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THE EFFECT OF ADDING QUICKLIME ON STABILIZATION OF EXPANSIVE SOILS

The object of this research is Ampelgading clay (Malang, East Java), known for its high plasticity and low strength, which impact building stability. This study focuses on how varying proportions of quicklime affect soil properties. One of the main issues is clay instability, caused by volume changes due to water fluctuations, which poses a major challenge for infrastructure, particularly in high-rainfall and humid areas. In the study, expansive clay from Ampelgading with quicklime percentages of 0 %, 5 %, 10 %, 15 %, and 20 % was tested. Geotechnical and mechanical tests, including water content, specific gravity, Atterberg limits, compressive strength, and swelling, were conducted. The results show that adding quicklime significantly alters the physical and mechanical properties of the clay, reducing water content from 58.20 % to 35.64 % and specific gravity from 3.362 to 2.118. Volumetric weight initially increases at low quicklime levels but decreases at higher levels. Quicklime alters soil microstructure through a pozzolanic reaction with calcium hydroxide ($Ca(OH)_2$) and silica/alumina, forming calcium hydrates that enhance cohesion and strength. However, excessive quicklime creates non-uniform aggregates, reducing density and stability. Optimal compressive strength occurs at 15 % quicklime, but at 20 %, stability decreases, plasticity reduces, and swelling accelerates. Furthermore, lower moisture content improves compaction and enhances soil stability. Compared to cement or fly ash, quicklime reacts faster, provides immediate stability, and minimizes long-term swelling and shrinkage. The pozzolanic reaction further strengthens the soil by forming stable calcium hydrate and calcium aluminate compounds.

Keywords: *quicklime, soil water content, soil specific gravity, soil tension, volume swelling, soil stabilization, expansive soil.*

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1. Introduction

Many construction sites, especially in regions with expansive clay soils such as in areas of California, Texas, and parts of Southeast Asia, frequently encounter clay soil characterized by its low strength and high plasticity. This leads to a decrease in the structure's bearing capacity and stability, which poses significant challenges for infrastructure. Therefore, it is crucial to investigate the efficacy of quicklime as a soil stabilizer in enhancing the physical and mechanical properties of clay soils, such as its weight-bearing capacity, shear strength, and the reduction of expansion. The challenge in implementing this is determining the optimal dose of quicklime to improve soil performance without affecting other factors, such as cost, processing time, and environmental impact.

When clay soil is wet, it begins to change its volume. When water is present, expansive clay soil expands, and when it is not, it contracts [1]. This feature of expansive clay soil causes the ground to shift, posing a significant threat to public infrastructure such as roads, rail lines, and pipe networks [2]. Minerals such as calcite, quartz, and clay minerals compose expansive clay soil. Most wide soils, especially montmorillonite, belong to the smectite group [3, 4]. Expansive clay minerals in the soil can expand significantly when it absorbs water and contract when it dries out. This tendency for things to expand and contract can have a significant impact on buildings, foundations, and structures [5]. The cycle of wetting and drying makes the soil shrink and swell, especially in clay soils that are loose and clay-like. The process of shrinking and growing helps cracks form and spread [6]. Building deep foundations can be challenging due to the presence of clay layers that cover a large area and extend to great depths [7].

In places with a lot of water, the way expansive clay soil behaves affects how stable foundation buildings are. When soil expands and contracts, it often deforms the surface. Monitoring ground subsidence over time is crucial to prevent and control large-scale soil disasters, as it poses a serious engineering danger [8, 9]. In the humid tropics, where it rains a lot and tropical storms happen often, land degradation through mass movement is a big problem. Rainfall increases the amount of water in the soil. This can cause mass movement, especially in clay soils with minerals that expand, where changes in humidity can weaken the structure [10].

The expansiveness of clay soil influences the design of buildings. Expansive soils pose a significant challenge to the building industry due to their tendency to undergo significant volume changes when the water content varies. When these soils get wet, they expand, and when they dry out, they shrink, putting a lot of stress on the footing system [11, 12]. Clay-rich areas typically host them. Most estimates say that rebuilding and fixing up land costs 10–11 billion USD a year in the US, 2–3 billion USD in China, and 1–2 billion USD in the UK and India. Total yearly losses rose by about 160 % from 1990 to 2020, with 6 billion dollars in losses just for US pavement buildings [13]. To keep the pavement and structure stable and to lower the risk of damage, it is important to treat and stabilize expansive soil before building [14, 15]. It's clear from these numbers that expansive soils have a big effect on building, and it is necessary to find better ways to manage and stabilize the soil right away. Geotechnical studies and using the right engineering solutions during planning and construction are necessary to make sure that structures built on big areas of land are stable and last a long time, which lowers their economic and structural effects [16–18].

To keep expansive clays stable, two popular methods are chemical stabilization and mechanical stabilization [19, 20]. To change the physical features of expansive clay soils and make them stronger, mechanical stabilization uses non-cementitious materials like fibers [21], tires [22], glass [23, 24], and among others. By adding soil binders [25], chemical stabilization uses combinations of chemicals like fly ash [26], geopolymers [27], cement [28], lime [29], zeolites [30], and more to make clay soils better.

Studies have explored the use of quicklime as a stabilizer for expansive clay soils, but none have examined the optimal dosage. More research on the effects of adding quicklime (CaO) on the physical, mechanical, and volumetric swelling properties of expansive clay soils is necessary to stabilize them.

The aim of this research is to identify the pattern of soil nature change due to the addition of quicklime, understand the mechanism of chemical reactions that occur between quicklime and soil components, and determine the optimal dose of quicklime to increase the carrying capacity, shear strength, and reduce the volumetric expansion of the soil. Practically, this research is expected to provide applicative solutions in the stabilization of expansive clay soils to increase the stability of building structures and infrastructure. The results of this research can be used as a reference in soil improvement techniques in construction projects, especially in areas that have expansive clay.

2. Materials and Methods

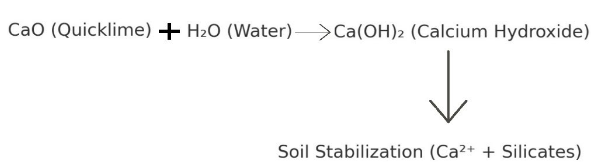
Expansive clay soil samples were collected in the Ampelgading area, Malang Regency, East Java. The test composition of the Ampelgading expansive clay soil includes both original, undisturbed soil and disturbed soil, as outlined in Table 1.

Table 1

The composition of mixtures used on passive soil and quicklime

Material	Percentage of test object weight				
Expansive clay soil	100 %	95 %	90 %	85 %	80 %
Quicklime	0 %	5 %	10 %	15 %	20 %

Let's conduct soil properties tests by taking, drying, storing, and filtering soil that passes sieve number 4. Then it is possible to use this soil for various tests such as water content, specific gravity, degree of saturation, grain gradation, Ateberg Limit, Standard Proctor, and soil that passes sieve number 200. The next step involved testing the physical and mechanical properties of expansive clay soil. Testing the physical properties of expansive clay soil, including the water content test, specific gravity, degree of saturation, grain gradation, Atterberg limits, standard proctor, and vertical swelling test:



The reaction diagram illustrates the process of stabilizing expansive soils using quicklime (calcium oxide, CaO). When quicklime is mixed with water (H_2O), it undergoes a reaction to form calcium hydroxide (Ca(OH) a compound that is highly alkaline. This reaction is as follows:

$$CaO + H_2O \rightarrow Ca(OH).$$

Calcium hydroxide, once formed, interacts with the minerals in the expansive soil, particularly with silicates present in the soil. This interaction results in the formation of calcium-silicate compounds, which improve the structure and stability of the soil. The stabilized soil exhibits reduced swelling, making it less susceptible to expansion when exposed to moisture changes. The overall effect of this process is enhanced soil strength, improved load-bearing capacity, and better overall soil stability, which is crucial in construction and engineering applications where expansive soils are encountered.

3. Results and Discussion

3.1. Effect of quicklime on water content

The original soil water content is 58.20 %; adding 5 % quicklime reduces it to 38.80 %; adding 10 % quicklime reduces it to 38.11 %; adding 15 % quicklime reduces it to 37.42 %; and adding 20 % quicklime reduces it to 35.64 %. Fig. 1 illustrates this. The addition of lime alters the physical properties of the soil by enhancing the cohesion between particles, which consequently decreases the soil's water-holding capacity. The microstructure of the soil becomes more granular and less dense, leading to a reduction in pore space and a subsequent decrease in the water absorption capacity.

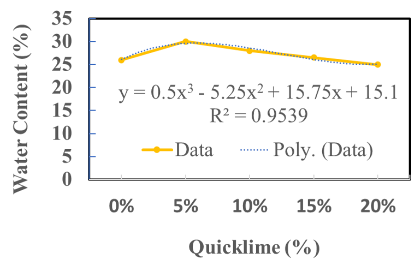


Fig. 1. Relationship of quicklime to water content

Fig. 1 shows the relationship between the percentage of quicklime (%) and Water Content (%) with the polynomial order three regression model, producing an equation $y=0.5x^3-5.25x^2+15.75x+15.1$ and the coefficient of determination $R^2=0.9539$, which shows a very high level of compatibility (95.39 %). From the graph, it can be seen that water content increases to the peak at around 5 % quicklime, then decreases with an increase in quicklime levels to 20 %, indicating the optimum point in the use of quicklime by around 5 %. This pattern reflects that the addition of quicklime initially increases the water content, but after passing a certain threshold it actually reduces it, which is most likely caused by a chemical reaction between quicklime and water.

The decline trend in the value of specific gravity (%) is in line with an increase in quicklime levels from 0 % to 20 % can be seen in Fig. 2. Initially, specific gravity is worth around 3.3 % when there is no quicklime, then experienced a significant decrease to around 2.2 % at 10 % quicklime, and after that it tends to be stable close to 2.0 % to 20 % quicklime. This pattern indicates that the addition of quicklime gradually decreases the relative density of the soil, possibly due to chemical reactions between quicklime and soil components that cause weathering particles and the formation of new or porous new compounds. The stability point began to be seen after 10 %, which indicated that the effect of adding quicklime to specific gravity was at least after that point.

Fig. 2 shows the relationship between the percentage of quicklime (%) and specific gravity (%) with the polynomial order two regression approach that produces equations $y=0.125x^2-1.033x+4.218$ and the coefficient of determination $R^2=0.9712$, which reflects a very good model compatibility (97.12 %). The pattern formed shows a decrease trend of specific gravity as the quicklime level increases, with the most significant decreases occurred between 0 % to 10 %, and tends to slop afterwards. This indicates that the addition of quicklime progressively decreases the value of specific gravity, the possibility of changes in material structure due to chemical reactions between quicklime and soil components, which causes a reduction in the relative density of the mixture.

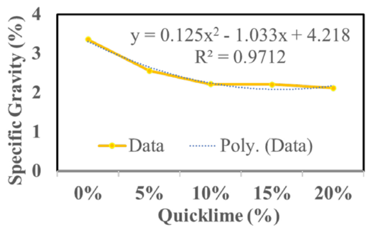


Fig. 2. Relationship between quicklime and specific gravity

The weight of the original dry volume of the soil is 1.48 g/cm^3, while the wet volume weight is 1.63 g/cm^3. The addition of 5 % quicklime increases the weight of the dry volume to 1.54 g/cm^3 and the weight of the wet volume to 1.69 g/cm^3. If the quicklime is added as much as 10 %, the weight of the dry volume rises to 1.61 g/cm^3. When adding 15 % quicklime, the dry volume weight decreases to 1.60 g/cm^3, and the wet volume weight also drops to 1.60 g/cm^3. Meanwhile, adding 20 % quicklime makes the dry volume weight return to 1.48 g/cm^3, while the wet volume weight stays at 1.48 g/cm^3 (Fig. 3).

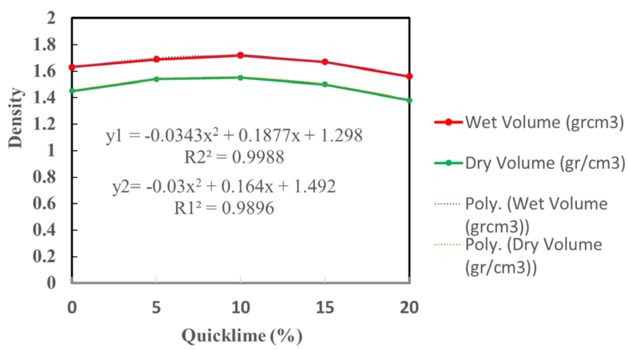


Fig. 3. Relationship between quicklime and density

It can be seen that the addition of quicklime affects the soil microstructure. At low concentrations, quicklime (CaO) reacts with water and soil, increasing cohesion between soil particles, which has the potential to increase dry and wet soil density due to decreasing voids between grains. When lime is added at 5 %, this reaction is optimal so that the volume weight increases. However, at higher lime additions (15 % or 20 %), excessive amounts of lime cause the formation of larger and non-uniform aggregates, which reduces the ability of soil particles to stick together, resulting in a decrease in dry and wet bulk weight. Meanwhile, chemically quicklime reacts with water to form calcium hydroxide ($Ca(OH)_2$) through an exothermic process. Initially, this reaction improves the bonds between soil particles and water, increasing the bulk weight. However, if excessive additions are made, the calcium hydroxide formed can cause saturation in the soil structure and chemical reactions that are not optimal, resulting in the formation of lime layers that are not evenly distributed, thereby reducing the volume weight. In addition, adding too much lime can also increase the stiffness of the soil, making it more difficult to compact the soil, which contributes to fluctuations in volumetric weight values.

3.2. Effect of quicklime on Atterberg limit

Fig. 4 shows that the addition of quicklime to the plastic index can reduce the IP value of the original soil. The original land plasticity index is 27.18 %. With 5 % quicklime, the value remains 27.18 %. The addition of 10 % quicklime reduced it to 12.97 %. If added 15 %, the index rose to 22.16 %. The addition of 20 % quicklime makes it down to 16.33 %.

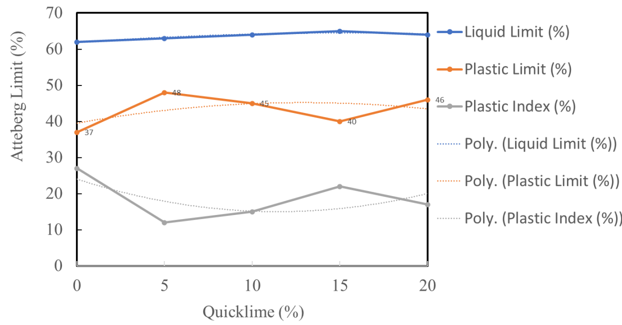


Fig. 4. Relationship between quicklime and the Atterberg limit

This shows that quicklime (CaO) has the ability to change the soil microstructure. When lime is added in certain amounts (for example, 5 % and 10 %), lime interacts with water and soil, causing changes in the soil texture to become more granular and reduced attraction between clay particles, which usually have high plasticity. This decrease in plasticity occurs because lime helps accelerate soil drying and reduces the soil's ability to absorb and retain water, which is an important factor in plasticity. Upon addition of 10 % lime, this optimal chemical reaction resulted in a significant reduction in IP, reflecting the reduced ability of the soil to deform without cracking or fracturing. Meanwhile, from a chemical point of view, the addition of lime triggers a pozzolanic reaction, where calcium hydroxide ($Ca(OH)_2$) formed from the reaction of lime and water reacts with silica and alumina in the soil, producing compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). This reaction reduces the active clay content, which is usually responsible for the plasticity of the soil, because they bind water more easily. At the addition of 15 %, there is an increase in IP again because excess lime can form large aggregates that maintain plasticity, although at 20 % lime, excess lime again reduces IP because the soil loses its flexibility due to calcium hydroxide saturation, which inhibits the mobility of clay particles.

Fig. 5 shows that the addition of quicklime to the relative unconfined compressive strength can increase the *Qu* of the original soil. The original soil has *Qu* of 1.200 kg/cm^2. Adding 5 % quicklime reduces this to 0.435 kg/cm^2, adding 10 % quicklime reduces this to 0.277 kg/cm^2, adding 15 % tohor increases the *Qu* to 0.517 kg/cm^2, and adding 20 % carbide waste mixture reduces *Qu* to 0.409 kg/cm. This is because quicklime plays a role in changing the structure and texture of the soil as well as influencing its mechanical properties, such as its unconfined compressive strength. Initially, the addition of quicklime at 5 % and 10 % resulted in a decrease in *Qu*, as the amount of lime was insufficient to trigger a significant chemical reaction.

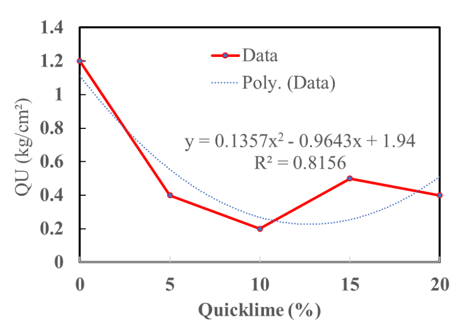


Fig. 5. Relationship between quicklime and free compressive strength

Fig. 5 shows the relationship between the percentage of quicklime (%) and the value of the free compressive strength (*Qu*) in kg/cm^2, with the polynomial order regression curve two is displayed as a blue dotted line. The regression equation obtained is $y=0.1357x^2-0.9643x+1.94$ with the coefficient of determination $R^2=0.8156$, which shows that this regression model is able to explain around 81.56 % data variation. From the curve form, it appears that the qual value decreases sharply to the minimum point at around 10 % quicklime, then increases again to 15 %, before decreases slightly at 20 %. This pattern indicates a nonlinear relationship, where the addition of quicklime to a certain extent actually decreases the strength of the soil, before experiencing an increase due to the process of more effective chemical stabilization at certain doses.

Suboptimal binding of soil particles, where lime is insufficient to transform clay soil into a stronger and more stable structure, leads to this decrease in *Qu*, as the soil tends to lose cohesion between its particles. Pressure at this concentration easily destroys the weaker soil structure, leading to a decrease in *Qu*. On the other hand, quicklime (CaO) reacts with water to make calcium hydroxide ($Ca(OH)_2$). This then reacts with silica and alumina in the soil in a process called pozzolanic reaction. Calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) are made when 15 % quicklime is added. These chemicals strengthen the bonds between soil particles, which makes the soil stronger and raises the Qu. However, when adding 20 % lime, excessive calcium hydroxide saturation occurs, which makes the pozzolanic reaction less optimal. Excess lime causes uneven distribution in the soil and results in brittle aggregates. This leads to a weakening of the soil and a subsequent decrease in *Qu*. This unbalanced chemical reaction causes fluctuations in the free compressive strength of the soil with variations in quicklime content.

3.3. Effect of quicklime on proctor standards

Fig. 6 shows that the addition of quicklime to the optimum water content can reduce the W_{opt} value of the original soil. The W_{opt} of the original Ampelgading soil is 26.50 %, if the soil is added with 5 % quicklime, it can increase the W_{opt} of the original soil by 29.50 %, with the addition of 10 % quicklime, it can reduce the W_{opt} of the original soil to 27.00 %, with the addition of 15 % quicklime, it can reduce the W_{opt} of the original soil to 25.67 %, and the addition of 20 % quicklime can reduce the W_{opt} of the original soil to 23.64 %.

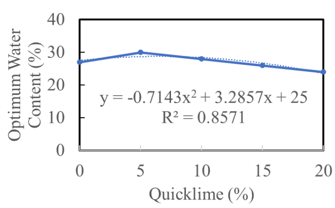


Fig. 6. Relationship between quicklime and W_{opt}

This is because quicklime (CaO) added to the soil functions to change the structure of the soil, especially by reducing the ability of soil particles, especially clay particles, to hold water. When to add 5 % lime to the soil, the initial hydration reaction of the lime absorbs water, causing the soil to require more water to reach optimum compaction conditions. However, along with the addition of lime up to 10 %, 15 %, and 20 %, the optimum water content decreases because the soil becomes stiffer and more granular. The chemical reaction between lime and soil causes a more stable and less plastic structure to form, so the soil requires less water to reach maximum density. A chemical reaction called pozzolanic reaction happens between calcium hydroxide ($Ca(OH)_2$) and the silica and alumina in the soil when lime is added. When there is more lime in the soil, this reaction makes calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) compounds. These compounds make the soil more stable and strengthen the bonds between the particles. With this stabilization, soil particles lose some of their ability to absorb and retain water, so that the optimum water content decreases. Additionally, the formation of a stiffer structure reduces the volume of soil pore space, allowing the soil to reach its maximum density with less water, leading to a further decrease in the optimum water content even with the addition of lime up to 20 %.

Fig. 6 shows the relationship between the percentage of quicklime (%) and optimum water content (OWC) (%), with the polynomial order regression curve two depicted in the blue dotted line. The regression equation obtained is $y=-0.7143x^2+3.2857x+25$, with the coefficient of determination $R^2=0.8571$, indicating that the regression model is able to explain around 85.71 % accurate data variations. From the graphics pattern, it appears that the OWC has increased to the maximum point at around 5 % quicklime, then gradually decreases with the addition of quicklime levels. This decreased parabolic pattern shows that the addition of early quicklime increases optimum water requirements due to calcification initial reactions, but after a certain point, the stabilization reaction causes reduced water needs due to the formation of more stable and dense compounds.

3.4. Effect of quicklime on γd_{max}

Fig. 7 shows that the addition of quicklime to the relative maximum dry volume can increase the γd_{max} of the original soil. The original soil's d_{max} is 1.180 g/cm^3. Adding 5 % quicklime to the soil can increase its d_{max} to 1.220 g/cm^3. Adding 10 % quicklime can further increase the dmax to 1.270 g/cm^3. Quicklime at 15 % can increase the γd_{max} of the original soil to 1.310 g/cm^3, and the addition of quicklime at 20 % can increase the γd_{max} of the original soil to 1.315 g/cm^3. This is because the addition of quicklime changes the mechanical properties of the soil, especially in terms of the ability of soil particles to bond and compact. Quicklime acts as a stabilizing agent that increases the stiffness and density of the soil. Adding 5 %, 10 %, 15 %, or up to 20 % lime leads to an increase in d_{max}, as it aids in reducing the plasticity of clay soil, thereby making soil particles more granular and easier to compact under pressure. The reduction in pore space between soil particles allows for the compacting of this more stable soil to a higher dry volume.

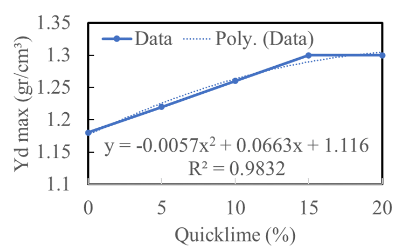


Fig. 7. Relationship between the addition of quicklime and the maximum dry volume weight (γd_{max})

Meanwhile, chemically, quicklime (CaO) reacts with water to form calcium hydroxide ($Ca(OH)_2$), which then reacts with silica and alumina components in the soil through a pozzolanic process. Compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) are made in this reaction. These compounds strengthen the bonds between soil particles and stop them from deforming because of mechanical loads. This process results in the soil becoming denser and more structurally stable. As lime content increases, soil stabilization increases, enabling soil particles to compact more efficiently and achieve a higher maximum dry volume weight. The increase in γd_{max} to 1.315 g/cm^3 with the addition of 20 % lime shows that the chemical reaction and physical changes are optimal in strengthening the soil structure.

Fig. 7 shows the relationship between the percentage of quicklime (%) and the maximum dry content weight (γd_{max}) in units of gr/cm^3, with the polynomial order regression two displayed as blue dotted lines. The regression equation is $y=-0.0057x^2+0.0663x+1.116$, with the coefficient of determination $R^2=0.9832$, which means this model is very accurate and is able to explain around 98.32 % data variation. From the graph, it can be seen that the addition of quicklime increases YD Max significantly to around 15 %, then the graphics start to slop. This shows that the addition of quicklime increases the maximum density of the soil due to the binding reaction of soil particles that make the structure denser, but after a certain point, the effect starts to be saturated. The curve pattern that is close to linear shows that quicklime is very effective in increasing soil density to a certain extent, making it efficient stabilization material.

Fig. 8 illustrates how the percentage of added quicklime influences the time for Ampelgading expansive clay soil to stop swelling. The more quicklime increases, the time required for the expansion process of expansive clay soil will decrease. This is because the addition of quicklime (CaO) to the soil alters its microstructure. Expansive clay soil has the unique property of being able to absorb large amounts of water, causing volume expansion. Adding lime causes the soil to become more stable and granular, which reduces the soil's ability to absorb water.

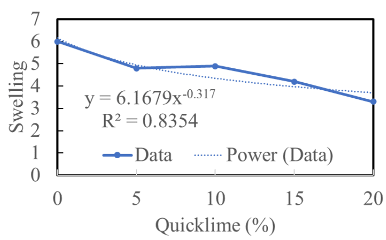


Fig. 8. Relationship between the addition of quicklime and volumetric swelling

When lime reacts with soil, it enhances the cohesiveness of soil particles and strengthens their bonds, thereby reducing the available pore space for water. As a result, the soil expansion process takes less time, as water cannot penetrate the soil as effectively as it used to. Meanwhile, if viewed from a chemical perspective, the addition of quicklime produces a hydration reaction, where the lime reacts with water to form calcium hydroxide ($Ca(OH)_2$). Aside from that, quicklime also reacts with silica and alumina in the soil to make calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH; see below). These compounds act as chemical binders that strengthen the soil's structure and reduce its plasticity and expansive capacity. This process reduces the ability of clay soil particles to absorb water, thereby accelerating the end of the soil expansion process. Adding more lime enhances the effectiveness of the pozzolanic reaction, which in turn reduces the amount of water the soil can absorb, leading to shorter swelling times.

Fig. 8 shows the relationship between the percentage of quicklime (%) and the value of swelling (soil development), with the type of function (power function) regression curve that is displayed as a blue dotted line. The regression equation is $y=6.1679x$. From the graph, it appears that the swelling value decreases consistently as the quicklime level increases, although there is a slight fluctuation at 10 %. This decline pattern reflects that the addition of quicklime is effective in reducing the potential for soil development, which is generally caused by active clay minerals. The regression model shows the inverse relationship, which means the higher the quicklime level, the lower the swelling value, so that the addition of quicklime is proven effective in stabilizing expansive soil.

The application is very useful for infrastructure projects such as roads, airports, and building foundations in high-risk areas to changes in soil volume due to humidity. Compared to cement or fly ash, quicklime reacts faster, provides long – term stability, and reduces soil shrinkage and swelling, making it efficient choice in soil stabilization.

This research is limited to one type of soil in Ampelgading, so the results are not necessarily applicable to soil with different characteristics. Long-term environmental impacts have not yet been analyzed. Further studies are needed to test the effectiveness of quicklime in various types of soil and explore combination with other stabilization materials to improve efficiency and sustainability.

4. Conclusions

The research findings support the following conclusion:

1. The addition of quicklime gradually reduces soil water content from 58.20 % to 35.64 % at a level of 20 %, indicating that lime is effective in reducing water absorption capacity and increasing soil microstructural stability. The specific gravity of the soil also decreased from 3.362 to 2.118 because the soil became more granular and less dense at high lime content.
2. Dry and wet volumetric weight varies with the addition of lime: at low levels, the density increases due to the hydration reaction, but at higher levels it decreases due to non-uniform structure formation. The plasticity index (IP) decreased from 27.18 % to 12.97 % at 10 % lime content due to changes in soil microstructure, although at higher levels, the IP increased again.
3. Unconfined compressive strength (Qu) reaches its peak at a lime content of 15 % but decreases at 20 % due to uneven lime distribution and the formation of weak aggregates. Lime also reduces the optimum water content (W_{opt}) from 26.50 % to 23.64 %, making the soil stiffer and requiring less water to reach maximum density.
4. The increase in maximum dry volume weight (γd_{max}) from 1.180 g/cm^3 to 1.315 g/cm^3 occurred because lime strengthened the soil structure by up to 20 % addition. The addition of lime accelerates the expansion time of expansive clay soils by reducing water absorption capacity, resulting in a more stable structure with smaller pore spaces.

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Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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