Expansive soil causes road construction damage in the form of cracks or deformations due to changes in moisture content. One method to address this issue is soil stabilization using additive materials. Special additives can sometimes be expensive; hence it is necessary to use additive materials based on industrial waste as a waste management solution to solve the problem of expansive soil as a road construction subgrade. This study aims to analyze the effects of adding two types of industrial waste, namely fly ash (FA) and waste foundry sand (WFS), regarding the microstructure, physical, and mechanical properties of expansive soil. The method of stabilizing expansive soil involves mixing the soil with 9 % FA and various levels of WFS (0 %, 7.5 %, 10 %, 15 %) based on the dry weight of the soil. Microstructure testing includes quantitative X-ray diffraction and scanning electron microscopy. Physical property testing includes specific gravity, Atterberg limits and sieve analysis. Mechanical testing, i. e. compaction, California Bearing Ratio, swelling, and Triaxial tests were conducted. Soil stabilized with 9 % FA and 15 % WFS shows a significant increase in the internal friction angle and cohesion, reducing swelling by 67.18 % compared to the original soil swelling. The addition of 9 % fly ash and 15 % WFS to expansive soil reduces the content of montmorillonite. Natural expansive soils have a very poor soaked CBR of 0.94 %, while stabilized soils with 9 % FA and 15 % WFS have a soaked CBR of 6.46 %. This means that the soaked CBR of the stabilized soil meets the minimum CBR required for road subgrade construction. A mixture of 9 % FA and 15 % WFS in expansive soil can be recommended as a material for stabilizing expansive soil due to its ability to improve microstructure and mechanical properties

Keywords: expansive soil, stabilization, WFS, FA, microstructure

UDC 666
DOI: 10.15587/1729-4061.2023.286991

IDENTIFYING THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF EXPANSIVE SOIL STABILIZED USING FLY ASH AND WASTE FOUNDRY SAND

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Received date 22.09.2023
Accepted date 04.12.2023
Published date 22.12.2023

How to Cite: *Gunarti, A. S. S., Zaika, Y., Munawir, A., Suryo, E. A., Harimurti (2023). Identifying the microstructure and mechanical properties of expansive soil stabilized using fly ash and waste foundry sand. Eastern-European Journal of Enterprise Technologies, 6 (6 (126)), 31–40. doi: https://doi.org/10.15587/1729-4061.2023.286991*

1. Introduction

The condition of transportation infrastructure in Ciampel district, West Java, Indonesia, often experiences damage due to the presence of expansive soil. Besides the significant issues related to shrink-swell behavior due to changes in moisture content, civil engineering constructions in expansive soil face various problems such as landslides, retaining wall failures, deformations, settlements, etc. This area mostly consists of expansive soil that doesn't meet the required subgrade specifications, thus requiring treatment.

Manufacturers frequently produce waste as a byproduct of their operations, which requires proper management to make it useful, particularly for soil improvement purposes. Industrial waste such as waste foundry sand (WFS) and fly ash (FA) contains specific components that can enhance the behavior of expansive soil. Foundry sand is the discarded sand from the production of solid metal casting molds. WFS is typically disposed of in landfills. However, the engineering properties of WFS make it suitable for use in highway structure systems, offering opportunities for high-volume reuse [1]. Industrial waste like fly ash contains specific compounds that can be utilized as a stabilizer for expansive soil [2]. The lack of innovation in waste management to address the issue of expansive soil as a road construction subgrade motivated this research.

Waste foundry sand and fly ash are prominently anticipated to serve as additive materials for expansive soil in road subgrades, offering a cost-effective alternative to expensive manufactured additives. Additionally, the local conditions in the West Java industrial area often involve expansive soils that frequently damage road structures. There is a need for soil improvement engineering using local content as an alternative additive for expansive soil, simultaneously addressing industrial waste management and environmental sustainability. Therefore, the effect of adding waste foundry sand and fly ash on expansive soils as stabilization additives to shear strength and swelling is very relevant and needs to be investigated for the improvement of road construction subgrades.

2. Literature review and problem statement

The improvement of expansive soil with lime for flexible pavement embankment was designed [3]. Based on Finite

Element Method (FEM) analysis using computer software, the results showed that the application of a 5 m high embankment with traffic load is considered a static load, leading to a reduction in the potential for damage, as there is compressive strain on the road surface subjected to traffic loads. Lime also reduces the overall settlement. This study used non-waste additives. The paper [4] also conducted research on lime and fly ash as expansive soil stabilization materials, which resulted in a reduction in the plasticity index. This study used two types of additives namely fly ash and lime. The process of soil stabilization with lime involves the cost of importing, grinding, and distributing lime to the project site so it is not quite easy to use. Expansive soil stabilized using shell ash [5] reported that the addition of shell ash to expansive soil can improve soil chemical properties and achieve better compaction. The soil that needs stabilization possesses a variety of traits, including soil type, clay content, and moisture level. Due to this diversity, shell ash stabilization may be challenging because different areas may see differing levels of success.

The improvement of expansive soil stabilized with industrial waste, specifically waste glass powder (WGP), was investigated [6]. The results reported by the researcher indicate that the addition of WGP to expansive soil has a significant impact on the consistency and shear strength of the soil samples. Furthermore, the improvement of the expansive subgrade soil with 15 % WGP resulted in a reduction in sub-base thickness of approximately 63 %. Water glass powder may not be widely available and can have a relatively high cost. This can be an obstacle in the application of soil stabilization using water glass powder, especially in projects with limited budgets. Another previous paper [7] conducted a study on expansive soil stabilized using metakaolin and fly ash modified with geopolymers, lime, and gypsum. The results reported a significant improvement in soil shrink-swell behavior. Based on previous research related to the stabilization of expansive soil using industrial waste, it not only provides an alternative to conventional material usage but also contributes to environmental pollution control. Several waste materials used include fly ash, marble dust, casting sand, rice husk ash, and others. In most places, these waste materials are disposed of in open areas, causing numerous problems for the local community and workers in the vicinity. Due to the depletion of natural resources, there is an increased utilization of waste materials for the same purpose, which is soil stabilization. Utilizing these waste materials will not only reduce pollution but also decrease human reliance on natural resources, thereby promoting a more sustainable construction approach.

A study on soil stabilization using marble dust and foundry sand was conducted [8]. The results showed that the soil stabilized with foundry sand showed a significant increase in California Bearing Ratio (CBR) value compared to the untreated soil without additives. This study used one type of industrial waste, WFS, and did not combine it with other industrial wastes. Research on the characteristics of subgrade soil using foundry sand and iron turning waste was conducted [9]. Based on the study, it can be concluded that foundry sand and iron turning, which are waste materials, can be utilized for the stabilization of weak subgrade soil materials to enhance soil strength. This, in turn, results in an increase in CBR and a reduction in pavement thickness, leading to cost savings in construction. Iron turning has the disadvantage of being susceptible to oxidation reactions with air and water. A study on soil stabilization using two types of industrial waste, namely dust sand foundry (DSF) waste and silica sand (SS) waste, has been conducted [10]. The research identified the best waste additive composition for the highest CBR value, which was 5 % DSF and 5 % SS, resulting in a 47.9 % increase in CBR value compared to the untreated soil without additives. This research uses similar waste, namely sand waste. Both of these wastes cannot function as cementation, only as fillers. Research on foundry sand waste has also been conducted by several previous researchers. The study of waste foundry sand used as backfill geomaterial for soil retaining structures was conducted [11]. The study reported that lateral displacement was reduced by 30 % and 50 % in single and double geogrid layers, correspondingly. This research only uses one type of waste used for geomaterial backfill. A review on the utilization of WFS, quarry dust, demolition wastes, and rubber scrap has been conducted [12]. They concluded that the engineering properties of expansive soils are improved and have the potential to be used as soil stabilizers in field construction and are also economical. This study does not review research that combines two types of waste as expansive soil stabilization material. The work [13] concluded that replacement of foundry sand to some extent improves the durability as well as strength properties of concrete but simultaneously decreases the slump value with increasing replacement level of waste foundry sand. This study uses WFS applied to concrete, not yet applied to expansive soil stabilization materials. The work [14] concluded that compaction efforts on compacted foundry sands treated with cement kiln dust can meet the minimum recommended CBR values. Cement kiln dust can have a relatively high cost, especially if it has to be imported or specially processed for soil stabilization projects. A study on expansive soil stabilization on subgrade using coir waste was conducted [15]. The results showed that stabilization of expansive soil with coir waste can improve compaction, modulus of elasticity and CBR. Coir waste is easily degraded by microorganisms and water. This can lead to long-term degradation in the mechanical properties of the improved soil, especially if exposed to moist environmental conditions.

Waste foundry sand is reported to be a viable and cost-effective alternative additive material. A study on the stabilization of expansive soil using industrial waste, specifically fly ash and dolochar was conducted [16]. The research encompassed the evaluation of engineering properties such as unconfined compressive strength and CBR of expansive soil collected from the Balasore district in Odisha. The soil was stabilized with varying proportions of fly ash and dolochar to predict the influence of these additives on the engineering properties and characteristics of expansive soil.

It was found that both fly ash and dolochar improved the CBR and reduced various index properties, including liquid limit, plastic limit, plasticity index, swelling index, and UCS, thereby enhancing the strength parameters of expansive soil. The availability of dolochar may be limited, especially in projects located in areas far from steel production sources. The use of Class C fly ash for stabilizing expansive soil, reporting that the addition of 20 % fly ash reduced the potential for expansion was investigated [17]. Changes in the physical properties and expansion potential of Sample

A due to the addition of fly ash resulted from an increase in particle size up to a certain limit and chemical reactions that caused direct flocculation of clay particles. The reduction in swelling potential during curing can be attributed to the pozzolanic properties and depends on the self-hardening time (formation of cementitious compounds) derived from fly ash. This study did not combine the two types of waste.

The work [18] reported that plasticity index, free swell, swelling potential and axial shrinkage decreased, and unconfined compressive strength increased. This study used one type of waste, fly ash, and did not combine it with other industrial wastes. Soil stabilization using a combination of fly ash and cement was conducted [19]. The results showed a significant increase in strength and durability and reduced swelling and plasticity. This study used fly ash but because it is combined with cement, it requires a lot of money. The paper [20] reported that a mixture of fly ash and reinforced fiber with a length of 12 mm and a percentage of 1 % can increase the bearing strength and reduce swelling. This research has a longer stage than the research with grained additives because the polypropylene fibers must first undergo a size change from their original size. The work [21] resulted in an increase in CBR and compressive strength values as a result of mixing soil with fly ash. This research only used one type of waste, not combining it with other wastes that require management.

The work [22] reported that the combination of fly ash and WFS improves bearing capacity and compaction. The paper [23] concluded that the use of FA and WFS as soil stabilization additives has a good effect with a large increase in the value of bearing capacity (CBR) that occurs. However, these studies have been limited to Proctor compaction tests and California Bearing Ratio (CBR) tests, without investigating the microstructure, swelling potential, and undrained shear strength through Triaxial Unconsolidated Undrained tests on expansive soil stabilized using a combination of these two types of waste materials, especially on the specific characteristics of expansive soil in Ciampel-Karawang, Indonesia.

Many studies of soil stabilization use expensive additive materials such as cement or lime, so there is a need for research utilizing industrial wastes such as FA and WFS, for environmental management and subgrade pavement of road construction, for economic value. Research with a combination of two types of waste FA and WFS is still very limited. Previous studies on soil stabilization using FA and WFS have not presented the swelling value, shear strength and microstructural changes that occur. Based on previous research studies, the current research is focused on the analysis of expansive soil stabilized using two types of industrial waste, namely waste foundry sand and fly ash, with a specific emphasis on swelling characteristics, shear strength, and microstructure.

3. The aim and objectives of the study

The aim of the study is to identify the microstructure and mechanical properties of expansive soil stabilized using fly ash and waste foundry sand, with a view to assessing the effectiveness of an environmentally friendly approach to soil improvement in civil engineering applications (road subgrades).

To achieve this aim, the following objectives are accomplished:

– to investigate the influence of adding fly ash and waste foundry sand on the physical and mechanical properties of expansive soil;

– to investigate the impact of the addition of WFS and FA on its microstructure.

4. Material and methods

The expansive soil from the village of Ciampel, Karawang, West Java, Indonesia is the subject of the research. Fly ash is gathered from the Steam Power Plant (PLTU) in Paiton, East Java, Indonesia, while WFS originates from a metal casting factory in the industrial area of East Karawang, West Java, Indonesia. The research aims to reuse industrial waste, WFS, and FA, by utilizing them as additive materials (stabilizers) for Ciampel's expansive soil. WFS acts as a filler, while FA serves as cementation. The impact of adding WFS and FA to Ciampel's expansive soil is evaluated based on the improvement of its mechanical properties. Mechanical properties of soil represent the behavior characteristics of soil mass structures when subjected to a force or pressure, explained in technical terms of mechanics.

Fig. 1 displays the waste materials used in this study, i.e. waste foundry sand and fly ash. Waste foundry sand is fine sand with a blackish grey color while fly ash is fine dust with a brownish grey color.

Fig. 1. Waste foundry sand and fly ash

In this study, variations of waste foundry sand additive material were set at 0 %, 7.5 %, 10 %, and 15 %, while fly ash was added at 9 % based on the dry weight of the soil.

The research process from start to finish can be explained in the research flowchart in Fig. 2. The soil, once mixed with WFS, FA, and with the optimum moisture content, was compacted using the Proctor test. Subsequently, it underwent curing for 4 days, followed by testing for physical properties, mechanical properties, and microstructure analysis.

The physical properties included specific gravity (ASTM D854), liquid limit, plastic limit, plasticity index (ASTM D4318), and shrinkage limit (ASTM D427). A sieve analysis (ASTM D421) was performed on natural soil to determine particle size distribution. Mechanical properties comprised compaction testing (ASTM D698), CBR (ASTM D1883), and Triaxial Unconsolidated Undrained (ASTM D2850) tests. Microstructure analysis was carried out by X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) testing. The research process from start to finish can be explained in the research flowchart in Fig. 2.

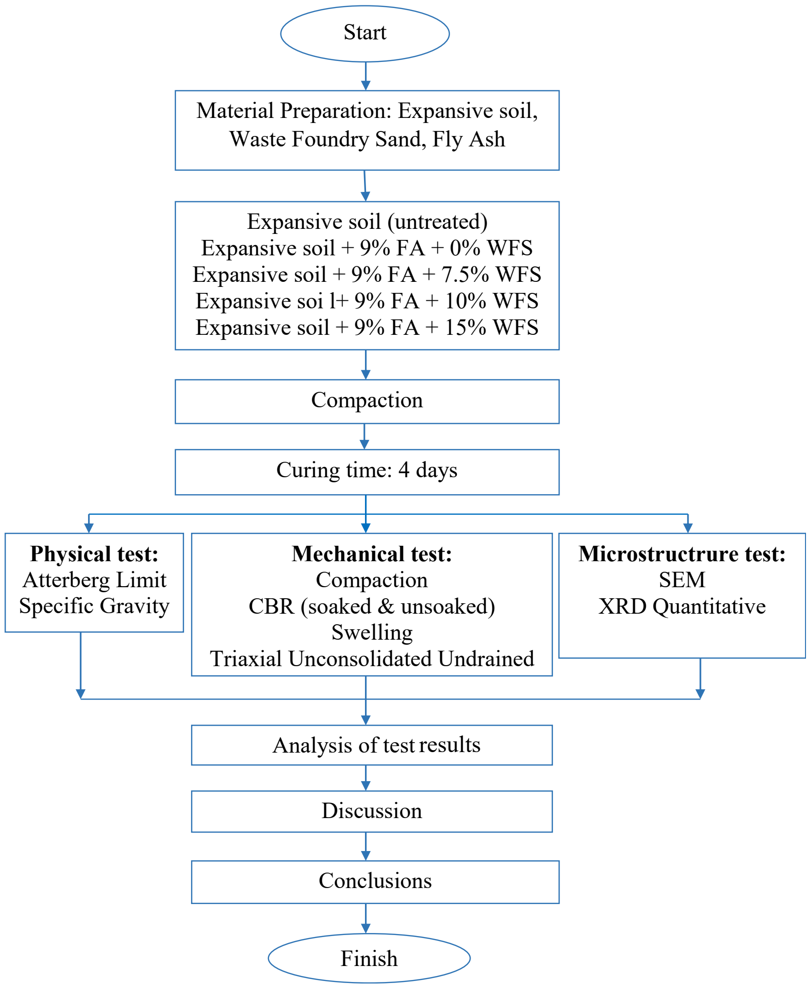


Fig. 2. Research flowchart

5. Results of the microstructure and mechanical properties of expansive soil stabilized using FA and WFS

5. 1. Physical and mechanical properties test

The USCS Classification System is divided into two groups, i. e. 1. The coarse-grained soil group (percentage passing sieve No. 200<50 %) and 2. The fine-grained soil group (percentage passing sieve No. 200>50 %). The results of the grain size analysis show that the percentage of soil particles passing sieve No. 200 is greater than 50 %, which is 89.64 %. This means that the natural soil falls into the fine-grained soil category. The physical test results are presented in Table 1. Table 1 presents a comparison of the liquid limit (LL), plastic limit (PL), shrinkage limit (SL), and plasticity index (PI), as well as the specific gravity (GS) of natural soils and variants of soil mixtures.

Table 1

Physical properties of soil

Variants of soil mixtures	LL (%)	PL (%)	SL (%)	PI (%)	Specific Gravity
Natural soil	72.27	21.51	10.68	50.77	2.634
Soil+9 %FA+0 %WFS	66.33	23.96	14.95	42.37	2.640
Soil+9 %FA+7.5 %WFS	56.27	27.62	19.02	28.65	2.671
Soil+9 %FA+10 %WFS	54.47	28.55	20.67	25.91	2.685
Soil+9 %FA+15 %WFS	52.81	29.10	21.05	23.71	2.707

The mechanical test results are presented in Table 2. The addition of FA and WFS to the soil shows improved density levels. The addition of 9 % FA waste to the soil mixed with varying percentages of WFS demonstrates a decrease in swelling values as the WFS content in the mixture increases. Conversely, the bearing capacity and shear strength values increase.

Fig. 3 presents the swelling values for each soil mixture variant. The greater the content of mixed WFS, the smaller the swelling that occurs. The natural soil has a swelling value of 9.820 %. The smallest swelling was found in the soil mixed with 9 % fly ash and 15 % waste foundry sand, which is 3.222 %. This means that the swelling value has been reduced by 67.19 % from the natural soil swelling. The addition of FA and WFS can improve the swelling of expansive natural soil.

Fig. 4 shows a comparison of the bearing capacity values between natural soil and soil mixtures. The soil's bearing capacity, as determined by the California Bearing Ratio (CBR) test, exhibits significant improvement in the soil mixtures. The unsoaked CBR value for natural soil is 8.98 %. Soil mixed with only 9 % FA without WFS has an unsoaked CBR value of 11.80 %. Meanwhile, the unsoaked CBR values for soil mixed with 9 % FA and various percentages of WFS (7.5 %, 10 %, 15 %) are 13.97 %, 15.61 %, and 16.02 %, respectively. The highest unsoaked CBR value is found in the soil mixture with 9 % FA and 15 % WFS, which experiences a 78.39 % increase in unsoaked CBR value compared to the original soil's unsoaked CBR value.

The natural soil has a very low soaked CBR value of 0.94 %. The soaked CBR value for soil mixed with only 9 % fly ash is 1.94 %. Soil mixed with 9 % fly ash and various levels of WFS (7.5 %, 10 %, and 15 %) has soaked CBR values of 3.81 %, 5.16 %, and 6.46 %, respectively. The best soaked CBR value is found in the soil with a mixture of 9 % fly ash and 15 % WFS, which experiences an increase of 587.23 % compared to the soaked CBR value of natural soil.

Fig. 5 presents the values of the internal friction angle (ϕ) and cohesion (c) from the Triaxial Unconsolidated Undrained tests. The natural soil has an internal friction angle value of 11.871° with a cohesion of 0.657 kg/cm^2. The soil mixed with 9 % fly ash without WFS has an internal friction angle of 14.504° with cohesion of 1.226 %. Meanwhile, the soil mixed with 9 % FA and varying percentages of WFS, 7.5 %, 10 %, 15 %, respectively, has internal friction angle values of 16.499°, 18.449°, 18.819°, and cohesion values of 1.484 kg/cm^2, 1.511 kg cm^2, 1.560 kg/cm^2, respectively. The highest internal friction angle and cohesion were found in the soil mixture with 9 % FA and 15 % WFS, resulting in an increase of 58.52 % in the internal friction angle compared to the natural soil and an increase of 137.443 % in cohesion compared to the natural soil.

Table 2

Mechanical properties of soil

Variants of soil mixtures	OMC (%)	MDD (gr/cm^3)	Swelling (%)	Unsoaked CBR (%)	Soaked CBR (%)	ϕ (°)	C kg/cm^2
Natural soil	25.30	1.42	9.820	8.98	0.94	11.871	0.657
Soil+9 %FA+0 % WFS	24.00	1.47	6.635	11.80	1.94	14.504	1.226
Soil+9 %FA+7.5 % WFS	22.00	1.54	5.077	13.97	3.81	16.499	1.484
Soil+9 %FA+10 % WFS	21.00	1.59	3.852	15.61	5.16	18.449	1.511
Soil+9 %FA+15 % WFS	20.00	1.62	3.222	16.02	6.46	18.819	1.560

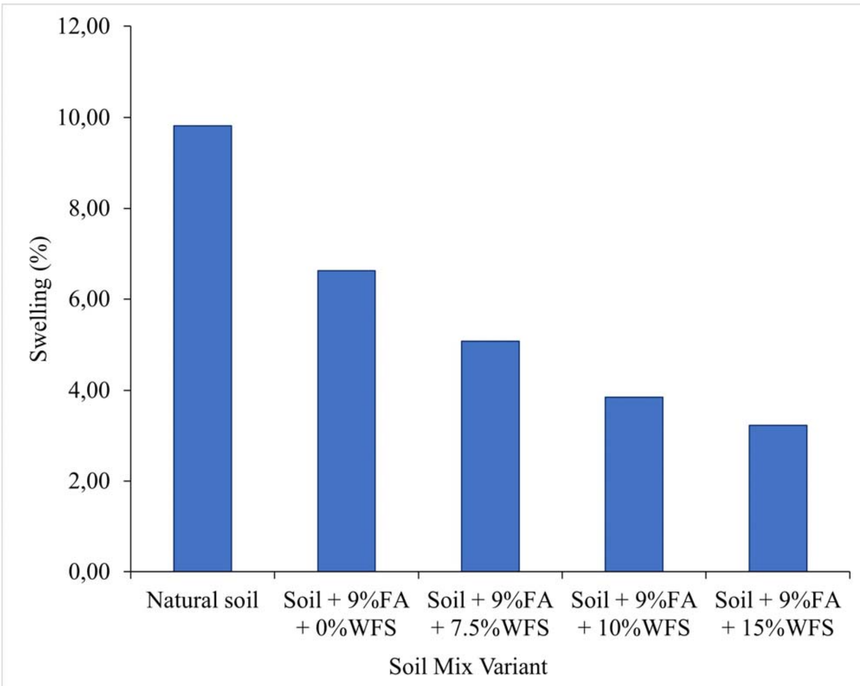


Fig. 3. Swelling of soil

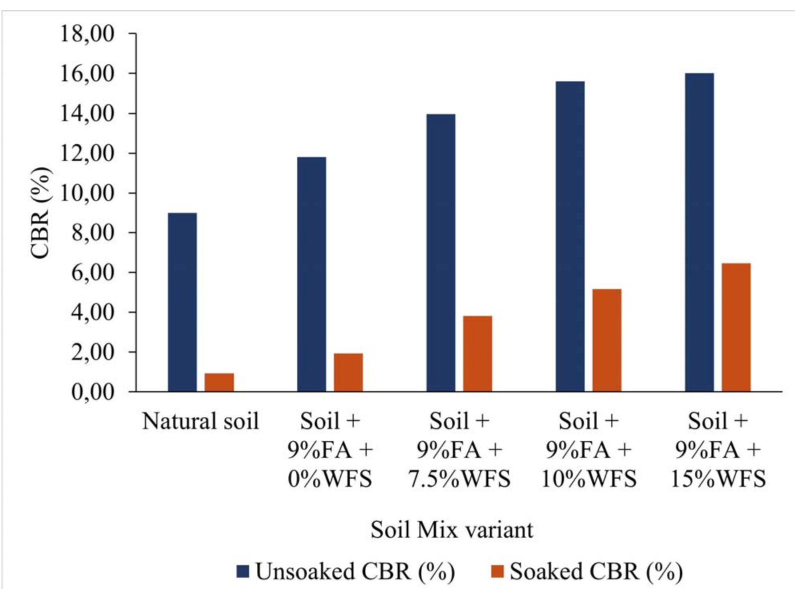


Fig. 4. California Bearing Ratio of soil

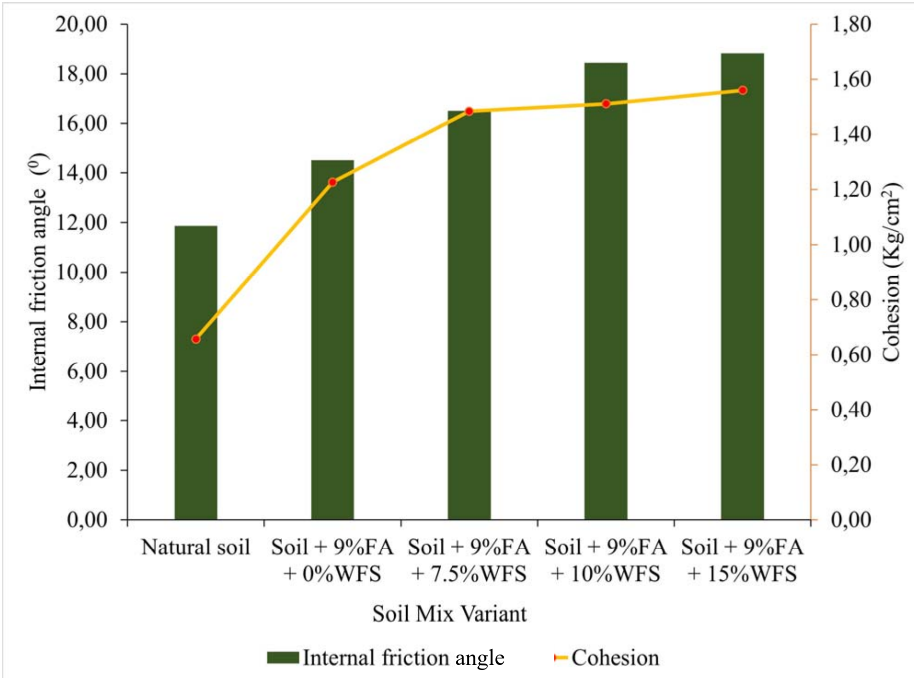


Fig. 5. Triaxial Unconsolidated Undrained tests of soil

5. 2. Mineral composition of the soil and microstructure

Mineral composition testing was conducted on natural soil and soil mixed with the waste composition that exhibited the best mechanical properties, namely the soil mixture with 9 % FA and 15 % WFS. Quantitative XRD analysis was performed to determine the dominant mineral composition, such as kaolinite, illite, montmorillonite, and other minerals commonly found in clayey soils. Microstructure analysis was carried out using Scanning Electron Microscopy (SEM). SEM was employed to analyze the grain morphology of the soil with high resolution, identify the shape and size of clay soil particles that can influence the physical properties of the soil, and identify minerals in the clay soil sample based on their morphology and microstructural characteristics.

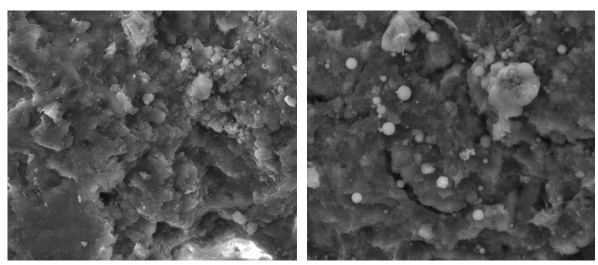
The soil mineral composition is presented in Table 3. Table 3 shows the most dominant mineral in the soil is quartz. The addition of waste materials, FA, and WFS to the soil results in changes in mineral content, with quartz becoming more abundant while montmorillonite decreases.

Table 3

Quantitative XRD analysis

Phase	Natural soil	Soil+9 %FA+15 %WFS
Quartz (%)	42.2	73.0
Albite (%)	21.2	4.1
Montmorillonite (%)	14.9	8.1
Kaolin (%)	11.6	–
Illite (%)	7.1	8.0
Pyrite (%)	1.5	<0.1
Siderite (%)	1.5	–
Cristobalite (%)	<0.1	–

SEM images are presented in Fig. 6. The basic concept of SEM analysis is to shoot/radiate a specimen with a beam of electrons accelerated under high vacuum conditions to produce particle images. The contrast in SEM images is a result of the diffraction scattering of light generated by various variations of microstructural elements. Fig. 6, *a* presents a photo of natural soil taken with SEM. Visually, the image in Fig. 6, *a* shows that the specimen material is composed of sheet-like mineral structures that can be classified as clay minerals.



a *b*

Fig. 6. SEM photos of soil:
a – Natural soil; *b* – Soil+9 %FA+15 %WFS

At the subsurface level, the sample exhibits a sheet-like mineral texture that appears to flocculate, resembling stacked sheets of paper. At the surface level, the sheet-like mineral texture appears to disperse with weak interlayer bonding. Detailed photos also reveal differences in the mineralogy and texture of each sample, which are undoubtedly influenced by their constituent minerals. Soil-forming elements are plate-shaped. Fig. 6, *b* presents SEM photos of soil with a mixture of 9 % FA and 15 % WFS. It can be observed that fly ash and WFS particles fill the soil voids, thus altering the arrangement of the soil's constituent minerals.

6. Discussion of the microstructure and mechanical properties of expansive soil stabilized using FA and WFS

Table 1 shows that the liquid limit (LL) of natural soil is 72.27 %, which is above 50 %. Therefore, after analysis using the plasticity chart with the plot line of plasticity index above line A, the soil falls into the category of high-plasticity non-organic clay soil (CH). The swelling value of natural soil (Table 2) is 9.82 %, classifying the soil as having a high degree of expansion [24]. The natural soil has a plasticity index of 50.77 % and a swelling value of 9.82 %. [25] states that a plasticity index ranging from 35–55 % and a volume change of 3–10 % are categorized as soils with high expansion potential. The addition of 9 % FA to the soil mixed with various percentages of WFS results in a reduction in the plasticity index as the WFS content in the mixture increases. In contrast, the specific gravity value increases.

These compounds (FA and WFS) can be added to reduce the possibility of swelling. Fig. 3 shows how swelling values decrease as the proportion of WFS in the soil combination with 9 % FA rises. The best swelling value was found in the combination of 9 % FA and 15 % WFS, which was 3.222 %, while the swelling value of natural soil was 9.820 %. The combination of 9 % FA and 15 % WFS soil had an improvement in swelling value of 67.19 % against the natural soil swelling. A pozzolanic substance called fly ash can be combined with calcium hydroxide to create cementitious compounds [21]. Fly ash can react with the soil's calcium ions to create calcium silicate hydrate (C-S-H) gel when it is introduced to expansive soil [21, 26]. Fly ash and calcium ions are combined to generate a C-S-H gel, which can lower soil porosity and fill up soil cavities [26]. This may result in a loss in the soil's ability to absorb water as well as a decrease in its capacity to swell [21, 26, 27]. Waste foundry sand is a byproduct of metal casting processes that can be used as a soil stabilizer [12, 28]. When leftover foundry sand is applied to expansive soil, it can fill voids and reduce porosity [12, 28]. The loss in porosity produced by the addition of fly ash and waste foundry sand might reduce the soil's water absorption capacity, which can lead to a drop in swelling potential [12, 21, 26–28].

Fly ash and waste foundry sand are industrial waste products that can be utilized to stabilize expansive soils at a minimal cost and in a sustainable way. The inclusion of these elements can raise the soil's California Bearing Ratio (CBR), an index used to assess the strength of soil subgrades and base course materials. Fig. 4 illustrates the comparison of CBR values between natural soil and the soil mixture with FA and WFS. The mixture of soil with 9 % FA and 15 % WFS produced the highest CBR value. In expansive soil, the mixture of fly ash and waste foundry sand generates a cementitious compound, filling pore spaces and lowering porosity. This reduction in porosity improves the soil's CBR value [21, 29, 30]. It also demonstrates that soaked CBR values are lower than unsoaked CBR values. Expansive soils have a high plasticity and swelling potential, which can reduce their load-bearing capability and strength when saturated [31–33]. Soaking expansive soils in water causes them to soften and become more malleable, which can reduce their strength and load-bearing capacity [31–33]. Soaking causes a decrease in strength due to various factors, including the dissolution of soil aggregates, the loss of soil structure, and an increase in water content [31, 33]. These factors can reduce the soil's ability to resist deformation and support loads [31, 33]. The soaked CBR value in the soil mixture with 9 % FA and 15 % WFS resulted in a soaked CBR value of 6.46 %. In Indonesia, the minimum required CBR value for subgrade in road construction is 6 % [34]. Therefore, the soaked CBR value in the soil mixture with 9 % FA and 15 % WFS meets the standards for the Indonesian highway subgrade.

Fig. 5 shows the values of the internal friction angle and cohesion in natural soil and soil mixtures with FA and WFS. The soil mixture containing 9 % FA and 15 % WFS had the highest internal friction angle and cohesiveness, with an increase of 58.52 % in internal friction angle compared to natural soil and a 137.443 % increase in cohesion compared to natural soil. Fly ash and waste foundry sand are industrial waste products that can be utilized to stabilize expansive soils at a minimal cost and in an environmentally friendly way. This combination can raise the soil's cohesion value and internal friction angle, both of which are critical factors for soil strength. A chemical reaction occurs when fly ash and WFS are combined into the soil, filling voids and decreasing soil porosity. The reduction in porosity caused by the addition of fly ash and WFS can enhance the soil's cohesiveness and internal friction angle [12, 21, 35, 36]. This is because decreasing porosity can improve soil strength by increasing the interlocking of soil particles [12, 21, 35, 36].

Based on Table 3, the soil mixture with 3 % FA and 15 % WFS confirms a lower montmorillonite content compared to the natural soil. The reduction in montmorillonite in the soil mixture of 9 % FA and 15 % WFS indicates that the soil is harder than the natural soil. Montmorillonite is a clay mineral with a high water absorption capacity and swelling potential [37]. The loss in porosity produced by the addition of fly ash might reduce the soil's water absorption capacity, which can lead to a drop in montmorillonite concentration [21, 28]. Reduced montmorillonite content in fly ash-stabilized soils can result in better soil qualities such as reduced flexibility and increased strength.

The microscopic morphology of the expansive soil modified by 9 % fly ash and 15 % WFS is shown in Fig. 6. Fig. 6 shows that the modified soil structure is more compact than the natural soil, and the pores or fine cracks are filled with fly ash and WFS particles. Enlargement of the image shows that the hydration product of fly ash (C-S-H) reacts with soil particles. Natural soil particles undergo a cementation process, forming a solid block structure, and the integrity of the soil particles increases [38, 39].

The use of FA and WFS as expansive soil stabilization materials has several positive effects including improving soil density, increasing cohesion and shear strength, increasing bearing capacity, reducing swelling and shrinkage. Because waste foundry sand and fly ash are readily available at low or no cost, using them in soil stabilization can be more affordable than conventional methods. It is also an environmentally friendly method that recycles industrial byproducts and lessens the need for landfill disposal. FA and WFS as expansive soil stabilization materials can be used as an alternative solution to expansive soil improvement in addition to conventional methods such as soil stabilization using lime, cement, and other additives.

The limitation of this study is the maximum set limit of waste foundry sand (WFS) at 15 % of the dry weight of the soil, while the mechanical property tests show that the best mechanical values are found in soil mixed with 9 % fly ash and the highest percentage of WFS, which is 15 %. Therefore, it is still possible that a higher WFS percentage may result in even better mechanical properties. Fig. 4, 5 show graphs that continue to rise as the WFS content in the soil increases, without showing a decrease in the graphs, indicating that the most optimal mechanical value has not yet been obtained. Hence, further research is needed to explore additional variations of WFS and FA mixtures to achieve the most effective mixture with the best mechanical values. Further research is needed on the durability of FA-WFS soil mixtures to wet-dry cycles as representative of seasonal changes.

7. Conclusions

1. The addition of FA and WFS to expansive soil has a significant effect on the physical and mechanical properties. Soil with an FA and WFS mixture can reduce the plasticity index. The combination of two types of waste materials (FA and WFS) can increase the bearing capacity and shear strength of soil. The soil with 9 % fly ash and higher WFS content (15 %) showed the highest bearing capacity (CBR) of 16.02 % and greater shear strength (internal friction angle of 18.819° and cohesion of 1.560 kg/cm^2). Swelling values can be decreased in expansive soils by adding FA and WFS. The best mechanical properties were observed in soil mixed with 9 % fly ash and 15 % waste foundry sand with the lowest swelling value of 3.222 %. This is because the chemicals in fly ash and WFS have chemical reactivity, which alters the structure and swelling properties of expansive soils. Due to their small particle sizes, FA and WFS can fill the pores in the soil, giving it a denser structure and higher strength.

2. The findings of a quantitative X-ray diffraction test revealed that the natural soil's montmorillonite content was 14.9 %, but the soil stabilized with 9 % FA and 15 % WFS had 8.1 % montmorillonite. The montmorillonite content in the stabilized soil was reduced. Waste materials can be added to expansive soils to reduce their concentration of montmorillonite. This is accomplished indirectly through dilution, chemical reactions, and improved soil characteristics, which ultimately reduce the expansiveness of the soil. Scanning electron microscopy showed that the microscopic morphology of the expansive soil stabilized with 9 % FA and 15 % WFS was more compact than the natural soil, and the pores or fine cracks were filled by fly ash and WFS particles.

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.

Financing

This research was funded by the Directorate General of Higher Education (DRTPM), Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, under the Doctoral Dissertation Research (PDD) scheme Grant, Contract Research number: 119/E5/PG.020.00.PL/2023, Sub-Contract Research number: 1133.4/UN10.C10/TU/2023 Fiscal Year 2023.

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.

Acknowledgments

The author would like to express gratitude to the Research and Community Service Institute (LPPM) of Brawijaya University and the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for their support and funding. This research was funded by the Directorate General of Higher Education (DRTPM), Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, under the Doctoral Dissertation Research (PDD) scheme Grant, Contract Research number: 119/E5/PG.020.00.PL/2023, Sub-Contract Research number: 1133.4/UN10.C10/TU/2023 Fiscal Year 2023.

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