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RESEARCH ARTICLE

Mechanical Characterizations of Oxidizing Steel Slag Soil and Application

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Abstract
In this paper, the mechanical properties and engineering application of electric furnace (EAF) slag mixed soil are investigated. The samples of steel slag are taken from a steel manufacturing company in Huangshi, a city of China. The mixed soil was firstly prepared by mixing the steel slag and clay mixture in different proportions. The optimal moisture content for mixing the soil is investigated from the experiment through direct shear test. Based on three axial compression tests, the optimum steel slag ratio is determined. Finally, the mechanical properties of steel slag mixed soil are tested in a practical engineering problem through a numerical simulation. The steel slag mixed soil is used to replace the original soil of the embankment and compared with that of the original one. The comparison study shows that the method proposed in this paper is simple and effective. Moreover, from the practical problem analysis, the optimal utilization of electric furnace slag can be achieved.

Keywords
oxidizing steel slag mixed soil, direct shear test, optimum moisture content, numerical simulation

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1 Introduction

With the rapid growth of steel production over the world, steel slag, as a by-product of steel production, has now been produced quite fast. According to the report in 2014, the production of steel slag is 100 million tons in China. Now the total amount of steel slag produced in China is around 1 billion tons. However, recognizing the large volume of production, the reuse of these produced steel slags is only about 10% [1]. Such a waste of steel slag could lead to not only the loss of money but also lots of environmental pollutions. Many former researchers [2–7] have investigated the use of steel slag, especially in the application of pavement improvement. As steel slag has many mechanical features including high hardness, high strength and low compression capability [8], it is widely used in foundation and road treatment in recent years. The steel slag is usually classified into two categories, namely, basic oxygen furnace (BOF) steel slag, and electric arc furnace (EAF) steel slag. BOF steel slag and EAF steel slag are steel making slags which are a byproduct from steelmaking processes. And during these processes, the components of pig iron and steel-scrap are modified in order to produce steel [32]. Therefore, the steel slag produced in this stage is highly valued for its excellent toughness and workability. BOF is cooled slowly by natural cooling and water spray in a cooling yard. EAF slag is generated when iron scrap is melted and refined. It consists of oxidizing slag that is generated during oxidation refining that is generated during reduction refining. Among these two, the BOF steel slag is believed to be produced much more than the other and is approximated to be the majority of all the steel slag at a percentage about 60% [9]. However, with an increasing of steel storage year by year, the demand of using the EAF steel is also becoming very high [10]. Moreover, the problem is even more critical in many small and medium-sized cities whose economy rely largely on their industrial productions. However, the technology of recycling the EAF slag is still been developing. And the use of EAF slag in civil engineering is rarely seen in China. Especially for the oxidizing EAF slag, a systematic investigation of how to utilize the oxidizing slag is still lacking. The understanding of the mechanical properties of electric arc furnace oxidizing (EAFO) slag is of great interest to the practitioners in the construction industry. Recognizing this, the significance of current study is justified.

This work aims to investigate the use of EAFO steel slag in the mixed soil. The study is based on an experiment conducted on the mixed soil samples which has mixtures of steel slag. The key issue of this work is to obtain the optimum mixing scenario for using the EAFO steel slag. Realizing these, the paper content is organized as below. In general, the optimum moisture contents of steel slag mixing soil materials shall be determined according to the maximum dry unit weights in the compaction tests. But due to the limited economic budget and time, the direct shear test is usually utilized instead of compaction test. This is mainly because the shear strength is also a reflection of the soil compactness. After the introduction, Section 2 will provide an overview of formal research works on the topic of using steel slag mixed soil. Section 3 would then details the experiments conducted in this study. The optimal ratio of mixing the soil for achieving the maximum mechanical properties is discussed. Based on the results, the mixed soil's stress-strain model is established in Section 4. To demonstrate the advantage of using the EAFO steel slag soil, a numerical study is conducted in Section 5. The mechanical properties of the EAFO steel slag soil is compared with the original soil in enhancing an embankment. Finally, Section 6 draws the conclusion.

2 Literature review

The application of steel slag in engineering practices has been extensively investigated in recent years. First of all, it has been concluded that steel slag has perfect durability which can be used for long term construction materials. Because of its economic, environmental and technical feasibility, steel slag is widely used in ground improvement [33]. The characteristics are proved to be adequate for its use as aggregate in road constructions [11–13]. Moreover, steel slag fly ash phosphogypsum solidified material was also introduced as a new type of mix material for concrete [14–15]. This is majorly because of steel slag's advantage of long-term strength and water stability [31]. With the good mechanical and cementitious property, steel slag is also used to improve the bearing capacity and control the ground settlement in soft soils [16]. For example, the BOF steel slag is a pozzolanic material with high proportion of SiO2 and Al2O3, these two constituents can very easily emerge into soil material and stabilize the soil content. Thus, they can be used for soil improvement purposes such as stabilization [17, 36]. The static and cyclic behaviour of steel slag mixed stabilized/cementitious material has been studied in the literature [18]. Results from several cementing systems containing steel slag indicate Portland steel slag blast furnace slag cement has the advantages of lower energy squander, better durability, lower hydration heat evolution, and higher later strength development than conventional cements [19]. The chemical, mineralogical and morphological properties of steel slag are also studied for its sustainable use in engineering practices [20]. The use of fresh and aged BOF as a fill material in geotechnical applications and its long term swelling characteristics were monitored in [21]. It was reported the use of steel slag could alleviate the ground settlement to some extent. Additionally, it was concluded that both types of steel slag fines and blast furnace fines appear to hold promise for mixing with dredged material from a geotechnical enhancement and environmental perspective to provide strength and immobilization of heavy metals in a single material [22]. Meanwhile, many experiment studies have conducted to understand the physical properties of mixed soils. Several tri-axial compression tests of steel slag mixed soil have been conducted to reveal the effect of water content on the mechanical properties [23]. Through the centrifuge model tests, it was proved that steel slag fines could be used instead of the natural depleted sand since steel slag and sand have similar characteristics in the deformation modes [24]. Akinwumi [25] has investigated how EAF steel slag fines modifies the plasticity, strength and permeability of a lateritic soil, and identifies the extent of the correlation between each of these geotechnical properties. And he suspects the main factor which affects the engineering properties of the soil modification by the addition of steel slag is the Cation exchanges [37]. All these pioneering studies demonstrate us the opportunity of using the steel slag materials in the engineering real practices [38,39].

However, a systematic way of handling steel slag mixed soil is still lacking. Investigation on the use of it in the real geotechnical practices, such as embankment, is yet demanding. Therefore, the following studies are provided to explore this topic.

3 Direct shear test and the optimum moisture content

3.1 Constituents of EAFO steel slag

In this study, the main raw materials that are used in mixing the soil is the EAF steel slag which is in the oxidation phase. The EAF steel slag is taken from a steel manufacturing company in the region of Huangshi, a city of China. Several treatments are applied on the original oxidizing steel slag including crushing and grinding. In a local factory, the grinding for steel slag per ton costs about 35kw·h electricity power which is about 21 Chinese RMB (3.04 dollars) [34,35]. After the treatment, and particle size of the steel slag is controlled to be less than 5 mm. Such a uniform size of steel slag could help the mixing of granules in the experiment. In order to know the constituents of the EAFO steel slag, chemical experiments are performed to analyze the EAFO steel slag composition [26]. Detailed information is provided in Table 1. It can be seen the majority of the steel slag composition are Al2O3, SiO2, CaO which takes a percentage of weight at 30.46%, 32.75% and 19.73% respectively. Nearly all the constituents are oxide.

And the metal oxides are the major category which can react with the water, for example Al2O3. Therefore, it is believed the water content is a dominant factor in the soil mixture. The mechanical properties of the mixed soil must rely on the moisture content.

Fig. 1 EAFO steel slag before grinding and sieving

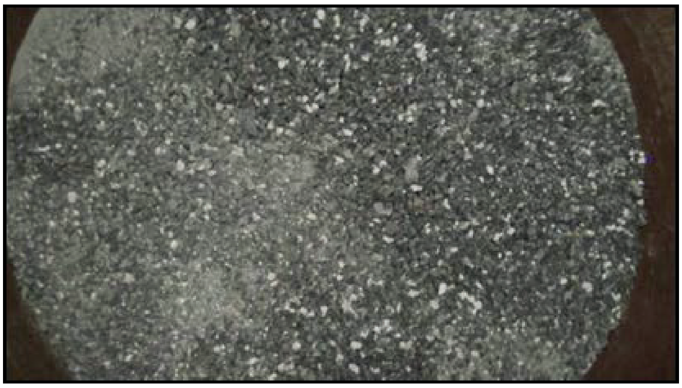


Fig. 2 EAFO steel slag after grinding and sieving

Table 1 Composition of EAFO steel slag

Ingredient	**MgO**	**Al2O3**	**SiO2**	**TiO2**
Weight percentage (%)	4.76	30.46	32.75	1.72
Ingredient	**P2O5**	**Cr2O3**	**CaO**	**MnO**
Weight percentage (%)	0.023	2.56	19.73	5.21

Besides the EAFO steel slag, the raw materials of soils are also taken from the local area. The soil used for this mixture is taken from the deep foundation. Before mixing, the soil is grinded and dried in laboratory. Soil samples are prepared according to the basic experimental procedures [27].

Step 1, drying the soil in the oven about 24 hours, then grinding and screening it by hand.

Step 2, grinding the EAFO by pulverizer and screening it by sieving machine.

Step 3, following the mixing ratio and prepare the soil and slag accordingly. Then mixing them and watering it to the desired moisture content, stirring them by hand at the same time.

Step 4, putting the mixed materials into the airtight container for curing.

Here, only the soil particles having diameter less than 2 mm are used in the mixing. Based on the experiment test the soil information is provided in Table 2. Relying on these specificities the soil can be graded as silty clay.

Table 2 Information of the raw material soils

Moisture content	**Dry density**	**Plasticity index**	**Initial void ratio**	**Specific gravity**
18.6%	1.52g/cm³	14.7	0.517	2.73

3.2 Constituents of EAFO steel slag

In order to search the optimum mix proportion of steel slag and clay, several samples are been mixed and tested. The moisture content in the mixture has been changed from 11.6% to 19.1% for testing the effect of water. For considering the quality of oxidizing steel slag, three different grades of steel slugs are also compared. The test is based on 1 day and 7 days curing time.

Table 3 Experiment samples

Specimen			**G10**		
Weight percentage (%)	12	14	16	18	20
Actual moisture content(%)	11.6	13.1	15.6	17.4	19.1
Density (g/cm³)	1.64	1.66	1.76	1.83	1.92
Specimen			G20		
Weight percentage (%)	12	14	16	18	20
Actual moisture content(%)	11.4	12.9	15.6	16.9	19.8
Density (g/cm³)	1.72	1.74	1.85	1.95	2.03
Specimen			G30		
Weight percentage (%)	14	16	18	20	
Actual moisture content(%)	13.3	15.1	17.0	18.9	
Density (g/cm³)	1.81	1.88	2.00	2.03	

Note: G10 implies 10% of the mixture materials are steel slag

To study the mechanical properties of EAFO steel slag mixing soil materials, direct shear test is directly applied to the mixture of EAFO steel slag and the soil. Four loading cases are applied with the vertical press set at 100kPa, 200kPa, 300kPa and 400kPa. Direct shear test is conducted by the strain controlled direct shear apparatus. Detailed experiment procedures are following the geotechnical experiment handouts [28].

The shear strength of prepared experiment samples are all tested through the oedometer. Based on the prepared experimental samples, the shear stress-strain curves are plotted for each of the sample. A typical plot showing the stress strain relationship of soil sample having steel slag G20 at a weight percentage of 14% with 15.6% moisture content is shown in Fig, 3. It is easy to see the shear strength of the sample increases with the increase of the vertical pressure which is in accordance with the change rule of shear strength.

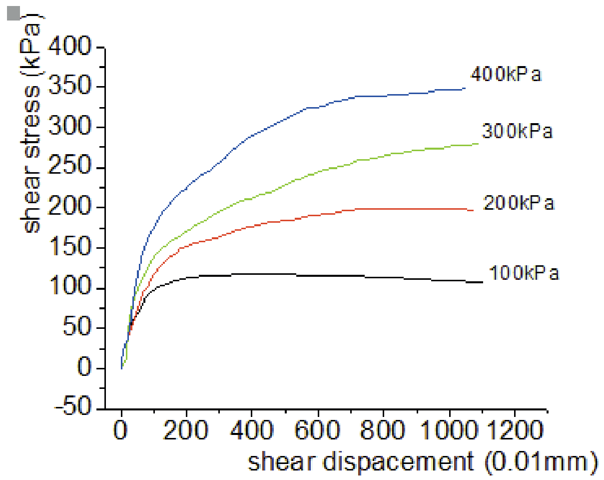
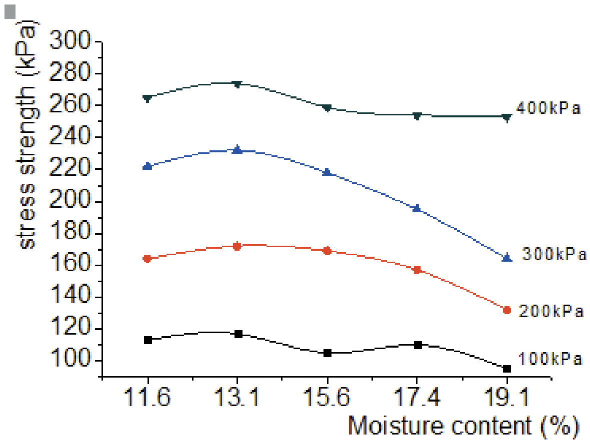
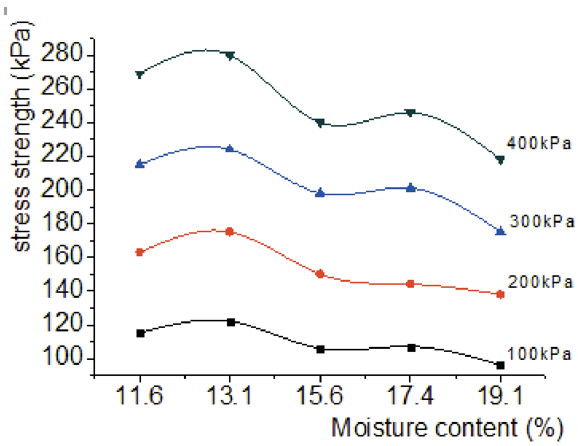


Fig. 3 Shear stress-shear displacement curve (14% moisture content of the G20 group for 1 day curing time)

In order to find the optimum moisture content ratio for mixing the soil, the shear strength-moisture content curves are plotted. These are illustrated in Figs. 4–6 for different grades of steel slags. To understand the time varying effects of the soil strength, the 1 day and 7 days shear strength are all plotted. The shear strength of the soil samples for using different steel slag grades are also compared and plotted in Fig. 7.



(a) 1 day



(b) 7 days

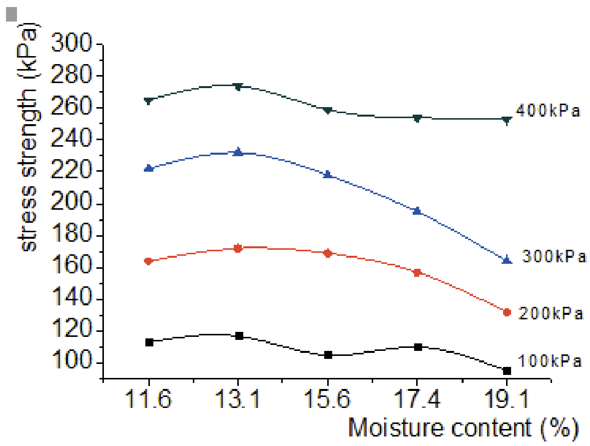
Fig. 4 Moisture content ~ shear strength curve for sample of G10

Some remarks can be concluded from the observation of Figs. 4–6:

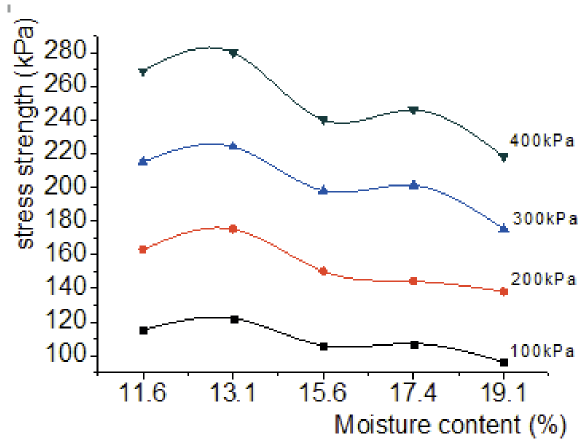
(1) The mixed soil shear strength increases with the increase of initial positive pressure;

(2) For all the mixed soil samples, the differences of 1 day shear strength and 7 days shear strength are minimal. This implies the curing time has very little effects on the mixed soil's shear strength;

(3) The moisture content for achieving the maximum shear strength is around 13% ~ 15%. It indicates the optimum mixing ratio for moisture content should be within this range.



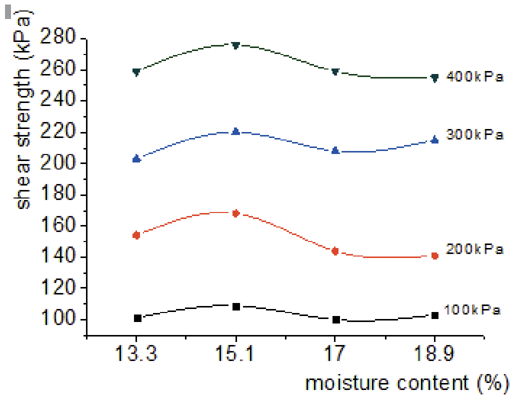
(a) 1 day



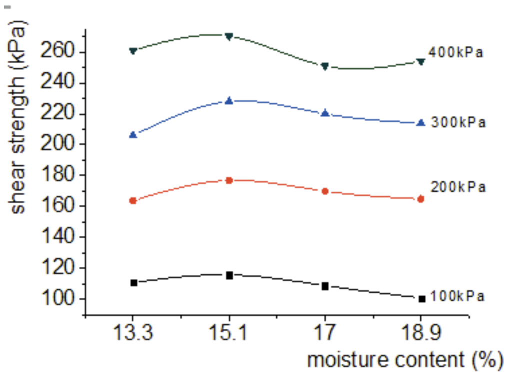
(b) 7 days

Fig. 5 Moisture content ~ shear strength curve for sample of G20

A final finding can be inspected from Fig. 7. Based on the comparison of soil samples having different steel slag grades, the maximum shear strength can be obtained by using the steel slag G20 with moisture content of 14%. This is the optimal mixing scenario for all the tested cases including the initial stress value changes from 100kPa to 400kPa. The shear strength envelope lines of the three different steel slag mixing soil materials at their optimum moisture contents are determined for the soil samples having different grades. Therefore, the best mixing ratio for using the oxidizing steel slug is confirmed.

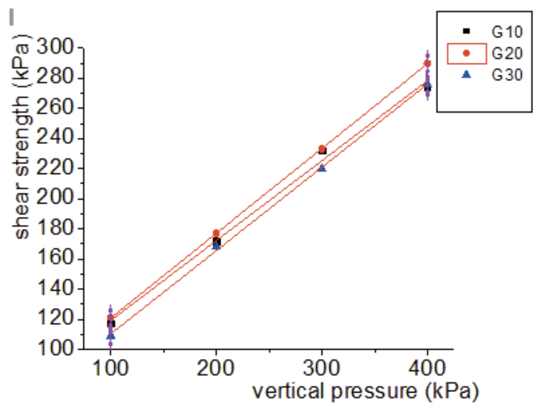


(a) 1 day

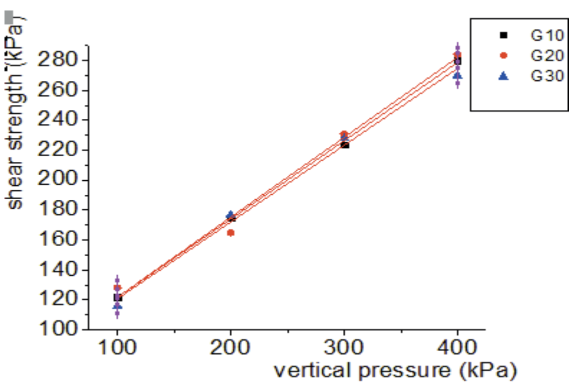


(b) 7 days

Fig. 6 Moisture content ~ shear strength curve for sample of G30



(a) 1 day



(b) 7 days

Fig. 7 Curve of different mixing proportion ~ shear strength envelope lines

4 Triaxial compression test

Based on the optimal mixing ratio of oxidizing steel slug, this work further conducts the experiment study to analyze the characteristics of the mixed soil.

The experiment utilizes the consolidated undrained triaxial compression test. The unsaturated soil triaxial compression test equipment of GDS HKUST type is adopted. Following the experiment procedures, the soil samples are prepared. Four tests are conducted with confining pressure set at 100kPa, 200kPa, 300kPa and 400kPa respectively.

Based on the experiment results, the data of the deviator stress (σ_1–σ_3) and axial strain (ε_1) are plotted in Fig. 8. It can be seen from the plot, the curve of (σ_1–σ_3)~(ε1) is nearly a part of hyperbolic function. Therefore, we can write the relationship between (σ_1–σ_3) and (ε_1) as a hyperbolic function.

Thus, we can roughly approximate the relationship between (σ_1–σ_3) and (ε_1) as a linear function. Based on this concept, the data $\frac{\varepsilon_1}{\sigma_1-\sigma_3}$ and ε1 for σ_3 = 300kPa are plotted. The initial elastic modulus can be estimated from the reciprocal intercept [29] which has the value of E_0 = 20.1MPa. Finally, based on the tested four cases, four Mohr circles are drawn. These are illustrated in Fig. 9. The shear strengths can then be calculated from the envelopes of these Mohr circles. It shows the soil cohesion value to be c = 109 kPa and friction angle to be Φ = 32°.

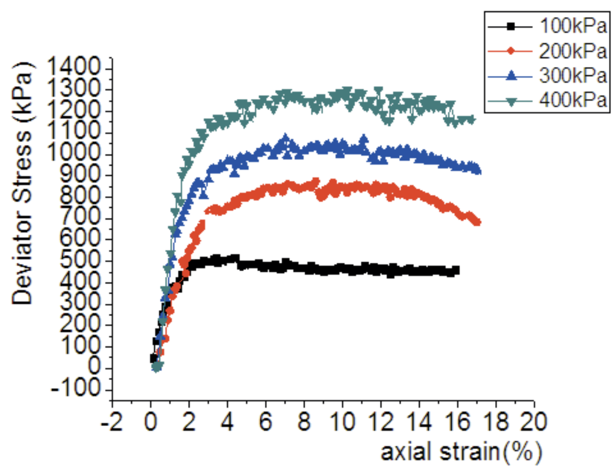


Fig. 8 Curve of deviator stress σ1-σ3 ~ axial strain ε1

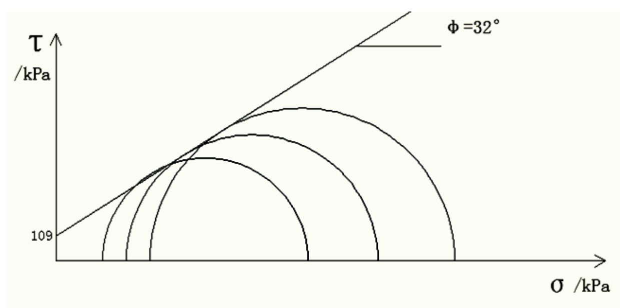


Fig. 9 Mohr circle and shear strength envelope

Based on the above analysis, the mechanical properties of the EAFO steel slug mixed soil are well characterized. However, whether the mixed soil has practical meanings is still a question. To understand the importance of this mixture in real applications, a further investigation of its usage in practical problem is needed. This is elucidated in the following section.

5 Case study – use of mixed soil in the embankment

5.1 Basic model

A simplified embankment model is used in this case study for demonstrating the practical advantages of the EAFO steel slug mixed soil. The material used to build the embankment is exactly the optimal mixed EAFO steel slug soil that is obtained in the above study. The embankment has a top width of 20m and a height of 5m. The slope has a ratio of 1:1.75 for height over width. A uniform load of 15kPa is carried by the embankment at the top. Detailed information are plotted in Fig.10.

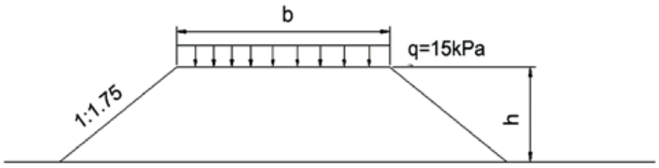


Fig. 10 Schematic diagram of embankment

Table 4 Information of soil conditions

Soil texture	Thickness of soil(m)	W(%)	γ (KN/m³)	I_p	e_0	C (kPa)
1st layer: filling soil	3.0	36.1	17.8	11.3	1.04	8.6
2nd layer: sludge	0.5	45.2	17.0	14.5	1.32	8.8
3rd layer: mucky soil	7	33.7	18.1	11.6	1.05	8.6
4th layer: clay	inf	51	16.9	20.5	1.48	9.0

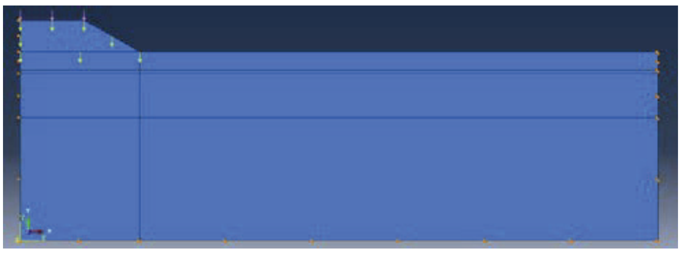
Soil texture	ψ(o)	a_{1-2}	f_{QK} (kPa)	v	Es (MPa)	E (MPa)
1st layer: filling soil	23	0.4	110	0.28	5.1	4.0
2nd layer: sludge	16	0.56	75	0.3	4.1	3.0
3rd layer: mucky soil	22	0.38	90	0.32	5.4	3.8
4th layer: clay	13	0.28	105	0.26	8.9	7.3

Meanwhile, the information of soil conditions under the embankment is provided. The first layer is the filling soil followed by sludge soil layer. Further deeper soil layers are mucky soil layer and clay soil layer. More detailed information can be found from Table 4. It is assumed the deformation of the embankment will not have any effect on the foundation soils.

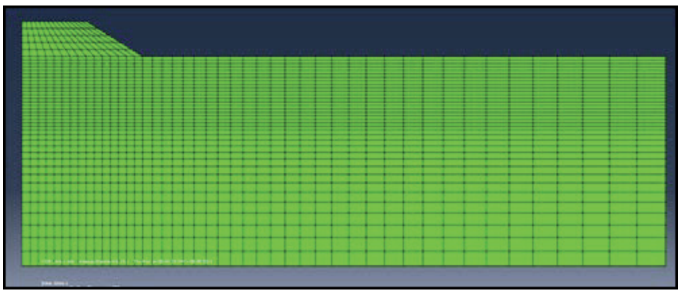
5.2 Results and discussion

To analyze problem, the software ABAQUS is used to perform the numerical analysis. Since the embankment is perfectly symmetric, the analysis will only investigate half of the soil embankment. A depth of 30 meters is used to analyze the soil foundation condition. In order to see the load effect on the surrounding soils, a horizontal length of 100 meters is used in the model. The horizontal displacements in the left and right sides are constrained. The vertical displacement along the down side is also constrained. The type of mesh for the numerical model is CPE4R [30] (four node quadrilateral plane strain units) and the total number of elements is 1695. In a previous test study, the type of mesh of eight node quadrilateral has also been tested. However, comparing these two cases using different meshing, the calculated results had the differences less than 1%. This means the currently adopted meshing is accurate enough for the numerical problem. Therefore, we adopt four node quadrilateral plane strain units for the following calculation. The embankment is treated as an elastic model and the soil foundations are modelled as an elastic-Mohr coulomb model. Detailed meshing and initial boundary conditions are shown in Fig. 11.

Unconstrained vertical motion

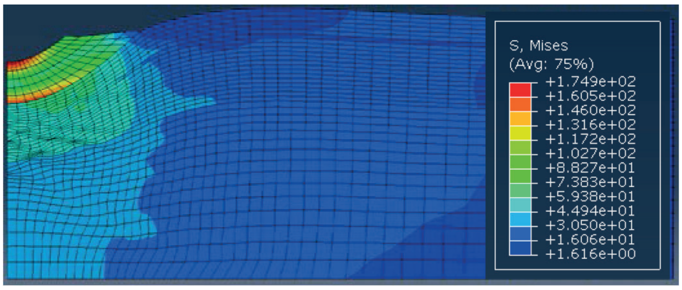


(a) Initial boundary conditions

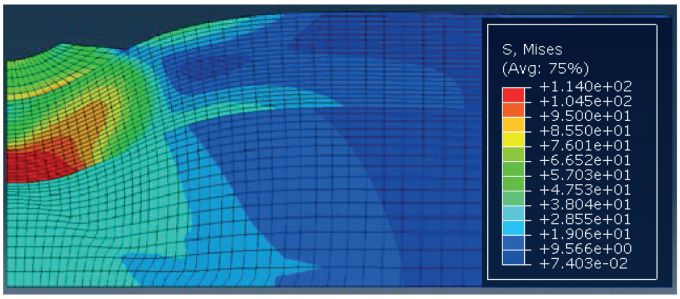


(b) Meshing of the numerical model

Fig. 11 Mesh partitions and the initial boundary conditions (before loading)

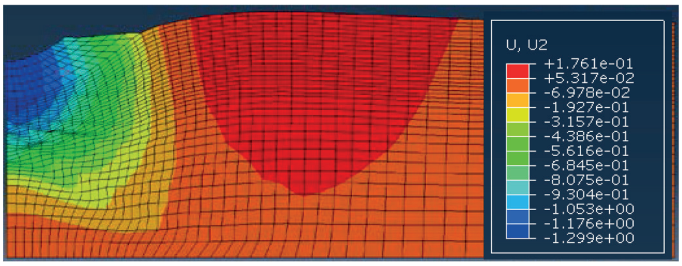


(a) Stress contours of the soil without embankment

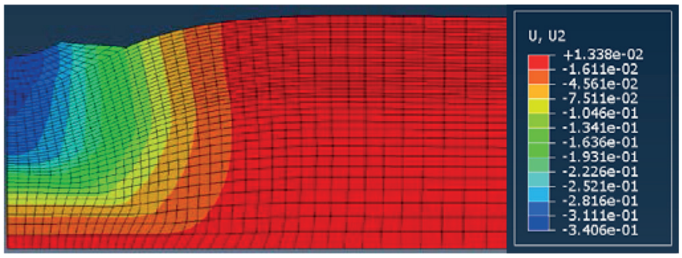


(b) Stress contours of the soil with embankment

Fig. 12 Stress distribution contours after loading



(a) The vertical settlement contours of the soil without embankment



(b) The vertical settlement contours of the soil with embankment

Fig. 13 The vertical settlement contours of soils after loading

The stress contours of the soil under loading are shown in Fig.12. Figure 12(a) shows the stress distribution without the embankment while Fig.12(b) shows the stress distribution with the embankment. It can be observed the stress tends to concentrate at the interfaces between different soil layers. However, the stress concentrates at a deeper soil layer interface for the case having the embankment. This simply implies the embankment could provide some resistance for carrying the load which will not make the soil directly exposed to the loading. The mitigation of the soil stress could help to reduce the settlement of the soil foundation. This can be seen from Fig.13 which illustrates the distribution of vertical settlement for the soil foundations. It would be easy to see the soil foundation settlement for the case having embankment is relatively lower compared to the case without embankment. And it has less effect on the soils which are close to the loading place.

Furthermore, settlement of the center line of the embankment is plotted in Fig.14. As seen in Fig.14, settlement of the soil foundation without embankment at the ground surface is more than 1 m. However, this settlement has been decreased by 69.9% in the case of having mixed soil made embankment. This further proves the applicability of the EAFO steel slag soil in the embankment.

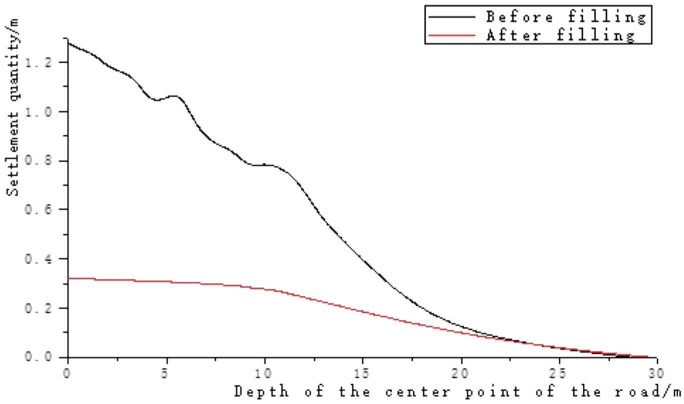


Fig. 14 Vertical settlement along the center line of the embankment

6 Conclusions

This paper conducted an experiment study to estimate the optimal mixing ratio for using the EAFO steel slag in the soil. It was found the optimum moisture content ratio in the mixed soil should be 14%. The optimal mixing ratio, which could obtain the maximum soil strength, for steel slag to the soil is 1:4. Based on the triaxial test, the initial elastic modulus E, friction angle φ and cohesion c of the mixed soil are estimated. The strength is proved adequate enough for its use in the engineering applications. To demonstrate this point, a numerical study is conducted to analyze the settlement of an embankment which utilizes the mixed soil material. It was proved the use of the mixed soil could help to reduce the soil settlement about 69.9%. The use of the EAFO steel slag soil can also help to mitigate the stress concentrations among the soil foundation.

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