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Stabilization of Krobokan Clay Soil with California Bearing Ratio (CBR) for Highway Pavement

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Abstract: In this research, clay soil will be stabilized in the Kerobokan Badung area by mixing the soil with various levels of lime. The problem to be solved is how much the CBR value of soil mixed with lime will increase and what is the most economical lime content associated with the minimum CBR requirements for the base soil layer. The aim is to determine the increase in CBR value from a mixture of clay with lime and to determine the most economical lime content associated with the minimum CBR requirements for the base layer of highway pavement structures. The research results show that adding lime to clay soil can increase its bearing capacity. For the standard compaction method, the CBR of the base soil which was initially 3.32% increased to 12.14, 21.86, and 26.24% for lime addition of 2.50, 5.00, and 10.00% respectively. For the modified compaction method, the CBR of the base soil which was initially 5.74% increased to 13.42, 25.69, and 38.15% for lime addition of 2.50, 5.00, and 10.00% respectively. To produce a base soil CBR of 6%, the modified compaction method requires less lime content than the standard method. The lime content required is 0.22% for modified compaction and 0.79% for standard compaction.

Keywords: CBR; Kerobokan clay soil; Slaked lime; Stabilization

Introduction

Soil is a material that is very influential in construction work, because one area will not have the same soil properties as another area (Andriani et al., 2012). In highway construction, the road or highway area consists of a hard surface known as a pavement. The pavement is constructed from strong materials and serves as a surface that distributes vehicle loads to the subgrade layer. The two types of pavement design used in road construction are flexible pavement and rigid pavement (Hamid et al., 2022). These pavements can differ based on how the load is distributed to the subgrade (Yoder et al., 1991). The material design of component layers in the pavement is made of sub-grade, sub-base, base, and surface layers. Figure 1 shows a typical pavement structure. The subgrade plays the role of a layer that resists the load generated by the traffic on the road. Usually, the subgrade layer consists of the original soil or filled soil. Subgrade soil can be defined as compacted or natural soil and typically stay in unsaturated condition (Khasawneh, 2005).

Basic earthwork is the first work that must be done on the project road construction development. Subgrade soil is the most important part of road construction because this section functions as a support for the largest traffic load (Indriani et al., 2016). The subgrade layer plays an important role in supporting the performance of the pavement structure built on it (Othman et al., 2021). The subgrade layer is a layer of soil 60 to 90 cm thick under the sub-foundation which is compacted so that its bearing capacity can be improved (Hardiyatmo, 2007). The most important thing that must be considered about the subgrade layer is its bearing capacity, namely

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its ability to accept loads, both due to traffic loads and due to the weight of the pavement structure above it (Chairullah, 2011). The bearing capacity of the subgrade will determine the thickness of the pavement layer structure. Therefore, it is not an exaggeration to say that preparing the subgrade layer is a fundamental job for construction (Sompie et al., 2019).

Apart from having a good bearing capacity, the subsoil must also have low sensitivity to changes in water content. Not all types of soil can meet these requirements. Clay soil, in dry conditions can be hard soil with a very high bearing capacity, but in wet conditions it becomes soft and sticky and if the water content becomes excessive it can become mud which has no bearing capacity at all (Zain et al., 2022). Clay soil with a high water content has a low bearing capacity, high plasticity, swelling of soil relatively large, low shear strength and low permeability causing in a huge settlement (Prastiwi et al., 2016). Soft clay soil with high water content can cause loss of adhesion between soil grains so that its bearing capacity becomes low and the settlement is large if the soil is burdened with a structure (Tjandra et al., 2009). Soil Research conducted by (Wiraga, 2009) shows that during the rainy season, the CBR value that can be exerted by the base soil layer consisting of clay is below 2%. CBR (California Bearing Ratio) is a comparison between the test load (Test Load) with a standard load (Standard Load) and expressed as a percentage (Prabowo H, 2008). According to Sukirman (1992) the minimum CBR value that the basic soil layer must have is 6%. So it is understandable why the rate of road damage during the rainy season is high, especially roads built on clay soil.

Even though we already know that the subgrade layer consisting of clay has a very low bearing capacity during the rainy season, we often cannot avoid building roads on soil that has a poor bearing capacity. To overcome this problem, efforts need to be made to improve the physical and mechanical properties of this soil by stabilizing it (Obianigwe et al., 2018). Soil stabilization is a critical step in numerous engineering projects, preventing soil erosion, increasing soil strength, and reducing the risk of subsidence (Umar et al., 2023). Soil stabilization is a technique that was developed many years ago to make inadequate soils capable of satisfying the needs of certain engineering projects (Sarkar et al., 2023). Soil stabilization is mixing soil with certain materials, in order to improve the technical properties of the soil, or can also soil stabilization is an effort to change or improve the properties of the soil so that it meets certain technical requirements (Hardiyatmo, 2010). Stabilization is efforts to make the land more stable. Stabilization can improve soil physical and mechanical properties such as strength, stiffness, compressibility, permeability, swelling potential and sensitivity to changes in water content (Kerbs et al., 1971). Stabilization methods can be divided into two, namely mechanical stabilization and chemical stabilization (Sompie et al., 2019). Mechanical stabilization is carried out by compaction, with the aim of closing the distance between soil particles so that it can increase strength and reduce settlement. Several studies have been carried out on the effectiveness of clay stabilization by RHA admixing (Khasawneh, 2005). According to Krebs et al. (1971), the best stabilizing material for clay soil is lime, namely calcium hydroxide $Ca(OH)_2$ or calcium oxide CaO, because apart from reducing plasticity, reducing water content and making compaction easier it can also increase bearing capacity. The use of lime as stabilization material can cause a weak ion exchange of sodium by calcium ions that are on the surface of the clay, so the percentage of fine particles tend to become coarse particles (Munirwansyah et al., 2017). Based on previous research about laboratory findings, lime can improve the engineering properties of expanding clay soils in a forest road (Obianigwe et al., 2018). The stabilization by lime is achieved through cation exchange, flocculation agglomeration, lime carbonation, and pozzolanic reactions (Saidate et al., 2022). To be able to find out how far stabilization efforts with limestone soil can increase the carrying capacity, it is necessary to carry out research.

According to Asiyanto (2008), in general the desired CBR value of basic land is 2% to 20% depending on the heavy traffic load of the vehicles that will be used that road. The problem to be solved through this research is how much increase in CBR value can be provided by a mixture of clay with lime and what is the most economical lime content associated with the minimum CBR requirements for the base soil layer. When carrying out road work, the basic soil bearing capacity parameter is expressed by the CBR value. Soil problems are not only limited to subsidence, but comprehensively include soil shrinkage and expansion which is generally owned by expansive clay soil. Therefore, the technical properties related to the subgrade must be taken into account so that a structure built on it can be stable against the influence of the soil (Permadi et al., 2016). Therefore, in this study we will only review the increase in the CBR value of the original soil after mixing it with lime. The original soil is clay taken from the Kerobokan area, Badung.

This research introduces a novel approach to enhancing the bearing capacity of subgrade clay soil, specifically sourced from the Kerobokan area in Badung, by mixing it with lime. Previous studies have established the challenges posed by clay soils, particularly their drastic reduction in bearing capacity during the rainy season and their high sensitivity to water content changes. While lime stabilization has been recognized for its potential to improve the engineering properties of expansive clay soils, there is limited specific data on its effectiveness for clay soils from this particular region. This study aims to fill this gap by systematically investigating the increase in California Bearing Ratio (CBR) values of Kerobokan clay when treated with varying lime contents. By identifying the most economical and effective lime content, this research not only provides practical insights for road construction in areas with similar soil conditions but also contributes to the broader understanding of soil stabilization techniques.

Method

Research Design

To achieve the objectives of this research, a series of research will be carried out in the laboratory which includes testing the physical and mechanical properties of original soil and soil mixed with lime. Before carrying out laboratory testing, this research began by taking soil samples in the Kerobokan area. Because this soil sample will later be compacted, the soil sample taken is an example of disturbed soil. Next, this soil is dried and the lumpy soil is crushed with a rubber hammer so that soil granules are produced that pass through the No. sieve. 4 for testing mechanical properties and soil grains that pass sieve No. 10 for testing soil physical properties. Physical property testing includes water content testing, Atterberg limits, specific gravity and grain size analysis (Saber et al., 2022). Mechanical properties testing includes compaction testing and CBR testing in submerged conditions.

First, physical properties will be tested on the original soil to obtain original soil parameters such as grain size distribution (gradation), specific gravity, liquid limit LL, plastic limit PL and plasticity index PI. The same test will be carried out on original soil that has been mixed with various levels of lime. Next, a test of the mechanical properties of the original soil was carried out, which was preceded by a compaction test, either using the standard compaction method or compaction using a modified method to determine the optimum water content (w_{opt}) and maximum dry volume weight (g_d max.). The w_{opt} value is then used as a basis for making test objects for CBR testing to determine the planned CBR size of the original soil. The same test was carried out on soil that had been mixed with various levels of lime.

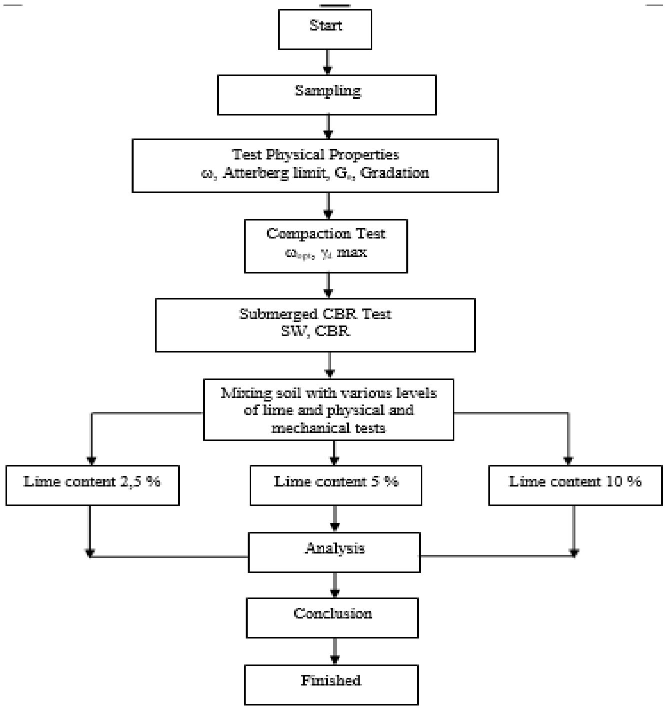

Figure 1. Research design scheme

Generally the amount of lime needed to modify a clay soil varies from 1 to 3% whereas that required for cementation varies from 2 to 8% (Bell et al., 1990). In order to achieve the aim of this research, namely to find out how much increase in CBR value can be provided by a mixture of clay with lime and what is the most economical lime content associated with the minimum CBR requirements for the base soil layer, the original soil is mixed with various levels of limestone, namely 2.5, 5, and 10%. The results were then compared with soil that was not mixed with limestone. The percentage of lime content is calculated against the dry weight of the soil. For example, to carry out a standard proctor test, 1500 grams of soil is required. If the original soil contains a water content of 7%, then the dry weight of the soil is 1500/(1+0.07), which is equal to 1401.9 gr. For a lime content of 2.5%, the limestone required is 2.5% x 1401.9 gr, equal to 35 gr. Calculation of the amount of lime required for compaction testing, both standard and modified methods is shown in Table 1. Calculation of lime requirements for CBR testing is shown in Table 2.

Table 1. Calculation of Lime for Compaction Testing

Soil Weight (gr)	Method	Water Content (%)	Dry Soil Wight (gr)	Lime Weight (gr)		
				2.50%	5.00%	10.00%
1500	Standard	7	1401.9	35.0	70.1	140.2
2500	Modification	7	2336.4	58.4	116.8	233.6

Table 2. Calculation of Lime Lime for CBR Testing

Soil Weight (gr)	Method	Water Content (%)	Dry Soil Wight (gr)	Lime Weight (gr)		
				2.50%	5.00%	10.00%
5000	Standard	7	4672.9	116.8	233.6	467.3
7500	Modification	7	7009.3	175.2	350.5	700.9

The results of testing the physical and mechanical properties between the original soil and the stabilized soil are then compared and analyzed to then draw conclusions which are the answers to the problems to be solved through this research. Schematically, the research design is shown in Figure 1.

Testing Procedure

The test procedures required to support this research refer to the procedures established by AASHTO and ASTM and the corresponding test procedures applicable in Indonesia as stated in the Road Material Inspection Manual No. 01/MN/BM/1976 issued by the Department of Public Works and Electrical Power, Directorate General of Highways. These procedures include water content testing (AASHTO T265, PB – 0117 - 76), specific gravity testing (AASHTO T100, PB – 0108 - 76), gradation analysis (AASHTO T87, AASHTO T88, PB – 0201 - 76), hydrometer analysis (AASHTO T87, AASHTO T88, PB – 0107 - 76), liquid limit testing (AASHTO T89, AASHTO T90, PB – 0109 - 76), plastic limit testing (AASHTO T89, AASHTO T90, PB – 0110 - 76), shrinkage limit testing (AASHTO T89, AASHTO T90, PB – 0110 - 76), Proctor testing (AASHTO T99, PB – 0111 - 76), and CBR testing (AASHTO T193, PB - 0102 - 76). These comprehensive testing procedures ensure that the research is thoroughly supported by accurate and reliable data.

Result and Discussion

Physical Properties Testing

A series of physical properties tests were carried out on both original soil and soil mixed with limestone. The purpose of this test is to determine the physical properties of the original soil and then compare it with the changes in physical properties that occur after it is mixed with lime.

Gradation Analysis

Soil grain size testing was carried out using gradation analysis for soil retained by filter No. 200 and hydrometer analysis for soil grains that pass sieve No. 200. The results are presented in the following tables.

Table 3. Analysis of Retained Soil Filter No. 200

Filter Number	Hole Size (mm)	Filter Weight (gr)	Filter Weight and Soil (gr)	Retained Soil Weight (gr)	Cumulative Retained Soil Weight (gr)	Cumulative Retained Soil Weight (%)	Pass Percentage (%)
4	4.75						
10	2	428.3	428.3	0	0	0	100
20	0.841	418.8	422.3	3.5	3.5	0.7	99.3
40	0.42	408.4	415.9	7.5	11	2.2	97.8
60	0.25	408.8	415.2	8.4	19.4	3.88	96.12
100	0.149			0	19.4	3.88	96.12
140	0.15	398.1	412.4	14.3	33.7	6.74	93.26
200	0.074	474.1	478.2	4.1	37.8	7.56	92.44
Pan	0	415.2	888.5	462.2	500	100	0

Table 4. Hydrometer Analysis (Equipment Type 152)

Time (t) minute	Temperature	Actual Hydrometer Reading (Ra)	Correction of Hydrometer Readings (Rc)	% Get Away (Rc.a/Ws)	Correction of Meniscus Effect (R)	L	L/t	K Table 6-4	K(L/T) ½ D (mm)
0.25	29	46	49.4	98.1	47	8.6	34.349	0.0123	0.0721
0.50	29	44.2	46.3	91.9	45.2	8.9	17.765	0.0123	0.0518
1.00	29	42.1	44.2	87.7	43.1	9.2	9.227	0.0123	0.0374
2.00	29	40.3	42.4	84.1	41.3	9.5	4.761	0.0123	0.0268
5.00	29	35	37.1	73.6	36	10.4	2.078	0.0123	0.0177
15.0	29	23.4	25.5	50.6	24.4	12.3	0.820	0.0123	0.0111
30.0	29	19.8	21.9	43.4	20.8	12.9	0.430	0.0123	0.0081
60.0	29	17.2	19.3	38.2	18.2	13.3	0.222	0.0123	0.0058
240	29	14.7	16.8	33.3	15.7	13.7	0.057	0.0123	0.0029
1440	29	11.6	13.7	27.1	12.6	14.2	0.010	0.0123	0.0012
Soil Description									Kerobokan Clay

Time (t) minute	Temperature	Actual Hydrometer Reading (Ra)	Correction of Hydrometer Readings (Rc)	% Get Away (Rc.a/Ws)	Correction of Meniscus Effect (R)	L	L/t	K Table 6-4	K(L/T) ½	D (mm)
Soil Gs										2.658
Correction Gs (a)										0.9932645
Dispersing Agent										Calgon 4% (125 ml)
Soil Weight (Ws)										50 gr
Zero reading correction										1
Meniscus Corecction										1

Table 5. Combined Sieve Analysis

Filter Number	Hole Size (mm)	Pass Percentage (%)
4	4.75	0.0
10	2	100.0
20	0.841	99.3
40	0.42	97.8
60	0.25	96.1
100	0.149	96.1
200	0.075	92.4
	0.072	90.7
	0.052	84.9
	0.037	81.1
	0.027	77.8
	0.018	68.0
	0.011	46.7
	0.008	40.1
	0.006	35.3
	0.003	30.8
	0.001	25.1

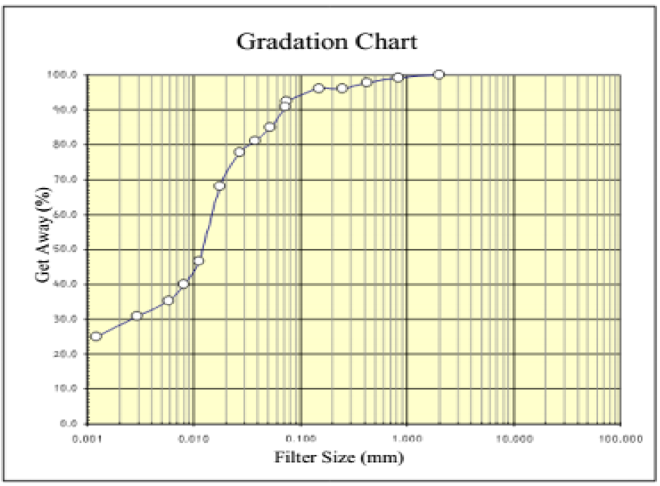

Figure 2. Clay soil gradation graph

Table 6. Soil Grouping Based on Grain Size

Description	Grain Size (mm)	%
Clay	< 0.002	28.00
Silt	0.002 < d < 0.075	64.00
Fine sand	0.075 < d < 0.42	6.00
Medium Gradation Sand	0.42 < d < 2	2.00
Rough sands	2 < d < 4.75	0.00
Fine Gravel	4.75 < d < 19.1	0.00
Coarse Gravel	19.1 < d < 76.20	0.00

Based on the data contained in Table 5, a gradation graph was then created, as presented in Figure 2. From Figure 2, soil types can be grouped based on their grain size, as presented in Table 6.

Testing Atterberg Limits

Based on the data in Table 7 for liquid limit testing, a graph of the relationship between the number of blows (N) and water content (w) was then made to determine the liquid limit of the soil, as shown in Figure 3. The liquid limit is the water content at a number of strokes equal to 25, so that based on Figure 3, the liquid limit (LL) is 71%.

Table 7. Liquid Limit and Plastic Limit Tests

	Liquid Limit (LL)				Plastic Limit (PL)	
Number of Stokes	18	32	23	54	-	-
Cup Number	1	2	3	4	5	6
Cup Weight (gr)	6.40	6.30	6.30	6.30	6.40	6.20
Cup Weight + Wet Soil (gr)	23.20	25.10	22.20	19.60	10.20	10.00
Cup Weight + Dry Soil (gr)	16.00	17.50	15.50	14.70	9.30	9.10
Water Weight (gr)	7.20	7.60	6.70	4.90	0.90	0.90
Dry Soil Weight (gr)	9.60	11.20	9.20	8.40	2.90	2.90
Water Content (%)	75.00	67.86	72.83	58.33	31.03	31.03

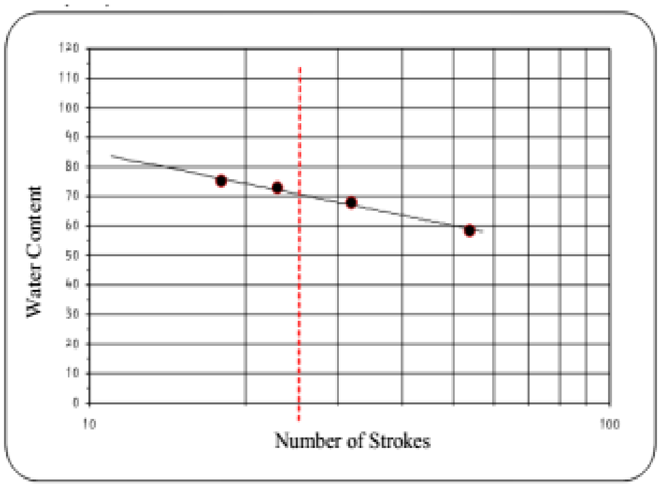

Figure 3. Liquid limit graph

Table 8. Shrinkage Limit (SL) Test

Cup Number	1	2
Cup Weight (gr)	10.20	10.30
Cup Weight + Wet Soil (gr)	32.90	33.10
Cup Weight + Dry Soil (gr)	23.50	23.60
Water Weight (gr)	9.40	9.50
Wet Soil Weight (W) (gr)	22.70	22.80
Dry Soil Weight (Wo) (gr)	13.30	13.30
Wet Soil Volume (V) (cm^3)	13.12	13.12
Dry Soil Volume (Vo) (cm^3)	6.90	6.80
Water Content (w) (%)	70.68	71.43
SL = w - (V-Vo)/Wo x 100 %	23.91	23.91

A summary of the Atterberg limit test results is presented in Table 9. The Plastic Index (PI) value is the difference between the Liquid Limit (LL) value and the Plastic Limit (PL).

Table 9. Summary of Atterberg Limit Test Results for Native Soil

Shrinkage Limit (%)	23.91
Plastic Limit (%)	31.03
Liquid Limit (%)	81.00
Plastic Index (%)	49.97

Atterberg limit tests were also carried out on soil mixtures with various levels of lime. The results of this test are summarized in Table 10.

Table 10. Summary of Atterberg Limit Test Results

Description	Atterberg Limits			
	LL	PL	SL	PI
Pure Soil	71	31	22	40
Soil + 2.50% limestone	66	36	25	30
Soil + 5.00% limestone	58	40	29	18
Soil + 10.00% limestone	Non Plastic			

Specific Gravity Test

Apart from being used for hydrometer analysis, the specific gravity test is also used to describe the ZAV line on the compaction curve (Equation 3). The ZAV line is the maximum density limit that can be achieved by a soil mass, where all soil cavities are filled with water without any air in it. The ZAV line is also a control tool for compaction testing, where the compaction curve obtained must not cross the ZAV line. This specific gravity testing procedure is based on the concept that the specific gravity of a material is a comparison between the mass of the material and the mass of water of the same volume. Specific gravity test results are shown in Table 11.

In the same way, the specific gravity for mixtures with various lime contents was also calculated, the complete results of which can be seen in the appendix. A summary of the test results is shown in Table 12.

Table 11. Specific Gravity Test for Original Soil

Description	Sample	
	I	II
Pycnometer Weight (gr)	20.5	32.3
Pycnometer Weight + sample (gr)	36.1	46.9
Pycnometer + Sample + Water (W1) (gr)	80.4	92.9
Pycnometer Weight + Water (W2) (gr)	70.7	83.8
Temperature ^oC	29	29
Temperature correction (k)	0.998	0.998
Dry sample weight (Ws) (gr)	15.6	14.6
Specific Gravity: Gs = {Ws/(W2.k-W1+Ws)}k	2.639	2.649
Average specific Gravity (Gs)		2.644

Table 12. Summary of Specific Gravity Test Results

Description	Specific Gravity Gs
Pure Soil	2.644
Soil + 2.50% limestone	2.658
Soil + 5.00% limestone	2.665
Soil + 10.00% limestone	2.682

The results of testing the Atterberg limits for original soil (soil that is not mixed with lime) show that the soil used as a sample in this study is classified as clay soil with high plasticity (CH). This can be seen by plotting the liquid limit (LL) value of 71% and plastic index (IP) of 39.97% into the Casagrande plasticity chart (Figure 4), as shown by point S.

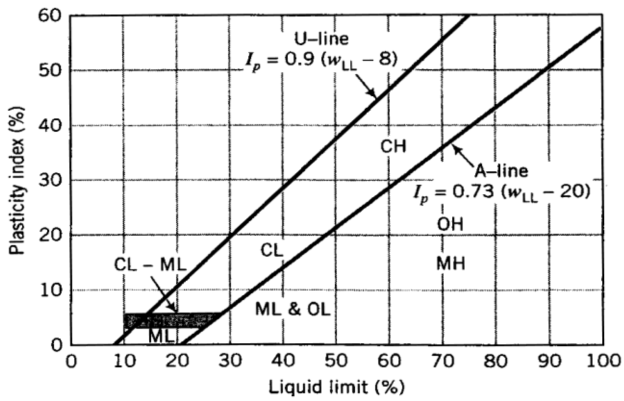

Figure 4. Casagrande plasticity chart

The results of testing the Atterberg limits for soil mixtures with various levels of lime showed that there was a decrease in the value of the Atterberg limits. The greater the lime content in the mixture, the smaller the Atterberg limits, especially in this case the LL and PL values. The smaller the LL and PL values will result in the smaller the plasticity index (IP) value. Thus, the addition of lime to the soil mass has been proven to reduce the plasticity of the soil, which means it also reduces the potential for expansion.

Compaction Testing

This compaction test is carried out with the aim of finding the optimum water content that must be added to the soil mass, both original soil and soil mixed with lime. This optimum water content will later be used as a basis for making test objects for CBR testing. To be able to see the effect of compaction energy on the planned CBR value, compaction tests are carried out using both standard and modified methods.

Before the compaction test is carried out, the original water content of the clay soil is first sought. The aim is to find the dry weight of the soil, because mixing with lime is done based on the dry weight of the soil. Next, calculate the weight of lime that must be added according to the lime content, as shown in Table 1. For each level of lime, 5 test specimens were made and then water was added so that it was estimated that some of the specimens would be on the dry side and the rest would be on the wet side of the compaction curve. Next, the test object is compacted according to standard and modified compaction procedures. Sufficient soil from each test object was taken to check the water content. From the results of this compaction test, data will be obtained on the relationship between dry unit weight and the corresponding water content, which can be depicted in a compaction curve. From this curve, the optimum water content and maximum dry weight of the soil mixture can be determined. The results of standard compaction tests for original soil are shown in Table 13, while the compaction curve is depicted in Figure 5.

Table 13. Original Soil Standard Compaction Test

Mold	1	2	3	4	5
Sample Weight (gr)	2000	2000	2000	2000	2000
Water Adding (cc)	200	300	400	500	600
Wet weight					
Mold weight + soil (gr)	4789	4875	4953	5005	5050
Mold weight (gr)	3500	3500	3500	3500	3500
Mold Volume (cm^3)	944.32	944.32	944.32	944.32	944.32
Wet wight g (3 - 4) / 5 (gr/cm^3)	1.365	1.456	1.539	1.594	1.641
Water Content					
Cup weight (gr)	9.70	9.90	10.00	9.80	9.80
Cup weight +wet soil (gr)	54.80	50.40	46.00	41.00	46.50
Cup weight + dry soil (gr)	49.00	43.90	39.00	34.00	36.90
Water content w (8-9)/(9-7) (%)	14.76	19.12	24.14	28.93	35.42
Dry weight gd = g/(1+w) = 6 / (1+w) gr/cm^3	1.189	1.222	1.239	1.236	1.212
Specific gravity Gs					2.644
Z.A.V: Gs/(1+wGs)	1.902	1.756	1.614	1.498	1.365

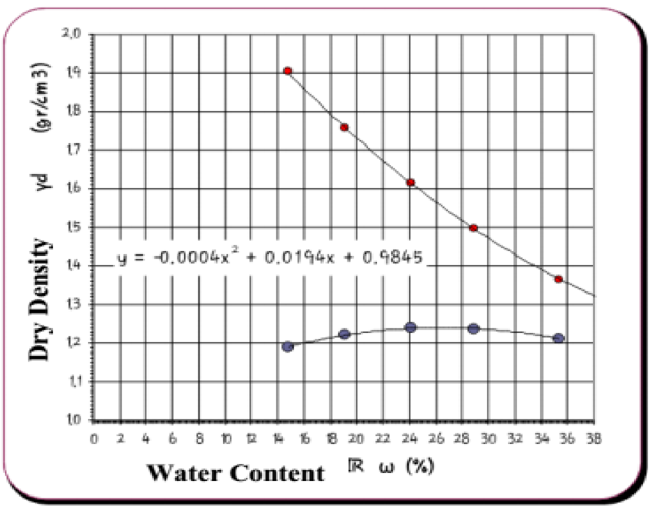

Figure 5. Original Soil Compaction Curve

From Figure 5, it can be determined that the optimum water content (w_{opt}) is 26.2% and the maximum dry density (g_d mak) is 1.245 gr/cm^3. The same test procedure was carried out for other soil mixtures, the complete results of which can be seen in the attachment. A summary of the test results is presented in Table 14, both for compaction using standard and modified methods.

Table 14. Summary of Compaction Tests

Description	Compaction Method			
	Standard		Modification	
	ω_{opt} (%)	g_d mak (gr/cm^3)	ω_{opt} (%)	g_d mak (gr/cm^3)
Pure Soil	26.20	1.245	20.23	1.462
Soil + 2.50% limestone	21.00	1.253	21.54	1.500
Soil + 5.00% limestone	28.91	1.279	15.25	1.550
Soil + 10.00% limestone	28.64	1.267	25.82	1.497

CBR Testing

This CBR test was carried out to find out what CBR value can be exerted by a mixture of limestone soil with various levels of lime and what level of lime is needed to achieve the minimum CBR requirements for the subgrade layer of a highway construction. Compaction of test specimens for CBR testing follows standard and modified Proctor compaction procedures. The CBR value of the original soil will be used as a control and then compared with the CBR value that can be exerted by a mixture of soil with lime. Below we will describe the results of CBR testing for original soil using standard compaction methods. In this test, 3 test objects were prepared, which were mixed with water at the optimum water content, then compacted successively with 15, 25 and 56 impacts, for the standard compaction method. For the modified compaction method, the specimens were compacted successively with 15, 35 and 65 impacts. Before carrying out the penetration test, the three test objects were soaked for 4 days. The purpose of this immersion is to condition the test object to suit the worst soil conditions in the field. The results of this test are shown in Table 13 – 15. Test results for mixed soil, both for standard and modified compaction methods, can be seen in the attachment.

Table 15. Original Soil CBR Test for 10 Impacts, Standard Compaction

			10 x Collision	
			Before	After
Cylinder weight + sample (gr)			10,262	11,062
Cylinder weight + sample (gr)			7,195	7,195
Sample weight (gr)			3,067	3,867
Volume cylinder (cm^3)			2,394	2,394
Wet wight (gr/cm^3)			1.281	1.615
Dry weight (gr/cm^3)			1.087	0.998
Expansion (%)				
Date	21/8/09	22/8/09	23/8/09	25/8/09
Time	-	-	-	-
Reading	0.00	7.25	7.42	7.53
Change	0.00	7.25	0.17	0.11
Time (Minute)	Penetration (inch)	Load reading		Load (lb)
0	0	0		0
0.25	0.0125	2		16
0.5	0.025	3		24
1	0.05	3		24
1.5	0.075	4		32
2	0.1	4		32
3	0.15	5		40
4	0.2	6		48
6	0.3	7		56
8	0.4	8		64
10	0.5	10		80
Water content			Before	After
Container weight (gr)			9.80	9.80
Container weight + wet sample (gr)			39.70	50.60
Container weight + dry sample (gr)			35.40	36.50
Water wight (gr)			4.30	14.10
Dry sample weight (gr)			25.60	26.70
Water content (%)			16.80	52.81
Note:				
1 Div	7.95264	lb		

Based on the data on the relationship between penetration and load in Table 13 - 15, a graph of the relationship between load and penetration can then be made, which is used to calculate the CBR value for the corresponding number of blows. The CBR value used is the largest CBR value between 0.1" and 0.2" penetration. The results are presented in Figures 6 – 8.

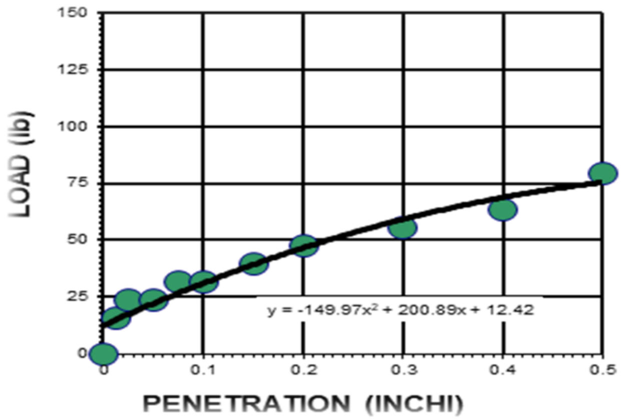

Figure 6. Penetration – load relationship for 10 strokes

Table 16. Original Soil CBR Test for 25 Impacts, Standard Compaction

			25 x collision	
			Before	After
Silinder weight + sample (gr)			10,627	11,322
Silinder weight (gr)			7,272	7,272
Sample wight (gr)			3,355	4,050
Volume silinder (cm^3)			2,394	2,394
Wet weight (gr/cm^3)			1.401	1.692
Dry weight (gr/cm^3)			1.186	1.044
Expansion (%)				
Date	21/8/09	22/8/09	23/8/09	25/8/09
Time	-	-	-	-
Reading	0.00	11.82	12.06	12.28
Change	0.00	11.82	0.24	0.22
1 Div	7.95264	lb		
Time (Minute)	Penetration (inchi)	Load reading		Load (lb)
0	0	0		0
0.25	0.0125	2		16
0.5	0.025	3		24
1	0.05	4		32
1.5	0.075	5		40
2	0.1	6		48
3	0.15	8		64
4	0.2	9		72
6	0.3	12		95
8	0.4	14		111
10	0.5	16		127
Water content			Before	After
Container weight (gr)			9.80	9.80
Cont weight + wet sample (gr)			42.30	46.60
Cont weight + Dry sample (gr)			37.30	32.50
Water weight (gr)			5.00	14.10
Dry sample weight (gr)			27.50	22.70
Water content (%)			18.18	62.11
Note:				
1 Div	7.95264	lb		

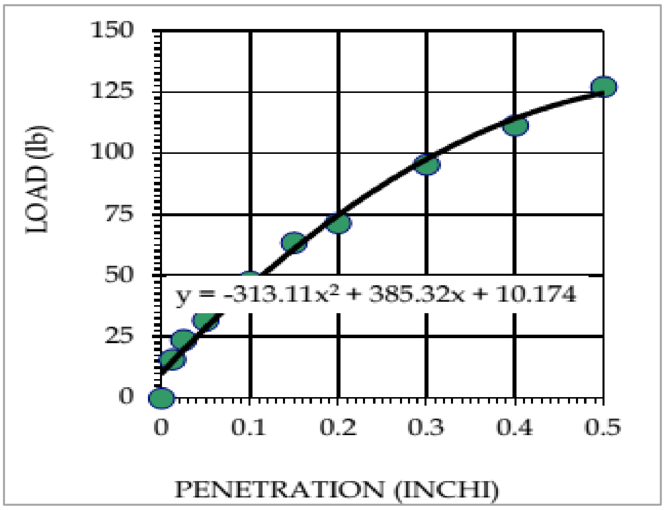

Figure 7. Penetration – load relationship for 25 strokes

Table 17. Original Soil CBR Test for 56 Impacts, Standard Compaction

			56 x collision	
			Before	After
Silinder weight + sample (gr)			10607	11187
Silinder weight (gr)			7054	7054
Sample weight (gr)			3553	4133
Volume silinder (cm^3)			2394	2394
Wet weight (gr/cm^3)			1.484	1.726
Dry weight (gr/cm^3)			1.239	1.096
Expansion (%)				
Date	21/8/09	22/8/09	23/8/09	25/8/09
Time	-	-	-	-
Reading	0.00	10.94	11.91	12.7
Change	0.00	10.94	0.97	0.79
Time (Minute)	Penetration (inchi)	Load reading	Load (lb)	
0	0	0	0	
0.25	0.0125	3	16	
0.5	0.025	4	24	
1	0.05	5	32	
1.5	0.075	6	40	
2	0.1	7	48	
3	0.15	9	64	
4	0.2	10	72	
6	0.3	13	95	
8	0.4	15	111	
10	0.5	17	127	
Water Content			Before	After
Container weight(gr)			9.70	9.70
Cont weight + wet sample (gr)			37.00	42.00
Cont weight + dry sample (gr)			32.50	30.20
Water weight (gr)			4.50	11.80
Dry sample weight (gr)			22.80	20.50
Water content (%)			19.74	57.56
Note				
1 Div	7.95264	lb		

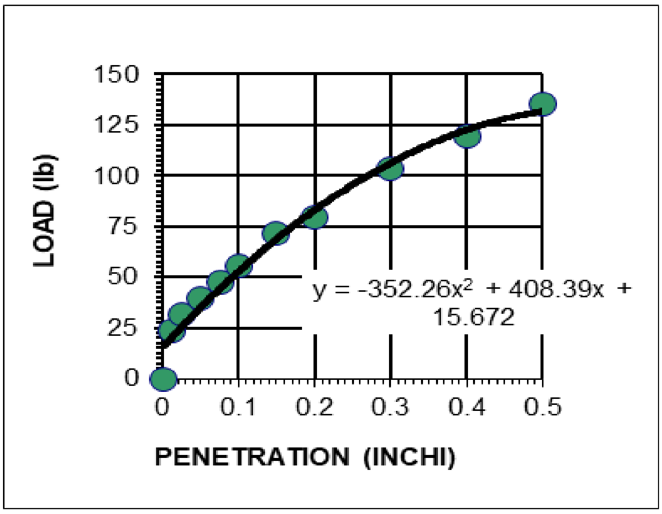

Figure 8. Penetration – load relationship for 56 strokes

Determine the CBR Plan

Based on the data presented in Tables 13 – 15 and Figures 7 – 9, a table of the relationship between dry density (g_d) and CBR values can be created, as presented in Table 19. Based on Table 19, a graph of the relationship between g_d and CBR was created as presented in Figure 9 which was used to determine the planned CBR value of the original land.

Table 18. Relationship between g_d and CBR

	10 x collision	25 x collision	56 x collision
CBR (%)	1.08	1.70	1.91
g_d (gr/cm^3)	0.998	1.044	1.096

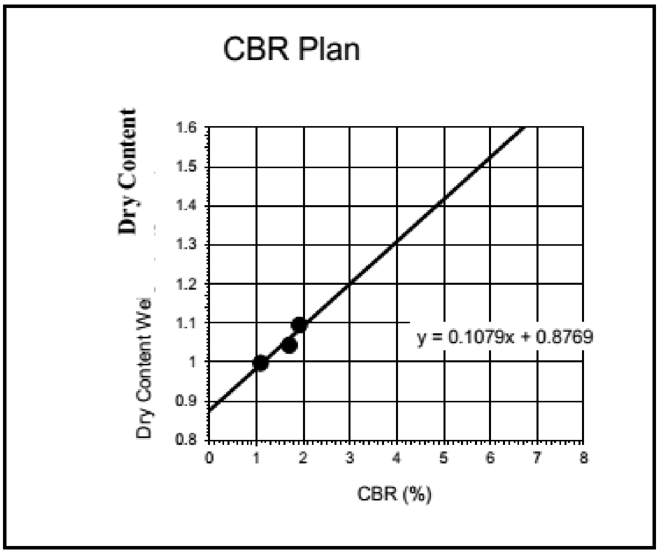

Figure 9. Relationship between g_d and original soil CBR for standard compaction

Based on Figure 9, it can be determined what the planned CBR value can be exerted by the original land. The method is to plot the g_d value of the original soil obtained from the proctor compaction results on the Y axis (Point A). From this point a horizontal line is drawn until it intersects the graph at point B. From point B a vertical line is drawn until it intersects the X axis at point C. Point C is the planned CBR value that is sought.

For original soil, the g_d mak value is 1.245 gr/cm3. Based on the procedure explained above, the planned CBR value for the original land is 3.32%. Apart from the graphical method as described above, the planned CBR value can also be searched based on the trend line equation of the relationship between g_d and CBR. From Figure 4.8 it can be seen that the relationship between g_d and CBR is expressed by the equation: y = 0.1079x + 0.8769, where y is the g_d value and x is the CBR value. By entering the value g_d = 1.245 into this equation, the planned CBR value = 3.32%.

The same testing and calculation procedures are also applied to obtain the planned CBR value for each type of mixture. Complete results can be seen in the attachment. A summary of the test results is presented in Table 19.

Table 19. Summary of Planned CBR Testing

Lime	CBR Plan (%)	
Content (%)	Standar Compaction	Modification Compaction
0.00	3.32	5.74
2.50	12.14	13.42
5.00	21.86	25.69
10.00	26.24	38.15

Determining Minimum Lime Content

To answer the problem of what lime content is needed to produce the minimum CBR value required by the base layer of a highway pavement structure, a graph of the relationship between lime content and the planned CBR can be made as shown in Table 19. The results are presented in Figure 9 for standard compaction and Figure 10 for modified compaction.

From Figure 9, the relationship between lime content and CBR value for compaction using the standard method is expressed by the equation:

$$y = -0.2508x2 + 4.8648x + 2.8353 \quad (1)$$

where y represents the CBR value and x represents the lime content.

Because the minimum CBR required for the base soil layer of highway pavement structures is 6% (Sukirman, 1992), then by entering the value y = 6 into equation (1), the value x = 0.79% is obtained. This means that to produce a planned CBR value of 6%, 0.79% lime must be added to the original soil. This lime content of 0.79% is equivalent to 7.9 kg of lime per one ton of dry soil. The relationship between lime content and CBR value as stated in equation (1) is a quadratic equation, where there is a maximum lime content which can also provide a maximum CBR value. This means that there is a certain limit of lime content that can be added to the base soil. Subsequent increases in lime content will not increase the CBR value, but will actually result in a decrease in the CBR value. By taking the first derivative of equation (1) to be equal to zero, the maximum lime content that can be added to the soil mixture is 9.34%, which will produce a maximum CBR value of 26.49%.

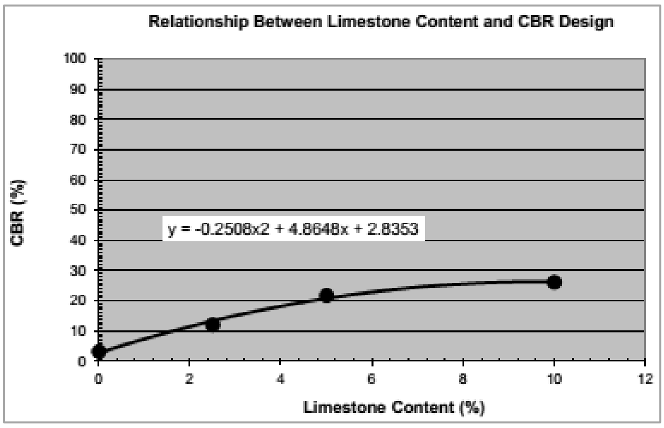

Figure 10. Relationship between lime content and CBR for standard compaction

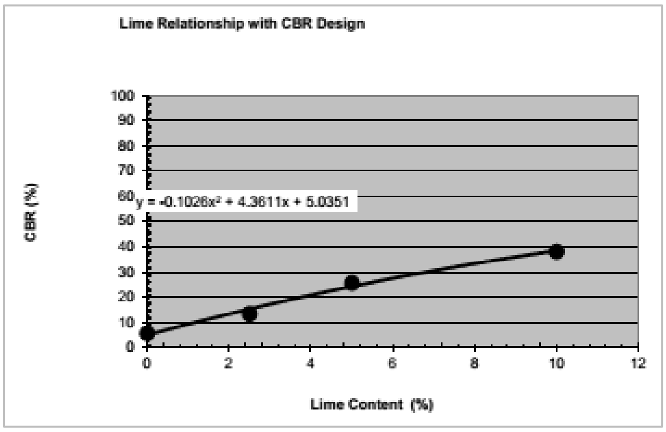

Figure 11. Relationship between lime content and CBR for modified compaction

From Figure 11, the relationship between lime content and CBR value for compaction using the modified method is expressed by the equation:

$$y = -0.1026x2 + 4.3611x + 5.0351 \quad (2)$$

where y represents the CBR value and x represents the lime content. By entering the value y = 6 into equation (2), we get the value x = 0.22%. This means that to produce a planned CBR value of 6%, for soil compacted using the modified compaction method, 0.22% lime is needed. With this modified proctor compaction method, the maximum lime content that can be added to the soil is 21.25%, which will produce a maximum planned CBR of 51.38%.

From the results of the discussion above, it is clear that adding lime to the original soil can increase the CBR value of the soil. If we look at the compaction method used, for adding the same lime content, it can be seen that the modified compaction method will produce a higher CBR value when compared to the standard compaction method (Table 19). This also means that to produce the same CBR value, the amount of lime required in the modified compaction method will be less than the lime required in the standard compaction method. This will appear more clearly if we enter the same value of x (lime content) into equations (1) and (2), as shown in Table 20.

Table 20. Comparison of CBR Values Produced between Standard Compaction Methods and Modified Compaction Methods

Lime Content (%)	The Resulting CBR Value	
	Standar Compaction Method	Modification Compaction Method
1	6.6	9.3
2	11.1	13.3
3	15.0	17.2
4	18.3	20.8
5	21.1	24.3
6	23.3	27.5
7	24.9	30.5
8	26.0	33.4
9	26.5	36.0
10	26.4	38.4

Conclusion

From the test results and discussions, the following conclusions can be drawn: Adding lime to clay soil significantly increases the CBR value. Using the standard compaction method, the CBR of the base soil initially at 3.32% increased to 12.14, 21.86, and 26.24% for lime additions of 2.5, 5, and 10%, respectively. For the modified compaction method, the initial CBR of 5.74% increased to 13.42, 25.69, and 38.15% for the same respective lime additions. To achieve a base soil CBR of 6%, the modified compaction method requires less lime (0.22%) compared to the standard method (0.79%). The maximum lime content that can be added using the standard compaction method is 9.34%, yielding a maximum CBR of 26.4%, whereas the modified compaction method allows for up to 21.25% lime, resulting in a maximum CBR of 51.38%. Although the research results show that the modified compaction method will provide a greater planned CBR value for the same addition of lime, to determine which compaction method to use, it is necessary to consider the economic value of each compaction method. In road embankment work, for the same embankment thickness, the amount of embankment material required will be greater, due to greater soil compression caused by greater compaction energy when compared to standard methods.

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Author Contributions

Conceptualization, N.K.S.A.S; methodology, I.M.J.; software I.M.J.; validation, I.M.J.; formal analysis, I.M.S.W; investigation, I.G.N.S.; resources, I.M.N; data curation, N.K.S.A.S and I.M.J; writing—original draft preparation, N.K.S.A.S; writing—review and editing, N.K.S.A.S and I.M.J; visualization, I.M.J.; supervision, I.M.S.W; project administration I.G.N.S; funding acquisition, N.K.S.A.S and I.M.J All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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