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Effect of Soil Physical Parameters and Foam Injection Ratio on Soil Shear Strength in EPB Tunneling

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Abstract

EPB machines have been the most applicable for tunneling in urban areas over the last decades. To increase soil consistency, reduce machine torque, and stabilize the tunnel face in EPB tunneling, foam injection is essential. The shear strength of the soil in the EPB chamber affects the machine torque. Therefore, in this research, the effects of soil water content, clay percentage, foam injection ratio, and soil granular size on the shear strength are investigated. The Isfahan subway line 2 in Iran was selected as a case study. Based on the results of the vane shear test, the shear strength of soil first increases rapidly and then gradually with an increase in soil particle size, and particle size is the most significant parameter that controls the shear strength of soil samples. The result of the analysis also indicates that increasing FIR up to 40% can lead to a 44% reduction in soil shear strength and, as a result, a decrease in excavation power. Increasing the clay percentage from 20 to 40 percent reduces the soil shear strength by up to 36 percent. The lowest shear strength of soil is achieved when the water content is 5 percent. By increasing the FIR from 10 to 20 percent, the shear strength of samples decreases rapidly and remains constant when the FIR rises up to 40 percent.

1. Introduction

The most popular full-face machines applied for soft tunneling while the working face is unstable are slurry and earth pressure balance (EPB) machines. In recent decades, due to recent developments, the lack of separation plants, and cost benefits, EPB machines have been applied in a wide range of ground conditions and are more widespread compared to slurry machines [1-3]. For the efficient application of EPB machines, the conveying of excavated materials and the ability to apply pressure on the face mean that the soil workability must be increased in the EPB chamber. Soil workability depends on soil geotechnical parameters such as plastic limit, liquid limit, water content, and granular size distribution, and it can be modified by the use of additives such as polymers, surfactants, and clay. Increasing soil workability through foam and polymer injection in the EPB chamber is called soil conditioning, which is one of the key factors in EPB tunneling. Proper soil workability results in faster conveying of excavated soil, lower excavation power, higher penetration rate, and a reduced risk of cutterhead clogging [4-6].

In EPB tunneling, soil conditioning can be done based on the excavation data that are recorded by a data logger and through trial and error. However, the application of some simple tests to optimize soil conditioning and determine the type and quantity of additives during excavation is easier, faster, and more practical [7]. The first attempts to design soil conditioning using laboratory test results were done by the European Federation for Specialist Construction Chemicals and Concrete (EFNARC) [8]. Although these tests were not done on soil samples, they are applicable to optimize soil conditioning design [3,9-10]. One of the main and simple tests applied to analyze the effects of additives on soil consistency and workability is the slump test [7,11-18]. Another class of tests includes

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a rotating blade inside a mixture of soil and chemical additives. In this group of tests, based on blade torque variation and energy consumption, the effect of foam injection and other additives on power and soil cohesion reduction is investigated [1,16,19-23]. An apparatus that can be used to investigate the effect of foam injection on soil shear strength is the vane shear test [3,24].

Duarte (2007) investigated the shear strength of sand samples and pointed out that by increasing the Foam Injection Ratio (FIR), the void ratio increases, leading to a decrease in shear strength [25]. Messerklinger et al. (2011) studied the shear strength of Kaolinite and Illite samples while the FIR was changed and concluded that by increasing the FIR, the shear strength decreases for different values of confining pressure [26]. Meng et al. (2011) considered the viscoplastic characteristics of sand samples using a modified vane shear apparatus and pointed out that increasing confining pressure, viscoplastic parameters increase, and they decrease with an increase in FIR [27]. Mori (2016) analyzed the void ratio and compressibility of soil samples using the vane shear test, and concluded that void ratio and compressibility depend on FIR [24]. Spagnoli et al. (2018) investigated the effect of ethanol on the undrained shear strength of clay, and pointed out that ethanol reduces the shear strength of clay [28]. Hu and Rostami (2021) examined the effect of commercial surfactants on the rheology parameters of conditioned soil [29]. Lee et al. (2022), applying a pressurized vane shear test, investigated the rheological parameters of foam agents in EPB tunneling and the effect of FIR and water content have been discussed [30]. Lee et al. (2024) based on the couple DEM-FDM numerical simulation analyzed the effect of foam conditioning on the EPB tunnelling. The model calibration was done based on the triaxial compression and vane shear tests [31]. Guixiao et al. (2025) considered the effects of different foam agents on the shear strength of gravel-clay strata applying vane shear test [32]. The effect of foam type and FIR on excavation costs, tool consumption, delay, clogging, Atterberg limits, and maintenance time were the objectives of many studies [33-44].

Based on the literature review, most studies are focused on the rheologic behavior of soil in the EPB chamber, and there is a lack of studies considering the effect of soil particle size on excavation power in EPB tunneling. Therefore, in this research, the Isfahan subway line 2, Iran, is considered as a case study. Then, based on in-situ sampling, the fabrication of physical samples that are similar to Isfahan subway line 2 soil samples, and laboratory tests, the effect of particle size distribution of soil, water content, FIR, and clay percentage on soil shear strength are investigated.

2. Geology

The Isfahan subway line 2 starts from Zeinbiyeh Street in the northeast of Isfahan and, with a length of 24.4 km, ends at Kohandezh Street in the west of Isfahan. The Isfahan subway lines are depicted in Figure 1. It runs through floodplain sediment deposits. These sediments are generally categorized into four layers: man-made fill, upper fine-grained sediments, riverine coarse-grained sediments, and lower fine-grained sediments. The boreholes, which have been drilled to the planned excavation depth, do not reach the bedrock. Therefore, the entire tunnel alignment and station structures will be situated within alluvial deposits. Given that Earth Pressure Balance (EPB) tunneling is being used, special attention must be paid to the distribution of the cemented coarse-grained sediment layers. The geomechanical properties of the mentioned strata are summarized in Table 1. These parameters were determined using data from 31 boreholes. During drilling, in addition to core sampling, Standard Penetration Tests (SPT) and downhole seismic tests were conducted [45]. Figure 2 shows the geological profile of Isfahan subway line 2.

Table 1. The geomechanical parameters of each stratum in Isfahan subway line 2 [45]

	E (MPa)	ν	C (kPa)	φ (Degree)
Man fill	(41-86) Ave:62	(0.34-0.35) Ave:0.35	(25-29) Ave:27	(26-37) Ave:31
Clay	(33-104) Ave:65	(0.33-0.38) Ave:0.35	(2-27) Ave:15	(1-56) Ave:25
Gravel Medium	(37-118) Ave:84	(0.30-0.35) Ave:0.34	33	11
Sand Medium	(53-106) Ave:78	(0.3-0.35) Ave:0.33	(34-37) Ave:35	(12 -20) Ave:16

Where C is cohesion, φ is friction angle, ν is Poisson's ratio and E is elastic modulus.
Ave means average and the values in parentheses are min and max values.

3. Samples Preparation and Laboratory Tests

3.1. Samples Preparation

To prepare the physical samples similar to the soil units encountered along the Isfahan subway line 2, the particle size distribution function, clay portion, and water content of the soil units along the tunnel were investigated in the Azmouneh Foulad laboratory, and the variation range for the particle size, water content, and clay portion was determined. To determine how each mentioned parameter affects the soil shear strength,

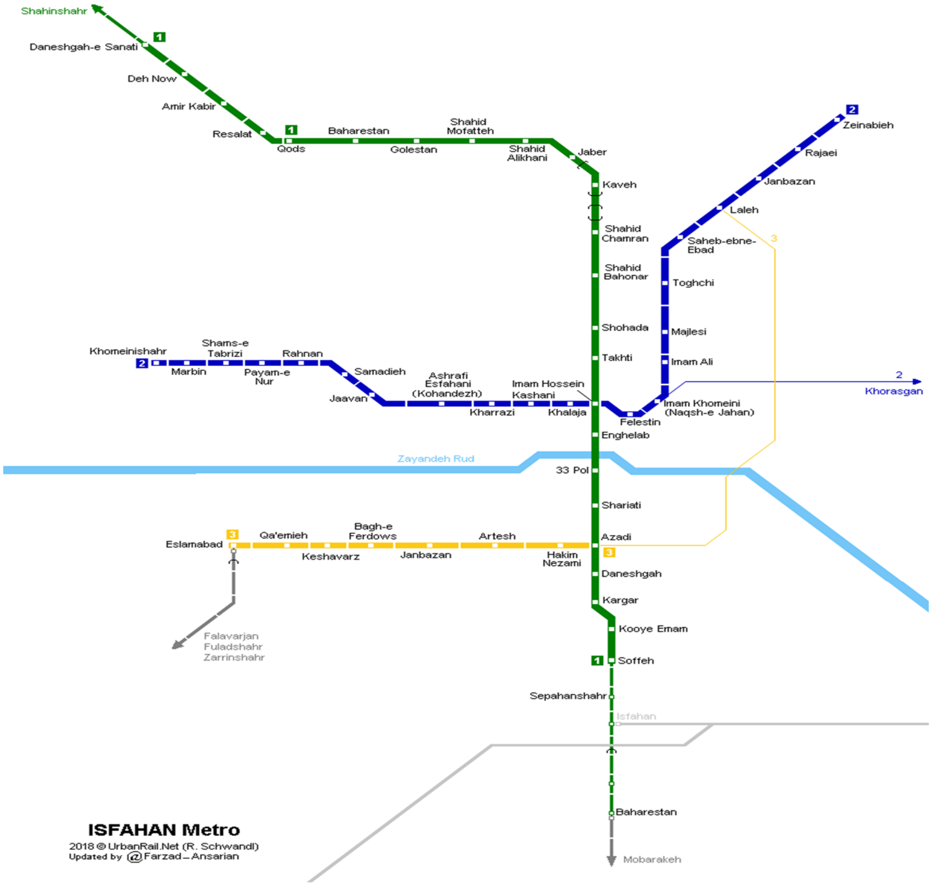


Figure 1. The Isfahan subway lines, the blue line is the subway line 2 [45]

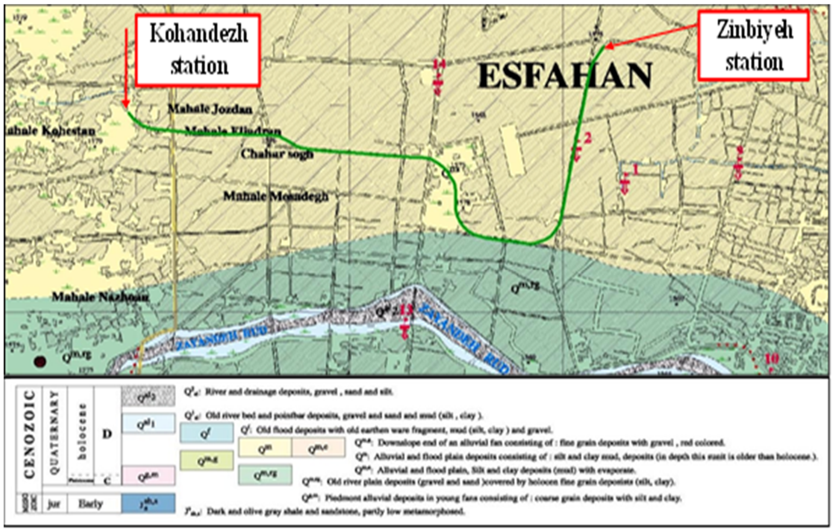
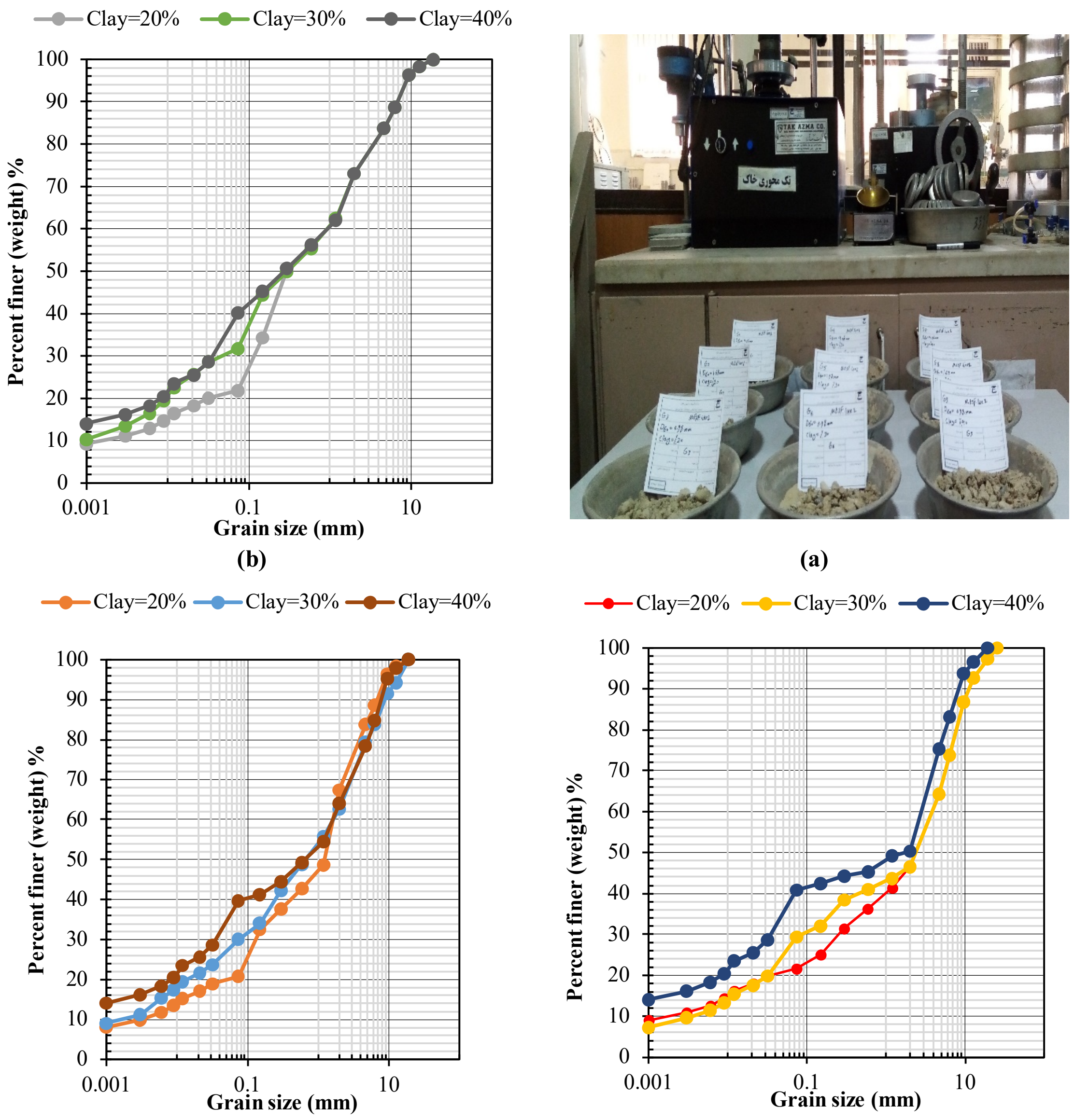


Figure 2. The geological profile of Isfahan subway line 2 [45]

one of the effective parameters needs to be changed while the others are kept constant. For the samples collected from the Isfahan subway line, controlling the way of variation in effective parameters is impossible. The fabrication of physical samples similar to natural ones allows us to analyze the role of each parameter in the soil shear strength, as the variation of each effective parameter is controllable. To consider the effect of the coarse portion of the soil samples on the soil shear strength, D60 (the diameter at which sixty percent of the particles are finer) is selected, and three values are nominated for D60, which are 4.05, 1.68, and 0.98 mm, according to the analysis conducted on the particle size distribution of Isfahan subway line 2 soil units. In addition, three values of 20, 30, and 40 percent are selected for the clay portion of physical samples, and the range of water content variations is considered to be 0, 5, and 7.5 percent, similar to the water content variation of the subway line samples. The particle size distribution function of fabricated physical samples for three values of D60 are depicted in Fig 3 As a result of three values for clay percent and three values for D60, nine physical samples have been fabricated which are depicted in Figure 3-a.



(b) (a)

(c) (d)

Figure 3. The particle size distribution function, a: Physical samples, b: D60=0.98 mm, c: D60=1.68 mm and d: D60=4.05 mm

3.2. Laboratory Tests

The vane shear test apparatus was used to determine the shear strength of fabricated physical samples. For each sample, the test was repeated six times to increase the reliability and accuracy of the test results. Three levels of variation were assumed for FIR, which are 10, 20, and 40 percent. As three levels of variation are considered for each effective parameter, and there are four parameters that have to be analyzed to determine how they affect soil shear strength, 81 combinations of effective parameters have to be tested. To decrease the number of combinations, the Taguchi approach was applied. Based on the Taguchi method the level of variation for each parameter in each combination and the total combinations of effective parameters that need to be analyzed to recognize how each parameter controls soil shear strength is suggested and presented in Table 2 [46]. For each combination, five physical samples were prepared and tested.

To fabricate the physical samples, based on the particle size distribution functions depicted in Figure 3 and taking into account the percent of clay assumed for each physical sample (Table 2), the mass of each fraction was determined. Then, all fractions and clay were mixed together, and water was added to achieve the designed value of water content. The intervals between fractions were selected based on the standard sieve sizes. The foam was prepared using a 5 percent surfactant solution and an expansion ratio of 10. Then, the foam volume was determined according to the designed value of FIR (Table 2) and the volume of the fabricated samples, and it was mixed with physical samples properly.

Table 2. The total combination of effective parameters which are suggested by the Taguchi approach

Test combination	FIR (%)	Water Content (%)	Clay (%)	D60 (mm)
1	10	0	20	4.05
2	10	5	30	1.68
3	10	7.5	40	0.98
4	20	0	30	4.05
5	20	5	40	0.98
6	20	7.5	20	1.68
7	40	0	40	1.68
8	40	5	20	0.98
9	40	7.5	30	4.05

4. Discussion

The vane shear test was conducted on each fabricated sample six times in order to increase reliability and accuracy, and the average value of these six tests was used to investigate the role of each effective parameter in soil shear strength. The output of Minitab software, which highlights the role of each parameter in soil shear strength, is shown in Figure 4.

The numbers 1, 2, and 3 refer to three levels of variation for each effective parameter from minimum to maximum, and the vertical axis shows the ratio of the mean (Signal) to the standard deviation (Noise). Based on this graph, the most effective parameters controlling the soil shear strength are D60 and FIR, while the least effective parameters are water content and clay percentage. In the following, the effect of soil particle size, clay portion, water content, and FIR on soil shear strength is investigated in detail.

4.1. Soil Grain Size

Figure 5 illustrates how the particle size of physical samples affects soil shear strength. The shear strength of samples increases sharply when D60 changes from 0.98 to 1.68 mm, and by further increasing D60 up to 4.05 mm, the shear strength of physical samples increases gradually. In addition, there is the same trend for the other 8 combinations of FIR and water content. Two components control the shear strength of soil samples: friction and cohesion between soil particles. The quantity of these components changes according to the clay portion, coarse grain portion, and coarse grain size. In other words, the soil samples could be assumed as a block in a matrix where clay is the matrix and coarse grains play the role of blocks. The shear strength results from failure plane propagation between soil granular and inter-soil granular. Because of the low level of normal stress, the probability of inter-granular failure is very low, and the most dominant mechanism of failure is the between-granular one. By increasing the soil grain diameter from 0.98 to 1.68 mm, the failure plane length increases because of the propagation of the failure plane inside the space between soil grains, which is depicted in Figure 6. However, as a result of the limitation of failure plane deviation in the space between the grains, there is not the same trend for an increase in failure plane length when D60 increases from 1.68 to 4.05 mm. Moreover, because of a low level of normal stress, the shear strength of physical samples is a function of cohesion, which is linearly related to failure plane length, and friction does not affect the shear strength significantly. In addition, increased interlocking in the physical samples with D60 equal to 1.68 mm could be another reason for the rise in shear strength**.**

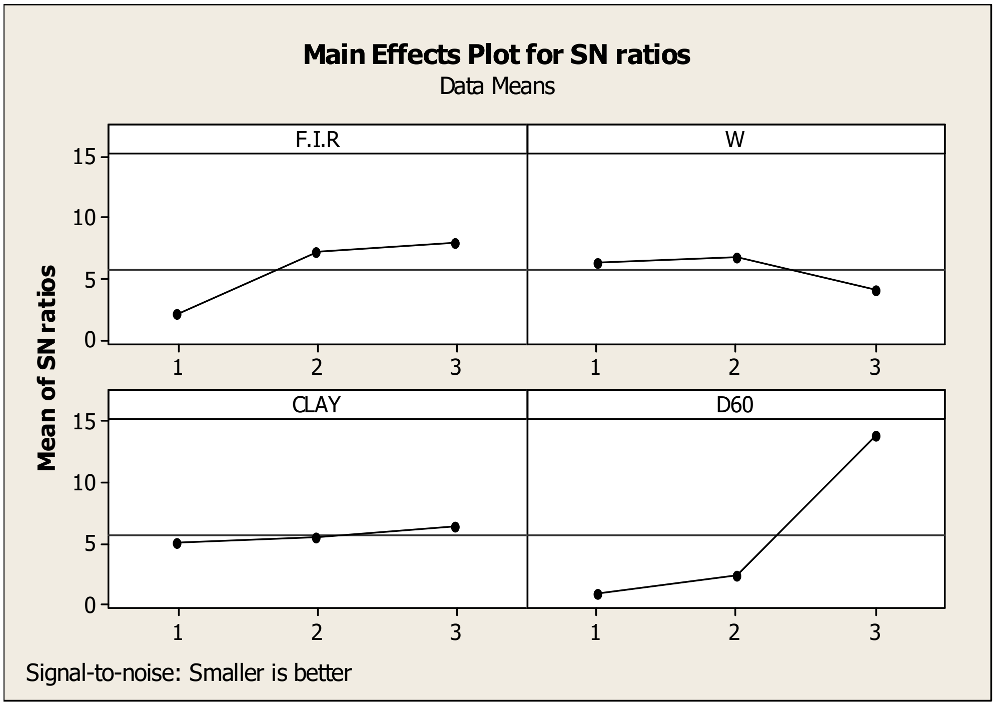


Figure 4. The particle size distribution function, a: Physical samples, b: D60=0.98 mm, c: D60=1.68 mm and d: D60=4.05 mm

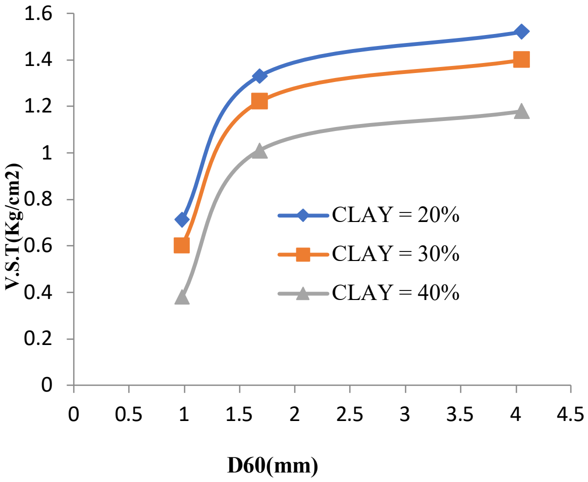


Figure 5. Physical samples shear strength versus D60, when the value of water content is 0 and FIR is equal to 10 percent

4.2. Clay Percentage

Figure 7 shows how the clay content of physical samples affects shear strength. It is clear that increasing the clay content up to 40 percent decreases the shear strength of physical samples. Although the amount of variation is different for each combination, the trend of variation is the same in all combinations of considered parameters. On average, when the clay content changes from 20 to 30 percent, the shear strength reduces by up to 13 percent, and when it varies from 30 to 40 percent, the shear strength shows a reduction of up to 26 percent. (The average values of V.S.T for clay contents of 20, 30, and 40% are 0.86, 0.74, and 0.55 Kg/cm², respectively.) In other words, the variation in clay content from 30 to 40 percent affects the shear strength of physical samples more significantly compared to changes in clay content from 20 to 30 percent. Figure 8 illustrates a schematic diagram of the arrangement of soil particles with increasing clay content. By increasing the clay percentage, the interlocking between soil particles decreases, and the failure plane propagates through the clay, which is placed between the soil particles. Clay cohesion controls the shear strength of physical samples. In other words, as the failure plane passes through the clay and the geometry of soil particles does not significantly affect the geometry of the failure plane, when the clay portion increases, the area of the failure plane decreases, and because cohesion of the clay controls the shear strength, as the failure area decreases, the shear strength also decreases.

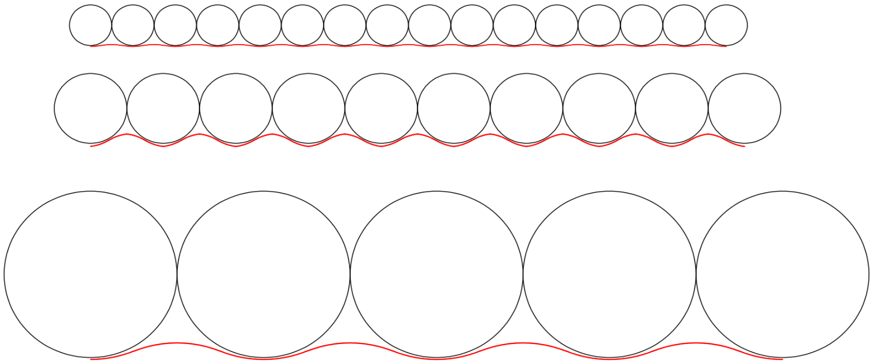


Figure 6. The simplified failure plane propagation when the grain size increases from 0.98 to 4.05 mm

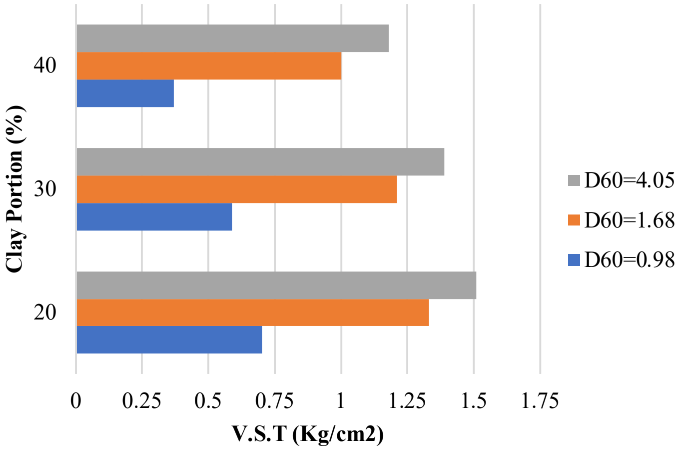
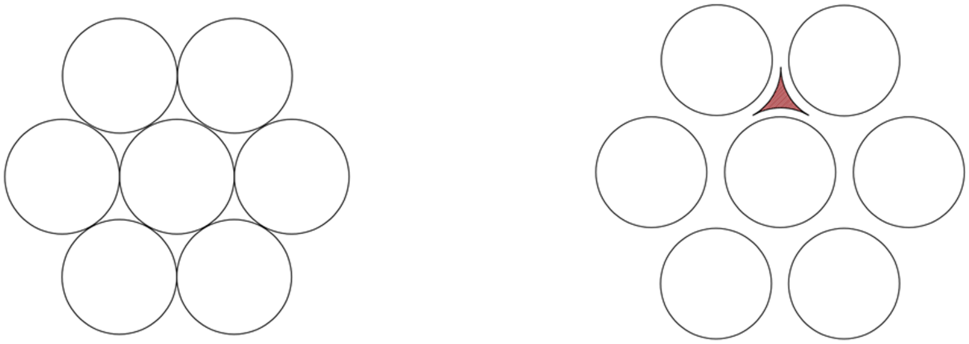


Figure 7. The shear strength of physical samples versus clay portion when water content is equal to 7.5 % and FIR is 10 %

4.3. Water Content

The variation of physical samples' shear strength versus water content is depicted in Figure 9 In all combinations of FIR, clay percentage, and D60, by increasing the water content from 0 to 5 percent, the shear strength of physical samples decreases slightly, and it increases when the water content reaches 7.5%. Achieving the maximum shear strength of soil samples when the water content is 7.5% is confirmed by other researchers [29].



(a) **(b)**

Figure 8. Arrangement of soil particles, a: clay content is 17%, b: clay content is 40%

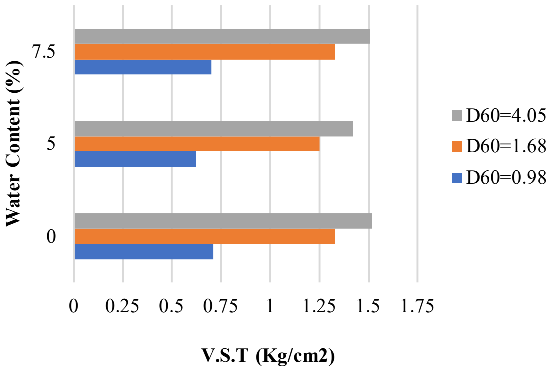
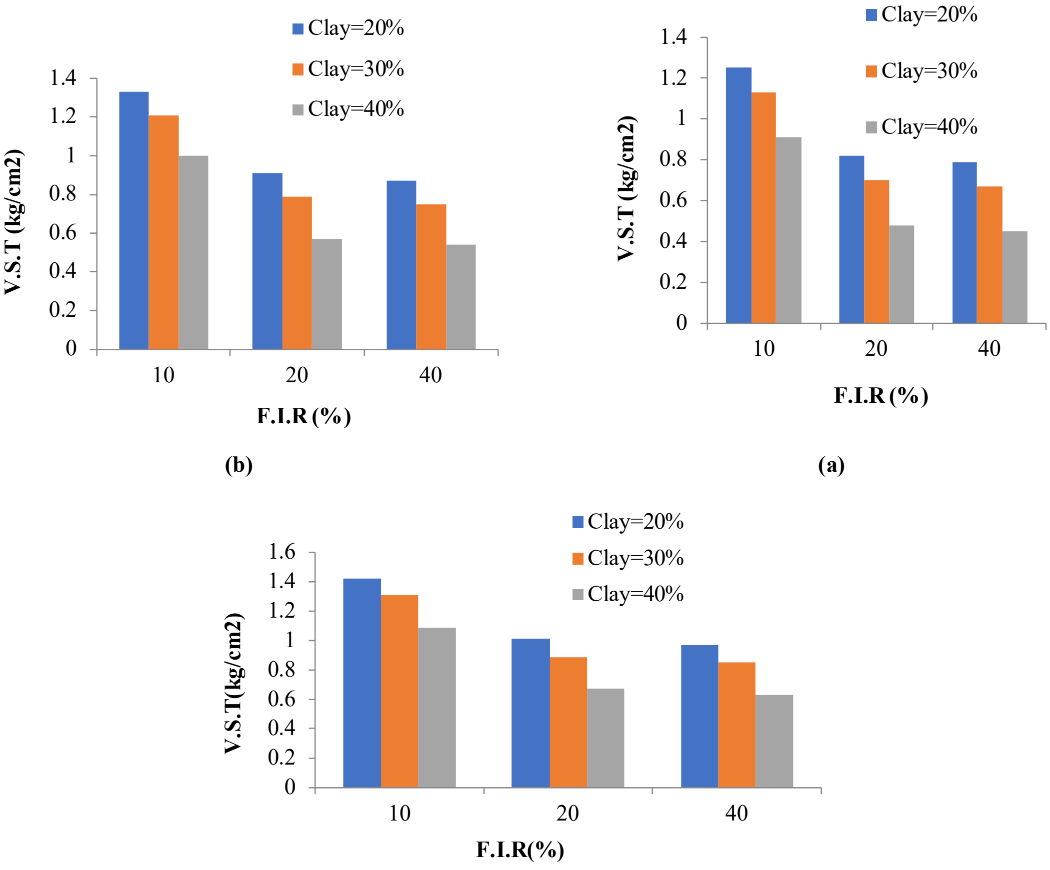


Figure 9. The shear strength of physical samples versus water content when the FIR is 10% and clay content is 20%

4.4. FIR

Figure 10 demonstrates how the FIR affects the shear strength of physical samples when the water content is 5% and soil particle size changes from 0.98 to 4.05 mm. By increasing the FIR from 10 to 20%, the shear strength of physical samples decreases rapidly in all combinations of considered parameters, and when the FIR increases up to 40%, the shear strength of physical samples remains almost constant. If the objective of foam injection is shear strength and power consumption reduction, a FIR of 20% could be assumed as an optimal value for foam injection. On average, for all combinations of considered parameters, when FIR increases up to 20%, there is a reduction in shear strength of samples by up to 41%, and when it changes from 20 to 40%, the shear strength of samples is reduced by just 5%. The power consumption for excavation has a linear relation with the soil shear strength in the EPB chamber, and a 41% reduction in shear strength is equal to a 41% reduction in power consumption, confirming the importance of foam injection in EPB tunneling. Increasing the FIR up to 40% reduces the shear strength of samples by up to 44% in comparison with an FIR of 10%.



(b)

(a)

(c)

Figure 10. The shear strength of physical samples versus FIR when the water content is 5%, a: D60=0.98 mm, b: D60=1.68 mm, and c: D60=4.05

5. Conclusions

In this research, the effects of FIR, water content, soil particle size, and clay content on soil shear strength in EPB tunneling were investigated by fabricating physical samples and performing laboratory tests. The foam type and expansion ratio that were assumed constant in this research could be analyzed for future studies. The Isfahan subway line 2 was chosen as a case study, and the physical samples were prepared to be similar to the soil units along the subway line. The result of the analysis indicates that increasing FIR up to 40% can lead to a 44% reduction in soil shear strength and, as a result, a decrease in excavation power. The variation of FIR from 10 to 20% affects soil shear strength more significantly than when it changes from 20 to 40%. An increase in clay content reduces the shear strength of soil samples, and when it changes from 20 to 30%, it affects the shear strength more. Soil particle size and FIR affect the shear strength of soil samples more than clay and water content. In the range of 0 to 7.5% water content variation, the minimum value of shear strength occurs when the water content is 5%. By increasing the soil particle size, the shear strength of physical samples increases, and most of the increment happens when the D60 rises from 0.98 to 1.68 mm.

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دانشگاه صنعتی شاهرود

اثر پارامترهای فیزیکی خاک و نسبت تزریق فوم بر مقاومت برشی خاک در حفاری تونل با دستگاه EPB

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کلمات کلیدی

خط ۲ متروی اصفهان
ماشین‌های حفاری سپر تعادلی زمین
محتوی آب
نسبت تزریق فوم
تابع توزیع سایز ذرات

چکیده

ماشین‌های حفاری سپر تعادلی فشار زمین طی دهه‌های گذشته به‌عنوان رایج‌ترین ماشین حفاری تونل در مناطق شهری مورد استفاده قرار گرفته‌اند. به منظور افزایش کارپذیری خاک، کاهش گشتاور ماشین و پایداری جبهه کار در حفاری با این ماشین‌ها، تزریق فوم نقش حیاتی ایفا می‌کند. مقاومت برشی خاک در محفظه ماشین تأثیر قابل‌توجهی بر گشتاور مورد نیاز حفاری دارد. در این پژوهش، تأثیر میزان رطوبت خاک، درصد رس، نسبت تزریق فوم و تابع توزیع ذرات خاک بر مقاومت برشی مورد بررسی قرار گرفته است. خط ۲ مترو اصفهان در ایران به عنوان مطالعه موردی انتخاب شده است. نتایج حاصل از آزمایش برشی پره‌ای نشان می‌دهد که با افزایش اندازه ذرات، مقاومت برشی ابتدا به صورت سریع و سپس به تدریج افزایش می‌یابد، به‌طوری‌که اندازه ذرات به عنوان مهم‌ترین عامل مؤثر بر مقاومت برشی خاک شناخته می‌شود. همچنین، افزایش نسبت تزریق فوم تا ۴۰ درصد منجر به کاهش ۴۴ درصدی مقاومت برشی خاک و در نتیجه کاهش توان مورد نیاز برای حفاری می‌شود. افزایش درصد رس از ۲۰ تا ۴۰ درصد نیز باعث کاهش مقاومت برشی خاک تا حدود ۳۶ درصد می‌شود. کمترین میزان مقاومت برشی در رطوبت ۵ درصد مشاهده شده است. علاوه بر این، افزایش نسبت تزریق فوم از ۱۰ تا ۲۰ درصد باعث کاهش شدید مقاومت برشی می‌شود و با افزایش بیشتر آن تا ۴۰ درصد، مقاومت برشی تقریباً ثابت باقی می‌ماند.

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