

An experimental investigation on dispersion and geotechnical properties of dispersive clay soil stabilized with Metakaolin and Zeolite

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Abstract. Dispersion occurs when clay soil disperses under specific conditions and is rapidly washed away. While there are numerous methods for rectifying it, they are neither cost nor time-effective. The current study used metakaolin and zeolite to improve heavily dispersive clay soil either separately or in combination at 0%, 2%, 4%, 6%, and 8% of the soil weight. After 7 days of curing, the samples were tested to determine the extent of change in the dispersion potential, as well as the improvement of the geotechnical properties of the soil. The results indicated that the addition of 2% zeolite with 6% to 8% metakaolin decreased the dispersion potential considerably. Double hydrometry test findings revealed that the dispersion potential decreased by almost 70% and entered the non-dispersive group; the crumb test also revealed this. Atterberg limits testing indicated a decrease in the plasticity index which reduced the flexibility of the samples. The greatest decrease in PI (67.5%) was achieved with the addition of 8% zeolite plus 8% metakaolin to the soil. The results of density tests revealed that a decrease in the optimal moisture content increased the maximum dry density of soil. This increase in density was a response to the high reactivity of metakaolin with calcium hydroxide and the formation of calcium hydroxide hydrate gel. This eventually caused an increase in the unconfined compressive strength, the greatest increase in strength of about 1.8-fold was observed with a combination of 2% zeolite and 6% metakaolin compared to the unmodified sample.

Keywords: crumb test; dispersive clay soil; double hydrometry test; metakaolin; soil stabilization; zeolite

1. Introduction

Dispersive soil can cause damage to civil, and agricultural projects. Dispersive soils are those that can be easily washed away when subjected to water with a low salt concentration. Dispersive clay soil has a high amount of sodium ions in its absorptive cations (Abbaslou *et al.* 2016). Dispersive soil is present worldwide, including in Australia, Brazil, Iran, and the US. It can be identified using four recommended types of test: pinhole, crumb, double hydrometry and chemical tests.

Exchangeable sodium ions are the main factor behind the development of dispersion in clay soil, which is a physiochemical phenomenon in which clay particles exposed to water lose their cohesion, and repulse each other (Singh and Purohit 2018). Studies suggest that the presence of active clay minerals with low electrolyte concentrations, such as montmorillonite, and exchangeable sodium ions contribute to dispersive behavior (Salehi and Heidari 2022). Clay is primarily formed by plane-shaped crystalline particles consisting of units of Si₂O₅ tetrahedral silicate and Al(OH)₃ octahedral aluminum hydroxide. These are stacked

on top of each other in alternating layers and, from a defect in the structure of the crystalline lattice, the Al³⁺ ions replace Si⁴⁺ ions, and some Al³⁺ ions are replaced by Mg²⁺ ions. It means that the clay minerals have weak positive electrical charges; they compensate for their permanently negative charge by absorbing the water cations around them (Van de Graaff and Patterson 2001). The presence of sodium ions on the surface of dispersive soil particles has a weaker effect on neutralizing the charge on colloidal particles and preventing the inflation or dispersion of soil particles compared to bivalent or trivalent ions such as calcium and aluminum (Fan and Kong 2013). When the repulsive force outweighs the attraction force, water can easily separate the soil particles from each other and displace them. Erosion of this type does not require high-velocity water flow and clay particles may even float in still water as colloidal because of the repulsive forces (Flores-Berrones and Acosta 2011).

Using traditional stabilizers, such as cement, lime, and volcanic ash can cause environmental problems such as increasing the pH of the soil and groundwater, causing corrosion of structures buried in the soil. Moreover, the production of these stabilizers consumes large amounts of energy and emits greenhouse gases into the atmosphere (Roohbakhshan and Kalantari 2016). The manufacturing process of cement and lime, releases a huge amount of Carbon footprints. To reduce the emission of CO₂, usage of virgin cement can be minimized by partially replacing with pozzolanic materials or industrial wastes like zeolite, metakaolin and silica fume (Iswarya and Beulah 2021).

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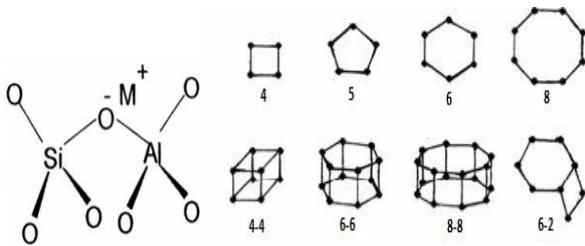


Fig. 1 Structural units in zeolite molecular structure

Researchers have evaluated many chemical additives but, despite their positive effects on the engineering properties of the soil, they are not cost-effective, which limits their use (Taherkhani 2016).

Using zeolite, a natural pozzolan, as a replacement for cement and lime is a significant choice for decreasing the use of conventional stabilizers. The production of zeolite in Iran is cost-effective and readily available. Iran has a significant number of zeolite mines, particularly in the Semnan area. The price of zeolite in the Iranian market is approximately 8 dollars per ton, which is very reasonable compared to the price of cement (approximately 32 dollars per ton) and lime (approximately 14 dollars per ton). The loss of water by zeolite occurs easily, and reversibly because it contains alkali and alkaline earth metals that can participate in reversible substitution reactions. Chemical and structural analysis indicates that zeolite primarily contains silica, aluminum, and oxygen (Fig. 1). Zeolite is a crystalline and hydrate solid with identical pores and 3-10 Å dimensions within the molecular range.

Makwin (2021) investigated the effect of zeolite on the strength and microstructure development of cement-stabilized clay soil (CH). They found that the UCS increased from 71 kN/m² for untreated soil to a maximum value of 1746 kN/m² for the soil treated with 4% cement and 6% zeolite. The study established that clay of high plasticity can be treated with 6% zeolite and less cement content. Shang (2015) investigated the geotechnical properties of sand, and zeolite mixtures containing 25%, 50% or 75% zeolite. They reported that, as the zeolite mass ratio in the mixture increased, the optimal moisture content decreased, while the maximum dry specific weight tended to increase. MolaAbasi *et al.* (2022) investigated how low plasticity clay responded to cement and zeolite. According to UCS data, strength rose when zeolite was used to replace up to 15% of the cement content, but it decreased beyond that. Regarding variations in moisture content, mechanical characteristics, and environmental factors, they discovered that using zeolite rather than cement is strongly advised. Demirbas (2009) examined stabilization of expansive soil using zeolite and lime. They found that an increase in the amount of zeolite caused the soil particles to become coarser because of the pozzolanic reactions. Furthermore, the liquid limit (LL) and plastic limit (PL) decreased. The optimal composition to reduce the elasticity potential of the soil was 10% zeolite mixed with 5% lime.

Metakaolin is a natural pozzolan with high reactivity that usually contains 50% to 55% SiO₂ and contains 40% to

45% Al₂O₃, which reacts with calcium hydrate (CH) to produce aluminate phases. Metakaolin is obtained via the calcination of kaolin soil at temperatures of 550 to 900°C (Batis *et al.* 2005). Mixing of metakaolin and materials, such as zeolite, nanosilica, kaolin and cement indicate that metakaolin improves the physical and mechanical properties and reduces environmental pollution (Sudagar *et al.* 2018).

Kolovos *et al.* (2013) explored the mechanical properties of cement soil modified with metakaolin. The results indicated an improvement of the mechanical properties of cement mixture. The study examined the effect of metakaolin on the hydraulic conductivity and mechanical behavior of clay improved with cement and reported that an increase in the metakaolin content from 3% to 5% decreased the hydraulic conductivity 10- to 100-fold. The uniaxial compressive strength (UCS) of soil containing 3% cement and 5% metakaolin was found to be 2-3 times greater than that of soil without metakaolin. The metakaolin seems to expedite the pozzolanic response. In their study, Wu *et al.* (2016) examined the impact of metakaolin and cement on the strength and structure of MHS clay soil. Their research shown that incorporating metakaolin into the cement-stabilized soil resulted in a notable decrease in the soil's susceptibility to water and a significant enhancement in both the unconfined compressive strength (UCS) and tensile strength of the soil. The optimal ratio of cement to metakaolin in that study was 2 to 3. Microstructural investigations also indicated an increase in the pozzolanic reactions, and the production of new minerals, including calcium aluminate hydrate (CSH), and calcium silicate hydrate (CAH). Wianglor *et al.* (2017) inspected the effect of alkaline-active metakaolin on the compressive strength and structure of mortar particles treated at 23 and 60°C. They found that an increase in the metakaolin content and curing temperature increased the UCS of the samples. Aluminate and silicate gel were clearly observed within the structure of the treated mortar particles.

The current study investigated the effects of different percentages of metakaolin, and zeolite on reducing the dispersion potential of clay soil using the crumb and double hydrometry tests. It evaluated their Atterberg limits, maximum dry density, optimal water content, soil UCS and pH as well as the use of scanning electron microscopy (SEM), and the determination of optimal composition.

2. Materials and methods

The clay soil used had naturally severe dispersive properties. The samples were collected from the area around the city of Ardakan in Yazd province in Iran. The results of gradation and Atterberg limits tests, as well as soil classification using the Unified Soil Classification System (USCS) showed that this soil had an LL of 33%, soil water content of 3.5%, PI of 11, in-situ dry density of 1.54 kg/m³ and was of the CL soil type. Samples were collected from the floor of a borehole of 2 m in depth and were transferred to the laboratory in plastic bags. The area of focus is economically significant and now undergoing development.

Table 1 Chemical analysis of zeolite and metakaolin based on XRF analysis

| Chemical Composition | Zeolite | Metakaolin |
|--------------------------------|------------|------------|
| | Weight (%) | Weight (%) |
| SiO ₂ | 72.00 | 70.46 |
| CaO | 1.50 | 0.68 |
| Al ₂ O ₃ | 11.70 | 22.48 |
| Fe ₂ O ₃ | 1.20 | 0.45 |
| K ₂ O | 2.70 | 2.03 |
| Na ₂ O | 0.60 | 0.62 |
| MgO | 0.33 | 0.24 |
| L.O.I | 6.70 | 3.17 |

*L.O.I: Loss on Ignition

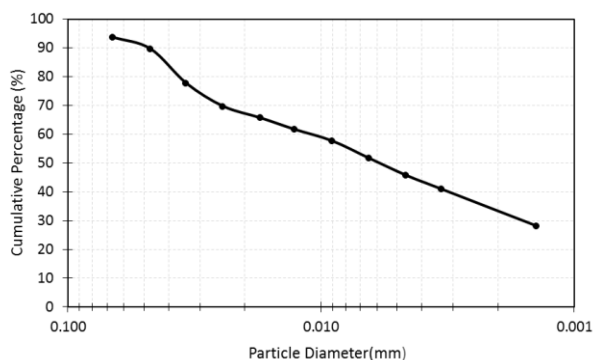


Fig. 2 The particle size distributions of clay soil in study region

Techniques such as excavating the soil and replacing it with superior materials and geogrids have been used to provide appropriate foundations for the building of industrial sheds, access routes, and landscaping. Fig. 2 displays the gradation curve of the clay soil in the research area based on the findings of traditional hydrometry experiments.

The zeolite used was of clinoptilolite type which was sodium and potassium silicate aluminum extracted from mines in Semnan, Iran. The percentage of water absorption of the clinoptilolite was 60%, it had a specific weight of 1.19 g/cm³, specific surface area of 1000 cm²/g and contained the chemical compounds listed in Table 1. These results were obtained from X-ray fluorescence (XRF) chemical analysis.

The metakaolin used was procured from Jahan Poodr Company (Delijan, Iran) and had a specific weight of 2.63 g/cm³ and a specific surface area of 9169 cm²/g and its production temperature is 700°C. The results of chemical analysis are listed in Table 1. The pozzolan material of the metakaolin was the product of the activation of kaolinite (China clay) via the calcination. It has to be processed in a burning process like cement, although the temperature of production is between 700 and 900°C as opposed to 1450°C in the case of cement (Glavind 2009). As the percentage of calcination increased, the output material became more reactive. Heating the kaolinite converted the crystalline form to amorphous reactive forms. The resulting material was very reactive, and determined the geopolymer strength (Caballero *et al.* 2019).

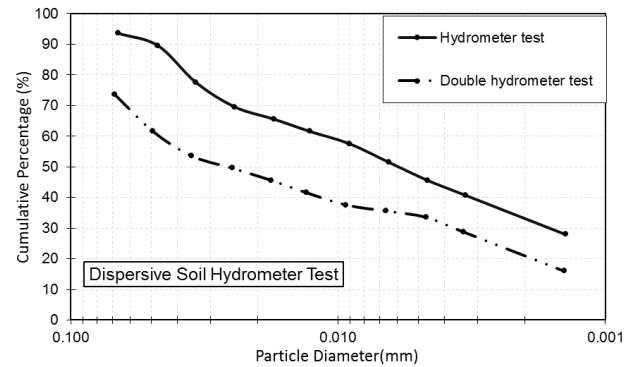


Fig. 3 The particle size distributions of dispersive clay soil in double hydrometry test

For various zeolite and metakaolin mix designs, the soil dispersion intensity was ascertained using the double hydrometry and crumb tests. According to ASTM D6572, the pinhole and double hydrometry tests should be carried out in addition to the crumb test, even though it is a reliable and quick indication of soil dispersion. This implies that the accuracy of the crumb test is not particularly high. Based on ASTM D6572 standards, the soil materials were converted to finer particles in a crusher and then passed via a #10 mesh sieve before fabrication of the reconstructed samples. Then, the soil was brought to the optimal water content with the addition of water. Once the water content reached equilibrium, gentle hand pressure was applied to form cubes of approximately 15 mm³. These were gently placed inside a container containing 250 ml of distilled water. At 2 min, 60 min and 6 h, the extent of activity of cubes in relation to the water was determined. The soil of study region then was classified as having strong reactivity.

Then, to gain more confidence about the results obtained from the soil samples with different mix designs, double hydrometry testing was carried out based on ASTM D4221 to measure the extent of change in dispersion. The tests are done twice on each sample, once according to ASTM D422-63 standard using 4% sodium hexametaphosphate disperser and a mechanical stirrer to separate the particles, and once based on ASTM D4221-99 without a disperser using a manual stirrer. The percentage of dispersion of the samples was calculated using Eq. (1) as

$$\text{Dispersion Percentage} = \frac{F_2(0.005)}{F_1(0.005)} * 100 \quad (1)$$

Where $F_1(0.005)$ is the percentage passing through a 0.005 mm diameter in the conventional hydrometry test (with disperser) and $F_2(0.005)$ is the percentage passing via a 0.005 mm diameter in the double hydrometry test (without disperser). This percentage was classified using the Bell and Maud criterion (Bell and Maud 1994). Fig. 3 shows that the soil of study region had 73.68% dispersion and was classified as strongly dispersive.

In accordance with ASTM 4972, a pH meter (Lovibond Senso Direct 150) was used to test the soil sample's pH values. To find out how zeolite and metakaolin affected changes in the soil dispersion potential and enhanced the

Table 2 Geotechnical properties of dispersive clay soil

| Physical properties of Dispersive Soil | Quantity measured | References for method of measurement |
|--|-------------------|--------------------------------------|
| Classification | CL | ASTM, D3282 |
| Liquid limit (%) | 29.4 | ASTM, D4318 |
| Plastic limit (%) | 18.1 | ASTM, D4318 |
| Plasticity Index (%) | 11.3 | ASTM, D4318 |
| Unconfined compression strength (kPa) | 329.5 | ASTM, D2166 |
| Maximum dry density (g/cm ³) | 1.75 | ASTM, D698 |
| Optimum moisture content (%) | 17.21 | ASTM, D698 |
| pH | 9.55 | ASTM, D4972 |

geotechnical qualities of the dispersive soil, the region's produced samples were put into an electric crusher and run through a #40 mesh sieve. Different percentages of dry metakaolin (0%, 2%, 4%, 6%, and 8%) and zeolite (0%, 2%, 4%, 6% and 8%) were added to the dispersive soil. The samples were stored in plastic containers for 7 days of curing and then crumb, double hydrometry, Atterberg limits, standard density, pH and UCS tests were performed on the different samples based on ASTM standards. All experiment was performed three times on all samples containing the zeolite, and metakaolin.

Table 2 lists the geotechnical properties of dispersive soil samples examined. Scanning electron microscopy (SEM) imaging were taken after mixing to allow comparison of the structure of samples with different percentages of metakaolin and zeolite against the initial sample. Selection of the percentages of zeolite and metakaolin used were in accordance with those from previous studies (Wu *et al.* 2016 and Zhang *et al.* 2014).

3. Results and discussion

3.1 Dispersion test

Fig. 4 presents the rate of change in the soil sample dispersion potential at different zeolite contents based on the double hydrometry test results. They indicate that zeolite alone caused up to a 49% decrease in the dispersion potential from the sample containing 8% zeolite. This changed the soil classification from highly reactive to moderately reactive. It could be attributed to chemical reactions and the cationic exchange of zeolite with the soil.

The results for the addition of various percentages of metakaolin alone are shown in Fig. 5. Its addition had a negligible impact on the trend of change in the sample dispersion potential at low percentages. However, the dispersion potential dropped and changed to a moderate condition as the metakaolin concentration increased from 6% to 8%. Even at a low dispersion potential, it did not show a non-dispersive state. The greatest decrease in dispersion occurred by adding 8% metakaolin. Hence,

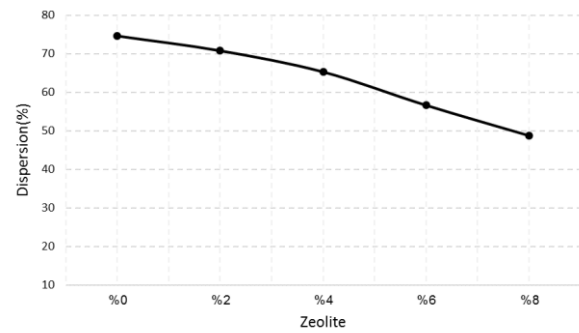


Fig. 4 Results of double hydrometry test for samples modified with zeolite

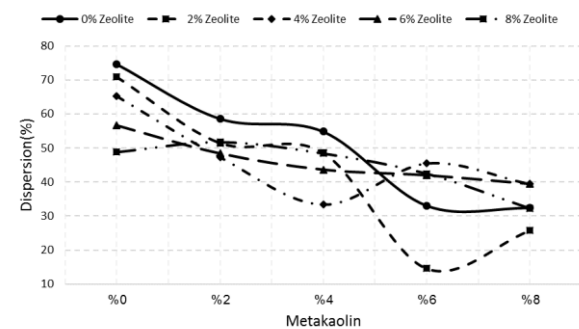


Fig. 5 Results of double hydrometry test for samples modified with zeolite and metakaolin

dispersion showed a 60% relative decrease from 74.7% to 32.4%. Based on the Bell and Maud criterion, this soil was considered to have negligible dispersion. It could be concluded that compounds with lower aluminum sulfate compositions had little effect on the soil dispersion results. The results of chemical testing on metakaolin indicated that the percentage of aluminum sulfate in metakaolin was suitable, with an increase in the metakaolin content, the extent of soil dispersion decreased.

Also Fig. 5 shows the dispersion percentages for the combined addition of different percentages of zeolite and metakaolin. The results showed that soil dispersion decreased considerably by adding zeolite and metakaolin. In the samples with 2% zeolite and various percentages of metakaolin, the dispersion potential rate showed acceptable change. The samples with 2% zeolite and 6% metakaolin and 2% zeolite and 8% metakaolin caused strong decreases, and even elimination of the dispersion potential of the soil samples. One possible explanation for this might be the high silica content of metakaolin and zeolite. The silicate found in the zeolite and metakaolin, together with the Ca²⁺ ions in the soil, interacted with their combined addition, speeding up pozzolanic processes and forming CSH cement gel. This improved bonding among the soil particles. As the attraction force among the clay minerals increased, the soil structure changed from dispersed to complex, ultimately causing a decrease in the dispersion intensity.

Table 3 Dispersion potential in double hydrometry test based on Bell and Maud criterion (1994)

| | Zeolite | | | | | |
|------------|---------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | 0 | 2 | 4 | 6 | 8 | |
| Metakaolin | 0 | Highly dispersive | Highly dispersive | Highly dispersive | Highly dispersive | Moderately dispersive |
| | 2 | Highly dispersive | Highly dispersive | Moderately dispersive | Moderately dispersive | Highly dispersive |
| | 4 | Highly dispersive | Moderately dispersive | Moderately dispersive | Moderately dispersive | Moderately dispersive |
| | 6 | Moderately dispersive | Non dispersive | Moderately dispersive | Moderately dispersive | Moderately dispersive |
| | 8 | Moderately dispersive | Slightly dispersive | Moderately dispersive | Moderately dispersive | Slightly dispersive |

Table 4 Soil dispersion potential for crumb test based on Walker criterion (1997)

| | Zeolite | | | | | |
|------------|---------|-----------------------|---------------------|---------------------|-----------------------|-----------------------|
| | 0 | 2 | 4 | 6 | 8 | |
| Metakaolin | 0 | Highly dispersive | Highly dispersive | Highly dispersive | Moderately dispersive | Slightly dispersive |
| | 2 | Moderately dispersive | Slightly dispersive | Slightly dispersive | Slightly dispersive | Moderately dispersive |
| | 4 | Moderately dispersive | Slightly dispersive | Slightly dispersive | Moderately dispersive | Moderately dispersive |
| | 6 | Slightly dispersive | Non dispersive | Slightly dispersive | Slightly dispersive | Moderately dispersive |
| | 8 | Slightly dispersive | Non dispersive | Slightly dispersive | Slightly dispersive | Slightly dispersive |

Table 3 shows the dispersion potential from double hydrometry tests based on Bell and Maud criterion (1994). The sample modified with 2% zeolite, and 8% metakaolin exhibited weak dispersion behavior, while the sample modified with 2% zeolite and 6% metakaolin showed non-dispersive behavior at 14.5% dispersion. The latter sample had the best composition of materials for controlling soil dispersion. As can be seen, as the metakaolin content increased, the soil shifted towards non- dispersion. The samples containing 6% to 8% metakaolin showed nearly non-dispersive behavior.

The crumb test was performed to validate the data based on the Walker criterion (Table 4). The modified samples were slightly dispersive or nondispersive based on Bell and Maud criterion (1994) and double hydrometry test, but were regarded as nondispersive in the crumb test based on the Walker criterion (1997). The composition containing 2% zeolite and 6% - 8% metakaolin was the optimal composition for reducing soil dispersion.

In the SEM images, the structure of dispersive soil (Fig. 6) changed to a modified structure (Fig. 7) by adding 2% zeolite and 6% metakaolin. The proportion of pores in the soil particles dropped when metakaolin was added, and the soil's dispersive structure transformed into a coherent and

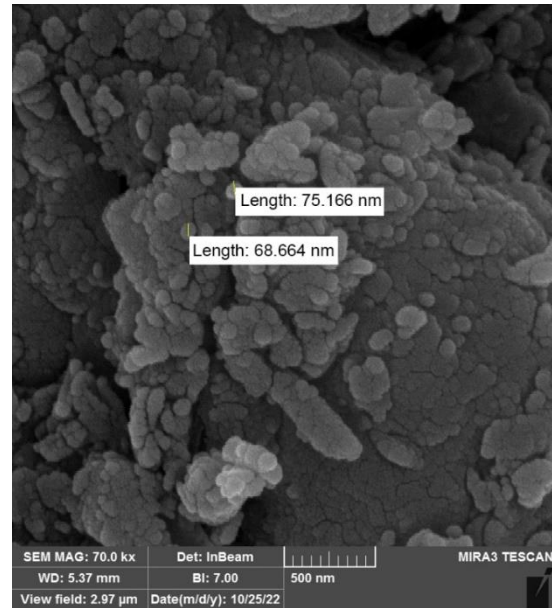


Fig. 6 Scanning electron microscopy (SEM) image of initial dispersive soil with scattered structure

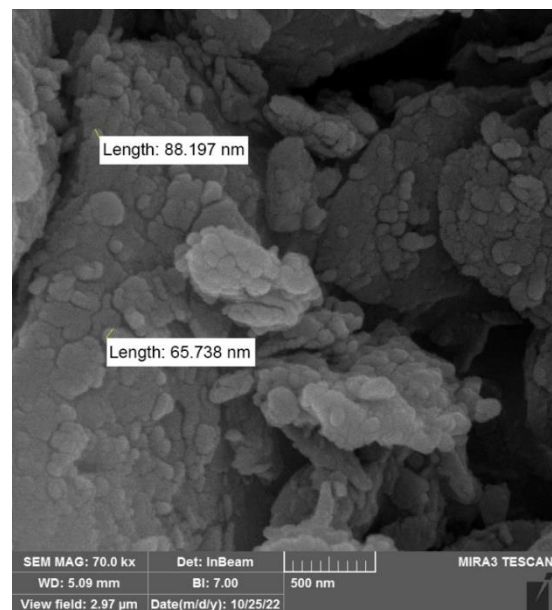


Fig. 7 Scanning electron microscopy (SEM) image of dispersive soil modified with 2% zeolite and 6% metakaolin with coherent and flocculent structure

flocculent structure. When metakaolin was added to the soil the hydration products, including CSH (calcium silicate hydrate gel) were obviously observed. These generated hydration products covered the surface of the soil particles, strengthening the bonding, while also filling the pores of the compacted soils (Wu *et al.* 2016).

3.2 Atterberg limits

The changes in the plasticity of soil can be identified from the liquid limit (LL), plastic limit (PL) and plasticity

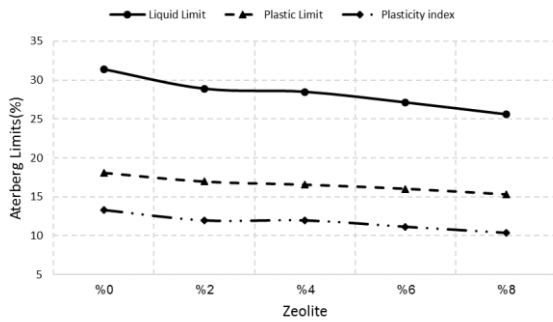


Fig. 8 Changes in Atterberg limits for samples modified with zeolite

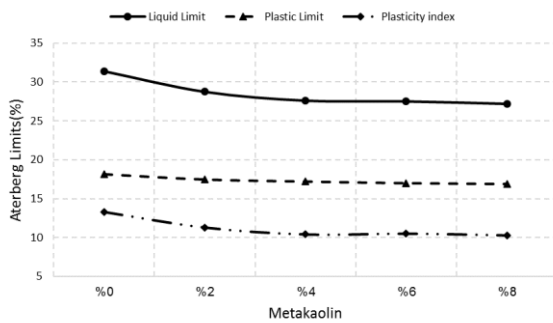


Fig. 9 Changes in Atterberg limits for samples modified with metakaolin

index (PI). Fig. 8 presents the trend of change in the Atterberg limits for different zeolite contents. The results indicate that adding zeolite to the samples caused decreases in the LL, PL and PI values. Adding 8% zeolite to the soil caused the greatest decrease in the Atterberg of about 18.5%, 15.5% and 23% for the LL, PL and PI of the soil, respectively. As zeolite has less ability to absorb water compared to clay soil, it caused a decrease in the liquid limit. However, the high percentage of silica in zeolite caused it to function as a non-plastic material with low flexibility, which then caused a decrease in the plastic limit and the soil PI also decreased. These results were confirmed by the findings of Khajeh *et al.* (2022).

Fig. 9 shows the trend of change in the Atterberg limits at different metakaolin contents. The results show that upon the addition of metakaolin to the samples, LL, PL and PI of the soil decreased compared to the initial sample. The observed behavior can be ascribed to the substantial proportion of silica present in metakaolin. This silica content rendered the material non-plastic and characterized by low flexibility, ultimately resulting in a reduction in the PL value. The substitution of calcium for sodium in metakaolin contributed to the reduction of the Atterberg limits, as the sodium content of the soil decreased in place of the calcium. Thus, when some of the soil was replaced with metakaolin, the PL and LL of the soil decreased, in addition to the PI, although this decrease was less compared to zeolite. These results were confirmed by the findings of Al-Khalili *et al.* (2021).

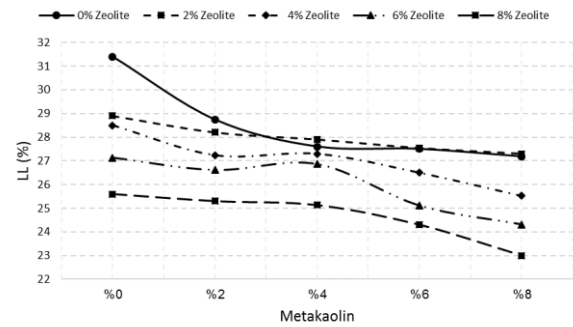


Fig. 10 Changes in LL for samples modified with metakaolin and zeolite

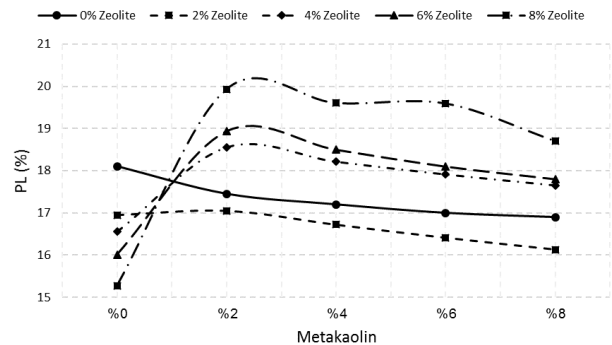


Fig. 11 Changes in PL for samples modified with metakaolin and zeolite

Figs. 10 and 11 present the trends of change in the Atterberg limits at different metakaolin, and zeolite contents. Zeolite caused a sharp decrease in the LL compared to the natural soil sample. By adding 8% zeolite to the soil, the LL of the soil has decreased from 31.4 to 25.6, which is about 18.5% reduction.

When metakaolin was used instead of zeolite, the decrease in LL was slight compared to the natural soil sample. When both materials were used, this trend of change was greater compared to metakaolin and zeolite alone; however, the soil did not approach the initial state. Using zeolite alone, PL showed a considerable decrease. When metakaolin was added, the decrease experienced an ascending trend, but did not approach the PL of the initial sample. In general, zeolite alone had a greater effect on reducing the PL than metakaolin alone. Generally, a decrease in the PL caused a decreased in the flexibility and an increase in the density of the dispersive clayey soil which affected the density, compressibility, expansion and strength of the soil.

Fig. 12 shows the trend of change in the plastic limit for samples with different zeolite and metakaolin contents. PI decreased in all of the samples modified with zeolite and metakaolin. The most significant reduction in PI, approximately 67.5 percent, was observed when 8% zeolite and 8% metakaolin were added to the soil. In addition to facilitating cationic exchange and chemical reactions, the incorporation of metakaolin and zeolite into the soil led to

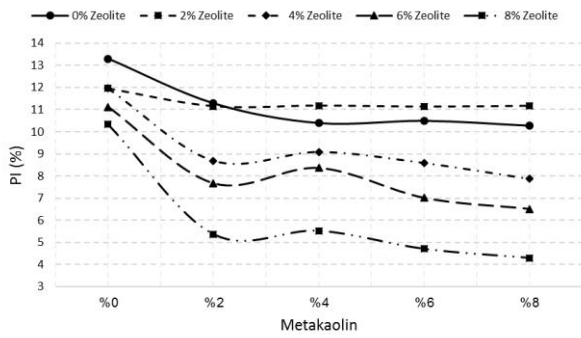


Fig. 12 Changes in PI for samples modified with metakaolin and zeolite

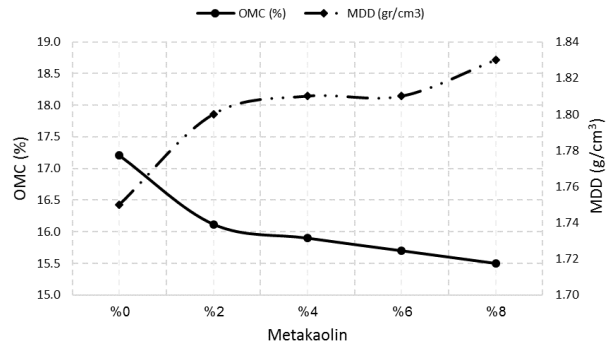


Fig. 14 Results of standard compression test for samples modified with metakaolin

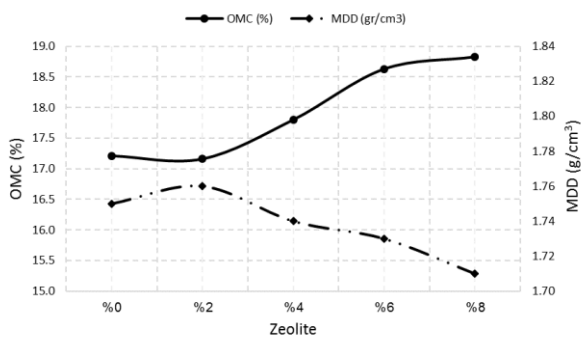


Fig. 13 Results of standard compression test for samples modified with zeolite

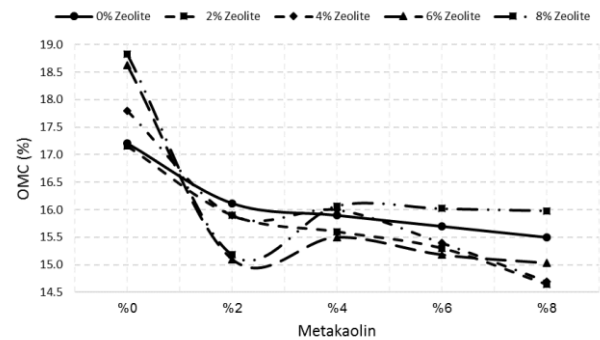


Fig. 15 Changes in Optimal moisture content for samples modified with zeolite and metakaolin

the formation of CSH gel via pozzolanic reactions. This provided the conditions necessary for a decrease in the double layer thickness and in LL, as well as an increase in PL. Thus, the PI, which is a function of the double layer thickness, decreased with a decrease in the thickness of this layer. Therefore, a decrease in the PI can be considered as improving the efficiency of modified soil samples.

3.3 Compression test

The results of compression tests for compounds containing different percentages of zeolite are presented in Fig. 13. Adding the zeolite to the soil increased the optimum moisture content (OMC) and decreased the maximum dry density (MDD) of the soil. The greatest change occurred by adding 8% zeolite, which increased the optimum moisture content by about 9% and decreased the maximum dry density by about 2%. Zeolite particles feature fine intra-particle pores in which they retain water as well as a relatively high specific surface area. They rapidly absorbed the environmental water, which increased the optimum moisture content and decreased the maximum soil dry density.

Fig. 14 presents the results of compression testing on samples containing different percentages of metakaolin. An increase in the metakaolin content decreased optimum moisture content. The greatest decrease of about 10% occurred with the addition of 8%. It can be deduced that the hydrophobic characteristics of metakaolin result in

diminished water absorption, thereby contributing to the reduced optimum moisture content in comparison to the initial sample. Additionally, a reduction in the optimum moisture content resulted in an elevation of the soil's maximal dry density. This behavior could be in terms of the tendency of metakaolin to absorb water for pozzolanic reactions with the clayey or silty parts of the soil.

These results were confirmed by the findings of Attah *et al.* (2019). Further, the decreasing trend in optimum moisture content could be due to cationic exchange reactions, which caused flocculation of the clayey parts of the soil (Salahudeen and Ochepe 2015). The decrease in the optimum moisture content occurred because the soil surface area decreased upon the addition of metakaolin because less water was required for the compression of mixtures, decreasing the optimum moisture content (Al-Khalili *et al.* 2021). The metakaolin had a specific weight of 2.63 g/cm³ and the study soil had a specific weight 2.40 g/cm³. Metakaolin, with its higher specific weight, replaced the soil having a lower specific weight, which increased the maximum dry density of the soil. This increase was related to the flocculation and accumulation of clay particles via the cationic exchange with the soil (Osinubi *et al.* 2015). Thus, to achieve the desired outcome, the metakaolin content consumed should constitute a larger percentage of composition.

The results of compression testing for the samples with different zeolite and metakaolin contents are presented in Figs. 15 and 16. The initial soil sample had an optimum

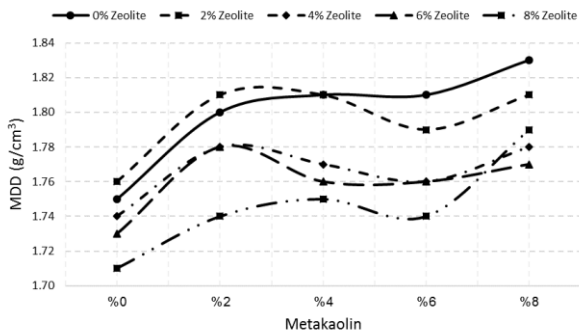


Fig. 16 Changes in Maximum dry density for samples modified with zeolite and metakaolin

moisture content of 17.21. By adding the zeolite, the optimum moisture content increased compared to the initial sample. Nevertheless, upon the addition of metakaolin both individually and in conjunction with zeolite, the optimum moisture content of the compounds diminished in comparison to the initial sample. This implies that the zeolite possessed hydrophilic characteristics, which led to significant water absorption and resulted in an optimum moisture content that was higher than that of the initial sample. Furthermore, by increasing the optimum moisture content, the maximum dry density of the soil decreased.

Adding the zeolite and metakaolin to the soil decreased the optimum moisture content and increased the maximum dry density of the soil. The greatest decrease in the optimum moisture content and greater increase in the maximum dry density occurred in the compound with 2% zeolite and 8% metakaolin. The greatest decrease in the optimum moisture content was about 15%, and the greatest increase in the maximum dry density was about 5%. Pozzolanic reactions among the metakaolin, zeolite and soil led to the formation of new cement compounds. This provided the necessary conditions for compression and continuity among soil particles, causing further compression of the clay soil particles. Thus, as the percentage of voids among the particles decreased, the optimum moisture content decreased. In soil samples undergoing compression, fairly suitable continuity occurred among the soil particles, which increased compression of the particles and increased the maximum dry density of the soil.

As the difference between the soil moisture content and the optimal value increased, the water particles functioned like oil, allowing the soil particles to slide over one another. In this state, the finer particles filled in the gaps between the coarser particles, causing an increase in the density of the soil. Moreover, as the water content increased beyond the optimum moisture content, water settled in the voids among the soil particles, which replaced the soil particles and reduced the density. The compounds having a lower optimum moisture content required less water for the development of this process. Therefore, in order to achieve a more desirable outcome, it would be preferable for zeolite to constitute a lower percentage of the compound.

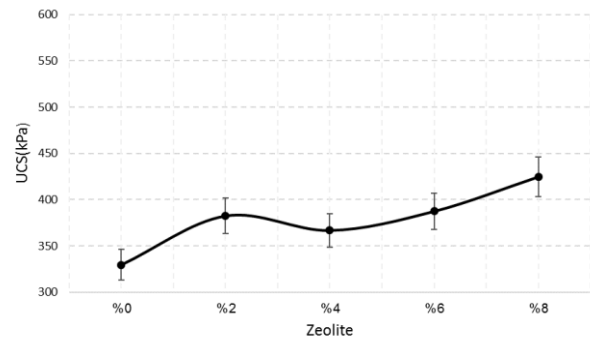


Fig. 17 Changes in uniaxial compressive strength and error bars for samples modified with zeolite

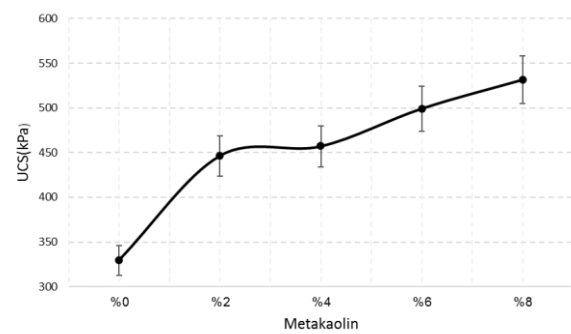


Fig. 18 Changes in uniaxial compressive strength and error bars for samples modified with metakaolin

3.4 Unconfined compressive strength test

Fig. 17 shows the results of UCS testing on samples modified with zeolite with the margins of error shown by the error bars. During hydration, zeolite reacted strongly with the soil, which contained aluminum silicate, which improved the stability of soil. This increased the soil compressive strength in the samples containing zeolite (Shahriarkian *et al.* 2021). The greatest increase in UCS of about 1.3-fold occurred in samples containing 8% zeolite.

Fig. 18 shows that, by adding 2%, 4%, 6% and 8% metakaolin to the soil, the UCS increased. The greatest increase in UCS of about 1.65-fold, was in samples containing 8% metakaolin. This increase in strength could be attributed to changes in the physical texture of the soil. The fineness of the metakaolin grains and the higher activity of this additive compared to the soil caused an increase in the UCS of the stabilized samples. (error bars represent standard deviations).

The effect of adding zeolite and metakaolin on the UCS of the samples after a 7-day curing period is shown in Fig. 19. It can be seen that adding both compounds increased the UCS of the samples. The greatest increase in strength of about 1.8-fold was observed with the addition of 2% zeolite and 6% metakaolin compared to the unmodified samples. Thus, metakaolin had a significant influence on the 7-day compressive strength.

A substantial quantity of amorphous silicate particles is

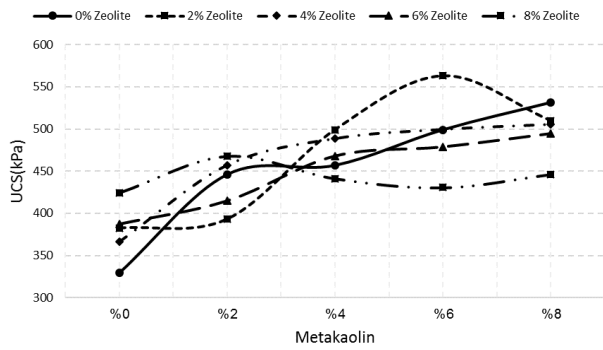


Fig. 19 Changes in Seven-day uniaxial compressive strength of samples modified with zeolite and metakaolin

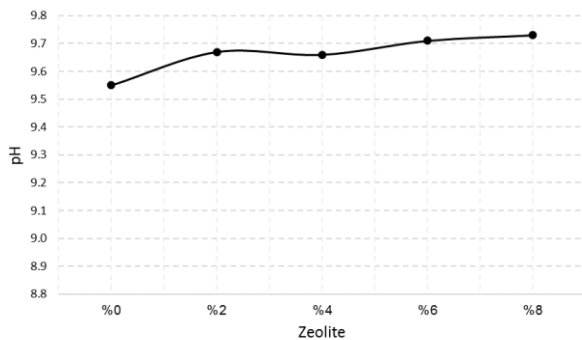


Fig. 20 Changes in pH for samples modified with zeolite

necessary to establish favorable conditions for pozzolanic reactions and the development of CSH cement gel (Wu *et al.* 2016). Due to the substantial quantities of amorphous silicate particles present in metakaolin, its combination with zeolite in the soil resulted in an increase of the pozzolanic reactions. Consequently, this resulted in the formation of CSH cement gel and the development of a denser soil structure, which ultimately raised the UCS.

3.5 pH test

The results of pH testing on samples modified with zeolite and metakaolin alone are presented in Figs. 20 and 21, respectively. Natural zeolite is slightly alkaline, which can cause changes in the soil pH. As zeolite has a high specific surface area and entraps cations, and anions in its crystalline structure, it contains large amounts of minerals, which can release ions into the soil solution. Their addition to the soil environment increased the electrical conductivity and soil pH (Shahriarkian *et al.* 2021). The greatest change of about 2% occurred with the addition of about 8% zeolite. Fig. 21 shows that the addition of metakaolin caused a decrease in the soil pH. This indicates that metakaolin is not useful to maintain a strong alkaline environment (Sun *et al.* 2020). The greatest change occurred with the addition of 8% zeolite, whereby soil pH decreased by about 5%.

Fig. 22 shows the effect of adding zeolite and metakaolin on the pH of modified samples. The ion exchange reaction in fine-grained soil occurs with cation

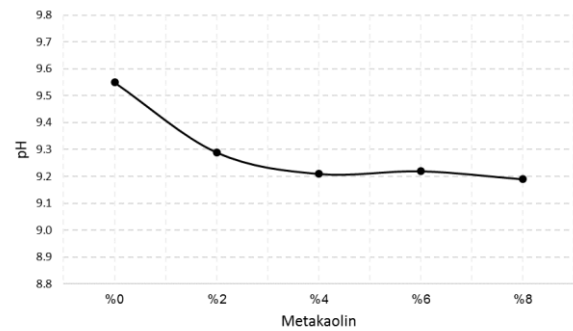


Fig. 21 Changes in pH for samples modified with metakaolin

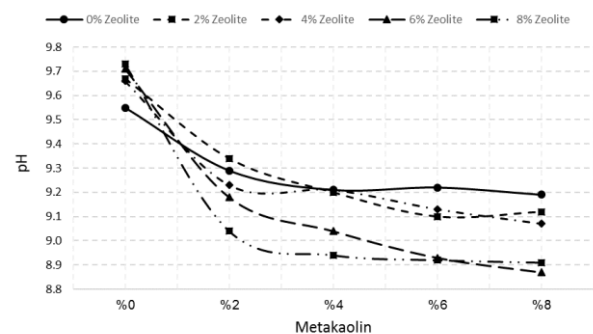


Fig. 22 Changes in pH for samples modified with zeolite and metakaolin

exchange and the presence of water. After an increase in calcium bivalent ions and aluminum trivalent ions around the clay minerals, these ions replaced the sodium ions, which lowered the electronegativity because they were monovalent. This continued until the amount of zeolite and metakaolin consumed provided sufficient aluminum to cause the solubility of the silicate and aluminate in the clay minerals. By adding different percentages of zeolite and metakaolin, the extent of alkalinity decreased and shifted towards neutrality.

4. Conclusions

This research was performed to explore the effect of the addition of zeolite and metakaolin both alone, and in combination at contents of 0%, 2%, 4%, 6%, and 8% of the soil weight on heavily dispersive soil. The following results were achieved:

- The double hydrometry and crumb test results showed that soil that was initially highly dispersive experienced a sharp decrease in dispersion by adding 2% zeolite and 6% or 8% metakaolin, which produced nondispersive behavior. For the addition of both additives, it was concluded that a composition of 2% zeolite and 6% metakaolin was the optimal composition for complete modification of dispersion for soil having a relatively high degree of dispersion.

- The results for the optimal water content indicated that zeolite is hydrophilic and water absorbent. This caused the optimal water content of the samples with high zeolite contents to increase. With an increase in the optimal water content of a sample, the maximum dry density of the soil decreased, causing decreases in the soil density and the UCS of the soil. This was contrary to the results for metakaolin, where compounds with higher metakaolin contents offered more desirable outcomes. As the extent of metakaolin consumed was greater than the zeolite content, it produced more desirable results.
 - SEM images indicated that the additives caused the soil structure to become more coherent. Their particles filled in the voids and pores and conferred an integrated and flocculent structure to the soil.
 - The liquid limit (LL) decreased in the presence of the additives both separately and in combination, except that a higher zeolite content produced a greater decrease in LL. This downward trend occurred for the plastic limit (PL) when the additives were used separately. However, when a mixture of both additives was used at different percentages, PL increased compared to the initial sample. This was true for compounds containing more than 4% zeolite and different metakaolin contents. The greatest decrease in PI (67.5%) was achieved with the addition of 8% zeolite plus 8% metakaolin to the soil. This is related to the addition of zeolite and metakaolin to the soil, the occurrence of chemical reactions and cationic exchange on the one hand, and the formation of calcium silicate hydrate (CSH) gel from pozzolanic reaction, on the other. The conditions required for a decrease in the double layer thickness and LL, as well as an increase in PL, caused a decrease in the PI, which is a function of the double-layer thickness.
 - Adding metakaolin and zeolite increased the UCS of the samples. The greatest increase in strength of about 1.8-fold was observed with a combination of 2% zeolite and 6% metakaolin compared to the unmodified sample. It indicates that the metakaolin had a considerable influence on the 7-day compressive strength. To provide suitable conditions for pozzolanic reactions and the formation of CSH cement gel, sufficient amounts of amorphous silicate particles are required. Because metakaolin contained large amounts of amorphous silicate particles, its addition with zeolite to the soil increased the rate of pozzolanic reactions, causing the formation of CSH cement gel and the development of a denser structure in the soil. These occurrences eventually increased the UCS.
 - Natural zeolite is slightly alkaline and can increase the soil pH. Because zeolite has a high specific surface area and entraps cations, and anions within its crystalline structure, it contains considerable amounts of minerals which are released into the soil medium. Thus, its addition to the soil caused an increase in the soil pH. Metakaolin, however, will reduce the soil pH. Therefore, the addition of metakaolin is not suitable for maintaining a strong alkaline medium. By adding different amounts of zeolite and metakaolin to the soil samples, the pH of the soil and the intensity of alkalinity decreased, which then tended towards neutrality.
- The possible limitations of the conducted study may include the study of the effect of experimental conditions such as temperature, humidity on the accuracy of the results, it is also better to examine the curing time of the samples for different tests. Environmental issues are not

addressed in this paper, although they are of the most relevance when using zeolite and metakaolin in soil improvement. Based on this study, future studies should focus on the microstructure of dispersive clay soil and the effects of additives on it with tests, such as XRD test. What changes are made in clay minerals by adding additives and how these changes contribute to geotechnical properties, and dispersion potential of soil need more research.

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