



Research paper

Application of metakaolin and cement in the stabilisation of expansive soil: an experimental study

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Abstract: Expansive soils have the inherent property of swelling when they have adsorbed water and shrink when dried. This property of expansive soil causes damage to structures constructed on it. To minimise the impact of the expansive soil, it is necessary to improve existing soil before commencing infrastructural construction activity. Samples were collected from Debre Tabor City from three test pits and tested for identification and characterisation. The soil was improved with cement content of 3%, 5%, 8%, and 10% by the dry weight of the soil. The results show that the optimum cement content was obtained at 10% and that half of the optimum cement content was replaced by metakaolin with 5%, 8%, 11%, and 14%, respectively, 7%, 20%, 23%, 26%, and 29%. The optimum combined additive decreases the plasticity index from 64.76% to 27.5%, free swell index from 134% to 45%, maximum dry density from 1.33 g/cm³ to 1.36 g/cm³, California bearing ratio value from 1.28% to 5.15% at 5% cement and 17% metakaolin. **Keywords:**

Keywords: cement stabilisation, expansive soil, metakaolin stabilisation

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1. Introduction

Expansive soils experience significant volume change in response to changes in soil moisture content. This volume change comes from swelling upon wetting and shrinkage upon drying. Buildings built on expansive soils are frequently subjected to severe movement caused by nonuniform soil moisture changes, resulting in cracking and distortion-related damage. [1,2]. Rainfall, evaporation, garden watering, leaking pipes, or tree root activity can cause these moisture changes.

Many areas of our country are covered in expansive soils, such as dark and light grey clay soils. These clays are common in Ethiopia and have caused persistent difficulties in road construction. [3]. The problem of expansive soils can be solved by removing the soil and replacing it with non-expansive soil, using chemical soil stabilisation, or building a foundation treatment that resists expansive soil uplift [4–7]. To address expansive soil problems, several alternative solutions can be implemented, one of which is stabilisation [8–10]. Stabilisation techniques can also improve engineering properties in less expansive and non-expansive soils. The physical and chemical properties of the soil influence the effectiveness of chemical stabilisers [11, 12]. Soil plasticity, grain size distribution, and mineralogy.

This study introduces a novel approach for evaluating the effectiveness of expansive soil stabilisation by replacing cement with metakaolin, particularly in Ethiopia. Using pozzolanic materials like metakaolin in cement stabilisation offers environmental benefits by reducing the demand for Portland cement, a major contributor to carbon dioxide emissions. Additionally, incorporating pozzolans can utilise industrial by-products or natural materials, reducing waste and conserving resources.

2. Materials and methodology

2.1. Description of the study area

Debre Tabor is a town and woreda in north-central Ethiopia. Located in the Debu Gondar Zone of the Amhara Region, about 100 kilometres southeast of Gondar and 50 kilometres east of Lake Tana, this historic town has a latitude and longitude of 11°51' N, 38°1' E with an elevation of 2,706 meters above sea level. The soil in Debre Tabor is primarily composed of residual fine soils such as clays and silt-clays formed on basaltic bedrock. These soils are classified into two types. The first type is red clay soil, which is coloured due to magnetic mineral reduction. The dark and dark brown soil, which dominates the area south and southwest of town, is the second type. Soil samples in the study area were taken at a depth of 1.5 m. Three test pits were excavated at different locations in Debre Tabor City. As shown in Fig. 1, using ArcGIS 10.7 software, test pit one was taken by Begimder (391047.3 E, 1312091.6 N, 2597.7 Z), test pit Kebero Meda (39113.0 E, 1312675.46 N, 2599.5 Z) and Ajbar (39297.2 E, 1310510.49 N, 2654.7 Z).

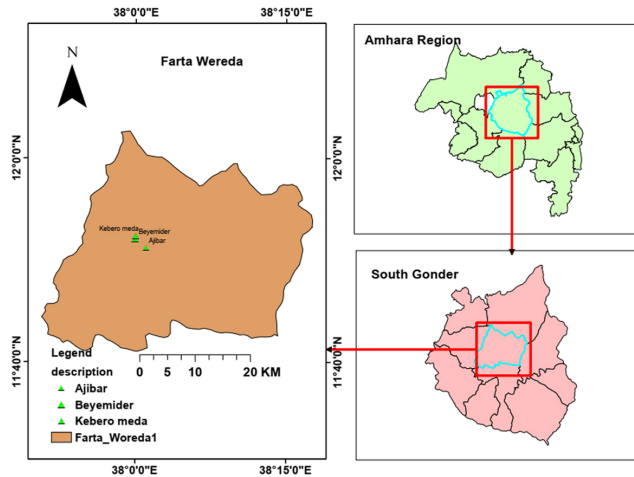


Fig. 1. Location map of the study area

2.2. Materials

Expansive soil, metakaolin, and cement are used in laboratory tests. Both undisturbed and disturbed soil samples were collected from three different test pit locations of Debre Tabor at a depth of 1.5 m, found in the southeastern part of Bahir Dar city in the Amhara region, Ethiopia. The kaolin used in this research was taken from Debre Tabor and heated under 600°C using a furnace, while the cement was purchased from the local market. To begin, three soil samples were characterised, and one with a high free swell index and a high plasticity index (PI) value was selected.

2.2.1. Expansive soils

Soil samples were prepared according to ASTM D 421-85, before being treated and tested. This Method involves exposing soil samples to the air to dry them at room temperature, then breaking up the air-dried soil aggregates with a rubber-covered pestle in the mortar. The dried soils are then sieved to separate them into several laboratory tests, such as PH, Atterberg limits (LL, PL), free swell (FS), Specific Gravity, Linear Shrinkage (LS), and Modified compaction test [13]. The soil samples taken from the test pits for the study are classified as A-7-5 according to the American Association of State Highway and Transportation Officials, and according to the Unified soil classification system, test pit one and test pit three are classified as CH (high plasticity clay) soils and test pit two is classified as MH (high plasticity silt) soils. The swelling characteristics of the soil show that the soil is expansive with a free swell index of 134%, indicating that the mineralogical composition of this highly expansive clay is montmorillonite.

Table 1 shows the geotechnical properties of expansive soils. Based on a free swell in Table 1, which is greater than 100%, the natural soil has montmorillonite mineral content. The minimum requirement for stabilisation is based on the Ethiopian Road Authority (ERA), free swell, CBR, and Atterberg limit values.

Table 1. The geotechnical properties of the expansive soil

Geotechnical parameters		Locations of test pits		
		Test pit 1	Test pit 2	Test pit 3
Specific gravity	Gs (-)	2.72	2.75	2.78
Atterberg limits	LL (%)	95.81	101.78	89.28
	PL (%)	34.99	37.02	32.52
	PI (%)	60.82	64.76	56.76
Free swell	Fr (%)	128	140	135
Maximum dry density	MDD (g/cm ³)	1.3	1.33	1.28
Optimum moisture content	OMC (%)	42.63	44.58	45.39
California bearing ratio	CBR (%)	1.6	1.27	1.7

2.3. Metakaolin

2.3.1. Chemical properties

The chemical composition of metakaolin was carried out by the Geological Survey of Ethiopia. The results are presented in Table 2. The combined per cent composition of Al₂O₃, SiO₂, and Fe₂O₃ was more than 70%. This was adequate to meet the requirement of ASTM C618 standard for pozzolanic materials [14].

The sum of Silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), and iron oxide (Fe₂O₃) is 93.9%, which is greater than the 70% set (ASTM C618-08, 1993) for pozzolanic material [15, 16]. According to this standard, metakaolin is classified as N pozzolan. The H₂O content of 0.78% and 2.16% of LoI value also complies with the ASTM standard, which sets the maximum value at 3% and 10%, respectively. SiO₂ was the most common component of metakaolin in this study, followed by Al₂O₃, K₂O, Fe₂O₃, H₂O, TiO₂, P₂O₃, Na₂O, and CaO.

Table 2. Oxide composition of metakaolin

Oxide	Percentage	Oxide	Percentage
SiO ₂	62.62	MnO	0.02
Al ₂ O ₃	29.38	P ₂ O ₃	0.12
Fe ₂ O ₃	1.9	TiO ₂	0.16
CaO	< 0.01	LoI	2.16
K ₂ O	1.98	MgO	< 0.01
H ₂ O	0.78	Na ₂ O	< 0.01

2.3.2. Physical properties

Metakaolin is a soft, lightweight, and often chalk-like mineral derived from kaoline clay. When touched, it has an earthy odour and feel, and its crystal morphology is plate-like. The Atterberg limits, moisture density relationship, and specific gravity of metakaolin were determined in the laboratory. The physical properties of metakaolin clay are summarised in Table 3.

Table 3. Physical properties of metakaolin

Properties	Symbol	Test Result
Liquid Limit (%)	LL	38.05
Plastic Limit, (%)	PL	27.20
Plasticity Index, (%)	PI	10.85
Maximum Dry Density, (g/cm ³)	MDD	1.45
Optimum Moisture Content, (%)	OMC	26.3
Specific Gravity	Gs	2.6

2.4. Methodology

2.4.1. Sample preparation

Soil samples were prepared according to ASTM D 421 - 85, before being treated and tested. This Method involves exposing soil samples to the air to dry them at room temperature, then breaking up the air-dried soil aggregates with a rubber-covered pestle in the mortar. The dried soils are then sieved to separate them into several laboratory tests, such as PH, Atterberg limits (LL, PL), free swell (FS), Specific Gravity, linear shrinkage (LS), and Modified compaction test.

This study used Dangote cement, manufactured in Ethiopia and owned by Nigerian billionaire Aliko Dangote, for treatment. In Ethiopia, Dangote cement produces ordinary Portland cement (OPC) and Portland pozzolana cement (PPC), but in this research, ordinary Portland cement (OPC) was used in different percentages for treatment purposes.

3. Results and discussions

3.1. Laboratory test result of metakaolin-soil properties of expansive soil

3.1.1. Effect of metakaolin on the free swell value

The free swell index of the soil can be used to determine the expansiveness of the soil. To Indian standard IS 1498 of the free swell testing manual if the value of the free swell index is greater than 100% the effect causes extreme damage to the structure, whereas if the value is less than 100% but greater than 50% causes considerable damage on light weighted structure and seldom effect on the structure of the value is less than 50% [17]. As shown in Fig. 2 the free

swell index of the soil is decreased as the percentage of the metakaolin increases. When the % of metakaolin increases the free swell index effect is decreased rapidly up to 17%, beyond this point the free swell index value is not significantly changed.

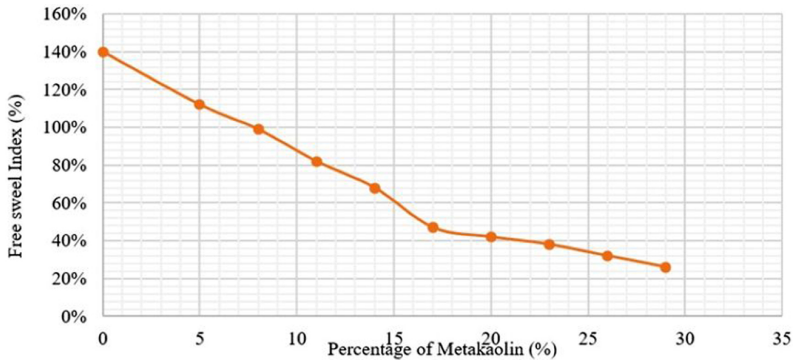


Fig. 2. Free swell index effect of metakaolin on natural soil

3.1.2. Effect of metakaolin on linear shrinkage

As shown in Fig. 3 the addition of metakaolin has a decremental effect on the shrinkage limit value of the expansive soils. The shrinkage limit value decreased linearly as the metakaolin percentage (%) increased.

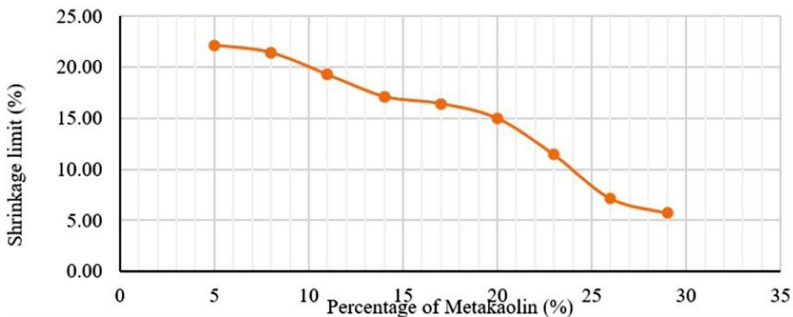


Fig. 3. Effect of metakaolin on shrinkage limit values

3.1.3. Effect of metakaolin on consistency limits

Adding metakaolin to the consistency limit has its effect, as shown in Table 4. It summarised the value of the consistency index of the soil for different percentages of metakaolin added to the naturally expansive soil [18]. As shown in Table 4, as the content of metakaolin increases, the soil's liquid limit decreases, and the plastic limit increases. Correspondingly, the soil's plastic index decreases with the metakaolin percentage increase.

From the test result shown in Table 4, the liquid limit and the plastic index were decreased, but the decrement content was higher in the plastic index of all test pits. The Atterberg limit depends on the predominant clay minerals in the soil structure. For instance, if montmorillonite is present in the soil structure, the liquid limit of the soil is more significant than 100%, but the Atterberg limit values are less in the case of Illite clay mineral and less in the case of metakaolin. The effect of the additive was more on the plastic index of the soil than a liquid limit. Figure 4 shows the effect of additives on Atterberg limit values of expansive soil. As shown in Fig. 4, the decrement of the plastic index corresponds to the increment of metakaolin content.

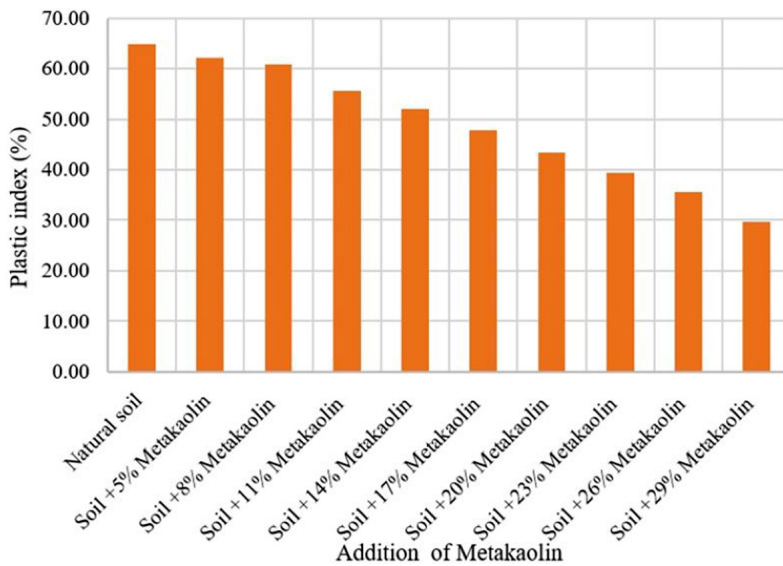


Fig. 4. Effect of metakaolin on Atterberg limit values

Table 4. Consistency index of metakaolin stabilised soil

Percentage of Metakaolin (%)	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)
5	99.95	37.92	62.03
8	99.15	38.32	60.83
11	94.61	39.04	55.57
14	92.82	40.77	52.05
17	88.80	41.03	47.77
20	85.15	41.87	43.28
23	81.62	42.25	39.37
26	79.04	43.39	35.65
29	74.08	44.51	29.57

3.1.4. Effect of metakaolin on moisture-density

The effect of the Metakaolin on the compaction characteristics of the expansive soil is shown in Fig. 5. The moisture-density test was used, to ascertain the material’s optimum moisture content as well as its dry density [19]. The effect of metakaolin on the compaction properties was studied with 5%, 8%, 11%, 14%, 17%, 20%, 23%, 27% and 29% of expansive soil by mass. Figure 5 shows the moisture density relation of expansive soil treated with metakaolin.

From the test result shown in Fig. 5, the maximum dry density was increased as the metakaolin percentage increased. The optimum moisture content of the soil mix decreased as the percentage of metakaolin increased due to the denser material of metakaolin. The denser the material more permeability of the soil and the decrease in OMC due to the metakaolin caused by the high absorption of water by metakaolin. This implies that less water is needed to compact the soil with a metakaolin mixture.

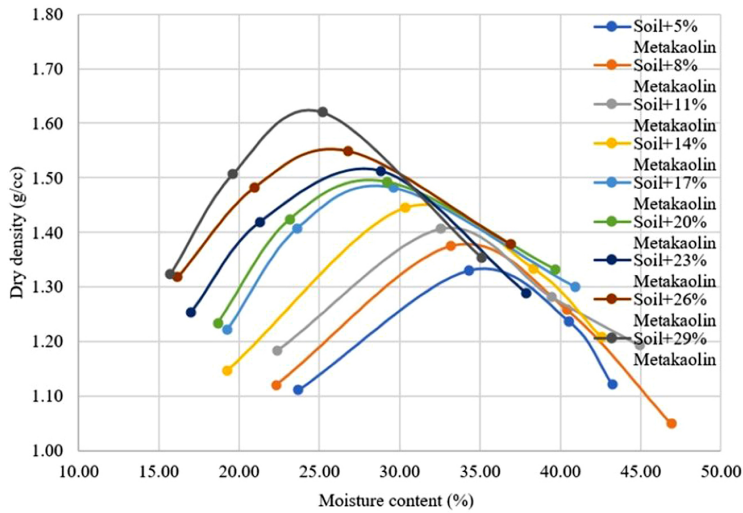


Fig. 5. Effect of metakaolin stabilised expansive on MDD and OMC

3.1.5. Effect of metakaolin on California Bearing Ratio (CBR)

As shown in Fig. 6, when the percentage of metakaolin increases, the CBR value increases in parabolic trend [20]. The CBR value of samples increased by 125%, increasing metakaolin content from 0% to 29%. The 2.85% CBR value was achieved at 29% of the metakaolin content [21].

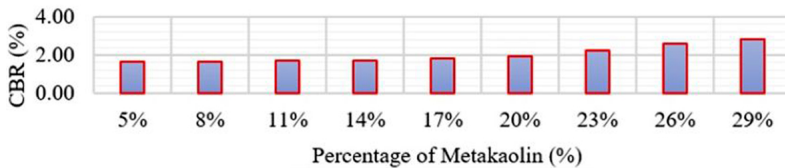


Fig. 6. Effect of metakaolin stabilised expansive soil on CBR values

3.2. Laboratory test results of cement-soil properties of expansive soil

3.2.1. Effect of cement on the free swell value

The free swell index value of cement-stabilized expansive soil is presented as shown in Table 5. It shows the effect of cement-stabilized expansive soil with 3%, 5%, 8%, and 10% percentages of cement. There is a noticeable decrease in the free swell index with increasing cement content [22]. The free swell Index decreases by 140% to 48% for soils mixed with 10% cement. When 10% cement was added to trial samples (expansive soil), the free swell index was less than 50%, which indicates that the blended sample was classified as less expansive soil. Based on this research, civil engineering infrastructure can be constructed using such a percentage of cement (10%).

Table 5. Effect of cement on free swell index

Cement (%)	Free Swell
3%	112%
5%	88%
8%	68%
10%	48%

3.2.2. Effect of cement on consistency limits

The addition of cement to the expansive soil decreased the plasticity effect of the expansive soil as shown in Table 6. It can be noticed that there is a significant decrease in all indices as cement content increases [23, 24]. This can be explained by cement being a soft and very fine matter that can occupy the voids between soil particles instead of water. This will reduce the water content of the treated soils. Soil with low consistency limits is considered good soil that can be used as a base layer in constructing roads and airports because of its high shear resistance.

Table 6. Effect of cement-stabilized expansive soil on Atterberg limit

Percentage of Cement (%)	Liquid limit (%)	Plastic limit (%)	Plastic index (%)
3%	99.33	48.09	51.24
5%	87.25	43.24	44.01
8%	75.49	40.33	35.16
10%	58.43	31.24	26.19

3.2.3. Effect of cement on moisture-density

Compaction curves for samples with different cement dust content were determined using the Standard Proctor Test, as demonstrated in Fig. 7. The maximum dry unit weight and the optimum moisture content were determined for each curve [18]. It can be noticed that the soil

sample with higher cement content has a lower maximum dry unit weight with an increase in its moisture content [25]. The increase in the optimum water content can be related to the increase in the surface area of soil particles mixed with cement [26,27]. Moreover, the increase in optimum moisture content is thought to result from the increasing desire for water, as more water is required for the dissociation of cement.

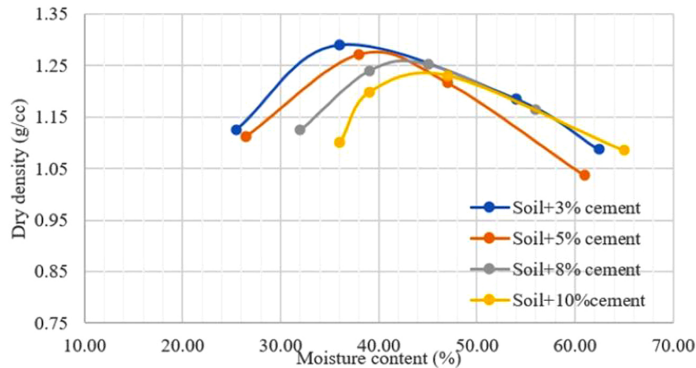


Fig. 7. Effect of cement on maximum dry density (MDD) and optimum moisture content (OMC)

3.2.4. Effect of cement on California Bearing Ratio (CBR)

Figure 8 shows the effect of cement on the soil's CBR value. The expansive soils were treated with 3%, 5%, 8%, and 10% cement. The CBR value at 10% cement satisfied the ERA requirements for subgrade material. The CBR of the expansive soil increases as the percentage of cement increases. Table 7 shows that 10% of cement was the optimum percentage based on CBR value.

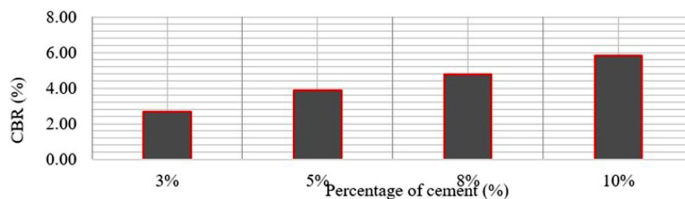


Fig. 8. Effect of cement on CBR values

3.3. Laboratory test result of metakaolin-cement on expansive soil

3.3.1. Effect of addition of metakaolin-cement on Atterberg properties of soil

The addition of cement-metakaolin in different proportions with naturally expansive soil was studied on Atterberg limit values. From the test results, the percentage of cement and metakaolin increased, the liquid limit decreased, and the plastic limit decreased. As a result, the plasticity index of the specimen, which is the blending of cement-metakaolin and expansive soil, decreased. The laboratory test result is summarised in Table 7 below. From the test result, the liquid limit decreased as the percentage of cement was constant and the metakaolin proportion varied.

As shown in Table 7, the liquid limit of the soil was decreased from 79.69 to 57.3%. The plasticity of the soil was decreased. The reason may be reduced particle attractions, which relate to a lower value for the liquid limit. Hence, the amount of calcium ions in metakaolin was insufficient to replace the sodium ion in soil particle montmorillonite. Therefore, it is necessary to have a confident amount of calcium ions from cement in anticipation of replacing the sodium montmorillonite. According to the Ethiopian Road Administration (ERA), 2013, the plastic index of the subgrade material is less than 30%, and the liquid limit is 60%. The laboratory result of the plastic index in this study was greater than 30%, and the liquid limit of the specimen was greater than 60%, except for 17 % metakaolin and 5% cement. Based on this paper, cement-metakaolin stabilised expansive soil at 5% cement, and 17% metakaolin can satisfy the ERA 2013 subgrade specification requirement.

Table 7. Effect of cement and metakaolin on Atterberg limit

Mix-proportion of Additives (%)		Atterberg limit (%)		
Cement (%)	Metakaolin (%)	Liquid Limit	Plastic Limit	Plastic Index
5%	5	75.69	37.7	38.00
	8	70.97	35.10	35.87
	11	66.25	32.37	33.88
	14	62.62	31.48	31.14
	17	57.3	29.8	27.5

3.3.2. Effect of the addition of cement-metakaolin on free swell index

As discussed, soil with a free swell value above 100% can cause damage, whereas less than 100% can cause considerable damage to light-loaded structures. Soils with a free swell value below 50% seldom exhibit an appreciable value change, even under light loads. The effect of Cement and Metakaolin on free swell index values is presented in Table 8.

Table 8. Effect of cement and metakaolin on free swell index values

Mix-Proportion of Additives (%)		
Cement (%)	Metakaolin (%)	Free Swell Index (%)
5	5	80
	8	74
	11	63
	14	53
	17	45

As shown in Table 8, when the percentage of metakaolin increases, the free swell value decreases. At a constant percentage of cement (5%), the free swell index value decreased from 80% to 45%, with metakolin added from 5% to 17%. As shown in Table 8, the free swell index value is less than 50% when the percentage of metakolin is 17%. Therefore, based on the free swell index value 5% cement and 17 metakaolin can be utilised as stabilisers of expansive soil.

3.3.3. Effect of addition of cement-metakaolin on moisture-density relation

As discussed in the section above, the modified compaction method was applied. As shown in Fig. 9, when the percentage of metakaolin increased the optimum moisture content of the specimen was decreased due to fine and light particles in the mixtures. The pozzolanic reaction between clay, metakaolin, and cement reduces the OMC and increases MDD [28].

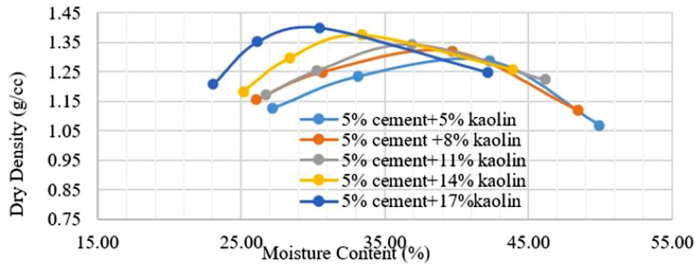


Fig. 9. Effect of 5% cement added with different percentages of metakaolin moisture density relationship

3.3.4. Effect of addition of cement-metakaolin on California Bearing Ratio

The effect of cement and metakaolin on the soil’s CBR value is shown in Table 9 below. The expansive soils were treated with 5% cement blended with 5%, 8%, 11%, 14%, and 17% metakaolin. Stabilising the expansive soil with 5% cement and 17% metakaolin improved its CBR value from 1.27 % to 5.15%. This result fulfils the requirement of the ERA specification as subgrade material.

Table 9. CBR values of 5% cement with different % of metakaolin

No.	Specimen type	Dry density (g/cc)			Soaked CBR (%)			95% MDD	CBR (%)
		10	30	65	10	30	65		
1	Soil+5% Cement+5% Metakaolin	1.17	1.26	1.38	3.24	3.98	4.99	1.29	4.30
2	Soil+5% Cement+8% Metakaolin	1.19	1.29	1.41	3.56	4.15	5.34	1.31	4.50
3	Soil+5% Cement+11% Metakaolin	1.25	1.30	1.44	3.68	4.26	5.53	1.35	4.70
4	Soil+5% Cement+14% Metakaolin	1.29	1.34	1.48	3.67	4.65	5.71	1.38	4.90
5	Soil+5% Cement+17% Metakaolin	1.30	1.36	1.48	3.87	4.90	6.02	1.39	5.15

The expansive soil’s CBR increases with the percentage of cement and metakaolin compared to the natural soil. The increase in CBR value was due to cation exchange flocculation, agglomeration of the soil particle, and variation in the clay mineralogy of expansive soils. This is due to replacing some of the volume previously occupied by expansive clay minerals (montmorillonite and Illite clay minerals) with metakaolin and cement by using both stabilisers for the stability and strength of the subgrade soil. The reason for the soil strength increase after stabilisation was higher energy at the initial stage of the reaction and a faster hydration process, resulting in the completion of their pozzolanic reactions in a short period. During pozzolanic reactions, the silica and alumina minerals increase.

4. Conclusions

This study highlights the fulfilment of the minimum subgrade strength of soil based on the Atterberg limit, free swell and compaction characteristics of the soil. Based on the results obtained from experimental work, the following conclusions can be drawn:

1. The soils stabilised at the cement content of 3%, 5%, 8%, and 10% by the dry weight of the soils. According to ERA, the 10% of cement content satisfies the minimum values of California bearing ratio (CBR).
2. Plasticity index, free swell index, maximum dry density, and California bearing ratio swell were reduced to 5% cement and 17% metakaolin and fulfilled/met the Ethiopian Roads Authority manual, Indian standard, and ASTM D 4609 standard requirements.
3. The combined additives mix proportion of cement and metakaolin produces a better result as a stabiliser, allowing for the use of locally available materials, and reducing the amount of cement and its environmental impact during the production process.

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