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The Impact of Coal Combustion Waste (Fly Ash and Bottom Ash) on The Properties of Clay Soil (Case Study: National Road Section Demak – Kudus, Indonesia)

Alien Maulida Nurtaqwim[1,a], Ria Asih Aryani Soemitro[2,b], Dwa Desa Warnana[3,c] Trihanyndio Rendy Satrya[2,d] & Yanuar Dwi Putra[4,e]

[1]Master Degree Student, Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya
[2]Civil Engineering Departement, Institut Teknologi Sepuluh Nopember, Surabaya
[3]Geophysical Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
[4]The National Road Construction Agency (BBPJN) for Central Java – Special Region of Yogyakarta, Directorate General of Highways, Ministry of Public Work and Housing (PUPR), Semarang, Indonesia

Correspondent : [a]alien.maulida@gmail.com, [b]soemitroraa@gmail.com,
[c]dwa_desa@yahoo.co.uk, [d]trendysatrya@gmail.com
[e]bbpjn_jatengdiy@pu.go.id

ABSTRACT

The National Road Section Demak - Kudus is one of the most populous road sections connecting East Java province with West Java province through the city of Semarang. Repeated damage conditions raise the suspicion that the subgrade under the road body has special criteria that need further handling before repairs are made to the pavement. In addition, based on the soft soil distribution map and soil data with the results of existing laboratory testing, categorized as soft soil. For this reason, it is necessary to handle the subgrade to improve soil parameters, which is physical and mechanical. Therefore, chemical stabilization was chosen to obtain a chemical reaction from the soil. The selected chemicals to induce these reactions is coal combustion waste which are fly ash and bottom ash. Exhibiting pozzolanic properties that can react and cause flocculation in the soil. The research involves mixing the soil with stabilizing materials in three different combinations: first, soil mixed by fly ash (FA); second, soil mixed by bottom ash (BA); and third, soil mixed by both fly ash with bottom ash (FABA), optimum stabilizing mixture material at 20%. The initial soil, which is highly plastic clay with a classification of CH/A-7-6, having a plasticity index (PI) of 43.23% and California Bearing Ratio (CBR) of 0.92%, undergoes improvement with adding FA stabilizer, resulting in MH/A-7-5 with a PI of 27.07% and CBR of 12.39%. The mixture of soil with FABA is MH/A-7-5 with a PI of 28.87% and CBR of 9.60%. However, the improvement in the mixture of soil with BA is not as significant, remaining in the CH/A-7-6 category with a PI of 31.83% and CBR of 3.00%.

Keywords: Soft Soil, Clay Soil, Stabilization, Fly Ash, Bottom Ash

INTRODUCTION

Infrastructure is constructed with the purpose of serving the needs of the residents in a particular area (Suprayitno & Soemitro, 2018). National Road Section Trengguli - Bts. Demak/Kudus is one of the national road sections in Central Java Province that maintenance under Ministry of Public Works and Housing. This section has a total length of 13.32 km connecting Demak Regency and Kudus Regency shown in **Figure 1.** A well-maintained road network is an essential requirement for any region or country, and it is imperative that the quality of the roads is consistently upheld (Babo and Suprayitno, 2019). In order to achieve this, Infrastructure Asset Management (IAM) needs to address the complete lifecycle of infrastructure, with the key aim of ensuring that infrastructure and facilities can operate efficiently, economically, and sustainably, while also aligning with environmental principles (Sumitro & Suprayitno, 2018). Meanwhile, the concept of sustainable construction has predominantly been introduced in developed nations, with comparatively less emphasis placed on it in developing countries (Jimoh, et al, 2021). So it is necessary to carry out road preservation on the basis of sustainable construction that emphasizes the environment.

Figure 1. Trengguli – Bts. Kab. Demak/Kudus Site Map
(PPK 3.1 Provinsi Jawa Tengah, 2023)

The condition of the road in this section has some damage to the pavement as shown in **Figure 2.**

(a) (b)

Figure 2. Pavement Defects of Trengguli – Bts. Kab. Demak/Kudus
(PPK 3.1 Provinsi Jawa Tengah, 2023)

The Infrastructure of Public Works must always remain in excellent operational condition (Soemitro and Suprayitno, 2020). But, from the picture above, it can be seen that the pavement damage that occurs is longitudinal and transverse cracks, as well as damage in the form of small to large holes in the pavement layer. In addition to damage to the pavement, there is also soil deformation at the edge of the road towards the chanal. In a study conducted by Hartanti and Ari (2009) on the Trengguli - Jati road section of Kudus Regency, data on pavement damage on the section from Km 36+600 to 46+000 showed similarities with what is happening today, so this damage was repeated within 14 years. From the soft soil distribution map of Central Java Province (2019) shown in Figure 3, where the area from Demak Regency to Kudus Regency is colored green which is soft soil.

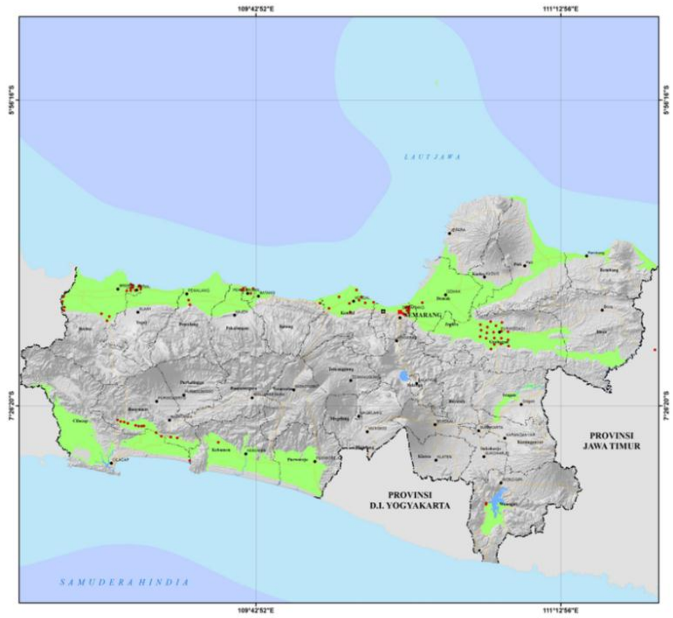

Figure 3. Soft Soil Distribution Map of Central Java Province
(Atlas of Soft Soil Distribution, 2019)

Soft soil generally has low bearing capacity, prompting the need for efforts to improve its condition. One of the ways to enhance the soil parameters is through soil stabilization. Soil stabilization is divided into two methods. Mechanical stabilization involves adding one or two materials to the soil to increase bearing capacity and grain gradation. Chemical stabilization involves adding chemicals that induce chemical reactions with the soil, aiming to improve both the physical and mechanical properties. It's crucial to optimize the use of environmentally friendly materials derived from waste, to enrich the efficient of natural resources utilization in road construction (Widayanti, et al, 2019). The chemical that can be used as a stabilizing agent is fly ash (FA) and bottom ash (BA). FA and BA are residual materials (waste) from coal combustion, which FA being fine dust emitted from the combustion chimney and BA being coarse dust at the bottom of the furnace. FA and BA are waste materials resulting from coal combustion that have pozzolanic properties that produce Calcium Silica Hydrate (CSH) and Calcium Alumina Hydrate (CAH) formations that can reduce development pressure along with the increase in the percentage of FA and BA and curing time (Dissanayake, et al., 2017). To achieve sustainable construction, the use of residual materials or materials with improved conditions for utilization in road construction is prioritized. In this case, the utilization of FA and BA materials is emphasized to enhance the soil conditions for use as embankment in road construction. From the various backgrounds above, it is necessary to conduct soil stabilization research using FA and BA to improve soil parameters. Research conduct with three variations involves the first scenario where the soil is mixed with FA, the second scenario where the soil is mixed with BA, and the third scenario where the soil is mixed with both FA and BA (FABA). Indeed, it is important to conduct such research, given the limited number of studies that simultaneously investigate the characteristics of these three stabilization variations.

LITERATUR REVIEW

FA and BA as Soil Stabiliser

The addition of 15% fly ash to clay soil with a curing period of 14 days can increase the CBR (California Bearing Ratio) value by 23.89% and reduce the water content, leading to a decrease in the soil's plasticity (Wahyuni et al., 2021). Similar plasticity behavior of clay soil was demonstrated by Leliana and Anjani (2015) with a 20% addition of FA, resulting in an increase in unconfined compressive strength by 5,009 kg/cm2. In addition to the improvement in the unconfined compressive strength value with a 20% FA addition, the soil's swelling pressure can also decrease by 1.2 kg/cm2 with a curing period of 14 days (Budi et al., 2003). The incorporation of 37.5% bottom ash into the soil can reduce the water content, leading to a decrease in the soil's plasticity, and achieve an unconfined compressive strength of 1,950 kg/cm2 compared to the initial value of 0.990 kg/cm2 (Purnama and Ridwan, 2018). Adding 30% BA to the soil with a curing period of 90 days can increase the unconfined compressive strength by 1182 kPa and the CBR value by 10.18% (Navagire et al., 2022). The reduction in swelling pressure occurs with an increase in the percentage of BA in the soil, but the optimum mixture for the greatest CBR increase is found to be 30% (Cadersa et al., 2014). Both FA and BA can be used together as soil stabilization materials. The addition of 12% FA and 18% BA to clayey soil can enhance the CBR value by 13.7% (Sharma and Singh, 2020).

Requirements for Ordinary Embankments and Selected Embankments

Based from General Spesification 2018 Second Revised for Highway and Bridge Construction for ordinary embankments and selected embankment requirements are:

Ordinary Embankments Requirements:

1. CBR Lab (soaked) ≥6%
2. Not high plasticity
3. Not A-7-6 in AASHTO Classification
4. Not CH in USCS Classification
5. Not Organic Low Plasticity (OL), Organic Low Plasticity (OH), and Peat (Pt) Classification
6. Activity value ≤1,25

Selected Embankments Requirements:

1. CBR Lab (soaked) ≥10%
2. Not high plasticity
3. Not A-7-6 in AASHTO Classification
4. Not CH in USCS Classification
5. Not OL, OH, and Pt Classification
6. Activity value ≤1,25

RESEARCH METHOD

In this study, series of tests were conducted in Laboratorium to determine the initial physical and mechanical parameters of soil using both disturbed and undisturbed soil samples. Subsequently, compaction tests were performed on soil mixed with each stabilization material (FA, BA, and FABA) in proportions of 10, 15, 20 and 25 percent by soil dry weigth to obtain the optimal mixture composition with the maximum dry density values (γ_d). For a better understanding of the increase in soil strength, 0, 7, and 14 days of curing were conducted to mechanical parameters test.

Physical properties test:

1. Volumetric Gravimetry Test, Indonesia National Standard (SNI) 1965:2008; SNI 1964:2008; SNI 03-3637-1994;
2. Atterberg Limit Test, SNI 1967:2008; SNI 1966:2008; SNI 3422:2008;
3. Shieve Analysis and Hydrometer Test, SNI 3423:2008.

Mechanical properties test:

1. Standard Proctor Test, SNI 1742:2008
2. Unconfined Compressive Strength Test, SNI 3638:2012
3. California Bearing Capacity Test, SNI 1744:2012

FA and BA materials come from Sudimoro Pacitan Steam Power Plant (PLTU Sudimoro, Pacitan), East Java, Indonesia. XRF (X-Ray fluorescence) test carried out on the two materials to determine their content.

DATA COLLECTION

Soil Investigation

To find out the condition of the subgrade at the present time, it can be reviewed from the soil investigation report from PPK 3.1 BPJN Central Java-DI Yogyakarta as an initial identification step of the subgrade condition. The existing soil investigation data consists of drill-log test data, sondir test data, and laboratory test data on soil samples. Two drill points with several depth variations were tested in the laboratory to obtain the physical and mechanical parameters of the subgrade are shown at **Table 1**. From the drill-log results at two drilling points, it is known that up to a depth of 20 meters the highest N-SPT value is 6 with a large enough percentage of clay, so the soil is a cohesive soil with a soft consistency in accordance with soil conditions based on the N-SPT value of J. E. Bowles in Wahyudi, 1999.

Table 1. Soil Layer Classification at National Road Section Trengguli - Bts. Demak/Kudus

Bor	Depth (m)	N-SPT	PI (%)	LL (%)	PL (%)	*Gravel* (%)	*Sand* (%)	*Silt* (%)	*Clay* (%)
BH-01	4,5 - 5,0	2	[redacted]						
	9,5 - 10,0	0	38,72	64,97	26,25	3,12	10,68	13,76	72,44
	14,5 - 15,0	2	37,41	66,38	28,97	0,12	3,48	7,68	88,72
	19,5 - 20,0	6	41,8	73,21	31,41	1,09	2,84	6,31	89,76
BH-02	4,5 - 5,0	6	30,5	62,01	30,05	0,52	3	6,88	89,6
	9,5 - 10,0	0	[redacted]						
	14,5 - 15,0	4	40,86	63,95	23,09	0,25	3,5	7,52	88,73
	19,5 - 20,0	6	41,66	63,97	22,31	0,35	3	6,59	90,06

X-Ray Fluorescence (XRF) Test Result

From the FA and BA X-ray fluorescence (XRF) Test Result that shown in **Table 2.** It is known that the calcium oxide (CaO) content in the FA is 21.92%. Therefore, based on the provisions in ASTM C618 revised in 2019, this FA classified as Class C.

Table 2. FA and BA X-Ray fluorescence (XRF) Test Result

Parameters	Units	Contents	
		FA	**BA**
SiO_2 (Silicon Dioxide)	%	32,73	39,15
Al_2O_3 (Aluminium Oxide)	%	13,81	7,97
Fe_2O_3 (Iron Trioxide)	%	13,53	17,3
CaO (Calcium Oxide)	%	21,92	9,6
MgO (Magnesium Oxide)	%	8,7	4,79
Na_2O (Sodium Oxide)	%	1,21	0,56
K_2O (Potassium Oxide)	%	0,82	0,44
TiO_2 (Titanium Oxide)	%	0,64	0,41
MnO_2 (Manganese Dioxide)	%	0,26	0,3
Cr_2O_3 (Chromium Trioxide)	%	0,01	0,01
P_2O_5 (Diphosphorus pentoxide)	%	1,78	0,08
SO_3 (Sulphur Trioxide)	%	4,08	1,47

RESEARCH ANALYSIS

Initial Soil Parameter

From the results of the soil properties test, the surface layer soil sample taken from STA 41+700 at a depth of -2,6 m with the results classified according to USCS as CH and according to AAHSTO classified A-7-6. The data of the tested properties test results can be seen in **Table 3.**

Table 3a. Initial Soil Parameters

No	Parameters	Units	Initial Soil
1	**Soil Physical**		
a	Volumetri - Gravimetri		
	- Water Content (wc)	%	37,46
	- Specific Gravity (Gs)		2,636
	- Dry Density (γd)	gr/cm^3	1,220
	- Void Ratio (e)	%	1,16
b	Sieve Analysis & Hydrometer		
	- Gravel	%	1,25
	- Sand	%	12,12
	- Silt	%	24,63
	- Clay	%	62,00
c	Atterberg Limit		
	- Liquid Limit (LL)	%	71,73
	- Plastic Limit (PL)	%	28,50
	- Plasticity Index (PI)	%	43,23
2	**Soil Classification**		
	- USCS		CH
	- AASHTO		A-7-6
3	**Soil Mechanical**		

Table 3b. Initial Soil Parameters

No	Parameters	Units	Initial Soil
a	Compaction Proctor Standard		
	- Optimum Water Content (OMC)	%	26,05
	- Maximum Dry Density (MDD)	gr/cm^3	1,326
b	Unconfined Compressive Strength	kg/cm^2	1,086
c	California Bearing Capacity (CBR) Laboratorium	%	0,92

Compaction Standard Proctor Test Result

Compaction Standard Proctor Test Result shown in **Figure 4.** It can be concluded that the mixing level that has the highest maximum dry density (γ_{dmax}) value for FA (1,487 gr/cm^3), BA (1,426 gr/cm^3), and FABA (1,430 gr/cm^3) mixtures is 20% with optimum moisture content (w_{opt}) of 23.70% for FA mixture, 23.81% for BA mixture, and 28.75% for FABA mixture, respectively.

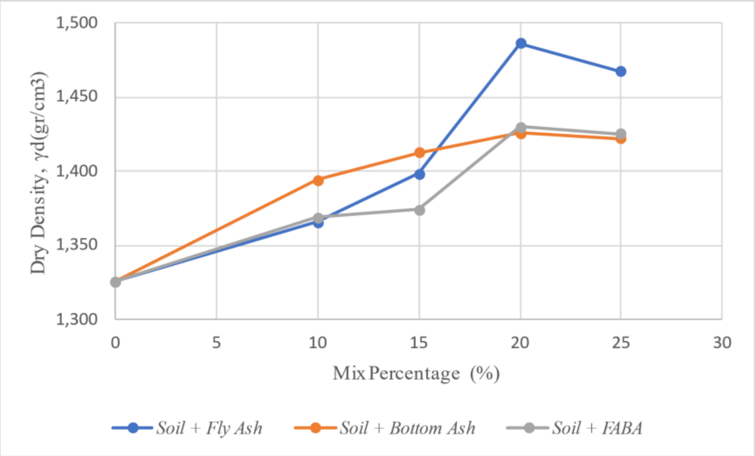

Figure 4. Compaction Standard Proctor Test Result

Stabilized Soil Parameter

Stabilized soil parameter test result shown in **Table 4.**

Table 4a. Stabilized Soil Parameter

No	Parameters	Units	Soil + FA 20%	Soil + BA 20%	Soil + FABA 20%
1	**Soil Physical**				
a	Volumetri - Gravimetri				
	- Water Content (wc)	%	23,71	23,89	28,62
	- Specific Gravity (Gs)		2,639	2,798	2,782
	- Dry Density (γd)	gr/cm^3	1,483	1,425	1,427
	- Void Ratio (e)	%	0,78	0,96	0,95
b	Sieve Analysis & Hydrometer				
	- Gravel	%	0,95	4,95	2,16
	- Sand	%	6,22	18,23	13,43

Table 4b. Stabilized Soil Parameter

No	Parameters	Units	Soil + FA 20%	Soil + BA 20%	Soil + FABA 20%
	- Silt	%	68,83	25,32	56,42
	- Clay	%	24,00	51,50	28,00
c	Atterberg Limit				
	- Liquid Limit (LL)	%	63,21	60,65	61,12
	- Plastic Limit (PL)	%	36,15	28,82	32,25
	- Plasticity Index (PI)	%	27,07	31,83	28,87
2	**Soil Classification**				
	- USCS		MH	CH	MH
	- AASHTO		A-7-5	A-7-6	A-7-5
3	**Soil Mechanical**				
a	Compaction Proctor Standard				
	- Optimum Water Content (OMC)	%	23,70	23,81	28,75
	- Maximum Dry Density (MDD)	gr/cm^3	1,487	1,426	1,430
b	Unconfined Compressive Strength (q_u)				
	- 0 day of curing	kg/cm^2	3,709	1,740	1,811
	- 7 days of curing	kg/cm^2	4,649	1,802	2,099
	- 14 days of curing	kg/cm^2	4,971	1,831	3,035
c	California Bearing Capacity (CBR) Lab.				
	- 0 day of curing	%	5,73	2,21	4,37
	- 7 days of curing	%	9,14	2,45	7,09
	- 14 days of curing	%	12,39	3,00	9,60

It can be concluded in general that stabilization with FA, BA, and FABA can improve the parameters of soil physical properties, marked by an increase in the soil volume weight value which indicates an increase in soil density and from the Atterberg limit test shows a reduction in soil plasticity. Classification of stabilized soil with FA and FABA improved from initial soil to inorganic silt MH according to USCS and according to AASHTO claasified as A-7-5. Different condition shown in stabilized soil with BA that have no improvement in soil classification. The classification is same with initial soil that calssified as CH according to USCS and according to AASHTO claasified as A-7-6. For the better understanding of grain gradation of the initial soil and stabilized soil can be seen in **Figure 5.** The soil stabilized with BA and FABA has more coarse grains than the initial soil, while the soil stabilized with FA has more fine grains than the initial soil. The Improvement of the mechanical properties marked by increase of CBR value and unconfined compressive strength (q_u). The curing performed on the q_u and CBR samples before testing showed improved results on increasing the q_u and CBR values. It can be seen in Error! Reference source not found.**.** and Error! ference source not found.**.** increase in value of q_u and CBR along with the length of curing. Initial soil consintency categorized as medium, while stabilized soil with FA categorized as very stiff then stabilized soil with BA and FABA categorized as stiff. After 14 days curing, showed an increase in the consistency category on stabilized soil with FABA categorized as very stiff, while stabilized soil with FA and BA still in the same categorized eventhough the value shown increase. The CBR value of initial soil categorized as very poor, same with stabilized soil with BA CBR value category. Despite the stabilized soil with FA and FABA categorized as poor to fair. After 14 days curing, showed an increase of the CBR value categorize on stabilized soil. Stabilized soil with FA and FABA shown CBR result as fair and stabilized soil with BA categorized as poor to fair.

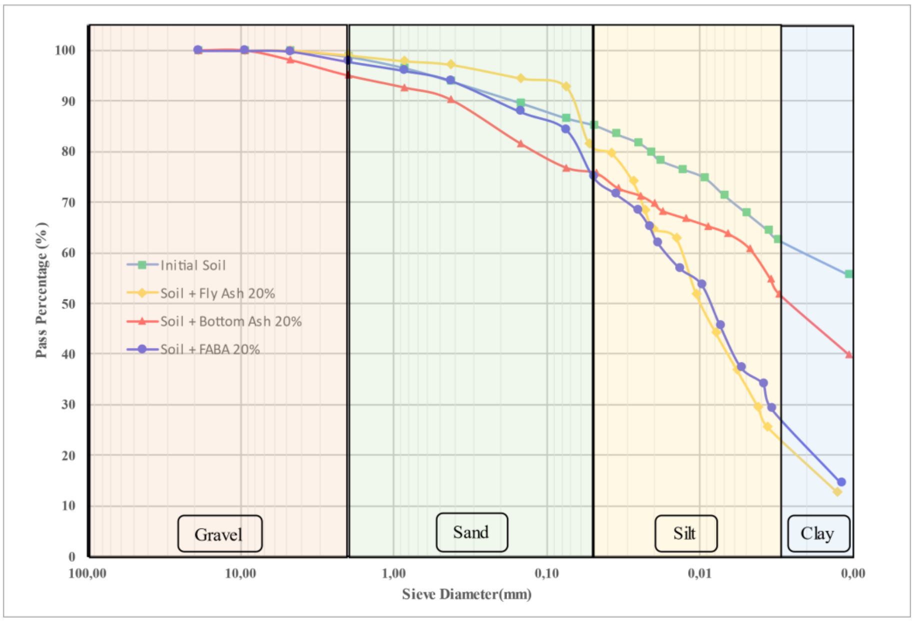

Figure 5. Soil Grain Gradation

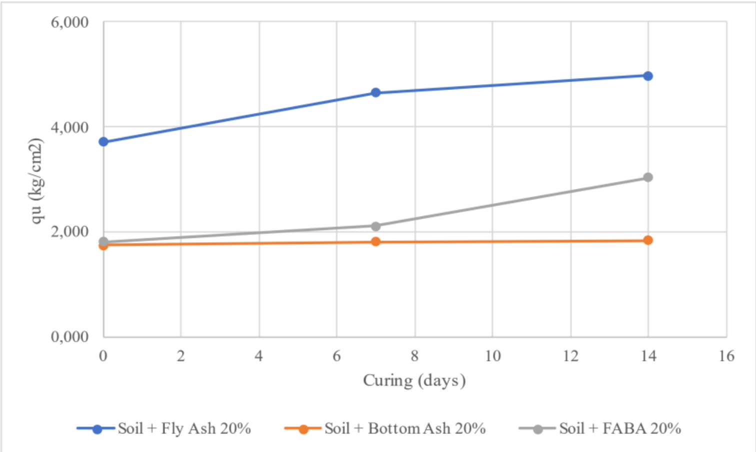

Figure 6. Effect of Curing on Unconfined Compressive Strength Values

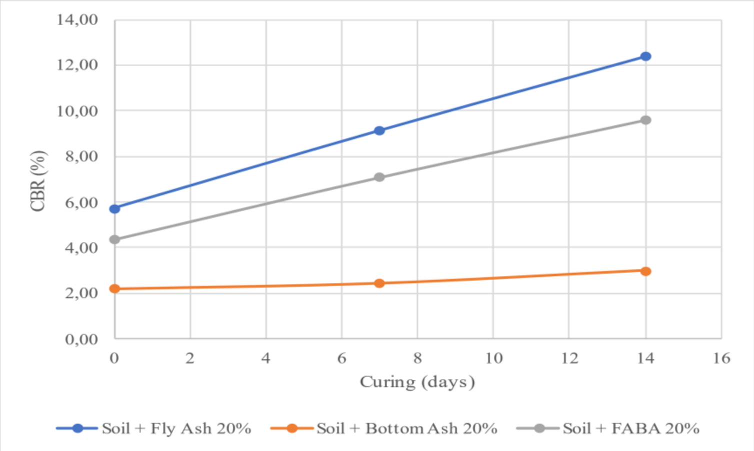

Figure 7. Effect Of Curing on CBR Values

From several soil parameter test results, it is known that soil stabilized with FA shows the best improvement, followed by soil stabilization with FABA. Meanwhile, soil stabilization with BA does not show significant improvement. This is in line with previous research by Dissanayake, et al. (2017) comparing the performance of stabilized soil with FA and BA, where soil stabilization with FA showed better improvement compared to soil stabilization with BA. This is evidenced by a decrease in soil PI by -25% and an increase in q_u value by 439.8% for soil stabilized with FA, while the decrease in soil PI stabilized with BA is -20.83% % and an increase in q_u value by 129,9%.

Thus, it can be concluded that soil stabilization on the Trengguli National Road Section - Bts. Demak/Kudus Regency is most suitable using FA. This is due to the pozzolanic reaction of calcium oxide (CaO) minerals in FA and BA presented by Onyelowe, et al. (2021), where based on the results of XRF testing (**Table 2.**) shows that FA has more CaO content when compared to BA. And in the 50:50 composition FABA mixture, the CaO content is still below FA for the same mixture level.

Table 5. Suitability of Embankment Material Requirements

Types of Embankment	Embankments Requirement	Soil + FA 20%		Soil + BA 20%		Soil + FABA 20%	
Ordinary Embankments	1.CBR Lab (soaked) ≥6%	12,39	Match	3	Unmatch	9,6	Match
	2.Not high plasticity	No	Match	No	Match	No	Match
	3.Not A-7-6 in AASHTO Classification	A-7-5	Match	A-7-6	Unmatch	A-7-5	Match
	4.Not CH in USCS Classification	MH	Match	CH	Unmatch	MH	Match
	5.Not OL, OH and Pt Classification	No	Match	No	Match	No	Match
	6.Activity value ≤1,25	1,13	Match	0,62	Match	1,03	Match
Selected Embankments	1.CBR Lab (soaked) ≥6%	12,39	Match	3	Unmatch	9,6	Unmatch
	2.Not high plasticity	No	Match	No	Match	No	Match
	3.Not A-7-6 in AASHTO Classification	A-7-5	Match	A-7-6	Unmatch	A-7-5	Match
	4.Not CH in USCS Classification	MH	Match	CH	Unmatch	MH	Match
	5.Not OL, OH and Pt Classification	No	Match	No	Match	No	Match
	6.Activity value ≤1,25	1,13	Match	0,62	Match	1,03	Match

To support sustainable construction, from the **Table 5.** above conclude that FA stabilized soil can be used as selected embankment material and ordinary backfill, while FABA stabilized soil can be used as ordinary embankment material in highway construction with activity value as shown in **Table 6.**

Table 6. Soil Activity Value

Value	Initial Soil	Soil + FA 20%	Soil + BA 20%	Soil + FABA 20%
PI	43,23	27,07	31,83	28,87
% Clay	62,00	24,00	51,50	28,00
Activity (A)	0,70	1,13	0,62	1,03

CONCLUSION

From the laboratorium test result of soil parameters, can be concluded that:

1. Initial Soil of National Road Section Trengguli - Bts. Demak/Kudus is one of the national road sections in Central Java Province categorized as fat clay (CH) occording to USCS and according to AASTHO as A-7-6 with medium consistency and very poor CBR.
2. The optimum mix percentage of stabilization material by maximum dry density of compaction standard proctor are soil with 20% of FA, soil with 20% of BA, and soil with 20% FABA.
3. Stabilized soil shown an improvement condition from initial soil conditiona as followed:
   a. Soil with 20% FA categorized as inorganic silt (MH) occording to USCS and according to AASTHO as A-7-5 with very stiff consistency and fair CBR after 14 days that fitted to selected and ordinary embankment material requirements.
   b. Soil with 20% BA categorized as fat clay (CH) occording to USCS and according to AASTHO as A-7-6 with stiff consistency and poor to fair CBR after 14 days that didn't fit to selected and ordinary embankment material requirements.
   c. Soil with 20% FABA categorized as inorganic silt (MH) occording to USCS and according to AASTHO as A-7-5 with very stiff consistency and fair CBR after 14 days that fitted to ordinary embankment material requirements.

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