ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 32, No. 2. \ 2024 ISSN: 2616 - 9916

Studying the Effect of Improving the Weak Subgrade by Use Halloysite Nanotubes on the Performance of Pavement Layers Using the Kenpave Program

Itimad Abdulmahdi Mukheef[a], Abdul Rudha I. Ahmed Al – Kremy[b], and Ibtehaj Taha Jawad[c]

[a,b,c]*Department of Civil Engineering, College of Engineering, University of Babylon, Babylon, Iraq.*

itimadmu@gmail.com eng. abdul. rudha @uobabylon. edu. iq
Eng.Ibtehaj.taha@uobabylon.edu.iq

Received:	27/12/2023	Accepted:	5/2/2024	Published:	15/4/2024

Abstract

The highways built on gypseous soil, often experience pavement cracking and early serviceability loss due to volume shifts caused by moisture content changes and traffic loads. This study aims to improve the geotechnical properties of gypseous soil using Halloysite nanotubes. The soil sample obtained from Ayn Al-Tamr in Karbala in southwest Iraq, has an average gypsum content of 30%. This soil is classified as SP according to [4] USCS and A-3 according to AASHTO. The laboratory experiment was done to evaluate the properties of untreated and treated samples using CBR test. The proportions (1.5, 2.5, 5, 7.5)% of Halloysite were added to the soil, and then these samples were subjected to testing. The laboratory data were analyzed using the Kenpave programme. The findings indicated that using Halloysite is a good and effective alternative to treatment the characteristics of gypseous soil by preventing gypsum from dissolving when it comes in contact with water and by enhancing the soil strength by increasing CBR values. The 2.5% Halloysite is the ideal percentage for enhancing the physical properties by filling voids between soil particles. An analytical method were used to study the behavior of gypseous soil that had been treated with 2.5% Halloysite. The data of the soil samples were fed into the Kenpave program. The analysis results used in the program indicate a decrease in strains. The fatigue and rutting of modified soil were low compared with natural soil because Resilient Modulus increased which leads to increasing fatigue and rutting life.

Keywords: Gypseous subgrade, Kenlayer, Halloysite Nanotubes, Stabilizing, Pavement failure.

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بـــابـل للعلـــوم الهندسية
Vol. 32, No. 2. \ 2024 ISSN: 2616 - 9916

1. Introduction

The extent development of a country is dependent upon the quality of its infrastructure, which encompasses structural, transportation, and geotechnical engineering. All of these disciplines are closely related to the study of soil and its engineering characteristics. The path of the road crosses various sites with variable subgrade conditions. In many places, the engineering qualities of soil in their natural form are so unfavorable for engineering building, especially for the construction of pavements, that some method or measure must be utilized for their improvement prior to the construction of the pavement [11]. The nanotechnology has attracted considerable scientific interest due to the new potential uses of particles in nanometer scale. The nano-scale size of particles can result in dramatically improved properties compared to conventional grain size materials of the same chemical composition [18]. Halloysite ($Al_2Si_2O_5(OH)_4.2H_2O$) is a hydrated polymorph of kaolinite with a distinct naturally occurring tubular clay mineral [20]. Through drying or heating, the interlayer water in Halloysite can be irreversibly lost, but the tubular morphology is retained. Halloysite, in its tubular morphology, has a length that varies from 500 nm to over 1.2 µm and diameter typically smaller than 100 nm. There are various kinds of Halloysite nanotubes such as DG-Hal (Dragonite Halloysite), MB-Hal (Matauri Bay Halloysite), and UHP-Hal (Ultra Hallopure Halloysite) [6].

The thickness selection of pavement structure, as well as its design, are greatly influenced by the characteristics of the subgrade, as pavements are specifically engineered to reduce the stresses caused by traffic to the subgrade. To provide enough support for the pavement over its design life, the subgrade may need to be modified mechanically, chemically, or both depending on the underlying soils and project design [13]. The subgrade, sub-base, base, as well as surface layers are all used in the construction of roads. As seen in Figure 1, these components constitute the pavement [14], [7].

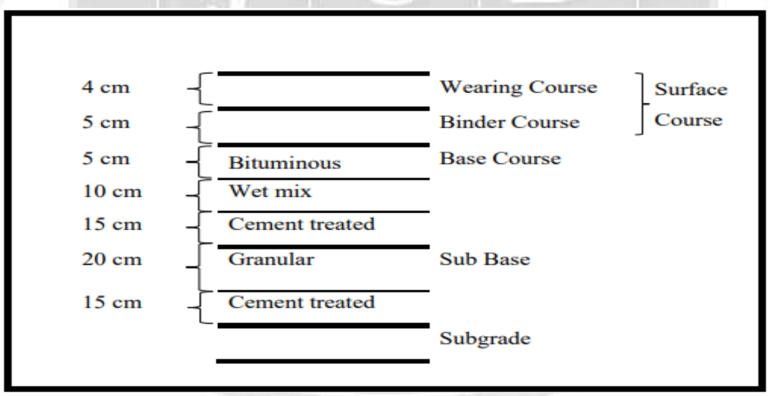

Figure (1): Flexible pavement cross section with the smallest layer thickness [14].

Pavement structural consists of selected materials laid evenly over a prepared soil subgrade, serving as highway pavement or carriageway for road vehicle movement [16], [15]. Flexible pavement fails due to any combination of subgrade, subbase, base and wearing course failures.

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جــــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 32, No. 2. \ 2024 ISSN: 2616 - 9916

In addition to poor design or construction, other factors that contribute to pavement deterioration include the natural damage that develops over time, climatic variations, an increase in multi axle vehicles, and traffic volume [2]. [9] implemented Burmister's theory on a computer to analyze a multilayer system. Huang was the developer of the KENLAYER computer program, designed to deal with the analysis of elastic multilayer systems subjected to circular loading. It should be noted that this program is specifically applicable to flexible pavements lacking joints or rigid layers. Fatigue and rutting cracking are the most common types of failure in flexible pavements. Horizontal strain at the bottom of the asphaltic concrete causes fatigue cracking in flexible pavement. The failure criterion establishes the permissible number of load repetitions in relation to tensile strain, and this correlation can be ascertained by a particular equation. Permanent deformation or the depth of the rut along the wheel path are indicators of rutting in flexible pavements [12]. Figure 2 illustrates the crucial areas for fatigue cracking and rutting.

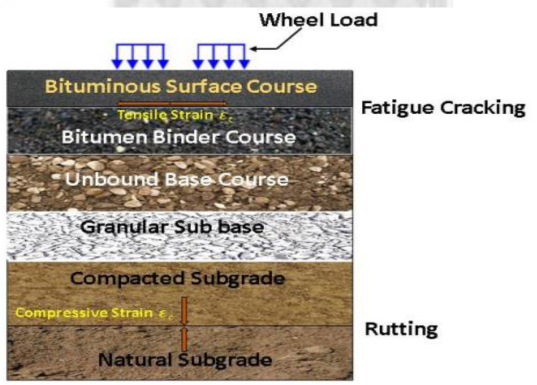

Figure (2): Typical cross section of pavement with critical locations [19].

The major study objectives are to determine and establish a relationship between the Halloysite material and Mr by CBR test. To create a novel framework for flexible pavement design that takes into account the impact of subgrade improvement on pavement layers thickness. To determine the optimal percentage of Halloysite material that can effectively prevent or reduce damages (rutting and fatigue) for subgrade and asphalt layers by using Kenpave program.

2. Sampling of Materials

The materials utilized in this study have been composed of the gypseous soil and Halloysite nanotubes. A soil sample with an average gypsum content of 30% has been collected from Ayn al-Tamr, a city located roughly 67 kilometers west of Karbala province, near Razzaza Lake, in central Iraq. The aforementioned sample is meticulously packaged and thereafter delivered to the soil mechanics laboratory centered at the University of Babylon in Babel province, for investigation.

3. Test Methodology

The soil with a 30% gypsum content has been air dried for several days and finely ground by tamping. The samples are then thoroughly mixed by hand with four different concentrations of

Halloysite nanotubes (1.5, 2.5, 5, and 7.5) to create homogeneously improved soil samples. Both the treated and untreated soil are subjected to CBR test.

3.1 CBR Test

CBR testing is carried out in a laboratory once a soil sample has been compacted to the specified MDD and OWC according to [5]. Both soaked and unsoaked samples have been prepared for CBR testing. In order to compare the potential strength of the treated and untreated soil, laboratory compressed samples were exposed to the CBR test.

3.2 KENPAVE Software Program Requirements

When compared to Microsoft Windows Kenlayer, the Kenpave programmes is seen as more basic. Kenslab and Kenlayer are the primary parts of Kenpave. The Kenslab programme was used for rigid pavement analysis, whereas the Kenlayer programme was used for flexible pavement analysis. Within each level, linearity features were evaluated. Loading states, material features, layer thickness, and material type were the primary inputs for Kenlayer parameters.

3.2.1. Resilient modulus (MR) It is a crucial material feature employed for the characterization of unbound pavement materials. It's a way of measuring the stiffness of various materials under varying environmental conditions including humidity, density, and stress. [8] adopted a widely used equation that was incorporated into the [1] Guide:

$$MR\ (psi) = (1500)(CBR) \qquad (1)$$

It is important to note that this equation only applies to fine-grained materials with soaking CBR values of 10 or less. The model used for estimating MR from CBR for all types of soil according to [16] and [9] is:

$$MR\ (psi) = 2555 \times CBR^{0.64} \qquad (2)$$

General input and output pavement parameters are as shown in Table (1).

Table (1): Input parameters and output obtained.

Input Parameters	
D1, D2 and D3 in inch	Thickness of surface course, base course, subbase
E1,E2 & E3 in psi	Young's modulus of Surface,subbase and Subgrade
µ1, µ2 & µ3	Poisson ratio of Surface , base and Subgrade
Output Obtained	
€t &€c	Tensile and compressive strains

4. Results and Discussion

4.1 Halloysite Nanotubes Effect of on CBR and Mr

CBR (California bearing ratio) is the most frequently used test to determine the bearing capacity of subgrade soils. It determines whether a plunger penetration force of 2.5 or 5 mm is necessary under unsoaked and soaked conditions, respectively. Based on laboratory tests, a number of results were obtained. The calculation of the resilient modulus of the subgrade layer was based on the CBR values obtained for each mixing ratio of Halloysite and soil, as outlined in Table (2). According to Equation (2), thus, this equation utilized in the present study to calculate the resilient modulus (Mr) for the samples with Halloysite nanotubes. The resilient modulus values increase at 2.5% of Halloysite content mixed with soil more than other percentages. Therefore, it is considered the optimum percent of Halloysite nanotubes for soil. The modulus of elasticity decreases as the amount of Halloysite nanotubes increases due to the softness of Halloysite nanotubes, causing the particles to bond together.

Table (2): Resilient modulus values for soils.

Soil	Halloysite%	Unsoaked CBR%	Mr (psi)	Soaked CBR%	Mr (psi)
Ayn AlTamar soil	0	9.85	11046	6.08	8111
	1.5	21.75	18339	19.20	16932
	2.5	31.46	23225	24.37	19723
	5	23.76	19406	20.16	17469
	7.5	11.96	12507	5.37	7492

4.2. Kenpave Software Program Results and Analysis

This program was used to determine the impact of improve subgrade on the road layers after the work of laboratory tests and data collection . The different parameters utilized can be seen in Table (3). The suggested thickness of flexible pavement constructions has been determined by the AASHTO pavement design guidelines.

Table (3): Various factors influencing pavement performance.

Variable	Value
Initial Serviceability, Po	4.5
Terminal Serviceability, Pt	2.5
Reliability Level, R	90%
Overall Standard Deviation, So	0.45
Performance Period (years)	15
ESALs over fifteen years	15000000

4.2.1 Design Thickness

The design values were calculated according to the [1]. The design process was carried out for natural soil and the soil with additive. A layer (asphalt, spacer, soil) for the soil mixed with the contents of the Halloysite nanotubes as in Figure (3). The optimum proportion of Halloysite was taken to design the paving layers. The treated soil exhibit an observable increase in the thickness of the base layer and the substitution of the subbase layer with an enhanced subgrade layer. The reason of this occurrence is that the modulus of elasticity of the subgrade layer experiences an increase that is greater than the modulus of elasticity of the subbase layer, which gives better stability strength to the road base as well as better in the drainage process. Complete asphalt pavements are created by applying layers of bitumen to the subgrade soil. The process of stabilization yields both engineering and economic advantages. The design outcomes pertaining to the pavement layers are presented in Tables (4) and (5).

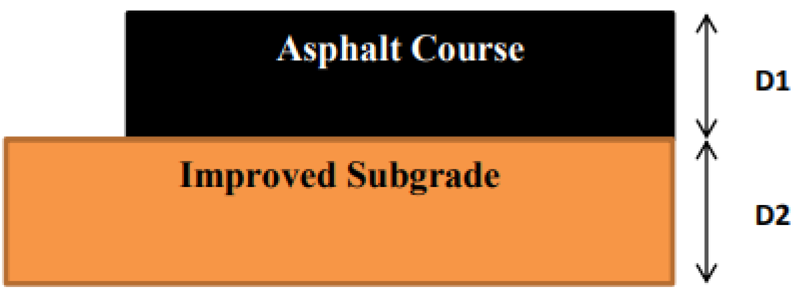

Figure (3): The pavement layers from add Halloysite with soil.

Table (4): Proposed thickness of flexible pavement structures for untreated soil and treated (unsoaked case)

Soils	Layer	Material	Layer Coefficient	Drainage Coefficient	SN	Thickness ,in
Ayn Altamar soil	1	Wearing Course	0.44	1	1.916	2
	2	Binder course	0.38	1		3
	3	Base Course	0.34	1	3.8	6
	4	Subbase	0.11	0.8	4.7	11
Ayn Altamar (Halloysite 2.5%)	1	Binder course	0.38	1	1.05	3
	2	Base Course	0.34	1	3.6	8
	3	Improved Subgrade	0.11	0.8	4.7	13

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــــامعة بـــــــابـل للعلـــــوم الهندسية
Vol. 32, No. 2. \ 2024 ISSN: 2616 - 9916

Table (5): Proposed thickness layers for control and modified soil for Ayn Altamar (Soaked case).

Soils	Layer	Material	Layer Coefficient	Drainage Coefficient	SN	Thickness ,in
Ayn Altamar (Soaked)	1	Wearing Course	0.44	1	1.916	2
	2	Binder course	0.38	1		3
	3	Base Course	0.34	1	3.8	6
	4	Subbase	0.11	0.8	5	14
Ayn Altamar (Halloysite 2.5%)	1	Binder course	0.38	1	1.05	3
	2	Base Course	0.34	1	3.7	8
	3	Improved Subgrade	0.10	0.8	5	16

4.2.2 Determination of Critical Strains

A pair of tires arranged in a dual configuration, with a space between them measuring 13.5 inches (343 millimeters). In the context of dual tires, it is the contact radius measures 4.51 inches (114.5 millimeters). The radii mentioned in this context are derived from an 18-kip (80kN) single axle load, which applies a contact pressure of 70 psi (483 kPa). The Kenlayer software output values of the tensile strain at the bottom of the asphalt layer(s) and the vertical strain at the top of the subgrade were chosen and are presented in Tables (6) ,(7) and (8). The utilization of a 2.5% concentration of Halloysite in the modification of subgrade during the construction of pavement layers has been found to result in a reduction of tensile strain at the bottom of the surface course. Additionally, this modification leads to a decrease in compressive strain and displacement at the top of the subgrade. These effects are observed with an increase in the resilient modulus (Mr) for improved soil.

Table (6): Vertical stress and tensile strain of asphalt concrete layers for untreated and treated Ayn Al-Tamar gypseous soil (un soaked case).

Soil	Asphalt layers	Vertical Stress (kPa)	Tensile Strain
Ayn Altamar soil (unsoaked)	Wearing course	63.716	3.305E-05
	Binder course	37.758	-2.201E-05
	Base course	11.899	-1.205E-04
Ayn Altamar soil (2.5% Halloysite)	Binder course	58.833	2.448E-05
	Base course	5.486	-1.099E-04

Table (7): Vertical stress and tensile strain of asphalt concrete layers for untreated and treated Ayn Al-Tamar gypseous soil (Soaked case).

Soil	Asphalt layers	Vertical Stress (kPa)	Tensile Strain
Ayn Altamar soil (soaked)	Wearing course	63.700	3.596E-05
	Binder course	37.688	-2.109E-05
	Base course	4.428	-1.239E-04
Ayn Altamar soil (2.5% Halloysite)	Binder course	58.971	2.643E-05
	Base course	4.948	-1.073E-04

Table (8): Pavement Responses for untreated and treated gypseous subgrade.

Soil	Top Subgrade	
	Compressive Strain	Displacement(in)
Ayn Altamar (unsoaked)	1.854E-04	0.01037
Ayn Altamar (2.5%Halloysite)	1.636E-04	0.00970
Ayn Altamar (soaked)	1.856E-04	0.01216
Ayn Altamar (2.5%Halloysite)	1.601E-04	0.01124

4.2.3 Failure of Pavement

The correlation between fatigue failure of asphalt concrete and tensile strain εt, namely at the lower portion of the asphalt layer, is expressed in terms of the number of repetitions, as recommended by the Asphalt Institute, in the following manner:

$$N_f = 0.0796\,(\varepsilon)^{-3.291}\,(E)^{-0.854} \quad \text{………… [3, eq. (4)].}$$

Where:

N_f : Number of load repetitions to prevent fatigue cracking

Vol. 32, No. 2. \ 2024 ISSN: 2616 - 9916

εt ; Tensile strain at the bottom of asphalt layer.

E ; Elastic modulus of asphalt layer.

The relationship between rutting failure and compressive strain at the top of subgrade is represented by the number of load applications as suggested by Asphalt Institute in the following form:

$N_r = 1.365 \times 10^{-9} (\varepsilon c)^{-4.477}$ ….. [3, eq. (5)].

Where:

N_r :Number of load repetitions to limit Rutting.

εc :Vertical compressive strain at the top of Subgrade.

4.2.3.1 Effect of Halloysite on Fatigue Life

Table (9) demonstrates the patterns of the estimated number of load repetitions to failure (fatigue life) for the base layer, untreated soil, and treated soil (unsoaked and soaked case). The results of this study indicate a positive correlation between the resilient modulus and the fatigue life. Table 9 illustrates the data according to the number of repeats until failure increased from 10.33×10^6 to 13.99×10^6 for base layer in unsoaked case for Ayn Al-Tamar soil without and with 2.5%Halloysite respectively. While the number of repeats to failure of modified layers at soaked case with Halloysite additive were increase by $15.14\text{x}10^6$ compare with control soil at $9.43\text{x}10^6$ for Ayn Al-Tamar soil.

Table (9): The data about the number of repeats to failure (Nf) for both the Control and Modified Layers.

Soil	Horizontal Strain, Base Layer	N_f Base Layer
Ayn Altamar (unsoaked)	**-1.205E-04**	**10332977**
Ayn Altamar (2.5%Halloysite)	**-1.099E-04**	**13990410**
Ayn Altamar (soaked)	**-1.239E-04**	**9428794**
Ayn Altamar (2.5%Halloysite)	**-1.073E-04**	**15137360**

4.2.3.2 Effect of Halloysite on Rutting Life

The number of repeats caused by rutting is correlated with the level of compressive strain experienced above the subgrade. Table (10) shows the rutting life increased as a result of resilient of modulus (Mr). This table can be seen the number of repeats to failure ,increased from 69.6×10^6 to 121.6×10^6 for Ayn AlTamar (unsoaked) without and with Halloysite. While the number of repetitions to failure Nr increased from 69.3×10^6 to 134.3×10^6 for Ayn Al-Tamar (soaked) without and with Halloysite.

Table (10): The data about the number of repeats to failure (Nr) for both the Control and Modified Layers.

Soils	Vertical Strain, Top Subgrade	N_r Subgrade Layer
Ayn Altamar (unsoaked)	1.854E-04	69631442
Ayn Altamar (2.5%Halloysite)	1.636E-04	121905926
Ayn Altamar (soaked)	1.856E-04	69296144
Ayn Altamar (2.5%Halloysite)	1.601E-04	134298962

5. Conclusions

Based on laboratory experimentation and the utilization of the KENPAVE software program, the present study arrived at the following findings:

1.The maximum value of unsoaked and soaked (CBR) was obtained at (2.5%) of Halloysite content.

2.The resilience modulus of Ayn Al Tamar soil was found to be optimal under unsoaked and soaked conditions, with the highest values achieved after incorporating 2.5% Halloysite nanotubes.

3.The thickness of the pavement component above the subgrade, particularly the base layer, increases as the Mr (modulus of resilience) increases. However, the thickness of the binder layer remains constant in the absence of a wearing layer. Additionally, the subbase layer was substituted with an improved subgrade.

4.The vertical strain, horizontal strain, and displacement for bottom asphalt and top subgrade respectively, show a reduction as the value of Mr increases.

5.The fatigue and rutting of modified mixtures were low compared with natural soil because Mr increased that leads to reduce fatigue and rutting.

6.A Halloysite content of 2.5% is considered the most economical for improving the subgrade soil layer.

References

[1] AASHTO (1993) ―AASHTO Guide for Design of Pavement Structures‖, American Association of State Highway and Transportation Officials. 444 N. Capitol Street N. W., Suite 249. Washington, D.C. 20001.

[2] Ali, M. *et al.* (2021) 'Evaluation of Flexible Pavement Distresses-A Case Study of Northern Bypass Peshawar, Pakistan', in *2021 Third International Sustainability and Resilience Conference: Climate Change*. IEEE, pp. 399–404.

[3] Asphalt institute (1982)." Research and development of asphalt institute thickness design manual.9th Ed. Research report 82-2,the asphalt institute.

[4] ASTM, D. (2007) 'Standard Test Method for Particle-Size Analysis of Soils (D422-63)', *ASTM International, West Conshohocken, PA. doi*, 10.

[5] ASTM D4429 (1883) 'Standard Test Method for CBR (California Bearing Ratio) of Soils in Place 1', (50 mm), pp. 4–7.

[6] Emmanuel, E. *et al.* (2019) 'Stabilization of a soft marine clay using halloysite nanotubes: A multi-scale approach', *Applied Clay Science*, 173, pp. 65–78.

[7] Gör, M. and Aksoy, H.S. (2016) 'The Effect of Natural Resin Addition on Strength Parameters of Railway Embankment', (October).

[8] Heukelom, W. and Klomp, A. (1962) 'Dynamic testing as a means of controlling pavements during and after construction', in *International Conference on the Structural Design of Asphalt PavementsUniversity of Michigan, Ann Arbor*.

[9] Huang, Y.H., (2004)"Pavement analysis and design", ed. P.H. 2nd Edition, Englewood Cliffs, New Jersey, USA

[10] Jerod Gross, Snyder & Associates, I.W.A. (2020) 'Cement-Stabilized Subgrade Soils'.

[11] Khan, B., Siraj, A. and Khattak, R.A. (2012) 'Pavement subgrade improvement by lime', *Advanced Materials Research*, 587, pp. 93–96. Available at: https://doi.org/10.4028/www.scientific.net/AMR.587.93.

[12] Kumar, H. (2013) 'Analysis of Flexible Pavement Using', 136119, pp. 1–40.

[13] Kuttah, D. and Sato, K. (2015) 'Review on the effect of gypsum content on soil behavior', *Transportation Geotechnics*, 4, pp. 28–37. Available at: https://doi.org/10.1016/j.trgeo.2015.06.003.

[14] Mamat, R.C. (2013) 'Engineering properties of Batu Pahat soft clay stabilized with lime, cement and bentonite for subgrade in road construction', *Universiti Tun Hussein Onn Malaysia*, March(September), pp. 1–45. Available at: https://doi.org/10.13140/RG.2.2.32176.40968.

[15] Muhammad, H. and Hamza, A. (2020) 'Tire Pressure Effects on The Performance of Locally Flexible Pavements with Aided of KENPAVE Program'.

[16] Naveen, N. *et al.* (2018) 'Improvement of Pavement Subgrade Soil By Compaction Techniques', *International Journal of Creative Research Thoughts*, 6(1), pp. 1393–1400.

[17] Rabab'ah, S. *et al.* (2021) 'Effect of glass fiber on the properties of expansive soil and its utilization as subgrade reinforcement in pavement applications', *Case Studies in Construction Materials*, 14. Available at: https://doi.org/10.1016/j.cscm.2020.e00485.
[18] Salemi, N. and Behfarnia, K. (2013) 'Effect of nano-particles on durability of fiber-reinforced concrete pavement', *Construction and Building Materials*, 48, pp. 934–941.

[19] Srikanth M R (2015) 'Study on Analysis of Flexible Pavement using Finite Element based Software Tool', *International Journal of Engineering Research and*, V4(09), pp. 771–774. Available at: https://doi.org/10.17577/ijertv4is090865.
[20] Yuan, P. *et al.* (2008) 'Functionalization of halloysite clay nanotubes by grafting with γ-aminopropyltriethoxysilane', *The Journal of Physical Chemistry C*, 112(40), pp. 15742–15751.

دراسة تأثير تحسين الطبقة التحتية الضعيفة بواسطة استخدام انابيب الهالوسايت النانوية على أداء طبقات Kenpave الرصف باستخدام برنامج

اعتماد عبد المهدي مخيف عبد الرضا ابراهيم احمد الكريمي ابتهاج طه جواد

قسم الهندسة المدنية/كلية الهندسة/جامعة بابل

المستخلص

غالبًا ما تواجه الطرق السريعة التي تم بناؤها على التربة الجبسية تشققات في الرصيف وفقدان مبكر للخدمة بسبب تغيرات الحجم الناتجة عن تغيرات محتوى الرطوبة والأحمال المرورية. تهدف هذه الدراسة إلى تحسين الخواص الجيوتقنية للتربة الجبسية باستخدام أنابيب الهالوسايت النانوية. عينة التربة التي تم الحصول عليها من عين التمر في كربلاء جنوب غرب العراق تحتوي على متوسط محتوى الجبس بنسبة 30%. تم تصنيف هذه التربة على أنها SP وفقًا لـ USCS وA-3 وفقًا لـ AASHTO. أجريت التجربة المختبرية لتقييم خواص العينات غير المعالجة والمعالجة باستخدام اختبار CBR. تمت إضافة أربع نسب مختلفة من الهالوسايت إلى عينات التربة لتكون بمثابة مادة رابطة. وكانت هذه النسب 1.5%، 2.5%، 5%، 7.5%. وبعد ذلك تم إخضاع عينات التربة للاختبار. تم تحليل البيانات المختبرية بشكل أكبر باستخدام برنامج Kenpave. أشارت النتائج إلى أن استخدام الهالوسايت يعد بديلاً جيداً وفعالاً لمعالجة خصائص الترب الجبسية من خلال منع ذوبان الجبس عند ملامسته للماء ومن خلال تعزيز قوة التربة وثباتها من خلال زيادة قيم CBR. كما يشار إلى أن نسبة الهالوسايت 2.5% هي النسبة المثالية لتعزيز الخواص الفيزيائية والقوة لهذه التربة من خلال ملء الفراغات بين جزيئات التربة. تم استخدام الطريقة التحليلية لدراسة سلوك الترب الجبسية المعاملة بمادة الهالوسايت 2.5%. تم إدخال بيانات عينات التربة إلى برنامج Kenpave لحساب إجهاد الشد في أسفل الطبقة الإسفلتية وإجهاد الانضغاط في أعلى طبقة الأساس. وتشير نتائج تحليل التربة المستخدمة في البرنامج إلى انخفاض هذه الانفعالات. كان اجهاد الكلل والتخدد في الترب المعدلة منخفضا مقارنة بالترب الطبيعية بسبب زيادة معامل المرونة مما يؤدي إلى زيادة عمر الكلل و التخدد.

الكلمات الدالة: الطبقة السفلية الجبسية، Kenlayer، أنابيب الهالوسايت النانوية، التثبيت، فشل التبليط.