et al., 1996), without adequate alkaline reserve as a buffer, acid attack will directly decompose the soil's primary binding compounds. There is no "shield" protecting the core structure; thus, strength degradation occurs very rapidly, drastically, and significantly, potentially causing total failure of the soil's bearing capacity.

Destabilization and Decalcification of Cementation Gel (CSH)

The degradation process does not stop at the neutralization of free lime ($\text{Ca}(\text{OH})_2$). Once the lime reserve in the 10% variation is consumed by acid, the soil environment pH drops drastically below the stability equilibrium point of cementation compounds. Calcium Silicate Hydrate (CSH), the "backbone" of soil strength, is only stable in high-pH alkaline environments. When the environment becomes acidic, a subsequent mechanism called decalcification occurs. In this phase, hydrogen ions (H^+) from the acid attack the CSH crystal structure and release calcium ions (Ca^{2+}) from their silicate bonds (Izzat et al., 2013). This reaction effectively breaks down the previously hard and rigid CSH gel into soft amorphous silica gel (Nabhan, 2023). This collapse of the CSH structure leads to a material lacking binding strength, similar to failures observed in other stabilization mixtures (Saputra, 2021). This point marks where the soil fundamentally loses its material integrity, beyond mere physical softening.

Mechanism of Structural Damage due to Acid Rain Exposure

Acid rain is an environmental factor capable of causing gradual structural damage through chemical degradation processes. Acidic rainwater does not act as a direct load, but as a chemical substance interacting with structural constituent materials. This interaction can reduce material resistance and accelerate structural performance decline over the long term. (Okochi et al., 2000) explain that repeated acid rain exposure, even at relatively low acidity levels, can trigger cumulative material degradation processes. The resulting damage is progressive and does not immediately cause collapse, but contributes to reduced durability and structural service life.

Problem Formulation

Based on the background and literature review above, the problem formulation is as follows:

- What is the CBR value of 10% lime soil under control conditions (unsoaked) and normal water soaking?
- What is the magnitude of the CBR value reduction when the soil is soaked in a simulated acid rain solution (pH 5.21)?

- Is the difference in reduction between water soaking and acid soaking significant enough to prove chemical damage?

Research Objectives

- To measure the bearing capacity of 10% lime soil under 3 conditions (dry, wet, acidic).
- To calculate the specific magnitude of degradation due to chemical acid factors.
- To evaluate the vulnerability of soil improved with optimum lime content in an environment exposed to acidic solutions.

2. RESEARCH METHODOLOGY

This research was conducted experimentally at the Soil Mechanics Laboratory, Tarumanagara University. The complete research methodology, from soil preparation to final testing, is outlined in the flowchart presented in Figure 1.

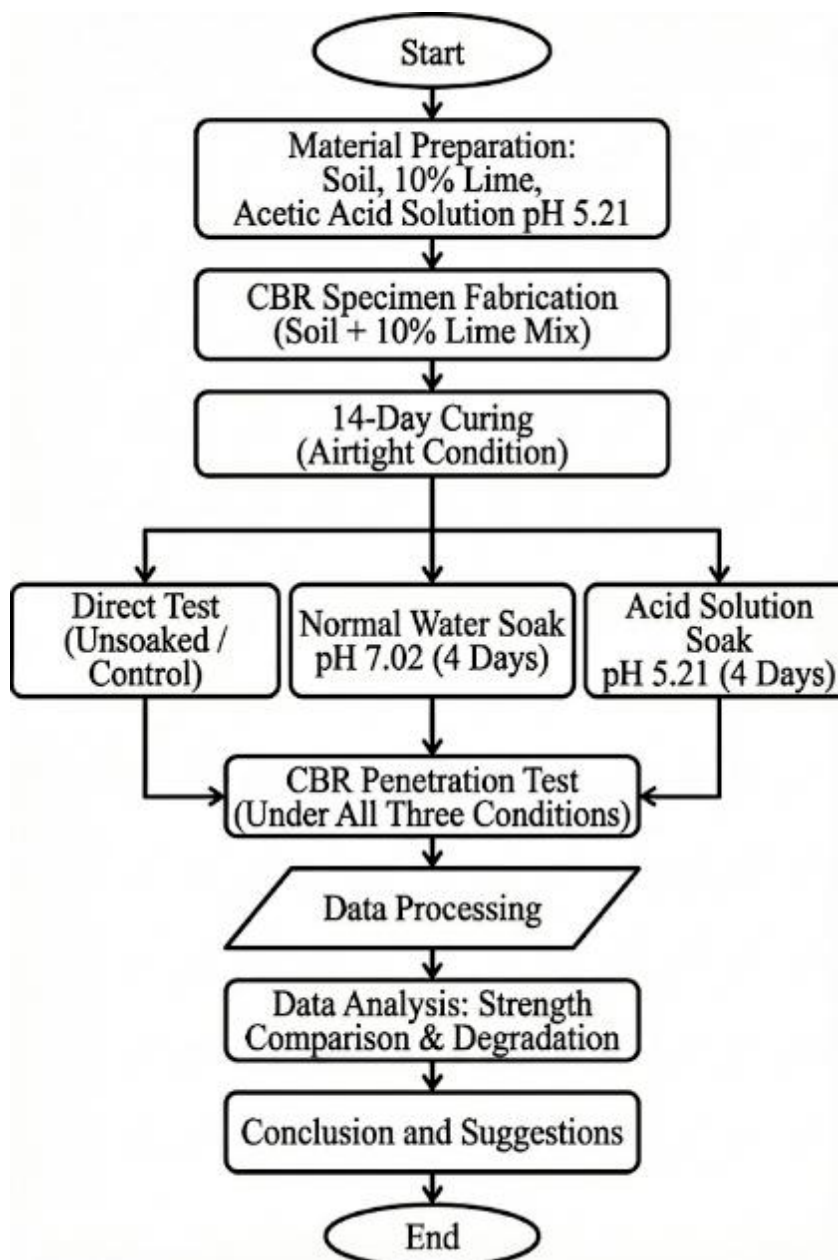


Figure 1. Research Process Flowchart

Materials and Preparation

The soil samples were obtained from Puri Indah, West Jakarta, and classified as High Plasticity Silt (MH) according to the USCS standard i.e. ASTM D2487-17 (ASTM International, 2017). The stabilizing agent used was hydrated lime ($\text{Ca}(\text{OH})_2$) with a content of 10% by dry weight of soil. The samples were compacted to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) following SNI 1742:2008 (Badan Standardisasi Nasional, 2008).

Curing Process

Following compaction, all stabilized soil samples underwent a strict 14-day curing process in sealed containers. This curing duration is critical to allow for the optimal formation of cementation bonds through pozzolanic reactions, which significantly influence the final strength of the stabilized soil (Afriani, 2018). The condition of the samples during this curing period is shown in Figure 2.



Figure 2. Samples undergoing the 14-day curing period

Soaking and Durability Testing

To evaluate durability, the California Bearing Ratio (CBR) test (Badan Standardisasi Nasional, 2012) was conducted under three environmental conditions: Unsoaked (control), Normal Water Soaking (pH 7.02) for 4 days to simulate standard inundation, and Acid Soaking. For the acid simulation, samples were likewise submerged in a diluted acetic acid solution (CH_3COOH) with a controlled pH of 5.21 for 4 days to mimic severe environmental exposure (Nabhan, 2023). The soaking setup used to mimic this acid rain inundation is displayed in Figure 3.

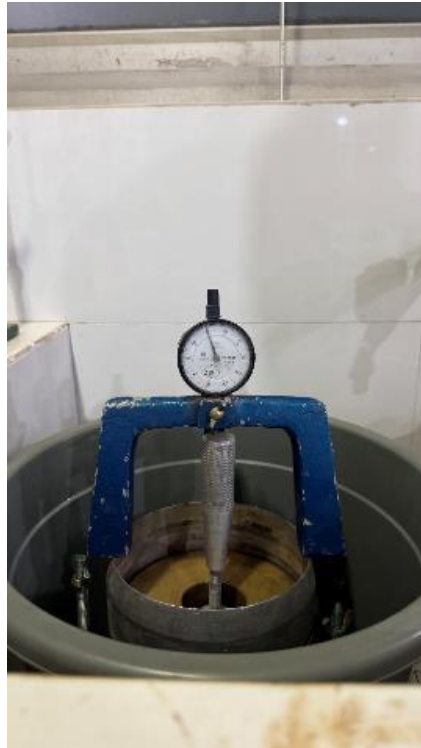


Figure 3. Soaking Process with Acid Simulation Fluid (pH 5.21)

3. RESULTS AND DISCUSSION

Testing Execution

The analysis of soil bearing capacity performance began by subjecting the prepared samples to penetration testing. The setup for the CBR penetration test, where a plunger is forced into the soil sample to measure resistance, is displayed in Figure 4.



Figure 4. CBR Penetration Test Setup

Analysis of Strength Degradation

The results demonstrated a clear degradation pattern due to environmental exposure. In the Control (Unsoaked) condition, the 10% lime-stabilized soil achieved a CBR value of 46%. This high value indicates that the pozzolanic reaction during the 14-day curing period successfully formed strong cementitious bonds within the soil matrix, consistent with findings that lime effectively improves the bearing capacity of soft soils (Fathonah et al., 2022).

Upon exposure to water (Normal Soaking), the CBR value decreased slightly to 44%. This reduction is attributed to the physical softening of the soil pores due to water infiltration, which is a typical response of soil structures to saturation (Andrean A. et al., 2016).

However, the impact of acid exposure was significantly more severe. Under Acid Soaking (pH 5.21) conditions, the CBR value dropped drastically to 27%. The comparative analysis of these CBR values is presented in the graph in Figure 5.

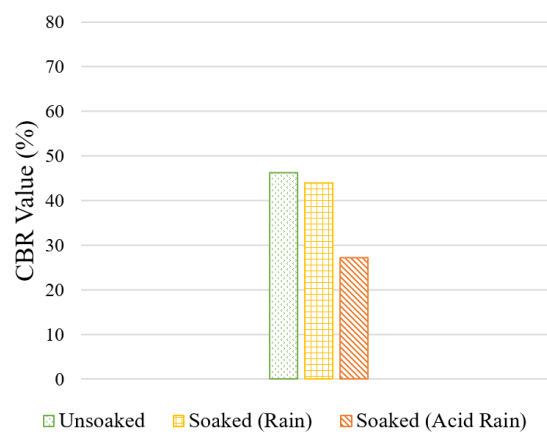


Figure 5. Comparison of CBR Values under Different Soaking Conditions

As observed in Figure 5, the steep decline in the acidic environment confirms that the degradation mechanism is predominantly chemical. The acid solution reacts with the calcium hydroxide in the lime, neutralizing the alkaline environment required for stability. This reaction leads to the dissolution (leaching) of the calcium-silicate-hydrate (C-S-H) gel, which acts as the primary binder in the soil (Jawahar & Bhavana, 2016).

Consequently, the soil matrix loses its rigidity and cohesive strength, reverting to a more granular and unstable state. This chemical breakdown explains the severe structural failure observed in the 10% lime samples, where the CBR value plummeted to 27%.

The significant disparity between the normal water soaked CBR (44%) and the acid soaked CBR (27%) further isolates the chemical attack as the primary cause of failure. In the normal water condition, the slight reduction in strength is merely due to pore saturation. However, in the acidic environment, the neutralization reaction consumes the available calcium hydroxide and subsequently attacks the cementitious products. Without sufficient alkalinity to maintain a high pH environment, the calcium-silicate-hydrate (C-S-H) bonds undergo decalcification, leading to a rapid loss of structural integrity (Nabhan, 2023). This confirms that for the 10% lime content, the chemical bonds formed are highly vulnerable to acidic infiltration, resulting in irreversible material degradation (Mangelep & Simanjuntak, 2020).

4. CONCLUSION AND SUGGESTIONS

Conclusion

Based on the comprehensive analysis of the experimental results, several critical conclusions are drawn regarding the stability of the soil from Puri Indah. First, the native soil is classified as High Plasticity Silt (MH), which inherently possesses low bearing capacity and is susceptible to environmental changes. Second, the stabilization process using an optimum lime content of 10% proved highly effective in the short term, successfully enhancing the soil's structural integrity by increasing the California Bearing Ratio (CBR) to a significant 46% under unsoaked conditions. This indicates that the pozzolanic reaction was sufficient to form rigid cementitious bonds. However, the third and most crucial conclusion is that the durability of this stabilized soil is severely compromised when exposed to acidic environments. While soaking in normal water only caused a minor physical reduction in strength to 44%, exposure to simulated acid rain (pH 5.21) resulted in a drastic degradation, with the CBR value plummeting to 27%. This sharp statistical decline confirms that the damage mechanism is not merely physical softening but is predominantly driven

by chemical neutralization. The acidic solution attacks the calcium-based binding agents, leading to the leaching of the cementation gel, which proves that a 10% lime content provides an insufficient alkalinity reserve to buffer against severe chemical attacks.

Suggestions

In light of the findings regarding the vulnerability of 10% lime-stabilized soil to acid attack, several recommendations are proposed for infrastructure development in regions prone to high pollution. First, relying solely on a 10% lime content is deemed risky; therefore, it is strongly recommended to increase the lime dosage to a higher content, such as 15% or more. This excess alkalinity is necessary to create a "sacrificial buffer" that neutralizes infiltrating acid before it can degrade the primary structural bonds of the soil. Second, practical engineering designs should incorporate complementary protective measures to mitigate chemical exposure. This includes the installation of efficient surface drainage systems to prevent water stagnation and minimize the infiltration of acidic runoff. Finally, the application of impermeable barriers, such as geotextiles or bituminous layers, should be considered to physically shield the stabilized subgrade from direct contact with acid rain, thereby significantly extending the service life of the pavement structure.

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