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Effect of Gradation on the Permeability of Foam-conditioned Soils in Mechanized Excavation

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Abstract

Tunnel excavation in a soft ground is often conducted utilizing excavation machines, including earth pressure balance (EPB) boring machines. A safe and economical excavation using this method requires adding materials such as foam and polymer to the soil inside the chamber and the tunnel face to control parameters like permeability, plasticity, shear resistance, and compressibility. Using an experimental method, the present study investigates the effects of granulation, soil moisture content, and pressure on the permeability of a soil conditioned with foam. According to the results, as the effective grain size (d_{10}) increased from 0.1 to 0.4 mm, the permeability of the conditioned soil grew from 2.28 × 10^{-5} m/s to 12.3 × 10^{-5} m/s. A rise in the coefficient of curvature (C_c), while the percentage of the materials passing through the sieve No. 200 was kept constant, increased the permeability coefficient (k_i) of the specimens since the medium-grained particles (d_{30}) became coarser. A rise in C_c and the percentage of materials passing through sieve No. 200 resulted in an initial rise in the k_i due to the lack of contribution of d_{30} and a subsequent reduction in it caused by the rise in fine-grained materials. The k_i was also found to have inverse relationships with the uniformity coefficient (C_u) and pressure. As C_u increased from 3 to 20, the k_i declined from 1.23 × 10^{-5} m/s to 0.71 × 10^{-5} m/s.

Keywords

EPB, soil conditioned with foam, permeability, granulation, pressure, moisture content

1 Introduction

A suitable soil for excavation with earth pressure balance (EPB) shield tunnelling is one that can form a soft plastic material capable of applying pressure to the tunnel face and has low permeability to prevent underground water drainage after excavation and entering the pressure chamber. Accordingly, soil permeability is an effective parameter in the performance of an excavator, especially in tunnels located below the water table. Permeability of granular soils is strongly related to the grain size [1]. According to the literature, the appropriate value of soil permeability for EPB machines is less than 1 × 10^{-5} m/s. In grounds such as alluvial lands where the underground water table is above the tunnel, the permeability value is higher than 1 × 10^{-5} m/s, which should be reduced by applying appropriate materials to prevent the flow of underground water into the spiral conveyor [2]. Foam is among the materials usually used in such conditions to improve soil properties. Foam, which is produced by mixing a foam solution with air, is injected into the tunnel face through nozzles to create an impermeable layer. It is worth noting that the mixture must be injected immediately as long as the air bubbles exist. When the foam is added, the air bubbles reduce the density of the excavated soil and the friction between soil particles, reducing the power required for an excavation machine. Moreover, the bulk modulus of the soil conditioned with foam is lower, allowing for controlling the pressure of the tunnel face [3]. A number of studies have been performed on the permeability of soils conditioned with foam. The following mentions a few examples of such studies.

Borio and Peila [4], conducted experiments to study the permeability of a soil conditioned with foam. The tests were performed on two different types of clay at the pressures of 0.1 and 1 bar (according to ASTM D2434-19 [5] standard). The studied foam had a C_f of 3%, a half-life of

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200 sec at foam expansion ratio (FER) = 12 and a half-life of 110 sec at FER = 7.5. The results of the tests on clay (fluvial sand) indicated that the addition of foam to the samples increased the time required for water to pass through the specimens. Moreover, increasing the applied pressure to one bar played a crucial role in soil permeability although it did not become completely impermeable.

Peila [6], investigated the permeability of the soil with 0%, 40%, and 60% foam injected. They found that the permeability of the soil decreased as the percentage of the injected foam increased.

Using slump and permeability tests, Kim et al. [7], studied the improvement of two types of weathered granite soil. In the first soil with a moisture content of 30% and a foam injection ratio (FIR) of 22–67%, the slump values varied between 10 cm and 20 cm, indicating good workability according to the standards. Meanwhile, the optimal workability occurred at the moisture content of 15% and FIR of 22–67% in the second soil. Accordingly, they concluded that the moisture content had a great effect on the slump value.

Changing foam parameters (FIR, FER, and half-life), Zhou and Yang [8], studied the permeability of cohesive soils. They found an inverse relationship between the half-life of the foam and the permeability of the soil conditioned with it. For instance, with a half-life of greater than 30 minutes (40 ZD, 50 ZD, and 60 ZD), FER = 10, and FIR = 50, the permeability of soils decreased to less than 2×10^{-4} cm/s. Furthermore, higher values of FER resulted in higher foam stability and lower soil permeability. The results of permeability experiments and field tests indicated highly stable foaming agents with a moderate FER (= 10–20%) and FIR (= 50%–75%) as an effective means to reduce the permeability of cohesionless soils and prevent water seepage from screw conveyors.

Hu et al. [9], investigated the effects of hydraulic gradient on the permeability characteristics, including the initial permeability coefficient (k_i), initial stability time (t_s), and the increase rate of k_i on a soil conditioned with foam. According to the outcomes, k_i increased with the hydraulic gradient, having significant values at hydraulic gradients of greater than 11. An inverse relationship was also found between the hydraulic gradient and the initial t_s.

Kim et al. [10], explored the workability of five types of weathered granite soils using the slump and permeability tests. They found that the amount of moisture required to achieve optimal workability increased with the amount of fine-grained materials in the soils.

Tao et al. [11], investigated the effectiveness of soil conditioning with foam on fully weathered granite in Guangzhou Metro Line 21. They found that the type of foaming agent, pressure, and foam injection ratio affected the performance of the soil conditioned with foam. They also proposed a conditioning design to improve tunneling efficiency.

Sebastiani et al. [12], classified 15 commercial foaming products based on their half-life time for EPB mechanized tunneling. They divided the products into five classes based on their ability to generate stable foam. The proposed classification can be useful for manufacturers and engineers, allowing them to choose the most appropriate product by performing only a few laboratory experiments.

Wang et al. [13], expanded an analytical model based on the permeation theory of pure foam to estimate the coefficient of permeability of a soil conditioned with foam. They studied 18 foam-conditioned soils (with different conditioning parameters) through a series of large-scale permeability experiments to validate the analytical model. The results revealed a generally good agreement. Moreover, the coefficient of permeability was raised for fully conditioned soils with the effective particle sizes of the soil and foam.

Pasand Masoumi et al. [14], sought the optimum parameters of silty-clay (CL-ML) soils conditioned with different foam factors and water contents in EPB tunnelling. The optimum values of foam injection ratio, foam expansion ratio, and percentage ratio between surfactant agent and water volume equaled 157%, 10, and 2.07, respectively. Soil conditioning with the mentioned values was tested in two stages during the excavation. The results indicated a reduction in soil conditioning costs and a rise in the advance speed.

In the present study, mixtures of soil and foam were prepared to evaluate the effects of granulation, soil moisture content, and pressure on the soil permeability on a laboratory scale. In these experiments, the effect of d_{10} was investigated, as well as the effects of coefficient of curvature (C_c) and uniformity coefficient (C_u), using six and four types of soil with different grain sizes, respectively.

2 Tests and materials

As mentioned, to conduct experiments, six types of granular soil with different granularity (according to ASTM C136 [15] standard) were prepared using the dry method. Fig. 1 demonstrates the used soil types, along with their gradation curves. Moreover, the properties of the soils (prepared from Tabriz Subway [16]) are listed in Table 1.

Table 2 provides the properties of the used foam, produced by Kashan Komail Company (KF 168B). Foam parameters, including FER, FIR, half-life, and concentration, are among the factors that must be determined before

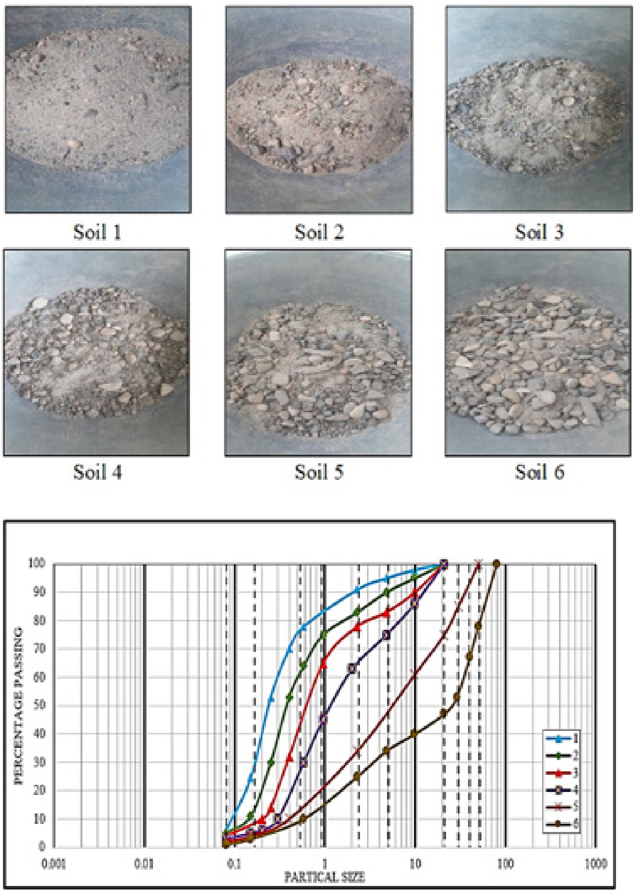


Fig. 1 Soil type and soil gradation curve

Table 1 Properties of the soils used in the experiments

Soil	d_{10}	d_{30}	d_{60}	C_c	C_u
1	0.1	0.16	0.3	0.85	**3**
2	0.15	0.27	0.5	0.97	**3.3**
3	0.2	0.39	0.8	0.95	**4**
4	0.3	0.6	1.7	0.7	**5.66**
5	0.4	1.7	10	0.72	**25**
6	0.6	3.5	35	0.29	**58.3**

Table 2 Properties of KF 168B and foam

Properties of KF 168B		Parameters of the foam	
State	Liquid	Density	3%
Color	Colorless	FER	7.5
Density at 20 °C (kg/m^3)	1035	FIR	60
Viscosity at 20 °C (m Pa s)	100	Half-life	10 min and 12 sec
pH at 20 °C	6.5–7.5		
Solubility in water	Completely soluble		

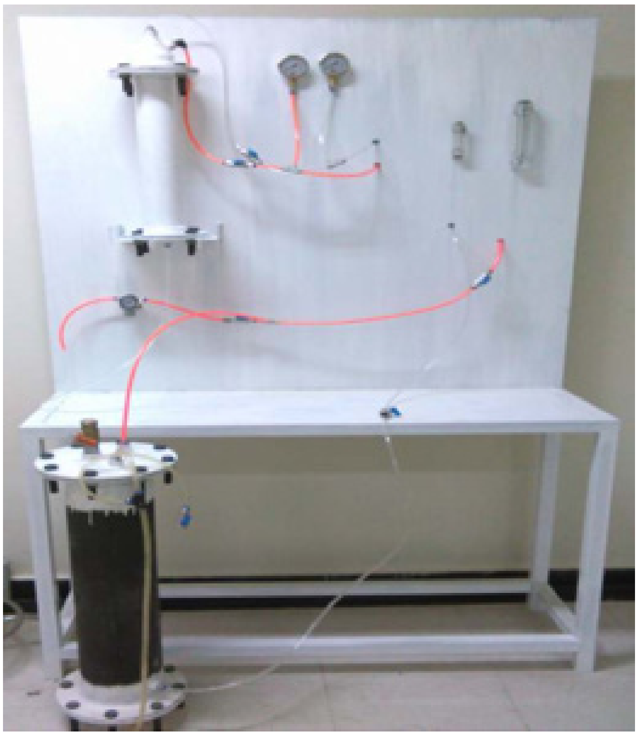


Fig. 2 The foam production machine

conducting tests. The foam was produced using the apparatus shown in Fig. 2.

The specimens were prepared using the same method in all tests. A mixing container was filled with a certain amount (4 kg) of soil in the dry state. Then, water was added to the specimens to provide the required soil moisture content (5%, 10%, and 15%). After creating a uniform state using a mixer, the foam with a certain expansion ratio was added to the mixture, and the mixing continued for about 120 sec until the material was completely mixed.

The slump test (according to the ASTM C143 [17] standard) was used to determine the plasticity of the soil conditioned with foam. To this end, the conditioned soil was poured in three layers, with each layer compacted with 25 strikes. Then, the cone was pulled up carefully about 30.5 cm for 5 sec and placed upside down next to the soil. The height difference between the steel cone and the soil cone indicated the slump value.

The soil permeability test under a constant load was performed according to the ASTM D2434-19 [5] standard using the apparatus shown in Fig. 2, which is usually used to measure the permeability using slow flow and constant load in coarse-grained soils.

3 Results and discussion

The permeability test on the mixture of soil and foam was performed in the following steps. First, the foam was produced using the foam machine according to the C_f and FER values, and the soil was prepared with a specific granulation and moisture content. After mixing the prepared soil and foam inside a mixer, the mixture was poured into a permeability chamber and compacted using a 5.5-lb proctor. Then, the metal cap was tightly closed. In the next step, the water with a certain pressure was injected into the mixture of the soil and foam, and when the water was drained towards the well at a constant speed, the time required for two liters of water to pass through the specimen was recorded. The permeability tests were conducted at pressures of 0.5, 1, and 1.5 bar and soil moisture contents of 5, 10, and 15%. Eventually, the effects of granulation, soil moisture content, and pressure on the permeability of the soil conditioned with foam were studied.

3.1 The effect of granulation on permeability

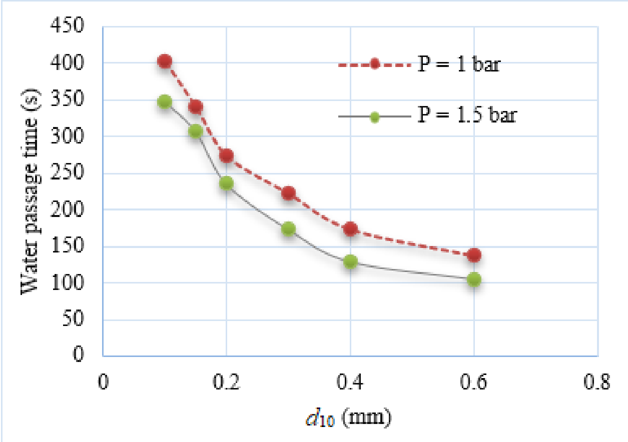
To investigate the effect of granulation on soil permeability, the effects of three parameters, i.e., d_{10}, C_c and C_u were studied in the experiments.

3.1.1 The effect of d_{10} on soil permeability

To investigate the effect of d_{10} on the soil permeability, the tests were carried out on the soil conditioned with foam with moisture contents of 10 and 15% and the properties mentioned in Table 2. The results obtained from the experiments Fig. 3 indicated the inverse and direct relationships of the water passage time with the pressure and soil moisture content, respectively, in all types of soils with different values of d_{10}.

As shown in Fig. 3, the change in soil granularity from fine grains to coarse grains caused a significant reduction in the time required for the water to pass through the conditioned soil. Fig. 4 depicts the obtained k_i versus different granularities at different pressures and soil moisture contents.

According to Fig. 3 and Fig. 4, as d_{10} increased from 0.1 mm to 0.6 mm, the time required for the water to pass through the soil-foam mixture decreased, i.e., the permeability increased. For instance, the ki of the soil conditioned with foam increased from 2.28×10^{-5} m/s to 12.3×10^{-5} m/s with the rise in d_{10} from 0.1 to 0.4 mm at the pressure of 1 bar and soil moisture content of 10%. This can be explained by the fact that when the soil is fine-grained, the particles can be easily mixed with foam and form an impermeable structure against water. In other words, the injection of foam is equivalent to the rise in fine-grained particles, which fill the pores between the coarse-grained particles. As a result, the structure of the soil becomes denser, and its permeability decreases. It should be noted that the slope of the rise in the k_i also increased with d_{10}. The following explains the reason behind this phenomenon. According to Hazen's [18] formula, proposed for the



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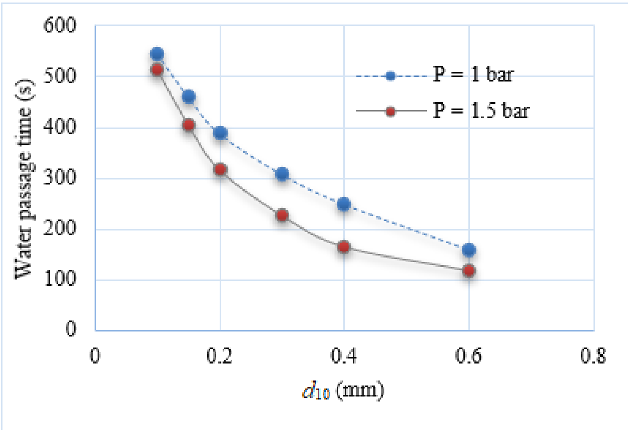


(b)

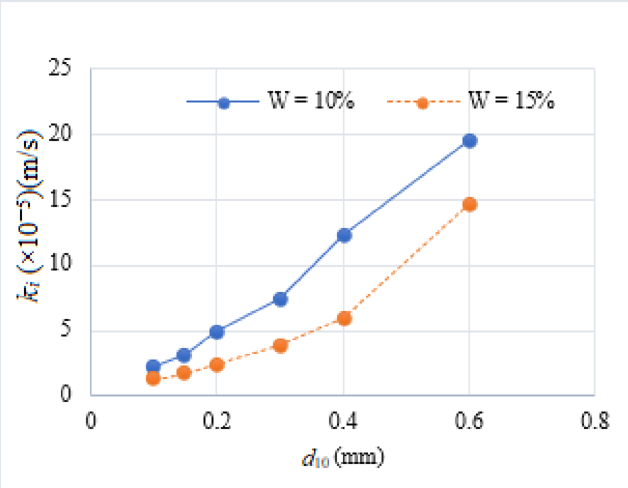
Fig. 3 Effect of d_{10} on the water passage time at pressures of 1 and 1.5 bar: (a) soil moisture content: 10%; (b) soil moisture content: 15%

k_i of unmodified clay soils that given in Eq. (1) as follows:

$$k_i = C_e \times d_{10}^2, \tag{1}$$

where k_i is the permeability coefficient (m/s), C_e is the parameter that depends on the holes in the soil and is constant and d_{10} is the effective grain size (mm).

A slight rise in d_{10} increases the k_i in the soil conditioned with foam. It seems that in a soil conditioned with foam, the soil plays a small role in reducing the permeability, and the ability to create an impermeable structure against water depends on the foam, which fills the voids of the soil. The rise in the k_i of the conditioned soil has a slight slope at low values of d_{10}. The rise in the value of d_{10} increases the number of coarse-grained particles, resulting in a sudden increase in voids among the soil particles so that the foam cannot fill them. Thus, a large volume of water flows directly from the soil, resulting in a sudden rise in the permeability and, consequently, a sudden rise in the slope of the graph.



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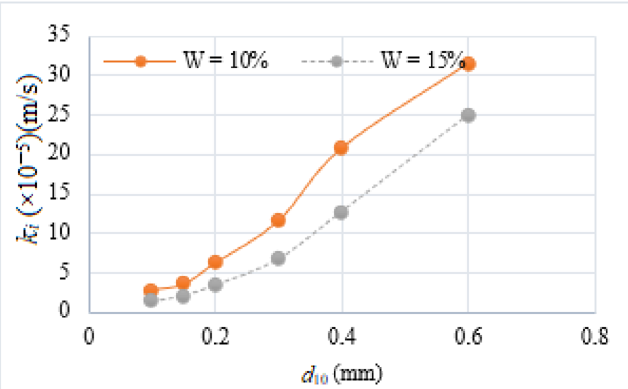

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Fig. 4 The permeability of the soil conditioned with foam versus d_{10} at the moisture contents of 10 and 15%: (a) the pressure of 1 bar; (b) the pressure of 1.5 bar

3.1.2 The effect of the coefficient of curvature (C_c) on permeability

Experiments were conducted with four different types of soil granularity to investigate the effect of the C_c on the permeability of the soil (Fig. 5).

Among the factors that affect the C_c, i.e., d_{10}, d_{30} and d_{60}, the value of d_{30} was changed while the values of d_{10} and d_{60} were kept constant at the moisture content of 15% and pressure of 1 bar (Table 3).

Fig. 6 depicts the water passage times and the C_c for the four soil types. It is worth noting that the experiments were carried out twice to improve the accuracy of the results.

The k_i of the soil conditioned with foam increased with C_c. However, given the constant value of d_{10}, the changes in permeability were not significant. The maximum and minimum kis equalled 2.42×10^{-5} and 1.23×10^{-5} m/s, respectively, i.e., the maximum k_i was 1.96 times the minimum k_i.

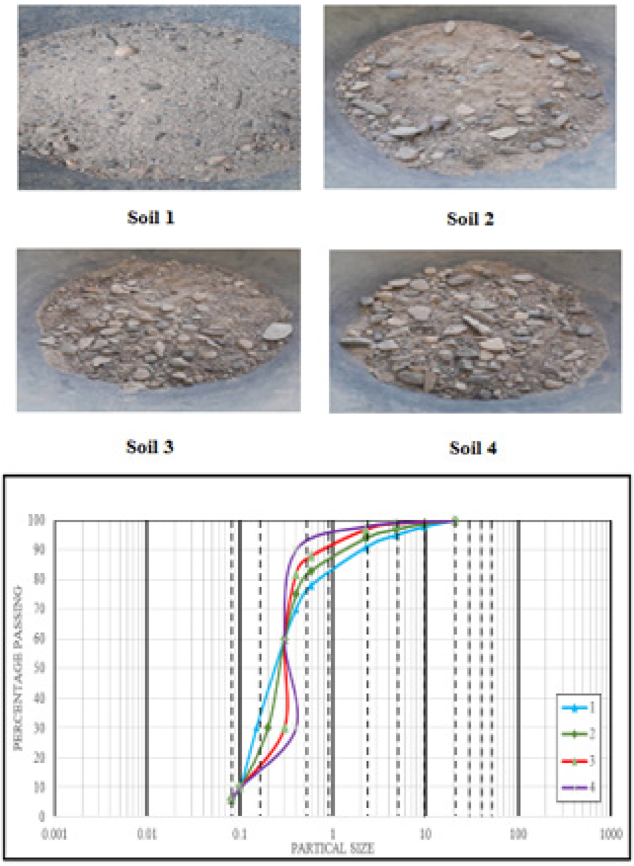


Fig. 5 Soil specimens and Granulation diagrams of the soils

Table 3 Physical properties of the soils

Soil	1	2	3	4
d_{10}	0.1	0.1	0.1	0.1
d_{30}	0.16	0.2	0.3	0.4
d_{60}	0.3	0.3	0.3	0.3
C_c	0.85	1.33	3	5.3
C_u	3	3	3	3

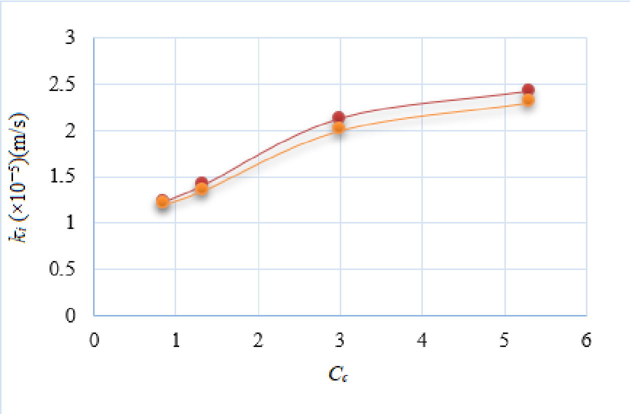
This can be explained by the fact that according to the relationship between the C_c and d_{30} that described in Eq. (2) as follows:

$$C_c = \frac{(d_{30})^2}{d_{10} \times d_{60}}, \tag{2}$$

where C_c is the coefficient of curvature, d_{30} is the medium-grained particles (mm), d_{10} is the effective grain size (mm) and d_{60} is the particle size at which 60% of the particles are finer than d_{60} size (mm).

The rise in C_c increases the amount of medium-sized grains and, thus, the k_i of the soil conditioned with foam.

The effect of C_c on the permeability of four types of conditioned soil was studied by adding fine particles passing through a sieve No. 200 at a moisture content of 15%. Fig. 7



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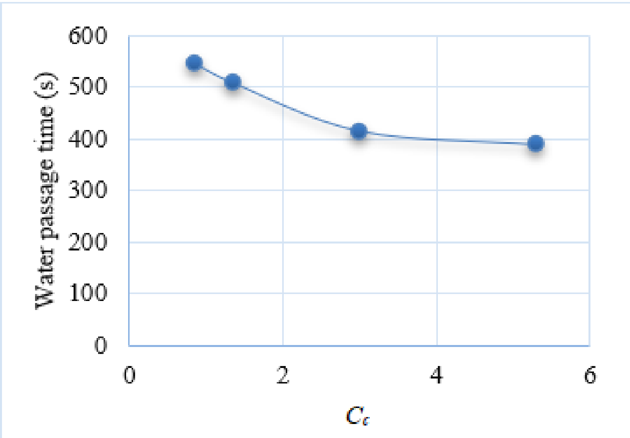

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Fig. 6 The effect of the C_c at the moisture content of 15% and pressure of 1 bar: (a) Water passage time; (b) Permeability

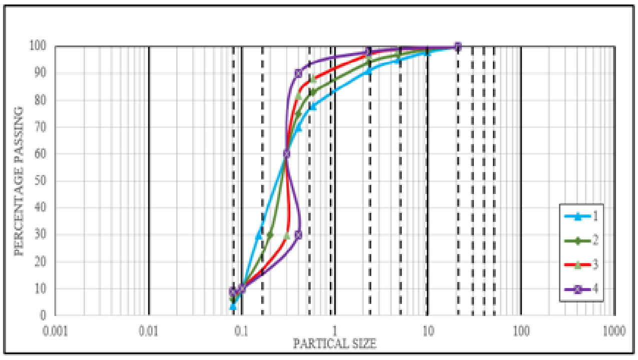


Fig. 7 Soil gradation (increase in the percentage of fine-grained particles)

Table 4 The physical properties of the soils (increase in the percentage of fine-grained particles)

Soil	1	2	3	4
d_{10}	0.1	0.1	0.1	0.1
d_{30}	0.16	0.2	0.3	0.4
d_{60}	0.3	0.3	0.3	0.3
C_c	0.85	1.33	3	5.3
C_u	3	3	3	3
The percentage of material passing through sieve No. 200	6	7	8	9

shows the diagram of the soil gradation, and Table 4 lists the physical properties of the soils. Fig. 8 demonstrates the graphs of water passage time and k_is of the conditioned soils.

According to the results, as the percentage of the material passing through sieve No. 200 increased, the permeability experienced an initial rise due to the reduction in d_{30}, while decreasing at higher percentages of the fine-grained material.

3.1.3 The effect of the uniformity coefficient (Cu) on the permeability

Experiments were conducted on four types of soil with different granularities (C_u = 3, 5, 10.5 and 20) to investigate the influence of the uniformity coefficient on the permeability of the soil conditioned with foam (Fig. 9).

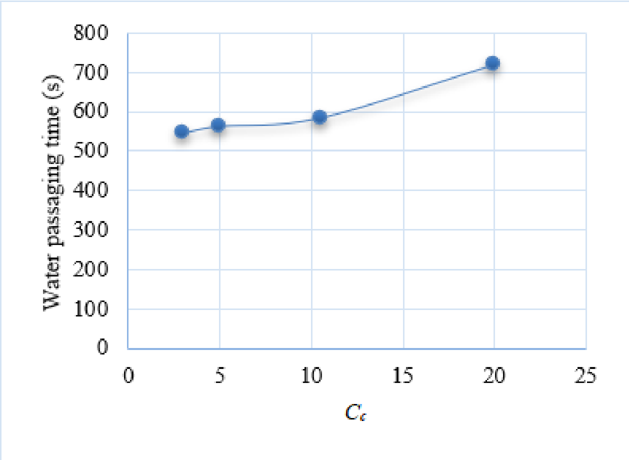
The experiments were carried out by changing the values of C_u while keeping d_{10} and C_c constant (Table 5) at the pressure of 1 bar and moisture content of 15%. Fig. 10 illustrates the results of the permeability tests on the soils. To increase the accuracy of the results, the tests were performed twice, which indicated good compliance.

According to Fig. 10, the ki of the soils conditioned with foam had an inverse relationship with the C_u. The rate of change was similar to that of C_c. The maximum and minimum k_is equaled 1.23 × 10^{-5} m/s and 0.71 × 10^{-5} m/s, respectively. It seems that with the rise in the C_u, the pores between the coarse grains can be filled with fine and medium grains, and the addition of the foam to the soil structure prevents the water from moving through the coarse particles, reducing the permeability of the soil.

3.2 The effect of moisture content on permeability

Soil moisture is an effective factor in permeability. In order to investigate the effect of moisture, tests were carried out on specimens 4, 5, and 6 (Table 1) that were conditioned with foam (whose properties are shown in Table 2) at the pressure of 0.5 bar and moisture contents of 5, 10, and 15%.

The outcomes revealed that with the rise in the moisture content from 5% to 15%, the time required for the water to pass through the specimens increased and, thus, the k_i decreased (Fig. 11). This reduction can be justified by the fact that with the rise in the soil moisture, the particles



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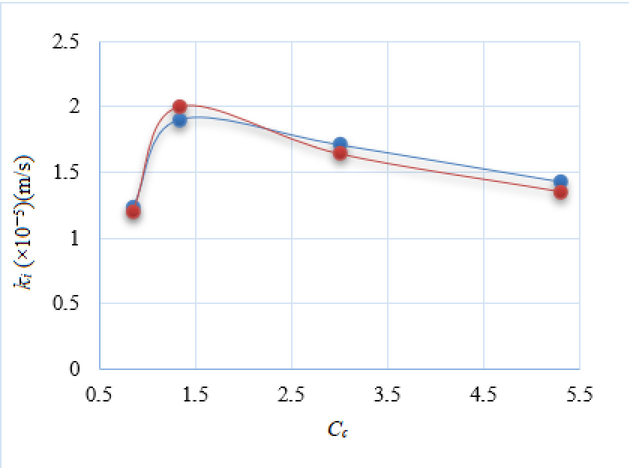

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Fig. 8 The influence of the C_c on the conditioned soil with an increase in the percentage of the fine-grained particles at the moisture content of 15% moisture and pressure of 1 bar: (a) Water passage time; (b) Permeability

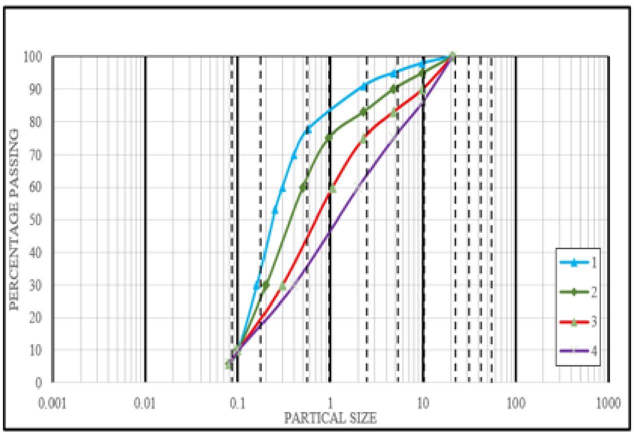
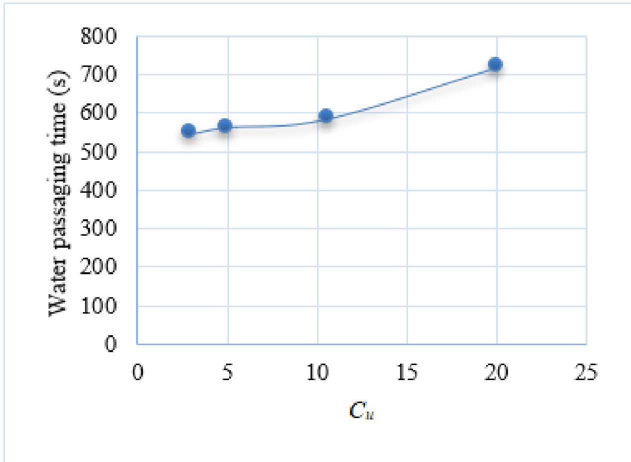


Fig. 9 Granulation diagrams of the soils (C_u = 3, 5, 10.5 and 20)

inside the soil become more mobile. In other words, as the moisture in the soil approaches the saturation state, it fills the pores and discontinuities, thus preventing the flow of water and reducing permeability. The conditioned soil type 4 became impermeable at a pressure of 0.5 bar and a moisture content of 15%.

Table 5 Physical properties of the soils

Soil	1	2	3	4
d_{10}	0.1	0.1	0.1	0.1
d_{30}	0.16	0.2	0.3	0.4
d_{60}	0.3	0.5	1.05	2
C_c	0.85	0.85	0.85	0.85
C_u	3	5	10.5	20



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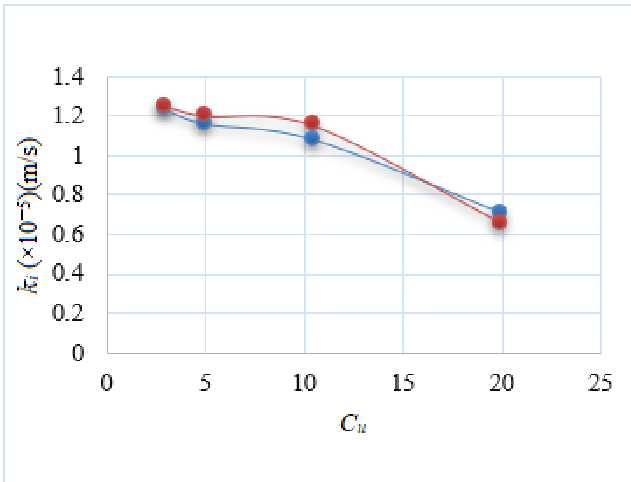

(b)

Fig. 10 Influence of the C_u on the permeability at the moisture content of 15% and pressure of 1 bar: (a) Water passage time; (b) Permeability

3.3 The effect of pressure on permeability

Permeability tests were performed on soil specimens 4, 5, and 6 (Table 1) that were conditioned with foam (Table 2) at a moisture content of 15% to investigate the impact of pressure. Fig. 12 shows the results.

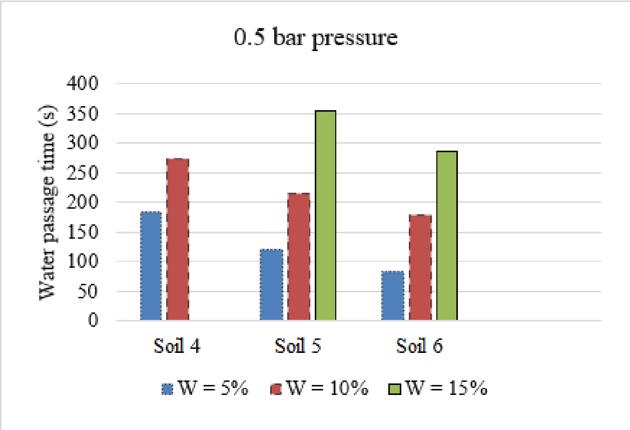

Fig. 11 Changes in the water passage time through the conditioned soil versus the moisture content at a constant pressure

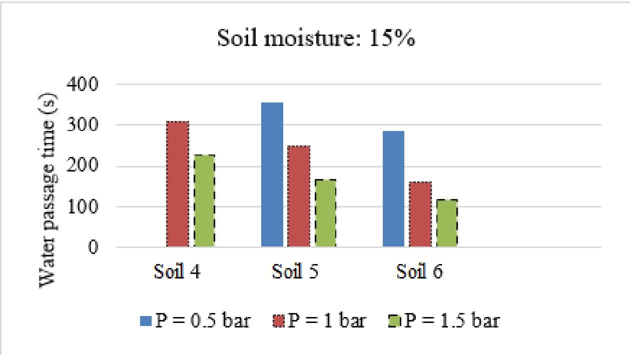

Fig. 12 Variations of water passage time through the conditioned soil with pressure at a constant moisture content

As the pressure on the conditioned soil increased, the time required for the water to pass through the specimens declined, and, thus, the ki grew. It is worth noting that soil-foam mixture No. 4 numbers became impermeable at a pressure of 0.5 bar and a moisture content of 15%.

4 Conclusions

This study investigated the impacts of several parameters, such as granulation, pressure, and moisture content, on the k_i of coarse-grained soils conditioned with foam. The following is a summary of the obtained results. As the value of d_{10} increased, soil particles could not be easily mixed with foam, and it was more difficult to create an impermeable structure against water. Accordingly, the permeability increased. For instance, the rise in d_{10} from 0.1 to 0.4 mm at the pressure of 1 bar and moisture content of 10% increased the k_i of the conditioned soil from 2.28×10^{-5} m/s to 12.3×10^{-5} m/s.

The rise in the C_c of the soils from 0.85 to 5.3 while the percentage of materials passing through sieve No. 200 was kept constant increased the k_i from 1.23×10^{-5} m/s to 2.42×10^{-5} m/s. Moreover, increasing the C_c of the soil and the percentage of materials passing through sieve No. 200 resulted in a rise in the k_i from 1.23×10^{-5} m/s to 1.9×10^{-5} m/s. A rise in the soil C_u from 3 to 20 reduced the ki from 1.23×10^{-5} m/s to 0.71×10^{-5} m/s due to the non-uniformity of the soil. At a constant pressure, the rise in the moisture content and addition of the foam increased the water passage time by filling the void spaces in the soil and, thus, reducing the permeability of the conditioned soil. With a rise in the pressure on the conditioned soils, the water passage time declined, and the k_i grew.

References

[1] Pap, M., Mahler, A. "Comparison of Different Empirical Correlations to Estimate Permeability Coefficient of Quaternary Danube Soils", Periodica Polytechnica Civil Engineering, 63(1), pp. 25–29, 2019. https://doi.org/10.3311/PPci.13108

[2] Pourmand, S., Chakeri, H., Sharghi, M., Bonab, M. H., Ozcelik, Y. "Laboratory Studies on Soil Conditioning of Sand in the Mechanized Tunneling", Journal of Testing and Evaluation, 48(5), pp. 3658–3672, 2020. https://doi.org/10.1520/JTE20170395

[3] Leinala, T., Grabinsky, M., Delmar, R., Collins, J. R. "Effects of Foam Soil Conditioning on EPBM Performance", In: North American Tunneling 2000, Boston, MA, USA, 2000, pp. 543–552. ISBN 9058091627

[4] Borio, L., Peila, D. "Study of the Permeability of Foam Conditioned Soils with Laboratory Tests", American Journal of Environmental Sciences, 6(4), pp. 365–370, 2010. https://doi.org/10.3844/AJESSP.2010.365.370

[5] ASTM "ASTM D2434-19 Standard Test Method for Permeability of Granular Soils (Constant Head)", ASTM International, West Conshohocken, PA, USA, 2019.

[6] Peila, D. "Soil conditioning for EPB shield tunnelling", KSCE Journal of Civil Engineering, 18(3), pp. 831–836, 2014. https://doi.org/10.1007/s12205-014-0023-3

[7] Kim, T.-H., Kim, B.-K., Lee, K.-H., Lee, I.-M. "Soil Conditioning of Weathered Granite Soil used for EPB Shield TBM: A Laboratory Scale Study", KSCE Journal of Civil Engineering, 23(4), pp. 1829–1838, 2019. https://doi.org/10.1007/s12205-019-1484-1

[8] Zhou, X., Yang, Y. "Effect of Foam Parameters on Cohesionless Soil Permeability and Its Application to Prevent the Water Spewing", Applied Sciences, 10(5), 1787, 2020. https://doi.org/10.3390/app10051787

[9] Hu, Q., Wang, S., Qu, T., Xu, T., Huang, S., Wang, H. "Effect of hydraulic gradient on the permeability characteristics of foam-conditioned sand for mechanized tunnelling", Tunnelling and Underground Space Technology, 99, 103377, 2020. https://doi.org/10.1016/j.tust.2020.103377

[10] Kim, T.-H., Lee, I.-M., Chung, H.-Y., Park, J.-J., Ryu, Y.-M. "Application Ranges of EPB Shield TBM in Weathered Granite Soil: A Laboratory Scale Study", Applied Sciences, 11(7), 2995, 2021. https://doi.org/10.3390/app11072995

[11] Tao, L., Chen, Z., Cui, J., Wang, H., Fang, Y. "Experimental Methods to Assess the Effectiveness of Soil Conditioning with Foam in Fully Weathered Granite", Advances in Materials Science and Engineering, 2019, 9046704, 2019. https://doi.org/10.1155/2019/9046704

[12] Sebastiani, D., Vilardi, G., Bavasso, I., Di Palma, L., Miliziano, S. "Classification of foam and foaming products for EPB mechanized tunnelling based on half-life time", Tunnelling and Underground Space Technology, 92, 103044, 2019. https://doi.org/10.1016/j.tust.2019.103044

[13] Wang, S., Huang, S., Qiu, T., Yang, J., Zhong, J., Hu, Q. "Analytical Study of the Permeability of a Foam-Conditioned Soil", International Journal of Geomechanics, 20(8), 06020019, 2020. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001750

[14] Pasand Masoumi, H. R., Abdollahipour, A., Baghernia, K. "Calculation of Optimum Soil Conditioning in EPB Tunneling (Case Study: Ahwaz Metro Project, Line 1)", Journal of Mining and Environment, 12(2), pp. 501–513, 2021. https://doi.org/10.22044/jme.2021.10664.2025

[15] ASTM "ASTM C136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates", ASTM International, West Conshohocken, PA, USA, 2001.

[16] Narimani, S., Chakeri, H., Davarpanah, S. M. "Simple and Non-Linear Regression Techniques Used in Sandy-Clayey Soils to Predict the Pressuremeter Modulus and Limit Pressure: A Case Study of Tabriz Subway", Periodica Polytechnica Civil Engineering, 62(3), pp. 825–839, 2018. https://doi.org/10.3311/PPci.12063

[17] ASTM "ASTM C143 Standard Test Method for Slump of Hydraulic-Cement Concrete", ASTM International, West Conshohocken, PA, USA, 2003.

[18] Hazen, A. "Some physical properties of sands and gravels, with special reference to their use in filtration", In: 24th Annual Report, Massachusetts State Board of Health, Boston, MA, USA, 1892, pp. 539–556.