Effect of Metakaolin on the geotechnical properties of Expansive Soil

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ABSTRACT

Expansive soil spreads in Iraq and some countries of the world. But there are many problems can be occurred to the structures that built on, so we must study the characteristics of these soils due to the problems that may be caused to these structures which built on these kinds of soil and then study the methods of treatment. The present study focuses on improving the geotechnical properties of expansive soils by treating it Metakaolin(M). Metakaolin (M) has never been used before as an improvement material for stabilizing the expansive soil . Metakaolin is a pozzolanic material. It's obtained by calcination of kaolinite clay at temperatures from 700°C to 800°C. Kaolin chemical composition is basically aluminous silicates hydrates associated with Mn, Fe, Ca, K, Na. Its crystal has a lattice structure of tetrahedral and octahedral layers with interplanar distance of 7.2 Å. The soil used in the present study can be classified according to the Unified Soil Classification System as clay with high plasticity (CH) .

Key words: expansive soil, improvement ,swelling, , swelling pressure, metakaolin

تأثير الميتاكولين على الخواص الهندسيه للتربه الانتفاخيه

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الخلاصة

تنتشر الترب الانتفاخية في العراق و بعض بلدان العالم غير أن هناك العديد من المشاكل التي من الممكن أن تسببها للمنشآت المستندة عليها لذا فأن دراسة خواص تلك الترب يجب ان يتم بسبب المشاكل التي من الممكن ان تحدثها للمنشات المستندة عليها ومن ثم يتم تحديد طرق معالجتها. حيث تناول البحث أمكانيه تحسين الخواص الهندسية للترب الانتفاخية بمادة الميتاكؤلين. الميتاكؤلين لم يتم استخدامها من قبل كمادة محسنه لتثبيت التربة الانتفاخيه . الميتاكؤلين هي مادة بوزولانية . تم الحصول علبها من قبل التكليس من الطين الكاؤليني في درجات الحرارة من 700 درجة مئوية إلى 800 درجة مئوية. التركيب الكيميائي للكاؤلين هو في الأساس هيدرات سيليكات المرتبطة بالمنغنيز ، الحديد ، الكالسيوم ، البوتاسيوم، الصوديوم . من الواضح ان لديها بنية من طبقات رباعية السطوح و ثمانية السطوح مع مسافة داخليه 7.2 Å . التربة المستخدمة في هذه الدراسة يمكن تصنيفها على انها تربة طينيه ذات لدونة عالية تبعا لنظام تصنيف التربة الموحد.

الكلمات المفتاحية : تربة انتفاخية , معالجة , انتفاخ , ضغط الانتفاخ, الميتاكؤلين .

1. INTRODUCTION
Expansive soil is one of the problematic soils that face many geotechnical engineers in the field (others include collapsible soil, quick clays, etc.). The expansive soil is known to cause severe damage structures that are founded on it. In Iraq, there is no confirmed information about the economic losses due to structures founded on expansive soils. However, there are several well-documented cases of studying the behavior of expansive soil in Iraq. Expansive soils are very sensitive to variations in water content and show excessive volume changes because of an increase in their water contents. Expansive soils have the tendency to swell when they become in contact with moisture and to shrink if moisture is removed from them. Expansive soils are a worldwide problem **, Seed et al., 1962, and Kormonik and David, 1969.** This highly plastic soil may create cracks and damage on the pavements, railways, highway embankments, roadways, building foundations, channel and reservoir, water lines, sewer lines etc.**,Gromko, 1974.** Swell response of expansive soils has been investigated by researchers since the 1950s based on Atterberg limits, index properties, and other soil tests carried out in the laboratory **,Seed et al., 1962.** These studies were a major success but they have failed to determine the associated engineering properties. This is mainly because soils with the same atterberg limits and index properties show different engineering properties. In order to control the volume change in expansive soils, many admixtures are adequately used in the researches **, Kehew,1995.** Metakaolin has never been studied its effect on the expansive soils. Metakaolin is a dehydroxylated form of the clay mineral kaolinite. Rocks that are rich in kaolinite are known as kaolin, traditionally used in the manufacture of porcelain. The particle size of metakaolin is smaller than cement particles, but not as fine as silica fume. Metakaolin is a pozzolanic material and has never been used before as an additive to improve the expansive soil therefore studying its effect will give us the way to use it as pozzolanic material to reduce the swelling potential. The standard chemical requirements of **ASTM C618-03** include the sum of SiO_2 , Al_2O_3 and Fe_2O_3 content ($\geq$ 70%) for class F and ($\geq$ 50%) for class C to define the material as pozzolanic.

2. MECHANISM OF SWELL
Mitchell, 1993 showed that soil swelling happens due to several factors:

1-Capillary Imbibition: The surface tension caused by air in the unsaturated soil and the soil suction caused water adsorption to the soil system.

2-Osmotic Imbibition: The double layer acts as semi permeable membrane with difference in the ion's concentration inside and outside of it causing the flow of water and increase in the soil volume.

3- Hydration of Exchangeable Cations: as described previously the cations attracted to the negatively charged soil surface causing an increase in the volume of the double layer. Then these cations will be hydrated causing an increase in the ion's volume and as a result an increase in the soil volume.

4-Van Der Waals forces: these forces are secondary in-directional forces and less strong than the hydrogen bonding and they connect the montmorillonite sheets, when adsorption of water happens a repulsion between these forces will happen leading to an increase in the volume of soil.

The objectives of this study are

1- Improve the properties of expansive soil to be used as construction material in the pavements, railways, highway embankments, roadways, building foundations, channel and reservoir linings, irrigation systems, water lines, sewer lines etc.
2- Reduce the industrial wastes, this reduction is considered one of the concept used in contamination control.
3- Use local materials in soil treatment which reduces the costs.

3. EXPERIMENTAL WORKS AND MATERIALS USED

3.1 Materials used

The materials used during the experiments were bentonite, sand, and metakaolin. **Table 1.** shows the physical properties of the materials that have been used in the study.

1-**Prepared soil**: mixture of bentonite (Ca-based bentonite manufactured by Al-Fallujah Cement Factory is used as the expansive soil) with sand (from Ali Al-Gharbi city south of Baghdad) were tested till getting the mixture of 85% of bentonite to 15% of sand (B-S) by dry weight depending on the required plasticity indices.

2- **Metakaolin (M)** is a pozzolanic material. It's obtained by calcination of kaolinite clay at temperatures from 700°C to 800°C as shown in Eq.(1).Kaolin chemical composition is basically aluminous silicates hydrates associated with Mn, Fe, Ca, K, Na. Its crystal has a lattice structure of tetrahedral and octahedral layers with interplanar distance of 7.2 ,**Cited, et al., 2004.**

$$\underset{\text{Kaolin}}{Al_2Si_2O_5(OH_4)} \xrightarrow{700°C} \underset{\text{Metakaolin}}{Al_2O_3.2SiO_2+2H_2O} \qquad (1)$$

The chemical properties of these materials are presented **Table 2**.

3.2 Physical Tests

3.2.1 Grain size distribution tests

The test was carried according to **,BS 1377: 1975.** and the prepared soil is composed of 72% of clay , 24% of silt ,and 4% of sand.

3.2.2 Specific gravity tests

The specific gravity of specimens was determined in accordance with the **(ASTM D-854).**

3.2.3 Compaction tests

Compaction tests were conducted using "standard" compaction test according to **(ASTM D-1557).**

3.3 Shear Strength Tests

3.3.1 Sample preparation

Remolded specimens were prepared in the laboratory depending on the proctors data at the required molding water content according to **(ASTM D 2850 – 03a) .**

3.3.2 Unconfined compression tests

The specimens were compacted statically for the maximum dry density and optimum moisture content values then sealed and allowed to cure for one day. The test has been carried according to **(ASTM D-2166).**

3.4 The Swelling Test

Three types of swelling tests have been made (free swell test, constant volume test, and consolidation test). The tests were done according to **Head 1984 and ASTM D 4829-03**. In these tests, the oven dried soil passing 2mm sieve was mixed with the required amount of water and were remolded at the oedometer ring (75 mm in diameter and 19 mm in height) but the sample was prepared by a height equal to 14 mm to insure that the specimen will be laterally confined , **Al-Omari, et al., 2010**. A load of about 7 KPa was applied as seating pressure, left for ten minutes then an initial reading was recorded. The soil sample was submerged with distilled water for 24 hours then the final reading was recorded. To measure the swelling pressure, weights will be added in increments to the soil sample to get the dial gage reading zero again.

4. RESULTS OF TESTS

4.1 Results of Grain Size Distribution

Fig. 1 shows the effect of metakaolin on the grain size analysis of the prepared soil. It can be noticed that metakaolin affects the prepared soil at the beginning and causes a reduction in the percentages of clay particles but eventually remains constant and causes a reduction in percentages of sand between 4% and 12% of M and that is due to the particle size of M which represents a fine material with diameter size less than 0.00325 mm. Soil M10 gives 31% reduction in the clay content , 42% increment in the silt content and 300% increment in the sand content, therefore 10% of M gives the best results for the grain size distribution. Soil M12 gives different behavior which shows 3% increment in the clay content (an increment more than Soil A) and 25% reduction in the Silt content, this behavior could be related to the pozzolanic reaction of M which take place during the process (The standard chemical requirements of **ASTM C618-03** include the sum of SiO_2 , Al_2O_3 and Fe_2O_3 content ($\geq$ 70%) for class F and ($\geq$ 50%) for class C to define the material as pozzolanic).**Table 3** shows the results of the grain size distribution test.

4.2 Results of Specific Gravity Tests

Fig. 2 shows the effect of metakaolin on the specific gravity results. it can be noticed that M causes a linearly reduction in the specific gravity of mixture. The reduction of specific gravity is because of lower specific gravity of M. Linear decrease in specific gravity indicate that no mineralogical alterations have occurred with M alone. At 12% replacement the specific gravity of mixture reduces to 2.72 **,Kumar, 2012.**

4.3 Results of the Compaction Tests

Fig. 3 shows the effect of metakaolin on the compaction results. Metakaolin increases the max dry unit weight from (13.5 to 13.66) KN/m^3 and decreases the optimum moisture content from (36 to 34.5) . As water is added to a soil (at low moisture content) it becomes easier for the particles to move past one another during the application of compacting forces. **Table 4** shows the results of the compaction and specific gravity tests results.

4.4 Results of Unconfined Compression Test

Fig. 4 shows effect of M on the unconfined compression strength of the expansive soil. This Figure illustrate the stress-strain behavior of prepared and treated soil under vertical load. Initially the stress gradually increases with the increase in strain. After attaining the peak stress, it decreases with the increase in strain for all the combinations of replacement materials and soil. Approximately all the specimens show shear failure after the failure of plane of specimens. Fig. 5 shows the effect of M on the c_u and **Table 5** shows the results of the unconfined compression tests .it can be noticed that the replacement material M causes a linear increment in c_u from (160.73 to 315.00) KPa for soil samples from (M4 to M10). This increment was due to the reactive silica which reacts and produce cementations material and binds soil particles together to increase strength **,Kumar, 2012.** The reduction in c_u at M12 to 258.90 KPa may be due to the excess M introduced to the soil and therefore forming weak bonds between the soil and the cementations compounds formed.

4.2 Results of Swelling Tests

Fig. 6 shows time – percent swell for the prepared soil and soil treated with M**.** The prepared soil shows a high rate of swell within the 11 days and then reaches a fix point ,whereas the treated soil reaches its point with less than that. It is due to the electrical equilibrium when the double layer arrives to its full required thickness to balance the net negative charges at the faces of clay particles. The swell percent decreases due to the effect of pozzolanic reaction for the replacement materials that have been used which take place during the process. **Fig. 7** shows the effect of metakaolin on the swelling pressure, it can be noticed that the metakaolin causes a reduction in the swelling pressure while the sudden increment in the swelling pressure at M8 and M12 were due to the reduction in water content from 32.5% at M6 to 30% at M8 and from 35% at M10 to 34.5% at M12 which means more adsorb water and that lead to more swelling potential. Swelling pressure obtained from free swell tests is higher than that obtained from the constant volume test .That is because the free swell test allows an increase in volume and that causes random arrangement for the parallel particles of the soil, in reloading an additional pressure was needed to rearrange the particles. **Fig. 8** shows e- $\log\sigma_v$ for the prepared soil and **Fig. 9** shows e- $\log\sigma_v$ for soils treated with M. **Fig. 10** shows the effect of metakaolin on the consolidation parameters, one can notice that M causes a linear reduction in the void ratio which can be related to the reduction in water content from 36% to 34.5%. the compression index decreased due to the reduction in the clay content from 72% to 50%. **Table 6** shows the results of the free swell and constant volume tests. The potential expansion has been classified according to **ASTM- D (4829 – 03)** as shown in **Table 7.** The soils samples turned from very high expansive to moderate and even very low expansion potential due to the effect of pozzolanic materials which could be due to the pozzolanic and cation exchange reactions which occurred between the soil and replacement materials. Eq.(2) shows the calculation of the expansion index according to **ASTM- D (4829-0).**

$$EI=(\Delta H/H)*1000 \qquad (2)$$

Where:
EI: Expansion Index,

ΔH = change in height, D2 − D1, mm,
H1 = initial height, mm,
D1 = initial dial reading, mm, and
D2 = final dial reading, mm.

Based on the results of consolidation ,the coefficient of permeability of the soil can be calculated from Eq. 3:

$$K = C_v \, m_v \, \gamma_w \tag{3}$$

where:
C_v = Coefficient of consolidation,
m_v = Coefficient of volume change, and
γ_w = Unit weight of water.

Fig .11 shows the effect of M on the coefficient of permeability. **Fig. 12** shows the effect of M on the coefficient of c of consolidation. **Fig .13** shows the effect of M on the coefficient of volume change. The calculation of m_v, C_v, and the coefficient of permeability were at stress equal to 400 Kpa. The coefficient of consolidation and the coefficient of permeability various from one soil to another for soils samples M4 to M12 in and this variation could be easily related to the variation in the sand content (increasing in sand content causes an increment in the permeability due to the coarser size of sand) ,for example at soils samples from M4 to M6 the coefficient of consolidation increased from (3.920 to 8.187) m^2/sec and the coefficient of permeability increased from (0.0087 to 0.0154) m/sec due to the increment in sand content from (4 to 20)% then the coefficient of consolidation and the coefficient of permeability began to decrease at M8 due to the reduction in sand content to 4%. And finally the coefficient of consolidation and the coefficient of permeability began to increase at M10 and then decrease at M12 due to the increment in sand content for M10 from (4 to 16) % and then the reduction in sand content from (16 to 8)% for M8. **Table 8** shows the results of the consolidation test.

5. CONCLUSIONS

Based on the experimental results of the experimental work, the following conclusions may be obtained:

1- The grain size distribution shows that the soil turn to more coarser size due to the pozzolanic reaction between the expansive soil and metakaolin.
2- The specific gravity decreased with the addition of M from 2.78 to 2.72
3- The compaction curves shows that, the addition of M increases the maximum dry density and decreases the optimum moisture content.
4- From the unconfined compression tests results show that the prepared soil A has (C_u=94.76 KPa). The optimum unconfined compressive strength was obtained for 10% of M content. The cohesion of soil shows an increasing order for first percentages of M and after that this value decreases at 12% of M to 258.90 KPa but it is still higher than the prepared soil type A.
5- From free swell tests, the following conclusions can be drawn.
   a- Soil sample M10 causes a reduction in the free swell about 91%. and after the addition of R (5, 8 and 11%), the reduction various to about (91%, 89%, 82%) respectively.
   b- The results of swelling pressure test using constant volume method show that the addition of the addition of (10%) M causes a reduction of about (87%).

c- From the consolidation test results, it can be concluded that the values of compression index increases and a linear reduction in the void ratio. The coefficient of permeability increases for all soil samples which is considered acceptable for construction of water retention and irrigation projects. It is evident from the test results that the soil sample M10 revealed a better improvement to the consolidation parameters.

6- It is worth mentioning that the best type of replacement from these five soils samples is soil sample M10 due to maximum reduction in the swelling potential.

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Table 1. The physical properties of materials used.

Physical properties	Index properties	Prepared soil	Bentonite	Sand	M	specification
Atterberg limits	Liquid limit,L.L(%)	112	150	NP	39	ASTM D-4318
	Plastic limit,L.L(%)	45	45	NP	22	
	Plasticity index,P.I(%)	67	105	NP	17	
Grain size analysis	% sand (0.06-2)mm	4	0	97.68	0	BS 1377-1975
	% silt (0.002-0.06)mm	24	5	2.32	0	
	% clay (<0.002)mm	72	95		100	
Specific gravity,Gs	-	2.78	2.89	2.63	2.57	ASTM D-854
Compaction test	Max dry density,(KN/m³)	13.4	12.64	15.15	-	ASTM D-1557
	Optimum moisture content,%	36	37	12.5	-	
USCS*		CH	CH	SP	-	ASTM D-2487

Table 2. Chemical properties of materials used.

Materials / Chemical properties	Bentonite	Sand	Metakaolin
SiO_2 %	51.92	55.55	59.62
Fe_2O_3 %	5.45	0.08	1.629
Al_2O_3 %	14.23	0.5	26.63
CaO %	8.24	11.25	0.74
MgO %	2.86	3.9	0.0034
Na_2O %	0.96	1.73	-
K_2O %	0.69		0.43
TiO_2 %	0.8	-	1.875
PH	7.7	7.6	-
SO_3 %	1.3	1.33	-
Gypsum %	2.64	2.86	-
T.S.S %	5.25	0.7	-
O.M %	0.7	1.3	-

Table 3. Results of the grain size distribution tests.

Soil Sample	% Sand	% Silt	%Clay
A	4	24	72
M4	4	26	70
M6	20	14	66
M8	4	36	60
M10	16	34	50
M12	8	18	74

Table 4. Results of the compaction and specific gravity tests.

Soil sample	Compaction characteristics		*Specific gravity*
	O.M.C %	Max. dry unit weight KN/m^3	
A	36.00	13.20	2.78
M4	35.00	13.50	2.78
M6	32.50	13.50	2.77
M8	30.00	13.66	2.76
M10	35.00	13.66	2.73
M12	35.00	13.50	2.72

Table 5. Results of the unconfined compression tests.

Soil Sample	Cu(KPa)
A	94.76
M4	160.73
M6	182.10
M8	283.82
M10	315.00
M12	258.90

Table 5. The results of the free swell and constant volume tests.

Soil Sample	Free Swell Test			Constant Volume Test			Potential Expansion for Constant Volume Test
	Free Swell, %	Expansion Index	Swelling pressure, kpa	Free Swell, %	Expansion Index	Swelling Pressure, KPa	
A	83	825	882	46	458	588	very high
M4	34	340	638	29	285	425	very high
M6	23	234	225	20	195	150	very high
M8	26	257	450	21	215	300	very high
M10	7	72	113	6	60	75	medium
M12	22	220	210	18	184	140	very high

Table 6. The classification of a potentially expansive soil **(ASTM- D 4829 – 03).**

Expansion Index, EI	Potential Expansion
0–20	Very Low
21–50	Low
51–90	Medium
91–130	High
>130	Very High

Table 7 . Results of Consolidation Tests.

Soil samples	e_o	C_C	Cs	$m_{v\ x10^{-4}}$ m^2/KN	$C_{v\ x10^{-8}}$ m^2/sec	$K_{x\ 10^{-8}}$ m/sec
A	1.106	0.290	0.032	2.030	1.949	0.004
M4	1.059	0.269	0.026	2.259	3.920	0.009
M6	1.046	0.167	0.029	1.919	8.187	0.015
M8	1.013	0.155	0.009	2.852	2.187	0.006
M10	0.999	0.116	0.019	3.711	19.125	0.070
M12	0.991	0.119	0.038	1.415	23.173	0.032

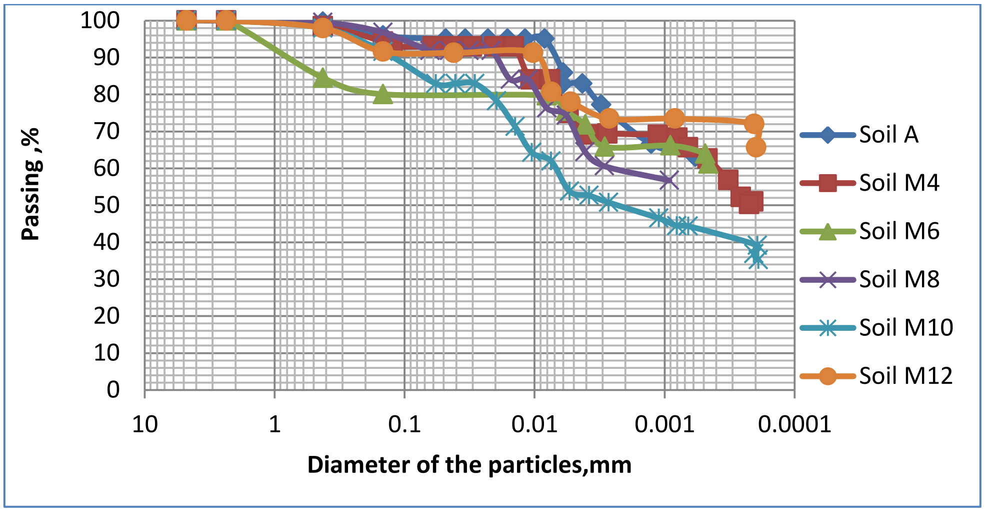


Figure 1. Effect of metakaolin on the grain size distribution.

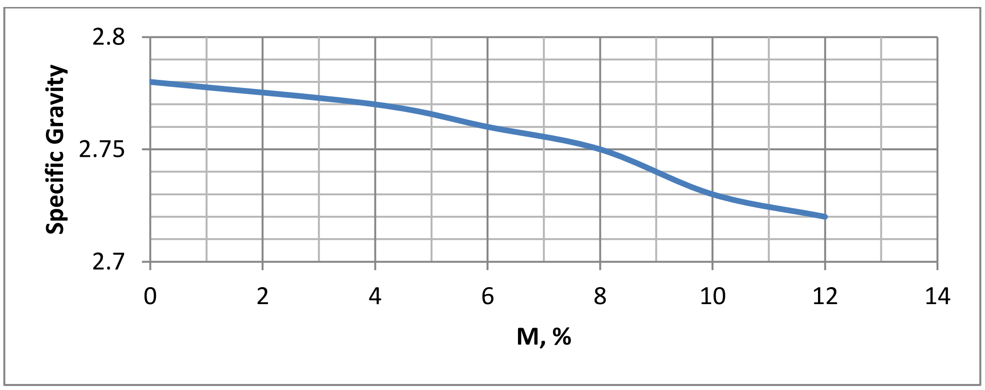


Figure 2. Effect of metakaolin on the specific gravity.

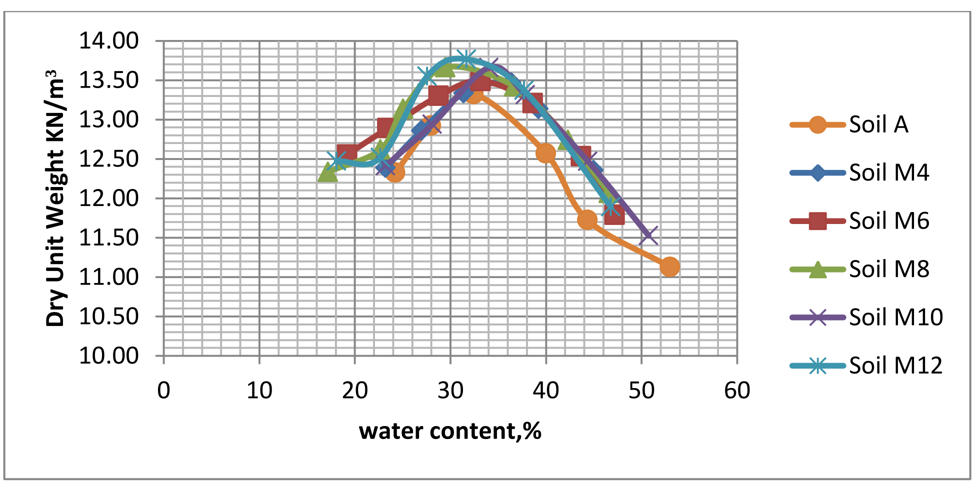


Figure 3 . Effect of metakaolin on the compaction test.

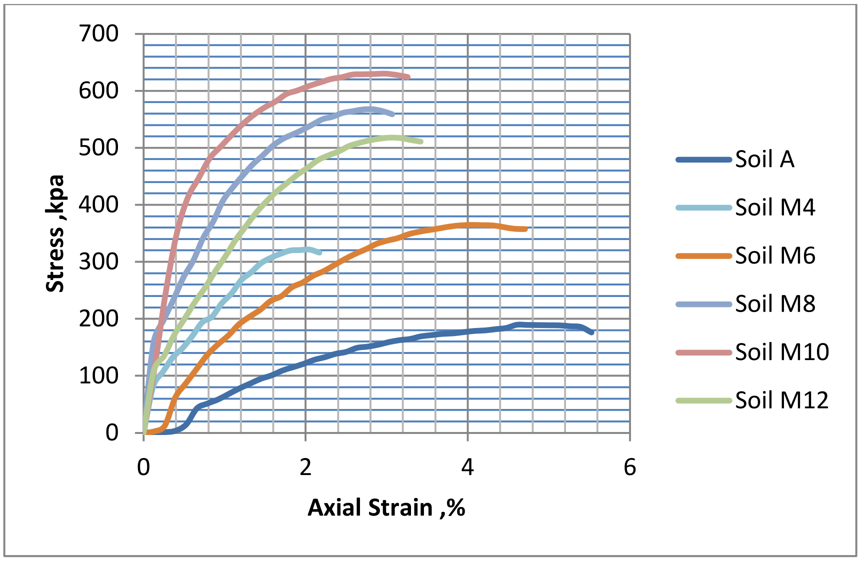


Figure 4. Effect of metakaolin on unconfined compression test results.

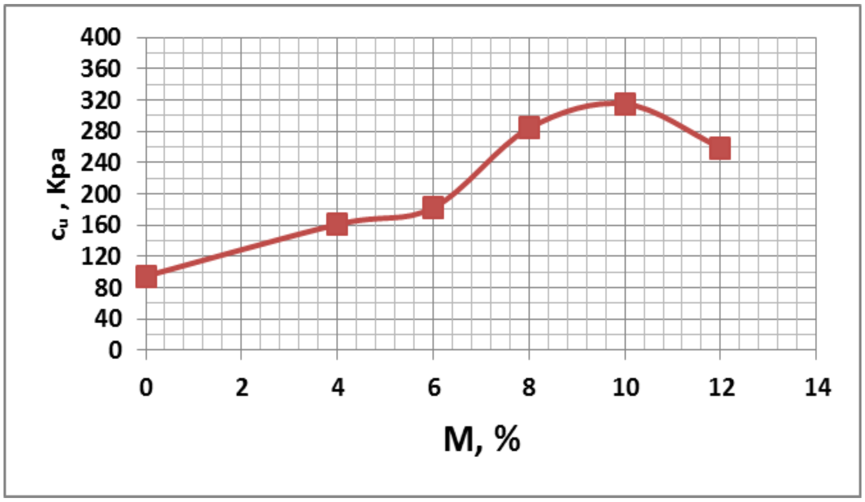


Figure 5. Effect of metakaolin on undrained cohesion.

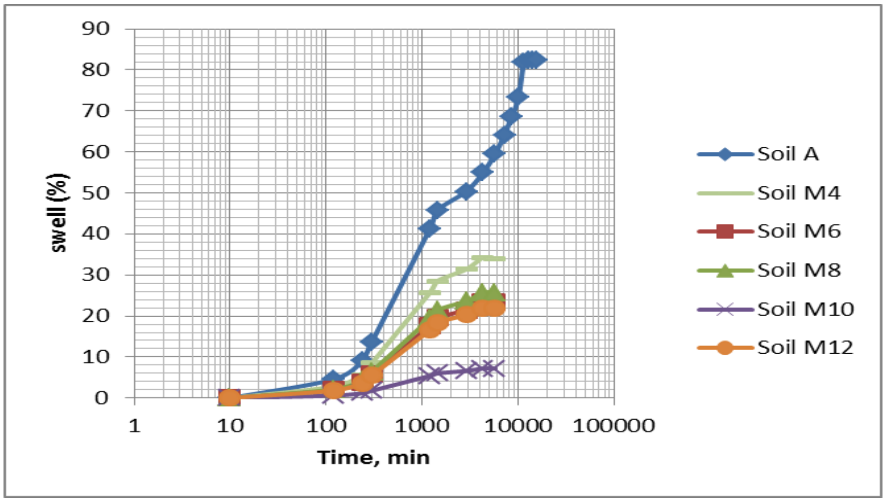


Figure 6 . Time – Percent Swell for the Prepared Soil and Soil Treated with M**.**

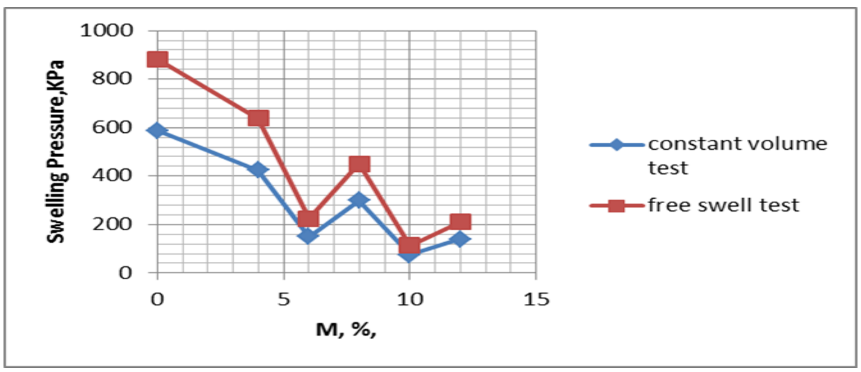


Figure 7. Effect of metakaolin on the swelling pressure.

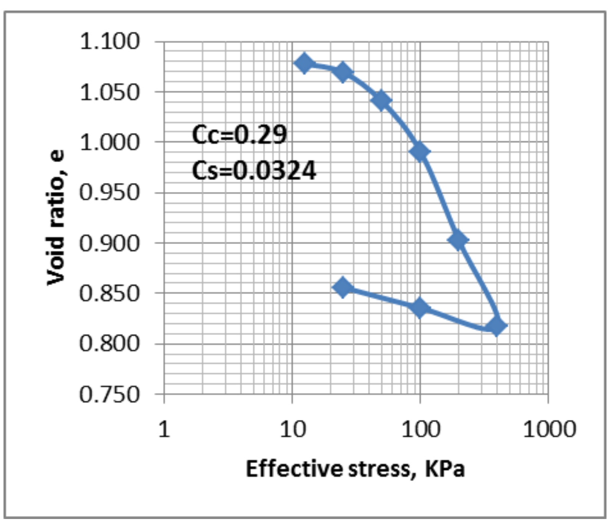
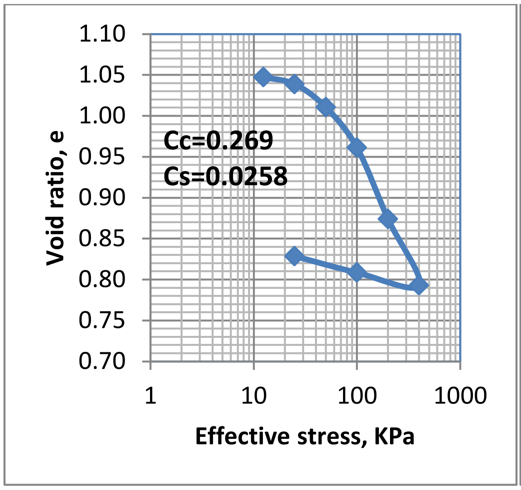
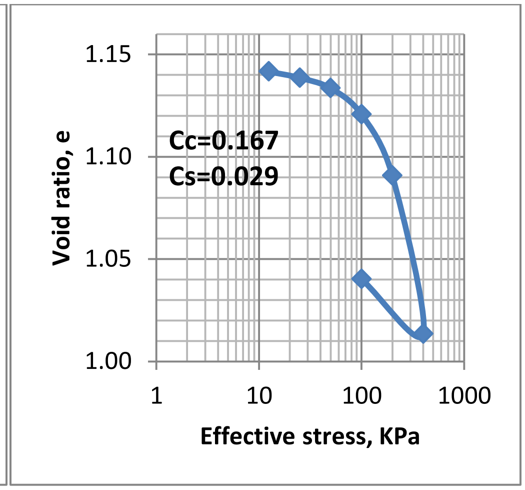


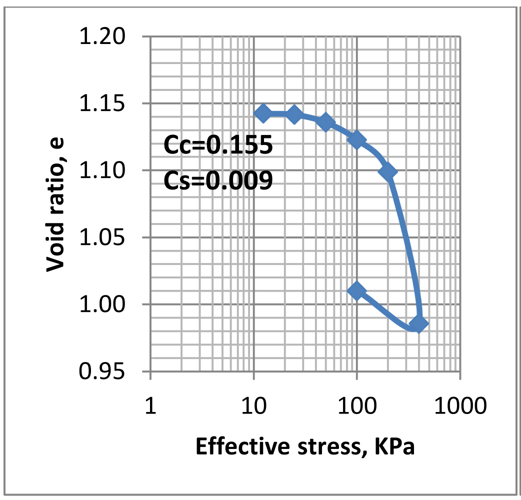
Figure 8. e- $\log\overline{\sigma}_v$ for prepared soil sample A.



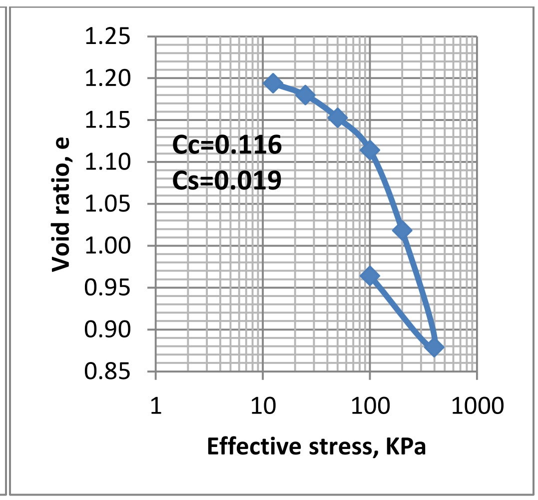
Soil Sample M4



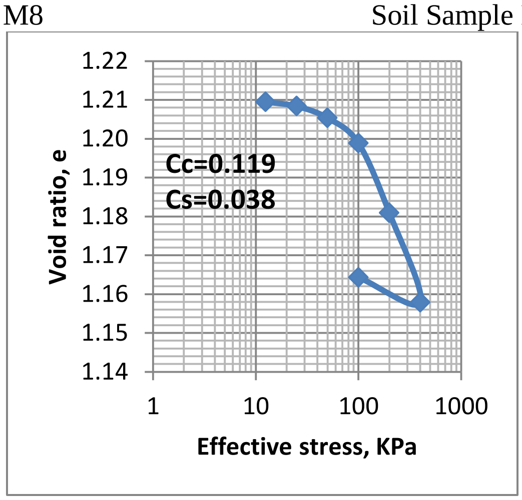
Soil Sample M6



Soil Sample M8



Soil Sample M10



Soil Sample M12

Figure 9 . e- log$\bar{\sigma}_v$ for soils treated with M.

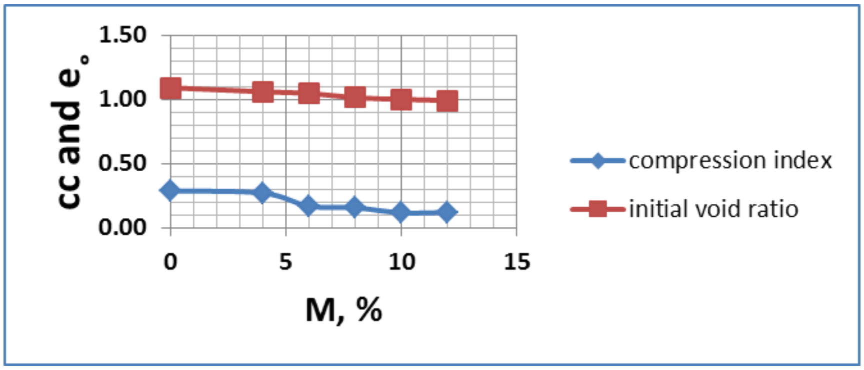


Figure 10. The effect of metakaolin on the consolidation parameters.

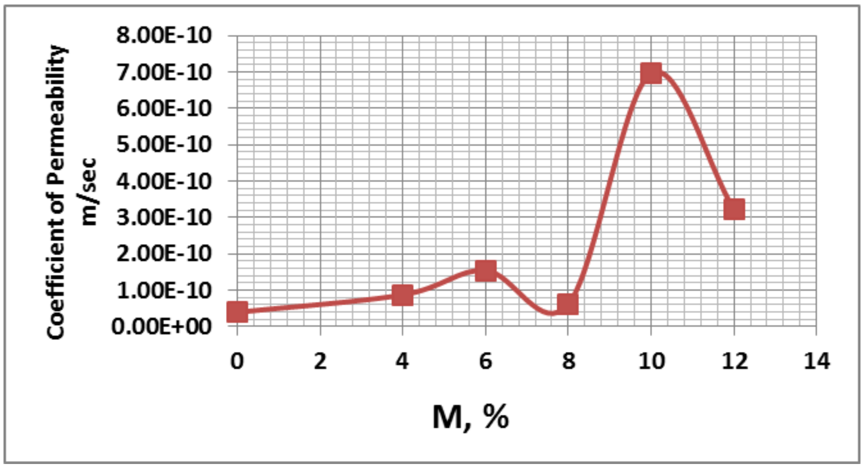


Figure 11. The effect of metakaolin on the coefficient of permeability.

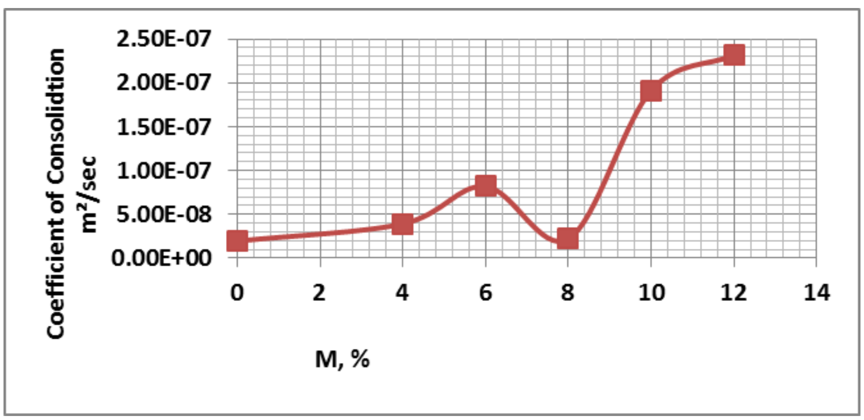


Figure 12. The effect of metakaolin on the coefficient of consolidation.

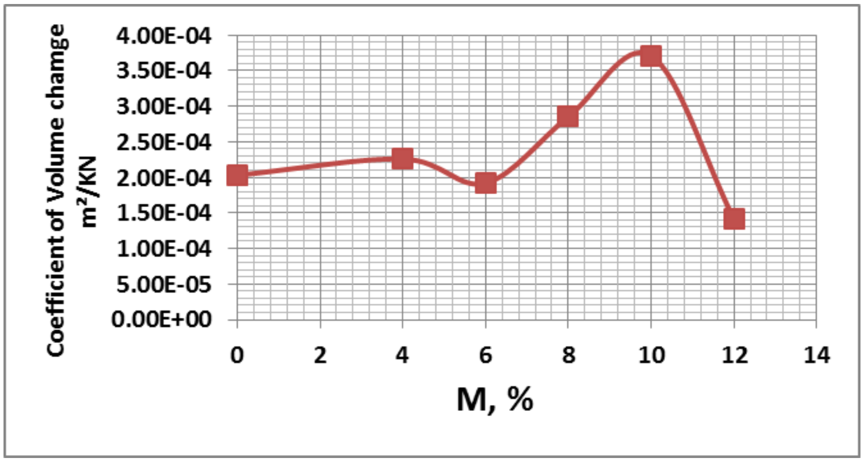


Figure 13. The effect of metakaolin on the coefficient of volume change.