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Research Article

THE EFFECT OF QUICKLIME ON THE CBR VALUE OF SOFT SOIL STABILIZED WITH NICKEL SLAG AND ALUMUNIUM HYDROXIDE

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ABSTRACT

The construction of road structures on soft soils is prone to structural damage due to the low bearing capacity of the soil under the load imposed by vehicles. Chemical stabilization is a popular method used to increase the bearing capacity of soft soils. This study aims to examine the effectiveness of soft soil stabilization using a mixture of lime, nickel slag, and aluminium hydroxide to enhance soil bearing capacity. The addition of lime as a binding agent is expected to reduce plasticity and increase soil strength, while nickel slag and aluminium hydroxide serve as additives that improve overall stabilization performance. The California Bearing Ratio (CBR) laboratory test was conducted by varying the proportions of stabilizing materials relative to the weight of the soft soil at its optimum moisture content. The lime addition variations used in this study were 2%, 4%, and 6%. The results showed that the lime, nickel slag, and aluminium hydroxide stabilization mixture significantly improved the soil's bearing capacity compared to untreated soil or soil stabilized only with nickel slag. The CBR value for soil stabilized with nickel slag, aluminium hydroxide, and lime reached 37.78% after 28 days of curing. This value is 7.6 times higher than that of natural soil and 1.3 times higher than soil stabilized with nickel slag alone. Thus, the use of a mixture of lime, nickel slag, and

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aluminium hydroxide is an effective method for increasing the bearing capacity of soft soils, making it applicable for road construction on soft soils requiring enhanced load-bearing capacity.

KEYWORDS

Soil stabilization, lime, nickel slag, aluminium hydroxide, soil bearing capacity, soft soil.

INTRODUCTION

Road construction on soft soils presents various technical challenges due to the soil's low bearing capacity, susceptibility to deformation, and high compressibility [1, 2]. Soft soils often cannot withstand heavy traffic loads, making roads built on them prone to structural damage, such as cracking and surface settlement. To address these issues, one commonly used method is soil stabilization, which aims to enhance the strength and stability of the soil so that it can better support vehicle loads and infrastructure.

Cement and lime are conventional materials commonly used in chemical soil improvement. This is due to their ability to enhance soil strength through the hydration reaction between water and these materials, forming calcium silicate hydrate (CSH) gel that binds soil particles together, thus affecting the soil's physical and mechanical properties [3, 4]. However, the use of cement in various construction applications can have environmental impacts due to pollution generated during cement production. The cement manufacturing process is highly energy-intensive and produces large amounts of carbon dioxide (CO_2) emissions [5], which significantly contribute to climate change. In the context of increasingly sustainability-focused development, the use of more environmentally friendly materials has become a priority.

In addition, the effectiveness of cement in stabilizing soft soils is often suboptimal under highly saturated conditions [6]. In soils with high moisture content, the hydration reaction of cement does not proceed effectively, resulting in less-than-optimal strength gains. In contrast, lime tends to be more effective in addressing this issue, as it can react with water in the soil to reduce plasticity and dry out the soil [7], making it a better choice for stabilizing soft soils with high moisture content.

The development of alternative stabilization materials is an effort to reduce reliance on cement. This decision is also driven by considerations of local material availability. North Maluku is one of Indonesia's provinces with a large nickel industry. Nickel slag, a by-product of this industry, has significant potential to be developed as an environmentally friendly advanced material [8]. Rauf et al. (2024) [9] reveal that the composition of nickel slag obtained from the nickel industry on Oba Island includes 44.89% SiO_2, 25.11% Fe_2O_3, 20.27% MgO, and 3.34% CaO. These results indicate that nickel slag has pozzolanic properties, making it suitable for development as a soil stabilization material.

In addition to nickel slag, North Maluku also has substantial limestone deposits located on Morotai Island. Lime has long been recognized as a stabilizing agent, particularly due to its role in drying out soil. In principle, the chemical reactions involved in lime soil improvement include cation exchange, flocculation and agglomeration, pozzolanic reactions, and carbonation [10]. Numerous studies have shown the physical property changes, mechanical strength gains, and microstructural improvements in soft soils stabilized with lime [11, 12, 13]. Therefore, developing the use of this local potential as a construction material can help reduce transportation costs and increase project efficiency, as it eliminates dependence on cement distribution, which may be limited in certain areas.

The combination of several stabilization materials can result in more effective soil stabilization than using a single material. Studies utilizing multiple mineral combinations show that these combined stabilization materials create a synergy that significantly improves the soil's physical properties and enhances its mechanical strength, both in the short and long term [14, 15]. Consequently, efforts to improve soft soils are expected to be more optimal, particularly in handling traffic loads and challenging environmental conditions.

Therefore, this study aims to evaluate the performance of soft soil stabilization using a combination of lime, nickel slag, and aluminium hydroxide. The results of this study are expected to provide practical and applicable solutions for enhancing the bearing capacity of soft soils for road construction, ensuring improved stability and a longer service life for roads built on such soils. The combination of these three materials is anticipated to serve as a more environmentally friendly and efficient alternative for future infrastructure development.

RESEARCH METHODS

This study is an experimental laboratory research conducted at the Soil Mechanics Laboratory, Faculty of Engineering, Khairun University. The materials used in this research are sourced locally from North Maluku Province. The soft soil was collected from an agricultural area in Subaim Village, East Halmahera Regency. Nickel slag was obtained from a nickel processing industry located on Obi Island, South Halmahera. Meanwhile, limestone was sourced from Morotai Island. Aluminium hydroxide [Al (OH)3] was purchased commercially.

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The series of tests conducted in this study include: physical and mechanical property tests on natural soft soil, as well as mechanical tests on soil stabilized with a mixture of nickel slag, limestone, and aluminium hydroxide. All testing procedures refer to the American Standard Test Materials (ASTM). The mechanical property focused on in this study is the bearing capacity value based on the California Bearing Ratio (CBR).

The pozzolanic reaction of stabilization materials is influenced by several factors, including cation exchange capacity, specific surface area of the material, and the molar ratio of Si/Al [16]. To increase the specific surface area of the stabilization materials, in this study, nickel slag and limestone were ground and sieved using a No. 400 sieve. Furthermore, to enhance the molar ratio between silica and alumina, aluminium hydroxide [$Al(OH)_3$] was also added in this study. Previous test results showed that the Si/Al ratio that provided the optimum unconfined compressive strength was achieved at a weight ratio of 1.5 between nickel slag and aluminium hydroxide. Therefore, in this study, to investigate the effect of limestone on soil stabilization engineering, the lime content was varied at 2%, 4%, and 6% of the dry soil weight (□dry).

The mechanical testing conducted in this study is the California Bearing Ratio (CBR) test, which follows the ASTM D1883 standard. The specimen preparation process involved mixing the soil and stabilization materials at the optimum moisture content. The mixing was done manually for 10-15 minutes until a homogeneous mixture was achieved [17]. The specimens were then prepared by compacting the mixture into a CBR mole, which is cylindrical in shape with a diameter of 6 inches and a height of 7 inches. To observe the effect of time on the improvement of CBR values, the specimens were cured for 3, 7, 14, 21, and 28 days.

RESULTS AND DISCUSSIONS

Physical and Mechanical Characteristics of Soil Samples

The results of the physical and mechanical characteristic tests on the clay soil used in this study are shown in Table 1. Based on the USCS soil classification, the test results indicate that the clay soil can be classified as organic soil with high plasticity. This is based on a liquid limit value of 64.92% and a plasticity index value of 23.58%. As for the mechanical properties, the CBR value obtained was 4.49%. This value is considered low and does not meet the technical requirements for use in road subbase construction, where the SNI standard specifies a minimum CBR value of 6% for subgrade layers. Therefore, soil improvement efforts are needed to increase the CBR value of the subgrade soil to meet the applicable technical requirements.

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Tabel 1. Soft soil properties

Soft soil properties		Value
Physical characteristics	Specific Gravity (Gs)	2,11
	Water Content ($w_{opt,}$ %)	33,08
	Sieve Analysis	
	Sand (%)	8,4
	Silt (%)	14,3
	Clay (%)	77,3
	Atterberg Limit	
	Liquid Limit (LL)	64,92
	Plastic Limit (PL)	41,34
	Plasticity Index (PI)	23,58
Mechanical characteristics	Density (kN/m^3)	10,9
	CBR (%)	4,49

Results of CBR Tests

The results of the soil bearing capacity test using the CBR method are shown in Figure 1. The CBR values for the soil stabilized with a mixture of nickel slag, aluminium hydroxide, and lime at 2%, 4%, and 6% significantly increased over the period from 3 to 28 days. On the third day, the addition of 2% lime resulted in a CBR value of 11,69% at a 0,1-inch penetration, while 4% lime reached 16,19%, and 6% lime reached 26,09%. The load-bearing capacity of the soil with 6% lime was 782,62 lbs; which is ten times greater than that of the natural soil, demonstrating a significant improvement in soil strength.

In the seventh-day testing, the CBR values continued to rise. At a 0.1-inch penetration, the CBR value for 6% lime reached 26.99% (809.61 lbs load). These CBR values indicate that the stabilized soil is well-suited for use as a subbase course in road construction. Meanwhile, the addition of 2% and 4% lime resulted in CBR values of 17.99% (536.74 lbs load) and 12.59% (377.82 lbs load), respectively. Both of these values are still higher than the CBR of the natural soil and meet the criteria for subgrade layers.

On the 14th day, the CBR value for 6% lime increased to 31.18% at a 0.2-inch penetration, with a load of 1403.32 lbs. This result meets the technical requirements for the subbase layer in road construction. Meanwhile, the addition of 2% and 4% lime showed CBR values of 13.49% (404.81 lbs) and 18.89% (566.73 lbs load), respectively. Both values are an improvement compared to the untreated soil and meet the technical criteria for the subgrade layer.

On the 28th day, the soil stabilized with 6% lime showed an exceptional increase in CBR, reaching 37.78% at a 0.1-inch penetration (1133.45 lbs load), while 4% lime reached 23.39% (701.66 lbs load). These

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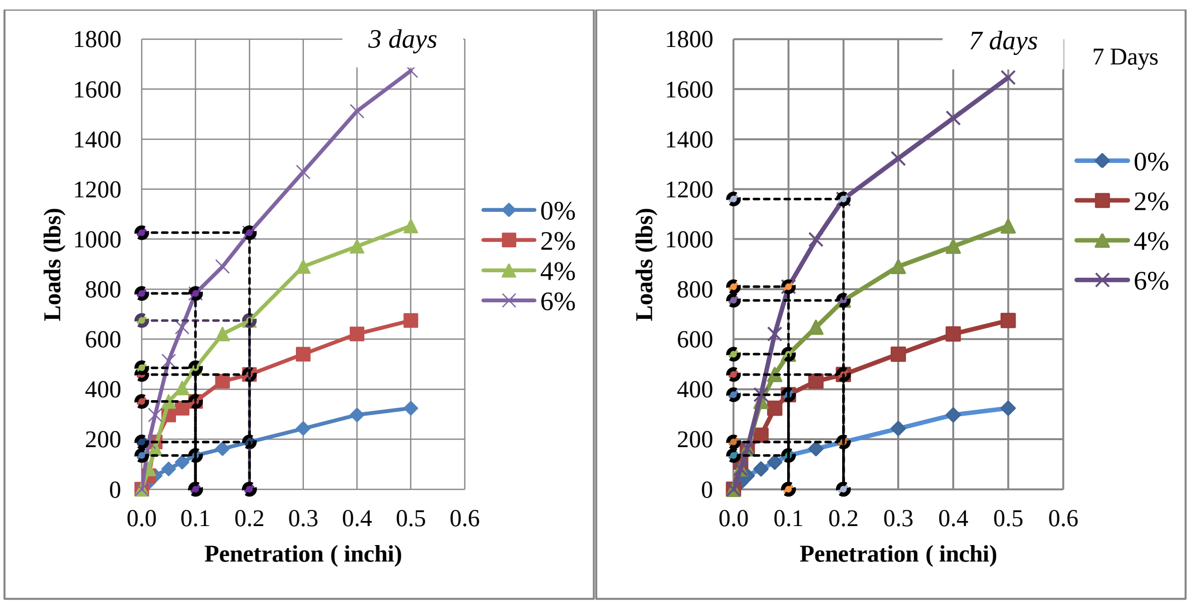
values indicate a very high soil strength, far exceeding the minimum standards required for the base course layer. The soil with 2% lime also showed good results, with a CBR value of 14.39% (431.79 lbs load), still well above the natural soil value.

From this comparison, it is clear that soil stabilization with the addition of lime, especially at 4% to 6%, has a very positive impact on strengthening soft soil. With significantly increased CBR values, even in a short period of time, soil that originally had a CBR value of 4% at a 0.1-inch penetration (134,94 lbs load) can be transformed into soil with a very strong bearing capacity. This makes it suitable for use in road pavement layers, both as a subbase and base course, in accordance with existing standards.



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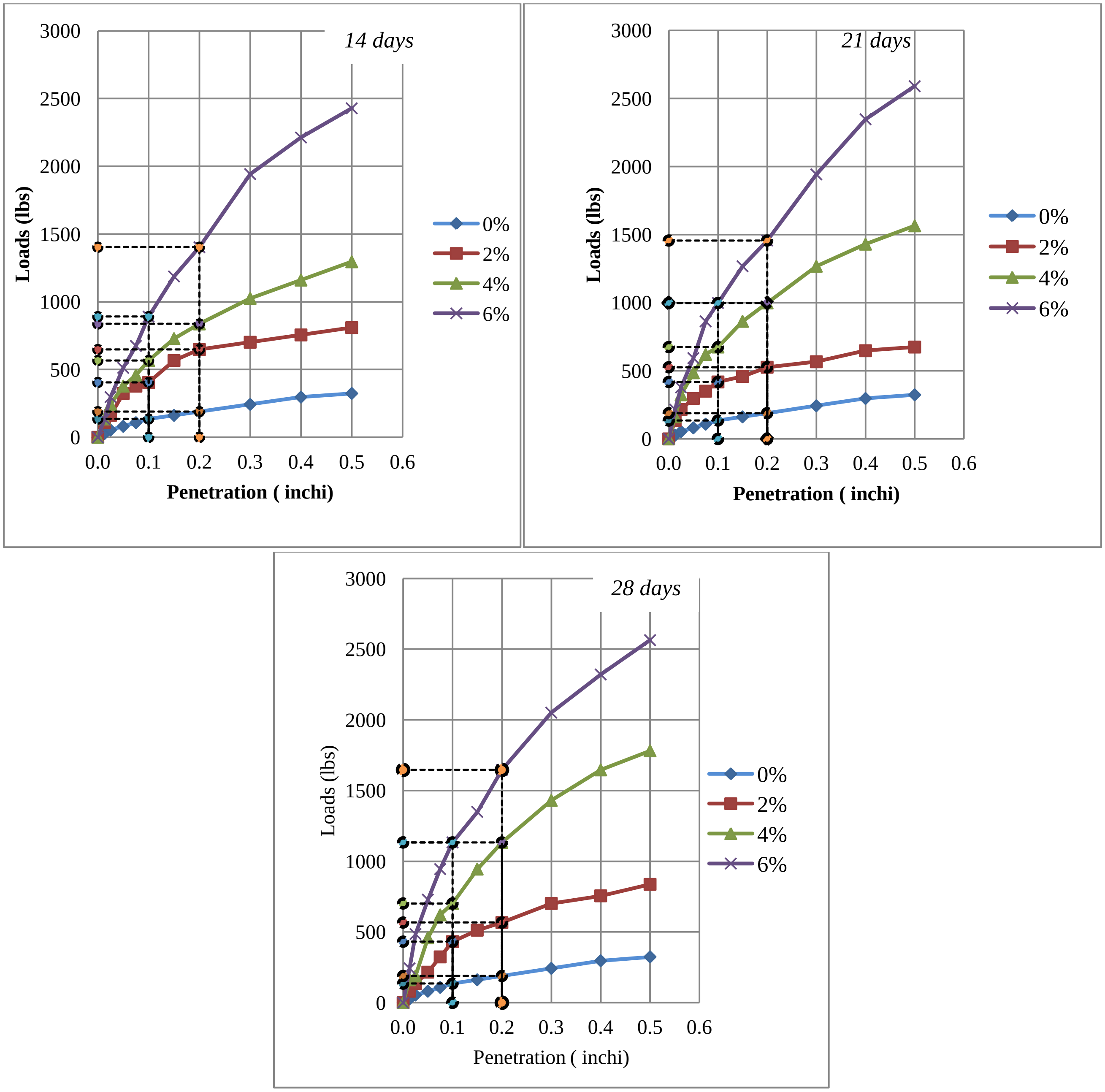

Figure 2. CBR Test Results Based on Lime Variations and Curing Time

Table 2. Results of CBR Testing

Stabilization Material	Penet (Inchi)	Day Variations									
		3 Days		7 Days		14 Days		21 Days		28 Days	
		Loads (Lbs)	CBR (%)	Loads (Lbs)	CBR (%)	Loads (Lbs)	CBR (%)	Loads (Lbs)	CBR (%)	Loads (Lbs)	CBR (%)
0%	**0,1"**	134,94	4,49								
	0,2"	188,91	4,20								
Soil + Nickel Slag	**0,1"**									890,57	29,69
	0,2"									1133,45	25,19
Soil + NS + 2% Lime	**0,1"**	350,83	11,69	377,82	12,59	404,81	13,49	418,30	13,94	431,79	14,39
	0,2"	458,78	10,20	458,78	10,20	647,69	12,99	526,25	11,69	566,73	12,59
Soil + NS + 4% Lime	**0,1"**	485,77	16,19	539,74	17,99	566,73	18,89	674,68	22,49	701,66	23,39
	0,2"	674,68	14,99	755,64	16,79	836,60	18,59	998,52	22,19	1133,45	25,19
Soil + NS + 6% Lime	**0,1"**	782,62	26,09	809,61	26,99	890,57	29,69	998,52	33,28	1133,45	37,78
	0,2"	1025,51	22,79	1160,44	25,79	1403,32	31,18	1457,30	32,38	1646,21	36,58

CBR value improvement ratio

Previous studies have shown that untreated soft soil has a low California Bearing Ratio (CBR) value of 4.95%, indicating that the soil lacks adequate strength and stability to be used as a base material in construction. Meanwhile, the addition of 6% slag to the soft soil resulted in a CBR value increase to 29.69% after 28 days of curing, demonstrating that slag can significantly strengthen soft soil. However, this improvement is still limited, and this study further explores whether the combination of nickel slag, lime, and aluminium hydroxide [Al(OH)3] can provide a more substantial increase in the strength of soft soil.

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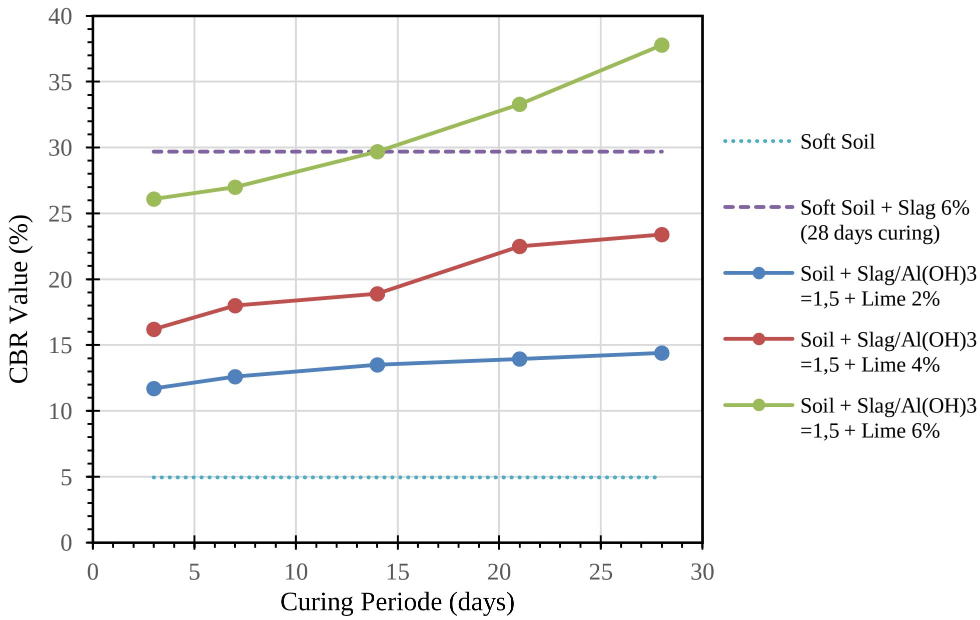

Figure 3. Comparison and improvement of CBR values based on lime variations and curing time

This study examines the effect of adding lime at concentrations of 2%, 4%, and 6% in combination with slag and Al(OH)3 on the improvement of soil CBR values. Based on the obtained data, the increase in CBR values varies depending on the lime concentration. The addition of 2% lime resulted in a CBR value of 15%, approximately three times higher than the initial soft soil. With the addition of 4% lime, the CBR value increased even further to 22%, or about 4.4 times the value of the soft soil. The highest lime concentration, 6%, provided the optimal result, with a CBR value reaching 35%, or about seven times the initial soil value. This shows that lime has a significant strengthening effect, especially when used at high concentrations, and can be more effective than stabilization with 6% slag alone.

The addition of lime and Al(OH)3 to soft soil provides a positive effect through both chemical and physical mechanisms. Lime, typically in the form of calcium oxide (CaO) or calcium hydroxide [$Ca(OH)_2$], acts as a binding agent that strengthens soil particles through pozzolanic reactions. In this reaction, lime interacts with clay minerals and silica present in the soil to form pozzolanic compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds are stable and have high binding capacity, which increases the soil's strength and makes it more resistant to volume changes and environmental influences. The addition of Al(OH)3 serves as a source of aluminates that accelerates the formation of CAH, further enhancing the bonding between soil particles. This is evidenced by the

increase in CBR values after 14 days of curing, surpassing the CBR values of soil stabilized with only nickel slag. However, at lime concentrations of 2% and 4%, the CBR values were lower compared to the soil stabilized with only nickel slag. This may be due to the influence of the effectiveness of the stabilization material used, which is the main factors affecting the chemical reaction [18]. The combination of the chemicals used can impact the overall water absorption and retention properties of the mixture, thereby affecting the mechanical behaviour of the test specimen [19]. Thus, at low lime concentrations (2% or 4%), it does not provide enough calcium hydroxide ($Ca(OH)_2$) to support the pozzolanic reaction optimally.

Overall, the combination of slag, lime, and Al(OH)3 proves effective as a soft soil stabilization method, with the most significant results at a 6% lime concentration. The CBR value for the 6% lime mixture is even higher than that of the 6% slag stabilization alone, showing that lime, with the aid of Al(OH)3, has a greater influence on strengthening the soil. From the perspective of civil engineering applications requiring high-strength subgrade layers, the use of multiple stabilization materials can be recommended as a more effective soil improvement approach compared to using a single stabilization material. This combination not only enhances the mechanical strength of the soil but also provides better stability against changes in moisture content and environmental conditions, making it an optimal choice for soil improvement in road foundation construction.

CONCLUSIONS

This study demonstrates that soft soil stabilization with a mixture of nickel slag, aluminium hydroxide [$Al(OH)_3$], and lime in concentrations of 2%, 4%, and 6% significantly improves the soil's California Bearing Ratio (CBR). After a 28-day curing period, the mixture with 6% lime achieved a CBR value of 37.78%, exceeding the required bearing capacity for road pavement subgrade and showing a significant improvement over the 6% slag alone, which only reached a CBR of 29.69%. These findings confirm that the addition of lime, particularly at concentrations of 4% to 6%, provides substantial mechanical strengthening, making soft soil more suitable for structural applications in road foundations.

The effectiveness of the lime and $Al(OH)_3$ combination is primarily due to the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) compounds through the pozzolanic reaction, which enhances the strength and resistance of the soil to environmental conditions. This stabilization method is significantly more effective at strengthening and stabilizing soft soil compared to the use of a single type of stabilization material. Therefore, this combination is highly recommended for civil

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engineering applications requiring high-bearing capacity subgrade layers, such as road foundations, as it provides optimal stability against moisture fluctuations and changing environmental conditions. Additionally, by utilizing industrial waste and local materials, this approach supports more sustainable and cost-effective construction practices.

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