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Use of steel slag to improve the mechanical properties of subgrades in clayey soils

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Abstract
Large quantities of steel slag are generated annually throughout the world. Some slag from steel manufacturing is reused in the generation of other materials, such as hot mix asphalt aggregate, pipe filling, concrete, among others. The research aims to enrich the mechanical characteristics of soils and minimize road construction costs. The objective of this research is to find a material that increases the mechanical properties of the subgrade in clay soils with different plasticity indices using Electric Arc Furnace Slag (EAF) in percentages: 5%, 15% and 25% of the weight of the soil. From the tests carried out on the soil samples using parameters, it was possible to classify them by the Unified Soil Classification System (USCS) and also by the American Association of Highway Transportation (AASHTO) as low and high clays. plasticity. When testing the samples in their natural state and the samples with EAF, results were obtained that showed an improvement in the physical and mechanical properties of the clay soils with the addition of EAF, increasing the values of the Bearing Capacity Ratio (CBR) and the maximum dry density. of the clay soil as the percentage of HAE in the mixture increased. The optimal HAE addition content corresponds to 25% of the weight of the soil.

Keywords: clay soils; EAF slag; stabilization; maximum dry density; CBR.

Uso de escoria de acero para mejorar las propiedades mecánicas de las subrasantes en suelos arcillosos

Resumen
Grandes cantidades de escoria de acero se generan anualmente en todo el mundo. Parte de la escoria de la fabricación de acero se reutiliza en la generación de otros materiales, como agregado asfáltico en mezclas calientes, relleno de tuberías, hormigón, entre otros. La investigación se centra en enriquecer las características mecánicas de los suelos y minimizar los costos de construcción de carreteras. El objetivo de esta investigación es encontrar un material que aumente las propiedades mecánicas de la subsección en suelos arcillosos con diferentes índices de plasticidad utilizando Escoria de Horno de Arco Eléctrico (EAF) en porcentajes: 5%, 15% y 25% del peso del suelo. A partir de las pruebas realizadas en las muestras de suelo utilizando parámetros, fue posible clasificarlas según el Sistema de Clasificación de Suelos Unificado (USCS) y también según el estado natural de la Asociación Americana de Oficiales de Transporte de Carreteras (AASHTO) como arcillas de baja y alta plasticidad. Al probar las muestras en su estado natural y las muestras con EAF, se obtuvieron resultados que mostraron una mejora en las propiedades físicas y mecánicas de los suelos arcillosos con la adición de EAF, aumentando los valores del Índice de Capacidad de Soporte (CBR) y la densidad máxima seca del suelo arcilloso a medida que aumentaba el porcentaje de EAF en la mezcla. El contenido óptimo de adición de EAF corresponde al 25% del peso del suelo.

Palabras clave: suelos arcillosos; escoria de EAF; subrasante; estabilización; CBR; densidad máxima seca.

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Notation

EAF	electric arc furnace slag
MDD	Maximum dry density
CBR	California Bearing Ratio
PI	Plasticity index
LL	Liquid limit
PL	plastic limit
C-1	Sample Calicata clay soil 1
C-2	Calicata sample clay soil 2
C-3	Calicata sample clay soil 3

1. Introduction

More than 1,951 million tons of crude steel have been produced globally in 2021 [28]. The manufacturing of this product generates a waste called “slag” that causes environmental problems [9], due to limitations in recycling [30].

In these last two decades there has been a growth in interest in the use of new materials in the construction industry (Rondon et al.,2018). Therefore, several studies have been carried out on the use of industrial waste in civil applications as an option for construction materials that can become less expensive and environmentally friendly and at the same time improve the physical and mechanical properties of the final result [21]. These residues can be used as replacement for soil and subgrade improvement of road pavement [21].

The subgrade is usually made up of natural soil, such as expansive clays. The clay material has characteristics that can be negative at the time of construction, such as: high potential for expansion and contraction, low load capacity and, finally, high compressibility; putting the age and performance of the pavement structure at great risk [24]. Therefore, it is important to make improvements to this type of soil, either with the incorporation of conventional or reusable materials (Shriful et al.,2022).

The stabilization of problematic soils with reusable byproducts is one of the most used procedures for the enrichment of their physical and mechanical characteristics [27]. This has increased the bearing capacity, increasing the mechanical resistance of the soil, the compressibility, durability and plasticity of the clay soil [22]. Many alternatives have been proposed as reusable industrial materials, from fly ash, silt, red mud [22]; including steel slag, the latter being the object of study for the stabilization of this investigation. The reuse of these slags would help in the elimination of these wastes and in reducing the excessive use of natural resources [9]. For Shalabi et al (2016), by using different percentages of added steel slag (0%, 15% and 30%), they demonstrate that, by increasing the steel content in clay soils, its CBR value increases and free swelling decreases. , this is why in this research a slag with different granulometry used in the research mentioned above and with different concentrations is used to determine if there is an improvement

This research is carried out with the objective of using steel slag in percentages of 5%, 15% and 25% depending on the weight of the soil, to improve the mechanical properties of subgrades in clay soils with different plasticity indices. For this, laboratory tests such as Modified Proctor and CBR will be carried out on three different samples of clay soils from the district of Chiclayo, Peru. Likewise, the maximum dry density (MDD) and the bearing capacity (CBR) will be determined for the three types of soil in their natural state and then for the soil with the additions in different percentages.

2. Methodology

2.1. Phase 1. Characteristics of the EAF

For the investigation it was necessary to obtain samples of waste from the steel industry. The slag came from the steel company SIDERPERÚ. The type of material used was Electric Arc Furnace Slag (EAF) with an average particle size of 1/2” as shown in Fig. 1. Finally, four bags of this material were obtained, with a total of 30 kilos each bag.

- Chemical composition of EAF

The chemical components of slag are affected by various factors, such as the type of material (scrap) that is melted, handling processes, operating variables and cooling rate (Guevara, 2022). Table 1 shows the percentages of the different chemical components present in the SIDERPERU slag.

2.2. Phase 2. Collection of clay soil samples

Clay soil samples were extracted from the excavation of 3 wells. They are called "sample in its natural state." The excavation was carried out at a depth of 1.50 m. Three bags of soil of approximately 80 kilograms each were obtained from each test pit.

Figure 1. SIDERPERU steel slags.
Source: self-made

Table 1.
Chemical composition of steelmaking slag (SIDERPERÚ, 2019)

Type of slag	%Oxides		% Metals	
Over , A, B, C	At $_{2}$ or $_{3}$	6.52	Ace	0.00089
	CaO	21.58	CD	0.00005
	Ugly	30.40	Cr	0.11
	MnO	6.14	Hg	0.00027
	MgO	10.62	Pb	0.009
	SiO_2	15.81	Zn	0.03
Fine	At $_{2}$ or $_{3}$	6.04	-	-
	CaO	29.60	-	-
	Ugly	20.10	-	
	MnO	4.53	-	-
	MgO	10.50	-	-
	SiO_2	15.05	-	-

Source: SIDERPERU company, 2016

2.3. Phase 3. Characteristics of the laboratory samples

- Physical properties of the sample in its natural state.

Laboratory tests were carried out to determine the physical characteristics of the three samples in their natural state. These were carried out at the Santo Toribio University of Mogrovejo. Within this, the following was determined: granulometric analysis, moisture content, Atterberg limits; and with these data determine the plasticity index of the samples in their natural state. All found according to MTC E 109 of MTC Materials Manual Testing.

a) First the water content was determined.
b) Then a granulometric analysis was carried out, this would determine what type of soil would be used by the USCS and AASHTO.
c) To calculate the liquid limit (LL), the sample was first mixed in a plastic container to properly homogenize it before carrying out the test. After this preparation, the resulting paste was placed in the Casa Grande glass, covering its entire surface. Using a groover, the sample was divided to begin the tapping process, following the guidelines established in the test method following the natural state given in ASTM D4318-05.
d) To determine the plastic limit (LP), a small portion of the previously homogenized container was extracted where its humidity was ideal to be able to form small bars with the soil with an approximate diameter of 3.2 mm as shown in Fig. 2, that will be necessary to make the present essay. The guidelines and parameters indicated in the ASTM D4318-05 standard were followed.
e) After finding the LL and PL values of each of the samples, the IP was calculated, using the following formula described by ASTM D4318-05.

$$IP=LL-LP$$

- Mechanical properties of the sample in its natural state.

To evaluate the mechanical properties of the samples, the Modified Proctor and CBR tests were carried out, which were carried out following the procedure described below:

a) A total of 5000 grams of soil from each of the extracted samples (C-1, C-2, C-3) were weighed, the slag from the Electric Arc Furnace (EAF) was also weighed to add them in the percentages. of 5%, 15% and 25%, both materials were placed together in an airtight bag to store them until the time of testing.
b) Using the modified Proctor test, the MDD and the optimal moisture content of the 3 samples were determined without addition and with the addition of slag. The method used in this test was method A as indicated in the MTC Materials Testing Manual, because the material of each of the samples passed through the No. 4 sieve and there was no retention, using the mold with a diameter of 4 inches with a total of 25 strokes per layer.
c) To carry out the CBR test and determine the resistant capacity of the soil as a subgrade, the following had to be carried out: the compaction of the clay sample in the CBR molds, the measurement of the expansion for a period of 4 days of each of the samples submerged in water. Subsequently, the penetration test was carried out on the samples in their natural state and with the addition of EAF.

Figure 2. 3.2 mm thick bars to determine the PL of C-3 clay soil samples.
Source: self-made

3. Results

3.1. Clay soils in their natural state

The results of the physical characteristics of the three samples in their natural state were obtained he following results in Table 2.

Table 2.
Results of physical properties of samples in the natural state C-1, C-2 and C-3.

Samples	C-1	C-2	C-3
% water content	19.92	20.96	19.71
L.L.	43.72	51.28	45.13
LP	20.18	22.83	20.47
IP	23.54	28.45	24.66

Source: self-made

Table 3.
Soil type classification using the USCS and AASHTO Systems.

Sample	SUCS Classification		AASHTO Classification	
	Symbol	Composition	Group	Symbol
C-1	CL	Low plasticity clay of sand	A-7-6 (14)	Clay soil of oor quality
C-2	CH	High plasticity clay with sand	A-7-6 (18)	Clay soil of poor quality
C-3	CL	Low plasticity clay of sand	A-7-6 (15)	Clay soil of oor quality

Source: self-made

Table 4.
Summary of mechanical property tests of samples in their natural state.

Properties	C-1	C-2	C-3	You
MDD 95%	1,701	1,729	1,682	g/cm4
Optimum toilet content	17	16.4	18.65	%
CBR at 100% MDD at 2.54 cm	5	4	3	%
CBR at 95% MDD up to 2.54 cm	4	3	3	%

Source: self-made

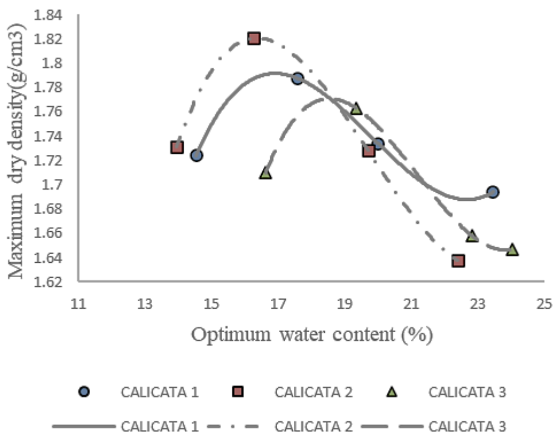

Figure 3. Modified Proctor plot of samples C-1, C-2 and C-3.
Source: self-made

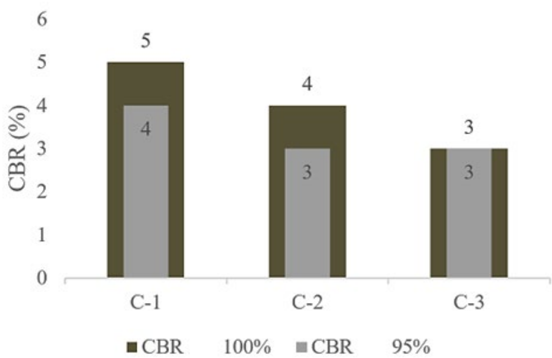

Figure 4. CBR at 1 inch (2.54 cm) penetration of raw samples C-1, C-2, and C-3.
Source: self-made

Table 5.
Maximum dry density and optimal moisture content of the experimental group of samples with addition.

Maximum dry density and optimum toilet content			
Samples	***% Addition of EAF slag***	***Maximum dry density (g/cm3)***	***Optimal Water Content (%)***
C-1	5	1,792	14
	15	1,881	13.5
	25	1921	13.2
C-2	5	1.84	15
	15	1,867	14.1
	25	1,859	14.6
C-3	5	1,786	17.6
	15	1.81	16.2
	25	1921	13.5

Source: self-made

In addition, the soil samples were classified by the USCS and AASHTO System, as can be seen in Table 3.

In the tests to determine the mechanical properties, the maximum dry density, the optimal water content and its CBR were obtained, obtaining the following results in Table 4.

Fig. 3 shows the Modified Proctor curves of sample 3 in its natural state, relating the dry density to the optimal moisture content.

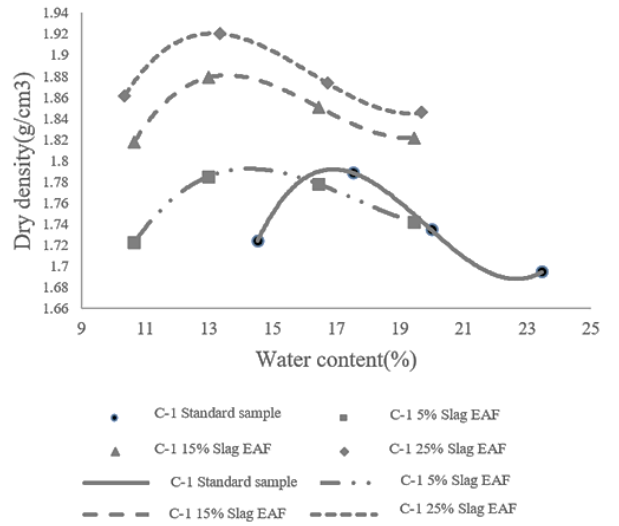

Figure 5. Modified Portfolio Graph of sample C-1 with addition of steel slag.
Source: self-made

For Fig. 4, the CBR results can be compared with the 95% and 100% of the three different natural state samples.

3.2. Clay soils with HAE

a) Maximum dry density

Below are the results to obtain the maximum dry density with the optimal moisture content for the experimental group by adding Electric Arc Furnace Slag in the doses of 5%, 15% and 25%.

Fig. 5 shows the Modified Proctor curves of C-1 with the addition of HAE slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal moisture content, also showing the behavior of C-1. sample in natural state.

Fig. 6 shows the Modified Proctor curves of C-2 with the addition of HAE slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal water content.

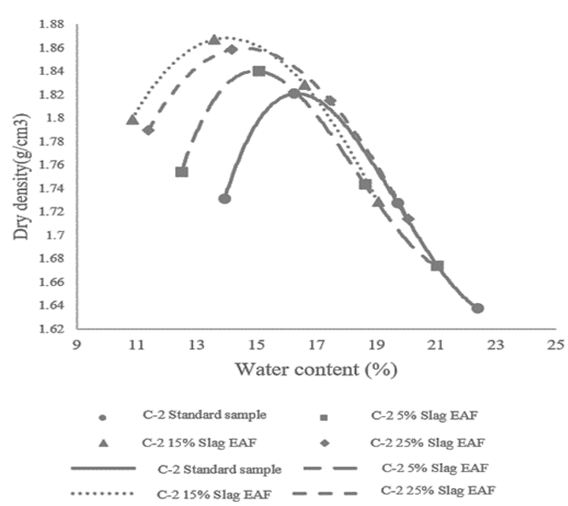

Figure 6. Modified Proctor plot of sample C-2 with addition of steel slag.
Source: self-made

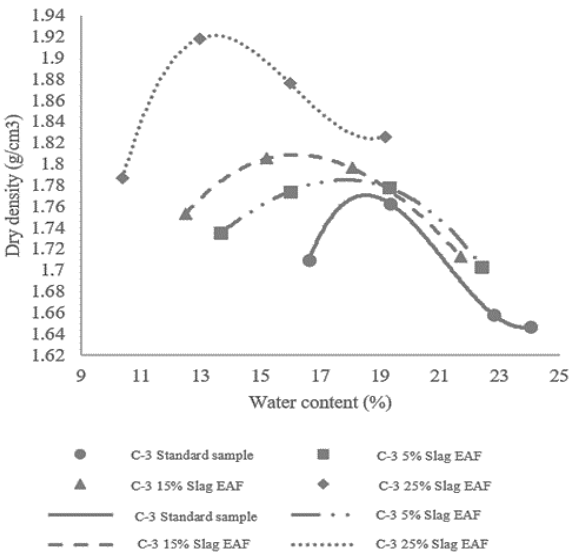

Figure 7. Modified Portfolio Graph of sample C-3 with addition of steel slag.
Source: self-made

Table 6.
Summary of mechanical property tests of the samples.

Properties	EAF	C-1	C-2	C-3	Und
MDD at 95%	5%	1702	1748	1687	g/cm4
	15%	1787	1774	172	
	25%	1825	1766	1825	
Optimum water content	5%	14	15	176	%
	15%	135	141	162	
	25%	132	146	135	
CBR 100% MDD at 2.54 cm	5%	6	6	7	%
	15%	7	7	8	
	25%	9	9	9	
CBR 95% MDD at 2.54 cm	5%	6	5	5	%
	15%	6	6	6	
	25%	8	8	8	

Source: self-made

And, finally, in Fig. 7, the Modified Proctor curves of C-3 are observed with the addition of EAF Slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal water content.

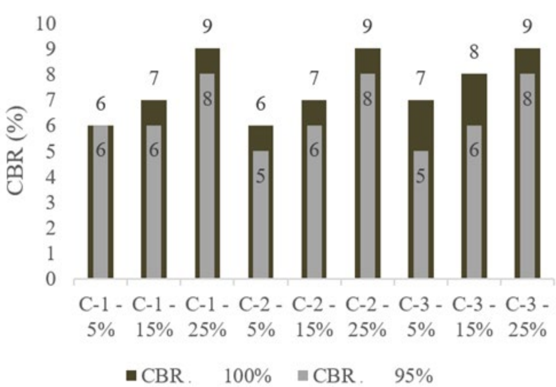

Figure 8. CBR at 1 inch (2.54 cm) penetration of C-1, C-2, and C-3 with EAF addition.
Source: self-made

a) Resistant capacity as subgrade by CBR

From the CBR test, the results are shown in Table 5 for the different clay soil samples with the addition of 5%, 15% and 25% HAE.

After the results, the CBR results can be compared with the 95% and 100% of the three samples with the different types of %EAF in Fig. 8.

4. Discussion

In the results, it was obtained that the moisture content of the samples in the natural state for C-1, C-2, C-3 was 19.92%, 20.96%, 19.71% respectively, as shown in Table 1. In addition, having found the LL and PL, the IP of all the samples was determined, with results of 23.54, 28.45 and 24.66, this characteristic is only shown by very clayey soils.

On the other hand, in the case of clay soils with the addition of electric arc furnace slag (EAF), the mixture with an addition of 25% of EAF achieved an DDM of 1,921 g/cm3 with an optimal moisture content of 13 .2%, as shown in Table 6. If sample C-1 in natural state is compared to samples C-1 with FAE, an increase in MDD can be observed from 1.701 g/cm3 to 1.921 g/cm3 with 25% incorporation of EAF, which represents a notable improvement of 13%.

In the case of sample C-2, it is observed that with the 25% EAF mixture, a DDM of 1,859 g/cm3 was achieved with an optimal moisture content of 14.6%, as shown in Table 6. In comparison with for the sample in the natural state C-2, there is a variation in the maximum dry density from 1.729 g/cm3 to 1.867g/cm3, which represents a variation of 8%.

Table 6 also presents the results corresponding to sample C-3 with the sum of different percentages of FAE. With an addition of 25% HAE, a DMD of 1,921 g/cm3 was achieved with an optimal moisture content of 13.5%. It is interesting to note that the increase in MDD between sample C-1, C-2 and C-3 with the addition of 25% FAE has the best results.

The CBR of the samples in the natural state gave results, the C-1 for 2.54 cm (1 in.) of penetration had that the 100% CBR is 5%, while the 95% CBR is 4%. For C-2 for 2.54 cm (1 in.) of penetration the 100% CBR had to be 4%, while the 95% CBR was 3%. Finally, C-3 for 2.54 cm (1 in.) of penetration had the 100% CBR is 6%, while the 95% CBR is 3%. In the subgrade categories of [15], it is mentioned that, if the CBR is less than 3%, this subgrade will be considered inadequate and when it is between 3% and 6%, it will be insufficient. Therefore, the natural samples taken in the investigation are inadequate and insufficient to be used as subgrade.

The 95% and 100% CBR results for 1 inch of the raw samples and the EAF samples can be seen in Fig. 4 and Fig. 8. For sample C-1, when it has no addition of EAF, it presents 100% CBR. 5%, while 95% CBR is 4%; when %EAF is added, the one that shows best results is 25% EAF, with 100% CBR of 9%, while 95% CBR is 8%. This improvement persists in samples C-2 and C-3 with the addition of 25% EAF. For the MTC Testing Manual (2016), the CBR performed with the maximum addition of 25%, they are between 6% and 10%, considered usable for regular subgrades. These results, being from clay soils, improve their conditions from inadequate and insufficient to adjustable to be worked.

For [30], in his research with residual steel slag added at 0%, 3%, 5%, 7% and 10%, in expansive soils, he indicated that the CBR increases with a higher % slag content, reaching 12 % CBR, with 10% steel slag added; satisfying the requirements as a road subbase according to the Chinese natural state. [22] carried out their study with 0%, 5%, 10%, 15%, 20%, 25% and 30% of slag additions as replacement for clay soils; showing you that as the slag content of steel increases, the CBR value increases.

The results obtained from the present investigation showed an improvement of up to 14% in the CBR of the clay soil with 25% EAF, making it the best mixture and making the soil suitable for subgrade.

5. Conclusions

An investigation was carried out into the potential of EAF slag, a by-product of the steel industry, for use in the modification of clay soils. The basic physical properties of the samples were evaluated in their natural state, including moisture percentage and plasticity index (PI). In addition to calculating the mechanical properties of the sample in the natural state and with the addition of EAF, such as the Maximum Dry Density (MDD), California Bearing Ratio (CBR and the optimal % of water), to understand the engineering behavior and the mechanism microstructural of the treated soils. The main results of this research are presented below.

1. The soil samples in their natural state (C-1, C-2 and C-3) were classified by USCS and AASHTO, demonstrating that they are considered low plasticity clay, sand and poor-quality clay soil, respectively. In addition, it was determined that the moisture content in the samples in the natural state for C-1, C-2 and C-3 was 19.92%, 20.96% and 19.71%, with a plasticity index of 23.54%, 28.45% and 24.66, respectively, resulting in a clay soil with high plasticity.
2. The Maximum Dry Density (MDD) of the samples in the natural state C-1, C-2 and C-3 had an increase of 7.26%, 2.14% and 8.53%, respectively, when adding 25% of EAF. Regarding the optimal moisture content, there was a decrease of 22.35%, 10.98%, 27.61%, respectively.
3. Sample C-1 with 25% EAF at 2.54 cm (1 in) of penetration, had a 100% CBR value of 9%, showing an 80% increase over its natural state sample C- 1, while sample C-1 95% is 8% with an increase of 100%.
4. Sample C-2 with 25% EAF at 2.54 cm (1 in) of penetration, had a 100% CBR value of 9%, showing a 125% increase over its natural sample C- 2, while sample C-2 with 95% is 8% with an increase of 167%.
5. Sample C-3 with 25% EAF at 2.54 cm (1 inch) penetration had a 100% CBR value of 6%, showing a 50% increase over its Sample C -3 in natural state, while sample C-3 at 95% is 8% with an increase of 167%.
6. According to the MTC Testing Manual (2016), the CBR obtained with the maximum addition of 25% are between 6% and 10%, considered usable for regular subgrades. These results, being clay soils, improve their conditions from inadequate and insufficient to adjustable to be worked.
7. Reusable materials can be used in the stabilization of clay soils, presenting improvements according to an optimal % of their addition to the normal soil used in subgrades.

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References

[1] Aamer, N., and AlRkaby, A., Strength, durability and microstructures characterization of sustainable geopolymer improved soil class. Case Studies in Construction Materials, 16, art. e00988, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e00988 ·

[2] Abdullah, H., Shahin, M., and Walske, M., Geo- mechanical behavior of clay soils stabilized at ambient temperature with fly-ash geopolymer-incorporated granulated slag. Soils and Foundations, 59, pp. 1906-1920, 2019. DOI: https://doi.org/10.1016/j.sandf.2019.08.005

[3] Adeyanju, E., Austin, C., Akinwumi, I., and Busari, A., Subgrade stabilization using rice husk ash- based geopolymer (GRHA) and cement kiln dust (CKD). Case Studies in Construction Materials, 13, pp. e00388, 2020. DOI: https://doi.org/10.1016/j.cscm.2020.e00388

[4] Aksu, G., and Eskisar, T., The geomechanical properties of soils treated with nanosilica particles. Journal of Rock Mechanics and Geotechnical Engineering, 15, PP. 954-969, 2023. DOI: https://doi.org/10.1016/j.jrmge.2022.06.013

[5] Amakye, S., and Abbey, S., Understanding the performance of expansive subgrade materials treated with non- traditional stabilizers: A review. cleaner Engineering and Technology, 4, art. 100159, 2021. DOI: https://doi.org/10.1016/j.clet.2021.100159

[6] Attom, M., Al-Akhras, N., and Malkawi, A., Effect of fibers on the mechanical properties of clayey soil - Geotechnical Engineering, 162, pp. 277-282, 2009. DOI: https://doi.org/10.1680/geng.2009.162.5.277

[7] Bakhshizadeh, A., Khayat, N., and Horpibulsuk, S., Surface stabilization of clay using sodium alginate - Case Studies in Construction Materials 16, art. e01006, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e01006

[8] Bernardi, C., Yamato, M., Silva, W., Reinaldo, V., Cavali, C., and Dos Santos, L., Mechanical properties of a clay soil reinforced with rice husk under drained and undrained conditions. Journal of Rock Mechanics and Geotechnical Engineering 10, pp. 2676-2686, 2023. DOI: https://doi.org/10.1016/j.jrmge.2023.02.022

[9] Cikmit, A.A., Tsuchida, T., Hashimoto, R., Honda, H., Kang, G., and Sogawa, K., Expansion characteristics of steel slag mixed with soft clay. Construction and Building Materials, 227, art. 116799, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2019.116799.

[10] Ebailila, M., Kinuthia, J., Oti, J., and Al- Qaked, Q., Sulfate soil stabilization with binary blends of lime- silica fume and lime- ground granulated blast furnace slag. Transportation Geotechnics, 37, art. 100888, 2022. DOI: https://doi.org/10.1016/j.trgeo.2022.100888

[11] Islam, S., Islam, J., and Robiul, N., Improvement of consolidation properties of clay soil using fine- grained construction and demolition waste. Helion, 8, art. e11029, 2022. DOI: https://doi.org/10.1016/j.heliyon.2022.e11029
[12] Juveria, F., Rajeev, P., Jegatheesan, P., and Sanjayan, J., Impact of stabilization of mechanical properties of recycled concrete aggregate mixed with waste tire rubber as a pavement material. Case Studies in Construction Materials, 18, art. e02001, 2023. DOI: https://doi.org/10.1016/j.cscm.2023.e02001
[13] Khodabandeh, M., Nagy, G., and Torok, A., Stabilization of collapsible soils with nanomaterials, fibers, polymers, industrial waste, and microbes: current trends. Construction and Building Materials, 368, art. 130463, 2023. DOI: https://doi.org/10.1016/j.conbuildmat.2023.130463
[14] Lopez, A., and Korkiala-Tanttu, L., Stabilization of malmi soft clay with traditional and low-CO2 binders. Transportation Geotechnics, 38, art. 100920, 2023. DOI: https://doi.org/10.1016/j.trgeo.2022.100920
[15] Ministry of Transportation and Communications Peru. Materials Testing Manual. [online]. 2016. Available at: https://portal.mtc.gob.pe/transportes/caminos/normas_carreteras/documentos/manuales/Manual%20Ensayo%20de%20Materiales.pdf.
[16] Miraki, H., Shariatmadari, N., Ghadir, P., Jahandari S., Tao, Z., and Siddique, R., Clayey soil stabilization using alkali-activated volcanic ash and slag. Journal of Rock Mechanics and Geotechnical Engineering, 14, pp. 576-591, 2022. DOI: https://doi.org/10.1016/j.jrmge.2021.08.012
[17] Mirzababaei, M., Arulrajah, A., and Ouston, M., Polymers for stabilization of soft clay soils. Proceeding Engineering, 189, pp. 25-32, 2017. DOI: https://doi.org/10.1016/j.proeng.2017.05.005
[18] Mujtaba, H., Khalid, U., Farooq, K., Elahi, M., Rehman, Z., and Shahzad, H.M. Sustainable utilization of powdered glass to improve the mechanical behavior of fat clay. KSCE Journal of Civil Engineering, 24(12), pp. 3628-3639, 2020. DOI: https://doi.org/10.1007/s12205-020-0159-2
[19] Ojuri, O., Ramdas, V., Aderibigbe, E., Williams, C., Ramchuran, S., and Al-Nageim, H., Improving strength and hydraulic characteristics of regional clayey soils using biopolymers. Case Studies in Construction Materials, 17, art., e01319, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e01319
[20] Parthiban, D., Sivalinga, D., Koda, E., Daria, M., Piechowicz, K., Osinski, P., and Van Duc, B., Role of industrial based precursors in the stabilization of weak soils with geopolymer - A review. Case Studies in Construction Materials, 16, art. e00886, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e00886
[21] Rezaei-Hosseinabadi, M., Bayat, M., Nadi, B., and Rahimi, A., Sustainable utilization of steel slag as granular column for ground improvement in geotechnical projects. Case Studies in Construction Materials, 17, art. e01333, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e01333
[22] Safi, W., and Singh, S., Efficient and effective improvement and stabilization of clay soil with waste materials. Materials Today: Proceedings, 51, pp. 947-955, 2022. DOI: https://doi.org/10.1016/j.matpr.2021.06.333
[23] Shalabi, F., Asi, I., and Qasrawi, H., Effect of by-product steel slag on the engineering properties of clay soils. Journal of King Saud University-Engineering Sciences, 29, pp. 394-399, 2017. DOI: https://doi.org/10.1016/j.jksues.2016.07.004
[24] Tajaddini, A., Saberian, M., Kamalzadeh, V., Li, J., and Maqsood, T., Improvement of mechanical strength of low-plasticity clay soil using geopolymer-based materials synthesized desde glass powder and copper slag. Case Studies in Construction, 18, art. e01820, 2023. DOI: https://doi.org/10.1016/j.cscm.2022.e01820
[25] Tholkamudalige, S., Perera, A., Saberian, M., Zhu J., Roychand, R., and Li, J., Effect of crushed glass on the mechanical and microstructural behavior of highly expansive clay subgrade. Case Studies in Construction Materials 17, art. e01244, 2022. DOI: https://doi.org/10.1016/j.cscm.2022.e01244
[26] Tran, T., Behravan, A., and Brand, A., Heat of hydration in clays stabilized by a high-aluminia steel furnace slag. Cleaner Materials, 5, art. 100105, 2022. DOI: https://doi.org/10.1016/j.clema.2022.100105
[27] Wang, S., Xue, Q., Ma, W.,, Zhao K., and Wu, Z., Experimental study on mechanical properties of fiber-reinforced and geopolymer-stabilized clay soil,_ Construction and Building Materials, 272, art. 121914, 2021. DOI: https://doi.org/10.1016/j.conbuildmat.2020.121914
[28] Wilkinson, A., Haque A., and Kodikara, J., Stabilization of clayey soils with industrial by+products: Part A. Proceedings of the Institution of Civil Engineers, 163(3), pp. 149-163, 2010. DOI: https://doi.org/10.1680/grim.2010.163.3.149
[29] World Stell Association, World Steel in Figures 2022). worldsteel.org. Ed. [online]. (sf). Available at: https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/#world-crude-steel-production-1950-to-2021
[30] Wu, J., Lui, Q., Deng, Y., Yu, X., Feng, Q., and Yan, Q., Expansive soil modified by waste steel slag and its application in subbase layer of highways. Soils and Foundations, 59, pp. 955-965, 2019. DOI: https://doi.org/10.1016/j.sandf.2019.03.009
[31] Wu, J., Min, Y., Li, B., and Zheng X., Stiffness and strength development of the soft clay stabilized by the one-part geopolymer under one dimensional- compressive loading. Soils and Foundations, 61, pp. 974-988, 2021. DOI: https://doi.org/10.1016/j.sandf.2021.06.001
[32] Xu, B., and Yi. Y., Stabilization / solidification of lead contaminated soil using ladle furnace slag and carbon dioxide. Soils and Foundations, 62, art. 101205, 2022. DOI: https://doi.org/10.1016/j.sandf.2022.101205
[33] Zornberg, J., and Roodi, G., Use of geosynthetics to mitigate problems associated with expansive clay subgrades. Geosynthetics International, 28(3), pp. 279-302, 2021. DOI: https://doi.org/10.1680/jgein.20.00043
[34] Zurinskas, D., Vaiciukyniene, D., Stelmokaitis, G., and Dorosevas, V., Clayey soil strength improvement by using alkali activated slag reinforcement. Minerals, 10(12), art. 1076, 2020. DOI: https://doi.org/10.3390/min10121076

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