Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

Shahrood University of Technology

Iranian Society of Mining Engineering (IRSME)

THOMSON REUTERS

Vol. 11, No. 3, 2020, 837-853.
DOI: 10.22044/jme.2020.9304.1860

Mechanical Properties of Low Plasticity Clay Soil Stabilized with Iron Ore Mine Tailing and Portland Cement

A.R. Ghanizadeh*, A. Yarmahmoudi and H. Abbaslou

Department of Civil Engineering, Sirjan University of Technology, Sirjan, Iran

Received 27 March 2020; received in revised form 15 May 2020; accepted 29 May 2020

Keywords

Clay Soil

Iron ore mine tailing

Portland cement

Soil stabilization

Abstract

Due to the economic and environmental issues, utilization of mineral wastes, e.g. iron ore mine tailing (IOMT), as road materials can be recommended as a sustainable alternative. In the present work, the mechanical properties as well as the resistance to freezing and thawing (F-T) cycles of low plasticity clay soil stabilized with different percentages of Portland cement (0%, 6%, 9%, 12%, and 15%) and different percentages of IOMT content (0%, 10%, 20%, 30 %, and 40%) are investigated. To this end, the unconfined compressive strength (UCS), initial elastic modulus (E0), and indirect tensile strength (ITS) at different curing times of 7, 14, 18, and 56 days for different admixtures are determined to select the optimum mix design for stabilization of clayey subgrade soil. This work shows that with increase in the percentage of cement, the strength parameters such as UCS, E0, and ITS increase, while increasing IOMT does not show a specific trend to increase the strength parameters. Evaluation of the strength parameters at different curing times shows that in the short-term curing times (7 and 14 days), the iron ore mine tailing has a positive effect on the strength parameters, while in the long-term curing times (28 and 56 days), the iron ore mine tailing has a negative effect on the strength parameters. In total, it was found that 12% of the Portland cement and 10-40% of IOMT passes the UCS and F-T criteria for stabilization of low plasticity clay soils, while clay soil (without IOMT) requires at least 15% of Portland cement for stabilization.

1. Introduction

In the recent decades, the demand for highways, buildings, and bridges has grown substantially, especially in areas where the population is growing rapidly. All of these structures or infrastructures require a stable foundation to transfer loads to the underlying soil. In most cases, the natural soil cannot sustain the load. In such a situation, before construction of the foundation, soil improvement should be taken into consideration. Several additives can be used for stabilization of weak or problematic soils including Portland cement and lime. Today, due to the environmental issues and accessibility, the use of iron ore mine tailing is considered by the researchers. The Golgohar mine of Sirjan annually produces 2.5 million tons of mine tailing. This amount also contributes to the environmental pollution and occupies a large area. The availability of space for waste disposal in the future is a major problem for the related industries. The mineral waste that is stored in tailing dams can have negative environmental effects through the geotechnical, physical, and chemical instabilities. Pollution of ground and surface waters by toxic substances such as soluble metals, cyanide, and sulphates, caused by mineral waste stored in tailing dams, has major negative effects on the environment [1]. Also the continuous accumulation of mineral waste in the environment contributes to many environmental problems such as loss of land fertility, dust, and erosion, and its effects on the ecosystem [2].

Corresponding author: ghanizadeh@sirjantech.ac.ir (A.R. Ghanizadeh).

The development of transportation infrastructure has increased the need for aggregate resources in the recent years, and it has led to the increasing use of aggregate natural resources to build road infrastructure. On the other hand, the environmental constraints and the haul distance from the deposits to the place of consumption have a major impact on the final cost of the road materials [3]. The use of IMOT as road materials, in addition to improving the strength and durability of road materials, can be introduced as a practical solution for the environmental issues of tailing dams.

To date, several studies have been accomplished on the stabilization of clay soils using cement and lime. These research works show that a compressive and tensile strength increase with increase in the Portland cement percentage and increase in the curing time. The results obtained also show that the optimum moisture content (OMC) is increased with increase in the percentage of Portland cement, while the maximum dry density (MDD) of soil decreases with increase in the percentage of the Portland cement. The previous studies also show that the clayey soils stabilized with the Portland cement have more durability against the freezing and thawing cycles [4-9].

On the other hand, the number of research works accomplished on the stabilization of soils using IOMT are limited.

Yang has used inorganic binder to stabilize IOMT. This study has shown that IOMT stabilized with 11% of Portland cement satisfies the strength criteria of the low grade road base [10].

Sun and Chen have conducted a study on the strength of iron tailing gravel stabilized using lime fly ash. The results of this study have shown that the stabilized materials meet the strength specifications, and may be used as road materials [11].

Manjunatha and Sunil have investigated the stabilization and solidification of IOMT using lime and class F type fly ash with the partial addition of Portland cement by means of the UCS, hydraulic conductivity, and leaching propensity tests. The results of their study showed that TM/10/0/0 (IOMT stabilized with 10% of Portland cement, 0% of lime, and 0% of fly ash), TM/5/0/20, TM/10/0/40, and TM/0/10/40 gained a good strength and a lower hydraulic conductivity value, and met the leaching criteria [12].

Xu has examined the possibility of using the cement-stabilized IOMT as base and subbase layers of road pavement. The results obtained showed that the cement-stabilized IOMT could be used as base and subbase layers for low-speed roads [13].

Hongbin has shown that IOMT utilization in the cement treated base, on the one hand can consume a large amount of these materials, and, on the one hand, can reduce the damage caused by its accumulation [14].

Kuranchie has conducted an investigation on the load-settlement behaviour of a strip footing resting on IOMT. The results obtained showed that the bearing capacity and modulus of subgrade reaction increased with increase in the foundation depth and relative density of IOMT. The results of this study also showed that the replacement of sandy soil with IOMT increased the bearing capacity as well as the stiffness of soil [2].

Osinubi *et al.* have investigated the effect of IOMT on the tropical black clay (TBC) soil modified with Portland cement using the sieve analysis, Atterberg limit, compaction, shear strength, and microanalysis tests. They treated the TBC soil with up to 10% IOMT and 4% cement by dry weight of soil. The experimental results showed that the maximum dry density value of stabilized soil increased, while the optimum moisture content (OMC) decreased with higher cement and iron ore tailing (IOT) contents. This study also showed that the shear strength of treated soil decreased to a minimum at 6% IOT content, and after that it increased [15].

Bastos *et al.* have evaluated the ability of using IOMT as an alternative material for road construction. The results obtained showed that IOMT could be used in the pavement layers after chemical stabilization. Also by increasing the percentage of the Portland cement, the amount of CBR increased. In addition, UCS of the samples containing cement was more than UCS of the samples containing lime. Cement was also the most effective stabilizer of IOMT in comparison with other additives [16].

Osinubi *et al*. have evaluated the application of lime and IOMT for stabilization of the Black Cotton soil. The results obtained showed that by increasing the amount of iron ore mine tailing up to 8%, the optimum moisture content was decreased. Also by increasing the amount of IOMT up to 8%, the dry density, UCS, and the amount of CBR increased and then decreased [17].

This papers aims to investigate the strength parameters (UCS, ITS, and initial elastic modulus) and resistance to the freezing and thawing cycles of low plasticity clay soil stabilized with different percentages of Portland cement and IOMT.

Contrary to the previous research works, a high percentage of IOMT (up to 40%) and a high percentage of Portland cement (up to 15%) was utilized for stabilization of low plasticity clay soil, and important strength parameters in the viewpoint of highway engineering including UCS, ITS, and initial elastic modulus at the different curing times of 7, 14, 28, and 56, and the resistance to the freezing and thawing cycles for optimum mixes was investigated. In fact, this paper tries to show the technical feasibility of clay stabilized by Portland cement by partial replacement of IOMT with clayey soil and how this could help to decrease the required Portland cement for stabilization of this soil.

2. Materials

The soil used in this research work was provided from 60 km NE of the Sirjan City in the Kerman Province (Iran). This soil is classified as clay with low plasticity based on the unified classification system. It covers a large area of subgrade soils in the Kerman Province in Iran, and due to low resistance, it is required to be stabilized for road construction projects. The iron ore mine tailing used in this research work was provided from the Golgohar mineral and industrial company in Sirjan. The Golgohar mine produces 6 million tons of concentrate by crushing, dry and wet grinding, and magnetic separation using low-intensity magnetic separators [18]. More than 780 L/s of wet tailings are discharged to a tailing dam, and the tailings do not produce acid mine drainage [18]. The basic properties of the clay soil and iron ore mine tailing are given in Table 1. The chemical composition of clay soil and iron ore is given in Table 2. The particle size distribution curve for soil and iron ore mine tailing is shown in Figure 1. Also the elemental analysis of the materials using an XRD device is represented in Figure 2. According to this figure, the clay soil has smectite minerals, mica, gypsum, kaolinite, quartz, and magnetite, while the iron ore mine tailing has hematite minerals, magnetite, quartz, feldspar, and spinel. Due to the possibility of low concentrations of sulfate ions in the soil, the type II of Portland cement was utilized as the stabilizing agent in this research work. The chemical composition of the Portland cement is represented in Table 3.

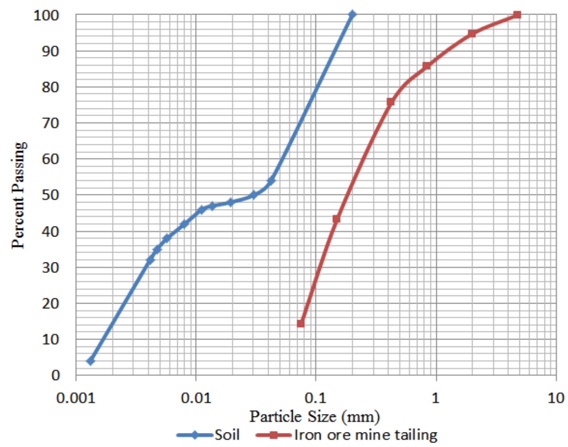
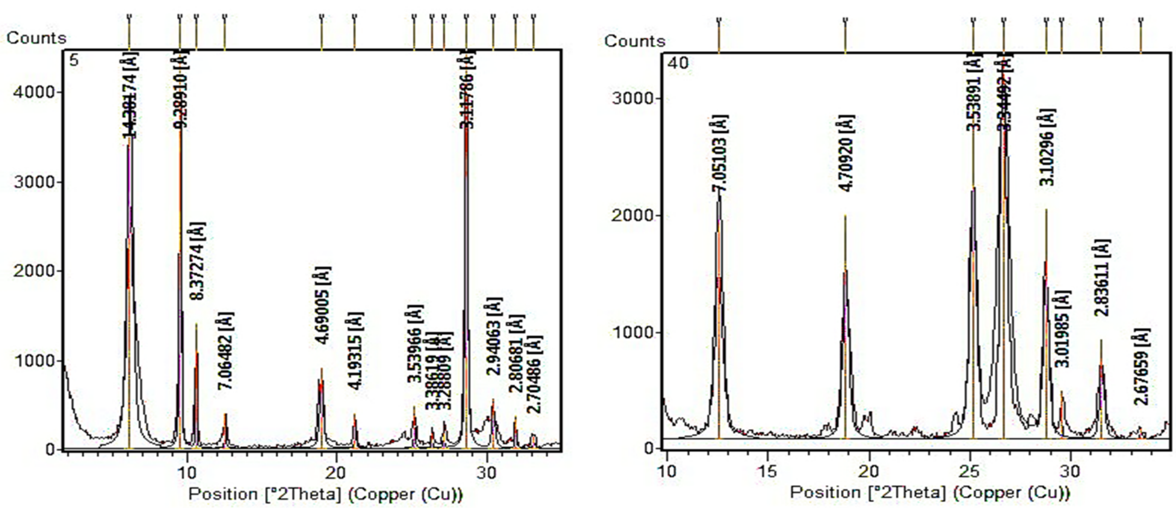


Figure 1. Particle size distribution curve for soil and iron ore mine tailing.



(a) Soil (b) Iron ore mine tailing

Figure 2. XRD results for soil and IOMT.

Table 1. Characteristics of soil materials and iron ore mine tailing.

Property	Standard	Soil	IOMT
Unified Classification	ASTM D3282 [19]	A-6	A-2-4
AASHTO Classification	ASTM D2487 [20]	CL	SM
Specific Gravity (G_s)	ASTM D854 [21]	2.45	2.95
Liquid Limit (LL)	ASTM D4318 [22]	36.58	NP
Plasticity Limit (PL)	ASTM D4318 [22]	22.24	NP
Plasticity Index (PI)	ASTM D4318 [22]	14.34	NP
Shrinkage Limit (SL)	ASTM D427 [23]	17.76	30.43
pH	ASTM D4972 [24]	7.70	8.81

NP: Non-Plastic

Table 2. Chemical composition of soil and iron ore mine tailing.

Chemical analysis	Soil (%)	IOMT (%)
SiO_2	49.482	35.952
Al_2O_3	12.377	5.907
Fe_2O_3	7.592	22.174
CaO	9.099	9.249
Na_2O	0.493	0.937
MgO	4.558	14.158
K_2O	2.856	1.855
TiO_2	0.643	0.629
MnO	0.098	0.077
P_2O_5	0.093	0.451
LOI	12.5	1.8

LOI: Loss On Ignition

Table 3. Chemical properties of the cement.

Chemical analysis	Content (%)
C_3A	6.5
SiO_2	21
Al_2O_3	4.6
Fe_2O_3	3.8
MgO	1.8
SO_3	2.5
LOI	1.5
I.R	0.5

3. Experimental program

3.1. Compaction test

In order to determine OMC for fabrication of the samples, the modified Proctor test was first performed according to the ASTM D1557 standard [25] on 25 different combinations of soil, IOMT, and Portland cement, and OMC as well as MDD for each combination were determined. The samples containing Portland cement in the stepped concentrations of 3%, 6%, 9%, 12%, and 15%, and IOMT with percentages of 0%, 10%, 20%, 30%, and 40% by dry weight of soil were prepared and tested without curing. Compaction was performed using 25 blows of a 4.5 kg hammer falling from a height of 450 mm onto five layers in a 946.45 cm^3 Proctor standard mould.

3.1. Fabrication of samples

In order to investigate the effect of cement content and iron ore mine tailing percentage on the UCS and ITS of the stabilized clay soil, 340 samples were fabricated in cylindrical mold (170 samples with replication). The UCS samples were fabricated with a height of 100 mm and a diameter of 50 mm, and the ITS samples were prepared with a height of 50 mm and a diameter of 50 mm. First, the IOMT and Portland cement were added to the dry soil and thoroughly mixed for 5 min to ensure homogeneity. The optimum moisture content was then added to the admixture and the samples were compacted at an optimum moisture content and then demolded and cured in nylon bags (Figure 3). The compaction energy for preparing these samples was considered equal to the compaction energy used in the modified Proctor test. In this research work, five percentages of the iron ore mine tailing (0%, 10%, 20%, 30%, and 40%) and five percentages of Portland cement (0%, 6%, 9%, 12%, and 15%) and four curing times (7, 14, 28, and 56 days) were considered.

Figure 3. Curing of UCS specimens in nylon bags.

3.2. UCS test

The UCS test was performed in accordance with the ASTM D2166 standard [26]. A deformation rate of 1 mm/min was applied until the failure of the samples. The device used to perform the UCS and ITS tests automatically measures the amount of forces and displacements during the tests and records the data (Figure 4). Using this device, the displacements were measured using a LVDT sensor. The failure mode for some samples is illustrated in Figure 5. In addition to UCS, the elastic modulus of stabilized soil was determined with respect to the stress-strain curve.

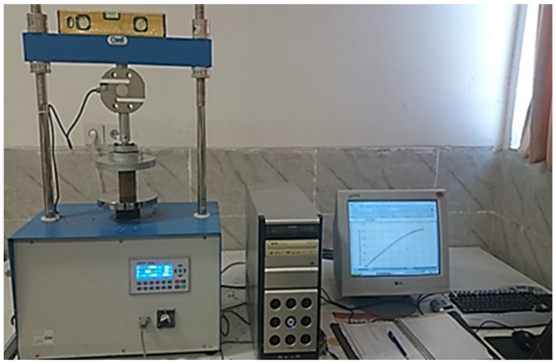


Figure 4. Automatic unconfined compressive strength device.

Figure 5. Samples after UCS test.

3.3. ITS test

ITS of the samples was measured using the method proposed by Dexter and Kroesbergen [27]. In this method, the samples should be placed horizontally between two flat plates of the UCS apparatus (Figure 6), and then a loading rate of 1 mm/min is applied until the failure of samples. The indirect tensile strength was determined according to ASTM C496 [28] and based on the following equation:

$$ITS = \frac{2P}{\pi . d . l} \quad (1)$$

where ITS is the indirect tensile strength (MPa), P is the maximum applied load (N), d is the specimen diameter (mm), and l is the specimen length (mm). The failure mode for some samples is illustrated in Figure 7.

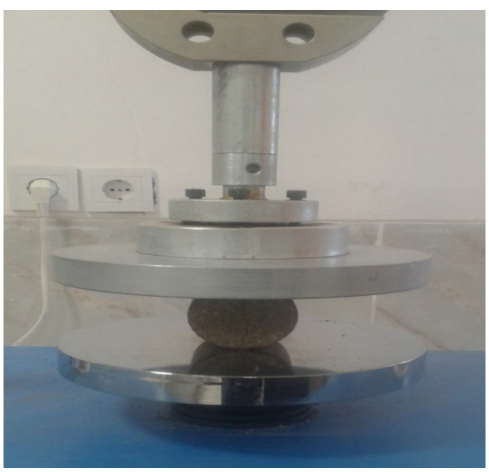


Figure 6. Placement of sample for measuring ITS.

Figure 7. Samples after ITS test.

3.4. CBT test

The California Bearing Ratio (CBR) test is the most common method used for determining the relative resistance and bearing capacity of soils for road construction. The CBR test was conducted in accordance with the ASTM D1883 standard [29]. After blending IOMT (0%, 10%, 20%, 30%, and 40%) and dry soil and mixing for 5 min, the optimum moisture content was added to the mixture and the samples were compacted in the CBR test mold using the modified proctor energy and tested with driving a piston into the compacted sample.

3.5. Resistance to freezing and thawing (F-T) cycles

The durability test against the F-T cycles was carried out in accordance with the ASTM D560 standard [30]. The purpose of this experiment is to determine the loss of volume and weight of samples after the freezing and thawing cycles. This experiment was performed for five different combinations of soil, IOMT, and Portland cement under five cycles of freezing and thawing. These five combinations were selected based on the optimum percentage of Portland cement obtained from the results of 7-day UCS tests. After curing the samples for 7 days, a solution of brine (3% salt) was purred in freezing and thawing dishes and then the samples were placed inside the dishes. The test was started with a freezing cycle so that the samples were placed at -18 °C for 5 h. The samples were then placed at 24 °C for 2.5 h. This procedure was repeated for five times, and then the volume and weight loss of the samples were measured. The freezing-thawing apparatus with stabilized samples after five cycles of freezing-thawing is illustrated in Figure 8.

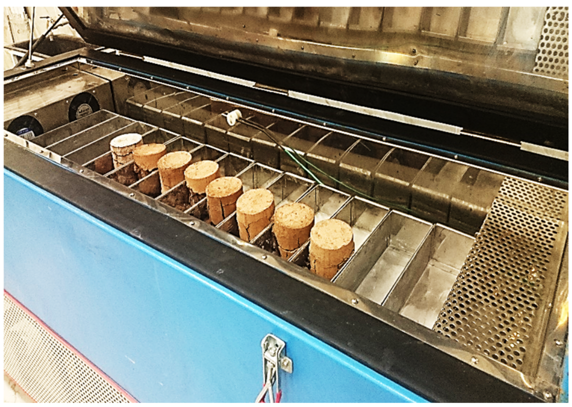


Figure 8. Samples after five cycles of freezing-thawing.

4. Results and discussion

4.1. Modified proctor test

The compaction curves for 25 combinations are shown in Figure 9. In this figure, S represents the percentage of soil, T represents the percentage of iron ore mine tailing, and C represents the percentage of cement.

According to Figure 9, by increasing the percentage of IOMT, OMC decreases. By increasing the percentage of IOMT from 0% to 40%, OMC decreases between almost 15% and 30% with respect to the percentage of Portland cement. This can be explained by decreasing the plasticity properties of clay soil after mixing with non-plastic IOMT. Sridharan and Nagaraj showed that with increase in the liquid limit and the plastic limit of fine grained soils, OMC increases and MDD decreases [31]. Also by increasing the percentage of iron ore mine tailing from 0% to 40%, MDD increases between almost 5% and 9%. The increase in MDD could also be explained by the high specific gravity of IOMT (2.95), which is replaced to soil particles with a lower specific gravity (2.45) matrix. The results obtained from this work are consistent with the results obtained by the other researchers [15]. They also said that by increasing the percentage of iron ore mine tailing, MDD increases and OMC is reduced. In addition, in the present research work, OMC for the samples is between 10.1 and 14.7 percent and MDD varies from 1.935 to 2.12 g/cm^3.

4.2. UCS

Figure 10 shows the results of UCS versus the IOMT content, and Figure 11 shows the results of UCS versus the percentage of Portland cement.

As evidence, by increasing the percentage of Portland cement, UCS increases, which indicates a direct relationship between the cement percentage and UCS. The Portland cement with cementitious properties occupied the voids in the soil structure and densified the soil matrix, which led to increase in UCS of the soil samples. The past findings also show that there is a direct relation between the cement content and UCS of stabilized soil [4, 5, 8, 14, 15, and 16]. According to Figure 11, there is no direct relationship between the percentages of IOMT and UCS of the samples. Osinubi *et al*. have shown that the IOMT content has no significant effect on the shear strength values of tropical black clay soil stabilized with Portland cement. They explained that IOMT contributed more to increasing the fine content of the soil that led to its flocculation with increase in the fine content of the soil that led to its flocculation with increasing cement percentage [15].

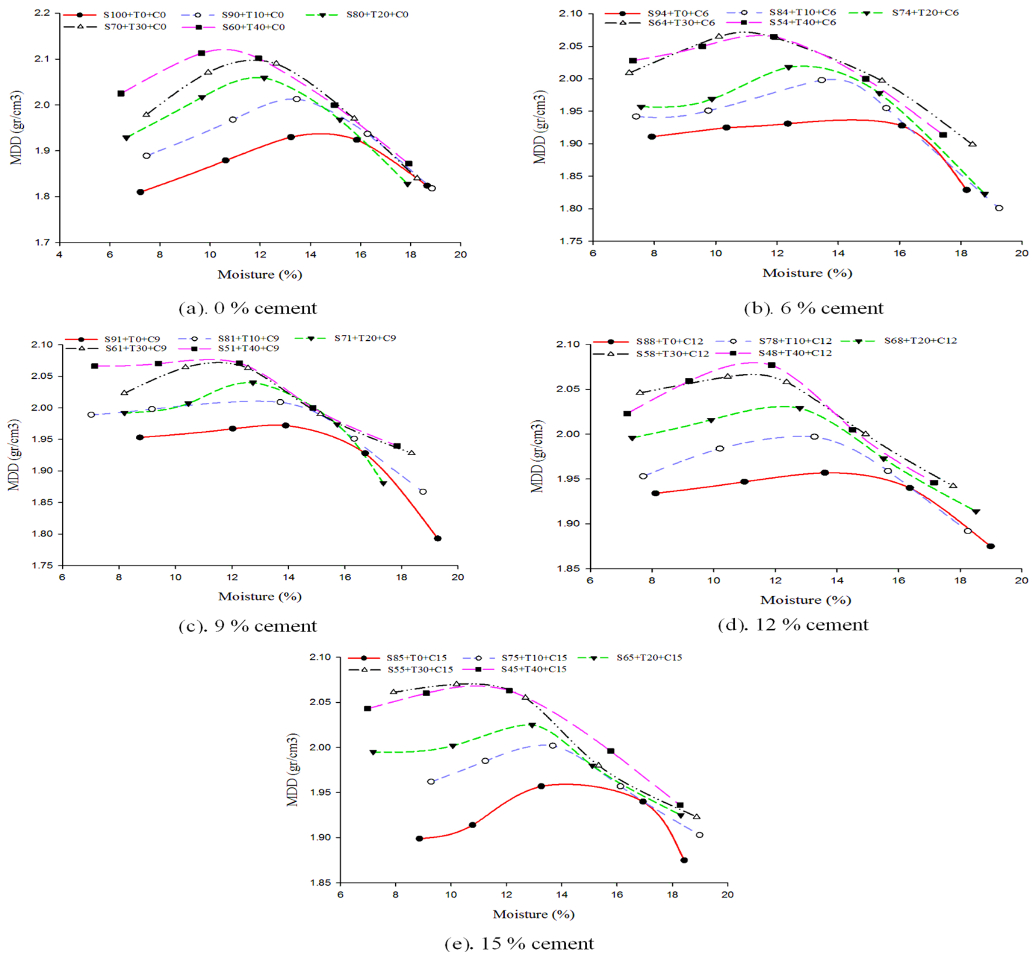


Figure 9. Results of compaction test for the mixtures of soil and IOMT stabilized by various cement percentages.

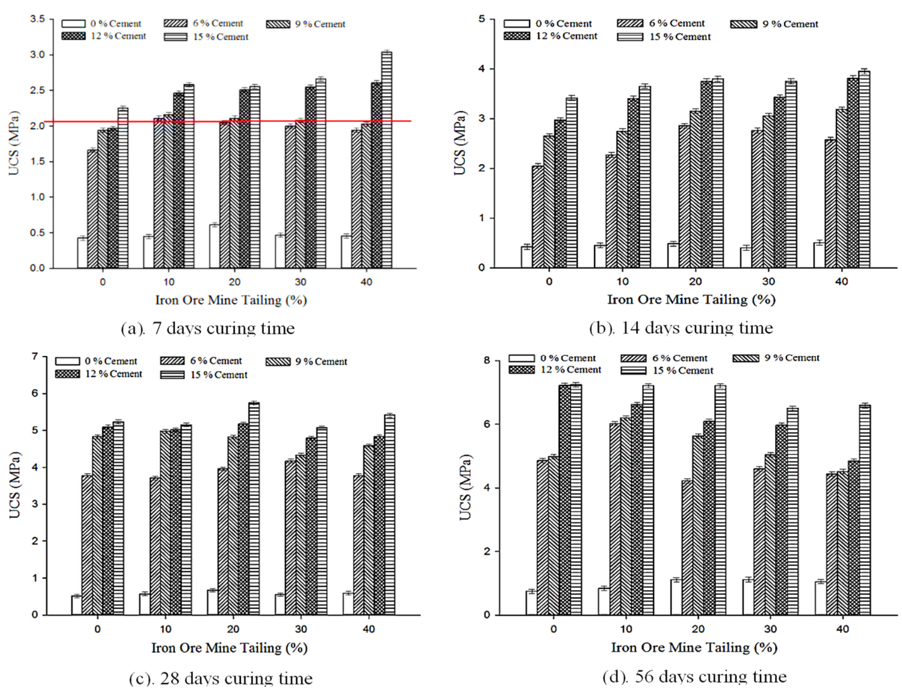
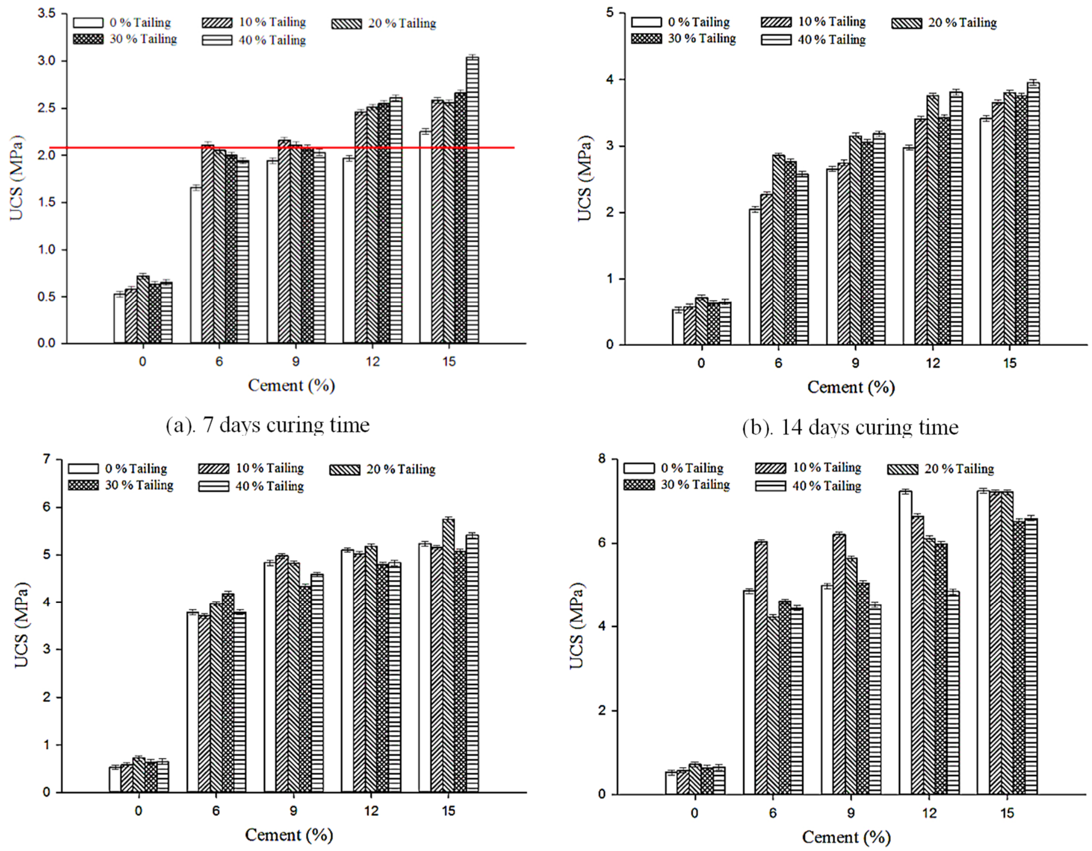


Figure 10. UCS versus IOMT content.

The minimum acceptable value for UCS of cement stabilized soil after 7 days of curing has been determined to be 2100 kPa (300 psi) by different agencies [32-34]. This criterion is plotted by a solid line in Figures 7(a) and 8(a). As it can be seen, all samples containing more than 12% of Portland cement and more than 10% of IOMT pass this criterion. In the case of IOMT-free admixtures, a minimum of 15% Portland cement is required to achieve a compressive strength of 2100 kPa, and therefore, it can be concluded that adding IOMT up to 10% will reduce the cement consumption by 3%.



(a). 7 days curing time

(b). 14 days curing time

(c). 28 days curing time

(d). 56 days curing time

Figure 11. UCS versus percentage of Portland cement.

Figure 12 shows the relation between UCS of 14-day, 28-day, and 56-day samples with UCS of 7-day samples. According to this figure, on average, the UCS of 14-day, 28-day, and 56-day samples is 39%, 104%, and 151% more than the 7-day samples, respectively. The unconfined compressive strength can be expressed as a function of the percentage of IOMT and Portland cement as follows:

$$UCS = a + bx + cy \qquad (2)$$

where UCS is the unconfined compressive strength in MPa, x is the percentage of IOMT, and y is the percentage of Portland cement. The constant coefficients a, b, and c along with other statistical data are given in Table 4.

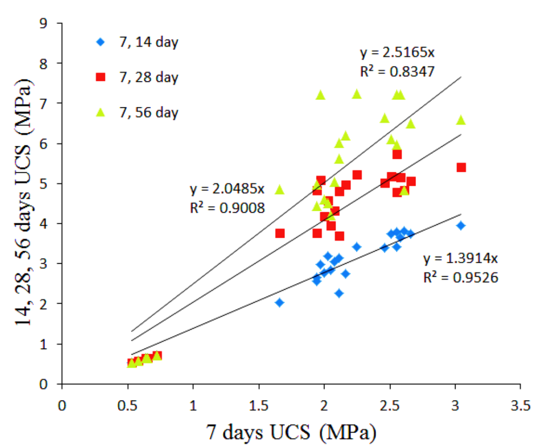


Figure 12. Relationship between compressive strength of 7 days samples with samples of 14, 28, and 56 days.

Table 4. Fitted exponential function for UCS results.

Curing time	a	b	c	R^2	FitStdErr	Fstat
7	0.6880	0.0077	0.1299	0.8912	0.2531	90.1179
14	0.6716	0.0122	0.2070	0.9283	0.3207	142.438
28	1.3301	-0.0017	0.3103	0.8699	0.6603	73.5565
56	1.7947	-0.0229	0.4083	0.8874	0.8094	86.7509

According to this table, for the curing times of 7 and 14 days, the constant coefficient b is a positive value and for the curing times of 28 and 56 days, the constant coefficient b is a negative value. This means that up to 14 days, the iron ore mine tailing has a positive effect on UCS, and after 14 days, the iron ore mine tailing has a negative effect on UCS. Therefore, it can be said that in the short-term curing times (7 and 14 days), the iron ore mine tailing has a positive effect on the compressive strength, while in the long-term curing times (28 and 56 days), the iron ore mine tailing has a negative effect on the compressive strength.
Kumar has also concluded that in the short-term curing times (3 and 7 days), the iron ore mine tailing has a positive effect on the compressive strength, while in the long-term curing times (28 and 56 days), the iron ore mine tailing has a negative effect on the compressive strength [35].

4.3. ITS

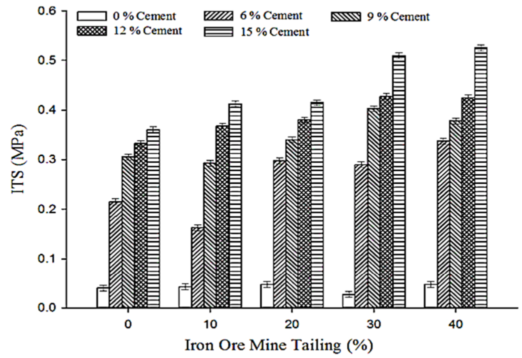
Figure 13 shows the results of ITS versus the IOMT percentage and Figure 14 shows the results of ITS versus the cement percentages.
According to Figure 13, with increase in the cement percentage, the tensile strength increases, which indicates a direct relationship between the cement percentage and the indirect tensile strength. The direct relationship between UCS and ITS of stabilized soils has been confirmed by other studies [36-38]. Figure 14 shows that there is no direct relationship between the percentages of IOMT and the ITS strength. Due to the relationship between UCS and ITS, the reason for this could be explained by what was explained in Section 4.2.
Figure 15 shows the relation between ITS of 14-day, 28-day, and 56-day samples with ITS of 7-day samples. According to this figure, on average, the ITS of 14-day, 28-day, and 56-day samples is 19%, 38%, and 84% more than the 7-day samples, respectively.
The results obtained also show that the ITS value is a function of the percentage of IOMT and Portland cement, which can be estimated by Equation (3):

$$ITS = a + bx + cy \quad (3)$$

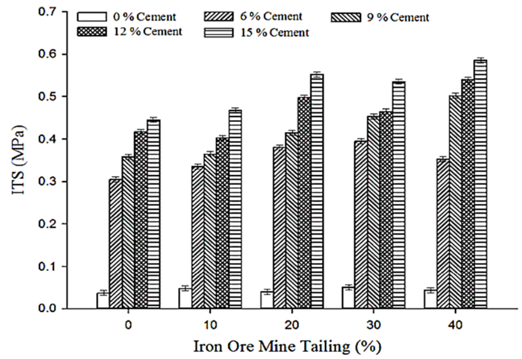
where ITS is the indirect tensile strength in MPa, x is the percentage of IOMT, and y is the percentage of Portland cement. The regression coefficients and statistics are given in Table 5 for different curing times.
According to this table, in the curing times of 7, 14, and 28 days, the constant coefficient b is a positive value, while in the curing time of 56 day, the constant coefficient b is a negative value. This means that up to 28 days, IOMT has a positive influence on the tensile strength, and after 28 days, IOMT has a negative influence on the tensile strength. This trend is almost similar to the UCS trend, which has been explained earlier.

Table 5. Fitted exponential function for ITS results.

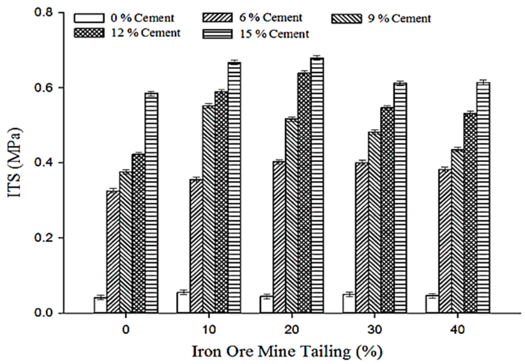
Curing time	a	b	c	R^2	FitStdErr	Fstat
7	0.0291	0.0026	0.0257	0.9328	0.0395	152.7904
14	0.0606	0.0023	0.0301	0.9009	0.0562	100.1079
28	0.0810	0.0008	0.0379	0.9187	0.0622	124.3264
56	0.2458	-0.0040	0.0477	0.8167	0.1277	49.0410



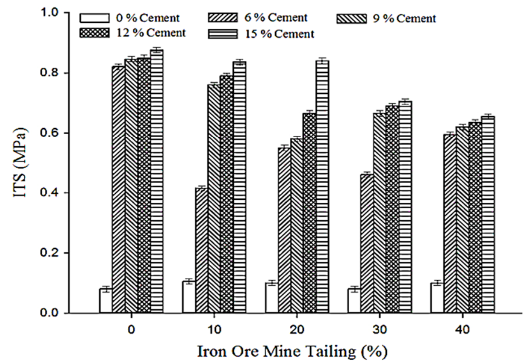
(a). 7 days curing time



(b). 14 days curing time

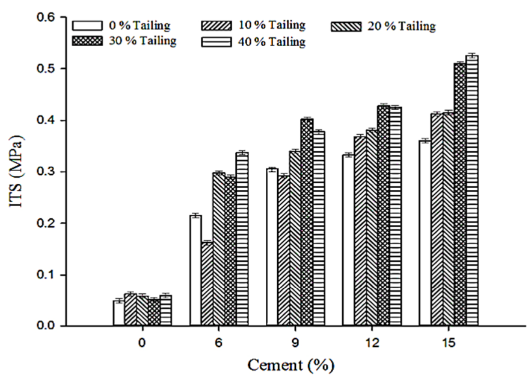


(c). 28 days curing time

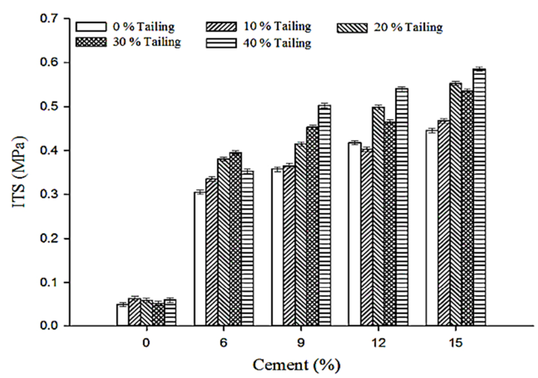


(d). 56 days curing time

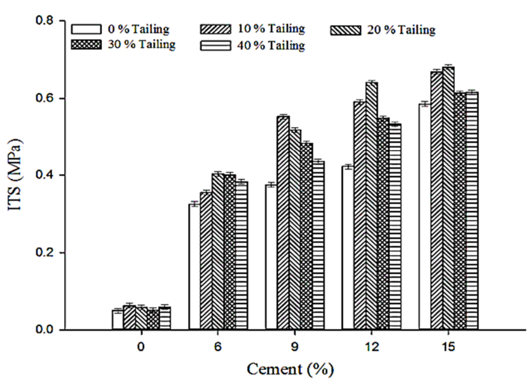
Figure 13. ITS versus IOMT content.



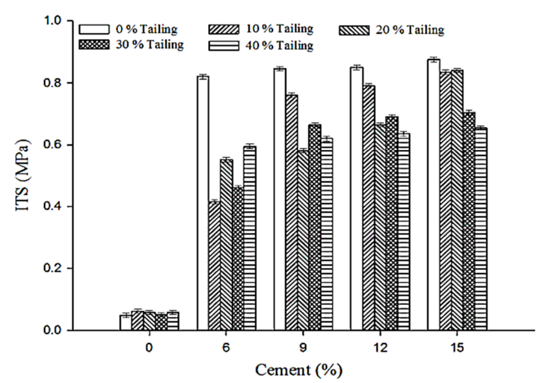
(a). 7 days curing time



(b). 14 days curing time



(c). 28 days curing time



(d). 56 days curing time

Figure 14. ITS versus percentage of Portland cement.

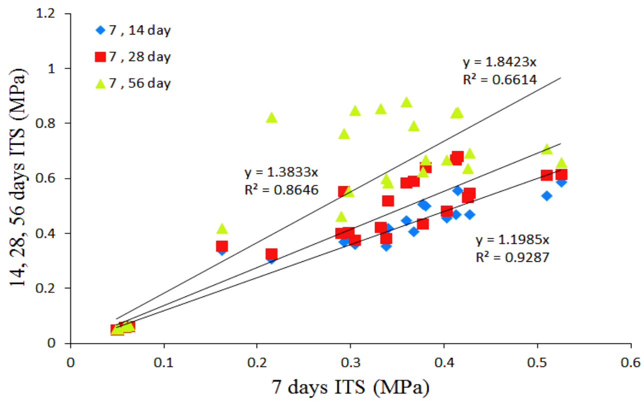


Figure 15. Relationship between ITS strength of 7-day samples with samples of 14, 28, and 56 days.

4.4. Relationship between UCS and ITS

Figure 16 shows the relation between UCS and ITS for different curing times. According to this figure, the ITS of the 7, 14, 28 and 56 days samples is 15%, 13%, 10%, and 11% of the UCS, respectively. Generally, the ITS of the samples is 12% of the UCS of the samples (Figure 17).

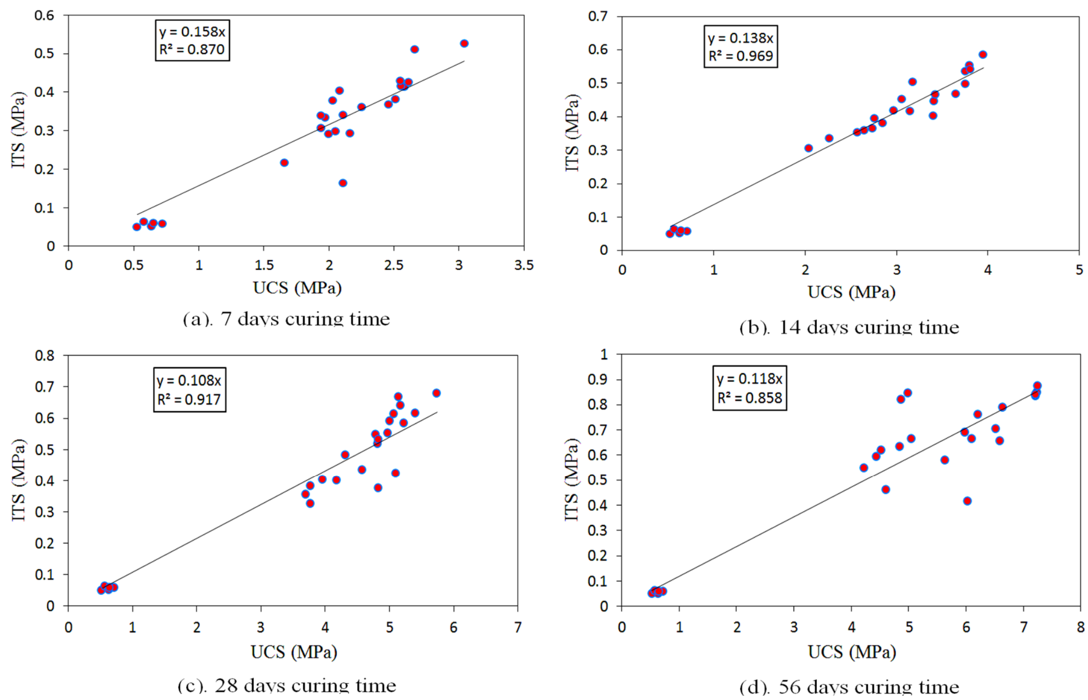


Figure 16. Relationship between compressive strength and tensile strength of samples.

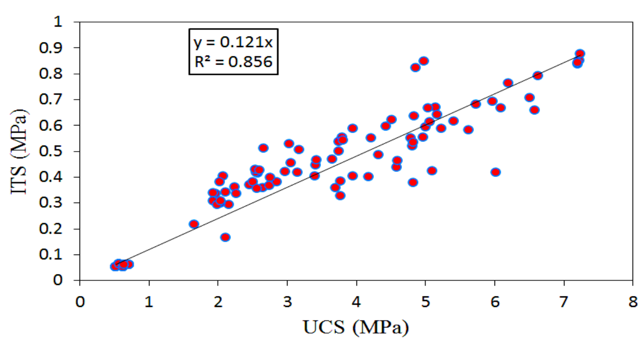


Figure 17. Relationship between compressive strength and tensile strength of all samples.

4.5. Elastic modulus (E_0)

In this research work, the elastic modulus was determined based on the initial tangent modulus (slope of the stress-strain curve from the origin). The values of the tangent modulus versus the IOMT percentages are shown in Figure 18 and the results of the tangential modulus versus the Portland cement percentages are shown in Figure 19.

As it can be seen, the general trend of elastic modulus changes according to the percentage of cement, and the percentage of IOMT is consistent with the trend of changes in the measured UCS. Other research works also confirm the strong relationship between the modulus and the compressive strength [39-40].

At all curing times, with increase in the cement percentage, the tangent modulus increases, which indicates a direct relationship between the percentage of cement and the tangent modulus (Figure 18). Samples with 20% of IOMT and 15% of Portland cement have the maximum value of tangent modulus. Figure 16 shows that no specific trend can be found between the tangent modulus and the percentage of IOMT. The amount of tangent modulus is a function of IOMT and cement percentage in stabilized soil, which can be predicted in accordance with Equation (4).

$$E_0 = a + bx + cy \quad (4)$$

where E_0 is the tangent modulus in MPa, x is the percentage of IOMT, and y is the percentage of Portland cement. The constant coefficients a, b, and c along with other statistical data are given in Table 6.

According to this table, the coefficient of regression in all cases is more than 0.85. In addition, according to this table, in the curing times of 7 and 14 days, the constant coefficient b is a positive value, while in the curing times of 28 and 56 days, the constant coefficient b is a negative value. This means that up to 14 days, IOMT has a positive effect on the tangent modulus, and after 14 days, IOMT has a negative effect on the tangential modulus. Therefore, it can be said that for the short-term curing times (7 and 14 days), IOMT has a positive effect on the tangent modulus, and in the long-term curing times (28 and 56 days), IOMT has a negative effect on the tangent modulus. The reason for this pattern could be inferred as it was said about the unconfined compressive strength.

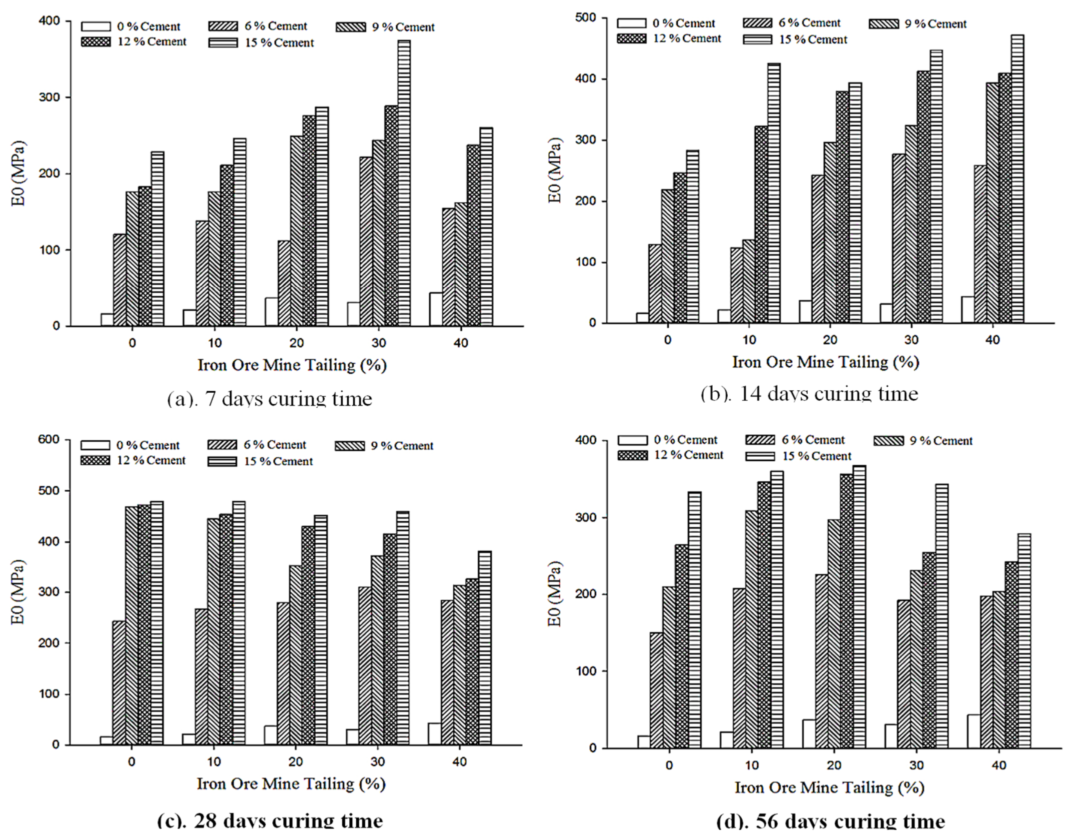
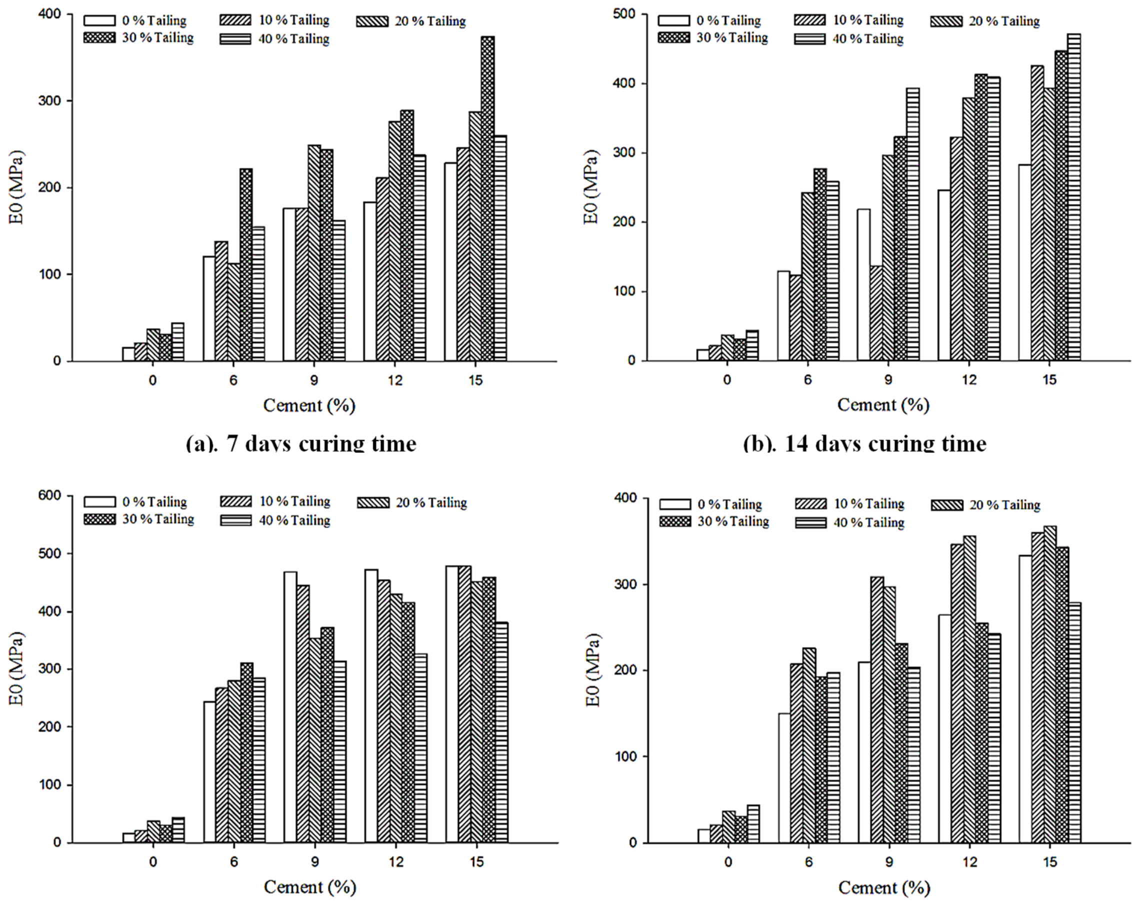


Figure 18. Tangent modulus versus IOMT.

Table 6. Fitted exponential function for E_0 results.

Curing time	a	b	c	R^2	FitStdErr	Fstat
7	15.3911	1.2632	16.5997	0.8630	37.1706	69.2992
14	36.5062	3.5720	25.8104	0.9214	44.3442	129.0349
28	100.1082	-1.5342	28.8971	0.8827	58.5497	82.8321
56	64.9330	-0.2625	19.4974	0.8744	40.6728	76.6271



(a). 7 days curing time

(b). 14 days curing time

(c). 28 days curing time

(d). 56 days curing time

Figure 19. Tangent modulus versus cement percentage.

4.6. CBR

The value of CBR for different compositions of clay soil and IOMT is shown in Figure 20. As it can be seen, with increase in the amount of IOMT, the CBR value increases. Etim *et al.* have shown that by adding IOMT to clay soils, the quality of soil in terms of soil classification will improve [17]. This can contribute to increase in CBR by increasing the IOMT content. This confirms the positive effect of adding IOMT on the strength of clay soils.

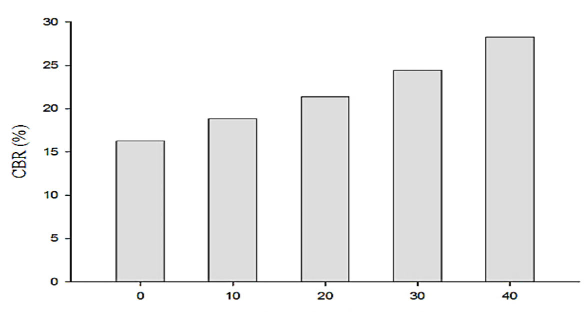
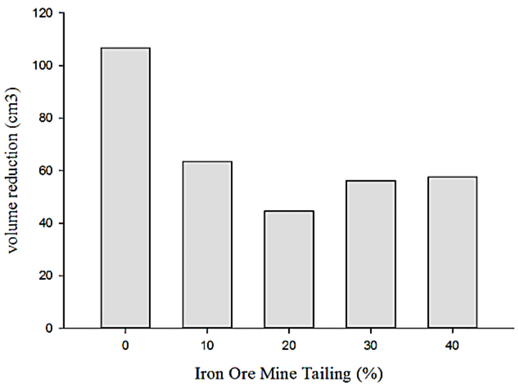


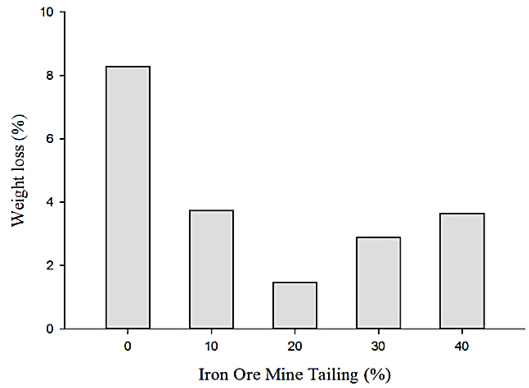
Figure 20. CBR test results.

4.7. Durability against freezing and thawing (F-T) cycles

After applying the freezing and thawing cycles to the samples, the volume reduction as well as the weight loss of the samples were measured. The results obtained are presented in Figure 21. As it can be seen, by increasing the percentage of IOMT up to 20%, the volume reduction and weight loss decrease and by increasing the percentage of IOMT to more than 20%, volume reduction, and weight loss increase. Therefore, it can be concluded that the optimum percentage of IOMT for stabilization of low plasticity clay soils with Portland cement from the perspective of resistant to the freezing-thawing cycles is 20%.



(a). Volume reduction



(b). Weight loss

Figure 21. Freezing and thawing cycle test results.

5. Conclusions

In the present work, UCS, initial tangent modulus, and ITS as well as resistance to freezing and thawing cycles (F-T) of low plasticity clay soil stabilized with Portland cement and Golgohar IOMT were investigated. The samples were fabricated with different percentages of Portland cement (0%, 6%, 9%, 12%, and 15%) and different IOMT percentages (0%, 10%, 20%, 30%, and 40%). According to the experiments performed, the following results were obtained:

(1) The modified proctor test results show that by increasing the amount of iron ore mine tailing in a constant amount of Portland cement, OMC decreases and MDD increases.

(2) The results of the UCS and ITS tests show that by increasing the percentage of cement in a constant amount of iron ore mine tailing, the compressive strength and tensile strength increase. However, there is no specific correlation between the percentage of iron ore mine tailing and the strength of stabilized soil.

(3) UCS and ITS can be predicted by a linear equation as a function of the IOMT percentage and cement content. The results obtained from this work also show that ITS of the samples is 12% of the UCS of the samples.

(4) The results of the tangent modulus indicate that, at all curing times, by increasing the cement percentage, the value of the tangent modulus increases.

(5) The results of the CBR test indicate that by increasing the IOMT percentage, CBR increases.

(6) The results of the F-T test indicate that the optimum percentage of IOMT for stabilization of clay soils with Portland cement from the perspective of resistant to the freezing-thawing cycles is 20%.

(7) In total, according to the experiments performed, it was found that the samples containing more than 12% of Portland cement and more than 10% of IOMT passed the strength as well as the weathering criteria, while clay soil (without IOMT) required at least 15% cement to achieve a UCS of 2100 kPa.

Further studies are recommended to investigate the durability of these materials against wet and dry cycles and also to investigate rutting, fatigue, and resilient modulus of these materials under cyclic loading.

References

[1]. Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. and Hudson-Edwards, K.A. (2014). Mine tailings dams: characteristics, failure, environmental impacts, and remediation. Applied Geochemistry, 51:229-245.

[2]. Kuranchie, F.A. (2015). Characterisation and applications of iron ore tailings in building and construction projects. PhD dissertation, School of Engineering, Faculty of Health, Engineering and Science.

[3]. Motz, H. and Geiseler, J. (2001). Products of steel slags: an opportunity to save natural resources. Waste management. 21 (3):285-293.

[4]. Basha, E.A., Hashim, R., Mahmud, H.B. and Muntohar, A.S. (2005). Stabilization of residual soil with rice husk ash and cement. Construction and Building Materials. 19 (6):448-453.

[5]. Wang, T., Liu, J. and Tian, Y. (2010). Experimental study of the dynamic properties of cement and lime-modified clay soils subjected to freeze–thaw cycles. Cold Regions Science and Technology. 61 (1): 29-33.

[6]. Kumar, A. and Gupta, D. (2015). Behavior of cement-stabilized fiber-reinforced pond ash, rice husk ashe soil mixtures. Geotextiles and Geomembranes. 44 (3):466-474

[7]. Solanki, P., Zaman, M., and Khalife, R. (2013). Effect of Freeze-Thaw Cycles on Performance of Stabilized Subgrade, Geo-Congress 2013, San Diego, California, United States, 567-581.

[8]. Shibi, T. and Kamei, T. (2014). Effect of freeze–thaw cycles on the strength and physical properties of cement-stabilised soil containing recycled bassanite and coal ash. Cold Regions Science and Technology. 106-107: 36-45.

[9]. Negi, A.S., Faizan, M., Siddharth, D.P. and Singh, R. (2013). Soil stabilization using lime. International Journal of Innovative Research in Science, Engineering and Technology. 2 (2): 448-453.

[10]. Yang, Q. (2008). Study on Road Performance of Iron Tailing Sand Stabilized by Inorganic Binder. Dalian university of technology.

[11]. Sun, J. and Chen, C. (2012). Research on the performances of lime fly ash stabilized iron tailing gravel in highway application. Journal of Wuhan University of Technology, 34 (3):59-62.

[12]. Manjunatha, L.S and Sunil, B.M. (2013). Stabilization/solidification of iron ore mine tailings using cement, lime and fly ash. International Journal of Research in Engineering and Technology. 2 (12):625-635.

[13]. Xu, S. (2013). Research on Application of Iron Tailings on Road Base. Advanced Materials Research. 743:54-57.

[14]. Hongbin, L. (2014). Experimental Research on Performance of Road Base with Cement Stabilized Iron Tailings Sand. Applied Mechanics and Materials. 513-517:60-64.

[15]. Osinubi, K.J., Yohanna, P. and Eberemu, A.O. (2015). Cement modification of tropical black clay using iron ore tailings as admixture. Transportation Geotechnics, 5:35-49.

[16]. Bastos, C.A.L., Silva, C.G., Mendes, C.J. and Peixoto, F.A.R. (2016). Using Iron Ore Tailings from Tailing Dams as Road Material. Journal of Materials in Civil Engineering. 28 (10):04016102.

[17]. Etim, R.K., Eberemu, A.O. and Osinubi, K.J. (2017). Stabilization of black cotton soil with lime and iron ore tailings admixture. Transportation Geotechnics, 10:85-95.

[18]. Jahanshahi, R., Zare, M. and Schneider, M. (2014). A metal sorption/desorption study to assess the potential efficiency of a tailings dam at the Golgohar Iron Ore Mine, Iran. Mine Water and the Environment. 33 (3):228-240.

[19]. ASTM D3282. (2015). Standard Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. West Conshohocken, PA, United States.

[20]. ASTM D2487. (2015). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). West Conshohocken, PA, United States.

[21]. ASTM D854. (2014). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. West Conshohocken, PA, United States.

[22]. ASTM D4318. (2014). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. West Conshohocken, PA, United States.

[23]. ASTM D427. (2008). Standard Test Method for Shrinkage Factors of Soils by the Mercury Method. West Conshohocken, PA, United States.

[24]. ASTM D4972. (2001). Standard test method for pH of soils. West Conshohocken, PA, United States.

[25]. ASTM D1557. (2012). Standard test methods for laboratory compaction characteristics of soil using modified effort. West Conshohocken, PA, United States.

[26]. ASTM D2166. (2015). Standard test method for unconfined compressive strength of cohesive soil. West Conshohocken, PA, United States.

[27]. Dexter, A. and Kroesbergen, B. (1985). Methodology for determination of tensile strength of soil aggregates. Journal of Agricultural Engineering Research. 31 (2):139-147.

[28]. ASTM C496. (2014). Standard test method for splitting tensile strength of cylindrical concrete specimens. West Conshohocken, PA, United States.

[29]. ASTM D1883. (2016). Standard test method for California bearing ratio (CBR) of laboratory-compacted soils. West Conshohocken, PA, United States.

[30]. ASTM D560. (2016). Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures. West Conshohocken, PA, United States.

[31]. Sridharan, A. and Nagaraj, H.B. (2005). Plastic limit and compaction characteristics of finegrained soils. Proceedings of the institution of civil engineers-ground improvement. 9 (1):17-22.

[32]. Texas Department of Transportation. Cement Treatment. ITEM 2762014.

[33]. I.M. Syed. (2007). Full-Depth Reclamation with Portland Cement: A Study of Long- Term Performance. Portland Cement Association.

[34]. Morian, D.A., Solaimanian, M., Scheetz, B. and Jahangirnejad, S. (2012). Developing Standards and Specifications for Full Depth Pavement Reclamation. Commonwealth of Pennsylvania Department of Transportation, USA, Harrisburg.

[35]. Kumar, B.N.S., Suhas, R., Santosh, U.S. and Srishaila. (2014). Utilization of Iron Ore Tailings as Replacement to Fine Aggregates in Cement Concrete Pavements. International Journal of Research in Engineering and Technology. 3 (7): 369-376.

[36]. Biswal, D. R., Sahoo, U. C., & Dash, S. R. (2018). Mechanical characteristics of cement stabilised granular lateritic soils for use as structural layer of pavement. Road Materials and Pavement Design, 1-23.

[37]. Diambra, A., Festugato, L., Ibraim, E., da Silva, A.P. and Consoli, N.C. (2018). Modelling tensile/ compressive strength ratio of artificially cemented clean sand. Soils and foundations. 58 (1): 199-211.

[38]. Baldovino, J.D. J.A., dos Santos Izzo, R. L., Feltrim, F. and da Silva, É.R. (2020). Experimental Study on Guabirotuba’s Soil Stabilization Using Extreme Molding Conditions. Geotechnical and Geological Engineering, 38: 2591–2607.

[39]. Chan, C. M. (2012). Strength and stiffness of a cement-stabilised lateritic soil with granulated rubber addition. Proceedings of the Institution of Civil Engineers-Ground Improvement. 165 1):41-52.

[40]. Biswal, D.R., Sahoo, U.C. and Dash, S.R. (2017). Strength and stiffness studies of cement stabilized granular lateritic soil. In International Congress and Exhibition" Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology" (pp. 320-336). Springer, Cham.

مشخصات مکانیکی خاک رس با خمیرایی کم تثبیت شده با سیمان پرتلند و باطلهٔ سنگ آهن

علیرضا غنی‌زاده*، **ابوذر یارمحمودی و حانیه عباسلو**

دانشکدهٔ مهندسی عمران، دانشگاه صنعتی سیرجان، سیرجان، ایران

ارسال 2020/03/27، پذیرش 2020/05/29

* نویسنده مسئول مکاتبات: ghanizadeh@sirjantech.ac.ir

چکیده:

با توجه به مسائل اقتصادی و زیست‌محیطی، استفاده از پسماندهای معدنی از جمله باطلهٔ سنگ‌آهن، به‌عنوان مصالح راهسازی می‌تواند به‌عنوان یک راهکار پایدار مطرح شود. در تحقیق حاضر، خصوصیات مکانیکی و همچنین دوام در برابر چرخه‌های ذوب و یخبندان (FT) خاک رس با خمیرایی کم تثبیت‌شده با درصدهای مختلف سیمان پرتلند (0٪، 6٪، 9٪، 12٪ و 15٪) و درصدهای مختلف باطلهٔ سنگ‌آهن (0٪، 10٪، 20٪، 30٪ و 40٪) بررسی شده است. برای این منظور، مقاومت فشاری تک‌محوری (UCS)، مدول الاستیک اولیه (E_0) و مقاومت کششی غیرمستقیم (ITS) در زمان‌های مختلف عمل‌آوری 7، 14، 18 و 56 روزه برای ترکیبات مختلف تعیین شد تا طرح اختلاط بهینه برای تثبیت بستر رسی مشخص شود. این تحقیق نشان داد که با افزایش درصد سیمان، پارامترهای مقاومتی مانند UCS، E_0 و ITS افزایش می‌یابند، در حالی که با افزایش باطلهٔ سنگ‌آهن، روند مشخصی از نظر افزایش پارامترهای مقاومتی دیده نمی‌شود. ارزیابی پارامترهای مقاومتی در زمان‌های مختلف عمل‌آوری نشان می‌دهد که در زمان‌های عمل‌آوری کوتاه‌مدت (7 و 14 روزه)، باطله سنگ‌آهن تأثیر مثبتی بر پارامترهای مقاومتی دارد، درحالی‌که در زمان عمل‌آوری طولانی مدت (28 و 56 روزه)، باطله سنگ‌آهن تأثیر منفی بر پارامترهای مقاومتی دارد. درمجموع مشخص شد که 12٪ سیمان پرتلند و 10-40٪ باطلهٔ سنگ‌آهن معیارهای مقاومت فشاری تک‌محوری و دوام در برابر سیکل‌های ذوب-یخبندان را برای تثبیت بسترهای رسی با خمیرایی کم تأمین می‌کنند و این در حالی است که برای تثبیت خاک رس به تنهایی (بدون باطلهٔ سنگ‌آهن) به حداقل 15٪ سیمان نیاز است.

کلمات کلیدی: خاک رس، باطلهٔ سنگ‌آهن، سیمان پرتلند، تثبیت خاک.