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COLLAPSE POTENTIAL AND ULTRASONIC PULSE VELOCITY OF LOESS SOILS AFTER TREATMENT WITH EXPANDED PERLITE AND METAKAOLIN

Mohammad Ali Khodabandeh*, Katalin Kopecskó, Gábor Nagy

Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Engineering Geology and Geotechnics, H-1111 Budapest, Műegyetem rkp. 3., Hungary

* corresponding author: mohammad.khodabandeh@emk.bme.hu

Abstract. Collapsible soils, including loess, can support heavy loads at their natural humidity but then collapse rapidly and lose a substantial volume when the humidity increases. Soil collapse potential at different immersion stresses was investigated according to ASTM D5333. Different immersion stresses, including 100, 200, 300, 400, and 500 kPa, were used to evaluate the stress-strain behavior of soils before and after saturation. The results indicated that soil collapse potential rose with a raising of immersion stress, resulting in the highest soil collapse potential at 500 kPa immersion stress. Furthermore, the effectiveness of expanded perlite and metakaolin in treating loess soils was examined. The results revealed that the soil collapse potential reduced with an increase in perlite and metakaolin up to 8 %. Also, perlite had a more significant impact on the soil collapse potential than metakaolin. The interlocking force between soil particles was enhanced as the perlite quantity rose, and perlite prohibited soil particles from slipping on each other. Metakaolin decreased the soil collapsibility due to the pozzolanic and chemical reactions which increased particle bonding. The ultrasonic pulse velocity of soils decreased as the percentage of perlite increased. Because the perlite was not spread homogeneously, and the waves can be stuck in the heterogeneities, Metakaolin acted as a filler and increased the ultrasonic pulse velocity of the soils.

Keywords: Collapse potential, collapsible soil, expanded perlite, loess, metakaolin, stabilization.

1. Introduction

Loess has a metastable structure and is found unsaturated in semi-arid regions [1]. Loess is prone to sudden collapse and settlement as a result of disturbance, stress, and soaking, as well as a variety of geotechnical hazards such as landslides, collapsibility, and seismic settlement [2–4]. The structures constructed on collapsible soils might settle due to the saturation of soils for various reasons such as water and oil pipe failure, sewage leakage, rising groundwater level, leaks of industrial effluents, and chemicals, etc. [5, 6]. Chemical stabilization of loess soils (e.g., lime, cement, nano, fibers, etc.) to achieve improved engineering characteristics is a widely used technique around the world [7, 8].

Two chemical reactions are involved in improving the geotechnical properties of collapsible soils and chemical stabilization including short-term and long-term reactions. Cation exchange, flocculation, and agglomeration are examples of short-term reactions that are responsible for changes in soil engineering properties such as workability and plasticity. Long-term reactions, known as pozzolanic reactions, result in the formation of new calcium silicate/aluminate hydrates, which enhance flocculation by connecting adjacent soil particles and improving the soil after cuing. Time and temperature affect pozzolanic reactions, resulting in a steady increase in strength over time [9].

Traditional stabilizers such as lime and Portland cement are the most extensively utilized chemical additives, according to Rauch et al. [16]. Cement stabilization improves soil strength and decreases compressibility [17–19]. The effects of lime and cement on the behavior of lime/cement-soil mixtures were studied by several authors [20–25]. They concluded that adding lime/cement to the mixture improves strength, substantially reduces moisture content, and reduces volume expansion or compressibility. Soil stabilization with new materials like fibres, polymers and nanoparticles has attracted a lot of interest in recent years. Adding fibres to soils was investigated by many researchers and it was found that fibres lowered soil cracking and increased soil strength while decreasing soil hardness [26, 27]. Biopolymers like xanthan and guar gums are found to be useful in reducing collapsibility of soils [28]. According to Tabarsa et al. [29] and Haeri and Valishzadeh [30], nanomaterials like nano-clay and nano-silica had also a significant effect on strengthening collapsible soil properties. However, finding innovative stabilizing materials is a concern for researchers. In the present study, the effect of perlite and metakaolin on the collapse potential and

Parameter	Soil 1 (Balatonakarattya)	Soil 2 (Vál)	Method used
LL, PL, PI [%]	30, 23, 7	26, 23, 3	ASTM D4318 [10]
Natural water content [%]	5.5	4.5	ASTM D2216 [11]
G_s	2.70	2.67	ASTM D854 [12]
Void ratio [e]	0.9	0.9	ASTM D7263 [13]
γ_{dry} [kN m^{-3}]	14.2	14.2	ASTM D7263 [13]
Soil classification [USCS]	CL-ML	ML	ASTM D2487 [14]
Soil classification [Euro code]	SiCL	SaSi	EN ISO 14688-2 [15]

Table 1. The basic properties of loess soils.

ultrasonic pulse velocity of loess soils was investigated.

2. Materials and methods

2.1. Properties of soils

Two loess soils used in this study was collected from two locations in Hungary: the first was in Balatonakarattya with coordinates of 47°1'14.93"N 18°8'38.64"E, and the second was in Vál with coordinates of 47°21'25.6"N 18°40'15.7"E. The characteristics of loess soils are presented in Table 1. Grain size distribution for both soils is presented in Figure 1.

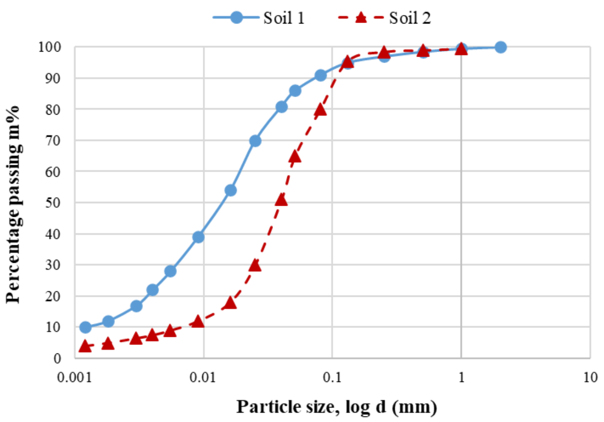

Figure 1. Grain size distribution curves for the samples Soil 1 and Soil 2.

2.2. Properties of stabilization materials

The expanded perlite utilized in this study was produced in accordance with MSZ EN 14316-1. The metakaolin utilized in this investigation was METAVERTM I type and was produced in Austria based on MSZ4798:(2015). The properties of perlite and metakaolin are presented in Table 2.

2.3. Laboratory program and sample preparation

The test schedule is as follows:

1) At first, the remoulded samples were prepared in the same density and same moisture content as the fields sampling. Then, the remoulded samples were subjected to collapse tests in different immersion stresses including 100, 200, 300, 400 and 500 kPa.
2) Regarding the treatment, the remoulded samples were mixed with 2, 4, 6, and 8 w/w % expanded perlite and metakaolin. The samples were then aged for 7 days in isolated plastic bagging to achieve an equilibrium condition and to enable probable interactions between soil and stabilization materials. Finally, the same collapse tests were performed on treated samples as on the remoulded samples.
3) Ultrasonic pulse velocity was performed on the soils stabilized with 2, 4, 6, and 8 w/w % expanded perlite and metakaolin after 7, 14 and 28 curing days.

Oxide compound	Perlite	Metakaolin
SiO_2	68–75%	52–54%
Al_2O_3	10–14%	40–43%
Fe_2O_3	$< 2\%$	$< 2.5\%$
CaO	$< 2\%$	$< 0.5\%$
MgO	$< 1\%$	$< 0.4\%$
K_2O	3.2–4.5%	$< 2.0\%$
SO_3	$< 1\%$	$< 1.0\%$
Na_2O	2.8–4.5%	$< 0.1\%$
Particle size	0–2 mm	$< 2\,\mu$m

Table 2. Properties of perlite and metakaolin.

2.4. Collapse testing

The collapse tests were performed in accordance with the ASTM D5333 [31] standard on remoulded samples with the same density and moisture content as the field samples. At first, the sample was inserted in the device and then it was subjected to an initial stress of 5 kPa. In the next stages, the sample was subjected to various levels of stress, including 12.5, 25, 50, 100, and 200 kPa, and the deformation (settlement) of the soil was measured at each step. The sample was then soaked 1 hour after adding 200 kPa, and the loading was carried out under saturated conditions for up to 24 hours while the settling was monitored. Equation (1) calculates the index of collapse, which represents the sample's settlement at a stress of 200 kPa.

$$I_C = \frac{d_f - d_i}{h_0 \times 100} \quad (1)$$

where I_C = the collapse index; d_f = height after soaking; d_i = height before soaking; and h_0 = the initial height of the soil.

2.5. Ultrasonic pulse velocity testing

The ultrasonic pulse velocity test is a non-destructive method to evaluate the physical and mechanical properties of different soils and rocks [32, 33]. In the present study, it was conducted using the PUNDIT device (Portable Ultrasonic Non-destructive Digital Indicating Tester) based on the ASTM C597. The equipment consists of a transducer and a receiver that are linked to an electronic timing device for timing the start of a pulse generated at the transmitting transducer and its arrival at the receiver [34]. The PUNDIT-Plus digital display screen can be used to read the travel time through the specimen. The effect of perlite and metakaolin and curing time (7, 14, and 28 days) on the ultrasonic pulse velocity of soils was evaluated. Pulse frequency was 54 Hz in the ultrasonic pulse velocity test. The ultrasonic pulse velocity of the sample was determined using the Equation (2) given the length of the wave transmission (sample length) and the recorded transmission times [35]:

$$V = L/t \quad (2)$$

where L is the length of the pulse transmission path, t is the pulse transmission time, and V is the ultrasonic pulse velocity within the sample.

3. Results

3.1. Effect of immersion stress on the collapse potential of soils

The collapse behavior of both soils is presented in Figure 2. Based on the ASTM classification, both soils were classified in a category of moderately severe collapsible.

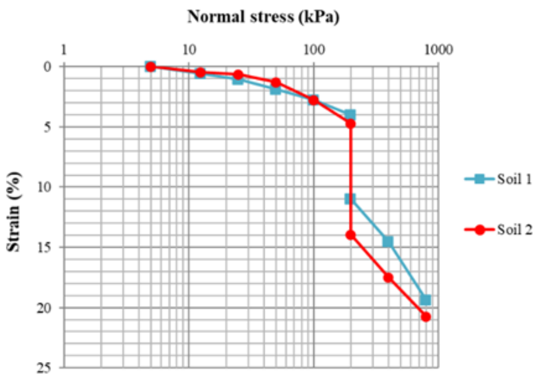

Figure 2. Comparison of soil collapse behavior.

The rates of soil collapse for both soils at various immersion stresses were determined. As shown in Figure 3, by increasing the immersion stresses from 100 to 500 kPa, the collapse potential of both soils increased. The lowest rate of collapse potential belonged to 100 kPa and the highest collapse potential obtained at 500 kPa for both soils. The rate of collapse at an immersion stress of 100 kPa for soil 1 was moderate and for soil 2 was moderately severe. The collapse potential for Soil 1 increased from 4.5 % at 100 kPa to 9.88 % at 500 kPa, and it increased from 6.9 % at 100 kPa to 11.3 % at 500 kPa for Soil 2. Soil 1 had a moderately severe collapse potential at immersion stresses of 200 to 500 kPa. Soil 2 had a moderately severe collapse potential at immersion stresses of 200 and 300 kPa and severe collapse potential at immersion stresses of 400 and 500 kPa. According to Figure 3c, at all stress levels, the difference in collapse potential between the two soils is almost the same.

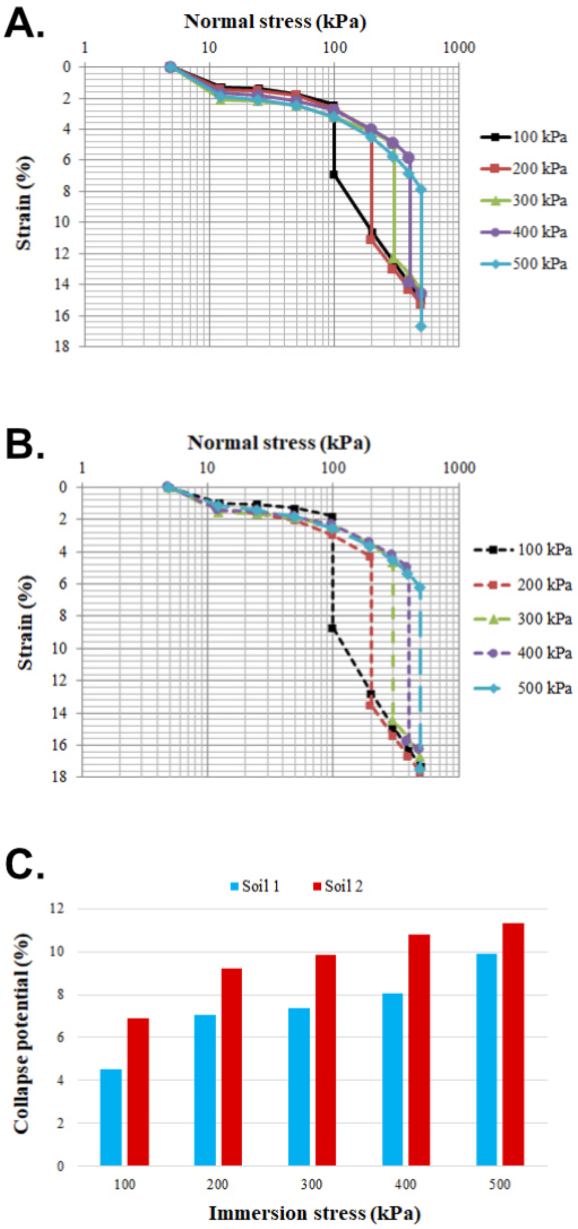

Figure 3. Comparison of soil collapse behavior at different immersion stresses (A.) soil 1 (B.) soil 2 (C.) comparison of soil 1 and soil 2.

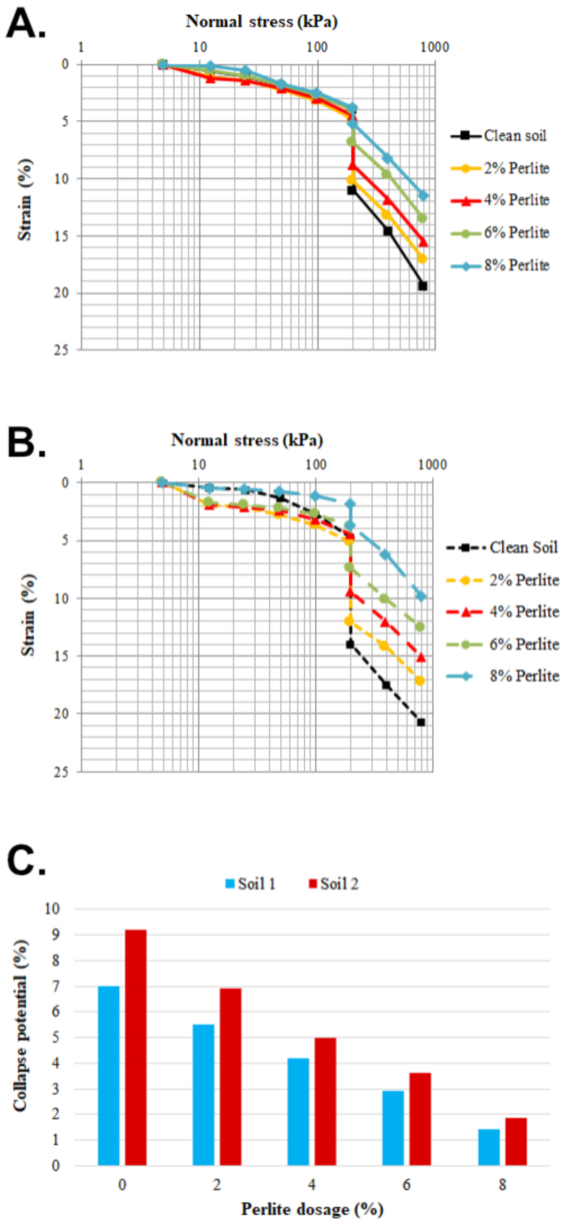

Figure 4. The collapse behavior of loess soils treated with perlite (A.) soil 1 (B.) soil 2 (C.) comparison of soil 1 and soil 2.

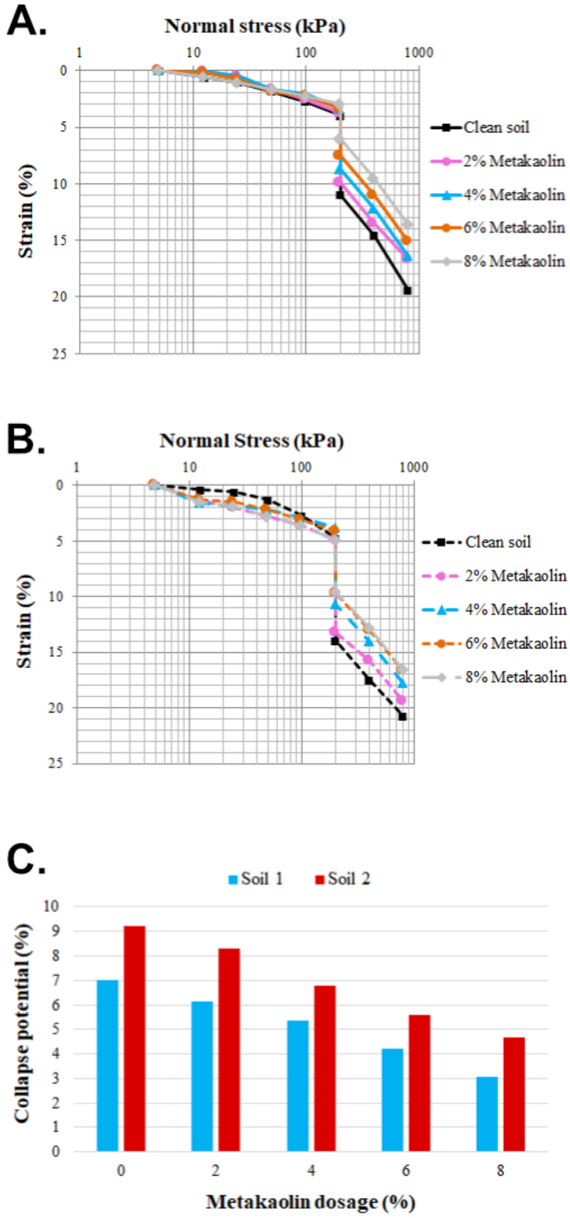

Figure 5. The collapse behavior of loess soils treated with metakaolin (A.) soil 1 (B.) soil 2 (C.) comparison of soil 1 and soil 2.

3.2. Effect of perlite and metakaolin on the collapse potential of soils

In the present study, the influence of stabilization with various percentages of perlite and metakaolin on two collapsible soils was investigated. The collapse behavior of soils treated with perlite is indicated in Figure 4. As shown in Figure 4, by increasing the perlite percentage by up to 8 % of the dry mass, the collapse potential of both loess soils decreased. Perlite had a significant effect in lowering the risk of collapse, whereas increasing perlite from 0 to 8 % has decreased the potential of soil collapse from 7 % and 9.20 % to 1.4 % and 1.88 % for soil 1 and soil 2, respectively.

Figure 5 shows the coxllapse behavior of soils treated with metakaolin (MK). The results show that as the content of MK increased, the soil collapse potential decreased. With an increasing of MK from 0 to 8 %, the collapse potential decreased from 7 % and 9.20 % to 3.05 % and 4.67 % for soil 1 and soil 2, respectively. The chemical reaction between MK and small particles in loess soils were responsible for the improved performance of adding MK in lowering the collapsibility index of the examined soils. Clay particles are integrated into larger particles because of flocculation and agglomeration reactions, leading to the changes in the soil texture. Hydration is another possible reaction. The MK's solid-forming components react with water-producing calcium-hydrated silicates (CSH), calcium hydrated alumina (CAH), during the hydration process. This reaction occurs quickly and lowers the moisture content of the mixture. Ion exchange processes are then initiated by the

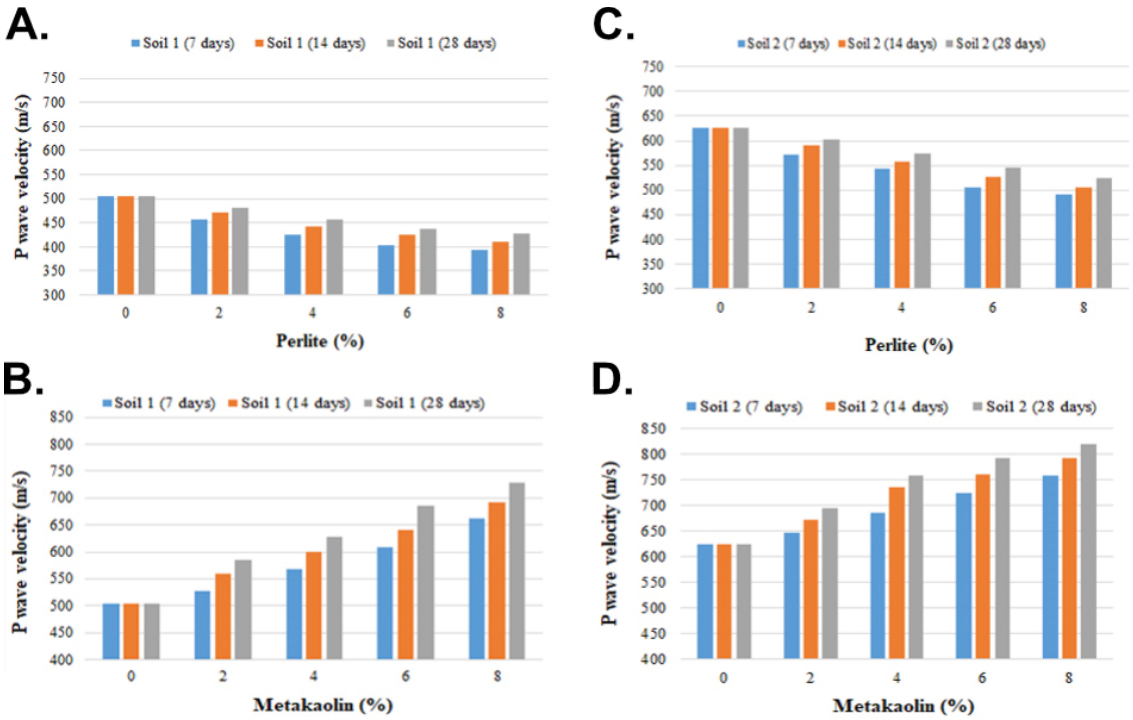

Figure 6. The results of ultrasonic pulse velocity (A.) soil 1 treated with perlite (B.) soil 2 treated with perlite (C.) soil 1 treated with metakaolin (D.) soil 2 treated with metakaolin.

released calcium and aluminium ions caused by MK hydration. As a result, the collapsibility of the soils treated with MK was reduced.

It is worth noting that metakaolin did not reduce the collapsibility index of the soil as much as perlite. However, the influence of both materials in both soils was almost the same and the collapse trend of both soils stabilized with perlite and metakaolin was found to be decreasing.

3.3. Effect of perlite and metakaolin on the ultrasonic pulse velocity of soils

The results of ultrasonic pulse velocity for soils treated by perlite and metakaolin are indicated in Figure 6. As shown in Figure 6a and Figure 6b, with an increasing perlite percentage, the ultrasonic pulse velocity of both soils decreased. Adding perlite slowed down the passage of waves, because the perlite is lighter than the soil matrix. Additionally, the pressure applied from the top during the sample preparation procedure causes the perlite to be oriented roughly horizontally, putting it sideways in the path of the incoming waves. This should take longer for the waves to pass the sample since they are more likely to diverge than to go directly along it. Furthermore, it would be quite complicated to ensure that perlite was spread uniformly and homogeneously on the sample. Consequently, because the waves can be stuck in the heterogeneities, the specimen had a multi-dimensional structure, that increases the chance of wave interference. As a result, this may also lower the wave velocity traversing the sample. This approach was mentioned by Fatahi et al. [36], who examined how ultrasonic wave velocity decreased in cemented clay samples with an increasing fibre percent. Choobbasti et al. Cristelo et al. [37] reported that by increasing carpet waste fibres, the ultrasonic pulse velocity of soil decreased because on the micro scale, the distribution of mixed fibre was heterogeneous.

Figure 6c and Figure 6d shows that as the percentage of metakaolin increased, the ultrasonic pulse velocity increased. This is due to the fact that the addition of metakaolin enhanced the soil consistency and density while also improving the microstructure in parallel to the sample length, creating a better path for the passage of waves and so increasing wave velocity. In other words, the soil matrix's microcracks and grooves can be reduced by the addition of metakaolin. Also, a cement type material bonds the soil particles together, transforming the soil matrix into an integrated structure. The intra-particle pore space should thus be reduced because of the addition of metakaolin. Higher wave velocities can be obtained because the ultrasonic pulses can travel through the path made by the integration of clay particles despite the expansion of the inter-particle pore space. Cristelo et al. [38] observed similar results for a Portland cement-sandy clay mixture.

4. Discussion

In the present study, the collapse behaviour of two soils were investigated. The results of collapse tests show that soil 1 (CL-ML) had a lower collapse potential than soil 2 (ML) which was due to the higher percentage of clay in soil 1. According to Zamani and Badv [39], the percentage of clay in collapsible soil affects its actual potential to collapse. The possibility of collapse could increase with a lower level of clay content. With less clay, there is less contact between soil grains, which might collapse in the presence of water. In the present study, according to the results of the collapse test, with increasing the immersion stress, the collapse potential of both soils (CL-ML and ML) increased which was consistent with the results of Zamani and Badv [39] but was inconsistent with the results of Arabani and Askari Lasaki [40]. the collapse potential of two CL soils and concluded that as the immersion stress increased, the collapse potential of fine-grained soils increased. Arabani and Askari Lasaki [40] conclude that there is a decreasing trend for the collapse potential of ML soil with increasing vertical stress.

In terms of the perlite treatment, the collapse potential of both soils decreased as the perlite concentration increased. Addition of perlite to the soils reduced the compressibility of soils under loading. In soils treated with perlite, a three-dimensional network of randomly dispersed perlite particles bind soil particles surfaces with the help of friction and interlocking force. This will enhance the strength properties of the soil / perlite mixture by preventing perlite from slipping out of the soil matrix. Hence, the reduction in soil collapse potential can be related to the prevention of soil particle slippage relative to each other, which reduces the soil volume change.

The improved performance by adding metakaolin in reducing the collapsibility index of the tested soils was due to the chemical interactions between metakaolin and small particles in loess soils (SiO_2, Al_2O_3) which generated an inter-particle bond that made the stabilized soils stiffer. The large surface-to-volume ratio of metakaolin improved particle-soil interaction at the nanoscale. As a result, even a little percentage of the metakaolin changed the physiochemical properties of the soil. It caused flocculation in loess particles, as well as increased particle bonding. As a result, improved collapsibility was attributed to increased inter-particle bonding.

5. Conclusions

The following findings may be taken as conclusions from the results of this study:

- The collapse potential of loess soils increased as the immersion stresses increased from 100 kPa to 500 kPa.
- By adding perlite up to 8 % of the dry mass, the collapse potential of loess soils decreased and both loess soils were classified as slight collapsible soils after perlite-treatment. With the aid of interlocking force, perlite particles bond soil particles. Consequently, soil particles were not able to slide on each other and after loading the soil settlement was significantly reduced.
- With increasing metakaolin up to 8 % of the dry mass, the collapse potential of loess soils reduced. This can be the consequence of the pozzolanic and chemical interactions between soil and metakaolin.
- As the content of metakaolin increased, the ultrasonic pulse velocity increased. With increasing perlite, the ultrasonic pulse velocity decreased.

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