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IDENTIFYING THE EFFECT OF SUBGRADE LAYER THICKNESS OF SOIL STABILIZED WITH WASTE FOUNDRY SAND AND FLY ASH ON BEARING CAPACITY

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The issue of subgrade soil often involves unstable soil properties, such as low bearing capacity, susceptibility to expansion and shrinkage, and vulnerability to erosion and deformation due to traffic loads and weather conditions. Unstable subgrade soil can cause various infrastructure problems, including cracks, settlement, and damage to road surfaces. Therefore, stabilizing subgrade soil is an important step to ensure the reliability and longevity of highways. One effective and sustainable method for subgrade soil stabilization is by utilizing local waste materials. The use of local waste materials such as fly ash (FA) and waste foundry sand (WFS) not only improves the physical and mechanical properties of the soil but also helps reduce environmental impact by repurposing pollutants. This study aims to analyze the effect of the thickness of subgrade layers stabilized with FA and WFS on bearing capacity. The initial stage includes examining the physical and mechanical properties of natural soil and soil stabilized with FA and WFS. The waste content used is 9 % FA and 15 % WFS by dry weight of the soil. Subgrade modeling was conducted using a steel box measuring 60×60×60 cm with a soil thickness of 30 cm. Load testing was carried out on 5 layer variants that had undergone 4 days of curing. The study results found that the ultimate bearing capacity (qult) of 890 kPa was produced by the V4 layer, which is a subgrade with a 30 cm thick layer of soil stabilized with FA and WFS at a settlement of 6 mm. The bearing capacity ratio of 2.87 means that the subgrade with a 30 cm thick layer of soil stabilized with FA and WFS experienced an improvement in bearing capacity of 2.87 times that of the subgrade with untreated soil material. The results obtained can be applied in practice to the local geotechnical conditions of the project site in West Java, including natural soil properties and seasonal changes

Keywords: subgrade, bearing capacity, stabilization, foundry sand, fly ash, plate load test, footing

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1. Introduction

Subgrade soil frequently lacks sufficient bearing capacity to support traffic loads, thereby failing to meet the necessary subgrade standards. The unstable subgrade soil can lead to various infrastructure issues, including cracks, settlement, and damage to road surfaces. Replacing subgrade soil with higher-quality material is not always economical due to the additional costs of excavation and transportation. In many cases, subgrade soil that does not meet the standard is stabilized using materials containing cement, such as lime, cement, and fly ash, to achieve a specific strength for supporting construction and subgrade loads. Several soil stabilization techniques have been studied and proven by researchers, including the use of cement, rice husk ash [1], lime, fly ash, and chemical solutions [2] to improve subgrade soil.

The final disposal of coal combustion waste (fly ash) and waste foundry sand has been a significant challenge for the industry for a long time. Therefore, proper industrial waste management is necessary, especially for subgrade improvement. Industrial wastes such as fly ash (FA) and waste foundry sand (WFS) contain specific compounds that can improve the bearing capacity of subgrade in highway structure systems. Waste foundry sand offers opportunities for large-scale reuse [3]. Cementitious fly ash can be utilized as a soil stabilizer material [4]. The motivation behind this research is the lack of innovation in waste management as a stabilizing material for road subgrade. Improving the subgrade using locally sourced industrial waste offers a cost-effective alternative compared to other expensive additives. The use of locally sourced industrial waste materials such as FA and WFS is expected to address industrial waste management and environmental sustainability.

The thickness of the subgrade layer is significant in determining the bearing capacity of the soil. By optimizing the thickness of the subgrade layer, it can be known that the subgrade structure can support the traffic load effectively [5].

Many studies have been conducted by researchers to strengthen the soil under the footing [6]. The research did not combine two types of waste that have different functions as an improvement in the subgrade layer. The mechanical properties of soil stabilized using FA and WFS have been known from preliminary research [7]. This research combined two types of waste with different functions, FA as a material that functions to produce cementitious properties while WFS functions as a filler material. The results concluded that the addition of FA and WFS to the soil improved its mechanical properties. However, the thickness of the stabilized subgrade layer using FA and WFS as additive materials to the soil mixture is not yet known.

Therefore, the effect of subgrade layer thickness on the bearing capacity of soil stabilized with FA and WFS is relevant and necessary to be investigated as an improvement in the bearing capacity of road construction subgrades. In addition, the results can contribute to the development of more efficient and cost-effective subgrade construction methods.

2. Literature review and problem statement

Soil improvement using additives containing cement or granular materials has been widely practiced. The paper [6] evaluates the performance of a very weak subgrade stabilized with cementitious materials, namely fly ash (or cement) and lime. This paper reports that the stabilizer content has a significant influence on the stabilized improvement. To achieve the target 7-day unconfined compression strength (UCS), each soil was treated with various combinations of lime and class C fly ash (or cement). Soil stabilized with lime and fly ash resulted in a UCS value of 345 kPa (50 psi), while soil stabilized with lime and cement yielded a UCS value of 690 kPa (100 psi) for subgrade stabilization intended for sub base use. This study was limited to laboratory testing, not performing small-scale modeling of the subgrade, so the bearing capacity of the subgrade through the plate load test is unknown.

The paper [4] reports that the stabilized mixture of waste foundry sand (WFS) and crushed rock shows increased strength and durability in the layers of road pavement structure. The use of WFS in the filter layer is beneficial in reducing costs and CO_2 emissions by up to 50 % compared to the reference structure. This paper is limited to laboratory testing and did not conduct plate load tests on small-scale subgrade modeling to analyze its bearing capacity improvement. This paper also does not use wastes that produce cementitious properties such as fly ash for soil improvement. The paper [7] reports that the use of a combination of fly ash (FA) and waste foundry sand (WFS) improves the bearing capacity and shear strength of soil. Soil with 9 % FA and 15 % WFS shows the highest California Bearing Ratio (CBR) value, specifically 16.02 %, an internal friction angle of 18.819 degrees, and cohesion of 1.560 kg/cm^2. This research is limited to laboratory testing and did not involve small-scale subgrade modeling to analyze load-bearing strength. This study suggests further research to obtain the bearing capacity and settlement occurring in stabilized soil subgrades using FA and WFS under specific loads through small-scale modeling. This is important to understand how the stabilized soil will behave under actual loads. Stabilizing expansive soil with industrial waste not only provides an alternative to conventional materials but also helps control environmental pollution. Industrial waste materials are often disposed of in open dumps, causing numerous issues for nearby residents. Utilizing these waste materials can reduce pollution and decrease human dependence on natural resources, as well as promote more sustainable development methods.

The paper [8] conducts experimental modeling to analyze the bearing capacity of foundations on soft clay stabilized with granular materials. The small-scale test results yield bearing capacity values that are nearly similar to those calculated using two methods, i.e. tangent intersection and the 0.1B method. The Bearing Capacity Ratio significantly increases with the widening of soil stabilized with granular materials. This study only utilized one type of stabilization material, which is a granular material, without combining it with cementitious materials. The paper [9] concludes that there is an increase in CBR for soil stabilized with FA and WFS. However, the study is limited to Proctor compaction tests and California Bearing Ratio (CBR) tests; it did not conduct small-scale subgrade modeling to analyze the ultimate bearing capacity using plate load tests. The paper [10] reveals that pozzolanic reactions are stronger compared to cation exchange during fly ash stabilization based on micro-level studies. UCS (Unconfined Compressive Strength) and CBR (California Bearing Ratio) increase with the addition of fly ash. Based on its mechanical and hydraulic characteristics, it is recommended to use Class C fly ash at 15 % with a curing time of 7 days to achieve optimal performance. This study did not conduct small-scale subgrade modeling to evaluate the ultimate bearing capacity of the stabilized subgrade.

The paper [11] conducts research on WFS used as a backfill geomaterial for retaining soil structures. The results indicate that single-layer and double-layer geogrids experienced reductions in lateral displacement of 30 % and 50 %, respectively. This study only utilized one type of waste for backfill. The paper [12] investigates the bearing capacity of square footings resting on fiber-reinforced pond ash overlying soft clay using plate load tests. Results have shown that there is a significant amount of improvement in ultimate bearing capacity as well as in the settlement of the soil system due to the provision of a pond ash layer over soft clay. This research exclusively utilizes pond ash as the waste material.

Research combining two types of waste, FA and WFS, for subgrade improvement remains very limited. Previous studies on soil stabilization using FA and WFS have not yet presented an analysis of ultimate bearing capacity based on small-scale subgrade modeling with load testing. Based on the literature review, several studies have discussed the use of stabilization materials such as FA and WFS to improve the bearing capacity of subgrade soils. However, there is a gap in understanding the effect of stabilization layer thickness on subgrade performance. The majority of previous studies have focused on the composition and mechanical properties of the stabilization material itself, without paying particular attention to the variation in layer thickness and how this variation affects the bearing capacity. Although many studies have explored the use of FA and WFS as stabilization materials, the effect of variant stabilization layer thickness on bearing capacity is less explored. This study offers a new approach by exploring the less discussed aspect of thickness. Knowing the optimal thickness of the stabilization layer can help in the design and construction of more economical and effective roads. This has direct implications for cost savings and improved infrastructure performance. The results of this study will enrich the literature with new empirical data, providing additional insights that can be used by other researchers and civil engineering practitioners in soil stabilization applications. The use of materials such as FA and WFS that are industrial waste products also supports more sustainable construction practices, reducing reliance on new materials and decreasing the environmental impact of waste disposal. All this allows us to assert that it is expedient to conduct a study on identifying the effect of variant subgrade layer thickness using untreated soil material layered with FA and WFS stabilized soil on bearing capacity.

3. The aim and objectives of the study

The aim of this study is to identify the effect of subgrade thickness stabilized using FA and WFS on bearing capacity. This will allow the application of smaller thickness subgrades with greater bearing capacity than conventional subgrades and thus lower construction costs.

To achieve this aim, the following objectives are accomplished:

– to investigate the effect of variant thickness of stabilized subgrade using FA and WFS on bearing pressure;

– to investigate the bearing pressure ratio at certain settlements;

– to investigate the effect of variant thickness of FA and WFS stabilized subgrade on ultimate bearing capacity and bearing capacity ratio.

4. Material and methods

The object of this study is a subgrade consisting of untreated soil material and soil stabilized using Fly ash and Waste Foundry Sand. The natural soil color ranges from dark brown to charcoal grey. Waste foundry sand is a fine sand with a blackish grey color while fly ash is a fine dust with a brownish grey color.

The main research hypothesis to be proven in this study is an increase in the bearing capacity of the subgrade consisting of soil material stabilized using FA and WFS with a specific thickness. This is supported by preliminary research showing changes in microstructure and an increase in CBR (California Bearing Ratio) in soil stabilized with FA and WFS [7]. The increase in CBR and changes in microstructure in soil stabilized with FA and WFS will affect the density and stiffness of the subgrade layer, thereby enhancing the bearing capacity during load testing.

In this study, variations of Waste Foundry Sand additive material were set at 15 %, while Fly Ash was added at 9 % based on the dry weight of the soil. The research focuses on natural soil from Ciampel Village, Karawang, West Java, Indonesia. Fly Ash is sourced from the Steam Power Plant (PLTU) in Paiton, East Java, Indonesia, while WFS (waste foundry sand) originates from a metal casting factory in the industrial area of East Karawang, West Java, Indonesia. The subgrade is modeled in a steel box measuring 60×60×60 cm with a soil thickness of 30 cm, followed by applying loads until the subgrade collapses (Fig. 1). Load tests are conducted on each layer variant to obtain maximum pressure and settlement, thereby determining the ultimate bearing capacity using the tangent intersection method [13]. The bearing capacity of the subgrade was analyzed based on the results of the plate load test (ASTM-1194) [14]. Based on the relationship of pressure and settlement curves, the bearing capacity value of each test model is obtained. The pressure is obtained from the load divided by the area of the test plate. The load can be determined from the proving ring reading multiplied by the calibration number. Pressure per deformation is used to analyze bearing pressure (q), bearing pressure at a certain settlement, and ultimate bearing capacity (q_{ult}). A summary of the laboratory test results is presented in Table 1.

The loading test of the subgrade model is presented in Fig. 1.

Table 1

Summary of Laboratory Tests

Test	Unit	Standard	Untreated Soil	Treated Soil (Soil+9 %FA+15 %WFS)
Specific gravity (G_s)	–	ASTM D 854	2.634	2.707
Liquid Limit (LL)	%	ASTM D 4318	72.27	52.81
Plastic Limit (PL)	%	ASTM D 4318	21.51	29.10
Plasticity index (PI)	%	ASTM D 4318	50.77	23.72
Optimum moisture content (OMC)	%	ASTM D 698	25.30	20.50
Maximum dry density (MDD)	kN/m^2	ASTM D 698	14.2	16.2
Triaxial UU (cohesion)	kPa	ASTM D 2850	65.7	156
Triaxial UU (φ)	(°)	ASTM D 2850	11.87	18.82
Classification of soil (USCS)	–	ASTM D 2487	CH	MH

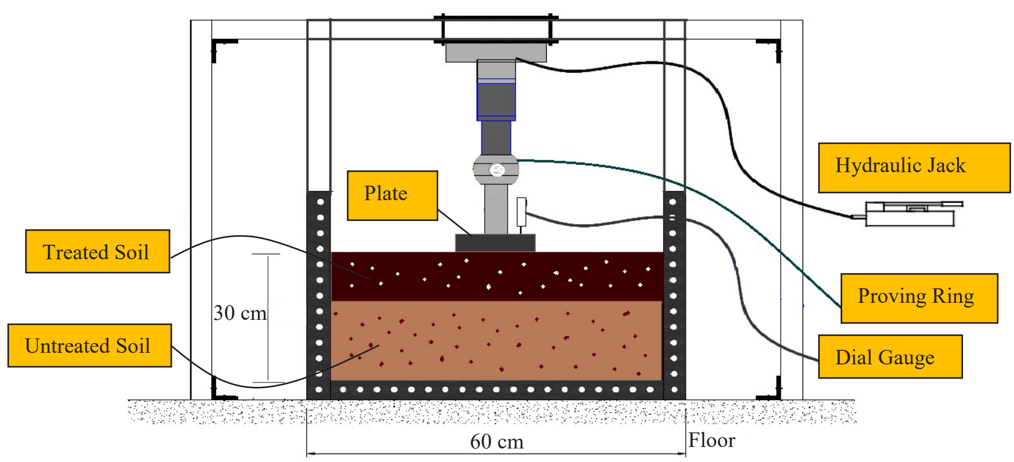

Fig. 1. Load testing of the subgrade model

Fig. 1 depicts the modeling of the subgrade with 2 layers of soil subjected to incremental loading until failure. This study used a plate load test with a square footing placed on top of a subgrade layer consisting of different layer variants as shown in Fig. 1. The tested soil layers consist of 5 variants (Table 2).

Table 2

Variants of subgrade layers

Soil layer thickness	Variant Code
US: 30 cm	Layer V0
US: 20 cm+TS: 10 cm	Layer V1
US: 15 cm+TS: 15 cm	Layer V2
US: 10 cm+TS: 20 cm	Layer V3
TS: 30 cm	Layer V4

Table 2 shows the details of subgrade layer variants. Untreated Soil (US) represents the native soil compacted to its optimal moisture content. Treated Soil (TS) denotes soil stabilized with 9 % FA and 15 % WFS based on dry soil weight, subsequently compacted to its optimal moisture content. Specifically, Layer V0 comprises 30 cm of untreated soil. Layer V1 consists of 20 cm of untreated soil at the bottom layer and 10 cm of treated soil at the top layer. Layer V2 includes 15 cm of untreated soil at the bottom and 15 cm of treated soil at the top. Layer V3 features 10 cm of untreated soil at the bottom and 20 cm of treated soil at the top. Finally, Layer V4 is composed entirely of 30 cm of treated soil. The experiment testing set up is presented in Fig. 2.

Fig. 2 illustrates the stages and process of preparing test specimens for subsequent testing. Air-dried native soil passing through a no. 4 sieve is mixed with 9 % FA and 15 % WFS based on the dry weight of the soil, along with water to reach its optimum moisture content.

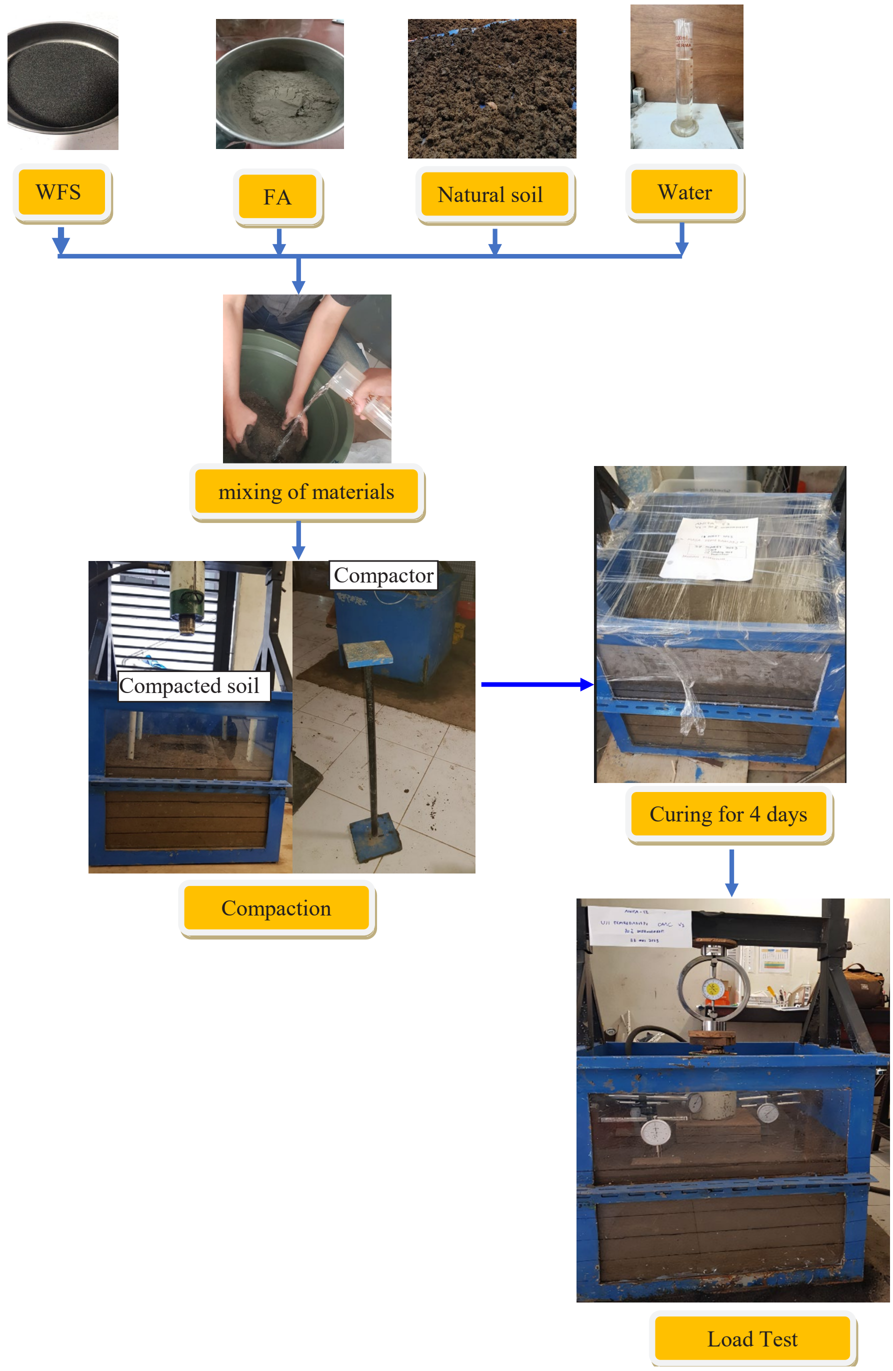

Fig. 2. Experiment Testing Set Up

This mixture is then left to homogenize in a covered container for 1 day. Subsequently, the mixture is spread and compacted in a steel box using a compaction rod, layer by layer, until reaching a thickness of 30 cm. The box is then covered to prevent excessive evaporation and left for 4 days. Density parameters are controlled based on Maximum Dry Density and the same optimum moisture content used in previous Proctor compaction tests [7]. After the 4-day curing period, the subgrade is ready for load testing. Loading is performed by connecting a hydraulic jack with a pump and applying gradual pressure on a 20×20×2 cm steel plate placed on the subgrade surface. Pressure readings on the proving ring are recorded periodically, along with deformation indicators shown on a dial gauge. Based on the relationship of pressure and settlement curves, the bearing capacity value of each test model is obtained. The pressure is obtained from the load divided by the area of the test plate. The load can be determined from the proving ring reading multiplied by the calibration number. Pressure per deformation is used to analyze bearing pressure (q), bearing pressure at a certain settlement, and ultimate bearing capacity (q_{ult}).

5. Results of the study on the effect of subgrade layer thickness of soil stabilized with waste foundry sand and fly ash on bearing capacity

5. 1. Pressure (q) and settlement of the subgrade layer

The results of the subgrade plate load test with various layer variants are presented in Fig. 3.

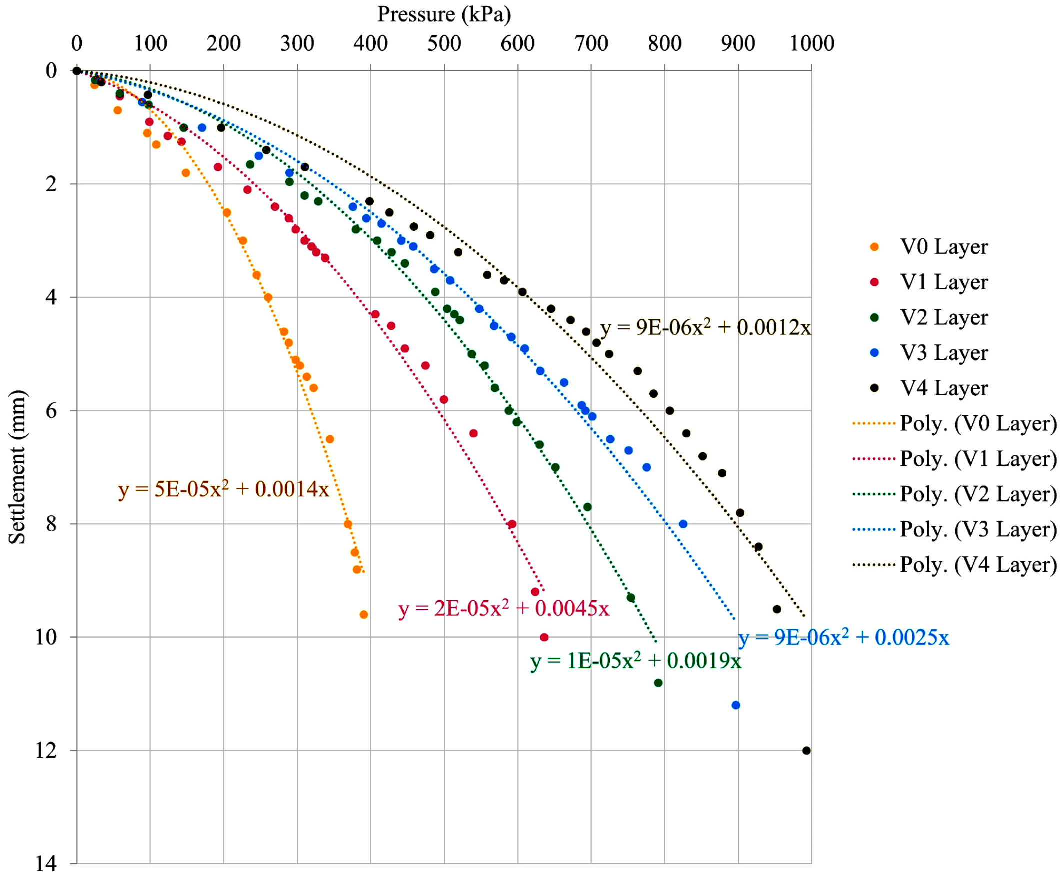

Fig. 3. Results of the plate load test of the subgrade

Fig. 3 shows that the subgrade of the combined layer as well as the layer stabilized with FA and WFS fully yielded higher pressures than that of the untreated soil layer (layer V0). Layer V0 produced a pressure of 390.40 kPa with a settlement of 9.6 mm. Layer V1 yielded a pressure of 635.64 kPa with a settlement of 10 mm. Layer V2 resulted in a pressure of 790.85 kPa with a settlement of 10.8 mm. Layer V3 yielded a pressure of 896.39 kPa with a settlement of 11.2 mm. Layer V4 generated a pressure of 992.62 kPa with a settlement of 12 mm. It is observed that increasing the thickness of the subgrade layer stabilized with 9 % FA and 15 % WFS results in higher pressures.

5. 2. Bearing pressure ratio at a 9.6 mm settlement

Bearing Pressure Ratio (BPR) is calculated by dividing the subgrade bearing pressure value in the stabilized soil layer variant with several thickness variants against the subgrade bearing pressure of untreated soil:

$$BPR = \frac{q_{ts}}{q_{us}}, \qquad (1)$$

where q_{ts} is the bearing pressure of the subgrade with variant layers of 9 % FA and 15 % WFS stabilized soil (layers V1, V2, V3, V4) and q_{us} is the bearing pressure on the untreated soil subgrade (layer V0) [12, 15].

In this study, BPR are analyzed based on the pressure generated by all layer variants at the same settlement point of 9.6 mm, called BPRs. The settlement of 9.6 mm is produced by the subgrade layer V0, which consists of untreated soil with a thickness of 30 cm, at a pressure of 390.40 kPa. This settlement of 9.6 mm will serve as the standard for comparing pressures in other layer variants. The pressures at a 9.6 mm settlement for all layer variants are presented in Table 3 and Fig. 4.

Table 3

Pressure at a 9.6 mm settlement

Layer variant	Settlement (mm)	Pressure (kPa)	BPRs	Percentage change in pressure (%)
Layer V0	9.6	390.40	1.00	–
Layer V1	9.6	626.95	1.61	60.59
Layer V2	9.6	761.04	1.95	94.94
Layer V3	9.6	860.69	2.20	120.46
Layer V4	9.6	953.88	2.44	144.33

Table 3 shows the comparison of pressures generated at a 9.6 mm settlement. At the same settlement point (9.6 mm), the pressure increases as the thickness of the layer with soil stabilized with 9 % FA and 15 % WFS increases. Layer V0 produces a pressure of 390.40 kPa, Layer V1 generates 626.95 kPa, Layer V2 results in 761.04 kPa, Layer V3 yields 860.69 kPa, and Layer V4 produces a pressure of 953.88 kPa.

The BPRs resulting from the comparison of pressures between soil stabilized with 9 % FA and 15 % WFS and untreated soil show increasing values as the thickness of the layer stabilized with 9 % FA and 15 % WFS increases. The BCRs for each layer variant V1, V2, V3, and V4 are 1.50, 1.80, 2.07, and 2.44, respectively. A comparison of pressures at a 9.6 mm settlement is presented in Fig. 4.

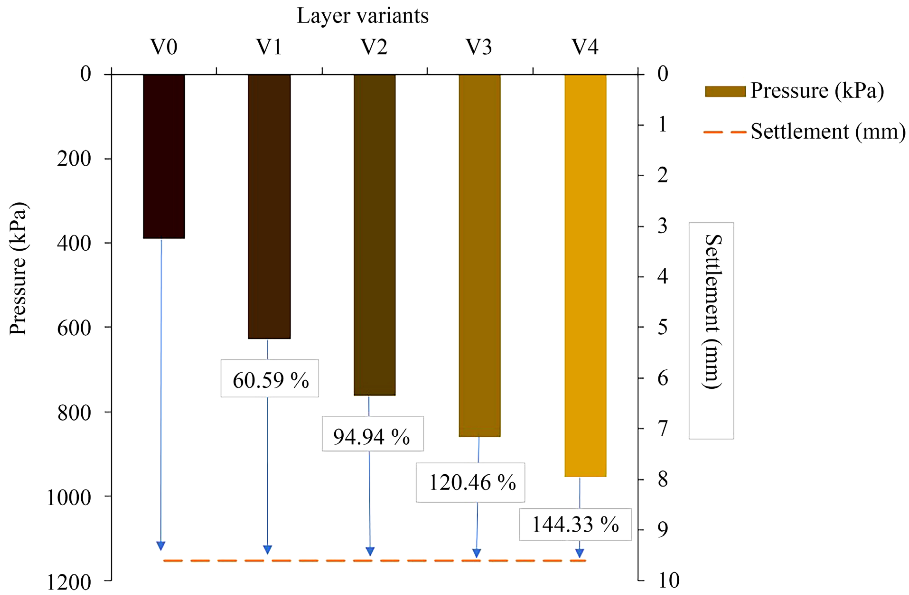

Fig. 4. Comparison of pressures at a 9.6 mm settlement

Fig. 4 presents the percentage change in pressure generated at a 9.6 mm settlement. Layer V1 experiences an increase in pressure by 60.59 %, Layer V2 experiences an increase by 94.94 %, Layer V3 experiences an increase by 120.46 %, and Layer V4 experiences an increase by 144.33 % compared to the pressure in Layer V0. BPRs for subgrade layer variants are presented in Fig. 5.

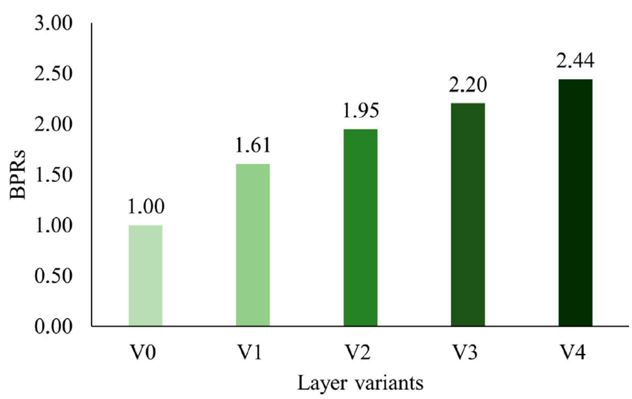

Fig. 5. BPRs for subgrade layer variants

Fig. 5 depicts BPRs for subgrade layer variants at a 9.6 mm settlement. There is an increase in pressure as the thickness of the soil layer stabilized with 9 % FA and 15 % WFS increases. Based on Fig. 5, the layer that performs best as a subgrade is the layer with 100 % improvement, which is the soil stabilized to a thickness of 30 cm, showing a percentage increase in pressure of 144.07 % compared to the pressure generated by untreated soil (Layer V0) at a 9.6 mm settlement, with a BPR of 2.44.

5. 3. Ultimate bearing capacity (q_{ult}) and bearing capacity ratio (BCR)

The tangent intersection method is used to determine the bearing capacity and settlement. This method involves drawing tangent lines – one from above and another from the side – on a graph to find the intersection point, which is used to determine the bearing capacity and settlement [13]. Analysis using the tangent intersection method yields a lower ultimate bearing capacity (q_{ult}) compared to the bearing capacity based on maximum pressure. The ultimate bearing capacity (q_{ult}) for all layer variants is presented in Fig. 6.

Fig. 6 shows that the largest q_{ult} was obtained from layer V4, which is a subgrade layer fully containing stabilized soil material (Soil+9 %FA+15 %WFS) with a thickness of 30 cm, without any combination of original soil layers. The largest ultimate bearing capacity was produced by the variant layer V4 with q_{ult} of 890 kPa and a settlement of 6 mm, while the original soil layer (Layer V0) produced q_{ult} of 310 kPa with a settlement of 3.9 mm. In layers with material combinations consisting of untreated soil and stabilized soil, the following results were observed: layer V1 produced q_{ult} of 500 kPa with a settlement of 4.3 mm, layer V2 produced q_{ult} of 597 kPa with a settlement of 4.7 mm, and layer V3 produced q_{ult} of 735 kPa with a settlement of 5.1 mm. This indicates that the thicker the stabilized soil layer, the greater the ultimate bearing capacity produced.

Bearing Capacity Ratio (BCRu) is a comparison of the ultimate bearing capacity of the subgrade in the FA and WFS stabilized soil layer variants to the ultimate bearing capacity in the untreated soil subgrade layer variant:

$$\text{BCRu} = \frac{q_{ult}(ts)}{q_{ult}(us)}, \quad (2)$$

where $q_{ult}(ts)$ is the ultimate bearing capacity of the soil subgrade with the variant layers of 9 % FA and 15 % WFS stabilized soil (Layer V1, V2, V3, V4) and $q_{ult}(us)$ is the ultimate bearing capacity of the variant layer of untreated soil subgrade (layer V0) [12, 15].

The percentage increase in q_{ult} and BCRu based on ultimate bearing capacity is presented in Table 4.

Table 4 shows the Bearing Capacity Ratio based on ultimate bearing capacity and the percentage increase in ultimate bearing capacity. The percentage increase in ultimate bearing capacity due to subgrade layers stabilized with 9 % FA and 15 % WFS is observed for BCRu values greater than 1. BCRu greater than 1 means that stabilization increases soil bearing capacity more than 1-fold compared to un-stabilized soil. The relationship between subgrade layer variants and BCRu is presented in Fig. 7.

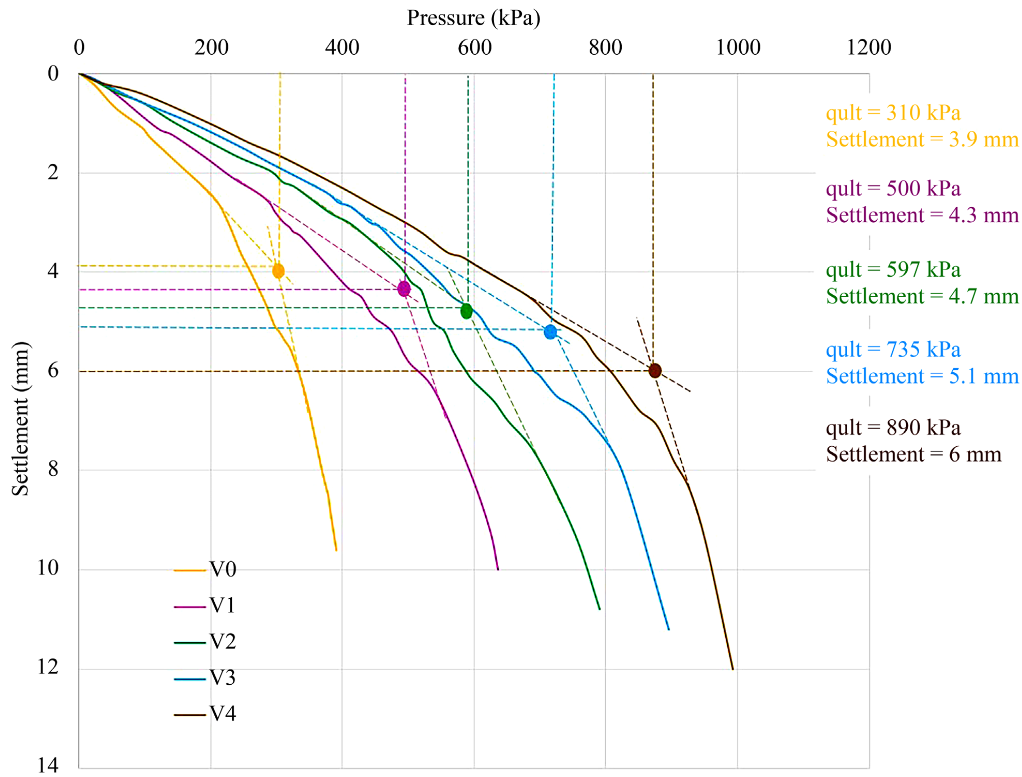

Fig. 6. Ultimate bearing capacity and settlement using the tangent intersection method

Table 4

BCRu and Percentage Increase in q_{ult}

Layer variant	q_{ult} (kPa)	q_{ult} of untreated soil layer (kPa)	BCRu	Percentage Increase of q_{ult} (%)
Layer V0	310	310	1.00	–
Layer V1	500	310	1.61	61.29
Layer V2	597	310	1.93	92.58
Layer V3	735	310	2.37	137.09
Layer V4	890	310	2.87	187.09

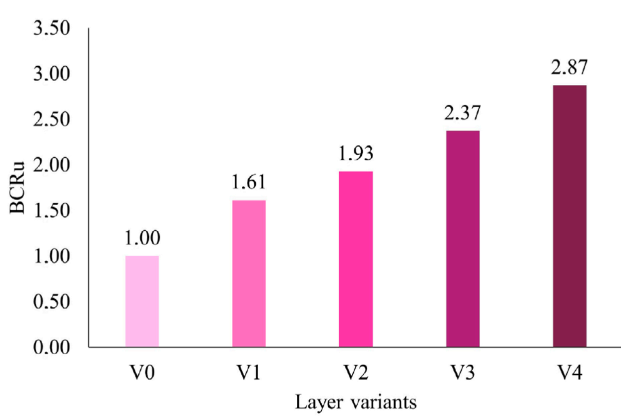

Fig. 7. BCRu against layer variants

Fig. 7 shows that the highest BCRu is produced by subgrade layer variant 4, which is a stabilized soil with 9 % FA and 15 % WFS with a thickness of 30 cm without any untreated soil layer with a BCRu of 2.87 with a percentage increase in q_{ult} of 187.09 %. The greater the thickness of FA and WFS stabilized soil in the subgrade, the BCRu value increases.

6. Discussion of the influence of subgrade layer thickness of WFS and FA stabilized soil on bearing capacity

Fig. 3 shows the pressure-settlement curve obtained from square footing experiment testing on soil layers. The values of bearing pressure for layer variants V0, V1, V2, V3, V4 are 390.40 kPa, 635.64 kPa, 790.85 kPa, 896.39 kPa, 992.62 kPa, respectively. Layer V0 exhibits smaller settlement and pressure compared to other layer variants. Layers composed of combination materials, such as untreated soil and stabilized soil as in layer variants V1, V2, and V3, show increased pressure compared to untreated soil layer (V0). Layer V4, composed of soil stabilized with 9 % FA and 15 % WFS without any original soil layer, produces the highest maximum pressure. This demonstrates that the thickness of soil stabilized with 9 % FA and 15 % WFS affects both pressure and settlement. Settlement increases with increasing pressure in subgrade layer variants, consistent with research [16]. Pressure increases with the thickness of soil stabilized with 9 % FA and 15 % WFS, in alignment with the studies [12, 17] showing increasing pressure with increasing stabilization thickness. Chemically, fly ash, waste foundry sand, and natural soil are formed from silica and alumina. After curing for 4 days, a pozzolanic reaction occurs. This reaction happens because silica and alumina in the soil-fly ash-waste foundry sand structure react with water to form calcium silicate hydrate and calcium aluminate hydrate gel, which crystallize to bind the structure solidly and compactly, thus enhancing strength [16, 18]. With the layer of soil stabilized with 9 % FA and 15 % WFS over untreated soil, significantly stiffer behavior is observed [18]. Preliminary tests have been carried out in the form of XRD tests on Fly ash, WFS, and natural soil. Based on the XRD test, the chemical composition of oxides in Fly ash consists of SiO_2 35.9 %, Al_2O_3 11 %, SO_3 0.61 %, K_2O 1.67 %, CaO 13.6 %,

TiO_2 1.48 %, V_2O_5 0.05 %, Cr_2O_3 0.087 %, MnO 0.37 %, Fe_2O_3 33.72 %, CuO 0.068 % and ZnO 0.03 %. The 13.6 % CaO content in fly ash reacts with water. Calcium oxide reacts to form calcium hydroxide: $CaO+H_2O \rightarrow Ca(OH)_2$. The calcium hydroxide formed can react with silica and alumina (pozzolanic reaction) to produce compounds that function in the formation of cement structures such as C-S-H and C-A-H, which provide strength and durability to the material [19, 20]. Table 2 shows the increase in pressure as the thickness of soil stabilized with 9 % FA and 15 % WFS increases in subgrade layer variants at a settlement of 9.6 mm. The 9.6 mm settlement represents the settlement from a pressure of 390.40 in layer V0, indicating that at a 9.6 mm settlement, the pressure in layer variant V0 is already at its maximum. In contrast to layer variants V1, V2, V3, and V4, at a settlement of 9.6 mm, the pressure generated is not yet at its maximum, meaning the subgrade can still support additional pressure up to its maximum limit. Fig. 4 presents the percentage change in pressure generated at a settlement of 9.6 mm. The percentage increase in pressure for layer variants V1, V2, V3, and V4 relative to layer V0 is 60.59 %, 94.94 %, 120.46 %, and 144.33 %, respectively. The largest improvement percentage is achieved by layer variant V4. In layers composed of a combination of two materials (V1, V2, V3), there is an increase in pressure but not as significant as in layer V4, which consists of a single type of material layer, stabilized soil using 9 % FA and 15 % WFS with a thickness of 30 cm. The contribution of WFS as a granular-filler material and FA as a cementitious material enhances the pressure in the subgrade layer, primarily due to interlocking between particles, which relatively restrains particle movement through interfacial friction and bonding forces [16]. WFS in the soil does not alter the microstructure but functions as a filler, unlike fly ash that produces hydration products of cement, binding soil and WFS particles together to form a denser soil matrix. Fig. 5 illustrates the relationship between BPRs and subgrade thickness variants. The greater the thickness of soil stabilized with 9 % FA and 15 % WFS, the higher the BPRs. BPRs are obtained based on the bearing pressure generated at a settlement of 9.6 mm. This aligns with research [12] indicating that stabilized soil layers experience increased bearing pressure.

Fig. 6 shows that the largest q_{ult} is obtained from layer V4, which is a subgrade layer fully composed of soil stabilized with 9 % FA and 15 % WFS with a thickness of 30 cm, without any combination of the original soil layer, using the tangent intersection method [13]. The highest ultimate bearing capacity is produced by layer variant V4 with q_{ult} of 890 kPa and a settlement of 6 mm, while the original soil layer (layer V0) produces q_{ult} of 310 kPa with a settlement of 3.9 mm. In the layers with a combination of materials consisting of untreated soil and stabilized soil, the results are as follows: layer V1 produces q_{ult} of 500 kPa with a settlement of 4.3 mm, layer V2 produces q_{ult} of 597 kPa with a settlement of 4.7 mm, and layer V3 produces q_{ult} of 735 kPa with a settlement of 5.1 mm. This shows that the thicker the stabilized soil layer, the greater the ultimate bearing capacity produced. The combination of FA and WFS in the soil increases the values of cohesion and internal friction angle as presented in Table 4. Fly ash and WFS reduce soil porosity and fill the voids, thereby increasing the maximum dry density and enhancing interlocking between soil particles [7, 18, 21–24]. Table 3 presents the values of BCRu and the percentage increase in q_{ult}. The highest BCRu is obtained from layer variant V4, which consists of stabilized soil with 9 % FA and 15 % WFS with a thickness of 30 cm. Layer V4 produces q_{ult} 2.87 times greater than q_{ult} of layer V0, with a percentage increase of 187.09 %. This is consistent with research [12, 17]. The increase in ultimate bearing capacity is due to the greater stiffness of the stabilized soil compared to untreated soil [18]. Fig. 7 shows the relationship between BCRu and layer thickness variants. The thicker the layer of soil stabilized with 9 % FA and 15 % WFS, the higher the BCRu. This is consistent with research [8, 12]. WFS is a granular material that functions as a filler, filling voids and increasing soil density, while FA functions as a cementing agent, binding soil and WFS particles. The increase in bearing capacity is due to improved cohesion and internal friction angle compared to untreated soil, enabling it to resist deformation and support loads [24–26]. Based on the general specifications of Indonesian road works [27], a subgrade with a minimum soakage CBR of 6 % is required. In the preliminary research [7], the CBR of natural soil was 0.94 %, while the stabilized soil with 9 % FA and 15 % WFS obtained a CBR of 6.46 %. Stabilized soil as a subgrade in this case has met the standards required as a road subgrade in Indonesia.

The limitations of this study are that only one variant of FA and WFS content was used. Based on previous research [7], the 9 % FA and 15 % WFS content represents the best mechanical value among several variants studied, but the optimum content has not yet been determined. Therefore, further research is needed to determine the optimum FA and WFS content for application in subgrade. Additionally, this study did not investigate suction and pore water pressure, so the effective stress cannot be determined through direct testing. Supporting instruments such as jet-fill tensiometers or other instruments are needed to measure the suction and pore water pressure occurring in the subgrade under load application. Furthermore, this study did not account for the impact of changes in moisture content. Changes in soil moisture content can be caused by seasonal variations (rainwater flooding, groundwater table fluctuations). Changes in soil moisture content will significantly affect its bearing capacity.

The weaknesses of this study include the application of a static load on a 20×20 mm square plate at the center of the subgrade surface, with a subgrade thickness of only 1.5 B, without considering other load shapes (such as a circular plate) with greater subgrade thickness. This study's results provide recommendations regarding the bearing capacity ratio of subgrade stabilized with FA and WFS at specific thickness variants. These results can serve as a basis for planning industrial area development, determining design concepts and parameters, and establishing soil stabilization materials as an alternative construction material for subgrade improvement in highways. Additionally, more detailed experimental testing is necessary to further develop the findings of this study.

7. Conclusions

1. The addition of 9 % fly ash and 15 % waste foundry sand to the subgrade with a thickness of 30 cm can increase the bearing pressure. The research results show that the greatest pressure is produced by layer V4, which is a subgrade with stabilized soil consisting of FA and WFS with a thick-

ness of 30 cm, resulting in a pressure of 992.62 kPa at a settlement of 12 mm. The thicker the layer of soil stabilized with FA and WFS at a subgrade thickness of 30 cm, the greater the pressure produced. The greater the pressure applied to the subgrade, the greater the settlement formed. WFS is a granular material that functions as a filler, filling the soil voids, thereby reducing porosity and increasing soil density. Fly ash is a cementitious material that produces cement hydration products that bind the soil and WFS particles, making the soil structure more robust. The stabilized soil with FA and WFS at a thickness of 30 cm was found to support loads better than subgrades with other thickness variants.

2. At a settlement of 9.6 mm, the greater the thickness of the subgrade layer with soil stabilized with FA and WFS, the greater the pressure produced. A BPR of 2.44 was found in layer V4, which is a subgrade with soil stabilized with FA and WFS at a thickness of 30 cm, meaning it increased 2.44 times greater than the subgrade with untreated soil (layer V0).

3. The ultimate bearing capacity obtained using the tangent intersection method increases with the thickness of the FA and WFS stabilized soil at a 30 cm subgrade. The greater the ultimate bearing capacity produced from all layer variants, the greater the resulting settlement. q_{ult} of 890 kPa with a settlement of 6 mm was found in the subgrade with FA and WFS stabilized soil at a thickness of 30 cm without any combination of untreated soil layers, with a percentage increase of 187.09 % compared to q_{ult} of layer V0 (30 cm thick untreated soil). A BCRu of 2.87 indicates that the FA and WFS stabilized soil.

Subgrade at a thickness of 30 cm experienced an improvement in bearing capacity of 2.87 times that of the untreated soil subgrade. This is because FA, being a cementitious material, changes the microstructure through a pozzolanic reaction, while WFS acts as a filler that fills the pore voids, so these two materials in the soil mixture increase cohesion and internal friction angle, resulting in increased bearing capacity and stiffness. Thus, the thicker the layer of FA and WFS stabilized soil in the subgrade, the more the soil stiffness increases, leading to an increase in ultimate bearing capacity.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

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

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