



Chemical Stabilization of Sustainable Subbase by the Addition of Cement and Cement Kiln Dust

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Abstract

Soil stabilization has obtained significant attention to overcome challenges associated with weak soils. These efforts focus on improving soil properties, achieving economic benefits, and reducing environmental impacts. This study aims to evaluate the efficiency of using waste or by-product materials to improve the characteristics of subbase layers through chemical stabilization, with a particular focus on reducing construction costs and enhancing structural performance. The methodology included the use of the Cement Kiln Dust (CKD) and ordinary Portland cement (OPC) as chemical stabilizers for two types of subbase materials (Type B and Type C). The percentage of stabilizers for each mixture was 7% by dry weight of subbase; three stabilizer combinations were used: 100% OPC, 100% CKD, and a 50/50 blend of OPC and CKD. Laboratory tests were conducted, including sieve analysis, modified Proctor, California Bearing Ratio, Atterberg limits, and unconfined compressive strength tests to assess the properties of the stabilized soils. The results showed that a mixture of OPC and CKD in equal proportions significantly enhanced the compressive strength of the subbase materials, performance was improved and the required thickness of pavement layers can be decreased, leading to a significant decrease in overall construction cost.

Keywords: California Bearing Ratio (CBR); pavement materials; unconfined, compressive strength; soil stabilizer; and supplementary cementitious material.

1. Introduction

Soil stabilization refers to numerous techniques intended to enhance the stability, strength, and general engineering performance of soil, particularly when the existing soil conditions are insufficient for construction purposes. The principal objectives of soil stabilization comprise increasing shear strength, enhancing bearing capacity, and minimizing shrink-swell behaviour to prevent undesirable engineering outcomes. Stabilization can be achieved through mechanical means such as compaction, pre-consolidation, and drainage without the use of additives. Otherwise, chemical stabilization methods include the addition of enhancement materials such as lime, lime-pozzolana, or cement to promote soil properties. Moreover, geotextiles or reinforcing strips are employed to additionally improve the soil's suitability for the intended construction application [1].

Cement (Ordinary Portland Cement, OPC) is among the most utilized additives for soil stabilization as a result of its effectiveness in enhancing soil strength and durability. Several studies have extensively inspected the behaviour of cement stabilized soils. While cement significantly increases stiffness, it also tends to induce brittleness in the treated soil. This characteristic can be harmful under dynamic loading conditions such as those experienced in pavement systems where flexibility and resistance to cracking are critical [2]. Numerous studies have examined the possibility of replacing conventional stabilizers as cement and lime, with industrial by-products in soil stabilization. These alternative materials have demonstrated promising performance as sustainable stabilizing agents. Examples comprise lime sludge and hypo sludge—by-products generated from paper and sugar milling industries, in addition to rice husk ash and fly ash, which are residues from rice milling and combustion processes [3].

Also, fly ash is a pozzolanic material that can be used in soil stabilization. It is the most promising waste material when it comes to the wide range of applications in construction. It is obtained by burning coal in thermal power plants to produce electricity [4]. Besides that, Cement kiln dust (CKD) is considered by by-product material from the cement manufacture that is fine-grained particulate dust collected from electrostatic precipitators during clinker production under high temperatures [5]. The generated CKD is estimated to be 15–20% of the produced cement. That means that hundreds of millions of metric tons

of CKD can be generated annually worldwide, synchronously with cement production. If they are not recycled in the cement industry or even used in other industrial applications, these large quantities are dumped into the landfills and negatively impact the air and surface, and groundwater. To overcome this problem, researchers have explored effective ways to utilize CKD for various applications, for example, in soil improvement [6]. According to AKINBULUMA [7], the addition of CKD resulted in a reduction in the plasticity index (PI) and maximum dry density of the studied soil. Also, a significant decrease in the swell potential was observed following CKD treatment. The incorporation of 5% CKD by dry weight notably improved the soil's engineering properties. The unconfined compressive strength increased by 43% after one day and 238% after 90 days of curing. Additionally, reductions in plasticity index and permeability were observed. The treated soil also demonstrated enhanced durability under both freeze–thaw and wetting–drying conditions, with improvements correlating to higher CKD content [6].

In this study, local CKD, a by-product generated during the production of cement, has been utilized as a stabilizing agent for the subbase layer of pavement structures. The primary objective is to evaluate the effectiveness of CKD in enhancing the engineering properties of subbase material.

2. Materials

2.1 Subbase

Generally, subbase material consists of a combination of sand, gravel, crushed stone and filler material. The subbase material was supplied from Karbala quarries, then was dried and separated to ensure its consistency with the specified particle size according to General Specifications for Roads and Bridges, R6 [8], as can be seen in Figure 1 and Table 1. Then, the materials are recombined according to the gradation percentages specified by the mentioned specification. Two types of subbase materials were used as type B and C. These classes are part of the materials used in Iraq as a subbase material. The selection of these two types is due to the following:

- Class B is the most common subbase class used widely as an unbound pavement layer.

- Class C is the subbase class used widely in road shoulder or filling materials with lower load-bearing requirements.



Figure 1: Subbase materials used in the experimental program

Table 1: shows the gradation for subbase types B and C.

Sieve No.	Sieve Diameter	Passing% of Type B	Passing% according to GSRB	Passing% of Type C	Passing% according to GSRB
75	3 in	-----	-----	-----	-----
50	2 in	100	100	-----	-----
25	1 in	85	75-95	100	100
9.5	3/8 in	58	40-75	68	50-85
4.75	No.4	45	30-60	50	35-65
2.36	No.8	34	21-47	39	26-52
0.3	No.50	21	14-28	21	14-28
0.075	No.200	10	5-15	10	5-15

2.2 Filler Material

In this study, two types of fillers were used: OPC and CKD. According to General Specifications for Roads and Bridges, R6 [8], the use of either ordinary Portland cement or sulphate-resistant cement is permitted, depending on the outcomes of laboratory evaluations. The Portland cement used conforms to one of the following standards: British Standard for Ordinary Portland Cement [9], or AASHTO [10] Type V for ordinary Portland cement. This cement was sourced from the Karbala Plant, and its physical and chemical properties are presented in Table 2.

The CKD used in the experimental program was obtained from a pre-calciner production process at the Karbala cement Plant. Its appearance is shown in Figure 2, and its physical and chemical properties are presented in Table 3.



Figure 2: Cement Kiln Dust used in the stud

Table 2: The properties of cement used

	Result	Iraqi Specification
Initial setting time(min.)	126	Not less than 45 min.
Final setting time(min.)	327	No more than 600 min.
Compressive strength (N/mm²)		
Age 3 days	21.3	Not less than 15 (N/mm ²)
Age 7 days	28.7	Not less than 23(N/mm ²)
Chemical Test		
Sio₂%	21.3	-----
Cao%	61	-----
Al₂O₃%	3.9	-----
Fe₂O₃%	4.9	-----
Mgo%	1.8	No more than 5%
So₃%	2.0	No more than 2.5%
Fe₂O₃/Al₂O₃ (%)	0.84	-----
Free Lime (%)	0.892	-----
Loss of Fire	3.7	No more than 4%
Factor of saturation	0.88	0.66-1.02
Material unable for soluble	1	No more than 1.5%
C₃S%	48.29	-----
C₂S%	26.35	-----
C₃A%	2.12	No more than 3.5%
C₄AF%	14.3	-----

Table 3: Properties of CKD

Chemical Analysis	Result
SiO₂%	17.62
Al₂O₃%	4.9
Fe₂O₃%	2.58
CaO%	62.09
MgO%	1.93
Na₂O%	0.56
K₂O%	3.76
So₃%	5.79
Moisture Content%	0.07
Loss of Ignition%	4.94
Available Lime index%	33.7
CL%	-----
PH	12.65
Physical Analysis	Result
Retained on No.325 sieve %	16.9
Gs	2.95
Unit weight(lb/ft³)	38.0
Volatiles%	0.65
Smaller than 0.075 mm %	65

3. Experimental works

3.1 Methodology of work

The stabilization procedure included the following steps for each mix and subbase type:

1. Dry Mixing: The required quantity of binder (OPC, CKD, or their combination) was thoroughly mixed with air-dried subbase using a mechanical mixer to ensure uniform distribution.
2. Moisture Conditioning: Water was added gradually to bring the mix to its Optimum Moisture Content (OMC), previously determined by the Modified Proctor test.
3. Compaction: The moist stabilized mix was compacted in standard cubes to the maximum dry density value previously achieved [11]
4. Curing: The compacted specimens were sealed in plastic wraps and cured at room temperature ($23 \pm 2^{\circ}\text{C}$) for 7 and 28 days in a humidity-controlled environment.
5. Testing: After the curing periods, specimens were subjected to Unconfined Compressive Strength (UCS).
6. This method provides a comparison between the mechanical performance of the three stabilizing systems across both subbase classes (Type B and Type C), as well as against the untreated soil condition.

Table 4 shows the percentages of stabilizers for each mixture and the test performed. Each mix was added at a fixed stabilizer content of 7% by dry weight of subbase, in accordance with the mid-range limit specified by the Iraqi Roads and Bridges Specification [8] for fine filler materials in subbase layers. This percentage was chosen to reflect a standard stabilization practice and ensure consistency across all treatments.

Table 4: stabiliser percentages and the test performed.

Subbase Type	Stabilizer Type and its percent%	Curing Periods(day)	Tests performed
B , C	100% OPC	7 and 28	UCS Test
	100% CKD	7 and 28	
	50% OPC + 50%CKD	7 and 28	

3.2 Laboratory Testing

A set of laboratory tests was conducted to evaluate the physical and mechanical properties of untreated and stabilized subbase materials. Standard procedures were followed to assess compaction behaviour, strength, plasticity, and bearing capacity. These tests provided a basis for comparing the performance of different stabilizer combinations.

3.2.1 Sieve analysis test

One of the earliest methods for determining particle size distribution is sieve analysis, which is also one of the few techniques that can be applied to fractionation. In the study used electrical vibration was used to analyse the particle size of type B&C according to General Specifications for Roads and Bridges, R6 [8]

3.2.2 Modified proctor compaction test

This test covers laboratory compaction techniques that is used in order to determine the compaction curve, which shows the relationship between soil's dry unit weight and water content, then determine the maximum dry density and optimum moisture content for each type of subbase according to the requirements specified in [11] as shown in Table 5.

Table 5: Requirements of the modified proctor compaction test.

Description	value
Diameter of Mould, cm	15.13
Height of Mould, cm	11.67
Volume of Mould, cm ³	2098.16
Weight of hammer, N	44.5N
Height of hammer drop, cm	45.72cm
Number of blows per layer	25
No. of layers	5
Test on soil fraction passing sieve	No.3/4

3.2.3 California Bearing Ratio Test

The CBR (California Bearing Ratio) of pavement subgrade, subbase, and base course materials from laboratory compacted specimens is determined in accordance with [12]. The test assesses cohesive materials' strength when their maximum particle sizes are less than 3/4 in. (19 mm).

3.2.4 Atterberg Limits

In accordance with ASTM D4318 [13], the Atterberg Limits test is carried out to ascertain the plastic and liquid limitations of a fine-grained soil that passes sieve No. 40.

3.2.5 Unconfined Compressive Strength

The unconfined compressive strength of the stabilized subbase specimens was determined using a standard compression testing machine in accordance with applicable procedures. Figure 3 shows the preparation and testing procedures for unconfined compressive strength. Each compacted cubic specimen was placed vertically between the loading plates, and a monotonic compressive load was applied at a constant rate until failure occurred. The maximum load (P_{max}) was recorded automatically by the testing apparatus at the moment the specimen could no longer sustain additional loading. The compressive strength (σ) was then calculated using the following equation:

$$\sigma = \frac{P_{max}}{A} \quad (1)$$

Where:

$P_{\max}$ = is the peak load (in N),

A = is the original cross-sectional area of the specimen (in mm²).



Figure 3: Preparation and Testing Procedures for unconfined compressive strength.

4. Experimental Results and Discussion

4.1 Laboratory Evaluation of Subbase

The AASHTO classification system for highway subgrade materials, as shown in Table 6 [14], was used to evaluate the subbase types B and C. Based on the plasticity limits (P.L. and L.L.) and gradation results presented in Tables 7, the soil was classified as Group A-2.

Table 6: AASHTO classification of highway subgrade material.

General Classification	Granular Materials (35% or less passing #200)							Silt-Clay Materials (More than 35% passing #200)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7 A-7-5 A-7-6
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				
Sieve Analysis Percent Passing :											
#10	0-50										
#40	0-30	0-50	51-100								
#200	0-15	0-25	0-10	0-35	0-35	0-35	0-35	36-100	36-100	36-100	36-100

Characteristics of fraction passing #40 :										
Liquid Limit			0-40	41	0-40	41	0-40	41	0-40	41
Plasticity Index	0-6	N.P	0-10	0-10	11	11	0-10	0-10	11	11
Group Index	0	0	0		0-4		0-8	0-12	0-16	0-20
Usual Types of Significant Constituent Materials	Stone fragments Gravel and Sand	Fine Sand	Silty or Clayey Gravel and Sand				Silty soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good				Fair to Poor					

Table 7: Results of Type B and C tests and their designation of ASTM.

Property	ASTM designation	Sub base type (B)	Sub base type (C)
Max dry density, gm/cm ³	[11]	2.100	2.070
Optimum moisture content, %	[15]	8.5%	9.0%
Liquid limit, %	[13]	43%	43%
Plastic Limit, %	[13]	21%	21%
Plasticity index %	[13]	22%	22%
CBR, %	[12]	36%	30%

The compressive strength at the age of 7 days was used to calculate the thickness of the subbase layer in case the subbase treatment with ordinary Portland cement (OPC), and replace the OPC partially and/or totally with local cement kiln dust (waste materials). The CKD percentage is dependent on the type of subbase, and it was 7% according to ACI, as shown in Table 8. Figures 4 and 5 show the results of compressive strength testing of types B and C, respectively.

Table 8: Typical cement requirements.

AASHTO Soil Classification	ASTM Soil Classification	Typical Range of Cement Requirements Percent by Weight	Typical Cement content for moisture density test (ASTM D 558) Percent by Weight	Typical Cement Contents for Durability Test (ASTM D 559 and D506) Percent by Weight
A-1-a	GW,GP,GM,SW,SP,SM	3-5	5	3-5-7
A-1-b	GM,GP,SM,SP	5-8	6	4-6-8
A-2	GM,GC,SM,SC	5-9	7	5-7-9
A-3	SP	7-11	9	7-9-11

A-4	CL,ML	7-12	10	8-10-12
A-5	ML,MH,CH	8-13	10	8-10-12
A-6	CL,CH	9-15	12	10-12-14
A-7	MH,CH	10-16	13	11-13-15

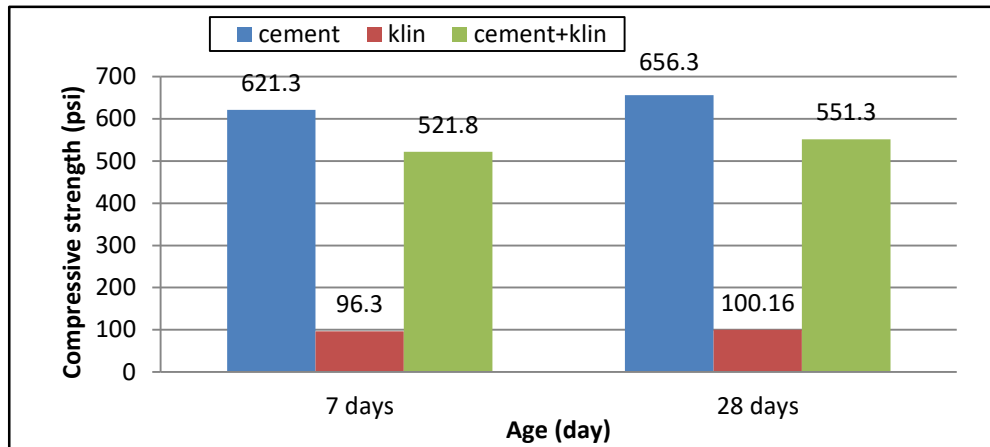


Figure 4: Results of testing the compressive strength of type B

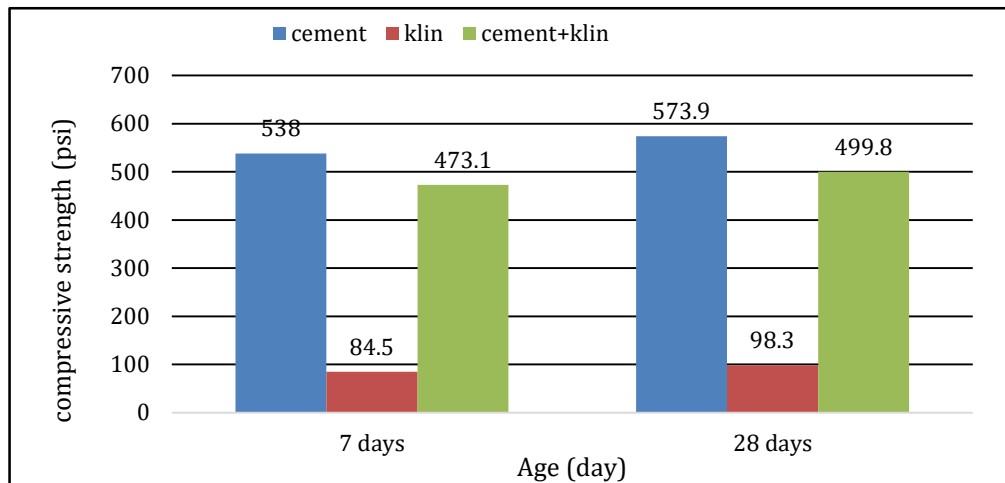


Figure 5: Results of testing the compressive strength of type C.

4.2 Thickness Design of Pavement Layers Using the AASHTO Method

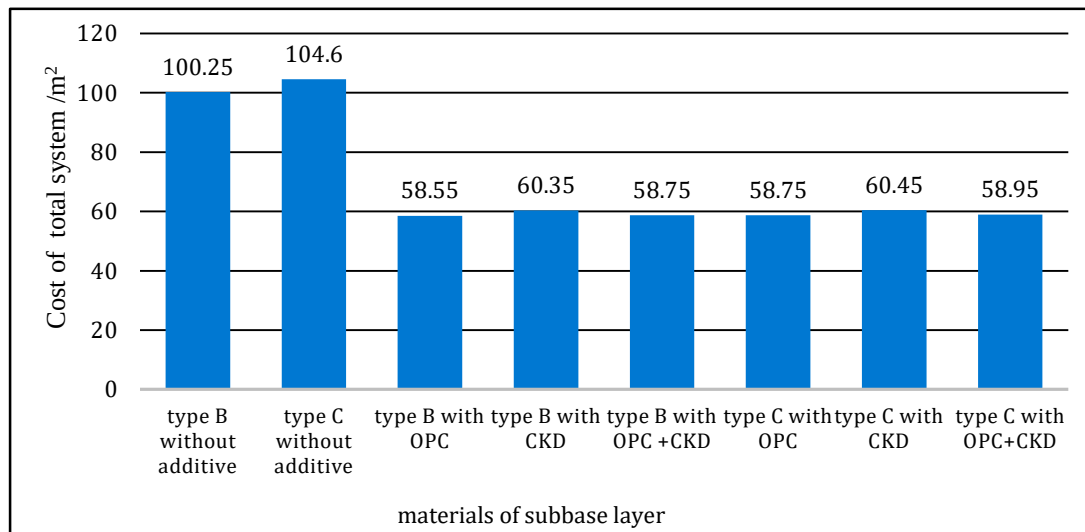
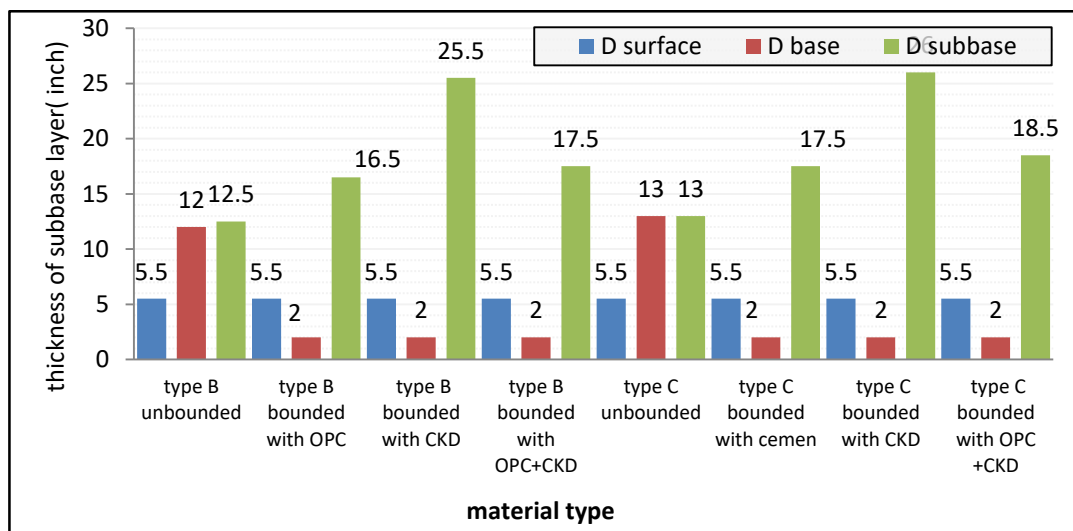
The AASHTO method for highway pavement design [16] was adopted in this study for the design of flexible pavement. Numerous key parameters were selected to reflect a typical local arterial pavement. These include an expected traffic load of 5,000,000 18-kip ESALs, a reliability level of 95%, and an overall standard deviation of 0.35. The subgrade

resilient modulus (M_r) was assumed to be 5000 psi. The Marshall Stability values for the surface and base courses were taken as 1800 lb. and 1500 lb., respectively. The initial and terminal Present Serviceability Index (PSI) values were set at 4.2 and 2.5. Additional design parameters related to the subbase characteristics were determined based on its mechanical properties. The California Bearing Ratio (CBR) was used to evaluate the performance of unbound subbase layers, while the 7-day compressive strength was used to represent the behaviour of the cement-modified subbase. The AASHTO design monograph was employed to determine the mechanical properties of the modified subbase layer and to calculate the required thicknesses of each pavement layer based on the input parameters.

The results presented in Table 9 and Figures 6 and 7 clearly demonstrate that chemical stabilization significantly decreases the required thicknesses of the pavement layers, particularly the base and subbase layers. In all treated scenarios, the base layer thickness was markedly reduced to 2 cm, in contrast to 12–13 cm in the untreated cases. To compensate for this reduction, the subbase thickness (D_i subbase) was increased in the treated samples. For Subbase B, subbase thickness increased from 12.5 cm (untreated) to a range of 16.5–25.5 cm, depending on the type of stabilizer used. While subbase C, it increased from 13 cm to 17.5–26 cm under treatment conditions. These results reflect that a chemically stabilized subbase with increased thickness can structurally replace part of the traditional untreated base layer, while maintaining or improving overall performance. In terms of cost, the untreated cases were used as the baseline (100%). The cement alone resulted in the greatest cost reduction, with 58% for Subbase type B and 59% for Subbase type C. CKD, while requiring a slightly thicker subbase, still achieved a cost ratio of 60%, confirming its potential as a low-cost and sustainable stabilizing agent. The combination of cement and CKD showed consistent and balanced performance in both subbase types, with a cost ratio of 59%. These findings show that chemical stabilization, particularly with CKD or cement-CKD blends, is an effective strategy for reducing pavement layer thickness and overall construction cost.

Table 9: Thickness of layers of pavement with subbase treatment and untreated.

Subbase layer materials	D surface	D base	Di subbase	Cost ratio*
Subbase B	5.5	12	12.5	100%
OPC	5.5	2	16.5	58%
CKD	5.5	2	25.5	60%
OPC+CKD	5.5	2	17.5	59%
Subbase C	5.5	13	13	100%
OPC	5.5	2	17.5	59%
CKD	5.5	2	26	60%
OPC+CKD	5.5	2	18.5	59%

**Figure 6: Relationship between the material of the subbase layer and the thickness of the total system.****Figure 7: Relationship between the material of the subbase layer and the Cost of the total system.**

5. Conclusion

Cement Kiln Dust (CKD) demonstrates its effectiveness as a valuable stabilizing material for improving the mechanical properties of pavement layers. Utilizing CKD in this manner offers a sustainable alternative to landfilling, contributing to both economic and environmental benefits. Also Incorporating Ordinary Portland Cement (OPC) into subbase materials can significantly reduce the overall cost of a typical main highway pavement by approximately 58% for type B subbase and 59% for type C subbase. Cement Kiln Dust (CKD) as a stabilizing agent in subbase materials can achieve a cost reduction of about 60% for pavements constructed with either type B or type C subbase and the combined use of Cement Kiln Dust (CKD) and Ordinary Portland Cement (OPC) in subbase materials can lead to a reduction of approximately 59% in the total cost of a typical main highway pavement utilizing either type B or type C subbase.

Declaration of generative AI and AI-assisted technologies in the writing process

-None

Disclosures

The authors have no conflicts of interest to declare in relation to this manuscript.

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التثبيت الكيميائي لطبقة السبيس المستدام باستخدام الاسمنت البورتلاندي و غبار فرن الاسمنت

الخلاصة: في الآونة الأخيرة أصبح تثبيت التربة يشغل اهتماما كبيرا للتغلب على العوائق المصاحبة لاستخدام الترب الضعيفة وقد تركزت هذه الجهود على تحسين خصائص التربة وتحقيق الفوائد الاقتصادية وتقليل التأثير السلبي على البيئة , تهدف هذه الدراسة الى تقييم كفاءة استخدام مواد المخلفات الصناعية لتحسين خصائص الطبقة تحت السطحية من خلال التثبيت الكيميائي مع الاخذ بنظر الاعتبار تقليل كلفة الانشاء وتطوير الأداء وتضمنت المنهجية استخدام فرن غبار الاسمنت (CKD) والاسمنت البورتلاندي الاعتيادي (OPC) كمثبتات كيميائية لنوعين من مادة السبيس (B) و (C) وكانت نسب المواد المثبتة المستخدمة هي (7%) من الوزن الجاف للسبيس ولكل خلطة من خلطات التثبيت حيث استخدمت ثلاثة خلطات تكونت الأولى من نسبة (100%) من (OPC) والثانية من نسبة (100%) من (CKD) والثالثة هي خليط من نسبة (50%) من (OPC) و (50%) من (CKD) وقد أجريت الفحوصات المختبرية التي تضمنت التحليل المنخلي وحدود اتربرك ونسبة التحمل الكاليفورني ومقاومة الانضغاط اللامقيد للحصول على خصائص المادة المثبتة وقد أظهرت النتائج ان مزيج ال (OPC) و (CKD) بنسب متساوية أدى الى تغيير في أداء المادة تحت السطحية وتحسين خواصها واصبح بالامكان تقليل سمك الطبقة تحت السطحية مما يؤدي الى تقليل الكلفة الاجمالية للانشاء .

الكلمات المفتاحية : فحص نسبة التحمل الكاليفورني, فحص الانضغاط غير المقيد للتربة و مثبتات التربة .