Improvement of unbound granular pavement layers and subgrade with cement dust in Egypt

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Abstract

The main goal of this study is to assess the technical viability of using cement dust as part of the fines percentage in the unbound granular base/subbase pavement layers' and subgrade soil as a viable sustainable solution. This study investigates the effect of adding cement dust to five types of pavement road materials which are collected from different ongoing roadway construction projects (1) Reclaimed Asphalt Pavement (RAP), (2) crushed stone base aggregates, (3) blend of crushed stone base aggregates with RAP, (4) crushed stone subbase aggregates, and (5) sandy subgrade soil. The resilient modulus (M_r) is selected as the main characteristic for evaluating the investigated materials' stiffness. The regression parameters (k_1 , k_2 , and k_3) of the universal M_r prediction model are found by fitting the experimental results of M_r testing for two replicates per each material type. The results show that using 3-5% of cement dust improves the estimated M_r of the investigated base/subbase materials and subgrades at the anticipated field stresses by 8-21%. As a result the structural layer coefficients are enhanced by 11-17%. KENLAYER nonlinear damage analysis confirms that using 3-5% of cement dust improves the predicted rutting life by up to 12% and the fatigue life up to 27%. Based on a typical pavement structure, enhancing pavement base/subbase layers and subgrade soils with 3-5% of cement dust reduces asphalt layer thickness from 11.25 to 12.50% and increases base/subbase layer thickness from 8.75 to 12.50% to maintain the same predicted rutting and fatigue lives of the typical structure. This positively affects the total construction cost in addition to the ecological benefits.

Keywords: Cement dust; Sustainability; Resilient modulus; Reclaimed asphalt pavement; Unbound granular base/subbase layers; Subgrade

1. Introduction

Due to global economic catastrophe and shortage in funding resources, it became necessary to construct cost effective pavement structures which can resist the increasing traffic volume/loading and ecological conditions. Most of Egyptian roadways are classified as traditional flexible pavement systems, which are composed of asphalt concrete layers (wearing surface and binder course layers) over unbound granular base and/or subbase layers, lying on top of a well-compacted subgrade soil [1]. Globally, the current trend in building new road networks supports using recycled, waste, or by-product materials as a sustainable

solution to save the usage of virgin materials and to get rid of the waste and undesirable materials. Using adequate materials with enhanced properties allows constructing durable and economic pavement structures with less thicknesses and high performance over their design life.

Many studies were conducted to enhance the strength of the unbound granular base/subbase layers and subgrades by adding additive materials such as Portland cement, asphalt, or even chemical additives at the expense of the negative impacts on the environment and construction cost. For example, lime treatment was used for enhancing the bearing capacity of subgrade soils in rail tracks and pavement layers as well as protecting side slopes and treating structure layers under shallow foundations [2]. Isola et al. [3] and Bessa et al. [4] concluded that stabilization practices increased the resilient modulus of unbound granular materials (UGMs), compared with their virgin state to the point that the overall thickness of pavement can be reduced resulting in further reduction of initial construction cost. In addition, Adam et al. [5] reported that adding lime to the subgrade decreased the required thickness of the pavement structure by about 50-60%. Moreover, adding lime significantly reduces the swelling potential (SP),

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liquid limit (LL), plasticity index (PI), and maximum dry density (MDD) of the subgrade soil, and increases the optimum moisture content (OMC), shrinkage limit (SL), and material strength [6-8].

Nowadays, tons of deteriorated asphalt concrete layers, which reached unacceptable level of service, have been scraped to be replaced with new asphalt layers. Annually in Egypt, continuous pavement milling or scraping processes approximately produce 4 million tons of RAP [9]. As a result of generating annual massive RAP amounts globally, highway experts exert many research efforts to investigate reusing this material in the pavement construction. Finally, RAP material was used either as a granular base/subbase material or mixed with virgin aggregate with specific ratio to reduce the amount of virgin aggregates [10]. Using RAP as a base/subbase material can preserve the natural environment, minimize the amounts of waste disposal, and reduce energy and transportation costs in delivering construction materials [11-13].

2. Cement dust as a filler

In Egypt, there is a big boom in the construction industry. Thus, there is a tremendous growth of cement manufacture in the country. One cement plant daily produces approximately 400 tons of cement dust which is available for free till now [14]. Hence, Egypt deems cement dust as a favorable choice among waste materials to be used in pavement construction instead of being buried in landfills.

Many studies concluded that adding cement dust on local expensive soil was able to enhance their properties such as decreasing the consistency limits, increasing the MDD corresponding to lower OMC, and decreasing the swelling pressure and swelling potential [7,8,15]. Moreover, Parsons et al. [15] reported that using Cement Kiln Dust (CKD) improved the strength of soil with 100-200% and enhanced the soil durability. Mosa et al. [16] used the California Bearing Ratio (CBR) test to evaluate stabilizing the poor subgrade soils using CKD. They concluded that adding 20% of CKD with 14-days curing can increase the CBR value from 3.4% to 48%. Accordingly, the pavement thicknesses were reduced and the construction cost was lowered consequently by \$25.875 per square meter [16]. Ekpo et al. [17] investigated two lateritic soils response to cement kiln dust-periwinkle shell ash (CKD-PSA) blends as road sub-base materials. Microstructural analysis using Scanning Electron Microscope (SEM) confirmed a formation of new compounds due to using CKD-PSA blends which improved MDD, CBR, and Unconfined Compressive Strength (UCS) for both investigated soils.

Moreover, other researchers focused on improving asphalt mixture performance with cement dust as well [18-20]. Abdul Wahhab [18] investigated the effect of different additives on the fatigue behavior of asphalt concrete mixes in the Gulf Cooperation Council countries (GCC). At strain level less than 250-300 mst, cement dust with Basalt aggregate gave the best fatigue behavior. Liao et al. [19] studied the mechanical properties of filler-binder mastics and found that filler interparticle interaction between cement dust filler particle and asphalt improved engineering properties of asphalt mixtures. The higher binder shear modulus and strengthening effect of the cement dust filler-asphalt mastics than those of traditional filler-asphalt mastics within a linear viscoelastic domain. Likitlersuang and Chompoorat [20] researched the impact of filler materials on volumetric and mechanical performances of asphalt concrete. Their results confirmed a significant improvement in the strength, stiffness and

moisture susceptibility performances of the asphalt concrete mixtures containing cement dust filler.

Nelson et al. [21] summarized recycling cement dust with road pavement layers: subgrades, bases, and asphalt mixtures. For subgrades, adding 5-10% cement dust enhanced soil properties and made the soil more homogeneous and better traffic load-resistant [21]. For base layers, adding cement dust as a filler minimized the voids between aggregate particles due to its softness which provided more protection against the negative impact of underground water and acidic sewage water. In addition, it increased base material density which improved the overall properties of aggregate binding [21]. For asphalt mixtures, as long as mixture density increases by adding very fine and soft materials like cement dust, asphalt mixture efficiency was enhanced, its creep behavior under loading conditions was decreased, and binding process between aggregate particles and asphalt binder was improved [21].

In summary, based on many published research reports and scientific periodicals, unlimited environmental and socioeconomic benefits can be gained by using cement dust as part of pavement construction process replacing its overstock as a by-product waste material. Utilizing cement dust can reduce air pollution problems and greenhouse gas emissions, improve pavement layer characteristics with very low cost, and reduce pavement layer thicknesses at the same required performance [22-25].

3. Material strength characterization

The resilient modulus (M_r), is determined by dividing the cyclic deviatoric stress (σ_d) by the recoverable axial strain (ϵ_r). It is a substantial material property that is used to characterize and assess the stiffness of pavement materials, in broad, and UGMs as well as subgrade soils in particular. The experimental test results showed that load duration/frequency and applied stress levels may also have an effect on the resilient modulus values for granular materials which are mixed with various percentages of RAP aggregate, as a result of presence of asphalt binder in the RAP mixtures [26]. As long as the location of pavement materials within the pavement structure, material strength characteristics, traffic loads, seasonal moisture contents, and climatic conditions affect the stress state levels on the pavement materials in the field. Thus, many researchers exerted their best efforts to develop predictive models based on the aforementioned factors [27-29]. These M_r -predictive models are substantial for the structural design of pavement structures. El-Ashwah et al. [28] summarized and reviewed the stress state-based M_r -predictive models from the literature. Eqs. (1) and (2) show the most used models: the k - θ model and universal model; respectively [28,30].

$$M_r = K_1 \theta^{K_2} \quad (1)$$

$$M_r = K_1 P_a \left(\frac{\theta}{P_a} \right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{K_3} \quad (2)$$

where, M_r is the resilient modulus, θ is the first stress invariant [$\theta = \sigma_n + 3\sigma_3$], σ_n is the cyclic deviatoric stress, σ_3 is the confining pressure, τ_{oct} is the octahedral shear stress [$\tau_{oct} = \frac{\sqrt{2}}{3} \sigma_D$], and P_a is the atmospheric pressure (101.325 kPa).

4. Objectives

In this research, cement dust as a by-product/waste material is

used as a part of the fines percentage within the unbound granular base/subbase pavement layers and subgrade soils. This study investigates the effect of adding cement dust to five types of pavement materials: RAP, crushed stone base aggregates, blend of 40% crushed stone aggregates with 60% RAP, crushed stone subbase aggregates, and sandy subgrade soil which are collected from different on-going roadway construction projects. The main goal of this study is to evaluate the effect of adding cement dust on the structural layer coefficient, performance enhancement, and thickness reduction of pavement layers using linear damage analysis of pavement layers.

5. Investigated materials

Cement dust was added as a filler to five assorted types of pavement materials that are usually used for constructing pavement layers of major roads in Egypt. The investigated pavement materials are classified as (1) RAP, (2) crushed stone base aggregates, (3) blend of 40% crushed stone aggregates with 60% RAP, (4) crushed stone subbase aggregates, and (5) sandy subgrade soil. Cement dust was added to each of the selected materials with the following percentages 5%, 5%, 3%, 4%, and 4%; respectively, replacing the same amount of fines (passing #200) percentages. These materials were provided to the Highway and Airport Engineering Lab (H&AEL) at Mansoura University by the Arab Contractors Company from various quarries and construction sites in Egypt (i.e., Cairo-Suez Roadway, Administrative Capital, Garga Roadway, and El-Katamia Group project).

6. Experimental testing scheme

The laboratory testing matrix included the routine tests to characterize the principal engineering characteristics of the selected unbound granular base/subbase materials and subgrades as well as advanced testing for evaluating their performance. The principal characteristics are the particle size distribution and modified Proctor compaction which were conducted at the central laboratories of the Arab Contractors Company. While, the main advanced testing for characterizing material performance, which is the Repeated Load Triaxial Test (RLTT) to determine M_r , was conducted at H&AEL.

6.1. Routine testing

Sieve analysis and modified Proctor tests were conducted to characterize the basic properties of the investigated materials. Fig. 1 and Table 1 present the grain size distribution according to (AASHTO T 27-20) [31] and modified proctor data according to

(AASHTO T 180-20) [32] for the selected materials, respectively. As observed from modified Proctor parameters, using cement dust as a filler material leads to a reduction in OMC and pronounced improvement in the MDD of each of the investigated materials.

6.2. Advanced testing

The RLTT mimics the behavior of UGMs and subgrade soils under repeated traffic loading in the field. In this study, RLTTs were performed to determine the M_r of the investigated UGMs and subgrades. The resilient modulus testing was conducted in accordance with AASHTO T307-17 [33] using the Universal Testing Machine (UTM-25) at H&AEL.

Each specimen of the UGMs was prepared in a split mould of 150-mm diameter and 300-mm height as the Nominal Maximum Aggregate Size (NMAS) of the UGMs was 19 mm. On the other hand, the subgrade specimens were prepared in a split mould of 100-mm diameter and 200-mm height as the NMAS of the subgrade soil was only 2 mm. RLTTs was performed on at least two replicate specimens for each material type, which were compacted at the OMC in accordance with AASHTO T 180-20 [32].

7. Analysis of testing results

In order to judge the performance of the investigated M_r -predictive models, different goodness-of-fit statistics were used. The precision (degree of scatter) is assessed by the coefficient of determination (R^2), the standard error ratio which is the ratio of standard error of estimate over standard deviation of measured values (Se/Sy), and root mean square error (RMSE). The R^2 ranges between zero (no correlation) and one (perfect correlation). The standard error ratio denotes the relative accuracy, the smaller the Se/Sy the better the accuracy. Moreover, the RMSE is used to

Fig. 1. Particle size distributions of the selected materials.

Table 1

Modified proctor values for the selected before and after adding cement dust percentages.

Material property	Material ID Source Spec.	B-V Administrative capital project	B-V CD Garga roadway	SB-V Cairo-Suez roadway	SB-V CD El-Katamia group project	SG N.A	SG CD N.A	B-R N.A	B-R CD N.A	B-RA N.A	B-RA CD N.A
MDD, g/cm ³	AASHTO	2.23	2.36	2.00	2.18	2.12	2.37	1.95	2.19	2.00	2.16
OMC, %	T 180-20	6.25	6.00	8.25	7.80	7.50	7.00	5.25	5.00	6.50	6.00

Where, (B-V)= crushed stone base aggregate; (B-V_CD)= crushed stone base aggregate with cement dust; (SB-V)= crushed stone subbase aggregate; (SB-V_CD)= crushed stone subbase aggregate with cement dust; (SG)= sandy subgrade soil; (SG_CD)= sandy subgrade soil with cement dust; (B-R)= RAP; (B-R_CD)= RAP with cement dust; (B-RA)= blend of 40% crushed stone aggregates with 60% RAP of the same main provided sources; (B-RA_CD)= blend of 40% crushed stone aggregates with 60% RAP of the same main provided sources with cement dust.

compare the errors of different models for a variable, as it is a scale-dependent [34]. The goodness-of-fit statistical parameters are classified as excellent, if the R^2 is more than 0.9 and Se/Sy is less than 0.35. However, the goodness-of-fit statistics is considered good when the R^2 ranges between 0.70 and 0.89, and Se/Sy ranges between 0.36 and 0.55 [35].

7.1. Mr modeling

The measured M_r values at different stress state levels (combinations of bulk and confining stresses) were used to determine the regression coefficients of the K- θ and universal which were models previously presented in Eqs. (1) and (2).

Table 2
Regression coefficients of the M_r -predictive models for the investigated UGMs and subgrades w/o cement dust.

Models				Investigated UGMs and subgrades w/o cement dust								
				B-V	B-V CD	SB-V	SB-V CE	SG	SG CD	B-R	B-R CD`	B-RA
K- θ Model (Eq. (1))	Goodness of fit Parameters Coefficient	K ₁	7413.71	5752.81	3979.16	4569.08	6587.94	10120.63	16304.32	18357.02	16961.14	21962.28
		K ₂	0.3444	0.4813	0.5180	0.5073	0.3188	0.1838	0.2138	0.2249	0.1345	0.1134
		Se/Sy	0.6018	0.42	0.0963	0.092	0.767	0.833	0.699	0.675	0.9694	0.922
		R ²	0.638	0.820	0.991	0.990	0.411	0.307	0.511	0.545	0.060	0.140
		RMSE	50.28	62.92	12.56	14.14	42.59	34.49	50.43	49.99	68.96	55.03
Universal Model (Eq. (2))	Goodness of fit Parameters Coefficient	K ₁	1072.03	1325.51	1089.44	1215.53	6587.94	918.94	1818.69	2109.33	1340.56	1780.75
		K ₂	0.110	0.271	0.518	0.507	0.319	0.073	0.039	0.047	-0.178	-0.080
		K ₃	1.144	0.769	-0.0003	-0.0003	1.739	1.389	0.685	0.693	1.449	0.893
		Se/Sy	0.249	0.244	0.10	0.10	0.144	0.155	0.492	0.458	0.556	0.671
		R ²	0.938	0.94	0.99	0.99	0.979	0.976	0.758	0.79	0.69	0.55
		RMSE	21.32	58.00	12.56	14.14	7.78	5.93	37.81	36.21	37.31	38.05

The regression coefficients of these models were determined by nonlinear numerical optimization via the minimization of the sum of squared errors using the solver function in Microsoft Excel®. The resulted values of the material-based regression coefficients are demonstrated in Table 2. In addition, the aforementioned goodness-of-fit statistics for the two stress-dependent models, which were used in this study, are also presented in Table 2. Fig. 2 summarizes a comparison example between the laboratory measured versus predicted data along with the equality line using the both models for one material type (B-V) with and without cement dust. Based on the goodness-of-fit statistics, the 2004 NCHRP Universal model was more capable of well predicting M_r values compared to the older K- θ model.

Fig. 2. Laboratory measured versus predicted M_r values for (B-V) and (B-V_CD) specimens by using both universal and K- Θ models. (a) material (B-V) universal model, (b) material (B-V) K- Θ model, (c) material (B-V_CD) universal model, and (d) material (B-V_CD) K- Θ model.

7.2. Effect of dust cement on pavement design

In Egypt, the AASHTO 1993 design method is still adopted as the structural design method for flexible pavements. It is a top-down design method which means that each layer thickness is determined based on the strength of the underneath layer as determined by the Structure Number (SN). The SN is a function of the structural layer coefficient (a_i) of each pavement layer, drainage layer coefficient, and layer thickness [36]. The a_i can be described as an empirical coefficient which is used to represent the comparative contribution of each layer to the pavement's strength. Recently, empirical equations were predicted to estimate the unbound material layers structural coefficients as a function of their modulus. Thus, the a_i increases with enhancing the modulus of the layer [36].

7.3. Effect on estimated Mr values

As mentioned earlier, the modulus of unbound materials depends on the actual field stresses. Thus, the predicted anticipated field stress range, which is reported by Ji et al. [37] is used to estimate the design values of Mr. Ji et al. [37] performed a mini study to estimate the anticipated field stresses in the UGMs and subgrade soils based on a linear analysis using the KENLAYER software. They denoted that the anticipated field deviatoric stress (σ_d) for the UGMs is in the range of 13 to 16 psi and 6 to 7 psi for subgrades; while the anticipated confining pressure (σ_3) varies from 4 to 8 kPa for the UGMs and 1 to 2 psi for subgrades [37]. Thus, the Mr values of the investigated UGMs and subgrades were estimated at the minimum, average, and maximum values of the anticipated field stresses using the universal model (Eq. (2)) and the predicted regression parameters for each investigated material. Fig. 3 shows the predicted values and the standard deviation for each of the investigated materials at the average anticipated field state of stresses.

It should be noted that using around 3–5% of cement dust can improve the estimated Mr of the UGMs at the anticipated field stresses by 10–21%. However, using 4% of cement dust in the selected subgrade soil slightly improved the Mr values at the anticipated field stresses by 8%. It is expected that these enhancements in the modulus values will lead to reduction in the required thicknesses of the pavement layers.

7.4. Effect on structural layer coefficient (a_i)

The a_2 values for the granular base materials were estimated for both original and enhanced material with cement dust by using Eq.

Fig. 3. Estimated Mr values at the anticipated field stress levels for the investigated UGMs and subgrade soil using 2004 NCHRP universal model.

(3) [36]. The estimated Mr values at anticipated field stresses were used to calculate the values of the structural layer coefficients for investigated base materials. Fig. 4 shows the structural layer coefficient values for each of the investigated unbound granular base materials with and without cement dust.

$$a_2 = 0.249(\log_{10}(E_{base})) - 0.977 \quad (3)$$

Based on Fig. 4 results, by using 3 to 5% cement dust the unbound granular base material, structural coefficient values were increased significantly around 11 to 17%.

7.5. Effect on allowable number of load repetitions for asphalt concrete fatigue (N_f) and subgrade rutting (N_d)

In this study, the KENLAYER, which is a Multi-Layer Elastic Analysis (MLEA) software designed to analyze flexible pavements, was used to conduct a nonlinear damage analysis [38]. It provides a structural analysis solution for an elastic multilayer system under a circular loaded area. The resulting pavement response parameters can be used to predict pavement life.

The properties of the selected base materials were used to predict the allowable number of load repetitions to Asphalt Concrete (AC) fatigue failure (N_f) and subgrade rutting (N_d) failure by using KENLAYER software through a nonlinear damage analysis. Table 3 presents the properties of the flexible pavement section as well as the main characteristics of the investigated base layer materials. A wheel load of 40 kN (9000 lbs) with a tire pressure of 827 kPa (120 psi) and a spacing between the dual tires of 33 cm (13 in.) were applied to the studied pavement sections as shown in Fig. 5. The K-θ model (Eq. (1)) was implemented in the KENLAYER software to describe the nonlinear behavior of unbound granular materials.

The damage analysis was determined at the critical locations, such as for estimating N_f the horizontal tensile strain at the bottom of the asphalt layer was determined and the vertical compressive strain on the top of the subgrade layer was also determined for estimating N_d . Fig. 6 shows the estimated (N_f and N_d) for pavement sections with and without cement dust.

It is noted that the allowable number of load repetitions for AC fatigue cracking (N_f) increased considerably by around 19 to 27% when using 3 to 5% cement dust, while the allowable Number of load repetitions for subgrade rutting (N_d) increased by 3 to 12%. This slight increase in the N_d is due to that the AASHTO 1993 is considered as an over design method. Therefore, any change in the modulus of unbound materials does not reflect great impact on the N_d value.

Fig. 4. Estimated structural layer coefficient values for the selected unbound granular base materials.

7.6. Effect on thicknesses of AC and base layers

As expected, using cement dust as a filler in unbound granular layers decreases the thickness of asphalt pavement layers due to the increased stiffness of the unbound granular materials. The KENLAYER software was used to estimate the equivalent thicknesses of pavement structural layers by maintaining the same damage values as was predicted in the control pavement structure. The characteristics of the typical flexible pavement section as well as the main characteristics of the base layers are the same as in Table 3. In addition, the loading properties are described in Fig. 5. Table 4 presents the predicted thicknesses of asphalt and granular base layers based on using enhanced base layers with cement dust, compared with the typical (control) pavement structure based on base layers without cement dust.

7.7. Using RAP material as a base course

Furthermore, the performance of using RAP material as a base/subbase layer in pavement structure or blending with virgin aggregate was assessed. The Mr test was conducted on three types of base materials [virgin base aggregate (B-V), RAP (B-R), and blend of 40% virgin aggregate materials with 60% RAP (B-RA)] to emphasize the impact of using RAP material on pavement performance besides its ecological benefits. As presented earlier in Fig. 3, the difference in the estimated Mr values at the mean anticipated field stresses of the investigated base materials was shown.

Although the percent of fines in RAP material (B-R) was lower than the virgin base aggregate (B-V), the performance of RAP material was the most significant compared to other materials. The estimated Mr values increased by blending RAP material with virgin aggregate (B-RA) compared to the value of virgin base aggregate (B-V). In addition, the thicknesses of pavement structural layers were estimated using the AASHTO 1993 design method to investigate the economic effect of using RAP as a material source for base layers rather than virgin materials. Fig. 7 shows the properties of pavement section used in estimating thicknesses of pavement layers by AASHTO 1993 design method. Table 5 presents the values of estimated thicknesses of AC and base layers.

Table 5 results exhibit the benefits of using RAP materials as a base layer in pavement sections. As expected, it reduced the thickness of AC layer and increased the thickness of base layers which will positively impact the economic and ecological sides at the same pavement performance level.

Table 3

Input characteristics of the pavement cross section for the nonlinear damage analysis using KENLAYER.

Layer type	Thickness, cm (in.)	Modulus, MPa (Psi)	Poisson's ratio*	Density, t/m ³	Internal friction angle (ϕ) *
AC layer	10 (4)	2758.0 (400,000)	0.35	2.40	---
Base Layer	B-V	$K_1 = 7413.71$	$K_2 = 0.344$	2.23	52.0
	B-R	$K_1 = 16304.32$	$K_2 = 0.213$	1.95	33.0
	B-RA	$K_1 = 16961.14$	$K_2 = 0.134$	2.00	43.0
	B-V_CD	$K_1 = 5752.81$	$K_2 = 0.481$	2.36	55.0
	B-R_CD	$K_1 = 18357.02$	$K_2 = 0.225$	2.19	35.0
	B-RA_CD	$K_1 = 21962.28$	$K_2 = 0.113$	2.16	45.0
Subgrade	---	110.3 (16,000)	0.40	2.12	---

* Estimated values.

Fig. 5 Pavement cross-section details for the nonlinear damage analysis.

Fig. 6 Allowable Number of Load Repetitions for (a) AC Fatigue Cracking (N_f) and (b) Subgrade Rutting (N_d).

Table 4
Thicknesses of AC and base layers.

Layer ID	$N_f \cdot 10^5$	$N_d \cdot 10^5$	AC thickness, cm (in)	Base thickness, cm (in)
B-V	2.741	4.786	10.0 (4.0)	20.0 (8.0)
B-V_CD	2.788	4.438	9.0 (3.5)	22.5 (8.8)
B-R	4.802	5.698	10.0 (4.0)	20.0 (8.0)
B-R_CD	4.68	5.682	9.0 (3.5)	22.0 (8.7)
B-RA	3.499	5.044	10.0 (4.0)	20.0 (8.0)
B-RA_CD	3.447	5.187	9.0 (3.5)	23.0 (9.0)

Table 5
Thicknesses of AC and base layers using AASHTO 1993 design method.

Layer ID	Resilient Modulus (Mr), MPa (Psi)	AC Thickness, cm (in)	Base Layer Properties	
			Structural layer coefficient (a_2)	Thickness, cm (in)
B-V	183.4 (26600)	16 (6.05)	0.125	8 (3.13)*
B-R	246.8 (35797)	14 (5.45)	0.160	12 (4.56)
B-RA	205.1 (29746)	15 (5.81)	0.135	11 (4.30)

* Use minimum required thickness for base layer (10 cm = 4 in.).

Fig. 7. Pavement cross-section properties for the AASHTO 1993 design method.

Table 4 results show that enhancing pavement base/subbases with 3–5% of cement dust reduces asphalt layer thickness by 11.25 to 12.50% and increases base/subbase layer thickness by 8.75 to 12.50% at the same predicted rutting and fatigue lives of the control structure which positively affects the total construction cost.

8. Conclusions

Generally, this research study magnifies the structural, economic, and ecological aspects of using cement dust as a filler material in base/subbase materials and subgrade soils. First, based on the modified proctor test, adding cement dust to the unbound materials leads to reducing the OMC and enhancing the MDD. As a result of adding cement dust by 3–5%, the modulus of the investigated materials with cement dust is higher than the original materials by about 8 to 21%. The structural layer coefficient of the base materials (a_2) is also enhanced by adding cement dust which leads to reduce the required base thickness.

Moreover, the nonlinear damage analysis using the multilayer elastic approach by KENLAYER software proved that using cement dust as a filler material increases the allowable number of load repetitions for AC fatigue cracking by 19 to 27% and for subgrade rutting by almost 3 to 12%.

As proved, adding cement dust by 3–5%, the construction cost of pavement structure is reduced compared with the traditional layer materials. In addition, by maintaining the same allowable number of load repetitions for AC fatigue and subgrade rutting for a typical pavement structure, the thickness of asphalt concrete layer is reduced by around 11.25 to 12.50% on the expense of increased base layer thickness of 8.75 to 12.50% which is still more economic in addition to the environmental benefits.

Finally, using RAP materials as a base layer shows a significant ameliorating in pavement performance compared with traditional base materials.

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Reference

- [1] F. Bayomy, K. Safwan, Dynamic Characterization of Egyptian Hot Mix Asphalt Concrete for Highway Pavement Design and Evaluation. NSF Project. National Institute for Advanced Transportation Technology, Idaho, USA, 2010.
- [2] N. Consoli, F. Zortéa, M. Souza, L. Festugato, Studies on the Dosage of Fiber-Reinforced Cemented Soils, J. Mater. Civ.

- Eng. 23 (12) (2011) 1624-1632.
- [3] M. Isola, G. Betti, A. Marradi, G. Tebaldi, Evaluation of Cement Treated Mixtures with High Percentage of Reclaimed Asphalt Pavement, *Constr. Build. Mater.* 48 (2013) 238-247.
  - [4] I. Bessa, A. Aranha, K. Vasconcelos, A. Silva, L. Bernucci, Laboratory and Field Evaluation of Recycled Unbound Layers with Cement for Use in Asphalt Pavement Rehabilitation, *Mater. Struct./Materiaux et Constructions* 49 (7) (2016) 2669-2680.
  - [5] A. Adam, I. Ibrahim, A. Alhardllo, A. Hadi, M. Ibrahim, Effect of Hydrated Lime on Behavior of Expansive Soil as Subgrade of Flexible Pavement Structural System, Second International Conference on Sustainable Construction Materials: Design, Performance, Application, Wuhan, China, 2012.
  - [6] J.B. Croft, The Influence of Soil Mineralogical Composition on Cement Stabilization, *Geotechnique* 17 (2) (1967) 119-135.
  - [7] R. Alzubaidi, K. AlRawi, A. AlFalahi, Using Cement Dust to Reduce Swelling of Expansive Soil, *Geomech. Eng.* 5 (6) (2013) 565-574.
  - [8] A. Almurshedi, J. Thajeel, H. Dekhn, Swelling Control of Expansive Soils Using Cement Dust, *IOP Conference Series: Mater. Sci. Eng.* 584 (1) (2019) <https://doi.org/10.1088/1757-899X/584/1/012021>.
  - [9] A. Behiry, A. Elmoher, Characterization of Recycled Asphalt Pavement (RAP) for Use in Flexible Pavement, *Amer. J. Eng. Appl. Sci.* 8 (2) (2015) 233-248.
  - [10] J. Thakur, J. Han, Recent Development of Recycled Asphalt Pavement (RAP) Bases Treated for Roadway Applications, *Transp. Infrast. Geotechnol.* 2 (2) (2015) 68-86.
  - [11] I. Carswell, J. Nicholls, R. Elliot, J. Harris, D. Strickland, Feasibility of Recycling Thin Surfacing Back into Thin Surfacing Systems. TRL Report: TRL645. Wokingham, UK, 2005.
  - [12] D. Yuan, S. Nazarian, L. Hoyos, A. Puppala, Cement Treated RAP Mixes for Roadway Bases. Report no. FHWA/TX-10/0-6084-1. Federal Highway administration, TX, USA, 2010.
  - [13] A. Copeland, Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice. Report no. FHWA-HR-11-021. Federal Highway administration, Office of Research, Development, Technology, VA, USA, 2011.
  - [14] B. Vanderborght, F. Koch, L. Grimmeissen, S. Wehner, P. Heersche, J. Degré, O. Square, Low-Carbon Roadmap for the Egyptian Cement Industry, Project Egypt: Technology and Policy Scoping for a Low-Carbon Egyptian Cement Industry, European Bank for Reconstruction and Development (EBRD), London, UK, 2016, pp. 1-35.
  - [15] R. Parsons, E. Kneebone, J. Milburn, Use of Cement Kiln Dust for Subgrade Stabilization. Report No. KS-04-3, Kansas Department of Transportation, KS, USA, 2004.
  - [16] A. Mosa, A. Taher, L. Al-Jaberi, Improvement of Poor Subgrade Soils Using Cement Kiln Dust, *Case Studies Constr. Mater.* 7 (2017) 138-143.
  - [17] D. Ekpo, A. Fajobi, A. Ayodele, Response of Two Lateritic Soils to Cement Kiln Dust-Periwinkle Shell Ash Blends as Road Subbase Materials, *Inter. J. Pavement Res. Technol.* (2020) <https://doi.org/10.1007/s42947-020-0219-5>.
  - [18] H. Al-Abdul Wahhab, Effect of Modifiers and Additives on Fatigue Behavior of Asphalt Concrete Mixes in the Gulf, *Inter. J. Pavement Res. Technol.* 5 (5) (2012) 326.
  - [19] M. Liao, G. Airey, J. Chen, Mechanical Properties of Filler-Asphalt Mastics, *Inter. J. Pavement Res. Technol.* 6 (5) (2013) 576-581.
  - [20] S. Likitlersuang, T. Chompoorat, Laboratory Investigation of the Performances of Cement and Fly Ash Modified Asphalt Concrete Mixtures, *Inter. J. Pavement Res. Technol.* 9 (5) (2016) 337-344.
  - [21] L. Nelson, J. Franklin, A. Joseph, Environmental Engineering: Environmental Health and Safety for Municipal Infrastructure, Land Use and Planning, Industry. 6th ed., John Wiley & Sons, Inc., Ontario, Canada, 2009, pp. 31-39.
  - [22] H. Van Oss, A. Padovani, Cement Manufacture and the Environment, Part 2: Environmental Challenges and Opportunities, *J. Industrial Ecology* 7 (1) (2002) 93-126.
  - [23] WBCSD, Guidelines for Emissions Monitoring and Reporting in the Cement Industry. World Business Council for Sustainable Development, Geneva, Switzerland, 2005.
  - [24] S. El-Haggar, Rural and Developing Country Solutions. Chapter 13 in Environmental Solutions. Ed. By Nelson Nemerow and Franklin Agardy, Elsevier Academic Press, Cambridge, MA, USA, 2005, pp. 313-400.
  - [25] K. Karstensen, Formation and Release of POPs in the Cement Industry. 2nd Ed., World Business Council for Sustainable Development, Geneva, Switzerland, 2006.
  - [26] E. Mousa, A. Azam, M. El-Shabrawy, S. El-Badawy, Laboratory Characterization of Reclaimed Asphalt Pavement for Road Construction in Egypt, *Can. J. Civ. Eng.* 44 (6) (2017) 417-425.
  - [27] F. Lekarp, U. Isacsson, A. Dawson, State of the Art I: Resilient Response of Unbound Aggregates, *J. Transp. Eng.* 126 (1) (2000) 66-75.
  - [28] A. El-Ashwah, A. Awed, S. El-Badawy, A. Gabr, A New Approach for Developing Resilient Modulus Master Surface to Characterize Granular Pavement Materials and Subgrade Soils, *Constr. Build. Mater.* 194 (2019) 372-385.
  - [29] A. El-Ashwah, E. Mousa, S. El-Badawy, M. Abo-Hashema, Advanced Characterization of Unbound Granular Materials for Pavement Structural Design in Egypt, *Inter. J. Pavement Eng.* (2020) <https://doi.org/10.1080/10298436.2020.1754416>.
  - [30] ARA, Inc., Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. NCHRP 1-37A Final Report, Champaign, IL, USA, 2004.
  - [31] American Association of State Highway and Transportation Officials, Sieve Analysis of Fine and Coarse Aggregates. AASHTO T 27-20. AASHTO, Washington DC, USA, 2020.
  - [32] American Association of State Highway and Transportation Officials, Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop. AASHTO T 180-20. AASHTO, Washington DC, USA, 2020.
  - [33] American Association of State Highway and Transportation Officials, Determining the Resilient Modulus of Soils and Aggregate Materials. AASHTO T 307-17. AASHTO, Washington DC, USA, 2017.
  - [34] R. Hyndman, A. Koehler, Another Look at Measures of Forecast Accuracy, *Inter. J. Forecast.* 22 (4) (2006) 679-688.
  - [35] T. Pellinen, Investigation of the Use of Dynamic Modulus as Indicator of Hot-Mix Asphalt Performance, (Ph.D. Dissertation), Department of Civil and Environmental

- Engineering, Arizona State University, Tempe, AZ, USA, 2001.
- [36] AASHTO (1993). AASHTO Guide for Design of Pavement Structure. American Association of State Highway and Transportation Officials, Washington, D.C.
- [37] R. Ji, N. Siddiki, T. Nantung, D. Kim, (2014). Evaluation of Resilient Modulus of Subgrade and Base Materials in Indiana and its Implementation in MEPDG. The Scientific World Journal, 2014.
- [38] Y. Huang, Pavement Analysis and Design. 2nd Ed., Prentice Hall, Upper Saddle River, 2004.